Flavour physics: the Kaon sector

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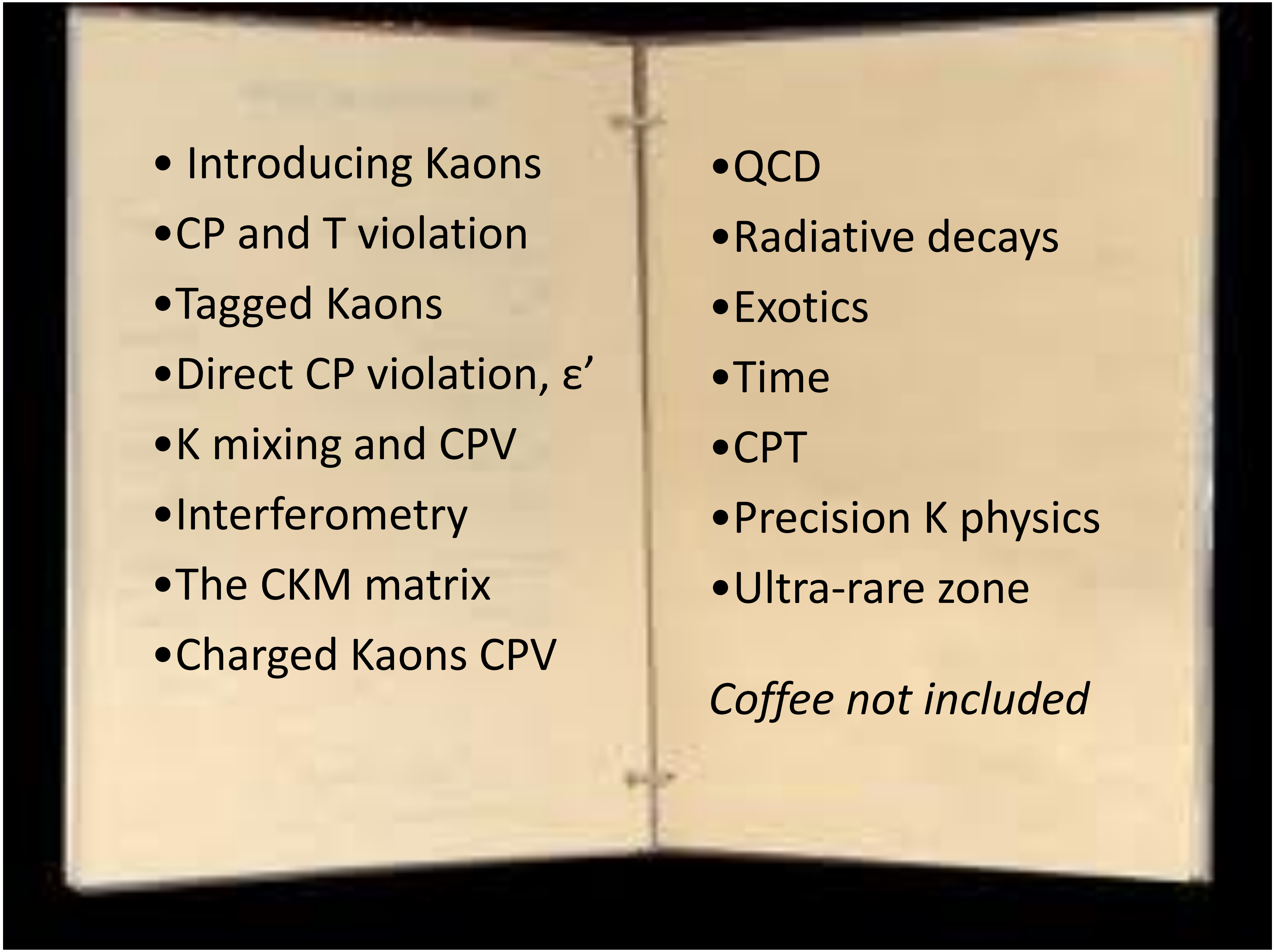
Niccolo' Cabeo school 2013



- Introducing Kaons
- CP and T violation
- Tagged Kaons
- Direct CP violation, ε'
- K mixing and CPV
- Interferometry
- The CKM matrix
- Charged Kaons CPV
- QCD
- Radiative decays
- Exotics
- Time
- CPT
- Precision K physics
- Ultra-rare zone

Coffee not included

Kaons: CV

- K discovered: first “non-earthly” matter (1944)
- Two neutral K mesons: birth of flavour physics (1955)
- Tau-theta puzzle: parity violation (1956)
- CP violation (1964)
- $K_L \rightarrow \mu^+\mu^-$ rate: prediction of charm quark (1970)
- Hypothesis of 3 quark generations (1974)
- Proof of time-reversal violation (1980s)
- Smallest BR ever measured (1997)
- Direct CP violation (1999): confirmation of CKM picture

Introducing Kaons

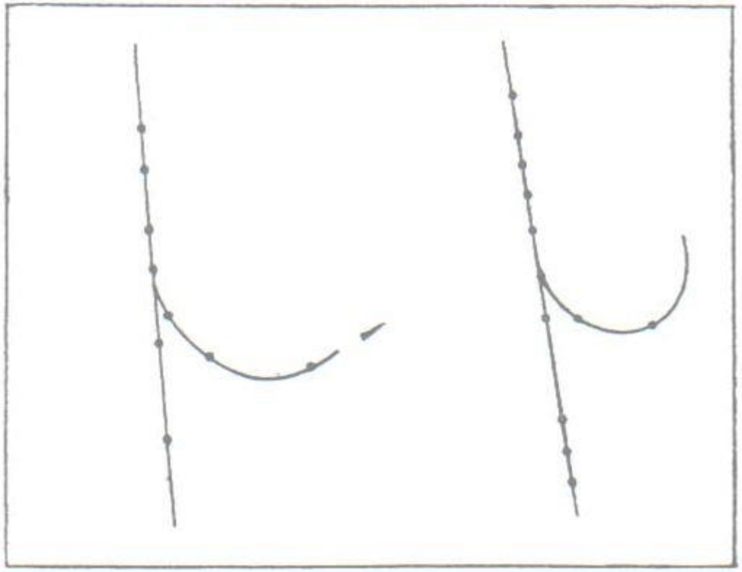
Kaons enter the scene (1)

Discovered in cosmic rays

L. Leprince-Ringuet, M. L'Heritier (1944):

Existence probable d'une particule de masse 990 m_0 *dans le rayonnement cosmique.*

Cloud chamber with B = 2500 G on French Alps.
Single image with positive particle ≈ 500 MeV/*c* producing a secondary ≈ 1 MeV/*c*.
Assuming elastic scattering on e^-, from scattering angle its mass is 506 ± 61 MeV/c^2 (K^+ mass = 493.68 MeV/c^2).
Incompatible with a pion, hardly with a proton.



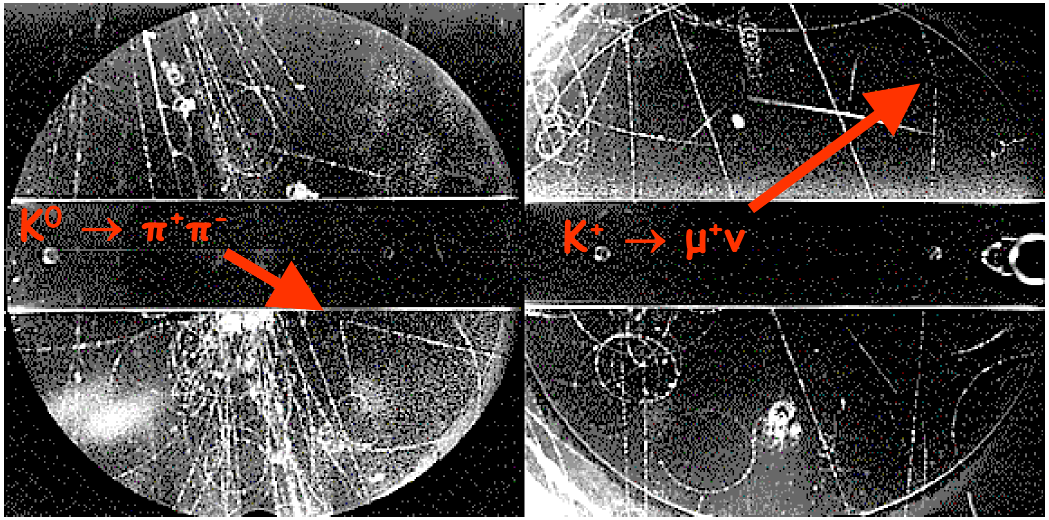
Dessin stéréoscopique de la collision.

A particle exists with $m_e < m < m_p$

Kaons enter the scene (2)

G.D. Rochester, C.C. Butler (1947):
Evidence for the existence of new unstable elementary particles.

Cloud chamber on cosmic rays, with a *single* absorber plate.
No electrons or positrons, only penetrating particles.



Neutral particle
mass 393 to 818 MeV/c^2

Charged particle
mass 500 MeV/c^2 to m_p

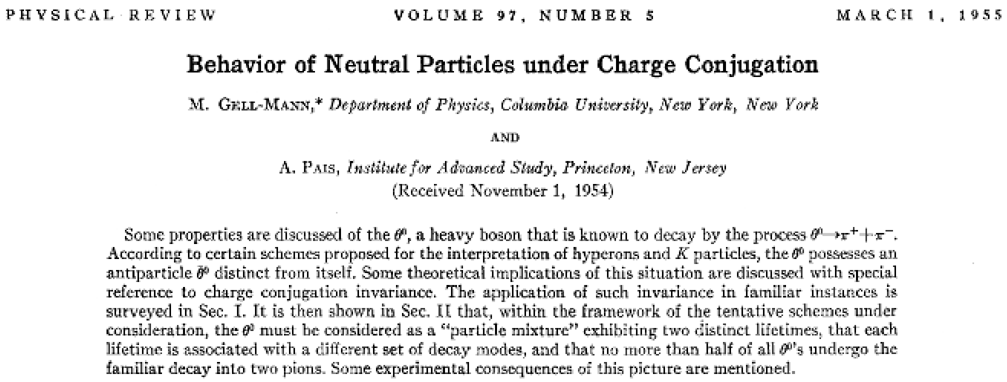
"V particles"

First evidence of "strange" matter, not present on Earth, unstable.

And many confirmations…

Weirdness...

M. Gell-Mann, A. Pais,
Phys. Rev. 97 (1955) 1387



PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

M. Gell-Mann
(1929-)

A. Pais
(1918-2000)

- Physical laws symmetric under C [later CP]
- Two kinds of neutral particles; behaviour under C:
  1. $\theta^0 \rightarrow \theta^0$ (self C-coniugate, e.g. γ,π^0)
  2. $\theta^0 \rightarrow \overline{\theta}^0$ (distinguished by conserved q. numbers; e.g. n)
- K^0 mesons belong to (2) with strong interactions only (strangeness conservation) but weak interactions do not conserve strangeness:
  $K^0 \rightarrow \overline{K}^0$ transitions are possible, with common decay modes

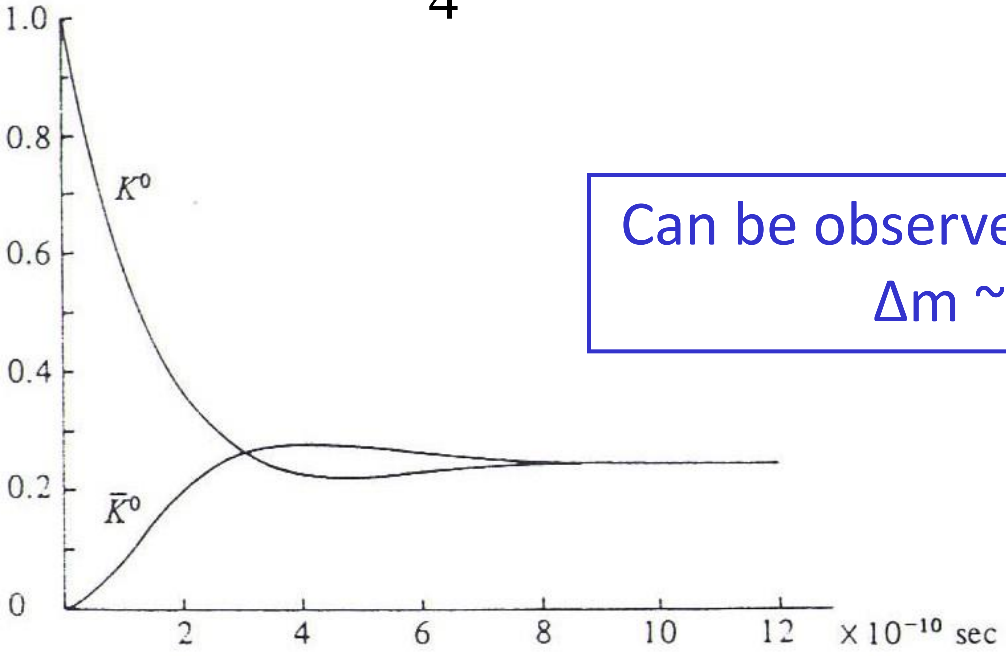
Strangeness (flavour) oscillations

A state (K^0, $\overline{K}^0$) produced with defined strangeness has such strangeness changing in time :

$$P[K^0(t=0) \rightarrow K^0(t)] = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right]$$

$$P[K^0(t=0) \rightarrow \overline{K^0}(t)] = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right]$$

$\Delta m = m_1 - m_2$



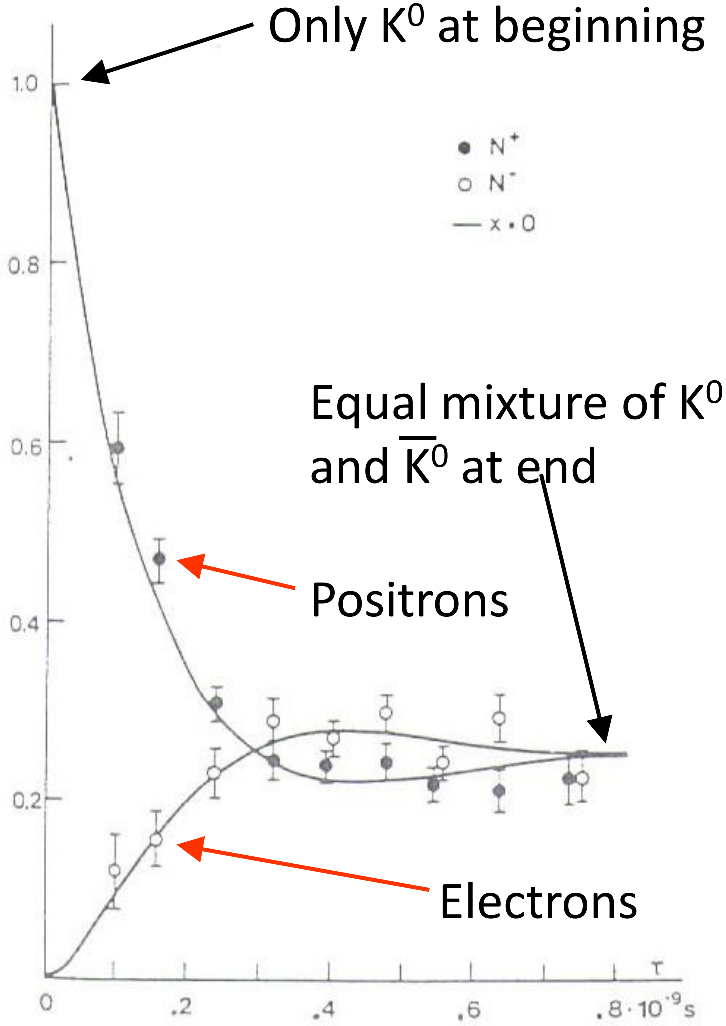
Can be observed because:
$\Delta m \sim \Gamma$

M.S. Sozzi

Strangeness oscillations detected exploiting *flavour-specific* decays only allowed for K^0 or $\overline{K^0}$ (*flavour tagging*).

Semi-leptonic decays:
$K^0 \rightarrow \pi^- e^+ \nu_e$ but not $\overline{K^0} \rightarrow \pi^- e^+ \nu_e$
because of the "$\Delta S = \Delta Q$ rule" (quarks).

Non-exponential decay of *strangeness eigenstates* (not H eigenstates): strangeness is not conserved



Only K^0 at beginning

Equal mixture of K^0 and $\overline{K^0}$ at end

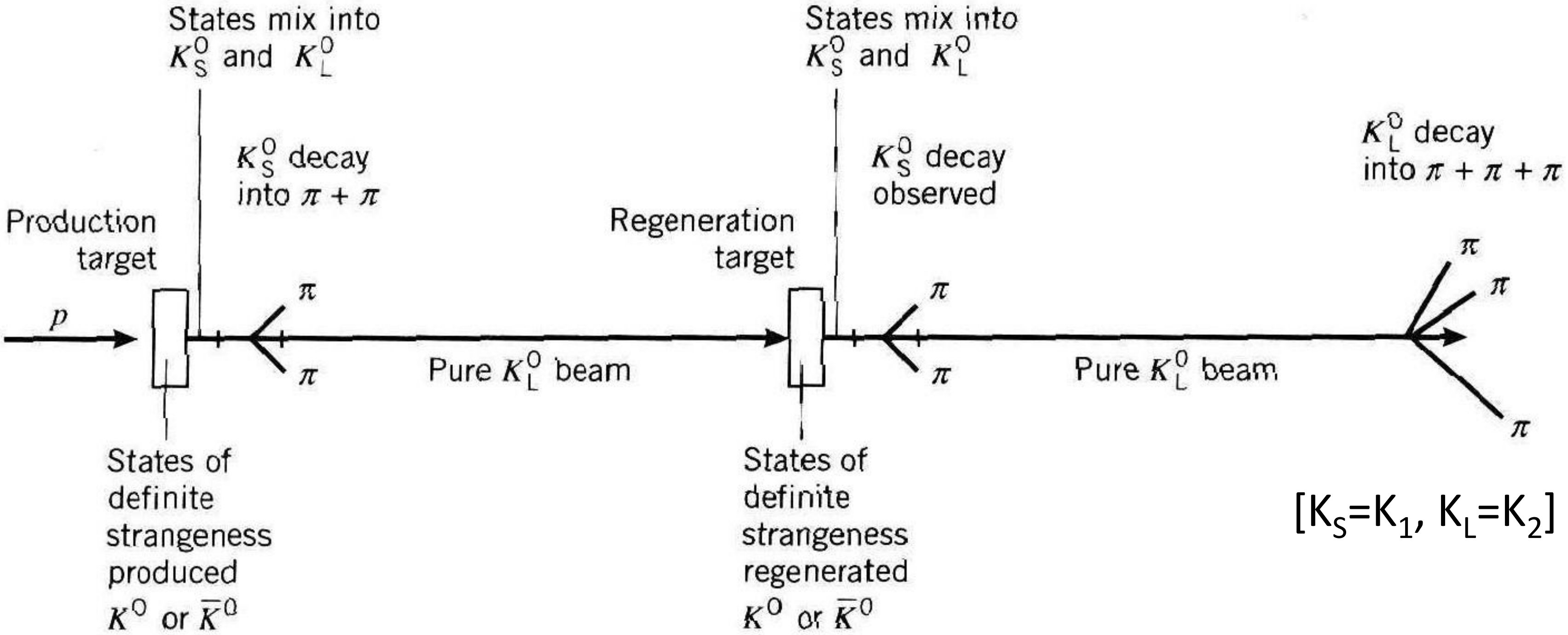
Positrons

Electrons

Ignoring strangeness (lepton charge): expon
decay

Regeneration

K^0 (or $\overline{K}^0$) $\propto K_1 \pm K_2 \rightarrow K_2 \rightarrow \overline{K}^0$ reduced in matter $\rightarrow K_1 + K_2$



[$K_S=K_1$, $K_L=K_2$]

"… the only instance where a forward coherently scattered beam can be distinguished from the original beam".

Two neutral K mesons

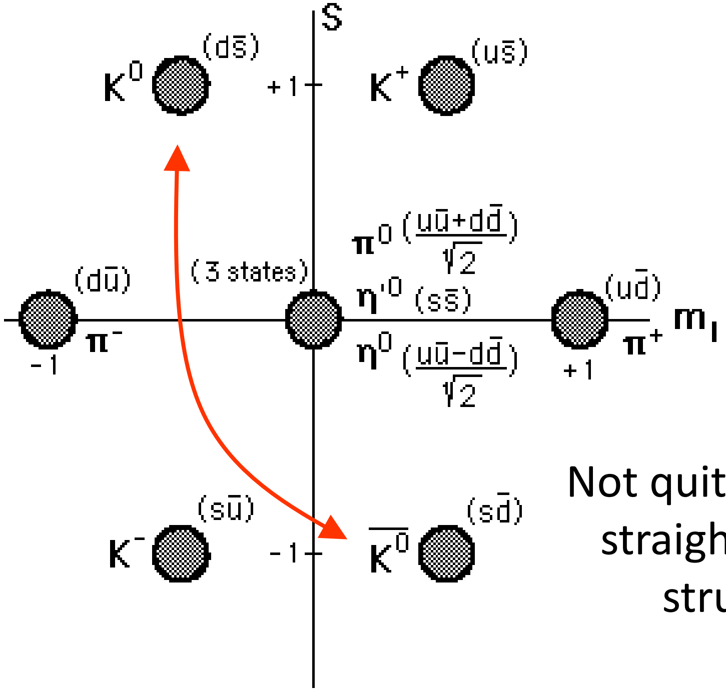
Example: $n \rightarrow \Lambda K^0$ and $\overline{K^0}\, n \rightarrow \Lambda$ do occur (strong interactions)
but if $K^0\, n \rightarrow \Lambda$ would occur
then $nn \rightarrow n\Lambda K^0 \rightarrow \Lambda\Lambda$ would occur (not observed)

$M(K^0) = 497.7\ \mathrm{MeV}/c^2$
$I(J^P) = ½(0^-)$

Quark picture
$K^0 = (d\bar{s})$ $S = +1$
$\overline{K^0} = (\bar{d}s)$ $S = -1$
or:

$$K^0 \neq \overline{K}^0$$

Compare to $\pi^0 = (u\bar{u}+d\bar{d})/\sqrt{2} = \overline{\pi^0}$



Not quite the most straightforward structure

K mesons are *the minimal flavour laboratory*

A bold, profound and fruitful conceptual step

“The search for ordering principles at this moment may indeed ultimately have to be likened to a chemist’s attempt to build up the periodic system if he were given only a dozen odd elements”.
(A. Pais, 1952)

“It is by no means certain that, if the complex ensemble of phenomena concerning the neutral K mesons were known without the benefit of the Gell-Mann – Pais theory, we could, even today, correctly interpret the behavior of these particles. That their theory, published in 1955, actually preceded most of the experimental evidence known at present, is one of the most astonishing and gratifying successes in the history of the elementary particles”.
(R.H. Good et al., 1961)

“Especially interesting is the fact that we have taken the principle of superposition to its ultimately logical conclusion”.
“… one of the greatest achievements of theoretical physics”.
(R. Feynman)

Physical states

In the meantime: C violated, physical states need not be C eigenstates. Use CP instead:

$$CP\left|K^0\right\rangle = (+1)\left|\overline{K^0}\right\rangle$$

Arbitrary choice of phase

$$\boxed{\begin{cases} CP\left|K_1\right\rangle = +\left|K_1\right\rangle \\ CP\left|K_2\right\rangle = -\left|K_2\right\rangle \end{cases}}$$

$\langle K_1 | K_2 \rangle = 0$

Quite different Q-values: 215 MeV vs. 78 MeV. $\tau(\pi\pi) \ll \tau(\pi\pi\pi)$

Since: $CP\left|\pi\pi\right\rangle_{J=0} = +\left|\pi\pi\right\rangle$ $\quad CP\left|\pi\pi\pi\right\rangle_{J,L=0} = -\left|\pi\pi\pi\right\rangle$

we write: $\left|K_S\right\rangle \equiv \left|K_1\right\rangle$ $\quad \left|K_L\right\rangle \equiv \left|K_2\right\rangle$

CP conserved ([CP,H]=0): physical states = CP eigenstates

(for the time being…)

Time evolution

Dual descriptions:

K^0 and $\overline{K}^0$: strangeness eigenstates (associate production):

$\pi^- p \rightarrow \Lambda K^0 \quad K^+ n \rightarrow p K^0$ [Strong interactions]

K_1 and K_2: mass and lifetime eigenstates:

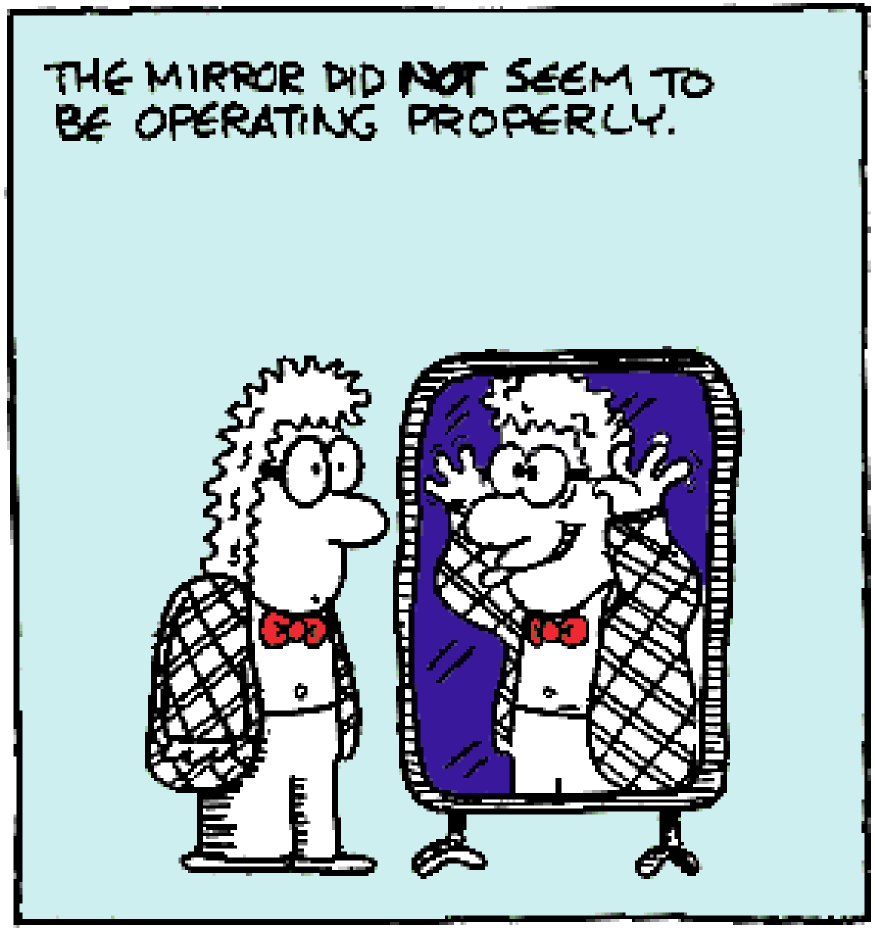
$$\left|K_1(t)\right\rangle = e^{-iE_1 t}\left|K_1(0)\right\rangle = e^{-i(m_1 - i\Gamma_1)t}\left|K_1(0)\right\rangle$$

$$\left|K_2(t)\right\rangle = e^{-iE_2 t}\left|K_2(0)\right\rangle = e^{-i(m_2 - i\Gamma_2)t}\left|K_2(0)\right\rangle$$

[Weak interactions]

$$\begin{cases} \left|K_1\right\rangle = \dfrac{1}{\sqrt{2}}\left[\left|K^0\right\rangle + \left|\overline{K^0}\right\rangle\right] \\ \left|K_2\right\rangle = \dfrac{1}{\sqrt{2}}\left[\left|K^0\right\rangle - \left|\overline{K^0}\right\rangle\right] \end{cases}$$

Kaons: the minimal flavour laboratory



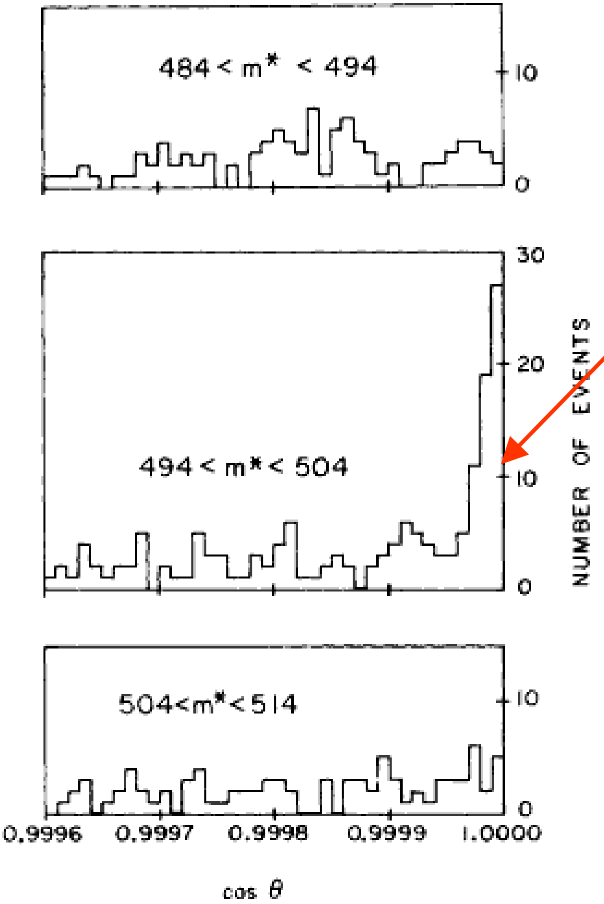
CP (and T) violation

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,[‡] V. L. Fitch,[‡] and R. Turlay[§]
Princeton University, Princeton, New Jersey

(Received 10 July 1964)



(45 ± 9)/22700

FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

"The events from the He gas appear identical with those from the coherent regeneration in tungsten in both mass and angular spread".

6 months of data analysis:
reject all alternative explanations
- coherent regeneration in He
- 3-body decays πμν or πeν
- ππγ decays with missing photon

There exists a pair (K_S,K_L) of non-degenerate states ($\Delta m \neq 0$), one of which can decay into final states with opposite CP parities

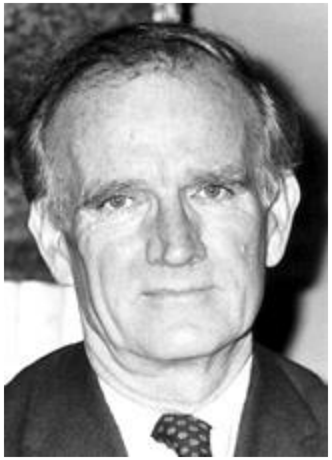
"But then in 1964 these same particles, in effect, dropped the other shoe".
(V. Fitch, 1980)

Evidence of
CP SYMMETRY VIOLATION

New York Times, August 6th 1964:
"High energy physics experiment finds time reversal may affect physics laws".

Nobel 1980

J. Cronin
(1931-)



V. Fitch
(1923-)

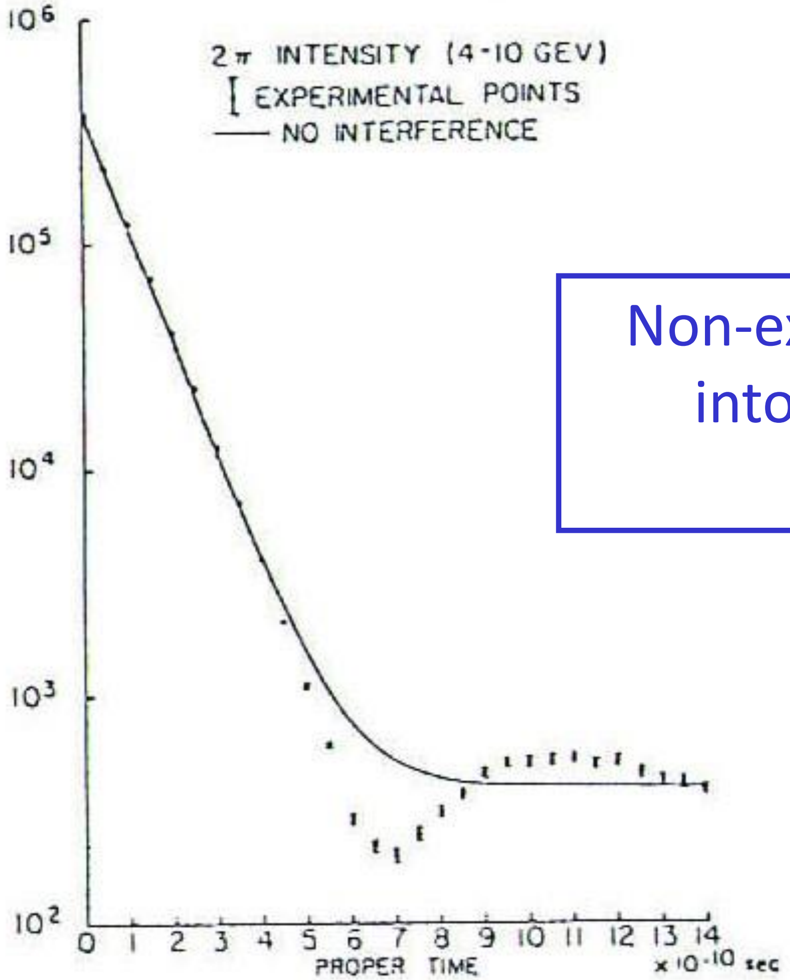
$$\frac{BR(K_L \rightarrow \pi^+\pi^-)}{BR(K_L \rightarrow charged)} = (2.0 \pm 0.4) \cdot 10^{-3}$$

"It was a very good year, 1964."
(A. Pais)

"… a purely experimental discovery, a discovery for which there were no precursive indications, either theoretical or experimental."
(V. Fitch)

The "gang of four": 30 years later

Once more

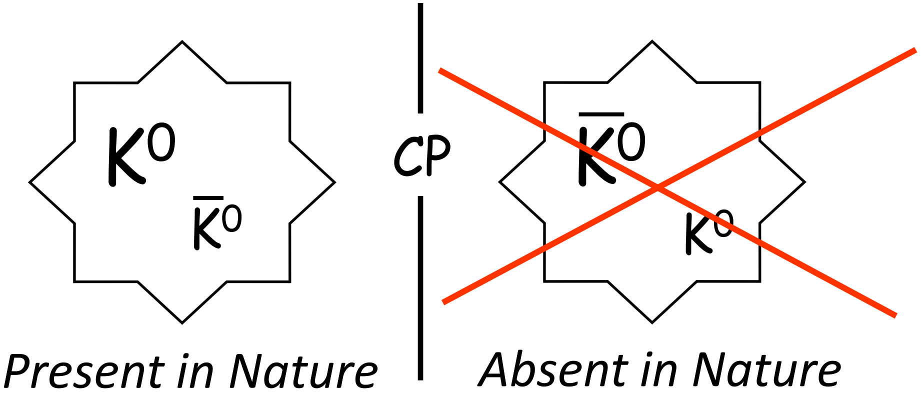


Non-exponential decay of
into a CP eigenstate:
CP violation

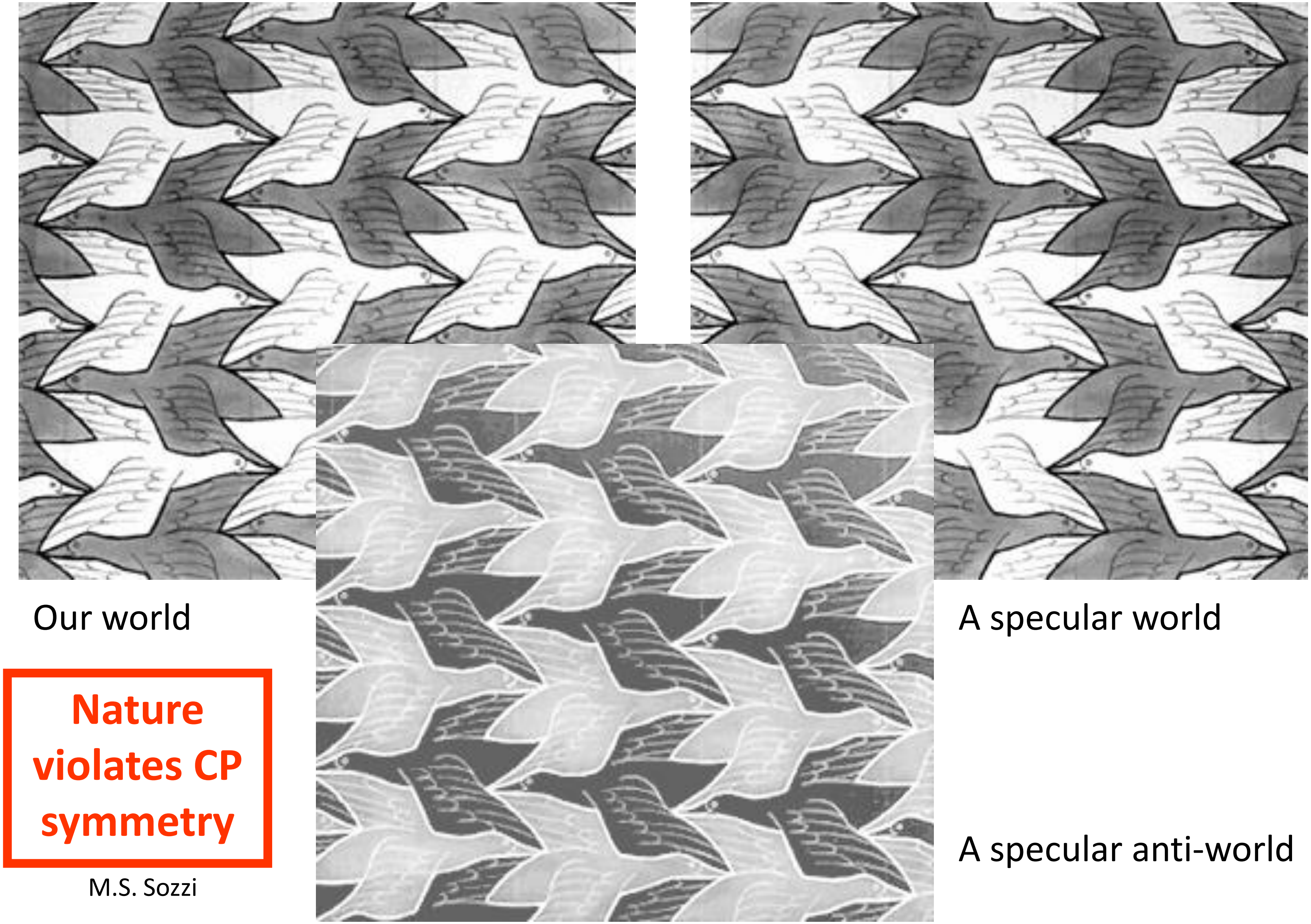
The new paradigm

Physical states (definite mass and lifetime, exponential decay) *are not* CP eigenstates: $K_S, K_L \neq K_1, K_2$

K_L is a superposition of strangeness eigenstates with a tiny (0.002) preponderance of K^0.



$$\begin{cases} |K_S\rangle \propto (1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\overline{K^0}\rangle \\ |K_L\rangle \propto (1+\varepsilon)|K^0\rangle - (1-\varepsilon)|\overline{K^0}\rangle \end{cases}$$



Our world

A specular world

A specular anti-world

Nature violates CP symmetry

M.S. Sozzi

Physical states

Physical states are "almost" CP eigenstates

$$\begin{cases} |K_S\rangle = \dfrac{1}{\sqrt{1+|\varepsilon_S|^2}}\left[|K_1\rangle + \varepsilon_S|K_2\rangle\right] = \dfrac{1}{\sqrt{2\left(1+|\varepsilon_S|^2\right)}}\left[(1+\varepsilon_S)|K^0\rangle + (1-\varepsilon_S)|\overline{K^0}\rangle\right] \\ |K_L\rangle = \dfrac{1}{\sqrt{1+|\varepsilon_L|^2}}\left[|K_2\rangle + \varepsilon_L|K_1\rangle\right] = \dfrac{1}{\sqrt{2\left(1+|\varepsilon_L|^2\right)}}\left[(1+\varepsilon_L)|K^0\rangle - (1-\varepsilon_L)|\overline{K^0}\rangle\right] \end{cases}$$

$$\begin{cases} |K_S\rangle = \dfrac{1}{\sqrt{2\left(1+\left|\bar{\varepsilon}^2 - \delta^2\right|\right)}}\left[(1+\bar{\varepsilon}-\delta)|K^0\rangle + (1-\bar{\varepsilon}+\delta)|\overline{K^0}\rangle\right] \\ |K_L\rangle = \dfrac{1}{\sqrt{2\left(1+\left|\bar{\varepsilon}^2 + \delta^2\right|\right)}}\left[(1+\bar{\varepsilon}+\delta)|K^0\rangle - (1-\bar{\varepsilon}-\delta)|\overline{K^0}\rangle\right] \end{cases}$$

$$\bar{\varepsilon} \equiv (\varepsilon_S + \varepsilon_L)/2$$

$$\delta \equiv (\varepsilon_L - \varepsilon_S)/2$$

If $\varepsilon_S, \varepsilon_L \neq 0$ CP symmetry is violated (physical states are not CP eigenstates)

$$\langle K_L | K_S \rangle = 2\,\mathrm{Re}\,\bar{\varepsilon} - 2i\,\mathrm{Im}\,\delta$$

Three descriptions

K^0, $\overline{K}^0$: Strangeness eigenstates, produced by strong interactions, relevant for propagation in matter. Particle/anti-particle pair (same mass by CPT), decaying in common final states (not orthogonal), undefined lifetime (non-exponential decay).

K_1, K_2: CP eigenstates, almost same as physical states, not particle/anti-particle pair, different masses and final states (almost) different, orthogonal.

K_S, K_L: Physical states, not particle/anti-particle pair, different masses and final states (almost) different, almost orthogonal.

"… there is scarcely a physical system which contains so many of the elements of modern physics".
(V. Fitch, 1980)

M.S. Sozzi

Diagonalization of the effective Hamiltonian:

$$\bar{\varepsilon} = \frac{\operatorname{Im} M_{12} - (i/2)\operatorname{Im}\Gamma_{12}}{i\Delta m - \Delta\Gamma/2} \qquad \delta = \frac{(M_{22} - M_{11}) - i(\Gamma_{22} - \Gamma_{11})}{2\left[\Delta m - (i/2)\Delta\Gamma\right]}$$

N.B. define: $\Delta m \equiv m_L - m_S > 0$ and $\Delta\Gamma \equiv \Gamma_S - \Gamma_L > 0$

If $\bar{\varepsilon} \neq 0$ or $\delta \neq 0$ CP symmetry is violated
(physical states not CP eigenstates)

If $\bar{\varepsilon} \neq 0$ T symmetry
is violated:
$M_{12} \neq M_{21} \quad \Gamma_{12} \neq \Gamma_{21}$

If $\delta \neq 0$ CPT symmetry
is violated:
$M_{11} \neq M_{22} \quad \Gamma_{11} \neq \Gamma_{22}$

K: measurements

$K^{\pm}$ ($\tau \approx$ 12 ns, $c\tau \approx$ 3.7 m) can be tracked, and can be identified by dE/dx or Čerenkov detectors

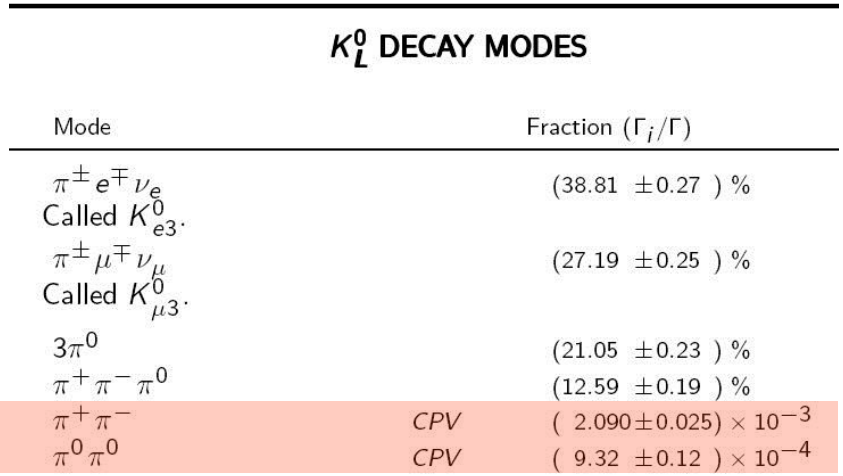
K^{+} can be stopped in a degrader (dE/dx) before decaying

K^{-} usually interacts strongly before decaying

K_S ($\tau \approx$ 90 ps, $c\tau \approx$ 2.7 cm) is reconstructed by its decay products (100% $\pi\pi$, tracking or calorimetry + $\gamma\gamma$ invariant mass constraints)

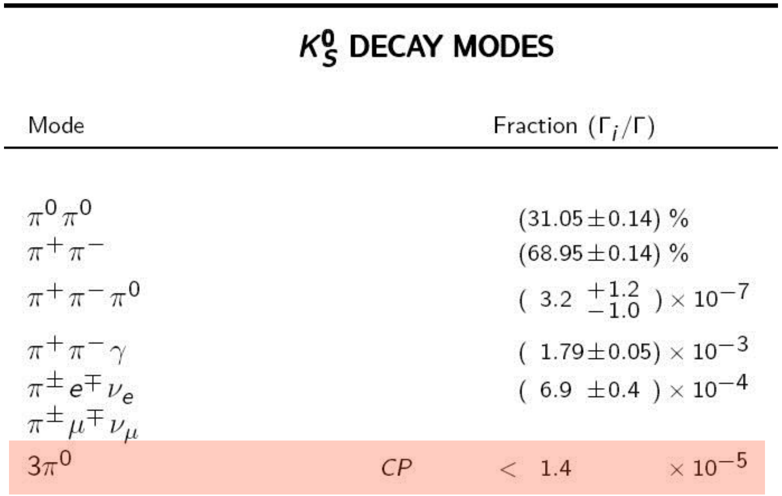
K_L ($\tau \approx$ 52 ns, $c\tau \approx$ 16 m) can be reconstructed by its decay products ($\pi\pi\pi$, tracking or calorimetry + constraints, or $\pi\ell\nu$, lepton ID and transverse momentum), or by its strong interaction with the detector.

K: decays



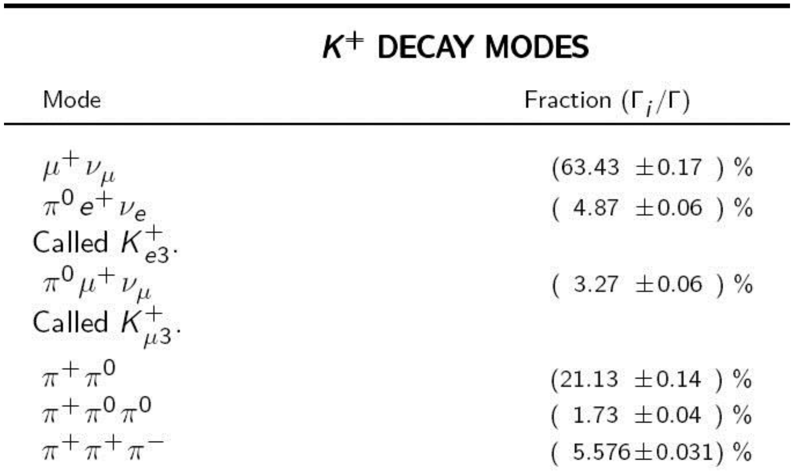
K^0_L DECAY MODES

Mode		Fraction (Γ_i/Γ)
$\pi^{\pm}e^{\mp}\nu_e$		(38.81 ± 0.27) %
Called K^0_{e3}.		
$\pi^{\pm}\mu^{\mp}\nu_\mu$		(27.19 ± 0.25) %
Called $K^0_{\mu 3}$.		
$3\pi^0$		(21.05 ± 0.23) %
$\pi^+\pi^-\pi^0$		(12.59 ± 0.19) %
$\pi^+\pi^-$	*CPV*	$(2.090 \pm 0.025) \times 10^{-3}$
$\pi^0\pi^0$	*CPV*	$(9.32 \pm 0.12) \times 10^{-4}$



K^0_S DECAY MODES

Mode		Fraction (Γ_i/Γ)
$\pi^0\pi^0$		(31.05 ± 0.14) %
$\pi^+\pi^-$		(68.95 ± 0.14) %
$\pi^+\pi^-\pi^0$		$(3.2\ ^{+1.2}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\gamma$		$(1.79 \pm 0.05) \times 10^{-3}$
$\pi^{\pm}e^{\mp}\nu_e$		$(6.9 \pm 0.4) \times 10^{-4}$
$\pi^{\pm}\mu^{\mp}\nu_\mu$		
$3\pi^0$	*CP*	$< 1.4 \times 10^{-5}$



K^+ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$\mu^+\nu_\mu$	(63.43 ± 0.17) %
$\pi^0 e^+\nu_e$	(4.87 ± 0.06) %
Called K^+_{e3}.	
$\pi^0\mu^+\nu_\mu$	(3.27 ± 0.06) %
Called $K^+_{\mu 3}$.	
$\pi^+\pi^0$	(21.13 ± 0.14) %
$\pi^+\pi^0\pi^0$	(1.73 ± 0.04) %
$\pi^+\pi^+\pi^-$	(5.576 ± 0.031) %

Relatively few major branching ratios, several in the 10% range (compare to B): a “simple” system

Searching for CP violation

	For kaons
Transitions among CP eigenstates with opposite eigenvalues	$K_2 \to \pi\pi$
Search for physical states not being CP eigenstates (non-exponential decay of CP eigenstates)	$K_L \to \pi\pi$ and $K_S \to \pi\pi\pi$
Differences in the partial decay widths or decay properties of particles and antiparticles	$\Delta\Gamma(K \to 3\pi)$ $\Delta g(K \to 3\pi)$
Test of time-reversibility (plus CPT)	$P(K^0 \to \overline{K}^0) \neq$ $P(\overline{K}^0 \to K^0)$
Measure of non-zero CP-odd quantities	$P_T(K_{\mu 3})$

Tagged Kaons

Hadronic production: strangeness eigenstates

By exploiting specific reactions strangeness tagging at production is possible:

$p\bar{p} \rightarrow K^+\bar{K}^0\pi^-$ and $p\bar{p} \rightarrow K^-K^0\pi^+$ (0.4% of $\sigma_{tot}(p\bar{p})$ at rest)

Known strangeness at production time

Measure strangeness ($\pi e\nu$) or CP ($\pi\pi$) at decay time

$$A_T = \frac{\left|\langle K^0|e^{-iHt}|\bar{K}^0\rangle\right|^2 - \left|\langle \bar{K}^0|e^{-iHt}|K^0\rangle\right|^2}{\left|\langle K^0|e^{-iHt}|\bar{K}^0\rangle\right|^2 + \left|\langle \bar{K}^0|e^{-iHt}|K^0\rangle\right|^2}$$

T violation (Kabir test)

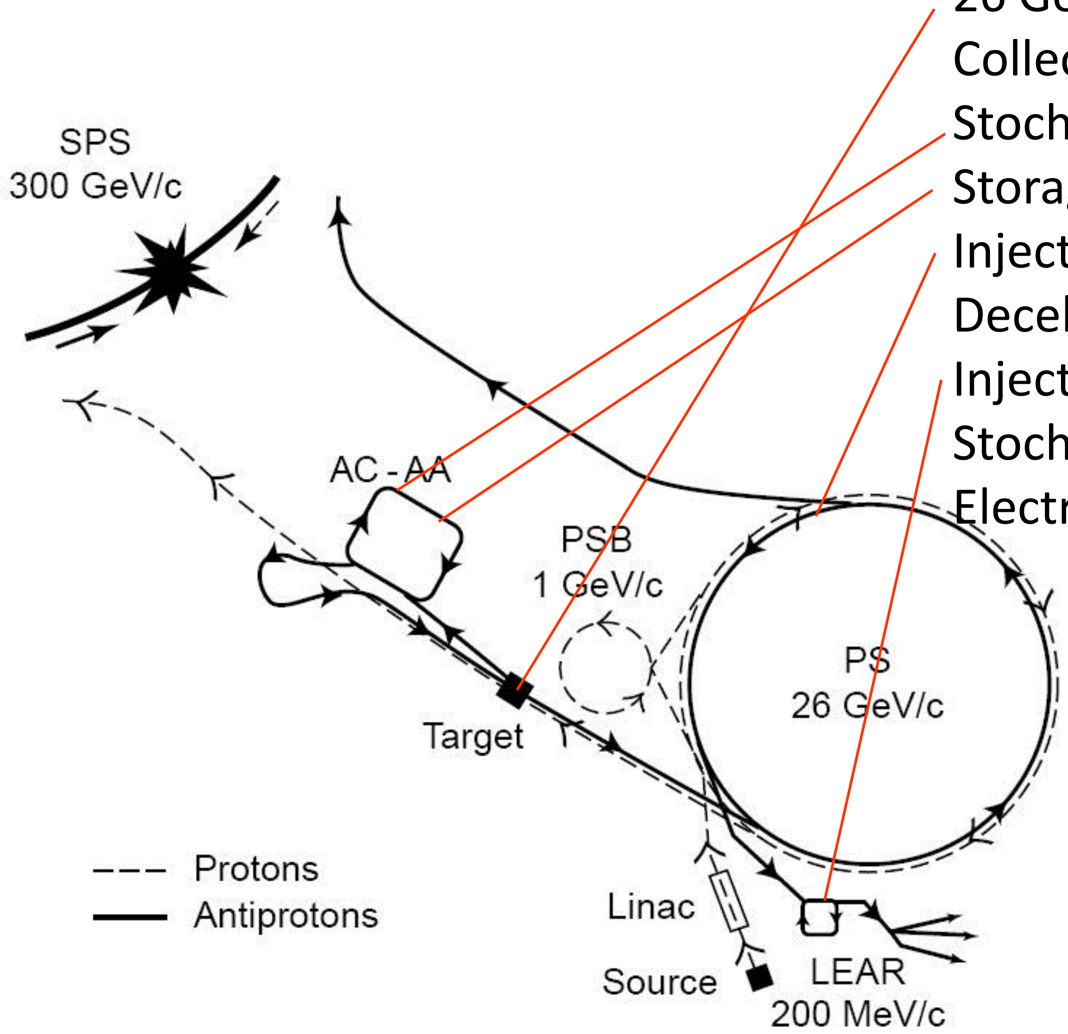
$$A_{CPT} = \frac{\left|\langle \bar{K}^0|e^{-iHt}|\bar{K}^0\rangle\right|^2 - \left|\langle K^0|e^{-iHt}|K^0\rangle\right|^2}{\left|\langle \bar{K}^0|e^{-iHt}|\bar{K}^0\rangle\right|^2 + \left|\langle K^0|e^{-iHt}|K^0\rangle\right|^2}$$

CPT violation

$$A_{CP} = \frac{\left|\langle f_{CP}|e^{-iHt}|\bar{K}^0\rangle\right|^2 - \left|\langle f_{CP}|e^{-iHt}|K^0\rangle\right|^2}{\left|\langle f_{CP}|e^{-iHt}|\bar{K}^0\rangle\right|^2 + \left|\langle f_{CP}|e^{-iHt}|K^0\rangle\right|^2}$$

CP violation parameters

LEAR @ CERN



26 GeV p on Ir target

Collect 3.6 GeV/*c* $\bar{p}$

Stochastically cooled in AC

Storage in AA

Inject $5 \cdot 10^9$ $\bar{p}$ into PS

Decelerated to 609 MeV/*c*

Inject into LEAR

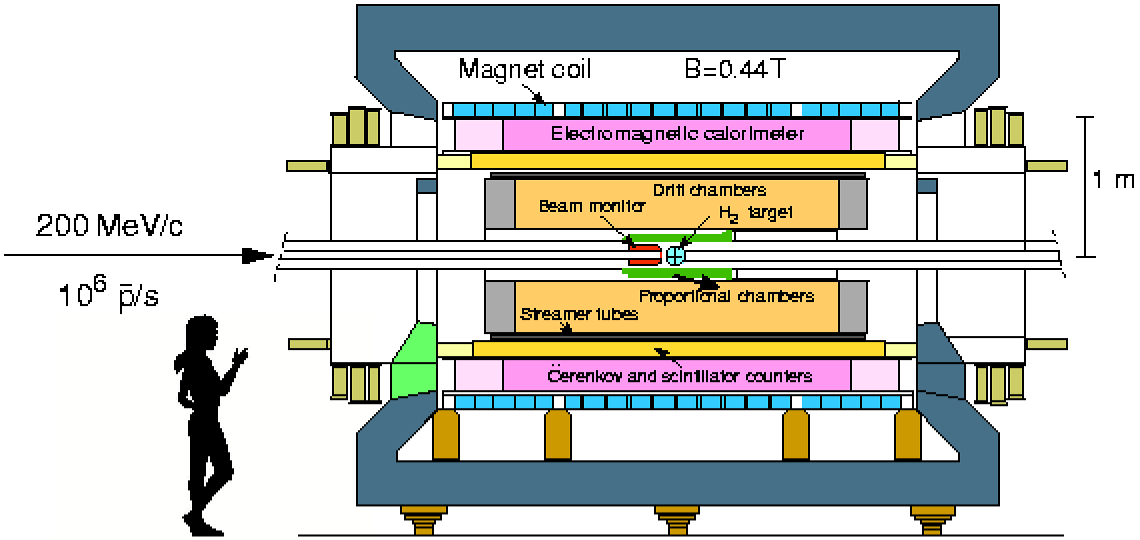
Stochastically cool to 10^{-3}

Electron cool down to 200 MeV/*c*

10^6 $\bar{p}$/s in 1 h spills

CPLEAR @CERN

Interaction at rest: 4π detector
Kaon ID: Čerenkov, dE/dx, time-of-flight
Tracking: r ~ 20 λ_S ~ 60 cm
Minimize material (regeneration)
“High” rate (1 MHz): fast trigger



High pressure gas H_2 target

Proportional and drift chambers:
$\sigma_x \approx 300\ \mu m$ $\sigma_p/p \approx 5\text{-}10\%$

EM calorimeter: 18-layers of limited-streamer tubes
$\sigma_x \approx 5$ mm $\sigma_E/E \approx 15\%/\sqrt{E(\text{GeV})}$

0.44 T warm solenoid

Lifetime resolution:
5-10 fs (with tracks)
70 fs ($\pi^0\pi^0$)

Run 1990-1996

5×10^9 events collected

CPLEAR: strangeness tagging

Associate K^0 production (strangeness conservation):

$\bar{p}p \to K^-\pi^+K^0$ $\bar{p}p \to K^+\pi^-\overline{K^0}$ $(BR \approx 2 \cdot 10^{-3})$

Charged K meson charge = strangeness of neutral K meson

Strangeness at decay time ($\Delta S=\Delta Q$):

$K^0 \to e^+\pi^-\nu$ $\overline{K^0} \to e^-\pi^+\nu$

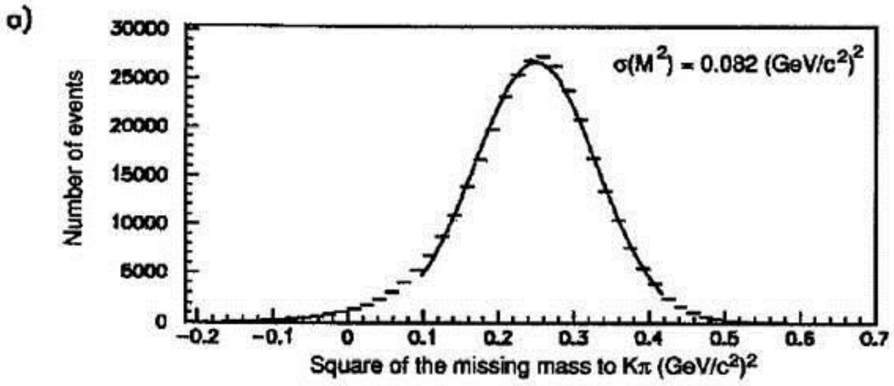
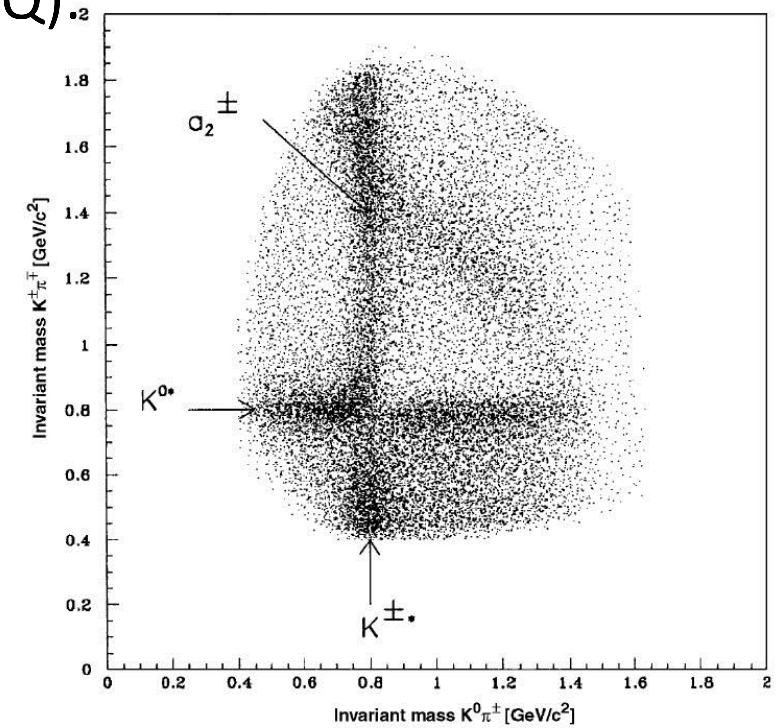
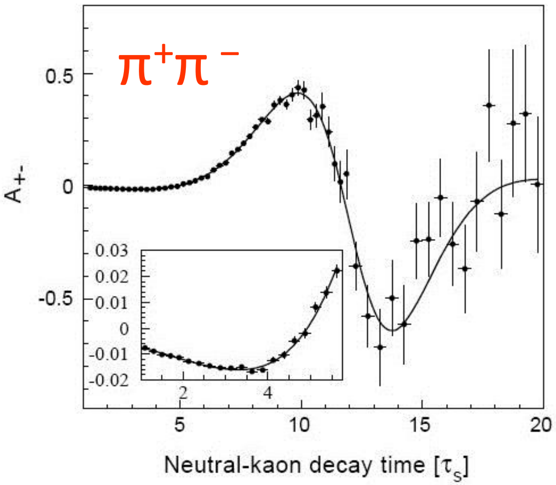


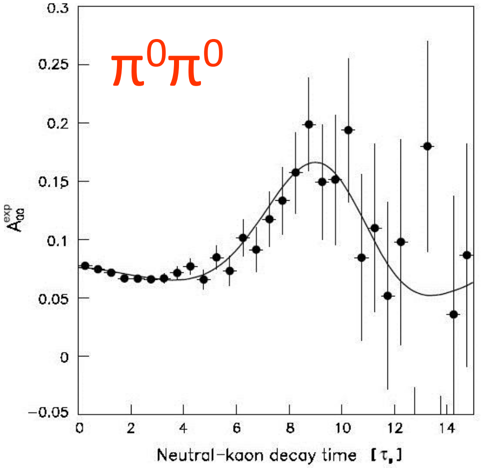
Fig. 20. (a) Square of the missing mass to the primary $K\pi$ pair for selected $p\bar{p} \to \pi KK^0$ events

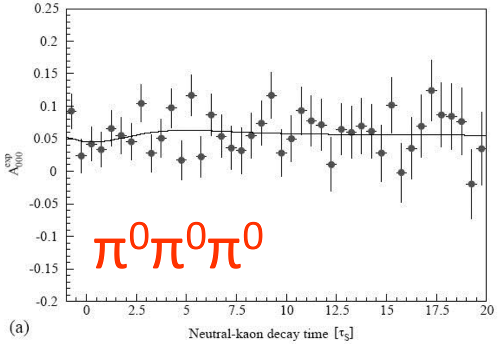


CPLEAR Asymmetries

Non flavour-specific final states





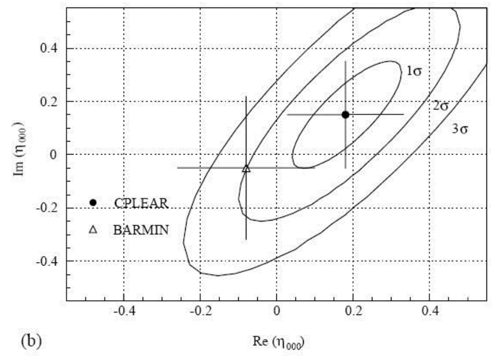


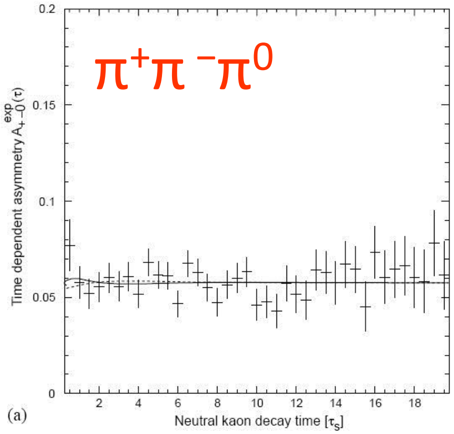
$$A_{CP}=\frac{\left|\langle f_{CP}|e^{-iHt}|\bar{K}^0\rangle\right|^2-\left|\langle f_{CP}|e^{-iHt}|K^0\rangle\right|^2}{\left|\langle f_{CP}|e^{-iHt}|\bar{K}^0\rangle\right|^2+\left|\langle f_{CP}|e^{-iHt}|K^0\rangle\right|^2}=2\,\mathrm{Re}(\varepsilon)-\frac{2|\eta_f|e^{(\Gamma_S-\Gamma_L)t/2}\cos(\Delta m t-\phi_f)}{1+|\eta_f|^2e^{(\Gamma_S-\Gamma_L)t}}$$

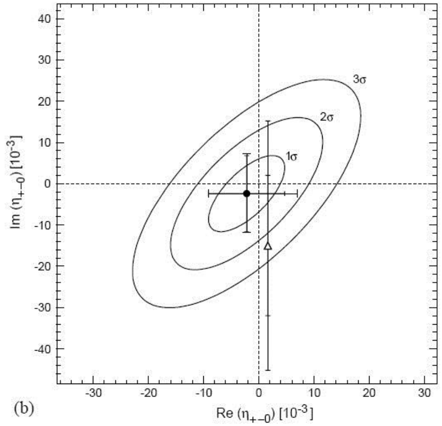
Acceptance cancellation

Rate difference

Measure η







Direct CP violation

Kinds of CP violation

CP violation in $\Delta S=2$ interactions is called

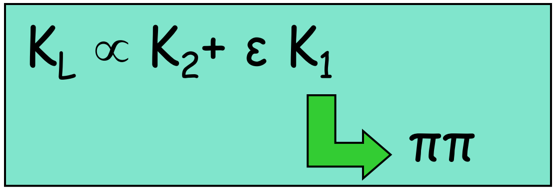
INDIRECT CP VIOLATION

CP violation in $\Delta S=1$ interactions is called

DIRECT CP VIOLATION

CP violation due to the CP impurity ($\bar{\varepsilon}$) of physical states is

CP VIOLATION IN MIXING

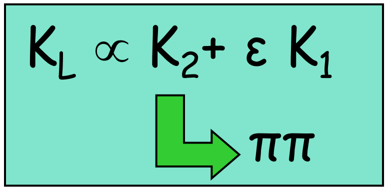


$$K_L \propto K_2 + \varepsilon\, K_1 \quad K_1 \to \pi\pi$$

It is of the *indirect* type

CP violation in the physical decay process is called

CP VIOLATION IN THE DECAY



$K_L \propto K_2 + \varepsilon K_1$

$\pi\pi$

It is of the *direct* type

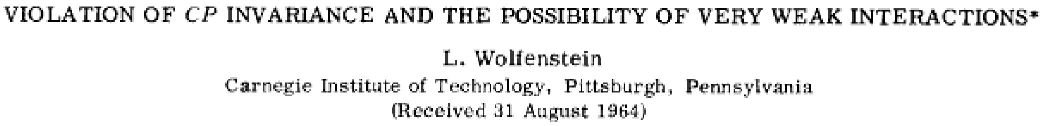
Transition from a CP eigenstate
to another one with opposite eigenvalue:

$$K_2\ (CP=-1) \rightarrow \pi\pi\ (CP=+1)$$

It represents an *intrinsic*
property of weak interactions

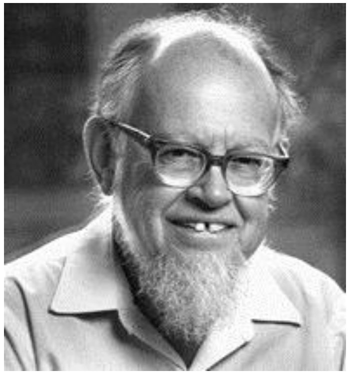
Not present in the superweak model

The superweak hypothesis



VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)



L. Wolfenstein
(1923-)

L. Wolfenstein (1964):
Hypothetical new interaction inducing $K^0 \leftrightarrow \overline{K}^0$ transitions ($\Delta S=2$) at first-order, with a coupling ~ 10^{-7} G_F would explain the effect while being *practically undetectable* elsewhere.

$$\bar{\varepsilon} = \frac{\mathrm{Im}\, M_{12} - (i/2)\,\mathrm{Im}\,\Gamma_{12}}{i\Delta m - \Delta\Gamma/2}$$

$$|\bar{\varepsilon}| \propto \frac{G_{SW}}{\Delta m} = \frac{\alpha\, G_F}{\Delta m}$$

$$|\bar{\varepsilon}| \approx \frac{\alpha\, G_F}{G_F^2} \frac{m_p^2}{m_p^4} \approx 2 \cdot 10^{-3}$$

Constraints on transition amplitudes

CPT $a(\bar{i} \to \bar{f}) = a^*(i \to f)$

T $a(i \to f) = a^*(i \to f)$

$a(\bar{i} \to \bar{f}) = a^*(\bar{i} \to \bar{f})$

CP $a(\bar{i} \to \bar{f}) = a(i \to f)$

Bars indicate CP-conjugate states

CP violation in decays

A complex amplitude *is not enough*

Two interfering amplitudes are required

$$A(i \to f) = e^{i\delta_1}|a_1|e^{i\phi_1} + e^{i\delta_2}|a_2|e^{i\phi_2}$$

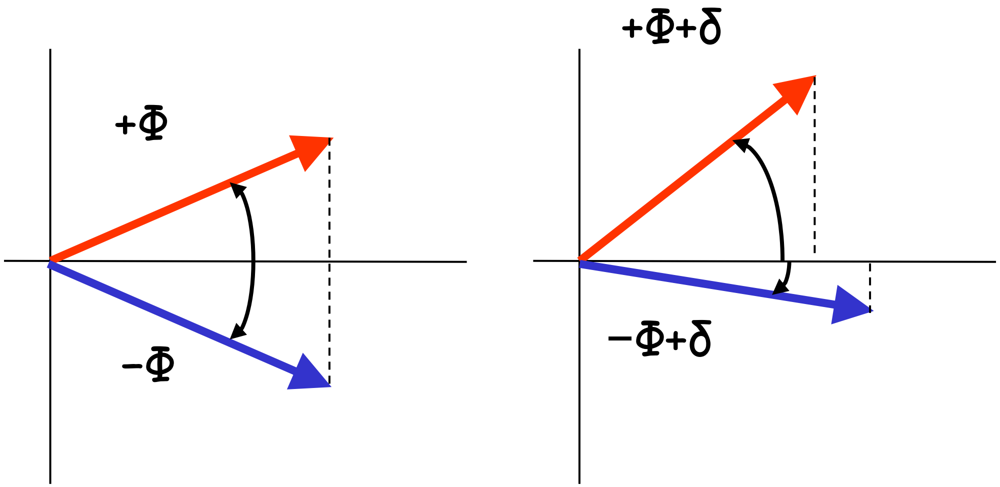
$$A(\bar{i} \to \bar{f}) = e^{i\delta_1}|a_1|e^{-i\phi_1} + e^{i\delta_2}|a_2|e^{-i\phi_2}$$

(Fermi-Watson)

$$\Gamma(\bar{i} \to \bar{f}) - \Gamma(i \to f) = 4|a_1||a_2|\sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

Need interfering amplitudes with different weak *(φ) and strong (δ)* phases

Large asymmetry if comparable amplitudes



Semi-leptonic decays ($K_{\ell 3}$)

BR($K_L \to \pi e \upsilon$) ≈ 0.39
BR($K_L \to \pi \mu \upsilon$) ≈ 0.28

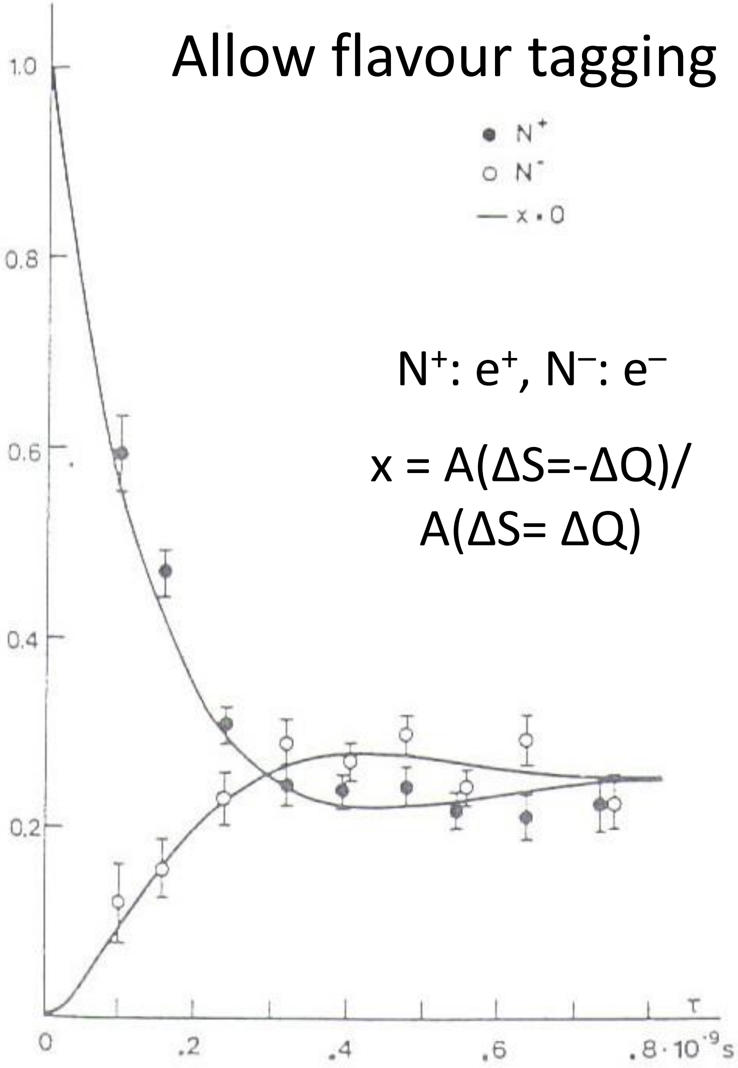
"ΔS= ΔQ rule" only allows
$K^0 \to \pi^- \ell^+ \nu$ and $\overline{K^0} \to \pi^+ \ell^- \overline{\nu}$

E.g. $\Sigma^- \to n e^- \overline{\nu}$ but not $\Sigma^+ \to n e^+ \nu$

Not CP eigenstates.

Only one decay amplitude

K^0 and $\overline{K}^0$ cannot both contribute.



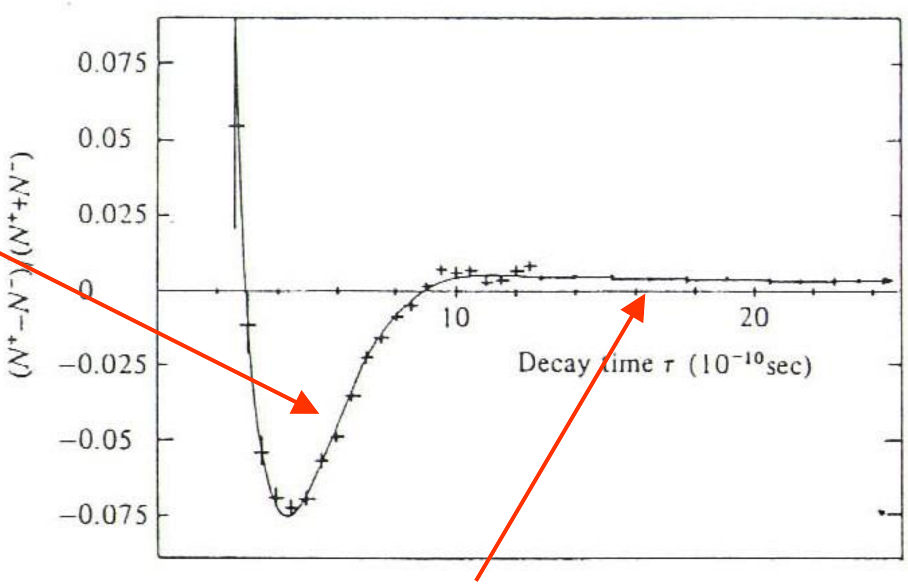
Allow flavour tagging

N^+: e^+, N^-: e^-

x = A(ΔS=-ΔQ)/
A(ΔS= ΔQ)

Charge asymmetry

Contribution from strangeness oscillations



If CP holds, with initial K^0:

$$A(t) = \frac{N^+ - N^-}{N^+ + N^-} = \frac{2\cos(\Delta m t)}{e^{+\Delta\Gamma t/2} + e^{-\Delta\Gamma t/2}}$$

CP violation

$$\delta_\ell = \frac{\Gamma(K_L \to \pi^- \ell^+ \upsilon) - \Gamma(K_L \to \pi^+ \ell^- \overline{\upsilon})}{\Gamma(K_L \to \pi^- \ell^+ \upsilon) + \Gamma(K_L \to \pi^+ \ell^- \overline{\upsilon})}$$

$\delta_e = (3.33 \pm 0.14) \cdot 10^{-3}$

$\delta_\mu = (3.04 \pm 0.25) \cdot 10^{-3}$

Absolute matter/anti-matter difference

More generally, starting from K^0 or $\overline{\text{K}}^0$:

$$A(t) \cong \frac{2(1-|x|^2)\left[\mathrm{Re}(\overline{\varepsilon})\,(e^{-\Gamma_S t}+e^{-\Gamma_L t}) \pm e^{-\overline{\Gamma} t}\cos(\Delta m t)\right]}{|1+x|^2 e^{-\Gamma_S t} + |1-x|^2 e^{-\Gamma_L t} \mp 4\,\mathrm{Im}(x) e^{-\overline{\Gamma} t}\sin(\Delta m t)}$$

If x=0 (ΔS = ΔQ holds):

$$A(t) \cong 2\,\mathrm{Re}(\overline{\varepsilon}) \pm \frac{2e^{-\overline{\Gamma} t}\cos(\Delta m t)}{e^{-\Gamma_S t}+e^{-\Gamma_L t}}$$

Incoherent mixture of K^0 and $\overline{\text{K}}^0$:
oscillating term multiplied by

$$D(p) = \frac{N(K^0,p) - N(\overline{K}^0,p)}{N(K^0,p) + N(\overline{K}^0,p)}$$

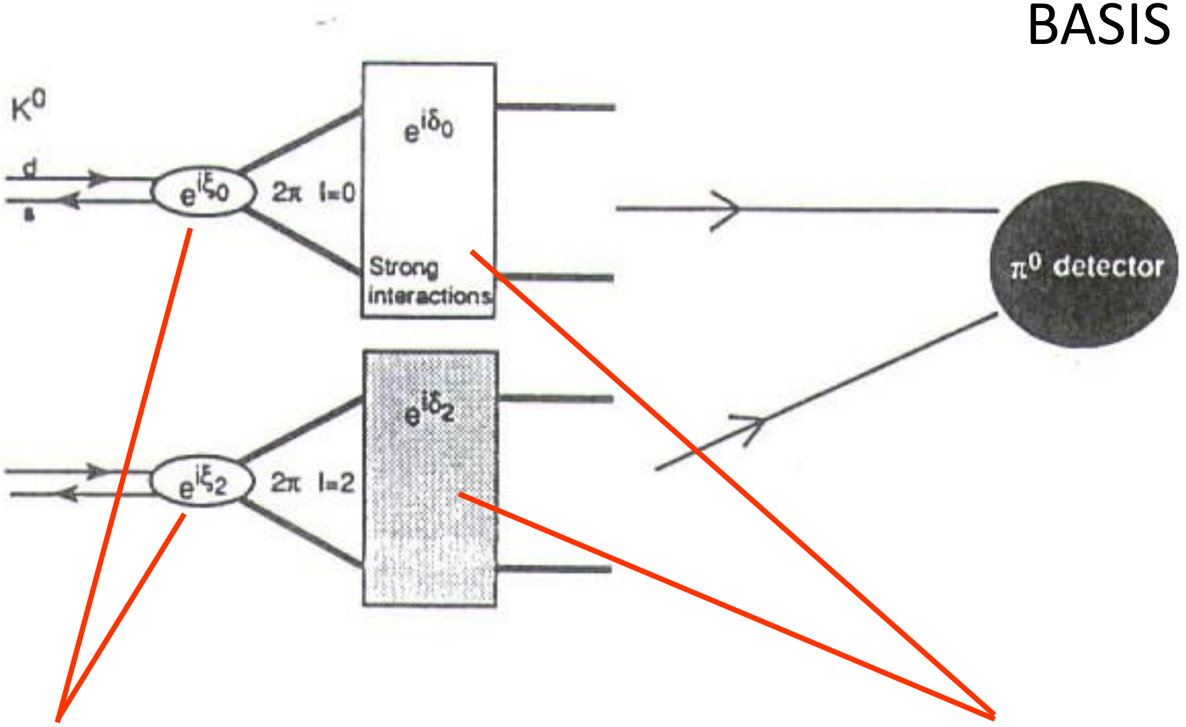
CP violation only from
mixing (indirect):

$$\delta_\ell = \frac{2\,\mathrm{Re}(\overline{\varepsilon})}{1+|\overline{\varepsilon}|^2} = \langle K_L | K_S \rangle$$

Example: CP violation in $K_L \to \pi^0\pi^0$ decay

ISOSPIN
BASIS

PHYSICAL
(CHARGE)
BASIS



Different weak phases:
CP violation

Different strong phases:
interference

The double ratio method

Comparing the CP-violating K_L decay widths.
Avoid isospin factors, normalize to the CP-conserving K_S decay widths:
measure and $|\eta_{00}|^2$ and $|\eta_{+-}|^2$:

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon) \approx 1 - 6\,\varepsilon'/\varepsilon$$

Need to measure accurately four decay widths:
$\Gamma(K_S \to \pi^+\pi^-)$, $\Gamma(K_S \to \pi^0\pi^0)$, $\Gamma(K_L \to \pi_+\pi^-)$, $\Gamma(K_L \to \pi^0\pi^0)$.

(1) **Statistics**: $BR(K_L \to \pi\pi) \sim 1 \div 2 \cdot 10^{-3}$
requires *intense K_L beam*

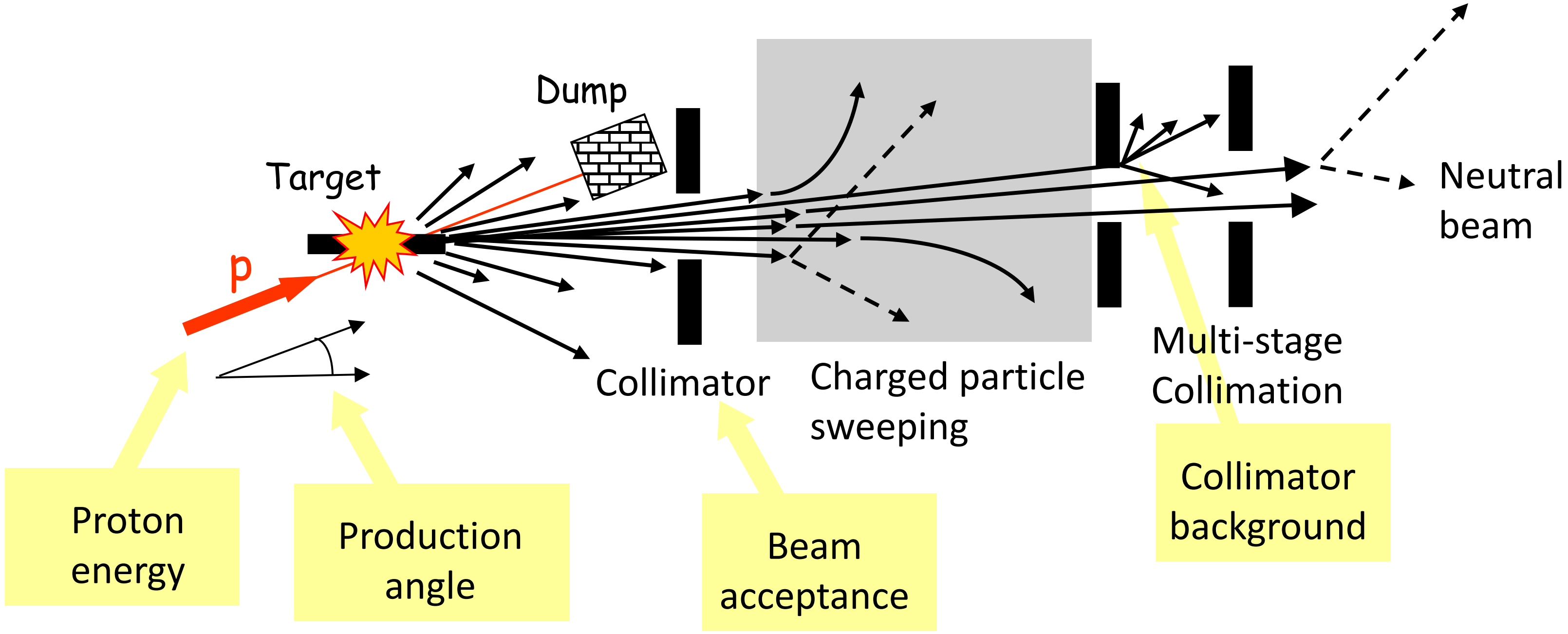
(2) **Systematics**: exploit *cancellations*

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)}$$

If concurrent $\pi^+\pi^-$ and $\pi^0\pi^0$: the K fluxes ($K_S \neq K_L$) do cancel

If concurrent K_S and K_L: detector inefficiencies ($\pi^+\pi^- \neq \pi^0\pi^0$) do cancel

K_L beam



Dump

Target

p

Collimator

Charged particle
sweeping

Multi-stage
Collimation

Neutral
beam

Proton
energy

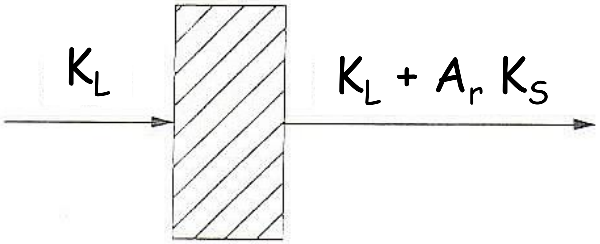
Production
angle

Beam
acceptance

Collimator
background

High energy p (~ 10-500 GeV), largest yield for $p_K \sim 0.3\, p_p$, long decay beam line (up to ~ 100 m), long decay volumes (up to ~ 100 m): long skinny experimental setups

K_S by regeneration

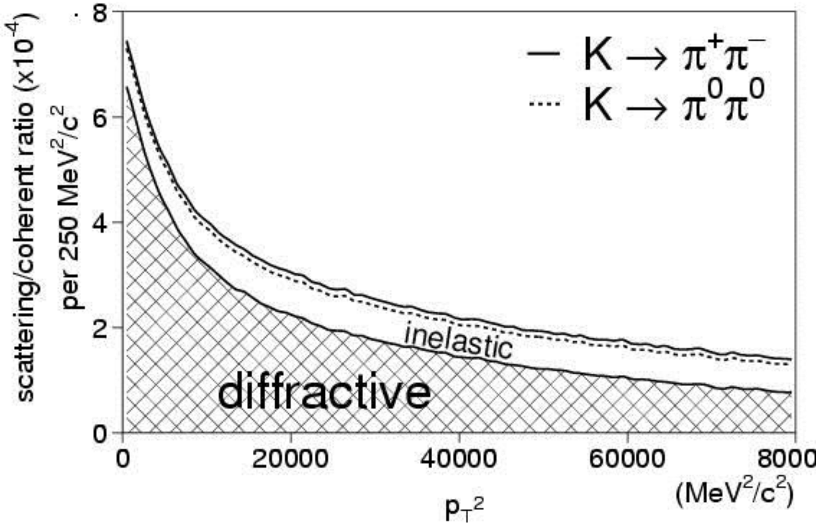


Coherent regeneration (transmission): same momentum and angle as incident beam

Diffractive regeneration:
interaction on nuclei, small angle

Inelastic regeneration:
interaction on nucleons, any angle
(scattered particles can be detected)

KTeV regenerator:
84 10x10x2 cm^2 scintillator modules (fully active), 170 cm long
$|A_r| \sim 0.03$
Diffractive/coherent: 0.09
Inelastic/coherent: 100 before veto



Measurement of direct CP violation

Simultaneous measurement of $|\eta_{00}|^2$ and $|\eta_{+-}|^2$ in a double ratio (same interval of p and z):

$$\frac{N(\overset{\text{A}}{K_L}\to\pi^0\pi^0)}{N(\underset{\text{B}}{K_S}\to\pi^0\pi^0)}\,\frac{N(\overset{\text{C}}{K_S}\to\pi^+\pi^-)}{N(\underset{\text{D}}{K_L}\to\pi^+\pi^-)}=\frac{|\eta_{00}|^2}{|\eta_{+-}|^2}\approx 1-6\,\varepsilon'/\varepsilon$$

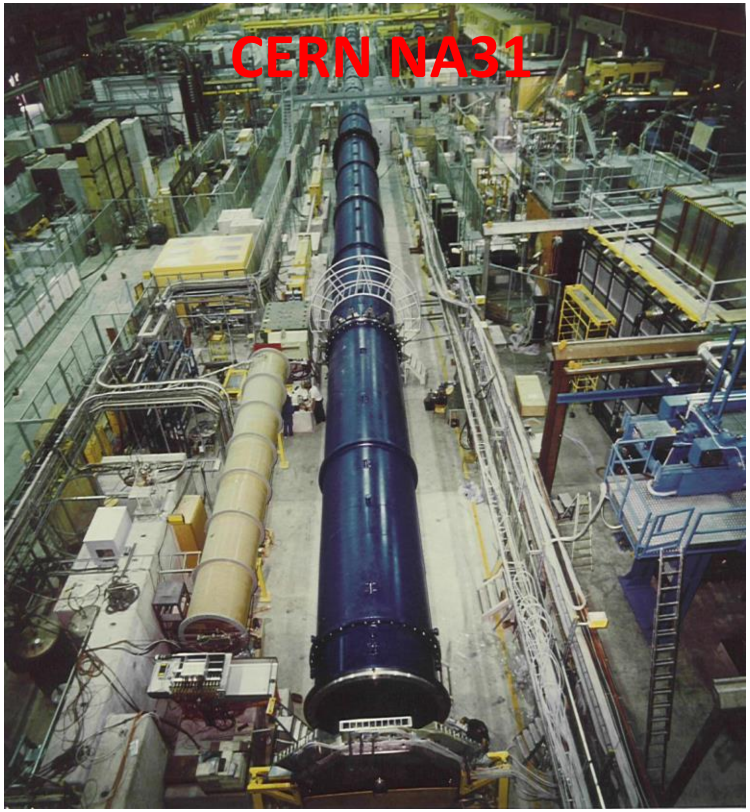
independent (at first order) from absolute detection efficiencies.

- A+D in vacuum and then B+C with regenerator (BNL)
- A+B with two beams and converter, and then C+D (FNAL E731)
- A+D in vacuum and then B+C with close target (CERN NA31)
- A+B+C+D with two beams and regenerator (FNAL KTeV)
- A+B+C+D with two beams and close target (CERN NA48)

Direct CPV: 1996 A.D.

$\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 6.0) \cdot 10^{-4}$

Not disproving superweak



$\mathrm{Re}(\varepsilon'/\varepsilon) = (23.0 \pm 6.5) \cdot 10^{-4}$

Inconsistent with superweak

KTEV

Kaons at the Tevatron

KTeV @ Fermilab

Two parallel K_L beams (70 GeV/*c*), regenerator for K_S (alternating)

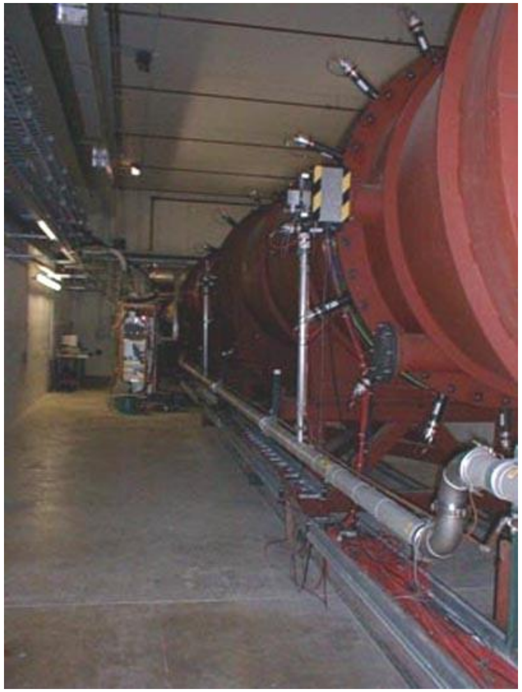
EM calorimeter with pure CsI crystals

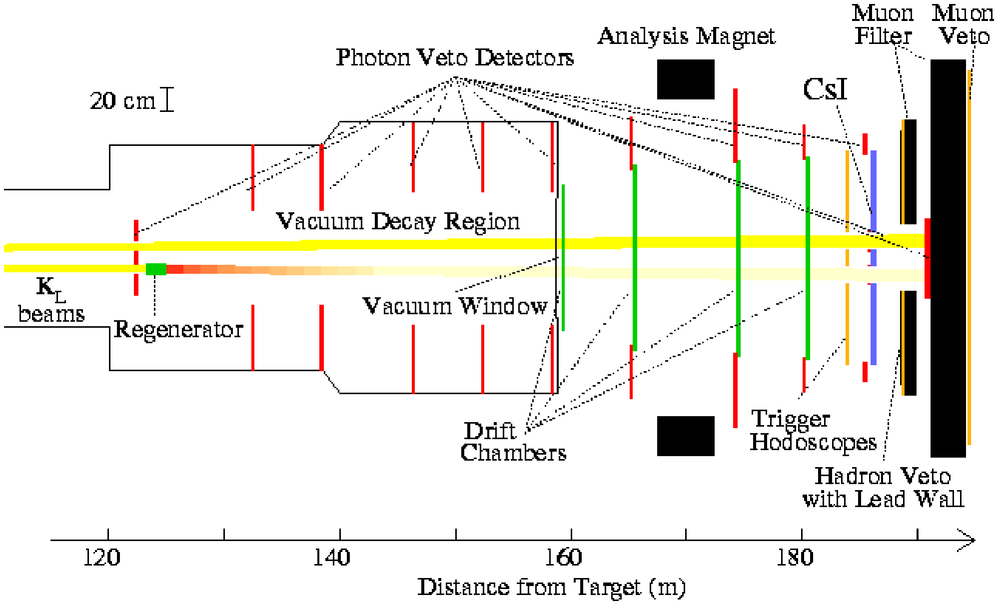
K tagging by event position

MonteCarlo correction for acceptance difference

Maximize statistics

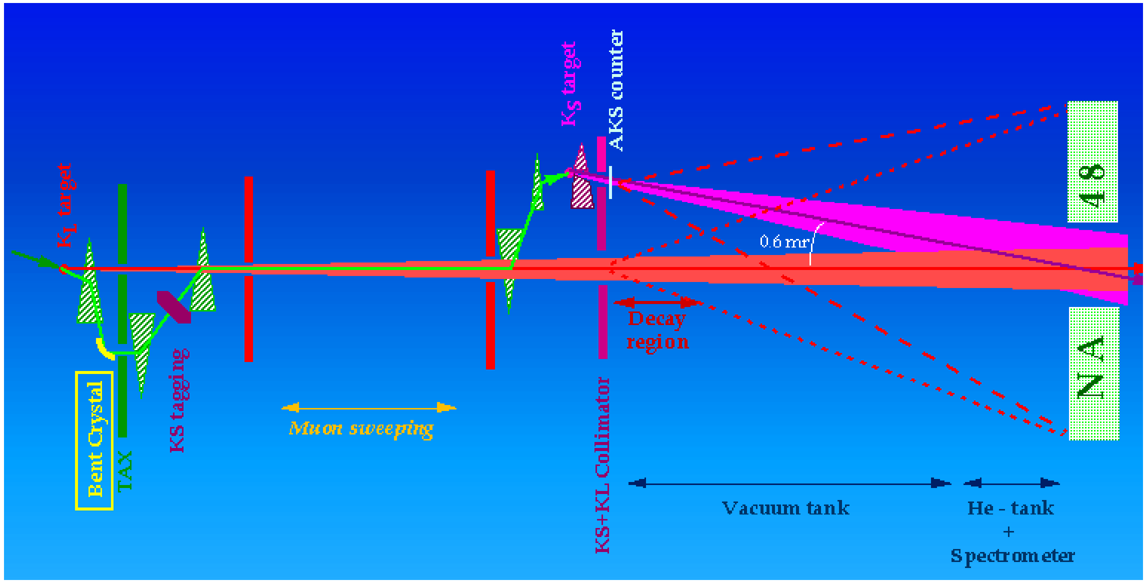
Data-taking 1997-1999



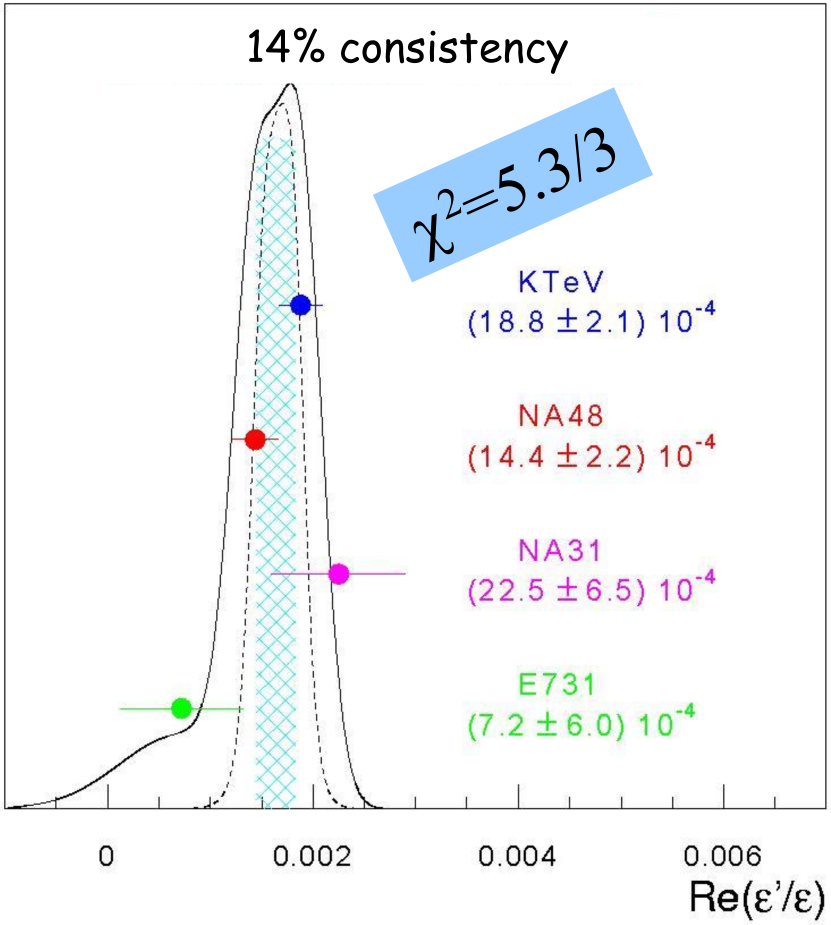


NA48 @ CERN

Two targets at different distances (K_L/K_S)
Converging beams (100 GeV/*c*)
Quasi-homogeneous liquid Krypton EM calorimeter
Kaon tagging by time of flight method
Event weighting minimizes acceptance correction
Data-taking 1997-2001



ε'/ε results



(Including ΔI=3/2 correction)

$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.4 \pm 1.9) \cdot 10^{-4}$

[PDG-rescaled error]

[Final 2008]

[Final 2003]

Direct CP violation
evidence > 9σ …
after 36 years!

ε'/ε – meaning

First test of CKM paradigm for CP violation

CPV as a property of weak interactions

$$\frac{\Gamma(K^0\to\pi^+\pi^-)-\Gamma(\overline{K}^0\to\pi^+\pi^-)}{\Gamma(K^0\to\pi^+\pi^-)+\Gamma(\overline{K}^0\to\pi^+\pi^-)}=(5.18\pm0.61)\times10^{-6}$$

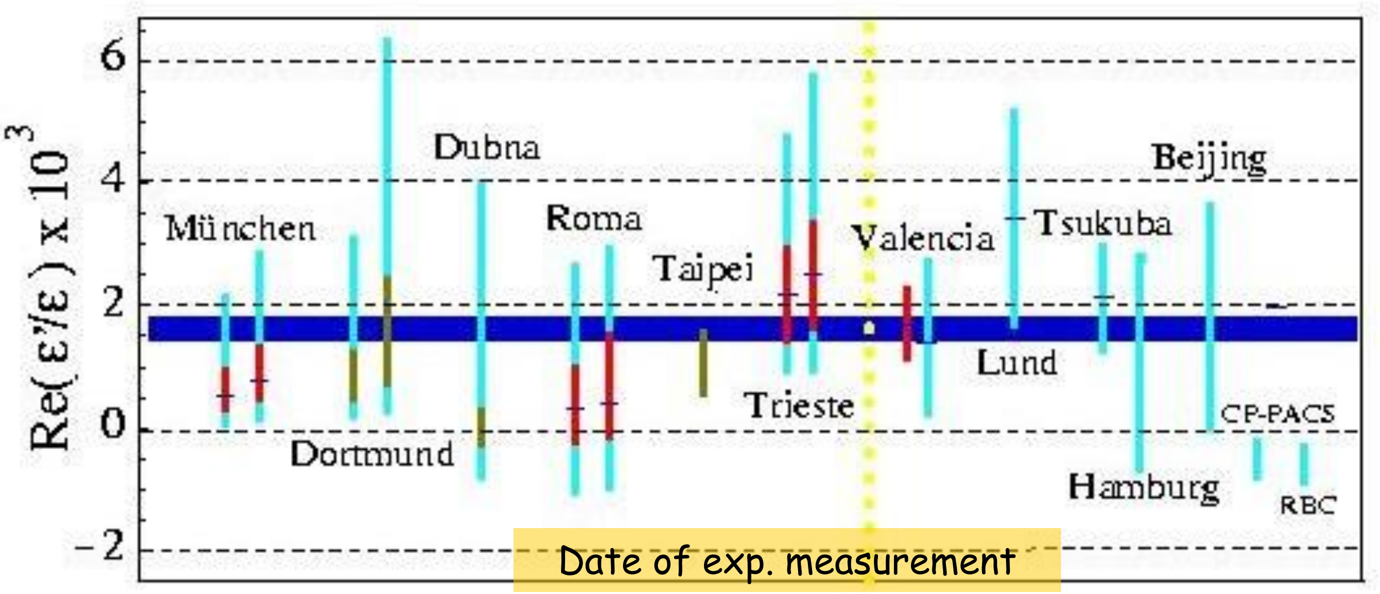
(BR=2.0·10^{-3})
O(10^7) events

Compare with e.g.

$$A_{CP}(B^0\to\eta K^*(892))=0.19\pm0.05$$

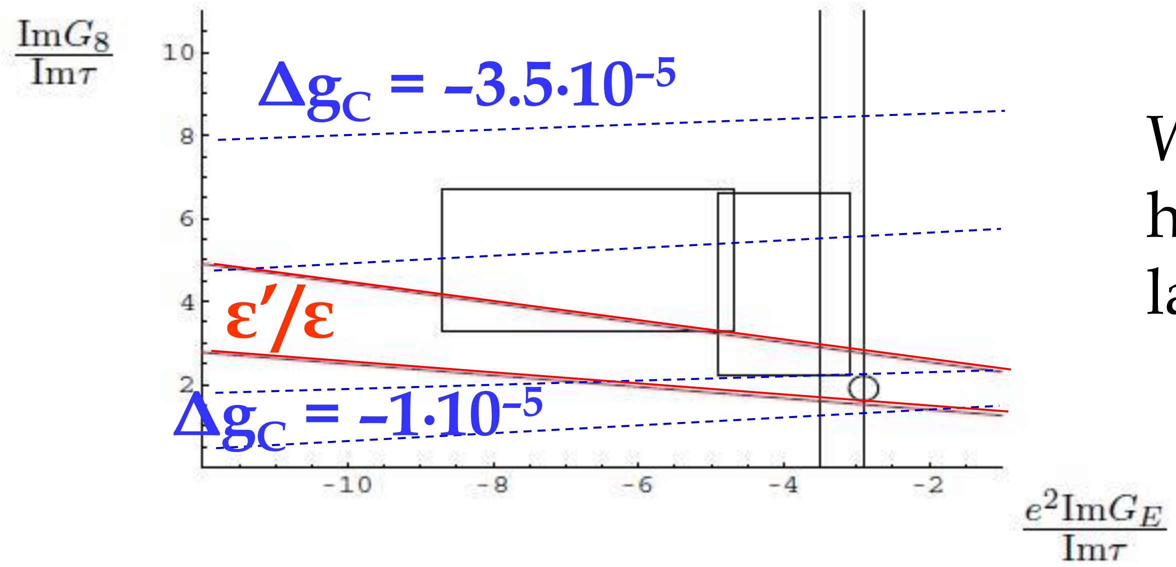
(BR=1.5·10^{-5})   O(10^3) events

ε'/ε - theory

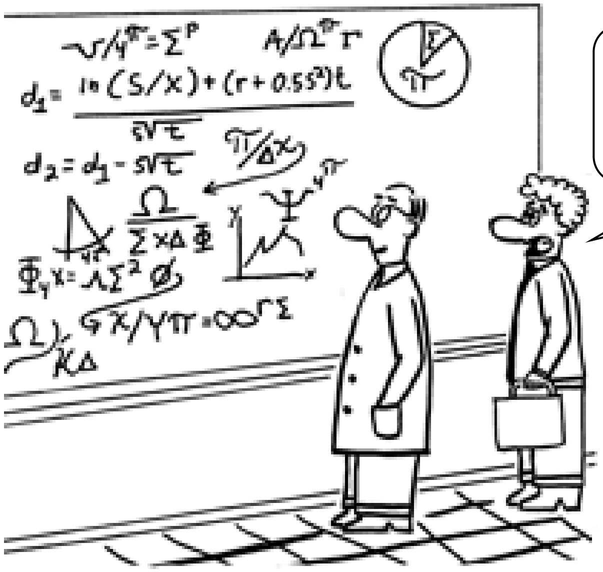


Extremely hard to keep the non-perturbative part of the computation under control: accidental cancellation of two terms. Lattice QCD challenge.

ε'/ε: quantitative ?



Worst theoretical hadronic nightmare, large cancellations



Expect 20% result on ε'/ε in ~3 years.

(June 10, 2009)

Not there yet but not giving up…

ε'/ε: quantitative ?

$\Delta I = 1/2$ $K \rightarrow \pi\pi$: **Future**

- Goal is a 20% calculation of ε'/ε with all errors controlled
- Repeat $\Delta I = 3/2$ kinematics
  - Use 32^3 x 64 volume with $1/a = 1.37$ GeV
  - Achieve $p = 205$ MeV from **G-parity** boundary conditions
- BG/Q gives 20 x speedup
- Begin configuration generation, 7/2013
- Result expected in 2 years

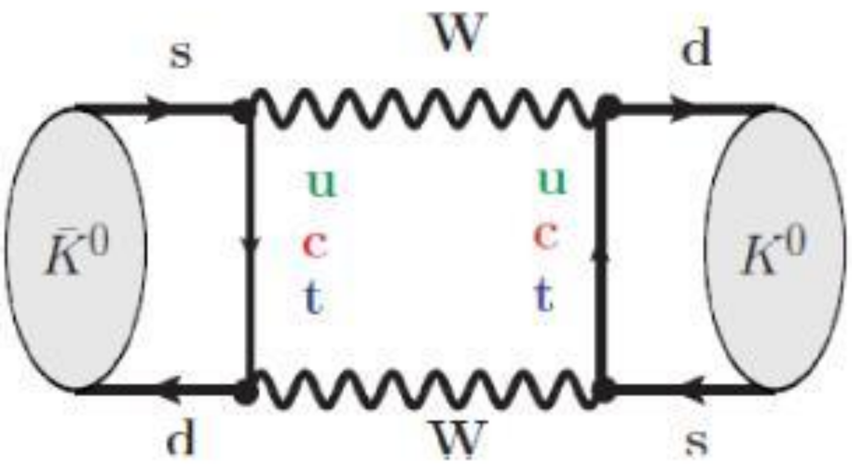
Kaon13 April 30, 2013

© N. Christ

Kaons come in different kinds…

The “well-known” CPV road

ε: indirect CPV in K mixing

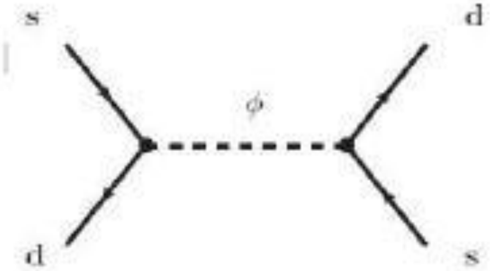


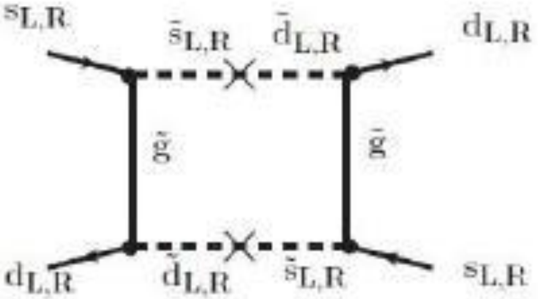
- governed by one single operator $(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}$
- CP-conserving quantities (e. g. ΔM_K) affected by long distance contributions
- CP-violation (ε_K) governed by short-distance physics
  ► theoretically much cleaner

© M. Blanke

ε: a powerful constraint

- small NP contribution welcome – but many models yield **huge** effects (e. g. SUSY, RS, TC, LHT, LR, . . .)





- chiral enhancement of non-SM operators and absence of NP flavor protection leads to strong generic constraint UTFIT (2007)

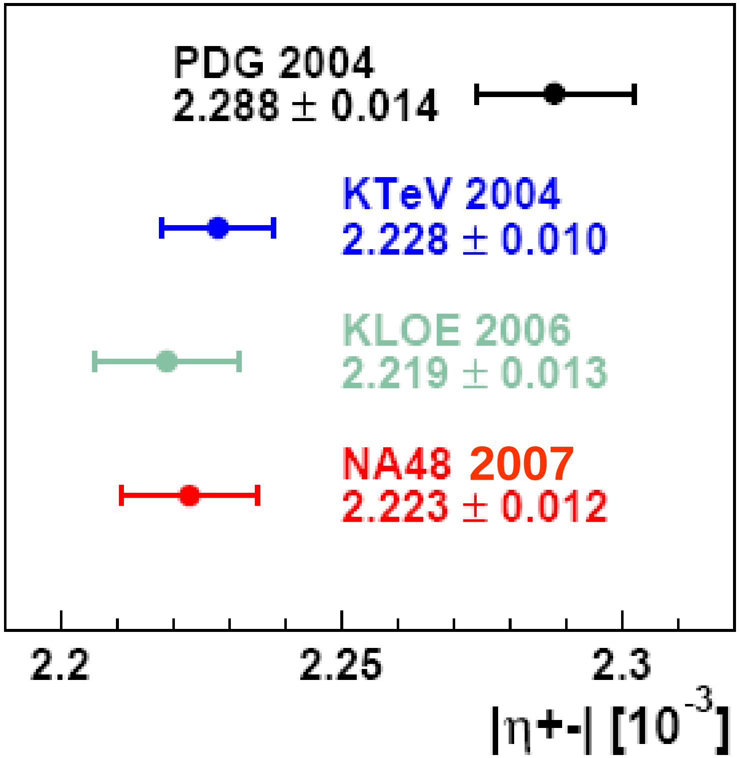
$\Lambda_{\text{NP}} \gtrsim 10^5$ TeV $\sim 10^5 \times$ scales probed by LHC!

► **TeV-scale NP must have a very non-generic flavor structure**

KTeV, KLOE, NA48: ε

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \cong \varepsilon + \varepsilon' \approx \varepsilon$$

KTeV: direct measurement of
BR(KL→$\pi^+\pi^-$)/BR(KL→πeν)
84K events in 1997
KLOE: direct measurement of
BR($K_L \to \pi^+\pi^-$)/BR($K_L \to \pi\mu\nu$)
45K events from subsample of 2001-2002 data
NA48: direct measurement of
BR(KL→$\pi^+\pi^-$)/BR(KL→πeν)
47K events from 2-day run in 1999



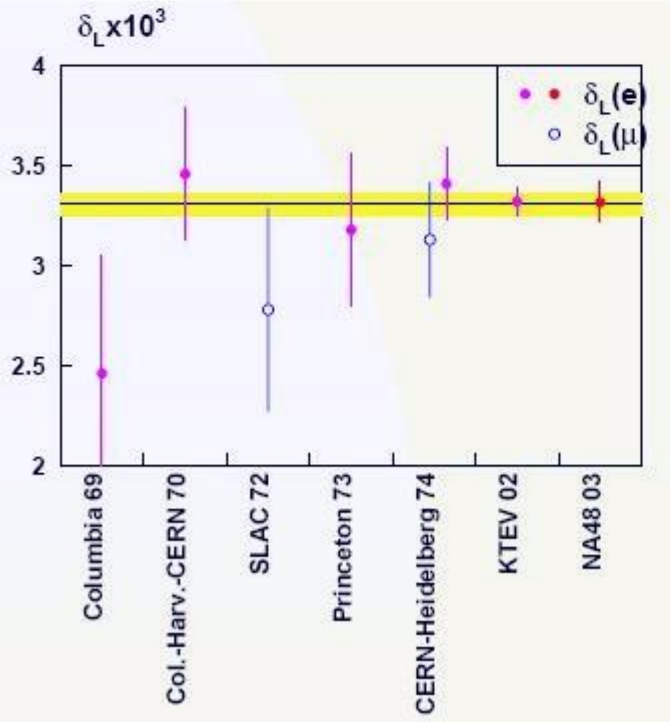
"The BR revolution"
- Proper treatment of radiative corrections
- Several correlations

KTeV, NA48: ε

Precision measurements from semi-leptonic K_L charge asymmetries at KTeV and NA48 using some 100M of decays per experiment:

$$\delta_L(\ell) = \frac{\Gamma(K_L \to \pi^- \ell^+ \nu) - \Gamma(K_L \to \pi^+ \ell^- \overline{\nu})}{\Gamma(K_L \to \pi^- \ell^+ \nu) + \Gamma(K_L \to \pi^+ \ell^- \overline{\nu})} = \frac{2\,\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}$$

(assuming CPT)



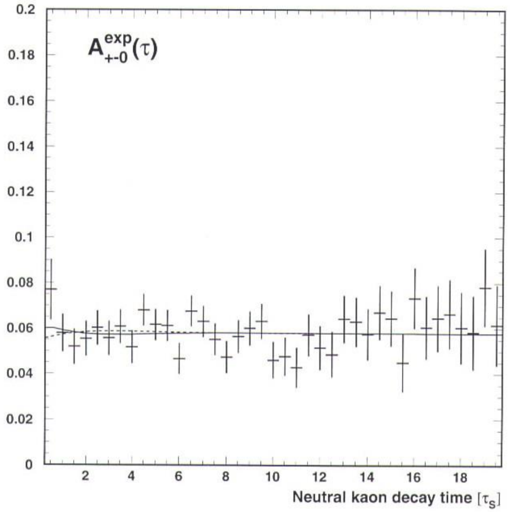
$$\delta_L(e) = (3.322 \pm 0.055)\cdot 10^{-3}$$

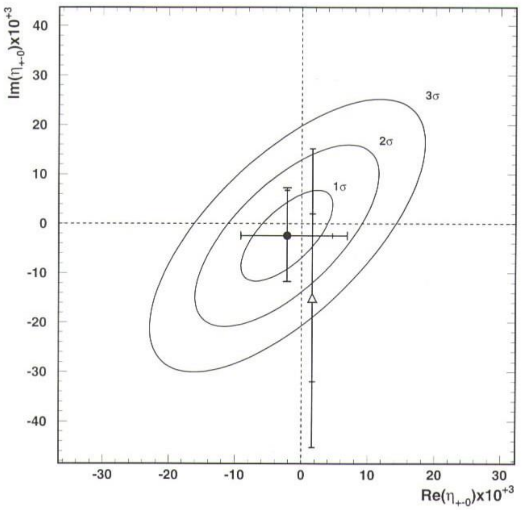
$K^0 \to \pi^+\pi^-\pi^0$

Not a CP eigenstate (but CP –1 dominant)

$$\eta_{\pi\pi\pi} = \frac{\int A^*(K_L \to 3\pi; CP=-1)\, A(K_S \to 3\pi; CP=-1)\, \mathrm{d}\Omega}{\int \left| A(K_L \to 3\pi; CP=-1) \right|^2 \mathrm{d}\Omega}$$

$$A_{CP}(3\pi) = \frac{P(\overline{K}^0 \to 3\pi) - P(K^0 \to 3\pi)}{P(\overline{K}^0 \to 3\pi) + P(K^0 \to 3\pi)} = 2\,\mathrm{Re}(\varepsilon + \delta) - 2\left|\eta_{3\pi}\right| e^{-\Delta\Gamma t/2} \cos(\Delta m + \phi_{3\pi})$$





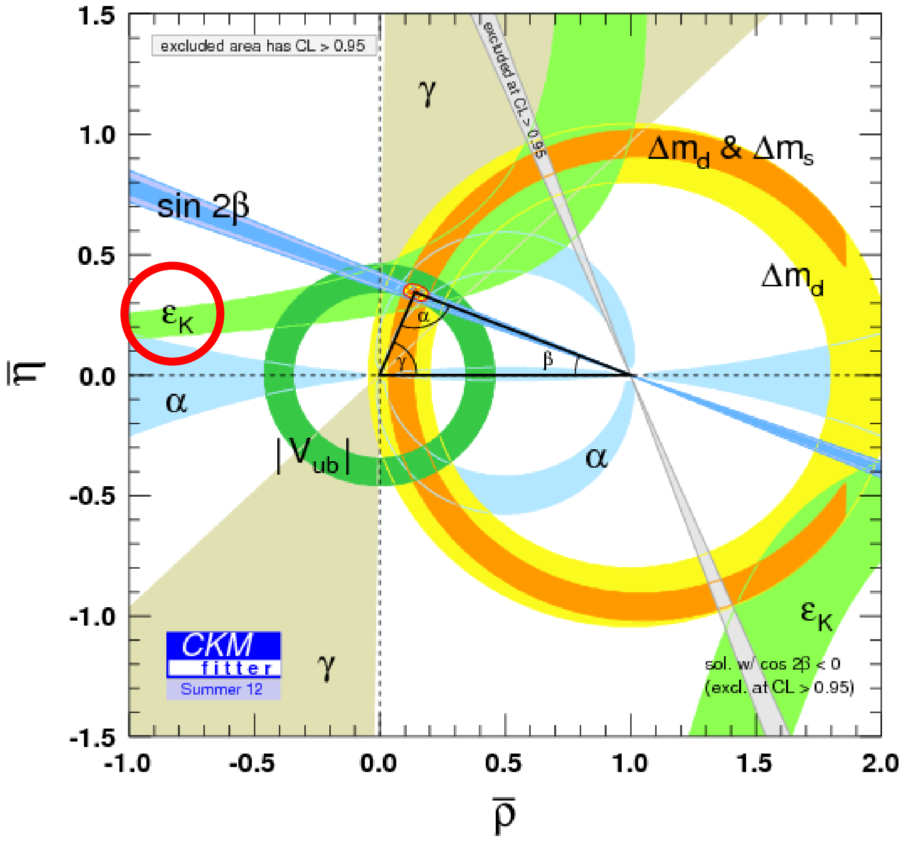
CPLEAR (1998):

$\mathrm{Re}(\eta_{+-0}) = (-2 \pm 8)\cdot 10^{-3}$

$\mathrm{Im}(\eta_{+-0}) = (-2 \pm 9)\cdot 10^{-3}$

ε confronts the SM

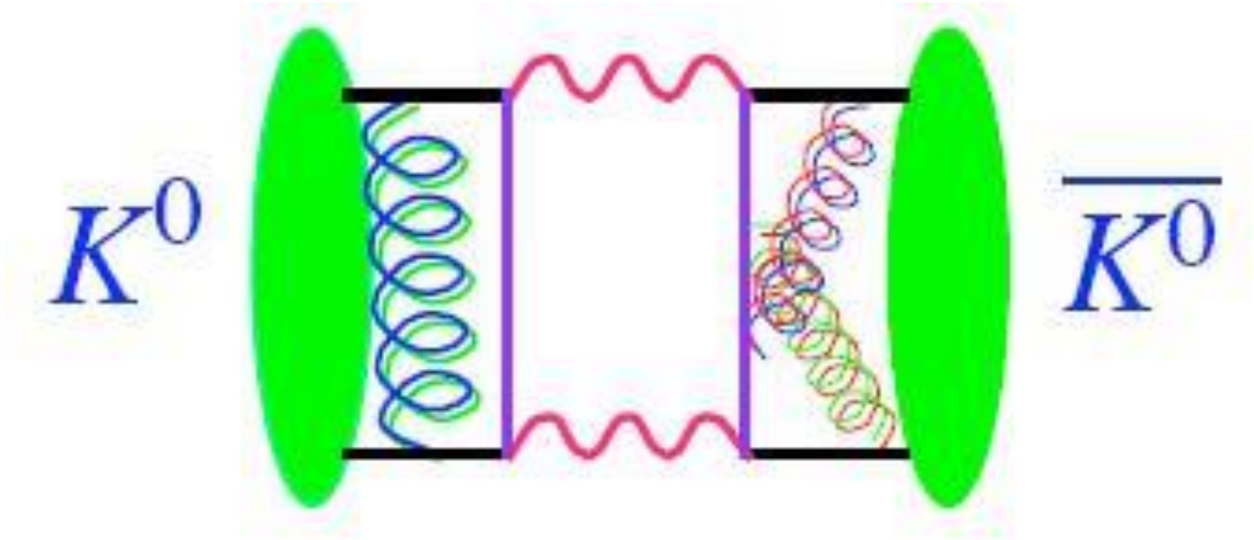
$\varepsilon \neq 0$ constrains (poorly) the apex of the Unitarity Triangle due to the theoretical difficulty in handling the hadronic uncertainties

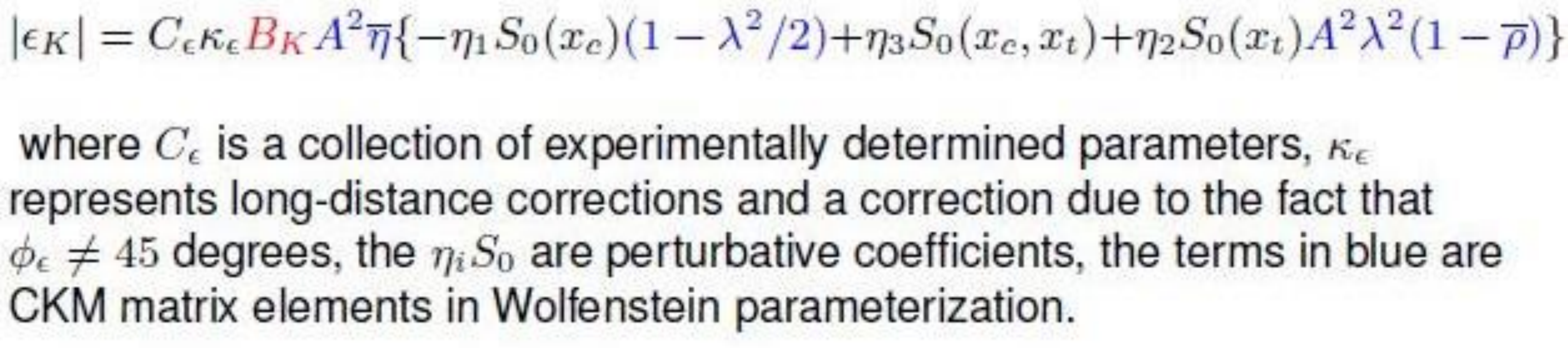


ε measured to 0.5%
With lattice QCD
K Now also contributing
to *quantitative* test of SM

Kaon sector

ε confronts theoreticians

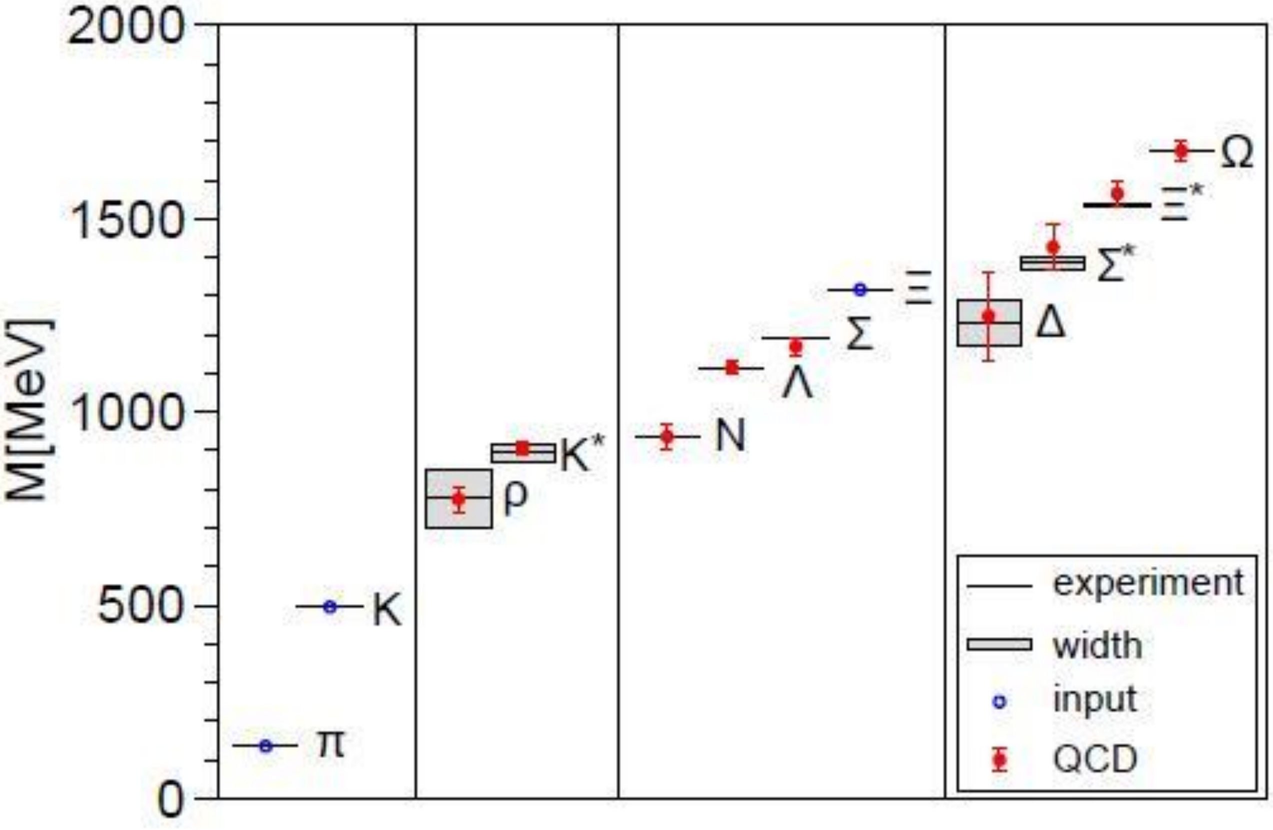




$$|\epsilon_K| = C_\epsilon \kappa_\epsilon B_K A^2 \overline{\eta} \{-\eta_1 S_0(x_c)(1-\lambda^2/2) + \eta_3 S_0(x_c, x_t) + \eta_2 S_0(x_t) A^2 \lambda^2 (1-\overline{\rho})\}$$

where C_ϵ is a collection of experimentally determined parameters, κ_ϵ represents long-distance corrections and a correction due to the fact that $\phi_\epsilon \neq 45$ degrees, the $\eta_i S_0$ are perturbative coefficients, the terms in blue are CKM matrix elements in Wolfenstein parameterization.

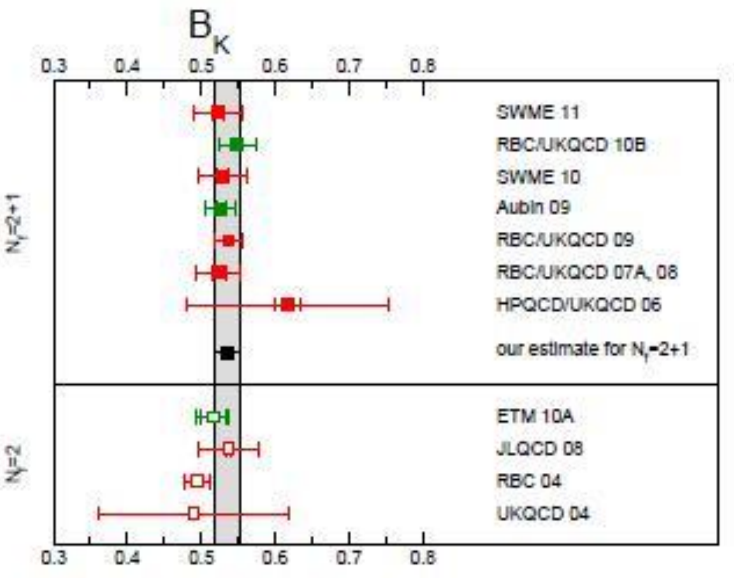
Lattice QCD

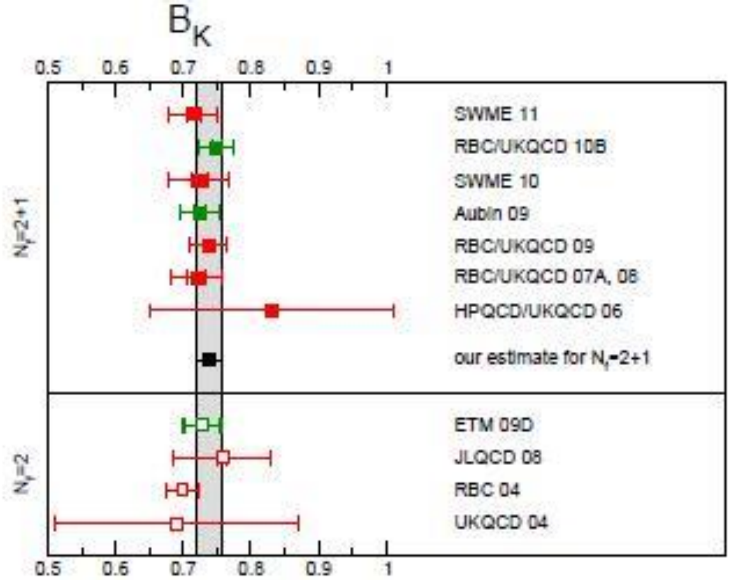


BMW Collaboration, Science 322:1224-1227, 2008.

M.S. Sozzi

The bag factor



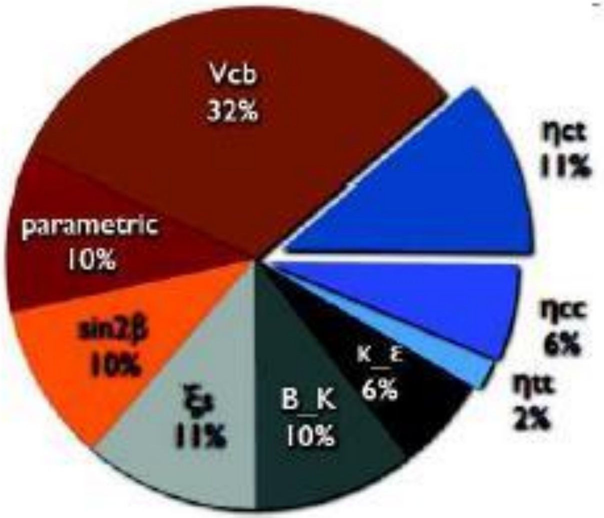


$$N_f = 2+1: \qquad B_K^{\overline{\mathrm{MS}}}(2\mathrm{GeV}) = 0.536(17) \qquad \hat{B}_K = 0.738(20)$$

$$N_f = 2: \qquad B_K^{\overline{\mathrm{MS}}}(2\mathrm{GeV}) = 0.516(18)(12) \qquad \hat{B}_K = 0.729(25)(17)$$

So, what about ε_K ?

- theory error now dominated by parametric uncertainties, in particular $|V_{cb}|$



SM prediction: Brod, Gorbahn (2011)

$$|\varepsilon_K| = 1.81(28) \cdot 10^{-3}$$

data: PDG (2010)

$$|\varepsilon_K| = 2.228(11) \cdot 10^{-3}$$

► a hint for new physics?

© M. Blanke

CPV in hadronic K_S decays

3π states are (predominantly) CP-odd

$CP(\pi^0\pi^0\pi^0) = -1$

$CP(\pi^+\pi^-\pi^0) = \pm1$ $(I=0,2: CP=+1, L>0;\ \ I=1,3: CP=-1, L=0)$

$$\eta_{+-0} = \frac{A(K_S \to \pi^+\pi^-\pi^0; CP=-1)}{A(K_L \to \pi^+\pi^-\pi^0)}$$

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)}$$

Assuming CPT and ΔI<5/2 for transitions:

$$\eta_{+-0} = \eta_{000} = \varepsilon + i\,\mathrm{Im}(A_1)/\mathrm{Re}(A_1)$$

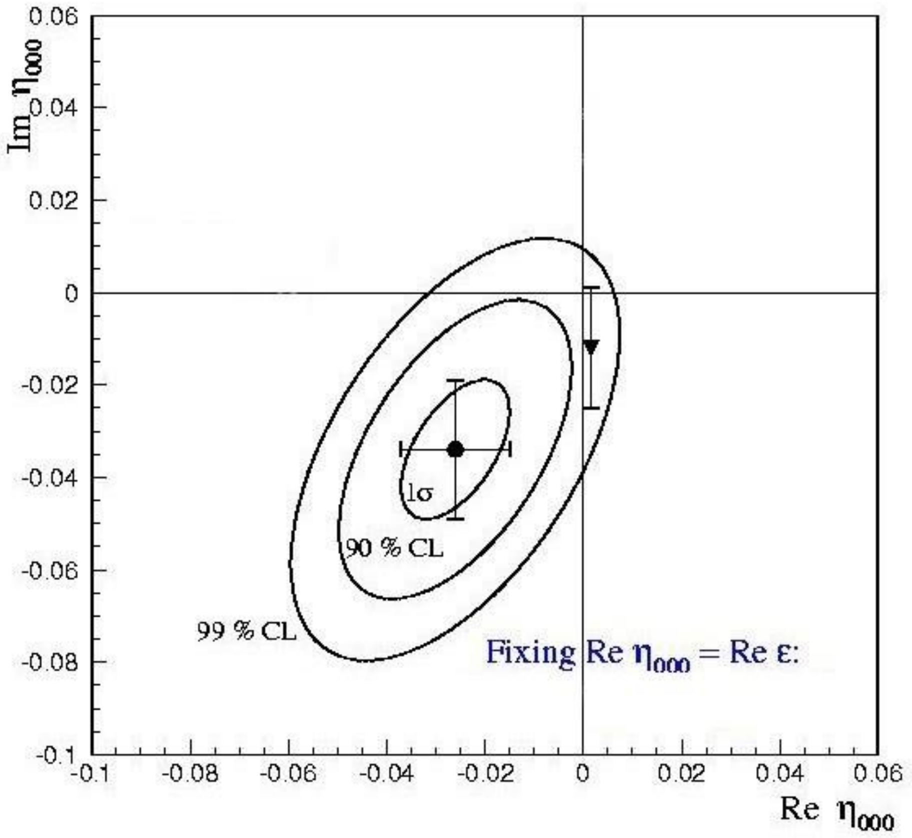
"Mixing" "Decay"

Estimate (indirect CPV): $\Gamma_S(3\pi) \approx \Gamma_L(3\pi)|\eta|^2$, or

$BR(K_S \to 3\pi^0) \approx BR(K_L \to 3\pi^0)\ |\varepsilon|^2\ (\tau_S/\tau_L) \approx 1.9\cdot10^{-9}$

$K_S \rightarrow 3\pi$ at hadron machines

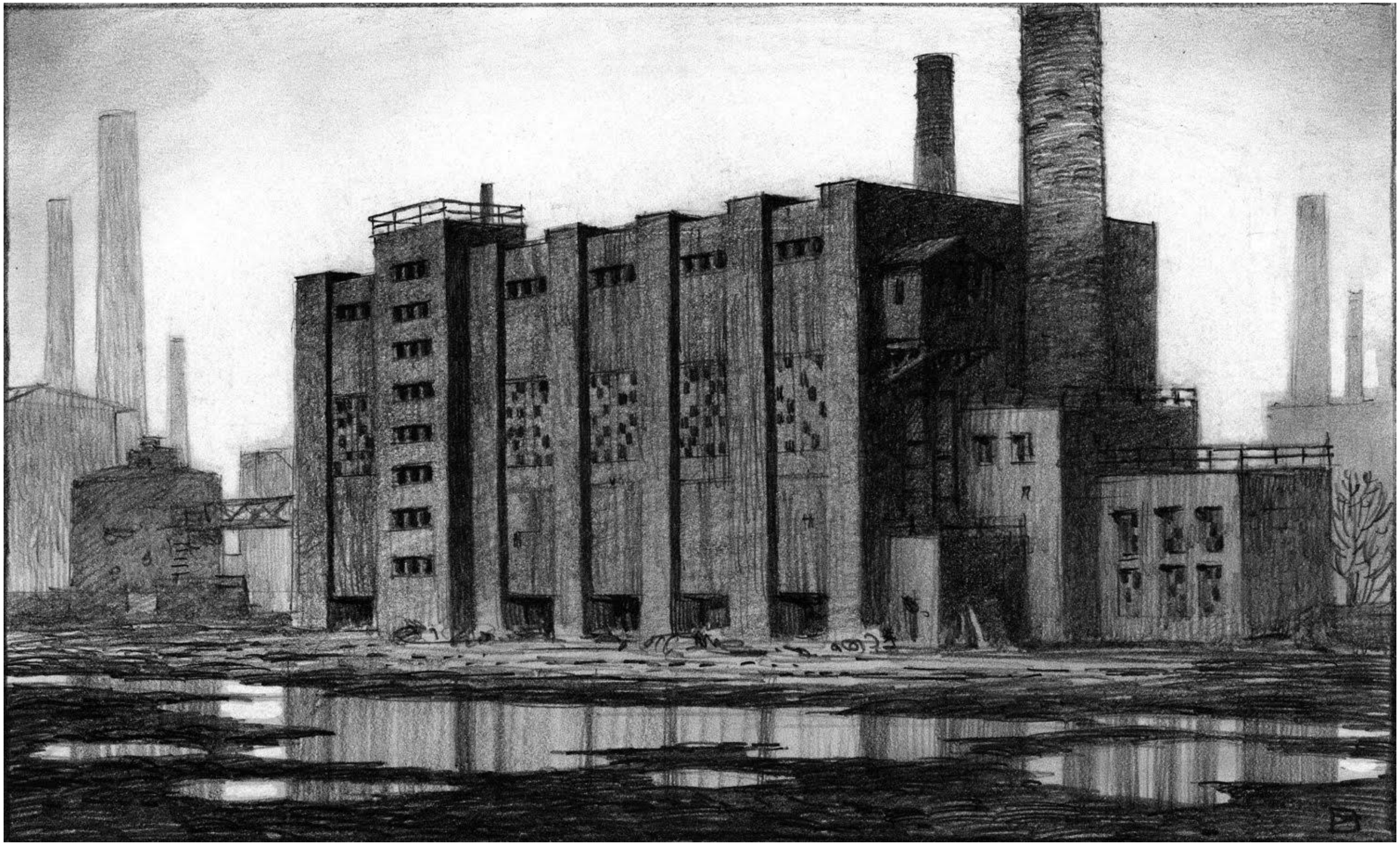
Look for K_S-K_L interference
NA48/1 @ CERN (2005)
with 5+100 million K decays



$\mathrm{Re}(\eta_{000}) = -0.002 \pm 0.019$
$\mathrm{Im}(\eta_{000}) = -0.003 \pm 0.021$

Assuming CPT:

$\mathrm{BR}(K_S \to 3\pi^0) < 2.3\times10^{-7}$ (90% CL)



K factories

K: production (colliders)

- K^+K^- or $K^0\overline{K}^0$ pairs can be produced at $p\overline{p}$ or e^+e^- colliders, enhanced at resonances.
  At high (>> threshold) energies relative production cross sections are small.
- For e^+e^- the production is EM.
  In particular a "strangeonium" ($s\overline{s}$) state, above open strangeness threshold, such as Φ(1020 MeV) has $BR(\Phi \to K\overline{K}) \approx 83\%$:
  A "kaon factory" or "Φ factory" (analogous to B-factories).

Kaon factories

[Lipkin (1968)]

$e^+e^- \to \Phi \to K\overline{K}$ at resonance $\sigma = 3.1\ \mu b$

$J^{PC}(\Phi) = 1^{--} \Rightarrow C(KK) = -1$ coherent state

($\Phi \to \overline{K}\underline{K}\gamma$, opposite C, negligible)

Bose statistics ⇒ Even with strangeness oscillations, the two K have to be always distinct (until one decays), i.e. K_SK_L or $K^0\overline{K}^0$ (and K^+K^-), but never K_SK_S, K^0K^0,…

EPR correlation: $$|i\rangle \propto \frac{1}{\sqrt{2}}\Big(|K_L,\mathbf{p}\rangle|K_S,-\mathbf{p}\rangle - |K_L,-\mathbf{p}\rangle|K_S,\mathbf{p}\rangle\Big)$$

- Tagging: observation of $K_S(K_L)$ signals presence of $K_L(K_S)$: unique "K_S beam" (almost monochromatic, kinematical constraints): absolute BR measurements, rare K_S decay searches

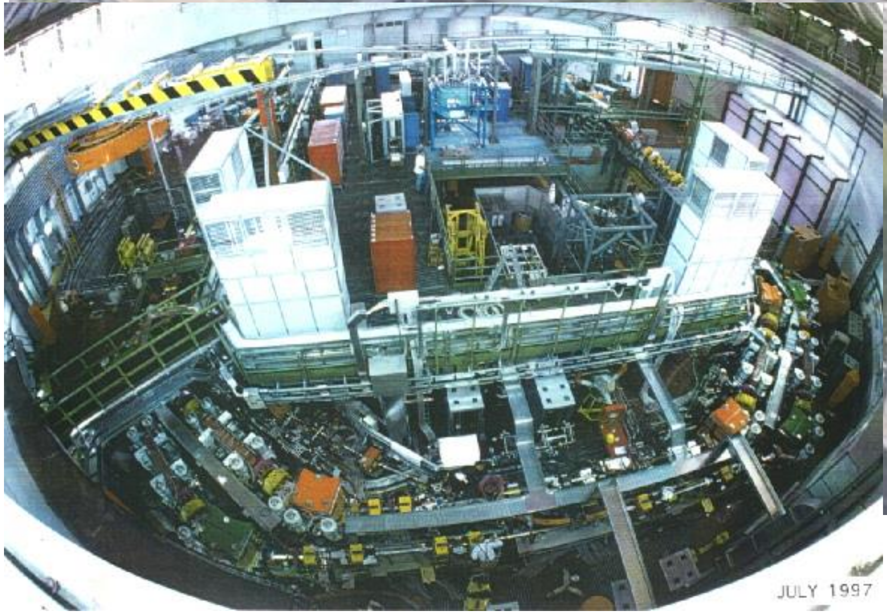
- QM correlation: allows interference measurements

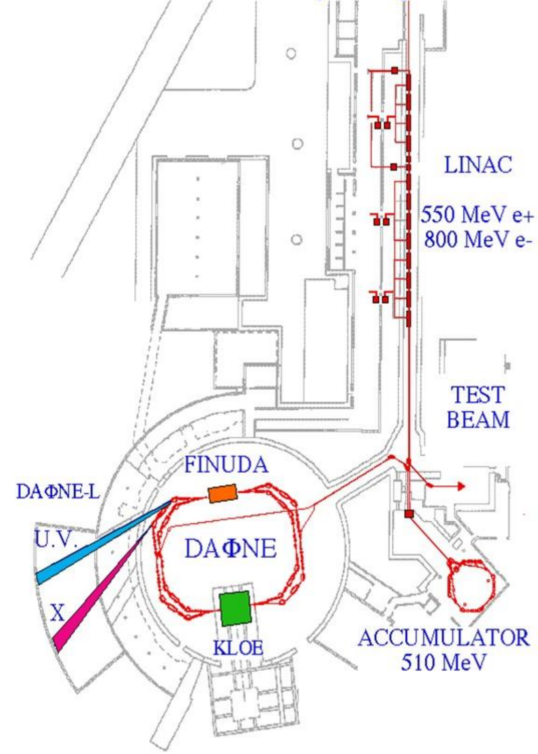
Resonant production (K-factory)

$\sigma(e^+ e^- \rightarrow \Phi) = 3.1\ \mu b$ $\sigma(e^+ e^-) = 0.17\ \mu b$

	BR	β_K	$\gamma\beta c\tau$ (cm)	P_{max} (MeV/c)
K^+K^-	0.49	0.249	95.4	127
K_SK_L	0.34	0.216	343.8	110
$\rho\pi$	0.13			182
$\pi^+\pi^-\pi^0$	0.02			462
$\eta\gamma$	0.013			362
Other	≈ 0.1			

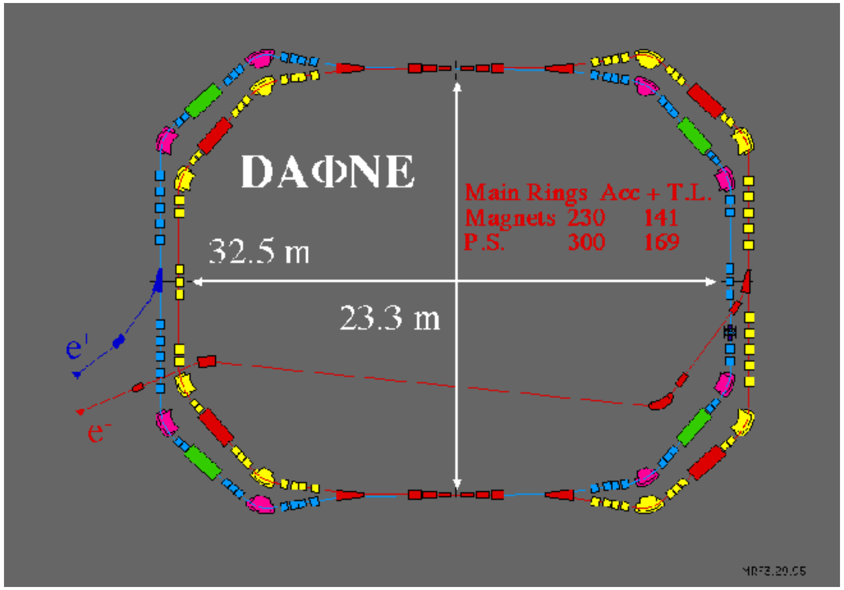
DAΦNE (Frascati)


JULY 1997



DAΦNE (Frascati)

- e^+e^- collider @ **$\sqrt{s}$ = m(Φ) = 1019.4 MeV**
- 2 interaction regions (KLOE – DEAR/FINUDA), 96m circumference
- Separate e^+ e^- rings to minimize beam-beam interactions
- Crossing angle: 12.5 mrad (p(Φ) ~ 12.5 MeV/c)
- Up to 120 bunches, spacing: 2.7 ns, E = 0.3-1.5 GeV (RMS ~ 10^{-3})



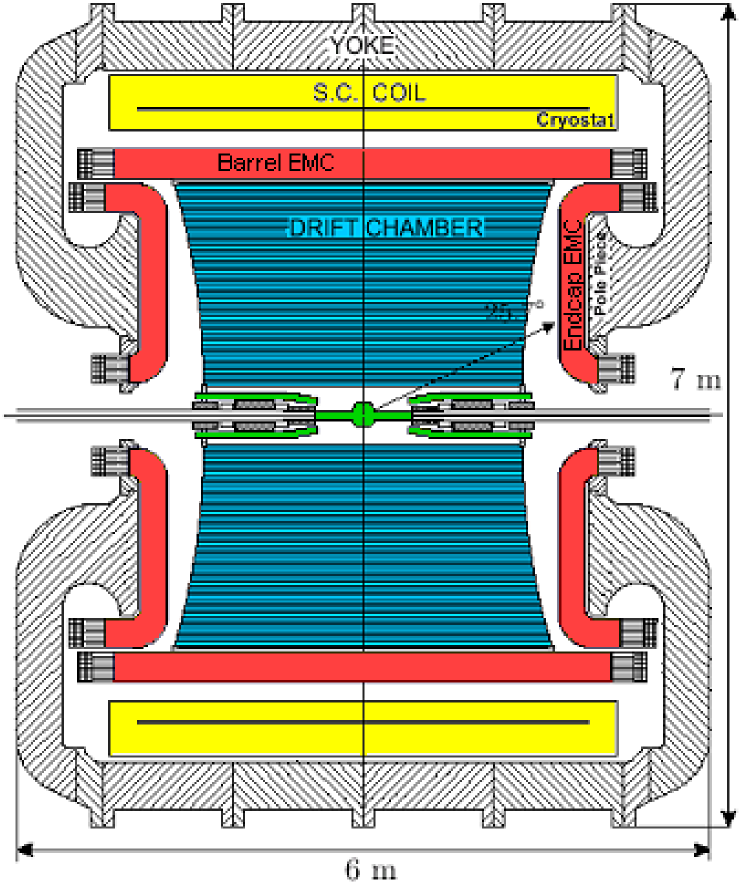
Design luminosity: **$5 \cdot 10^{32}$ cm^{-2} s^{-1}**
(1.5·10^{32} reached)

Integrated luminosity:
~ 2.7 fb-1 (2002-05)
(~ 8 · 10^9 Φ decays)

KLOE experiment

K^+K^-: $1.5 \times 10^6\,/\mathrm{pb}^{-1}$
$p^* = 127$ MeV/c
$\lambda = 95$ cm

K_LK_S: $10^6\,/\mathrm{pb}^{-1}$
$p^* = 110$ MeV/c
$\lambda_S = 6$ mm K_S decays near interaction point
$\lambda_L = 3.4$ m   Need large detector ($r \sim 0.3\,\lambda_L$)



Be beam pipe

Spherical, small (10 cm ∅), thin (0.5 mm)

Instrumented permanent magnet quadrupoles

Drift chamber

Light (MS), large (tracking)

Electromagnetic calorimeter

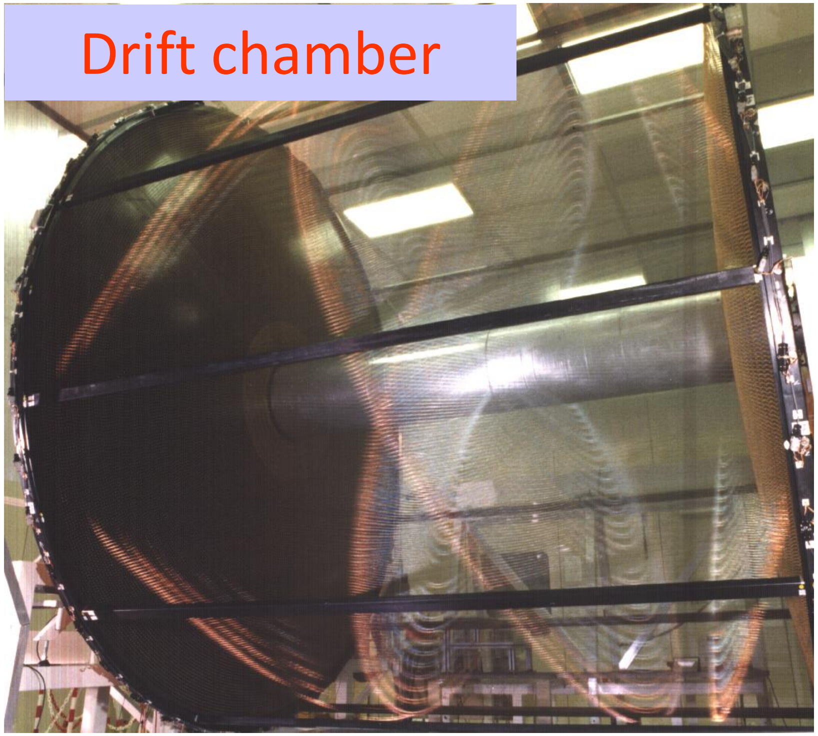
Inside coil. hermeticity, high resolution in E and time

Superconducting coil

(B = 0.52 T)

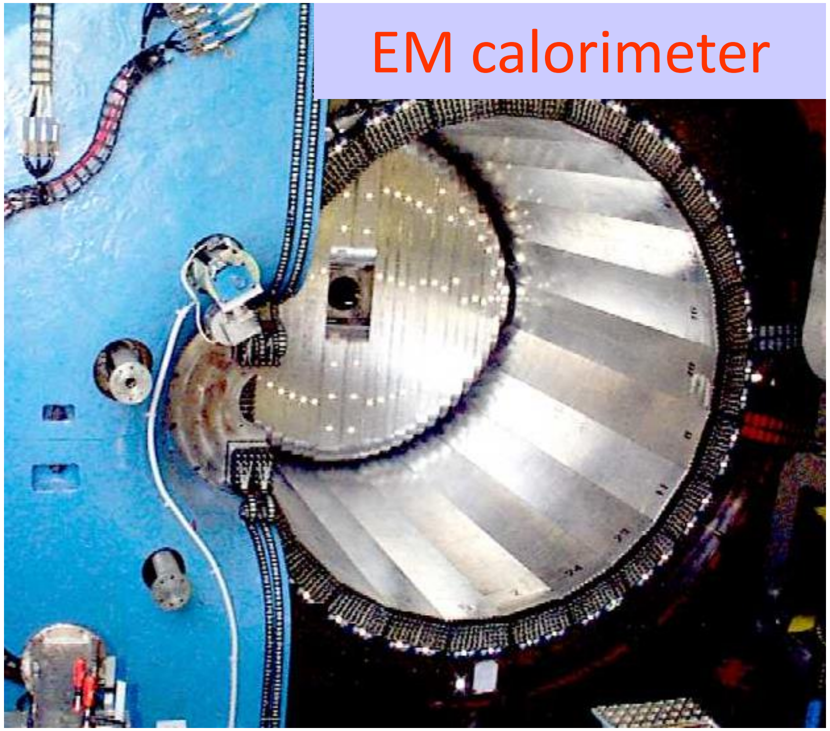
Physics: The Kaon sector

KLOE detector



Drift chamber

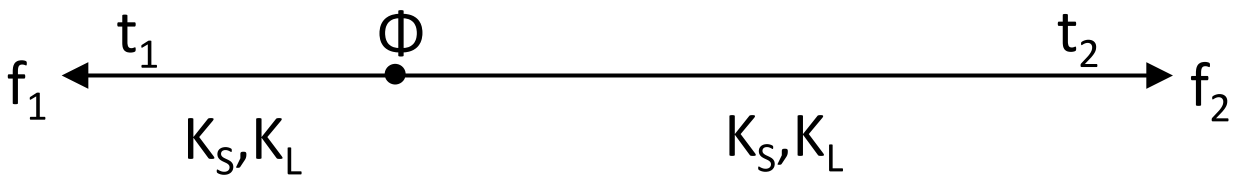
Large (4 m ∅ × 3.75 m, C frame)
Very light (gas: 90% He + 10% C_4H_{10})
12582 stereo–stereo sense wires
$\sigma_p/p = 0.4$ %
σ_x(hit) = 150 mm (*xy*), 2 mm (*z*)
σ_x(vertex) ~ 1 mm
$\sigma(m_{\pi\pi})$ ~ 1 MeV/c^2



EM calorimeter

Lead/scintillating fibres (1 mm ∅), 15 X_0
4880 PMTs
98% solid angle coverage
$\sigma_E/E = 5.7\% / \sqrt{E(\mathrm{GeV})}$
Excellent time resolution (vertexing):
$\sigma_t = 54$ ps $/\sqrt{E(\mathrm{GeV})} \oplus 50$ ps
$\sigma_x(\mathrm{vertex})_{\gamma\gamma}$ ~ 1.5 cm

Interferometry



$$I(f_1,f_2;\Delta t)=\frac{1}{2}\int_{\Delta t}^{\infty}\left|A(f_1,f_2;\Delta t,t)\right|^2 dt=$$

$$\frac{1}{2\Gamma}\left|\langle f_1|K_S\rangle\langle f_2|K_S\rangle\right|^2\left(|\eta_1|^2e^{-\Gamma_L\Delta t}+|\eta_2|^2e^{-\Gamma_S\Delta t}-2|\eta_1||\eta_2|e^{-\Gamma\Delta t/2}\cos(\Delta m\Delta t+\phi_1-\phi_2)\right)$$

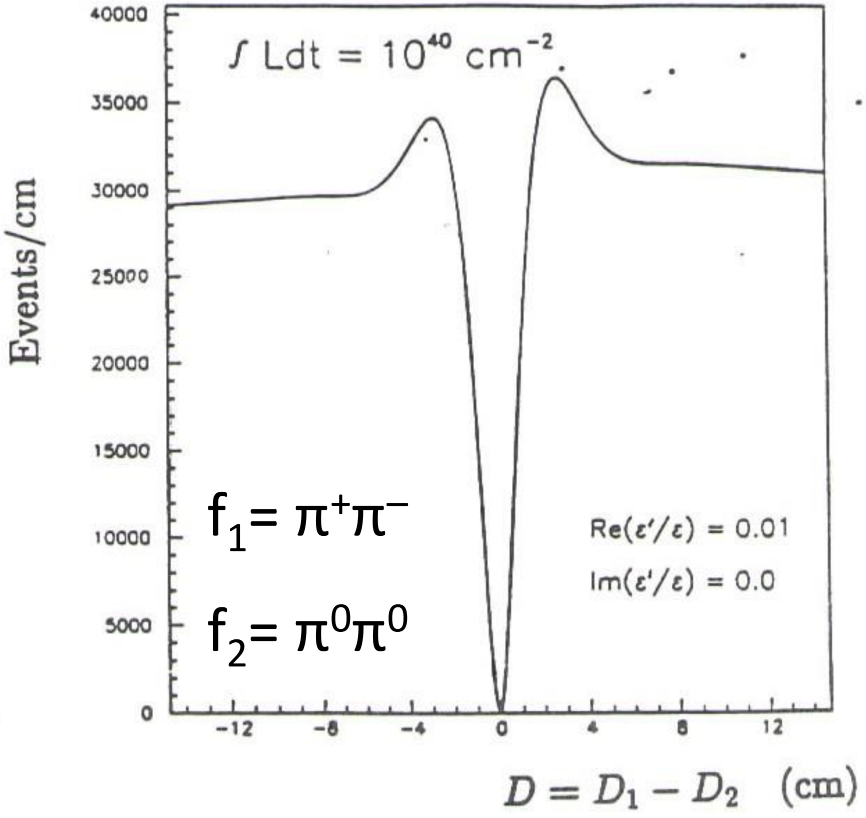
Correlated decays to same or different final states:

- $f_1 = f_2 \Rightarrow \Gamma_L, \Gamma_S, \Delta m$
- $\pi\pi, \pi\pi \Rightarrow \mathrm{Re}(\varepsilon'/\varepsilon), \mathrm{Im}(\varepsilon'/\varepsilon) \approx 3(\phi_1 - \phi_2)$
- $\pi\ell\nu, \pi\ell\nu \Rightarrow$ T,CPT
- $\pi\pi, \pi\ell\nu \Rightarrow$ CPT

Interferometry

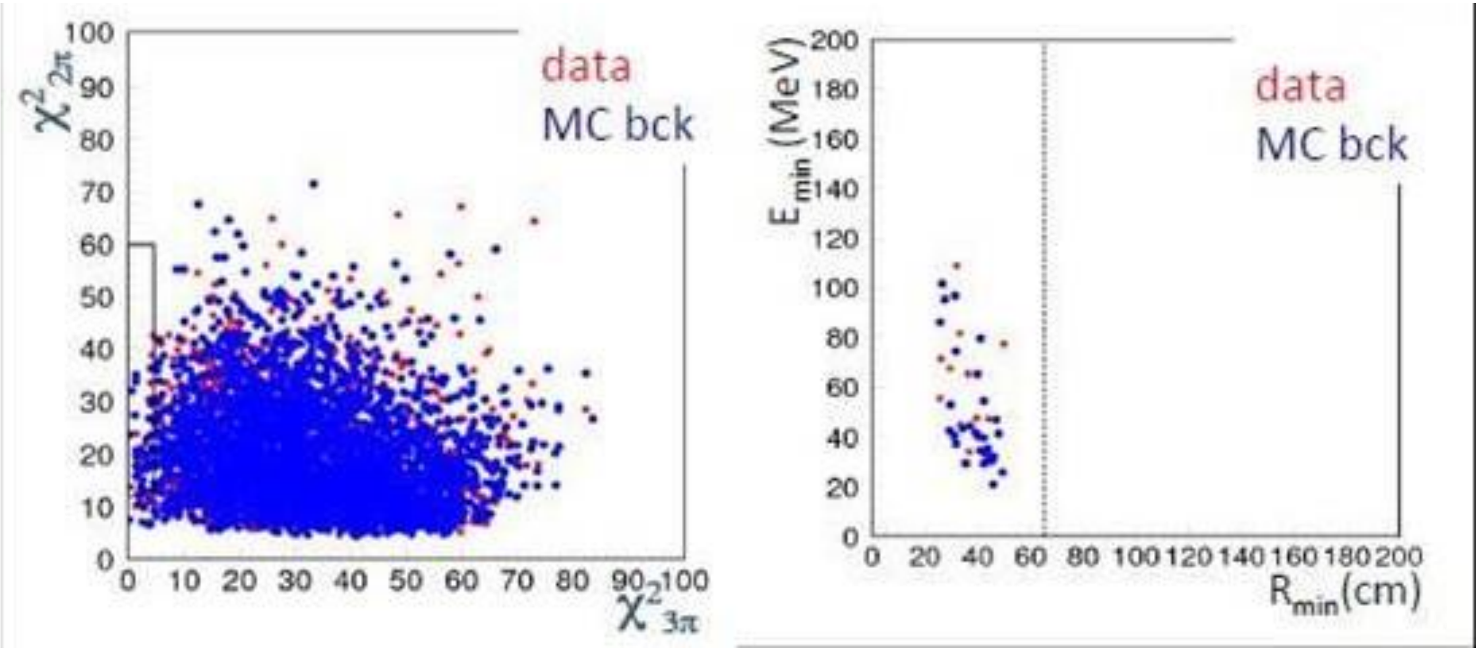
Measure of
$\mathrm{Im}(\varepsilon'/\varepsilon) = (\phi_{+-} - \phi_{00})/3$ by
interferometry
(region $\tau < 10\ \tau_S$)

Several tests of CP and CPT



$K_S \rightarrow 3\pi$ at ϕ factories

Search for tagged $K_S \to 3\pi^0$ decays



$BR(K_S \to 3\pi^0) < 2.6 \times 10^{-8}$ (90% CL)

No CPV in sight yet

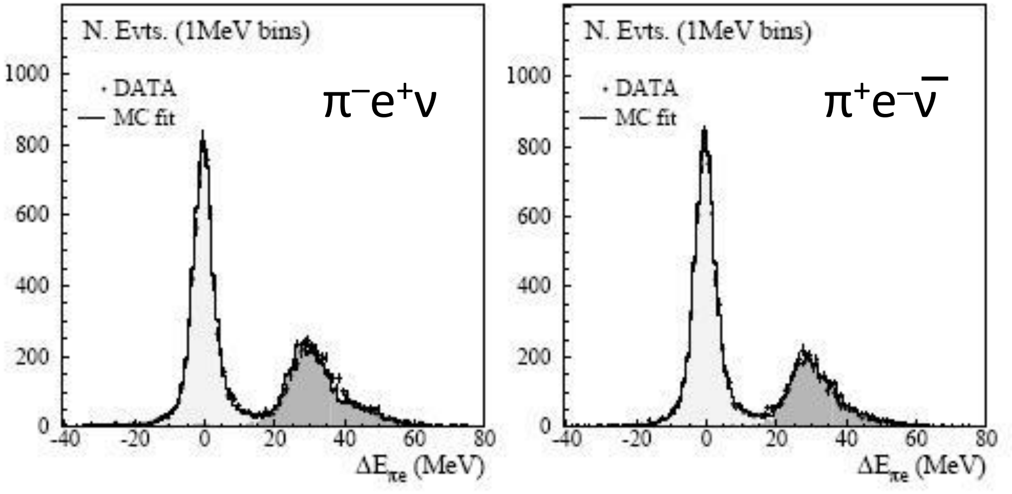
1.7 fb^{-1} of the statistics

KLOE: $\delta_S(e)$

First measurement of K_S semi-leptonic decays ($K_S \to \pi\mu\nu$ also seen):

$\mathrm{BR}(K_S \to \pi e \nu) = (7.028 \pm 0.092) \times 10^{-4}$

2001-2002 data (410 pb^{-1}):
13K events



(Indirect) CP-violating charge asymmetry:

$$\delta_S(e) = \frac{\Gamma(K_S \to \pi^- e^+ \nu) - \Gamma(K_S \to \pi^+ e^- \bar{\nu})}{\Gamma(K_S \to \pi^- e^+ \nu) + \Gamma(K_S \to \pi^+ e^- \bar{\nu})} = (1.5 \pm 9.6_{\mathrm{stat}} \pm 2.9_{\mathrm{syst}}) \cdot 10^{-3}$$

$\delta_S(\ell)$

$$\delta_S(\ell) = \frac{\Gamma(K_S \to \pi^- \ell^+ \nu) - \Gamma(K_S \to \pi^+ \ell^- \overline{\nu})}{\Gamma(K_S \to \pi^- \ell^+ \nu) + \Gamma(K_S \to \pi^+ \ell^- \overline{\nu})}$$

$$\delta_S = 2(\mathrm{Re}\,\varepsilon + \mathrm{Re}\,\delta - \mathrm{Re}\,y + \mathrm{Re}\,x_-)$$

$$\delta_L = 2(\mathrm{Re}\,\varepsilon - \mathrm{Re}\,\delta - \mathrm{Re}\,y - \mathrm{Re}\,x_-)$$

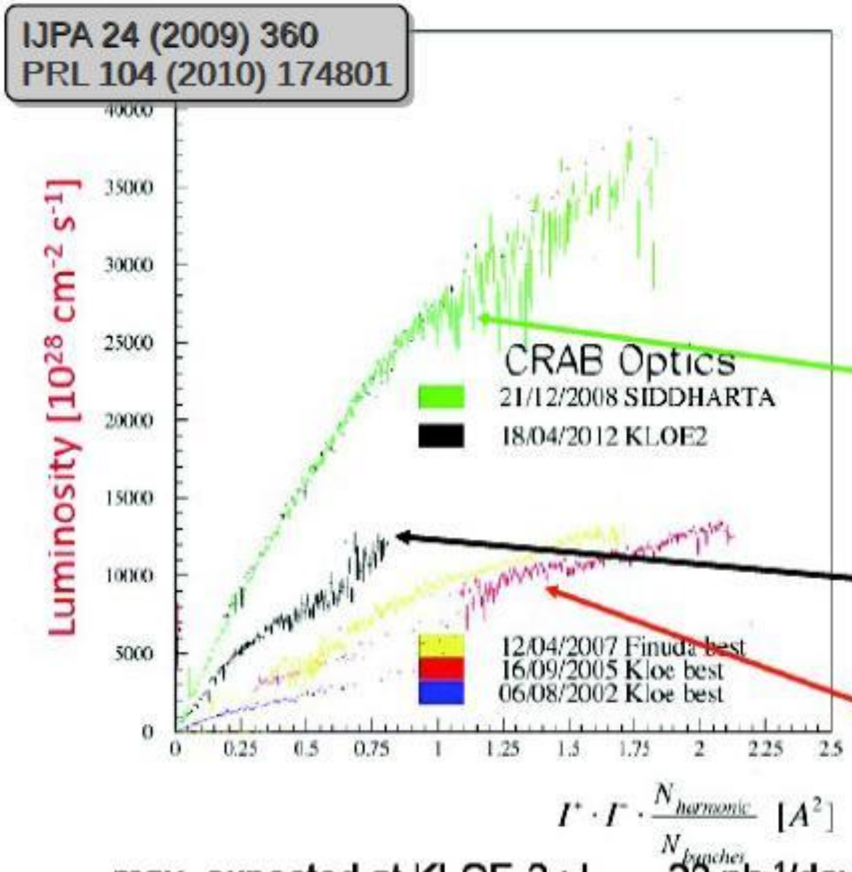
CPV in mixing	CPTV in mixing	CPTV in decay	CPTV and ΔS≠ΔQ

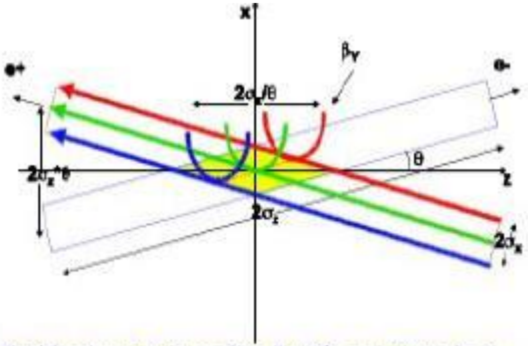
CPT test by comparison to $\delta_L(e)$ (still far from being significant)

Towards KLOE-2

Crabbed waist scheme at DAΦNE

IJPA 24 (2009) 360
PRL 104 (2010) 174801





Crabbed waist is realized with a sextupole in phase with the IP in X and at $\pi/2$ in Y

NEW COLLISION SCHEME:
Large Piwinski angle
Crab-Waist compensation SXTs

Present commissioning phase
New coll. scheme + KLOE det.

Old collision scheme

max. expected at KLOE-2 : L_{int} ~ 20 pb^{-1}/day x 200 dd/year = 4 fb^{-1} /year

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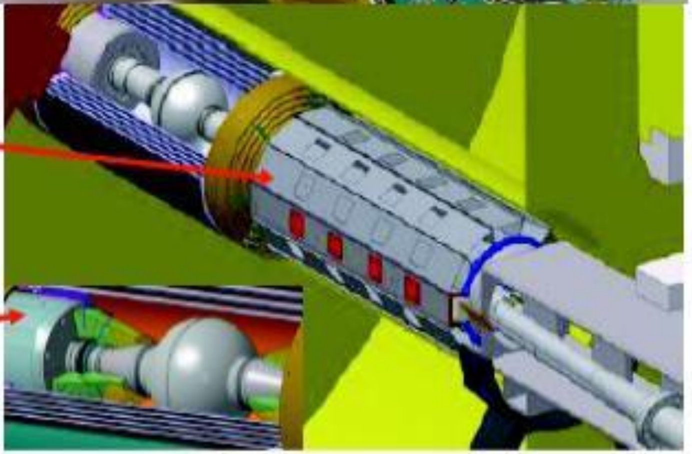
Towards KLOE-2



INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT

- W + scintillator tiles + SiPM/WLS
- Low-beta quadrupoles: coverage for K_L decays

CCALT

- LYSO + APD
- Increase acceptance for γ's from IP (21°→10°)

IT: NIMA 628 (2011),194
QCAL-T: NIMA 617 (2010),105
CCALT: NPB 197 (2009), 215

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Exploring the CKM matrix

Cabibbo angle from K_{l3}

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{Kl}(\lambda) (1+2\Delta_K^{SU(2)} +2\Delta_{Kl}^{EM})$$

Measure: radiation-inclusive **BRs** and **lifetimes**, **form-factors shapes** to compute phase-space integrals I_{Kl}

Compute: **vector form-factor scale** at zero momentum transfer f+(0), universal **short-distance EW correction** S_W, channel-dependent **isospin-breaking** $\Delta^{SU(2)}$ and **long-distance EM** Δ^{EM} corrections

Extract: modulus **$|V_{us}|$**

$$K^+ \rightarrow \pi^0 e^+ \nu \; (5.1\%)$$

$$K_L \rightarrow \pi^\pm e^\mp \nu \; (41\%)$$

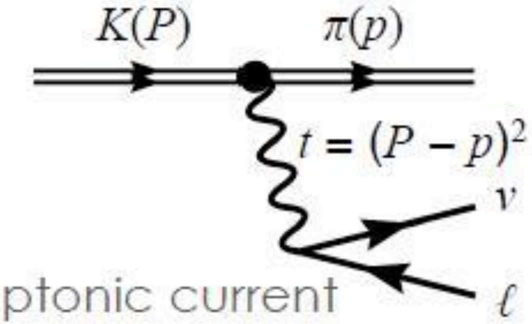
$$K_S \rightarrow \pi^\pm e^\mp \nu \; (7 \cdot 10^{-4})$$

$$K^+ \rightarrow \pi^0 \mu^+ \nu \; (3.4\%)$$

$$K_L \rightarrow \pi^\pm \mu^\mp \nu \; (27\%)$$

10^5-10^7 events samples
~0.1% background
(for K^+, K_L)

The small print...



Hadronic matrix element:

$$\langle \pi | J_\alpha | K \rangle = f(0) \times \left[\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha \right]$$

f_- term multiplied by m_ℓ when contracted with leptonic current

Ke3 decays: Only **vector form factor:** $\tilde{f}_+(t)$

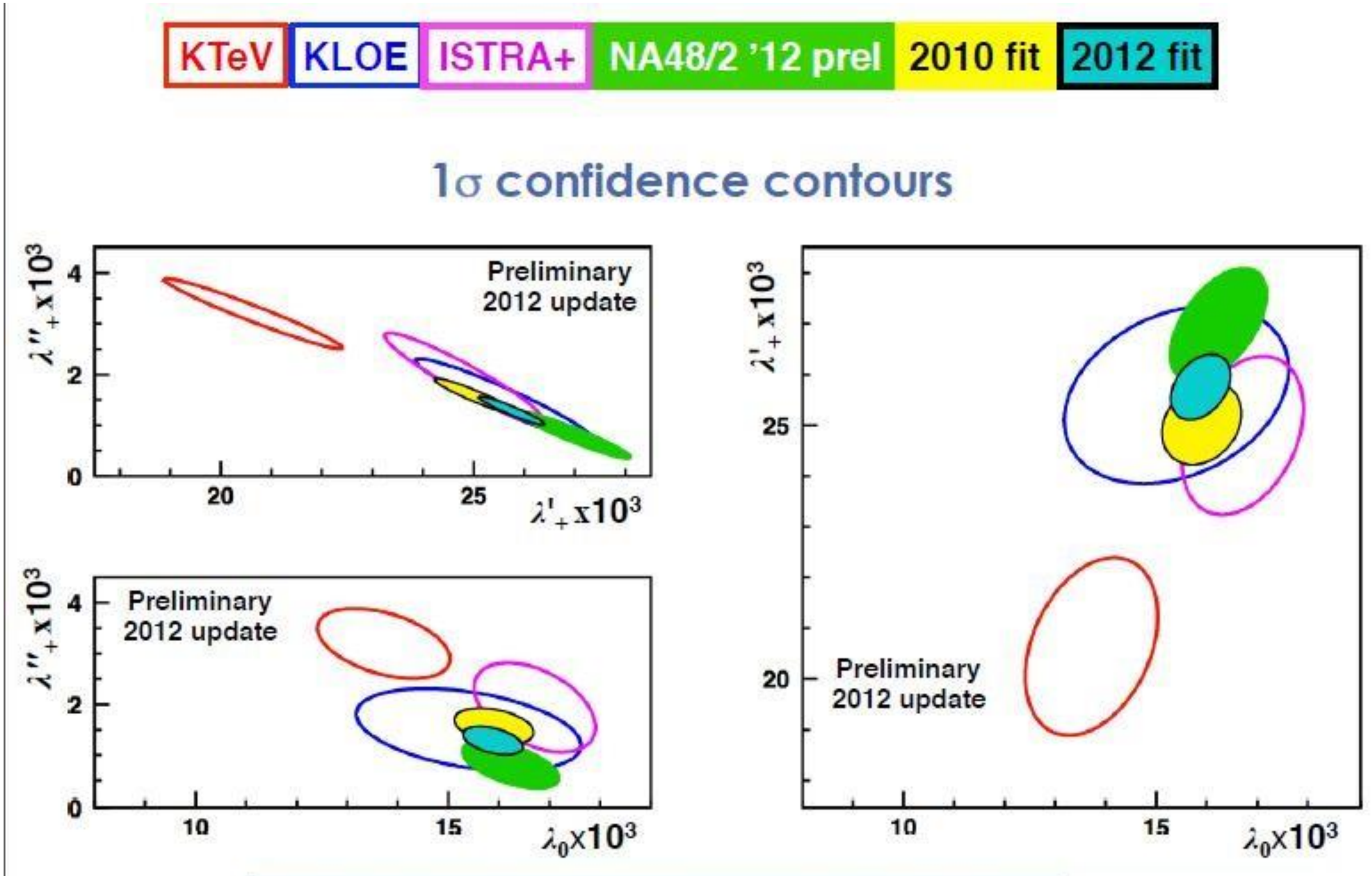
Kμ3 decays: Also need **scalar form factor:** $\tilde{f}_0(t) = \tilde{f}_+ + \tilde{f}_- \dfrac{t}{m_K^2 - m_\pi^2}$

$f_+(0)$ cannot be directly measured, therefore the form factors are normalised to $f_+(0)$:

$$\tilde{f}_+(t) = \frac{f_+(t)}{f_+(0)} \qquad \tilde{f}_0(t) = \frac{f_0(t)}{f_+(0)}$$

For V_{us}, need integral over phase space of squared matrix element
Parameterize form factors and fit distributions in t (or related variables)

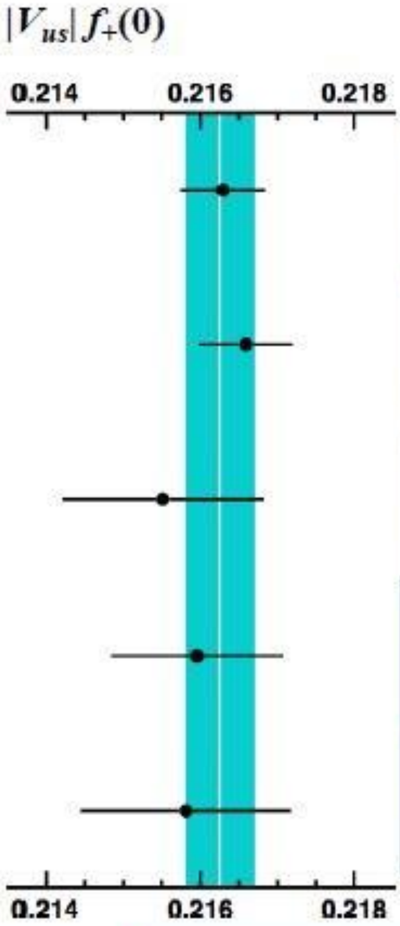
K_{l3} form factors



1σ confidence contours

M. Moulson, CKM 2012 Cincinnati Sept. 2012

Cabibbo angle (almost…)

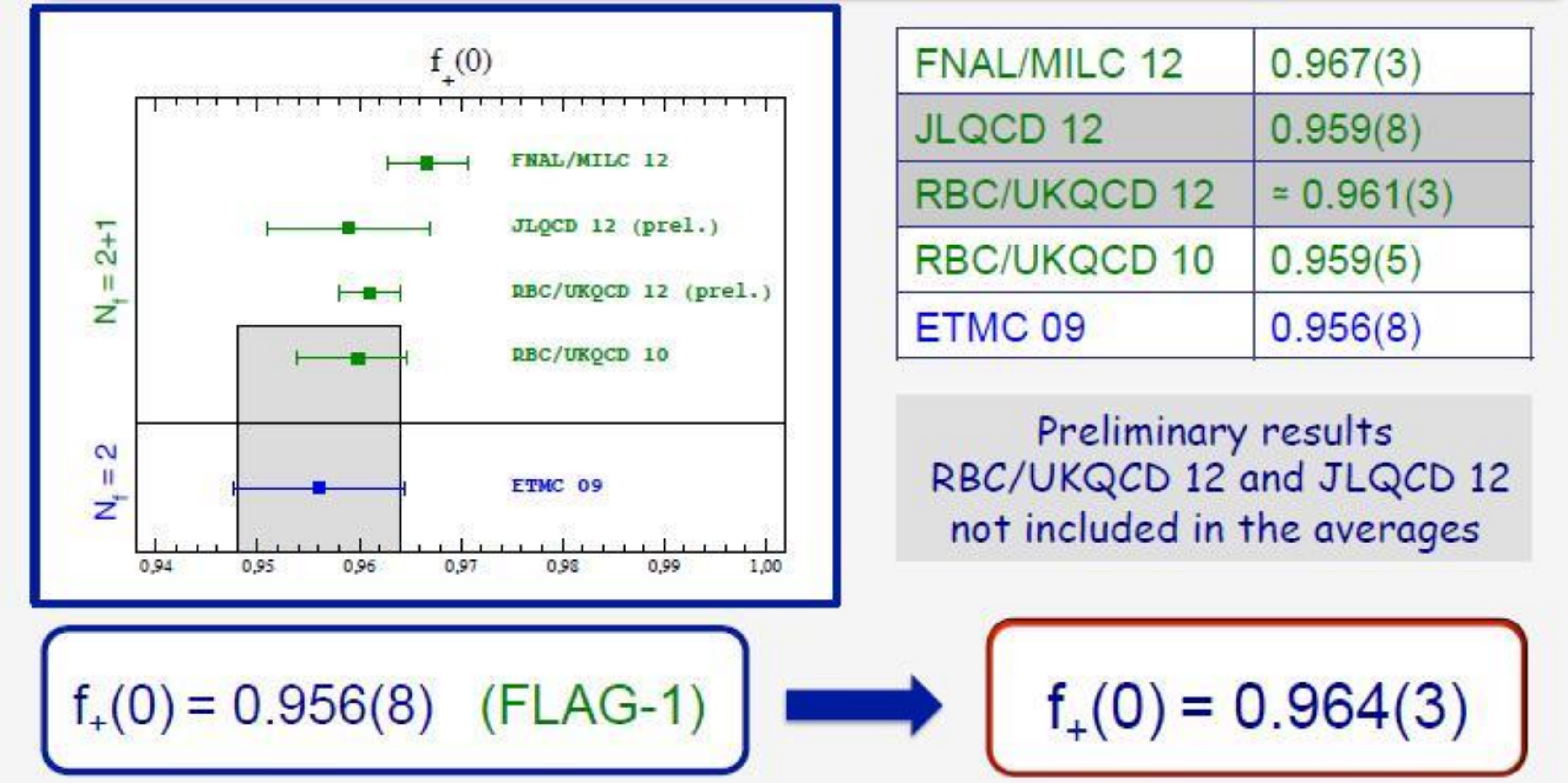


			Approx. contrib. to % err from:			
		% err	BR	τ	$\delta_{SU,EM}$	Int
K_Le3	0.2163(5)	0.26	0.09	0.20	0.11	0.05
$K_L\mu3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06
K_Se3	0.2155(13)	0.61	0.60	0.02	0.11	0.05
$K^{\pm}e3$	0.2160(11)	0.52	0.31	0.09	0.41	0.04
$K^{\pm}\mu3$	0.2158(13)	0.63	0.47	0.08	0.41	0.06

Average: $|V_{us}|\,f_+(0)$ = 0.2163(5) χ^2/ndf = 0.84/4 (93%)

M. Moulson CKM 2012 Cincinnati Sept. 2012

The lattice contribution: $f_+(0)$



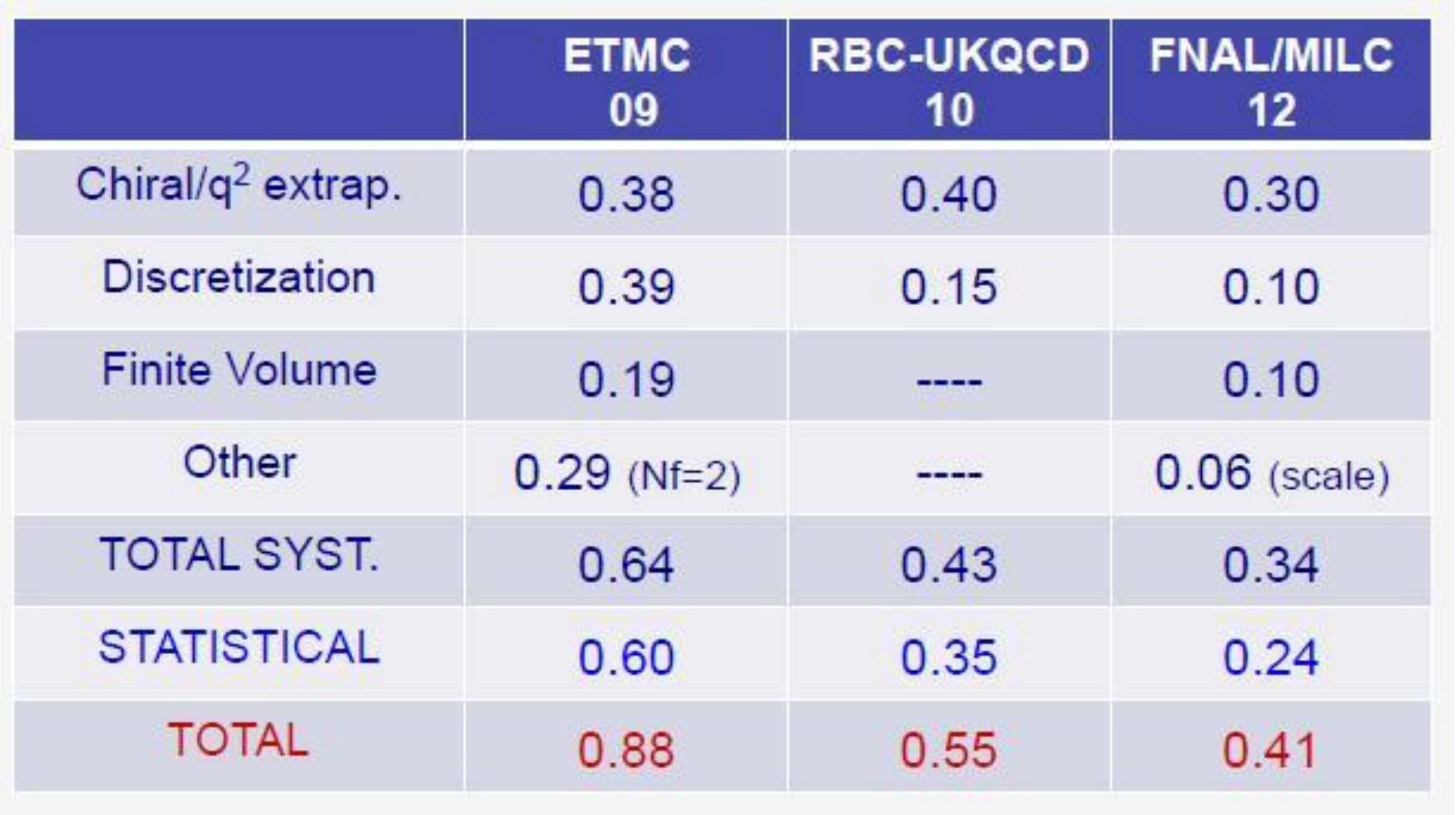
FNAL/MILC 12	0.967(3)
JLQCD 12	0.959(8)
RBC/UKQCD 12	≈ 0.961(3)
RBC/UKQCD 10	0.959(5)
ETMC 09	0.956(8)

Preliminary results
RBC/UKQCD 12 and JLQCD 12
not included in the averages

$f_+(0) = 0.956(8)$ (FLAG-1) → $f_+(0) = 0.964(3)$

© V. Lubicz

The lattice errors: $f_+(0)$



	ETMC 09	RBC-UKQCD 10	FNAL/MILC 12
Chiral/q^2 extrap.	0.38	0.40	0.30
Discretization	0.39	0.15	0.10
Finite Volume	0.19	----	0.10
Other	0.29 (Nf=2)	----	0.06 (scale)
TOTAL SYST.	0.64	0.43	0.34
STATISTICAL	0.60	0.35	0.24
TOTAL	0.88	0.55	0.41

Cabibbo angle from K_{l2} & π_{l2}

$$\frac{\Gamma_{K\ell 2}}{\Gamma_{\pi\ell 2}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\,\frac{f_K^2}{f_\pi^2}\,\frac{m_K(1-m_\ell^2/m_K^2)^2}{m_\pi(1-m_\ell^2/m_\pi^2)^2}\,(1+\delta_{\mathrm{EM}})$$

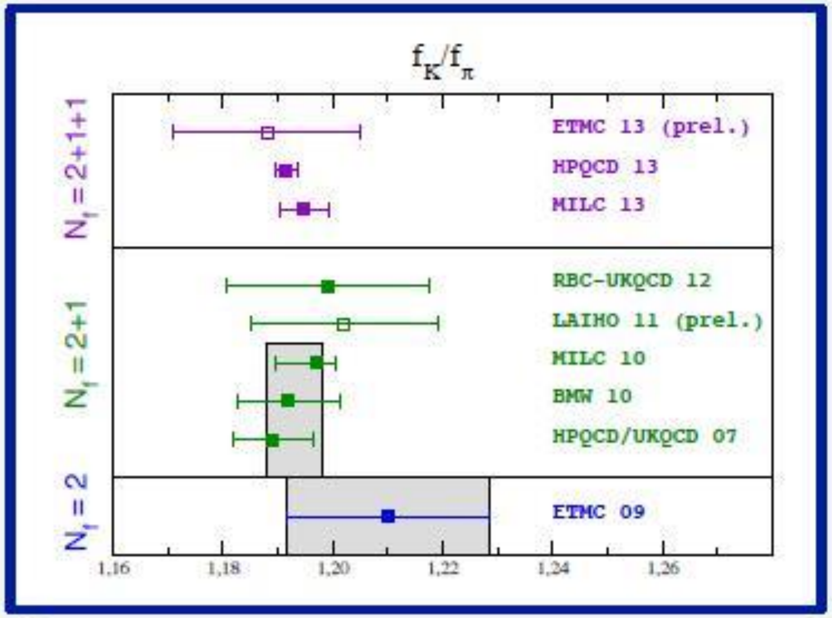
Measure: radiation-inclusive **ratio of BRs**

Compute: ratio of K, π decay constants, channel-dependent **long-distance EM** δ_{EM} corrections

Extract: ratio **$|V_{us}|/|V_{ud}|$**

© W. Marciano 2004

The lattice contribution: f_K/f_π



ETMC 13 (prel.)	1.188(17)
HPQCD 13	1.192(2)
MILC 13	1.195(5)
RBC-UKQCD 12	1.199(18) [*]
LAIHO 11 (prel.)	1.202(17)
MILC 10	1.197(+4−7)
BMW 10	1.192(9) [*]
HPQCD/UKQCD 07	1.189(7) [*]
ETMC 09	1.210(18) [*]

$f_K / f_\pi = 1.210(18)$ (Nf=2)

$f_K / f_\pi = 1.193(5)$ (Nf=2+1)

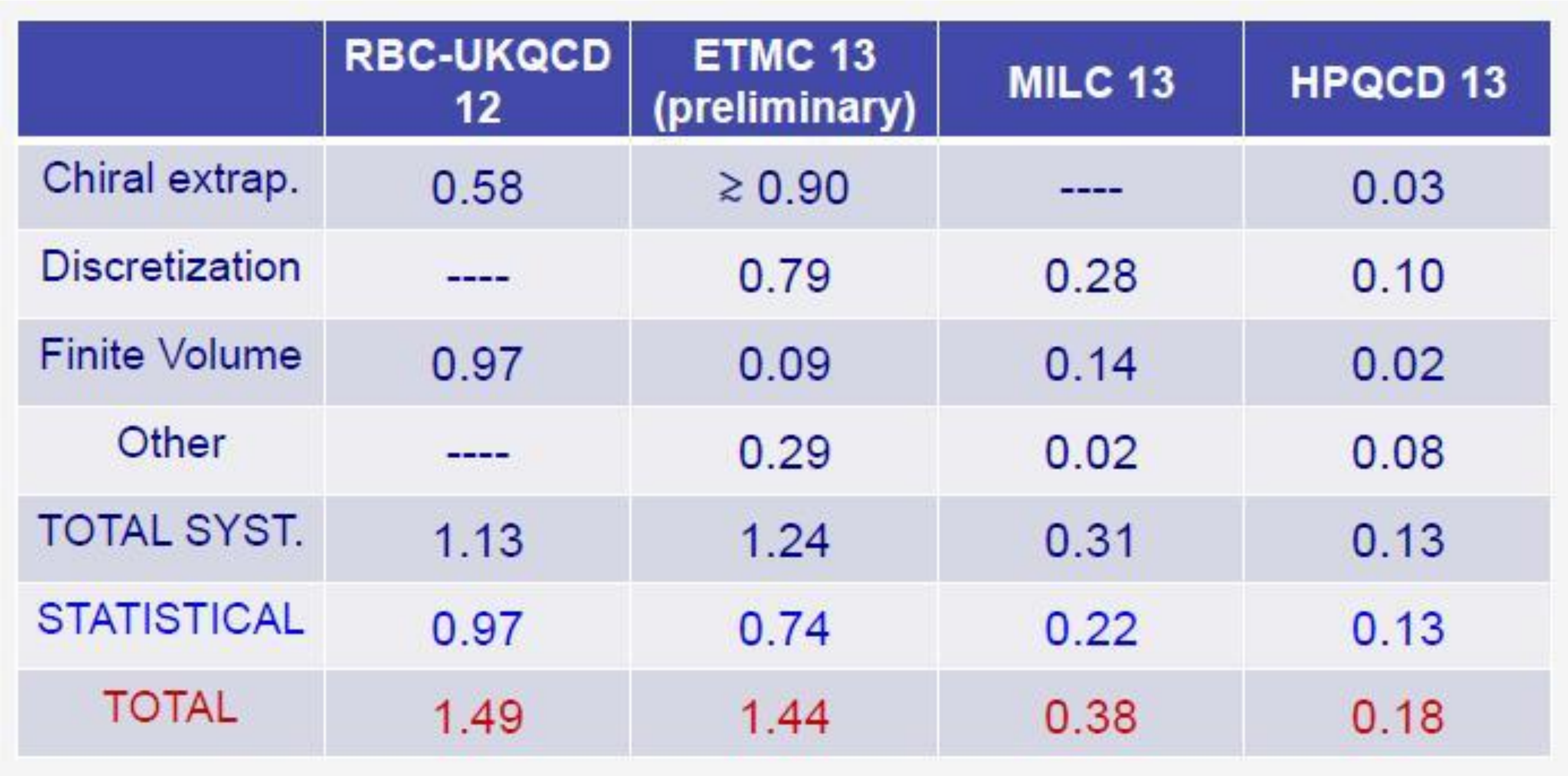
$f_K / f_\pi = 1.192(2)$ (Nf=2+1+1)

→ $f_K / f_\pi = 1.192(2)$

w/out HPQCD13: $f_K / f_\pi = 1.194(4)$

© V. Lubicz

The lattice errors: f_K/f_π



	RBC-UKQCD 12	ETMC 13 (preliminary)	MILC 13	HPQCD 13
Chiral extrap.	0.58	≳ 0.90	----	0.03
Discretization	----	0.79	0.28	0.10
Finite Volume	0.97	0.09	0.14	0.02
Other	----	0.29	0.02	0.08
TOTAL SYST.	1.13	1.24	0.31	0.13
STATISTICAL	0.97	0.74	0.22	0.13
TOTAL	1.49	1.44	0.38	0.18

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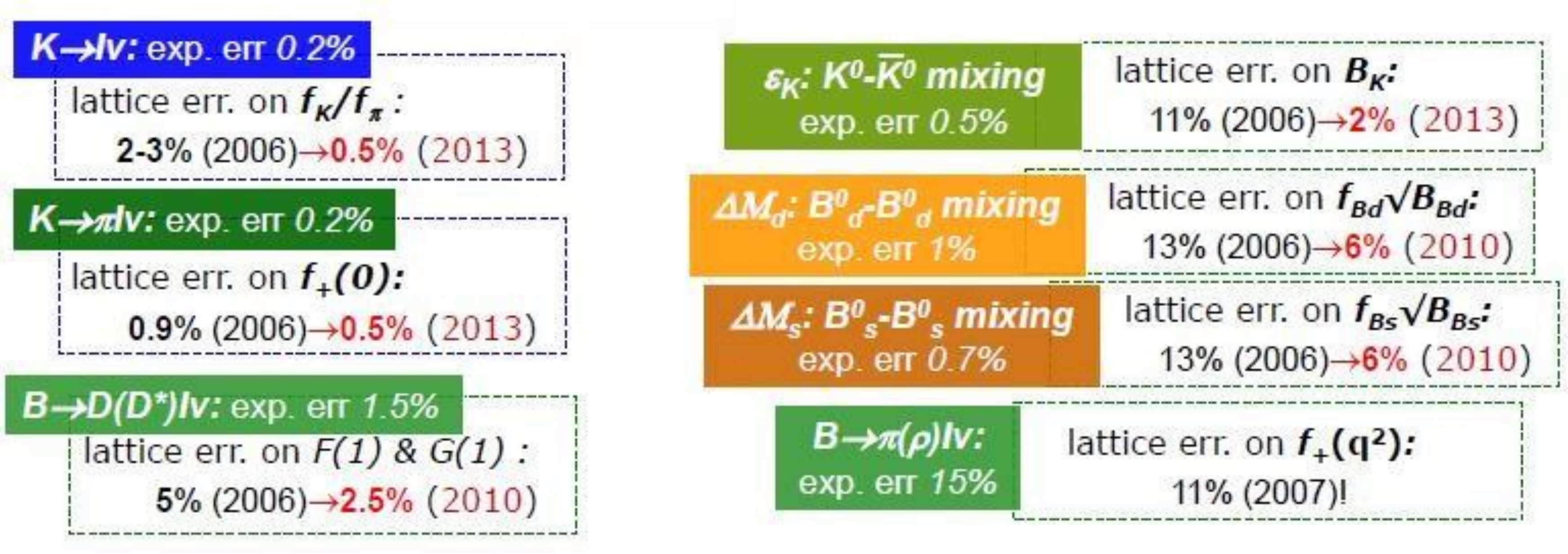
Theory vs. experiment



$K\to l\nu$: exp. err 0.2%

lattice err. on f_K/f_π :
2-3% (2006)→0.5% (2013)

$K\to\pi l\nu$: exp. err 0.2%

lattice err. on $f_+(0)$:
0.9% (2006)→0.5% (2013)

$B\to D(D^*)l\nu$: exp. err 1.5%

lattice err. on $F(1)$ & $G(1)$:
5% (2006)→2.5% (2010)

ε_K: K^0-$\bar{K}^0$ mixing
exp. err 0.5%

lattice err. on B_K:
11% (2006)→2% (2013)

ΔM_d: B^0_d-B^0_d mixing
exp. err 1%

lattice err. on $f_{Bd}\sqrt{B_{Bd}}$:
13% (2006)→6% (2010)

ΔM_s: B^0_s-B^0_s mixing
exp. err 0.7%

lattice err. on $f_{Bs}\sqrt{B_{Bs}}$:
13% (2006)→6% (2010)

$B\to\pi(\rho)l\nu$:
exp. err 15%

lattice err. on $f_+(q^2)$:
11% (2007)!

What about charged Kaons?

Hadronic production: charged K

$K^{\pm}$ beams readily obtained as secondary beams

Magnetic selection based on charge and momentum:

unseparated positive beam contains: p,π^+,K^+,μ^+,e^+,… ($\pi/K \sim 0.1$)

K can be *tagged* by velocity measurement, e.g. TOF or Čerenkov

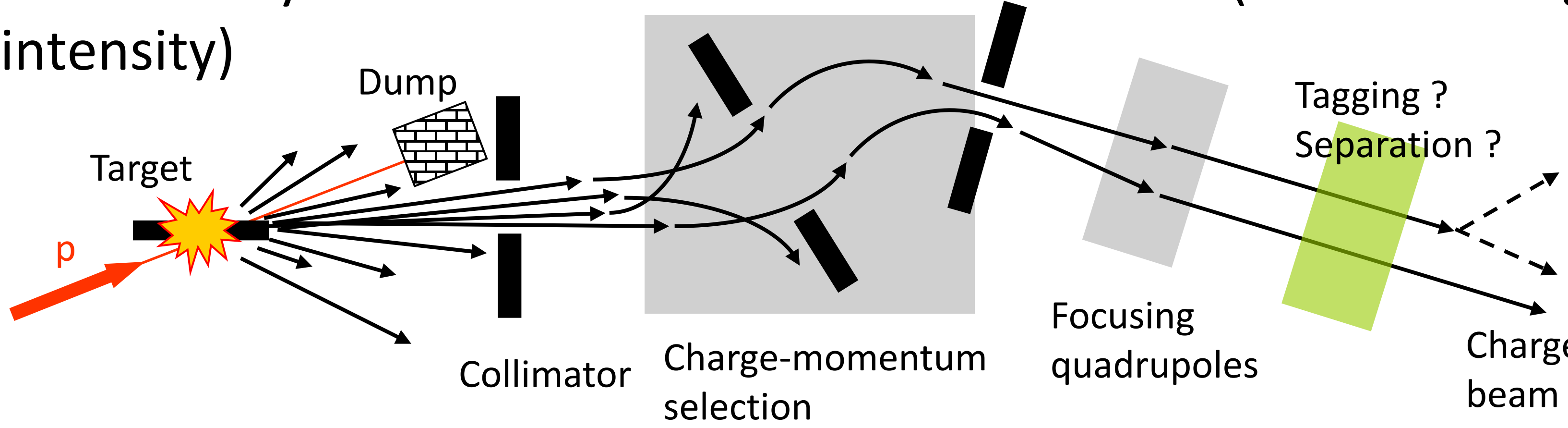
Beams can be *separated* to enrich K component with:

Electrostatic separators ≈ 1 GeV/c

RF separators (Panofsky) ≈ 10-60 GeV/c

to obtain e.g. $K/\pi \sim 3$ to 10

Beam intensity measurable: absolute normalization (difficult at high intensity)

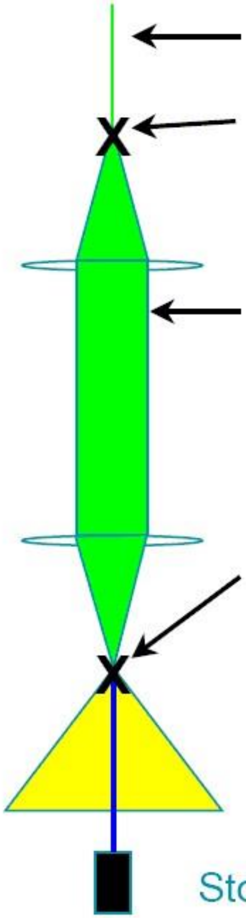


RF-separation (Panofsky)

Requires RF cavities with intense fields (SC)

Allows to greatly enhance K with respect to π and p, at the expense of beam intensity.

Practically limited to momenta below few tens of GeV.



Initial momentum-selected beam (π^+, p, K^+)

RF deflection: $A\,\sin(\omega t)$

Transport until $L/\beta_\pi c - L/\beta_p c = 1/f$

Pions then arrive one cycle before protons

2nd RF deflection *e.g.* 180° out of phase: $-A\sin(\omega t+\omega\Delta t)$

Stop π^+, p with beam plug, collect K^+

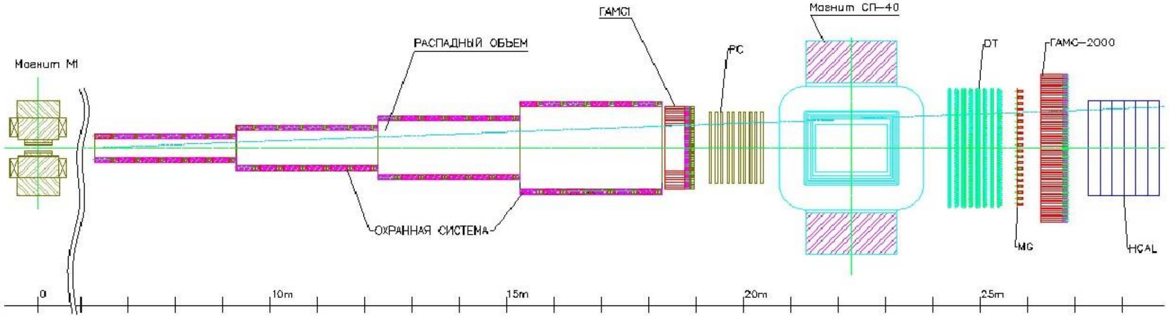
© L. Bellantoni

$K^{\pm}$ beams

Unseparated charged K beam at CERN SPS
Up to $3 \cdot 10^{12}$ ppp (400 GeV)
$5.5 \cdot 10^{7}$ particles/pulse in beam (6% K)
60 GeV/c narrow band (±5%)
K^{+} and K^{-} simultaneous, superimposed.

Used in 2003-2004 by NA48/2 experiment.
10^{11} K decays per year collected.

Using CERN-Karlsruhe SC cavities



RF-separated charged K beam at U-70 PS in Protvino.
10^{13} ppp (70 GeV)
$8 \cdot 10^{6}$ particles/pulse (>50% K)
15 GeV/c K^{+} or K^{-} alternated.
Used for OKA experiment at Protvino.

CP violation in $K_{\pi 3}$ decays (why?)

- CPV for charged particles is direct
- Most common decay modes which can exhibit CPV:

$K^{\pm} \to \mu^{\pm} \nu$ ✗

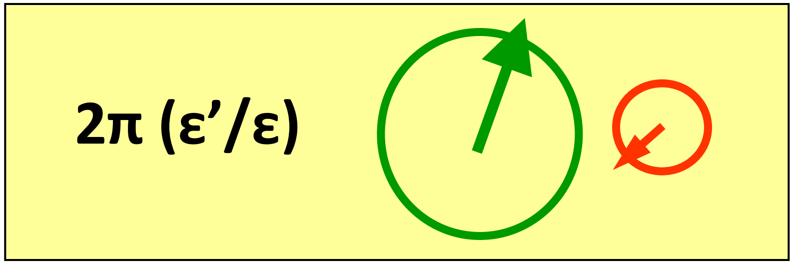
$K^{\pm} \to \pi^{\pm} \pi^{0}$ ✗

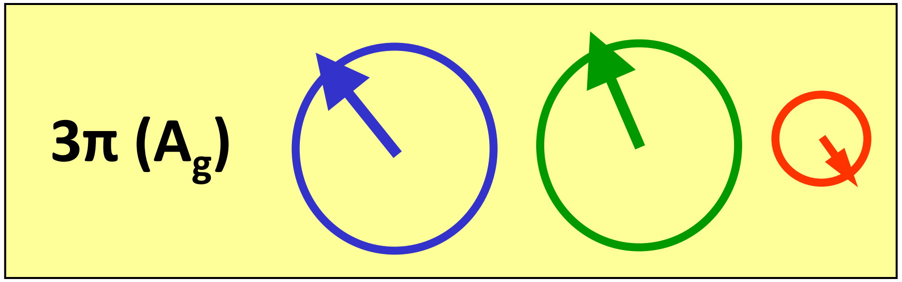
$K^{\pm} \to 3\pi$ ✓

Large statistics, easy selection, small backgrounds

Hadronic uncertainties, small FSI phases
→ Small asymmetries in SM

No intrinsic ΔI=1/2
suppression
(as it happens in ε'/ε)

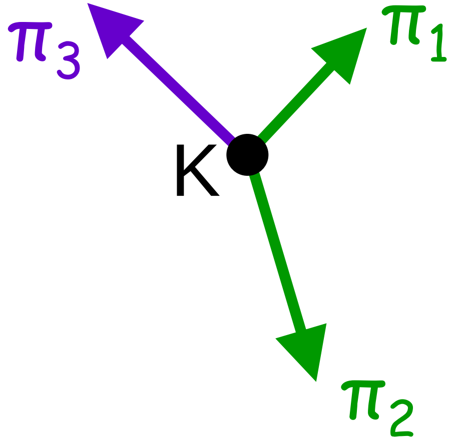




$K_{\pi3}$ decays

$BR(K^\pm \to \pi^\pm\pi^+\pi^-) = 5.57\%$ $BR(K^\pm \to \pi^\pm\pi^0\pi^0) = 1.73\%$.

"charged" "neutral"



Kinematics:

$s_i = (P_K - P_{\pi i})^2$ *i=1,2,3 (3=odd π)*

$s_0 = (s_1+s_2+s_3)/3$

$u = (s_3 - s_0)/m_\pi^2 = 2m_K\,(m_K/3 - E^*_{odd})/m_\pi^2$

$v = (s_2 - s_1)/m_\pi^2 = 2m_K(E^*_1 - E^*_2)/m_\pi^2$

Matrix element:

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

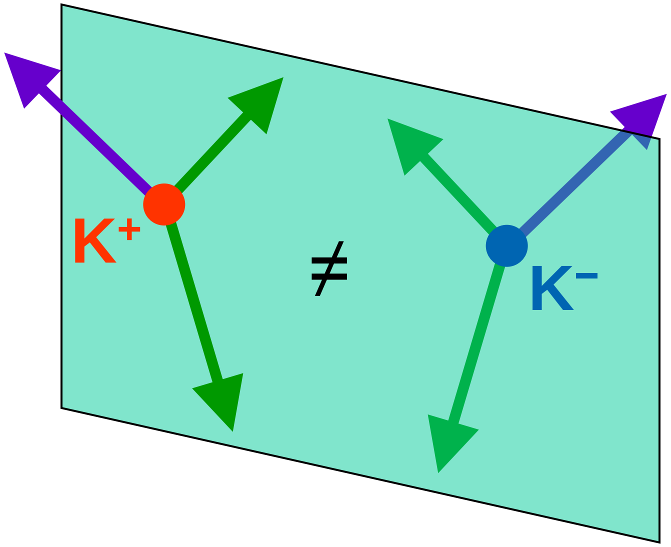
$K^\pm \to \pi^\pm\pi^+\pi^-$ $g = -0.2154 \pm 0.0035$

$K^\pm \to \pi^\pm\pi^0\pi^0$ $g = 0.652 \pm 0.031$

$|h|, |k| << |g|$

CP violation in $K_{\pi 3}$ (how)

No absolute K flux measurement: compare only Dalitz plot shapes



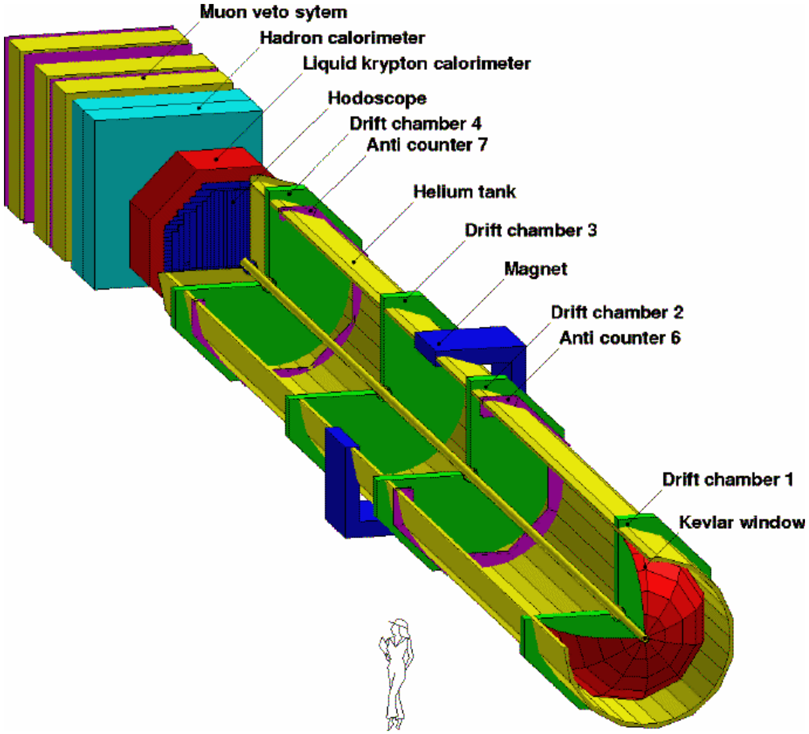
Measured CP–violating quantity:

$$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0 \,?$$

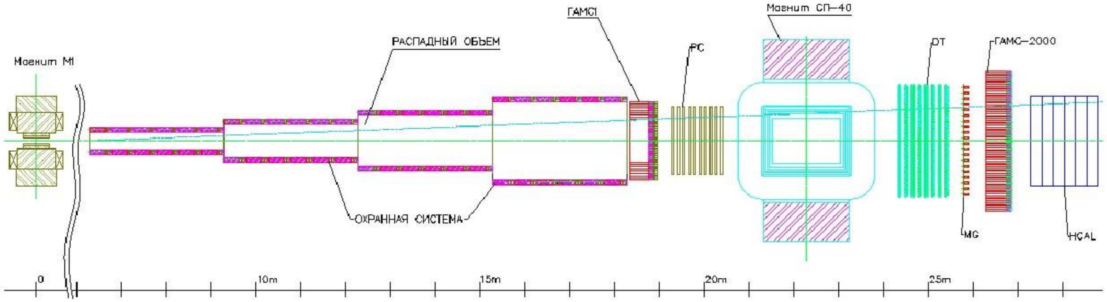
$K^{\pm} \rightarrow \pi^{+}\pi^{-}\pi^{\pm},\pi^{0}\pi^{0}\pi^{\pm}$

NA48/2 @ CERN exploit maximally all cancellations (robustness)

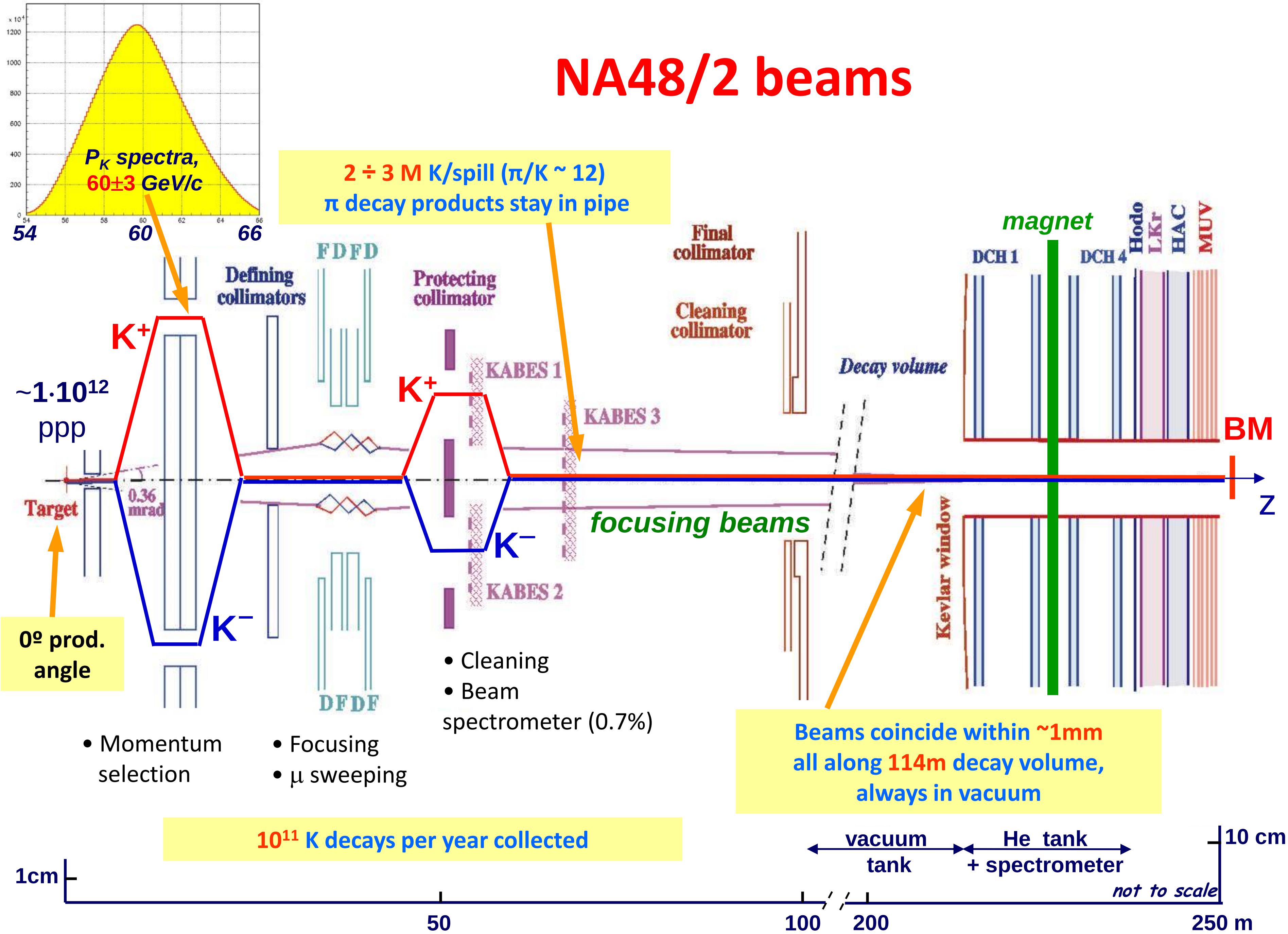
- K^+ and K^- beams: simultaneous, overlapping in space, with narrow momentum spectra
- Slope asymmetries on ratios of normalized u distributions
- Equalization of averaged acceptances for K^+ and K^- with frequent inversions of magnetic field polarities



Alternate proposal (Protvino) OKA (not done):
alternate separated beams: $K^{\pm}$ 15 GeV/c



NA48/2 beams



2 ÷ 3 M K/spill (π/K ~ 12)
π decay products stay in pipe

0º prod. angle

- Momentum selection
- Focusing
- μ sweeping
- Cleaning
- Beam spectrometer (0.7%)

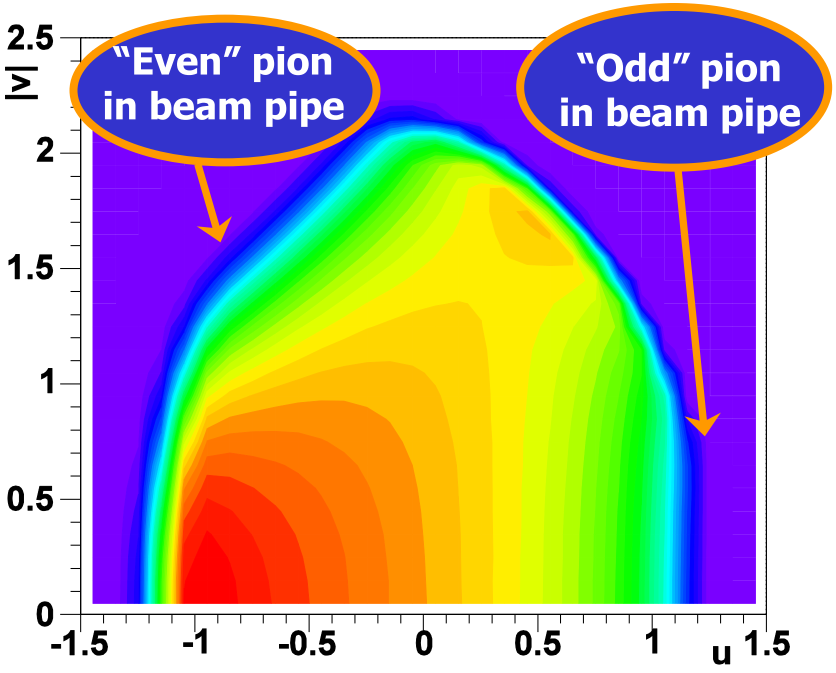
Beams coincide within ~1mm
all along 114m decay volume,
always in vacuum

10^{11} K decays per year collected

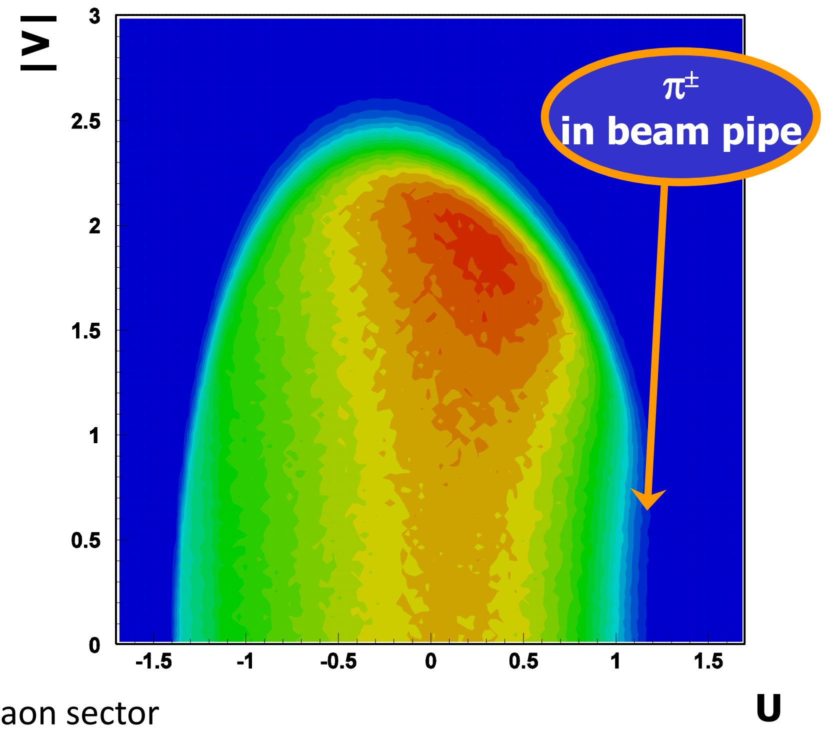
NA48/2: $K^{\pm} \rightarrow 3\pi$

Data-taking 2003-04: 3.1×10^9 + 9.1×10^7 selected events ($K^+/K^- \approx 1.8$)
Negligible backgrounds, complementary analyses (detectors) of two modes.
Ecploit multiple cancellations of instrumental effects with magnetic field inversions and simultaneous beams.

$3.1 \cdot 10^9$ $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$



$9.1 \cdot 10^7$ $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$



NA48/2: CPV in $K_{\pi 3}$

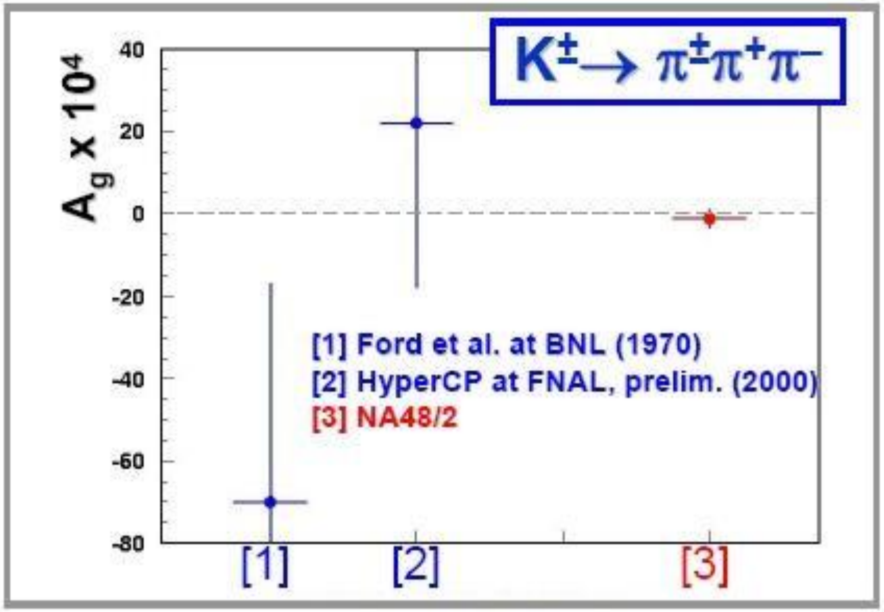
Final results (2003+2004)

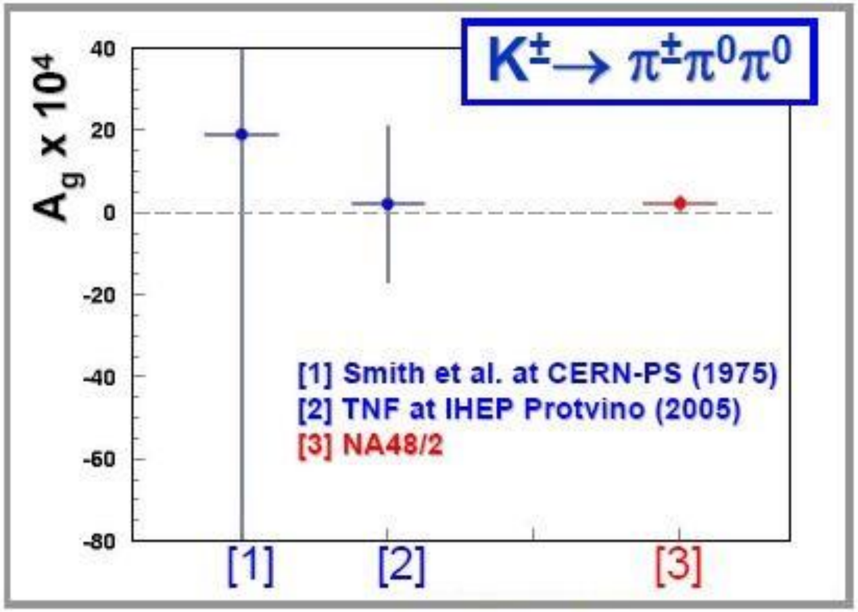
Ag(C)
$= (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \cdot 10^{-4}$
$= (-1.5 \pm 2.1) \cdot 10^{-4}$

(3.1·10^9 decays)

Ag(N)
$= (1.8 \pm 1.7_{stat} \pm 0.5_{syst}) \cdot 10^{-4}$
$= (1.8 \pm 1.8) \cdot 10^{-4}$

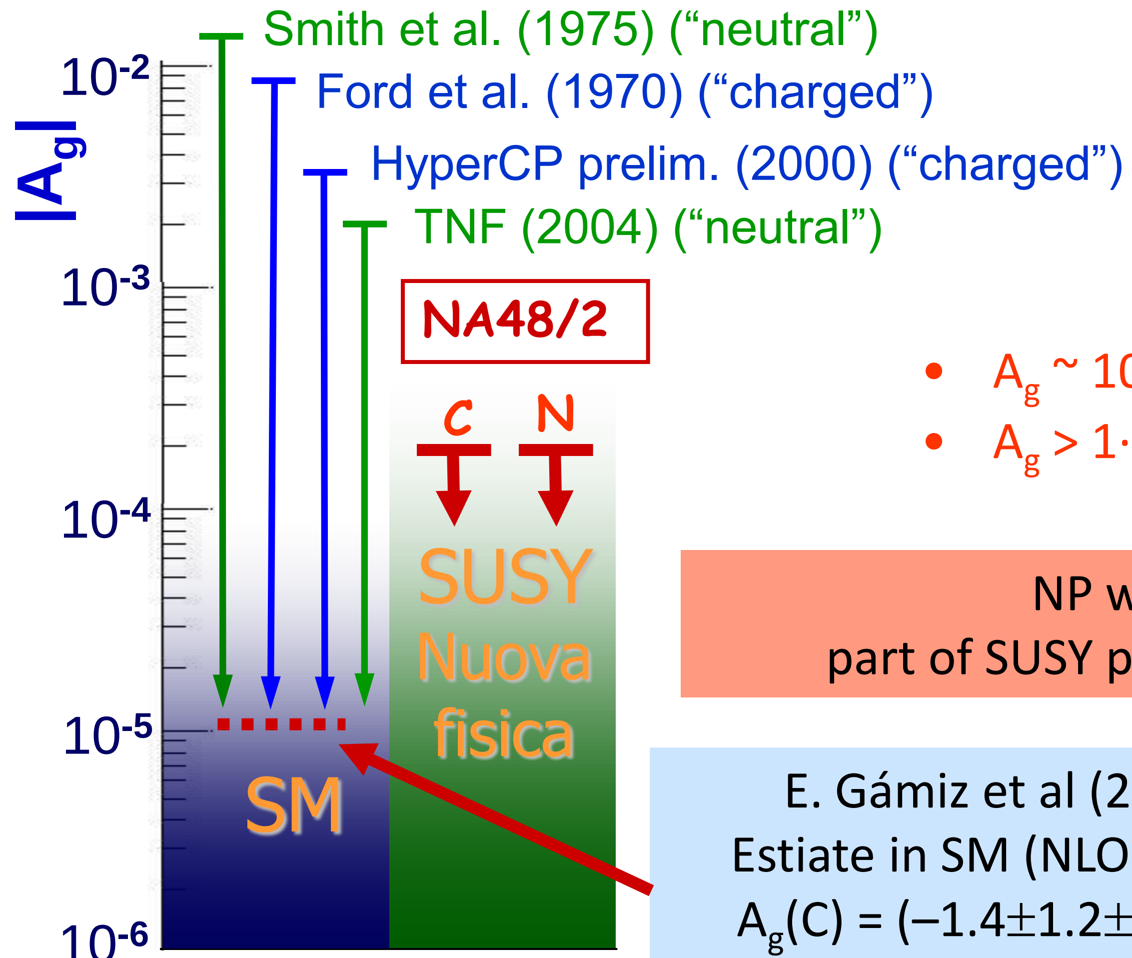
(9.1·10^7 decays)





Statistical errors dominate. Improvement x10. No CPV.

$K^{\pm}$ asymmetries and SM



THEORY:

SM contribution: several computations

Large hadronic uncertainties (~1 order of magnitude)

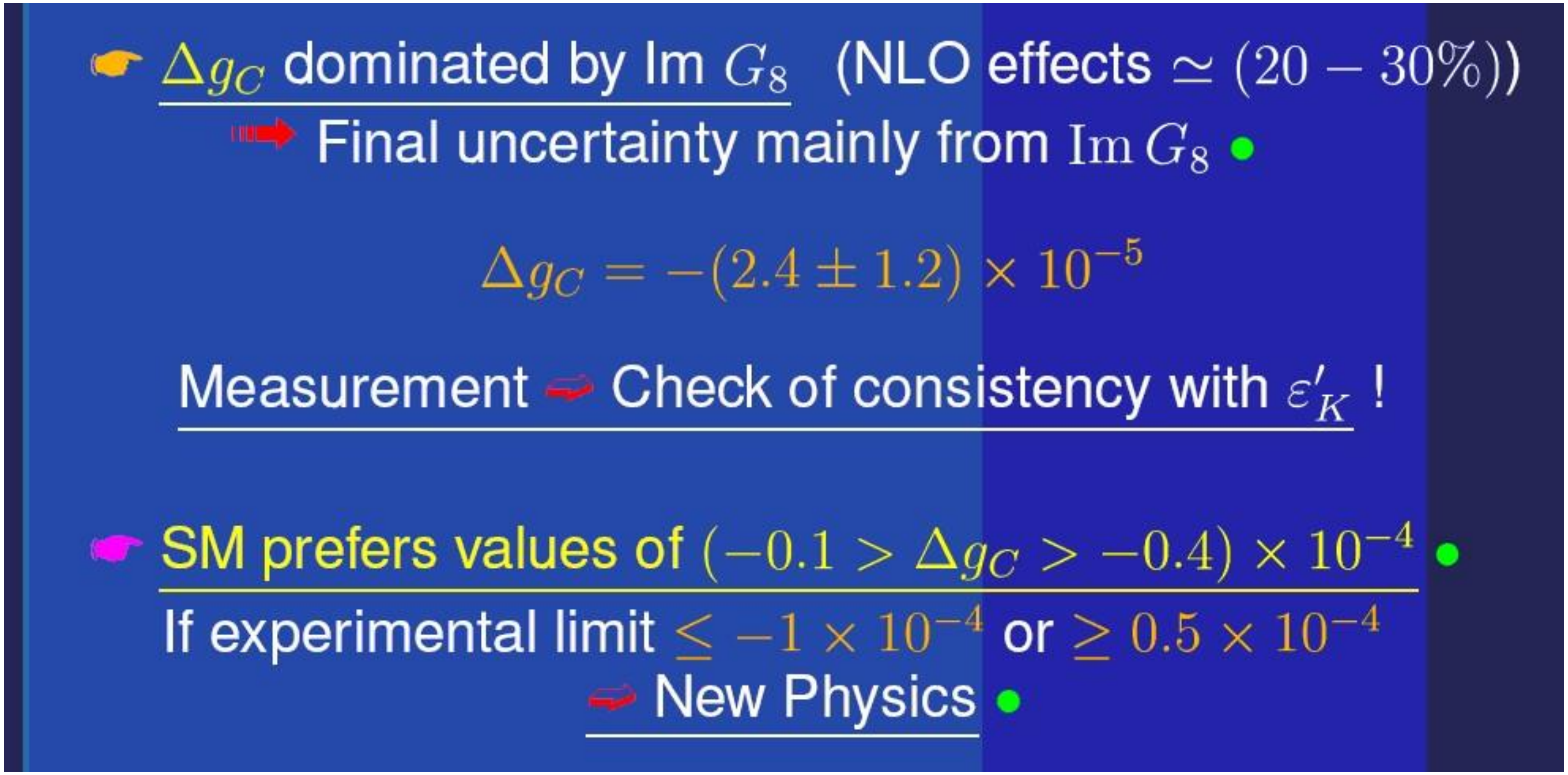
Possible enhancements beyond SM

- $A_g \sim 10^{-5}$ compatible with SM
- $A_g > 1\cdot10^{-4}$ SUSY / New Physics

NP window “closed”
part of SUSY parameter space excluded

E. Gámiz et al (2003)
Estiate in SM (NLO ChPT):
$A_g(C) = (-1.4\pm1.2\pm?)\cdot10^{-5}$
$A_g(N) = (1.1\pm0.7\pm?)\cdot10^{-5}$

K$^{\pm}$ asymmetries and SM



- Δg_C dominated by Im G_8 (NLO effects $\simeq (20-30\%)$)

  ⇒ Final uncertainty mainly from $\mathrm{Im}\, G_8$

$$\Delta g_C = -(2.4 \pm 1.2) \times 10^{-5}$$

Measurement ⇒ Check of consistency with ε'_K !

- SM prefers values of $(-0.1 > \Delta g_C > -0.4) \times 10^{-4}$

If experimental limit $\leq -1 \times 10^{-4}$ or $\geq 0.5 \times 10^{-4}$

⇒ New Physics

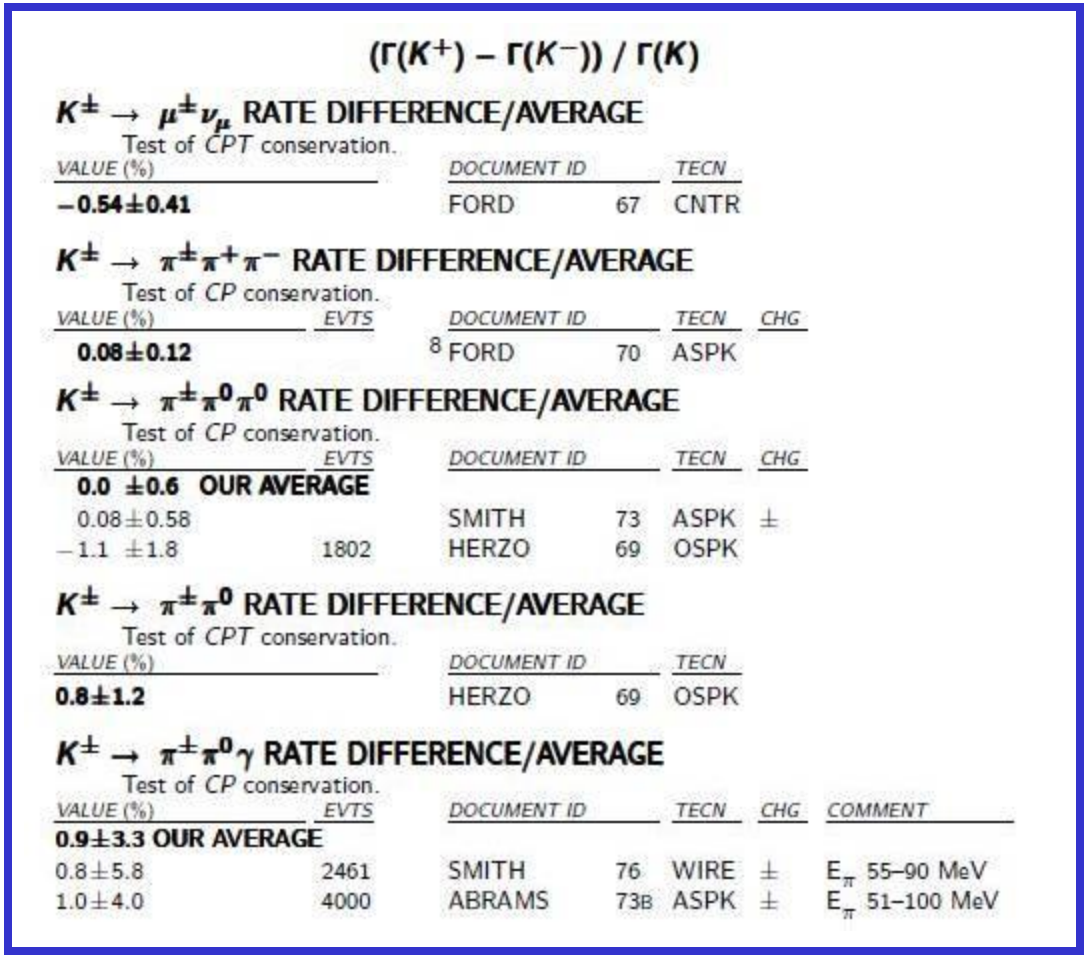
CP/CPT violation in $\Delta\Gamma$

Need twin beams

Need absolute flux normalization:

very hard experimentally

Anyway generally suppressed asymmetries



$(\Gamma(K^+) - \Gamma(K^-)) / \Gamma(K)$

$K^\pm \rightarrow \mu^\pm \nu_\mu$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	*DOCUMENT ID*	*TECN*
−0.54±0.41	FORD 67	CNTR

$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.08±0.12		[8] FORD 70	ASPK	

$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*
0.0 ±0.6 OUR AVERAGE				
0.08±0.58		SMITH 73	ASPK	±
−1.1 ±1.8	1802	HERZO 69	OSPK	

$K^\pm \rightarrow \pi^\pm \pi^0$ RATE DIFFERENCE/AVERAGE

Test of *CPT* conservation.

VALUE (%)	*DOCUMENT ID*	*TECN*
0.8±1.2	HERZO 69	OSPK

$K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ RATE DIFFERENCE/AVERAGE

Test of *CP* conservation.

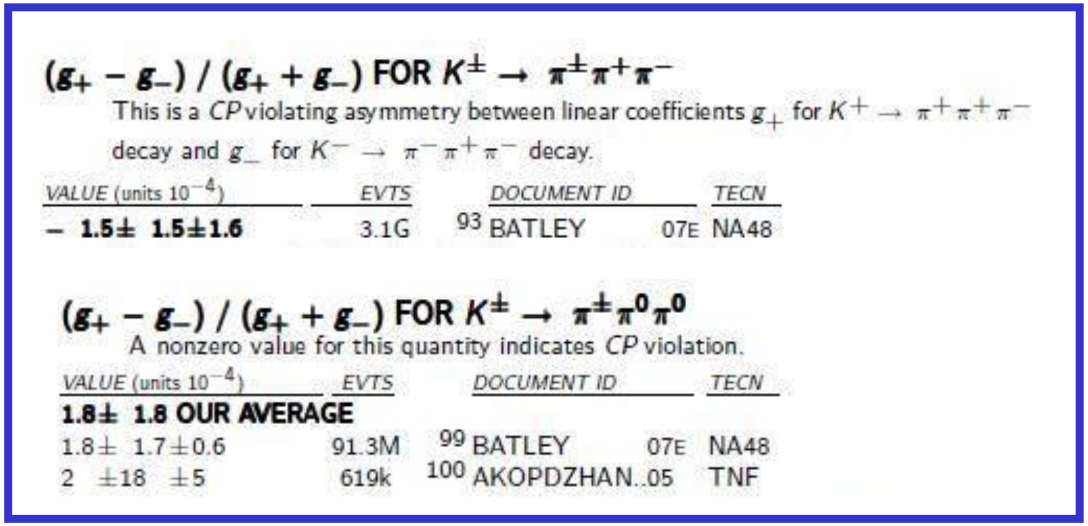
VALUE (%)	*EVTS*	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
0.9±3.3 OUR AVERAGE					
0.8±5.8	2461	SMITH 76	WIRE	±	E_π 55–90 MeV
1.0±4.0	4000	ABRAMS 73B	ASPK	±	E_π 51–100 MeV

CP violation in Dalitz plot

Need twin beams

Δg not necessarily the best quantity (what is "g"?)

Measured interference in $\pi\pi\gamma$ opens up new possibility: $\Delta(\partial\sigma/\partial E\gamma)$



$(g_+ - g_-) / (g_+ + g_-)$ FOR $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$

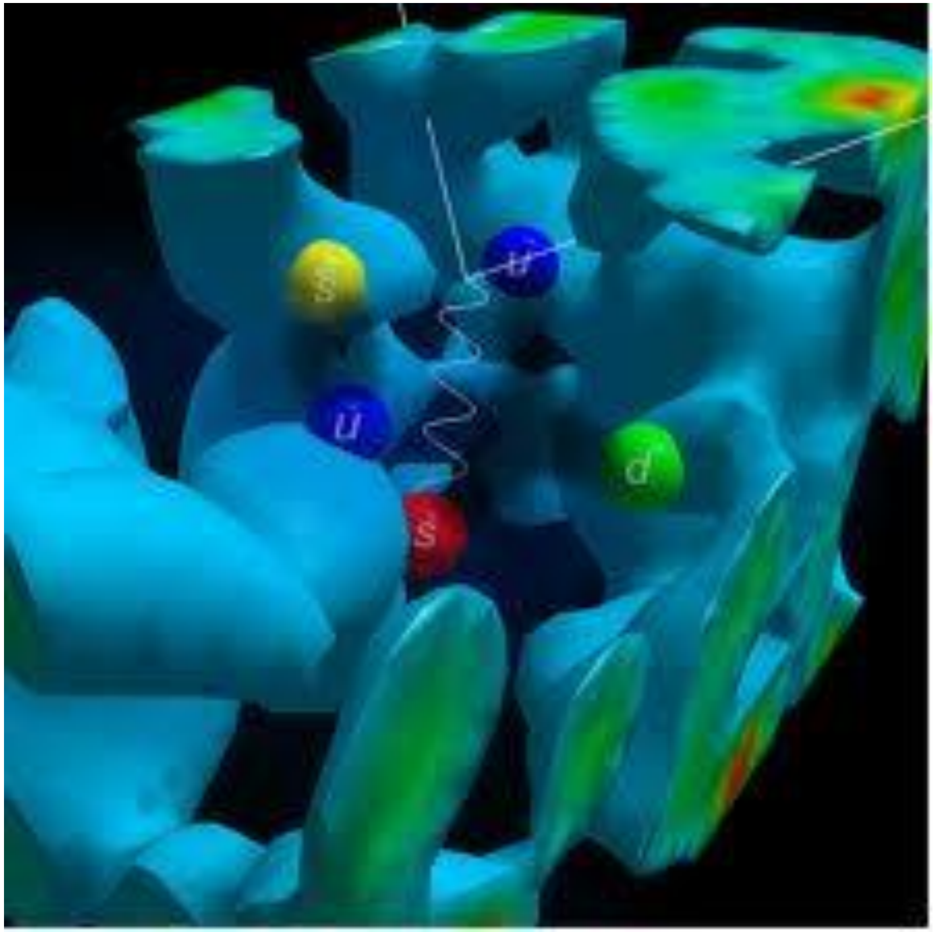
This is a *CP* violating asymmetry between linear coefficients g_+ for $K^+ \rightarrow \pi^+\pi^+\pi^-$ decay and g_- for $K^- \rightarrow \pi^-\pi^+\pi^-$ decay.

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*
− 1.5± 1.5±1.6	3.1G	[93] BATLEY 07E	NA48

$(g_+ - g_-) / (g_+ + g_-)$ FOR $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$

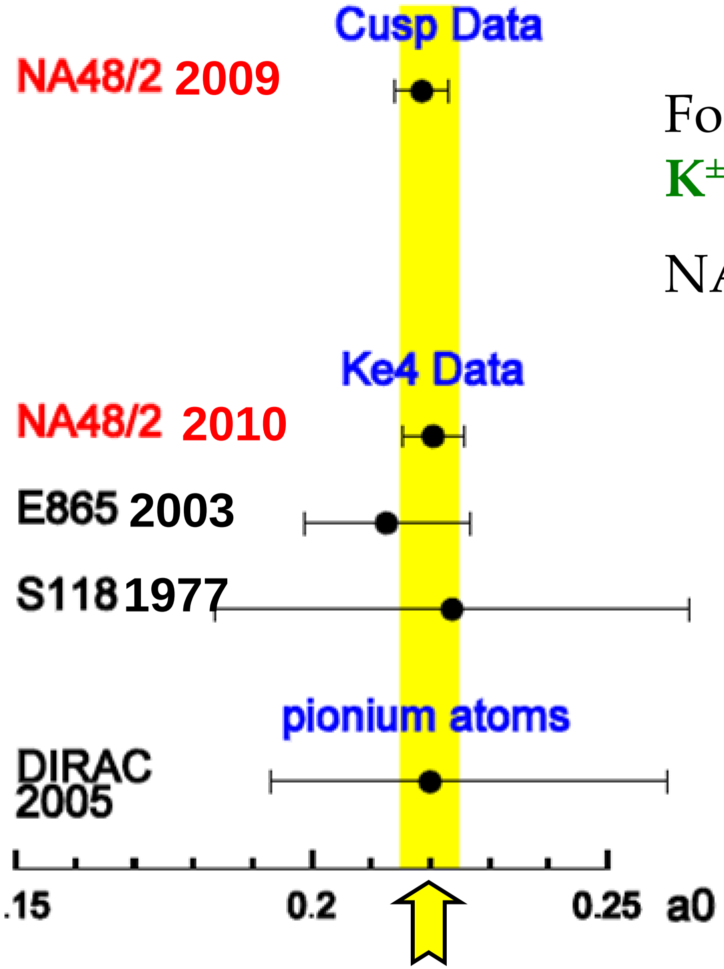
A nonzero value for this quantity indicates *CP* violation.

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*	*TECN*
1.8± 1.8 OUR AVERAGE			
1.8± 1.7±0.6	91.3M	[99] BATLEY 07E	NA48
2 ±18 ±5	619k	[100] AKOPDZHAN..05	TNF

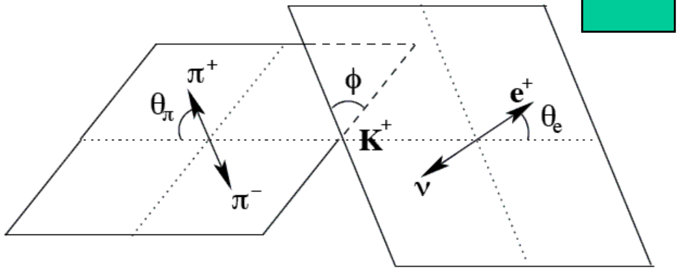


Learning about QCD

QCD from K: old way



ChPT prediction:
a_0=0.220±0.005

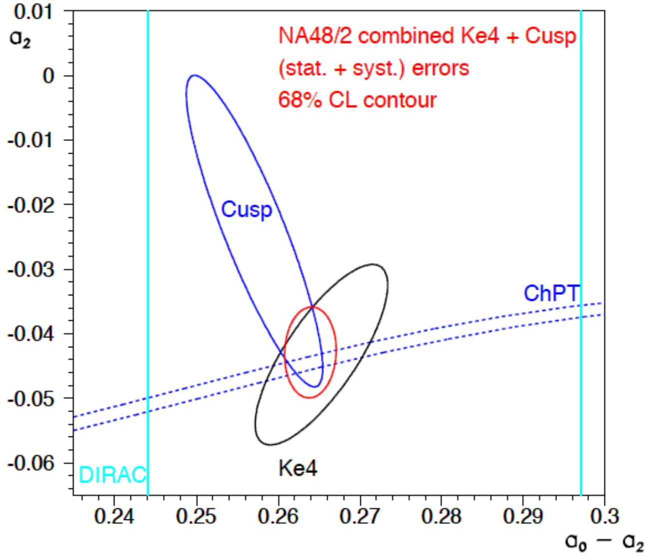


Form factor analysis of $K^\pm \to \pi^+\pi^- e^\pm \upsilon$ (Ke4) decays

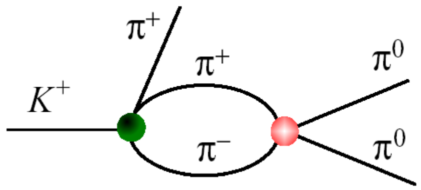
NA48/2 largest world statistics: $1.13 \cdot 10^6$ events

$$\begin{aligned} a_0 &= 0.2210 \pm 0.0047_{\text{stat}} \pm 0.0040_{\text{syst}} \\ a_2 &= -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0028_{\text{syst}} \\ a_0 - a_2 &= 0.2639 \pm 0.0020_{\text{stat}} \pm 0.0015_{\text{syst}} \end{aligned}$$

Combined NA48/2 results: Striking test of QCD

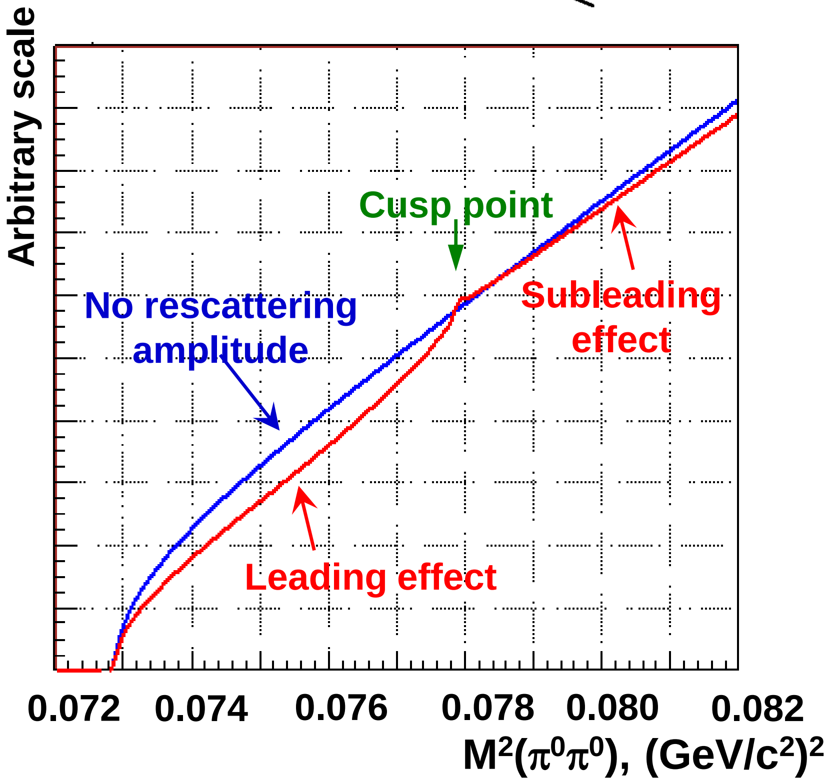


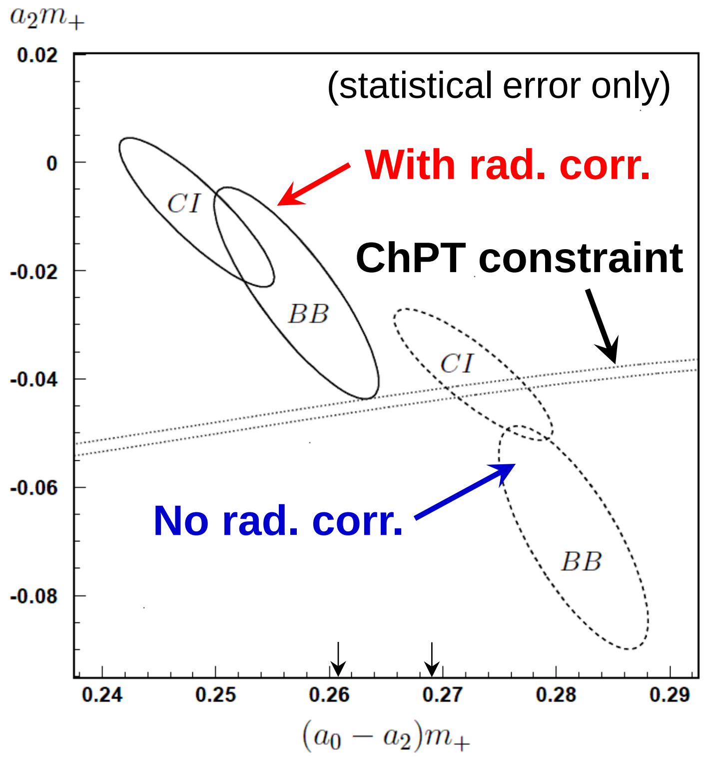
QCD from K: new way



$\pi^+\pi^-\to\pi^0\pi^0$ rescattering sensitive to S-wave pion scattering lengths

(Budini, Fonda 1961 – Cabibbo 2004, Improvements: Isidori *et al.*, Colangelo *et al.*, Bissinger *et al.*

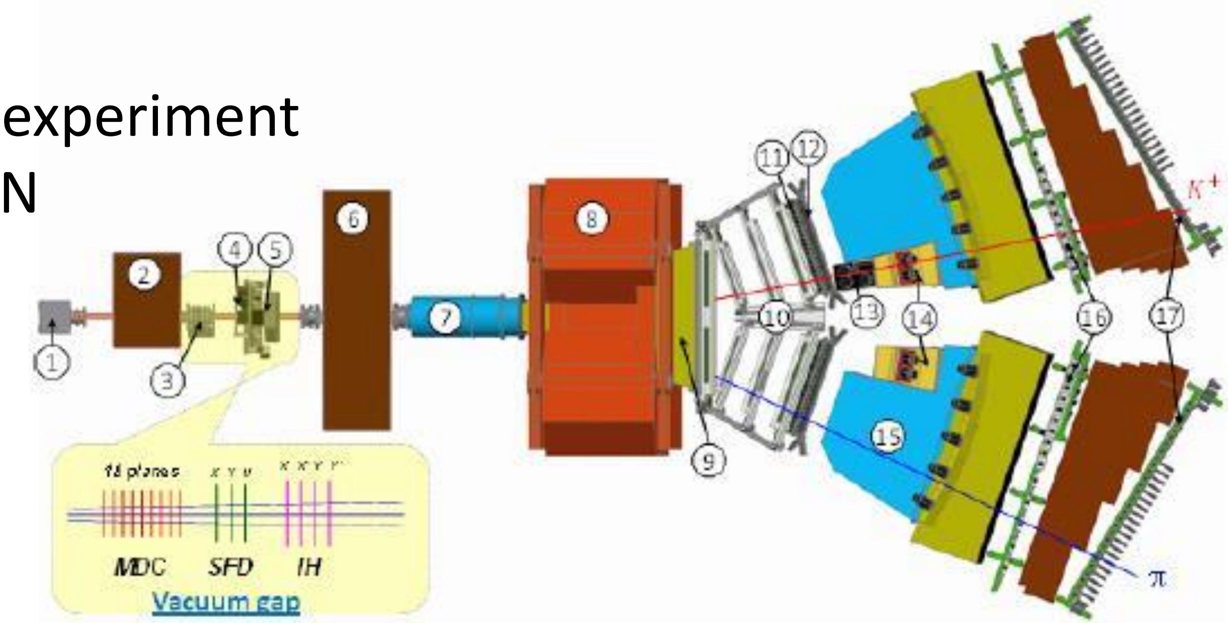




NA48/2 huge statistics

QCD from K: the other way

DIRAC experiment
@ CERN



1 Target station with Ni foil; **2** First shielding; **3** Micro Drift Chambers; **4** Scintillating Fiber Detector; **5** Ionization Hodoscope; **6** Second Shielding; **7** Vacuum Tube; **8** Spectrometer Magnet; **9** Vacuum Chamber; **10** Drift Chambers; **11** Vertical Hodoscope; **12** Horizontal Hodoscope; **13** Aerogel Čerenkov; **14** Heavy Gas Čerenkov; **15** Nitrogen Čerenkov; **16** Preshower; **17** Muon Detector

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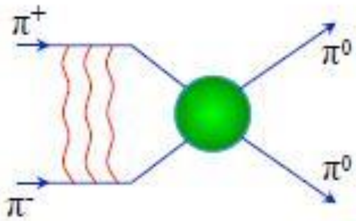
Pionium lifetime

Pionium ($A_{2\pi}$) is a hydrogen-like atom consisting of π^+ and π^- mesons:

E_B=-1.86 keV, r_B=387 fm, $p_B \approx$0.5 MeV

The lifetime of $\pi^+\pi^-$ atoms is dominated by the annihilation process into $\pi^0\pi^0$:



$$\Gamma = \frac{1}{\tau} = \Gamma_{2\pi_0} + \Gamma_{2\gamma} \quad \text{with} \quad \frac{\Gamma_{2\gamma}}{\Gamma_{2\pi_0}} \approx 4 \times 10^{-3}$$

$$\Gamma_{1S,2\pi^0} = R\left|a_0 - a_2\right|^2 \quad \text{with} \quad \frac{\Delta R}{R} \approx 1.2\%$$

$$\tau = (2.9 \pm 0.1) \times 10^{-15}\, s$$

Gasser et al. – 2001

a_0 and a_2 are the ππ S-wave scattering lengths for isospin I=0 and I=2.

If $$\frac{\Delta\tau}{\tau} = 4\% \quad \Rightarrow \quad \frac{\Delta\left|a_0 - a_2\right|}{\left|a_0 - a_2\right|} = 2\%$$

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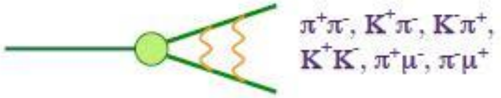


$\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$,
K^+K^-, $\pi^+\mu^-$, $\pi^-\mu^+$

Coulomb pairs

$(\pi^+\pi^-)$, $(K^+\pi^-)$, $(K^-\pi^+)$,
(K^+K^-), $(\pi^+\mu^-)$, $(\pi^-\mu^+)$

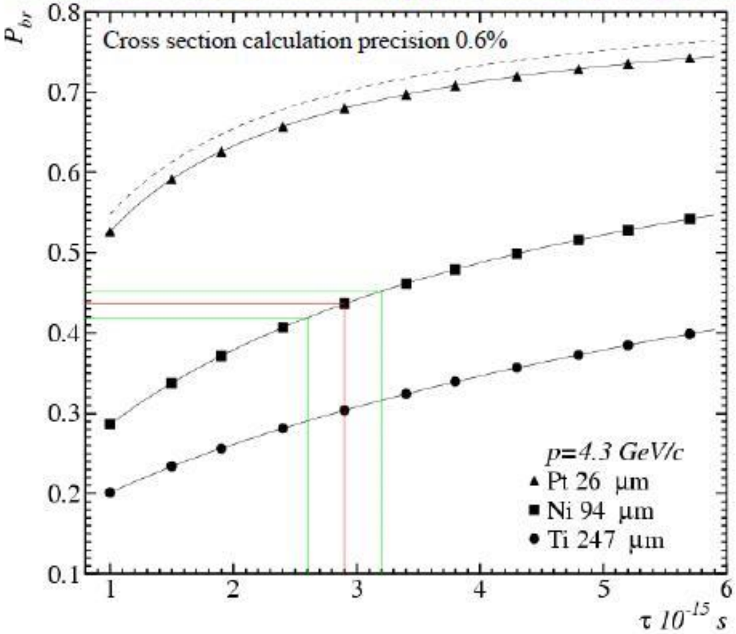
Atoms

There is precise ratio between the number of produced Coulomb pairs (N_C) with small Q and the number of atoms (N_A) produced simultaneously with these Coulomb pairs:

$$N_A = K(Q_0) N_C (Q \le Q_0), \frac{\delta K(Q_0)}{K(Q_0)} \le 10^{-2}$$

$$n_A \text{ - atomic pairs number,} \quad P_{br} = \frac{n_A}{N_A}$$

Solution of the transport equations provides one-to-one dependence of the measured break-up probability (P_{br}) on pionium lifetime τ

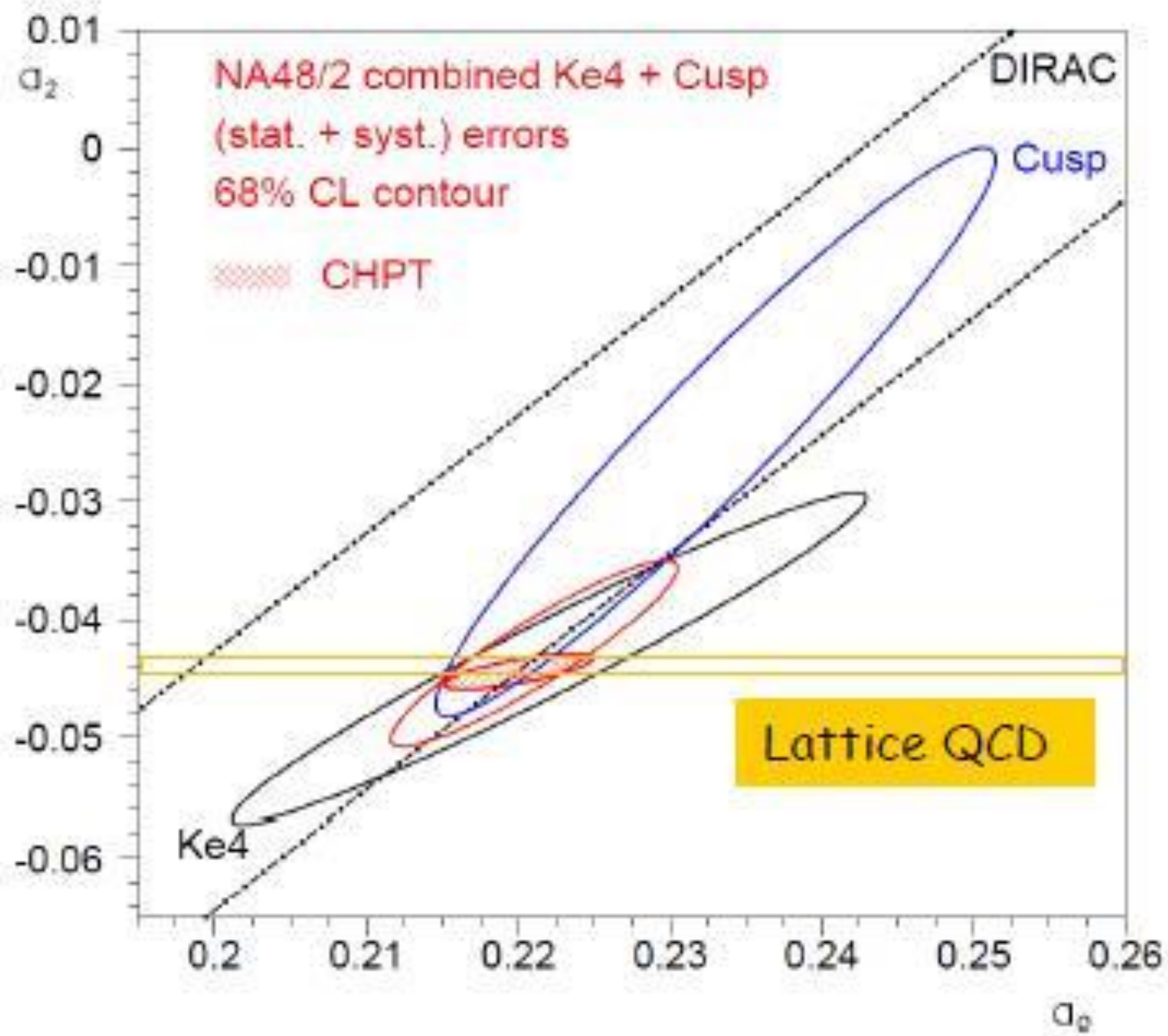


All targets have the same thickness in radiation lengths $6.7 \cdot 10^{-3}\ X_0$

There is an optimal target material for a given lifetime

© L. Nemenov

ππ scattering lengths



M.S. Sozzi

Radiative decays

The trouble is… QED

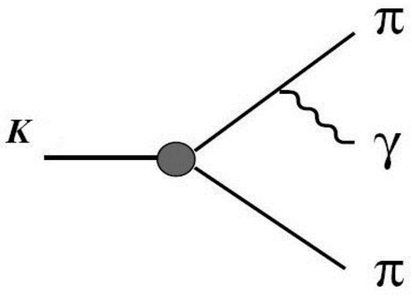
	IB	DE_{exp}	
$K_S \to \pi^+\pi^-\gamma$	10^{-3}	$< 9 \cdot 10^{-5}$	$E1$
$K^+ \to \pi^+\pi^0\gamma$	10^{-4} $(\Delta I = \frac{3}{2})$	$(0.6 \pm 0.04)10^{-5}$ PDG	$M1$,$E1$
$K_L \to \pi^+\pi^-\gamma$	10^{-5} (CPV)	$(2.84 \pm 0.11)10^{-5}$ KTeV	$M1$, VMD

CPV is only from IB K_L (also measured in $K_L \to \pi^+\pi^-e^+e^-$)

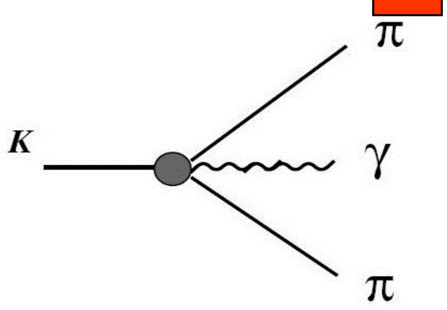
BUT IB suppressed in K^+ and K_L.

© G. D'Ambrosio

$K \to \pi\pi\gamma$

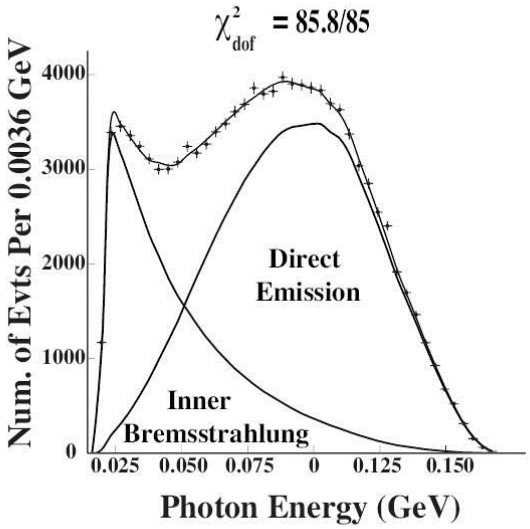


Inner *bremsstrahlung* (IB)

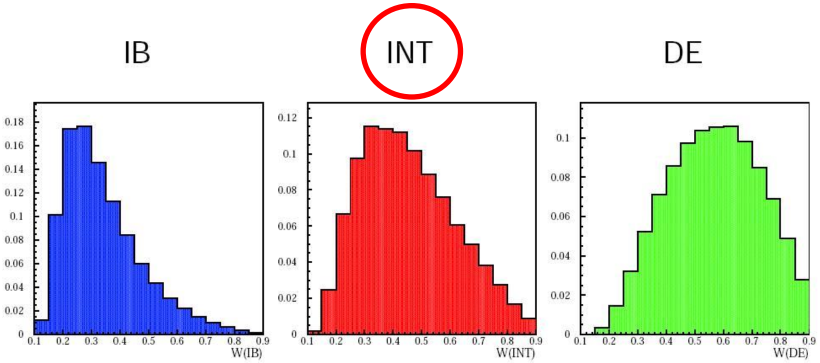


Direct emission (DE)

$K_L \to \pi^+\pi^-\gamma$



$K^\pm \to \pi^+\pi^0\gamma$



Separation by photon spectrum

KTeV (2006): 112K events (40% of total)

DE/(IB+DE) = 0.689 ± 0.021

for Eγ > 20 MeV

NA48/2: 220K events (20% of total)

DE = (3.35 ± 0.43)% INT = (2.67± 1.09)%

for $0 < T^*_\pi < 80$ MeV

INT could give (direct) CPV $O(10^{-4})$

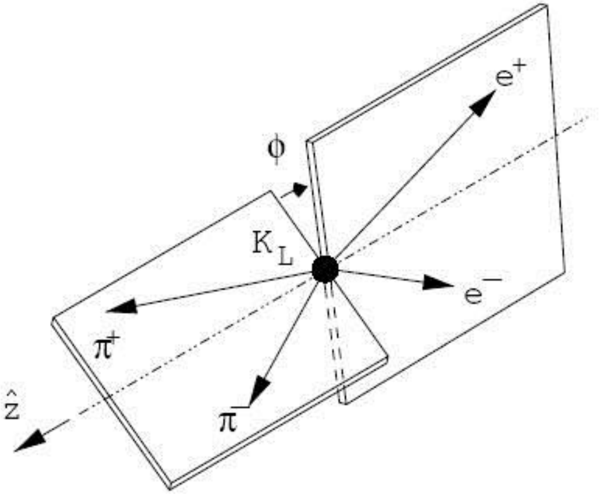
CPV in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

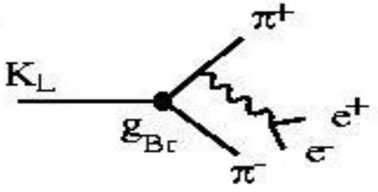
$$\frac{\partial\Gamma^{\pm}}{\partial W} = \frac{\partial\Gamma^{\pm}_{IB}}{\partial W}\left[1 + \underbrace{2\cos(\boxed{\pm\phi +}\, \delta_1^1 - \delta_0^2)\, m_\pi^2 m_K^2 \,|X_E|\, W^2}_{\textbf{INT}} + m_\pi^4 m_K^4 (|X_E|^2 + |X_M|^2) W^4\right]$$

- o Asymmetry can manifest itself in rates A_N and Dalitz plot A_W
- o If $\phi \neq 0$ then $\Gamma^{+} \neq \Gamma^{-}$ the number of events $K^{+} \rightarrow \pi^{+}\pi^{0}\gamma \neq K^{-} \rightarrow \pi^{-}\pi^{0}\gamma$
- o Theoretical range $2 \cdot 10^{-6}$ to $1 \cdot 10^{-5}$ with $50 < E_{\gamma}^{*} < 170$ MeV.
- o SUSY contributions can push the asymmetry to 10^{-4} in specific region of the Dalitz plot
- o Present experimental knowledge: (0.9±3.3)% PDG08
- o NA48/2 limit < 1.4×10^{-3} 90% CL based on 1.08 Million events

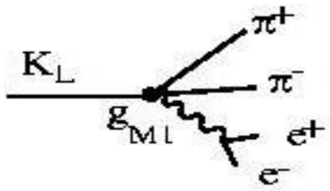
$K_{L,S} \to \pi^+\pi^-e^+e^-$ and CPV

Rare decay (BR ≈ $3 \cdot 10^{-7}$) first seen by KTeV
Internal γ conversion allows helicity analysis:
asymmetry in angle ϕ between ππ and ee planes,
in agreement with theory (indirect CPV)

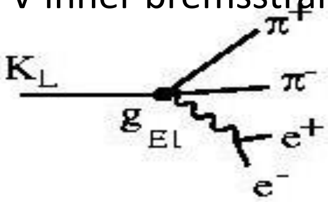




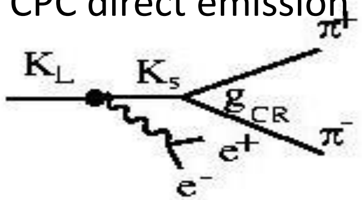
CPV inner bremsstrahlung



CPC direct emission



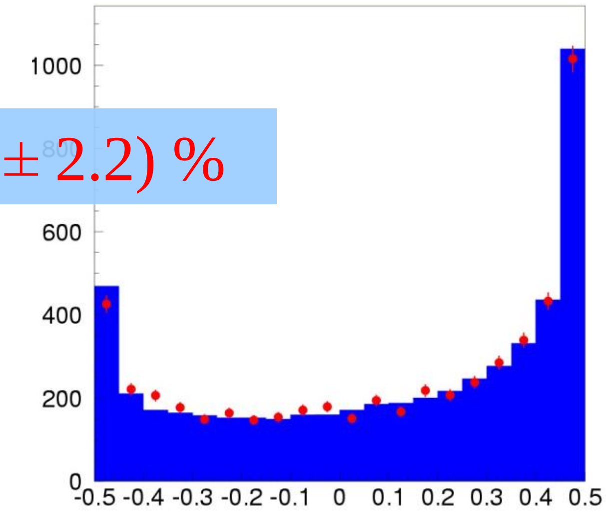
CPV direct emission



Charge radius

$A_\Phi = (13.8 \pm 2.2)$ %

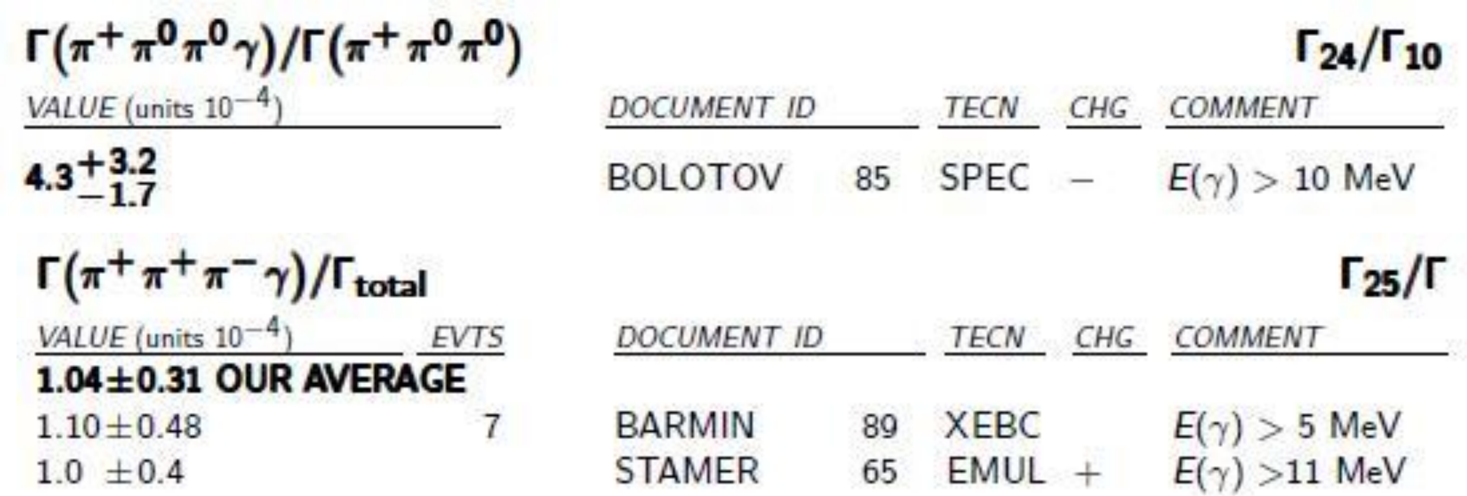
(KTeV + NA48)



Also $K_L \to e^+e^-e^+e^-$ (KTeV, NA48)
and related CPV parameters

All consistent with indirect (ε) CPV

K → 3πγ



$\Gamma(\pi^+\pi^0\pi^0\gamma)/\Gamma(\pi^+\pi^0\pi^0)$ Γ_{24}/Γ_{10}

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$4.3^{+3.2}_{-1.7}$	BOLOTOV	85	SPEC	−	$E(\gamma) > 10$ MeV

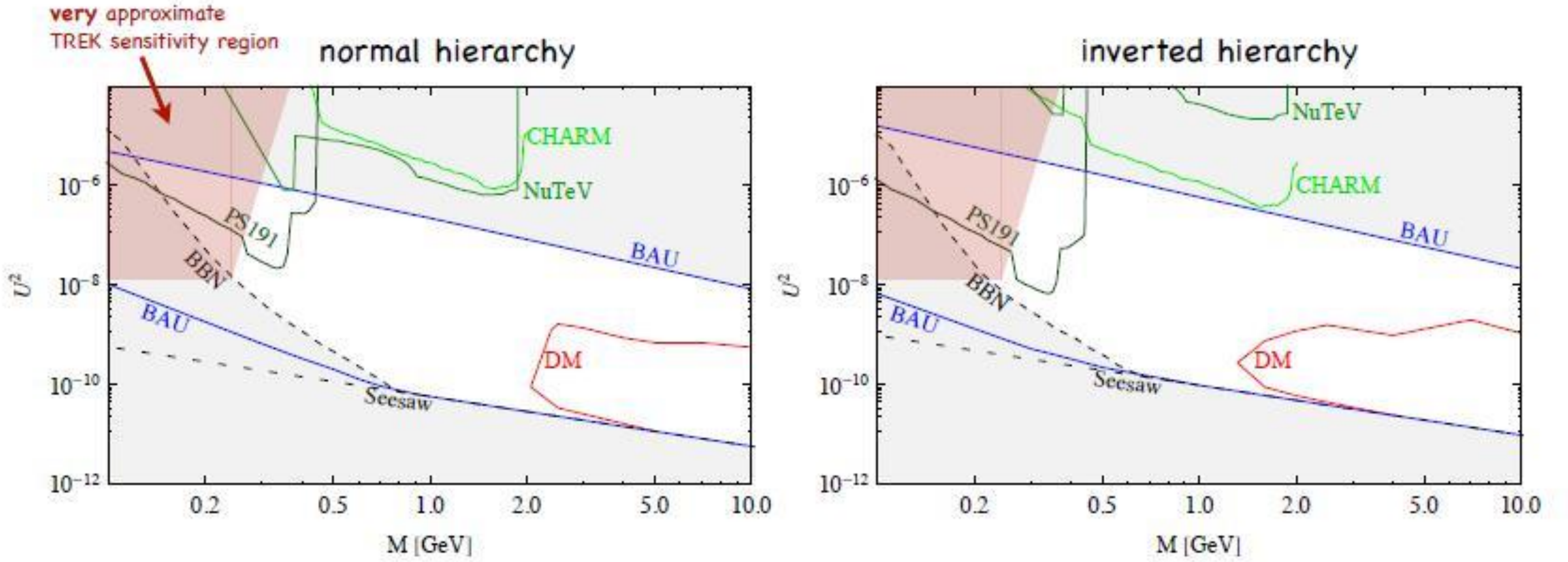
$\Gamma(\pi^+\pi^+\pi^-\gamma)/\Gamma_{\text{total}}$ Γ_{25}/Γ

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.04±0.31 OUR AVERAGE						
1.10±0.48	7	BARMIN	89	XEBC		$E(\gamma) > 5$ MeV
1.0 ±0.4		STAMER	65	EMUL	+	$E(\gamma) > 11$ MeV

Dominated by IB at $O(p^4)$ for unsuppressed decays (prediction only limited by knowledge of 3π), unlikely to extract direct weak part (low-energy constants)

Exotics

Sterile neutrinos



very approximate
TREK sensitivity region

BAU Baryon asymmetry of the Universe

DM Dark matter

BBN Big bang nucleosynthesis

≡ Bounds from sterile neutrino searches

S.N. Gninenko, D.S. Gorbunov, M.E. Shaposhnikov,
Phys. Rev. Lett. **110**, 061801 (2013)

Projected TREK E36

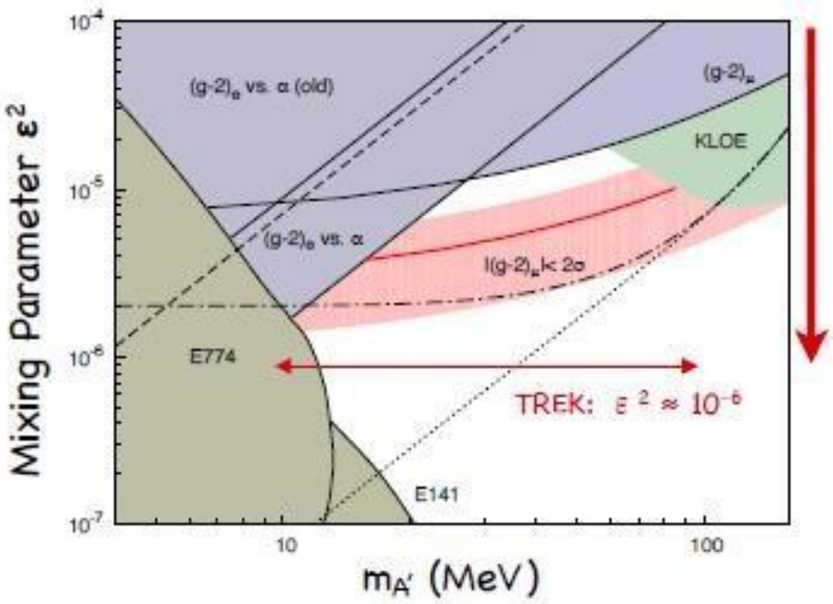
$BR(K^+ \rightarrow \mu^+ N) \lesssim 2 \times 10^{-8}$

$U^2 \lesssim 3 \times 10^{-8}$ for $M_N < 200$ MeV

sensitivity for $M_N > 200$ MeV needs more study.

“Dark light”

Very well suited to K low-energy sarches in radiative decays



T. Beranek and M. Vanderhaeghen, Phys. Rev. D **87**, 015024 (2013)

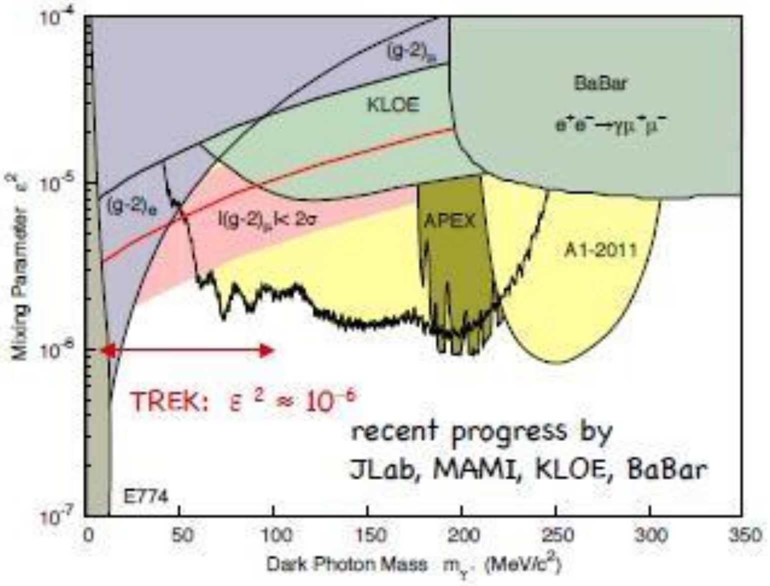


Fig. from M. Pospelov, PEB2013 workshop (2013)

Projected TREK E36

Full reconstruction of the $\mu^+\nu e^+e^-$ and $\pi^+e^+e^-$ final states

Possible improvement with projected E36 results: $\varepsilon^2 \approx 10^{-6}$

Signal:

- Peak in $M(e^+e^-)$ spectrum measured in the CsI(Tl) calorimeter
- Peak in the π^+ momentum spectrum for $K^+ \to \pi^+ A'$

$$K^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$$
$$K^+ \to \pi^+ A' \to \pi^+ e^+e^-$$

What about time?

Kabir Test: T violation in mixing

P.K. Kabir
(1933-2004)

Direct comparison of T-related transitions:

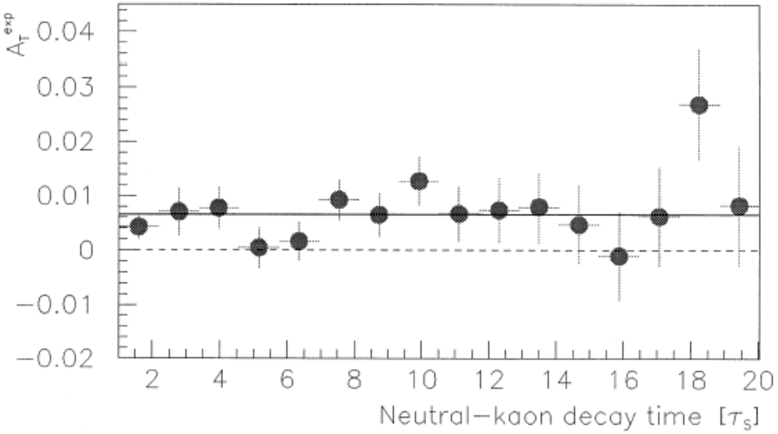
$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$

S_{prod} from flavour tag, S_{dec} from semileptonic decay.
Assuming CPT symmetry in decay:

$$A_T(t) = 4\,\mathrm{Re}(\varepsilon) + 2\,\frac{\mathrm{Re}(x_-)\left[e^{-\Delta\Gamma t/2} - \cos(\Delta m t)\right] + \mathrm{Im}(x_+)\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)}$$

CPLEAR (1998):

$\langle A_T \rangle = (6.6 \pm 1.3)\cdot 10^{-3}$



States are also CP-conjugate
Compatible with CPV in mixing

T violation in interference

Compare $\overline{B} \rightarrow B_-$ to $B_- \rightarrow \overline{B}$
and other 3 combinations

B_+: decay to $J/\psi K_L$ (CP = +1)
B_-: decay to $J/\psi K_S$ (CP = –1)

$\langle B_+ | B_- \rangle = 0$ if single phase

$$\Gamma(B^\alpha \rightarrow B^\beta) =$$

$$e^{-\Gamma\Delta t}\left[1 \pm S(\alpha \rightarrow \beta)\sin(\Delta m \Delta t) + C(\alpha \rightarrow \beta)\cos(\Delta m \Delta t)\right]$$

$B^{\alpha,\beta} = B, B, B_+, B_-$ Flavour-tagging and CP-tagging

$$\Delta S_T = S(\overline{B}^0 \rightarrow B_-) - S(B_- \rightarrow \overline{B}^0)$$

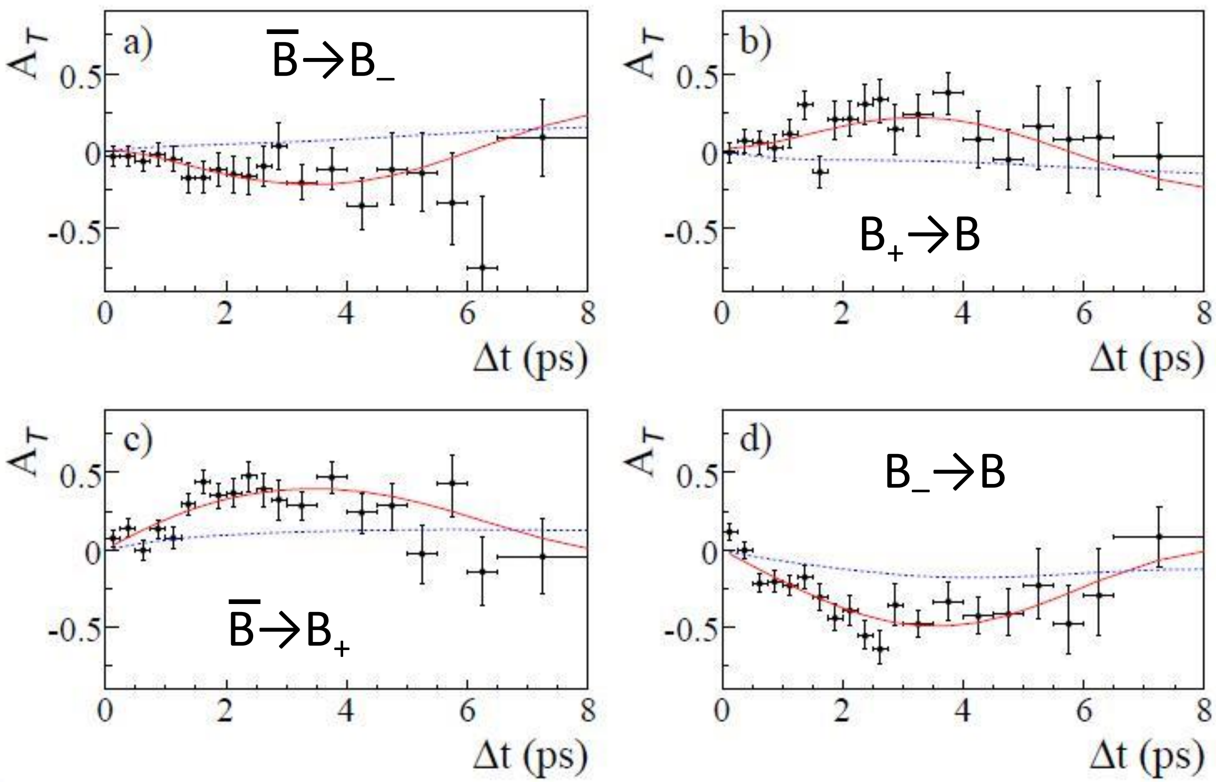
$$\Delta S_{CP} = S(\overline{B}^0 \rightarrow B_-) - S(B^0 \rightarrow B_-)$$

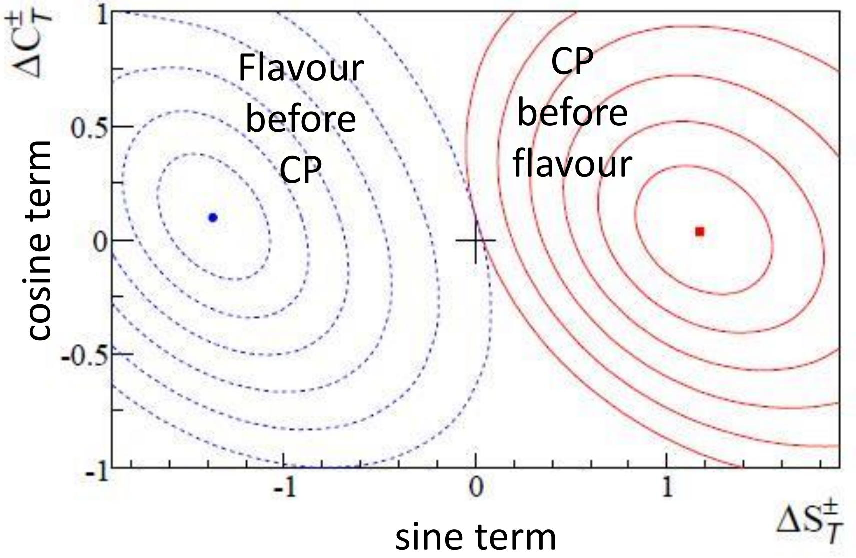
$$\Delta S_{CPT} = S(\overline{B}^0 \rightarrow B_-) - S(B_- \rightarrow B^0)$$

And similar for cosine

Other effects are small:
- B lifetime difference
- Direct CPV
- CPV in K

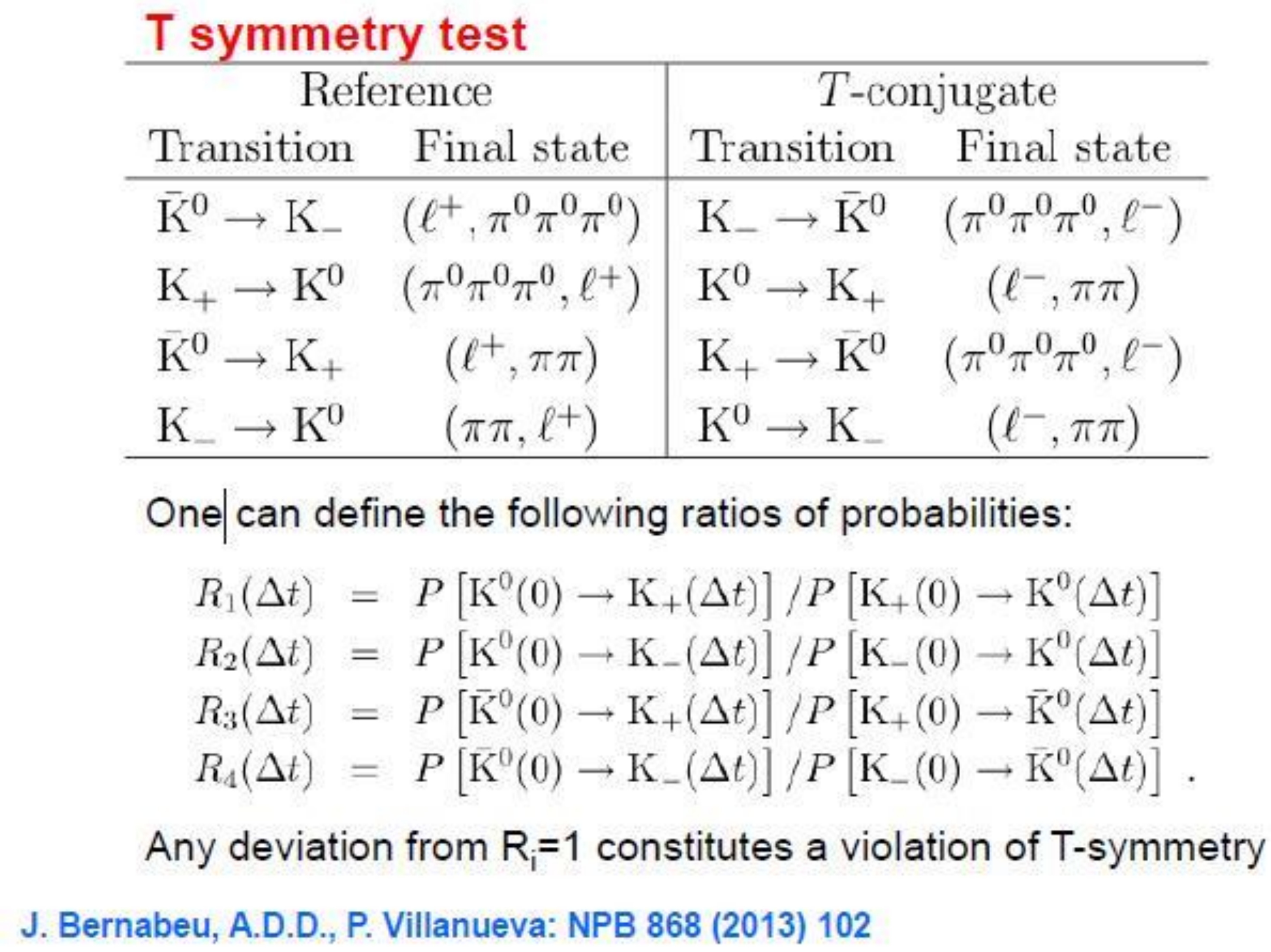
BABAR (2012)
500M BB pairs





T violation
significance: 14 σ

Direct time reversal test with K ?



T symmetry test

Reference		T-conjugate	
Transition	Final state	Transition	Final state
$\bar{K}^0 \to K_-$	$(\ell^+, \pi^0\pi^0\pi^0)$	$K_- \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_+ \to K^0$	$(\pi^0\pi^0\pi^0, \ell^+)$	$K^0 \to K_+$	$(\ell^-, \pi\pi)$
$\bar{K}^0 \to K_+$	$(\ell^+, \pi\pi)$	$K_+ \to \bar{K}^0$	$(\pi^0\pi^0\pi^0, \ell^-)$
$K_- \to K^0$	$(\pi\pi, \ell^+)$	$K^0 \to K_-$	$(\ell^-, \pi\pi)$

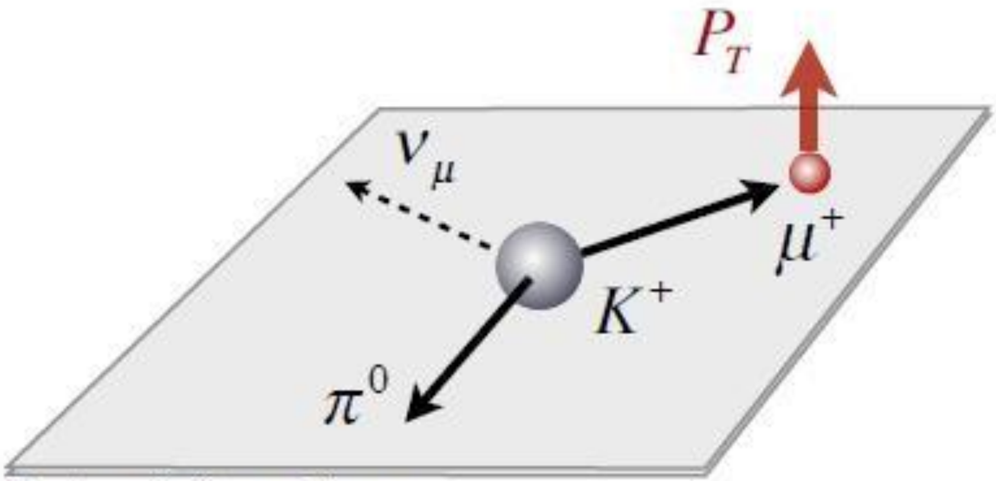
One can define the following ratios of probabilities:

$$
\begin{aligned}
R_1(\Delta t) &= P\left[K^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to K^0(\Delta t)\right] \\
R_2(\Delta t) &= P\left[K^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to K^0(\Delta t)\right] \\
R_3(\Delta t) &= P\left[\bar{K}^0(0) \to K_+(\Delta t)\right] / P\left[K_+(0) \to \bar{K}^0(\Delta t)\right] \\
R_4(\Delta t) &= P\left[\bar{K}^0(0) \to K_-(\Delta t)\right] / P\left[K_-(0) \to \bar{K}^0(\Delta t)\right] \ .
\end{aligned}
$$

Any deviation from R_i=1 constitutes a violation of T-symmetry

J. Bernabeu, A.D.D., P. Villanueva: NPB 868 (2013) 102

T-odd signatures



K+ decay in its rest frame

$$\boxed{K^+ \to \pi^0 \mu^+ \nu_\mu}$$

study of direct CP violation, possibly due to non-standard mechanisms, with the help of T-odd correlation variables

$$\boxed{P_T = \frac{\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{\left|\vec{p}_\pi \times \vec{p}_\mu\right|}}$$

KEK E246

Transverse μ^+ polarization in $K^+ \to \pi^0 \mu^+ \upsilon$ decay
CPV not suppressed by $\Delta I=1/2$ (can be 20x $\varepsilon'/\varepsilon \approx 10^{-4}$)
Tiny SM contribution ($\approx 10^{-7}$), small FSI ($\approx 10^{-5}$):
good window for New Physics search
Relative phase of scalar coupling FF

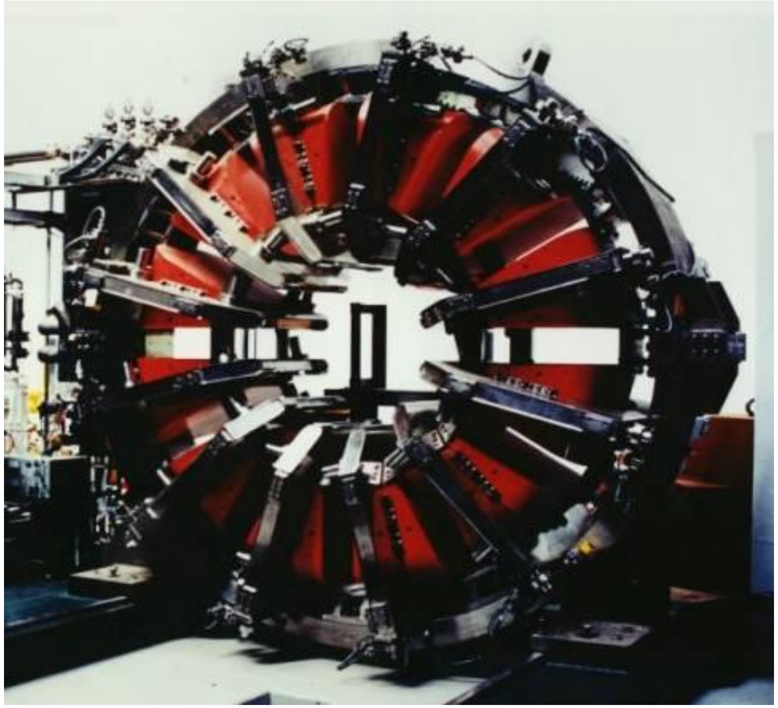
40 years of experimental history

KEK E246 experiment (final 2006):

$$P_T = -0.0017 \pm 0.0023 \pm 0.0011$$

$$P_T < 5 \cdot 10^{-3} \quad (90\% \, CL)$$

No sign of TRV
Statistically limited



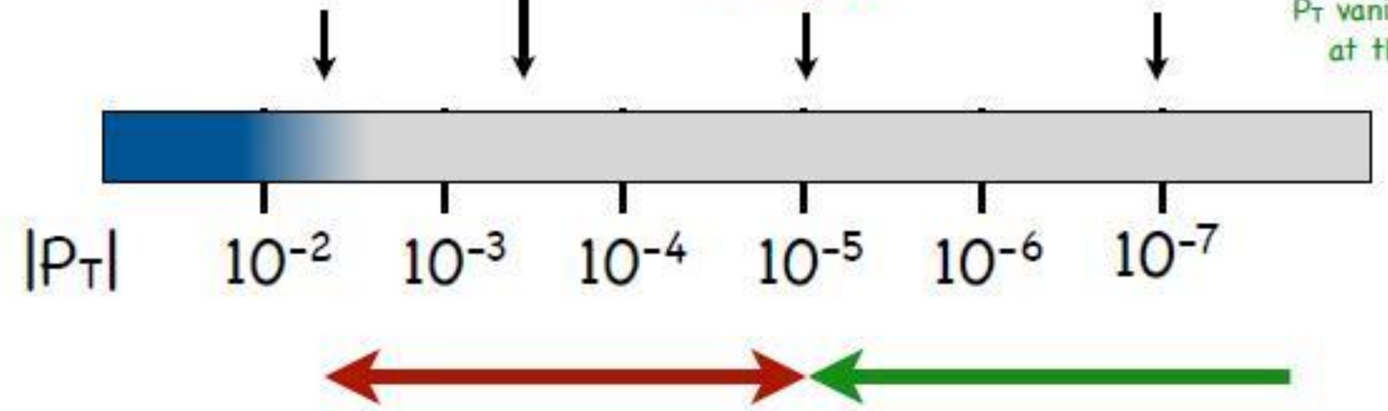
PT sensitive to new physics

KEK-E246:
$|P_T| < 5 \times 10^{-3}$ at 90% C.L.

Projected J-PARC E06:
$|P_T| < 2 \times 10^{-4}$ at 90% C.L.

S.M.
incl. FSI

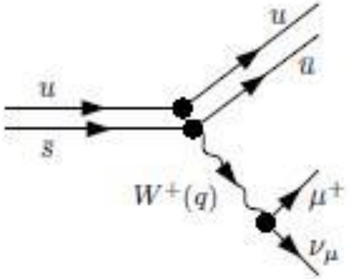
S.M.



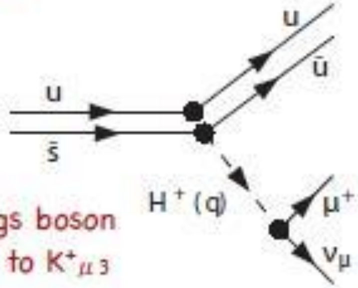
potential for physics beyond
the standard model

- Multi-Higgs,
- SUSY with squarks mixing,
- SUSY with R-parity breaking,
- Leptoquark model

SM background

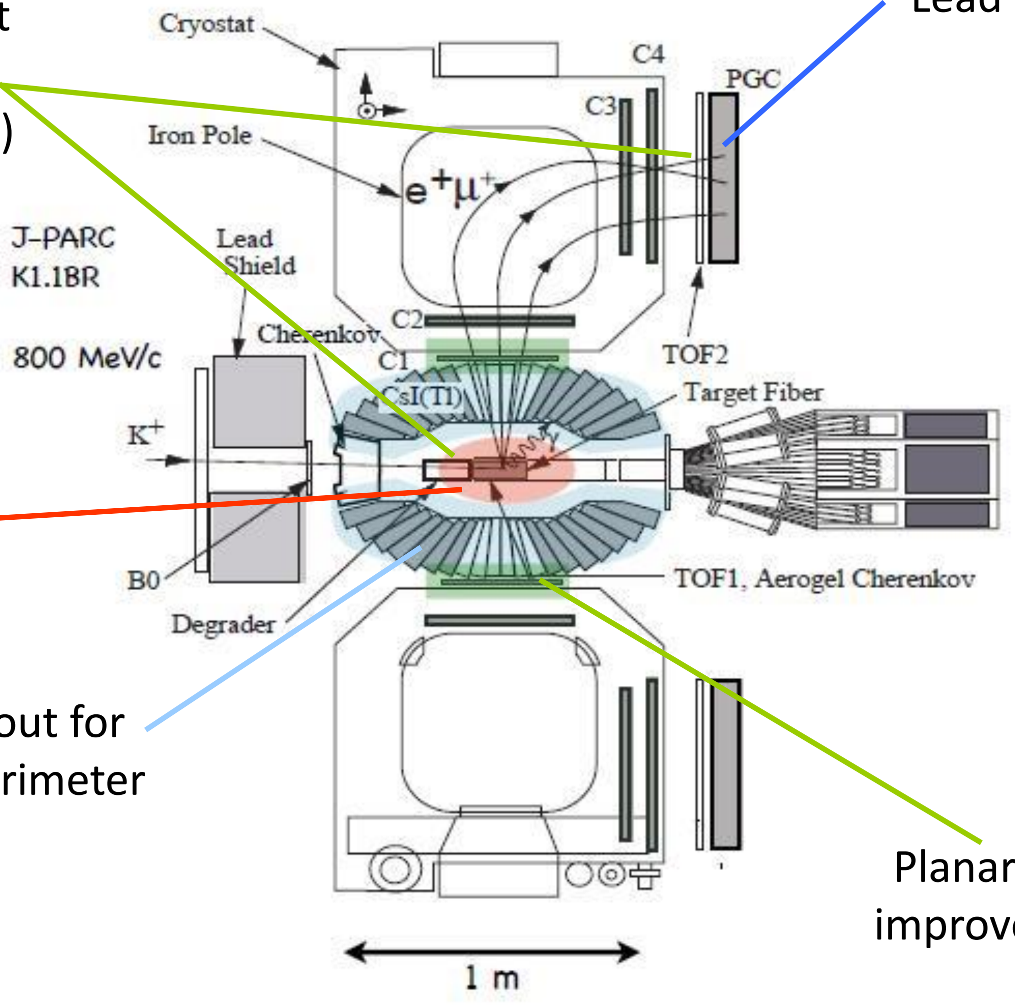


P_T vanishes in the SM
at the tree-level



Charged Higgs boson
contribution to $K^+_{\mu 3}$

TREK improvements



TOF measurement
for e/μ
(aerogel Cerenkov)

Lead glass Cerenkov

Fiber target
read with SiPM

APD readout for
CsI(Tl) calorimeter

Planar GEMs for
improved tracking

© S. Strauch

TREK experiment @ J-PARC

Goal: $\sigma(P_T) \approx 10^{-4}$ in 1 year

Factor **20** over E246:

0.8 GeV/*c* separated K+ branch line (K/π ≈ 2)

Higher beam **intensity** (2 MHz K^+), 1 year (300 kW beam)

Active polarimeter (lower systematics, higher acceptance)

New tracking (w. thinner target and He bags: higher background rejection)

45 people, 20 institutions
(Japan, Russia, USA, Canada, Vietnam, Thailand)

Where few dare: CPT

CPT test with K

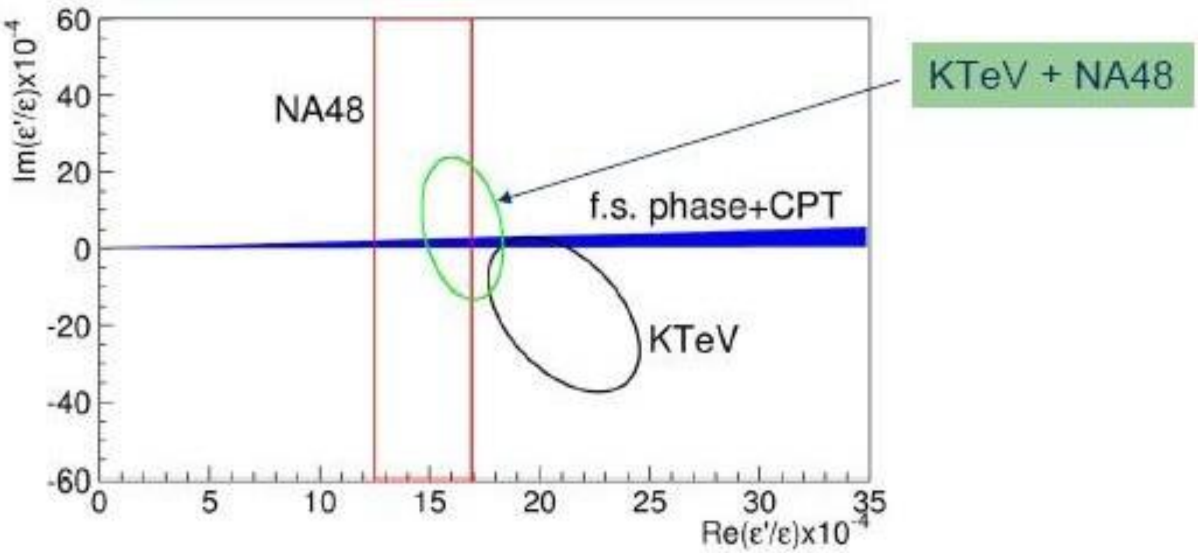
$\Delta m = (5269.9 \pm 12.3) \cdot 10^{6}\,\hbar\mathrm{s}^{-1}$ No CPT: $\Delta m = (5279.7 \pm 19.5) \cdot 10^{6}\,\hbar\mathrm{s}^{-1}$

$\tau_S = (89.623 \pm 0.047) \cdot 10^{-12}\,\mathrm{s}$ No CPT: $\tau_S = (89.589 \pm 0.070) \cdot 10^{-12}\,\mathrm{s}$

$\phi(\varepsilon) = (43.86 \pm 0.63)^{\circ}$

$\phi(\varepsilon) - \phi_{SW} = (0.40 \pm 0.56)^{\circ}$

$\phi_{00} - \phi_{+-} = (0.30 \pm 0.35)^{\circ}$



Fully consistent with CPT symmetry

Phases in K → ππ decays

If CPT holds: $\phi(\varepsilon) \cong \phi_{SW} = \arctan\left(2\Delta m / \Delta\Gamma\right) \cong 43.6°$ within 1%

ϕ(ε’) ≅ 42°: a component of ε’ orthogonal to ε violates CPT

Im(ε’/ε) could be measured at a *Φ factory*.

$$m_K - m_{\overline{K}} = \mathrm{Re}(H_{11} - H_{22}) \cong -2\delta\, \Delta m$$

$$\frac{|\eta_{+-}|\left(2\phi_{+-}/3 + \phi_{00}/3 - \phi_{SW}\right)}{\sin\phi_{SW}} = \frac{m_{\overline{K}} - m_K}{2\Delta m} + A_{dir}$$

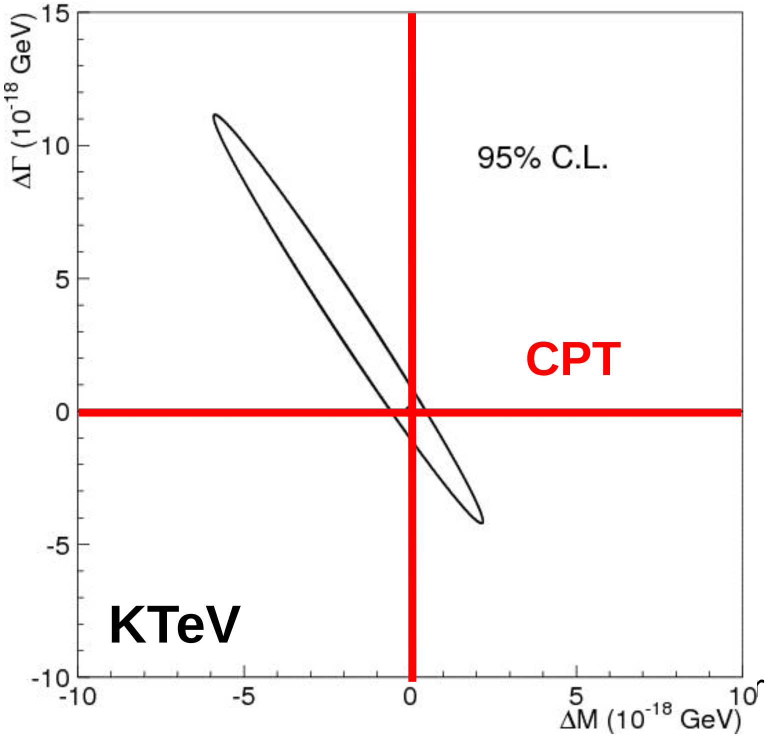
CPT violation in decays

And the winner is...

$$\mathrm{Im}(\delta) = (-1.5 \pm 1.6) \cdot 10^{-5}$$

(KTeV data (only) + PDG)

$$\delta = \frac{i(m_K - m_{\overline{K}}) + (\Gamma_K - \Gamma_{\overline{K}})/2}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}} [1 + O(\varepsilon)]$$



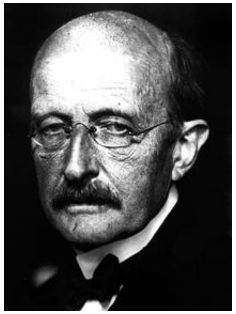
$$\left| m(K^0) - m(\overline{K}^0) \right| <$$

$$4.0 \cdot 10^{-19}\ \mathrm{GeV}/c^2 \quad (95\%\ CL)$$

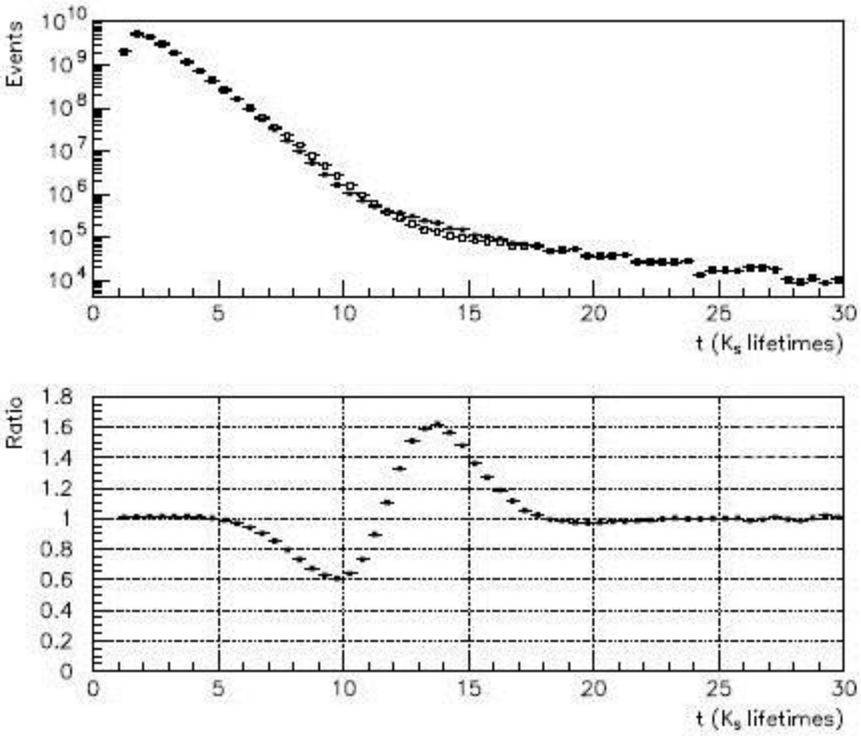
(world data,
assuming CPT in decays)

Ultimate CPT ?

$$\frac{\left|m_K - m_{\overline{K}}\right|}{m_K} < 8.0\cdot 10^{-19}\ (95\%\ CL) \quad \Longleftrightarrow \quad \boxed{\frac{m_K}{m_{Pl}} = 4.1\cdot 10^{-20}}$$



CP/T proposal (1997)



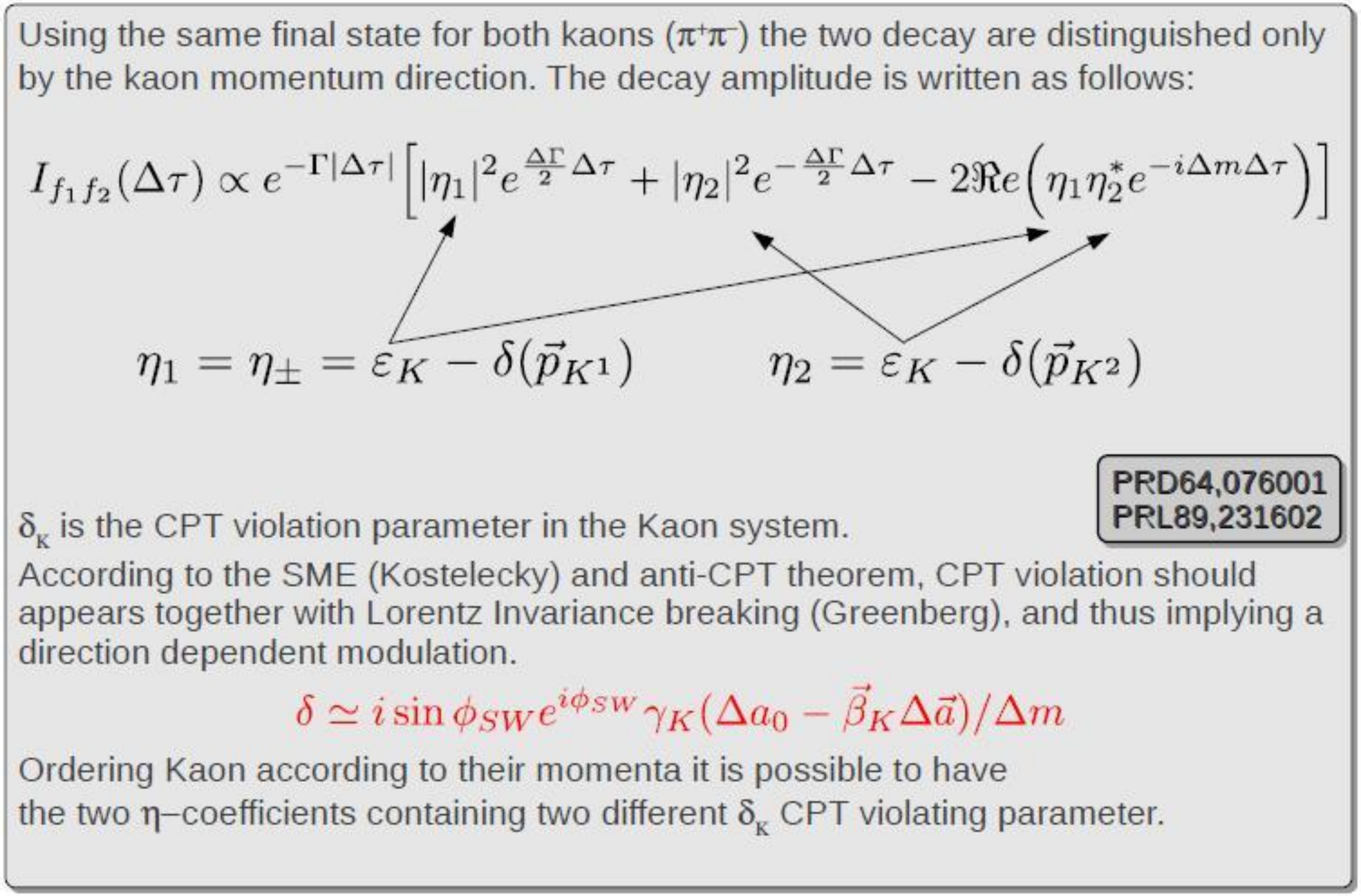
K_S/K_L interference experiment
No regenerator: pure tertiary K^0 beam from (separated) K^+

Project-X intensity

(1) $\phi_{+-} - \phi_{SW} \approx 0.06^\circ$

(2) Bell-Steinberger (+ancillary)

Lorentz, why not ?



Using the same final state for both kaons ($\pi^+\pi^-$) the two decay are distinguished only by the kaon momentum direction. The decay amplitude is written as follows:

$$I_{f_1 f_2}(\Delta\tau) \propto e^{-\Gamma|\Delta\tau|}\left[|\eta_1|^2 e^{\frac{\Delta\Gamma}{2}\Delta\tau} + |\eta_2|^2 e^{-\frac{\Delta\Gamma}{2}\Delta\tau} - 2\Re e\left(\eta_1 \eta_2^* e^{-i\Delta m \Delta\tau}\right)\right]$$

$$\eta_1 = \eta_\pm = \varepsilon_K - \delta(\vec{p}_{K^1}) \qquad \eta_2 = \varepsilon_K - \delta(\vec{p}_{K^2})$$

PRD64,076001
PRL89,231602

δ_K is the CPT violation parameter in the Kaon system.
According to the SME (Kostelecky) and anti-CPT theorem, CPT violation should appears together with Lorentz Invariance breaking (Greenberg), and thus implying a direction dependent modulation.

$$\delta \simeq i \sin\phi_{SW} e^{i\phi_{SW}} \gamma_K(\Delta a_0 - \vec{\beta}_K \Delta\vec{a})/\Delta m$$

Ordering Kaon according to their momenta it is possible to have the two η–coefficients containing two different δ_K CPT violating parameter.

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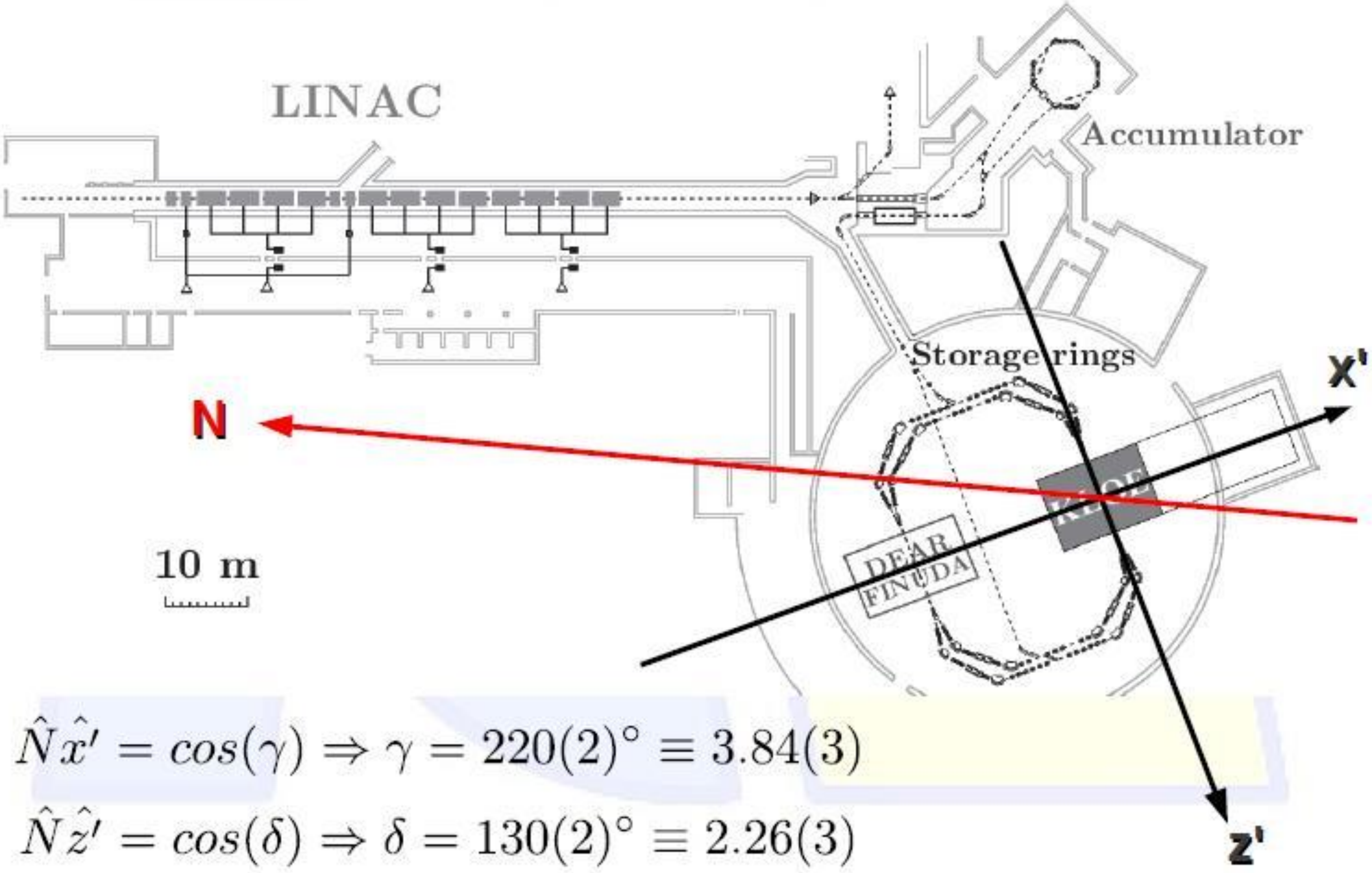
Lorentz @ DAΦNE



$$\hat{N}\hat{x}' = cos(\gamma) \Rightarrow \gamma = 220(2)^\circ \equiv 3.84(3)$$

$$\hat{N}\hat{z}' = cos(\delta) \Rightarrow \delta = 130(2)^\circ \equiv 2.26(3)$$

© A. De Santis

Lorentz test @ KLOE

$$\Delta a_0 = (-6.0 \pm 7.7_{\text{stat}} \pm 3.1_{\text{sys}})\ 10^{-18}\ \text{GeV}$$

$$\Delta a_X = (\ 0.9 \pm 1.5_{\text{stat}} \pm 0.6_{\text{sys}})\ 10^{-18}\ \text{GeV}$$

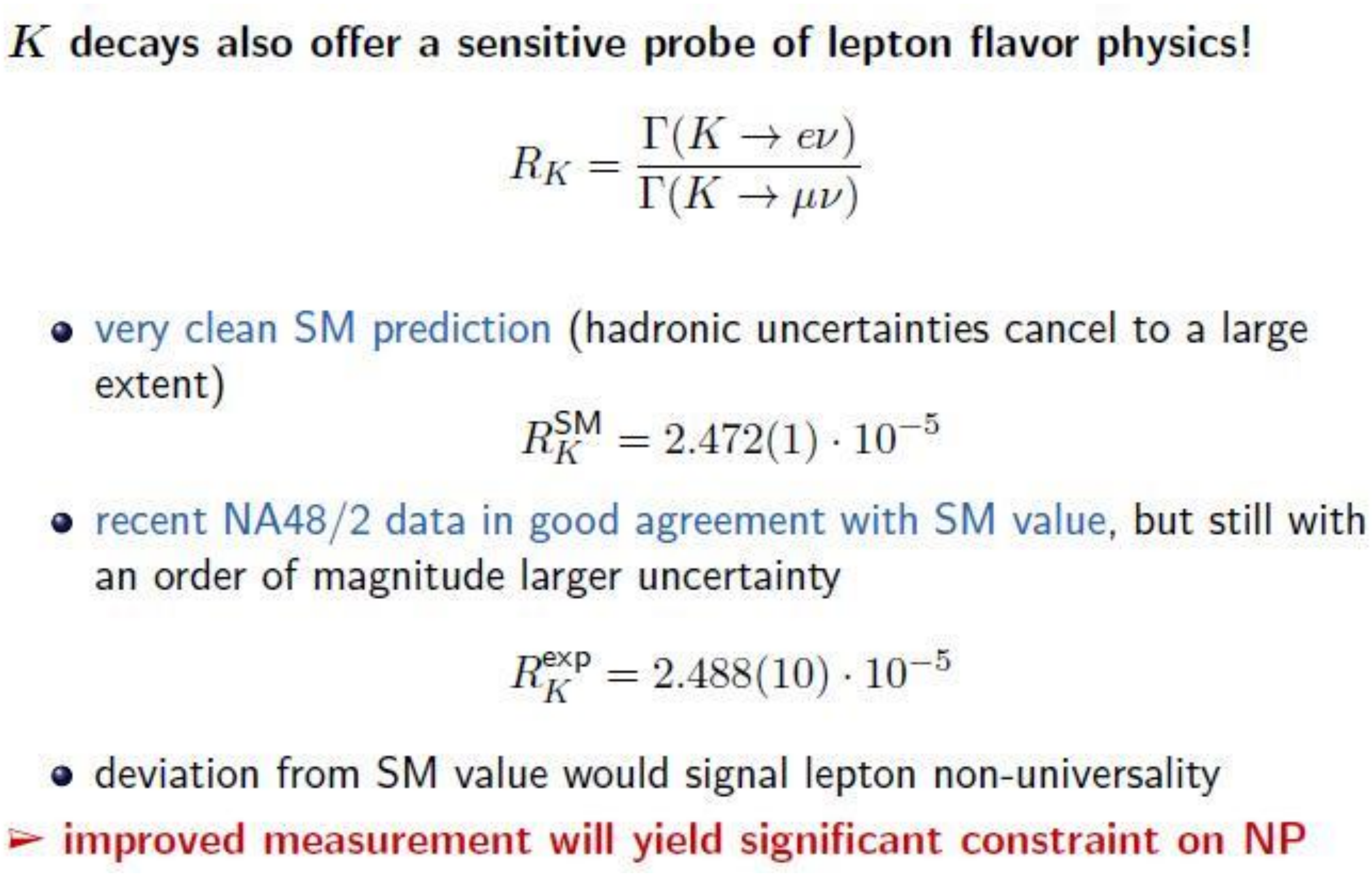
$$\Delta a_Y = (-2.0 \pm 1.5_{\text{stat}} \pm 0.5_{\text{sys}})\ 10^{-18}\ \text{GeV}$$

$$\Delta a_Z = (\ 3.1 \pm 1.7_{\text{stat}} \pm 0.6_{\text{sys}})\ 10^{-18}\ \text{GeV}$$

© A. De Santis

Precision (B)SM physics

Leptonic decays



K decays also offer a sensitive probe of lepton flavor physics!

$$R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$$

- very clean SM prediction (hadronic uncertainties cancel to a large extent)

$$R_K^{\mathsf{SM}} = 2.472(1) \cdot 10^{-5}$$

- recent NA48/2 data in good agreement with SM value, but still with an order of magnitude larger uncertainty

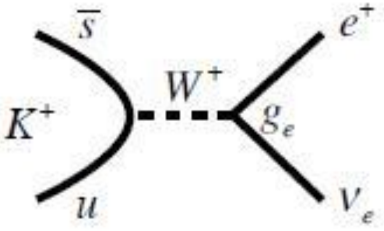
$$R_K^{\mathsf{exp}} = 2.488(10) \cdot 10^{-5}$$

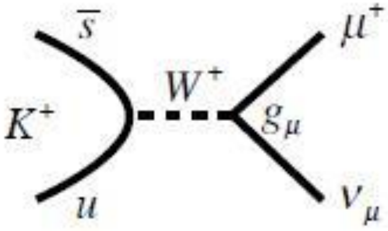
- deviation from SM value would signal lepton non-universality

➢ improved measurement will yield significant constraint on NP

Leptonic decays SM

$$\boxed{\begin{array}{l} K^+ \to e^+\nu(\gamma) \\ K^+ \to \mu^+\nu(\gamma) \end{array}}$$





Decay-width

$$\Gamma(K_{\ell 2}) = g_\ell^2 (G^2/8\pi) f_K^2 m_K m_\ell^2 \{1-(m_\ell^2/m_K^2)\}^2$$

Decay-width ratio

hadronic form factor f_K cancels

V. Cirigliano and I. Rosell, Phys. Rev. Lett. **99**, 231801 (2007)

$$R_K^{SM} = \frac{\Gamma(K^+\to e^+\nu_e[\gamma])}{\Gamma(K^+\to \mu^+\nu_\mu[\gamma])} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2-m_e^2}{m_K^2-m_\mu^2}\right)^2 (1+\delta R_{QED}) = 2.477(1)\times 10^{-5}$$

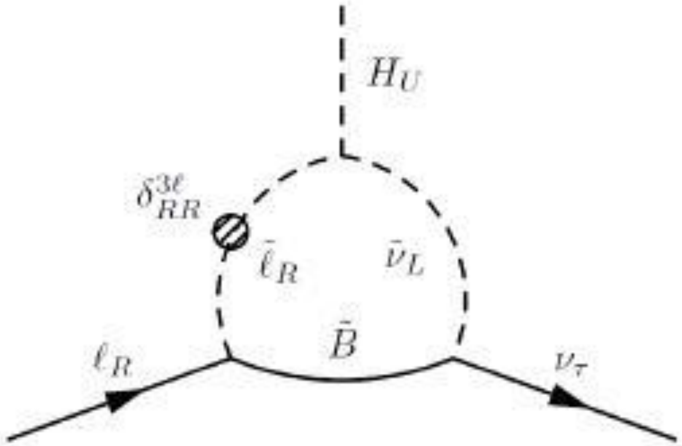
$g_e/g_\mu = 1$
in the standard model

helicity suppression

radiative correction
(incl. internal brems., IB)

Leptonic decays BSM

MSSM: dominant contribution through LFV interactions

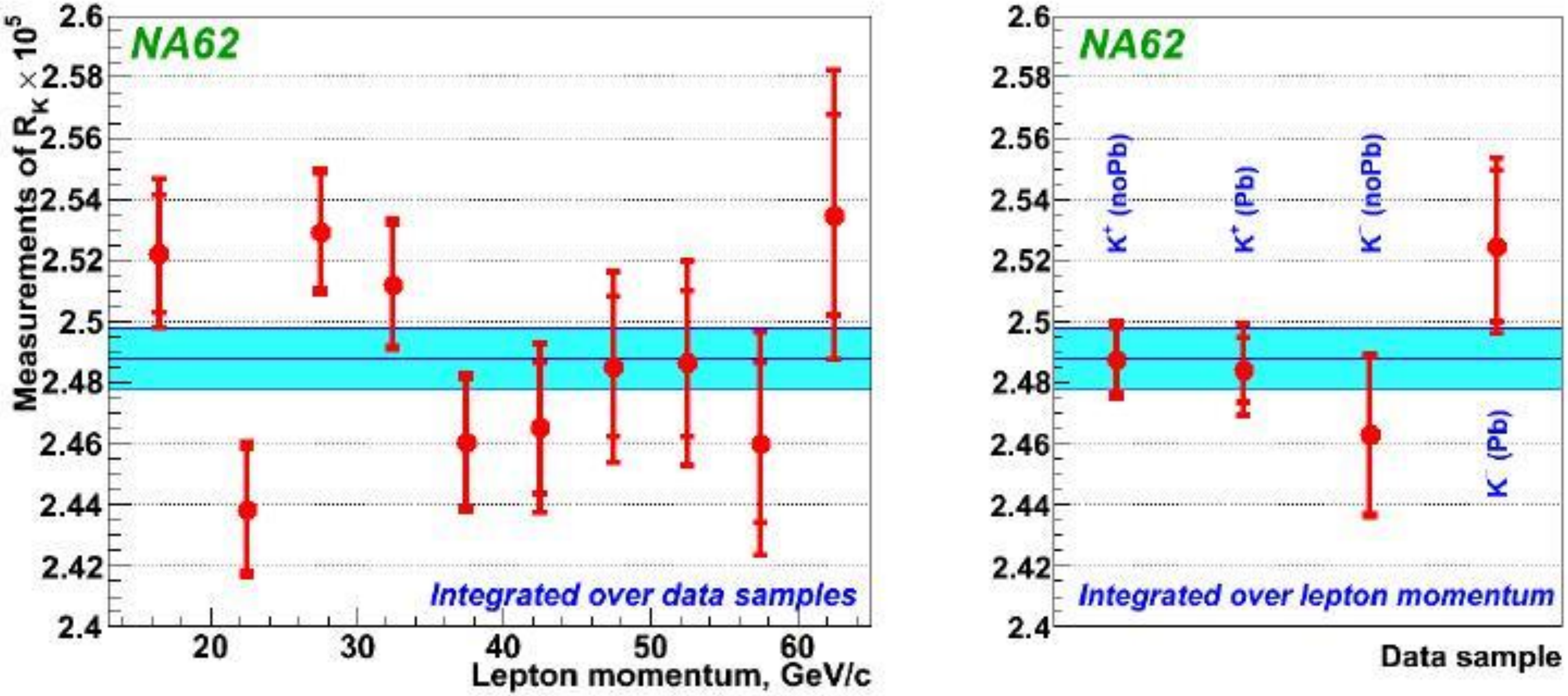


Masiero, Paradisi, Petronzio (2005) and others

- no interference with SM ► enhancement of R_K
- complementary to LFV μ and τ decays

© M. Blanke

$R_K = BR(K_{e2})/BR(K_{\mu2})$: NA62 @ CERN

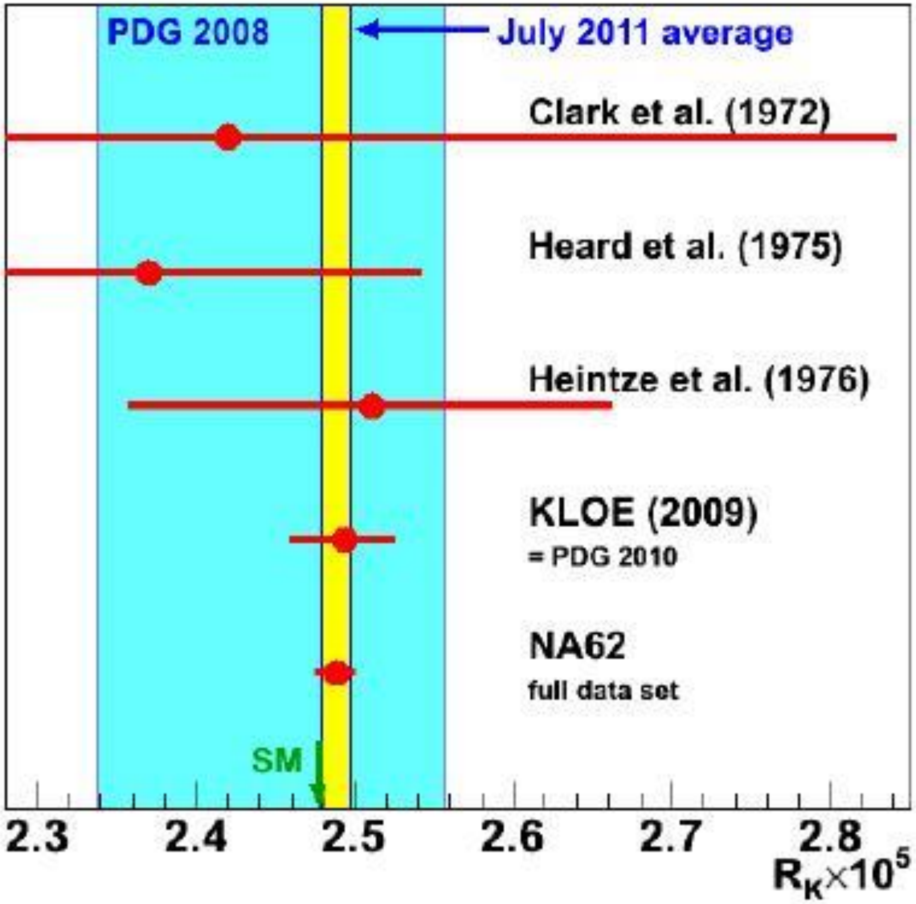


- $R_K = (2.488 \pm 0.007_{stat.} \pm 0.007_{syst.}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}$ $(\chi^2/\text{ndf} = 47/39)$

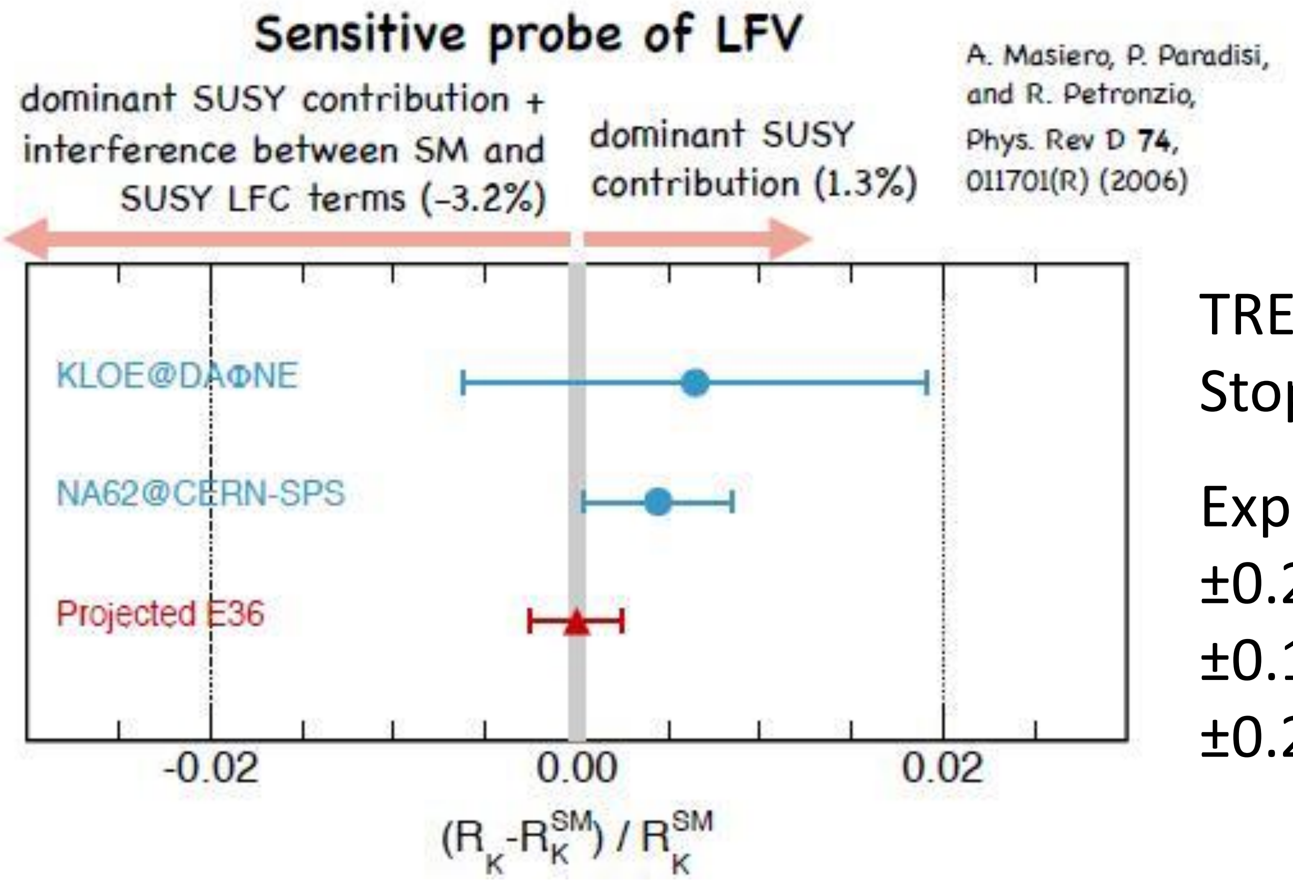
[Phys. Lett. B 719 (2013) 326]

$R_K = BR(K_{e2})/BR(K_{\mu2})$ now

- $R_K = (2.488 \pm 0.009) \times 10^{-5}$



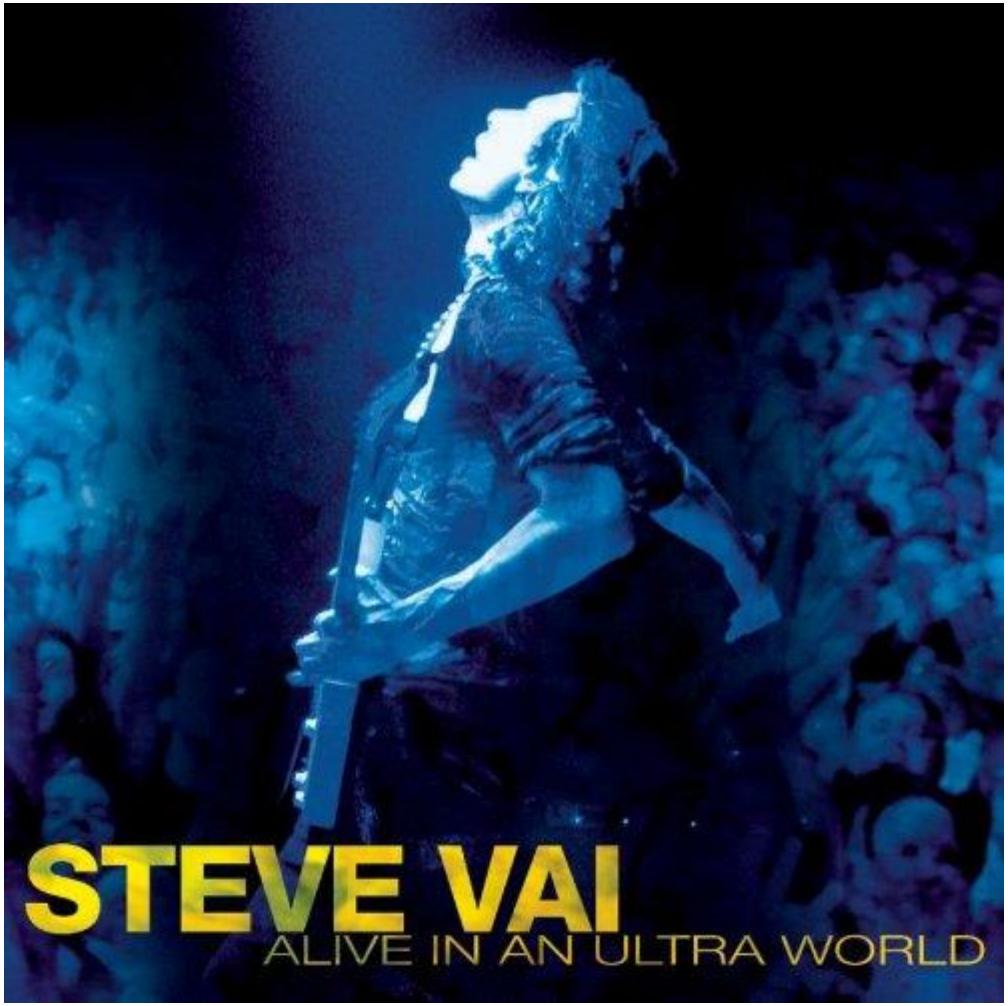
R_K = BR(K_{e2})/BR($K_{\mu 2}$) some more?



TREK (E36 @ J-PARC)
Stopped K beam

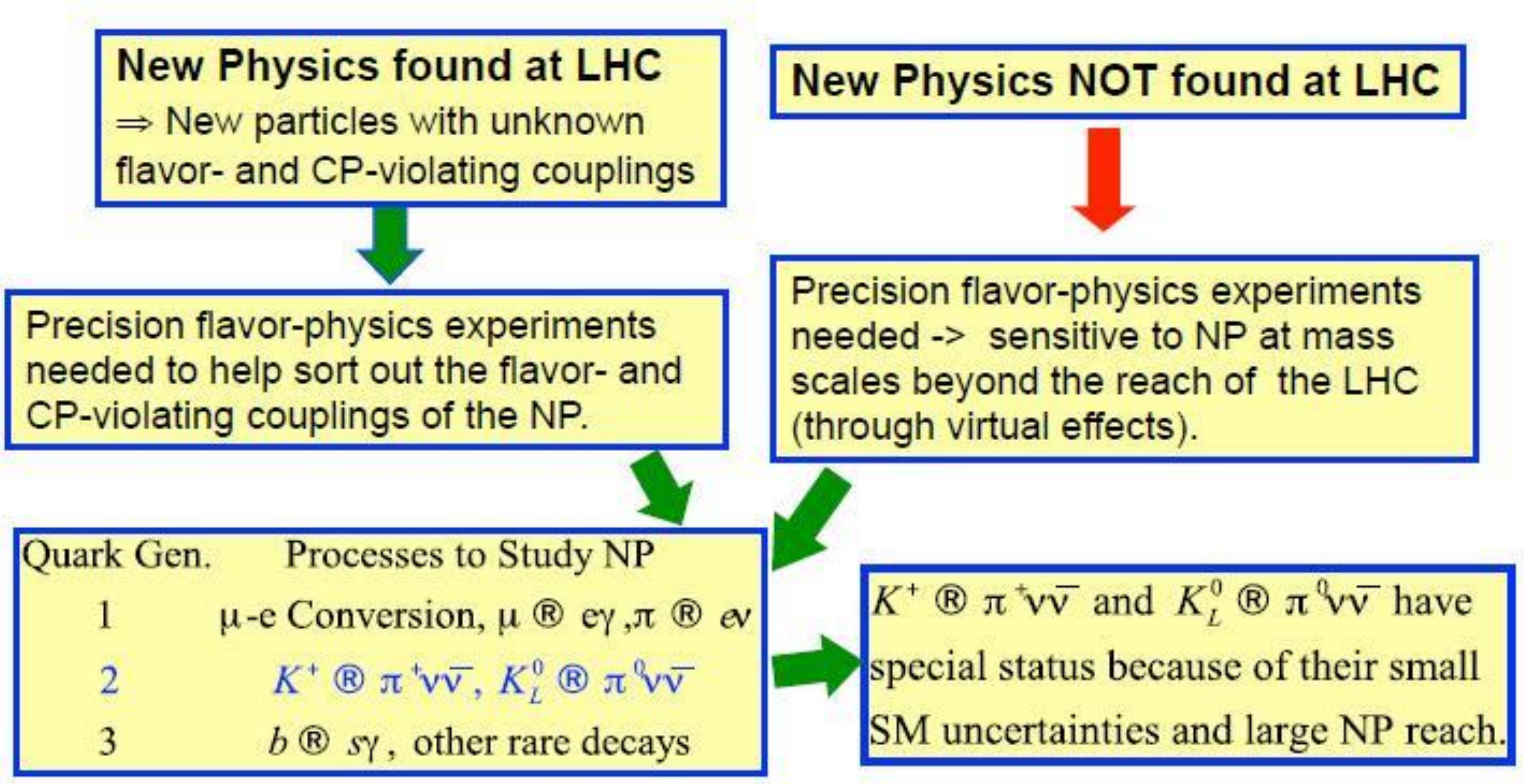
Expectations:
±0.20% (stat)
±0.15% (syst) =
±0.25%

© S. Strauch



The ultra-rare world

The win-win scenario



New Physics found at LHC
⇒ New particles with unknown flavor- and CP-violating couplings

Precision flavor-physics experiments needed to help sort out the flavor- and CP-violating couplings of the NP.

New Physics NOT found at LHC

Precision flavor-physics experiments needed -> sensitive to NP at mass scales beyond the reach of the LHC (through virtual effects).

Quark Gen.	Processes to Study NP
1	μ-e Conversion, $\mu \to e\gamma$, $\pi \to e\nu$
2	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L^0 \to \pi^0\nu\bar{\nu}$
3	$b \to s\gamma$, other rare decays

$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ have special status because of their small SM uncertainties and large NP reach.

© D. jaffe

Why ultra-rare K decays?

We now know that
the flavour structure of “TeV scale” BSM physics is not too weird

The easy (SM) stuff has been done

“When the going gets tough,
the tough get going”

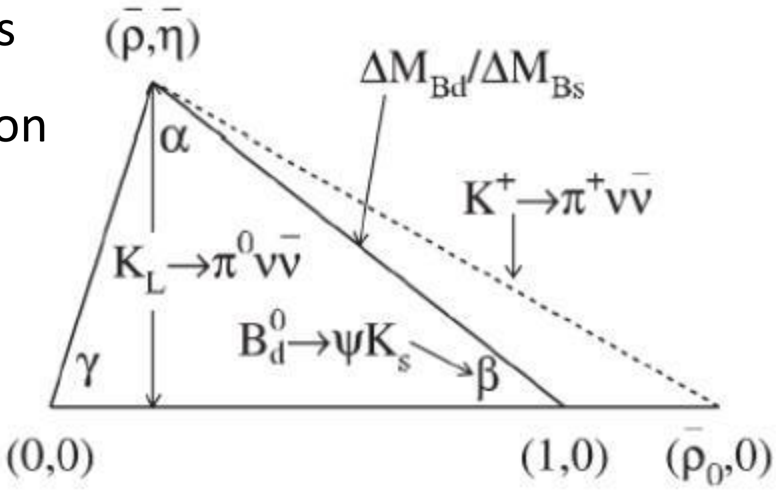
FCNC (Flavour-Changing Neutral Current) decays

Loop-induced: extreme hard-GIM SM suppression

Room for NP up to 10x SM

Highly sensitive to NP and discriminating

K is simple system, few decay channels



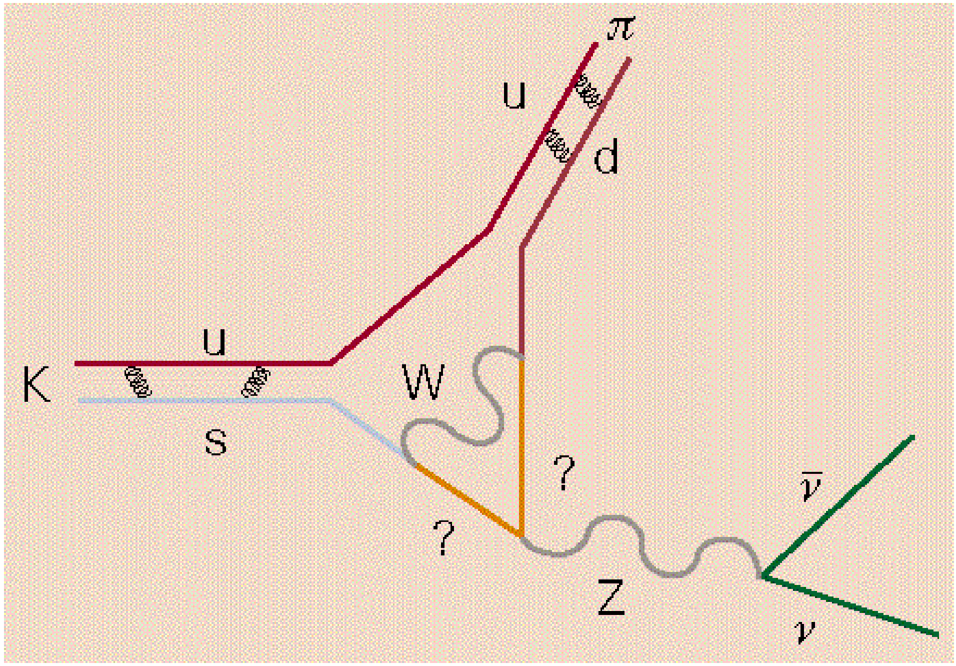
The goal: $K \to \pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

"Clean" physics dominates

"Dirty" physics gets eliminated



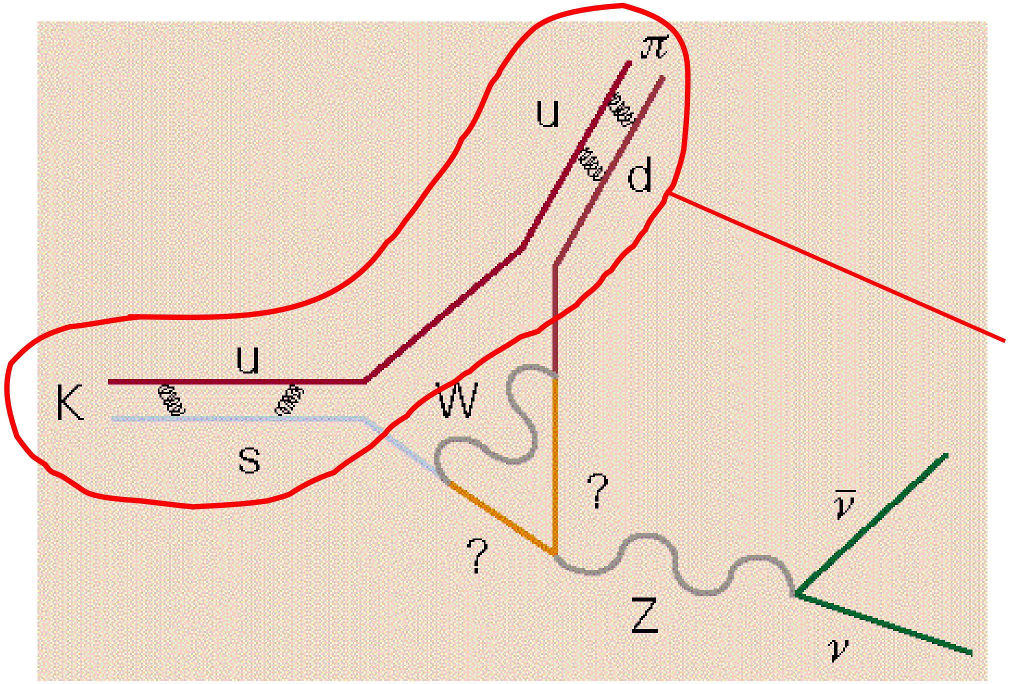
The goal: K → $\pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

"Clean" physics dominates

"Dirty" physics gets eliminated



Semileptonic: single hadronic operator
NP matrix element from Ke3 (by isospin)

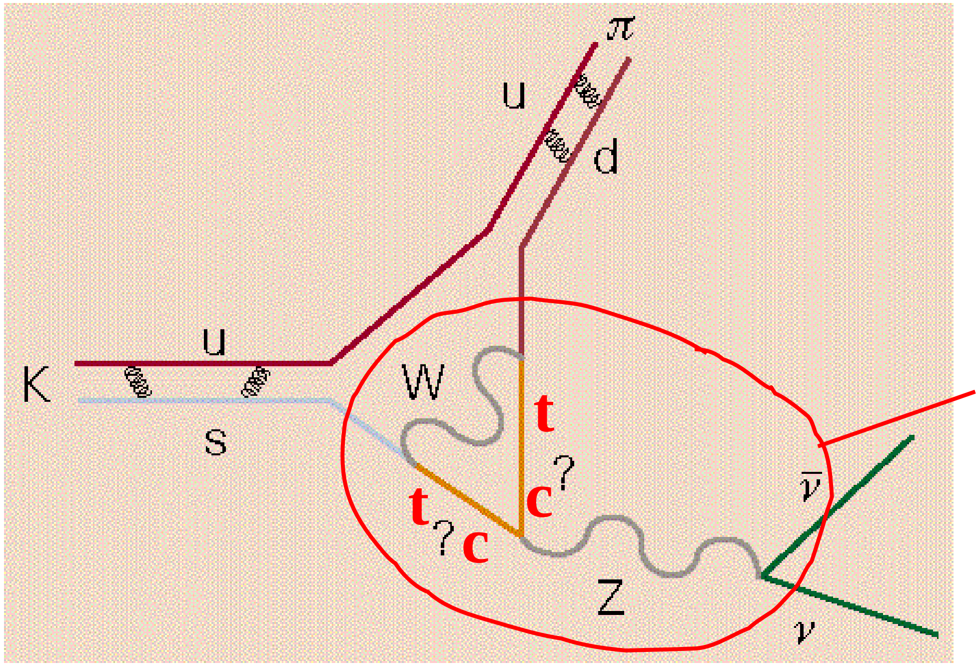
The goal: K $\rightarrow \pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

“Clean” physics dominates

“Dirty” physics gets eliminated



Very short distance physics dominates (GIM): perturbative, under control at NNLO

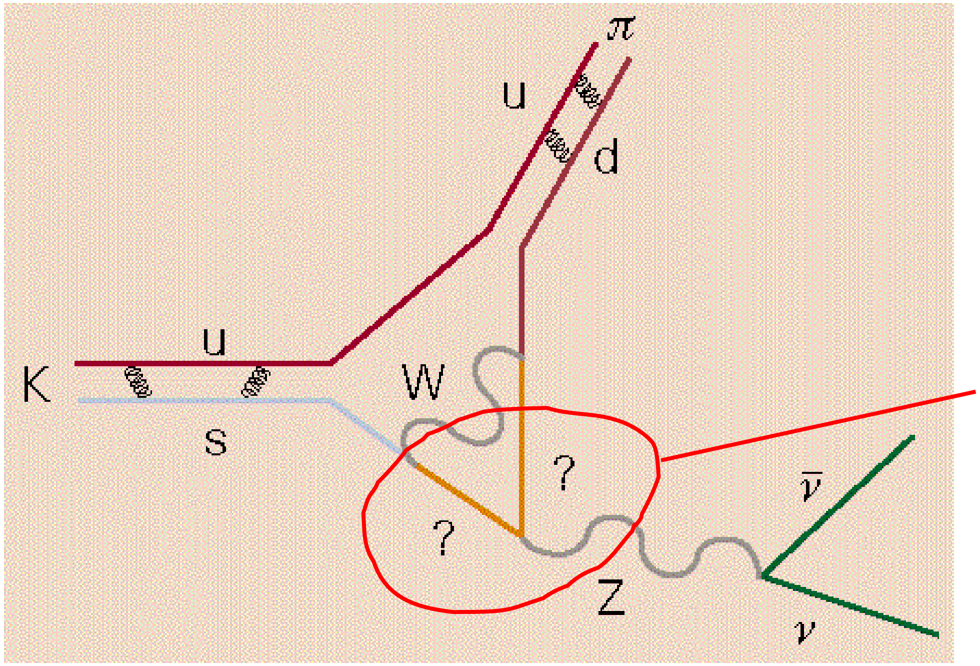
The goal: K $\rightarrow \pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

"Clean" physics dominates

"Dirty" physics gets eliminated



Sensitive to heavy NP particles in the loop

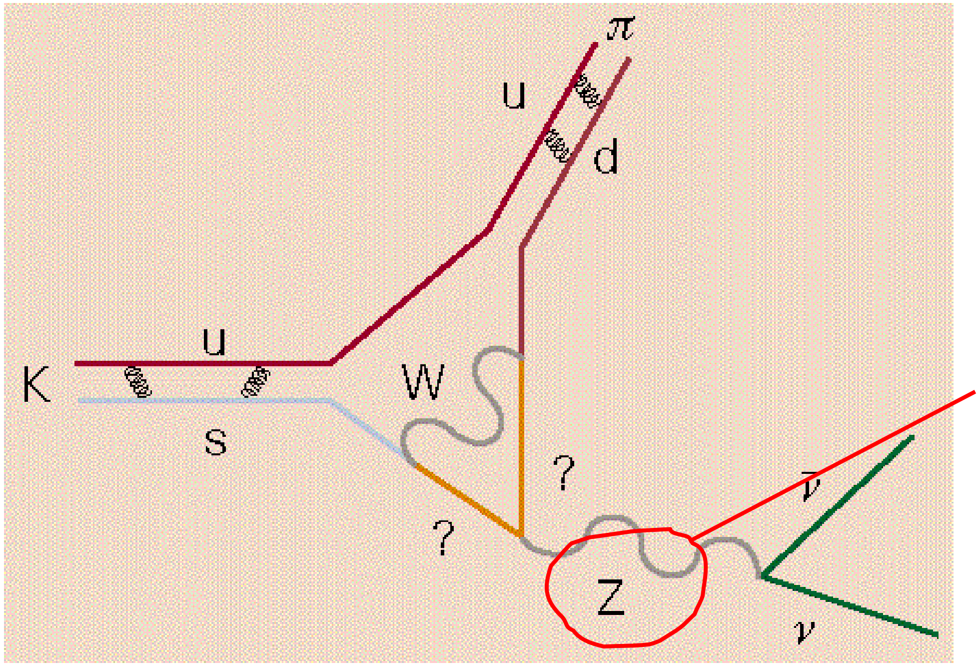
The goal: K $\rightarrow \pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

"Clean" physics dominates

"Dirty" physics gets eliminated



For ℓ = ν no photon long-distance contribution

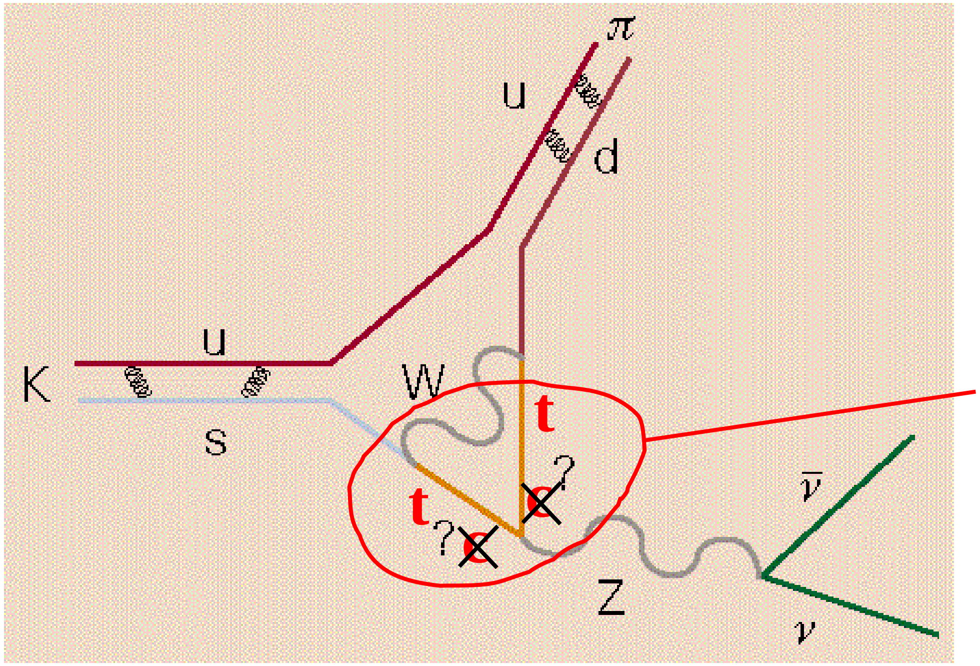
The goal: K $\rightarrow \pi\ell\bar{\ell}$

QUALITATIVE

QUANTITATIVE

“Clean” physics dominates

“Dirty” physics gets eliminated



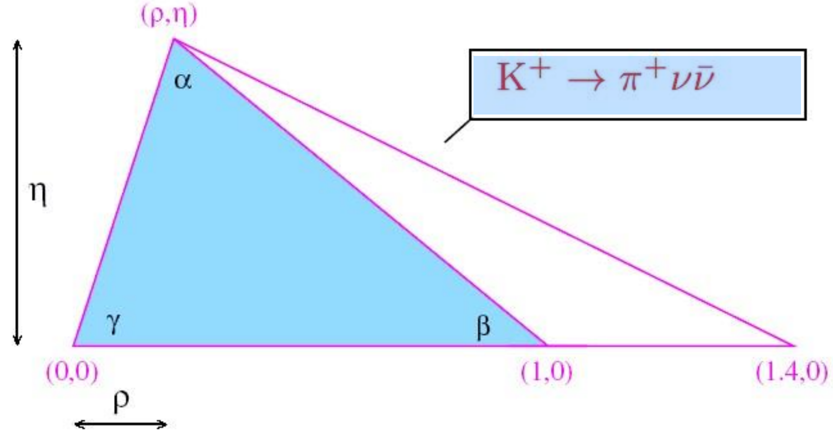
For the neutral K it is CP-violating and only top contributes

Unitarity triangle from K

$K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \pi^0 e^+ e^-$ $\left\{ \begin{array}{l} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \end{array} \right.$

ε, ε'



$K^+ \to \pi^+ \nu\bar{\nu}$

Ancillary measurements

$K_L \to e^+ e^-$ $\left\{ \begin{array}{l} K_L \to \gamma\gamma,\ K_L \to e^+ e^- \gamma \\ K_L \to e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{array} \right.$

$$V^*_{us}V_{ud} + V^*_{cs}V_{cd} + V^*_{ts}V_{td} = \lambda_u + \lambda_c + \lambda_t = 0$$

Height: Im(λ_t)

Ke3

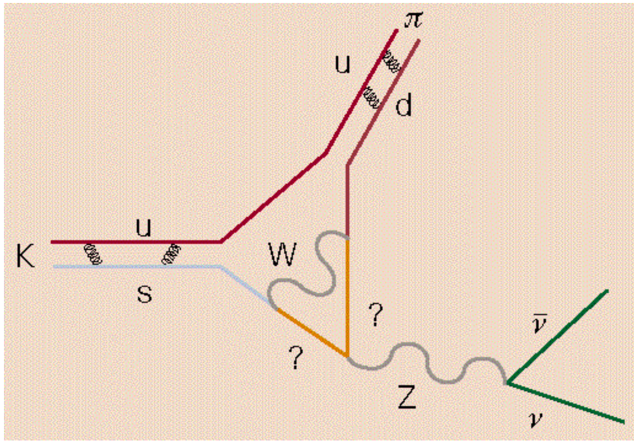
$K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$

$K \to \pi\ell\bar{\ell}$ decays

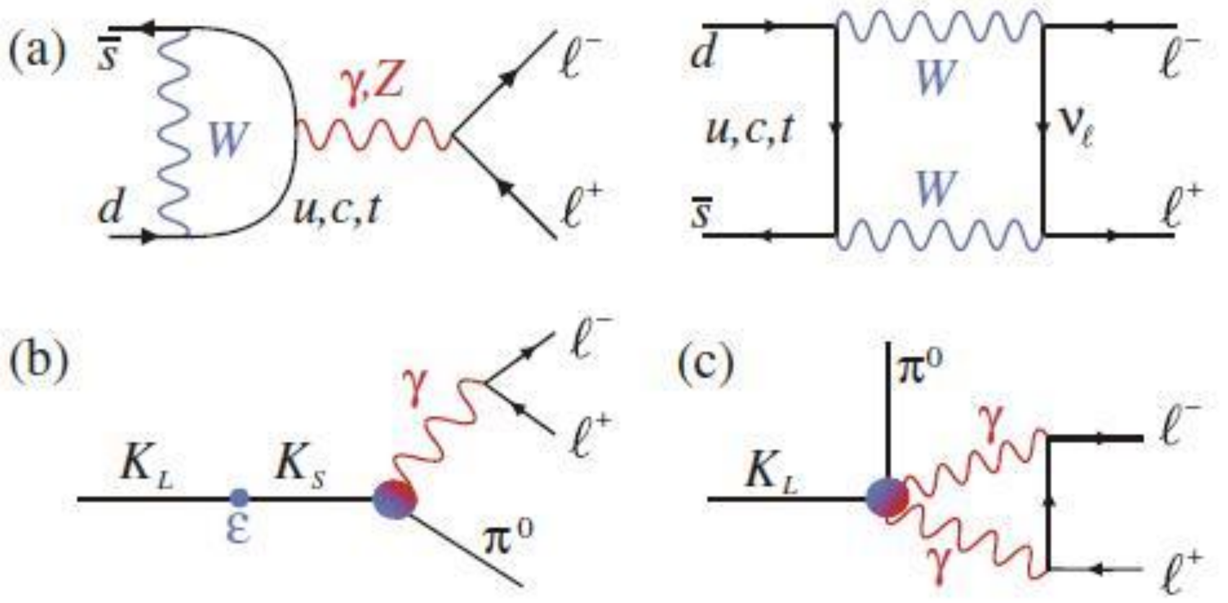
Switch to *quantitative* test of the SM Flavour sector, probing extremely high energy scales: precision frontier *complementary* to LHC energy frontier

Some (tiny!) BRs can be computed to *very high* (few percent) precision



$K_L \to \pi^0 e^+ e^-$	10^{-11} (CPV$_{dir}$ $3 \cdot 10^{-12}$)	$< 2.8 \cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 3 ev. (2.05 bkg)
$K_L \to \pi^0 \mu^+ \mu^-$	10^{-11} (CPV$_{dir}$ $1 \cdot 10^{-12}$)	$< 3.8 \cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 2 ev. (0.87 bkg)
$K^+ \to \pi^+ \nu\nu$	$8 \cdot 10^{-11}$ (at 7%)	$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949)	Dedicated expt. 3 evt. (bkg. 0.45)
$K_L \to \pi^0 \nu\nu$	$2.8 \cdot 10^{-11}$ (at 2%)	$< 6.7 \cdot 10^{-8}$ (KEK E391a)	CPV dir *“Nothing to nothing”*

$K_L \to \pi^0 \ell^+ \ell^-$



(a) Short-distance part

(b) Indirect CP-violating from $K_S \to \pi^0 \ell^+ \ell^-$ (meas. NA48/1)

(c) CP conserving long-distance: from $K_L \to \pi^0 \gamma\gamma$ (meas. KTeV, NA48)

$K_L \to \pi^0 \ell^+ \ell^-$

V.Cirigliano et al., arXiv1107.6001

$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} = 10^{-12} \times \left\{ 15.7|a_S|^2 \pm 6.2|a_S| \left(\frac{\mathrm{Im}\,\lambda_t}{10^{-4}}\right) + 2.4 \left(\frac{\mathrm{Im}\,\lambda_t}{10^{-4}}\right)^2 \right\}$$

$$\mathrm{Br}(K_L \to \pi^0 \mu^+ \mu^-)_{\mathrm{CPV}} = 10^{-12} \times \left\{ 3.7|a_S|^2 \pm 1.6|a_S| \left(\frac{\mathrm{Im}\,\lambda_t}{10^{-4}}\right) + 1.0 \left(\frac{\mathrm{Im}\,\lambda_t}{10^{-4}}\right)^2 \right\}$$

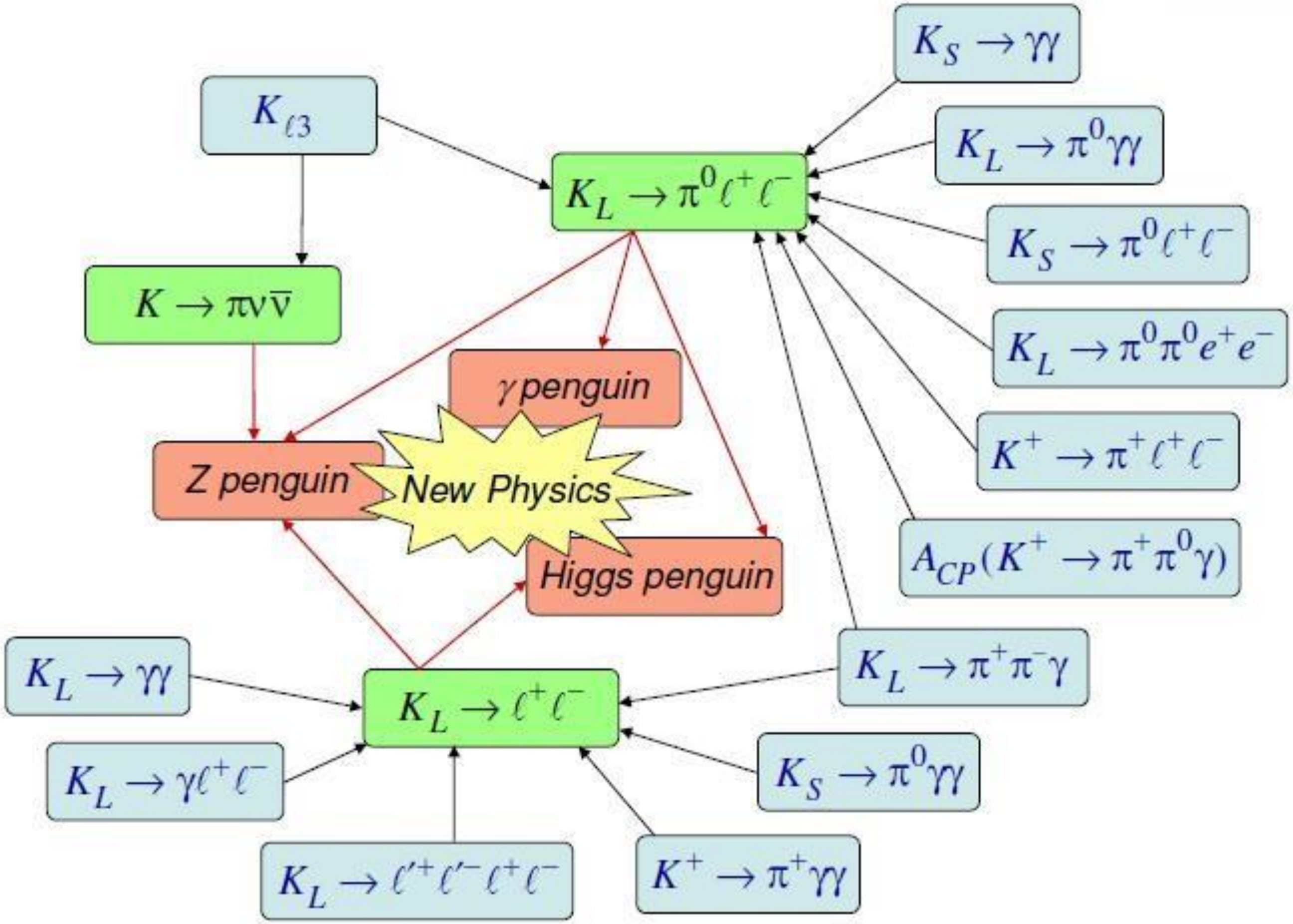
- $\lambda_t = V_{td}V_{ts}^*$ and Im $\lambda_t \simeq 1.35 \times 10^{-4}$.
- $|a_S|$, the amplitude for $K_S \to \pi^0 \ell^+ \ell^-$ at $q^2 = 0$ as defined below, is expected to be $O(1)$ but the sign of a_S is unknown. $|a_S| = 1.06^{+0.26}_{-0.21}$.
- For $\ell = e$ the two-photon contribution is negligible.
- Taking the positive sign (?) the prediction is

$$\begin{aligned} \mathrm{Br}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} &= (3.1 \pm 0.9) \times 10^{-11} \\ \mathrm{Br}(K_L \to \pi^0 \mu^+ \mu^-)_{\mathrm{CPV}} &= (1.4 \pm 0.5) \times 10^{-11} \\ \mathrm{Br}(K_L \to \pi^0 \mu^+ \mu^-)_{\mathrm{CPC}} &= (5.2 \pm 1.6) \times 10^{-12}. \end{aligned}$$

- The current experimental limits (KTeV) are:

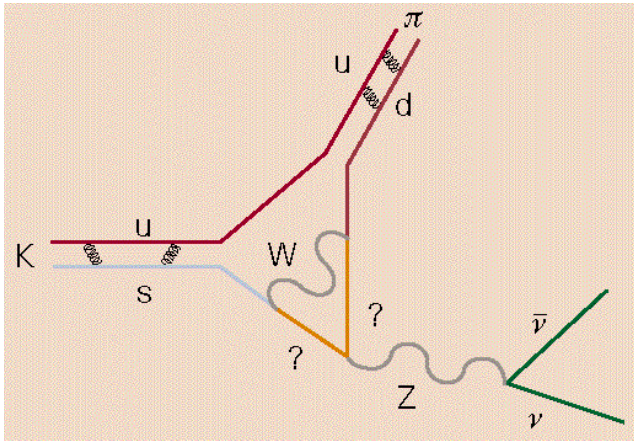
$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10} \quad \text{and} \quad \mathrm{Br}(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}.$$

Rare K decays: the full picture



© C. Smith

K → πnn̄ decays



Governed by single effective operator both in SM and beyond it:

$$(sd)_V(nn)_{V\text{-}A}$$

The hadronic matrix element is precisely measured by $K^+ \to \pi^0 e^+ n$ (with small and well known corrections)

$$Br(K^+)_{\text{SM}} = (8.5 \pm 0.7) \cdot 10^{-11} \qquad Br(K_L)_{\text{SM}} = (2.6 \pm 0.4) \cdot 10^{-11}$$

$$Br(K^+)_{\text{exp}} = 17.3^{+11.5}_{-10.5} \cdot 10^{-11} \qquad Br(K_L)_{\text{exp}} < 2.6 \cdot 10^{-8}$$

The (new) "holy grail"

$$BR_{SM}(K \to \pi \bar{\nu} \nu) \propto r_{IB}\, BR(K^+ \to \pi^0 e^+ \nu) \frac{\alpha^2}{\sin^4 \theta_W}$$

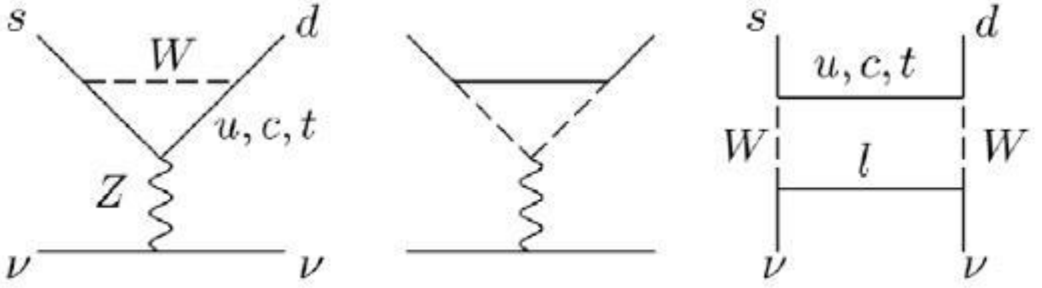
$$\sum_l \left[\frac{\mathrm{Im} V_{ts}^* V_{td}}{|V_{us}|} X(m_t, \alpha_S) + \boxed{\frac{\mathrm{Im} V_{cs}^* V_{cd}}{|V_{us}|} X_{NL}(m_c, m_l, \alpha_S)} \right]$$

Charged mode only

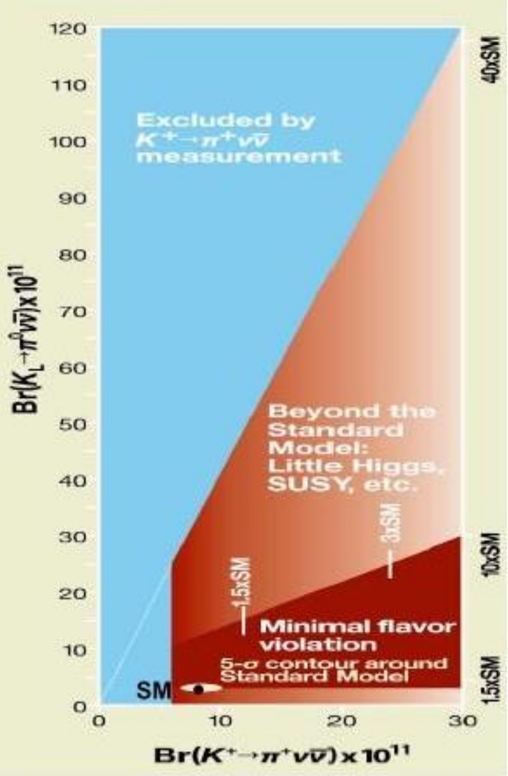
The best measurement of $|V_{td}|$?

Rather a highly-sensitive search for NP

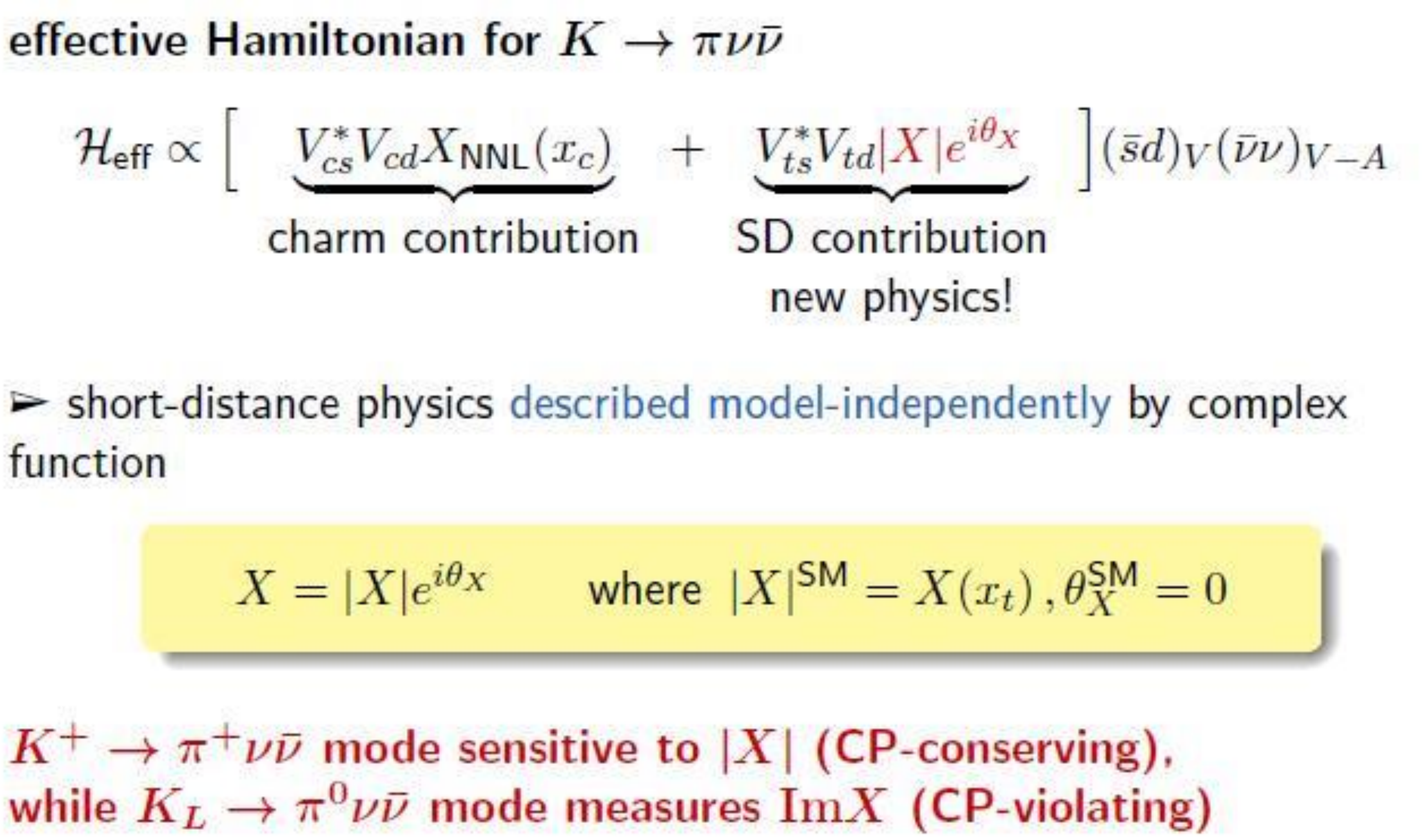
Comparison of the two can discriminate by itself the flavour structure of NP



SM Leading diagrams to K → πνν decays



K → πnn̄ decays



effective Hamiltonian for $K \to \pi\nu\bar\nu$

$$\mathcal{H}_{\rm eff} \propto \Big[\underbrace{V_{cs}^* V_{cd} X_{\rm NNL}(x_c)}_{\text{charm contribution}} + \underbrace{V_{ts}^* V_{td} |X| e^{i\theta_X}}_{\substack{\text{SD contribution}\\ \text{new physics!}}} \Big] (\bar s d)_V (\bar\nu\nu)_{V-A}$$

➢ short-distance physics described model-independently by complex function

$$\boxed{X = |X| e^{i\theta_X} \qquad \text{where } |X|^{\rm SM} = X(x_t)\,, \theta_X^{\rm SM} = 0}$$

$K^+ \to \pi^+\nu\bar\nu$ mode sensitive to $|X|$ (CP-conserving),
while $K_L \to \pi^0\nu\bar\nu$ mode measures ${\rm Im}X$ (CP-violating)

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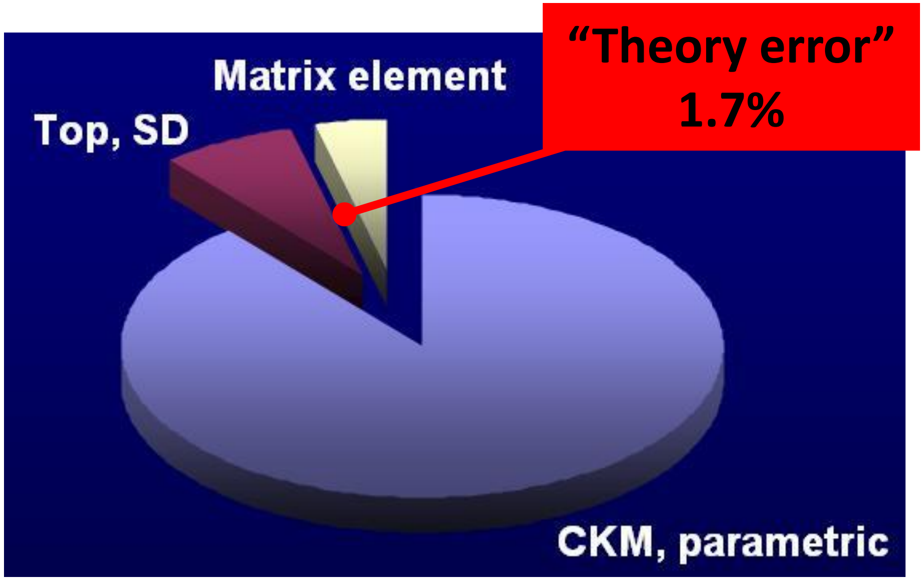
K→πυυ BR predictions

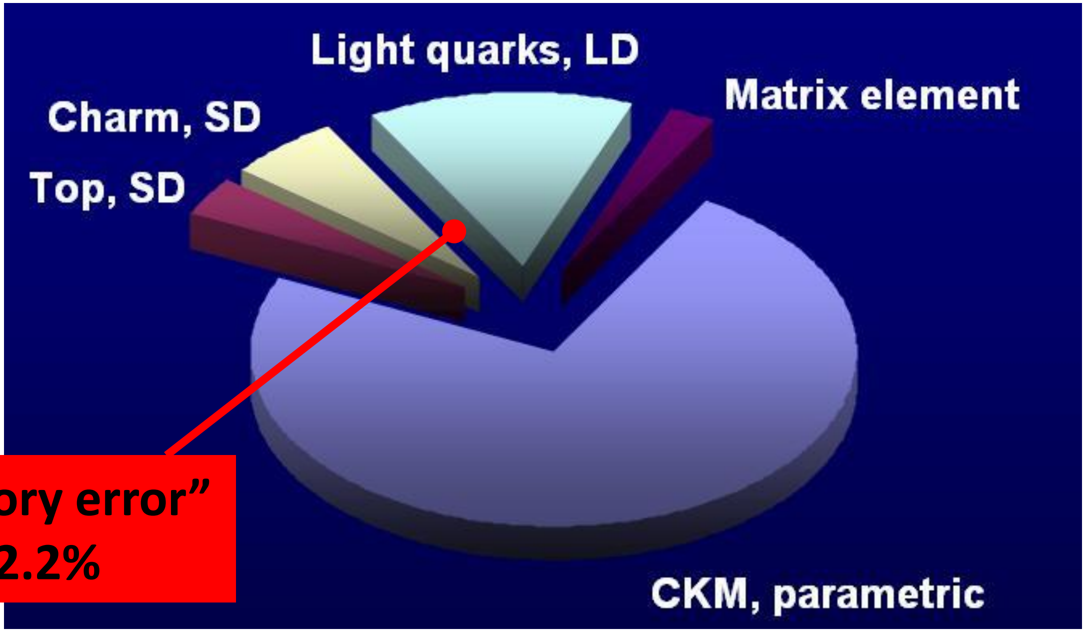
The experimental challenges stimulated a flurry of theoretical improvements



"Theory error"
1.7%

$K_L \rightarrow \pi^0 \upsilon\upsilon$

$$BR_{SM} = (0.26 \pm 0.04) \cdot 10^{-10}$$



"Theory error"
2.2%

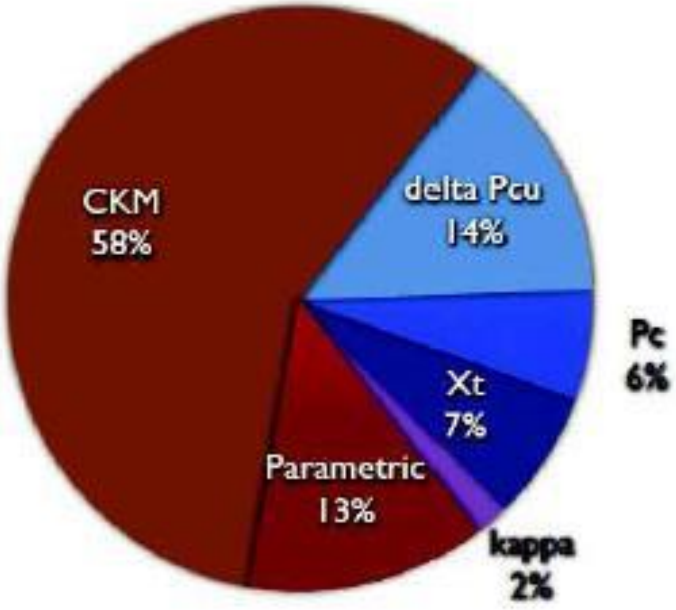
$K^+ \rightarrow \pi^+ \upsilon\upsilon$

$$BR_{SM} = (0.85 \pm 0.07) \cdot 10^{-10}$$

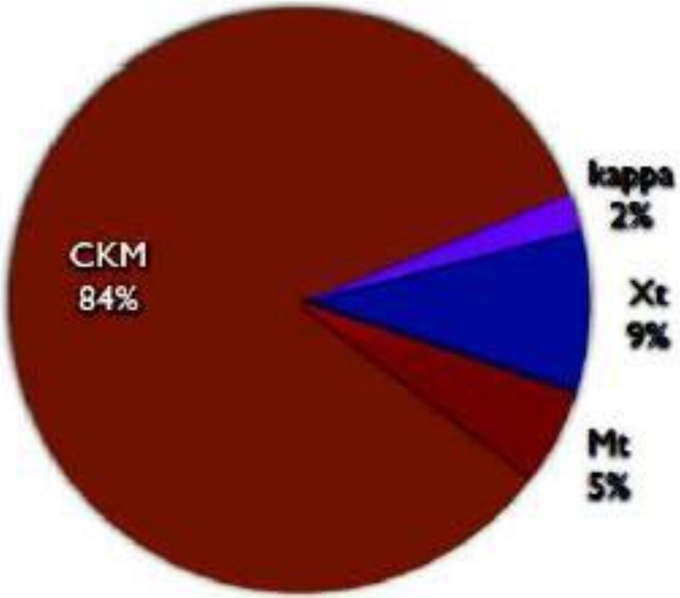
Comparable,
unprecedented,
***tiny* theoretical errors**

K → πnn̄ decays: SM prediction

$K^+ \rightarrow \pi^+\nu\bar{\nu}$



$K_L \rightarrow \pi^0\nu\bar{\nu}$



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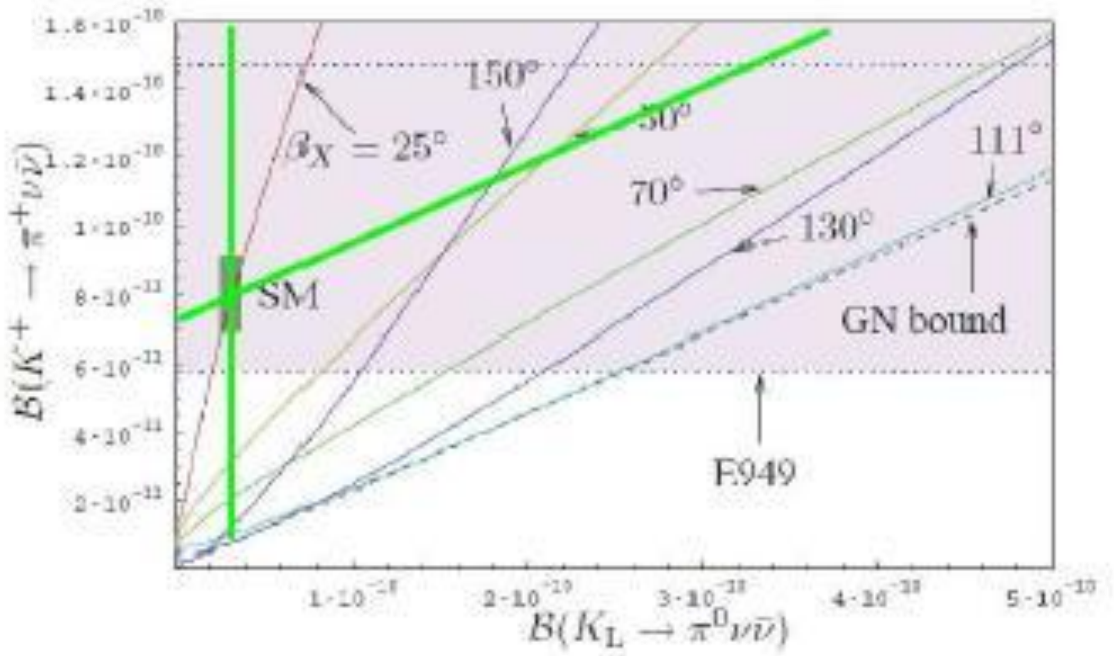
K → πnn̄ decays: SM prediction



Example:
pure V-A structure in ε_K: only two branches allowed

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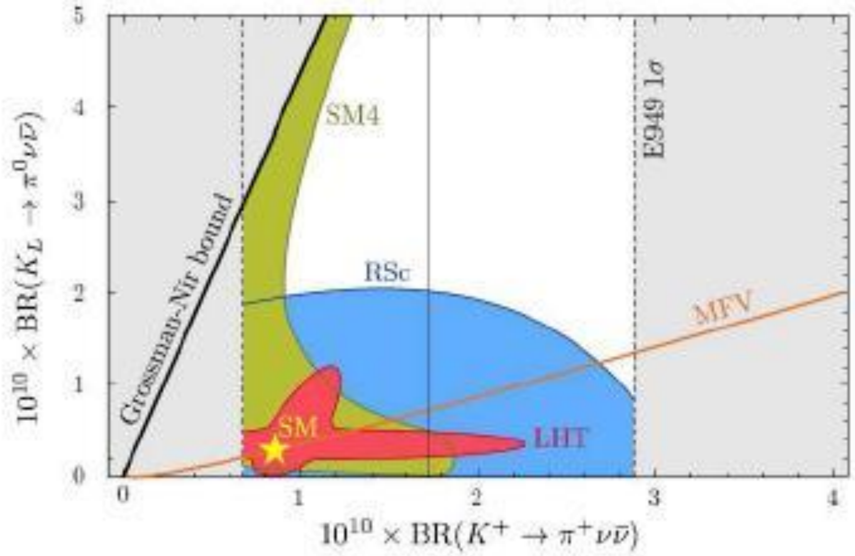
K → πnn̄ decays: BSM

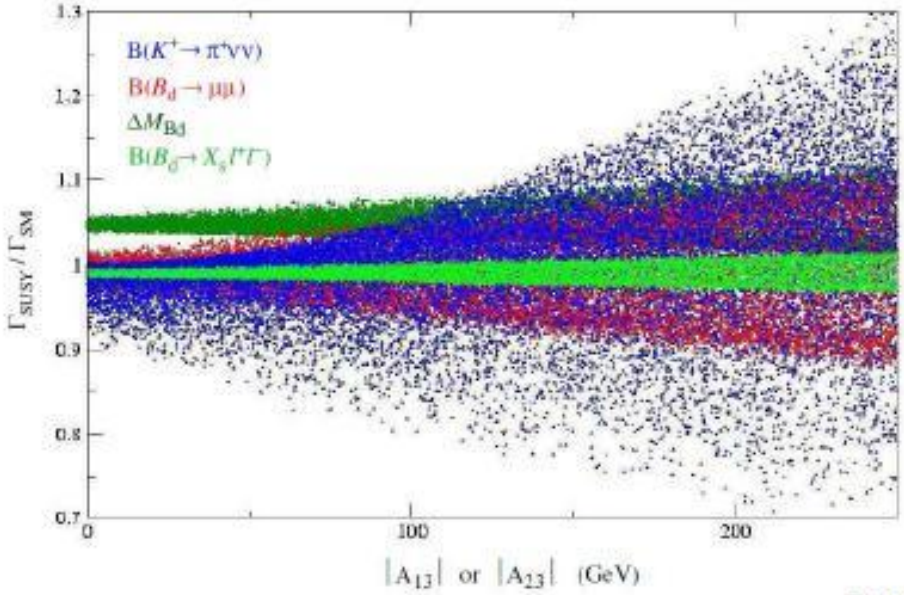


Randall-Sundrum w. custodial symmetry (RSc), Littlest Higgs w. T-parity (LHT), 4th generation (SM4)

MSSM

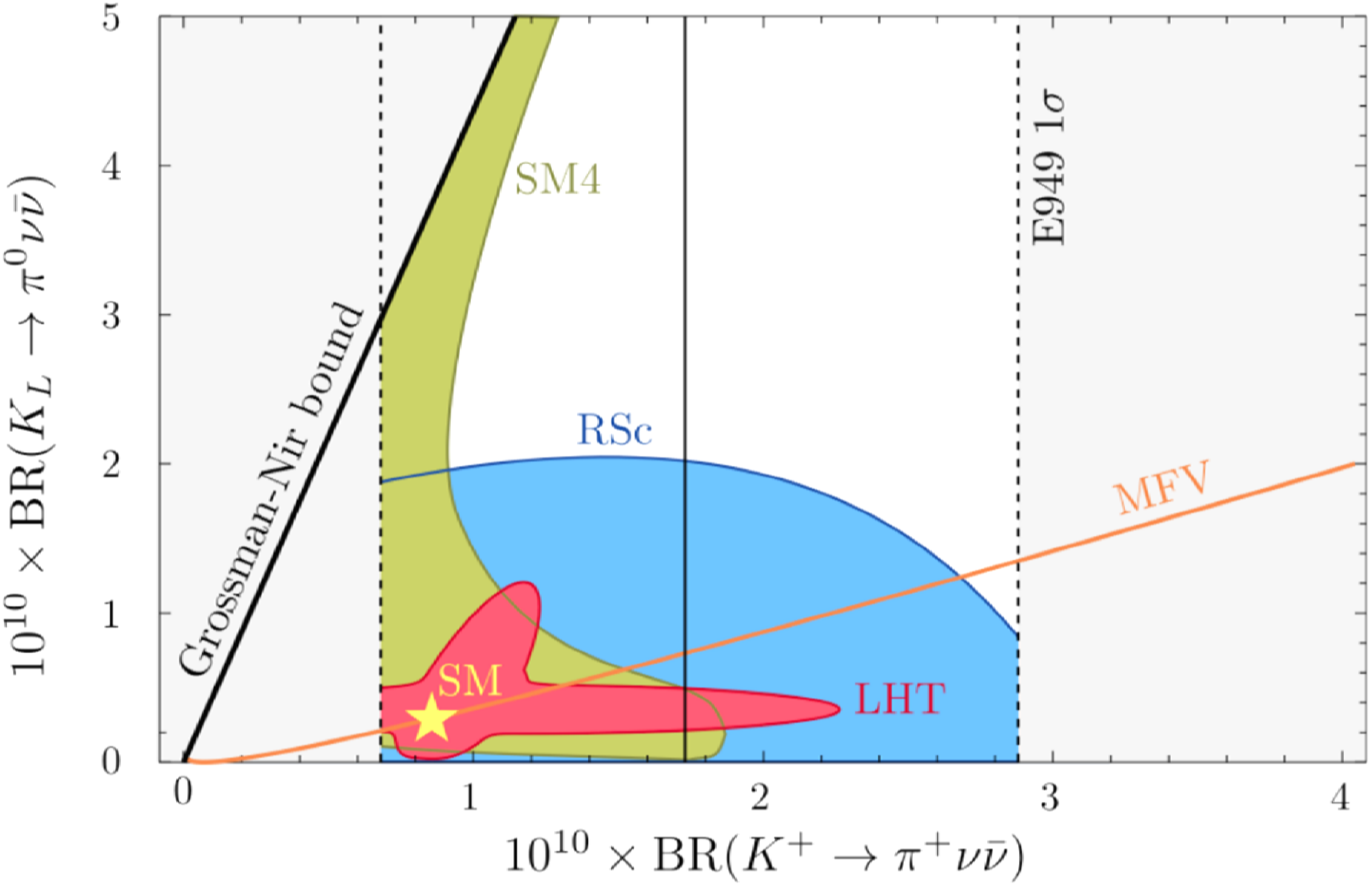
Chargino loops

Wide area open



Isidori et al. (2006)

K→πυυ **remains clean** also beyond SM:
single effective υυ operator, calculable Wilson coefficient,
no long-distance effects



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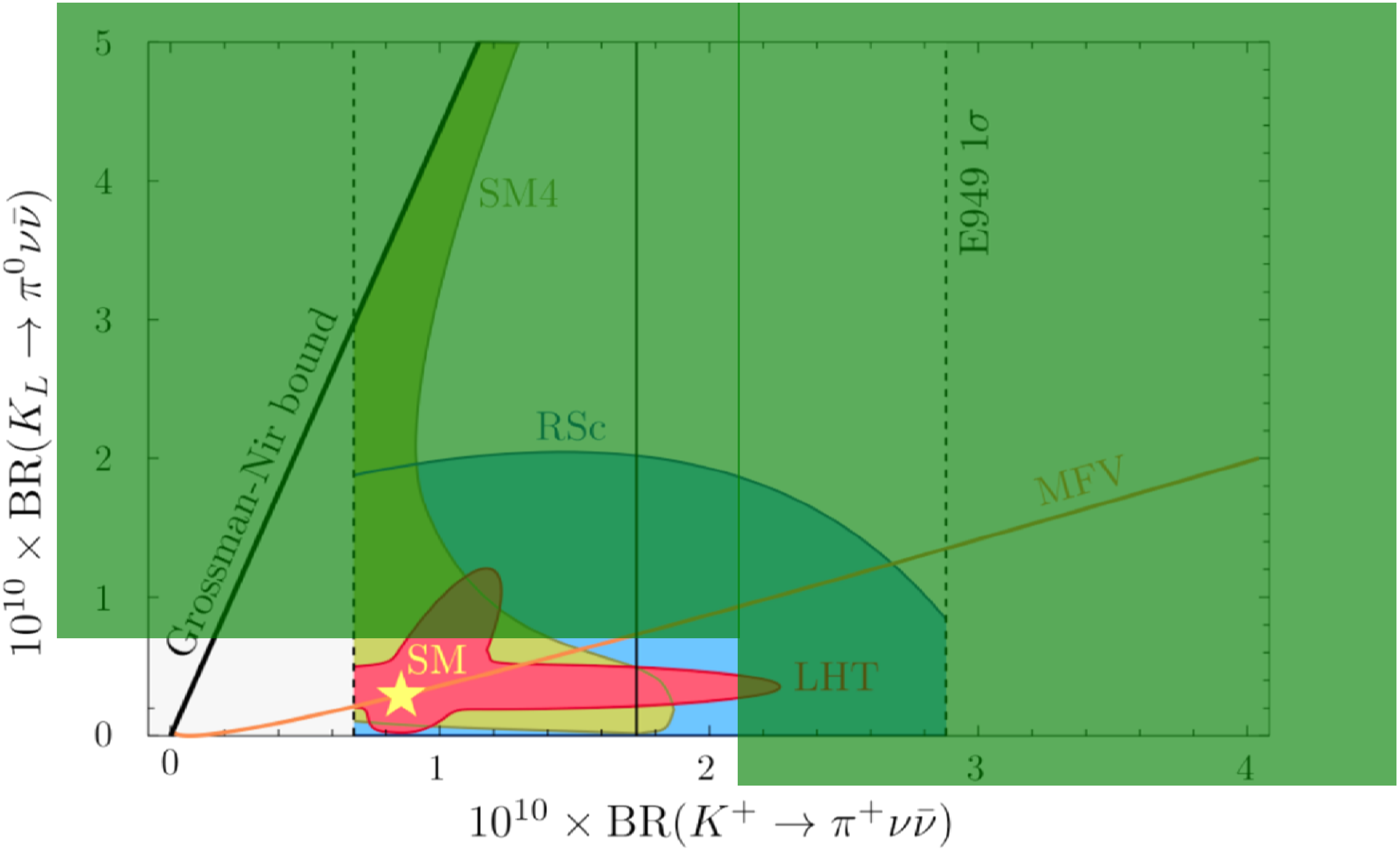
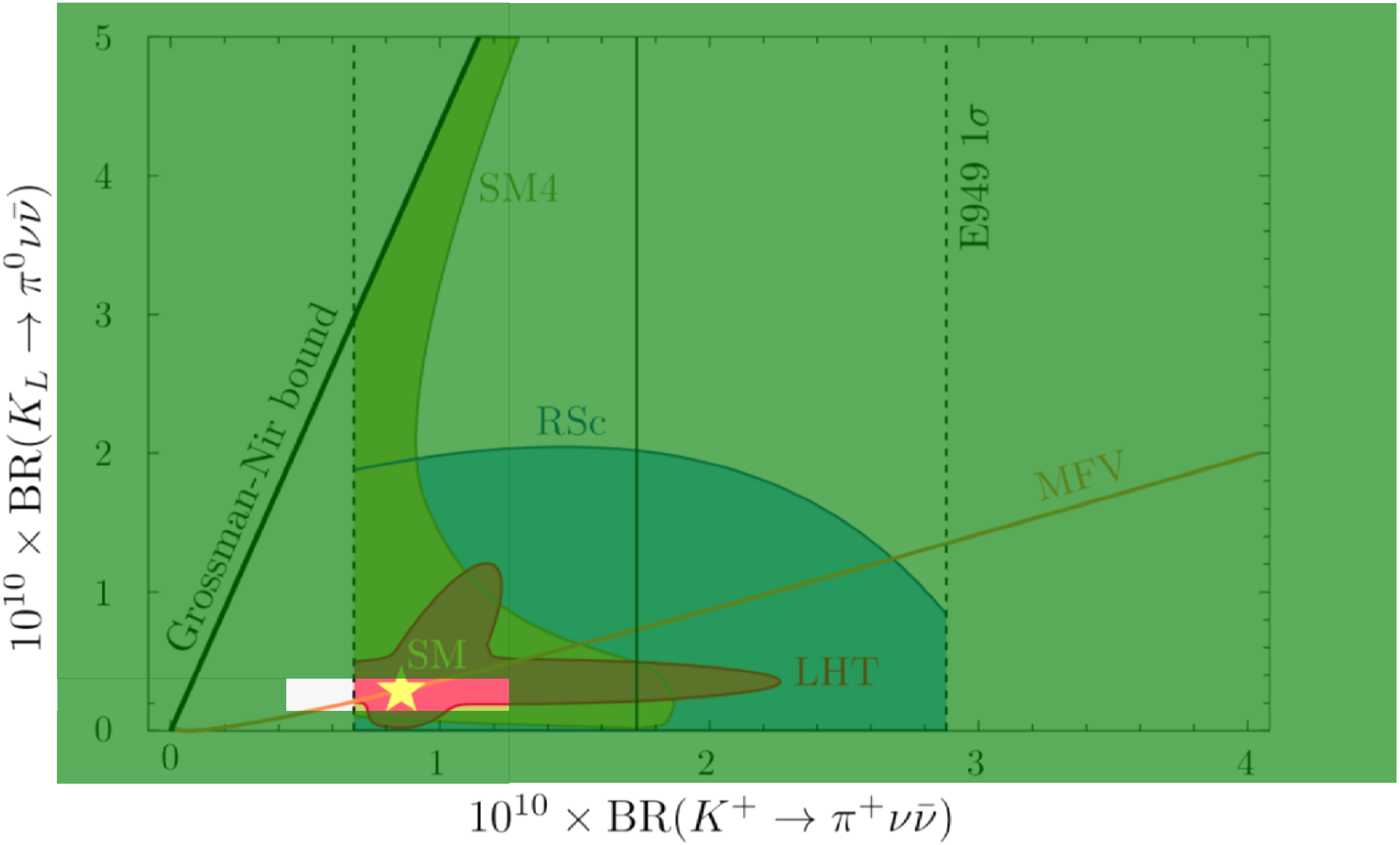
Zeroing in – 10 event experiments



Zeroing in – 100 event experiments



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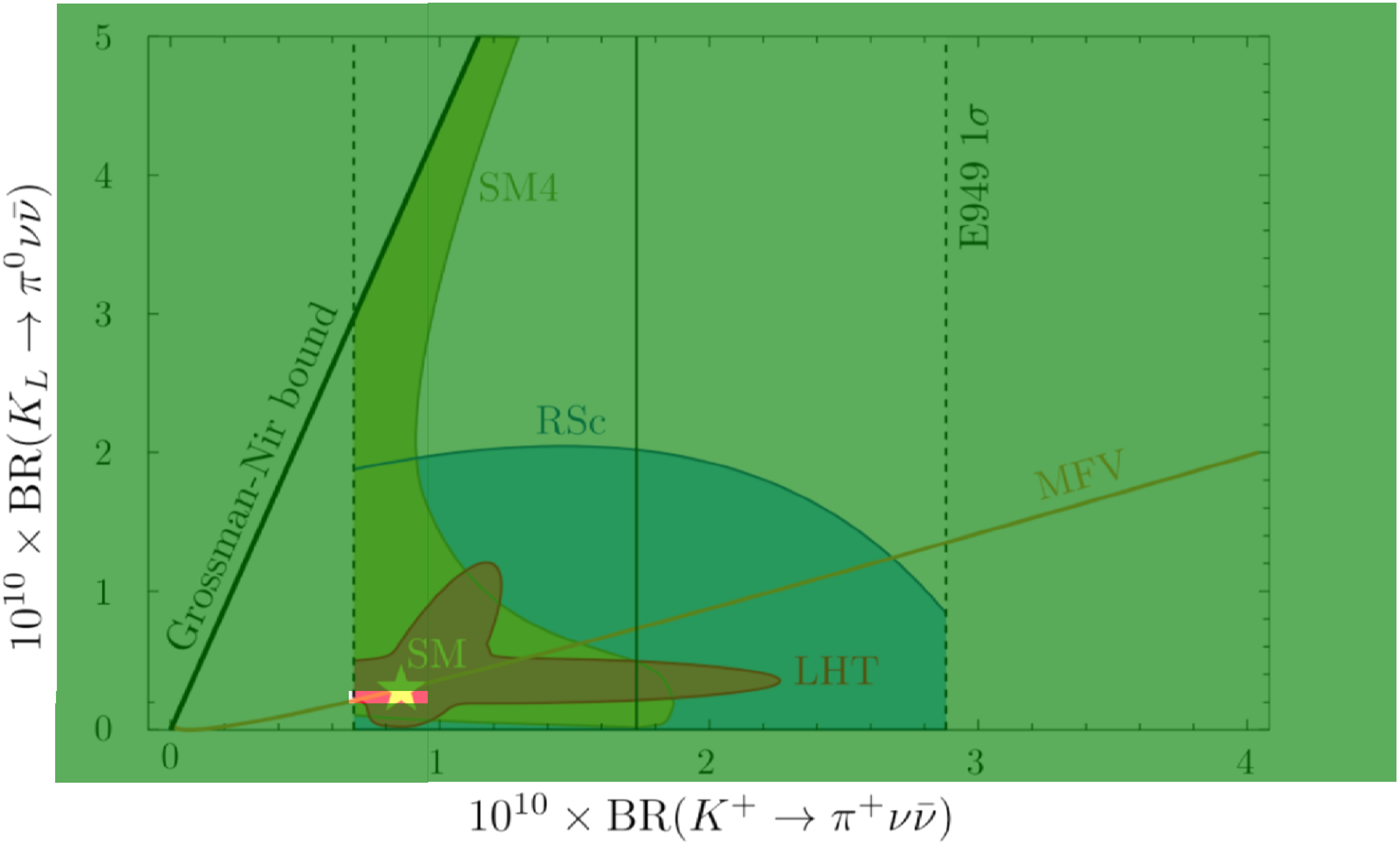
Zeroing in – 1000 event experiments



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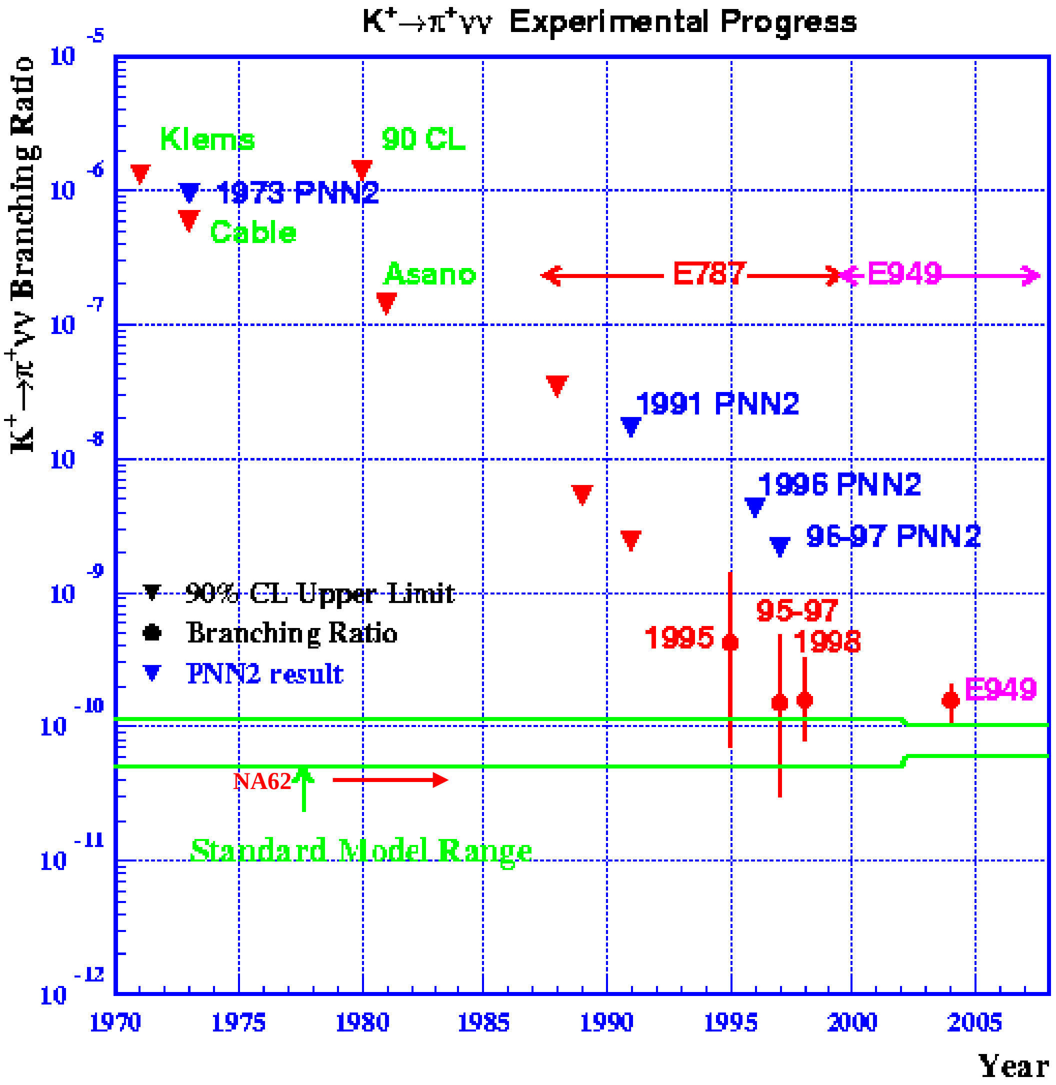
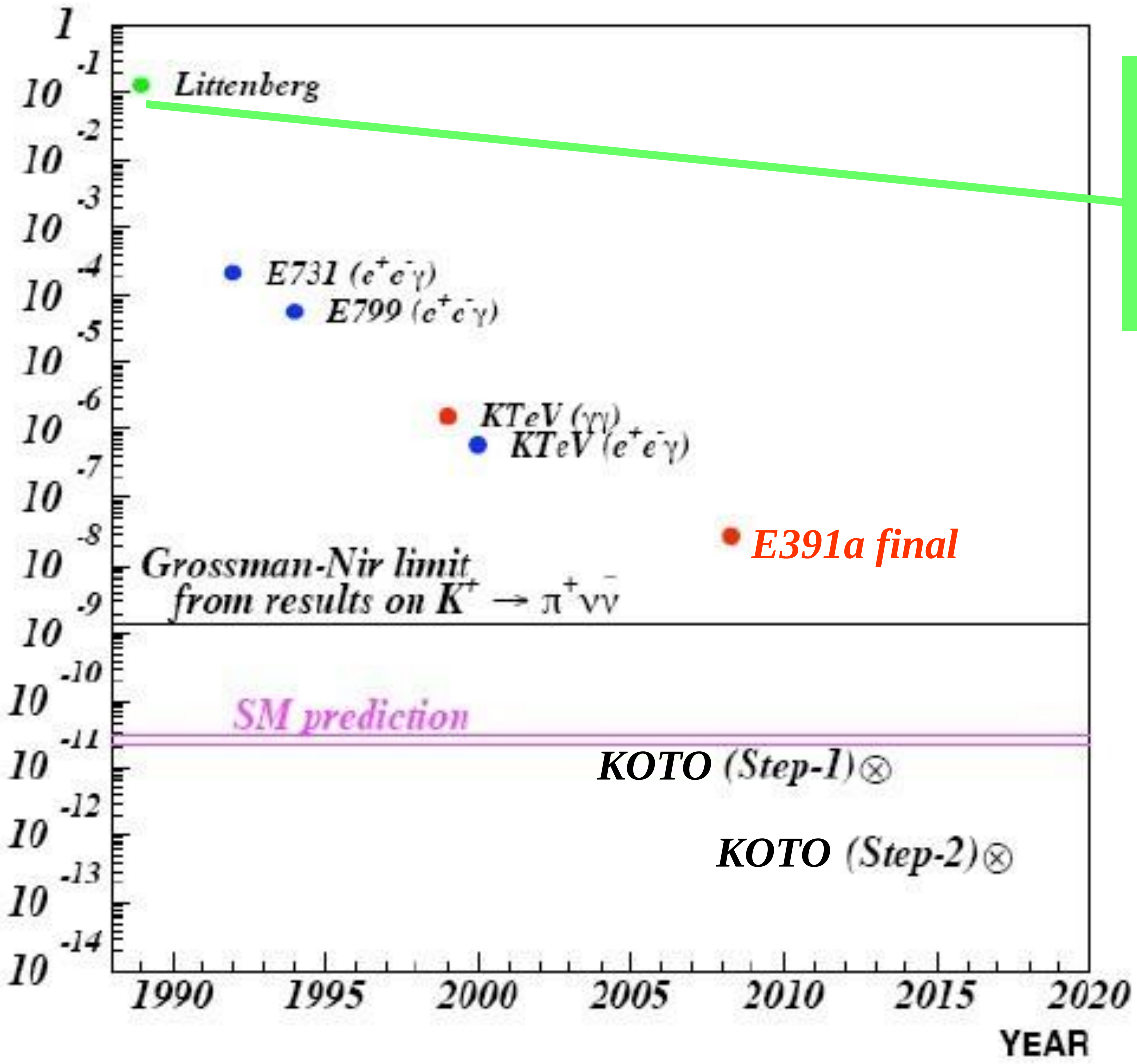
The long march

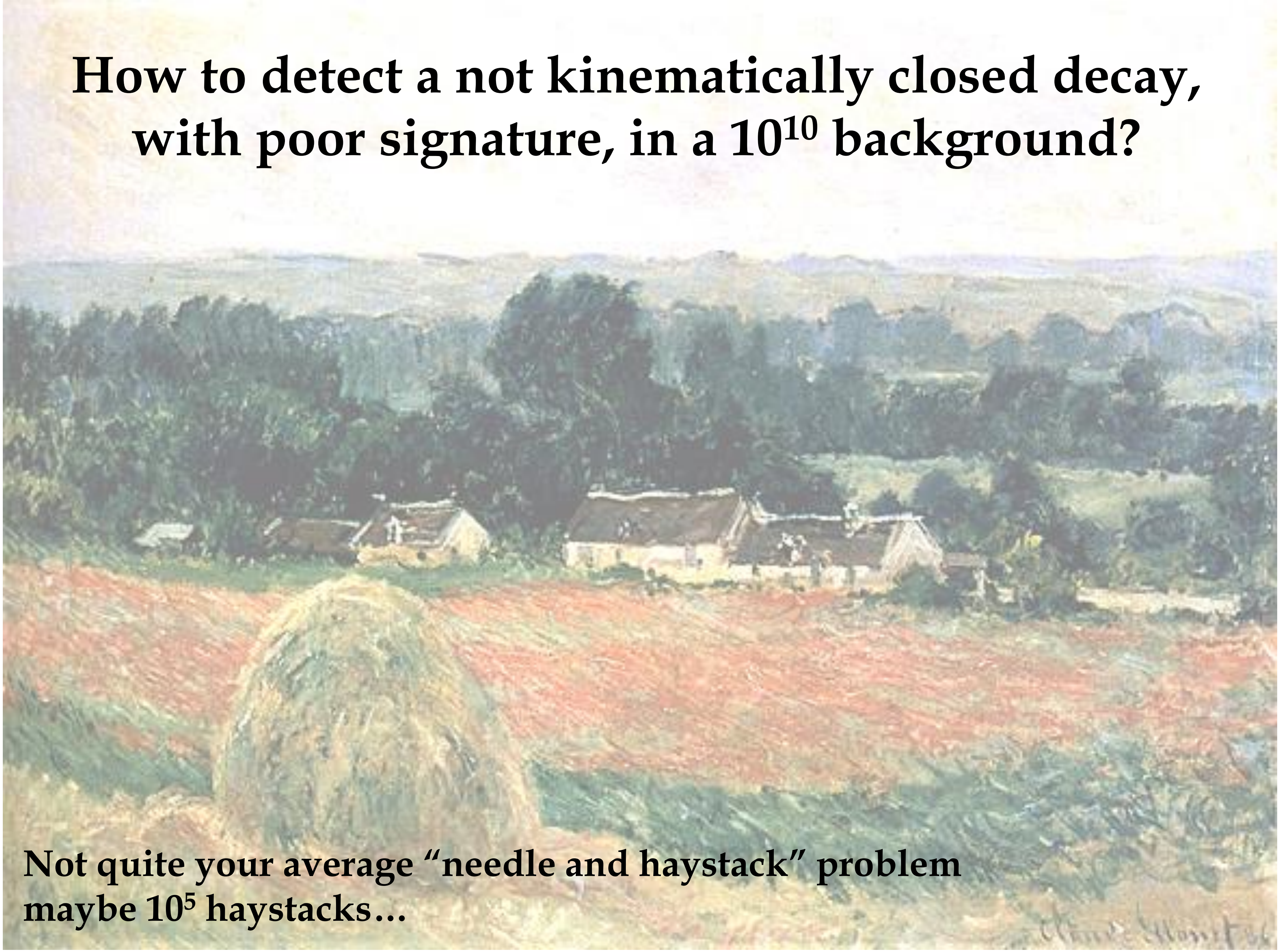


The new $K_L \rightarrow \pi^0 \upsilon\upsilon$ enterprise



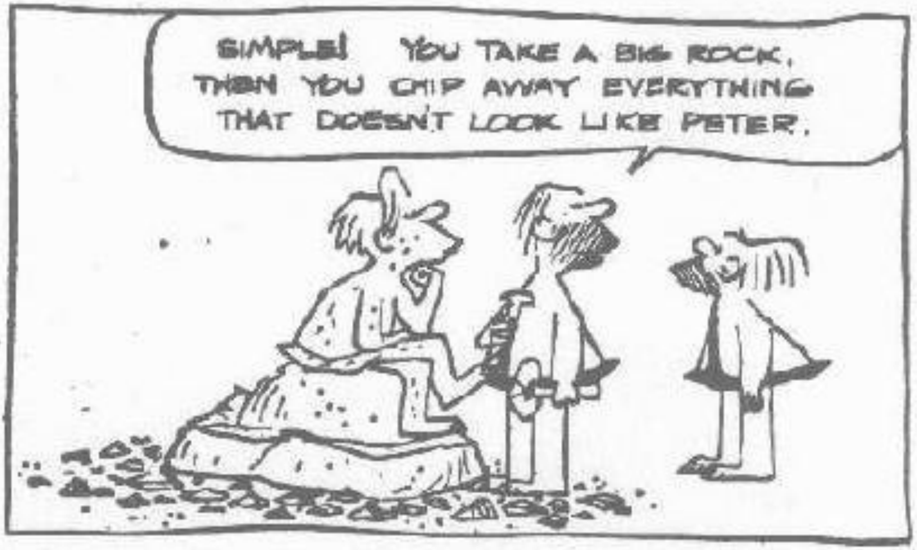
"The best it can be said is that so far nobody demonstrated conclusively that the measurement is impossible".

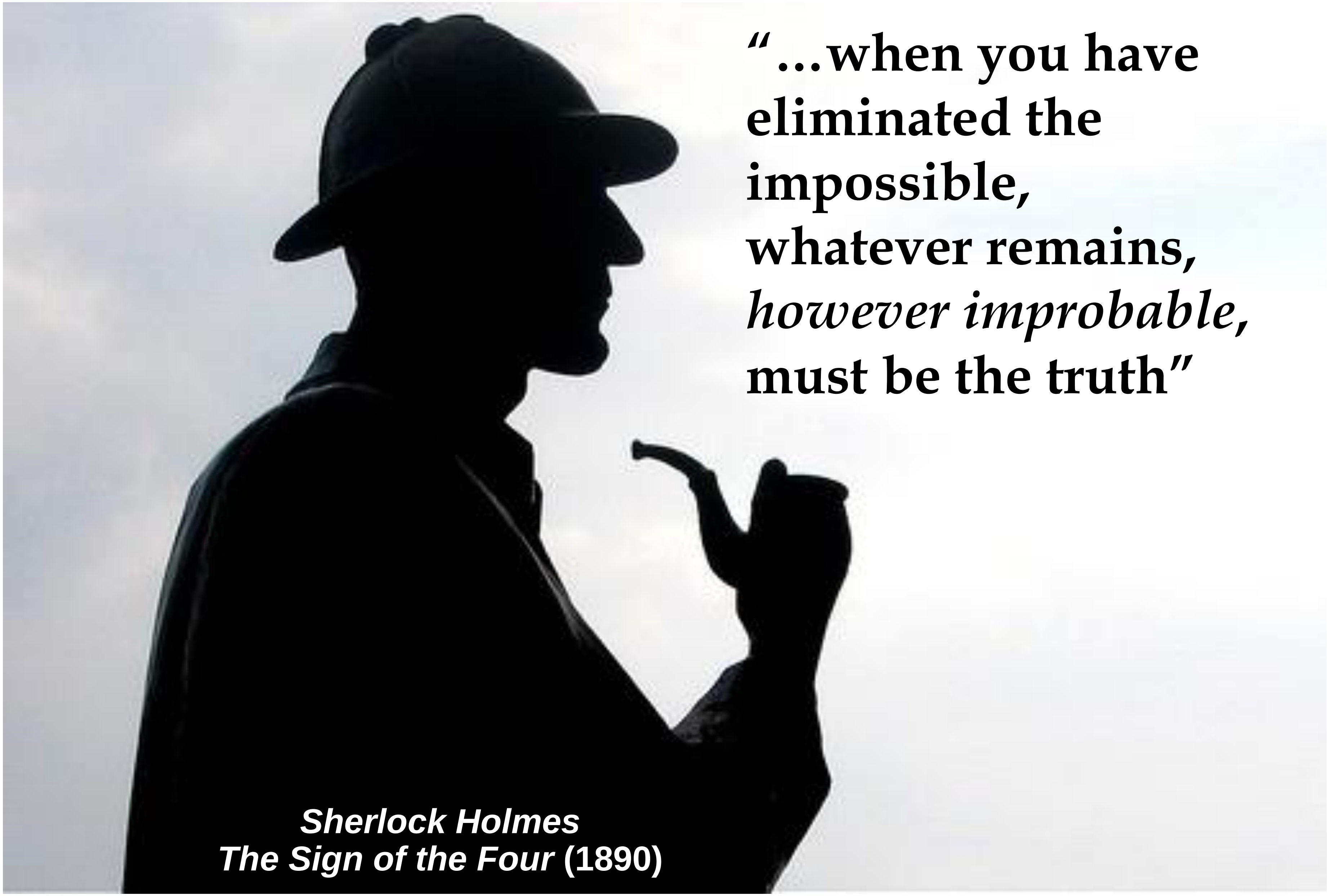
How to detect a not kinematically closed decay, with poor signature, in a 10^{10} background?



Not quite your average "needle and haystack" problem
maybe 10^5 haystacks…


A BEAUTIFUL LIKENESS OF PETER.
HOW DO YOU DO IT ?

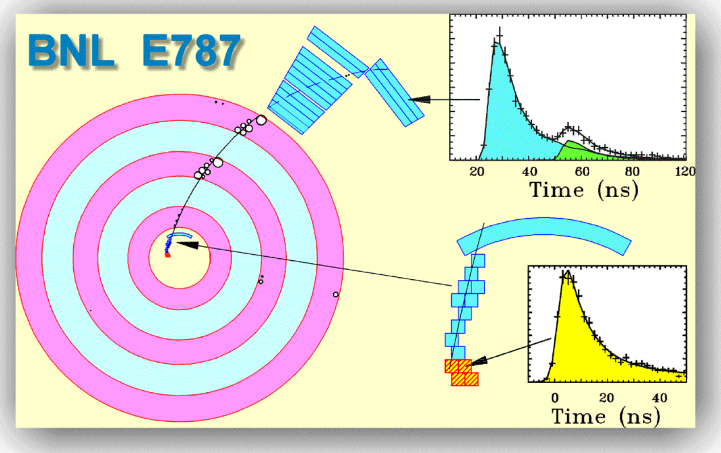

SIMPLE! YOU TAKE A BIG ROCK, THEN YOU CHIP AWAY EVERYTHING THAT DOESN'T LOOK LIKE PETER.



“…when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth”

Sherlock Holmes
***The Sign of the Four* (1890)**

$K^+ \to \pi^+\nu\bar{\nu}$ @ BNL



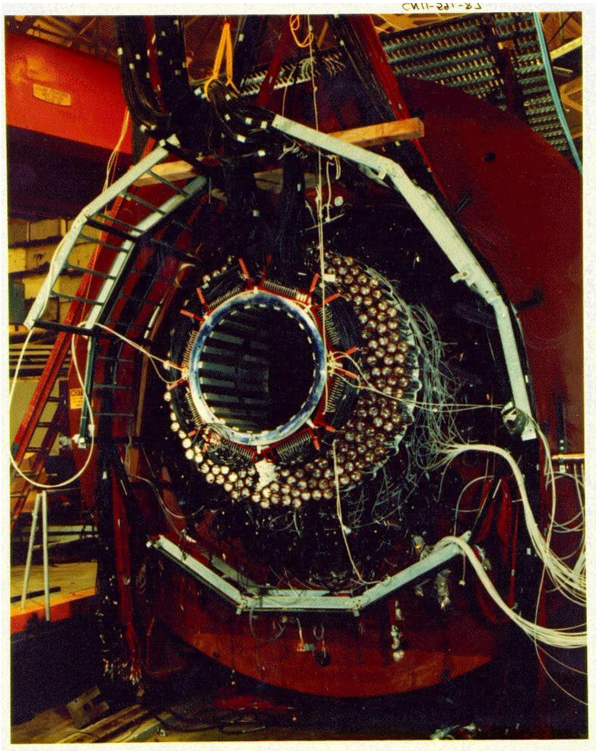
BNL E787: stopped low-energy K, many redundant measurements

Detect the sequence $\pi \to \mu \to e$

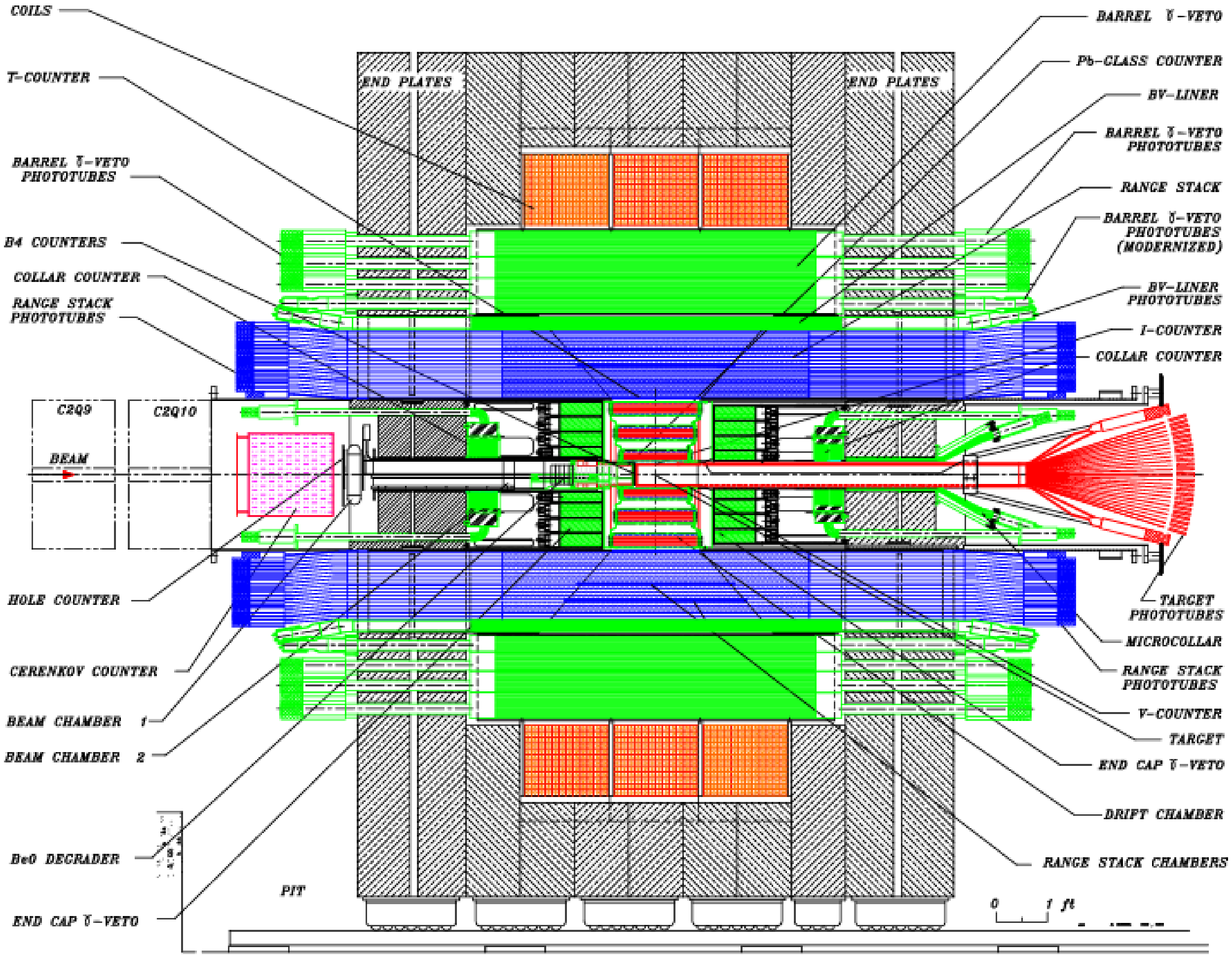
Momentum region between $\pi\pi$ and $\mu\nu$ peaks

Final result: 3 events (bkg 0.15)

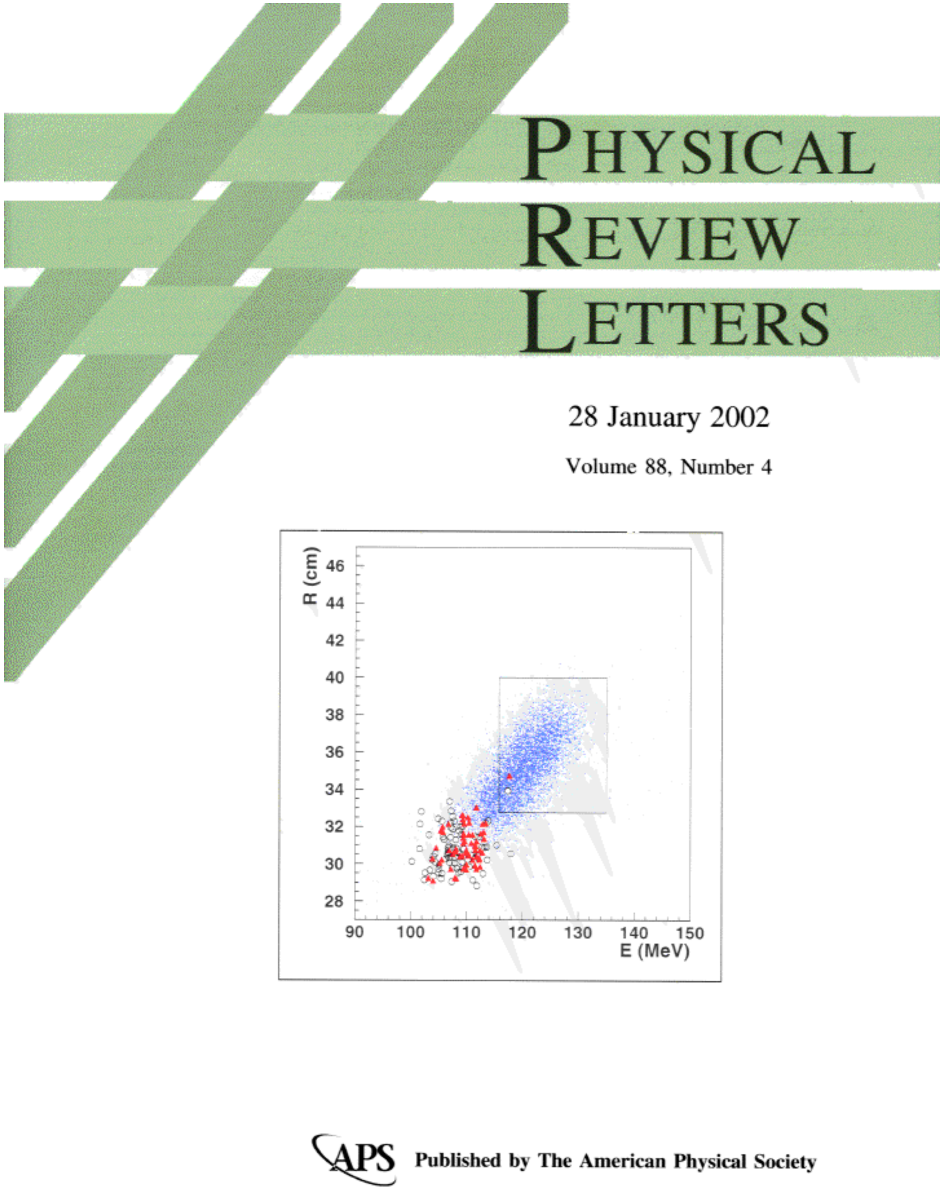
$$BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.56^{+1.75}_{-0.82} \times 10^{-10}$$



E949 @ BNL



Proved $K^+ \to \pi^+ \nu\nu$ could be done in the "traditional" way



PHYSICAL REVIEW LETTERS

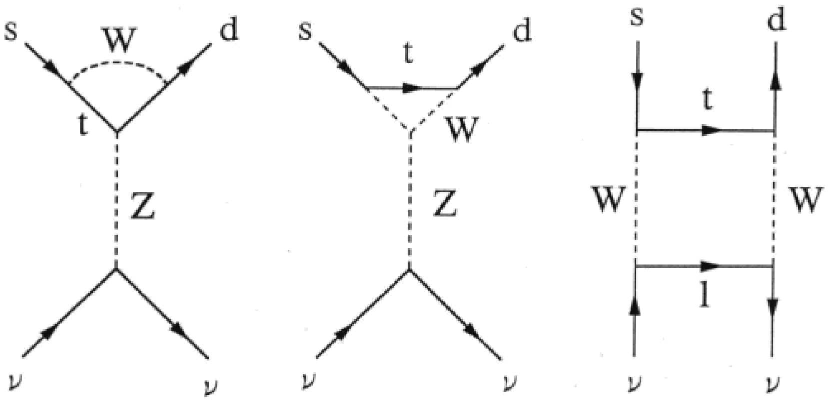
28 January 2002

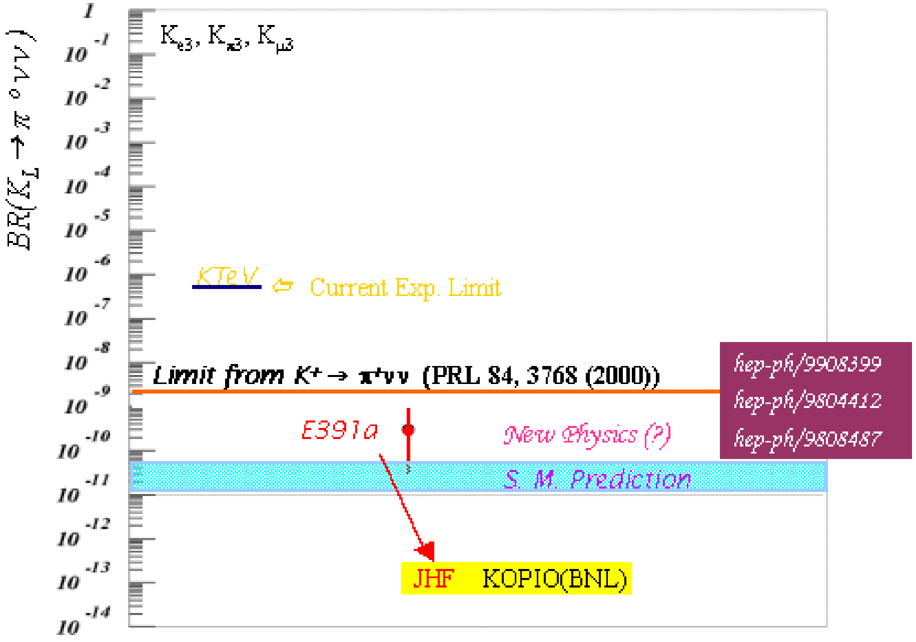
Volume 88, Number 4

APS Published by The American Physical Society

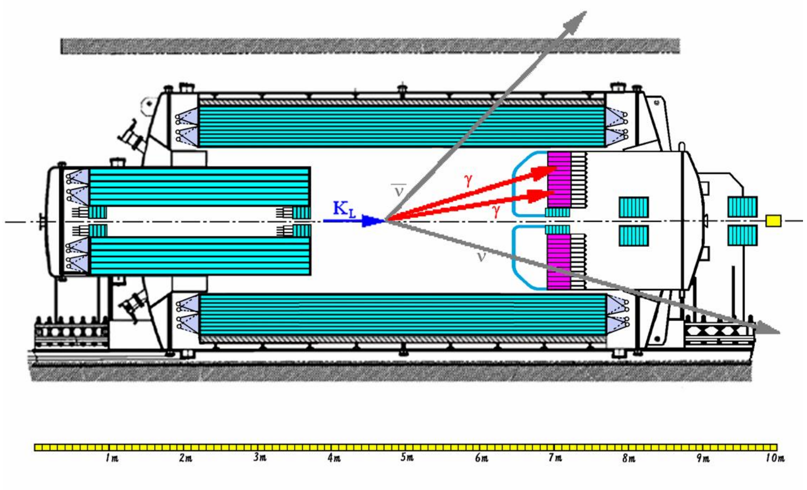
$K_L \rightarrow \pi^0\nu\bar{\nu}$

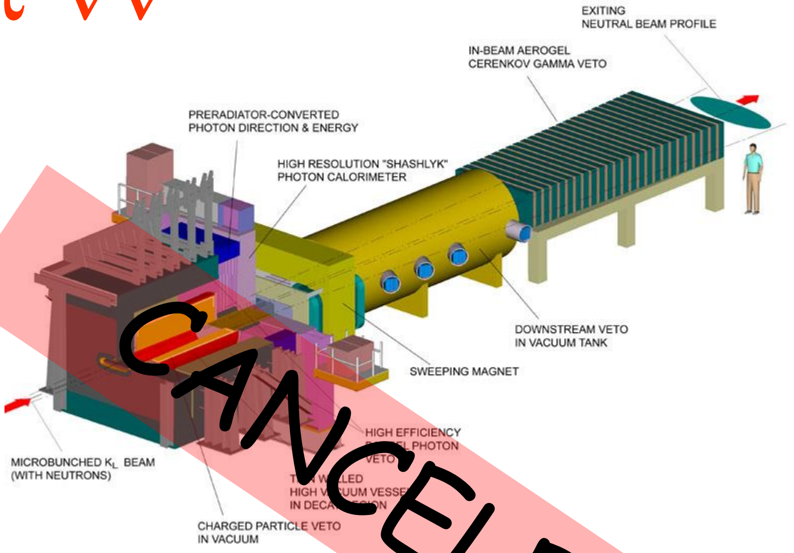
Only CP-violating term





$K_L \to \pi^0\nu\bar{\nu}$



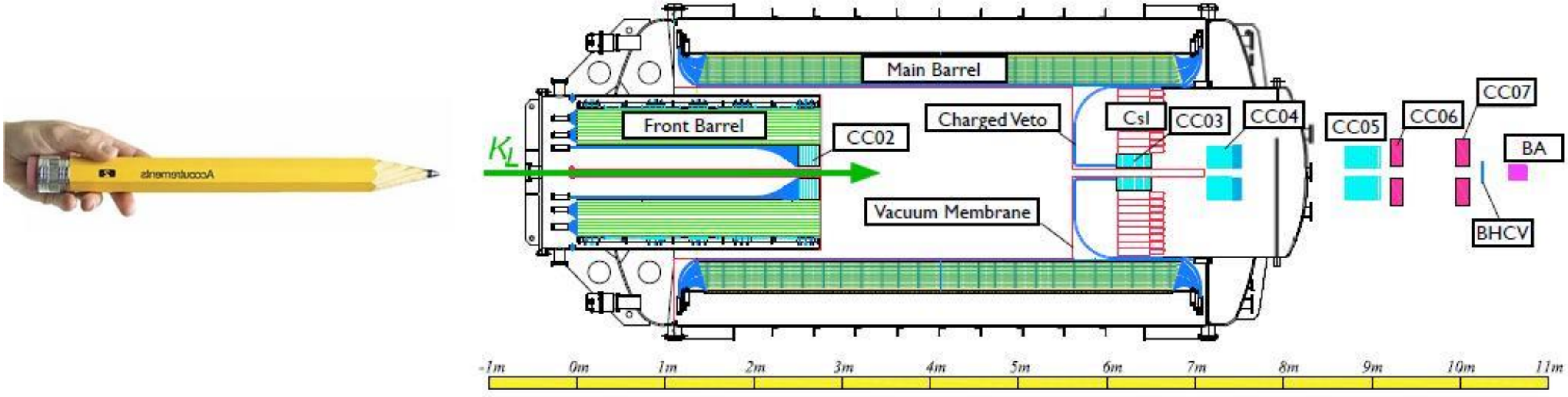


CANCELED

KEK E391-a (2004+): pilot project (does not reach SM)
2 GeV/*c* pencil beam, PT cut against $\pi^0\pi^0$.

BNL KOPIO (2006+): TOF with micro-buched 800 MeV/c beam
Pre-radiator for photon tracking
High-efficiency veto system
Goal: 50 eventi.

KEK E391a experiment



First dedicated pilot experiment to search for $K_L \to \pi^0 \upsilon\upsilon$ at the KEK-PS
Improve over KTeV (Dalitz) limit: BR < $5.9 \cdot 10^{-7}$

- High intensity: $2 \cdot 10^{12}$ ppp 12 GeV/*c* (50% DC)
- "Pencil" beam as transverse constraint: ~ 2 GeV/*c* $K_{\backslash}$ at 4° and 11m
- Photon veto hermeticity down to 1-2 MeV: Pb/scint in high vacuum
- Good EM calorimetry: ~500 pure CsI 7x7 cm^2, with central hole

Three runs (2004-2005): 12 month total

E391a (KEK)

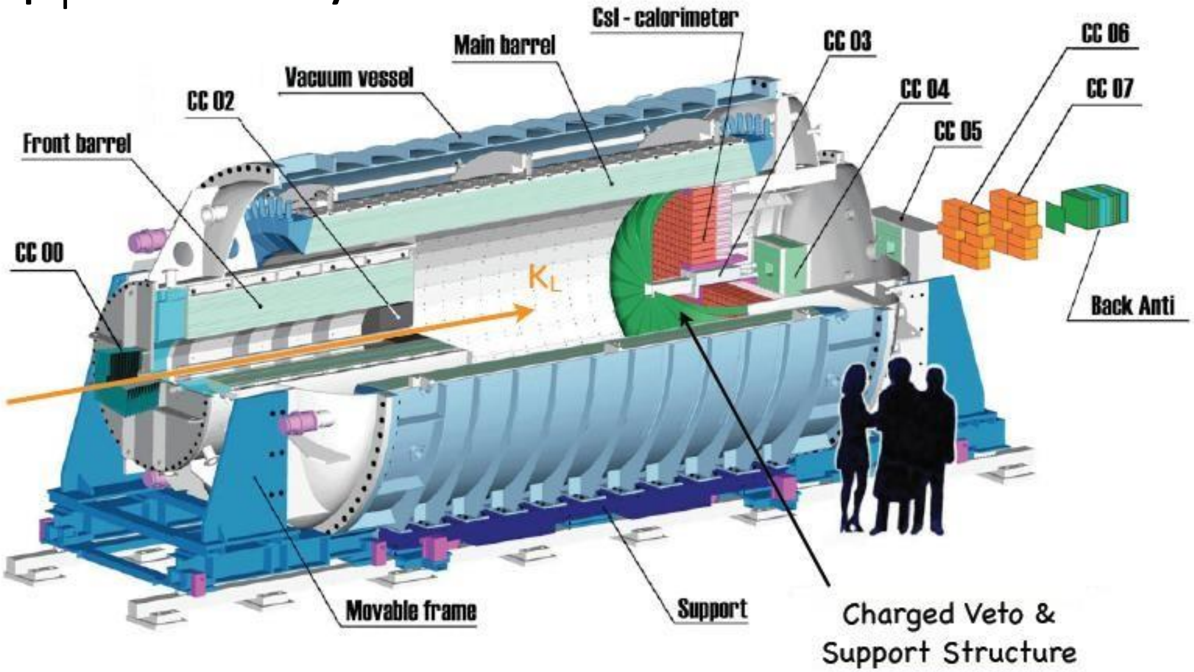
Pilot project for J-PARC experiment

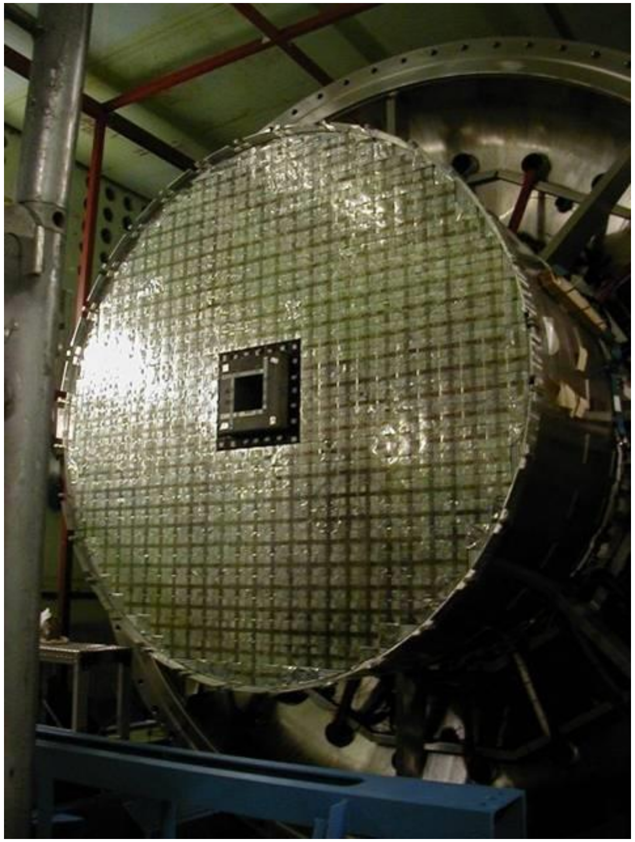
"Pencil" beam: ‹p› ≈ 3 GeV/c, n/K ≈ 60

Photon vetoes at 1 MeV level

Hadronic background MC

p_T and decay vertex cuts





E391a limits

Run I partial analysis (10% of data):

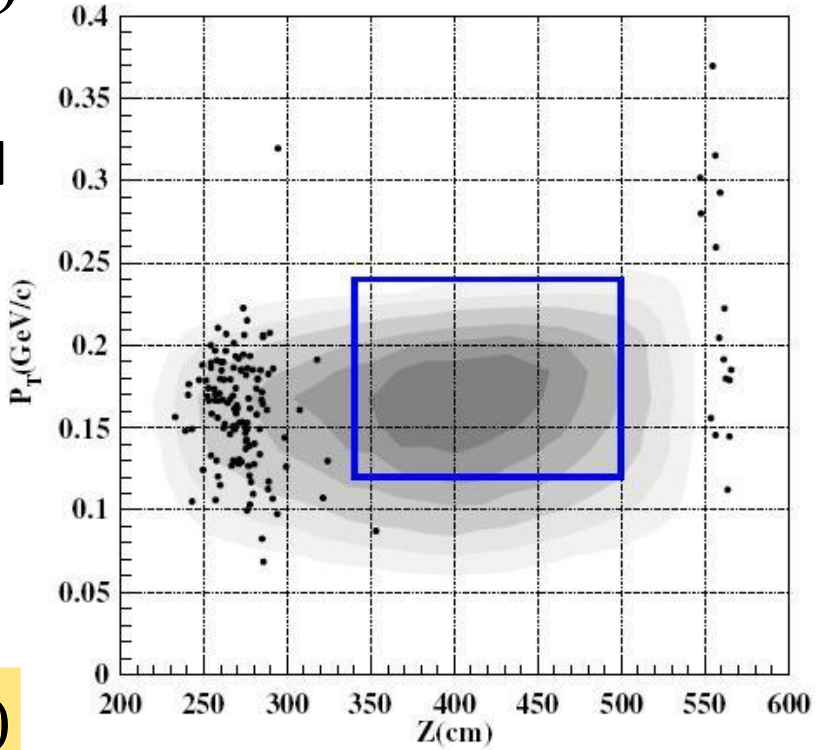
$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-7} \quad (90\%\ CL)$$

Run II: Solved problems with material on beam and DAQ inefficiency, reduced n flux

Control bkg: 1.9±0.2, obs. 3,
0.39±0.08, obs. 2
Background: exp. 0.44±0.11, obs. 0

Acceptance 0.67%

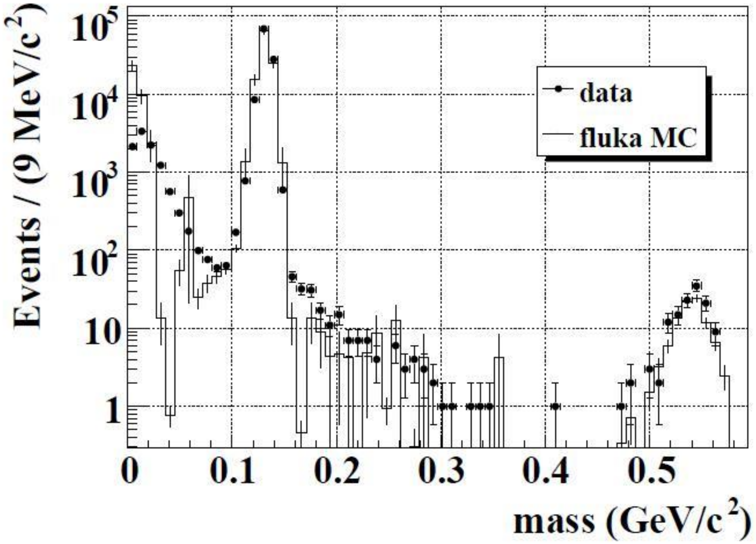
$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 6.7 \cdot 10^{-8} \quad (90\%\ CL)$$



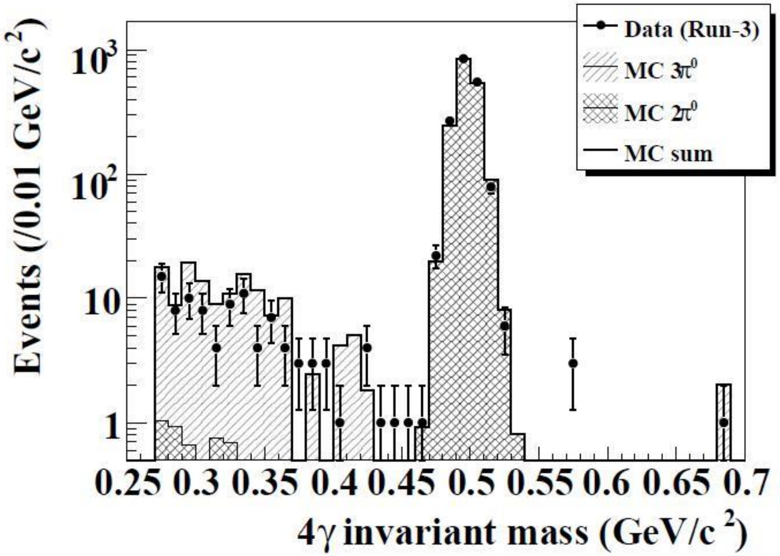
Single-event sensitivity: $2.89 \cdot 10^{-8}$
Still below Grossman-Nir bound

Also: $BR(K_L \to \pi^0 \pi^0 \nu\bar{\nu}) < 4.7 \cdot 10^{-5}$ $(90\%\ CL)$

KEK E391a final results



2γ mass with 5mm Al plate run



4γ mass in vacuum run

Detailed understanding of backgrounds

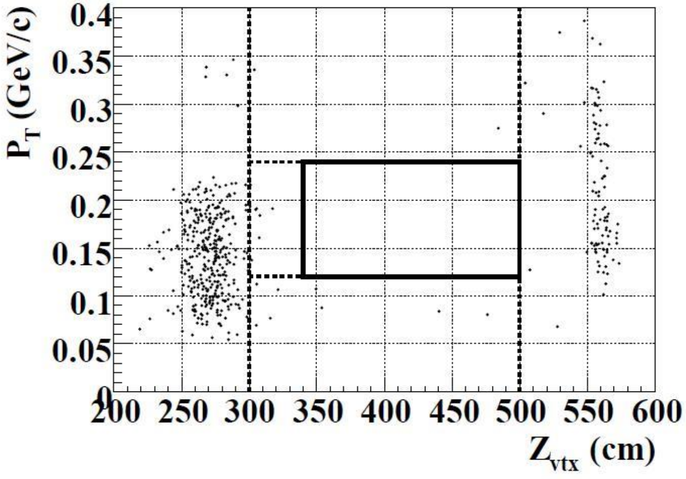
Bkg estimate: 0.87±0.41

3 flux normalizations

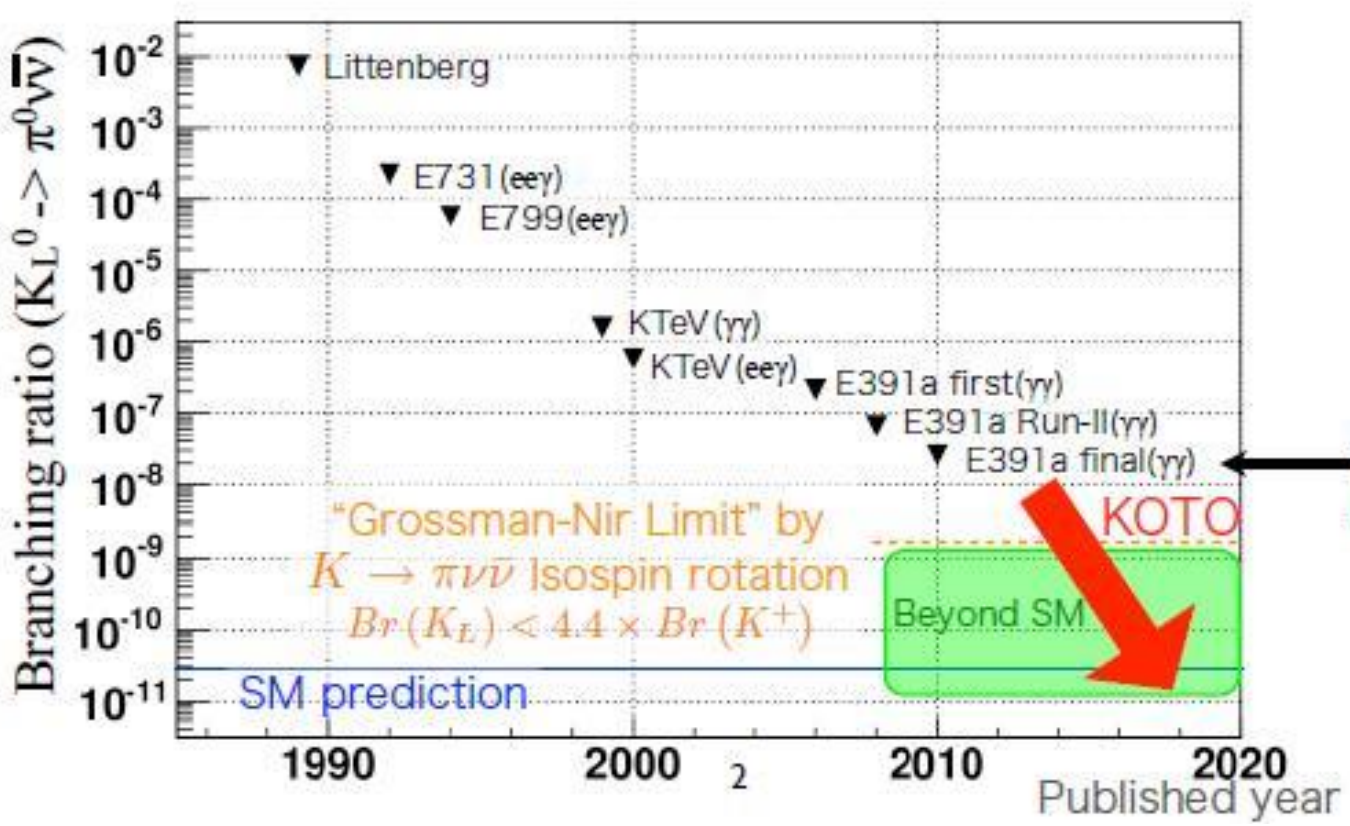
~1% total acceptance

SES $(1.11\pm0.02\pm0.10)\cdot10^{-8}$

BR($K_L \to \pi^0 \nu\nu$)<$2.6\cdot 10^{-8}$ (90% CL)



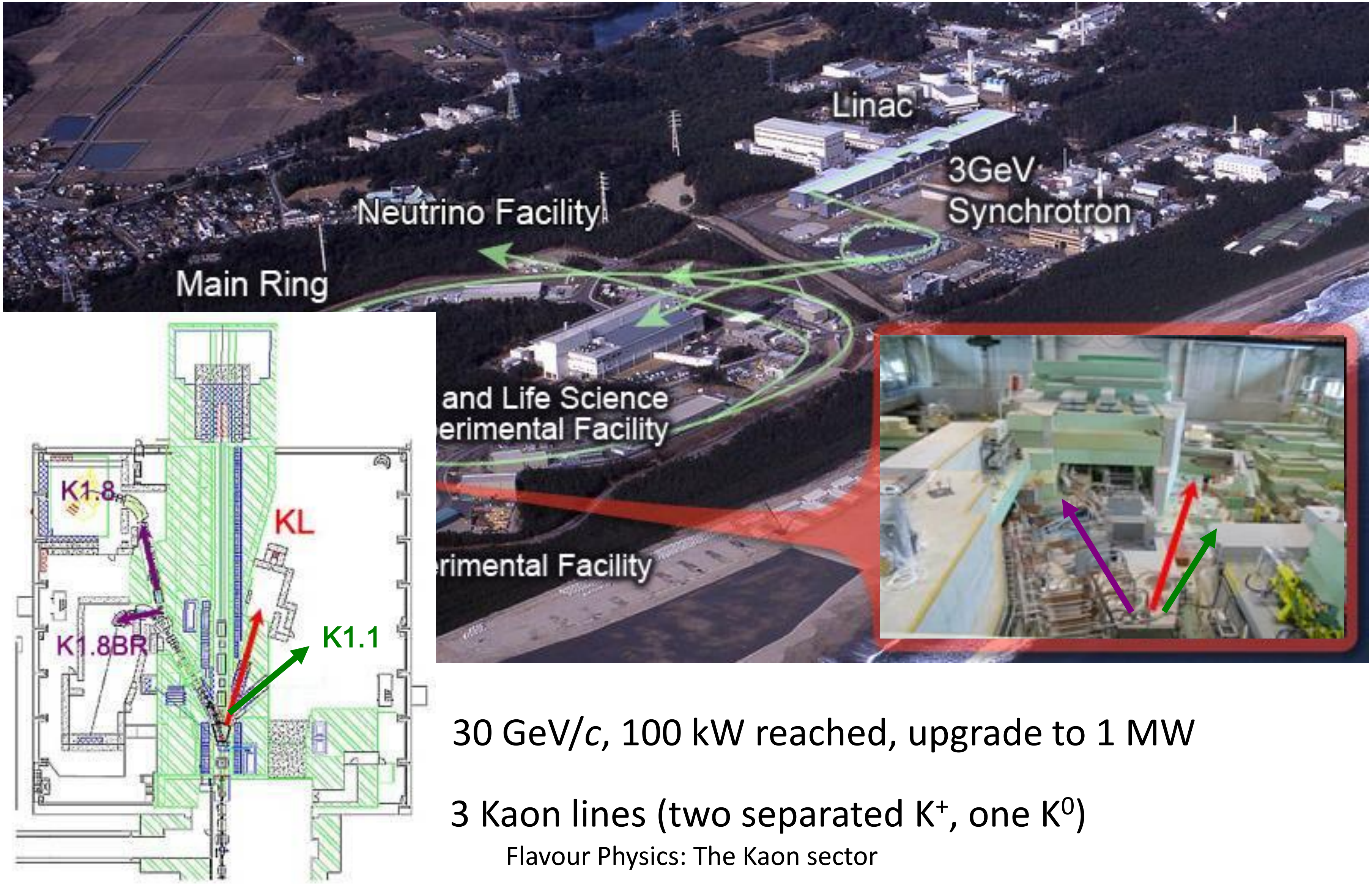
The story so far



Current upper limit : 2.6×10^{-8}

© M. Togawa

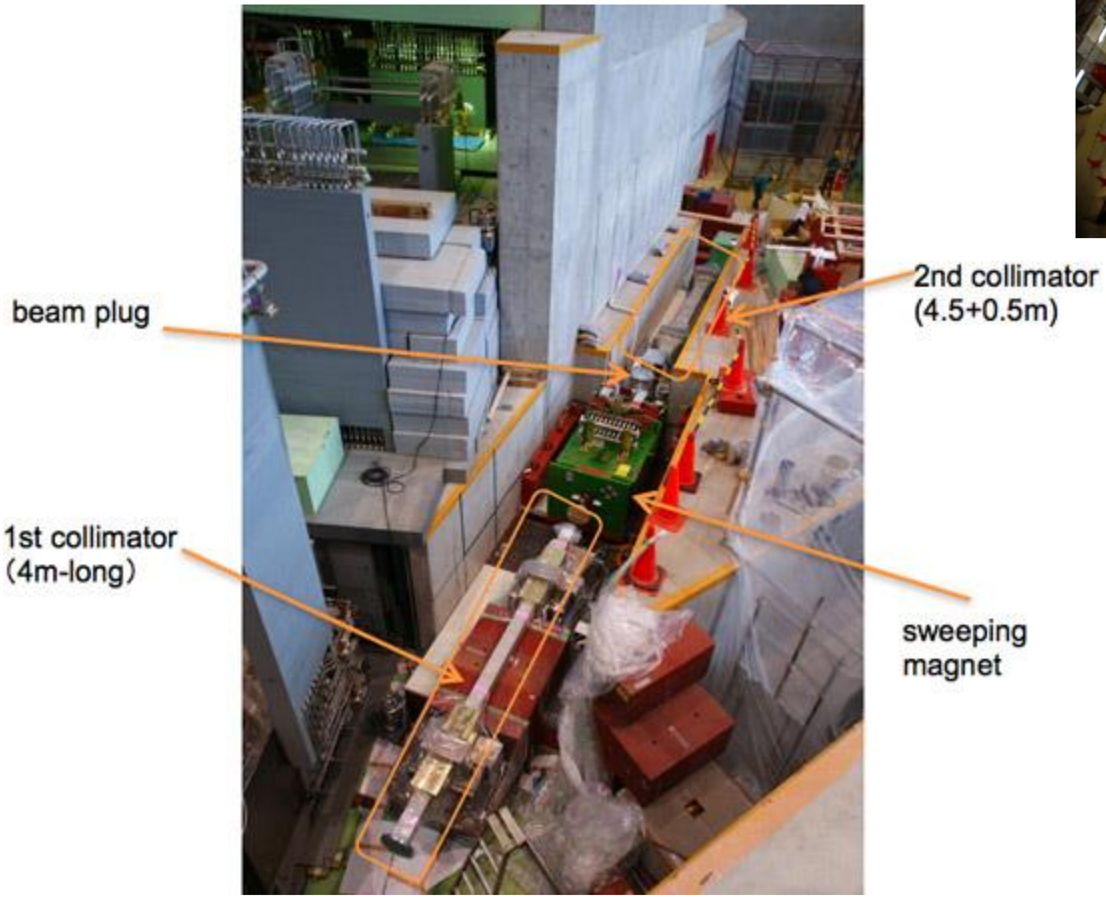
J-PARC



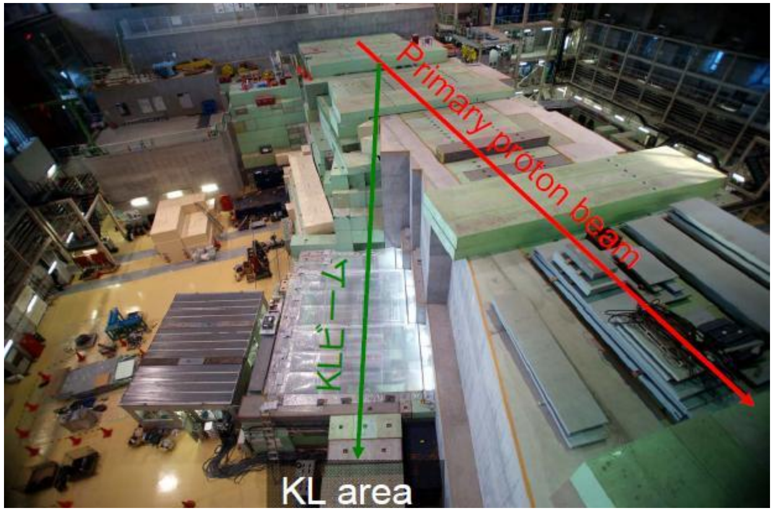
30 GeV/*c*, 100 kW reached, upgrade to 1 MW

3 Kaon lines (two separated K^+, one K^0)

J-PARC K_L beam



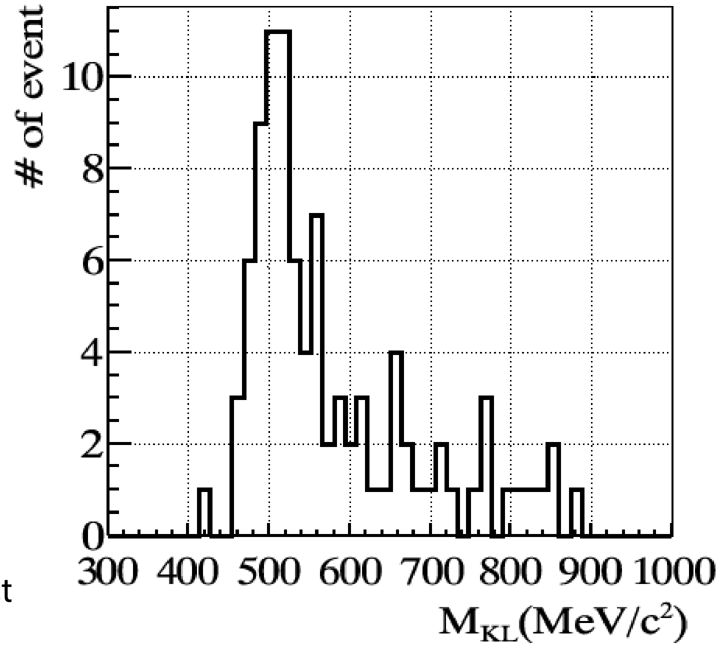
$0.2 \div 4$ GeV/*c* K_L



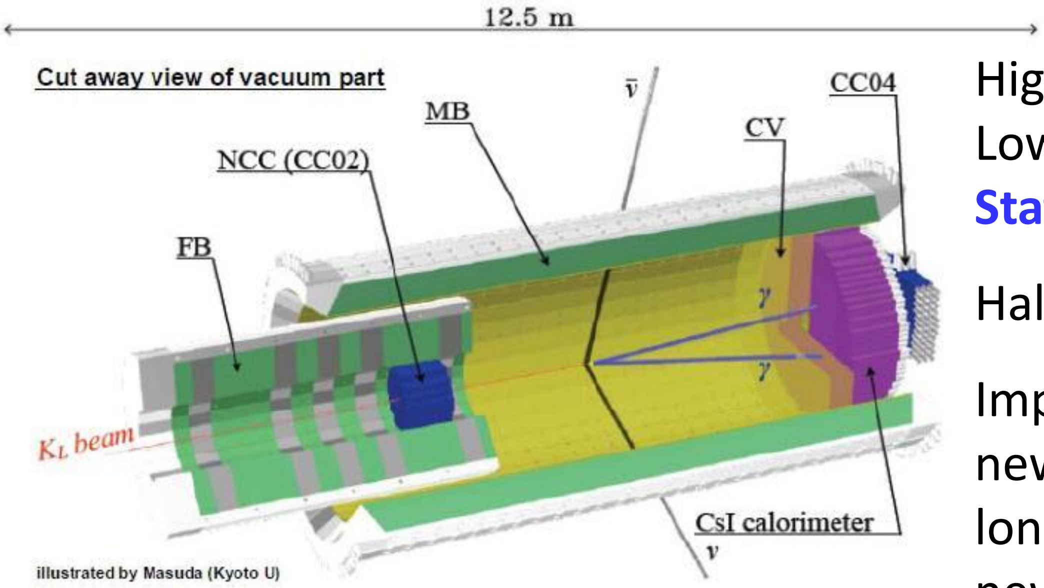
$K_L \to \pi^+\pi^-\pi^0$ detected

1-2 GeV/*c*

Yield: 2.3 x proposal



KOTO experiment



illustrated by Masuda (Kyoto U)

Higher beam intensity, acceptance
Lower DC, yield (angle):
Statistics: **3000 x E391a**

Halo n/K: **240x E391a: **new beam line

Improved background control:
new EM calorimeter (> granularity, longer), new backside charged veto, new beam-hole γ veto (25x Pb/aerogel)

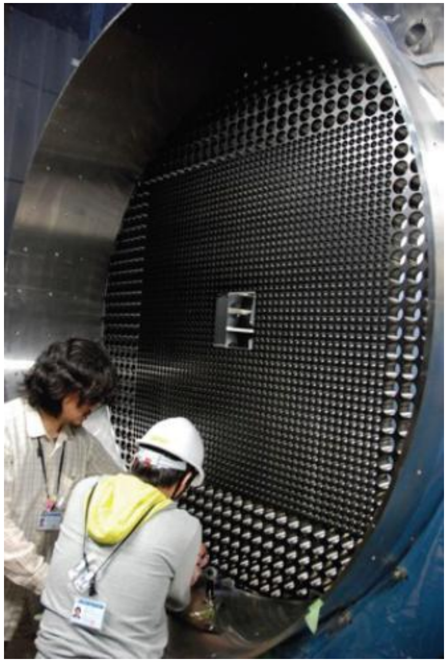
Step 1: SES = **2.7 SM events** (3 Snowmass years) with **2.2 background**

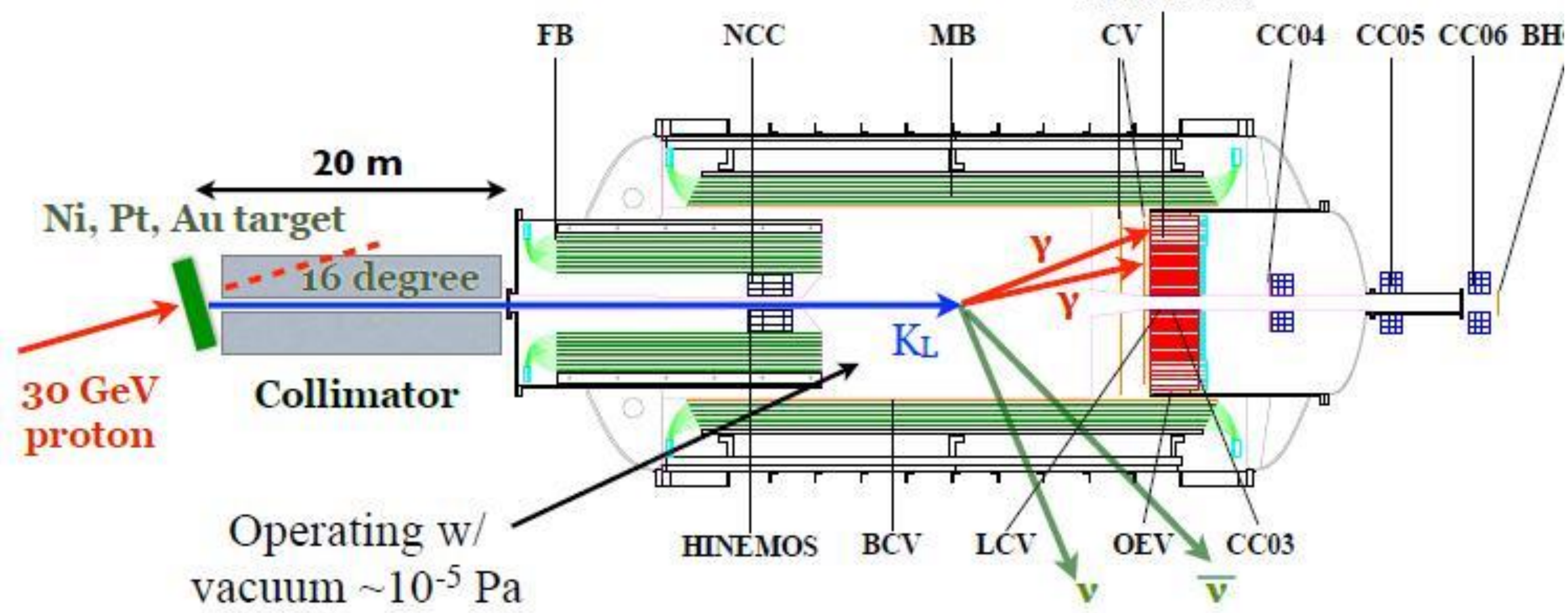
Step 2 upgrade**: 100 SM events**
(dedicated, smaller targeting angle beam line, larger detector)

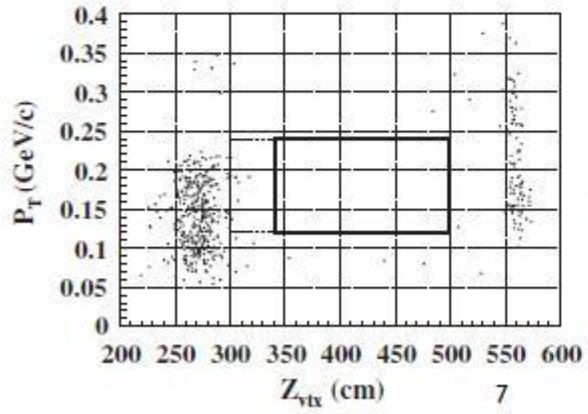
66 people, 16 institutions (Japan, Korea, USA, Russia, Taiwan)

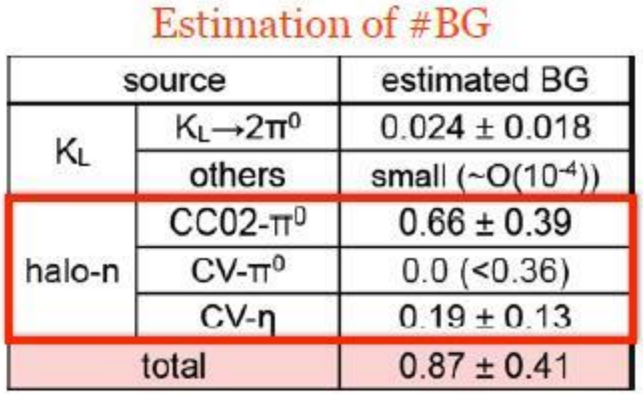
KOTO experiment

K0 at TOkai







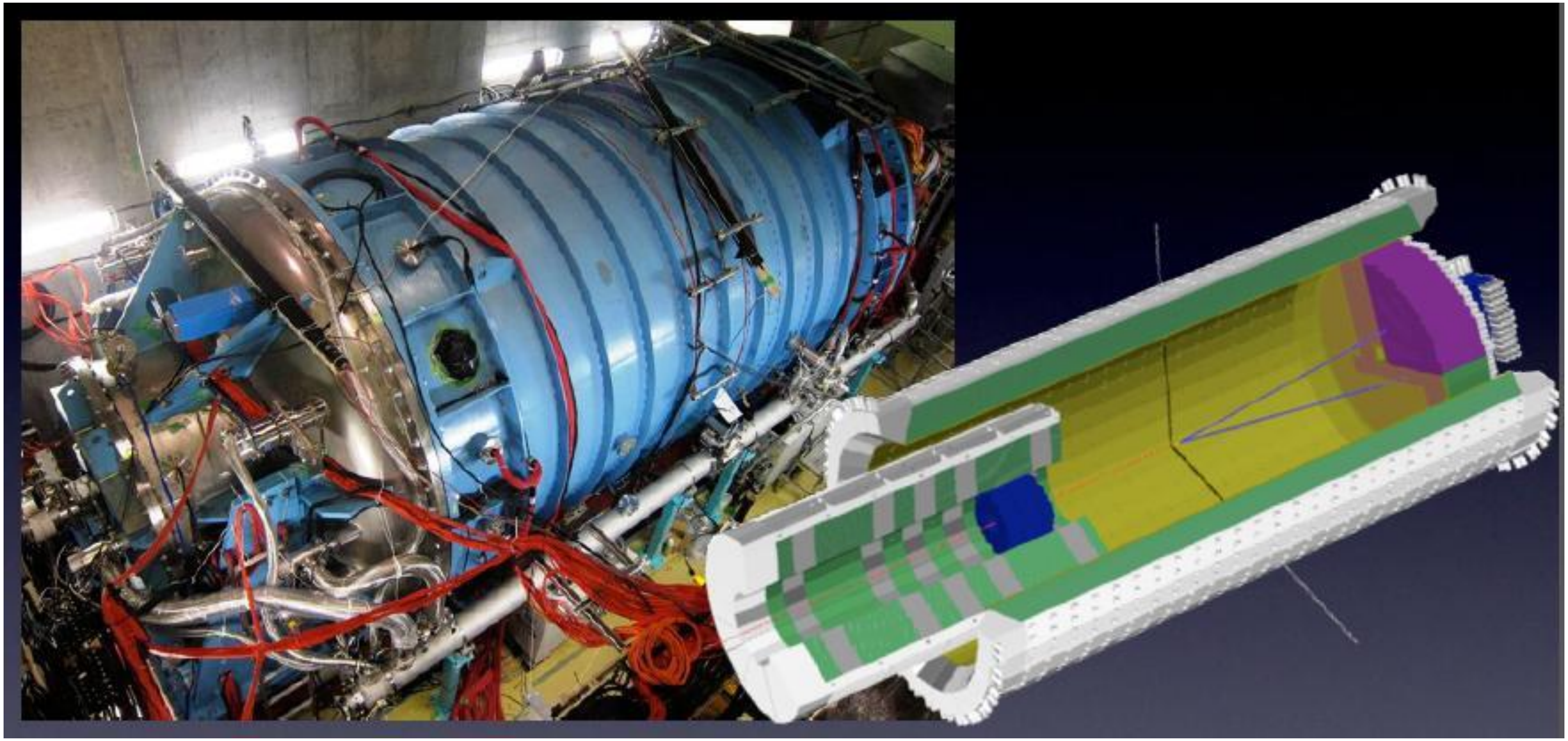


Estimation of #BG

source		estimated BG
K_L	$K_L \to 2\pi^0$	0.024 ± 0.018
	others	small (~$O(10^{-4})$)
halo-n	CC02-π^0	**0.66 ± 0.39**
	CV-π^0	0.0 (<0.36)
	CV-η	0.19 ± 0.13
total		0.87 ± 0.41

© M. Togawa

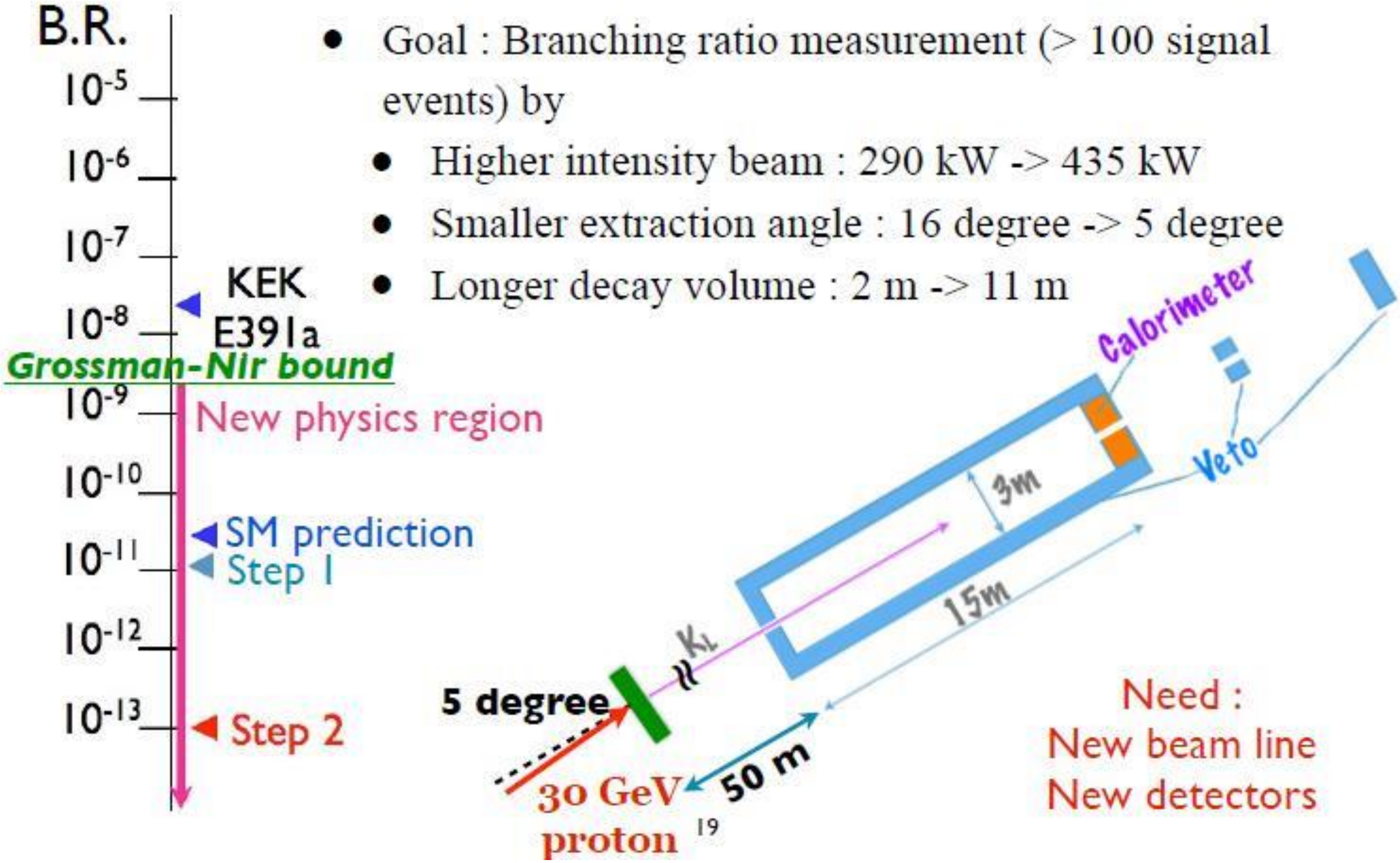
KOTO now



Engineering run Jan 2013, Short physics run 7-14 May 2013
Long physics run starting NOW: 30 days @ 15 kW (=10^{13} ppp)

KOTO Phase 2

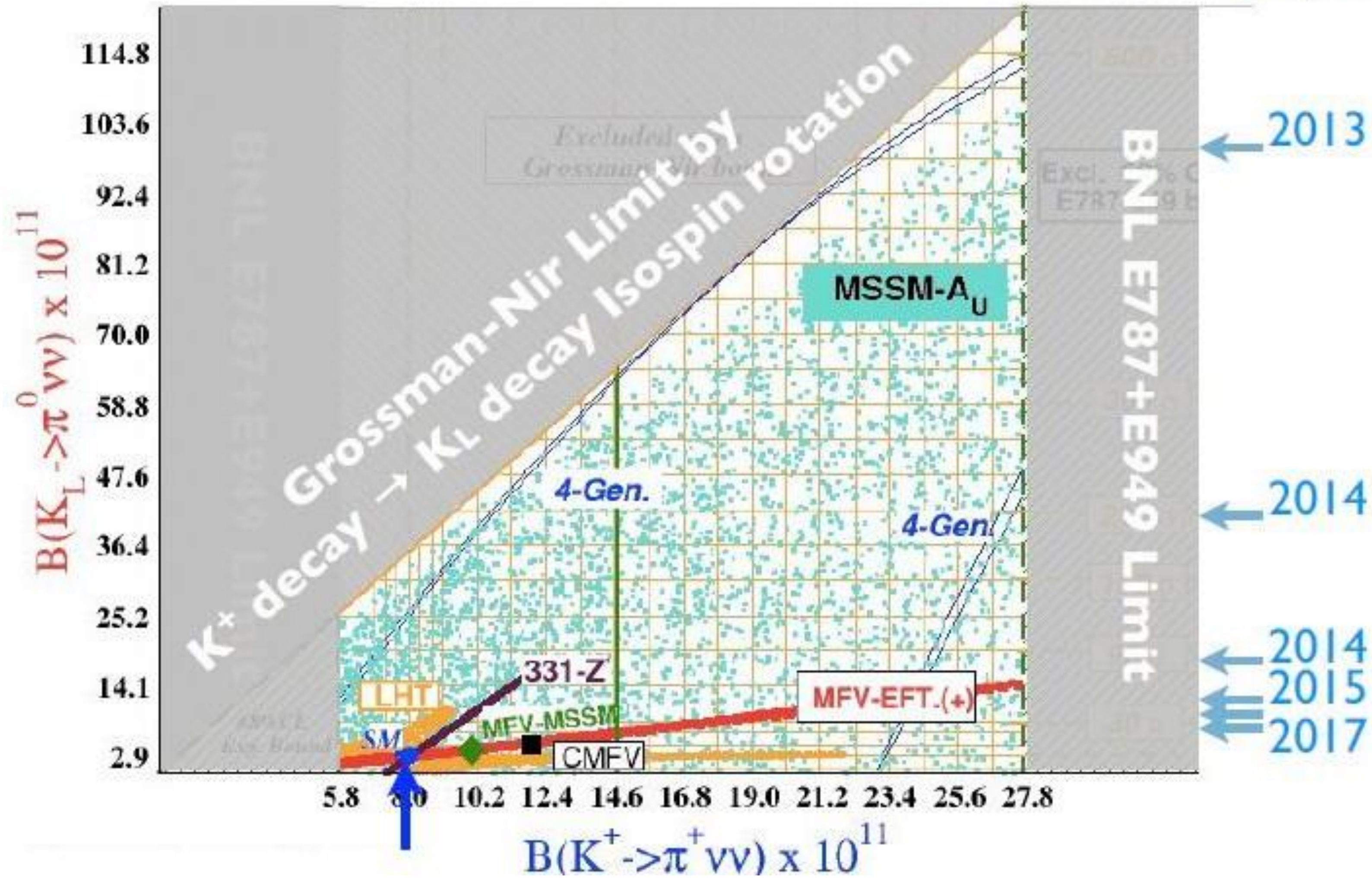
- Goal : Branching ratio measurement (> 100 signal events) by
  - Higher intensity beam : 290 kW -> 435 kW
  - Smaller extraction angle : 16 degree -> 5 degree
  - Longer decay volume : 2 m -> 11 m



Need :
New beam line
New detectors

© M. Togawa

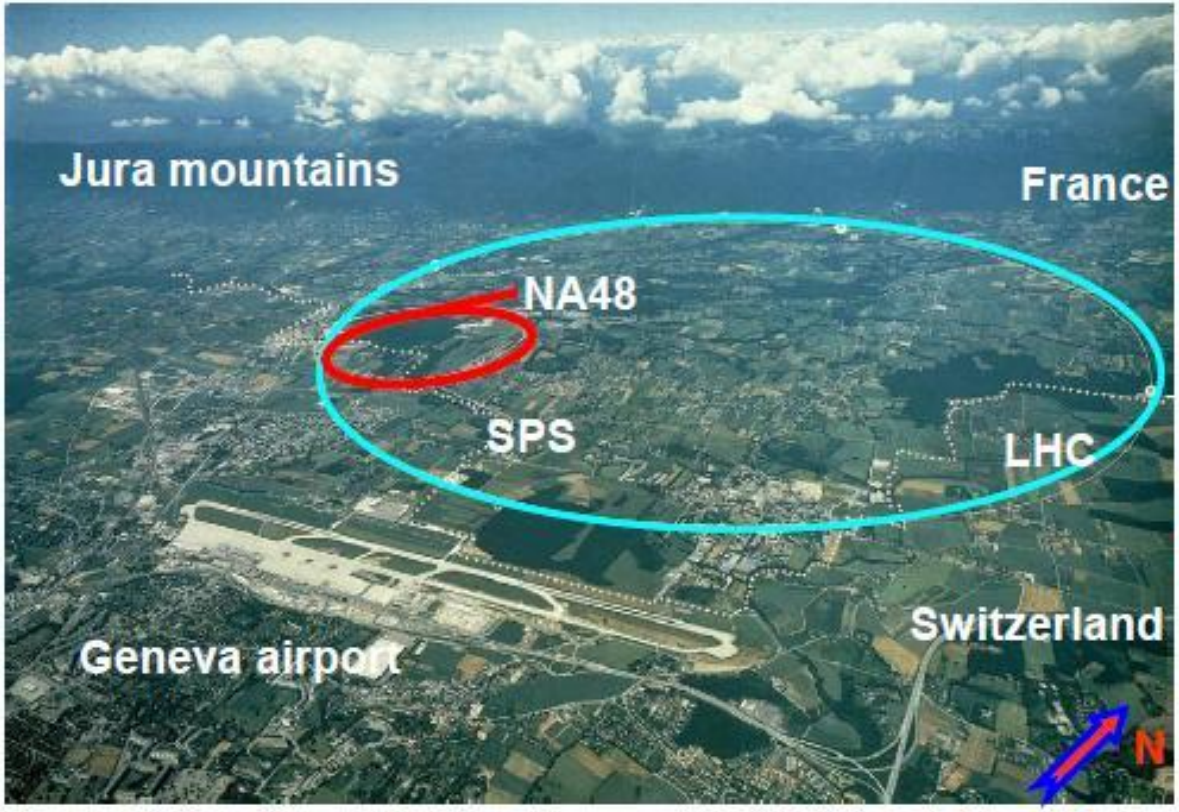
KOTO roadmap



3 sigma discovery level

© M. Togawa

Kaons @ CERN SPS



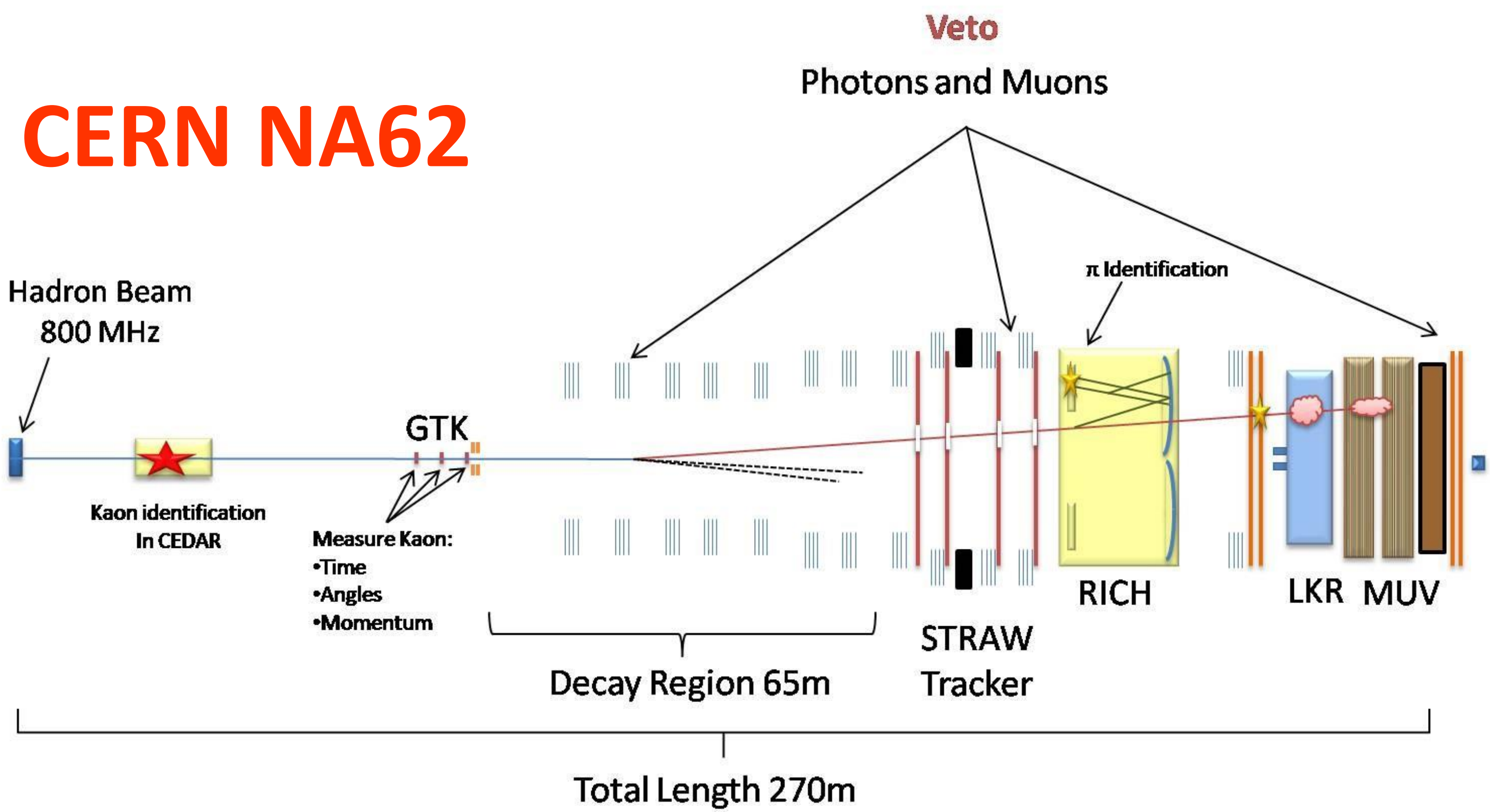
NA48 direct CPV ε'/ε	1997: $K_L + K_S$
	1998: $K_L + K_S$
	1999: $K_L + K_S$
	2000: K_L only
	2001: $K_L + K_S$
NA48/1	2002: K_S/hyperons
NA48/2	2003 $K^+ + K^-$ 2004 A_g(CPV)
NA62 (R_K)	2007 $K^+ + K^-$ 2008 R_K + tests
↓	2007 design & 2013 construction
NA62	2012technical run 2013 long shutdown 2014 2 years 2016 data taking

The NA48/2 collaboration:

~100 physicists from 15 Institutes in 8 countries

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien

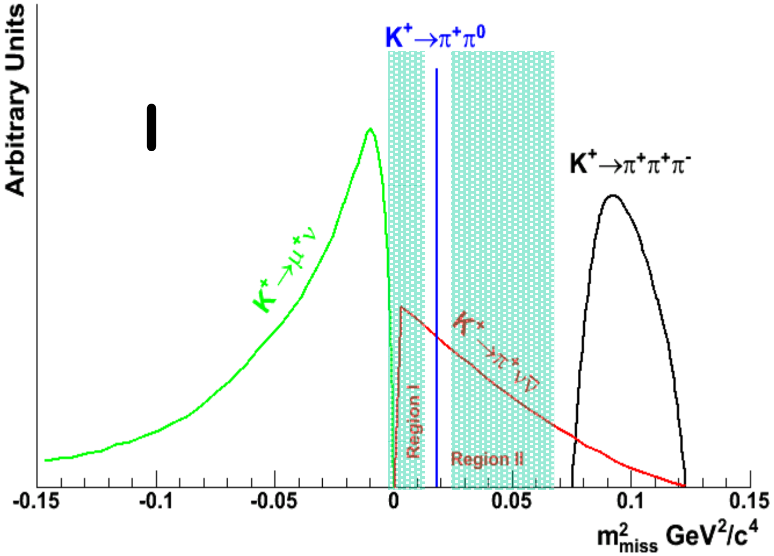
CERN NA62

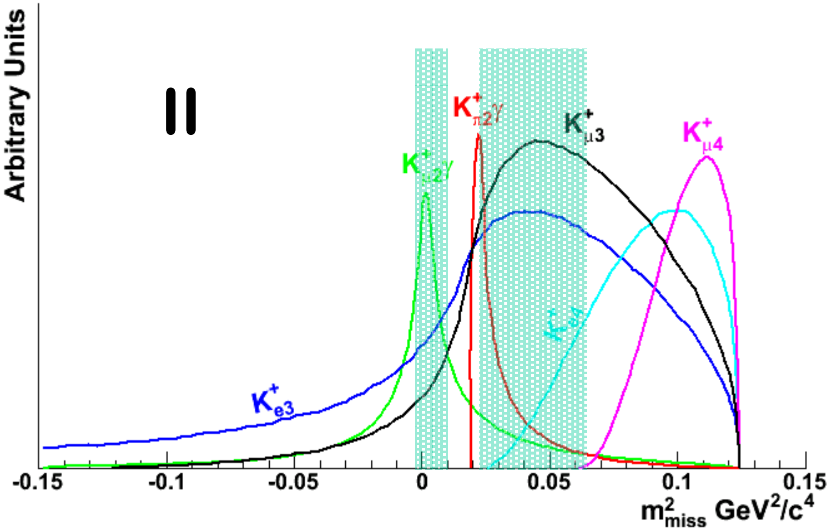


Measurement of $K^+ \to \pi^+ \nu\nu$ with new decay in-flight technique
Intense unseparated (6% K^+) 75 GeV/*c* hadron beam: $5 \cdot 10^{12}$ ppp
High-energy: high yield, large decay volume, more powerful vetoing
Track incoming K^+ in 800MHz beam, particle ID, photon vetoing

$5 \cdot 10^{12}$ K^+ decays/year

NA62 @ CERN

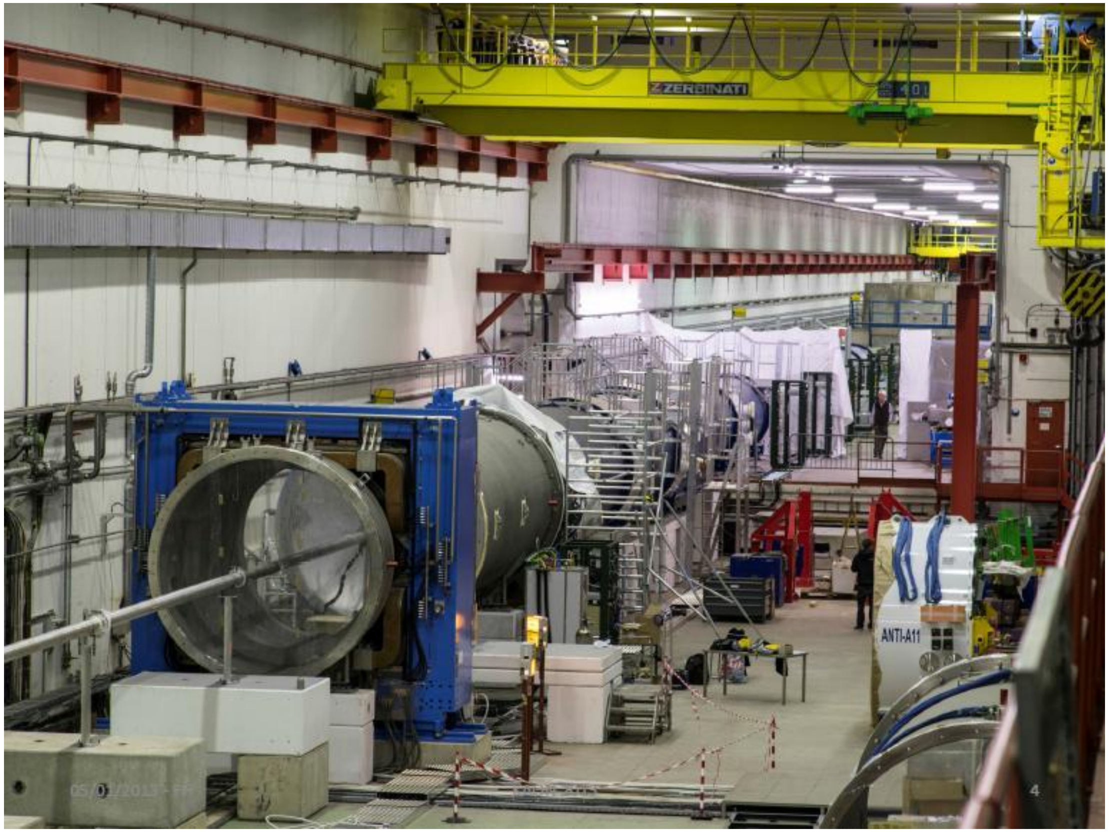


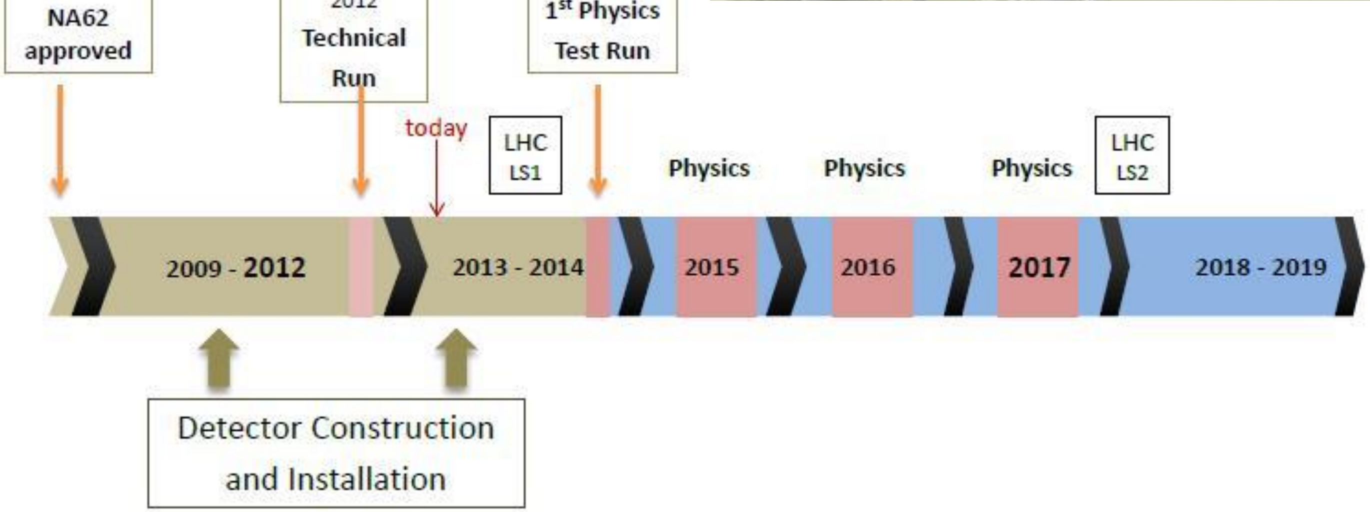


2 signal regions:
I (92% kinematically constrained bkg.)
II (8% not-constrained bkg.)

Expect ≈ 80 SM events
with S/N≈10 in 2 years (2014+)

NA62 @ CERN





Dec. 2008
NA62 approved

Oct/Nov. 2012
Technical Run

Oct. 2014
1st Physics Test Run

today

LHC LS1

Physics

Physics

Physics

LHC LS2

2009 - **2012**

2013 - 2014

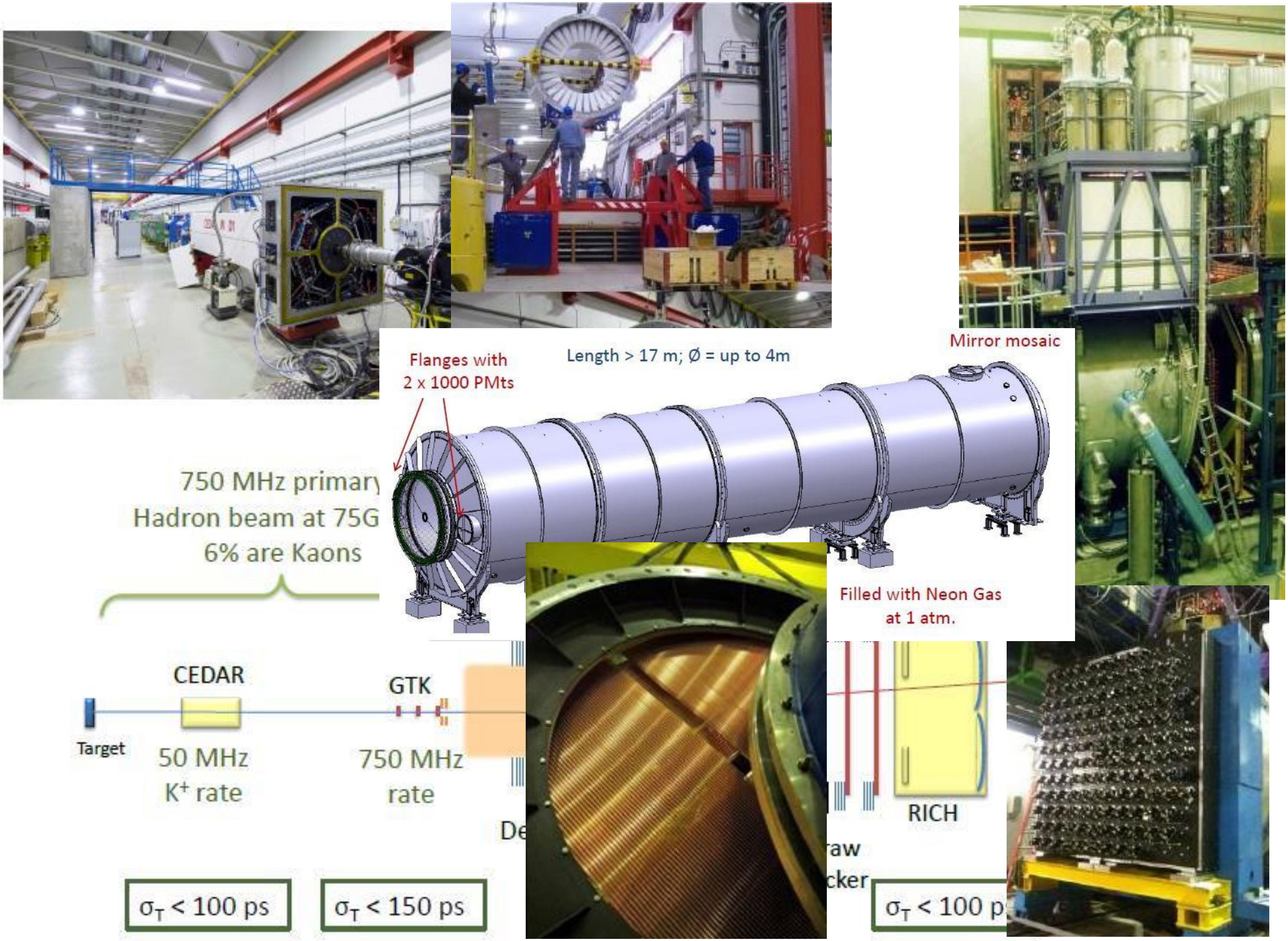
2015

2016

2017

2018 - 2019

Detector Construction and Installation



Flanges with
2 x 1000 PMts

Length > 17 m; Ø = up to 4m

Mirror mosaic

Filled with Neon Gas
at 1 atm.

750 MHz primar
Hadron beam at 75G
6% are Kaons

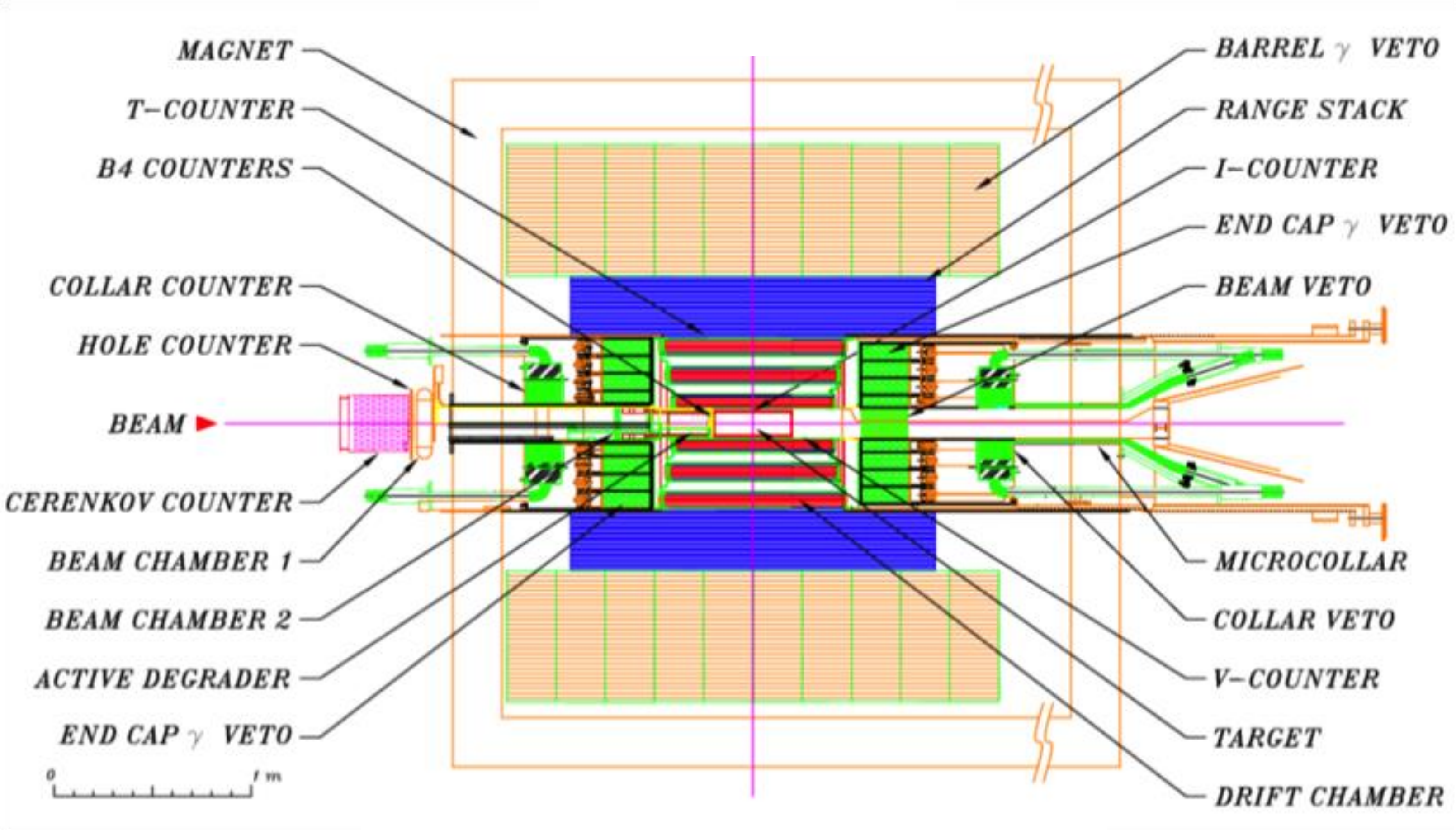
$\sigma_T < 100$ ps

$\sigma_T < 150$ ps

$\sigma_T < 100$ p

US: strong interest and many casualties

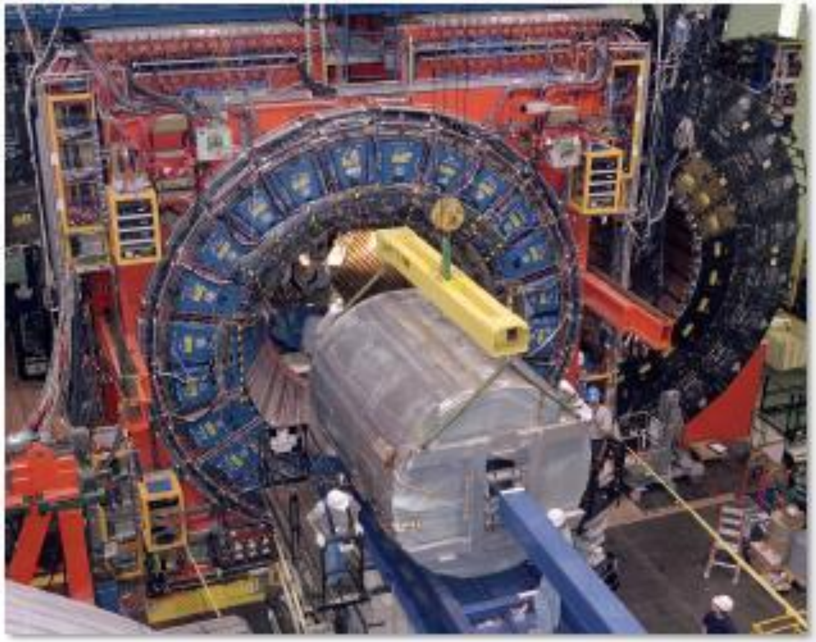
ORKA@FNAL



- 10x exposure of E949
- 10x better acceptance
- Scientific approval December 2011
- 400-event experiment

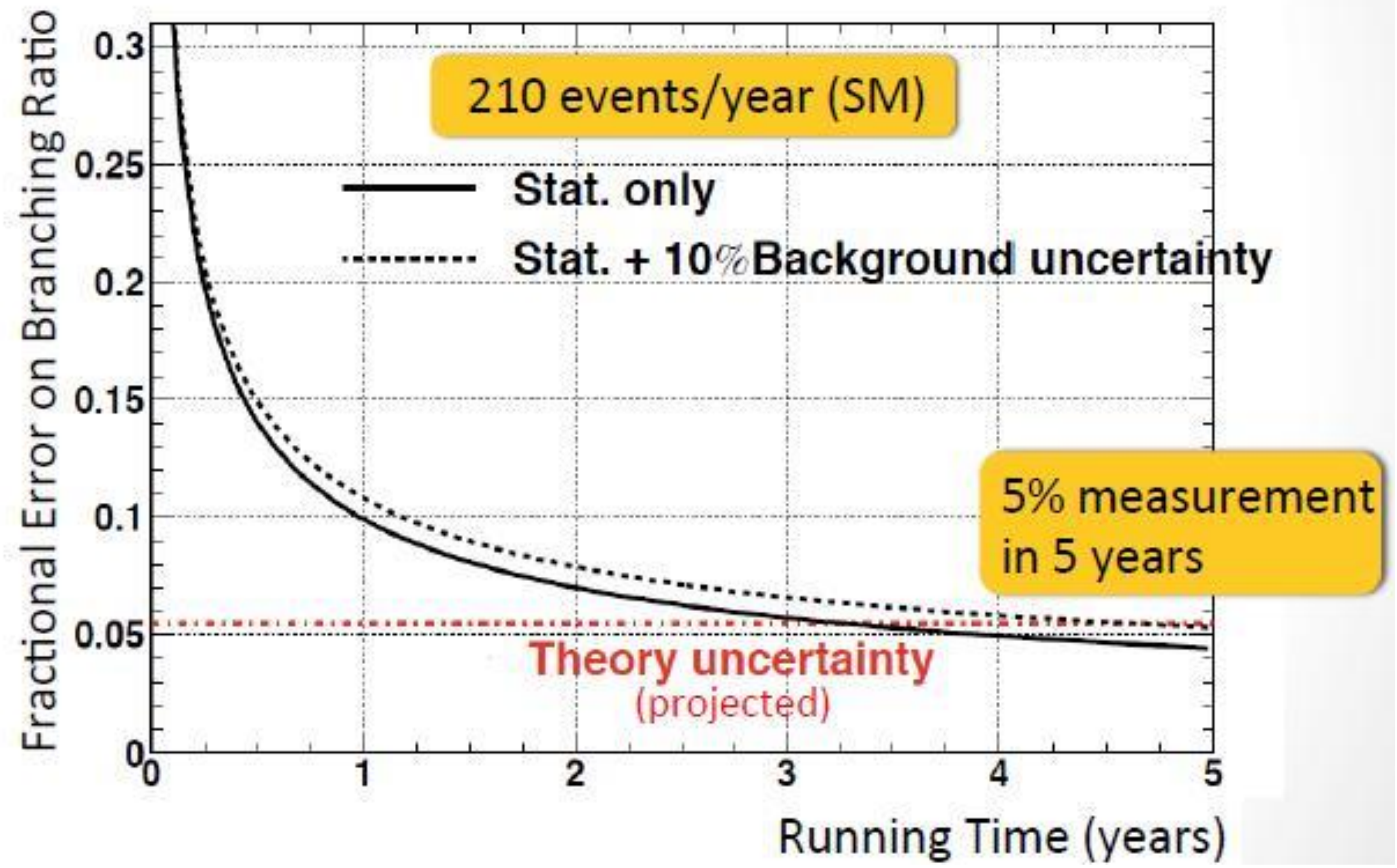
ORKA@FNAL

- ORKA detector fits inside CDF solenoid
- Re-use CDF solenoid, cryogenics, infrastructure
- Requires new beam line from A0-B0
- CDF decommissioning in preparation for ORKA ongoing



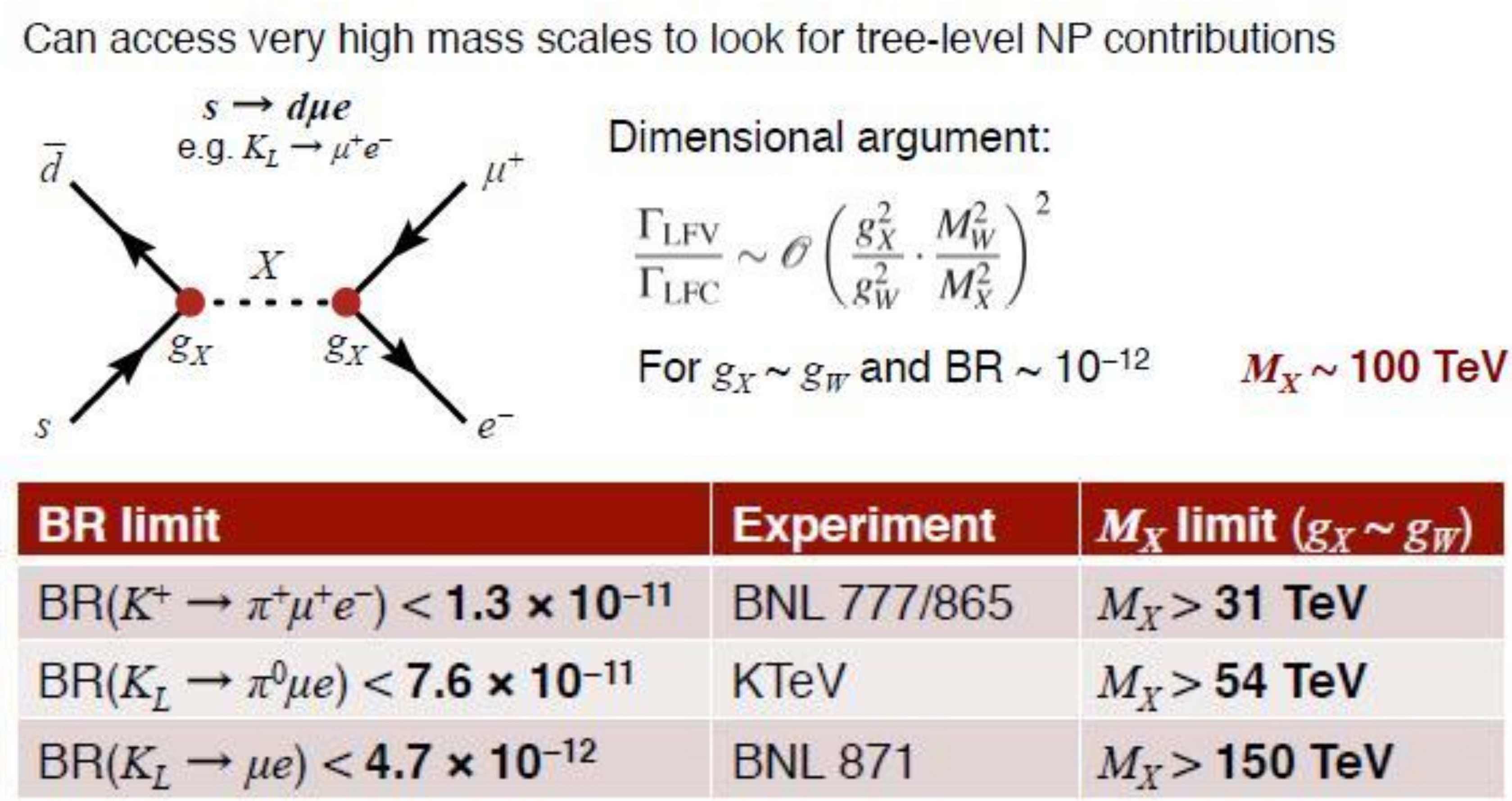
© E. Worcester

ORKA sensitivity



© E. Worcester

LFV with Kaons



Can access very high mass scales to look for tree-level NP contributions

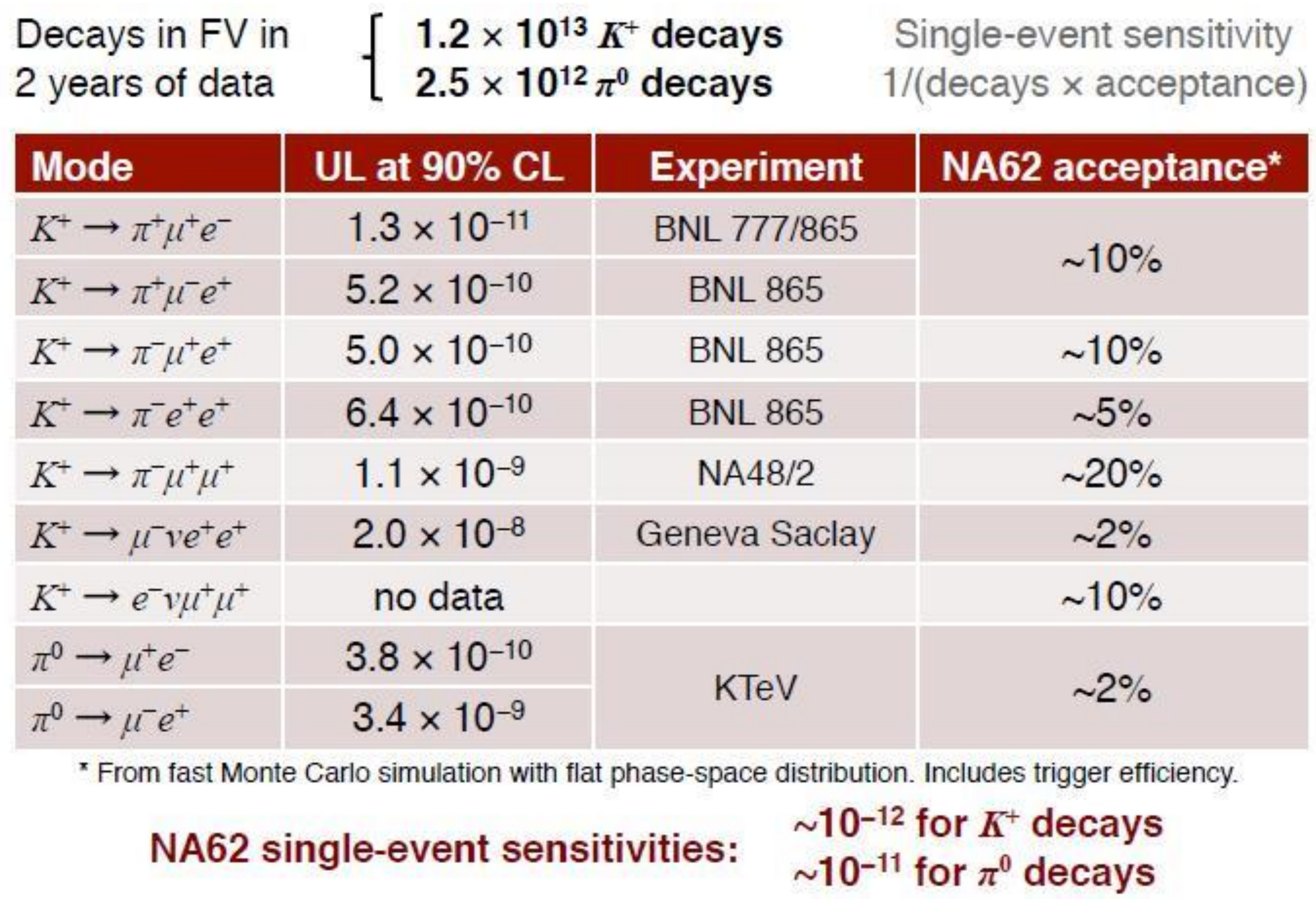
Dimensional argument:

$$\frac{\Gamma_{\mathrm{LFV}}}{\Gamma_{\mathrm{LFC}}} \sim \mathcal{O}\left(\frac{g_X^2}{g_W^2}\cdot\frac{M_W^2}{M_X^2}\right)^2$$

For $g_X \sim g_W$ and BR ~ 10^{-12} $M_X \sim$ **100 TeV**

BR limit	**Experiment**	**M_X limit ($g_X \sim g_W$)**
BR($K^+ \to \pi^+\mu^+e^-$) < **1.3 × 10^{-11}**	BNL 777/865	$M_X >$ **31 TeV**
BR($K_L \to \pi^0\mu e$) < **7.6 × 10^{-11}**	KTeV	$M_X >$ **54 TeV**
BR($K_L \to \mu e$) < **4.7 × 10^{-12}**	BNL 871	$M_X >$ **150 TeV**

LFV potential @ CERN NA62



Decays in FV in
2 years of data

1.2×10^{13} K^+ decays
2.5×10^{12} π^0 decays

Single-event sensitivity
1/(decays × acceptance)

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	~10%
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	~10%
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	~5%
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	~20%
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva Saclay	~2%
$K^+ \to e^-\nu\mu^+\mu^+$	no data		~10%
$\pi^0 \to \mu^+e^-$	3.8×10^{-10}	KTeV	~2%
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}		

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

NA62 single-event sensitivities:
~10^{-12} for K^+ decays
~10^{-11} for π^0 decays

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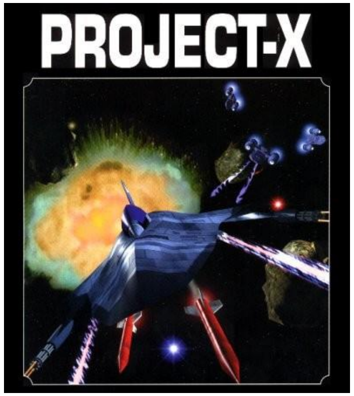
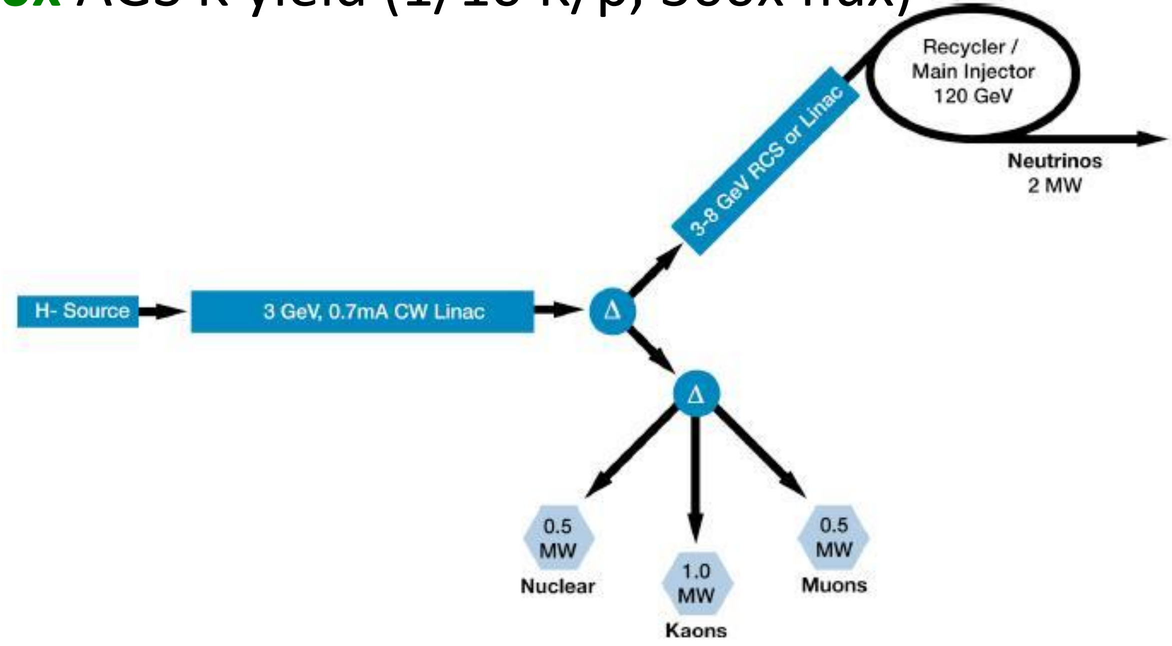
FNAL Project-X

(megatron, intensitron,…)



Ultimate proton driver for the next decade
50-120 GeV for υ, K, μ, n(EDM)

Slow extraction limited from circular machines (10s of kW):
Continuous-Wave LINAC (p or H^-), **3 MW** at 3 GeV, $3{\cdot}10^{15}$ p/s
30x AGS K yield (1/10 K/p, 300x flux)


H- Source
3 GeV, 0.7mA CW Linac
Δ
3-8 GeV RCS or Linac
Recycler / Main Injector 120 GeV
Neutrinos 2 MW
Δ
0.5 MW Nuclear
1.0 MW Kaons
0.5 MW Muons


9&10 November 2009
Project X Physics Workshop
Fermilab Batavia, Illinois USA

4th Workshop on Physics with a high intensity proton source

Kaons at Project-X

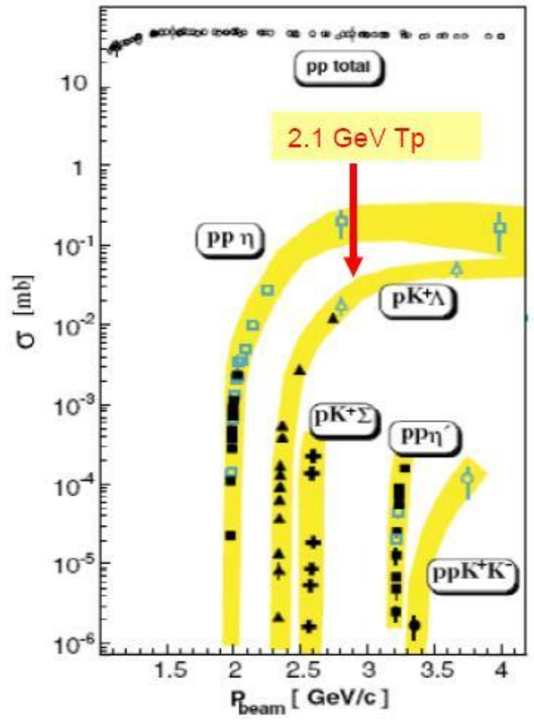
Flux potential for **ultimate** ultra-rare K decay measurements

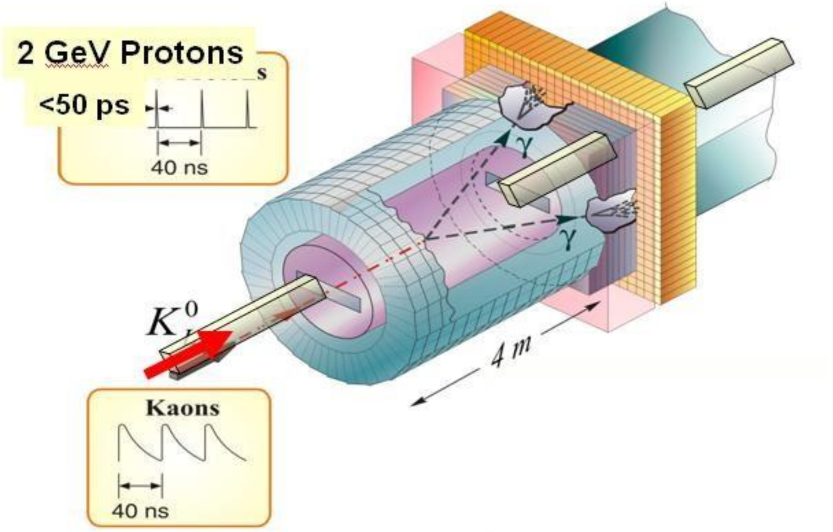
~500 $K^+ \rightarrow \pi^+ \upsilon\upsilon$ events/year (S/B ~ 4)

$K_L \rightarrow \pi^0 \upsilon\upsilon$ experiment: the best of both worlds
- Intrinsic high-precision timing:
TOF approach (KOPIO)
beam microbunching 50ps/40ns)
- Round and small beam
(acceptance and bkg rejection)

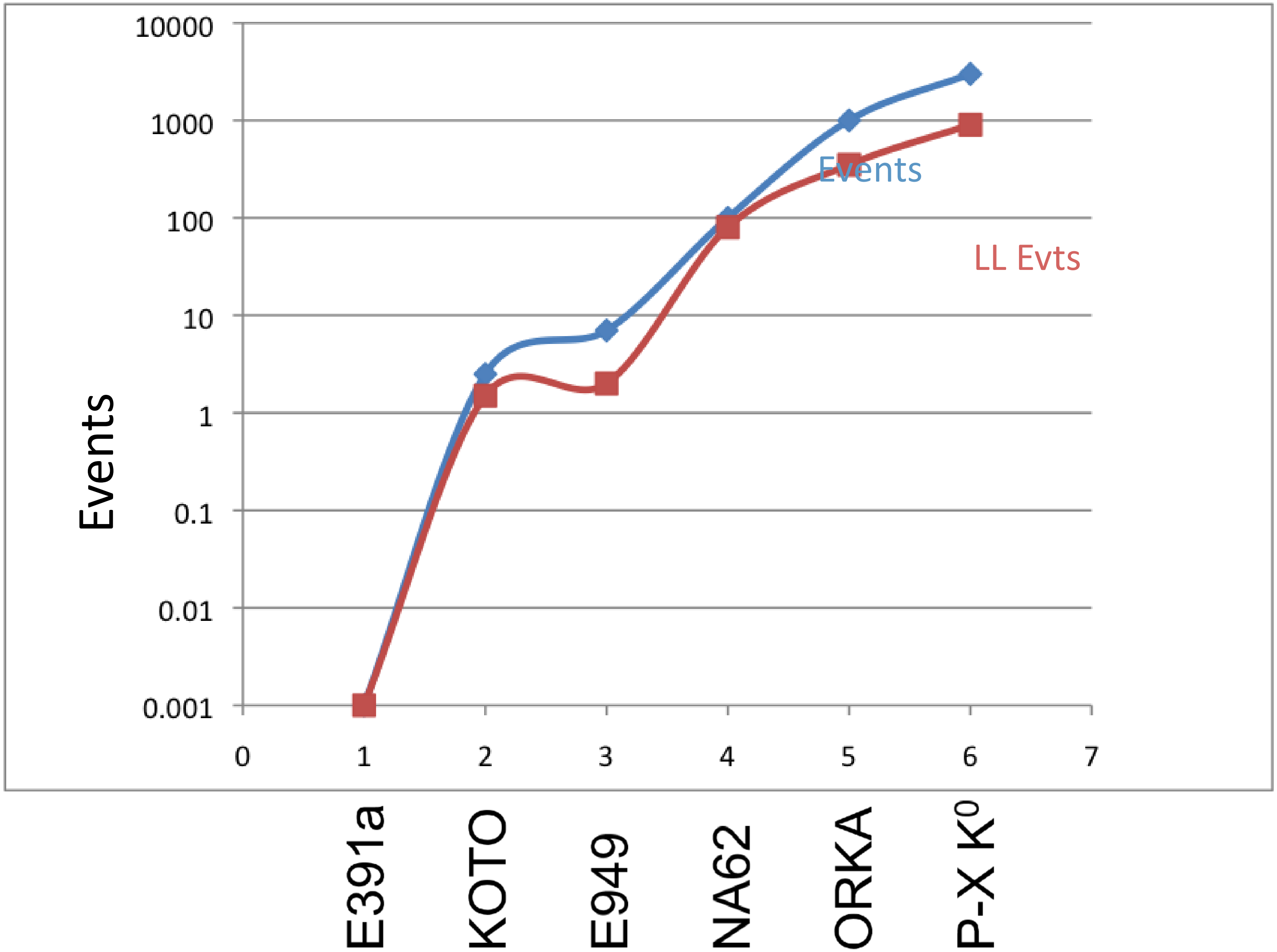
~200 $K_L \rightarrow \pi^0 \upsilon\upsilon$ evts/year (S/B ~ 5-10)

Ultimate CPT test at **Planck scale**:
interference from pure K^0 beam



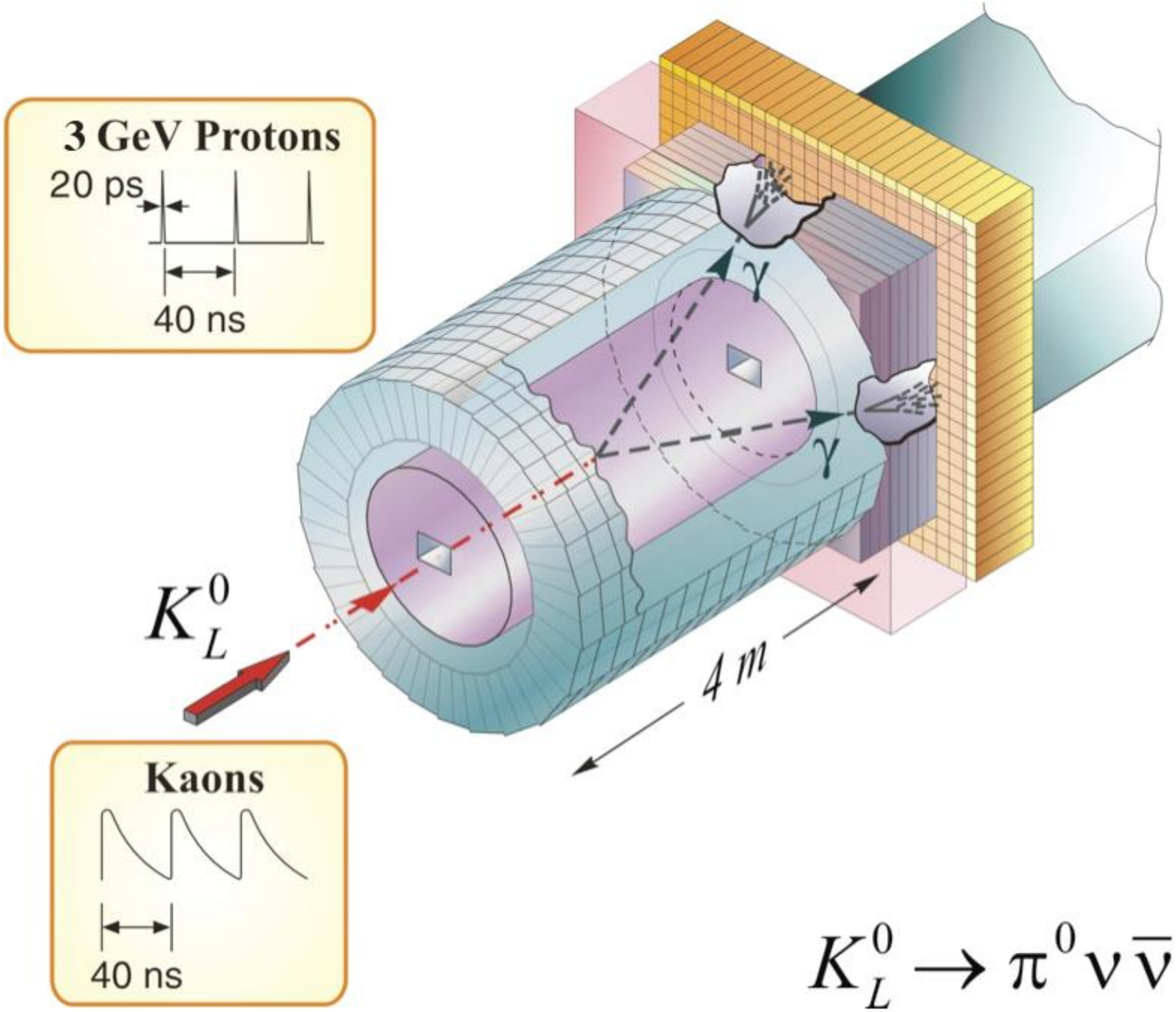


K experiments



KOPIO-like experiment for Project-X_2

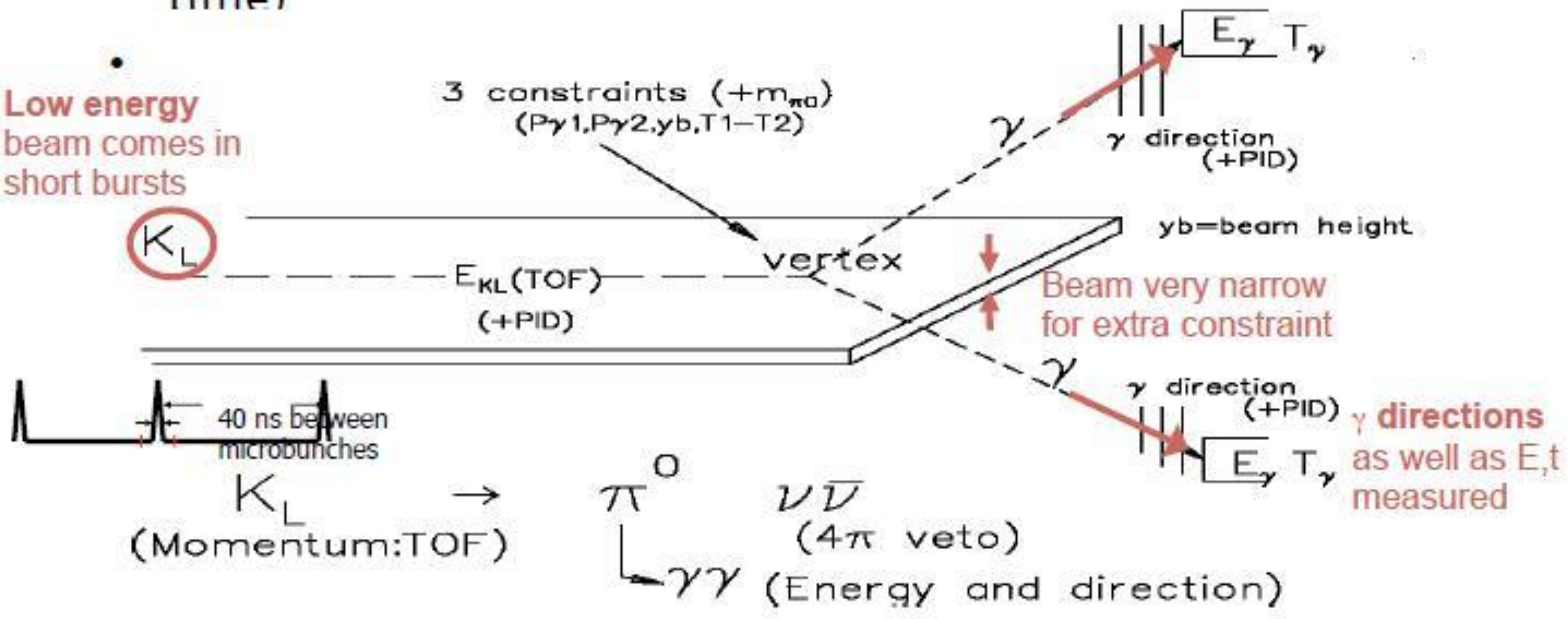
1000-event class
Really requires 3 GeV
Stage 2 of Project-X



$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$

KOPIO technique

- High intensity micro-bunched beam to measure K velocity
- Measure everything! (energy, position, **direction**, time)



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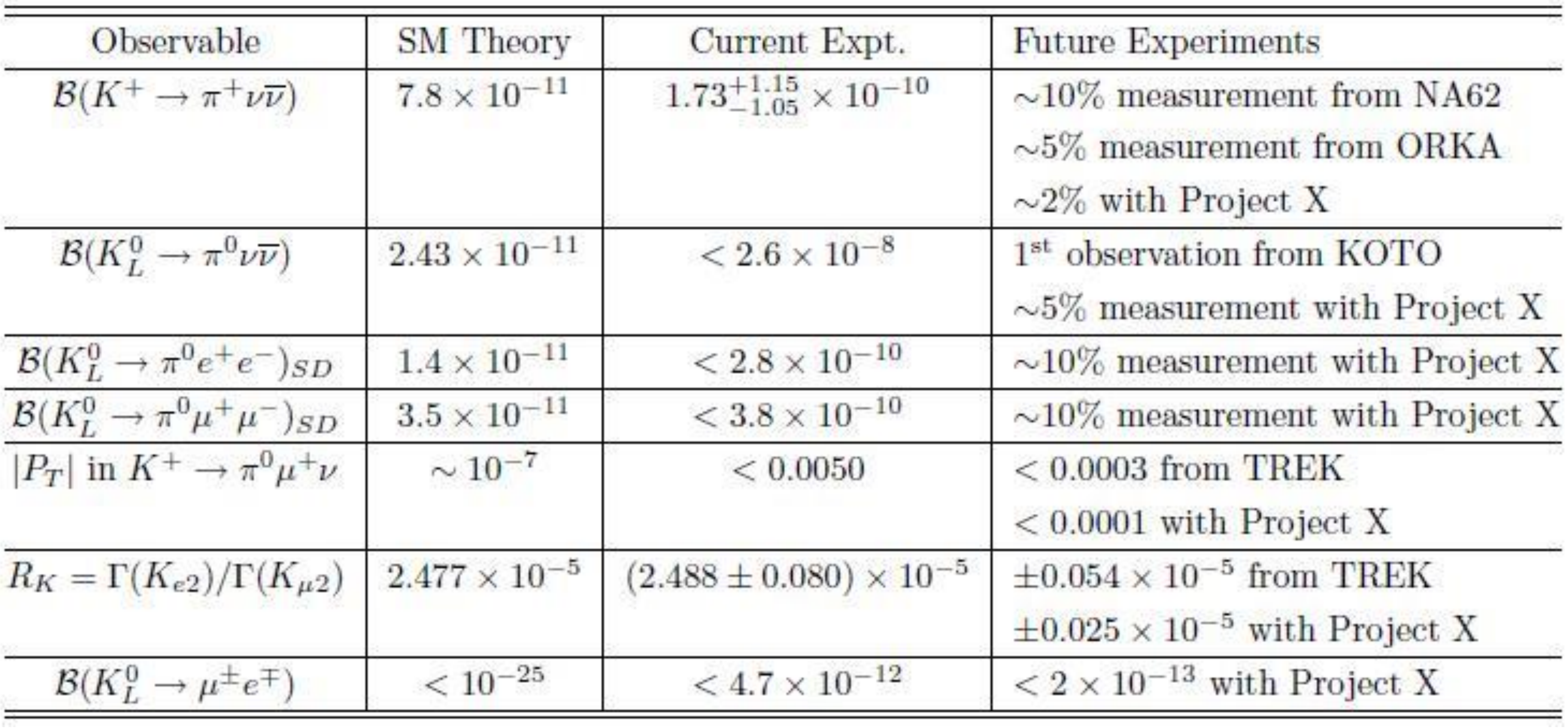
Rare K decays: now and future



Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu \overline{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	$\sim$10% measurement from NA62 $\sim$5% measurement from ORKA $\sim$2% with Project X
$\mathcal{B}(K^0_L \to \pi^0 \nu \overline{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1st observation from KOTO $\sim$5% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 \mu^+ \mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	$\sim$10% measurement with Project X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

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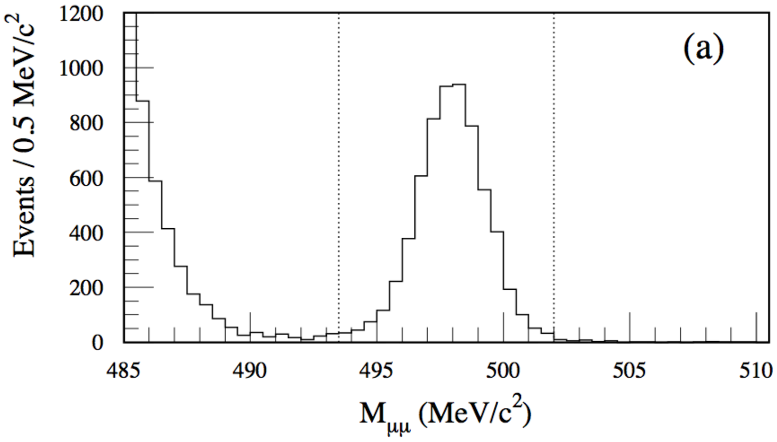
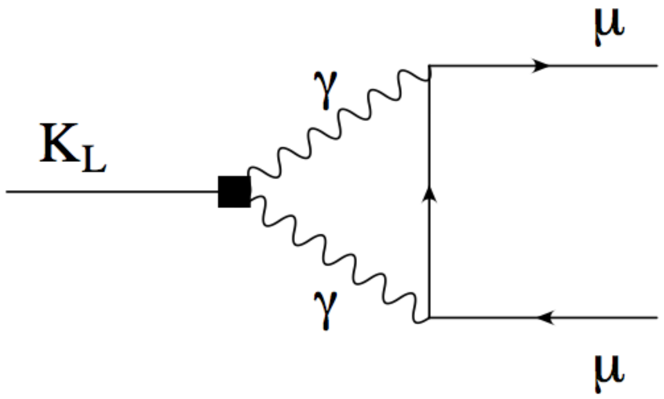
And $K_L \to \mu^+\mu^-$?

- BR ~ 7×10^{-9}
- Beautiful signature



- 1% background



BUT:
the above process introduces an absorptive part that is many times larger than the short-distance contribution plus a dispersive part that can interfere with it.

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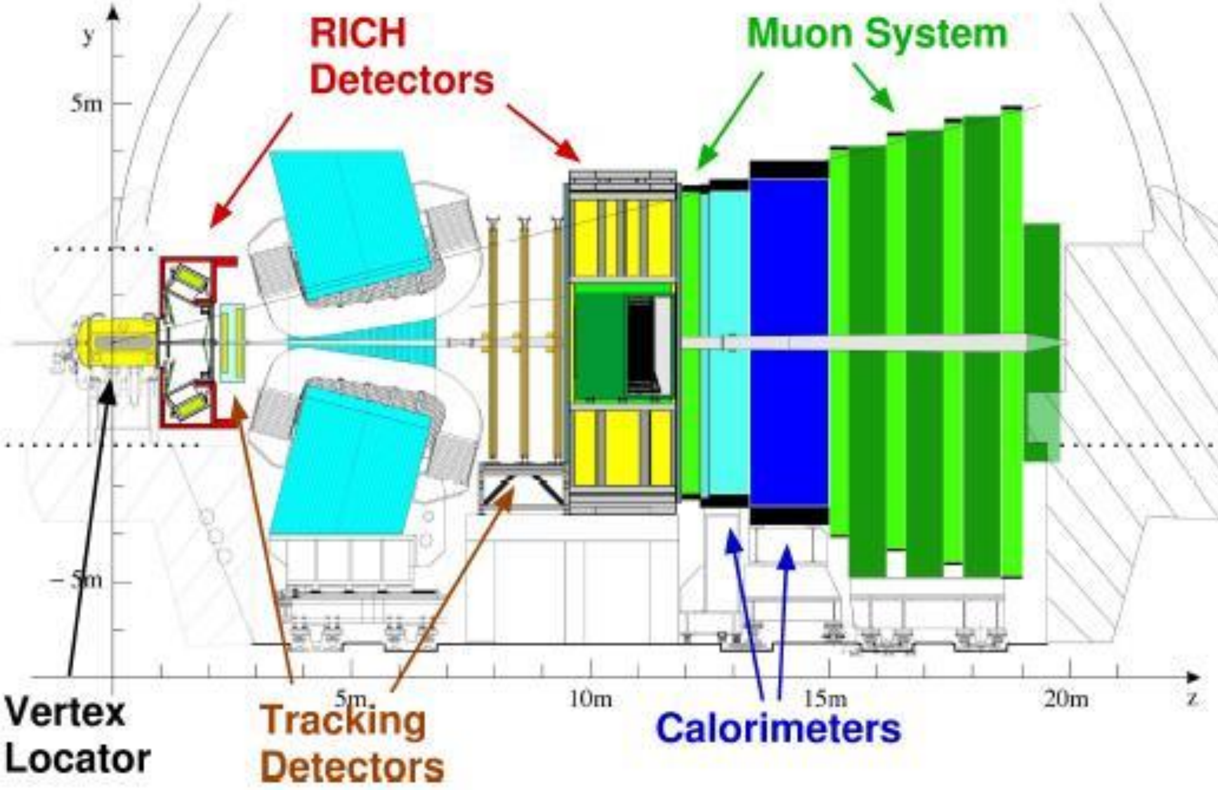
LHCb

optimized for b (and c) decays: emphasis on vertexing, p resolution, PID, trigger



but also a kaon factory: $\sim 10^{13}\ K^0_S$ per fb^{-1} within the acceptance,

$\sim 40\%$ decaying inside the vertex detector !

$K_S \to \mu^+\mu^-$

$K_S \to \mu\bar{\mu}$ **Ecker,Pich; Isidori, Unterdorfer**

- $A(K^0 \to l^+l^-) = \bar{u}_l(iB \; + \; A\gamma_5)v_l$
- $\Gamma(K_{L,S} \to \mu^+\mu^-) = \frac{m_K\ \beta_l}{8\pi}(|A|^2 \; + \; |B|^2)$ $\qquad \beta = \sqrt{1 - \frac{4m_\mu^2}{m_K^2}}$
- Short distance: **ONLY CP Violating from A**
- SM $B(K_S \to \mu\bar{\mu})_{SD} = 1 \times 10^{-5}|\Im(V_{ts}^* V_{td})|^2 \sim 10^{-13}$; NP $\sim 10^{-11}$ allowed;
- LD VERY ACCURATE 5×10^{-12}, error from expt $B(K_S \to \gamma\gamma)$
- LHCB $B(K_S \to \mu\bar{\mu}) < 11 \times 10^{-9}$ at 95% CL after 40 years

Kaons?

K experiments **complementary** to proton experiments (LHC)
after all Higgs (or his lookalike) is the source of flavour effects…

Measured BRs and sensitivities in the **10^{-12}** BR range

New Physics might already be there: ε_K? ε'/ε ?
Only Lattice knows… (at least LQCD *can* be done…)

From discovery tool to **quantitative probe** (CKM) field…

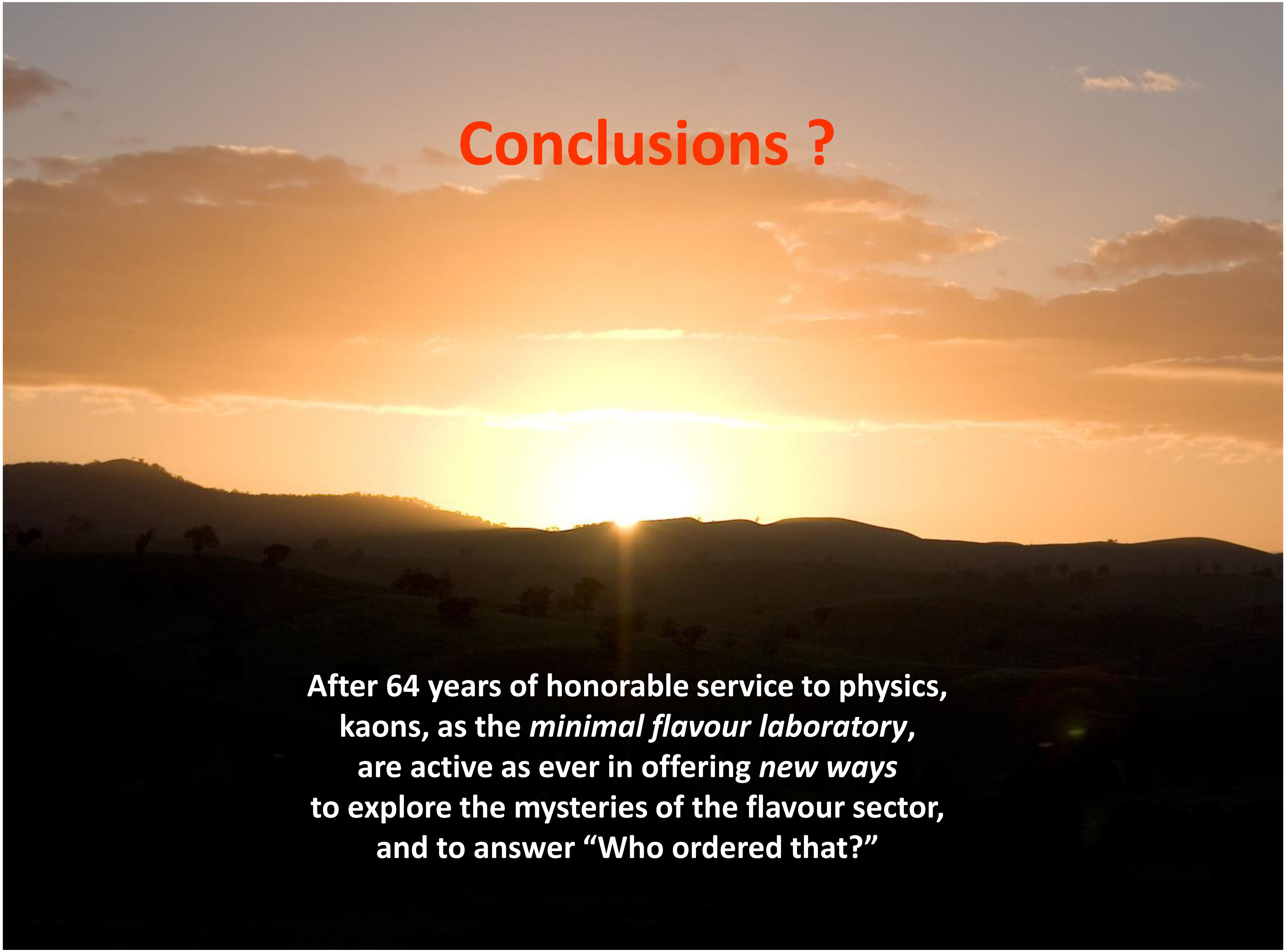
… working even beyond the SM: ultra-rare K decays are the holy grail

Effects seen with **10s of kW**, need **100s of kW** now

(and improved $|V_{cb}|$, $|V_{ub}|$ would help)

Kaons!

A flourishing of **challenging computations**
and **ultra-challenging experimental enterprises**



Conclusions ?

After 64 years of honorable service to physics,
kaons, as the *minimal flavour laboratory*,
are active as ever in offering *new ways*
to explore the mysteries of the flavour sector,
and to answer “Who ordered that?”


KAON FEVER
THERE IS NO CURE