Electromagnetic Formfactors (and other EM nucleon structure) in $\bar{\text{P}}$ANDA

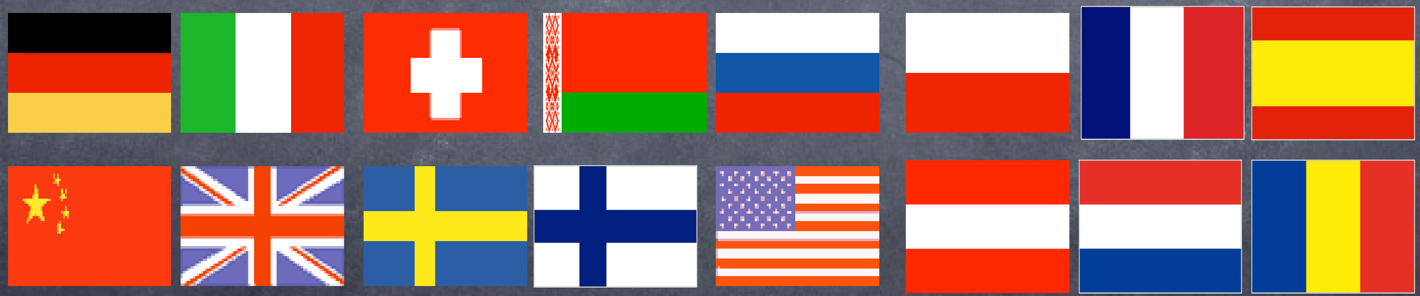
F. Maas
work done at IPN Orsay, IKP Mainz, GSI

Workshop at the IUSS, Ferrara
„Nucleon Structure at GSI FAIR"
(PANDA EM working group)
October 15 - 16, Ferrara, Italy

The $\bar{\text{P}}$ANDA Project

($\bar{p}$ ANnihilation experiment DArmstadt)

Basel, Beijing, Bochum, Bonn, IFIN Bucharest, Brescia, Catania, Cracow, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, KVI Groningen, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, Lanzhou, LNF, Mainz, Milano, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia, Piemonte Orientale, IPN Orsay, IHEP Protvino, PNPI St. Petersburg, KTH Stockholm,
Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien



400 physicists, 50 institutions from 16 countries

The Physics of PANDA

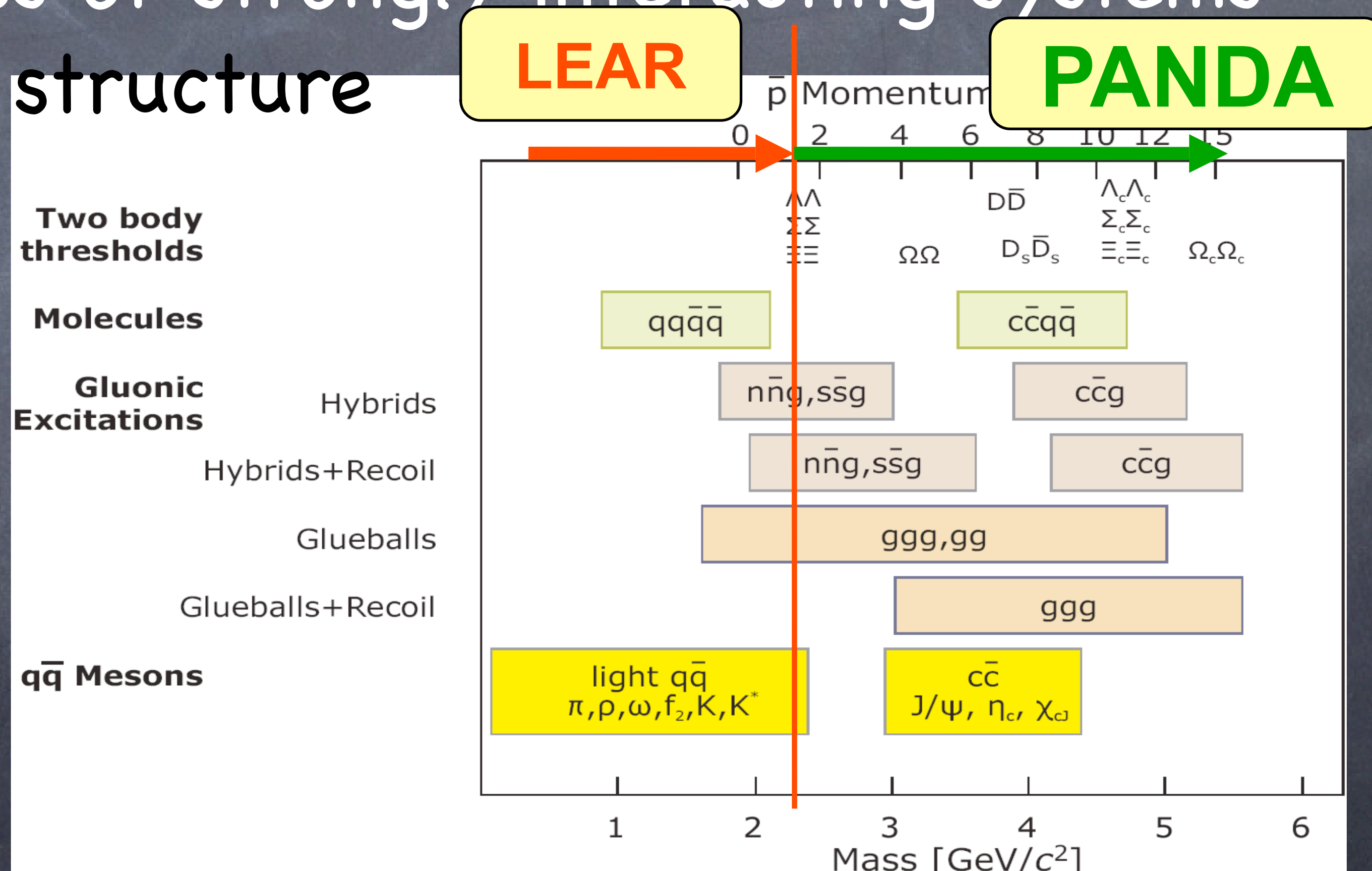
- QCD exotics (glueballs, hybrids)
- Charmonium spectroscopy
- electromagnetic Nucleon structure
- hypernuclear physics
- charm in matter
- baryon-antibaryon pair production
- CP violation in the charm sector
- J/ψ nucleon scattering
- open charm physics
- ...

The PANDA Physics Program

PANDA physics motivation

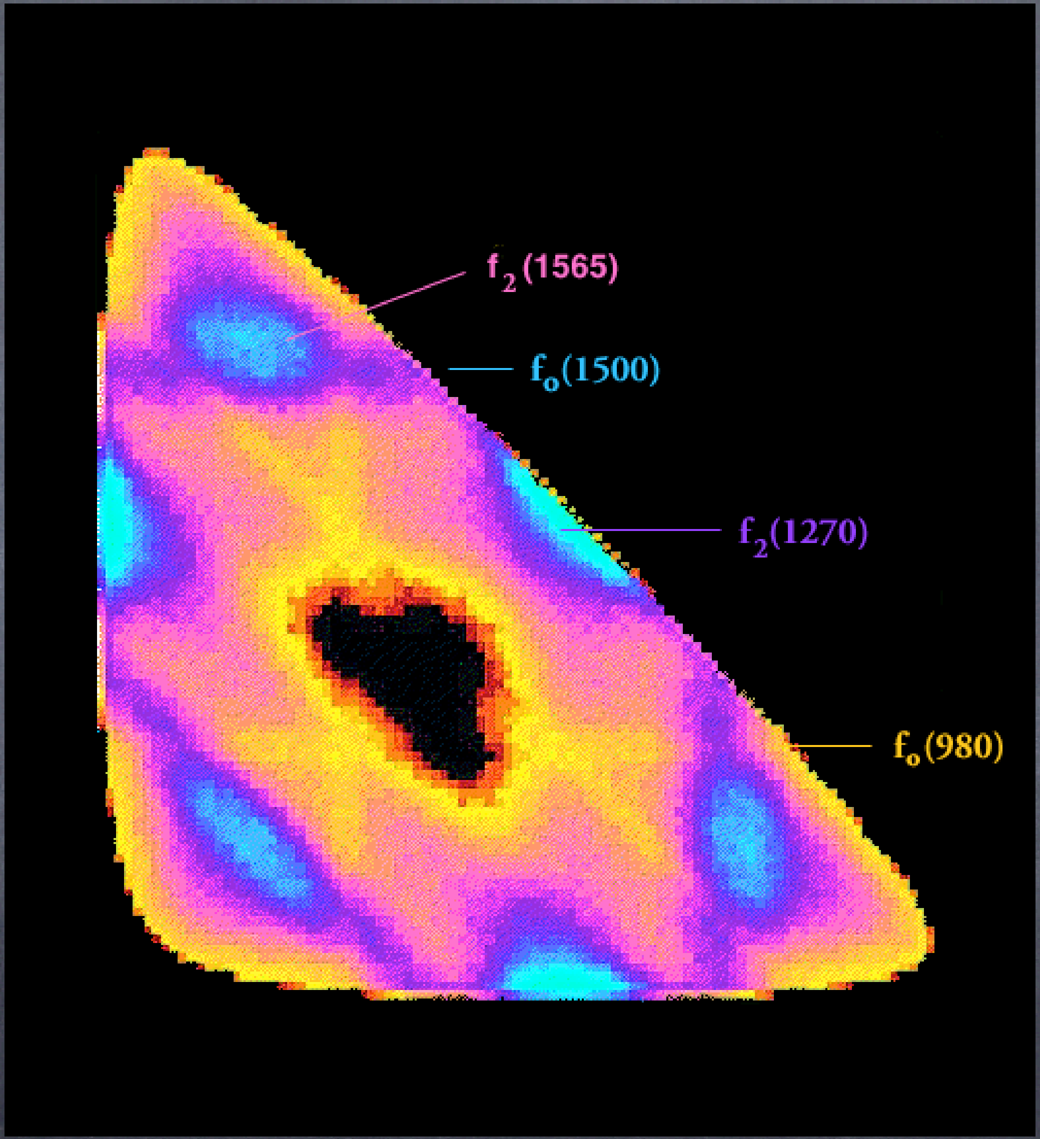
Broad spectrum of QCD objects

- understand (better) confinement
- find other forms of hadrons (glueballs, hybrids)
- origin of mass of strongly interacting systems
- EM hadronic structure



- high luminosity, high resolution -> high precision

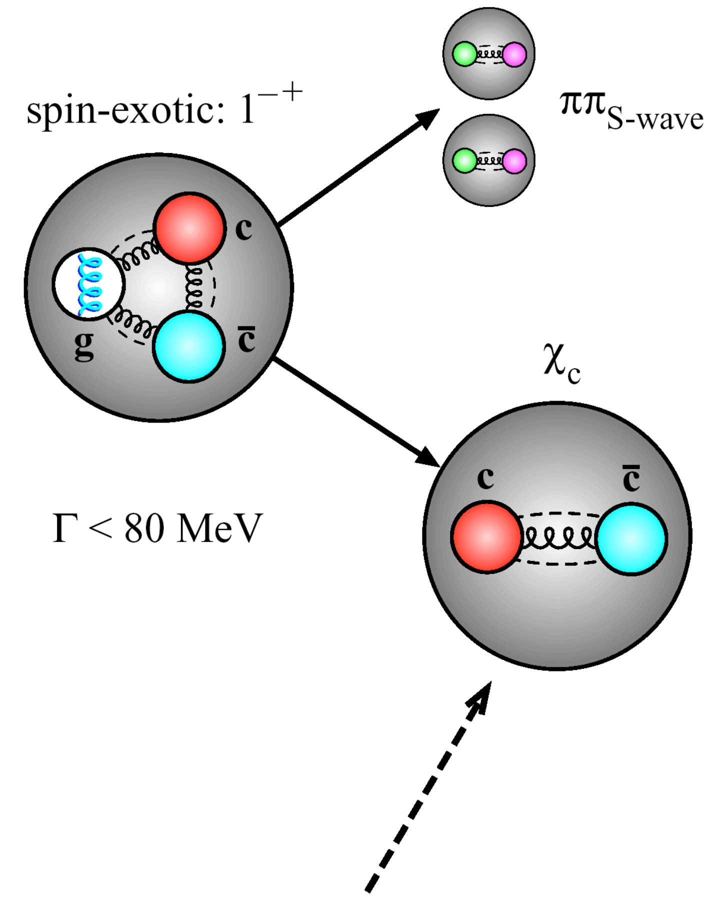
$p\bar{p} \to \pi^0\pi^0\pi^0$ Dalitz plot



high luminosity

from U. Wiedner

Decay of charmonium hybrids

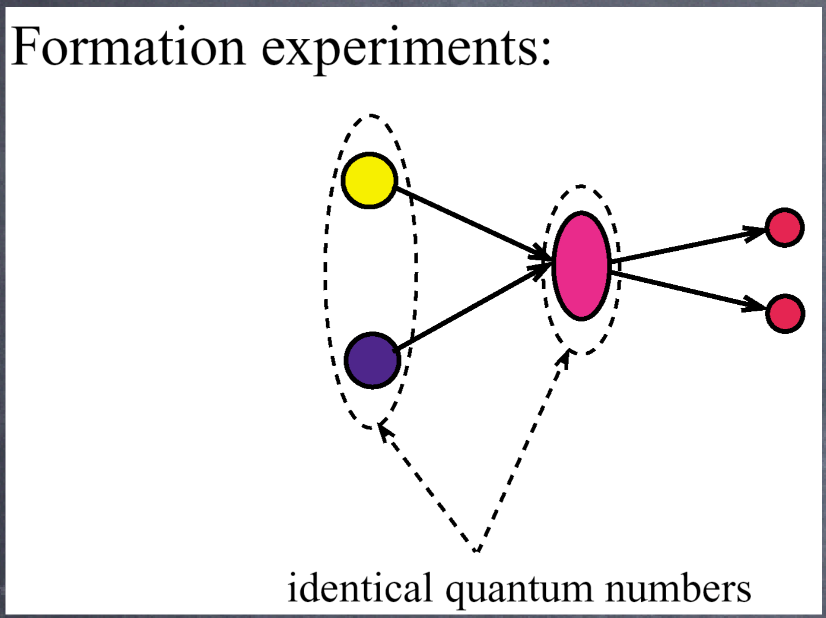


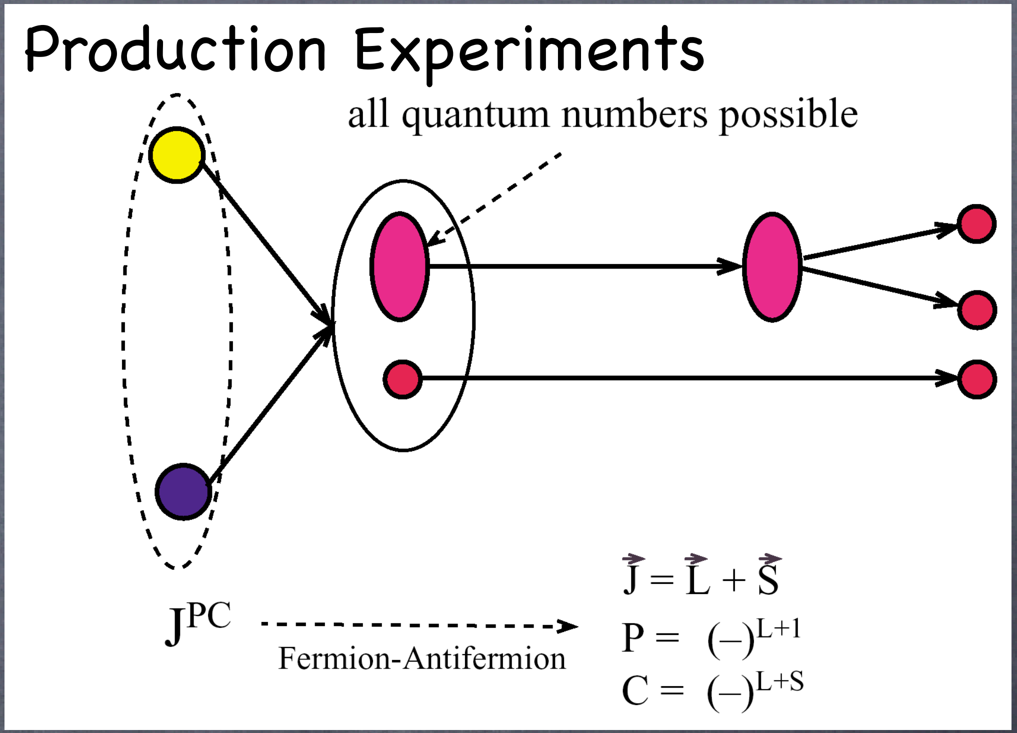
Decay of charmonium provides a clean "tag".

*UKQCD, C. McNeile et al.; Phys.Rev.D 65:094505, 2002; C. Michael, hep-lat/0207017.

from U. Wiedner

Production vs Formation to find exotics

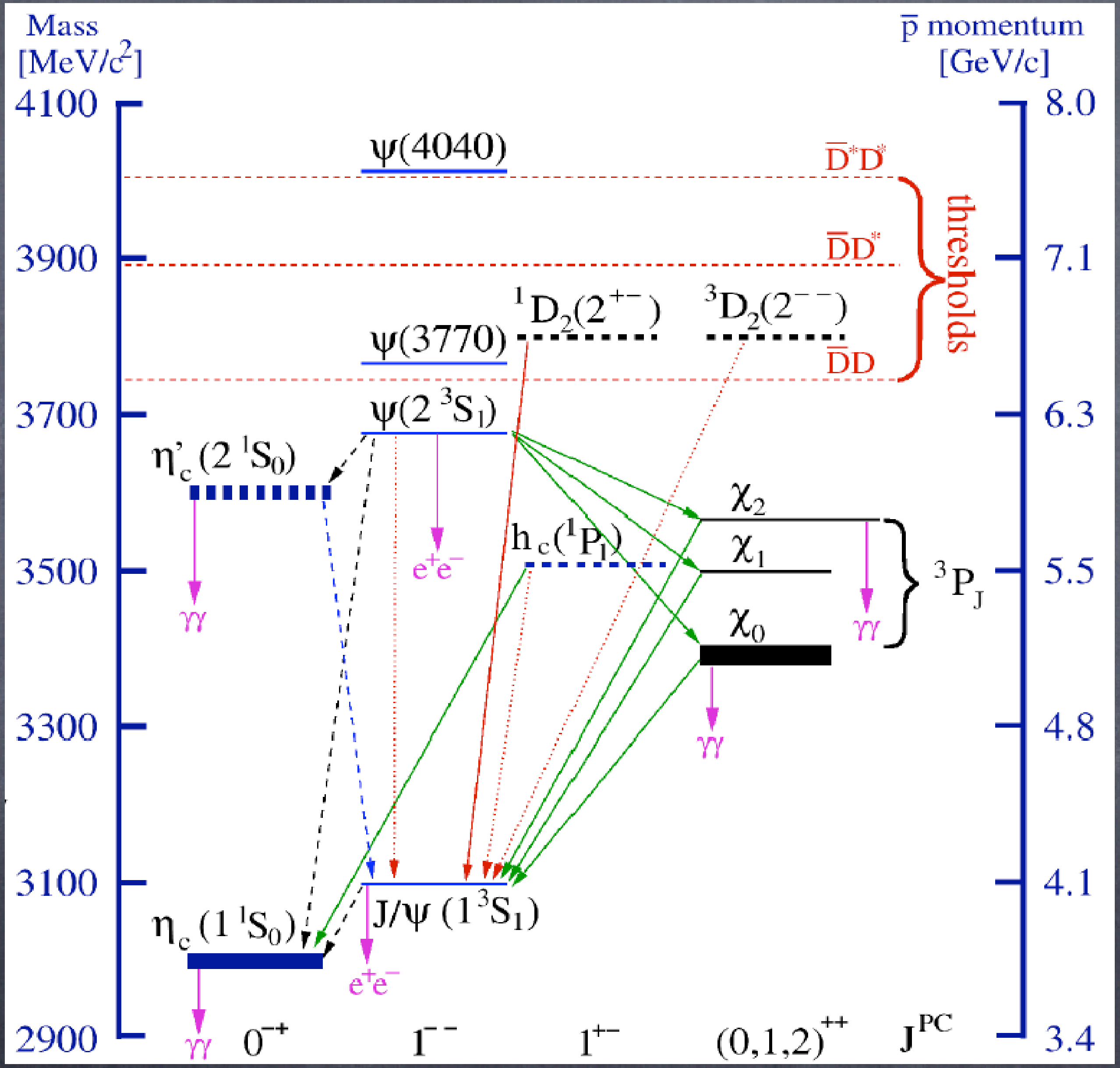




detect photons from radiative decay down to 10MeV

from U. Wiedner

Charmonium Spectroscopy



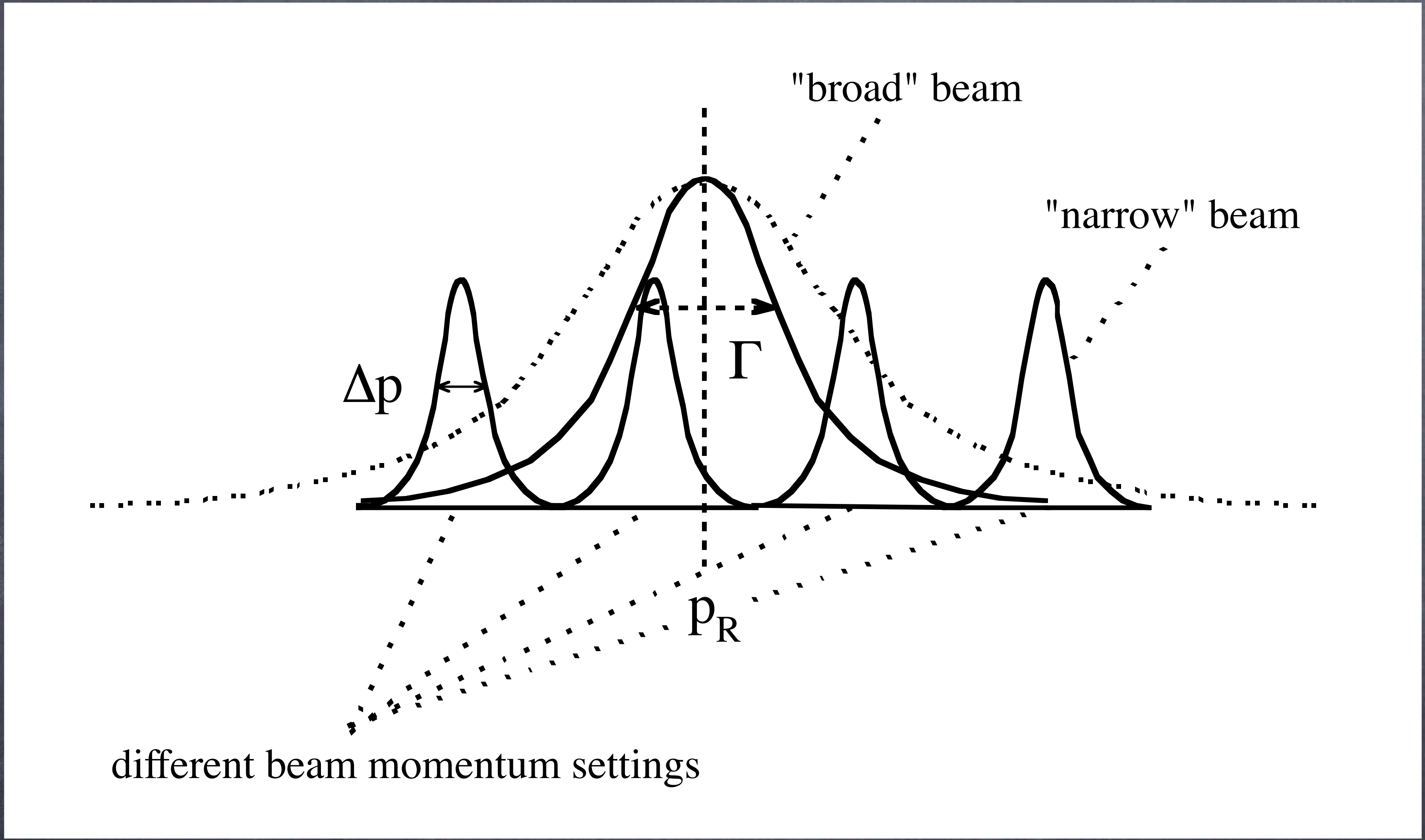
Prediction of Charmonium Production rates

Reaction	$\sigma^{max}_{p\bar{p}\to m\Psi}[pb]$	E^{max}_{cm} [GeV]	$A_D[\mathrm{GeV}^4]$
$p\bar{p} \to \pi^0 J/\psi$	420 ± 40	4.28	9.265
$p\bar{p} \to \eta J/\psi$	1520 ± 140	4.57	4.520
$p\bar{p} \to \rho^0 J/\psi$	< 450	4.80	2.114
$p\bar{p} \to \omega J/\psi$	1900 ± 400	4.80	2.053
$p\bar{p} \to \eta' J/\psi$	3300 ± 1500	4.99	0.765
$p\bar{p} \to \phi J/\psi$	280 ± 90	5.06	0.452
$p\bar{p} \to \pi^0 \psi'$	55 ± 8	5.14	30.50
$p\bar{p} \to \eta \psi'$	33 ± 8	5.38	20.98
$p\bar{p} \to \rho^0 \psi'$	38 ± 17	5.59	14.95
$p\bar{p} \to \omega \psi'$	46 ± 22	5.60	14.77
$p\bar{p} \to \phi \psi'$	< 28	5.84	9.12

Need to measure absolute cross section independent of detector resolution

A. Lundborg, T. Barnes, U. Wiedner: Phys. Rev. D73, 096003 (2006)

Resonance scan with narrow beam momentum



high resolution mode of HESR $\Delta p/p = 10^{-5}$

Recently discovered states in the charm sector

What is the nature of these states?

High Precision of beam and detector

Flatté form

Forschungszentrum Jülich
in der Helmholtz-Gemeinschaft

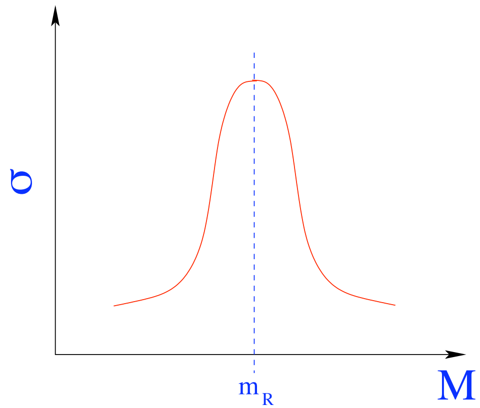
Introducing inelasticity (note $M = 2m + k^2/m$)

$$F \propto \frac{1}{M - m_R + i(g_M/2)\sqrt{m(M-2m)} + i\Gamma_l/2}$$

→ for quark states gives

$$F \simeq \frac{1}{M - m_R + i\Gamma_l/2}$$

Denominator
analytic in M
(Breit–Wigner)



Flatté form

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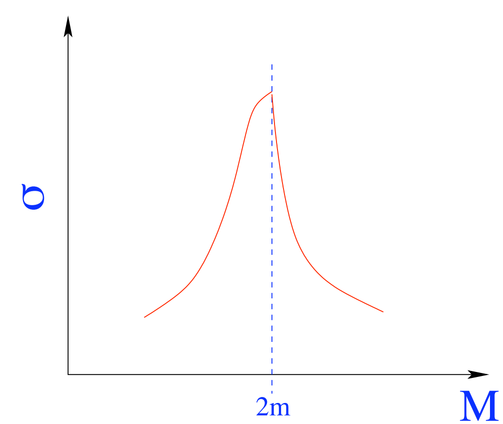
$$F \propto \frac{1}{M - m_R + i(g_M/2)\sqrt{m(M-2m)} + i\Gamma_l/2}$$

→ for molecules gives

$$F \propto \frac{1}{2m - m_R + i\frac{g_M}{2}k + i\frac{\Gamma_l}{2}}$$

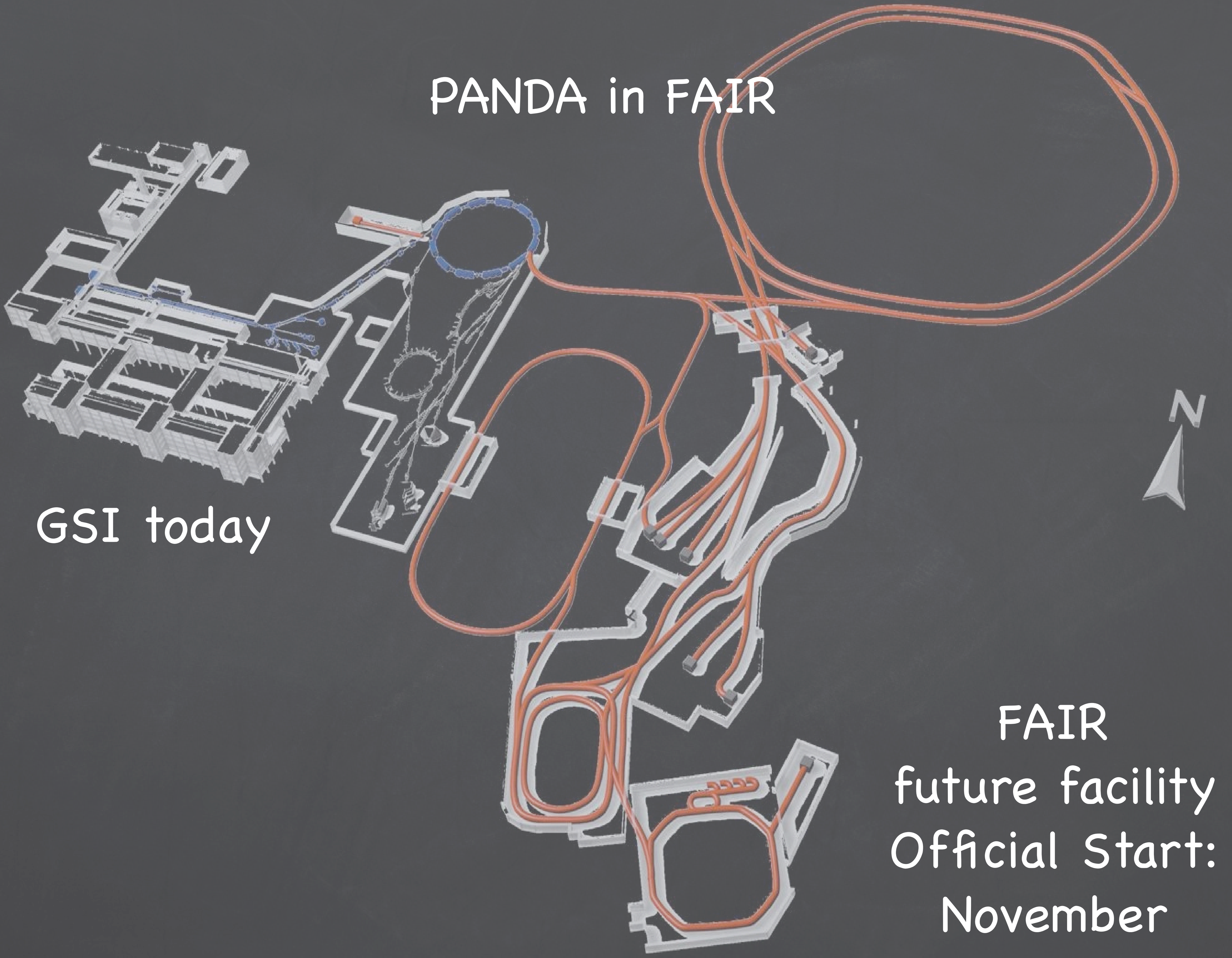
Denominator
non–analytic in M



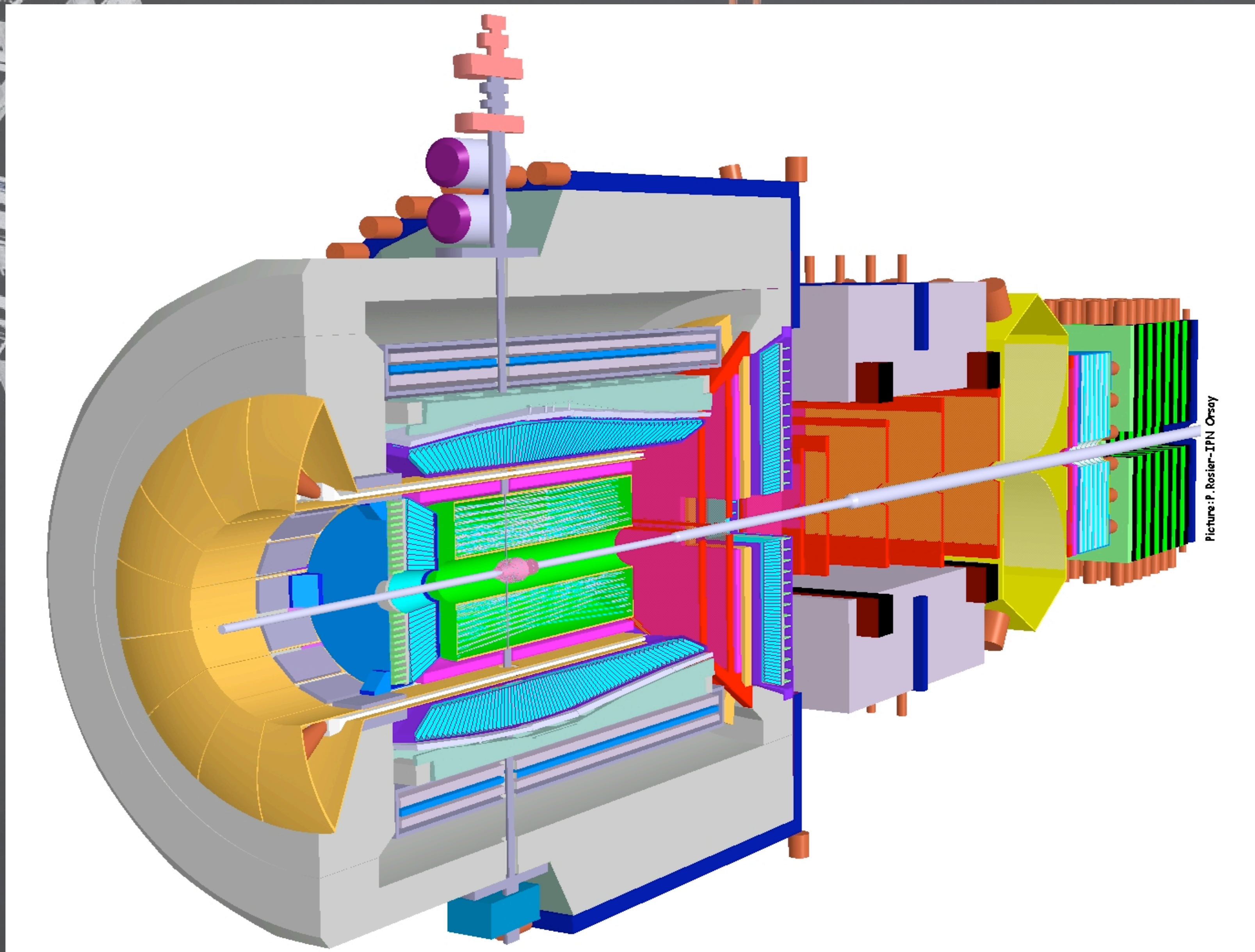
V. Baru, J. Haidenbauer, C. Hanhart, A. Kudryavtsev and U. G. Meissner
Eur. Phys. J. A 23, 523 (2005).

The PANDA Experiment in FAIR

PANDA in FAIR



PANDA in FAIR



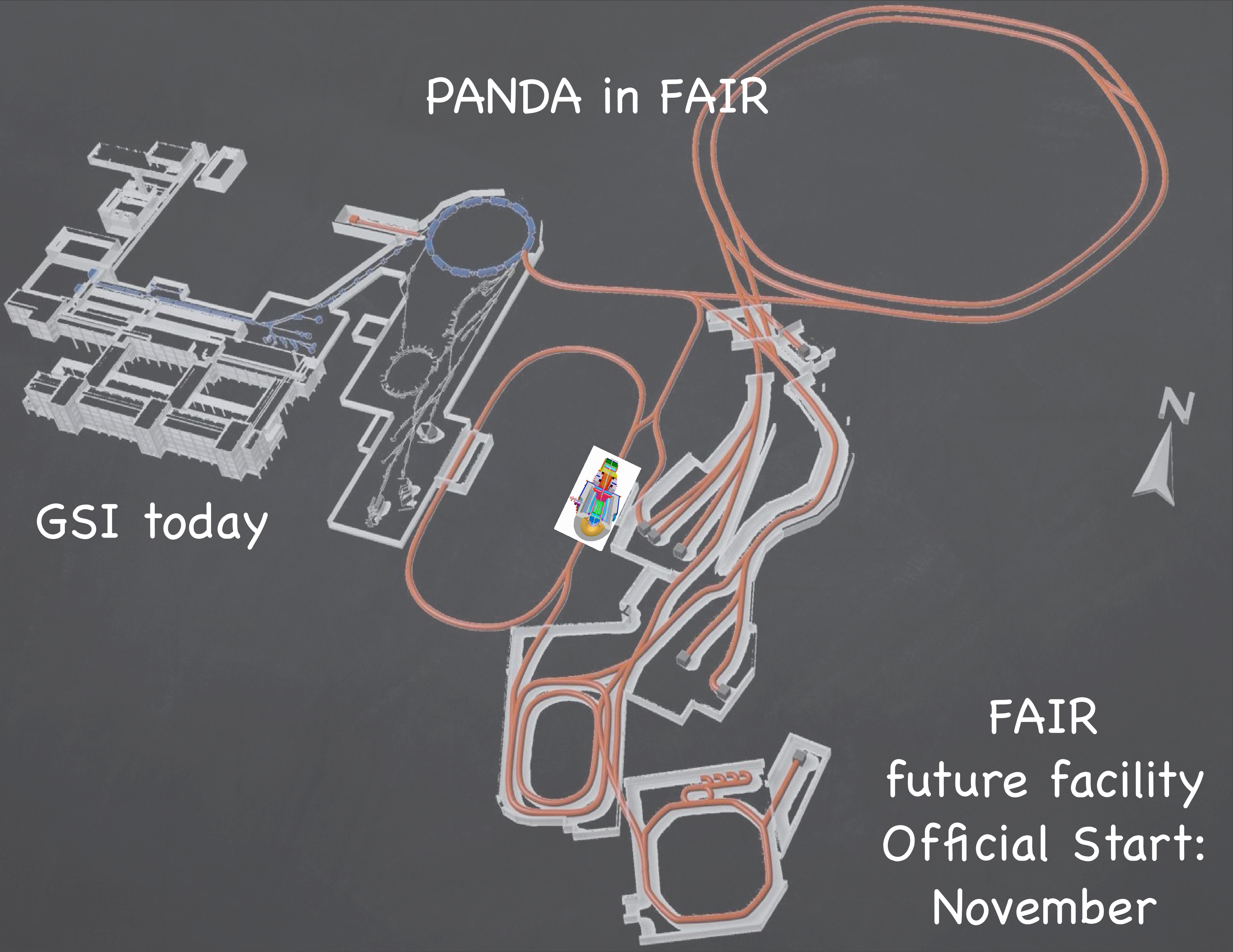
GSI

cility

tart:

November

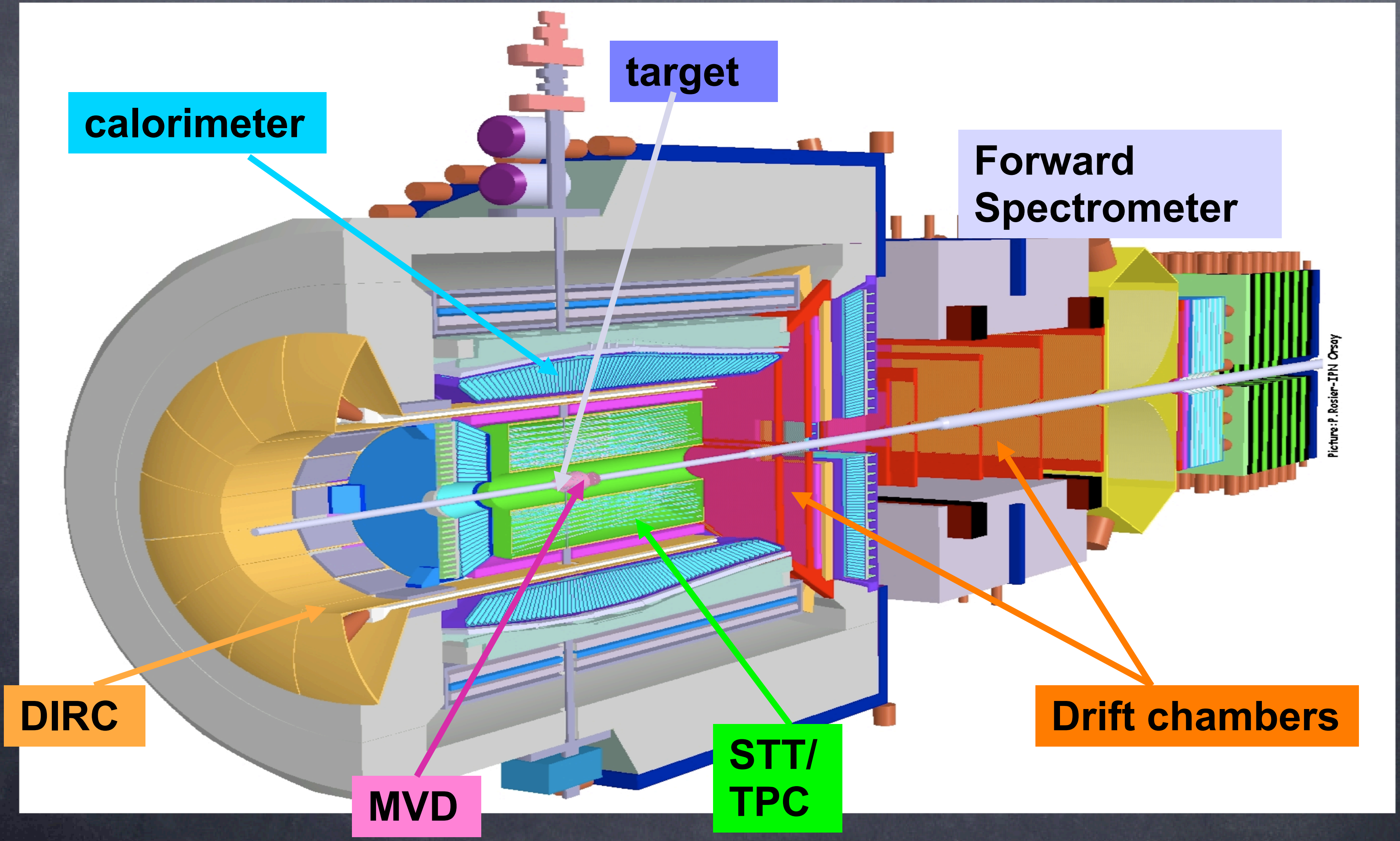
PANDA in FAIR



GSI today

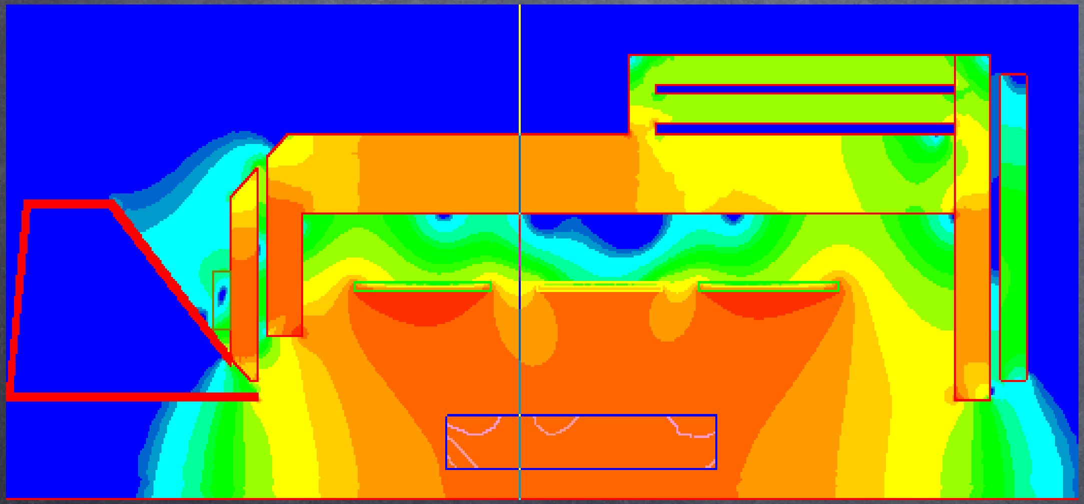
FAIR
future facility
Official Start:
November

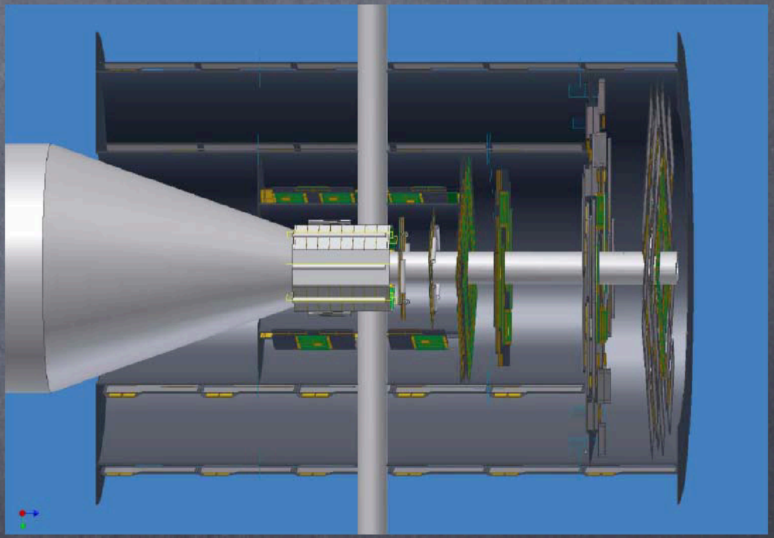
PANDA: the detector



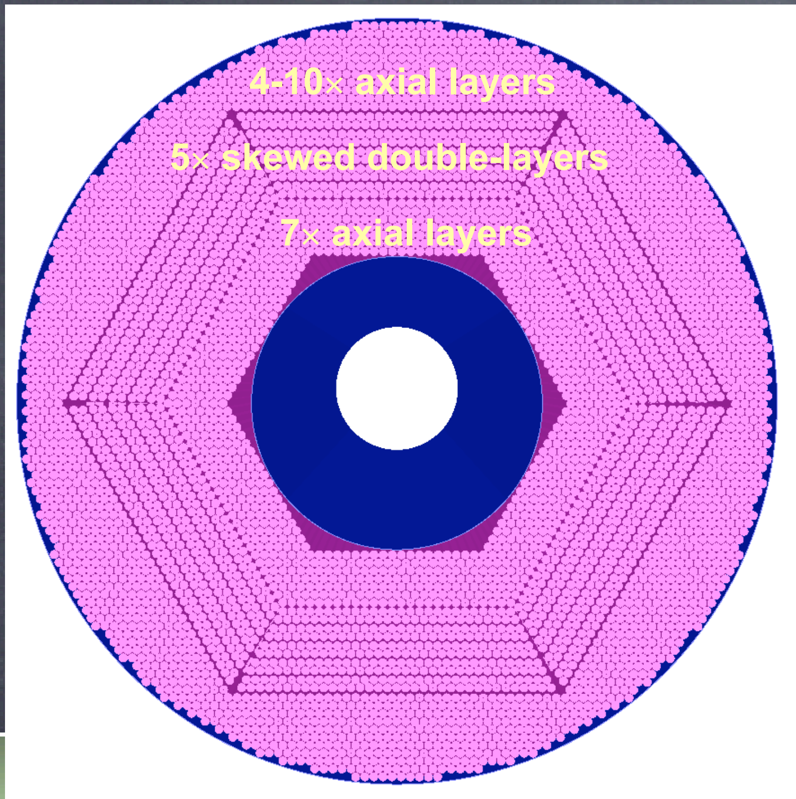
Target Spectrometer

- 2 T Solenoid, Uniformity 2%
- Gas Jet Droplet Target 2 10^{15} atoms/cm^{-2}
- Micro Vertex Detector (σ_{xyz} < 100 μm)

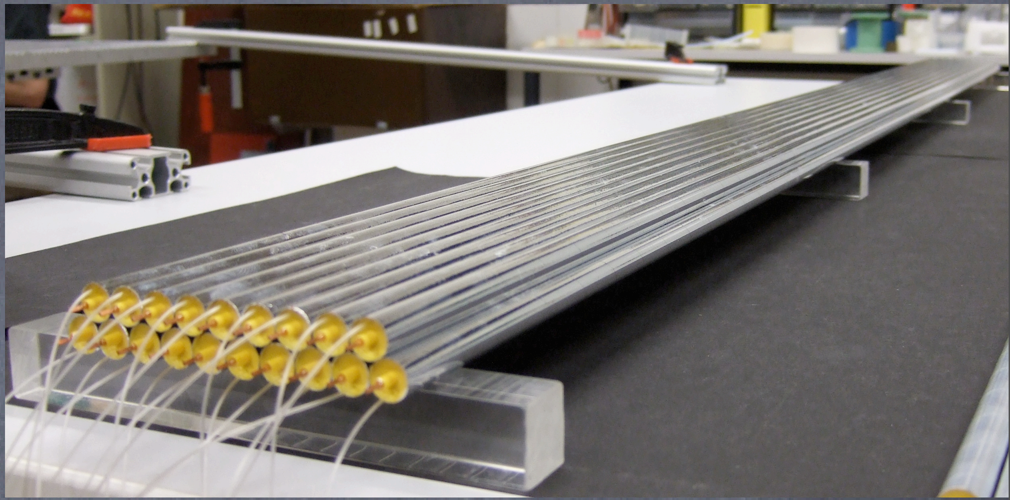


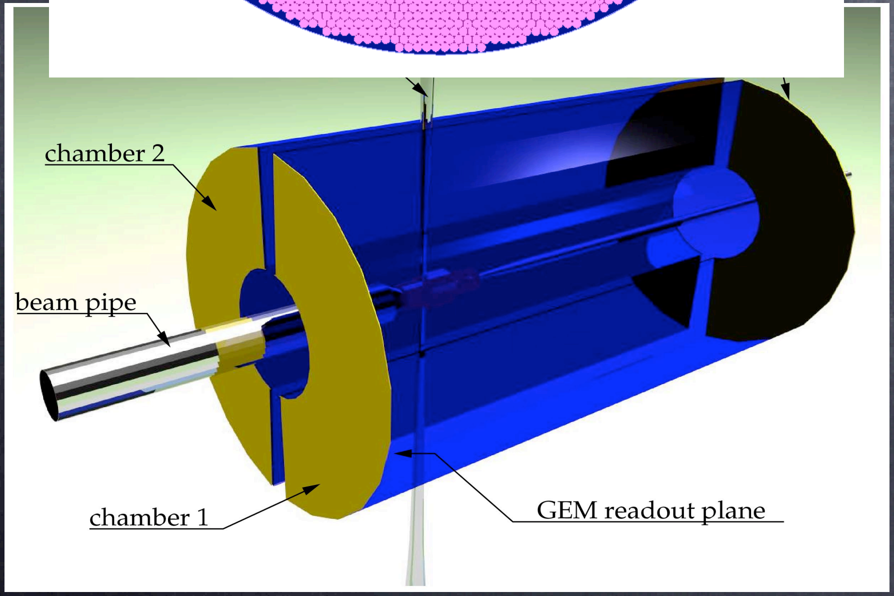


Target Spectrometer: Straw Tube Tracker <-> Time Projection Chamber

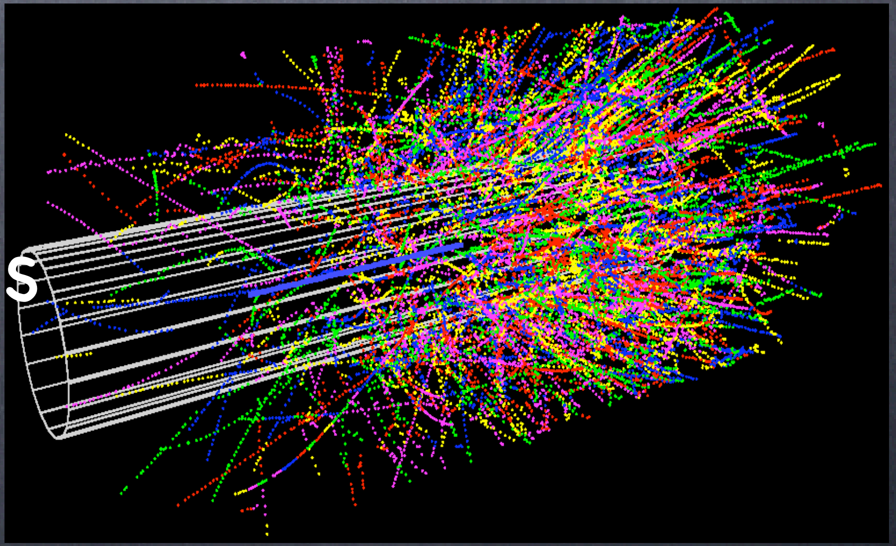


STT: 5000 Straws

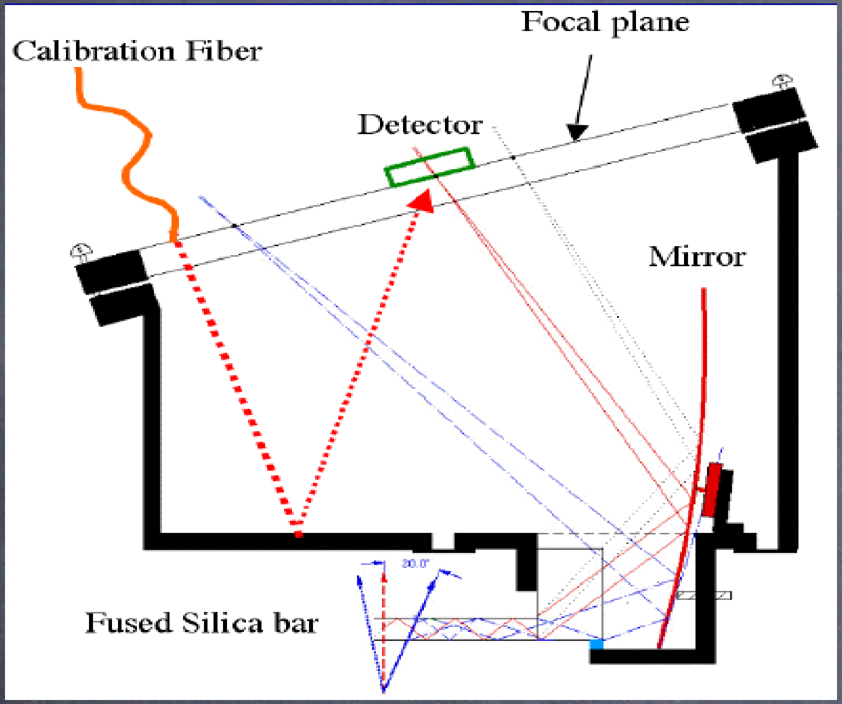


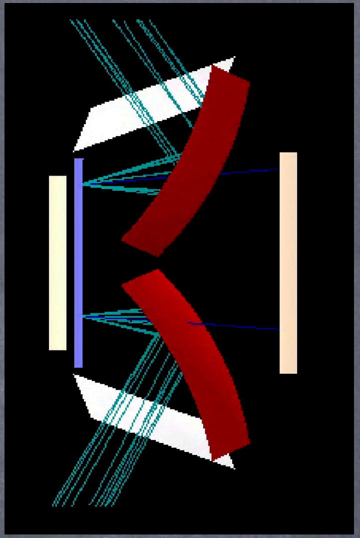


TPC: 10^5 channels

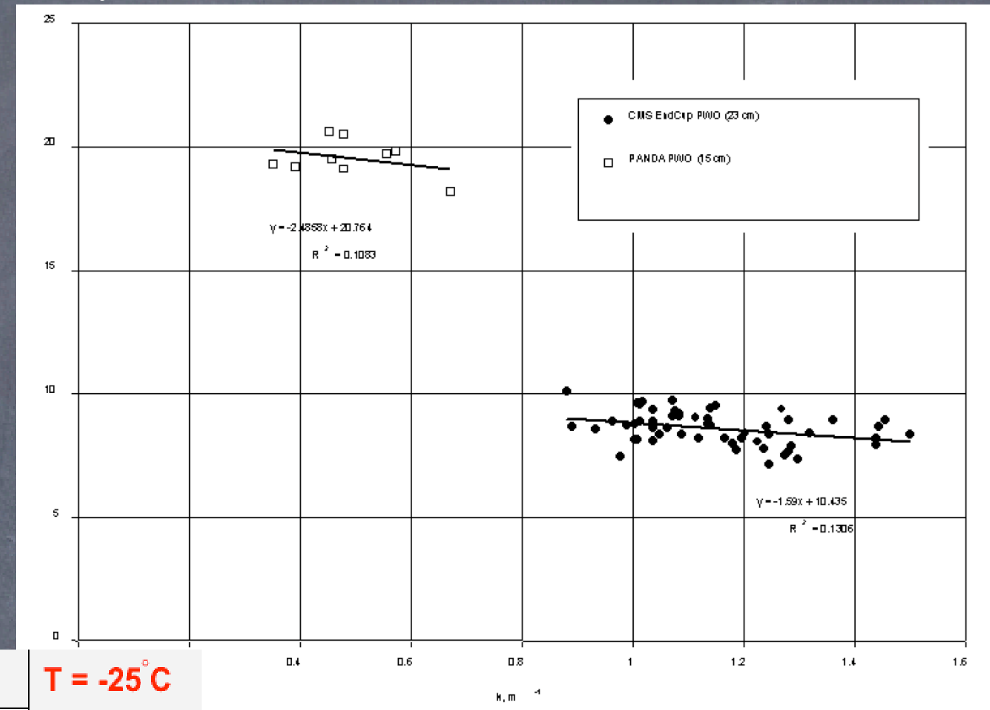


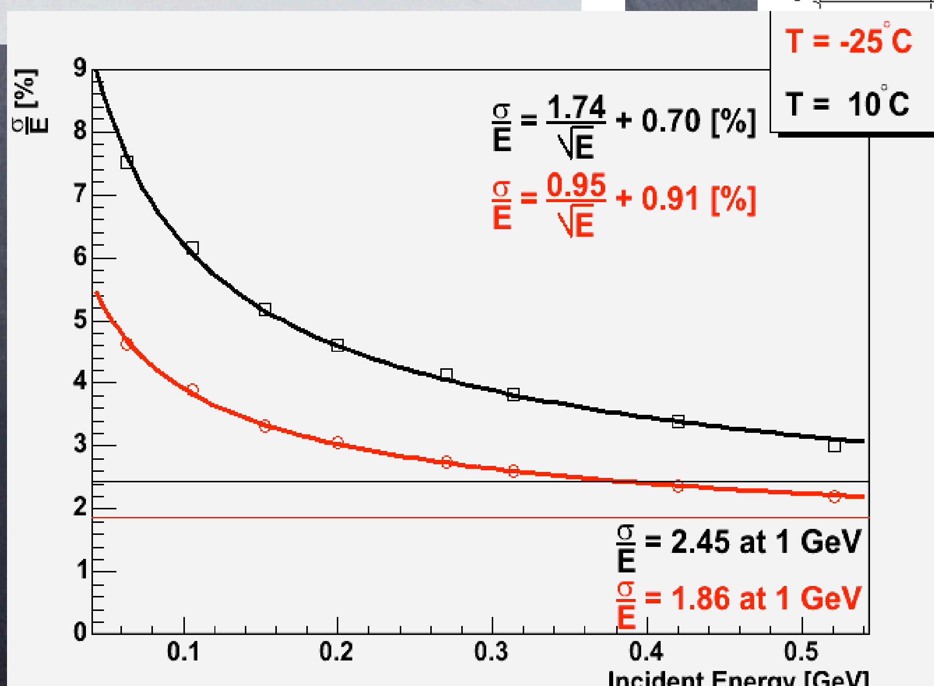
Particle Identification: DIRC and RICH





Electromagnetic Calorimeter
PWOII crystals

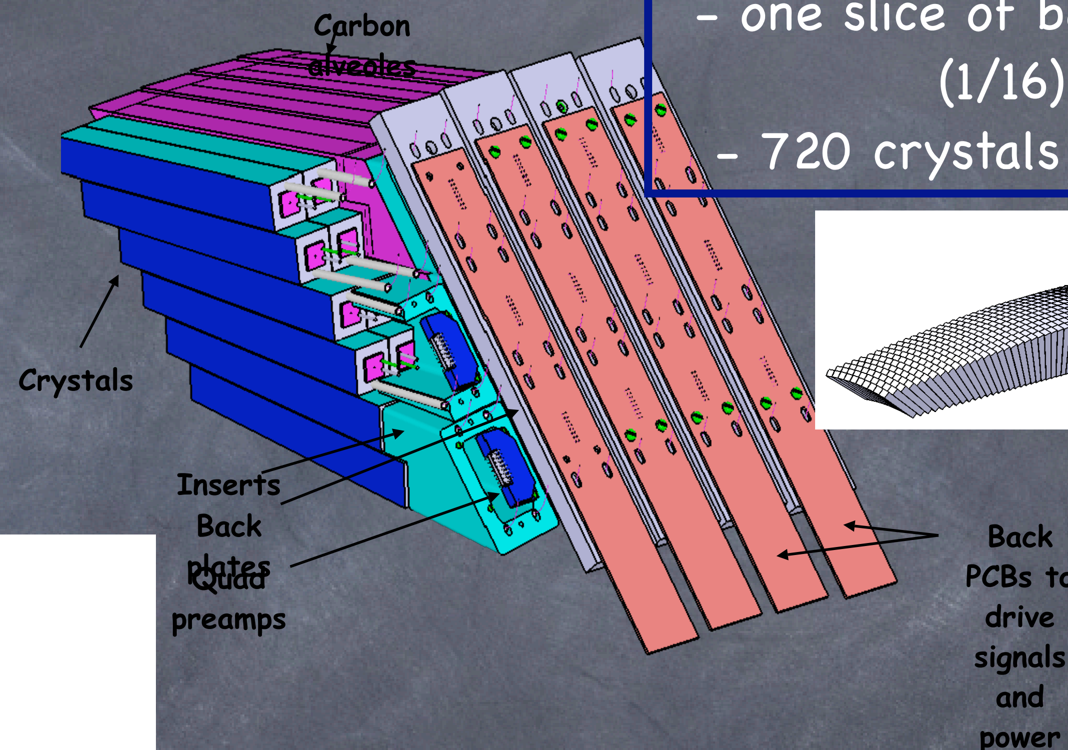




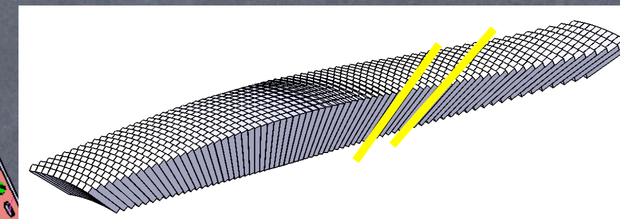
Light yield
and energy resolution
improved for PWOII
at -25°C

Mechanical and Thermal Design of the PANDA Barrel electromagnetic calorimeter

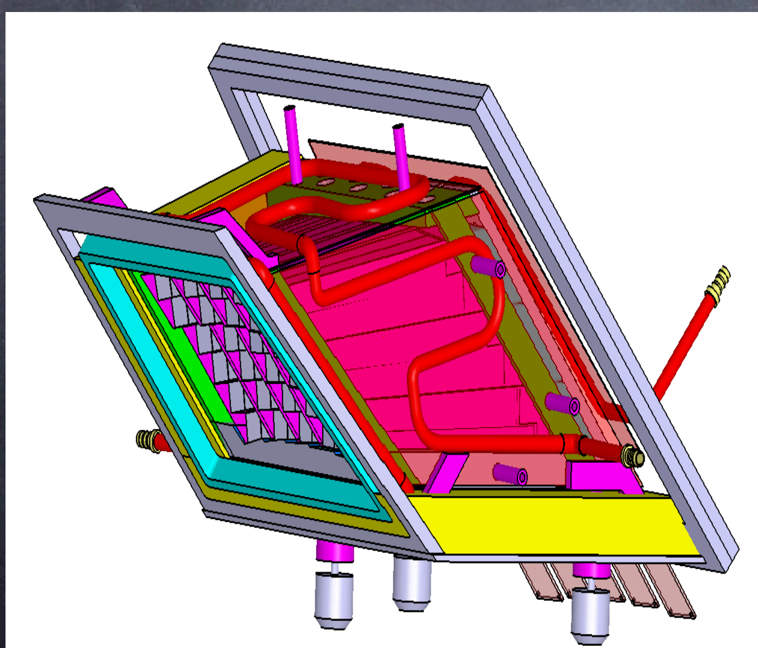
Carbon



- one slice of barrel ECAL (1/16)
- 720 crystals

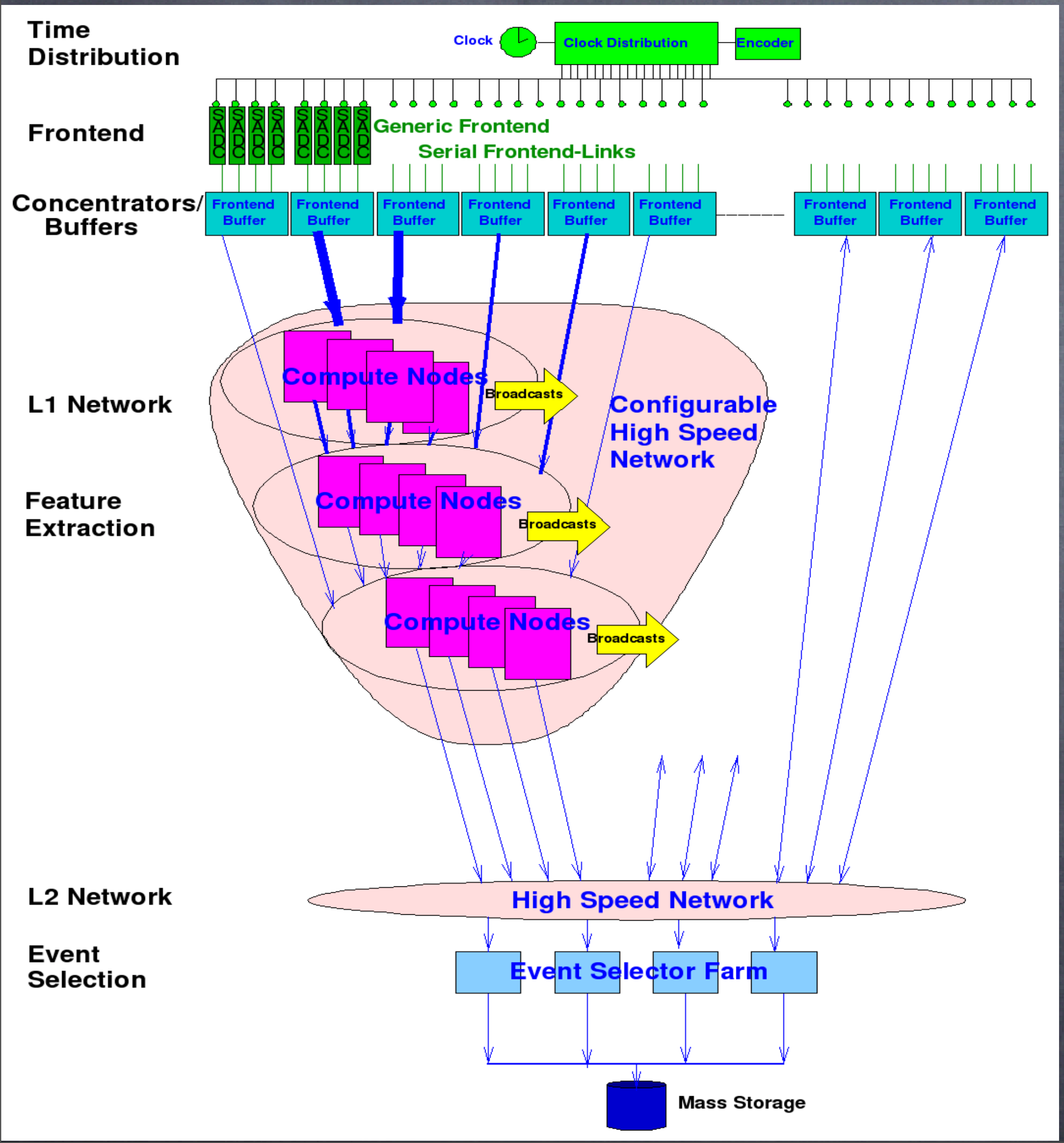


Thermal box -25°
stability~0.1°



60 crystals prototype now being tested (summer 2007)

Data Acquisition System



- high data rates: 50 - 200 GB/s
- up to 10^7 int/s
- self triggering
- parallel processing
- event selection
- time stamp

The Electromagnetic Form Factors with PANDA

Electromagnetic Form Factor

vector current of quarks $Q_f\, \bar{q}\gamma_\mu q$

Dirac — Pauli

$$\langle N(p')|\; Q_u \bar{u}\gamma_\mu u + Q_d \bar{d}\gamma_\mu d + \ldots \;|N(p)\rangle =$$

$$\langle \bar{p}|\; F_1(q^2)\, \gamma_\mu + i(\kappa_p/2M_p)\, F_2(q^2)\, \sigma_{\mu\upsilon} q^\mu \;|p\rangle$$

element of renormalisation group

vector current: two form factors

internal structure of hadron ground state

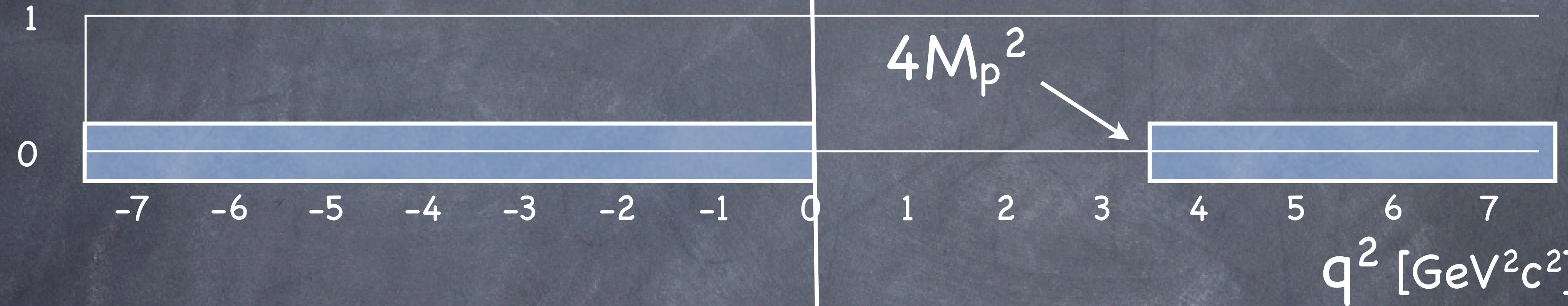
Dirac	Pauli
$F_1{}^p(q^2{=}0) = 1$	$F_2{}^p(q^2) = 1$
$F_1{}^n(q^2{=}0) = 0$	$F_2{}^n(q^2) = 1$

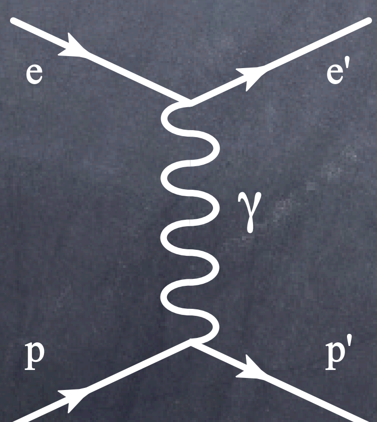
Definitions

$q^2 < 0$
space like

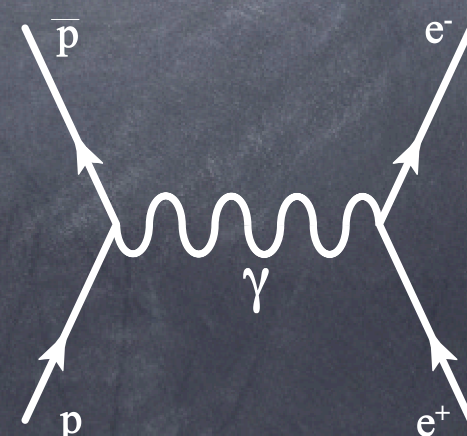
$q^2 > 0$
time like

$F_1(q^2)$





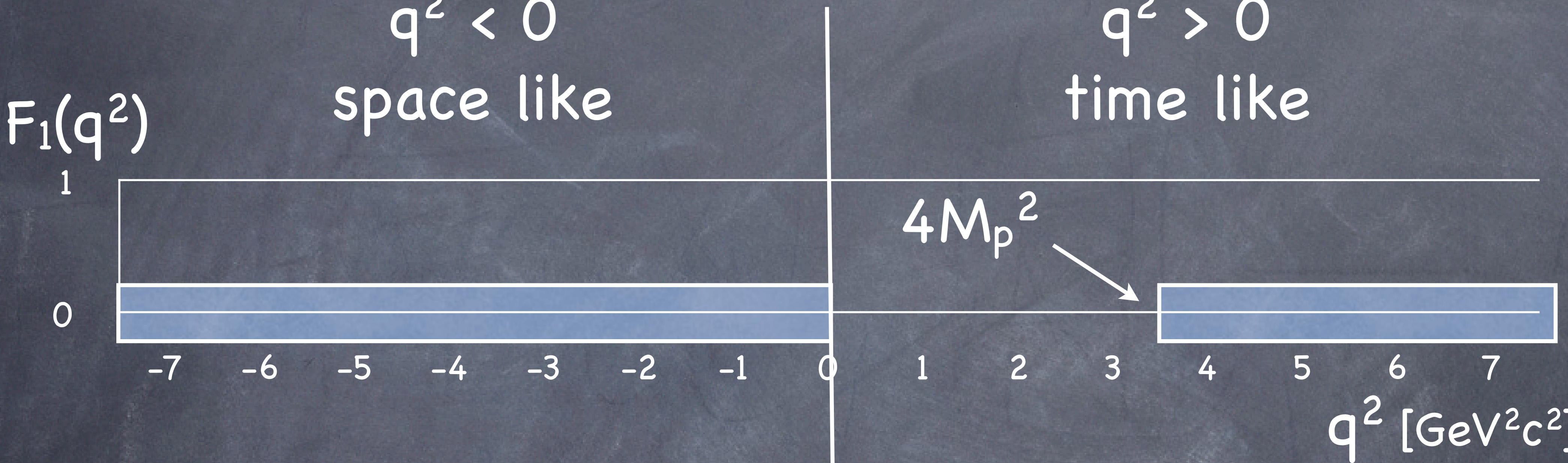
electron scattering



$m_e << m_p$

annihilation

Definitions



Form Factor real

Form Factor complex

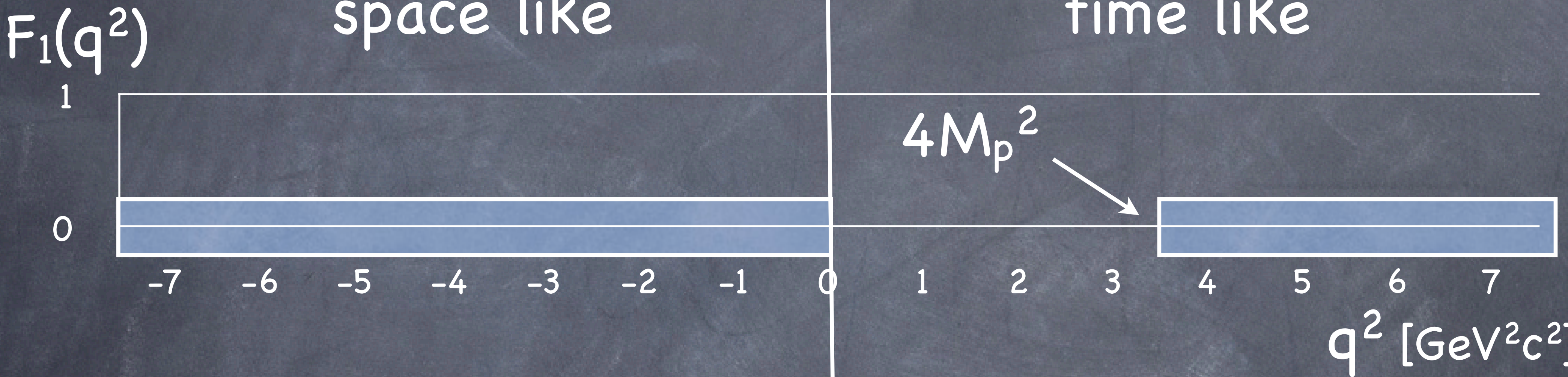
connected by Dispersion relations

no interference in cross section

$|F_1|, |F_2|$

Definitions

$q^2 < 0$ space like | $q^2 > 0$ time like



Form Factor real | Form Factor complex

connected by Dispersion relations

no interference in cross section

$|F_1|$, $|F_2|$

imaginary Part: Polarisation

Sachs Form Factor

$$G_E = F_1 + \tau F_2$$
$$G_M = F_1 + F_2$$

space like:

Fourier transform of charge and magnetisation

time like ($q^2 > 0$):

at threshold, $\tau = 1$

$G_E(4\ M_p^2) = G_M\ (4\ M_p^2)$

G_E, G_M analytical continuation of nonspinflip and spinflip spacelike FF

Sachs Form Factor

$$G_E = F_1 + \tau F_2$$
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Fourier transform of charge and magnetisation

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at threshold, $\tau = 1$

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G_E,G_M analytical continuation of nonspinflip and spinflip spacelike FF

$$R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)}$$

$$R(t) = R(0) + \frac{t}{\pi}\int_{s_0}^{\infty} \frac{\mathrm{Im}[R(s)]}{s(s-t)} ds$$

$$\mathrm{Re}[R(s)] = R(0) + \frac{s}{\pi}\mathcal{P}\int_{s_0}^{\infty} \frac{\mathrm{Im}[R(s')]}{s'(s'-s)} ds'$$

Perturbative QCD

$\lim_{q^2 \to \infty}$

$F_1(q^2) \propto \alpha_s \, q^{-4}$ $F_2(q^2) \propto \alpha_s \, q^{-6}$

$F_{1,2}(q^2)^{\text{time like}} = F_{1,2}(q^2)^{\text{space like}}$

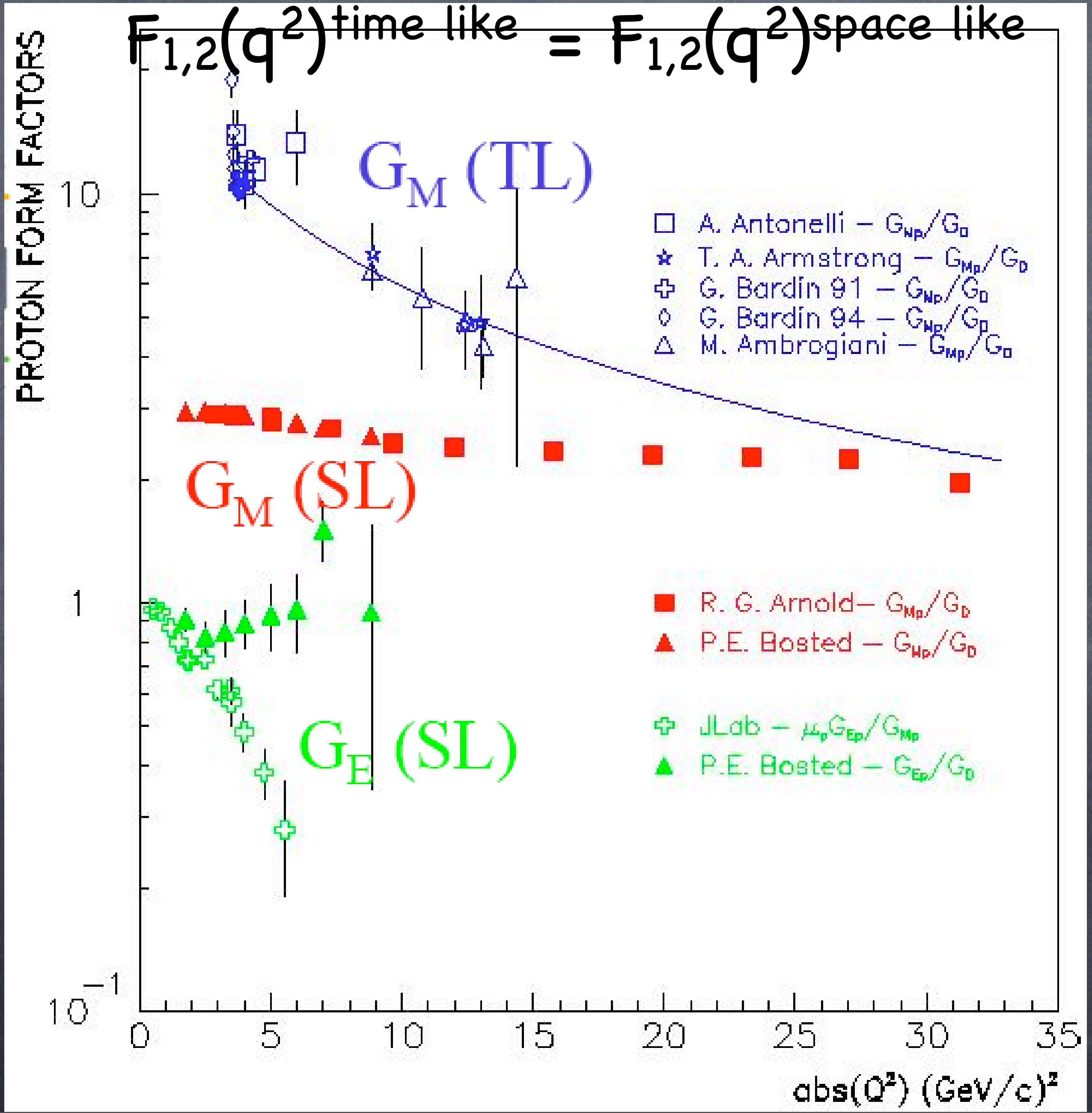
Form Factors in space like and time like intimately connected

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \rho(s)}{4s} \left(|G_M^p(s)|^2 (1 + \cos^2(\theta)) + \frac{1}{\tau} |G_E^p(s)|^2 \sin^2(\theta) \right)$$

$$\tau = s/4M_p^2$$

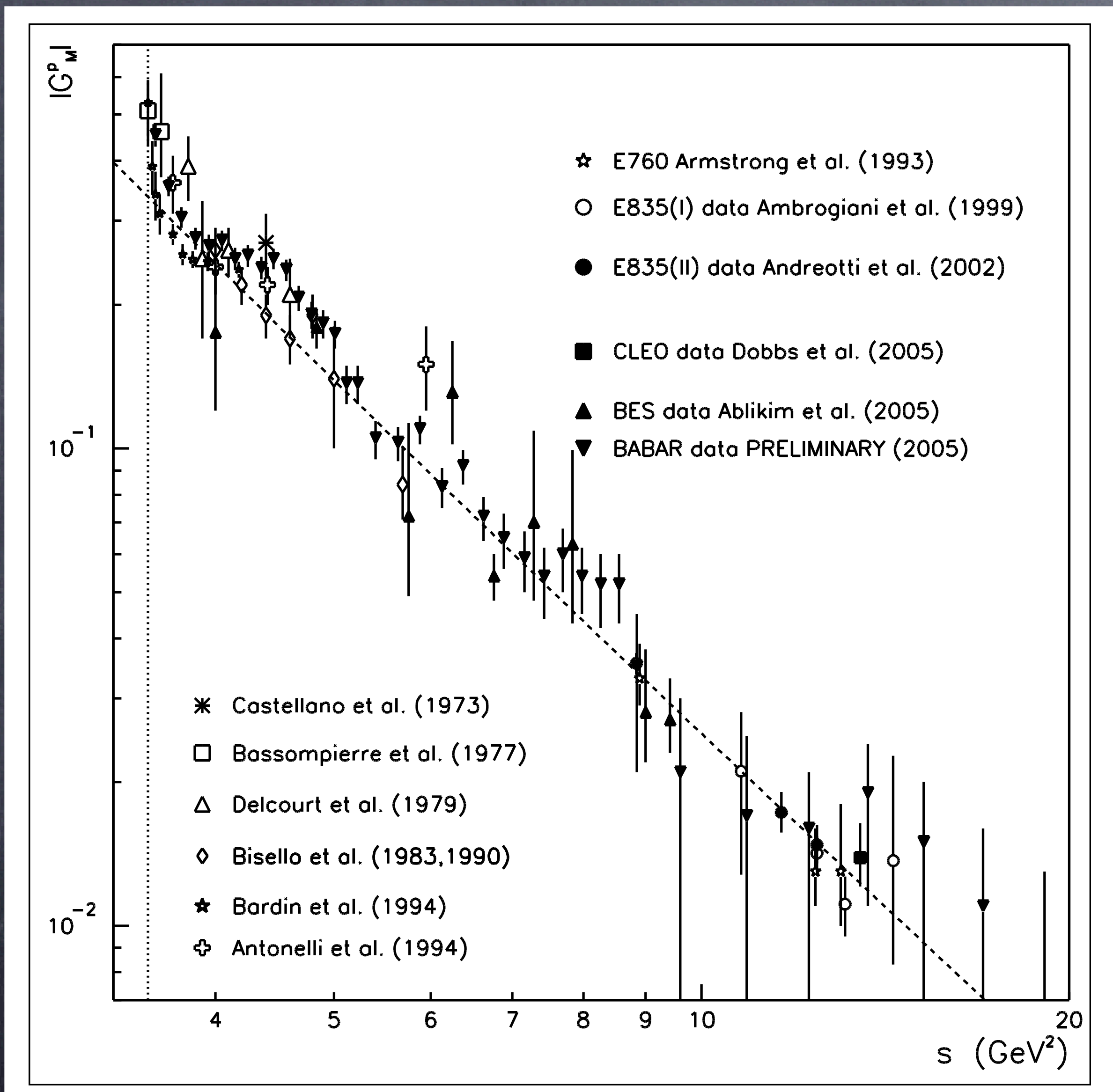
Perturbative QCD

$$F_{1,2}(q^2)^{\text{time like}} = F_{1,2}(q^2)^{\text{space like}}$$



from E. Tomasi-Gustafson

EM form factor ($q^2 > 0$)



Adone e^+e^-: 25, 69 ev.

ELPAR $\bar{p}p$: 34 ev.

DM1,2 e^+e^-: 63, 172 ev.

$|G_E|/|G_M| = 0.34$

PS170 $\bar{p}p$: 3667 ev.

$|G_E|/|G_M| \approx 1$

E760 $\bar{p}p$: 29 ev.

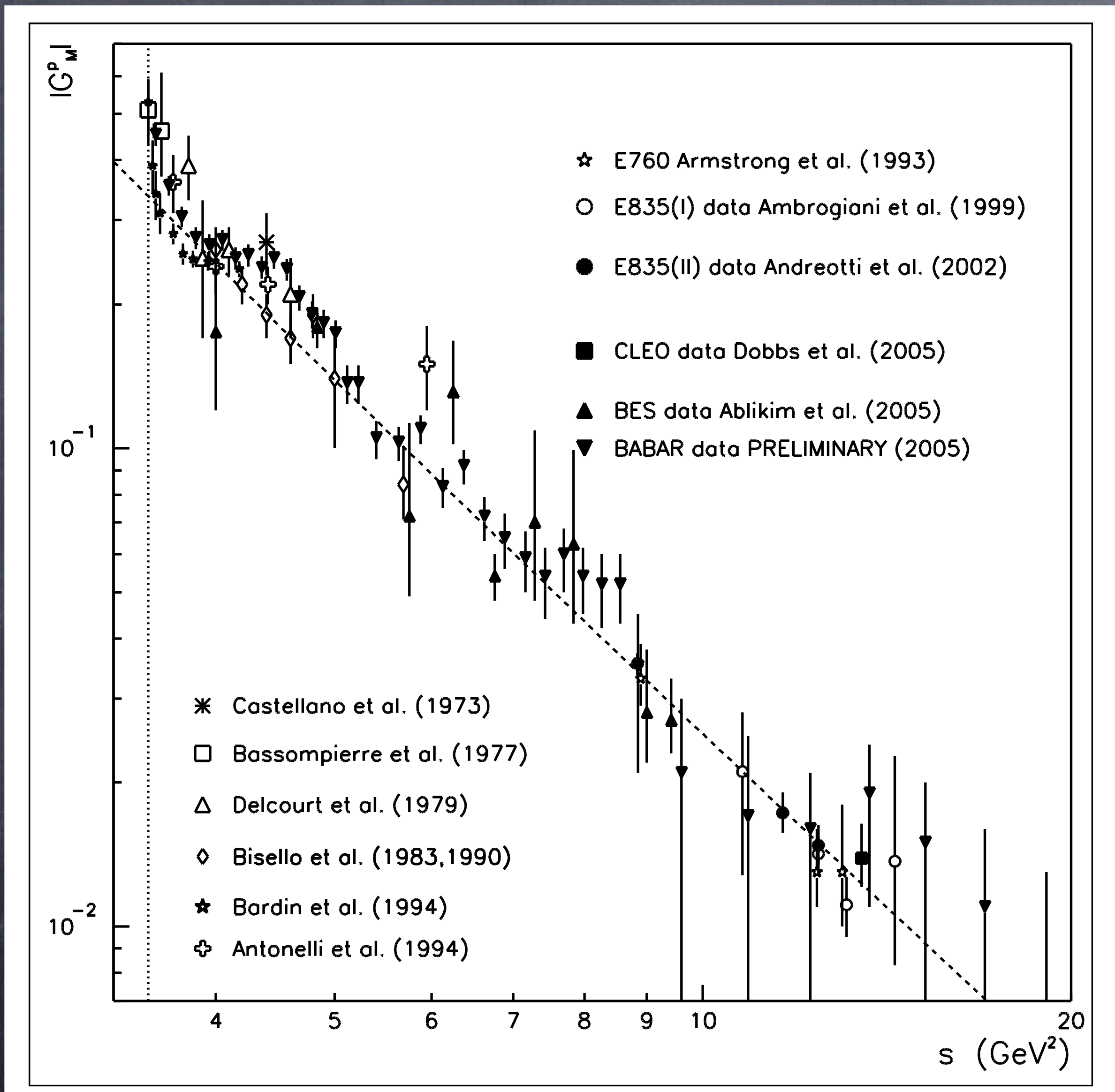
E835 $\bar{p}p$: 206 ev.

CLEO e^+e^-: 14 ev.

BES e^+e^-: higher stat

BaBar e^+e^-: high stat

EM form factor ($q^2 > 0$)



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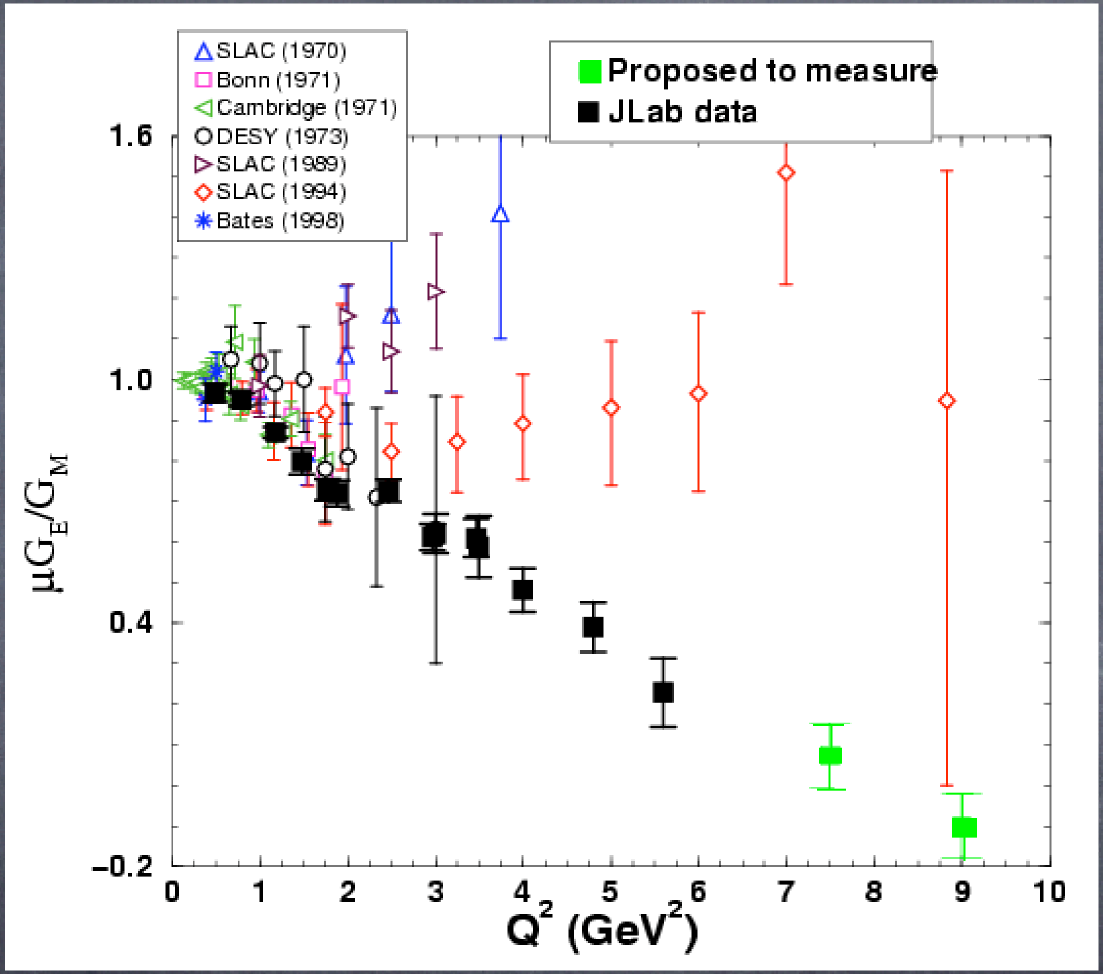
BaBar e^+e^-: high stat

All data: Measure absolute cross section $G_E = G_M$

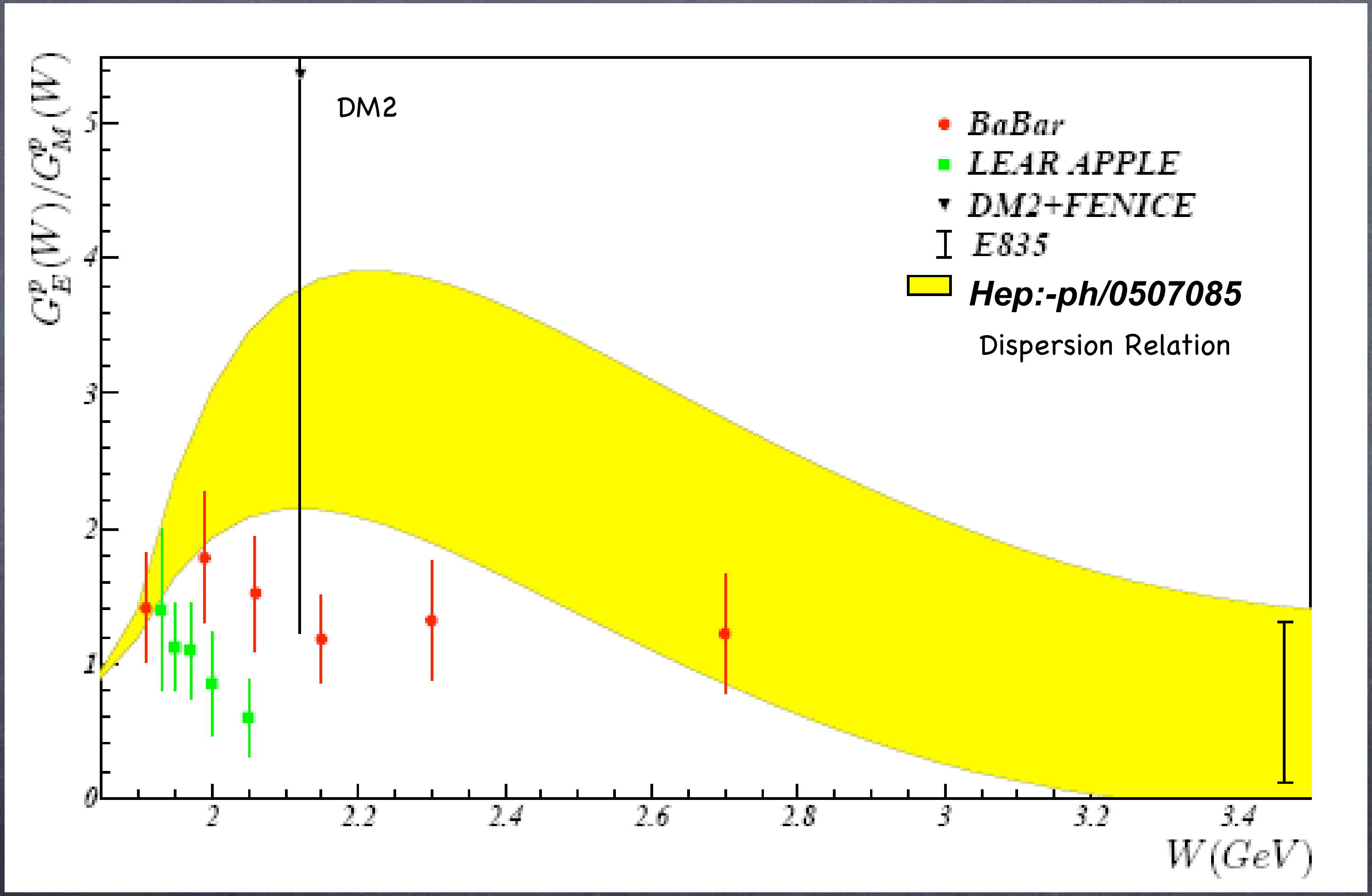
EM form factor ($q^2 < 0$) recent data



"Polarisation transfer"-technique:

$\mu_P \, G_E \neq G_M$

EM form factor ($q^2 > 0$)
$|G_E|/|G_M|$



$\sqrt{4M_p^2}$

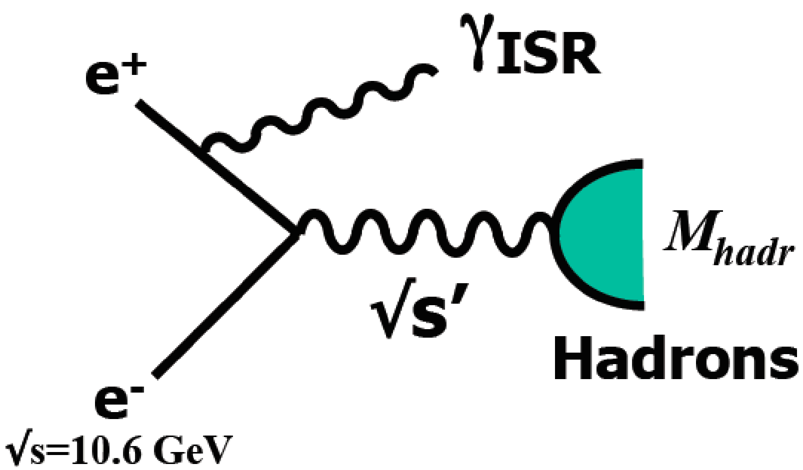
The Electromagnetic Form Factors with BaBar
(initial state radiation, ISR)

Radiative Return

Modern particle factories such as **DAΦNE or PEP-II are designed for a fixed center-of-mass-energy**: e.g. $\sqrt{s} = m_{\Upsilon(4S)} = 10.6$ GeV in case of PEP-II

Energy-Scan impossible!

Complementary approach :
Consider events with Initial State Radiation (***ISR***)



Master-Formula:

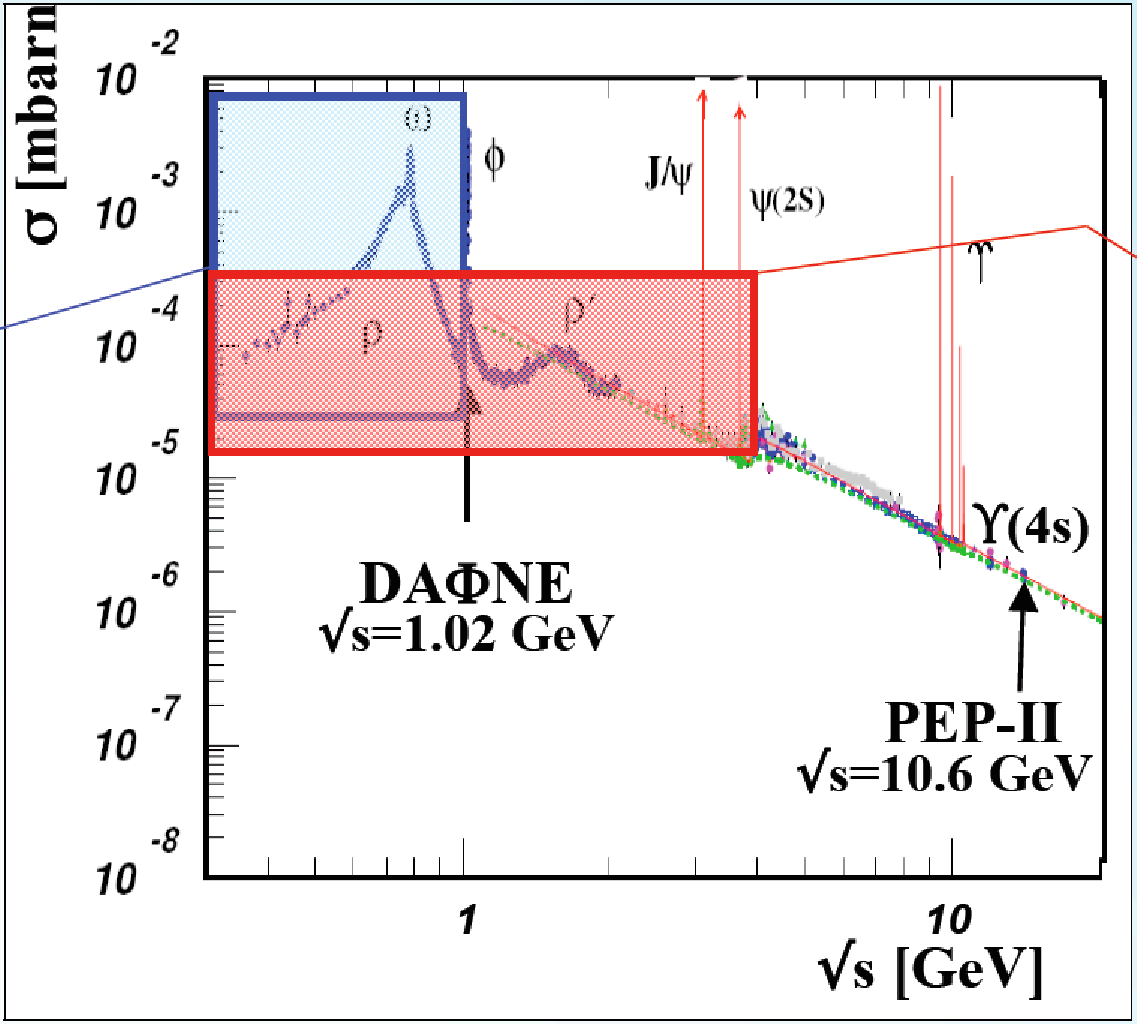
$$M_{hadr} \frac{d\sigma_{Hadr+\gamma}}{dM_{hadr}} = \sigma_{hadr}(s) \times H(s)$$

Radiator-Function (NLO)
MC-Generators EVA, Phokhara, AfkQed
J. Kühn, H. Czyz, G. Rodrigo

Data comes as a by-product to the main physics goals of the particle factories

Radiative Return at Particle Factories

Experiment KLOE:
Energy region < 1 GeV, dominated by 2π-channel (ρ-resonance)

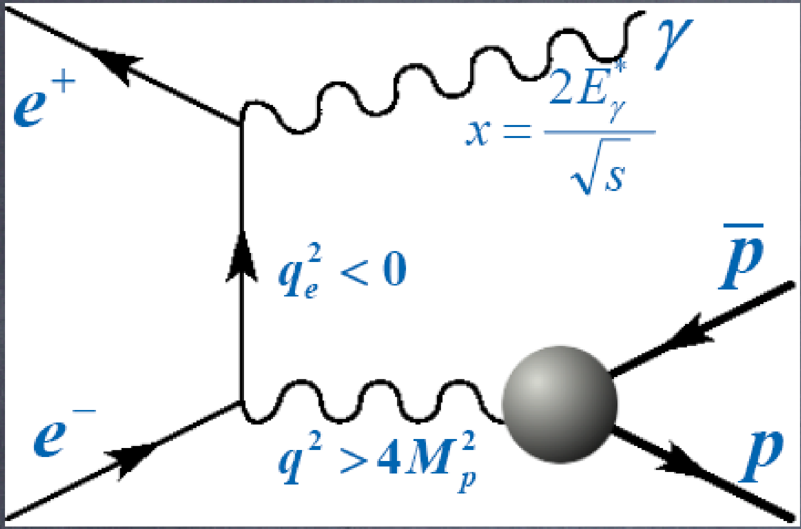


Experiment BaBar:
Energy region 1 ... 3 GeV, dominated by higher multi-plicities (esp. 4π), up to recently data with 20 ... 50% systematic errors!

Using the method of the **Radiative Return** one can study the entire **energy region below ca. 4...5 GeV**!

EM form factor ($q^2 > 0$)

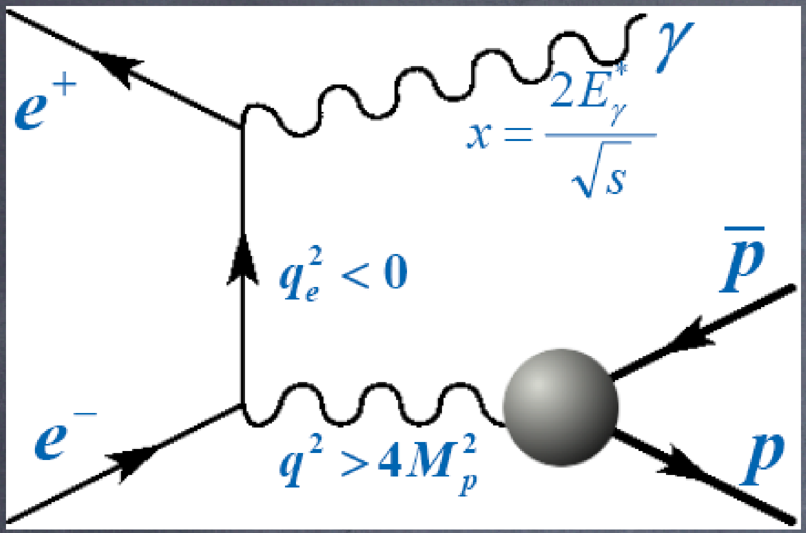
Babar: Initial state radiation (ISR), radiative return

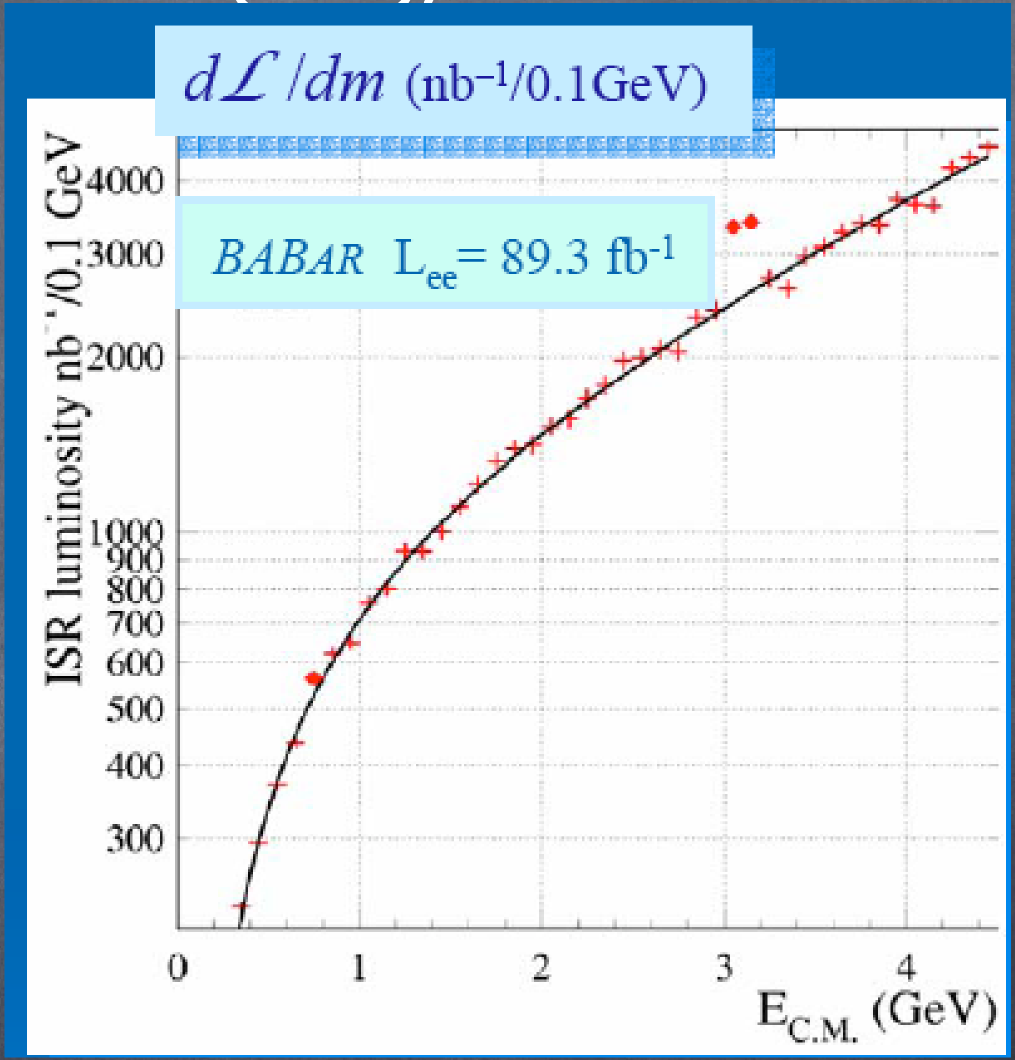


Thanks to V. Zallo and F. Annulli INFN Frascati

EM form factor ($q^2 > 0$)

Babar: Initial state radiation (ISR), radiative return

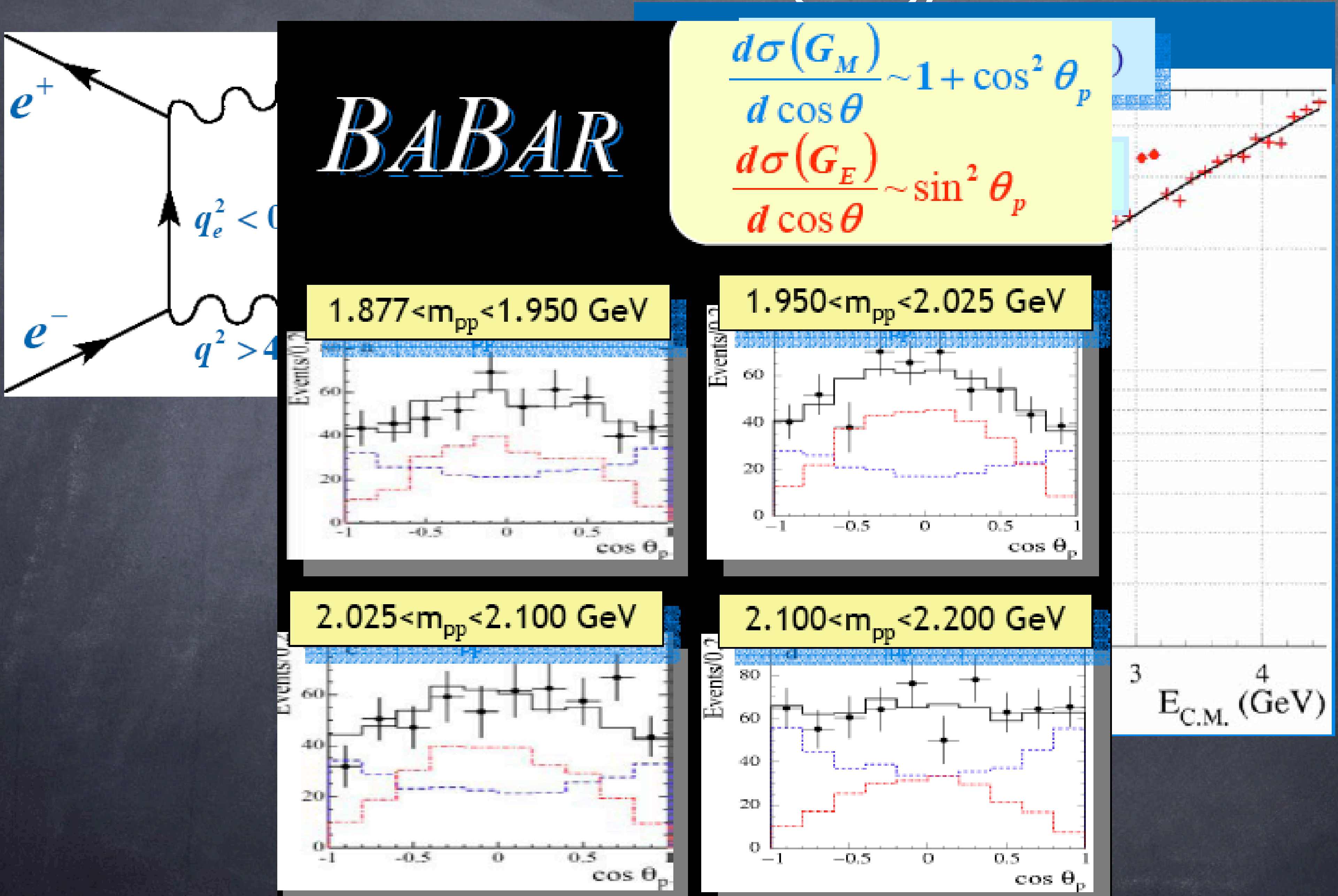




Thanks to V. Zallo and F. Annulli INFN Frascati

EM form factor ($q^2 > 0$)

Babar: Initial state radiation (ISR), radiative return



Thanks to V. Zallo and F. Annulli INFN Frascati

Synopsis

- cross section measurements in time like region
- electromagnetic form factors basically unknown
- space like $|G_E| \neq |G_M|$
- time like: fits to perturbative expectation

$$F_1(q^2) \propto \alpha_s\, q^{-4} \qquad F_2(q^2) \propto \alpha_s\, q^{-6}$$

but: $F_{1,2}(q^2)^{\text{time like}} = 2\, F_{1,2}(q^2)^{\text{space like}}$

- new proposals at BES, VEPP2000 and DAΦNE II

unique possibility to measure $|G_E|$ and $|G_M|$
with the PANDA - Detector at GSI with high stat.

The Electromagnetic Form Factors with PANDA

Rosenbluth Technique (time like)

$\bar{p}p \rightarrow e^+e^-$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\rho(s)}{4s}\left(|G_M^p(s)|^2(1+\cos^2(\theta)) + \frac{1}{\tau}|G_E^p(s)|^2\sin^2(\theta)\right)$$

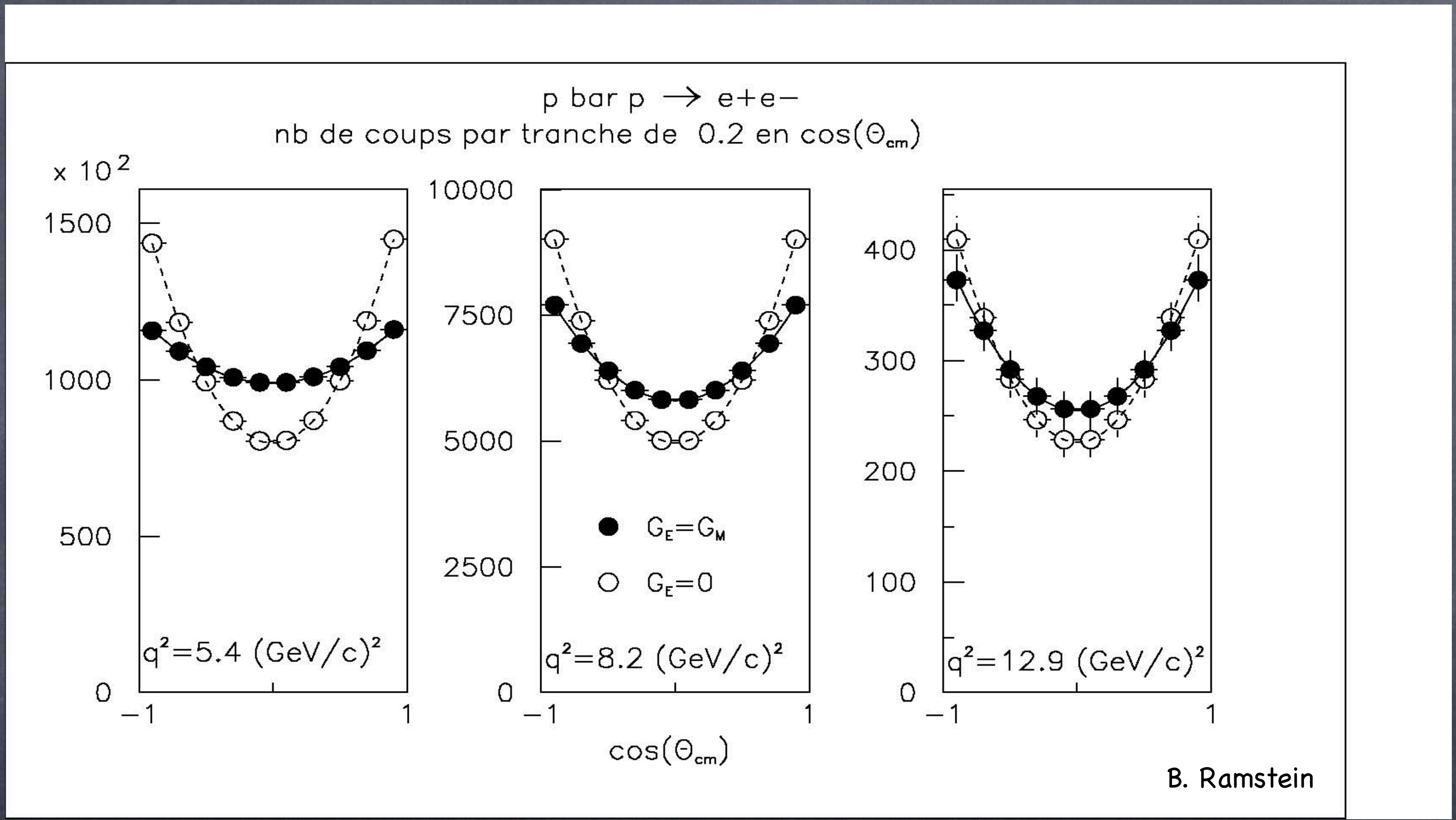
$$\tau = s/4M_p^2$$

$G_E = F_1 + F_2$

$G_M = F_1 + \tau F_2$

at threshold: $G_E = G_M$

Physics: Counting Rates and |G_E|/|G_M|separation



T=1 GeV T=5GeV T=10GeV

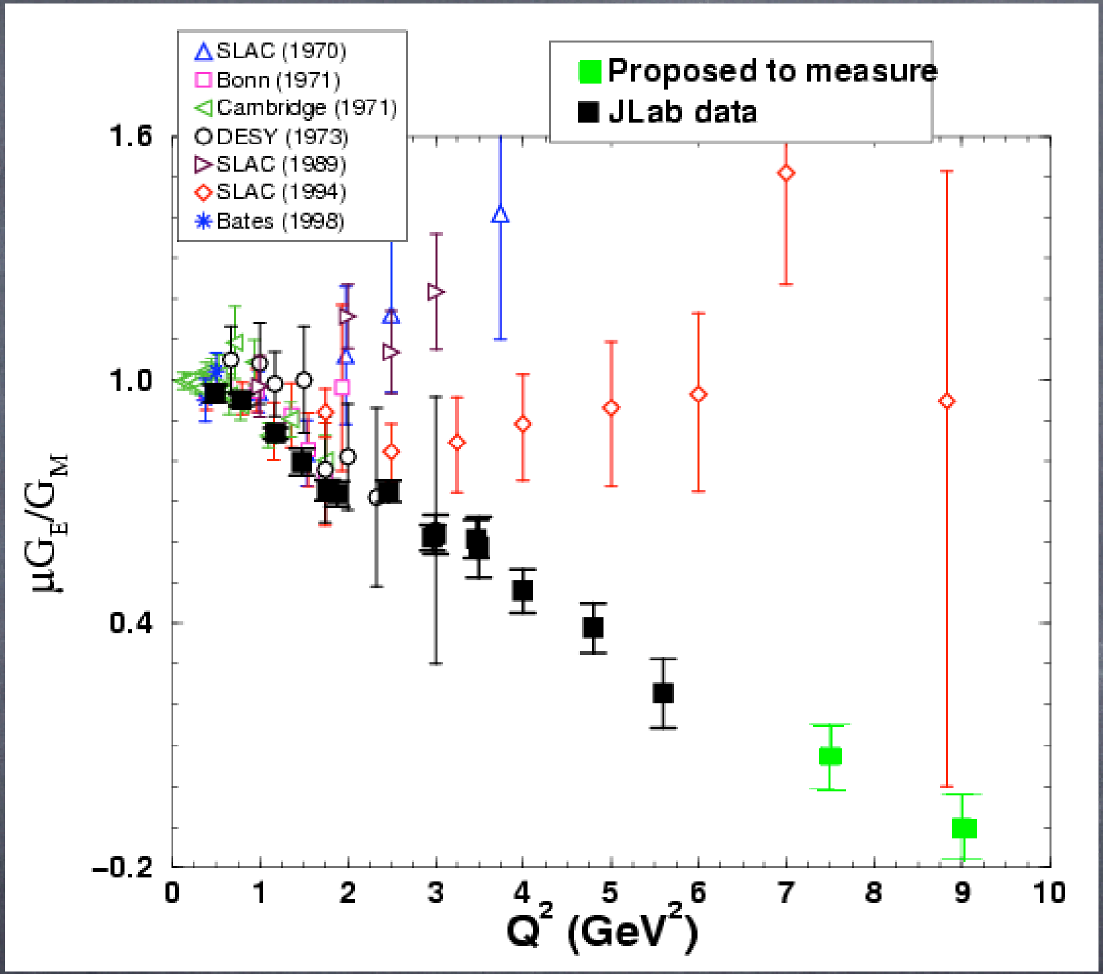
q^2=5.4(GeV^2/c) q^2=12.9(GeV^2/c) q^2=22.3(GeV^2/c)

100 days, L=2 10^{32} $cm^{-2}s^{-1}$, 2 fb^{-1}

N_{tot} = 10^6 N_{tot} = 2750 N_{tot} = 82

Fermilab: 14 evts at 13 $(GeV/c)^2$

EM form factor ($q^2 < 0$) recent data



"Polarisation transfer"-technique:

$$\mu_P \, G_E \neq G_M$$

Unpolarized cross section

dapnia
cea
saclay

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}D,$$

$$D = (1+\cos^2\theta)(|G_M|^2 + 2ReG_M\Delta G_M^*) + \frac{1}{\tau}\sin^2\theta(|G_E|^2 + 2ReG_E\Delta G_E^*) + 2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re(\frac{1}{\tau}G_E - G_M)F_3^*.$$

2γ–contribution:

- **Induces four new terms**
- **Odd function of *θ*:**
- **Does not contribute at *θ*=90°**

Background in $\bar{p}p \to e^+e^-$

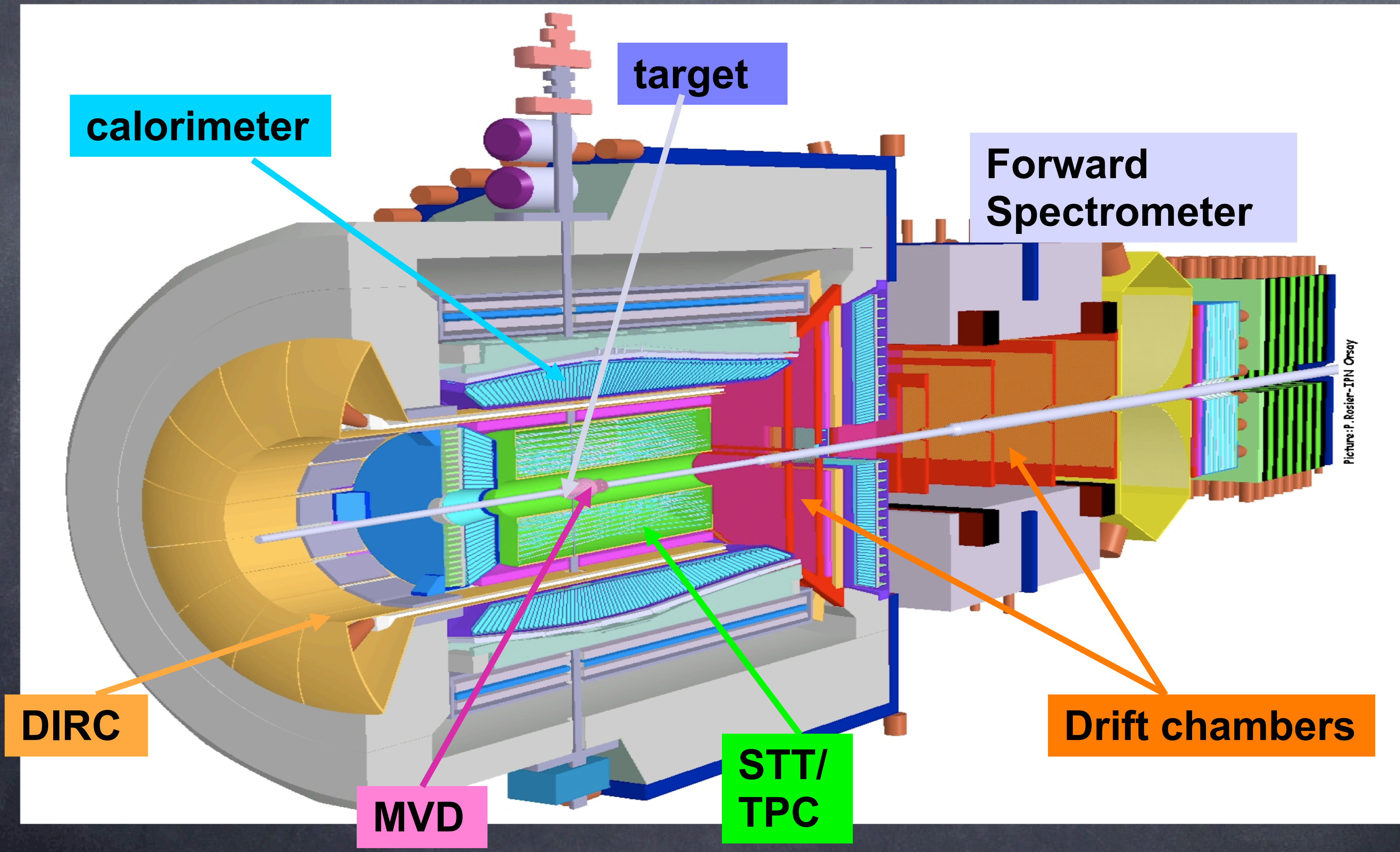
- ✓ **Reactions with at least 3 particles produced:**
  (e^+e^-X, $\pi^+\pi^-X$,...)
  Particle identification and kinematics constraints
  → no problem (still to be quantified)

- ✓ **Reactions with 2 charged particles ($\pi^+\pi^-$)**
  - **$\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \approx 10^6$ (2 μb / 8 pb at q^2=9. $(GeV/c)^2$)**

    need rejection of $\bar{p}p \to \pi^+\pi^-$ by 10^{-8}

    binary event, mean rejection of 10^{-4} per π^+ and per π^-
  - **very close kinematics**
  - **PID is crucial, EMC, DIRC, dE/dx**

PANDA: the detector



Detection and idenfication in the different regions

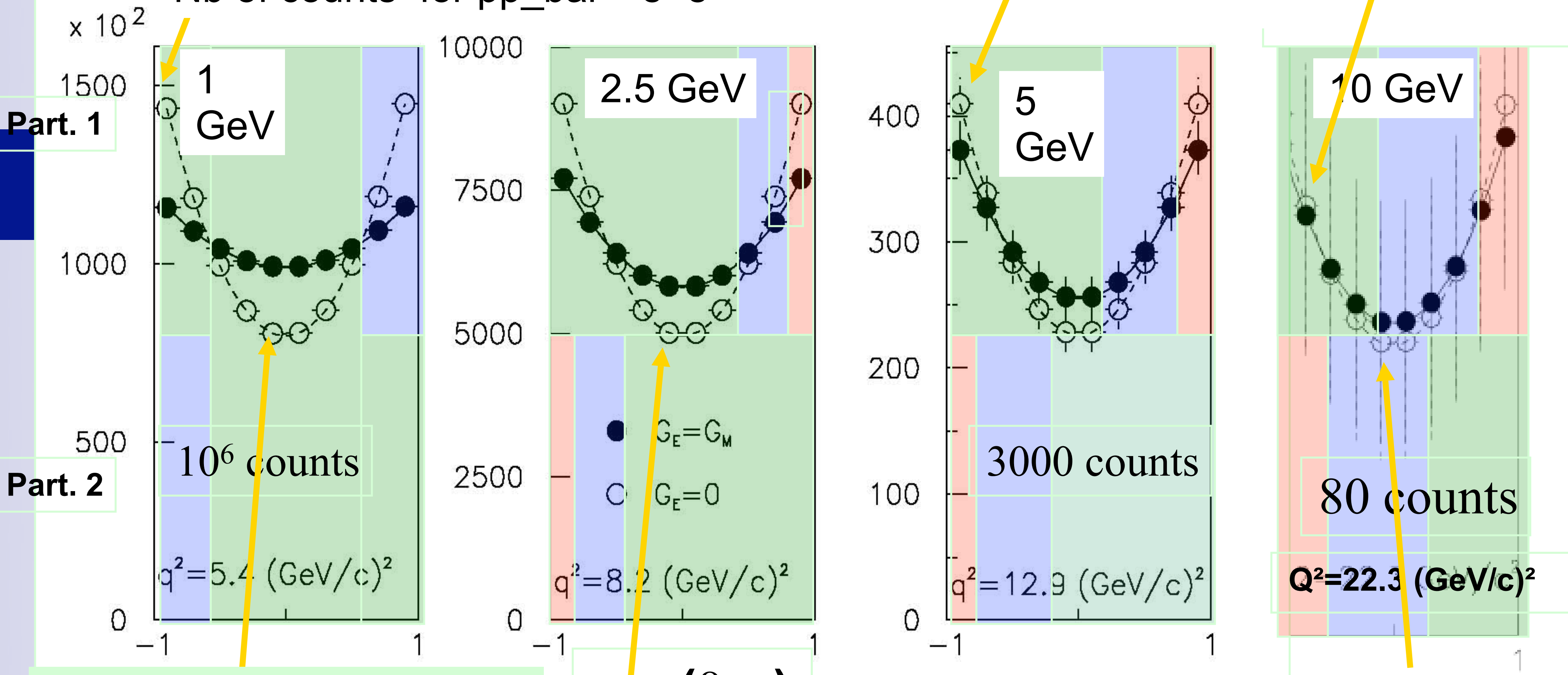
θ_1=13.°, p1=2.2 GeV
θ_2=132°, p_2=0.67 GeV

θ_1=7.4°, p1=6.1 GeV
θ_2=102°, p_2=0.8 GeV

θ_1=5.4 °, p1=10.9 GeV
θ_2=85°, p_2=1.0 GeV

Nb of counts for pp_bar→e+e-

•~100 days, $\mathcal{L}$ = 2. 10^{32} $cm^{-2}s^{-1}$ = 2 fb^{-1}



θ_1= θ_2=54 ° p1=p2=1.43 GeV

θ_1= θ_2= 41 °
p1=p2=2.2 GeV

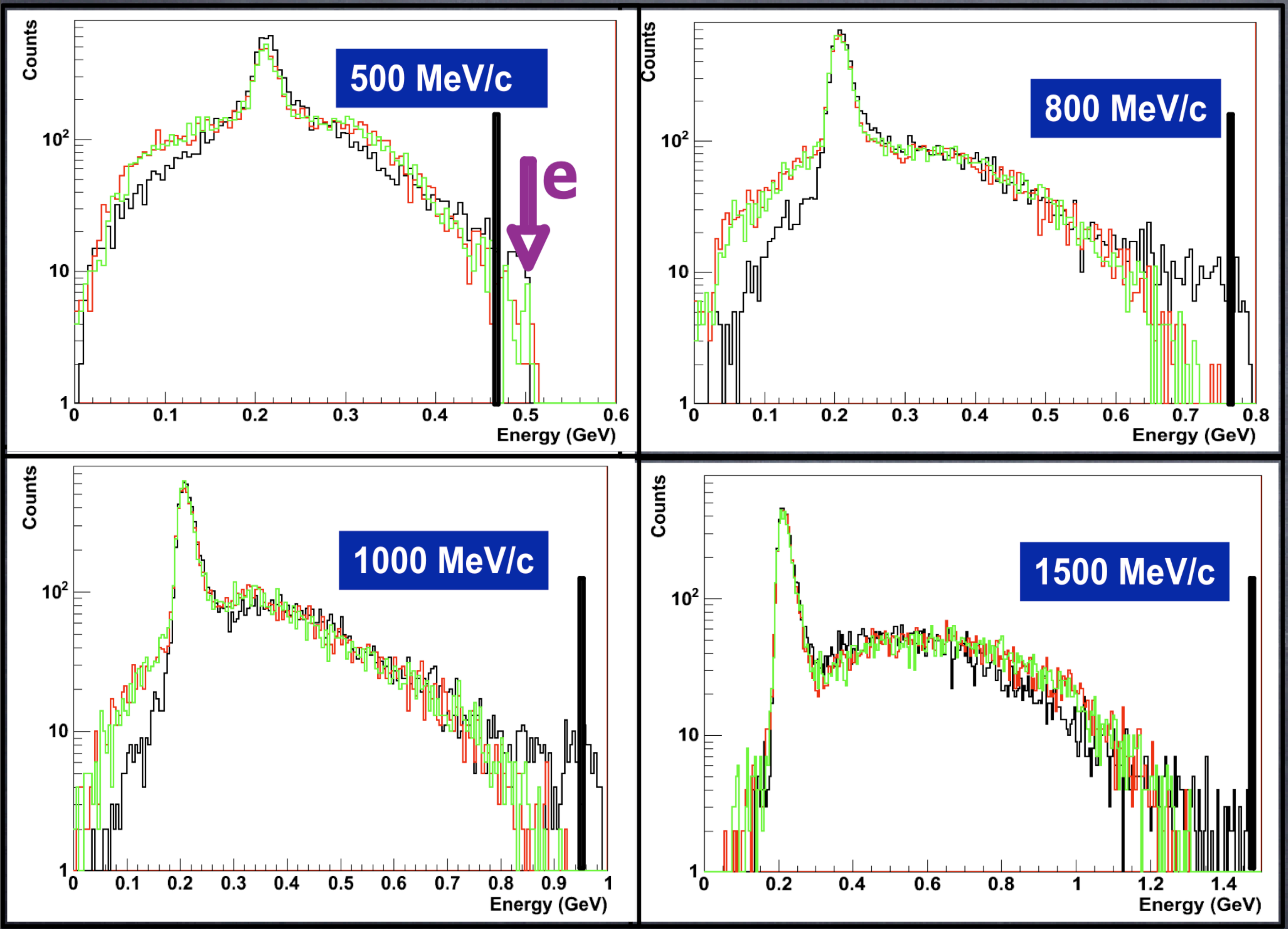
θ_1= θ_2= 23.5 °
p1=p2=5.95 GeV

Simulations
- „local" simulations
  response of individual detectors
  (Calorimeter, Cherenkov, Tracking)
  Orsay group (B.Ramstein)
- „full" simulations
  full PANDA detector response
  (material budget, QED rad. events)
  Bochum group (B. Kopf)

„local“ simulations

(π^+/e^+) Identification with EMC

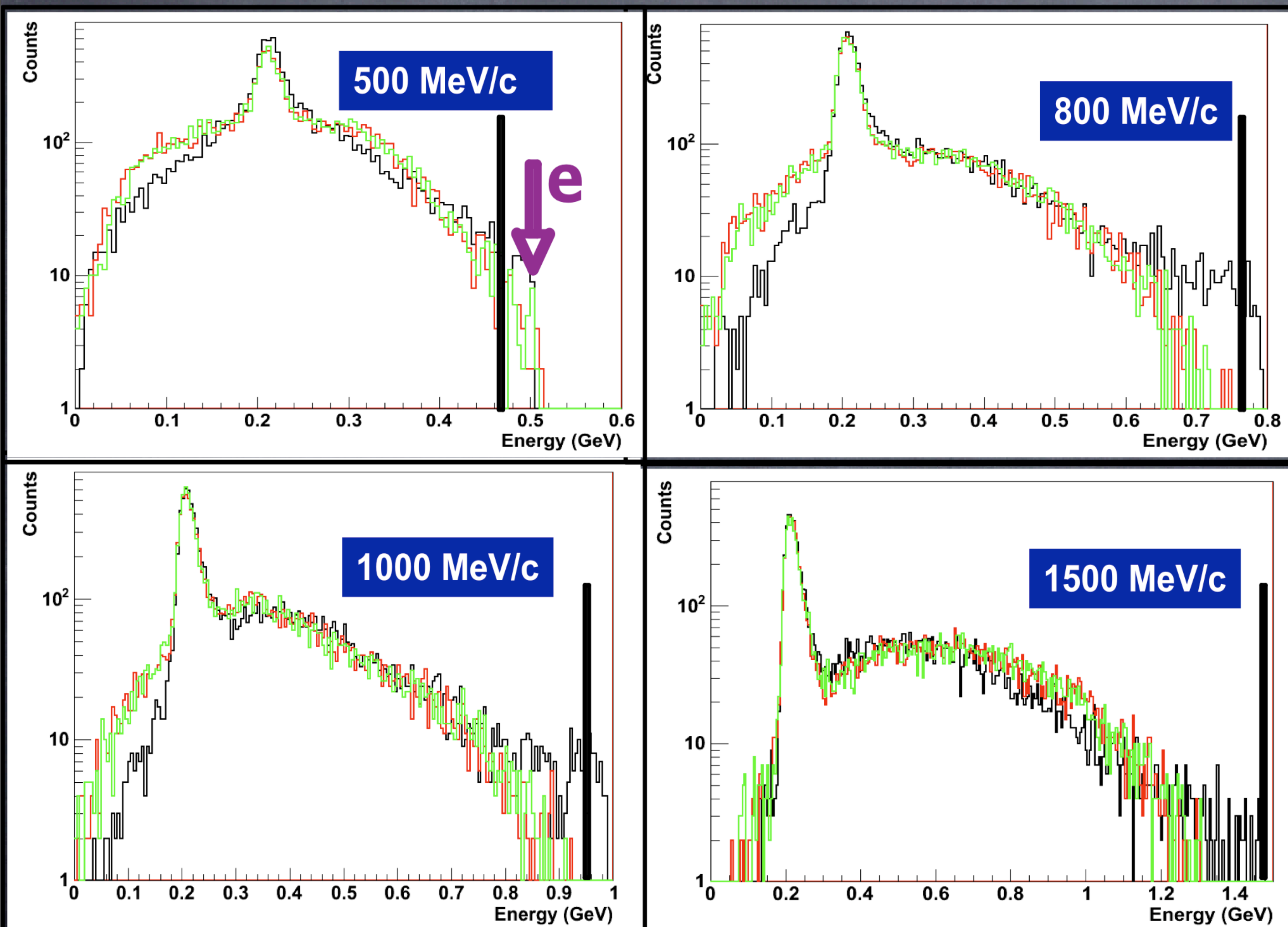
π^+ energy deposit in 3 different hadronic models



9x9 PbWO4 crystal matrix L=20 cm

(π^+/e^+) Identification with EMC

π^+ energy deposit in 3 different hadronic models



9x9 PbWO4
crystal matrix
L=20 cm

Charge exchange:
$\pi^+ + n \rightarrow \pi^0 + p \rightarrow 2\gamma + p$
Energy deposit = total π^+ energy

T_{p_bar} (GeV)	Q^2 $(GeV/c)^2$	θ_{CM}	θ_{lab}	p_{lab} (GeV/c)	one π Misident. Probability ECAL×DIRC×dE/dx	$\pi^+\pi^-$ Misident. Probability
1.	5.4	20°	13°	2.2	0.001 × 0.5 ×0.05 = 2.5 10^{-5}	0.1 10^{-9}
		160°	132°	0.57	0.033 × 0.003 ×0.03 = 3.0 10^{-6}	
		90°	54°	1.43	0.001 × 0.3 ×0.03 = 9. 10^{-6}	0.1 10^{-9}
		90°	54°	1.43	0.001 × 0.3 × 0.03 = 9. 10^{-6}	
2.5	8.2	20°	10°	3.7	0.001 × 1. ×0.05 = 5. 10^{-5}	0.3 10^{-9}
		160°	117°	0.7	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	0.9 10^{-9}
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	
5.	12.9	20°	7.4°	6.1	0.001 × 1. × 0.1 = 10^{-4}	0.6 10^{-9}
		160°	102°	0.8	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	2.5 10^{-9}
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	
10.	22.3	20°	5.4°	10.9	0.001 × 1. × 0.3 = 3. 10^{-4}	5.4 10^{-9}
		160°	85°	1.0	0.005 × 0.12 × 0.03 = 1.8 10^{-5}	
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	10. 10^{-9}
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	

„full" simulations

„full“ simulations

- $2\ 10^4$ e^+e^- (with QED corrections)
- 10^7 $\pi^+\pi^-$ (with QED corrections)
- at η_c–mass
- EM calorimeter
- tracking
- particle identification
- full material budget
- kinematical fits

preliminary intermediate results:
efficieny e^+e^-
misidentification probability

	$e^+ e^-$ no QED corr.	$e^+ e^-$ w/ QED corr.	$\pi^+ \pi^-$
charged	-	60,76%	$8{,}49 * 10^{-3}$
very loose	73,10%	57,69%	$5{,}0 * 10^{-6}$
loose	70,60%	55,81%	$6 * 10^{-7}$
tight	58,37%	46,15%	$1 * 10^{-7}$
very tight	48,91%	38,21%	$< 10^{-7}$

very promising!!

from B.Kopf, Bochum

Other EM structure physics in PANDA


Electromagnetic Form Factors
PORTA
PAVLA
e+e-/π+π-
foto

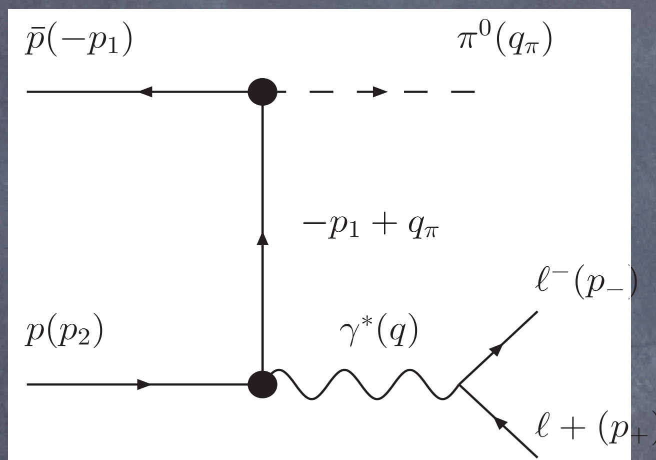

empty side road?
trash bin

ISR for time like form factors?
(unphysical region below threshold 4 m_p^2)

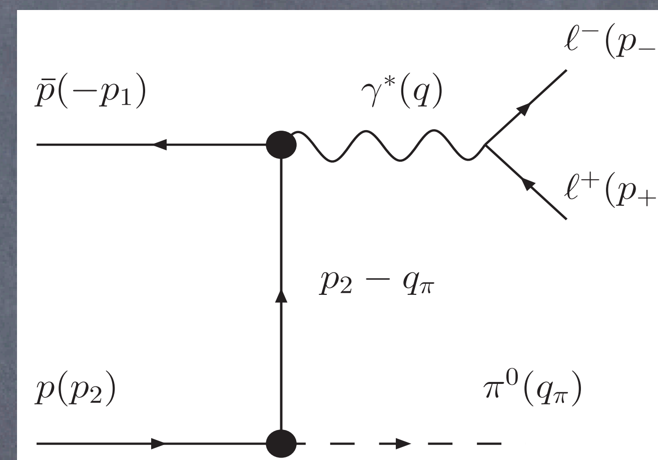
EM form factor below threshold

Process:

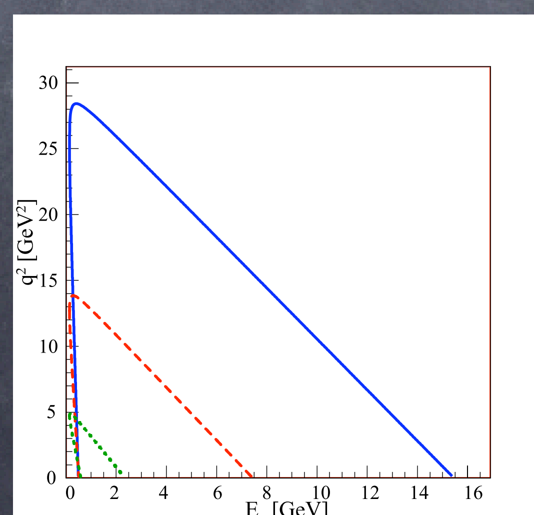
$\bar{p}p \to \pi^0 e^+e^-$ analogue to ISR



(a)



(b)

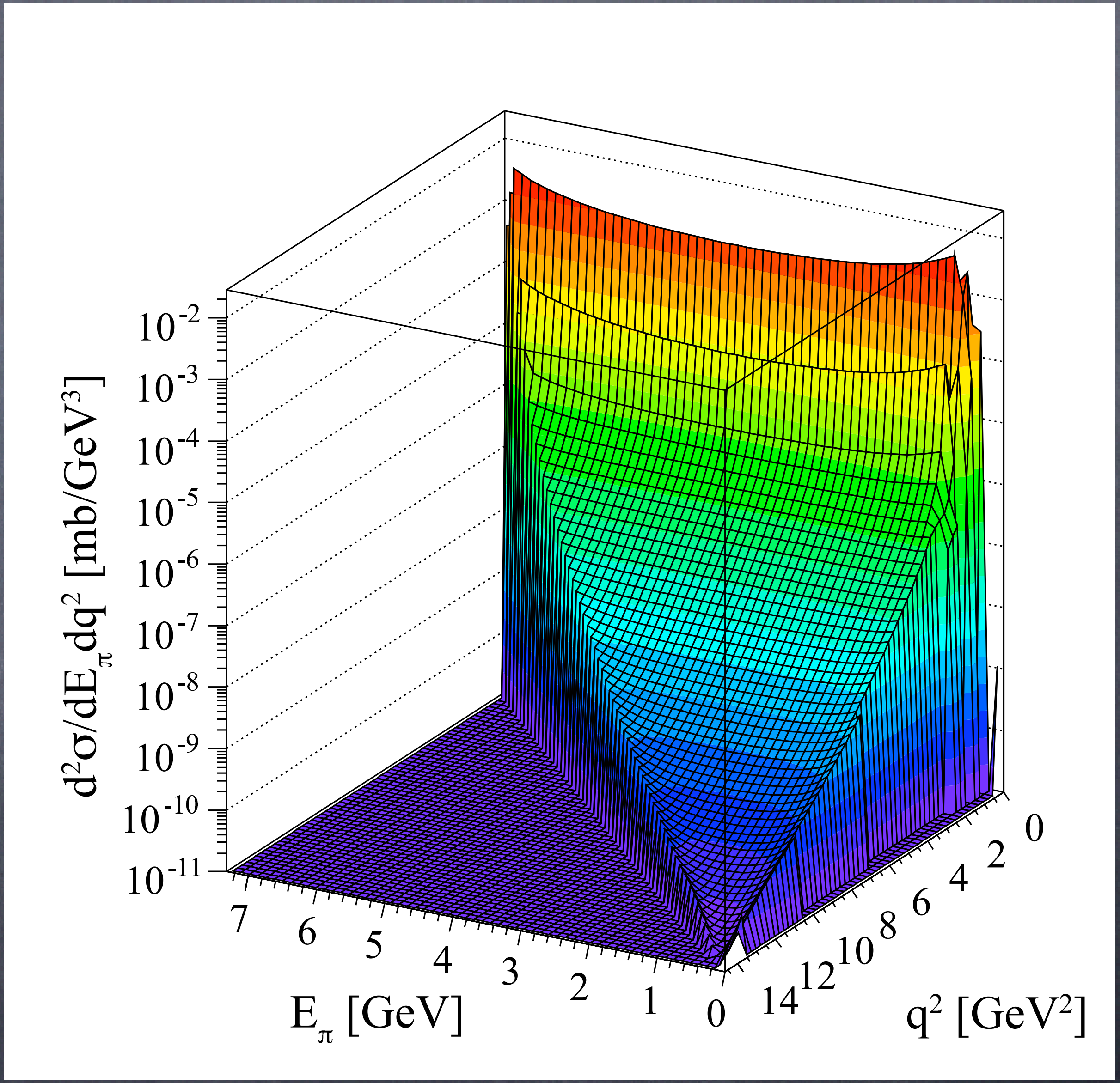


C. Adamuscin, E.A. Kuraev, E.Tomasi-Gustafsson, F.E. Maas, Phys.Rev.C75:045205,2007.

EM form factor below threshold

Process:

$\bar{p}p \rightarrow \pi^0 e^+e^-$



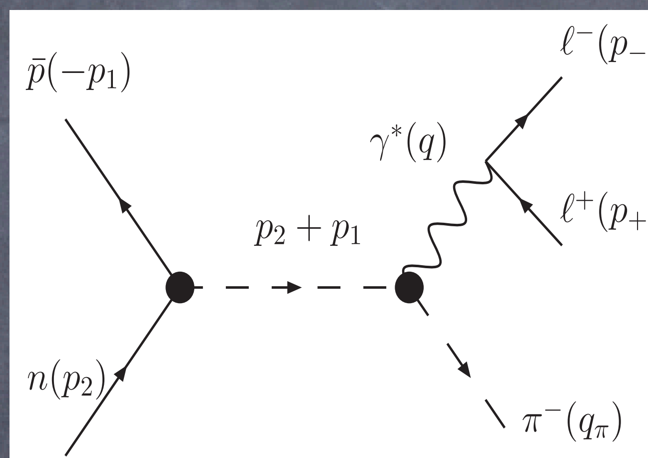
axial form factor in time like region

Axial form factor $Q_{wf}\ \bar{q}\gamma_\mu\gamma^5 q$

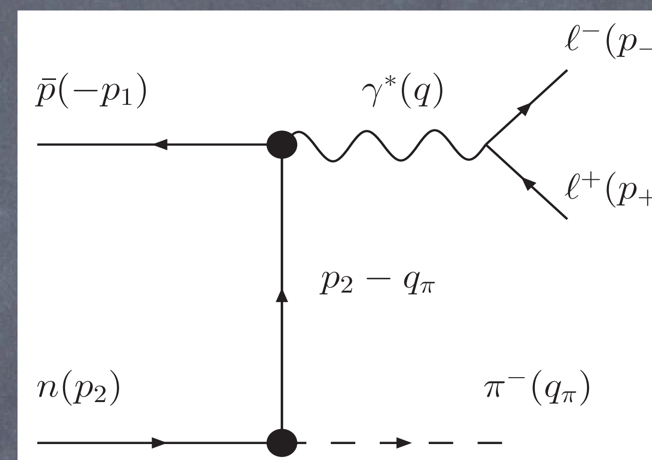
space like: - neutrino scattering

- electro-pion production

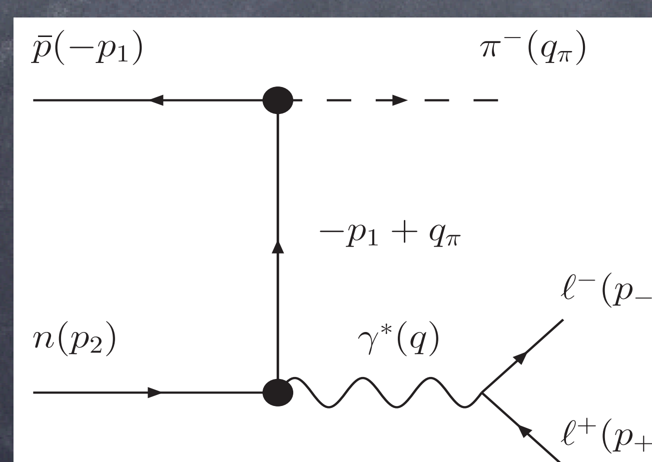
time like: - $\bar{p}n \to \pi^- e^+e^-$



(a)



(b)

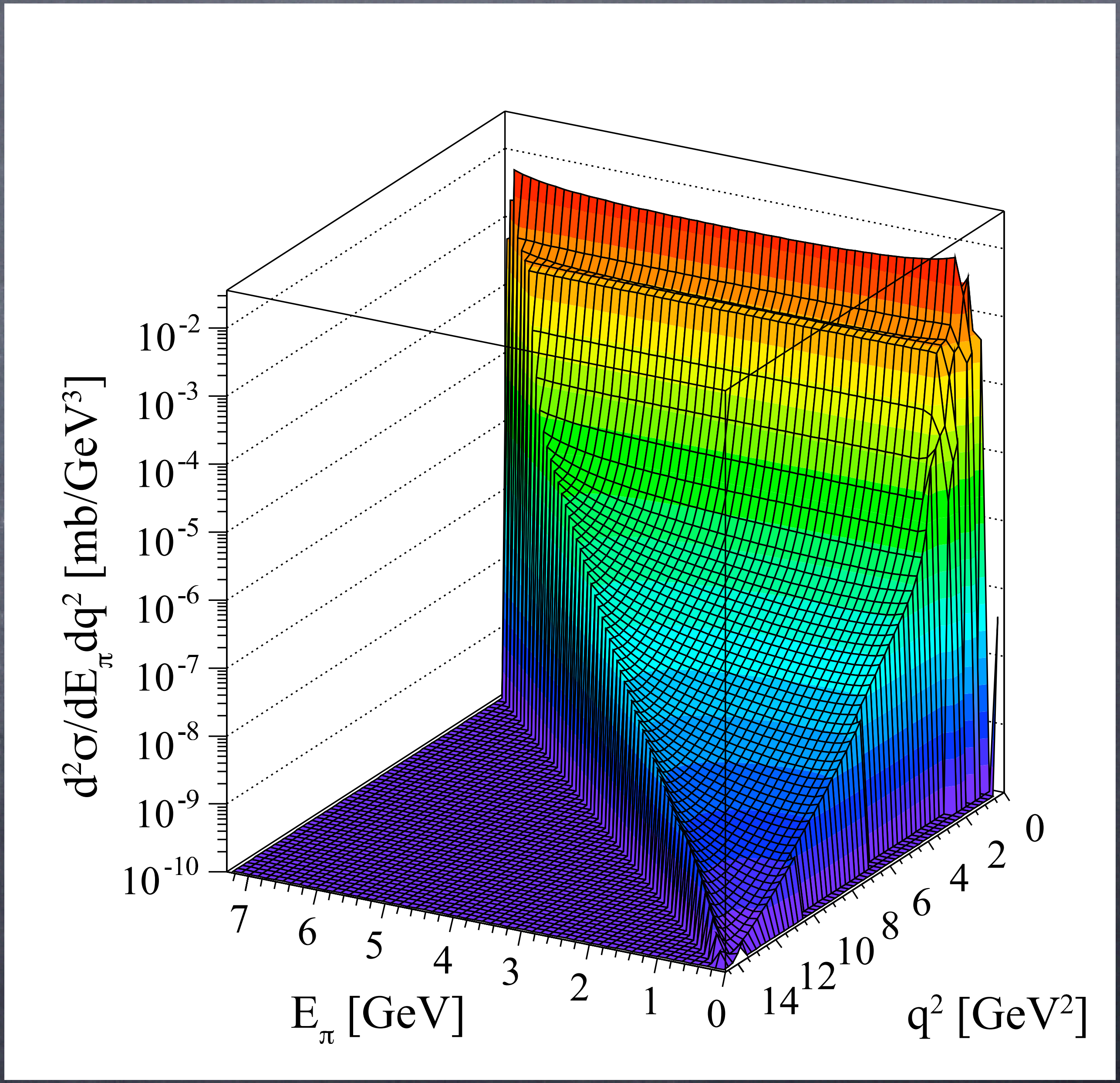


C. Adamuscin, E.A. Kuraev, E.Tomasi-Gustafsson, F.E. Maas Phys.Rev.C75:045205,2007.

Axial form factor

Process:

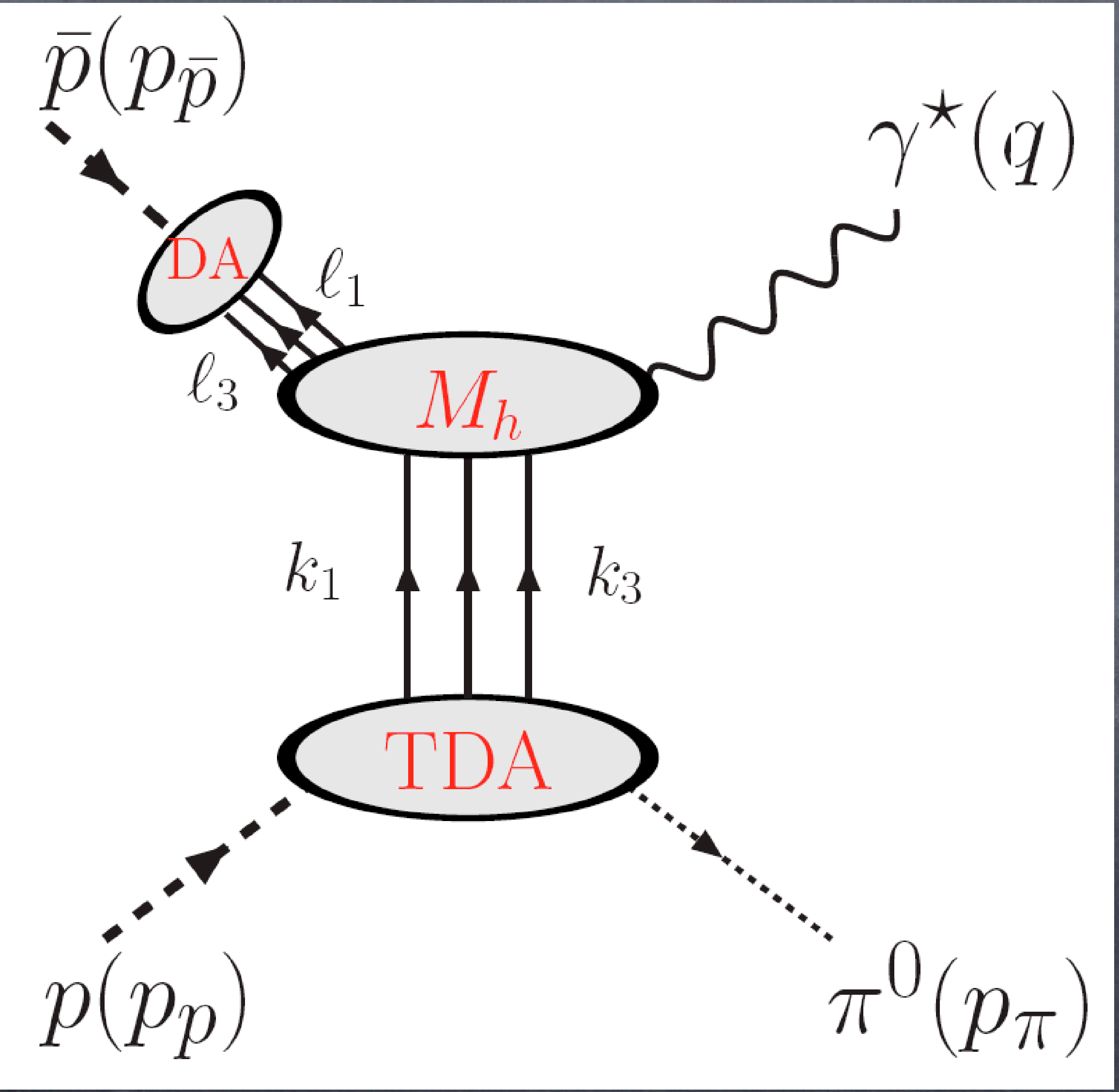
$\bar{p}n \to \pi^- e^+e^-$



transition distribution amplitudes (TDA)

transition distribution amplitudes (TDA)

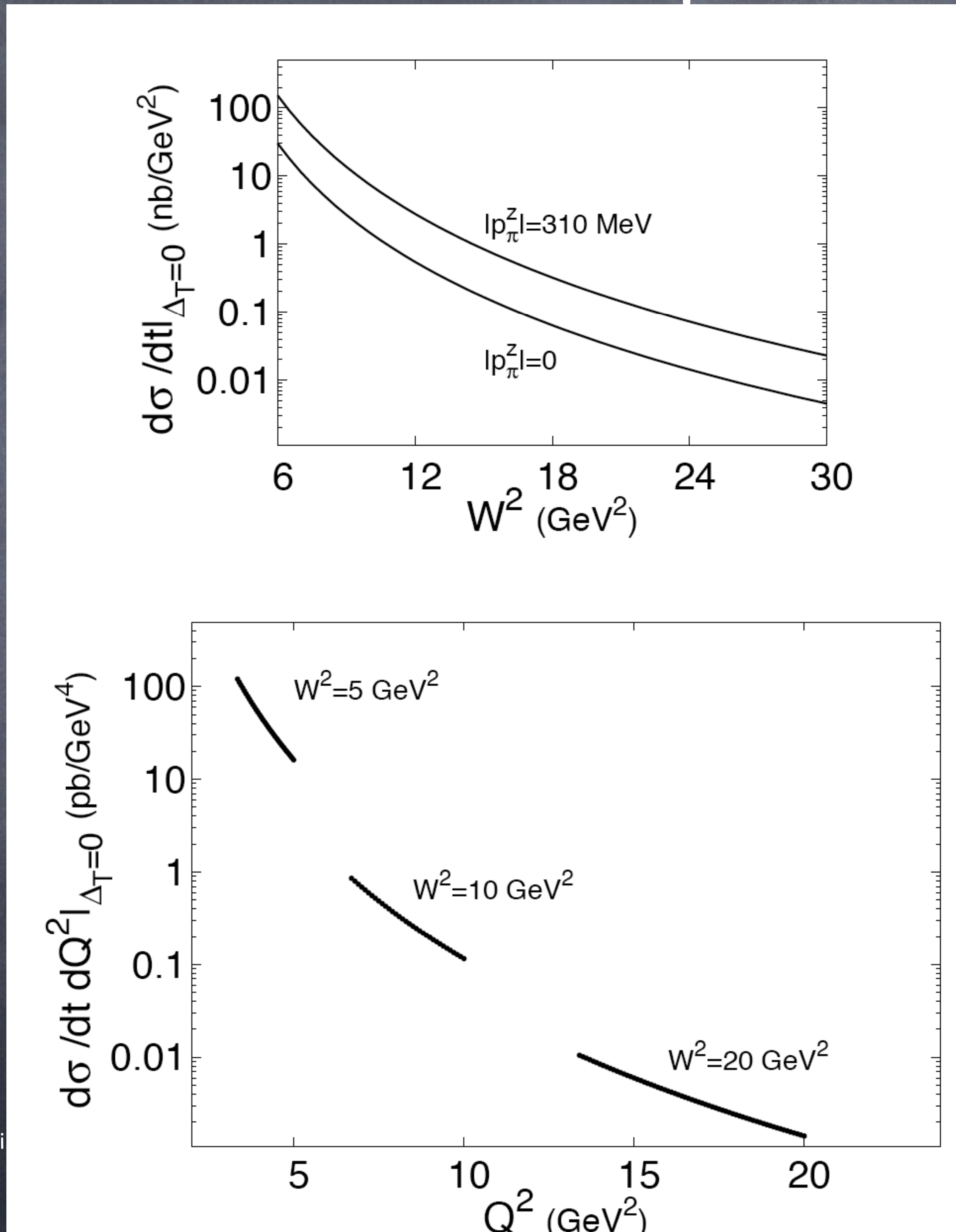
$\bar{p}p \to \pi^0 e^+e^-$



J.P.Lansberg, B. Pire and L.Szymanowski
arXiv:0710.1267v1 [hep-ph]

low energy π^0 under 0° and 180°

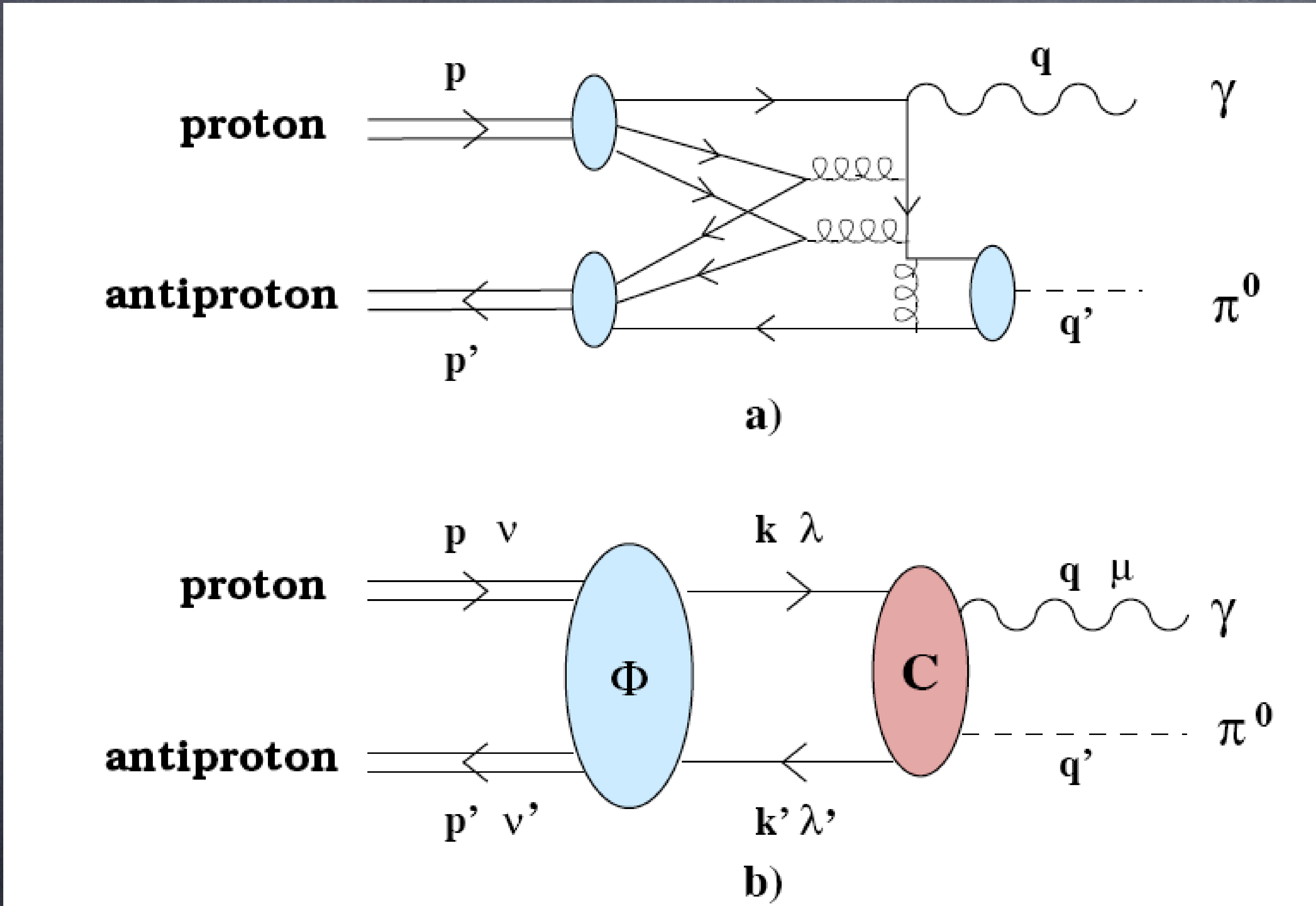
transition distribution amplitudes (TDAs)



J.P.Lansberg, B. Pire and L.Szymanowski
arXiv:0710.1267v1 [hep-ph]

generalised distribution amplitudes
(GDAs, time like analogon to GPDs)

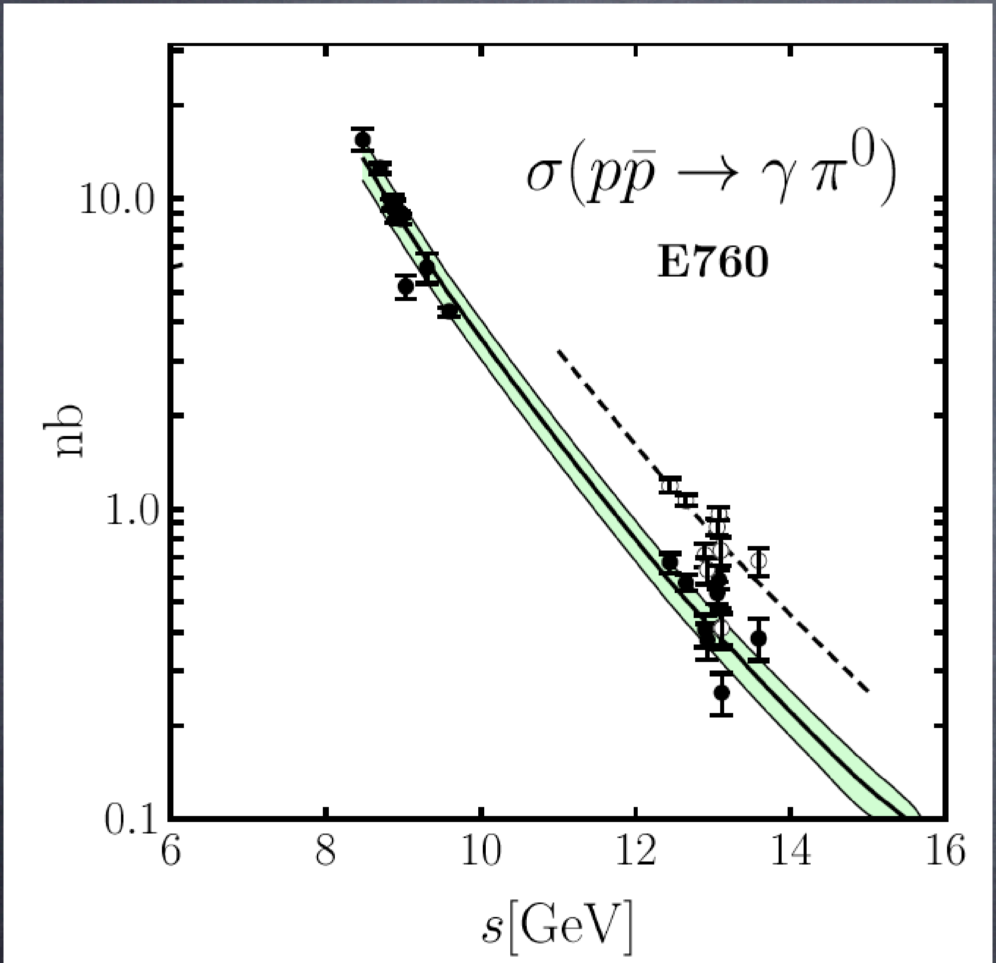
generalised distribution amplitudes (GDAs)

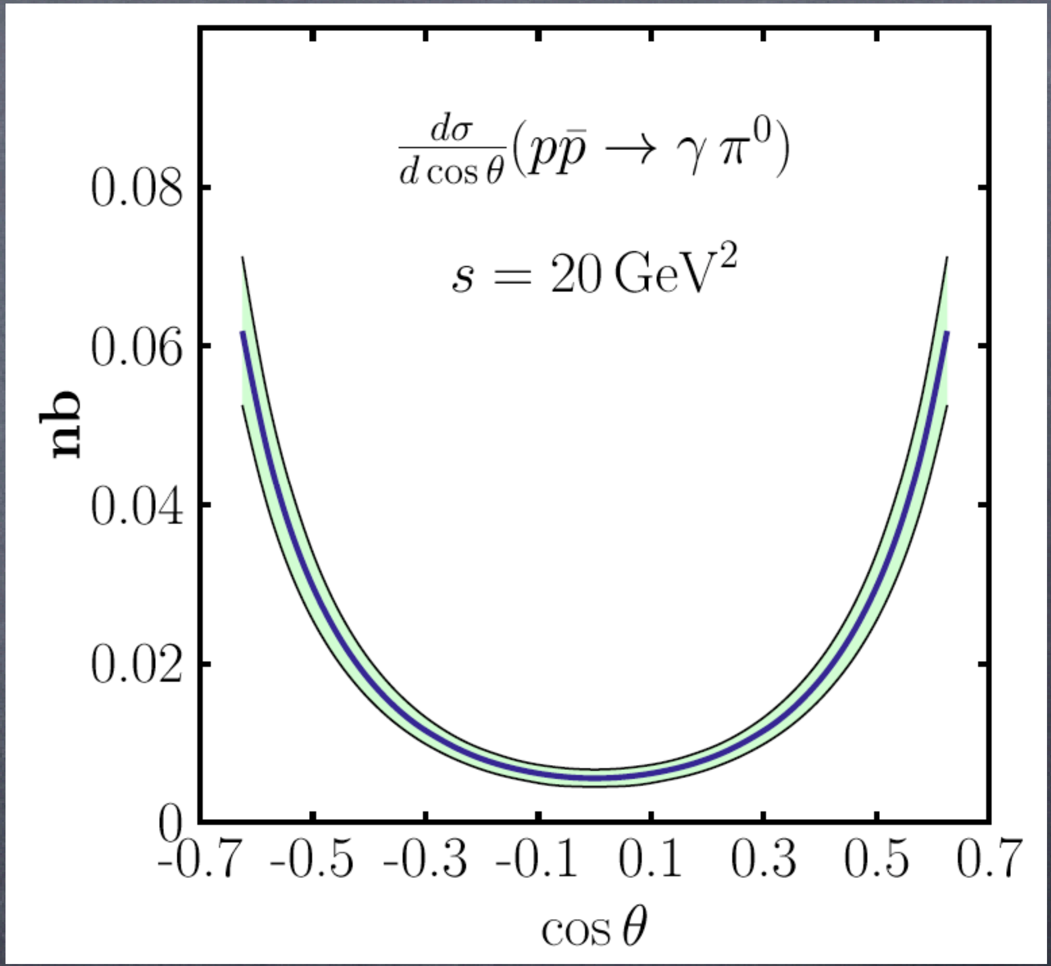


P. Kroll and A. Schäfer
arXiv:hep-ph/0505258v1

$\bar{p}p \to \pi^0 \gamma$

generalised distribution amplitudes (GDAs) prediction for PANDA





PANDA experiment

PANDA offers possibility for
high precision studies of QCD objects
- high luminosity (2 10^{32} cm^{-2} s^{-1})
- high resolution beam
- „high energy detector“

PANDA/FAIR (antiprotons) ready by 2014/2015

Measurement/Separation of G_E and G_M with high precision possibile, new door to EM structure of the Nucleon

Summary

- electromagnetic form factors:
  fundamental property of Nucleon
- poorly known in timelike region
  (pQCD not yet reached)
- unique possibility to measure in timelike domain
  with the PANDA detector up to s = 20 GeV^2
- PANDA opens door to new EM nucleon structure
  EM form factors below threshold
  Axial form factor
  TDAs (pion cloud, photon cloud, ...)
  space like GPDs -> time like GDAs
- cruxial: high luminosity and particle ID