

LEAP 2013

11th International Conference on Low Energy Antiproton Physics



Ångström Laboratory, Uppsala, Sweden, June 10 - 15, 2013

Proton Time-Like Form Factors at PANDA

Marco Maggiora on behalf of the PANDA Collaboration

Dipartimento di Fisica and INFN - Torino, Italy



Present interest

- **Precise data in new kinematical region:**
 - high intensity beams,
 - polarized targets,
 - hadron polarimeters
- **Space-like region:** MAMI, JLAB, Bates
- **Time-like region:** FERMILAB, FRASCATI, NOVOSIBIRSK, BES, PANDA@FAIR, BELLE, BABAR..

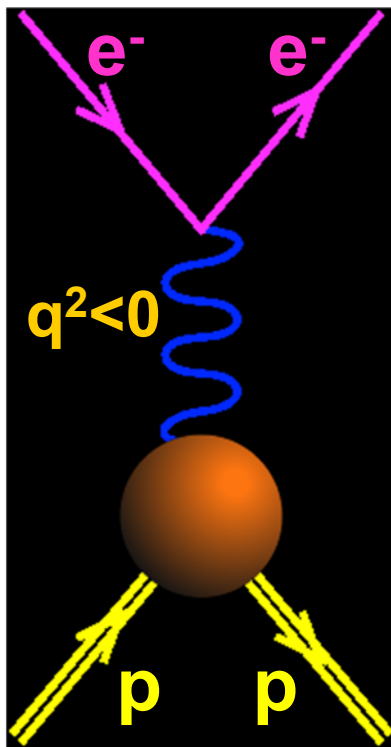
- ⊕ knowledge of proton form factors up to large q^2
- ⊕ transition to QCD: Asymptotics
- ⊕ reaction mechanism (1 or 2 photon exchange)



unified view of the nucleon EM structure

Nucleon Form Factors: analyticity

Space-Like



$$GE(0)=1$$

$$GM(0)=\mu_p$$

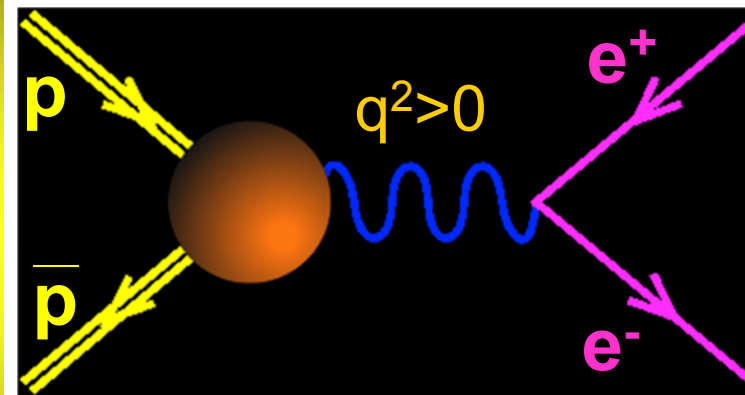
FFs are real

$$e+p \rightarrow e+p$$

Time-Like

Asymptotics

- QCD
- analyticity



FFs are complex

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

Unphysical region
 $p+\bar{p} \leftrightarrow e^++e^-+\pi$

$$q^2=4m_p^2$$

$$G_E=G_M$$

q^2

Nucleon Form Factors: from Space-Like to Time-Like

$$Q^2 = -q^2 = q^2 e^{-i\pi} \implies \begin{cases} \ln(Q^2) = \ln(q^2) - i\pi, \\ \sqrt{Q^2} = e^{-\frac{i\pi}{2}} \sqrt{q^2}. \end{cases}$$

The sign is relevant for polarisation observables

Scattering and annihilation channels:

- described by the same amplitude:

$$|\overline{\mathcal{M}}(e^\pm h \rightarrow e^\pm h)|^2 = f(s, t) = |\overline{\mathcal{M}}(e^+ e^- \rightarrow \bar{h} h)|^2$$

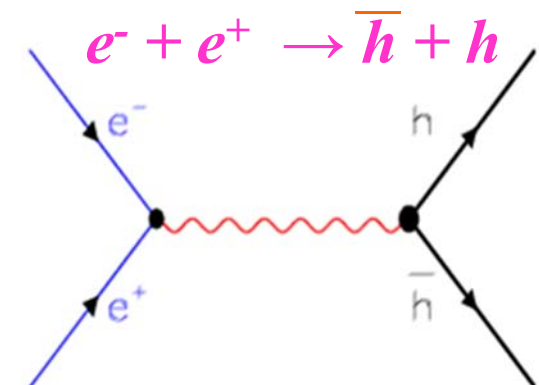
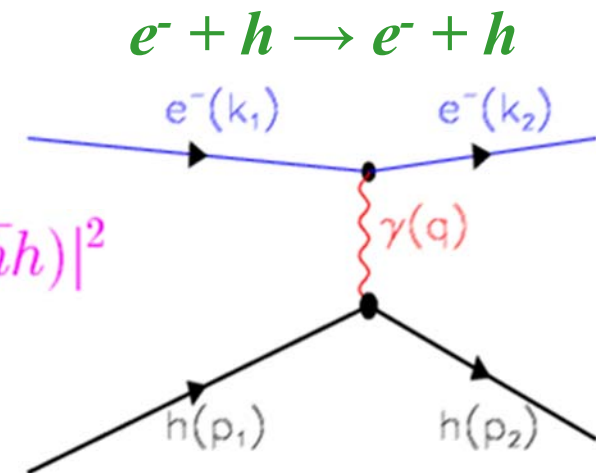
- function of two kinematical variables, s and t

$$s = (k_1 + p_1)^2 \quad t = (k_1 - k_2)^2$$

which scan different kinematical regions

$$\mathbf{p}_2 \rightarrow -\mathbf{p}_2$$

$$\cos^2 \tilde{\theta} = 1 + \frac{st + (s - M^2)^2}{t(\frac{t}{4} - M^2)} \rightarrow 1 + \frac{ctg^2 \frac{\theta}{2}}{1 + \tau}$$



Time-Like observables: $|G_E|^2$ and $|G_M|^2$

Cross section for $\bar{p} + p \rightarrow e^+ + e^-$ (1 γ -exchange):

$$\frac{d\sigma}{d(\cos \theta)} = \frac{\pi\alpha^2}{8m^2\sqrt{\tau-1}} [\tau |G_M|^2 (1 + \cos^2 \theta) + |G_E|^2 \sin^2 \theta]$$

θ : angle between e^- and $\bar{p}$ in cms.

As in Space-Like region:

- dependence on q^2 contained in FFs
- even dependence on $\cos^2\theta$ (1g exchange)
- no dependence on sign of FFs
- enhancement of magnetic term

but Time-Like form factors are complex!

$\bar{h} + h \rightarrow e^- + e^+$ angular distributions

The differential cross section:

$$\frac{d\sigma}{d(\cos \theta)} = \frac{\pi \alpha^2}{8m^2 \sqrt{\tau - 1}} [\tau |G_M|^2 (1 + \cos^2 \theta) + |G_E|^2 \sin^2 \theta]$$

can be parametrised as:

$$\frac{d\sigma}{d(\cos \theta)} = \sigma_0 [1 + \mathcal{A} \cos^2 \theta]$$

Cross section at 90°

$$\sigma_0 = \frac{\alpha^2}{4q^2} \sqrt{\frac{\tau}{\tau - 1}} \left(|G_M|^2 + \frac{1}{\tau} |G_E|^2 \right)$$

Angular asymmetry

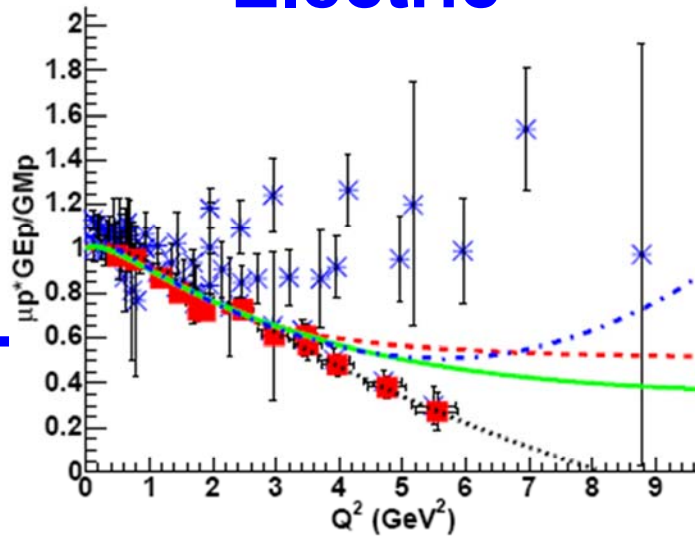
$$\mathcal{A} = \frac{\tau |G_M|^2 - |G_E|^2}{\tau |G_M|^2 + |G_E|^2} = \frac{\tau - \mathcal{R}^2}{\tau + \mathcal{R}^2}$$

$$\mathcal{R} = |G_E|/|G_M|$$

Nucleon Space-Like Form Factors modelisation

Electric

proton



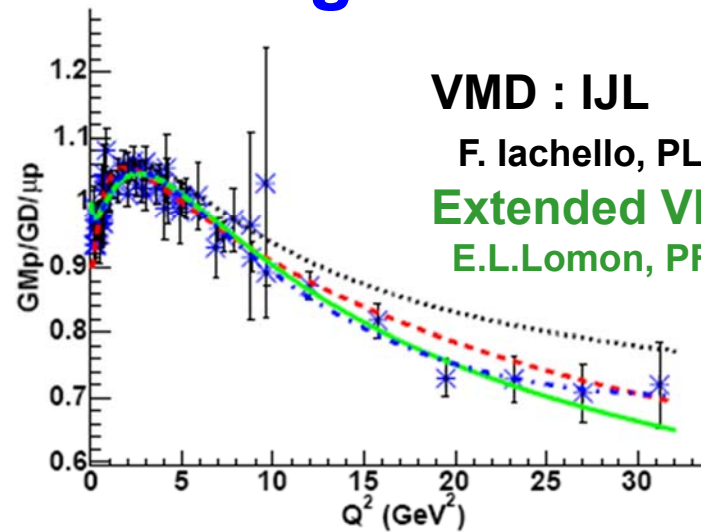
Magnetic

VMD : IJL

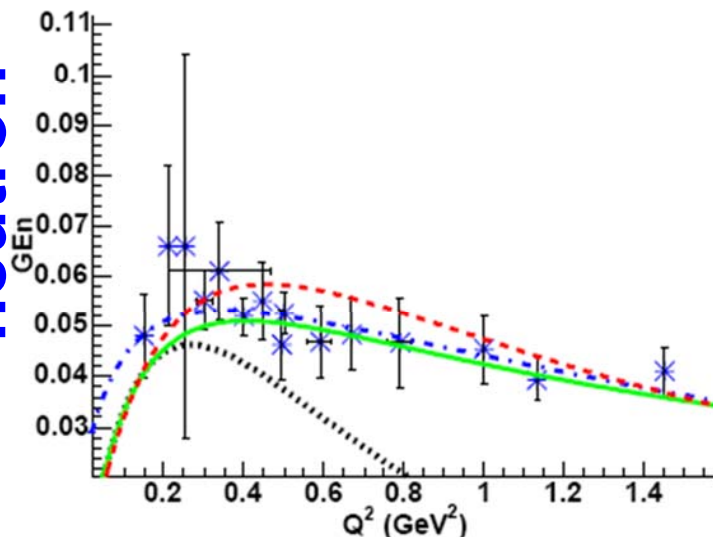
F. Iachello, PLB 43 (1973) 191

Extended VMD (G.K.-92):

E.L.Lomon, PRC 66 (2002) 045501

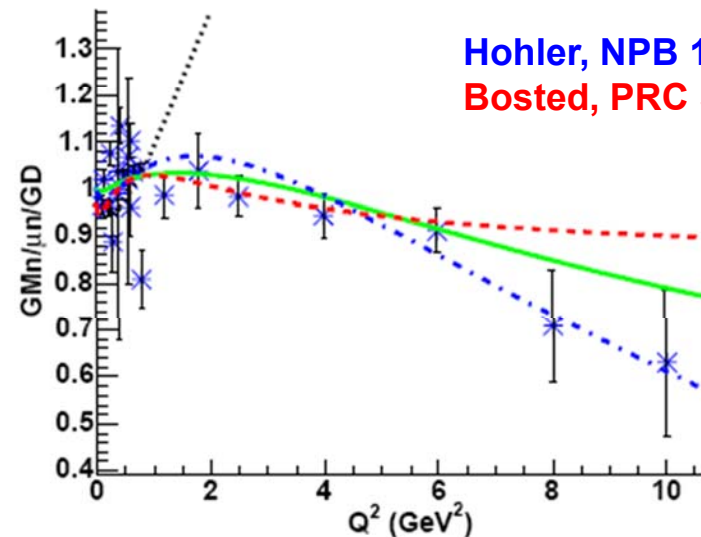


neutron



Hohler, NPB 114 (1976) 505

Bosted, PRC 51 (1995) 409

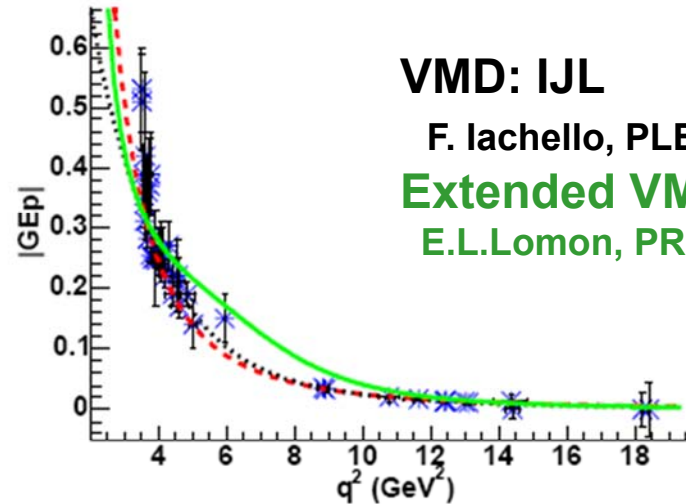
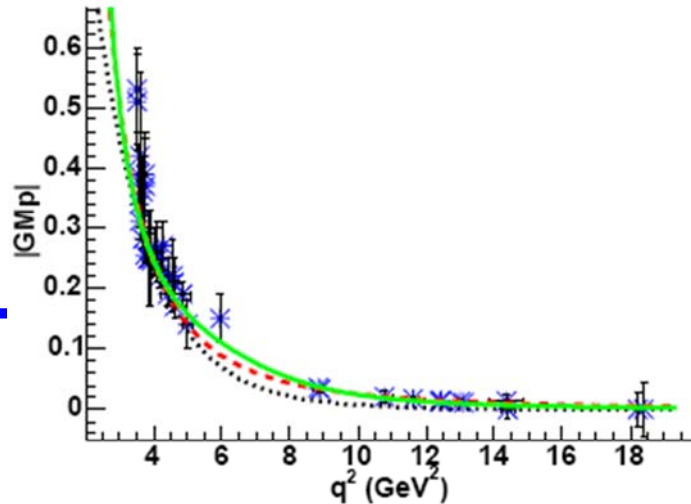


Nucleon Time-Like Form Factors modelisation

Electric

Magnetic

proton



VMD: IJL

F. Iachello, PLB 43 (1973) 191

Extended VMD: (G.K.-92)

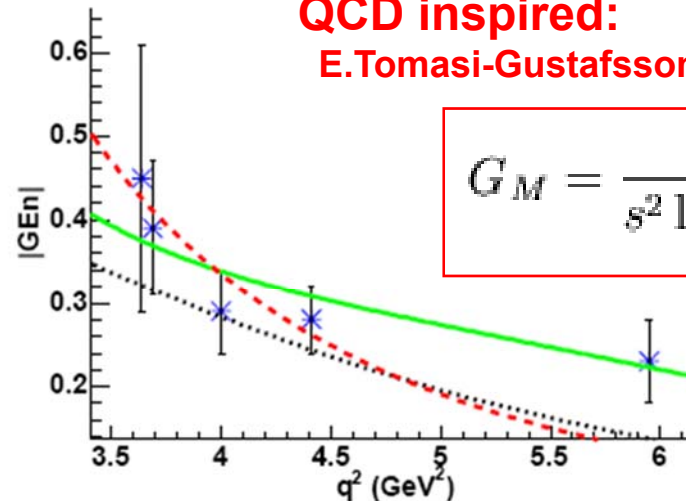
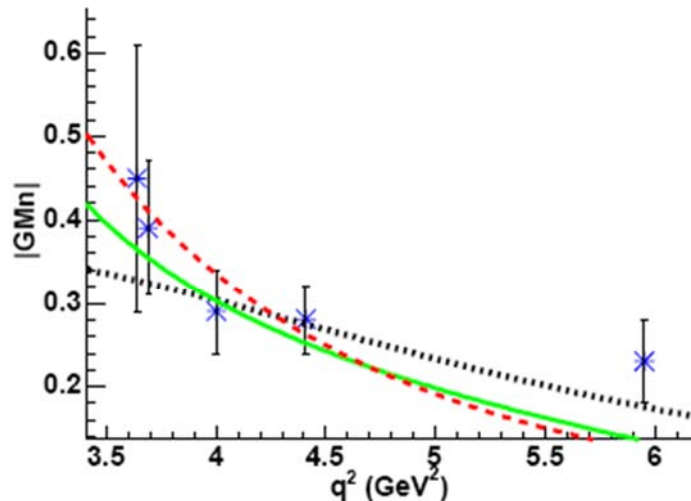
E.L.Lomon, PRC 66 (2002) 045501

Hohler, NPB 114 (1976) 505

QCD inspired:

E.Tomasi-Gustafsson, EPJA (2005) 419

neutron



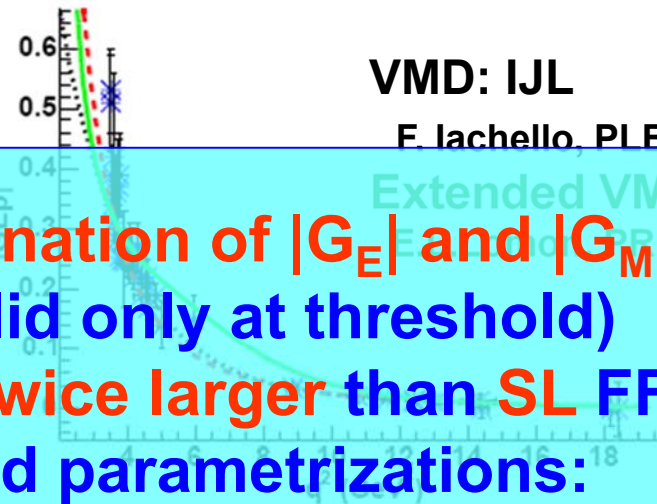
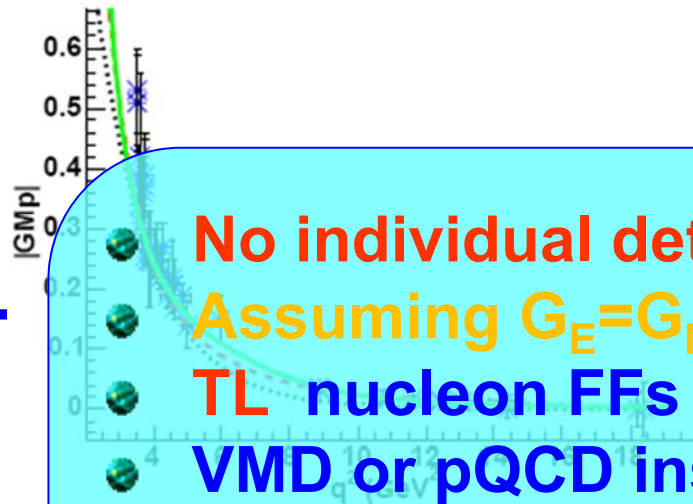
$$G_M = \frac{A}{s^2 \ln^2(s/\Lambda^2)}$$

Nucleon Time-Like Form Factors modelisation

Electric

Magnetic

proton



VMD: IJL

F. Iachello, PLB 43 (1973) 191

Extended VMD: (G.K.-92)
E. Lacroix, EPJ 66 (2002) 045501

No individual determination of $|G_E|$ and $|G_M|$
Assuming $G_E = G_M$ (valid only at threshold)
TL nucleon FFs are twice larger than SL FF
VMD or pQCD inspired parametrizations:

$$A(p) = 56.3 \text{ GeV}^4$$

$$A(n) = 77.15 \text{ GeV}^4$$

$$\Lambda_{\text{QCD}} = 0.3 \text{ GeV}$$

$$G_M = \frac{A}{s^2 [\pi^2 + \ln^2(s/\Lambda^2)]}$$

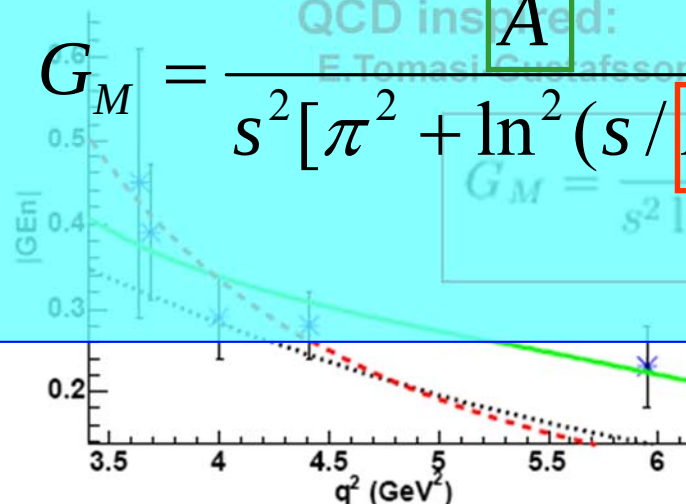
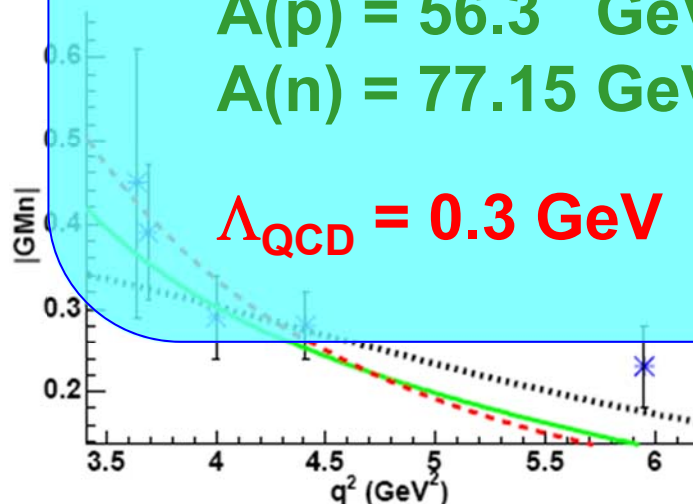
Hohler, NPB 114 (1976) 505

QCD inspired:

E. Tomasi-Gustafsson, EPJA (2005) 419

$$G_M = \frac{A}{s^2 \ln^2(s/\Lambda^2)}$$

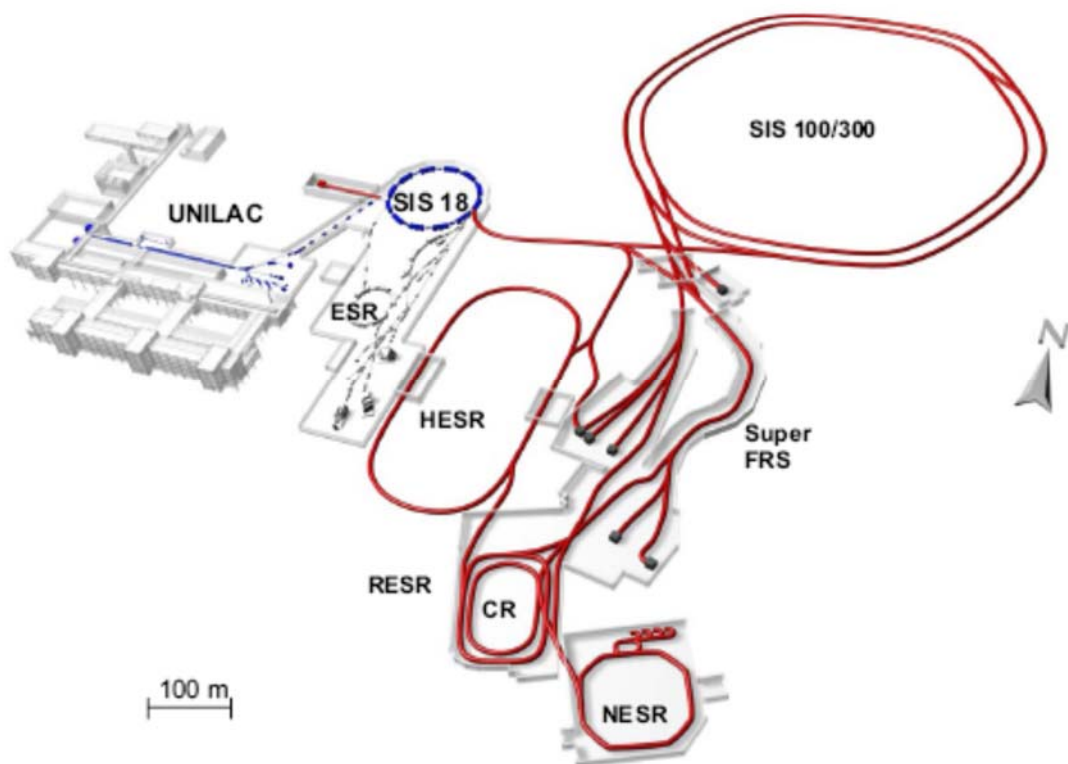
neutron



The future FAIR facility



**Facility for Antiproton
and Ion Research**



Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

Primary Beams

- $10^{12}/s$; 1.5 GeV/u; $^{238}\text{U}^{28+}$
- Factor 100-1000 present in intensity
- $2(4) \times 10^{13}/s$ 30 GeV protons
- $10^{10}/s$ $^{238}\text{U}^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

HESR - High Energy Storage Ring



- Production rate $2 \times 10^7/\text{sec}$

- $P_{\text{beam}} = 1 - 15 \text{ GeV/c}$

- $N_{\text{stored}} = 5 \times 10^{10} \bar{p}$

- Internal Target

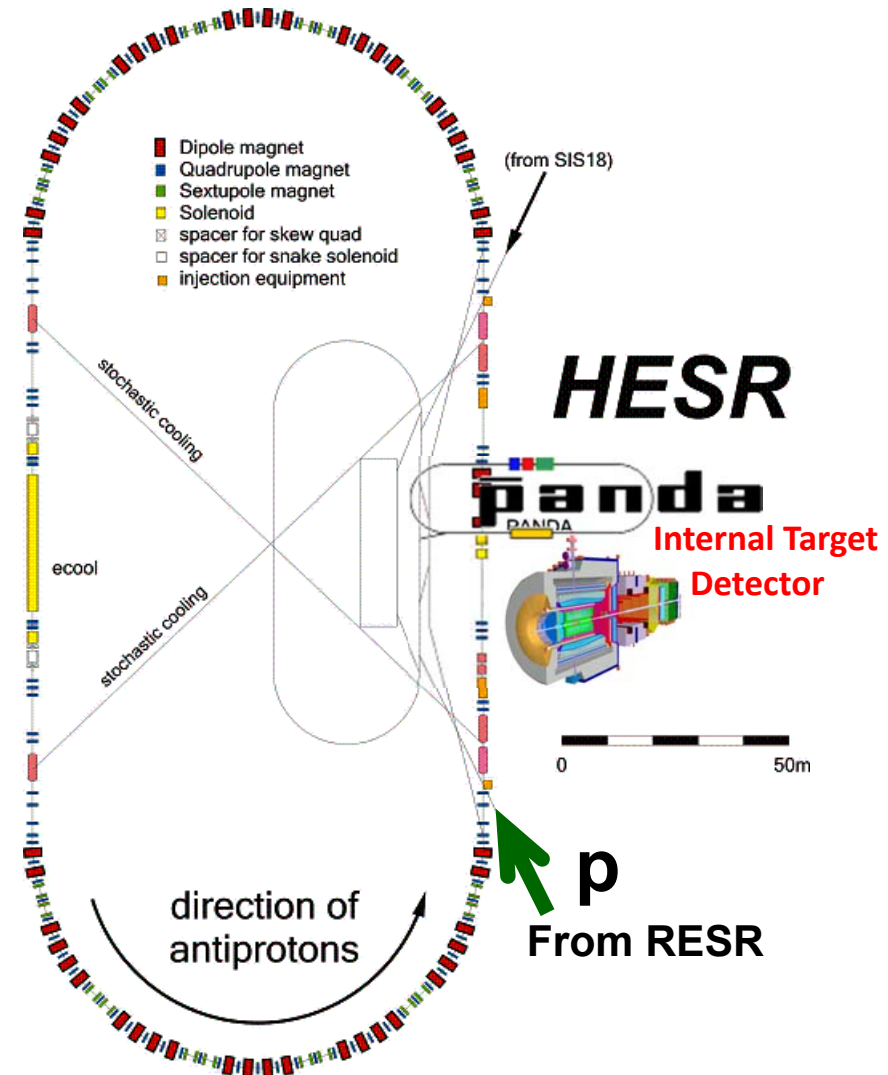
High resolution mode

- $\delta p/p \sim 10^{-5}$ (electron cooling)
- $\text{Lumin.} = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

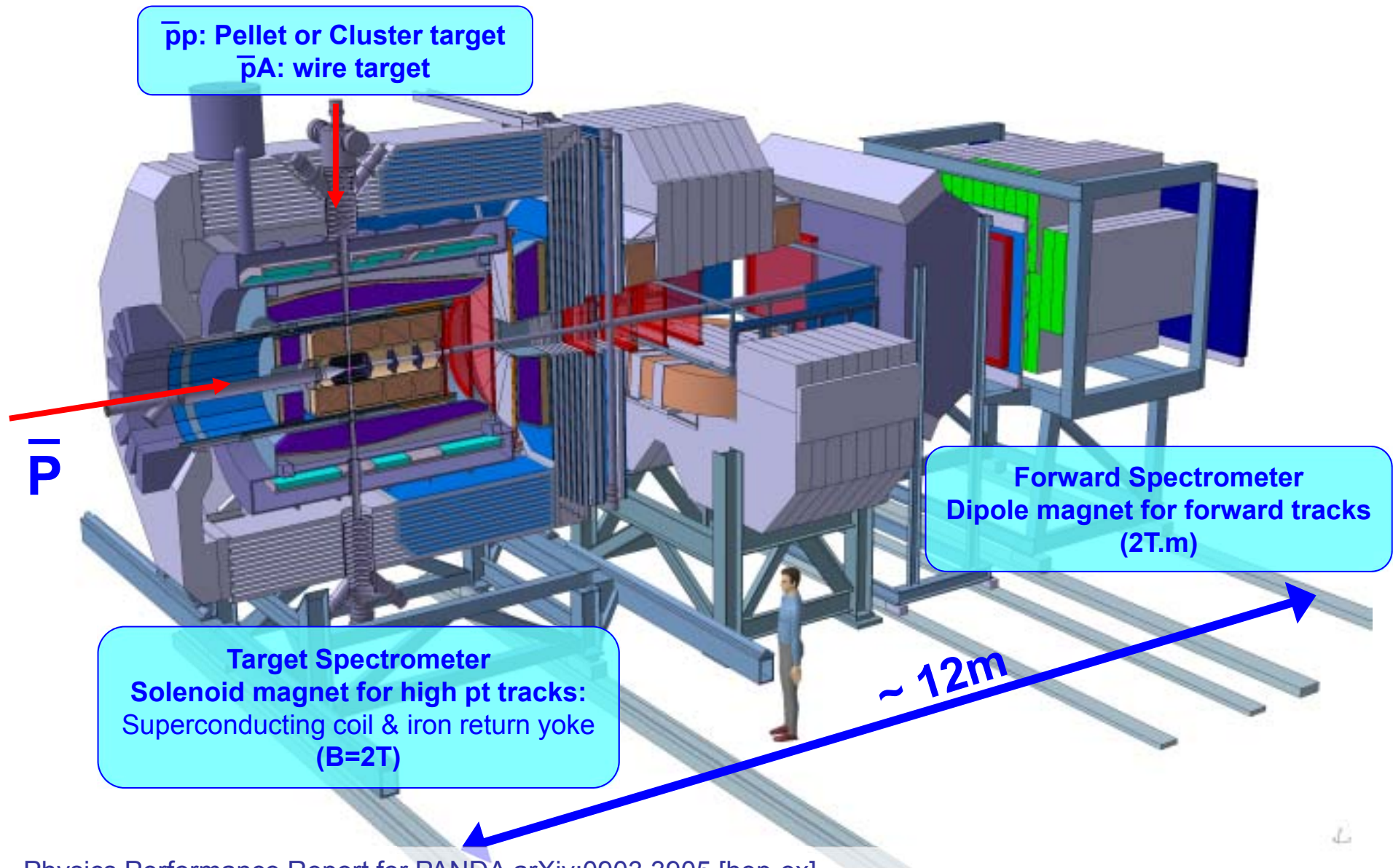
High luminosity mode

- $\text{Lumin.} = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)

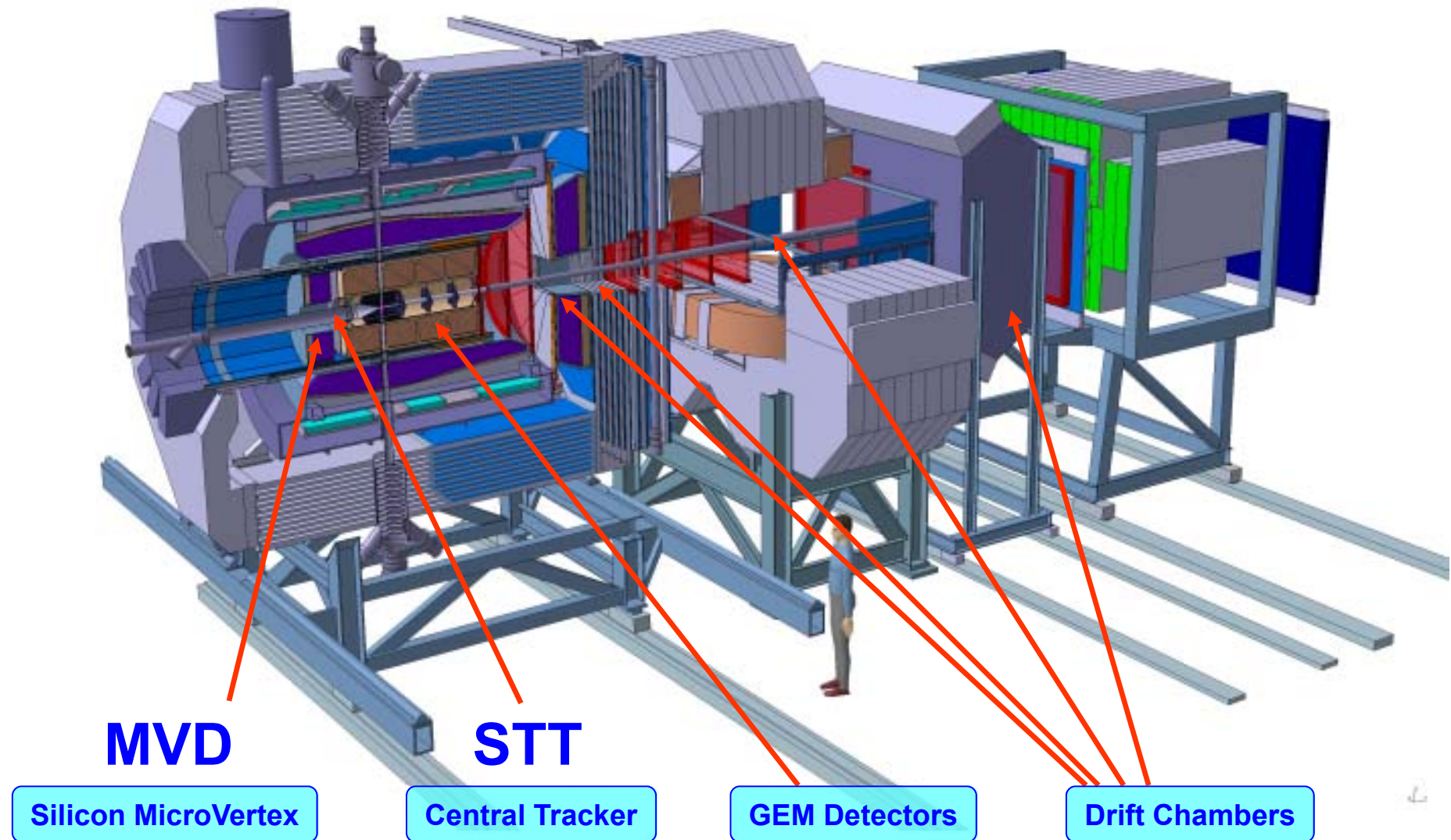
$$2.3 \leq \sqrt{s} \leq 5.5 \text{ GeV}$$



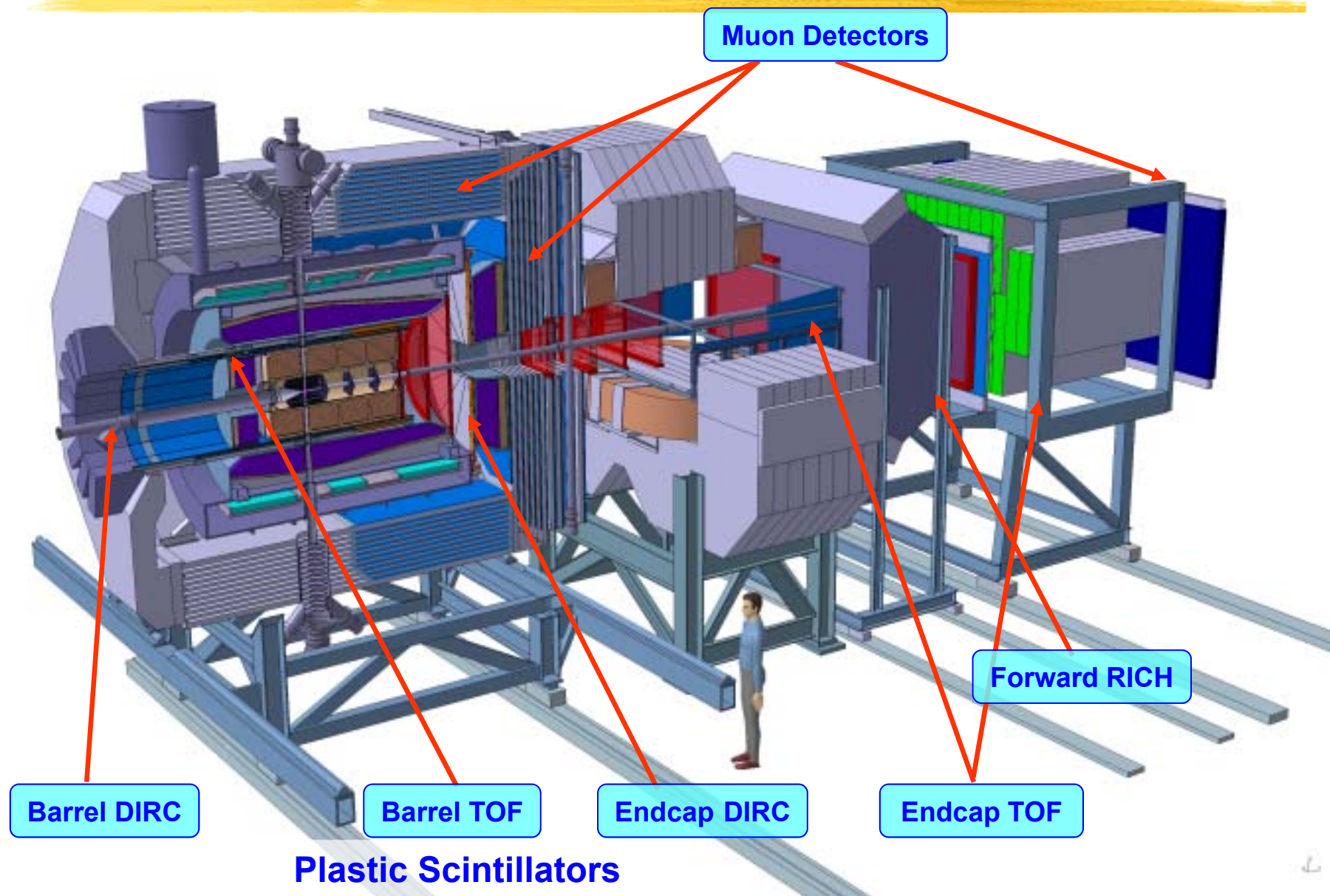
PANDA spectrometer



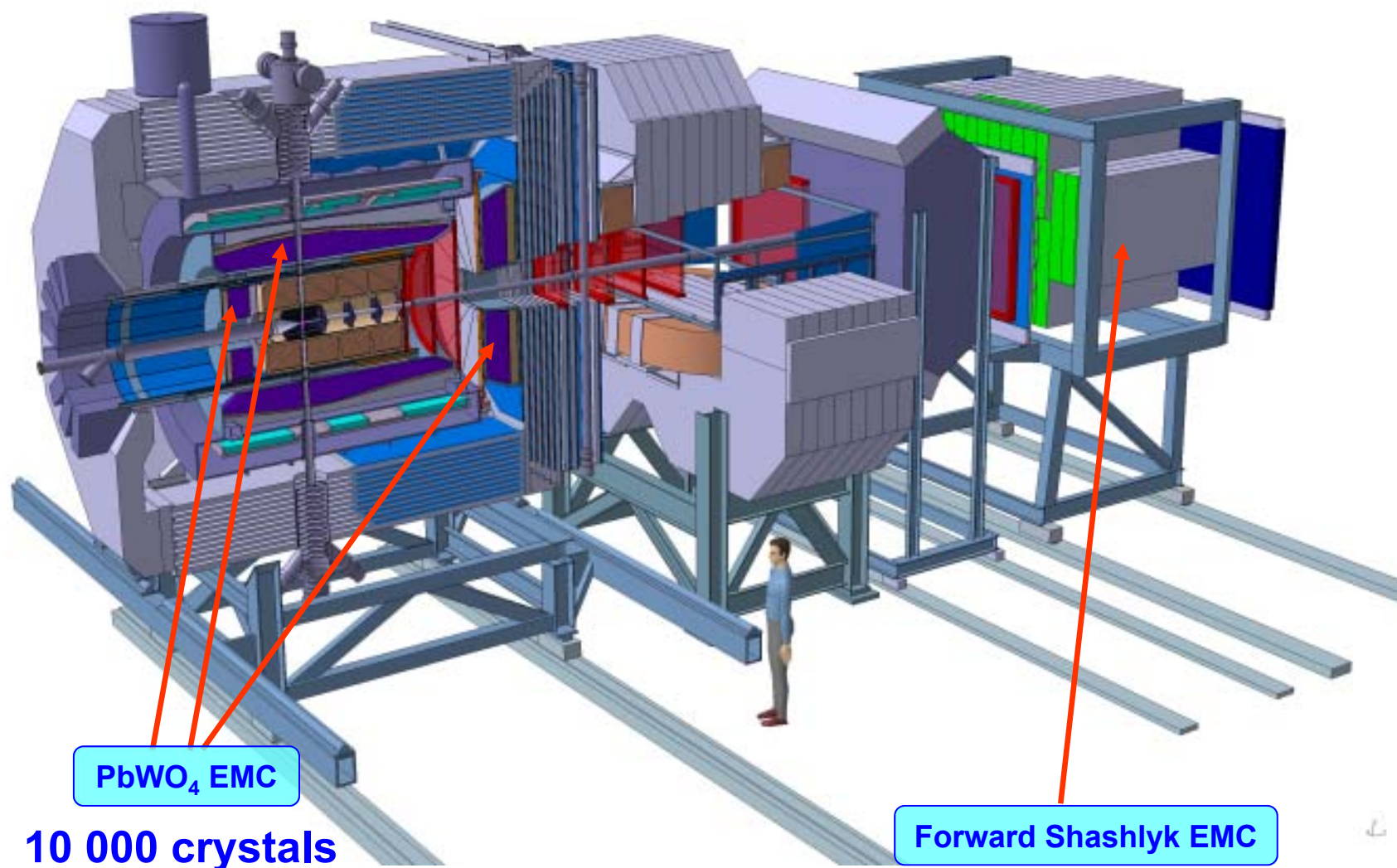
PANDA spectrometer: Tracking



PANDA spectrometer: Particle IDentification



PANDA spectrometer: Particle IDentification



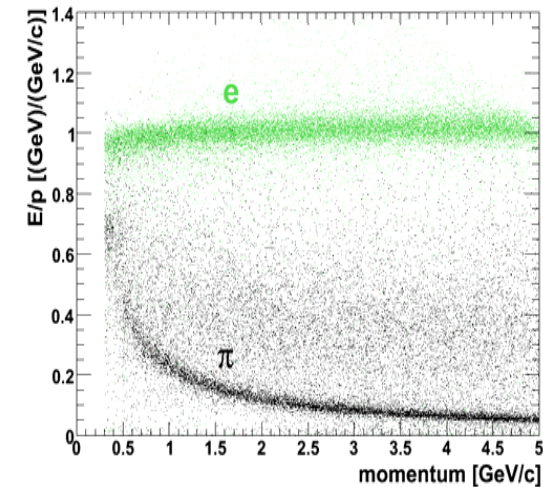
Particle IDentification with PANDA



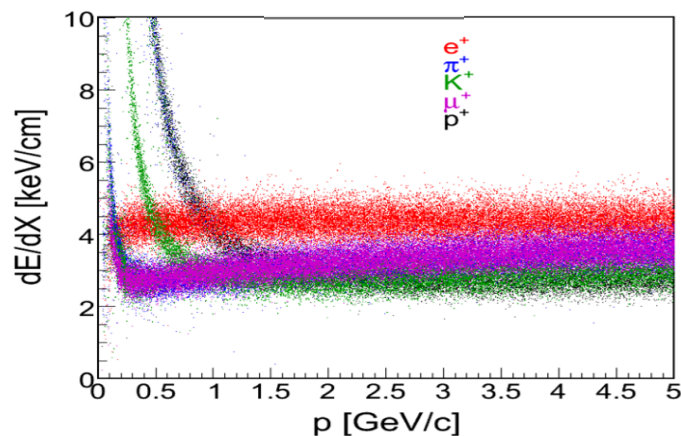
PANDA PID Requirements:

- particle identification essential for PANDA
- momentum range 200 MeV/c – 10 GeV/c
- Extreme high rates $2 \cdot 10^7$ Hz
- good particle separation (K - π , e - π)**
 - different detectors needed for PID

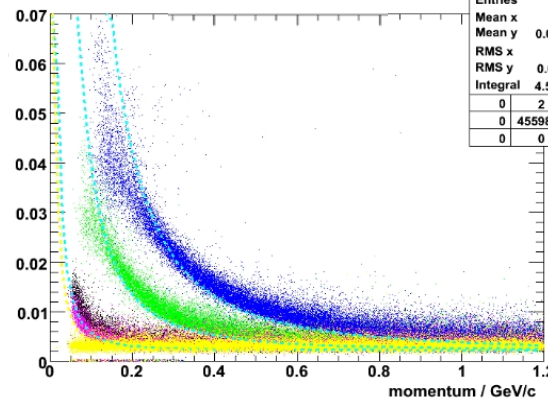
EMC



STT

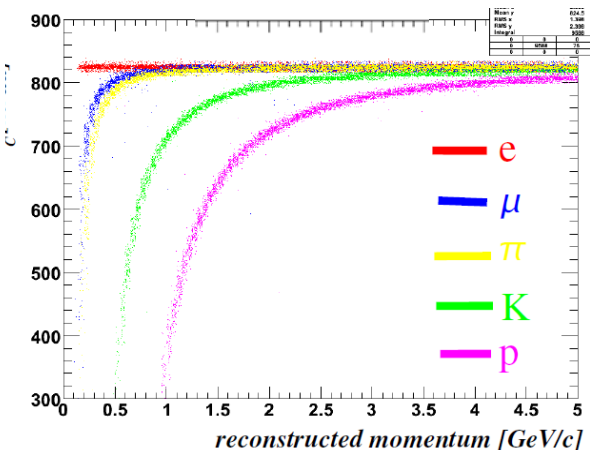


MVD



helosMomHistPI			
Entries	45925		
Mean x	0.6331		
Mean y	0.003784		
RMS x	0.3233		
RMS y	0.001891		
Integral	4.56e+04		
0	2	0	
0	45598	325	
0	0	0	

DIRC



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

$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$

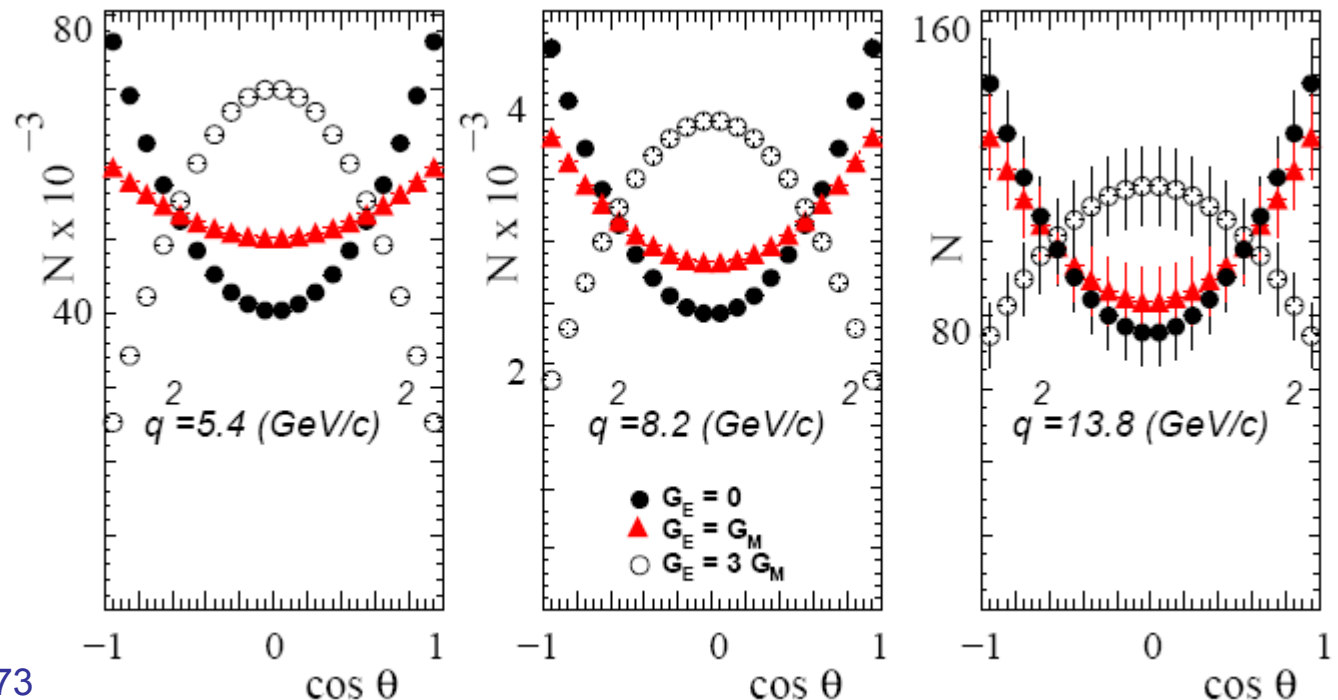
Generator:

- $|G_M| = 22.5 (1 + q^2 / 0.71)^{-2} (1 + q^2 / 3.6)^{-1}$

$$\frac{d\sigma}{d(\cos \theta)} = \frac{\pi \alpha^2}{8m^2 \sqrt{\tau - 1}} [\tau |G_M|^2 (1 + \cos^2 \theta) + |G_E|^2 \sin^2 \theta]$$

- $\mathcal{R} = |G_E|/|G_M|$

**lower sensitivity
@ higher q^2**

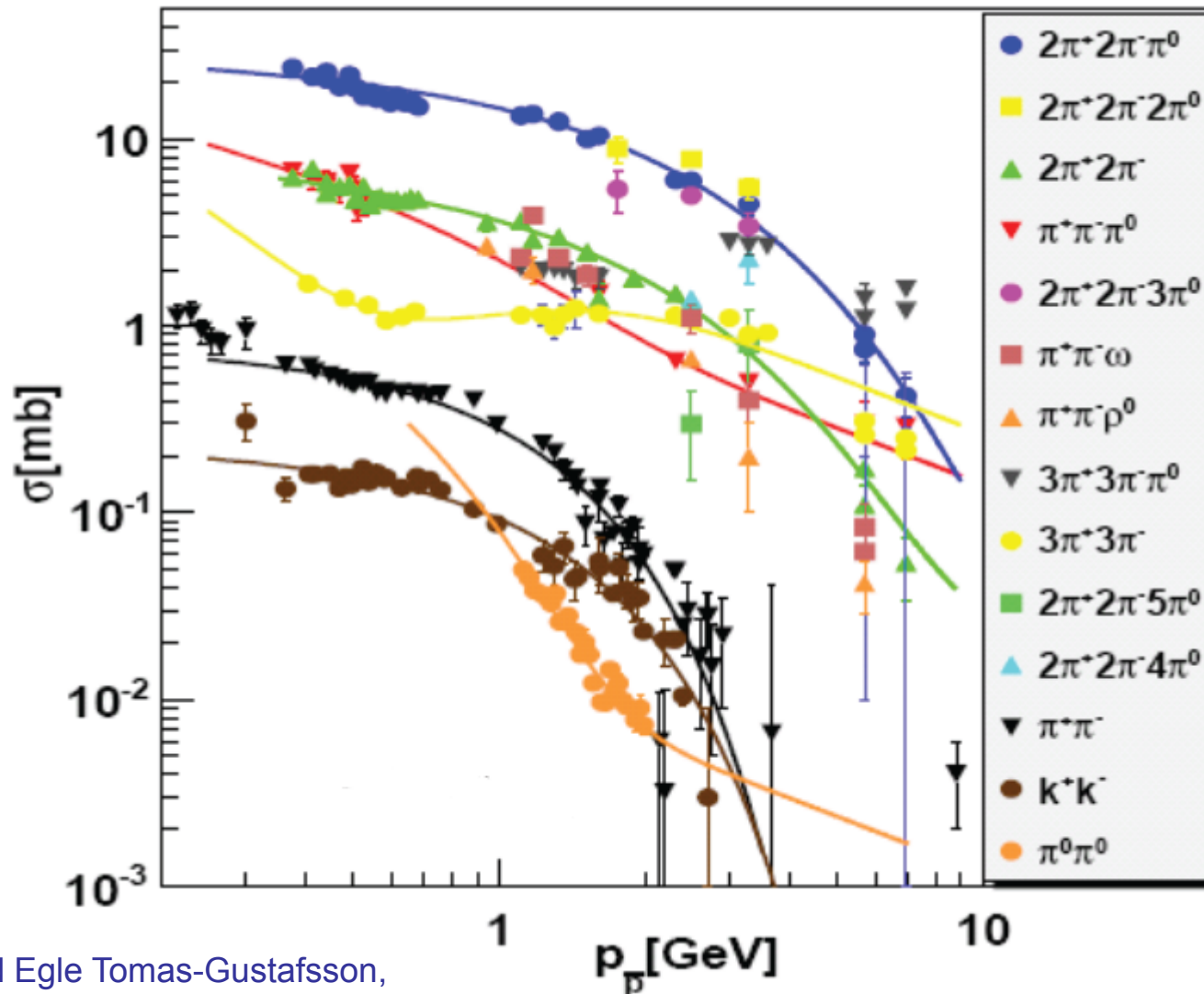


M. Sudol et al., EPJ A44 (2010) 373

E. Tomasi-Gustafsson, M.P. Rekalo, PLB 504 (2001) 291

$\bar{p} + p$ inelastic cross section

$$\sigma_{\text{inel}} \sim \text{mb} \quad , \quad \sigma_{(e-e^+)} \sim \text{nb}$$



A.Dbeyssi and Egle Tomas-Gustafsson,
3rd International Conference on Quantum Electrodynamics and Statistical Physics,
Aug. 29-Sept. 02, 2011, Kharkov, Ukraine

$\bar{p} + p \rightarrow \pi^- + \pi^+$ events generation

$$\frac{d\sigma}{dt} = C s^{-8} f(\theta), \quad f(\theta) = \frac{1}{2} (1 - z^2) [2(1 - z)^{-2} + (1 + z)^{-2}]^2, \quad z = \cos \theta$$

E. Eisenhandler et al., NPB 96 (1975) 109

A. Berglund et al., NPB 137 (1978) 276

T. Buran et al., NPB 116 (1976) 51



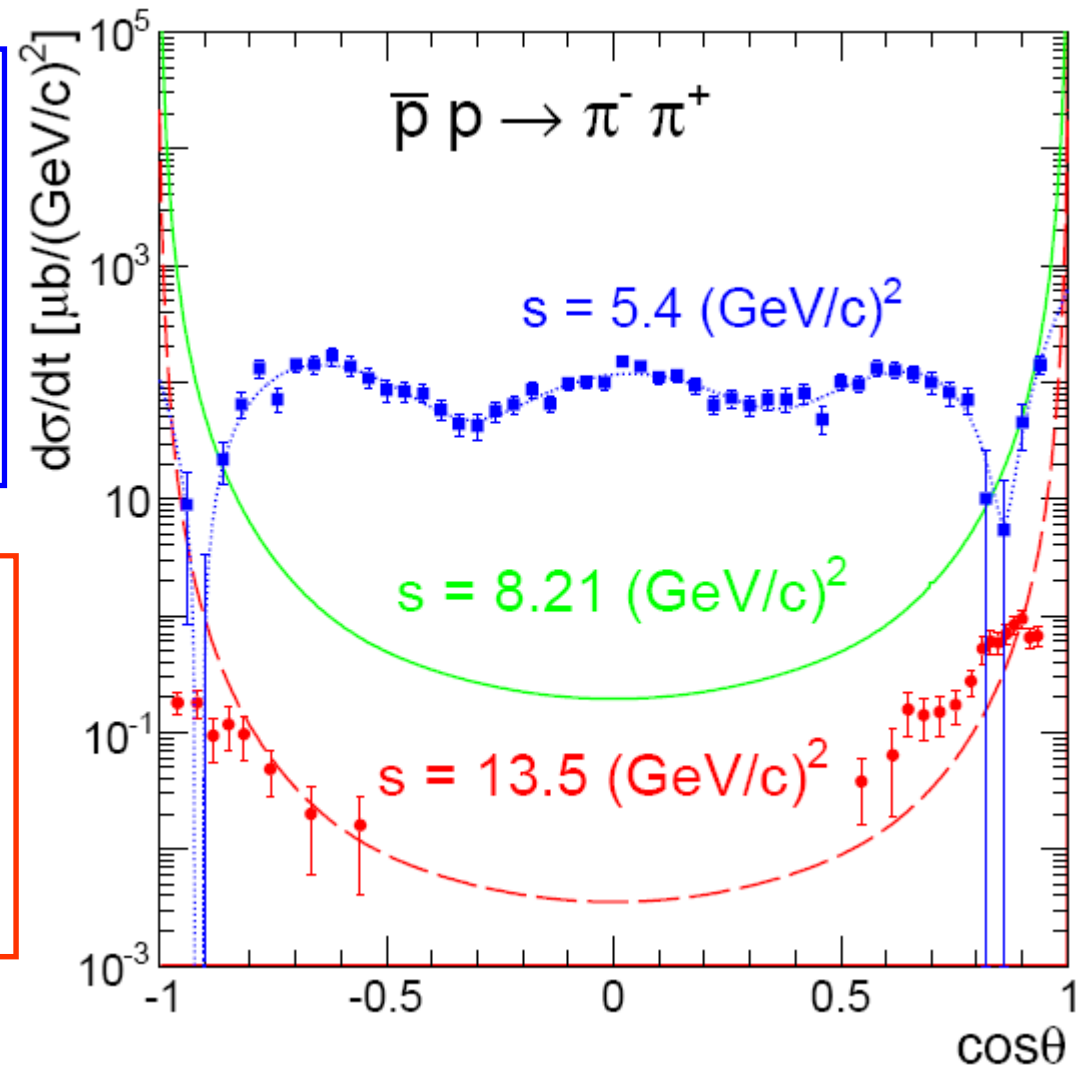
$$\cos(\theta) < 0.8$$

$$\sigma_{(\pi-\pi+)}/\sigma_{(e-e+)} \leq 3 \cdot 10^6$$

$$B/S \sim 0.1\%$$



$$\text{Rejection power} > 3 \cdot 10^9$$



$\bar{p} + p \rightarrow \pi^0 + \pi^0$ events generation

$$\frac{d\sigma}{d\cos\theta} = \frac{f(s, \theta)}{s^6 (\sqrt{tu}/s)^4}, \quad f(s, \theta) = \sum_i a_i(s) P_i(\cos\theta)$$

Fermilab E760 C., T. A. Armstrong et al.,
PRD 56 (1997) 2509

Fermilab E760 C., T. A. Armstrong et al.,
PRD 56 (1997) 2509



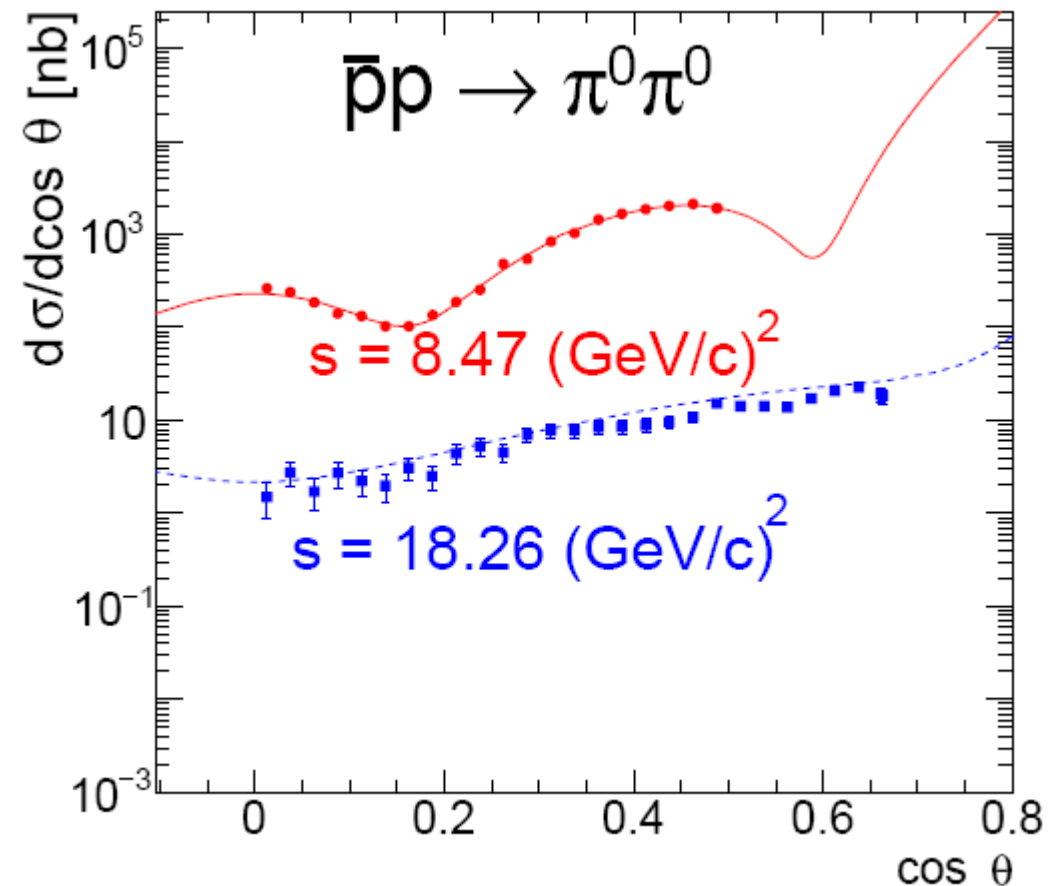
$$\cos(\theta) < 0.8$$

$$\sigma_{(\pi^0\pi^0)}/\sigma_{(e^+e^-)} \leq 3 \cdot 10^5$$

$$B/S \sim 0.1\%$$

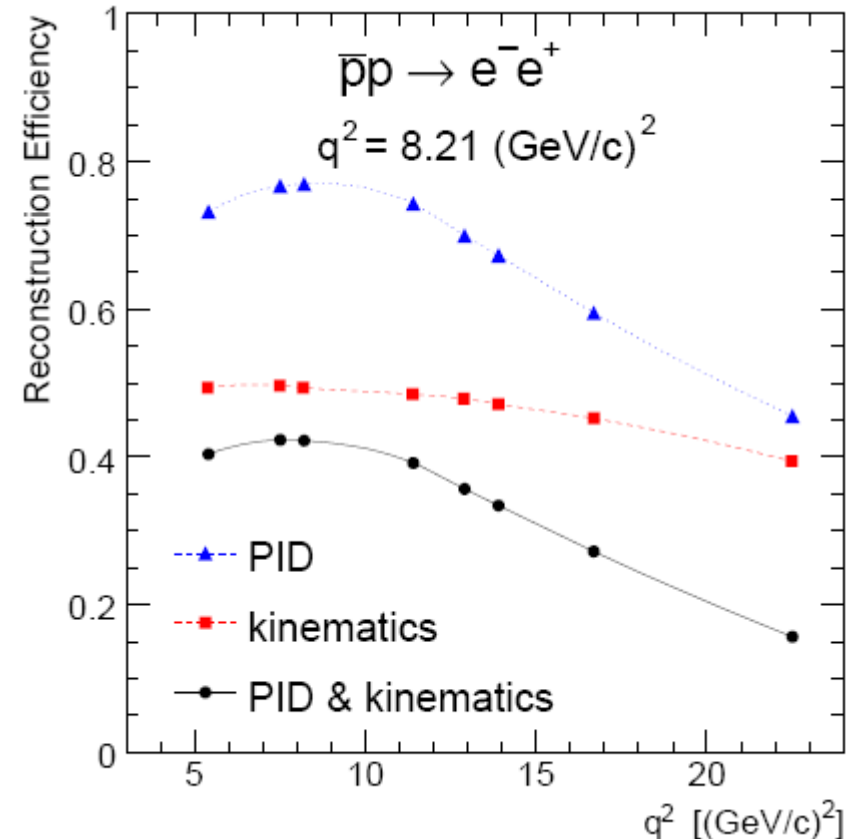
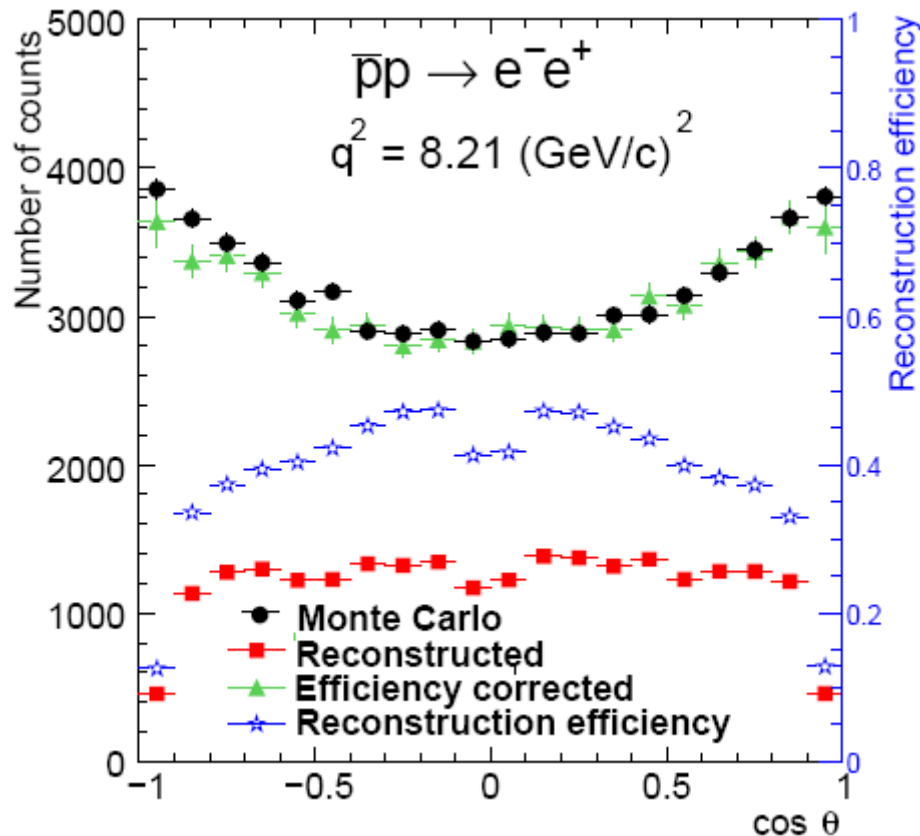


$$\text{Rejection power} > 3 \cdot 10^8$$



Signal description:

- good description of acceptance and efficiencies
- efficiency drops at higher q^2



- **3 body reactions**

- kinematical constraints
- PID

- **2 body reactions (hadrons)**

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

$$\sigma_{(\pi^-\pi^+)}/\sigma_{(e^+e^-)} \sim 10^6$$

$$\sigma_{(\pi^0\pi^0)}/\sigma_{(e^+e^-)} \sim 10^5$$

High statistics GEANT4 simulations:

- **< few % misidentified events per $\cos \theta_{CM}$ bin**
- **< 1% in the total cross section up to 16 GeV²**

e^+e^- can be safely resolved from $\pi^+\pi^-$ or $\pi^0\pi^0$

PANDA scenario: expected results



$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

$$N(\cos \theta) = \alpha[\tau(1 + \cos^2 \theta) + \mathcal{R}^2 \sin^2 \theta]$$

BABAR:

B. Aubert et al. PRD 73 (2006) 012005

PS170:

G. Bardin et al., NPB 411 (1994) 3

pQCD inspired:

V. A. Matveev et al., LNC 7 (1973) 719

S. J. Brodsky et al., PRL 31 (1973) 1153

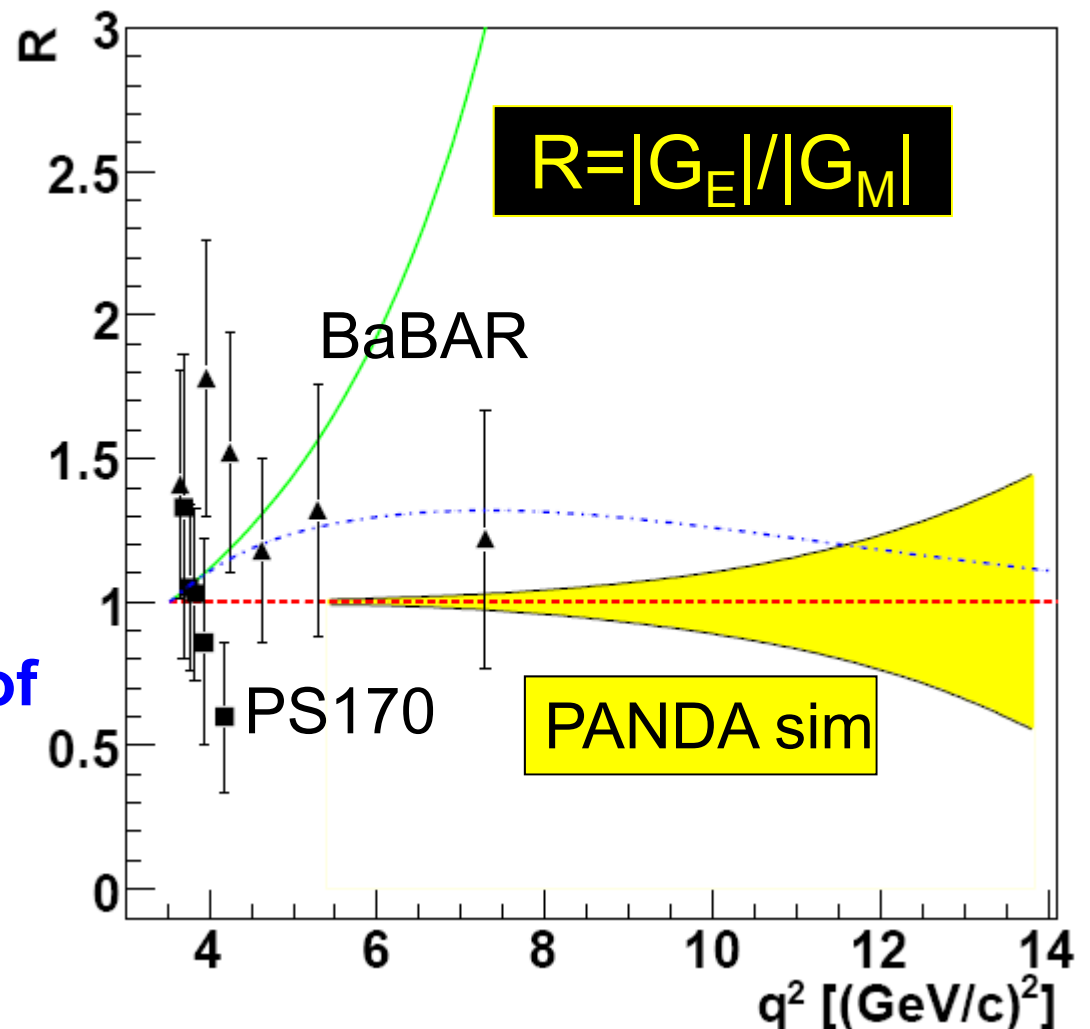
VDM:

F. Iachello, PLB 43 (1973) 191

Extended VDM:

E.L.Lomon, PRC 66 (2002) 045501

**Individual determination of
 $|G_E|$ and $|G_M|$
up to $q^2 \sim 14 \text{ (GeV/c)}^2$!!**



PANDA scenario: expected results



$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

BABAR:

B. Aubert et al. PRD 73 (2006) 012005

E835:

M. Andreotti et al., PLB 559 (2003) 20

M. Ambrogiani et al., PRD 60 (1999) 032002

Fenice:

A. Antonelli et al., NPB 517 (1998) 3

PS170:

G. Bardin et al., NPB 411 (1994) 3

E760:

T. A. Armstrong et al., PRD 56 (1997) 2509

CLEO:

T. K. Pedlar et al., PRL 95 (2005) 261803

DM1:

B. Delcourt et al., PLB 86 (1979) 395

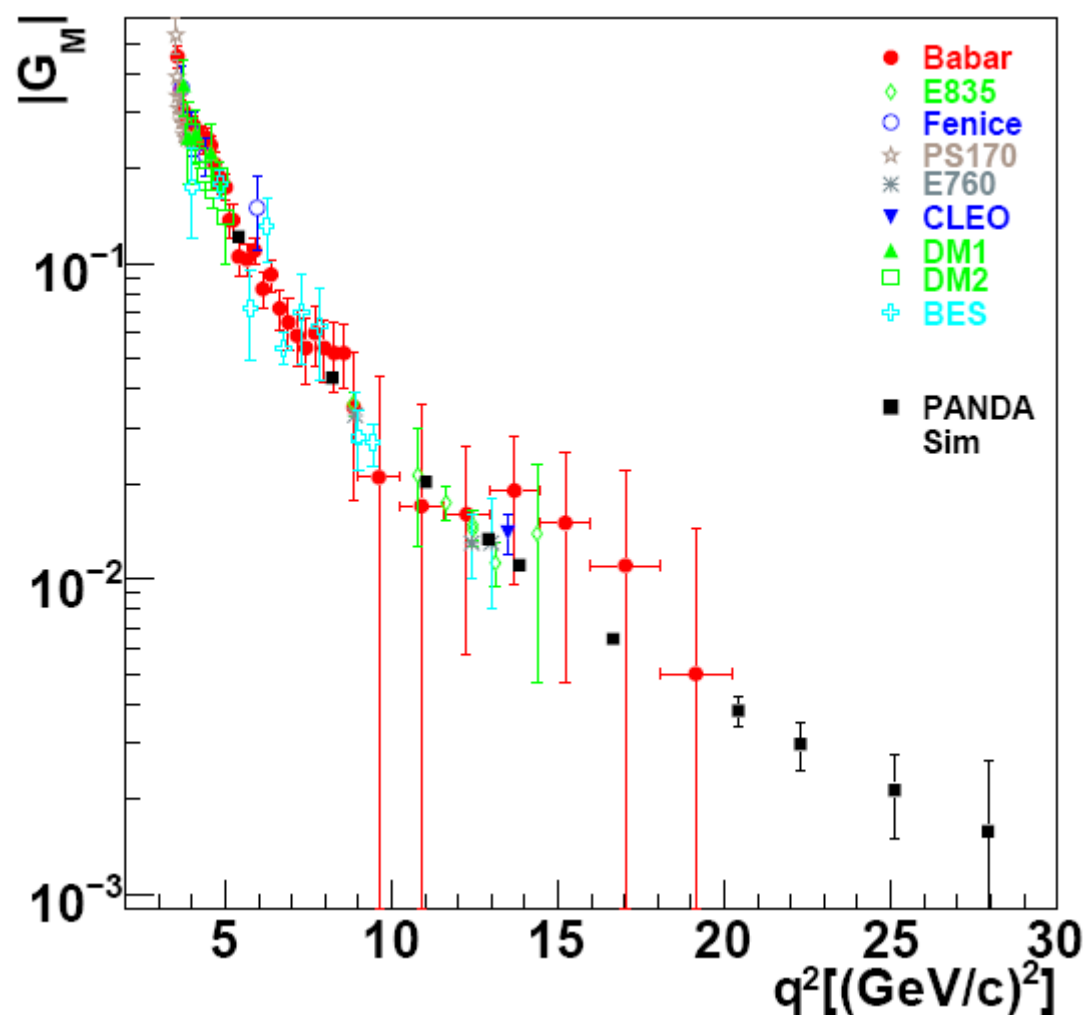
DM2:

D. Bisello et al., NPB 224 (1983) 379

BES:

M. Ablikim et al., PLB 630 (2005) 14

$$\mathcal{R} = 1$$



**Absolute σ accessible
up to $q^2 \sim 28 \text{ (GeV/c)}^2$**

PANDA scenario: asymptotic behaviours



$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

BABAR:

B. Aubert et al. PRD 73 (2006) 012005

E835:

M. Andreotti et al., PLB 559 (2003) 20

M. Ambrogiani et al., PRD 60 (1999) 032002

Fenice:

A. Antonelli et al., NPB 517 (1998) 3

PS170:

G. Bardin et al., NPB 411 (1994) 3

E760:

T. A. Armstrong et al., PRD 56 (1997) 2509

CLEO:

T. K. Pedlar et al., PRL 95 (2005) 261803

DM1:

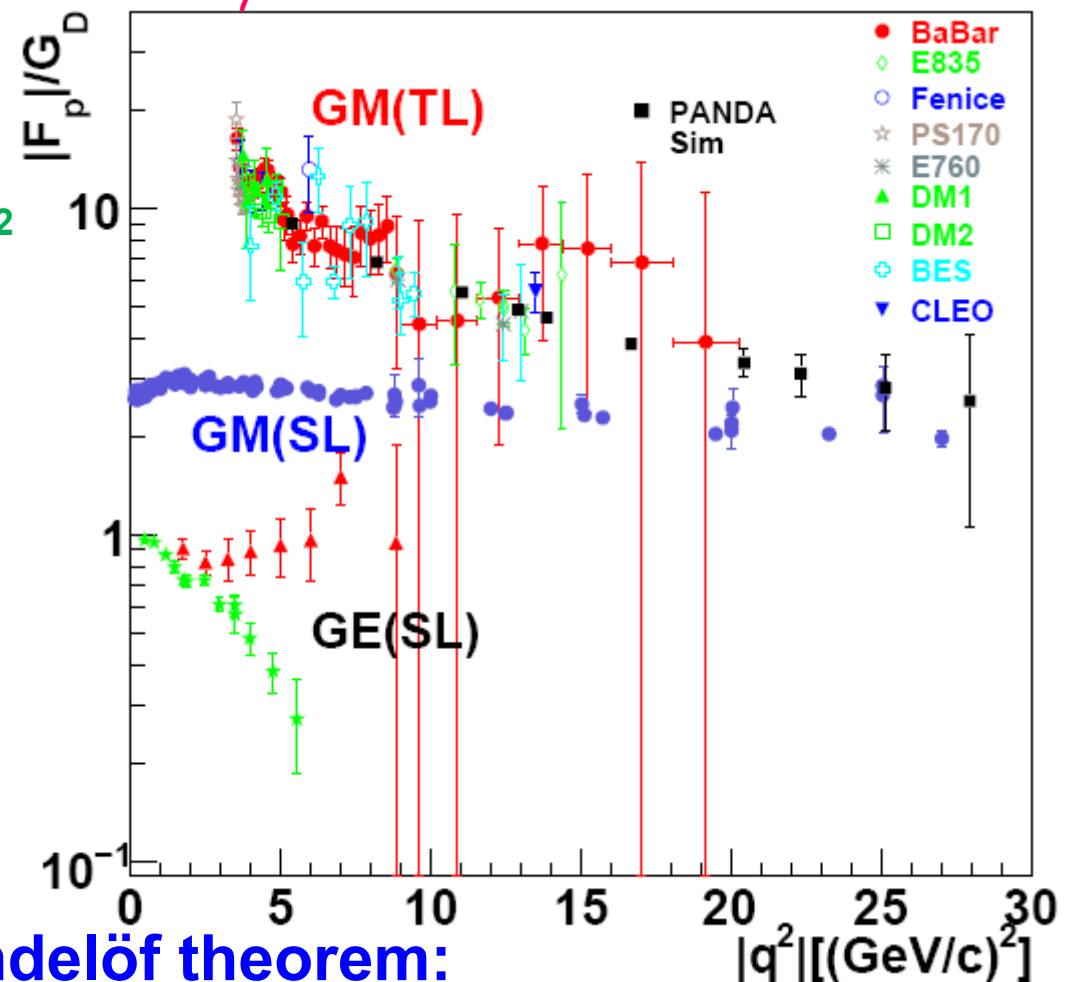
B. Delcourt et al., PLB 86 (1979) 395

DM2:

D. Bisello et al., NPB 224 (1983) 379

BES:

M. Ablikim et al., PLB 630 (2005) 14



Probing the Phragmén-Lindelöf theorem:

$$\lim_{q^2 \rightarrow -\infty} F^{(SL)}(q^2) = \lim_{q^2 \rightarrow \infty} F^{(TL)}(q^2) \quad \text{Im} F_i(q^2) \rightarrow 0, \quad q^2 \rightarrow \infty$$

PANDA scenario: sensitivity to odd $\cos\theta$ terms

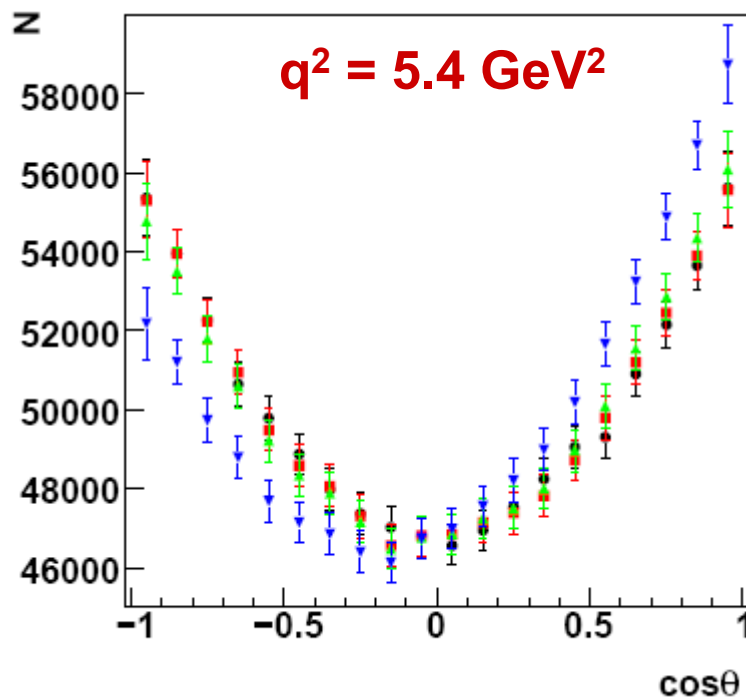


$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

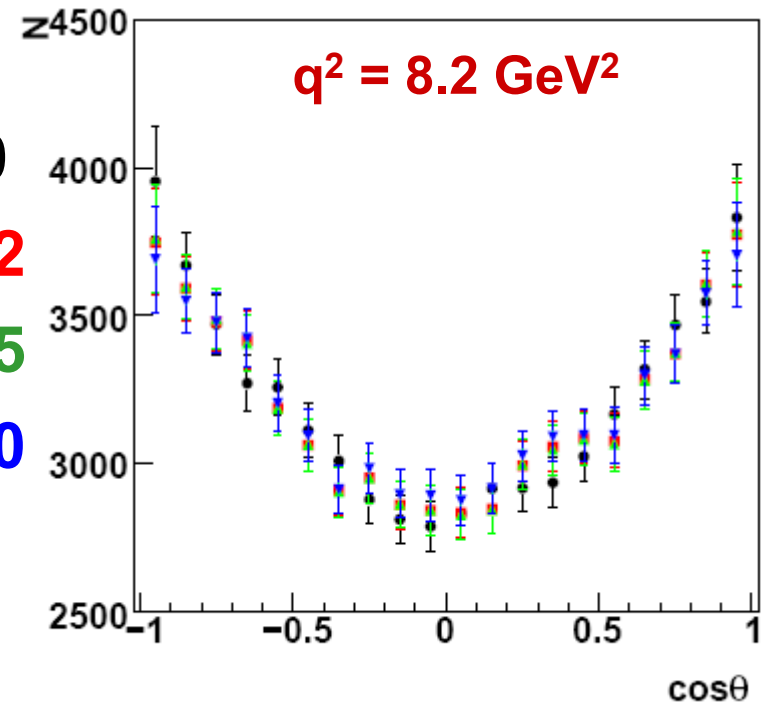
TPE:

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

Approximations: neglect contributions to G_E, G_M ; consider only real part; $|G_E|=|G_M|$



$$\begin{aligned} |F_3/G_M| &= 0.0 \\ |F_3/G_M| &= 0.02 \\ |F_3/G_M| &= 0.05 \\ |F_3/G_M| &= 0.20 \end{aligned}$$



Odd $\cos\theta$ terms related to: ISI-FSI interference, TPE..

5% odd contributions needed to explain JLAB data

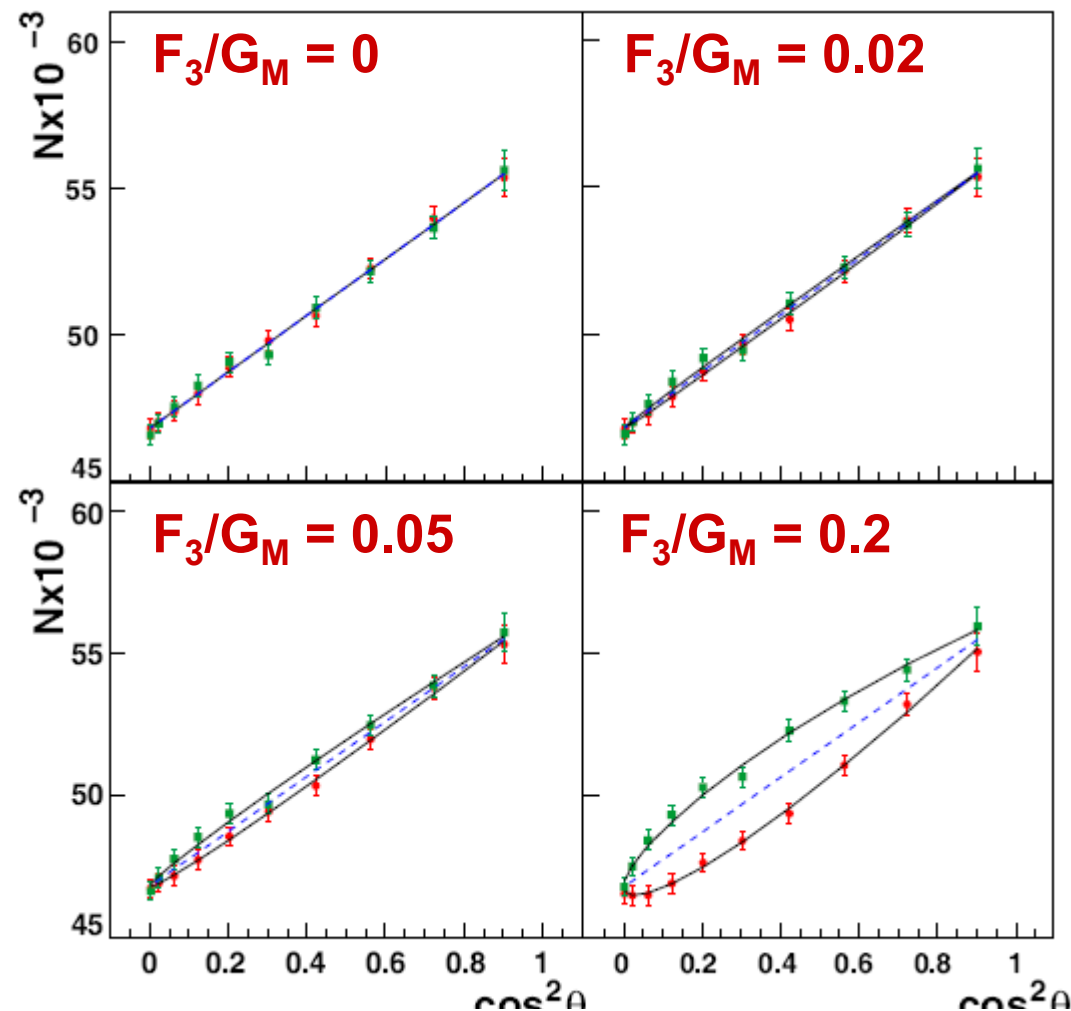
PANDA scenario: sensitivity to odd $\cos\theta$ terms



$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

TPE: $N = a_0 + a_1 \cos^2\theta + a_2 \cos\theta (1 - \cos^2\theta) ; a_2 = F_3/G_M \leftrightarrow 2\gamma?$

$q^2 = 5.4 \text{ GeV}^2$



PANDA scenario: sensitivity to odd $\cos\theta$ terms



$$\mathcal{L} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \text{ fb}^{-1} \text{ in } \sim 100 \text{ days}$$

$$q^2 = 5.4, 8.2 \text{ and } 13.84 \text{ GeV}^2$$

TPE: $N = a_0 + a_1 \cos^2\theta + a_2 \cos\theta (1 - \cos^2\theta) ; a_2 = F_3/G_M \leftrightarrow 2\gamma?$

q^2	F_3/G_M	a_0	a_1	a_2	$ \Delta\mathcal{R} $	$\mathcal{A} \pm \Delta\mathcal{A}$
5.4	0	46798 ± 118	9626 ± 320	-4 ± 288	0.008	0.21 ± 0.01
	2%	46795 ± 118	9638 ± 321	358 ± 289	0.008	0.21 ± 0.01
	5%	46794 ± 118	9634 ± 321	891 ± 289	0.008	0.21 ± 0.01
	20%	46789 ± 118	9655 ± 321	3539 ± 289	0.008	0.21 ± 0.01
8.2	0	2832 ± 28	1127 ± 82	-45 ± 72	0.035	0.40 ± 0.03
	2%	2859 ± 28	1057 ± 82	45 ± 72	0.035	0.37 ± 0.03
	5%	2857 ± 28	1065 ± 82	163 ± 72	0.036	0.37 ± 0.03
	20%	2863 ± 28	1042 ± 82	769 ± 72	0.035	0.36 ± 0.03
13.84	0	85 ± 5	39 ± 19	5 ± 14	0.385	0.47 ± 0.23
	2%	86 ± 5	41 ± 19	12 ± 14	0.385	0.47 ± 0.23
	5%	86 ± 5	41 ± 19	21 ± 14	0.385	0.47 ± 0.23
	20%	84 ± 5	49 ± 19	65 ± 14	0.382	0.57 ± 0.23

**A $F_3/G_M \sim 5\%$ could be detected
in the PANDA scenario!!**

Conclusions

Proton Time-Like Form Factors at PANDA

- a precise measurement of the angular distribution allow to access FFs AND reaction mechanism in annihilation processes
- TL G_E and G_M can be accessed independently up to $q^2 \sim 14$ (GeV/c)²
- G_M can be determined up to $q^2 \sim 28$ (GeV/c)² assuming $|G_E|=|G_M|$
- SL vs TL FFs: test of the validity of pQCD and analiticity
- probing the OPE approximation: implication on hadron structure and radiative corrections
- interesting threshold region can be investigated @ BESIII (pointlike FFs?); $s > 5.4$ GeV² @ PANDA, threshold and below accessible by $e^+e^-\pi^0$ final state

on behalf of the PANDA Collaboration

THANK YOU!