Study of the proton structure via $\bar{p}$ p annihilation at $\bar{P}$ANDA

J. Boucher, M. Gumberidze, T. Hennino, R. Kunne, D. Marchand, S. Ong, B. Ramstein, E. Tomasi-Gustafsson, J. Van de Wiele

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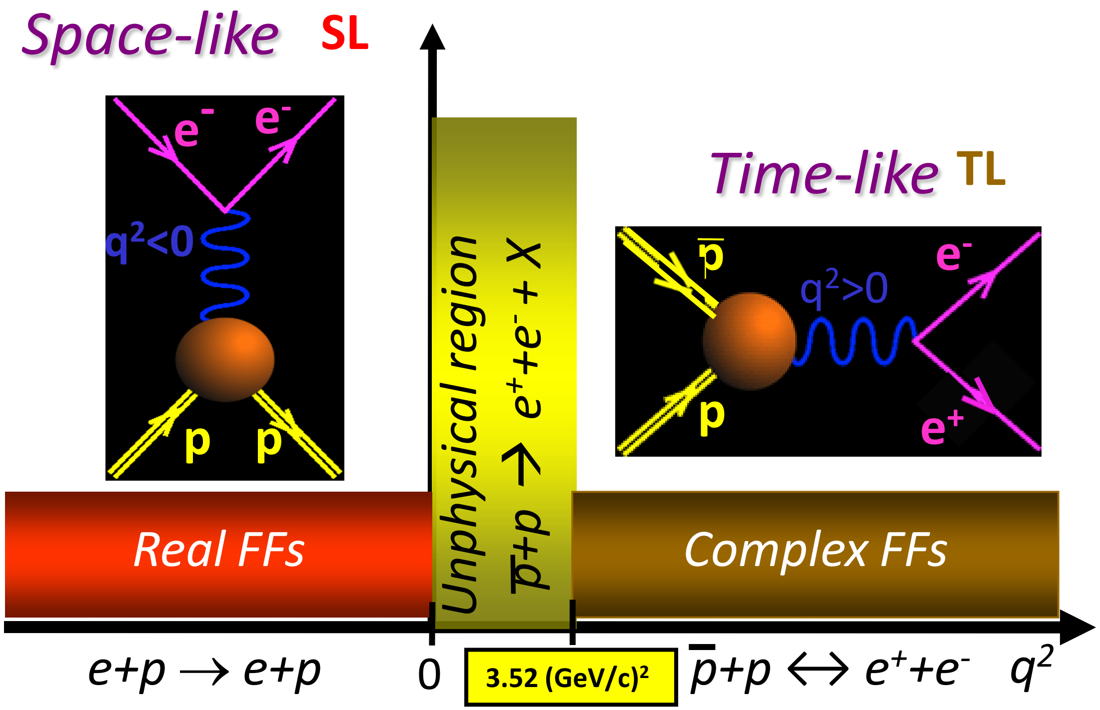
10/04/2010

Outline

- Motivations: proton electromagnetic form factors
- $\overline{\text{P}}$ANDA detector
- $\bar{p}p \rightarrow e^+e^-$ channel
  - Signal efficiency and background rejection
- $\bar{p}p \rightarrow \pi^0 e^+e^-$ channel
  - Models, first results
- Conclusion & future plans

Proton electromagnetic form factors



Normalization

- $G_E^p(0)=1$
- $G_M^p(0)=\mu_p$
- $G_E^p(4m_p^2)= G_M^p(4m_p^2)$

Asymptotics

- $|G_{E,M}(q^2)| \sim (q^2)^{-2}$
- $\dfrac{G_E}{G_M} \sim \text{real constant}$

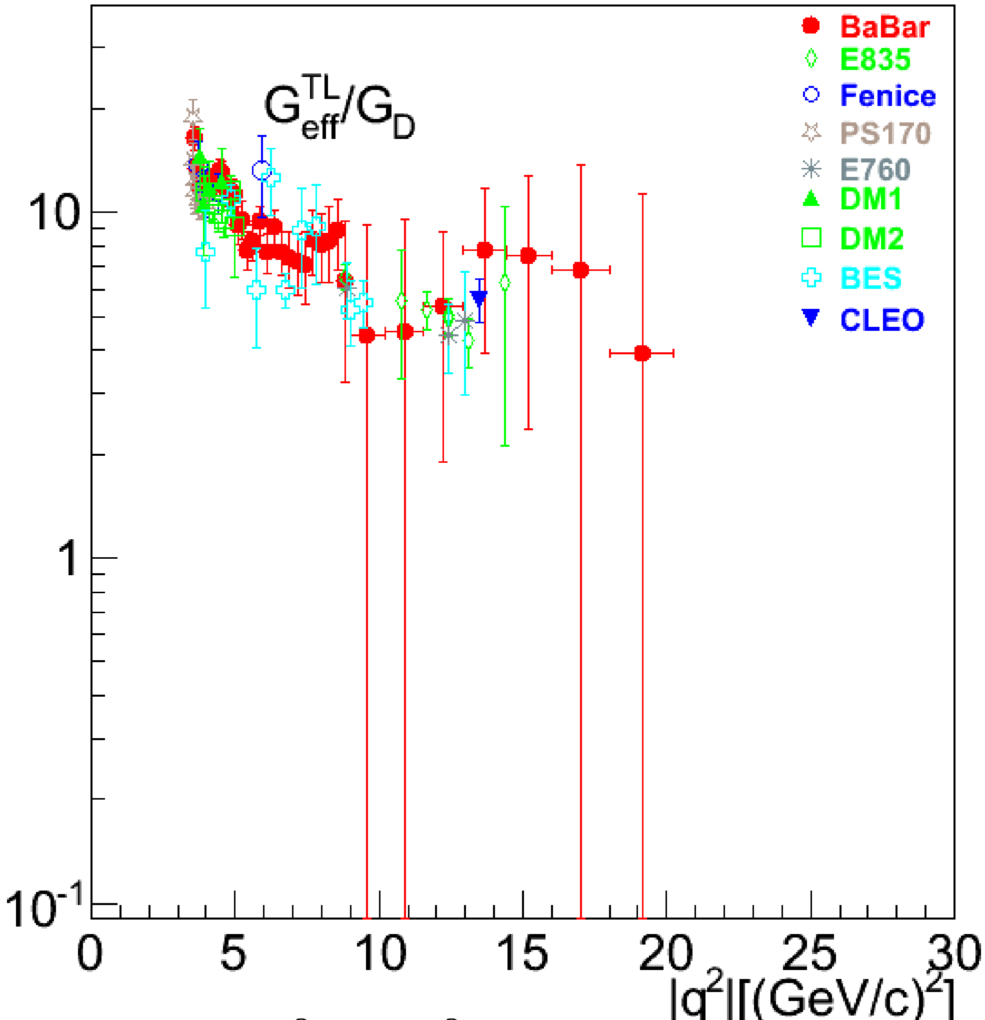
For $q^2 \to \pm\infty$

- $\lim\limits_{q^2\to-\infty} G^{SL}_{E,M}(q^2) = \lim\limits_{q^2\to+\infty} G^{TL}_{E,M}(q^2)$ (Phragmén-Lindelhöf theorem)
- Dispersion relation

$$G(q^2) = \frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2} \frac{\operatorname{Im} G(s)\,ds}{s-q^2} + \int_{4m_p^2}^{\infty} \frac{\operatorname{Im} G(s)\,ds}{s-q^2}\right]$$

Precise data (SL) **No data (TL)** **Low quality data (TL)**

Proton EM form factor data



$$G_{eff}{}^2 = \frac{2\tau|G_M|^2 + |G_E|^2}{2\tau + 1}$$

$$G_D = \left(1 + \frac{Q^2}{0.71^2}\right)^{-2}$$

TL:
- G_{eff}^{TL} extracted under the assumption $|G_E^{TL}| = |G_M^{TL}|$.
- Few data available at high q^2.
- No individual determination of $|G_E^{TL}|$ and $|G_M^{TL}|$.

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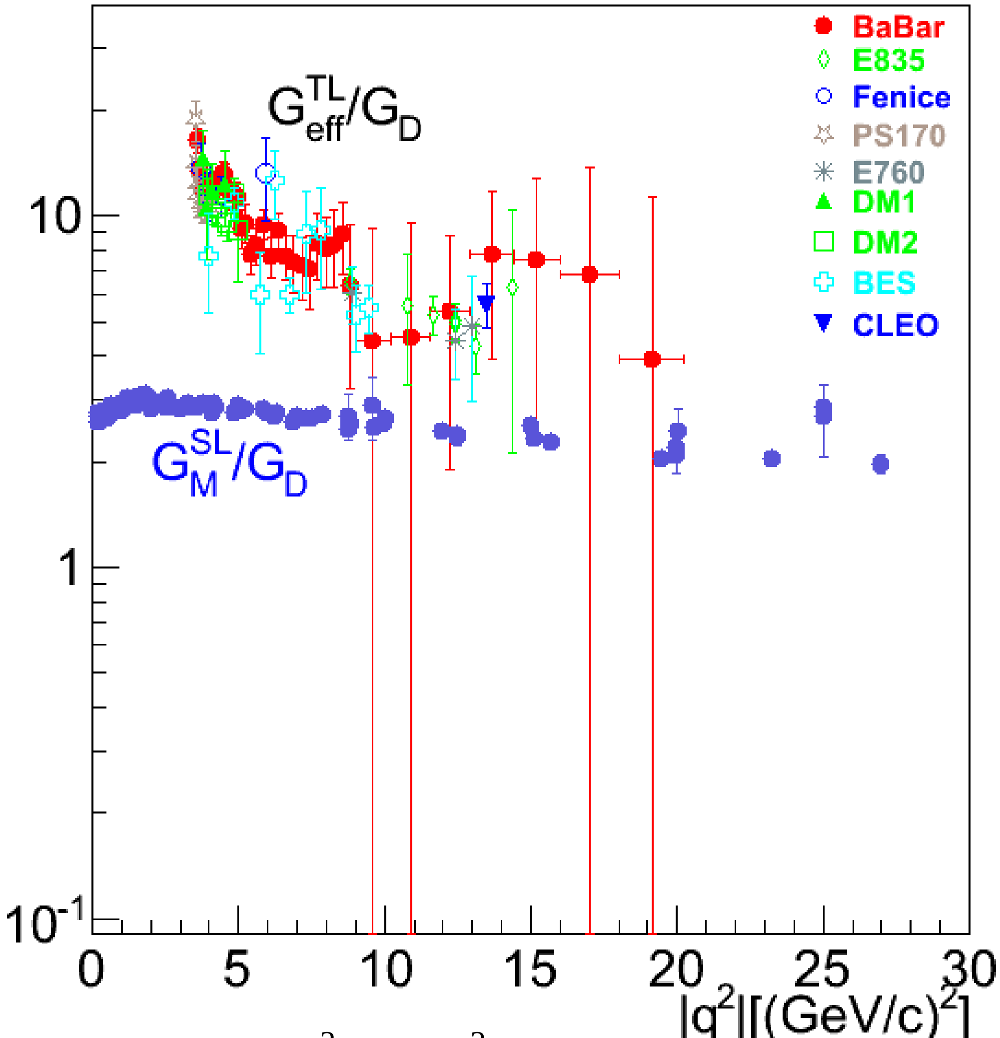

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- $|G_{eff}^{TL}| \approx |G_M^{TL}| \approx 2\,|G_M^{SL}|$
  ⮡ asymptotic regime not reached

$$|G_{eff}|^2 = \frac{2\tau|G_M|^2 + |G_E|^2}{2\tau + 1} \qquad G_D = \left(1 + \frac{Q^2}{0.71^2}\right)^{-2}$$

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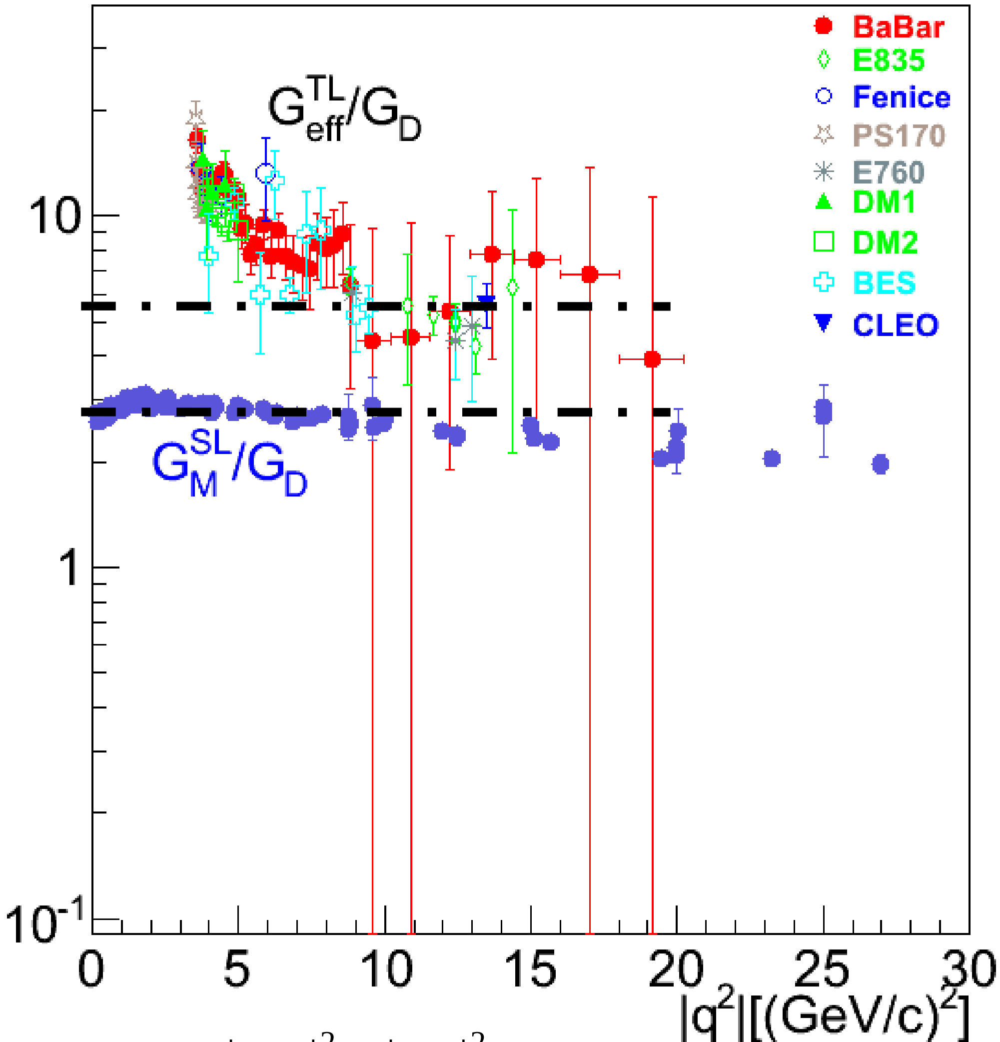

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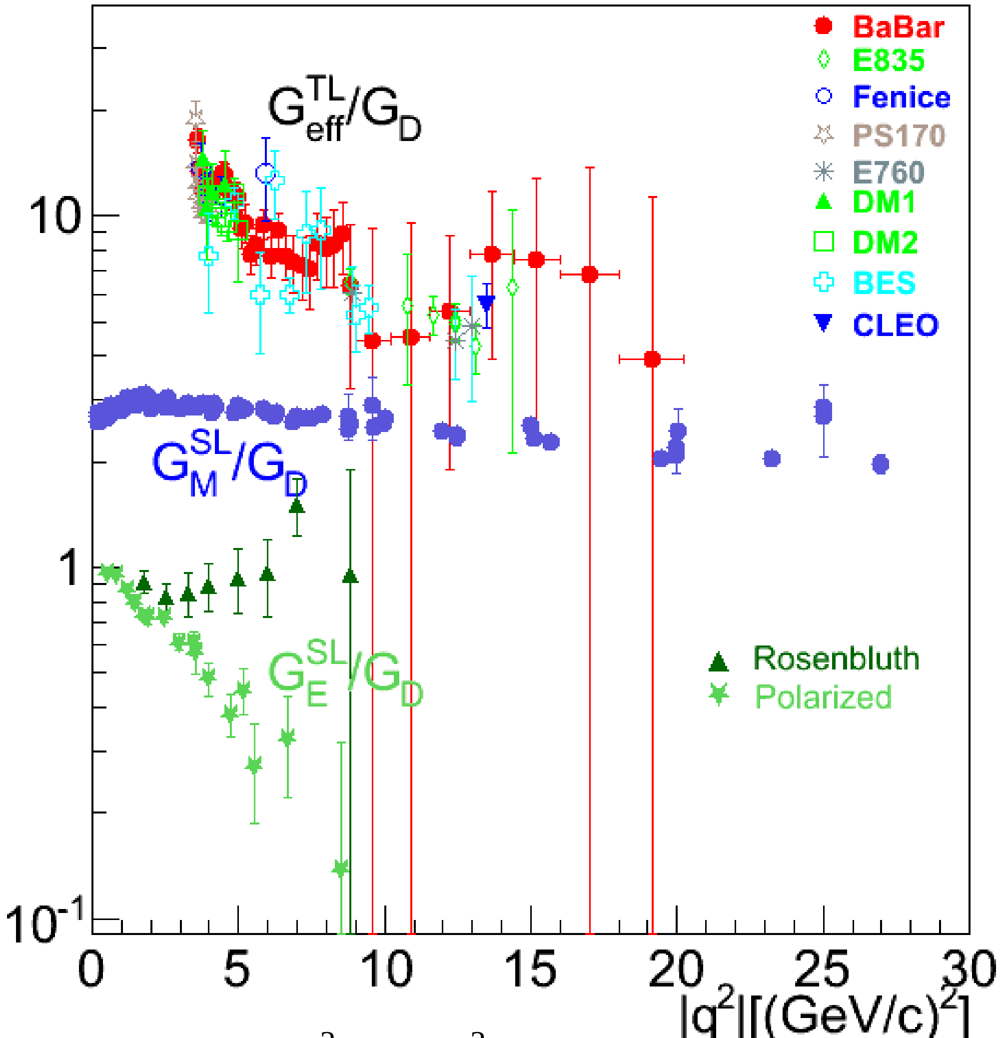

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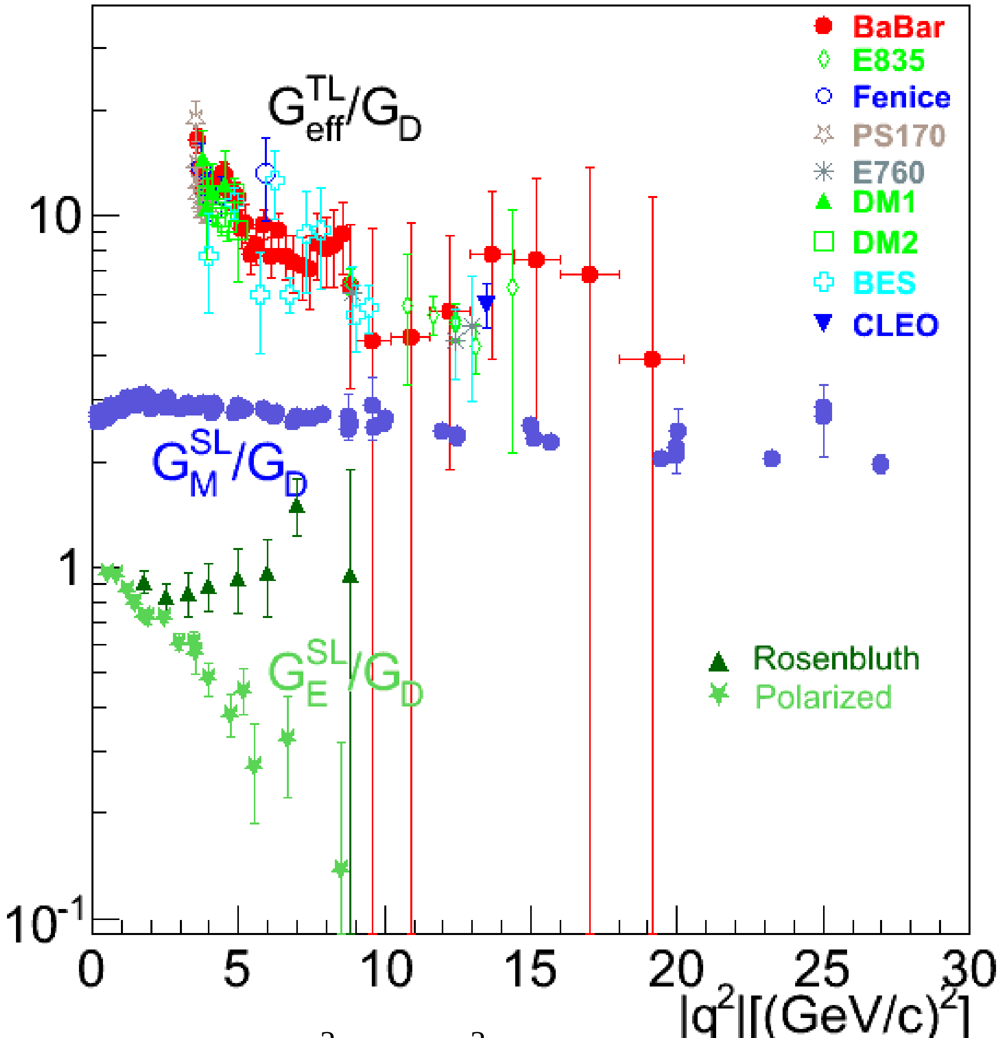

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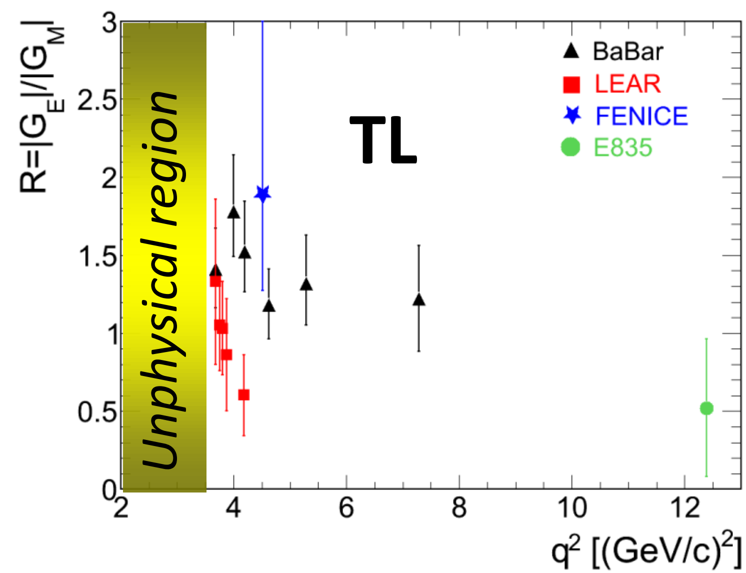

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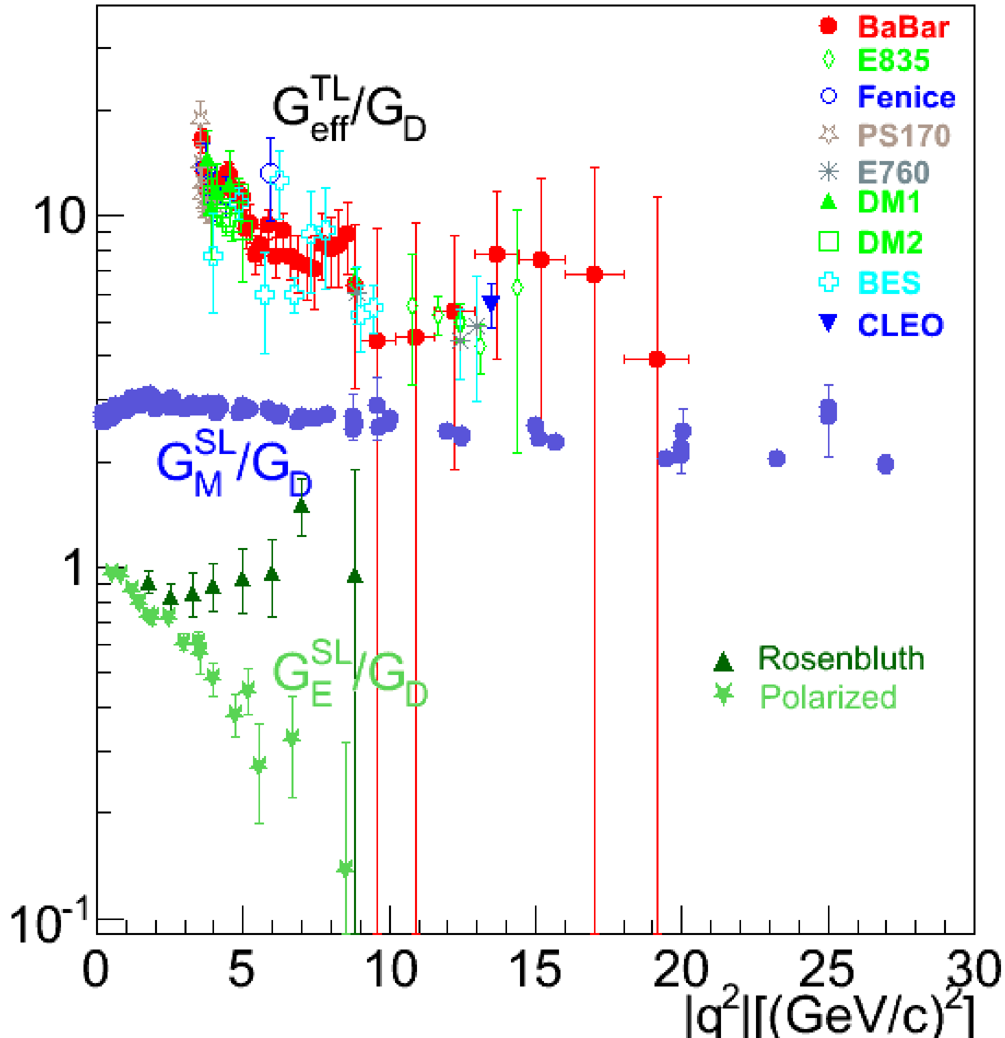

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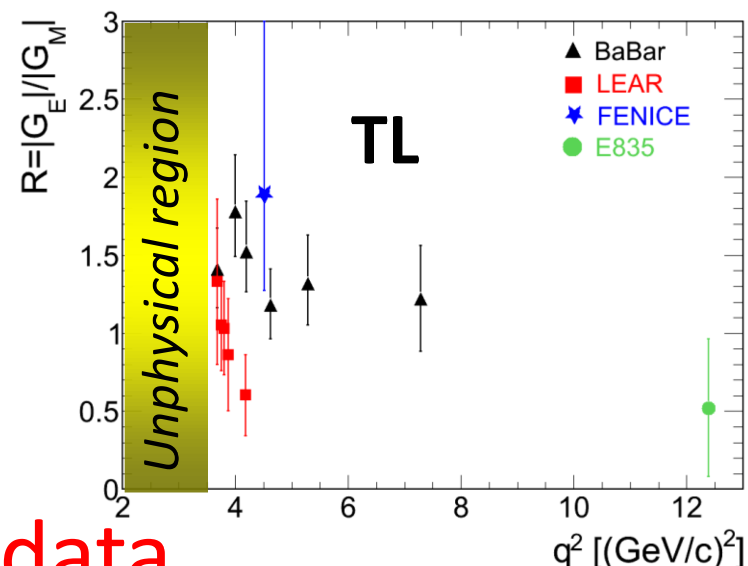


Need for precise data

FAIR, Facility for Antiproton and Ion Research, Darmstadt, Germany

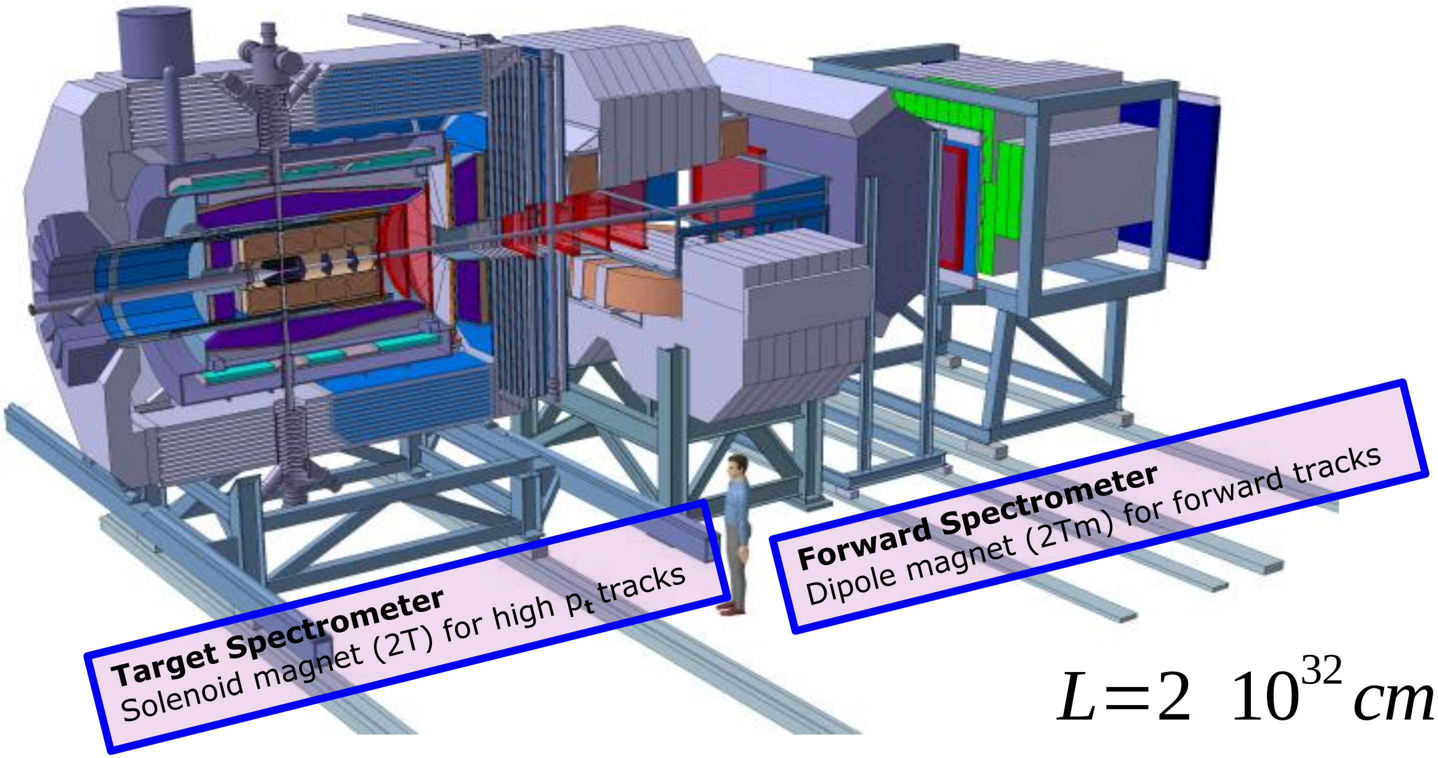
GSI, Darmstadt

- heavy ion physics
- nuclear structure
- atomic and plasma physics

FAIR, Darmstadt: New facility

- heavy ion physics & nuclear structure
- atomic, plasma and applied physics
- higher intensities & energies
- **antiproton physics**

PANDA detector



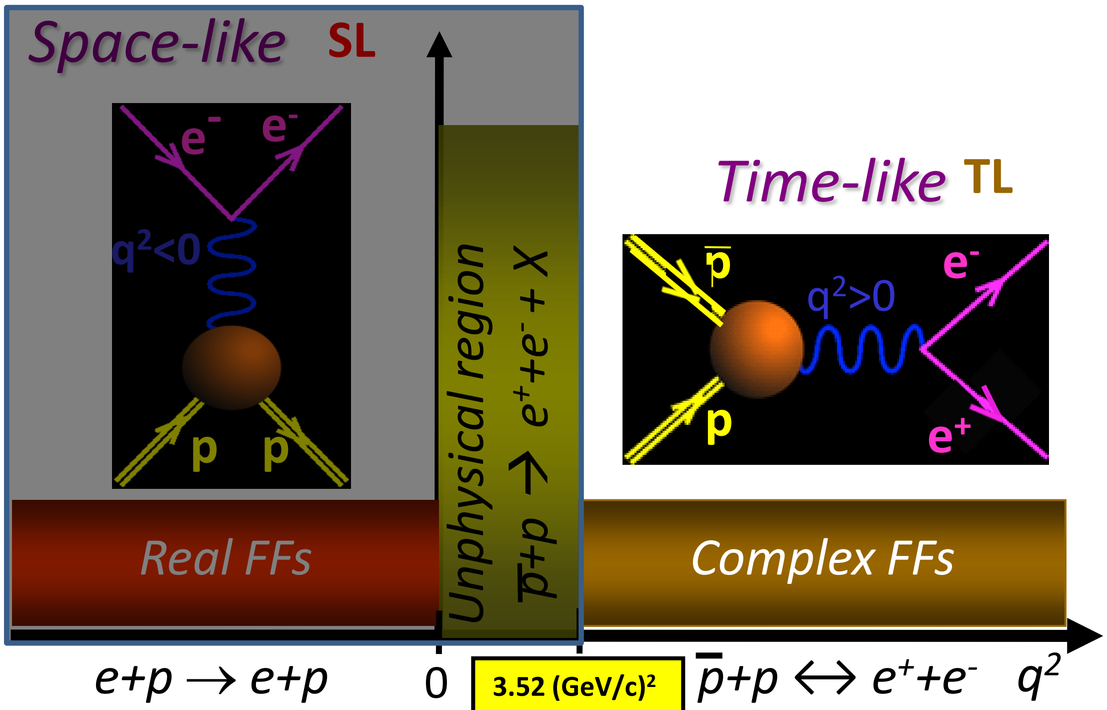
$$L = 2\ 10^{32}\, cm^{-2}\, s^{-1}$$

Detector requirements:

- nearly 4π solid angle;
- high rate capability: 2 10^7 interactions/s;
- efficient event selection;
- good momentum resolution $\Delta p/p \approx 1\%$ at 1 GeV/c;
- vertex resolution < 100 μm for K^0, Σ, Λ, ($D^{\pm}$, $c\tau \approx 317$ μm);
- good PID (γ, e, μ, π, K, p): dE/dx, Cerenkov, calorimetry, muons;
- γ detection: few MeV < E_γ < 10 GeV.

Simulation studies of $\bar{p}\, p \rightarrow e^+ e^-$

- Sensitivity to $|G_E|$ and $|G_M|$
- Background suppression



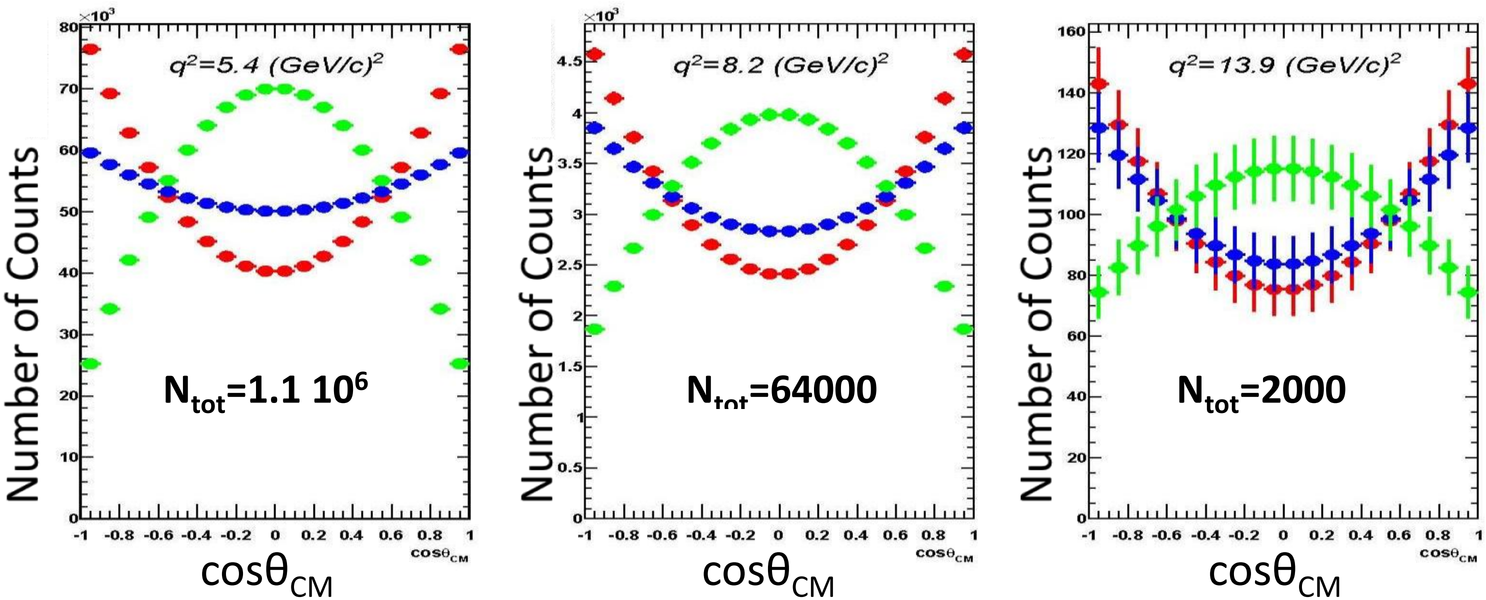
Sensitivity to $|G_E|$ and $|G_M|$

General expression for the differential cross section: $d^n\sigma \propto |M|^2 \propto L^{\mu\nu} H_{\mu\nu}(s, G_E, G_M)$

$$\frac{d\sigma}{d(\cos\theta_{CM})} = \frac{\pi(\alpha\hbar c)^2}{8m_p^2\sqrt{\tau(\tau-1)}}\left[\left|G_M^{TL}\right|^2(1+\cos^2\theta_{CM}) + \frac{1}{\tau}\left|G_E^{TL}\right|^2\sin^2\theta_{CM}\right] \qquad \tau = \frac{q^2}{4m_p^2}$$

Direct access to $|G_E|$ and $|G_M|$ via the lepton angular distribution

Bin size=0.1



$|G_E|=0$

$|G_E|=|G_M|$

$|G_E|=3|G_M|$

$\mathcal{L}_{int}$ = 2 fb^{-1}

Background suppression

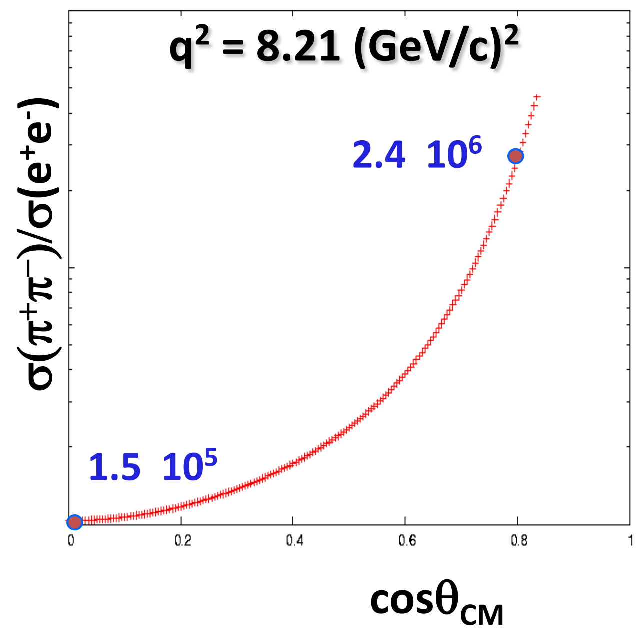
Background reactions

Dominated by 2-charged body reactions

(e.g.: $\bar{p}p$, $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-)

Most difficult background to suppress is $\pi^+\pi^-$,

- PID (Calorimeters, dE/dx, DIRC),
- Kinematical correlation $p=f(\theta)$.

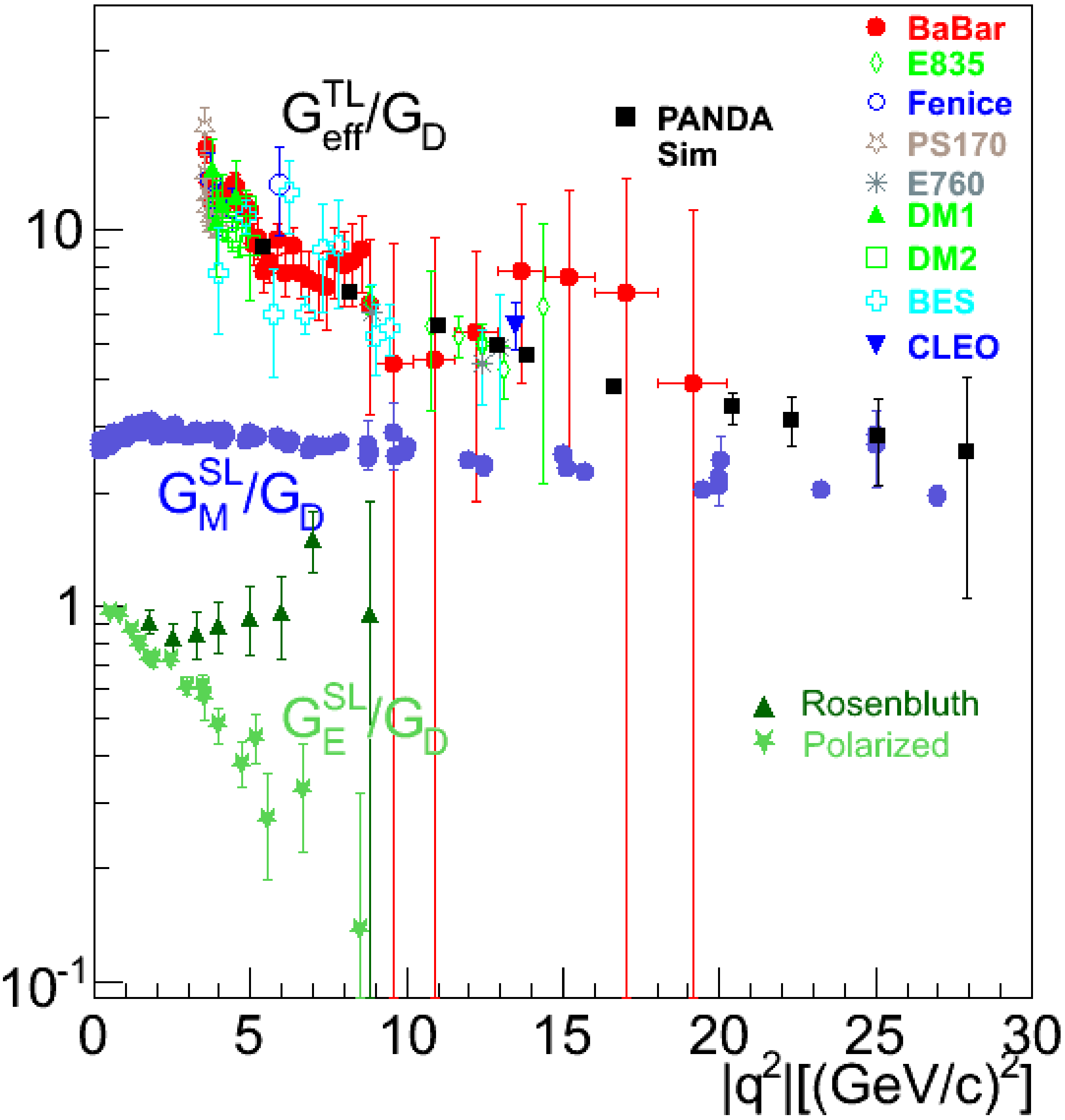


Background suppression factor is at least of the order of 10^9 taking into account PID & kinematic fit !!

q^2 [GeV/c]^2	$\pi^+\pi^-$ contamination
8.2	0.004 %
12.9	0.017 %
16.7	0.061 %

M. Sudol et al., Eur. Phys. J. A44, 373-384, 2010

Expected precision with $\overline{\text{P}}$ANDA



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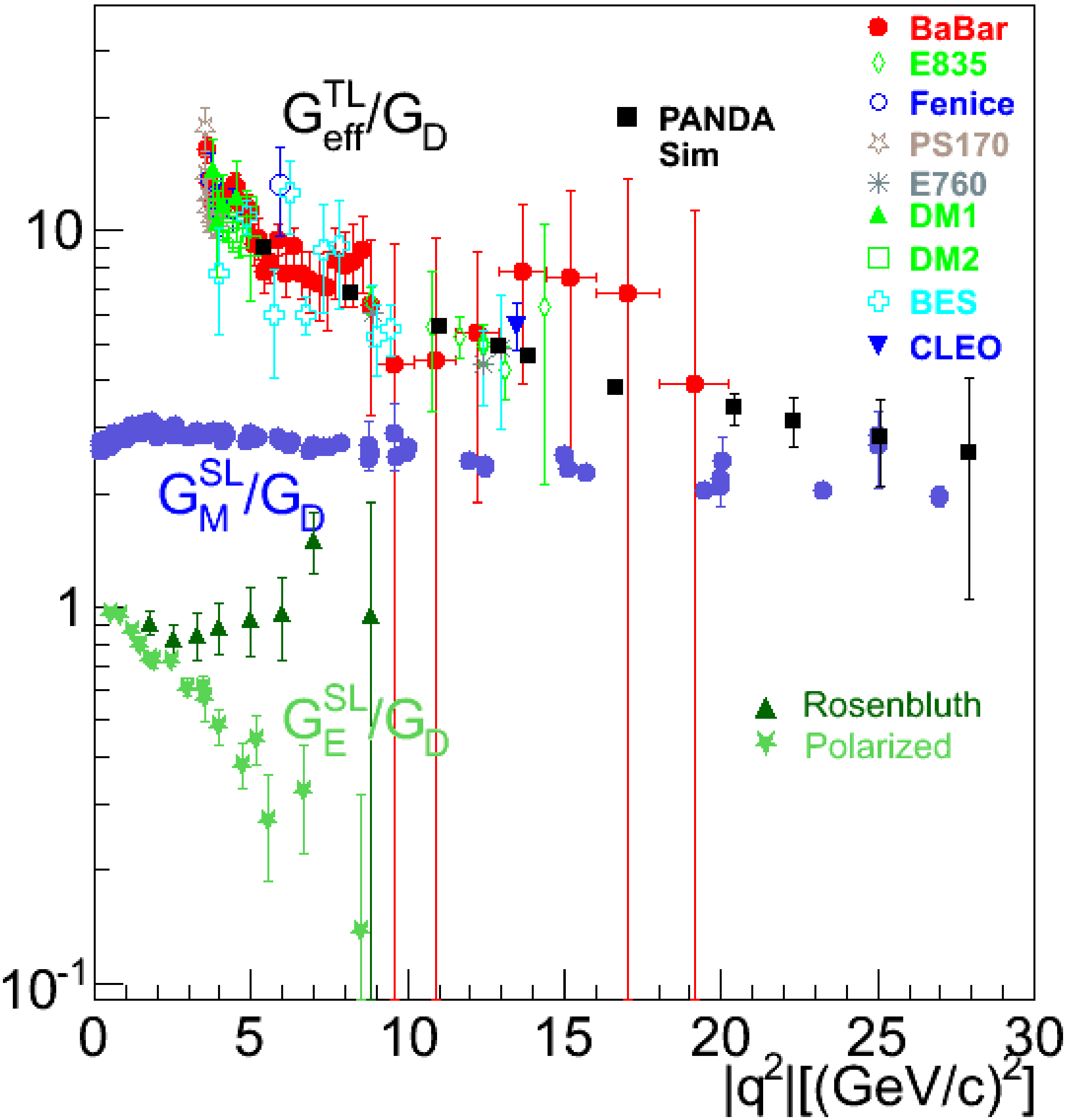
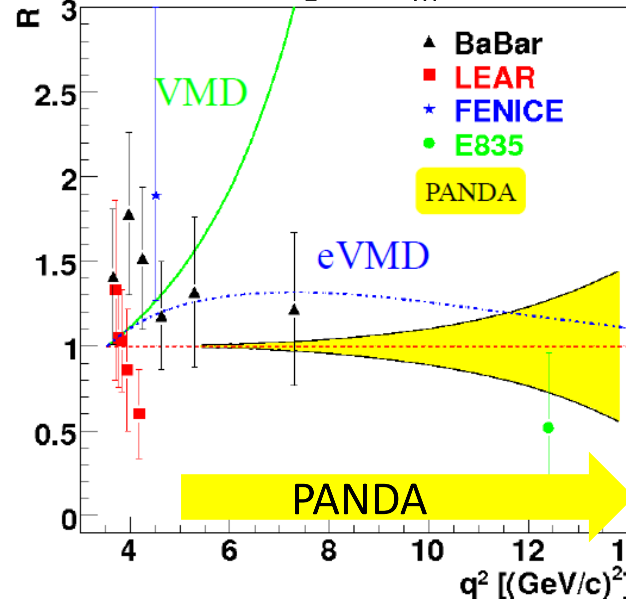


$R=|G_E|/|G_M|$



PANDA:

→ Separated determination of $|G_E^{TL}|$ and $|G_M^{TL}|$ up to 14 $(GeV/c)^2$

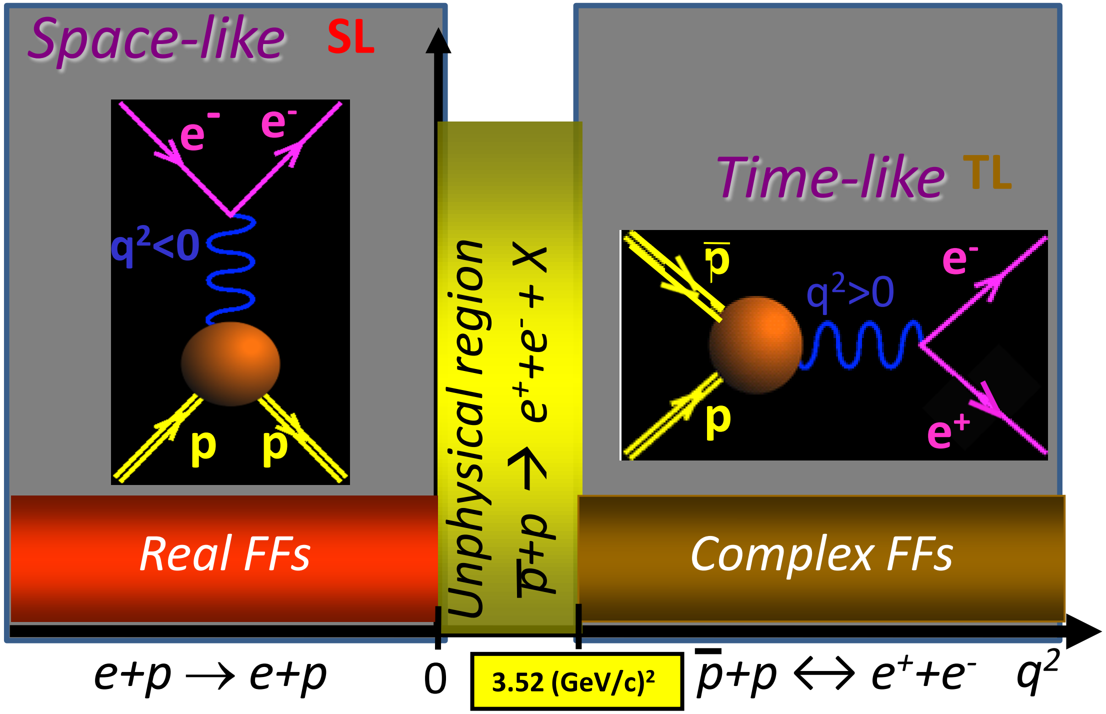
→ Measurement of $|G_{eff}^{TL}|$ at higher q^2

$$G_D = \left(1 + \frac{Q^2}{0.71^2}\right)^{-2}$$

$$|G_{eff}|^2 = \frac{2\tau|G_M|^2 + |G_E|^2}{2\tau + 1}$$

Simulation studies of $\bar{p}\,p \rightarrow \pi^0 e^+ e^-$

- Models
- Simulations



Form factors in the unphysical region

M. P. Rekalo, Sov. J. Nucl. Phys., vol1, 760 (1965)

Access the proton electromagnetic form factors in TL region

Form factor parametrizations

pQCD inspired :

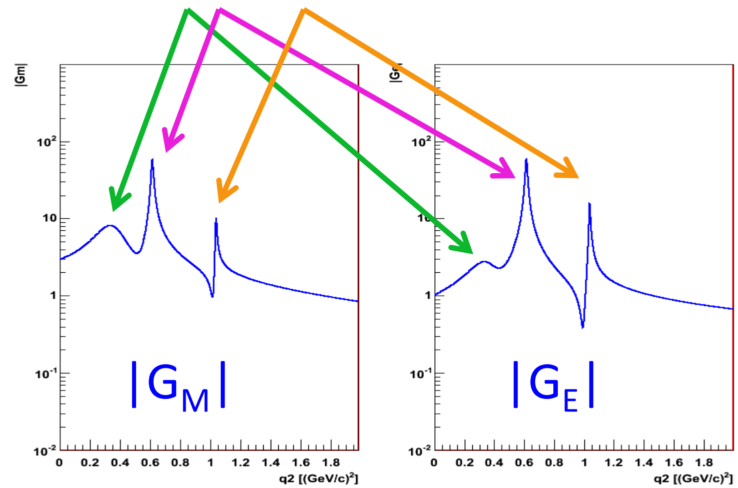
$$\left|G_E^p\right| = \left|G_M^p\right| = \frac{98\ GeV^4}{q^4\left(\ln^2\frac{q^2}{\Lambda^2}+\pi^2\right)}$$

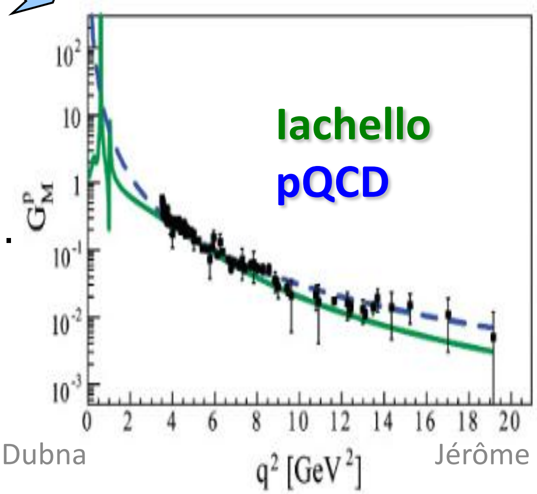
$$q^2 > \Lambda^2 = 0.3^2 (GeV/c)^2$$

Vector Meson Dominance (VMD):

- F. Iachello, Phys. Rev. C69, 055204, 2004

ρ, ω and ϕ resonances





C. Adamuščín et al. Phys. Rev. C 75, 045205, 2007

Feasability

Starting point:

C. Adamuščín, E.A. Kuraev, E. Tomasi-Gustafsson, F. Maas, Phys. Rev. C 75, 045205, 2007

Cross sections (s=8.21GeV²):

$\sigma(\bar{p}p \rightarrow \pi^0 e^+ e^-) : \sigma(\bar{p}p \rightarrow \pi\,\pi\,\pi) = 1 : 600$

(Adamuščín with VMD) (data)

From feasability study of ($\bar{p}p \rightarrow e^+e^-$):

$\sigma(\bar{p}p \rightarrow e^+ e^-) : \sigma(\bar{p}p \rightarrow \pi\,\pi) = 1 : 10^6$

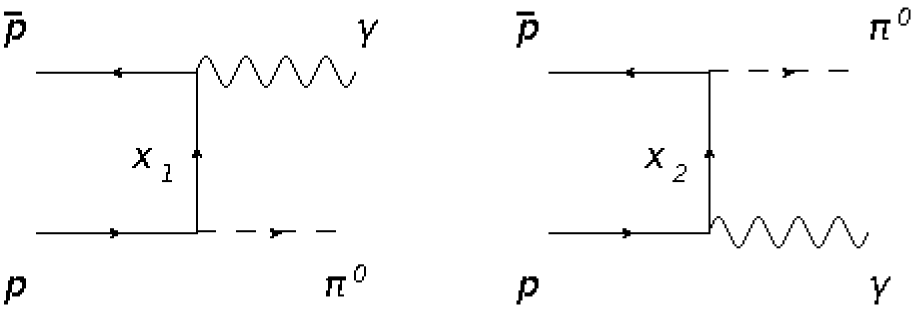
(almost independent on energy)

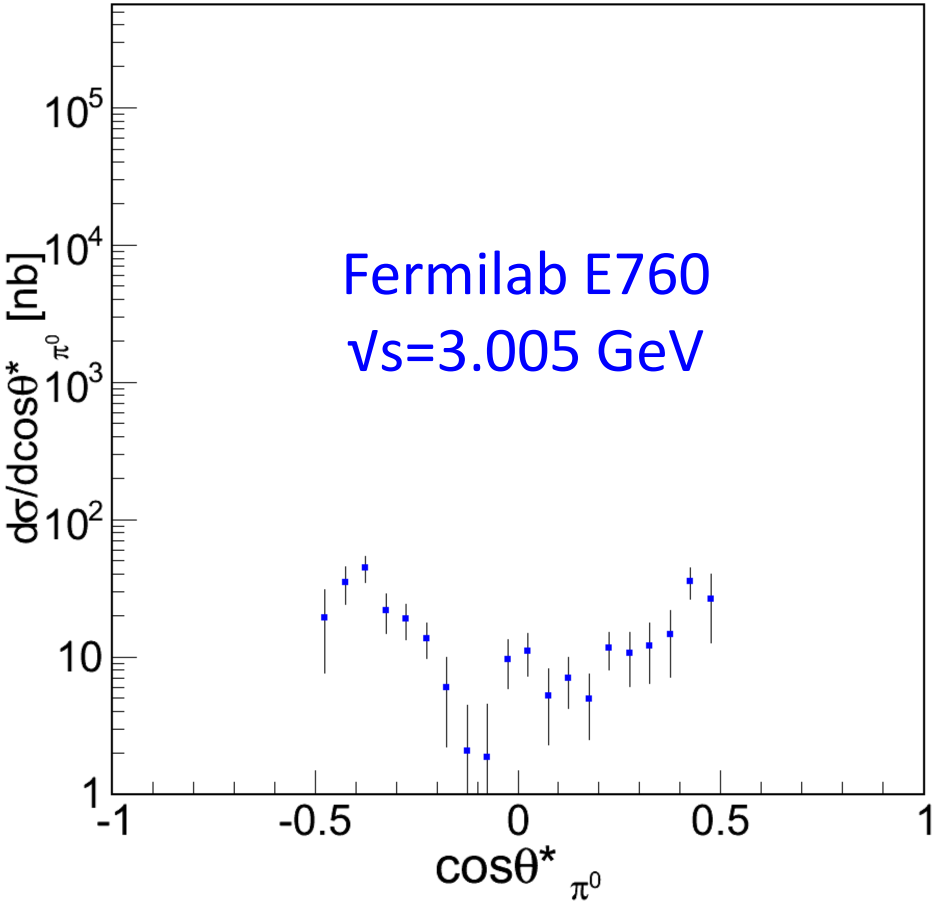
?

Need to constrain model by data

Calculation of p̄p → $\pi^0\gamma$

$$d^n\sigma \propto |M|^2 \propto g^{\mu\nu}H_{\mu\nu}\left(s,\theta_{\pi^0},G_E(q^2=0),G_M(q^2=0)\right)$$





Calculation of $\bar{p}p \rightarrow \pi^0\gamma$

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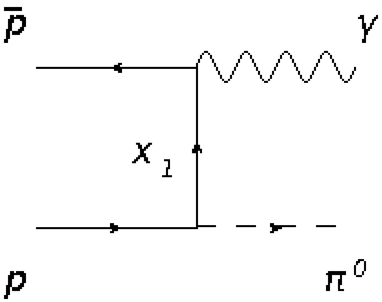

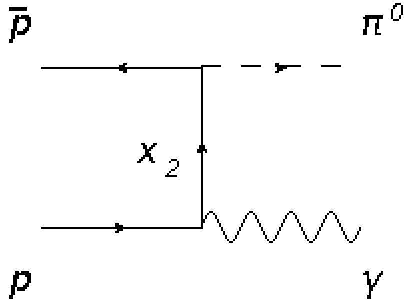

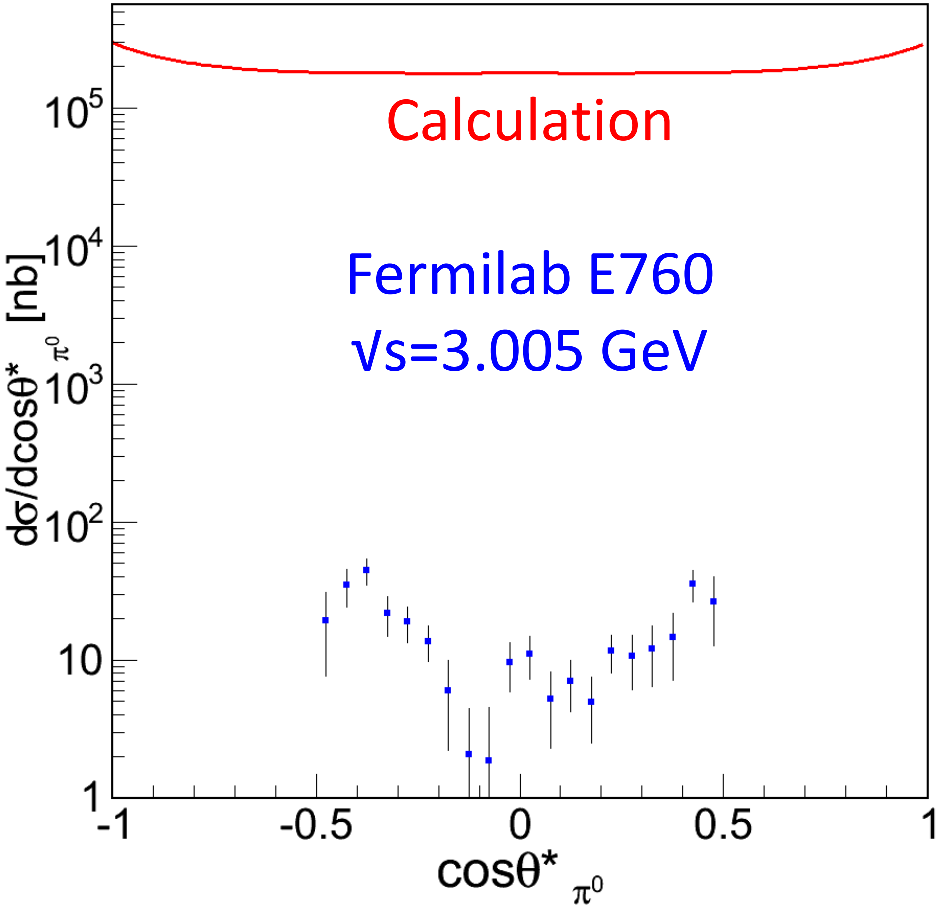

Calculation by
J. Van de Wiele

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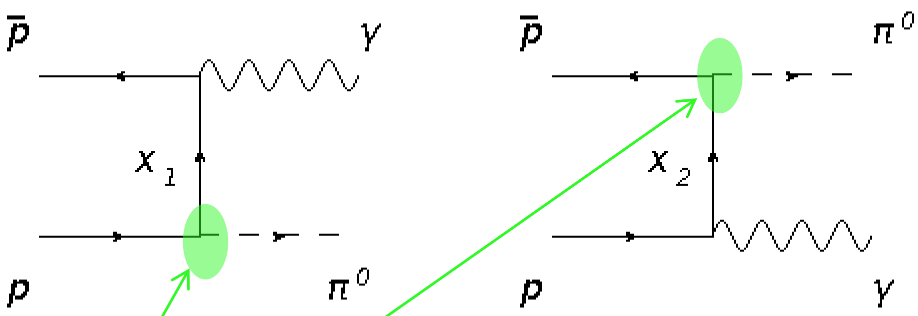

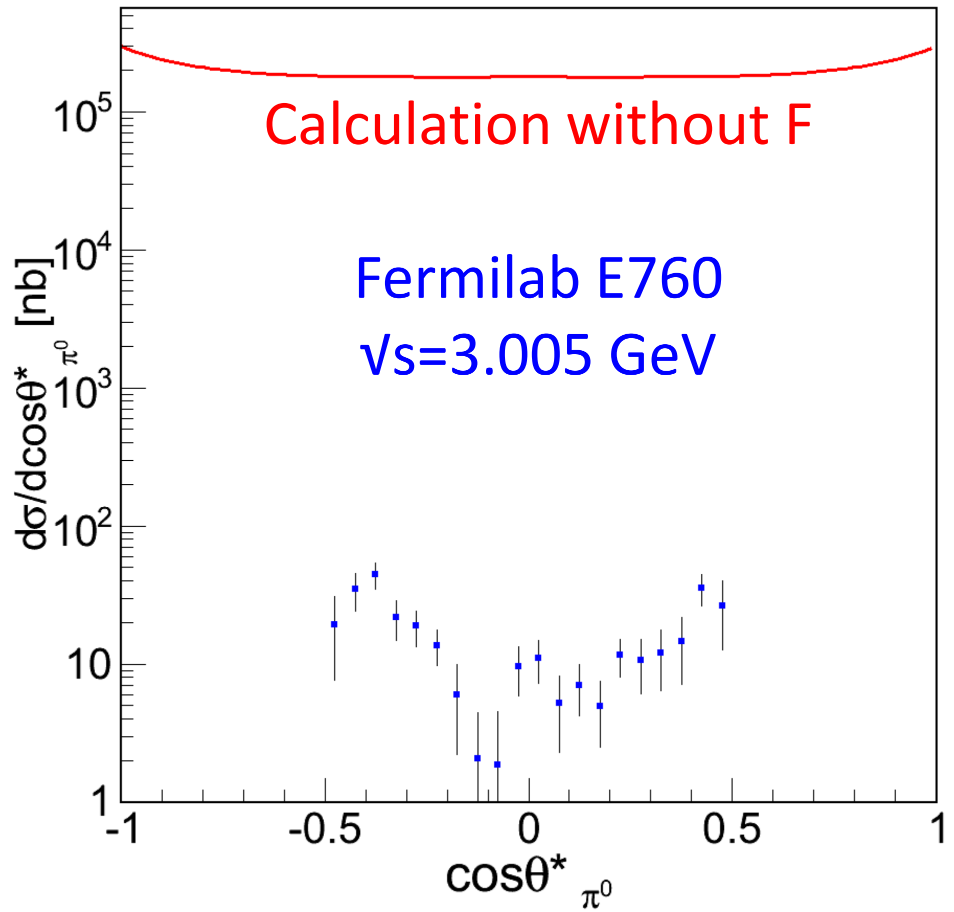

Hadronic Form factor F:

$$F = \sqrt{\left[\frac{\lambda^2 - m_p^2}{\lambda^2 - X_1^2}\right]^2 \left[\frac{\lambda^2 - m_p^2}{\lambda^2 - X_2^2}\right]^2}$$

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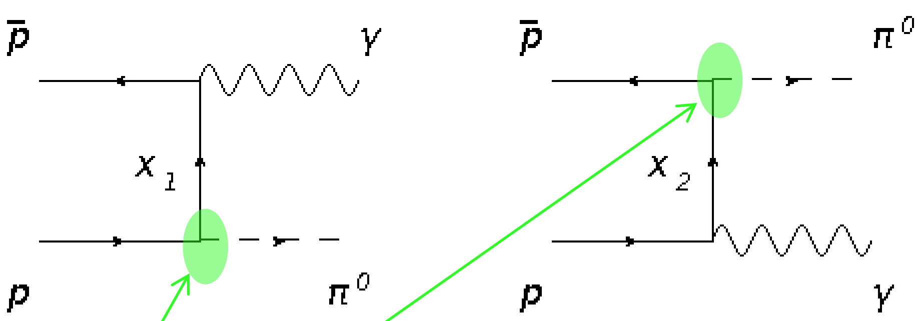

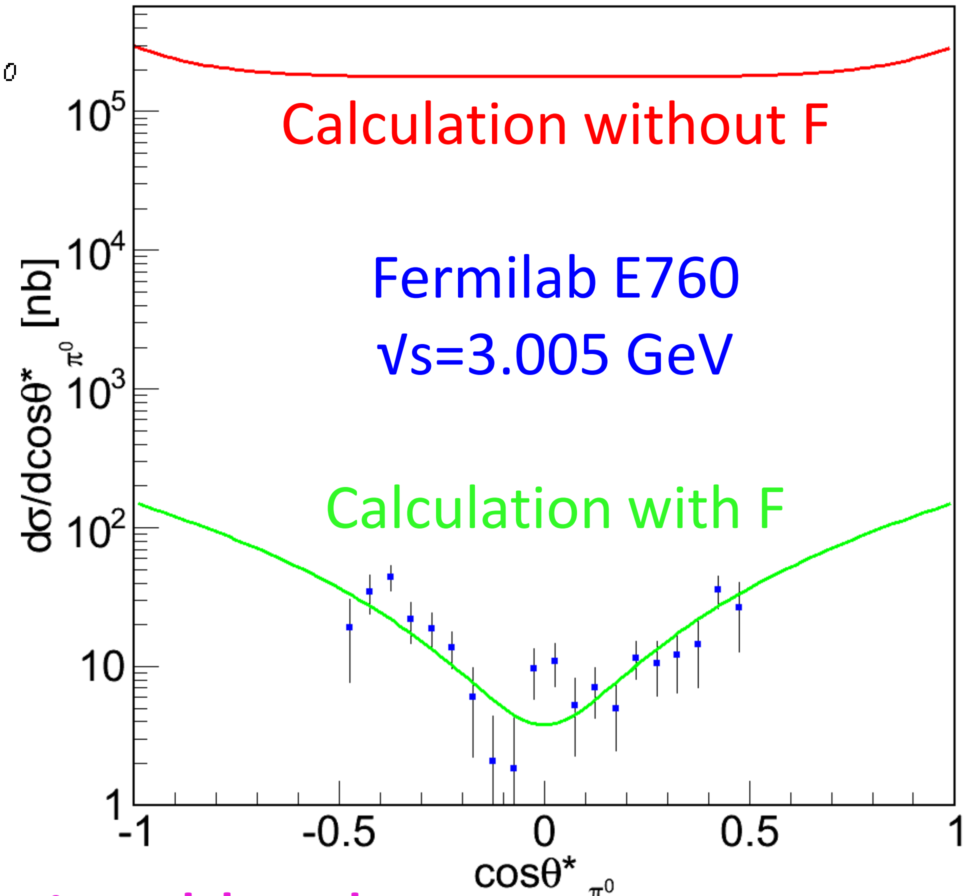

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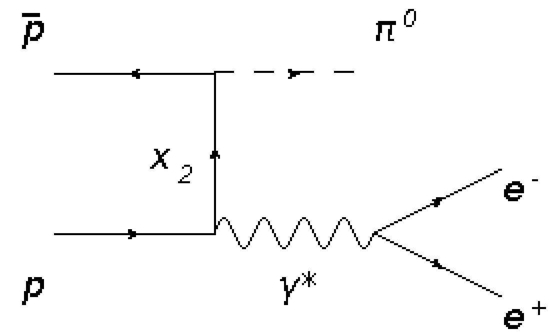
Calculation by
J. Van de Wiele

Model constrained by data

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

$$d^n\sigma \propto |M|^2 \propto \frac{1}{q^4} L^{\mu\nu} H_{\mu\nu}\left(s, q^2, \theta_{\pi^0}, G_E, G_M\right)$$



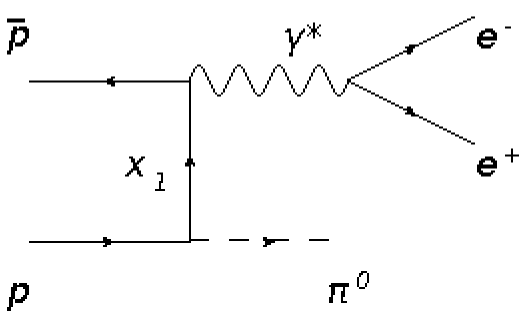
In the γ^* rest frame

$$L^{\mu\nu} H_{\mu\nu} = 4e^2 \frac{q^2}{2}\left(H_{11} + H_{22} + H_{33}\right)$$

$$-8e^2 p_e^2 \left(H_{11} \sin^2\theta_e \cos^2\varphi_e + 2H_{12} \sin^2\theta_e \sin\varphi_e \cos\varphi_e\right.$$

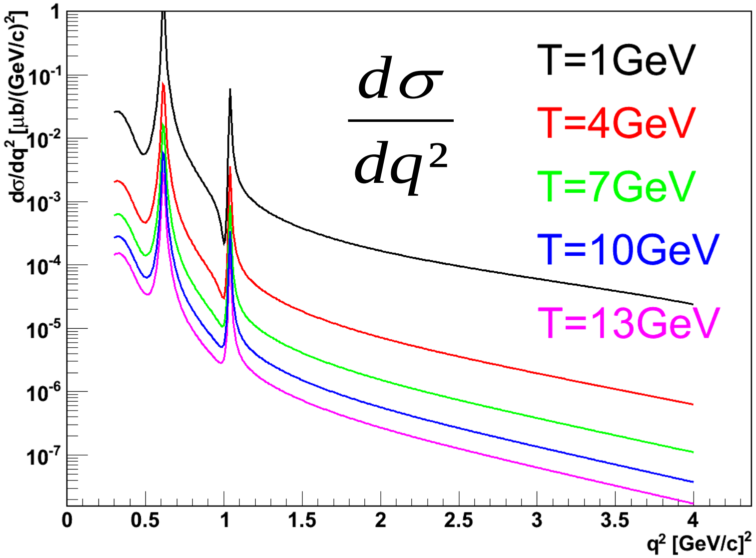
$$+ 2H_{13} \sin\theta_e \cos\theta_e \cos\varphi_e + H_{22} \sin^2\theta_e \sin^2\varphi_e$$

$$\left. + 2H_{23} \sin\theta_e \cos\theta_e \sin\varphi_e + H_{33} \cos^2\theta_e\right)$$

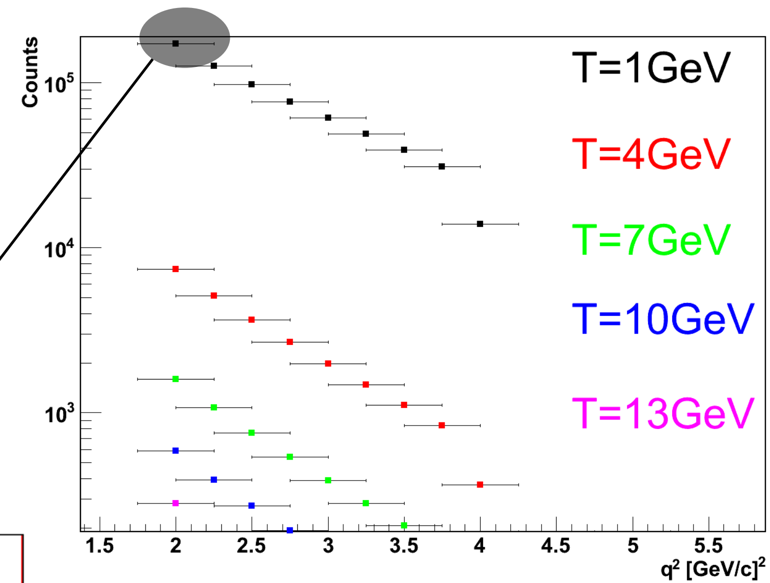


Calculation by
J. Van de Wiele

Dependence on beam kinetic energy



$$\int_{q^2-0.25}^{q^2+0.25} L_{\mathrm{int}} \frac{d\sigma}{dq^2} dq^2$$

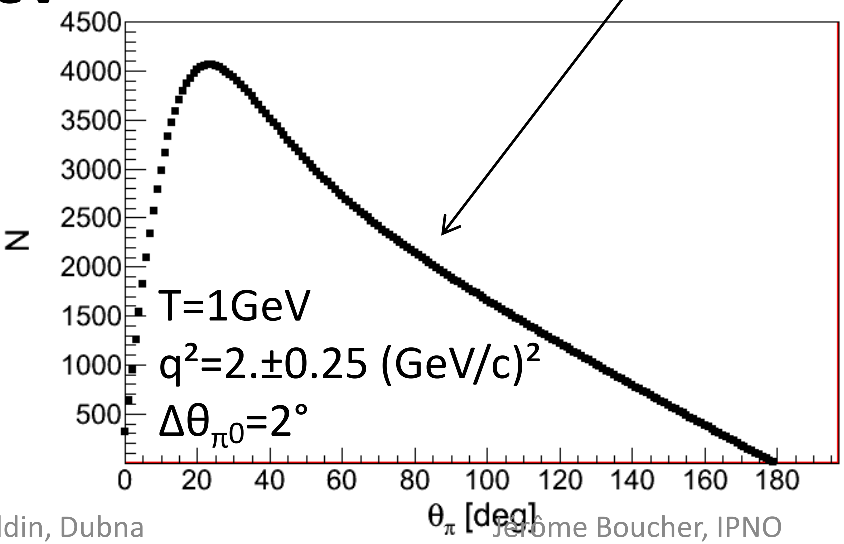


dσ/dq² decreases as T increases.

T=1GeV

Integrated over all π^0 angles.

q^2=2 (GeV/c)^2



L_{int}=2fb^{-1}

$H_{\mu\nu}$ versus fitted values

- T=1GeV
- $q^2=2.0 \pm 0.25$
- $\Delta\theta_{\pi 0}=2°$

172 076 events

- For each $\Delta\theta_{\pi 0}$:
  - $d^5\sigma$ is generated with well defined $H_{\mu\nu}$ (θ_e, ϕ_e:10°/bin)
  - $d^5\sigma$ is fitted →experimental determination of $H_{\mu\nu}$

$H_{\mu\nu}$ versus fitted values

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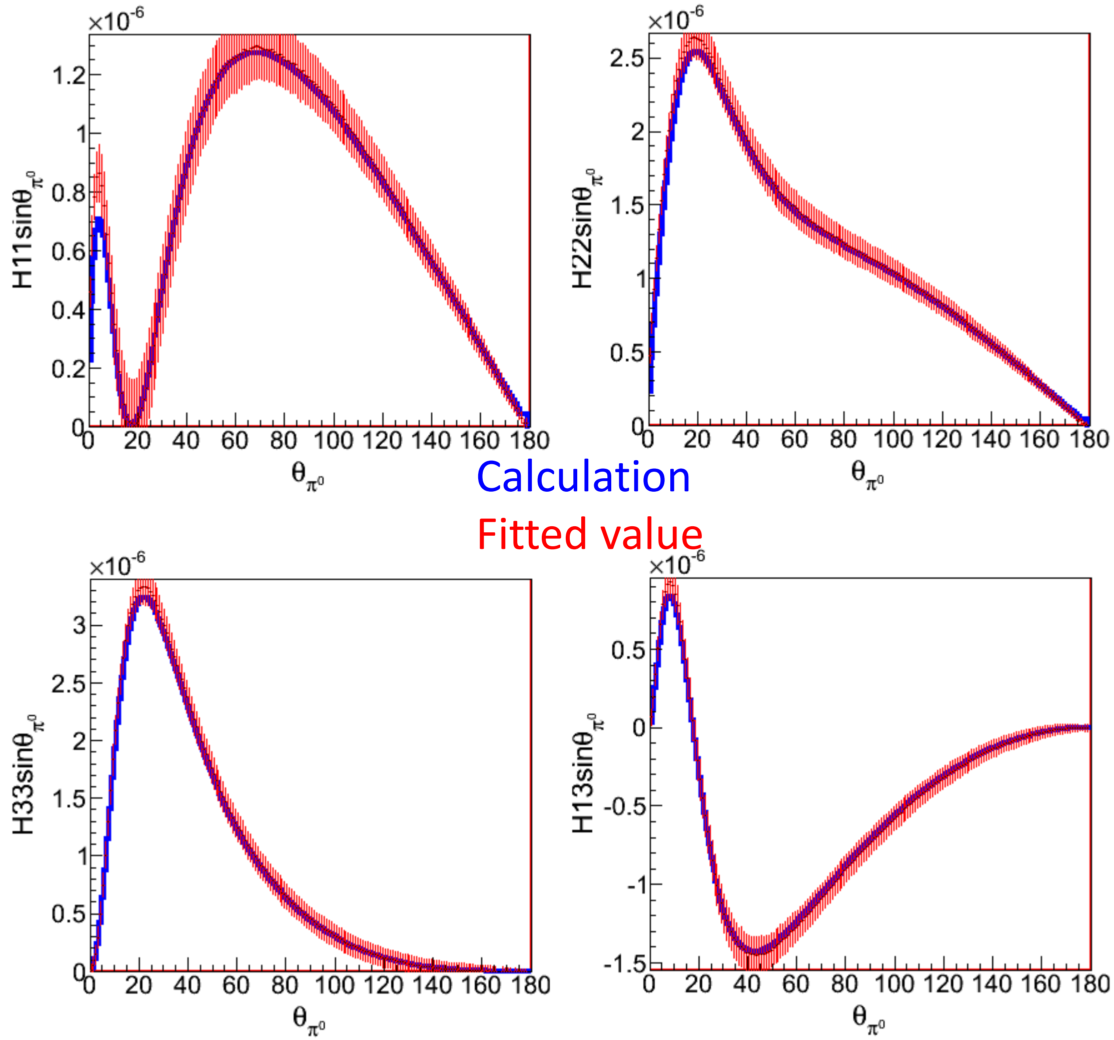

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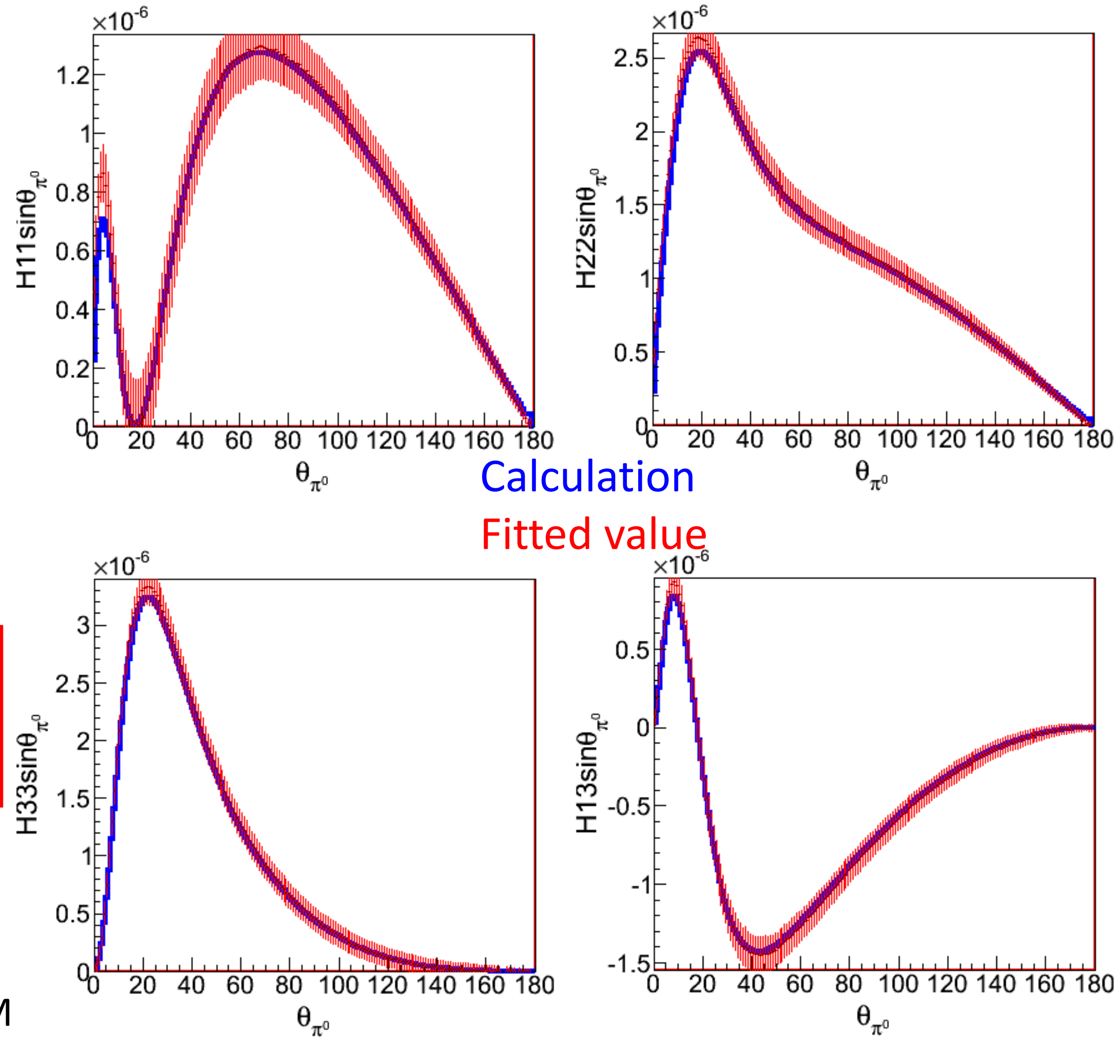


Direct access to $H_{\mu\nu}$ via the angular distribution

$H_{\mu\nu}$ linked to G_E, G_M, φ_E and φ_M

Ratios would provide constraints on $|G_E|/|G_M|$ and $\cos(\varphi_E-\varphi_M)$

Conclusions and outlook

- $\bar{\text{P}}$ANDA will improve results on $|G_E^{TL}|$ and $|G_M^{TL}|$ by measuring the $\bar{p}p \rightarrow e^+e^-$ angular distributions.

- Realistic model for $\bar{p}p \rightarrow \pi^0 e^+e^-$ in the unphysical region has been developped.

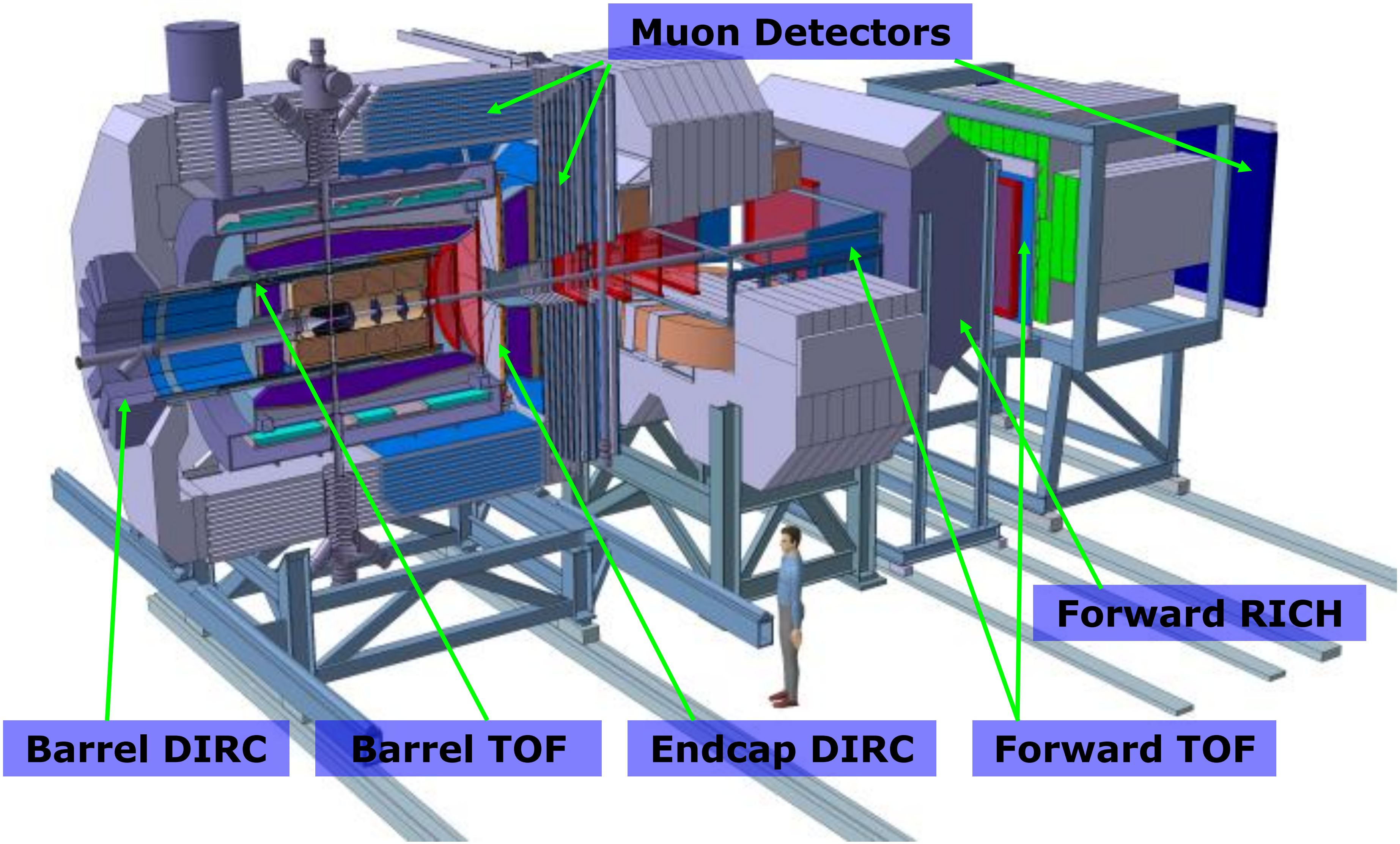
- Access to the hadronic tensors ($H_{\mu\nu}$) is possible via the e^+ (e^-) angular distribution.

  $\rightarrow |G_E|/|G_M|$ and $\cos(\varphi_E-\varphi_M)$.

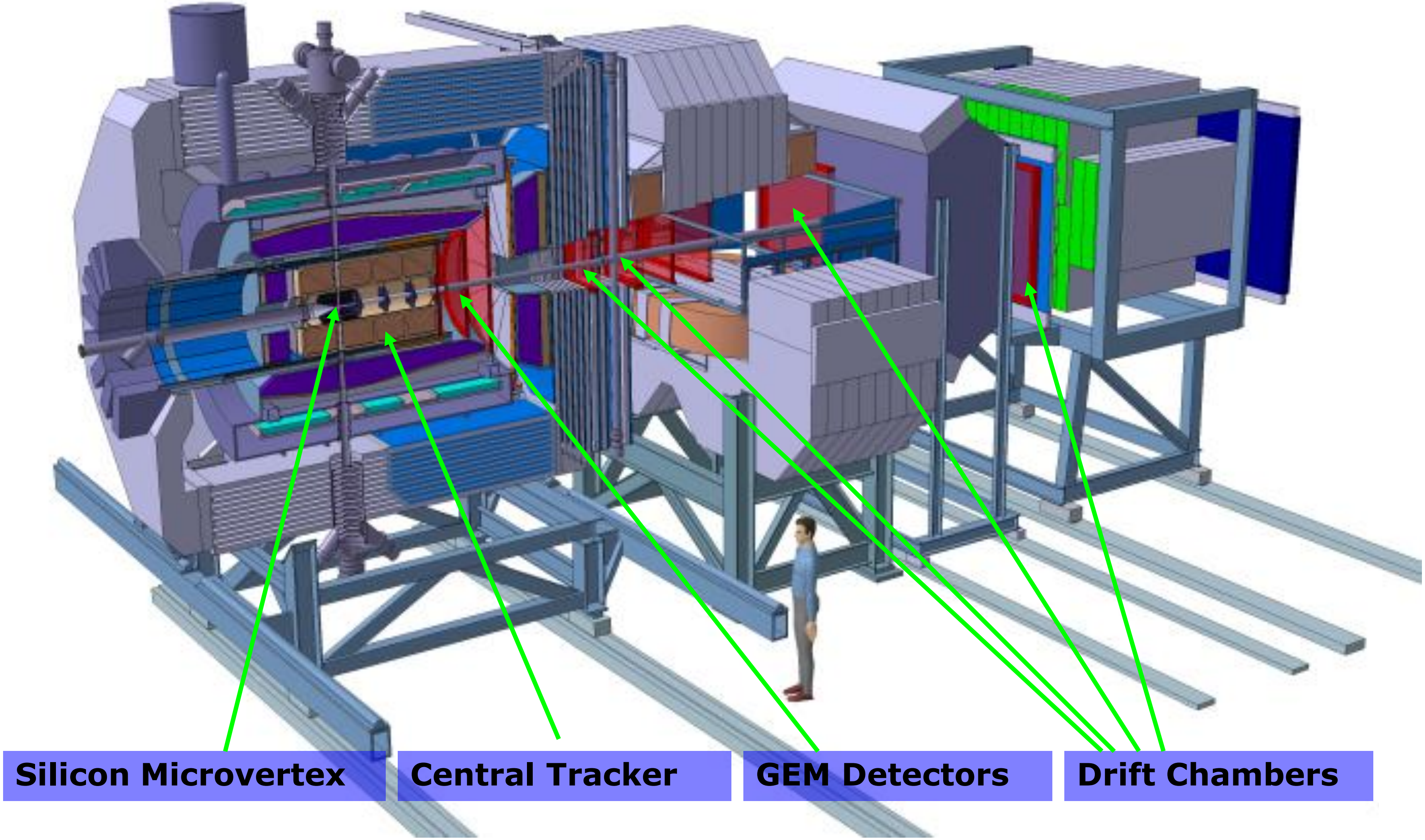
- Feasability of $\bar{p}p \rightarrow \pi^0 e^+e^-$ and background suppression under investigation.

- See E. Tomasi-Gustafsson talk (s-channel)

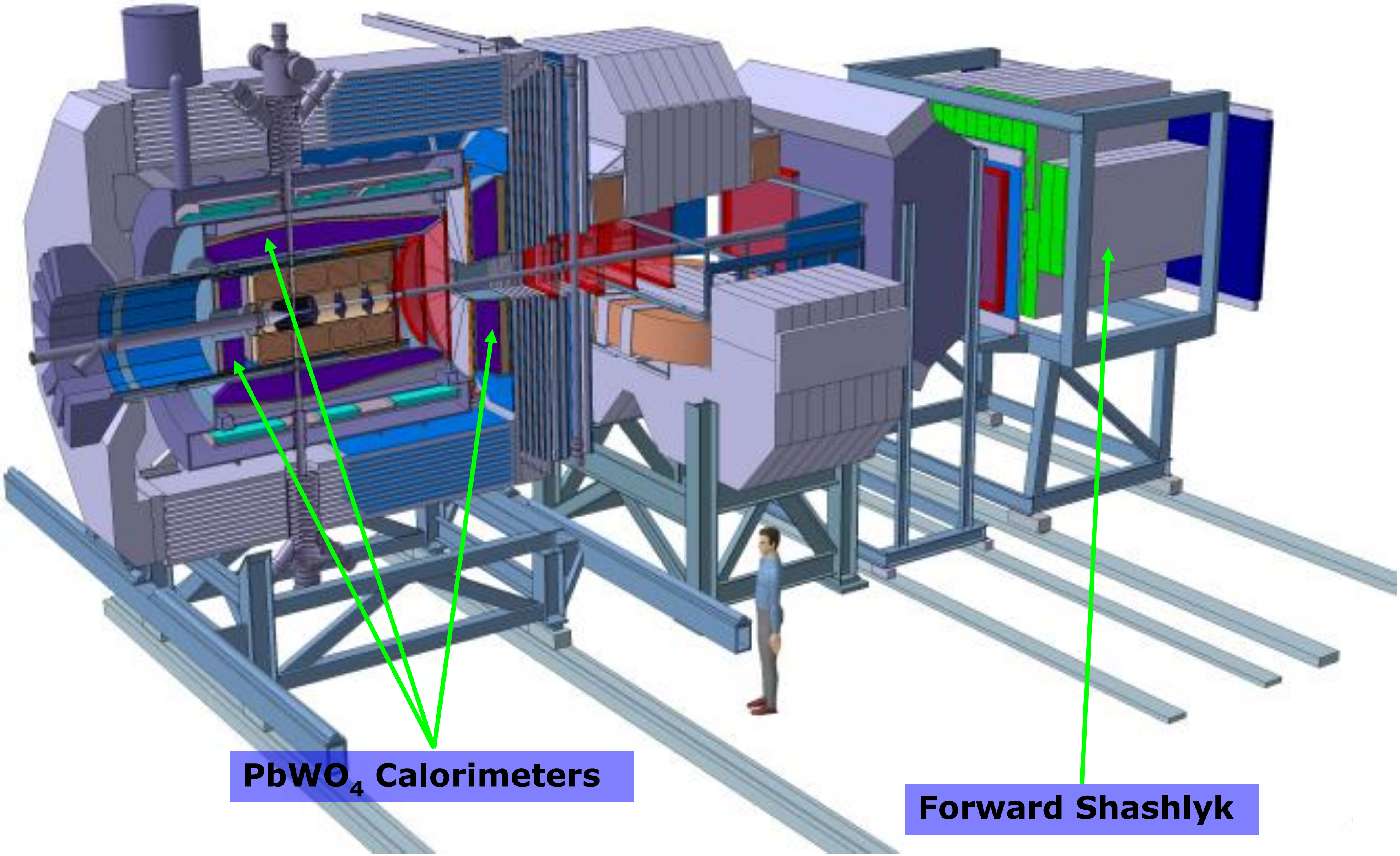
Detectors for charged particle identification



Tracking detectors



PANDA calorimeters



General information of the simulation

q^2	e^+e^-	$\pi^+\pi^-$	$\pi^0\pi^0$
$[(GeV/c)^2]$			
5.4	$4\ 10^6$	$1\ 10^8$	$3\ 10^6$
7.21	$4\ 10^6$	-	-
8.21	$4\ 10^6$	-	-
12.9	$4\ 10^6$	$1\ 10^8$	$3\ 10^6$
13.9	$4\ 10^6$	-	-
16.7	$4\ 10^6$	$2\ 10^8$	$3\ 10^6$
22.3	$4\ 10^6$	-	-

Signal has been simulated under 3 assumptions:

- $|G_E| = 0$
- $|G_E| = |G_M|$
- $|G_E| = 3\ |G_M|$

3 scenarios for the π^0 decay were taken into account

- $\pi^0\pi^0 \to \gamma\gamma\ \gamma\gamma$
- $\pi^0\pi^0 \to \gamma\gamma\ \gamma e^+e^-$
- $\pi^0\pi^0 \to \gamma e^+e^-\ \ \gamma e^+e^-$

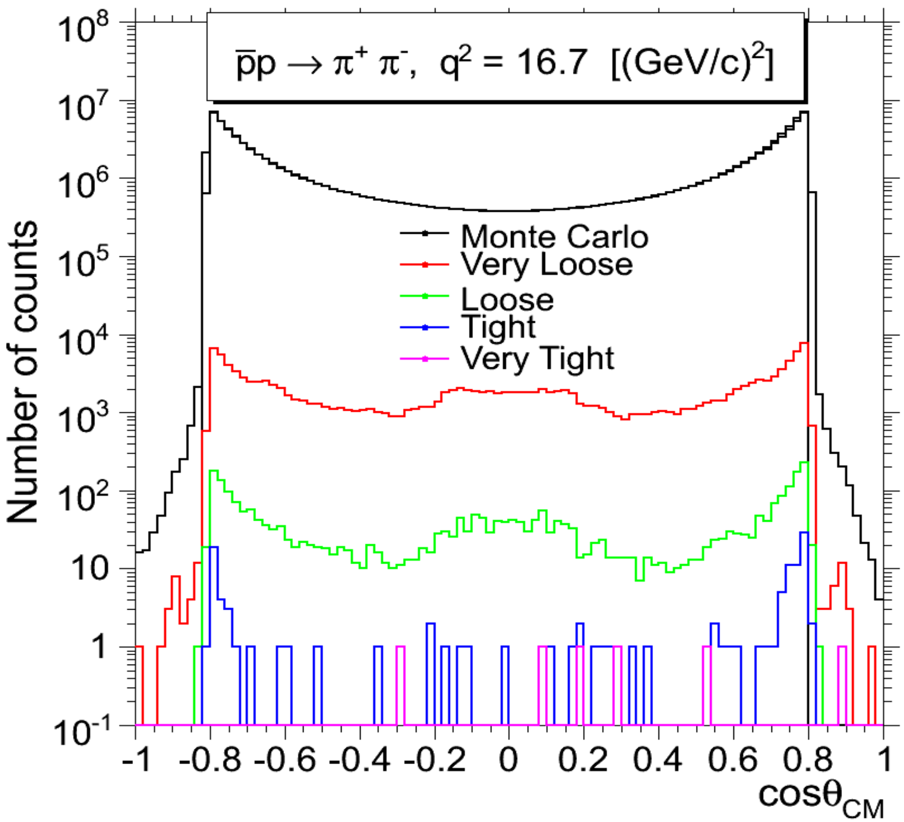
γ – convert in the detector material

→ Full scale simulation including GEANT4 and detector digitalization ,

→ Both the signal $\bar{p}\,p \to e^+ e^-$ and main background channel $\bar{p}\ p \to \pi^+ \pi^-$ analysed,

→ Detailed analysis for the PID response and also kinematic constraints were studied.

Hadronic background channel suppression



Definition of the PID cuts:
(particle probability of being an electron)

Very Loose : 19.9%
Loose : 85%
Tight : 99%
Very Tight : 99.8 %

PID from 5 detectors:
EMC, STT, DIRC, MVD and MUO

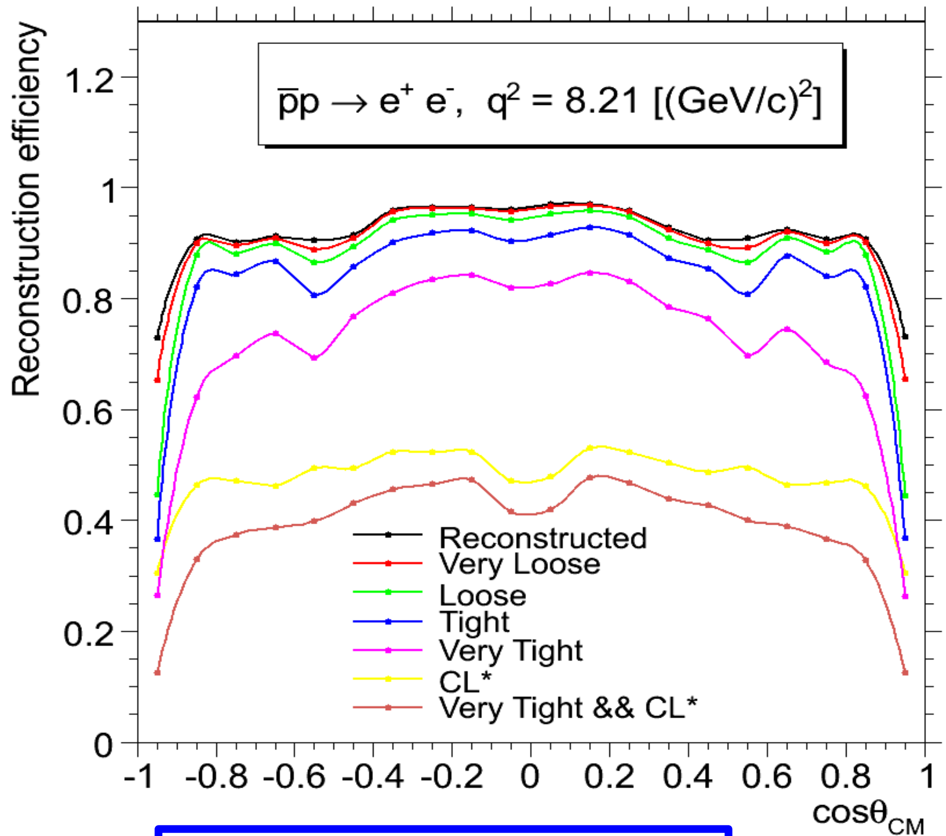
Background suppression after **Very Tight** PID cuts:

- 8.2 (GeV/c)^2 : 2/10^8
- 12.9 (GeV/c)^2 : 5/10^8
- 16.7 (GeV/c)^2 : 6/10^8

Additional factor ~100 applying the kinematic fit

Background suppression factor is at least of the order of 10^9 taking into account PID & kinematic fit !!

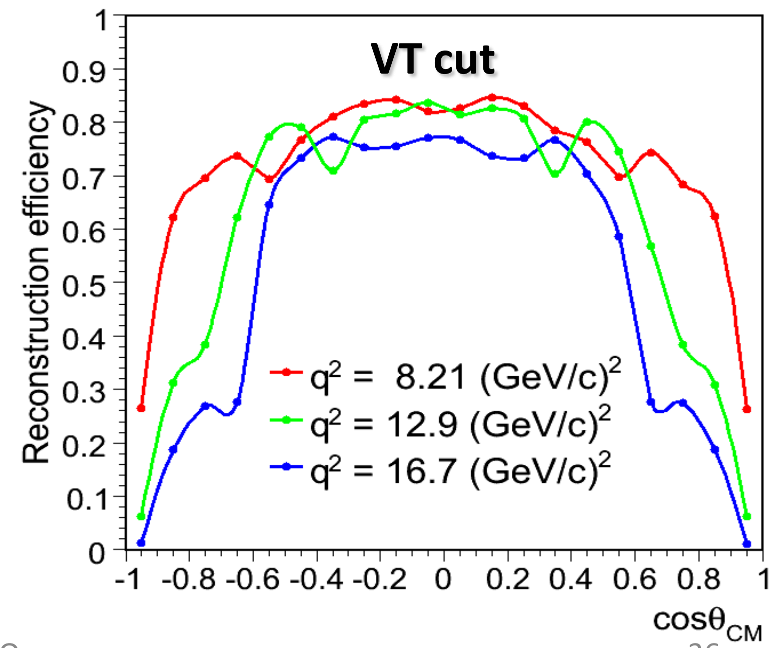
Electron reconstruction efficiency



e^+e^- signal:

- efficiency about 35 % at $\cos\theta_{CM} = 0$ after all cuts (Very Tight and CL*)
- decreases at forward/backward angles (combined effect with acceptance)
  - more pronounced for the high q^2
- still on average a factor 2 higher than BABAR experiment ($\varepsilon \sim 17$ %)

q^2 [GeV/c]^2	$\pi^+\pi^-$ contamination
8.2	0.004 %
12.9	0.017 %
16.7	0.061 %



2-dimensional fits

Default parameters:

- Chi-square method
- Empty bins are ignored
- Error = √(bin content)

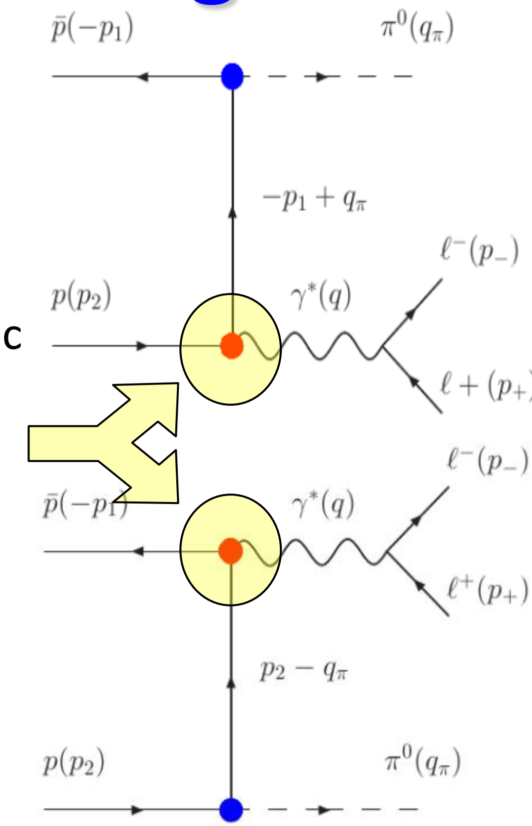
Options:

- W: Set weight to 1 for non empty bins
- WW: Set weight to 1 for all bins
- I: Integral of function instead of value at bin center
- …

Form factors and unphysical region

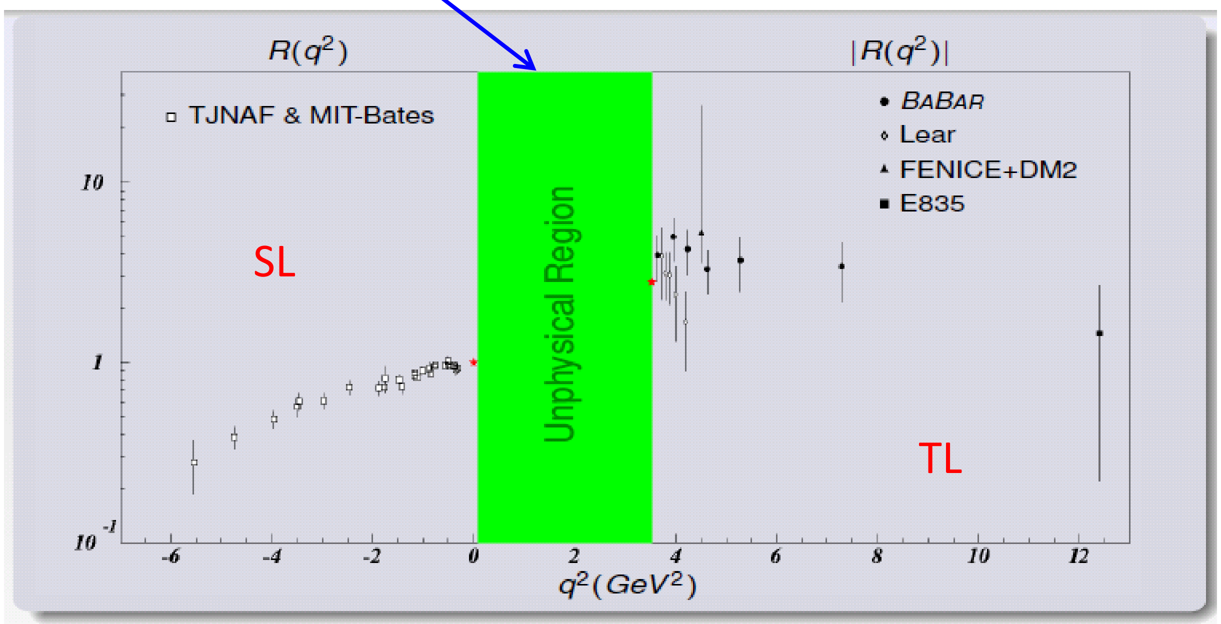
Motivations:

Access to the unphysical region, ($q^2 < 4m_p^2$) via reaction:



Electromagnetic Form Factors

Never measured.



$R=\mu_p G_E^p/G_M^p$

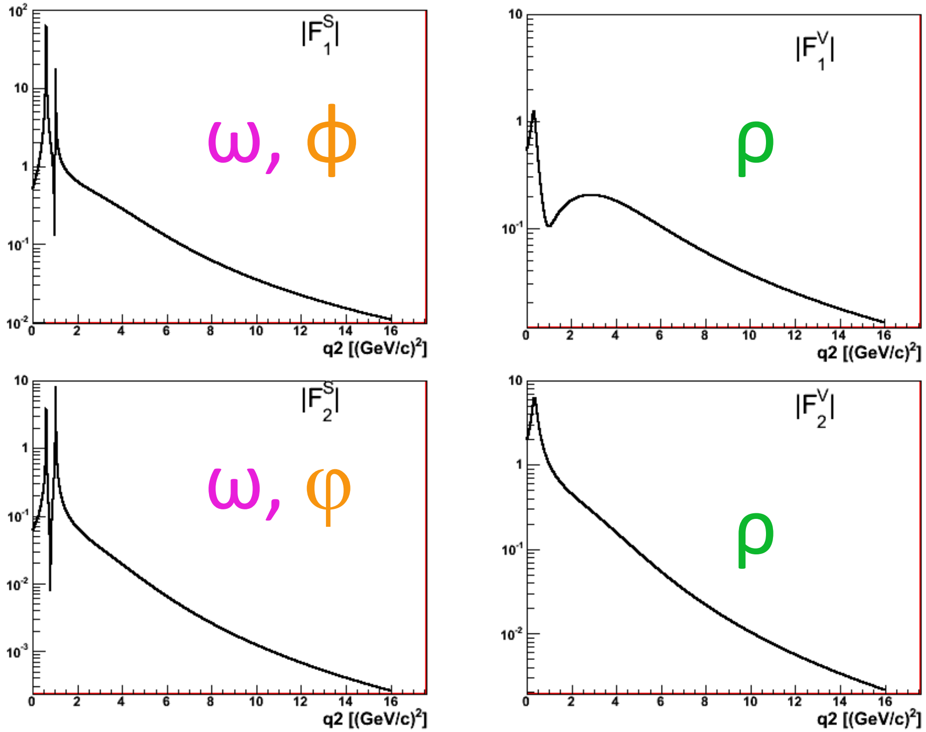
★ Theoretical constraints ★

$R(0) = 1$ $\quad R(4M_N^2) = \mu_p$

By Simone Pacetti
GDR Nucleon Meeting

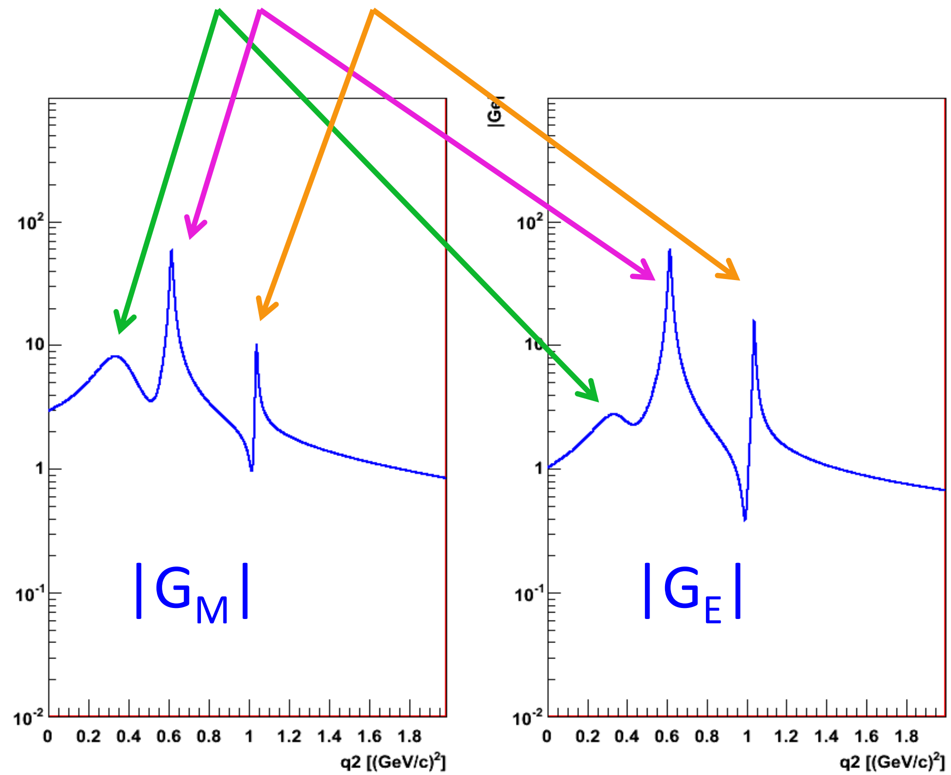
Iachello’s Form Factors

Isoscalar Isovector



Vector Meson Dominance (VMD):

ρ, ω and φ



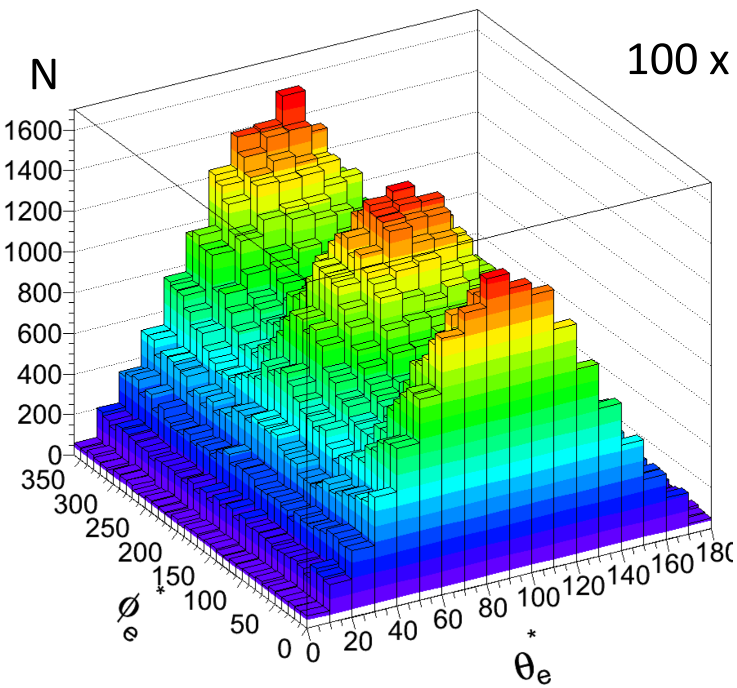
(F. Iachello, Phys. Rev. C 69, 055204, 2004)

$H_{\mu\nu}$ versus fitted values

- T=1GeV
- q^2=2.0 ± 0.25

172 076 events

- For each $\theta_{\pi 0}$ (θ_e, ϕ_e: 10° per bin):
  - $d^5\sigma$ is generated
  - $d^5\sigma$ is fitted



100 x statistics

Direct access to H_{ij} via the angular distribution

$H_{\mu\nu}$ versus fitted values

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172 076 events

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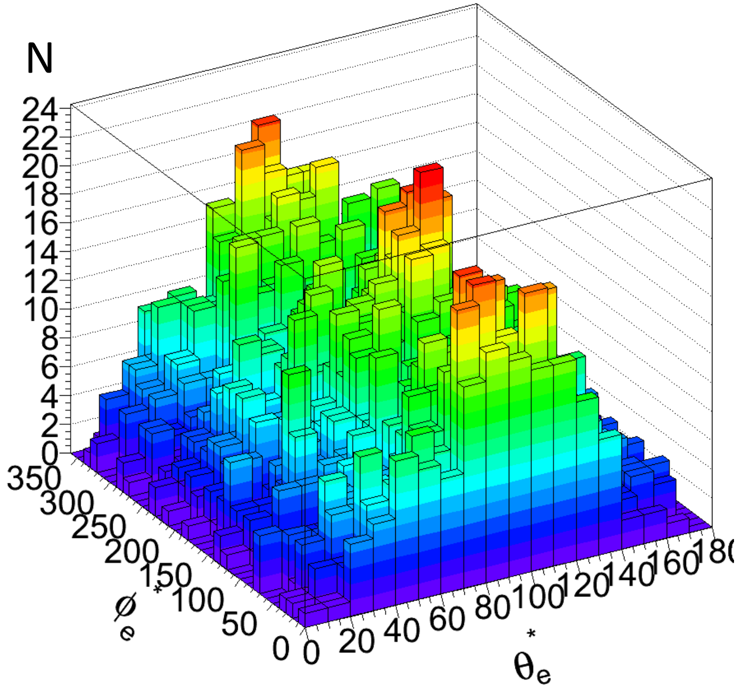

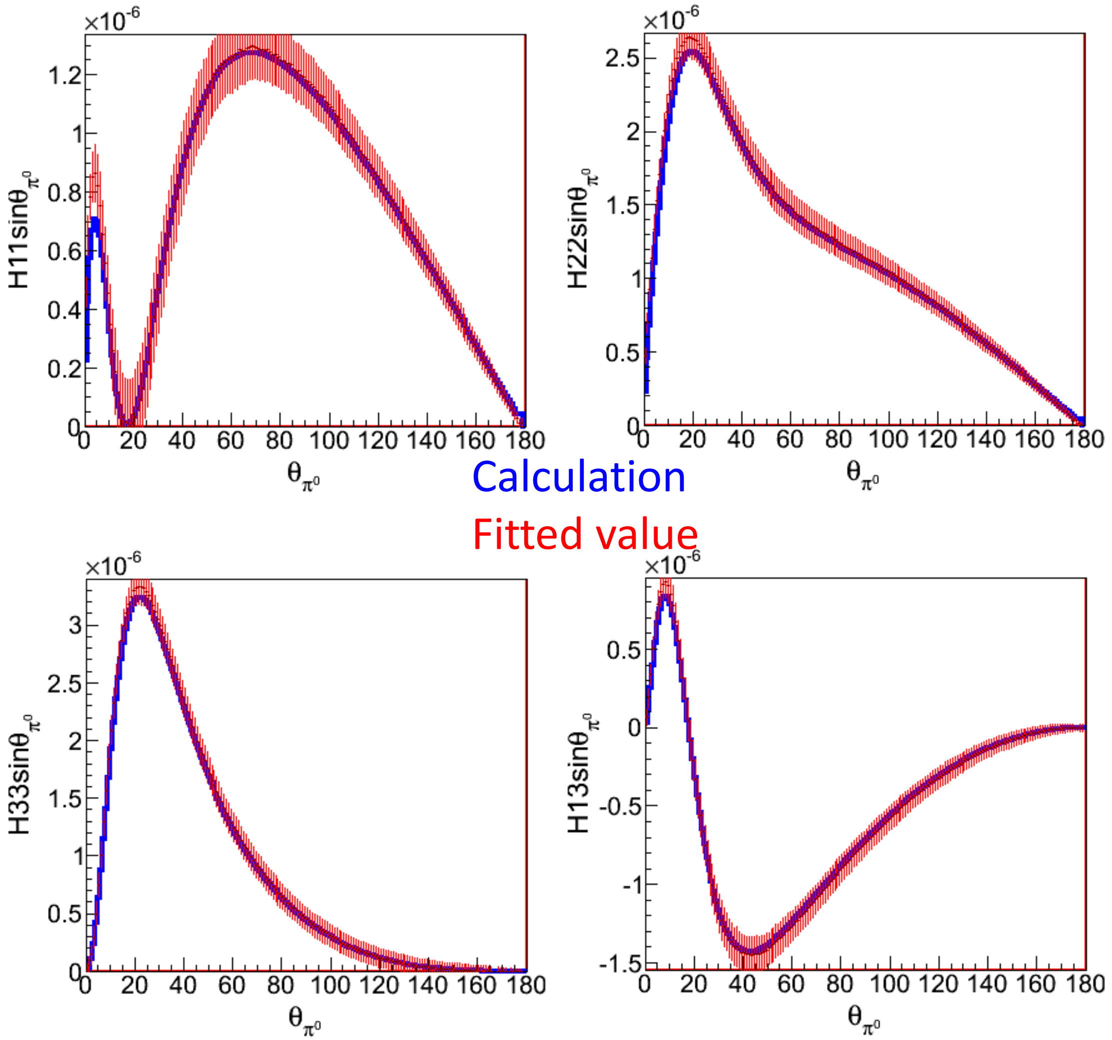

Direct access to H_{ij} via the angular distribution