Experimental tests of charged Lepton Flavor Violation (cLFV) with μ beams as one of the precision frontiers

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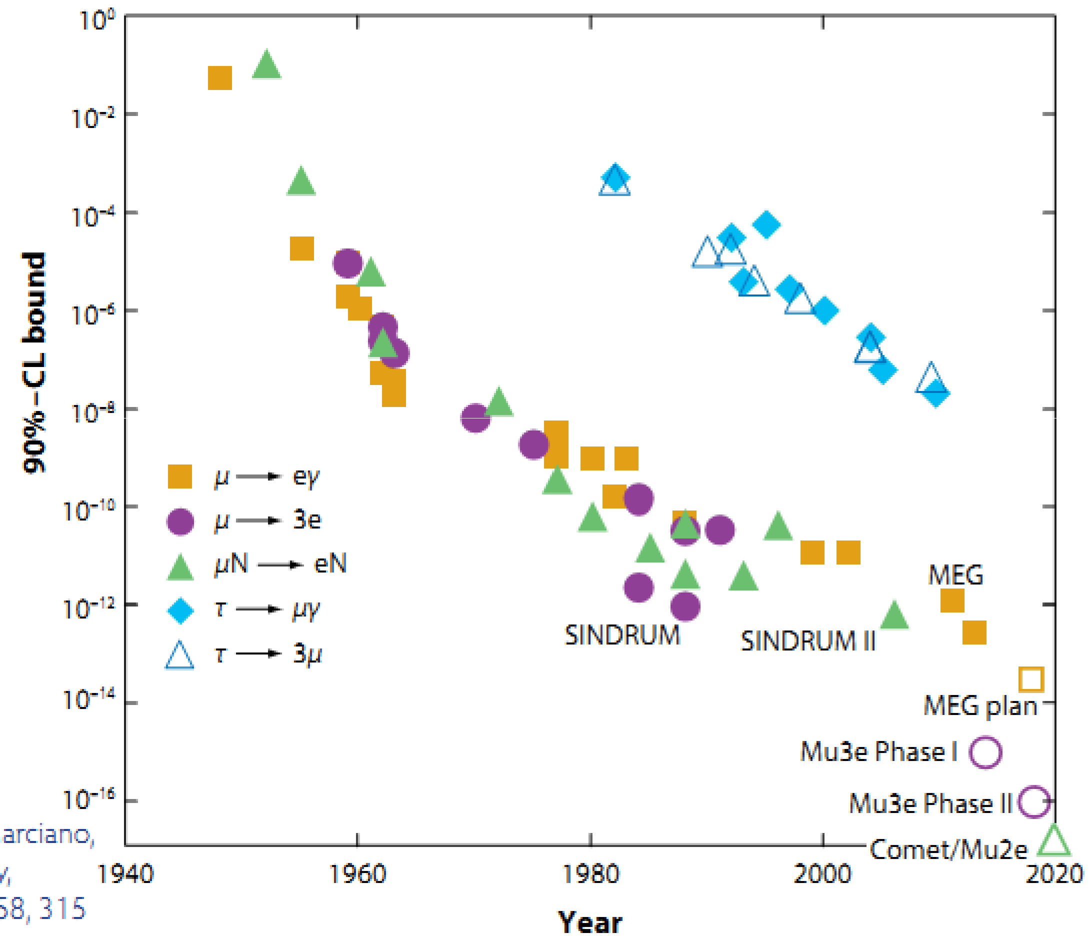
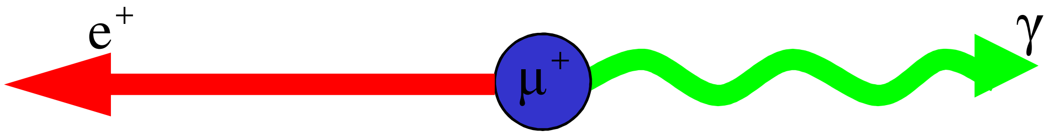
History of LFV experiments



(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

Muon decay at rest



$$E_e = E_\gamma = m_\mu c^2/2 = 52.8\,\mathrm{MeV}$$
$$\vec{p}_e = -\vec{p}_\gamma$$
$$t_e = t_\gamma$$

⇒Energy (E_e , E_γ)

⇒direction (Δθ)

⇒ Time (Δt)

First experiment: B.Pontecorvo and E.P.Hincks, PR 73 (1948) 257

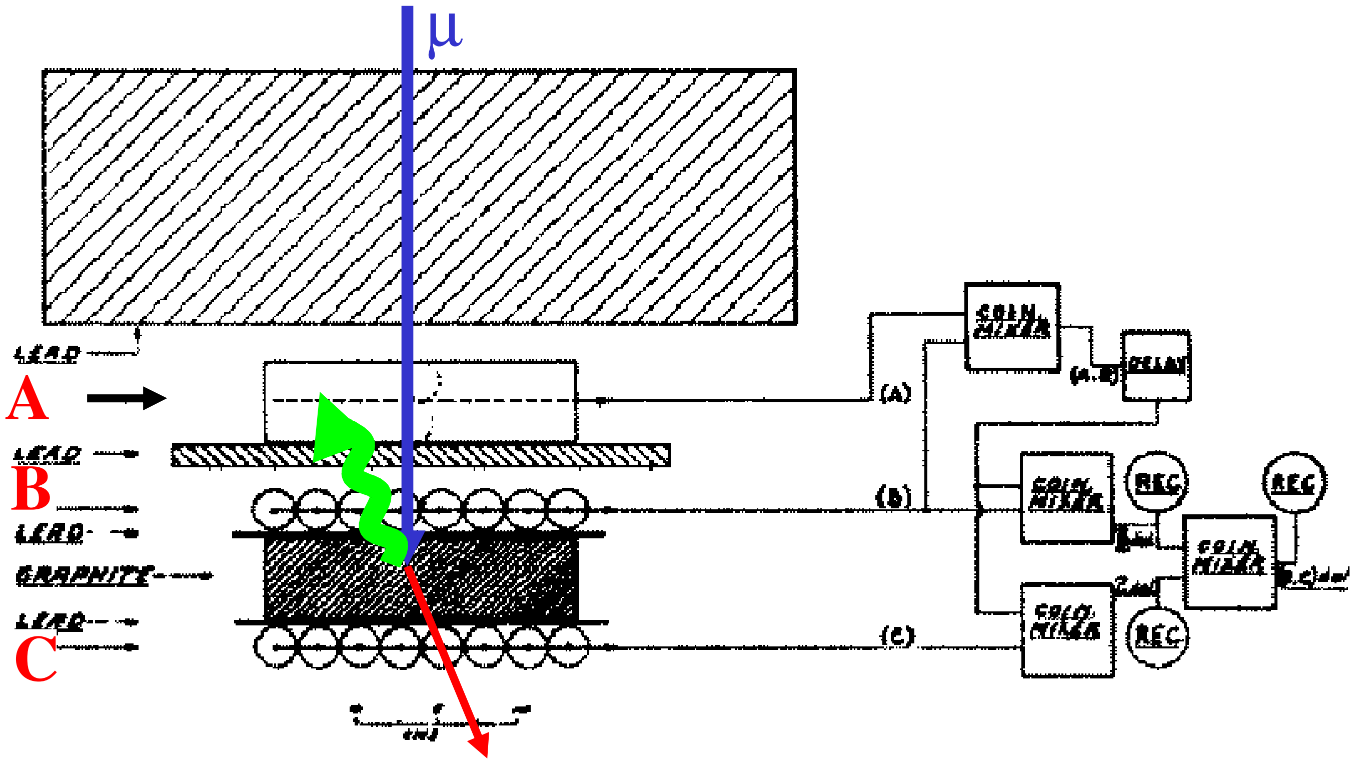
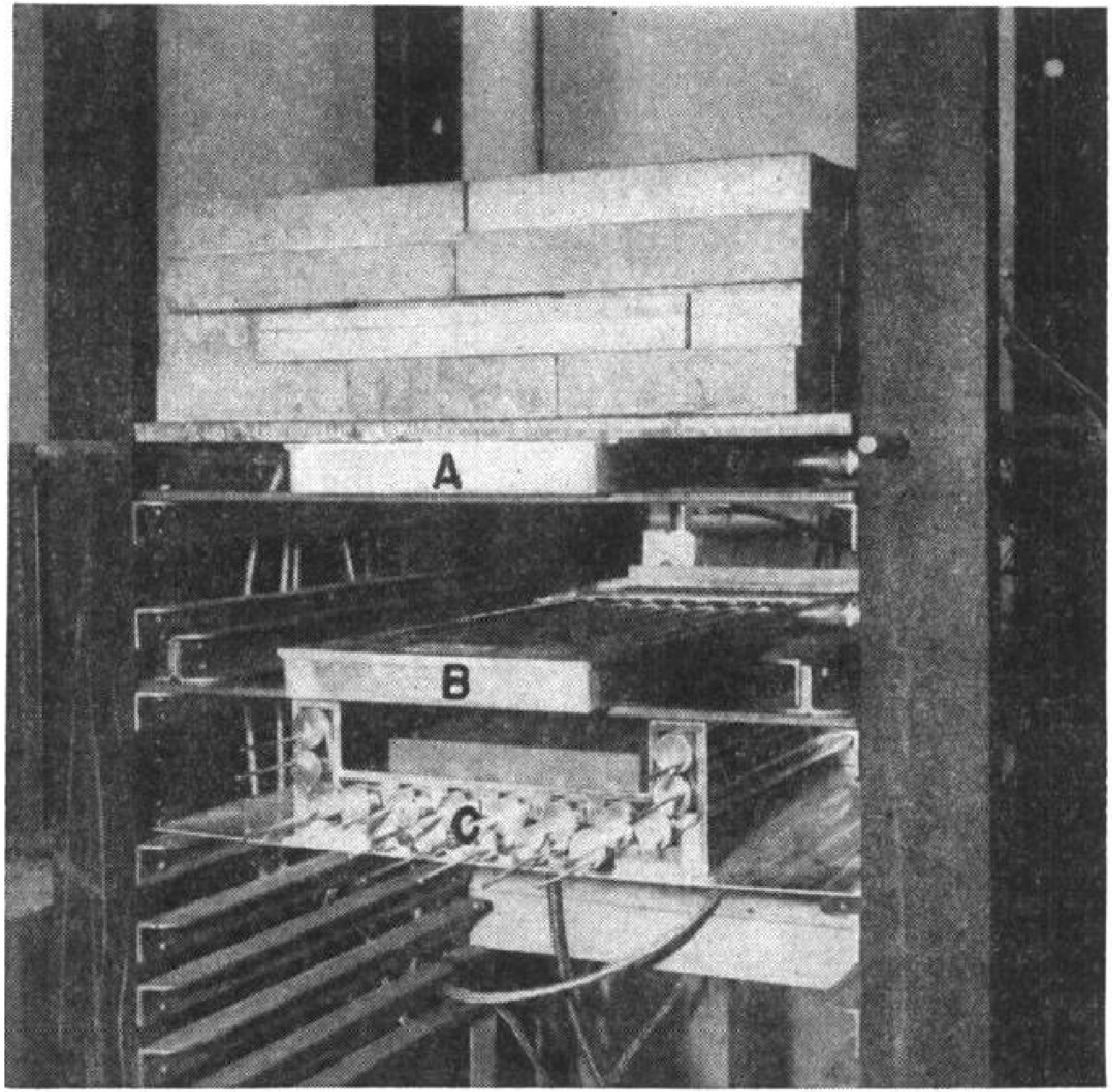


FIGURE 1 - ARRANGEMENT OF APPARATUS

$$\mu = A \bullet B$$

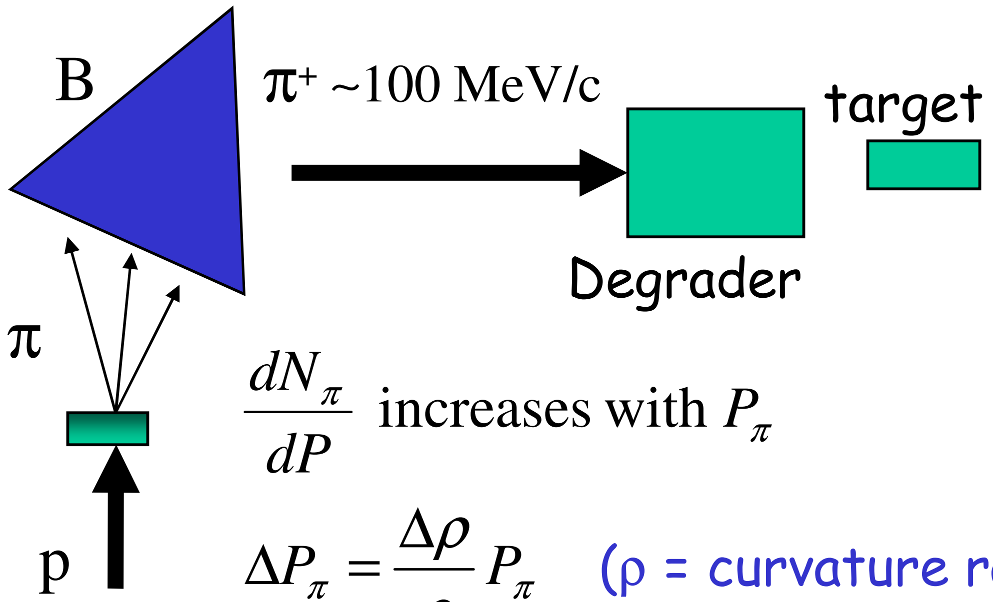
$$e\gamma = B \bullet C_{ritardato} \;(0.6\mu s < \Delta t < 5.3\mu s)$$



The apparatus used by Pontecorvo and Hincks in 1948

$BR < 10\%$ (90% CL)

The following experiments were performed with π^+ beams

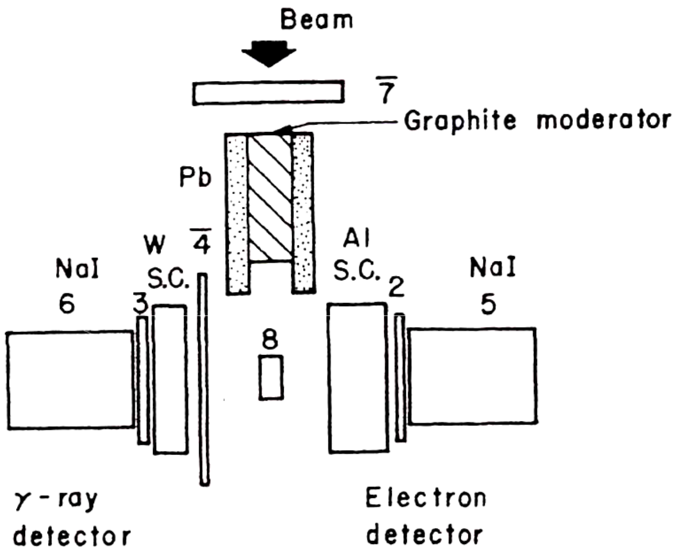


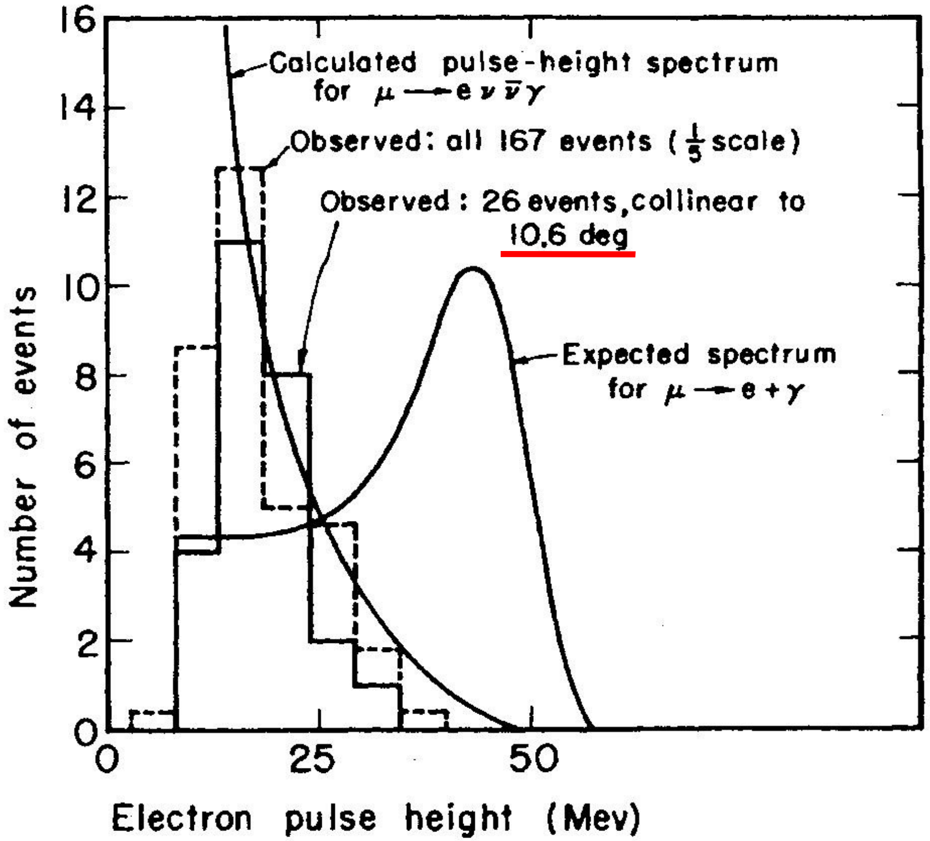
Needs a thick target (π straggling)

$$\frac{dN_\pi}{dP} \text{ increases with } P_\pi$$

$$\Delta P_\pi = \frac{\Delta\rho}{\rho} P_\pi$$ (ρ = curvature radius in B)

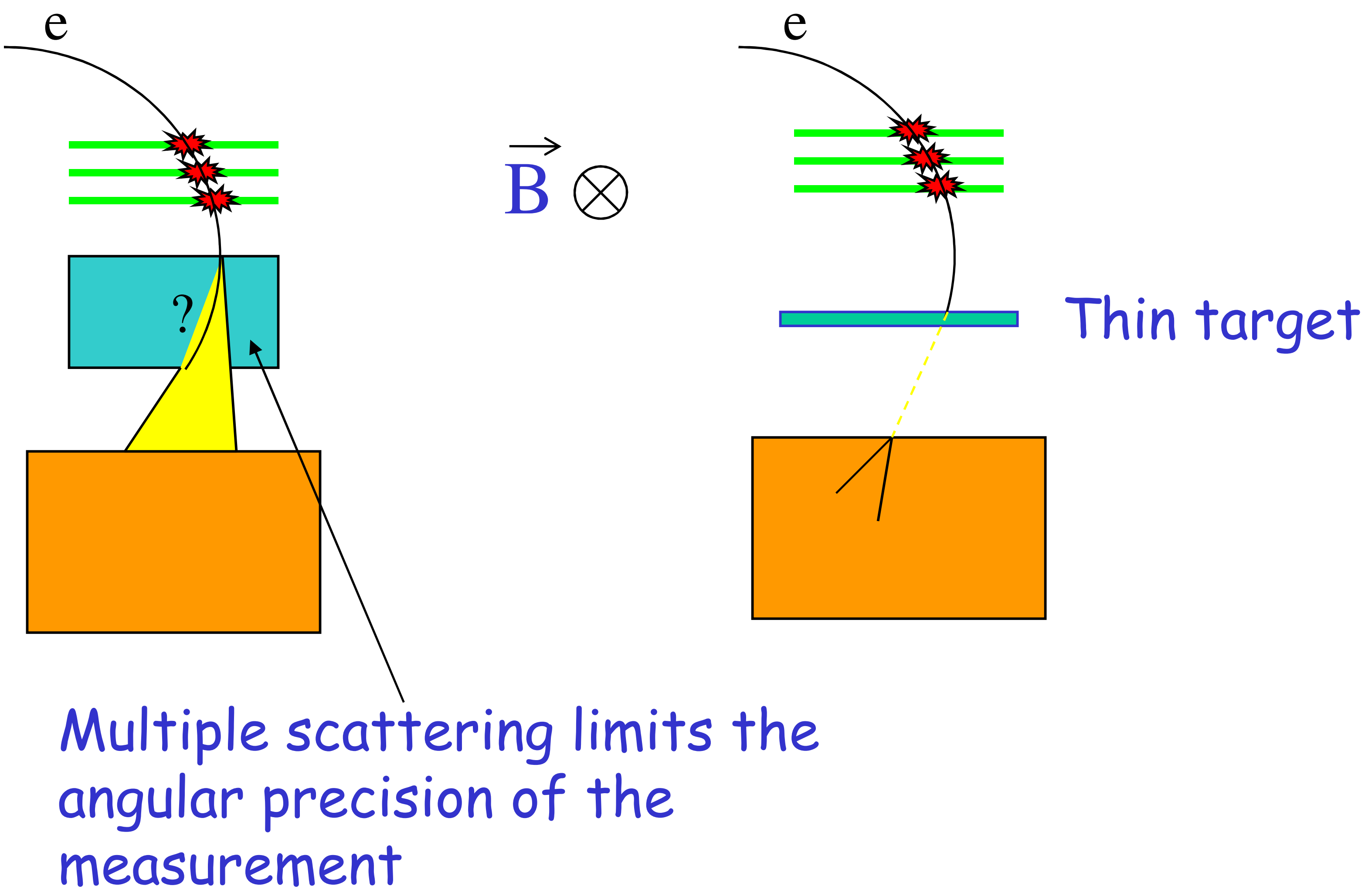
Frankel et al., PRL 8(1962) 123



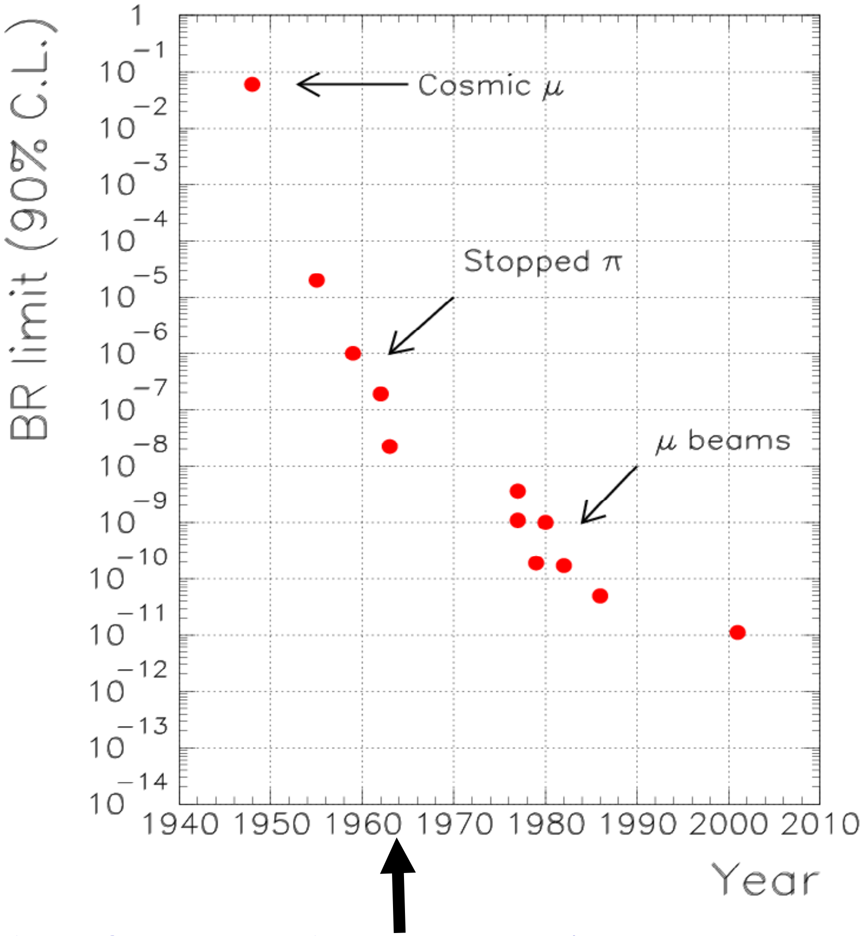


$$BR < 10^{-8} (90\% \ CL)$$

Surface muon beams: monochromatic low momentum muons (P_μ ~29 MeV/c) can be stopped in thin targets).



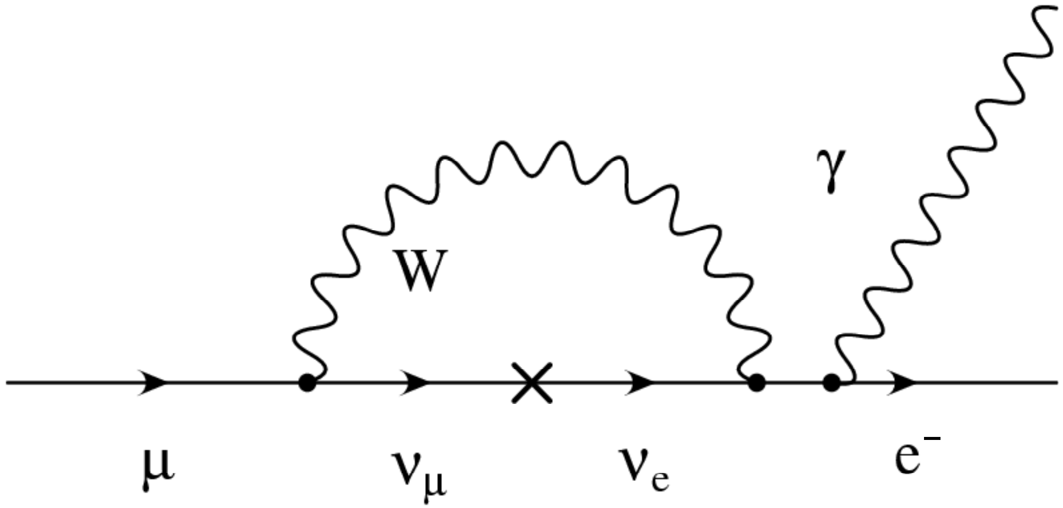
Upper limit vs year



2 different kinds of ν's: Lederman, Schwartz, Steinberger (driven by the absence of $\mu \to e\gamma$) G.Danby et al., PRL 9(1962) 36.

- The Standard Model (SM) of Particle Physics was built (also) on the basis of the absence of $\mu \rightarrow e\gamma$
- In the SM the difference between quarks and leptons (f.w.c the flavor conservation) is due to the zero mass of neutrinos
- $\mu \rightarrow e\gamma$ was however continued to be considered as "a natural theoretical possibility": Bjorken, Lane and Weinberg PRD 16(1977) 1474.
- Recently: ν oscillations (CKM ↔ PMNS) ...

$\mu \to e\gamma$ rate in the standard model



$$BR \sim \left(\frac{\delta m_\nu^2}{M_w^2}\right)^2 \; ; \delta m_\nu^2 \sim 10^{-5} eV^2 \Rightarrow BR \sim 10^{-54}$$

The SM predicts an unobservable rate→ very clean channel for new physics searches

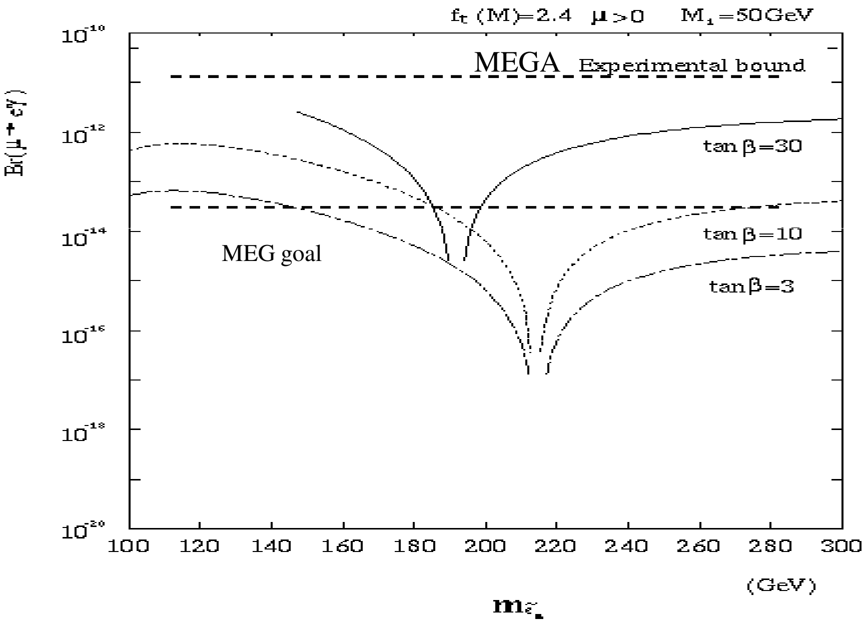
GUTs: quarks and leptons are deeply connected

- SUSY SU(5) predictions

Lepton Flavour Violation (LFV) induced by finite slepton mixing through radiative corrections

The mixing could be large due to the top-quark mass

$BR(\mu \to e\gamma) \approx 10^{-15} \div 10^{-13}$ in SU(5) (larger by ~30 order of magnitudes than SM predictions)



⇒ clear evidence for physics beyond the SM

R. Barbieri *e* L.J.Hall, PL B338(1994)212.

R. Barbieri *et al.*, Nucl. Phys. B445(1995) 215

J.Hisano et al., PL B391(1997) 341

Analisi combinate degli esperimenti a LEP favoriscono $\tan\beta > 10$

- SO(10) predicts even larger BR

$$\Gamma_{SO(10)}(\mu \to e\gamma) \approx \left(\frac{m_\tau}{m_\mu}\right)^2 \Gamma_{SU(5)}(\mu \to e\gamma) \approx 100\,\Gamma_{SU(5)}(\mu \to e\gamma)$$

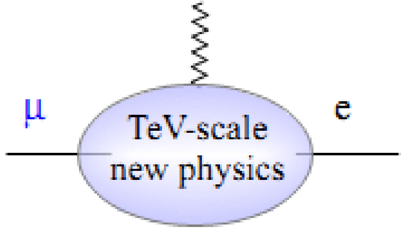
In non-GUT theories we can arbitrarily suppress LFV rates by lowering M_R (or the normalization of Y_n). This is not possible in GUT frameworks => contribution from quark Yukawas which are M_R-independent

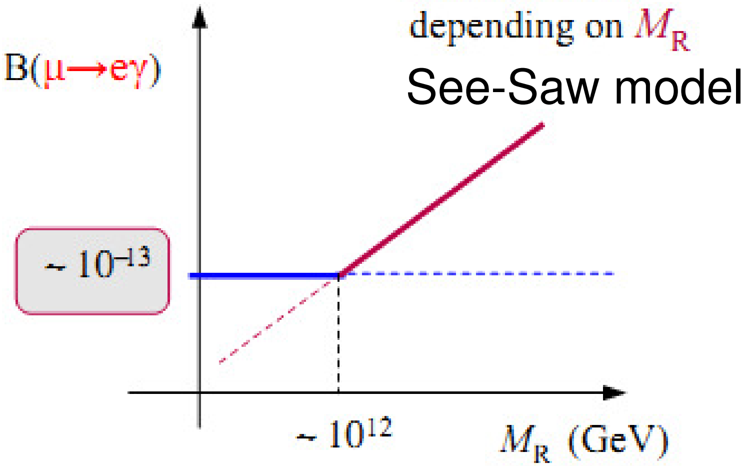
PMNS CKM

$$A(l_i \to l_j\,\gamma) = a\,[Y_e Y_n^+ Y_n]_{ij} + b\,[Y_U^+ Y_U Y_D]_{ij}$$

Normalization depending on M_R

M_R independent



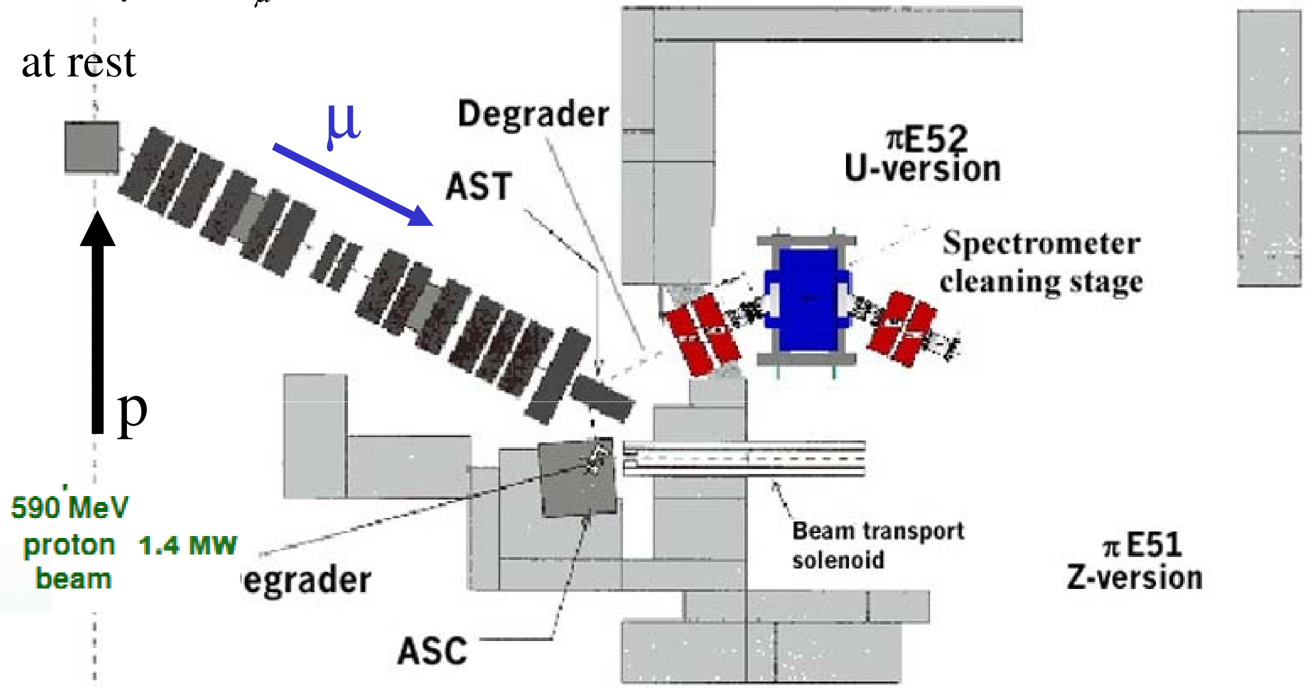


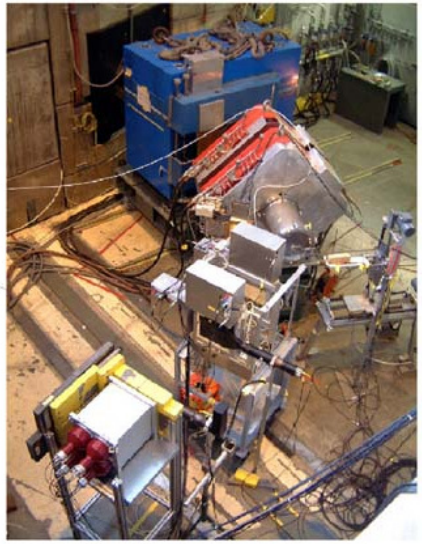
In GUT theories with new particles carrying lepton-flavor at the TeV scale (*e.g. the sleptons in the MSSM*)

MEG has high chances to see μ→eγ (*but remember that* $\Gamma \sim \Lambda^{-4}$)

Surface muon beams

$\pi \to \mu\nu$ $P_\mu \sim 29 MeV/c$



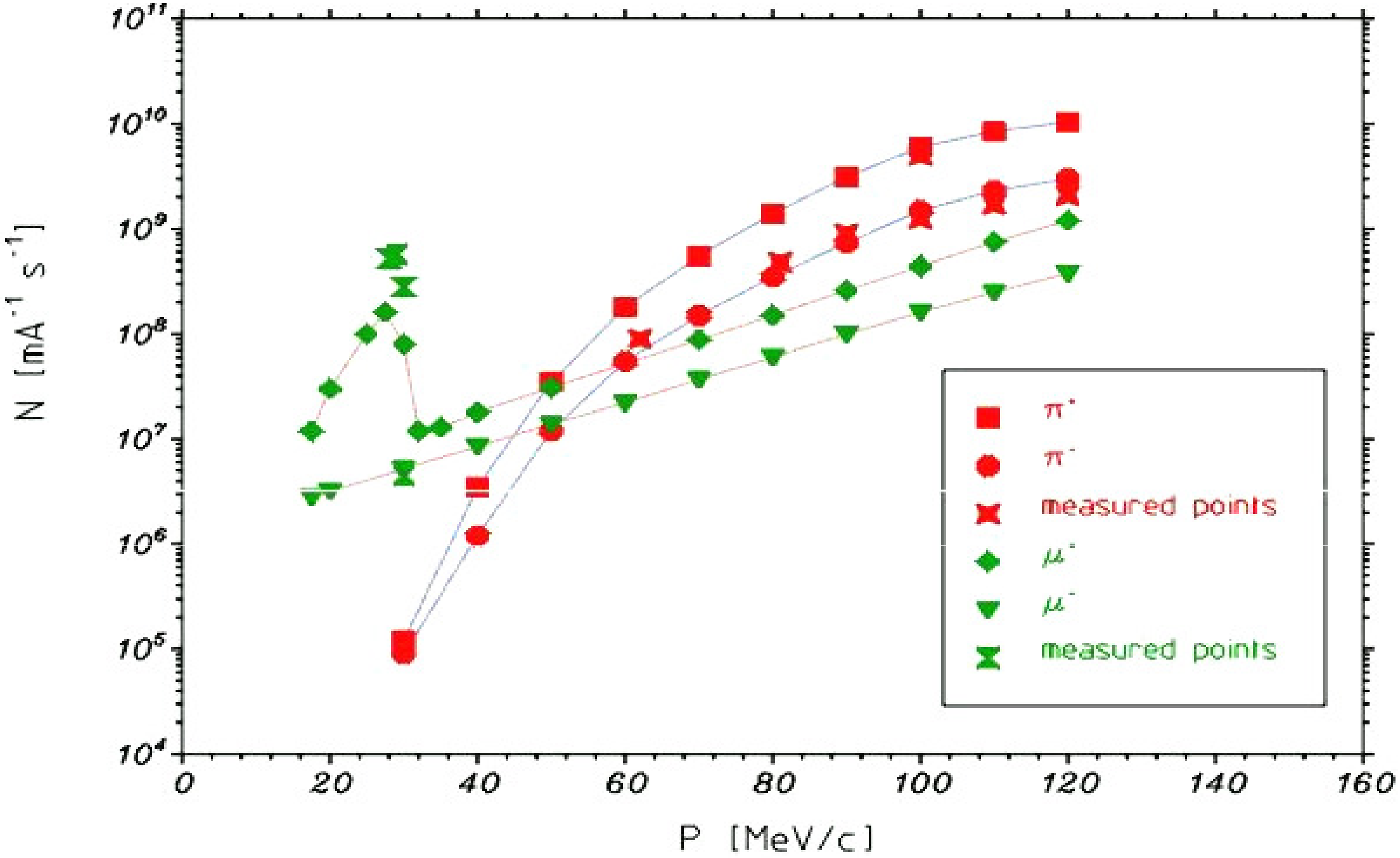


The layout of πE5

- μ^+ from decay at rest of π^+ on the target surface (the μ range is approx. .1 gr/cm^3): are totally polarized

- It is then possible to focalize and stop an intense μ beam in a thin target

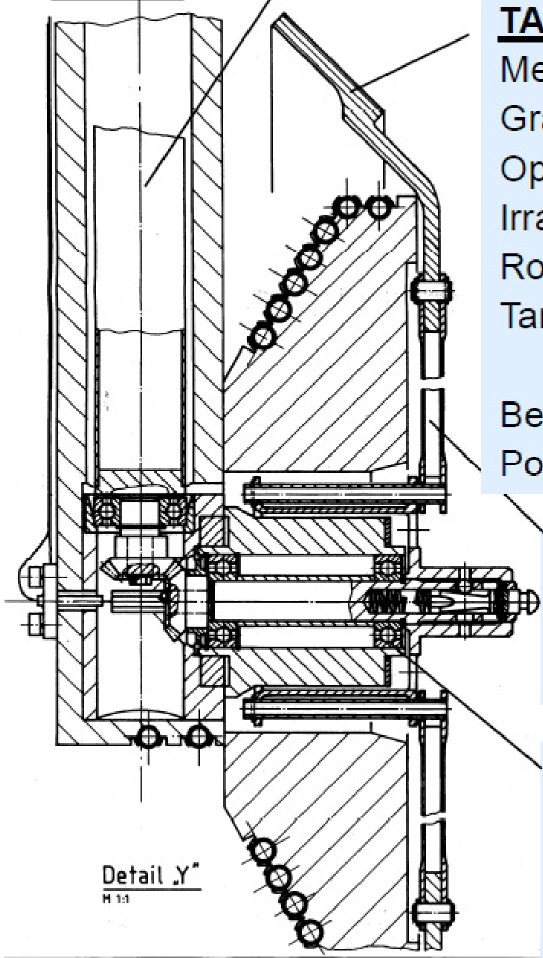
Momentum scan of the πe5 beam at PSI



- $R_{\mu\ stop} \approx 10^8 s^{-1}$ with a 10% e^+ contamination which can be eliminated by means of an elctrostatic separator

- 3 orders of magnitude higher than the previous muon stop rates + thin target

Target-E design



TARGET CONE

Mean diameter: 450 mm
Graphite density: 1.8 g/cm^3
Operating Temperature: 1700 K
Irradiation damage rate: 0.1 dpa/Ah
Rotational Speed: 1 Turn/s
Target thickness: 60 / 40 mm
10 / 7 g/cm^2
Beam loss: 18 / 12 %
Power deposition: 30 / 20 kW/mA

SPOKES

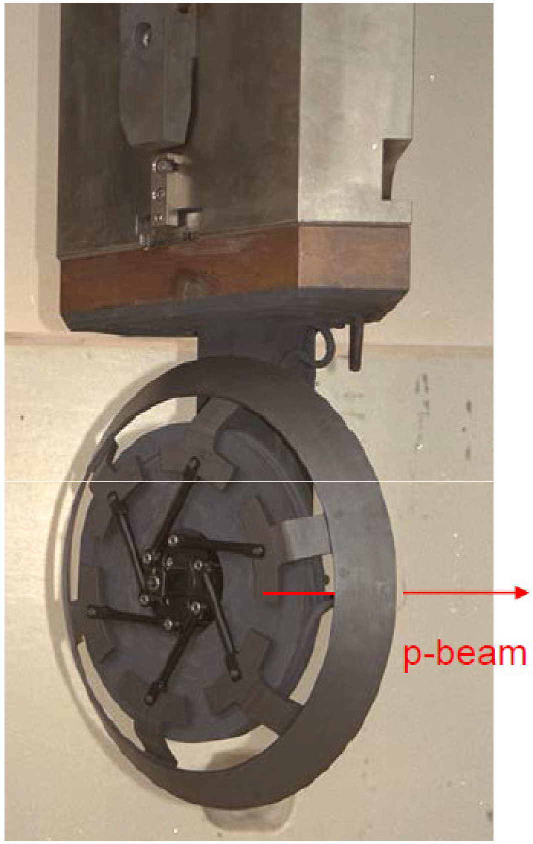
To enable the thermal expansion of the target cone

BALL BEARINGS *)

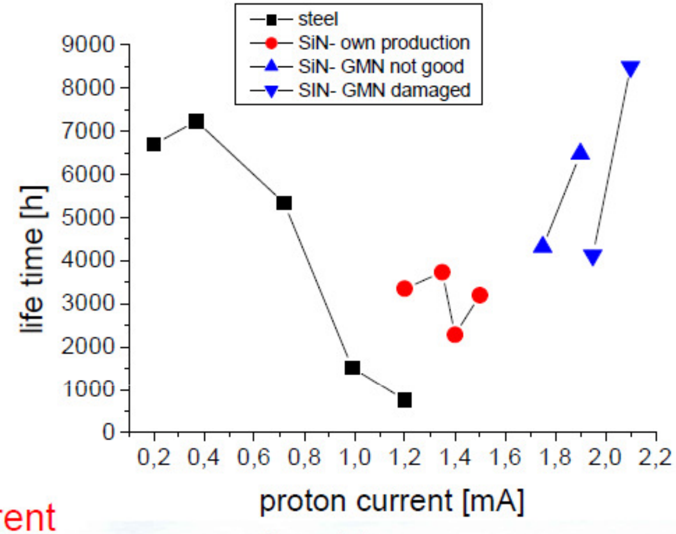
Silicon nitride balls, coated with MoS2

Rings and cage silver coated

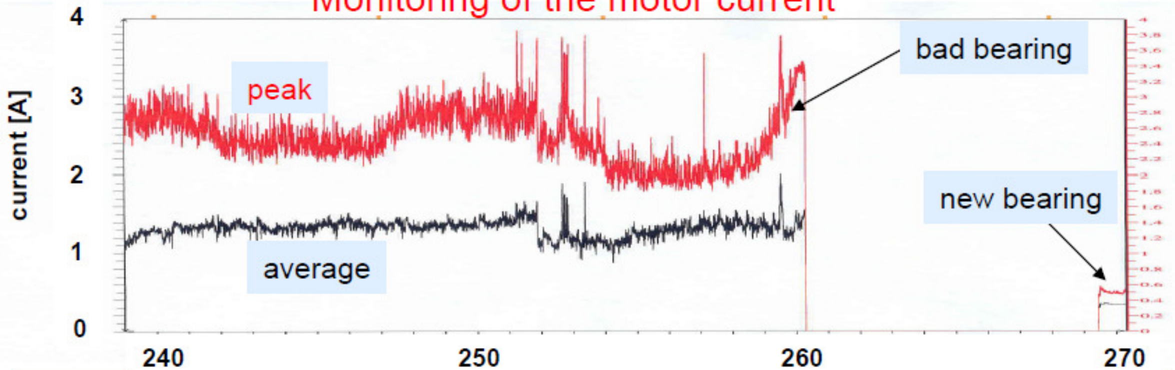
*) GMN, Nürnberg, Germany



Life time of the ball bearings



Monitoring of the motor current



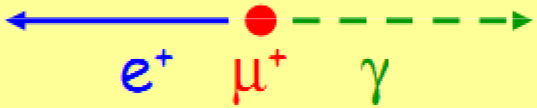
interlock at 5 A
= 40 Nm

muSR Workshop at FNAL Oct 17-19, 2012, Daniela Kiselev, Paul Scherrer Institut

Signal and background

signal

$\mu \rightarrow e\,\gamma$



$\theta_{e\gamma} = 180°$

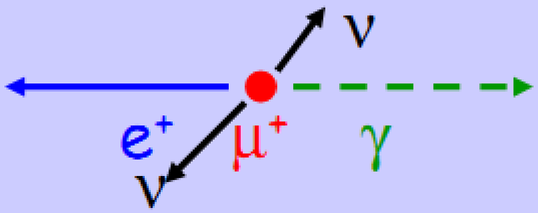
$E_e = E_\gamma = 52.8$ MeV

$T_e = T_\gamma$

background

physical

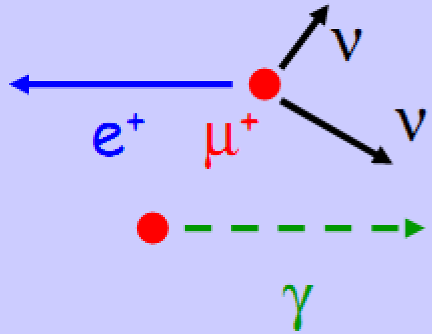
$\mu \rightarrow e\,\gamma\,\nu\,\nu$



accidental

$\mu \rightarrow e\,\nu\,\nu$

$$\left\{\begin{array}{l} \mu \rightarrow e\,\gamma\,\nu\,\nu \\ ee \rightarrow \gamma\,\gamma \\ eZ \rightarrow eZ\,\gamma \end{array}\right.$$



The sensitivity is limited by the accidental background

$$n_{sig} \propto R_\mu \; , n_{phys.b.} \propto R_\mu \; , \; n_{acc.b.} \propto R_\mu^2$$

The n. of acc. backg events ($n_{acc.b.}$) depends quadratically on the muon rateand on how well we measure the experimental quantities: e-γ relative timing and angle, positron and photon energy

Effective BRback (n_{back}/Rμ T)

$$BR_{acc} \propto \; R_\mu \times \; \Delta t_{e\gamma} \times \Delta\theta_{e\gamma}^2 \times \Delta E_e \times \Delta E_\gamma^2$$

Integral on the detector resolutions of the Michel and radiative decay spectra

Required Performances

BR ($\mu \to e\gamma$) ≈ 10^{-13} reachable

BRacc.b. ≈ 2 10^{-14} and BRphys.b. ≈ 0.1 BRacc.b. with the following resolutions

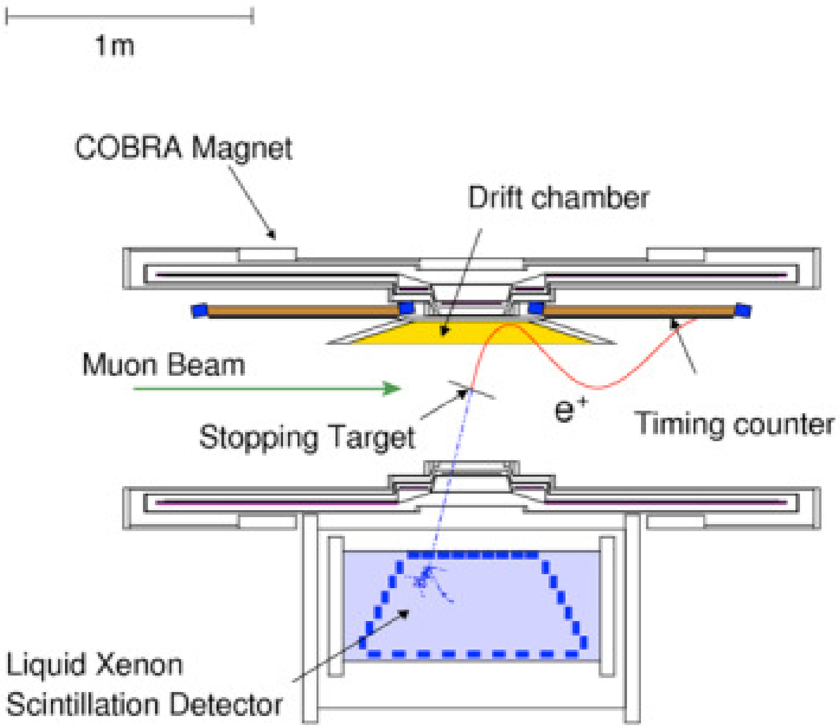
FWHM

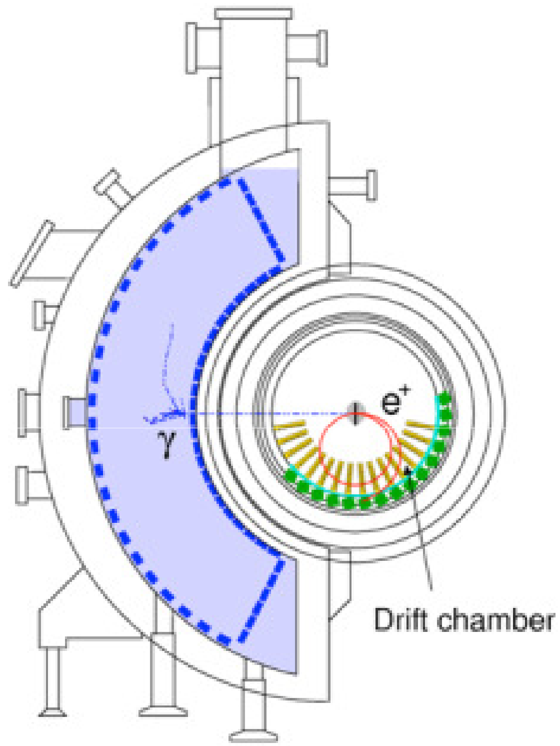
Exp./Lab	Year	$\Delta E_e/E_e$ (%)	$\Delta E_\gamma/E_\gamma$ (%)	$\Delta t_{e\gamma}$ (ns)	$\Delta\theta_{e\gamma}$ (mrad)	Stop rate (s^{-1})	Duty cyc.(%)	BR (90% CL)
SIN	1977	8.7	9.3	1.4	-	5 x 10^5	100	3.6 x 10^{-9}
TRIUMF	1977	10	8.7	6.7	-	2 x 10^5	100	1 x 10^{-9}
LANL	1979	8.8	8	1.9	37	2.4 x 10^5	6.4	1.7 x 10^{-10}
Crystal Box	1986	8	8	1.3	87	4 x 10^5	(6..9)	4.9 x 10^{-11}
MEGA	1999	1.2	4.5	1.6	17	2.5 x 10^8	(6..7)	1.2 x 10^{-11}
MEG	2009	0.8	4	0.15	19	2.5 x 10^7	100	1 x 10^{-13}

Need of a DC muon beam

MEG detector

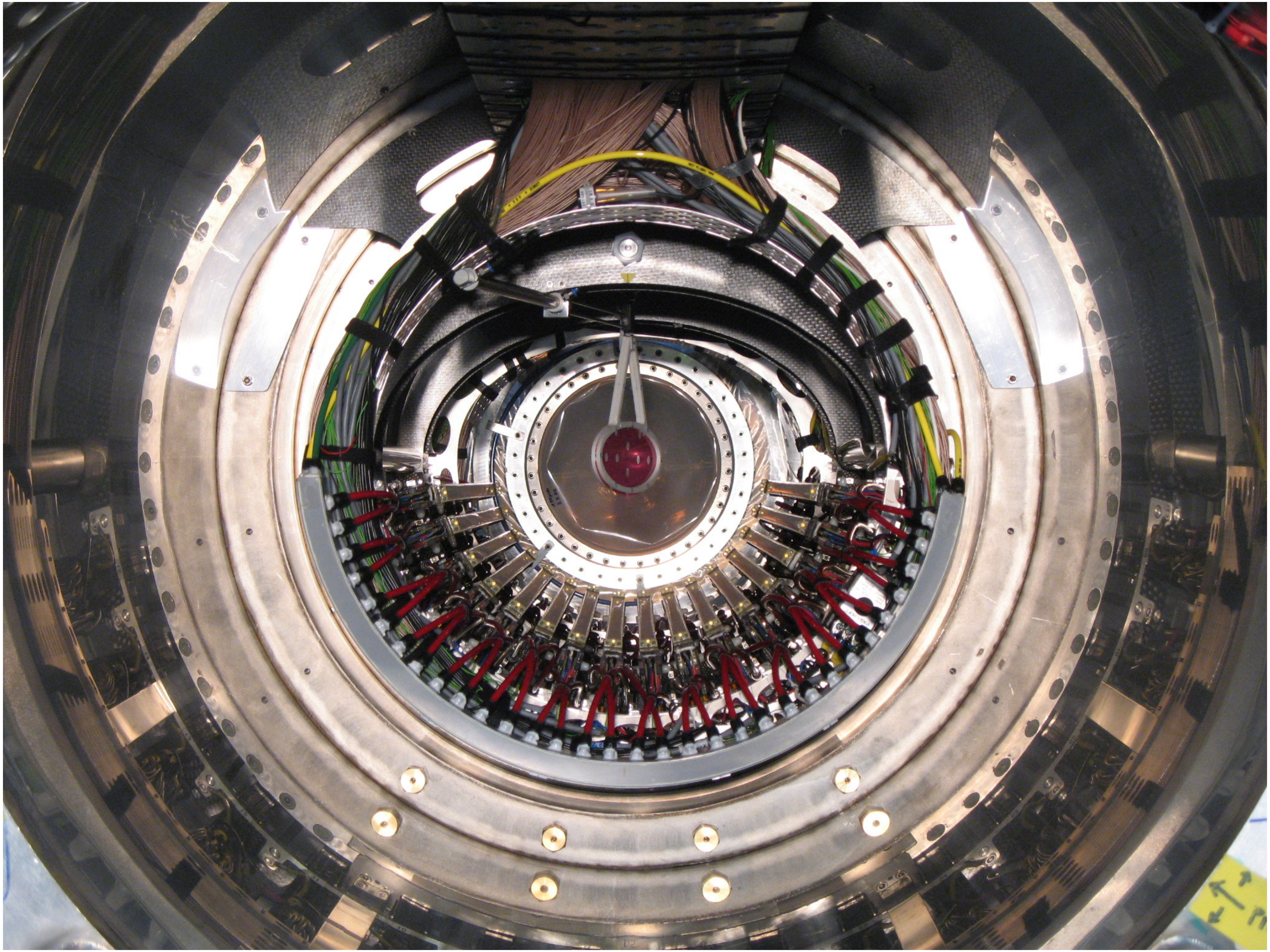
PSI in Switzerland





- Liquid Xe e.m. detector $\rightarrow (E_\gamma, \vec{p}_\gamma / E_\gamma, t_\gamma)$
- Magnetic spectrometer $\rightarrow \vec{p}_e$
- Timing counter $\rightarrow t_e$

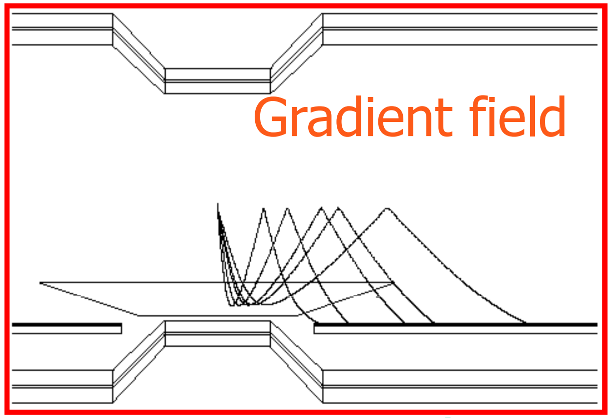
Eur. Phys. J. C, 73 (2013) 2365 .

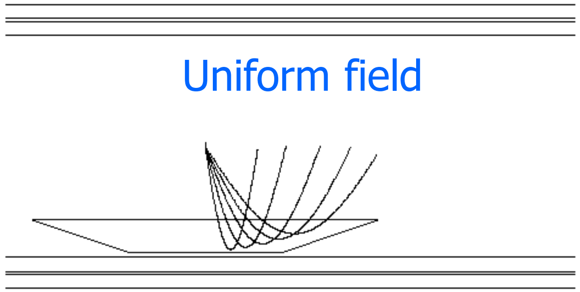


COBRA spectrometer

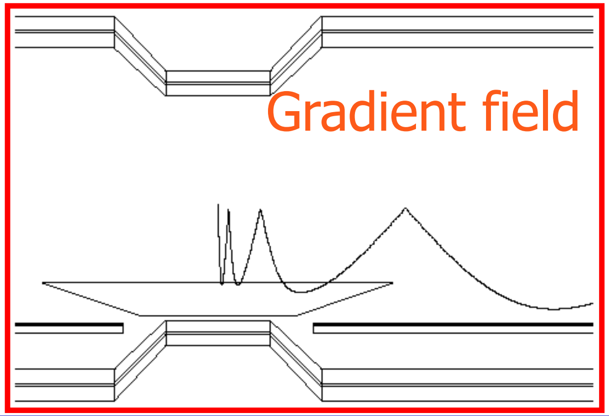
COnstant Bending RAdius (COBRA) spectrometer

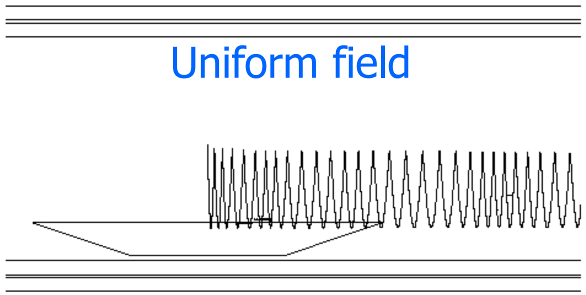
- Constant bending radius independent of emission angles





- Low energy positrons quickly swept out



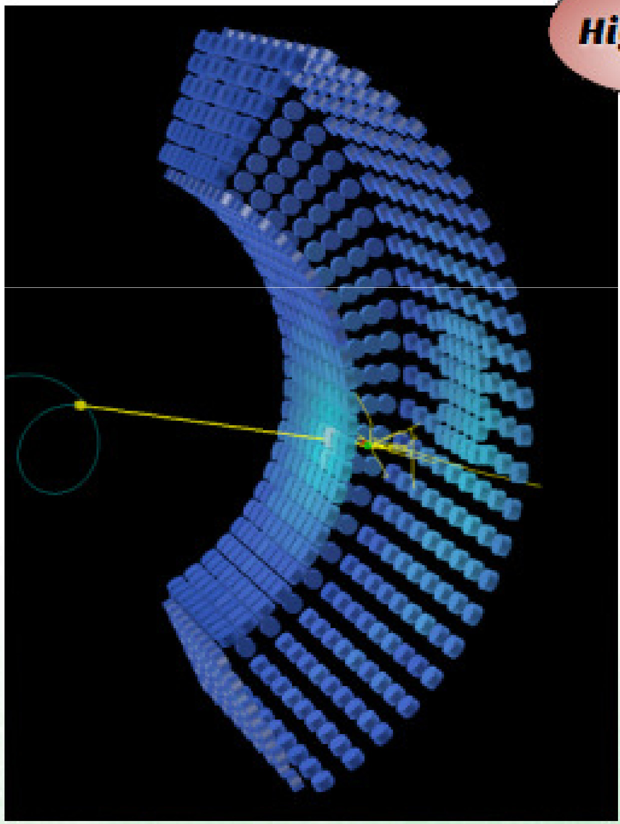


2.7t Liquid xenon gamma-ray detector

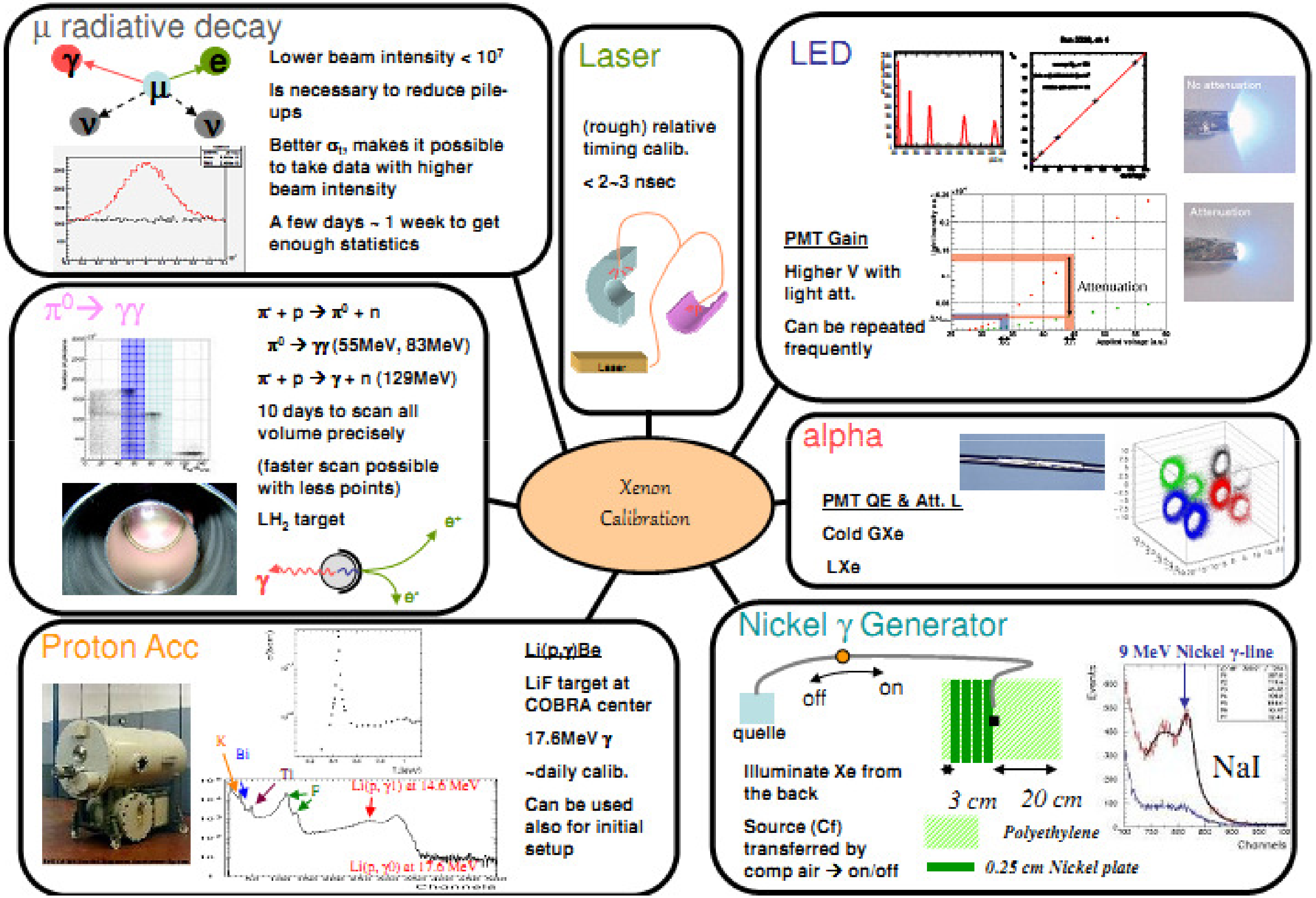
- γ measurement with high resolutions and efficiency in a large acceptance
- Pileup elimination in offline analysis

Resolution Efficiency

High rate



- 900L liquid xenon
- 846 2" PMTs (Hamamatsu)
  - Submerged in Liquid
- γ energy, position, and timing reconstruction
- Merits
  - High light output(80% of NaI)
  - Fast timing response(45ns)
  - Heavy(3g/cm^3)
- Challenges
  - Low temperature(160K)
    - 200W pulse tube cryocooler
  - Short scintillation wavelength (175nm)
  - Gas/liquid purification


μ radiative decay
Lower beam intensity < 10^7
Is necessary to reduce pile-ups
Better σ_t, makes it possible to take data with higher beam intensity
A few days ~ 1 week to get enough statistics
Laser
(rough) relative timing calib.
< 2~3 nsec
Laser
LED
No attenuation
Attenuation
PMT Gain
Higher V with light att.
Can be repeated frequently
Attenuation
π0→ γγ
π⁻ + p → π0 + n
π0 → γγ (55MeV, 83MeV)
π⁻ + p → γ + n (129MeV)
10 days to scan all volume precisely
(faster scan possible with less points)
LH2 target
γ
e+
e-
Xenon
Calibration
alpha
PMT QE & Att. L
Cold GXe
LXe
Proton Acc
Li(p,γ)Be
LiF target at COBRA center
17.6MeV γ
~daily calib.
Can be used also for initial setup
K
Bi
Tl
F
Li(p, γ1) at 14.6 MeV
Li(p, γ0) at 17.6 MeV
Channels
Nickel γ Generator
off
on
quelle
Illuminate Xe from the back
Source (Cf) transferred by comp air → on/off
3 cm
20 cm
Polyethylene
0.25 cm Nickel plate
9 MeV Nickel γ-line
NaI
Events
Channels

Calibration and monitoring

PMT

LED
Alpha source (5.5 MeV)

Energy

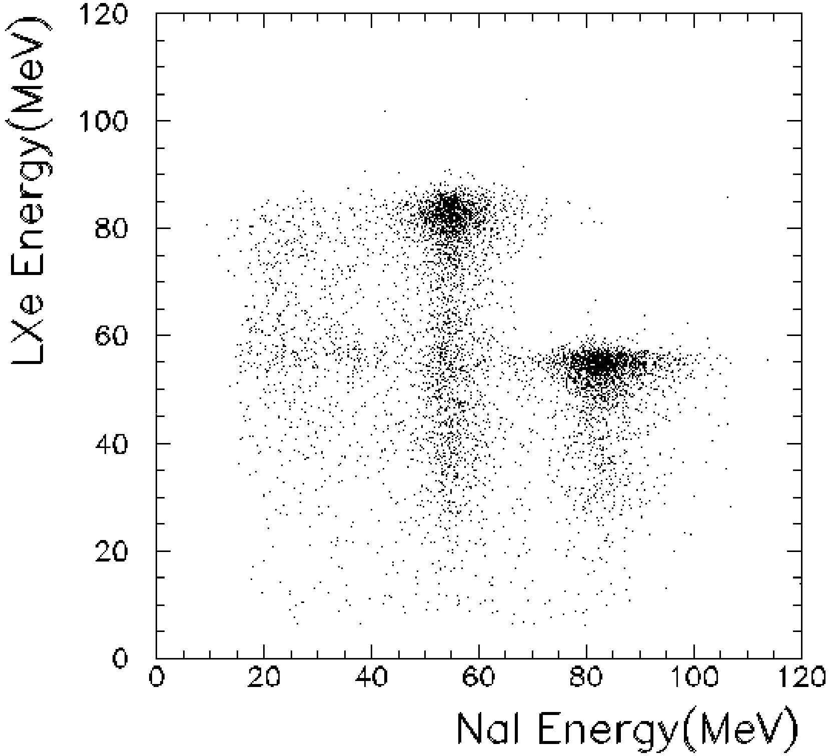
AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
$\pi 0 \rightarrow \gamma\gamma$ (55, 83 MeV)
Cosmic ray (160 MeV)

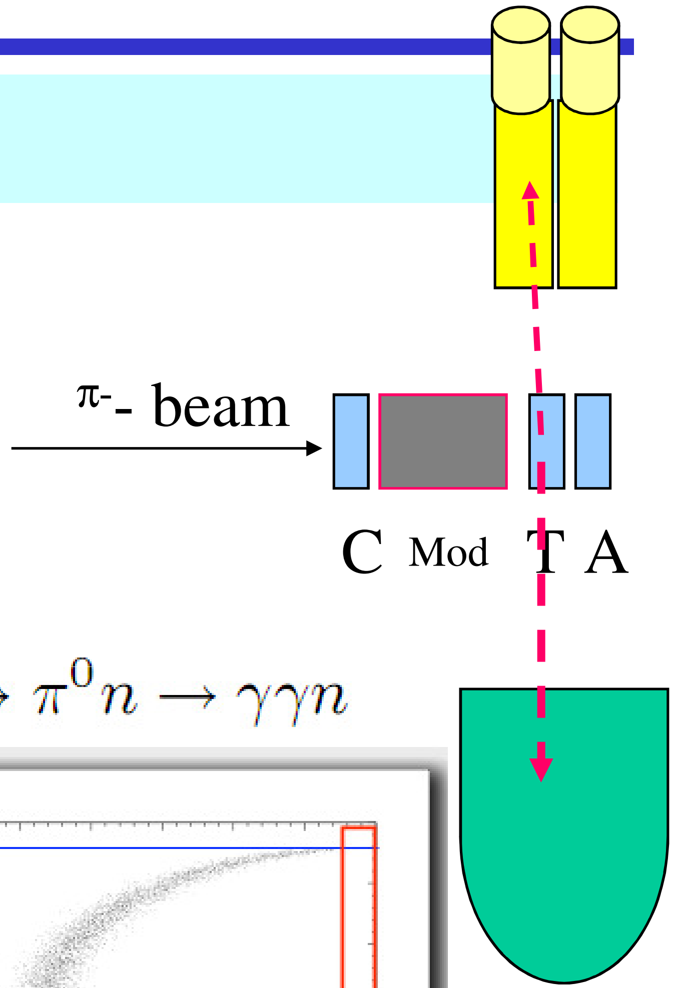
Time

B(p,γ) (4.4+11.7 MeV)
$\pi 0 \rightarrow e^+ e \gamma$ (55-83 MeV)
Muon radiative decay

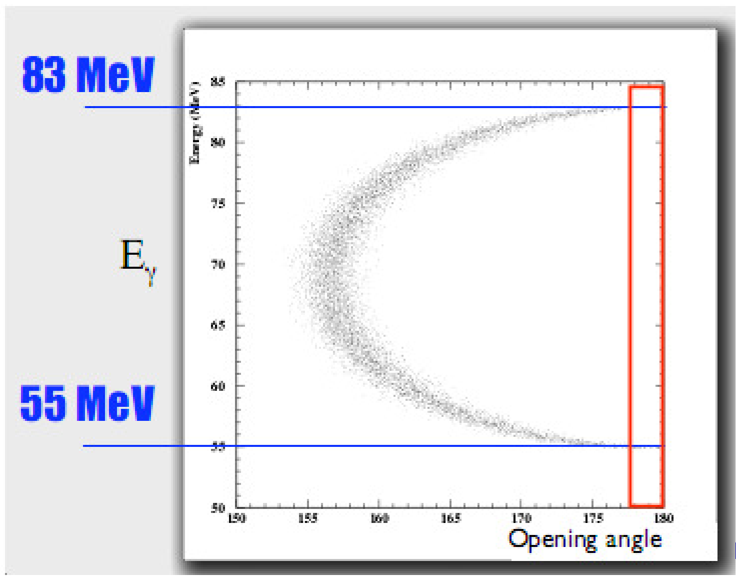
Process		Energy (MeV)	Frequency
Charge exchange	$\pi^- p \rightarrow \pi^0 n$	54.9, 82.9	yearly
	$\pi^0 \rightarrow \gamma\gamma$		
Charge exchange	$\pi^- p \rightarrow n\gamma$	129.0	yearly
Radiative μ^+ decay	$\mu^+ \rightarrow e^+ \gamma\nu\nu$	52.83 endpoint	weekly
Proton accelerator	$^7\mathrm{Li}(p, \gamma_{17.6(14.8)})^8\mathrm{Be}$	14.8, 17.6	weekly
	$^{11}\mathrm{B}(p, \gamma_{4.4}\gamma_{11.6})^{12}\mathrm{C}$	4.4, 11.6	weekly
Nuclear reaction	$^{58}\mathrm{Ni}(n, \gamma_{9.0})^{59}\mathrm{Ni}$	9.0	daily
AmBe source	$^9\mathrm{Be}(\alpha_{^{241}\mathrm{Am}}, n)^{12}\mathrm{C}_*$	4.4	daily
	$^{12}\mathrm{C}_* \rightarrow {}^{12}\mathrm{C}\gamma_{4.4}$		

LXe vs NaI



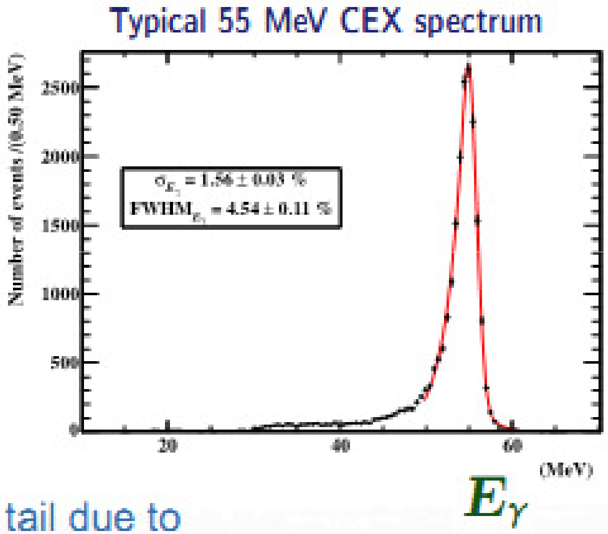


$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$$



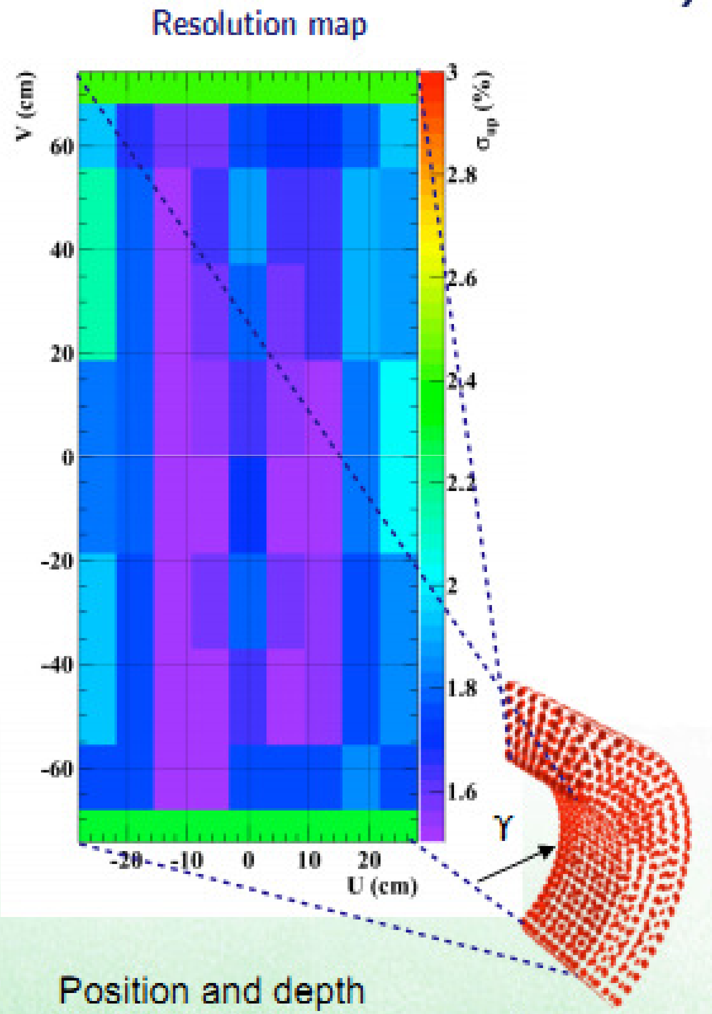
Energy resolution

Measured using 55 MeV CEX gamma rays



Lower tail due to

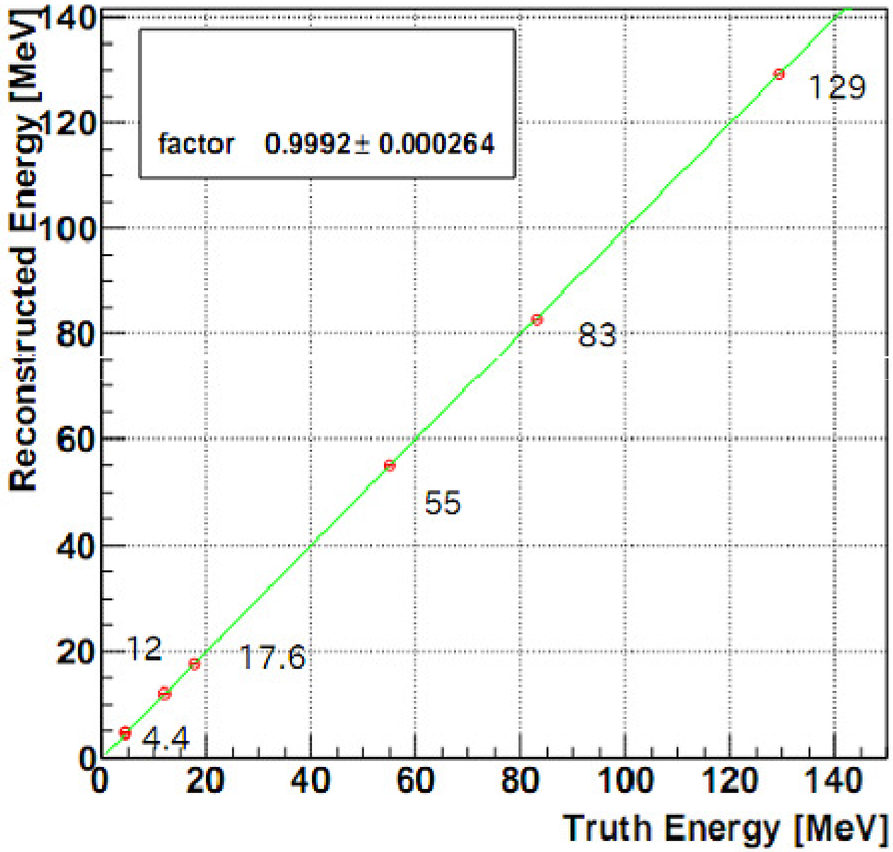
- Energy deposit in material before entering LXe (Magnet, cryostat, PMT holder etc.)
- Energy escape from LXe



Average resolutions
1.7% (depth>2cm), 2.4% (depth<2cm)

Position and depth dependences are measured

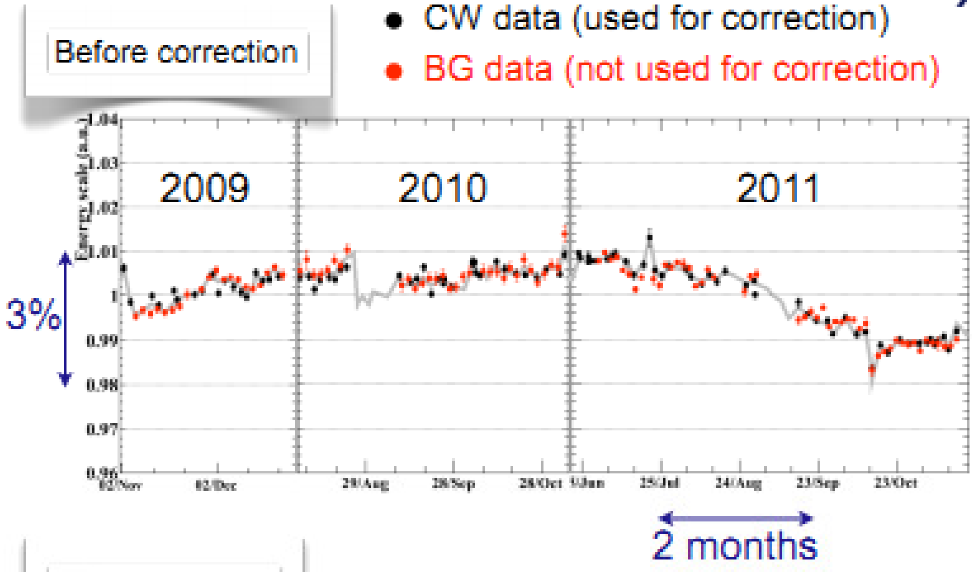
Linearity

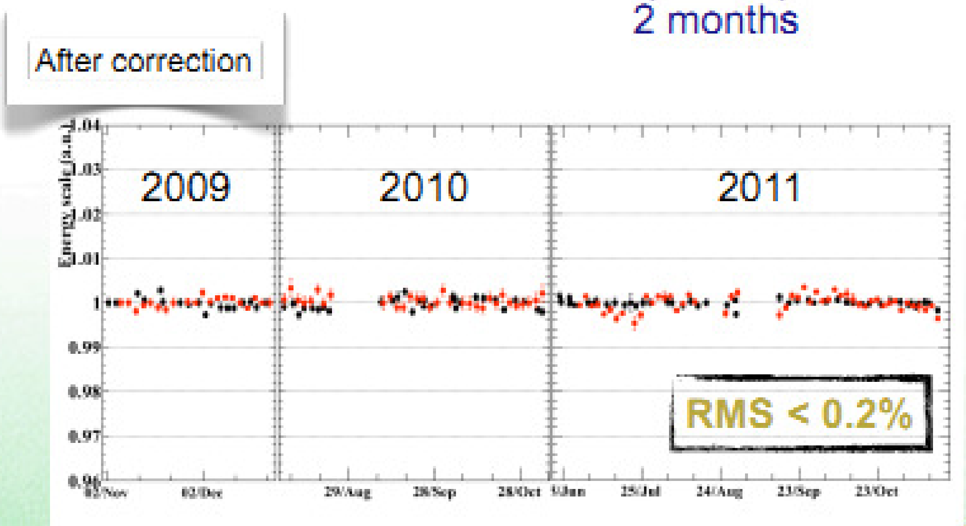


16/Feb/2011

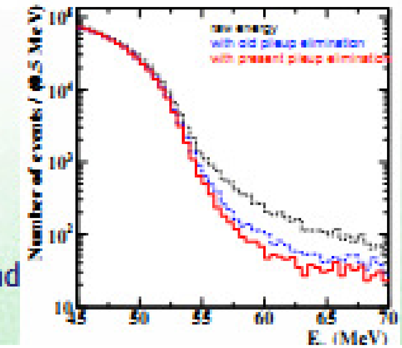
Energy Scale Stability

- Absolute scale calibration
  - 55 MeV CEX gamma
- Time variation corrected using
  - 17.6 MeV CW gamma
  - 9 MeV Ni-n gamma
  - 4.4 MeV AmBe gamma
  - Cosmic ray peak
- Checked using background gamma spectrum during physics run

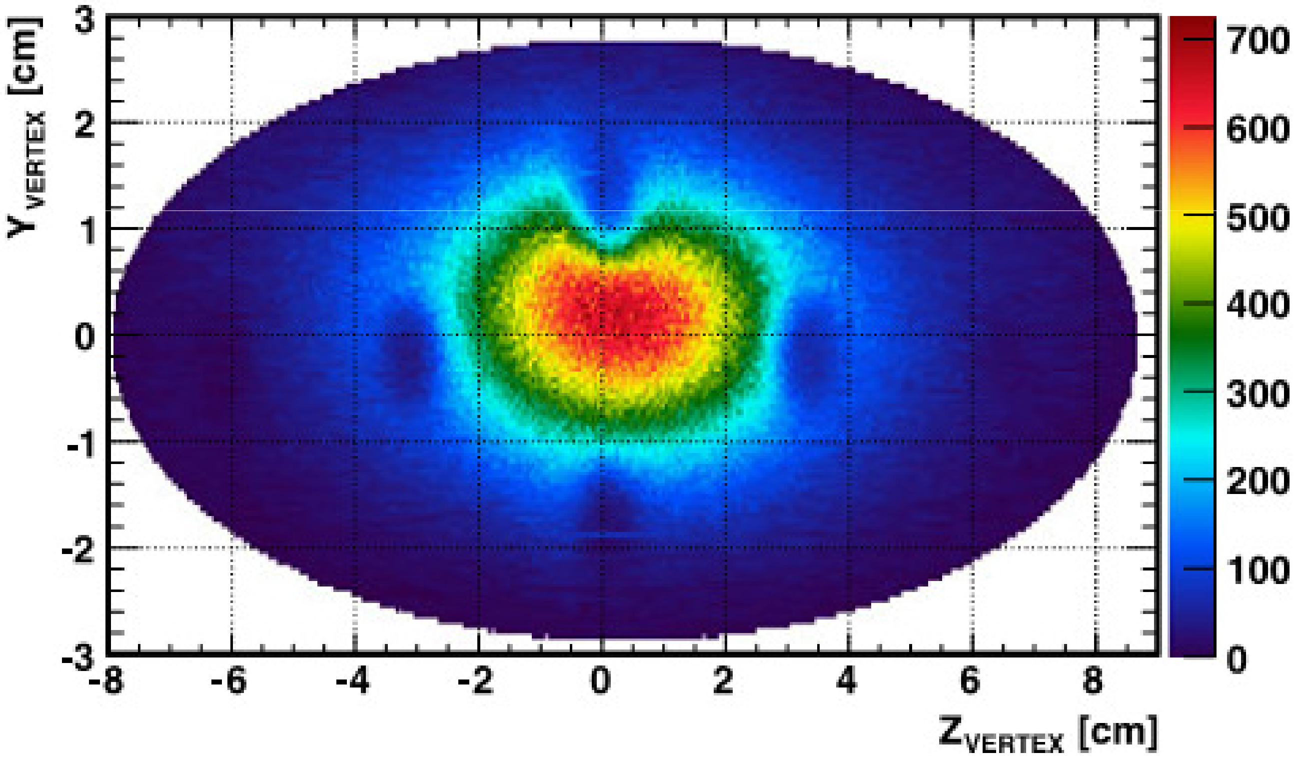




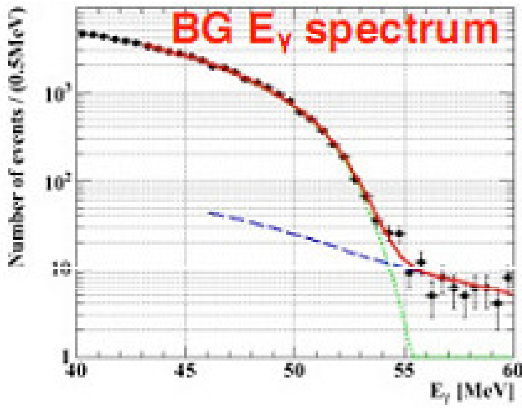
Background spectrum

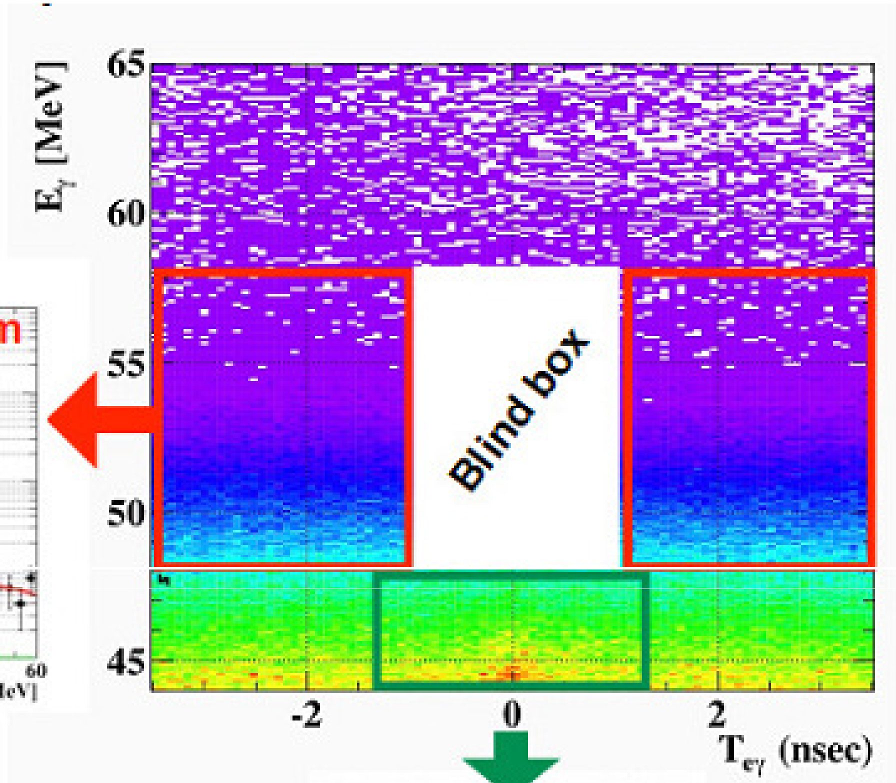


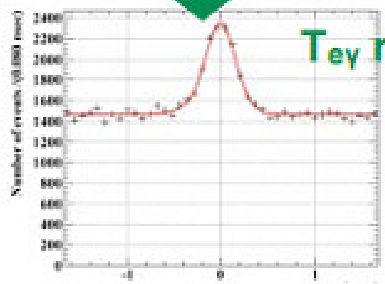
Target alignment



- **Blind analysis**
  - Optimization of analysis and BG study are done in sidebands







Δt ~ 130 ps

Physics Analysis in MEG

- **Maximum likelihood analysis** to extract N_{signal}
  - Observables: E_γ, E_e, $T_{e\gamma}$, $\theta_{e\gamma}$, $\Phi_{e\gamma}$
  - **PDFs are formed mostly from data.**
    - **Signal**: Measured resolutions
    - **Accidental BG** : Measured spectrum in sidebands
    - **RMD**: Theoretical spectrum smeared by detector resolutions
- Different likelihood analyses performed to check systematics
  - **PDF**: Event-by-event PDF, different PDFs according to tracking quality, averaged PDF
  - **Statistical approach**: Frequentist, Bayesian

$$\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}} \exp^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[\frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RMD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right]$$

PDF= Probabilty
Distribution Function

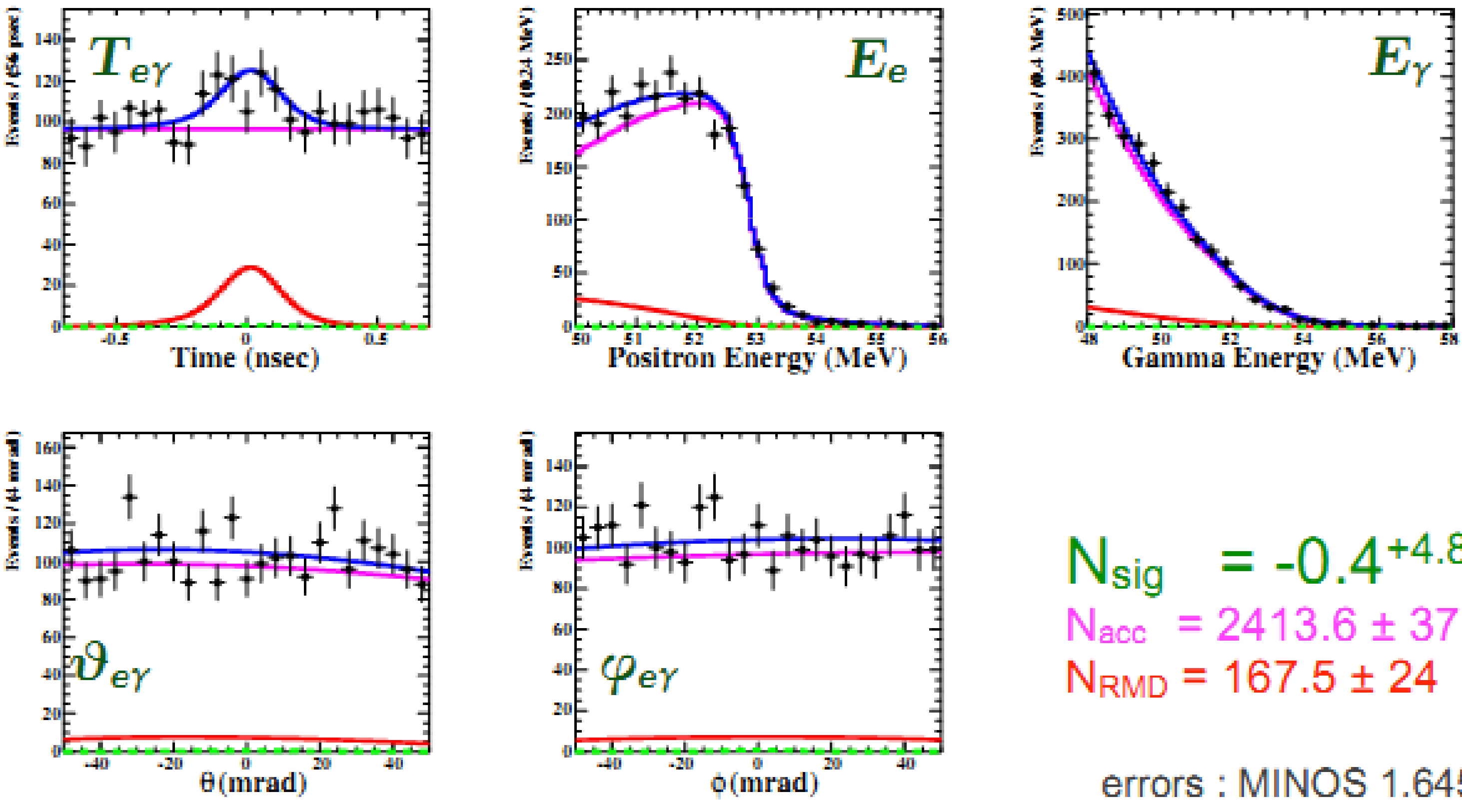
Signal PDF RMD PDF BG PDF

2009-2011 Fit Result

Unbinned likelihood fitting on 5 dimension observable data

Signal
RMD
BG
Total

dotted line : 90% UL



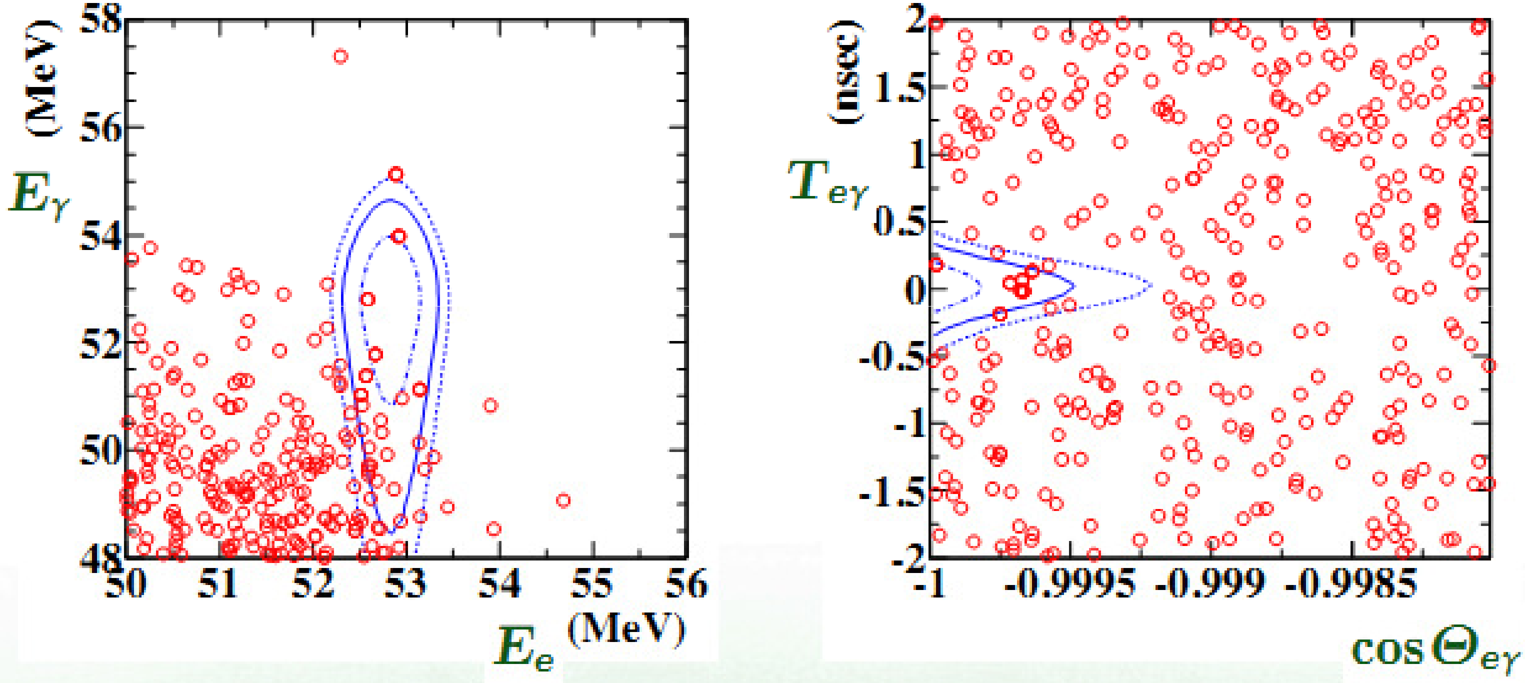
$N_{sig} = -0.4^{+4.8}_{-1.9}$

$N_{acc} = 2413.6 \pm 37$

$N_{RMD} = 167.5 \pm 24$

errors : MINOS 1.645σ

2009-2011 data



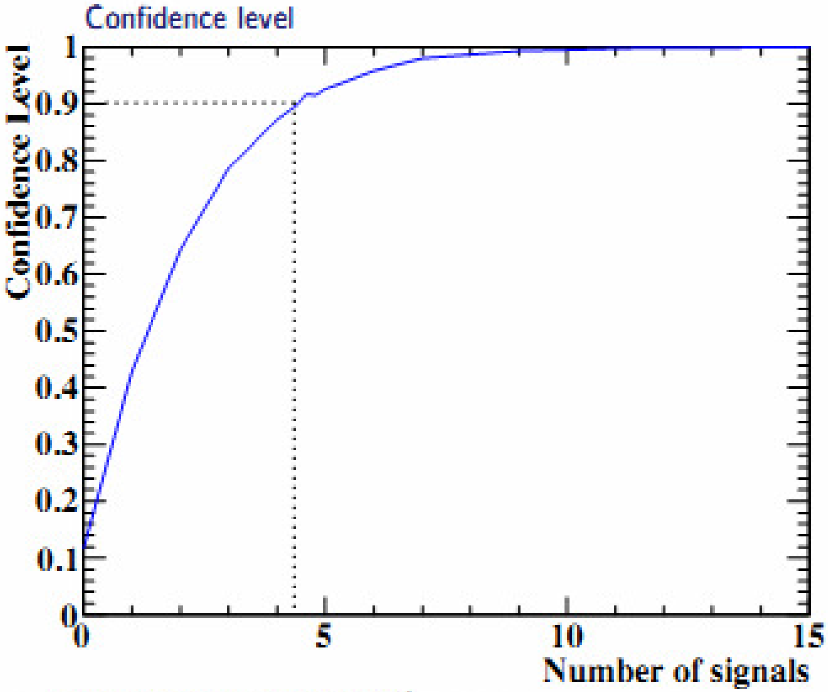
No excess: N_{signal} best fit is $-0.4^{+4.8}_{-1.9}$

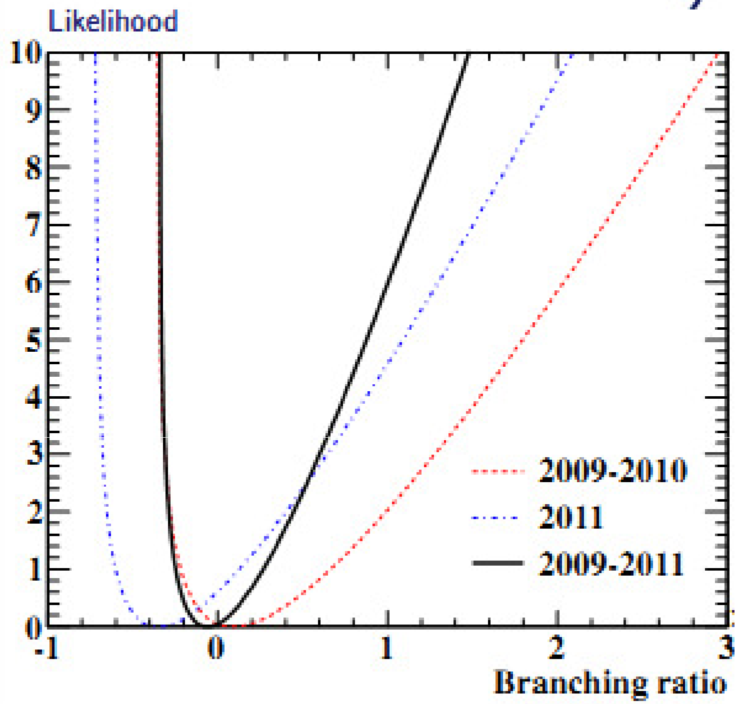
contour : signal PDF (39.3, 74.2, 86.5 %)

errors : MINOS 1.645σ

2009-2011 result

Previous limit : **2.4×10^{-12}** (MEG, 2011)





normalization : 7.77×10^{12}

$\mathcal{B} < 5.7\times10^{-13}$ @ 90% C.L.

Dataset	$\mathcal{B}_{\rm fit}\times10^{12}$	$\mathcal{B}_{90}\times10^{12}$	$\mathcal{S}_{90}\times10^{12}$
2009–2010	0.09	1.3	1.3
2011	−0.35	0.67	1.1
2009–2011	−0.06	0.57	0.77

arXiv:1303.0754 [hep-ex]
accepted by Phys. Rev. Lett.

Systematic uncertainties (in total 1% in UL)
- relative angle offsets
- correlations in e^+ observables

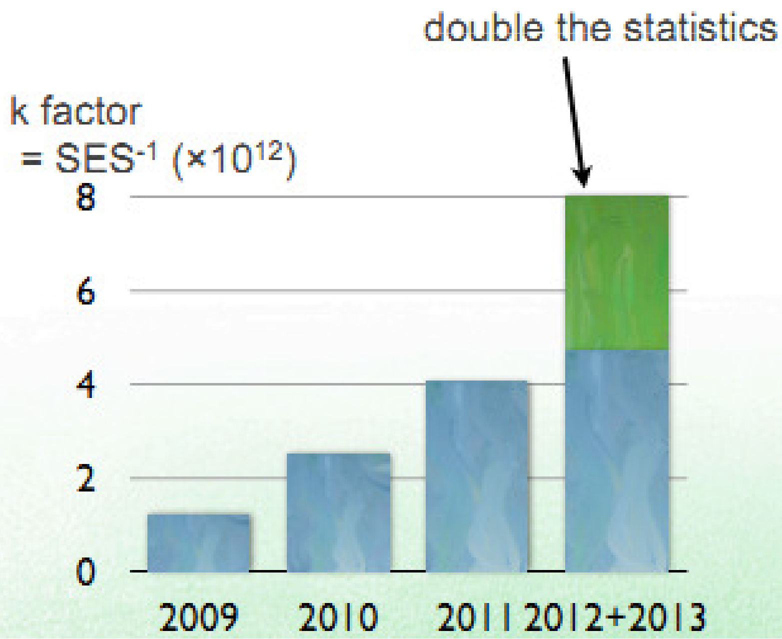
Expected final sensitivity

Data taking will be done until Summer 2013

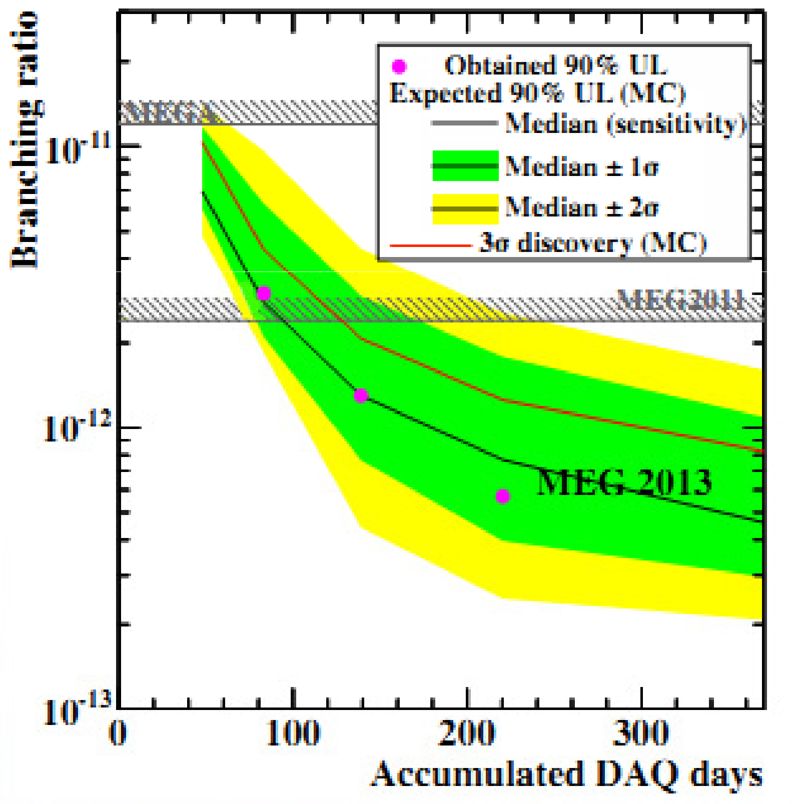
Since 2012, 15% higher beam rate is used

2009-2011 sensitivity
7.7×10^{-13}

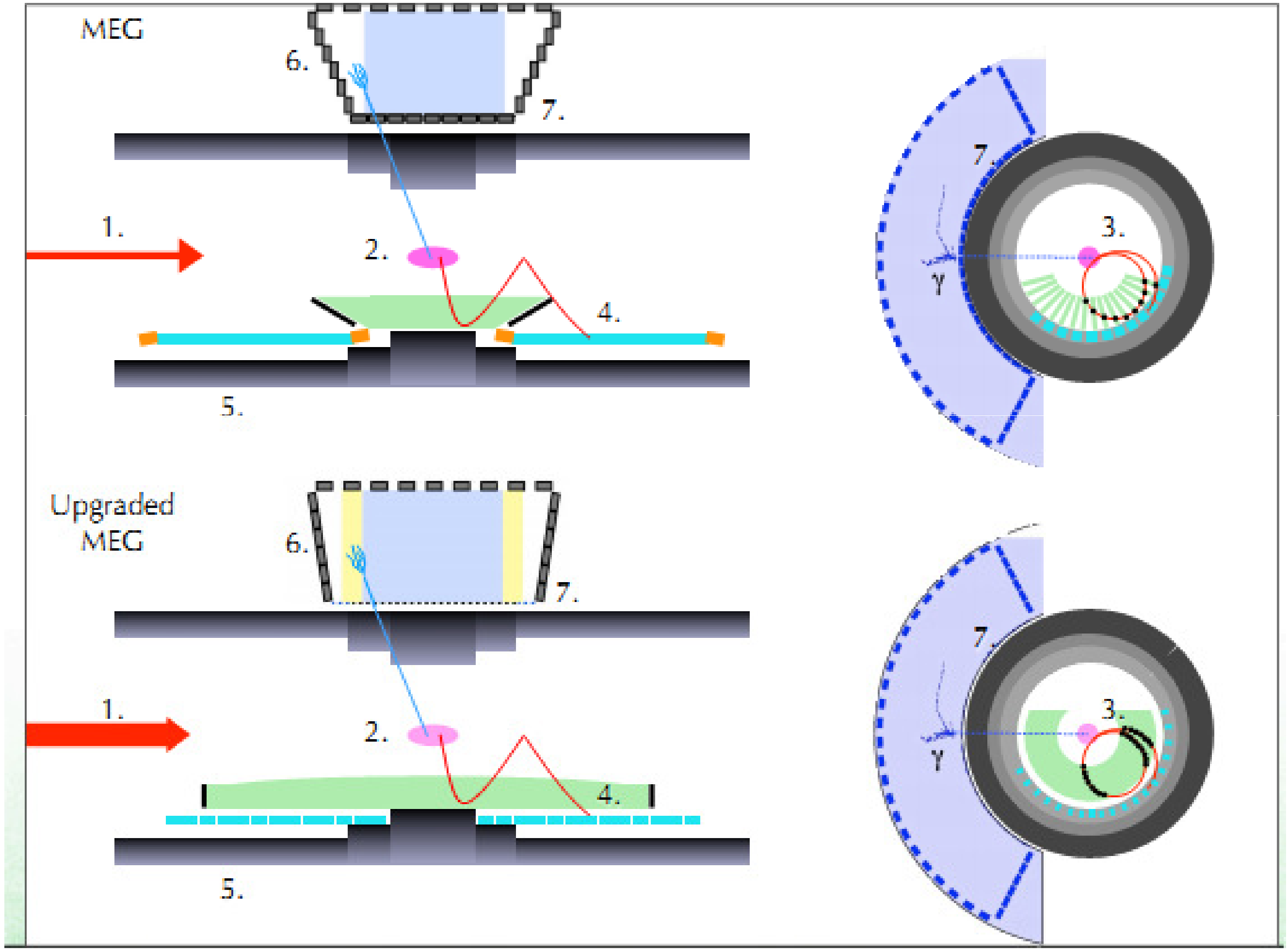
Expected 2009-2013 sensitivity
$\sim5\times10^{-13}$



Observed limits and sensitivity



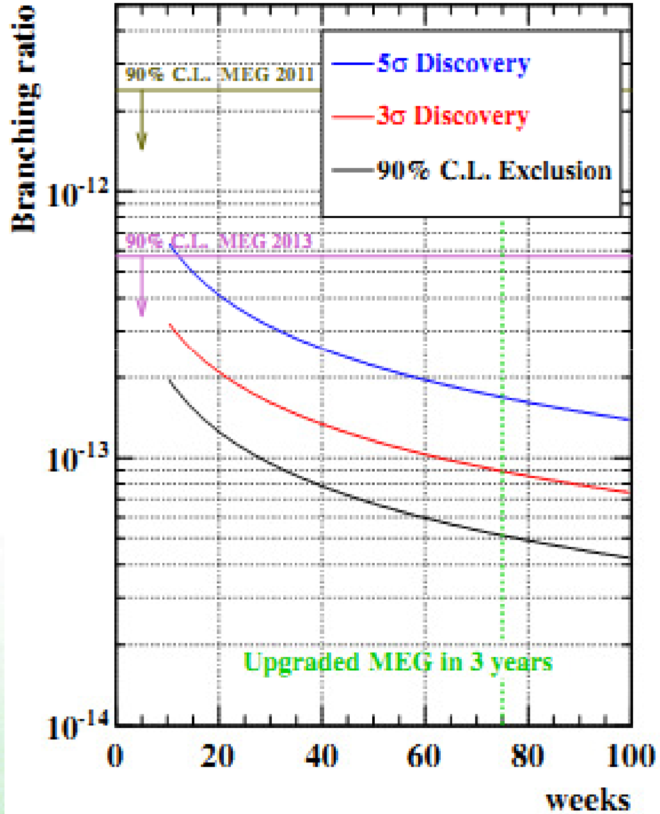
MEG upgrade



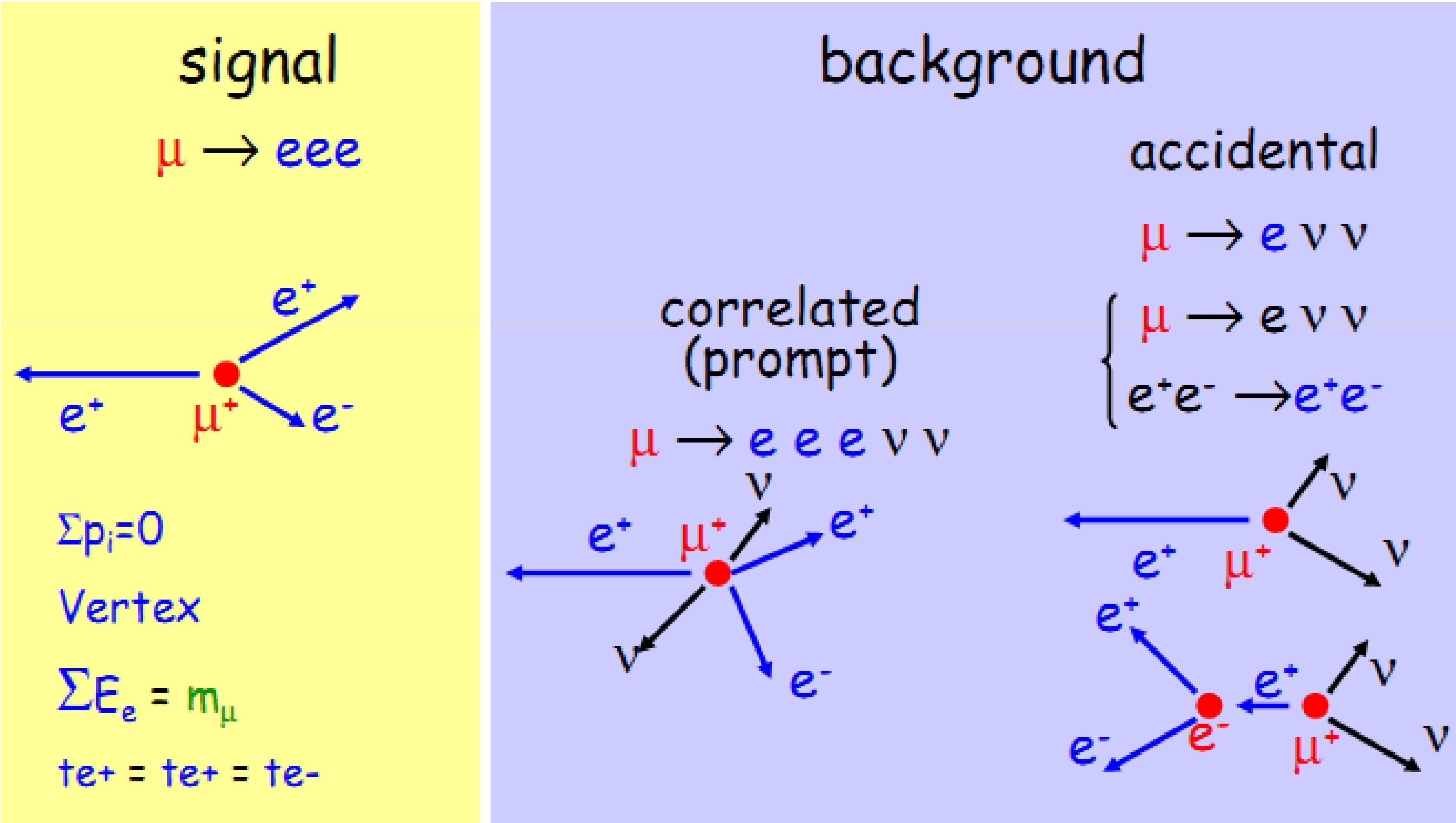
Expected performance and Sensitivity

PDF parameters	Present MEG	Upgrade scenario
e^+ energy (keV)	306 (core)	130
e^+ θ (mrad)	9.4	5.3
e^+ ϕ (mrad)	8.7	3.7
e^+ vertex (mm) Z/Y(core)	2.4 / 1.2	1.6 / 0.7
γ energy (%) (w <2 cm)/(w >2 cm)	2.4 / 1.7	1.1 / 1.0
γ position (mm) $u/v/w$	5 / 5 / 6	2.6 / 2.2 / 5
γ-e^+ timing (ps)	122	84
Efficiency (%)		
trigger	≈ 99	≈ 99
γ	63	69
e^+	40	88

Sensitivity in three years : ~5×10^{-14}

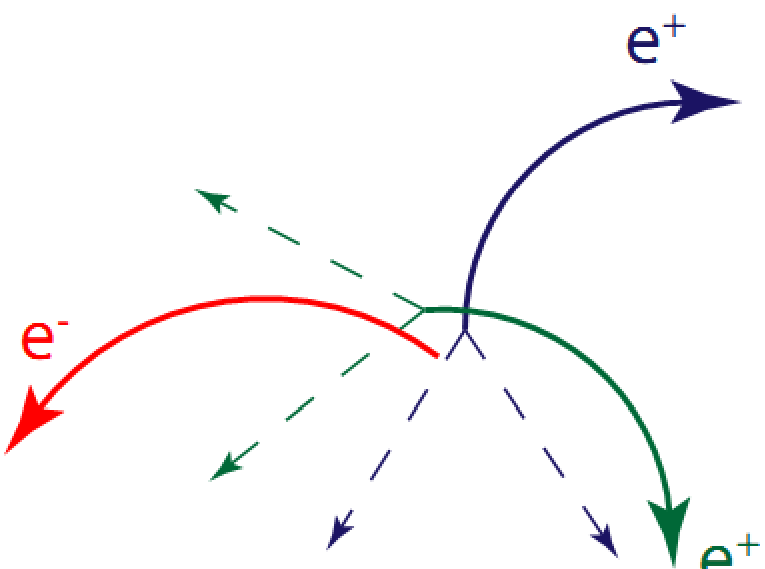


$\mu^+ \to e^+e^+e^-$



signal
μ → eee
e+
e+
μ+
e-
Σpi=0
Vertex
ΣEe = mμ
te+ = te+ = te-
background
correlated
(prompt)
μ → e e e ν ν
ν
e+
μ+
e+
ν
e-
accidental
μ → e ν ν
μ → e ν ν
e+e- → e+e-
ν
e+
μ+
ν
e+
e+
ν
e-
e-
μ+
ν

Accidental Background

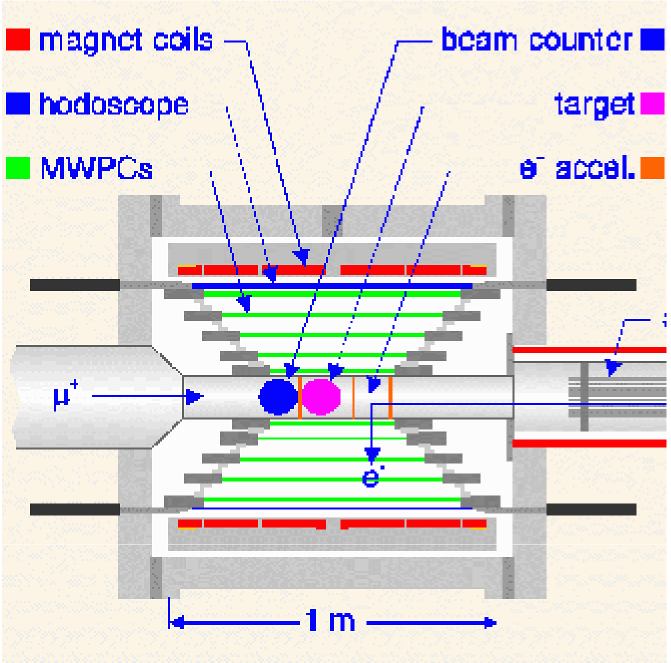


- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution

$\mu^+ \to e^+ e^+ e^-$: SINDRUM I

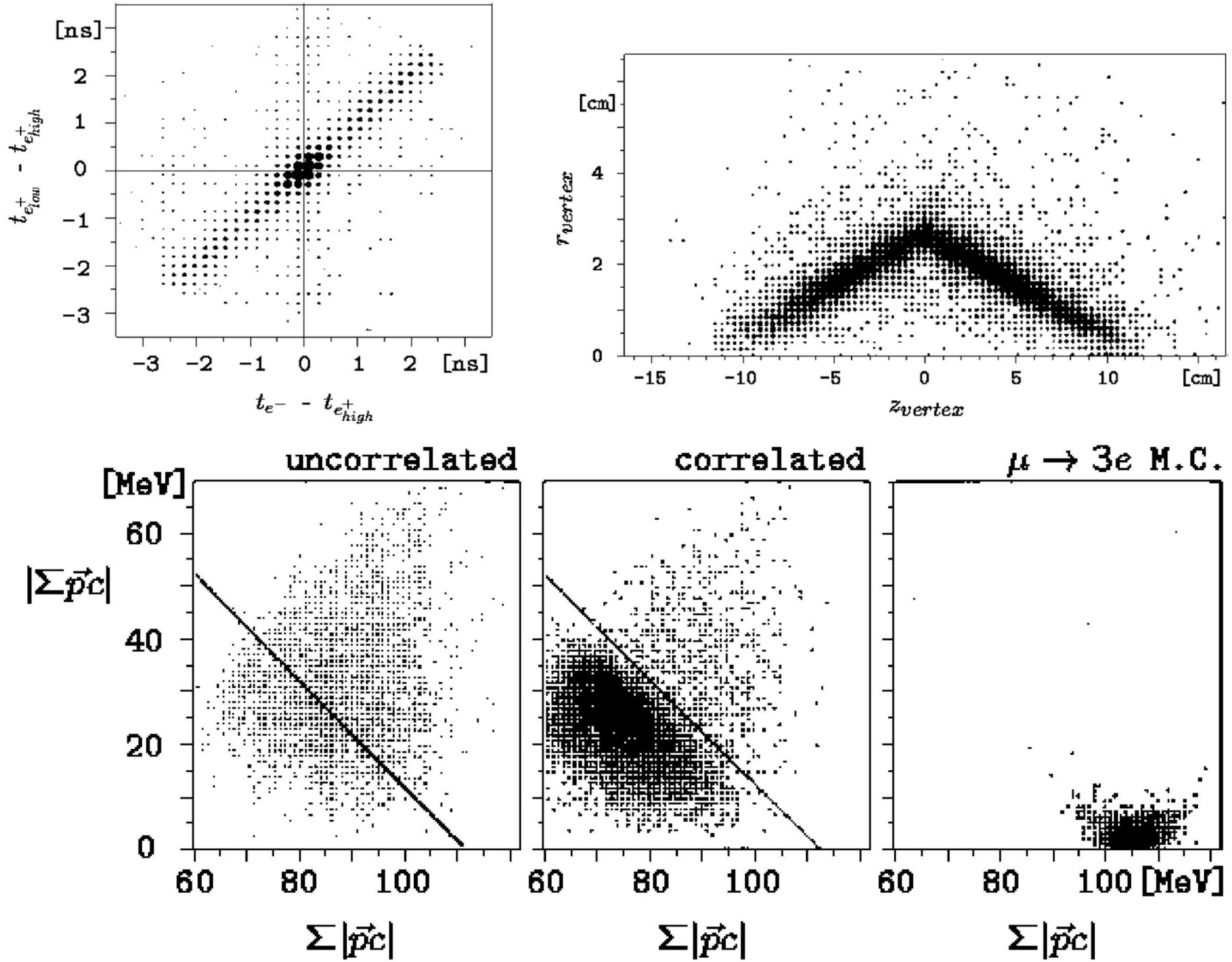
- Present limit $B(\mu \to 3e) < 1x10^{-12}$
  U.Bellgardt et al. Nucl.Phys. B299(1988)1
- Proposal at PSI to reach 10^{-15} in a first phase and 10^{-16} in a later one



SINDRUM I parameters

– beam intensity	$6x10^6$ μ^+/s
– μ^+ momentum	25 MeV/c
– magnetic field	0.33T
– acceptance	24%
– momentum resolution	10% FWHM
– vertex resolution	2 mm^2 FWHM
– timing resolution	~ ns
– target length	220 mm
– target density	11 mg/cm^2

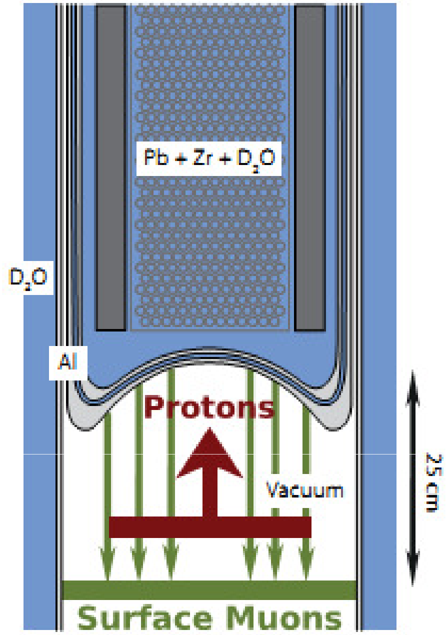
$\mu^+ \to e^+e^+e^-$: SINDRUM I

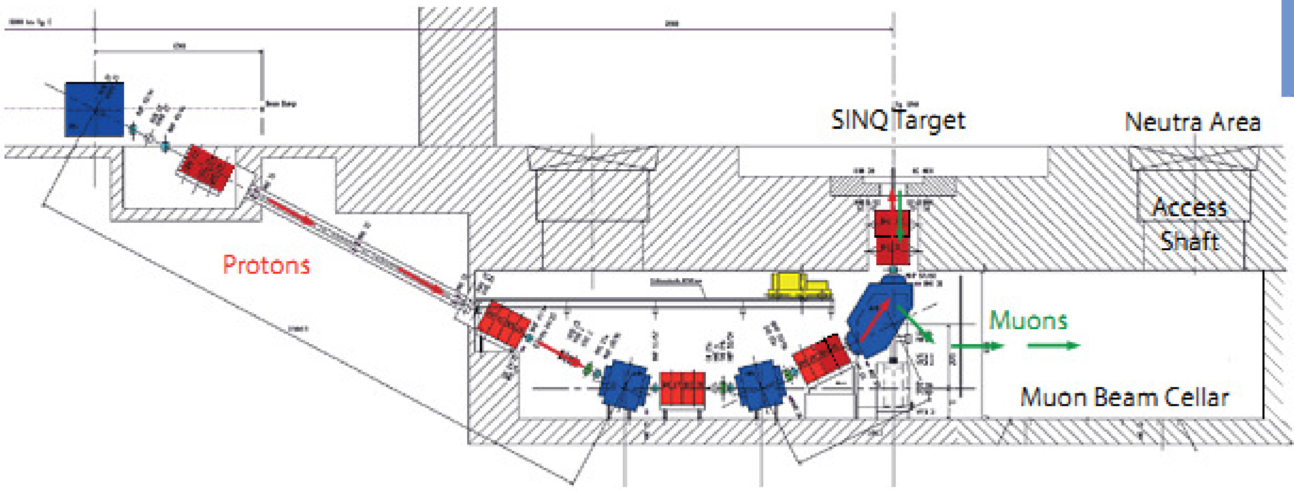


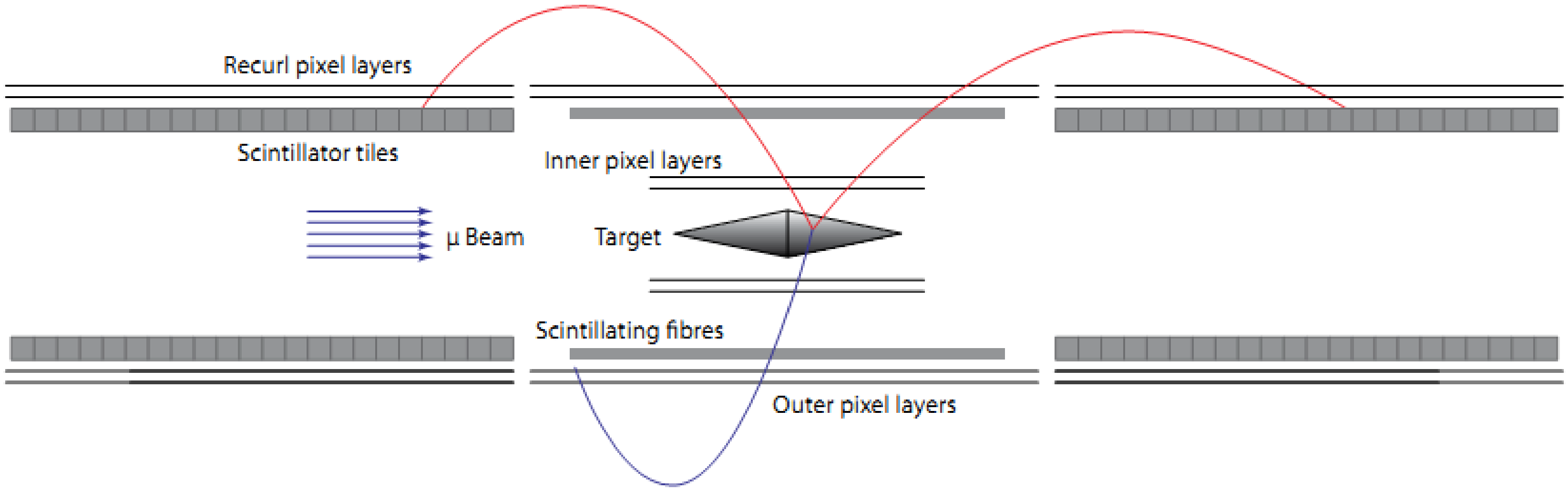
The High-Intensity Muon Beamline (HIMB)

- Muon rates in excess of 10^{10}/s in acceptance
- $2 \cdot 10^{9}$/s needed for $\mu \rightarrow eee$ at 10^{-16}
- Not before 2017

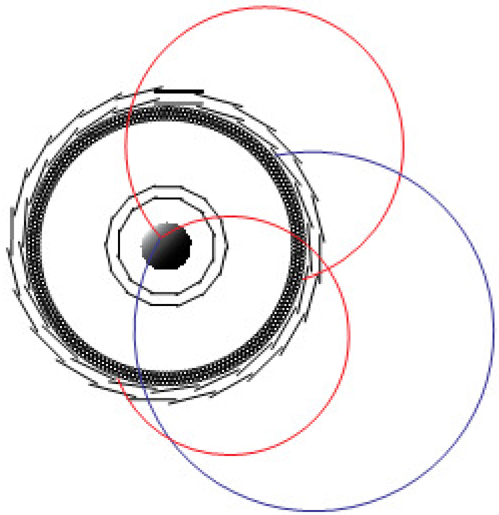
Same beam as MEG for the first phase

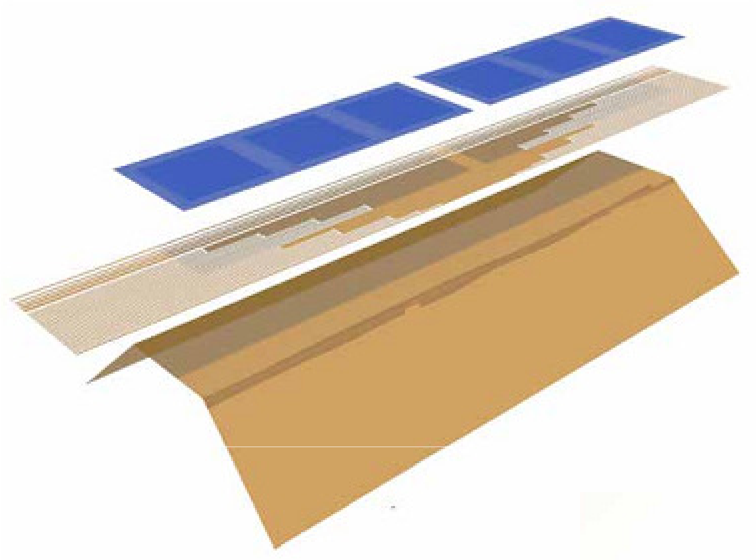






Detector Design

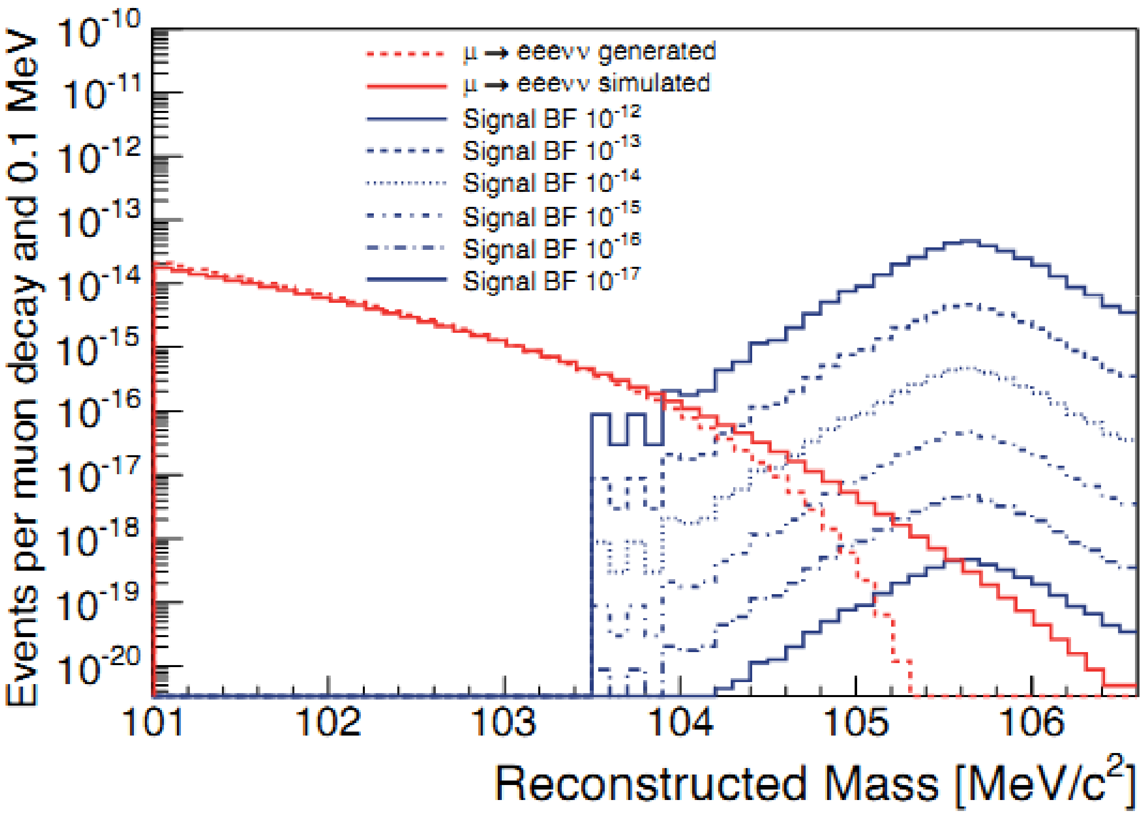




- 50 µm silicon pixel detectors (HV-MAPS)
- 25 µm Kapton™ flexprint with aluminium traces
- 25 µm Kapton™ frame as support
- Less than 1‰ of a radiation length per layer

Severe cooling problems

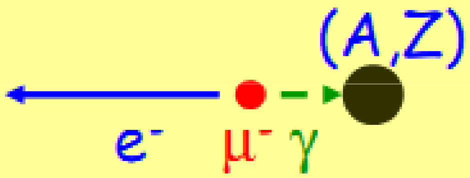
Simulated Performance



$\mu^- \to e^-$ conversion

signal

$\mu\ (A,Z) \to e\ (A,Z)$



$E_e = m_\mu - E_B$

~100 MeV !

main backgrounds

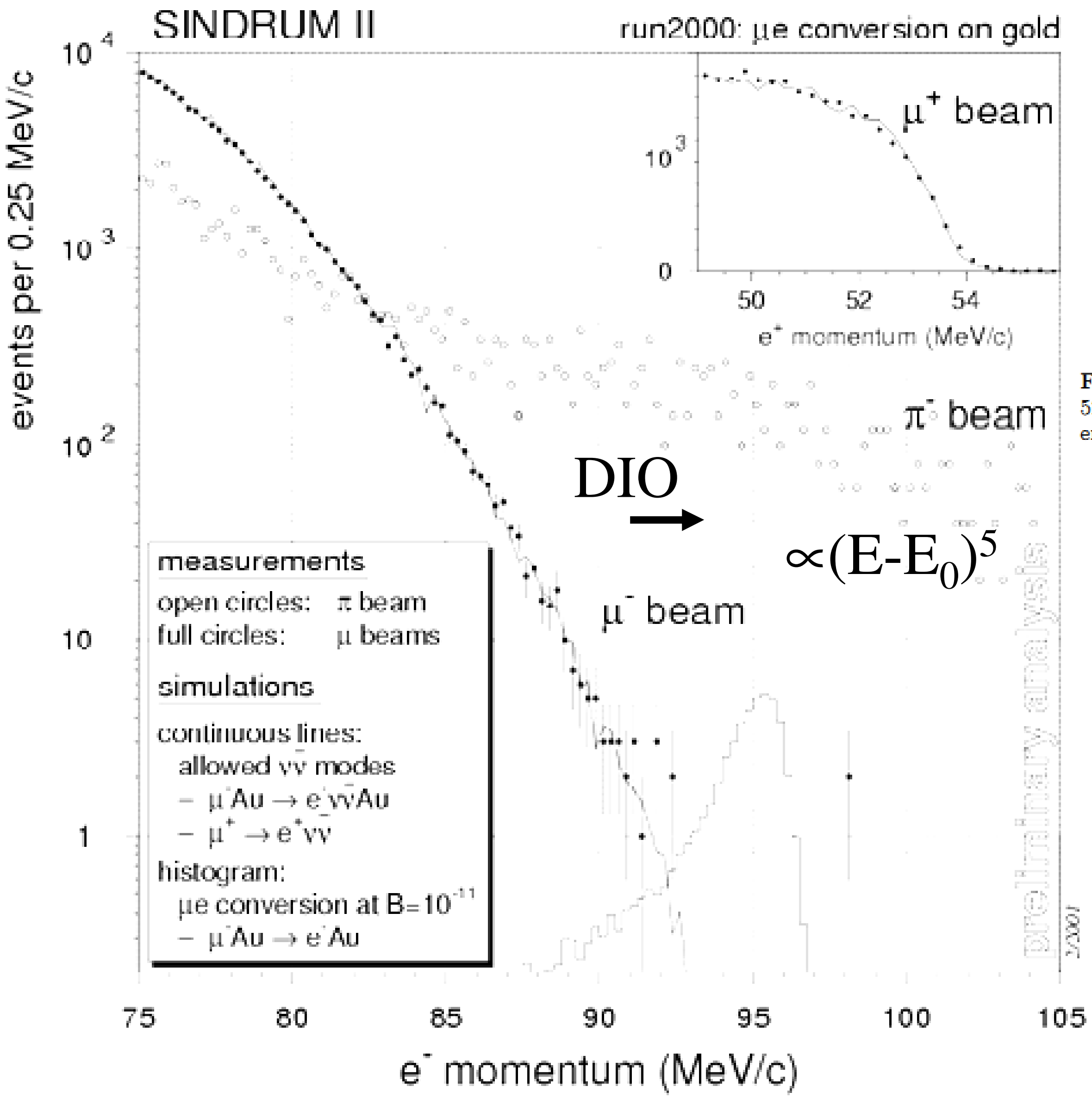
DIO (Decay In Orbit)

$\mu\ (A,Z) \to e\ \nu\ \nu\ (A,Z)$

RPC

$\pi\ (A,Z) \to \gamma\ (A,Z\text{-}1)$

Beam related background



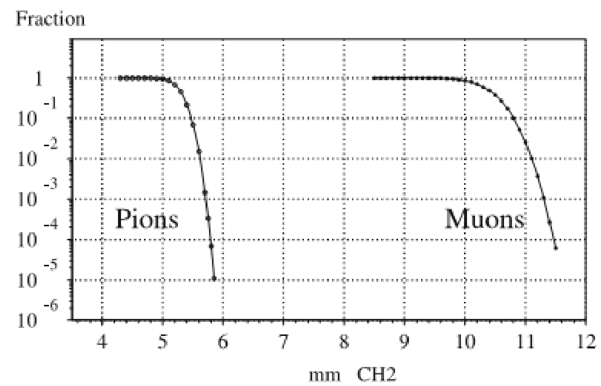


Fig. 1. Fraction of pions and muons with a momentum of 52 MeV/c that cross a CH_2 moderator as a function of the moderator thickness. GEANT [23] simulation

↑

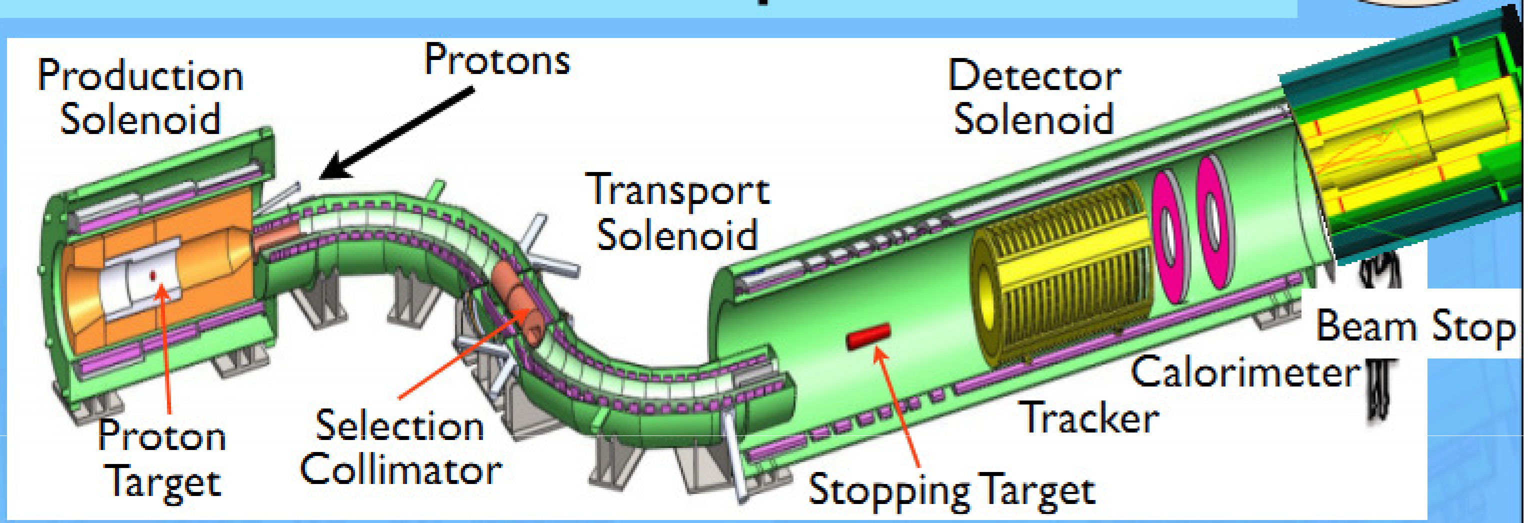
π suppressed by means of a moderator

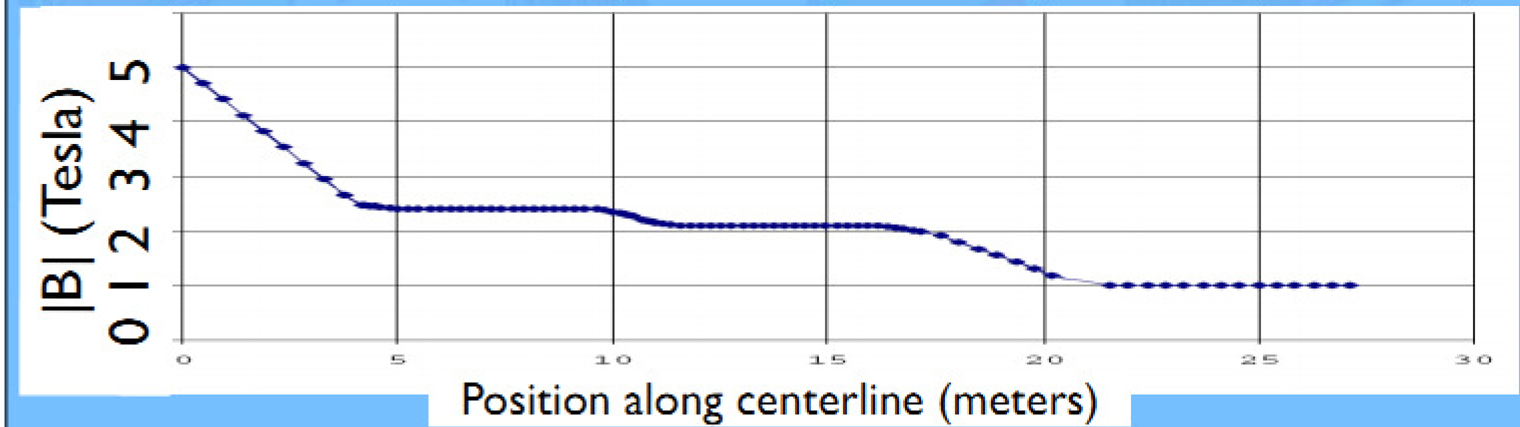
The Mu2e Experiment

- Goal: Discover μN→eN conversion
- Target sensitivity: $R_{\mu e} = 6\times10^{-17}$ @ 90% C.L.
  - 4 orders of magnitude better than current limits
- Requires ~ 10^{18} stopped muons $10^{10\div11}$muons/sec
  - ~ 4×10^{20} protons on target (3 year run @ 8 KW) (8 GeV)
- Requires negligible (<1) background events
- Many challenges for the beamline and detector design

David Brown, Lawrence Berkeley National Lab 12 mu2e conversion at FNAL CLFV, Lecce, 2013

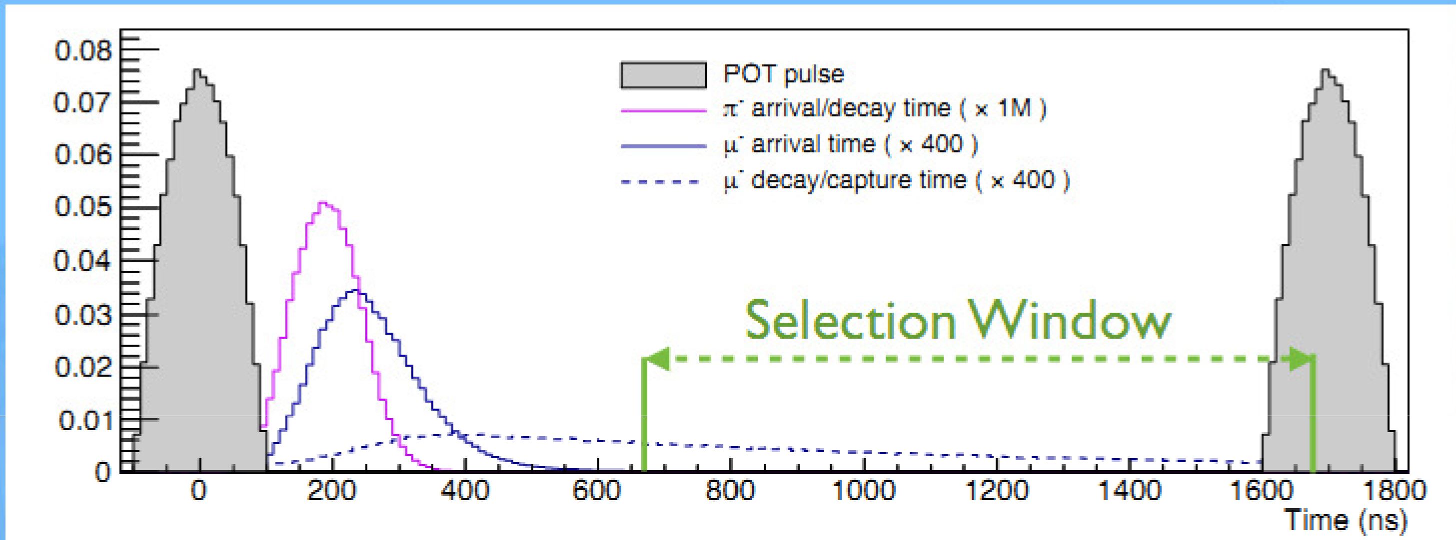
The Mu2e Experiment





David Brown, Lawrence Berkeley National Lab 14 mu2e conversion at FNAL CLFV, Lecce, 2013

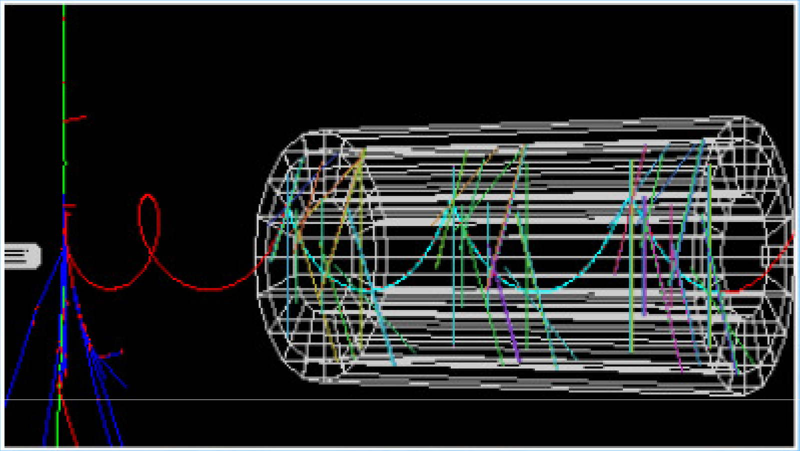
Timing (with Al target)



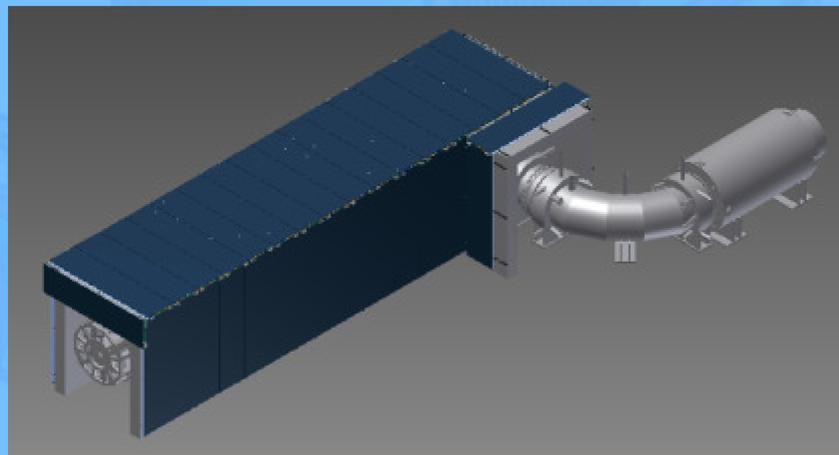
- Muons reach the stopping target in ~250 ns
  - Stopped muon lifetime on Al ~800 nsec
- Select tracks after beam, π^- decay
  - ~1 μsec window, ~50% acceptance

David Brown, Lawrence Berkeley National Lab 19 mu2e conversion at FNAL CLFV, Lecce, 2013

Cosmic Ray Backgrounds



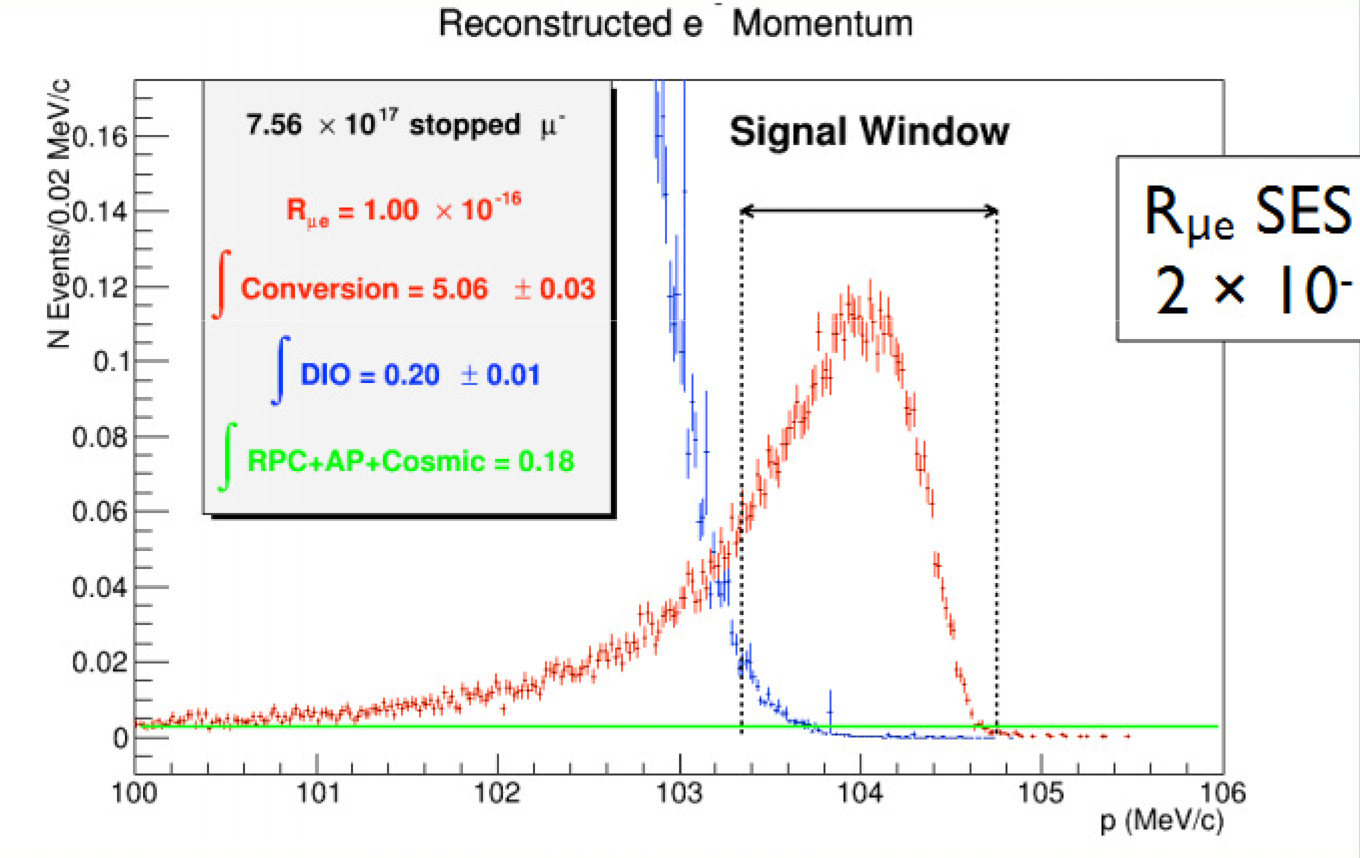
- Cosmic rays can produce e- that fake the signal
- Dedicated Cosmic Ray Veto (CRV) detector



- Overlapping scintillation counters
  - 99.99% efficiency
- Rejection also from tracker, calorimeter

Mu2e Signal Sensitivity

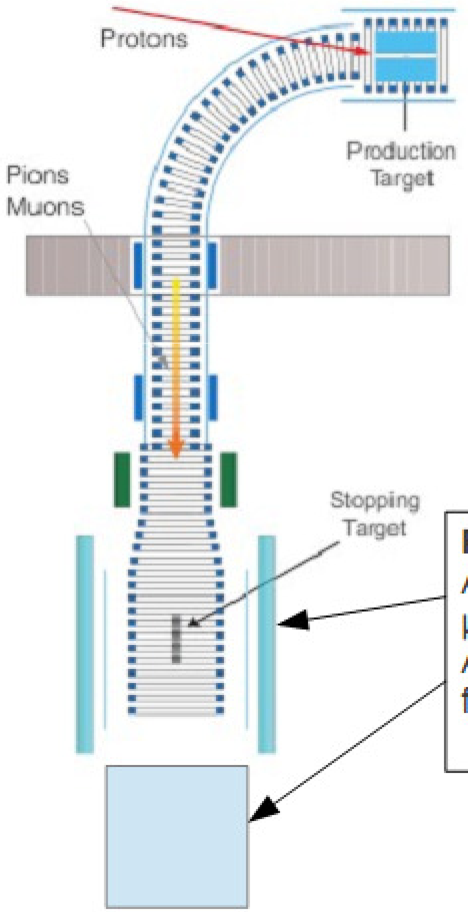
Full G4 detector simulation, background overlay, reconstruction



$R_{\mu e}$ SES = 2×10^{-17}

Starting in 2016
Measurement in 2017
S.E.S = 3×10^{-15}

COMET (Phase-I)



Phase-I Aims
Search for μ-e conversion process with a S.E.S of 3×10^{-15}
Study the backgrounds for Phase-II

Phase-I Detector
A cylindrical drift chamber (CDC) for the μ-e conversion search
A prototype ECAL and straw tube tracker for the background studies

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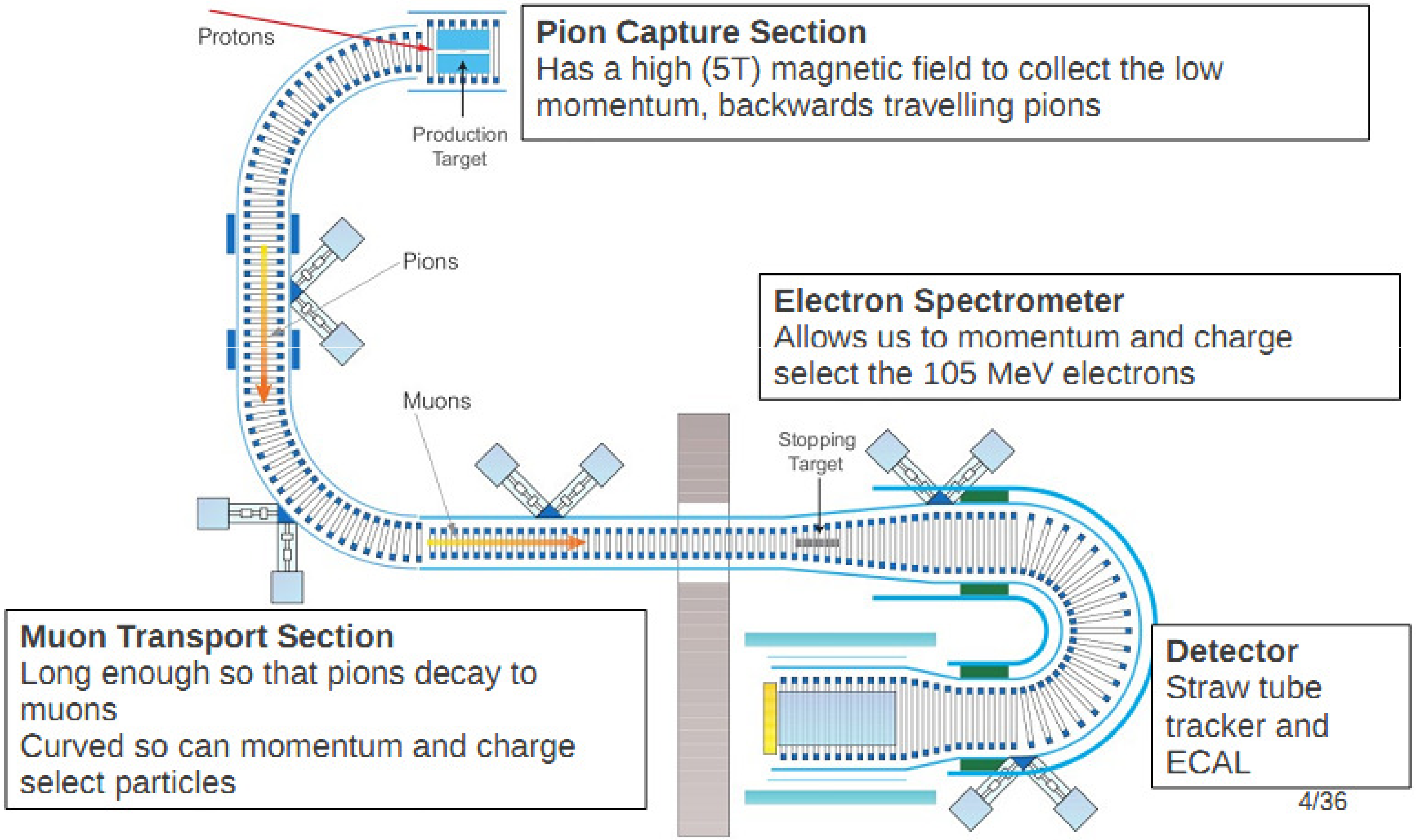
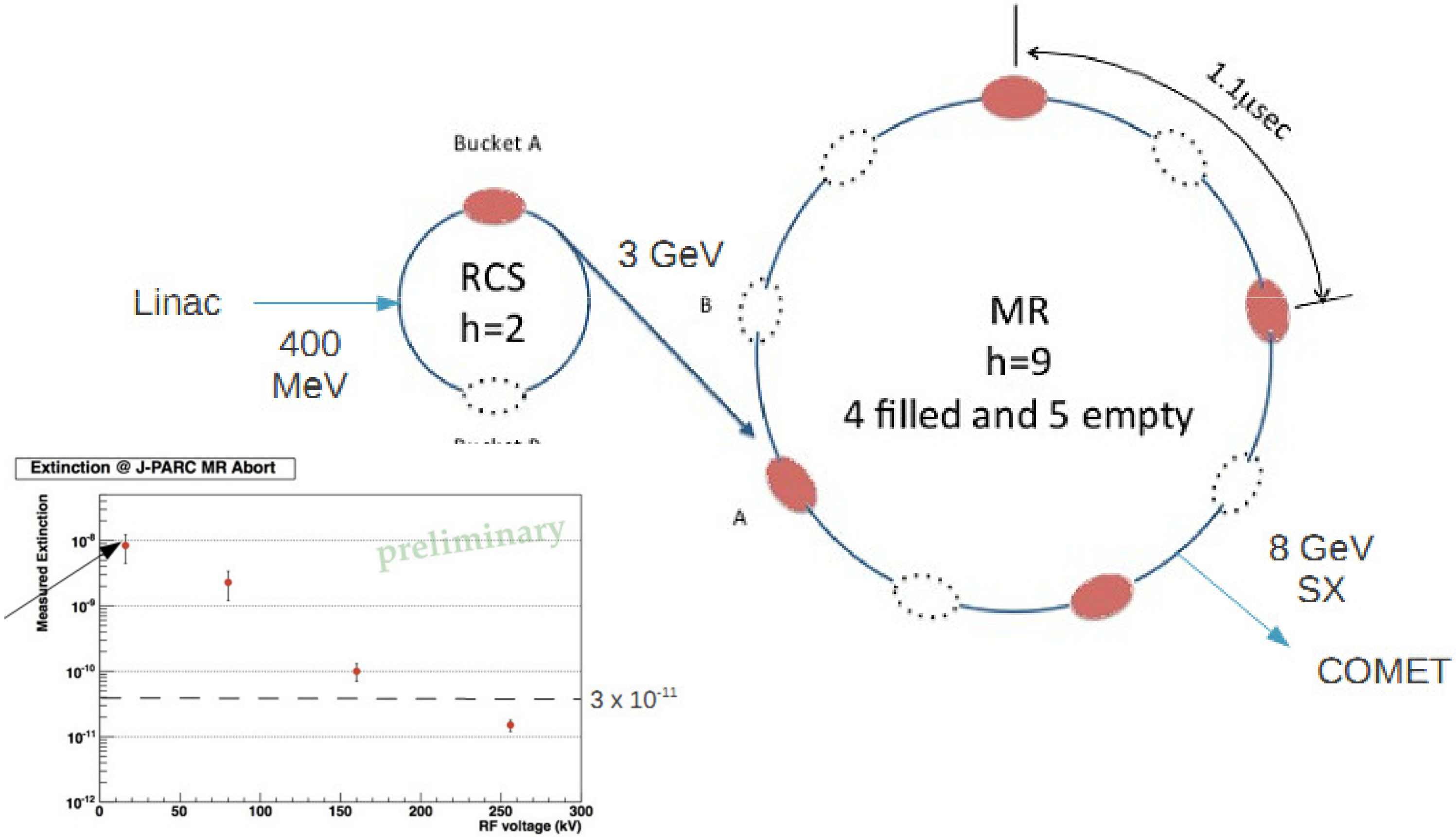
Starting in 2020
Measurement in 2022
S.E.S = 3×10^{-17}

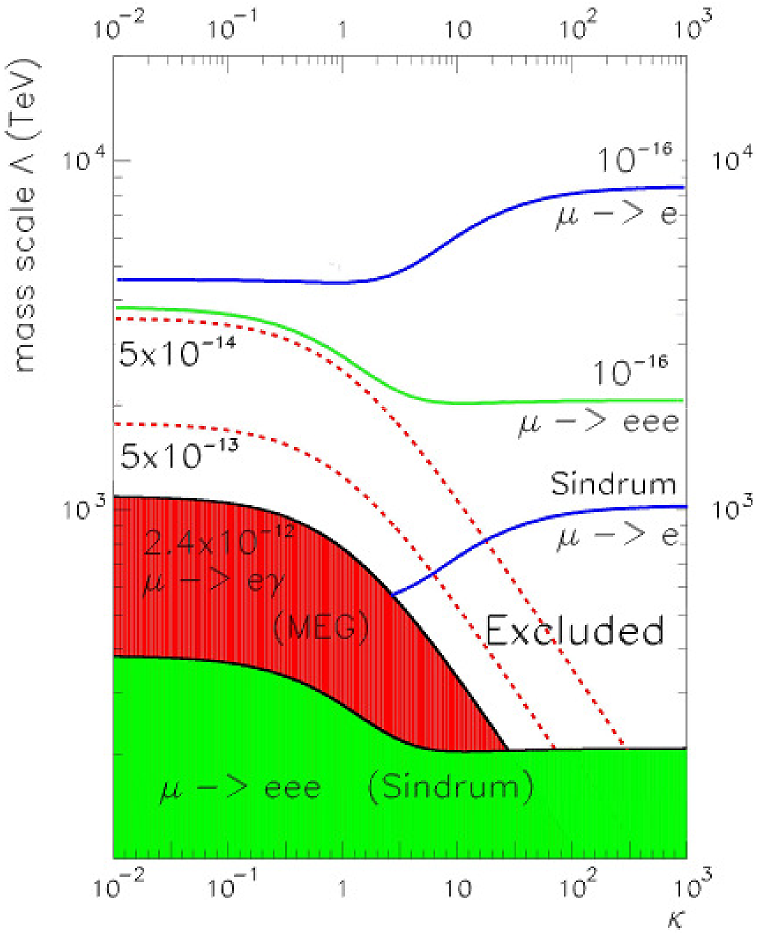
COMET (Phase-II)



Proton Beam Acceleration



μ→eγ vs μ→e and μ→3e



Effective lagrangian

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_R \gamma_\mu e_L \bar{e}\gamma^\mu e$$

- Precision really plays a major role in cLFV experiments !

- It may be that $\mu \rightarrow e\gamma$ has met the current technological limits

- possible big improvements can be foreseen especially for $\mu \rightarrow e$ conversion

- we hope to be more lucky in the near future