Time-like electromagnetic form factors from PANDA

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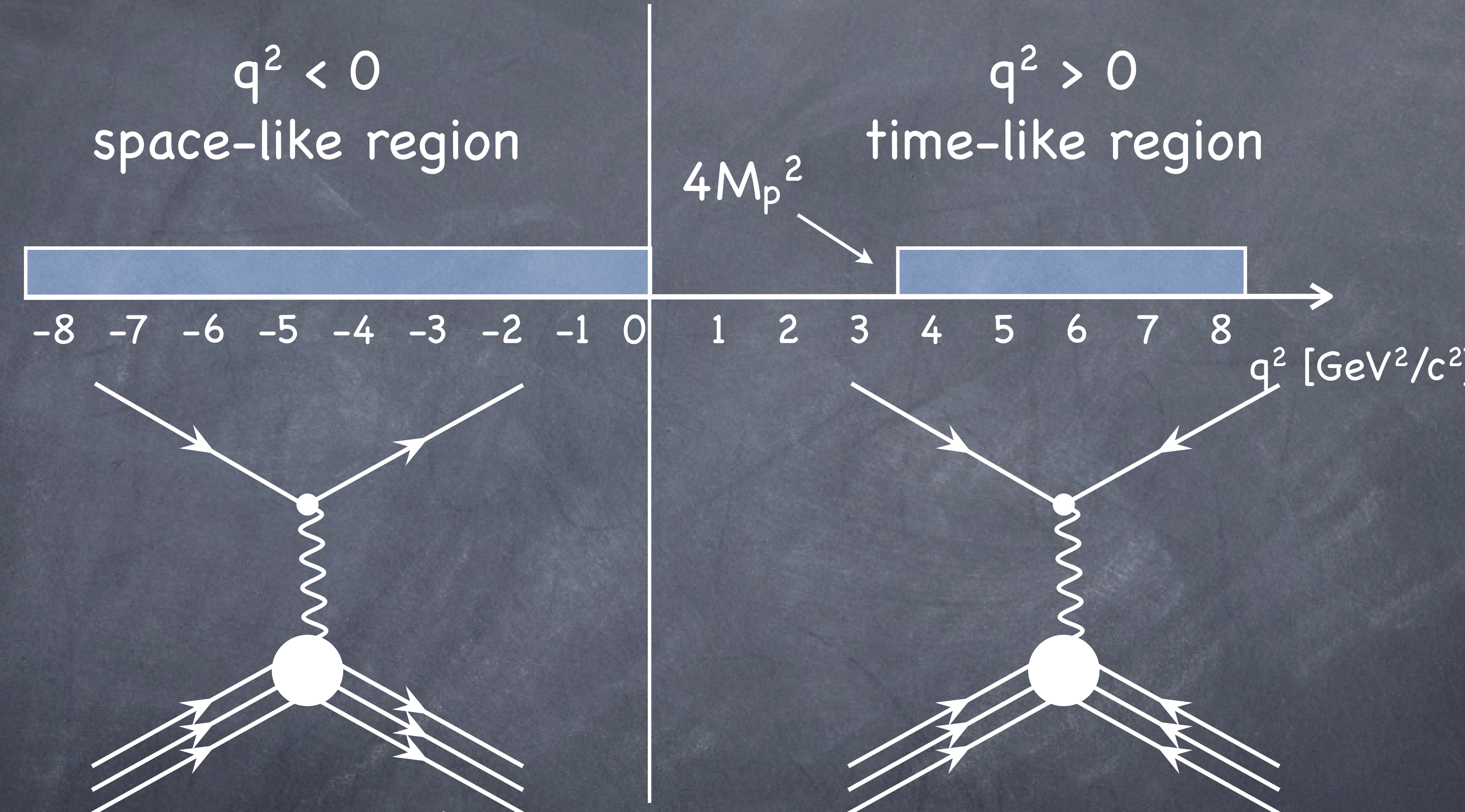
Outline

- Overview of EM form factors
- EM form factors in time-like region
  - Unpolarized cross section (Rosenbluth)
  - Polarization effect
  - Existing data
- Impact from PANDA
  - Improvements in precision
  - Panda vs two photon exchange (TPE)
  - Possibility of polarization
- Summary

Overview of EM form factors

EM form factors: different reactions

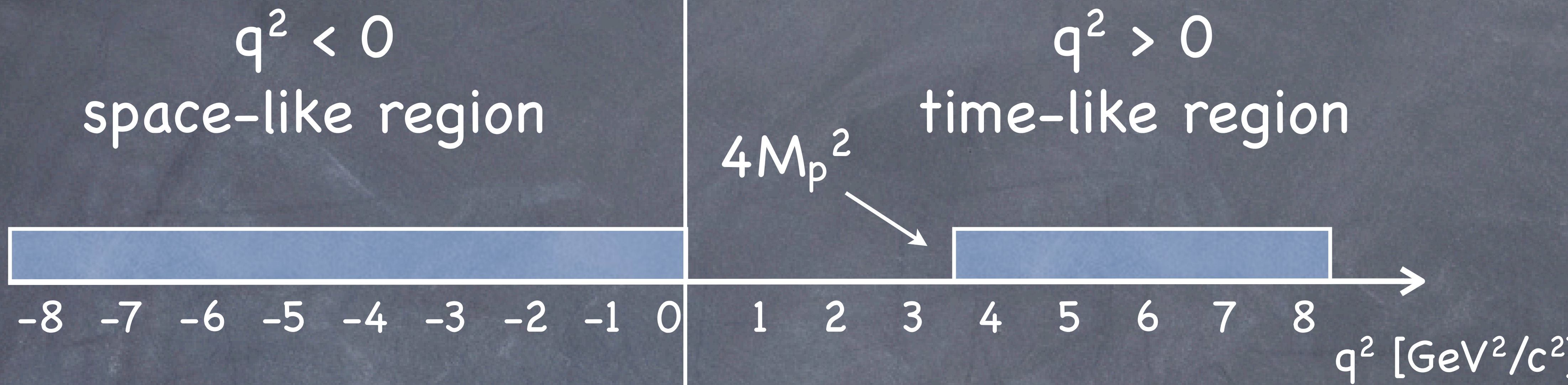


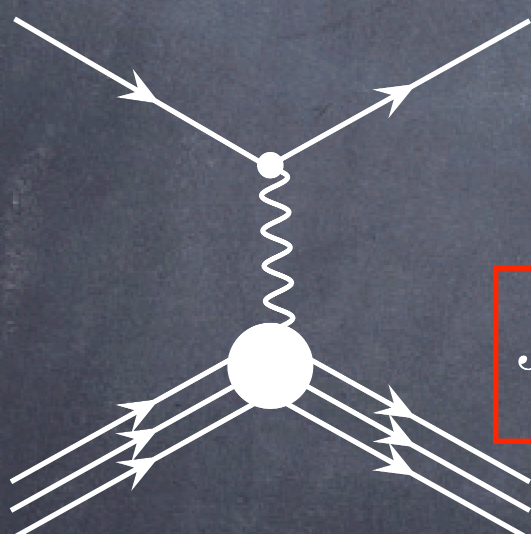
$$e^- + p \rightarrow e^{-\prime} + p'$$

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

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

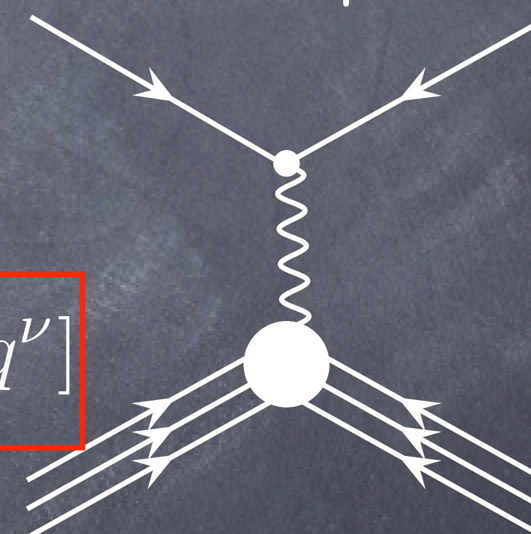
EM form factors: same matrix element





$$j_\mu = ie\gamma_\mu$$

$$J_\mu = ie[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma_{\mu\nu}q^\nu]$$



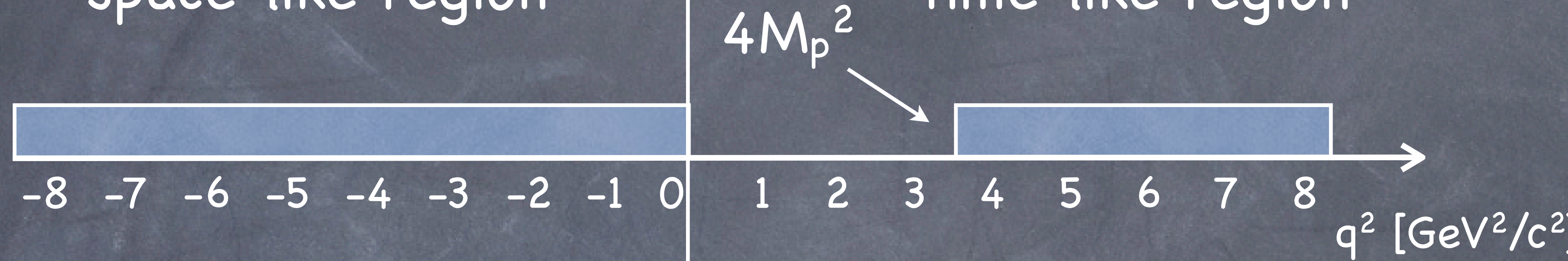
$$\langle \bar{u}_{p'}|J_\mu|u_p\rangle \frac{1}{q^2}\langle \bar{u}_{e'}|j_\mu|u_e\rangle \longleftrightarrow \langle \bar{u}_{p'}u_p|J_\mu|0\rangle \frac{1}{q^2}\langle 0|j_\mu|\bar{u}_{e'}u_e\rangle$$

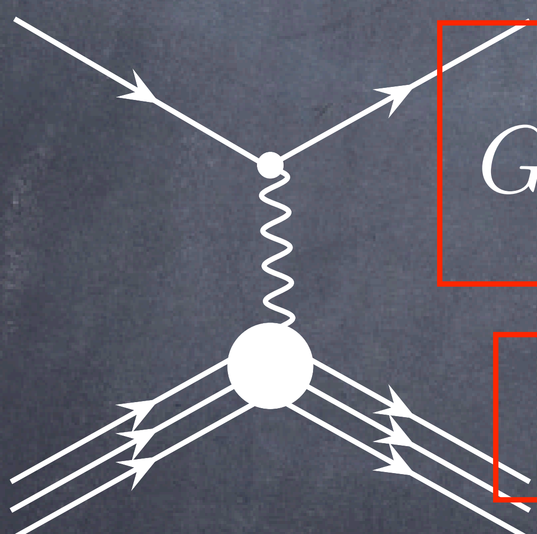
crossing symmetry

EM form factors: dispersion relation

$q^2 < 0$
space-like region

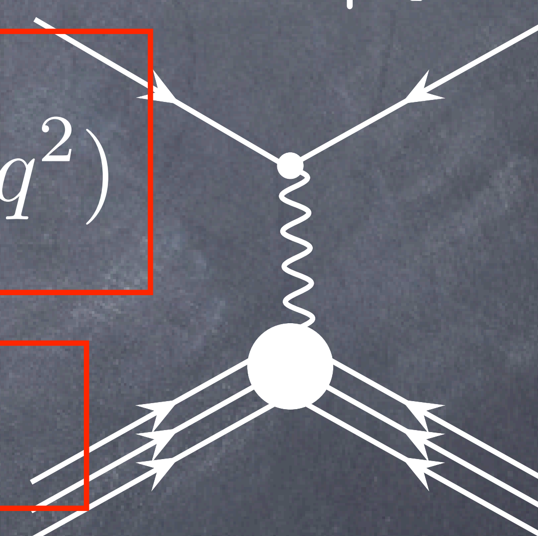
$q^2 > 0$
time-like region





$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M^2}\kappa F_2(q^2)$$

$$G_M(q^2) = F_1(q^2) + \kappa F_2(q^2)$$



dispersion relation

real value:
EM field distribution

complex value:
particle annihilation

EM from factors: asymptotic behavior

QCD counting rules:

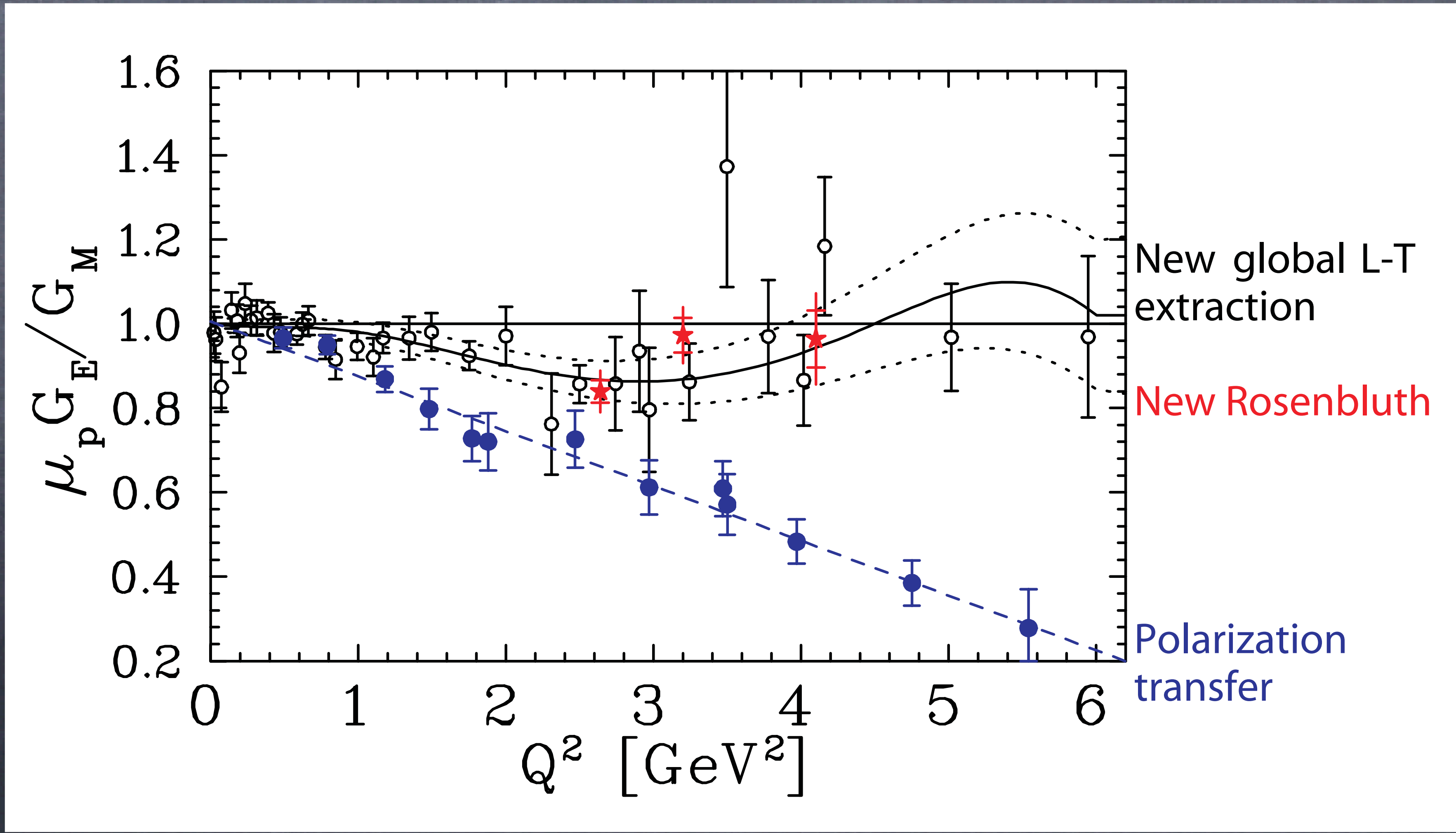
$$
\begin{aligned}
q^2 &\rightarrow -\infty \\
F_i(q^2) &\rightarrow (-q^2)^{-(i+1)} \\
i = 1 \ \text{DiracFF} & \qquad i = 2 \ \text{PauliFF} \\
G_{E,M} &\rightarrow (-q^2)^{-2}
\end{aligned}
$$

Analyticity:

$$
\begin{aligned}
q^2 &\rightarrow \pm\infty \quad \text{(Phragmen Lindeloef)} \\
G_{E,M}(-\infty) &= G_{E,M}(+\infty)
\end{aligned}
$$

EM from factors: experimental data

- rich data for space-like region
- feed to time-like region with dispersion relation
- new polarization data inspires intense study
- low statics for time-like region data

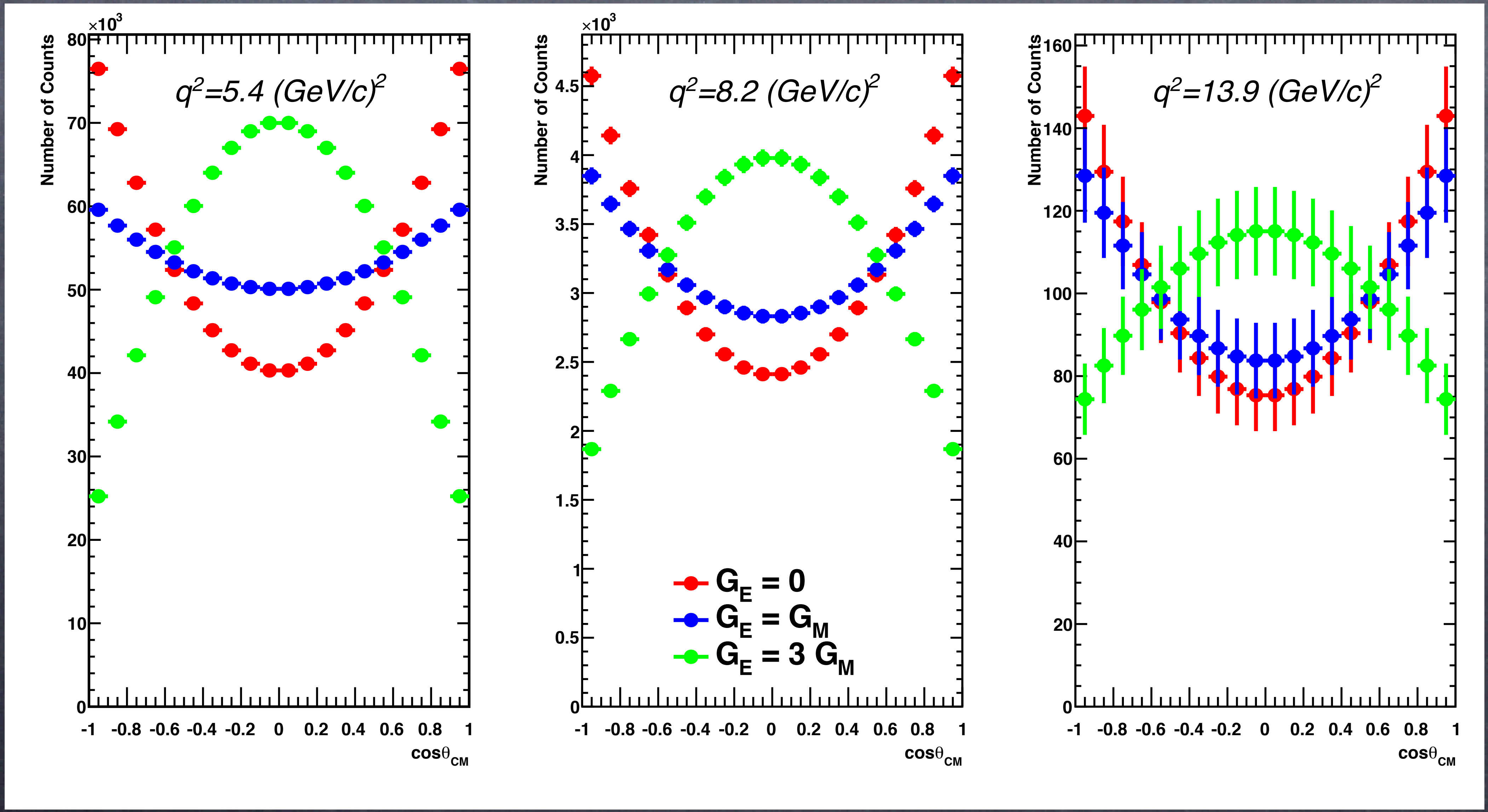


EM form factors in time-like region

Time-like EM form factors:

Rosenbluth cross section

$$\frac{d\sigma}{dcos\theta} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[|G_M|^2\left(1+cos^2\theta\right) + \frac{|G_E|^2}{\tau}(1-cos^2\theta)\right], \quad \tau = \frac{-q^2}{4M^2}$$



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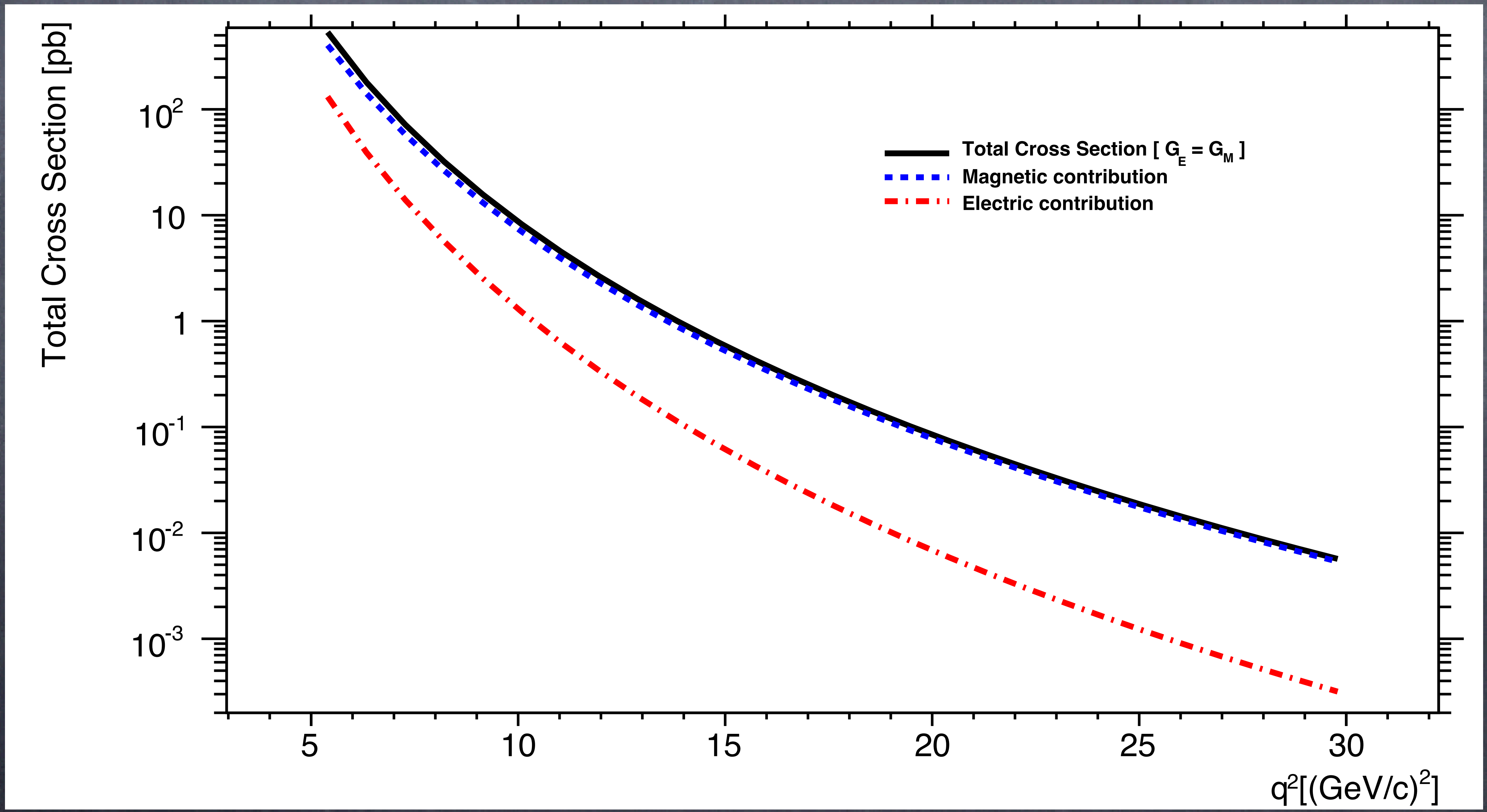
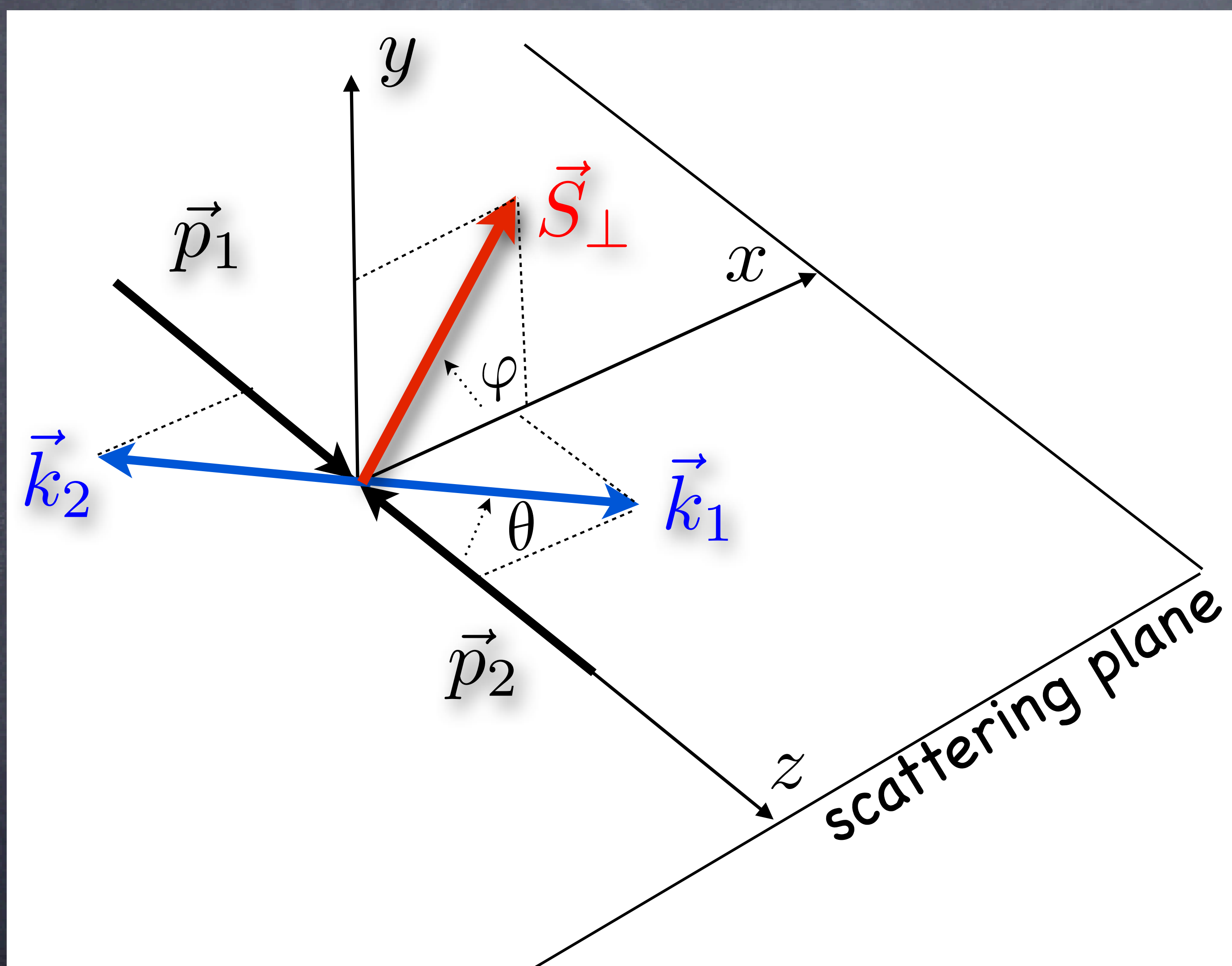


Time-like EM form factors:

polarization



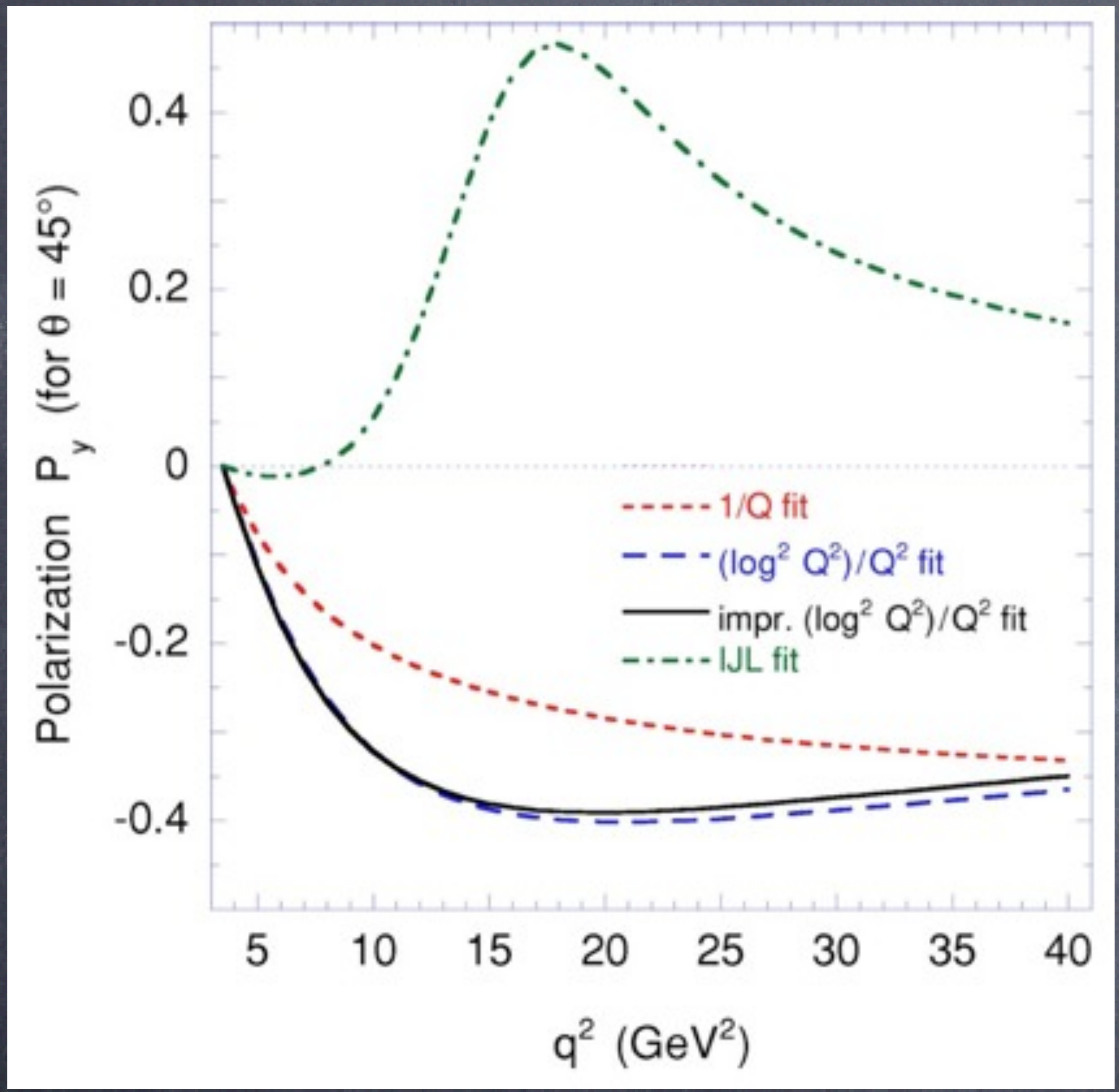
Px: perpendicular to beam
(inside scattering plane)

Py: normal to scattering plane

Pz: beam direction

Time-like EM form factors:

single polarization



P_y : perpendicular to scattering plane, either target or outgoing baryon

$$P_y \propto sin(2\theta) Im G_E^* G_M,$$

— doesn't require electron polarization
— contains Im part of relative phase
— good selection of different fitting

Phenomenological fitting based on VMD model;
JLab polarization data fitting;
pQCD fitting with logarithm correction;

E. Tomasi-Gustafsson, et al. Eur. Phys. J. A 24, 419-430 (2005)
S. Brodsky, et al. Phys. Rev. D 69 054022 (2004)

Time-like EM form factors:

double polarization

$$P_{zz} \propto (1+cos^2\theta)|G_M|^2 - \frac{1}{\tau}sin^2\theta|G_E|^2$$

$$P_{xx} \propto sin^2\theta(|G_M|^2 + \frac{1}{\tau}|G_E|^2)$$

$$P_{yy} \propto -sin^2\theta(|G_M|^2 - \frac{1}{\tau}|G_E|^2)$$

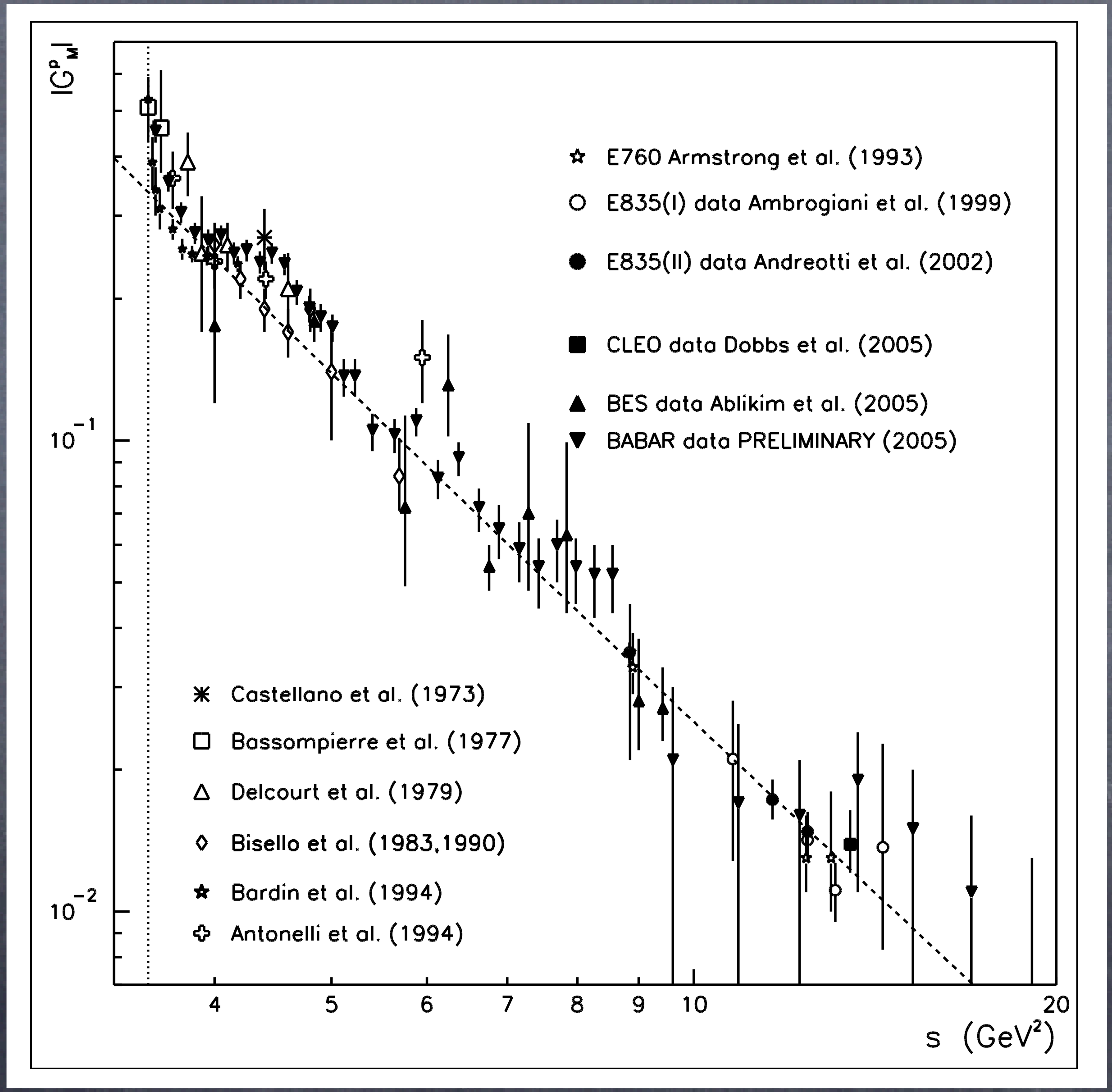
$$P_{zx} = P_{xz} \propto \frac{1}{\sqrt{\tau}}sin2\theta Re G_E G_M^*$$

P_{zx} :Sensitive to the real part of $G_E G_M$;
Together with P_y, a complete measurement of G_E and G_M in time like region can be made.

E. Tomasi-Gustafsson, et al. Eur. Phys. J. A 24, 419-430 (2005)

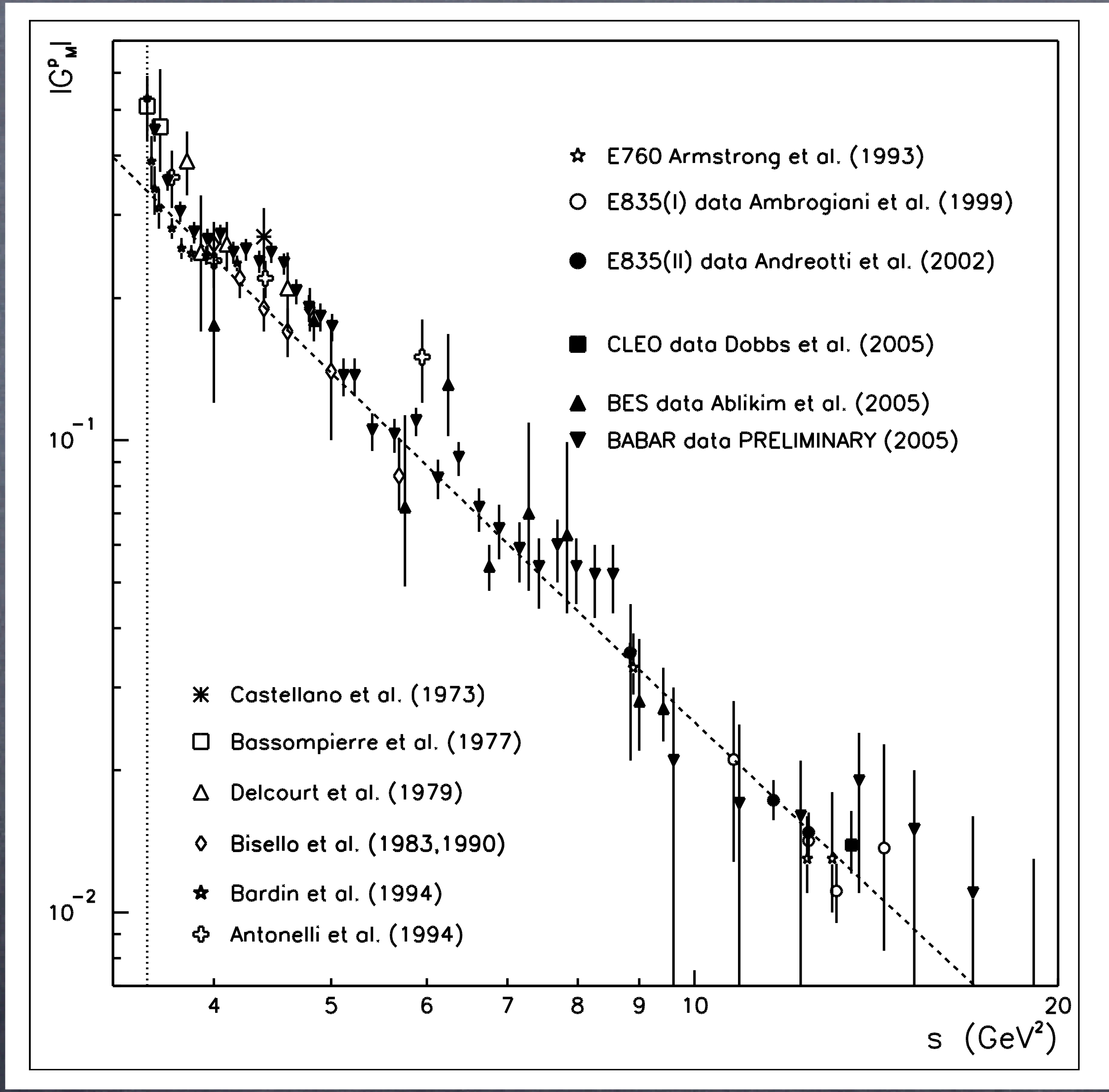
Time-like EM form factors:

existing data



Time-like EM form factors:

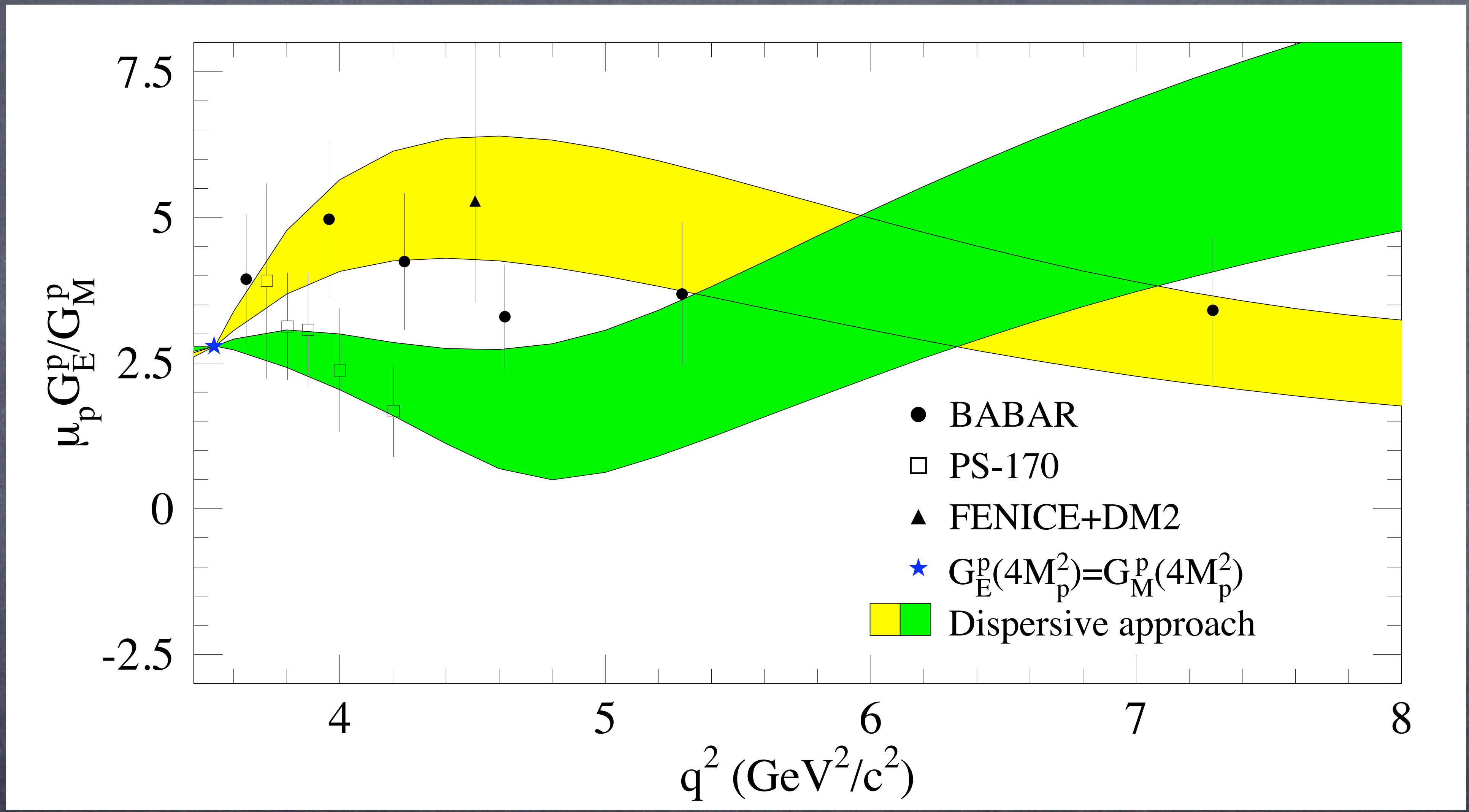
existing data



All data: absolute cross section, assume $G_E = G_M$

Time-like EM form factors:

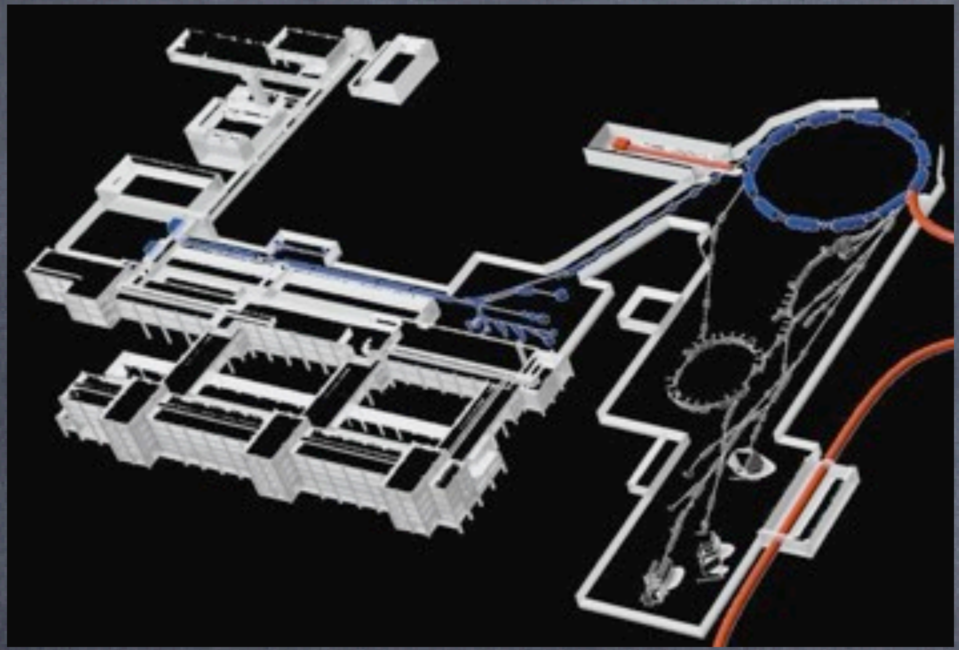
dispersion relation approach



Input for the space-like region: recent data from JLAB;
green band: fit result for PS170 data in the time-like region;
yellow band: fit result for the BABAR data.

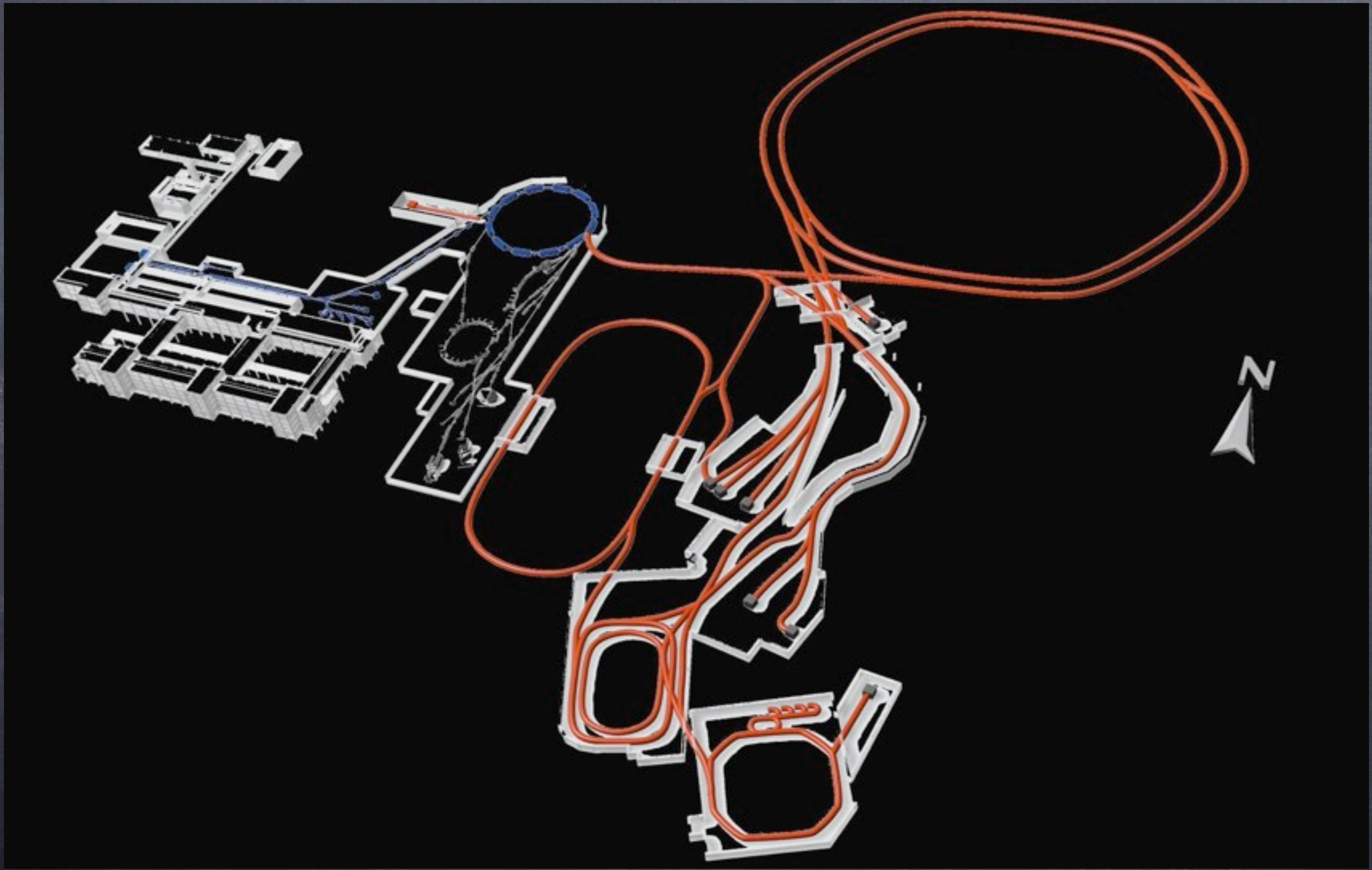
Impact from PANDA

PANDA experiment at FAIR:
layout of the future facility



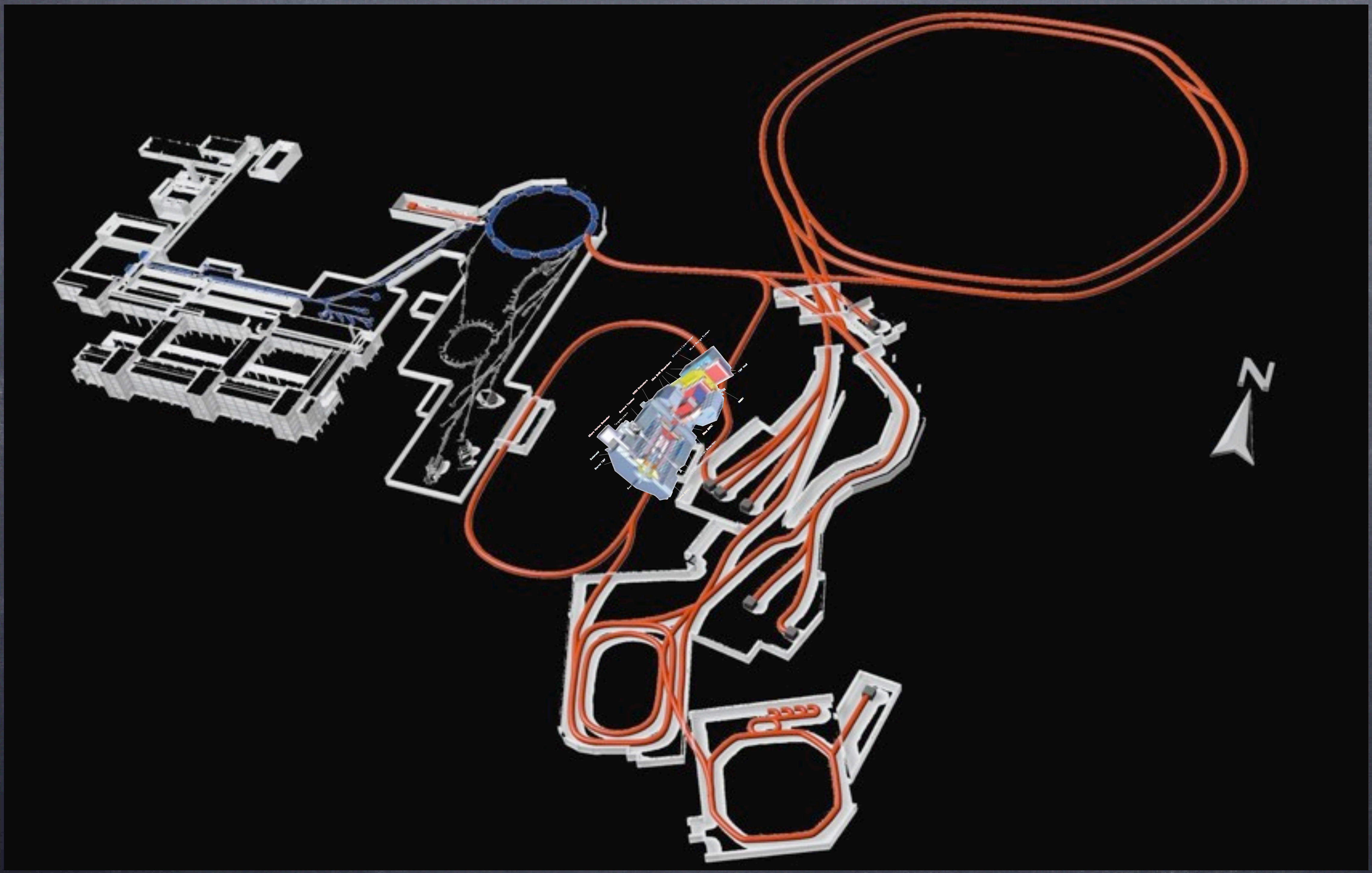
PANDA experiment at FAIR:

layout of the future facility



PANDA experiment at FAIR:

layout of the future facility



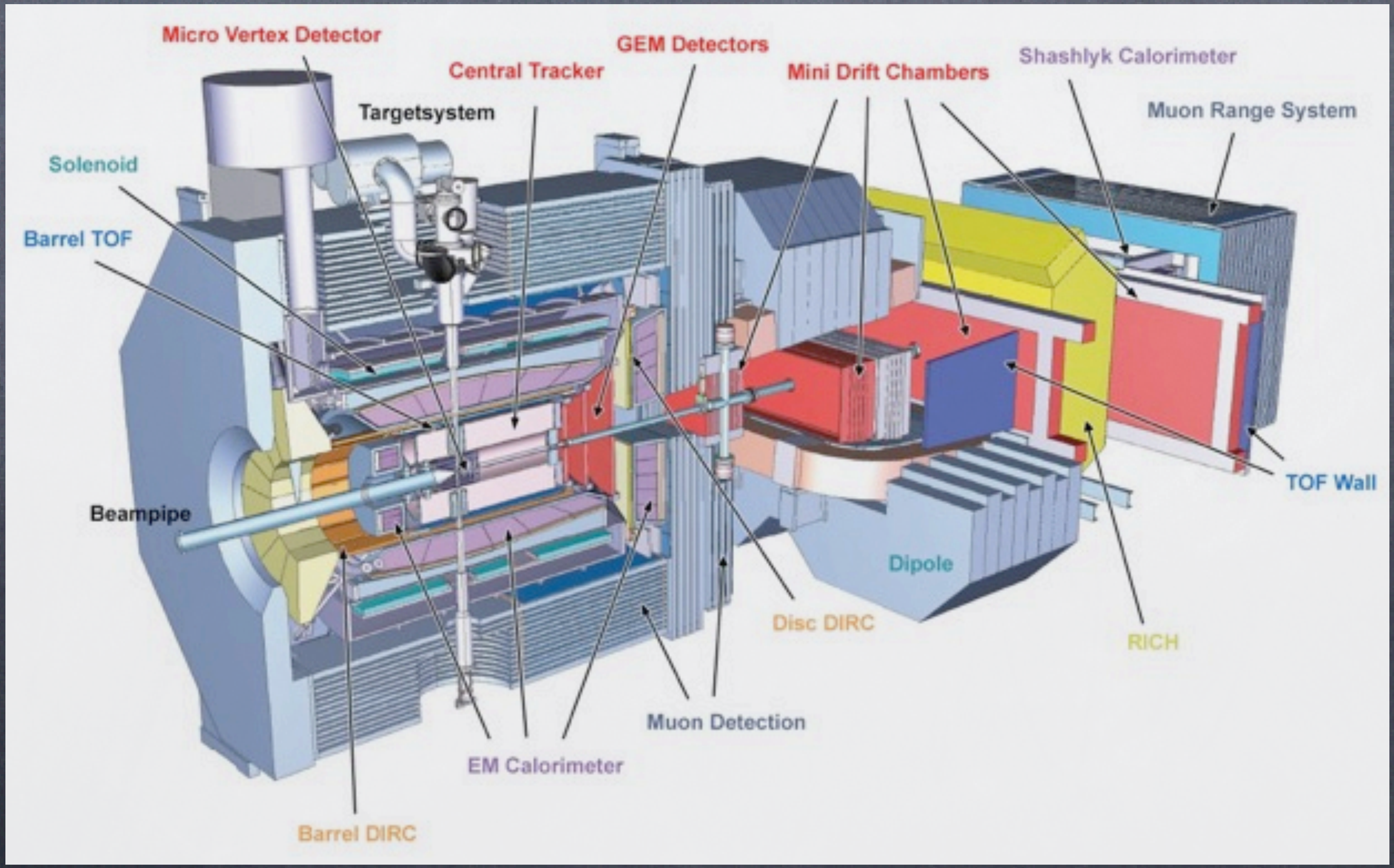
PANDA experiment at FAIR:
collaboration list

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

PANDA experiment at FAIR:

spectrometer

- Good tracking capability;
- High luminosity $L=1.6\times10^{32}cm^{-2}s^{-1}$;
- Wide momentum range: 1.5 GeV/c ~ 15 GeV/c



PANDA experiment at FAIR:

simulation

- large collaboration framework: computing resources, software package development
- parametrization of detector response, digitization, reconstruction, high level tools
- 100 CPUs in Orsay, 300 CPUs Lyon: $\pi^+\pi^-$ background ($< 10^9$ events)
- 200 CPUs at GSI: all other signals
- particle identification, just include dE/dx
- full material budget, radiative corrections, kinematical fits

M. Sudol, et al. Eur. Phys. J. A **44**, 373-384 (2010)

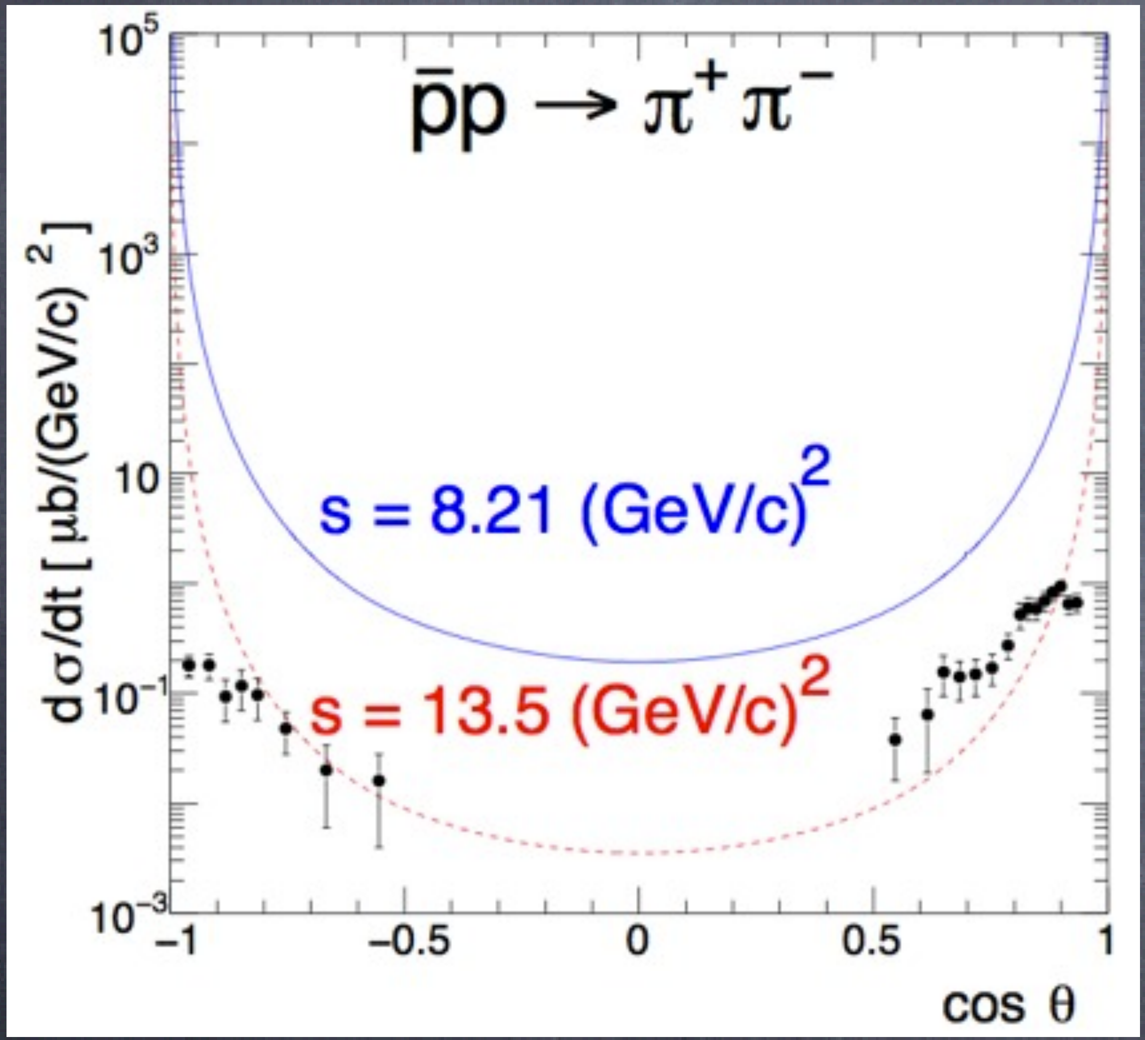
PANDA experiment at FAIR:

simulation

- Reactions with at least 3 particles produced: (e^+e^-X, $\pi^+\pi^-X$,...)
  - PID and kinematics constraints: no problem
- Reactions with 2 charged particles
  - $\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \approx 10^6$ (2μb/8pb at q^2=9.0(GeV/c)^2)need rejection of $pp \rightarrow \pi^+ \pi^-$ by 10^{-8} binary event, mean reject. of 10^{-4} per π^+ and per π^-
  - very close kinematics
  - PID is crucial, EMC, DIRC, dE/dx of straw tube

PANDA experiment at FAIR:

simulation



q^2 [GeV^2]	e^+e^-	$\mu^+\mu^-$	$\pi^+\pi^-$	$\pi^0\pi^0$
5.4	4×10^6	4×10^6	-	-
7.21	4×10^6	4×10^6	-	-
8.21	4×10^6	4×10^6	10^8	3×10^6
11.03	4×10^6	4×10^6	-	-
12.9	4×10^6	4×10^6	10^8	3×10^6
16.7	4×10^6	4×10^6	2.10^8	3×10^6
22.3	4×10^6	-	-	-

- $\pi^+\pi^-$ background distribution
- number of events simulated

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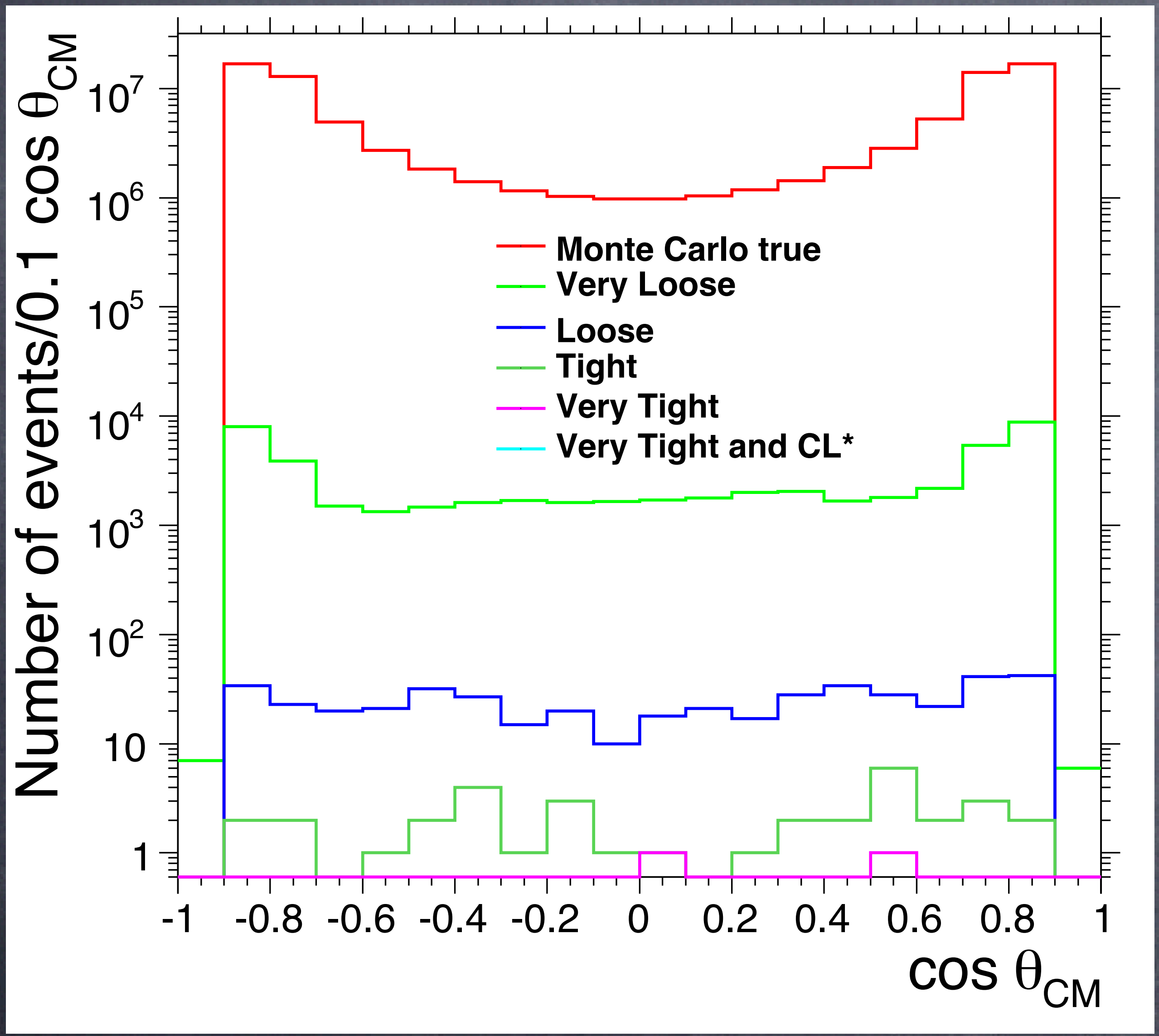
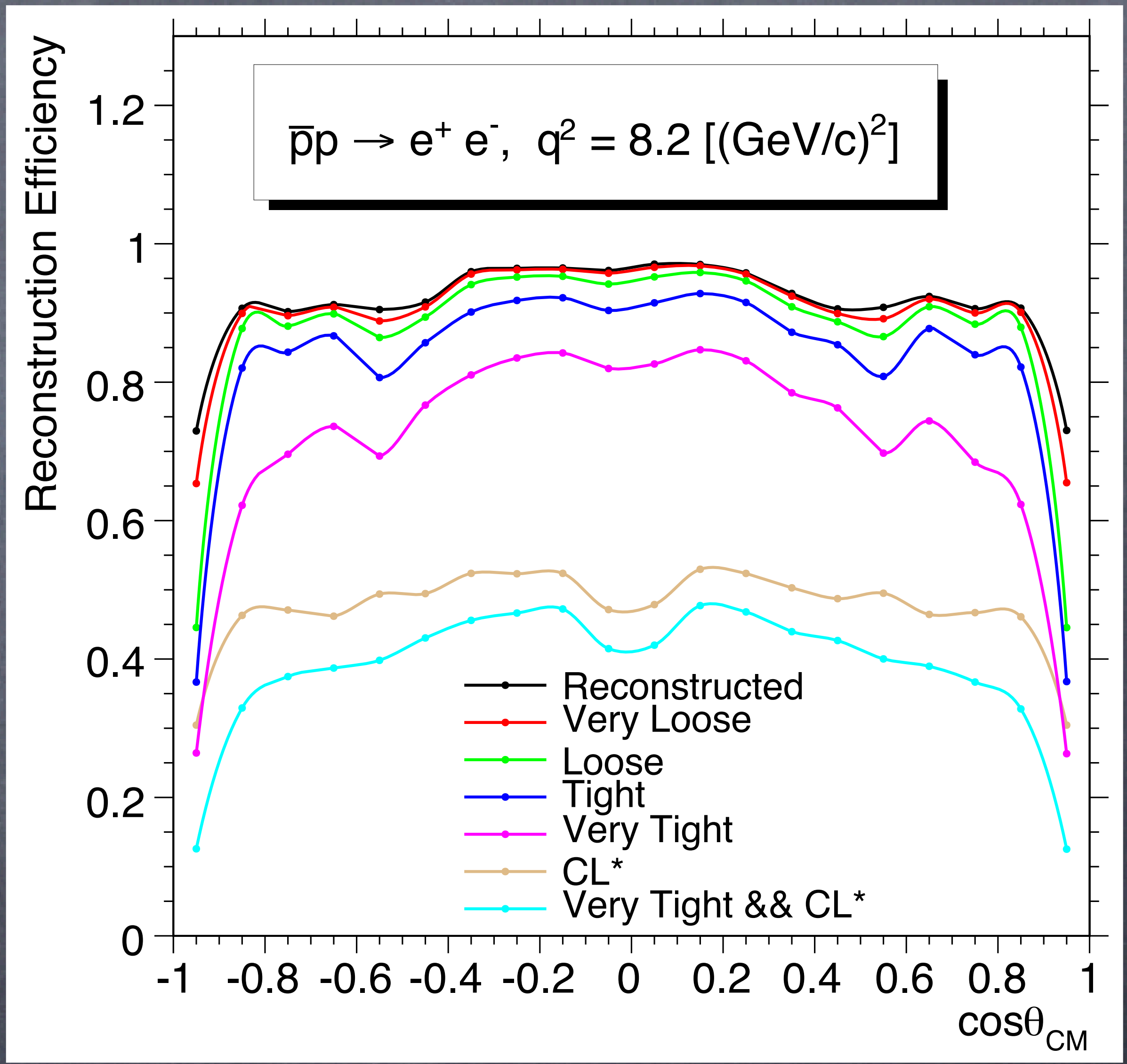
PANDA experiment at FAIR:

simulation: background suppression





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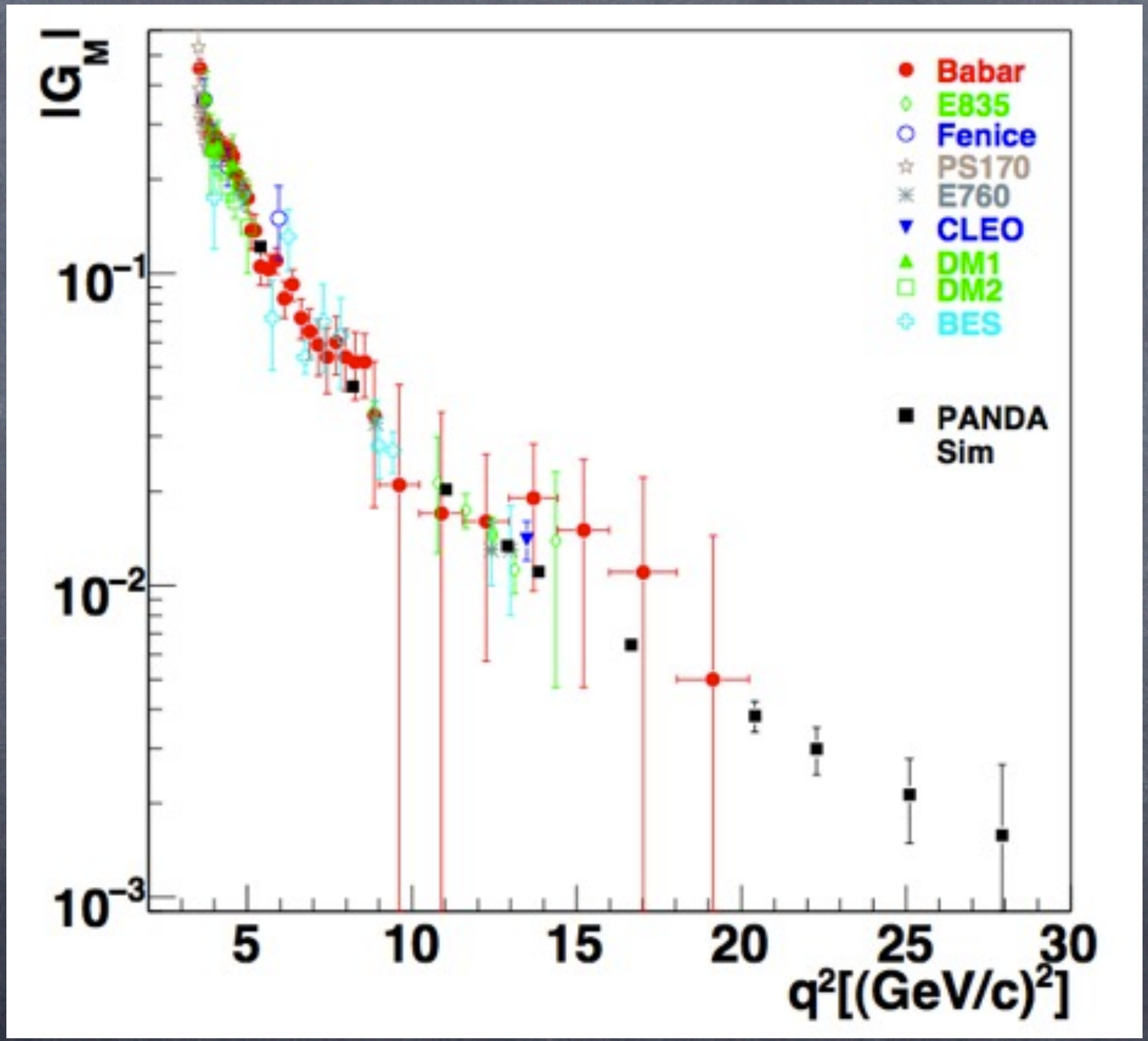
PANDA experiment at FAIR:

simulation: PANDA precision



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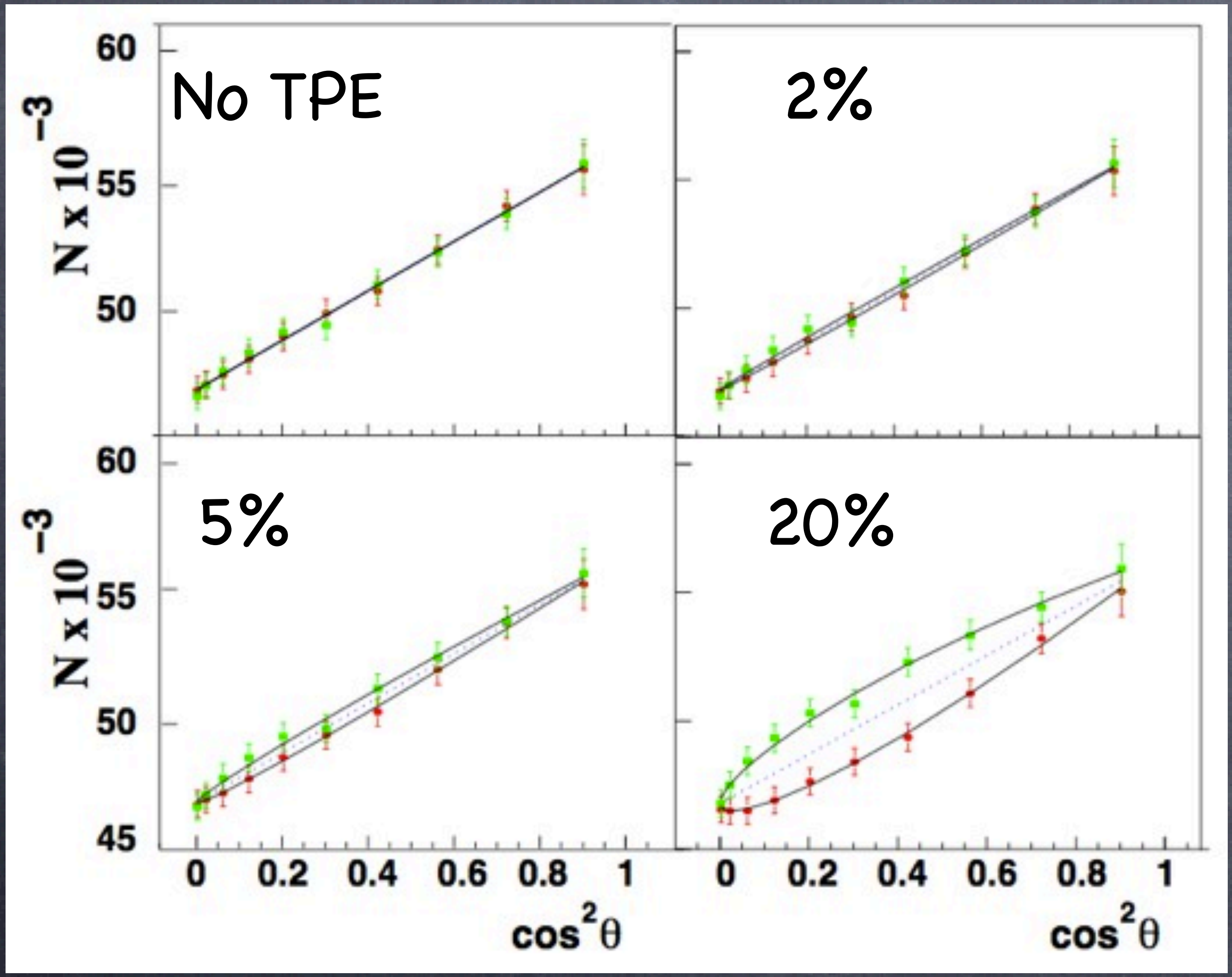
PANDA experiment at FAIR:

simulation: PANDA vs. TPE



$$\frac{d\sigma}{dcos\theta} = \sigma_0(1 + Acos^2\theta)$$

A: asymmetry due to TPE interference

$q^2 = 5.4\ (GeV/c)^2$

forward lepton

backward lepton

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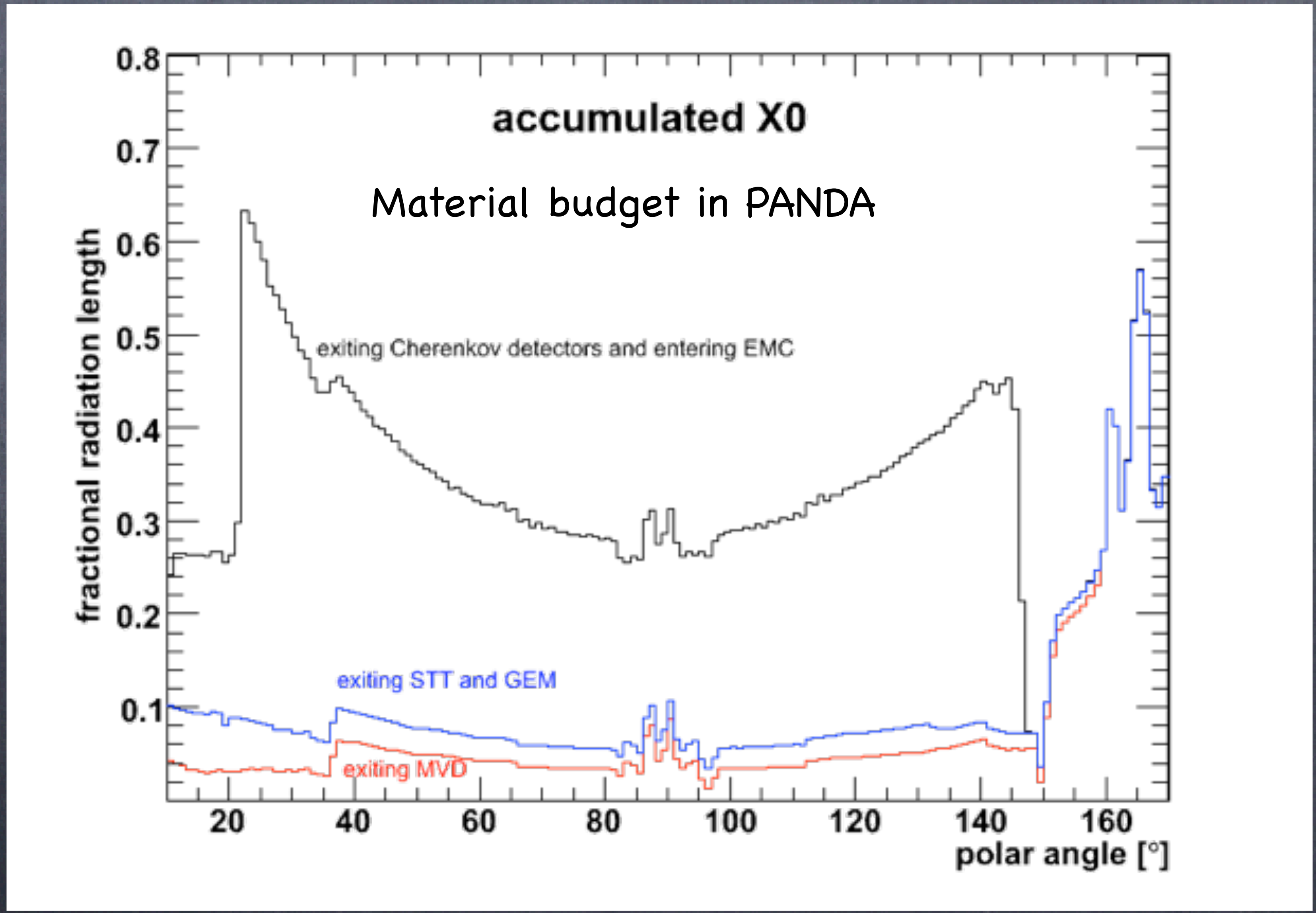
PANDA experiment at FAIR:

possibility of polarization

- Feasibility study (physics simulations & finite element analysis)
- PANDA: modular, exchange inner part in later stage



Summary:

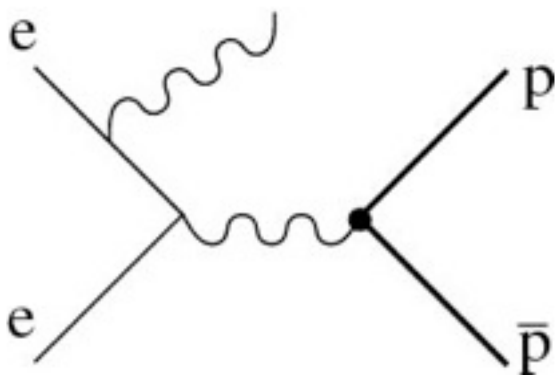
Panda can ...

- essentially improve data in TL region
- possibility to measure relative phase (G_E, G_M)
- determine contribution of TPE
- Other interesting EM processes

end

- matrix element
- space-like, time-like cross section (1 gamma)
- complex, dispersion relation
- two photon exchange
- polarization, spin observables, relative phase
- other physics: Drell Yan, transverse spin, GPD, TDA
- polarized target: physics, technique
- tau decay

ISR method



Mass spectrum of pp system in the $e^+e^- \to pp\gamma$ reaction is related to cross section of $e^+e^- \to pp$ reaction at E=m.

$$\frac{d\sigma(e^+e^- \longrightarrow p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\sigma(e^+e^- \longrightarrow p\bar{p})(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad \theta >> \frac{m_e}{\sqrt{s}}.$$

Unpolarized cross section

dapnia
cea
saclay

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

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

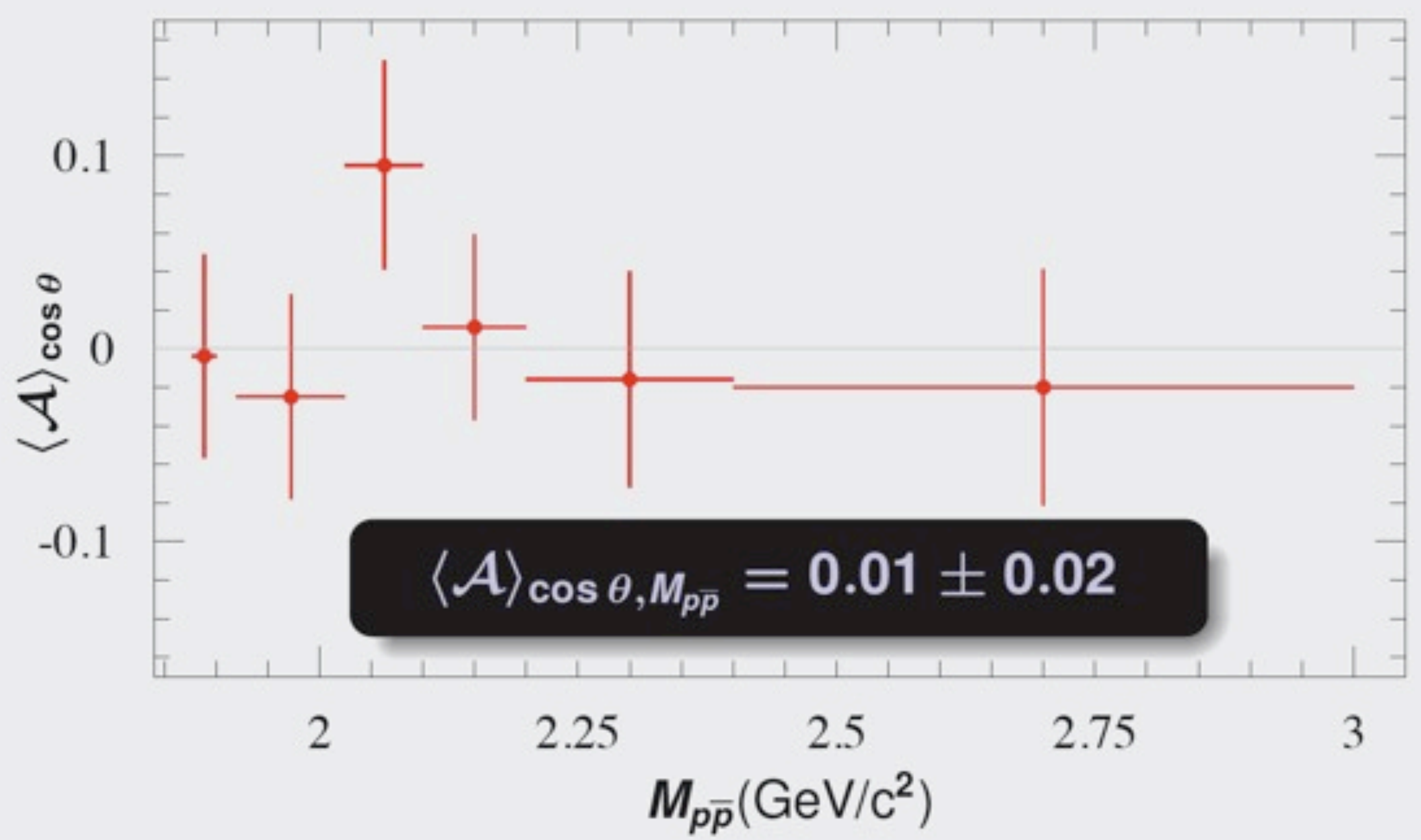
2γ–contribution:

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

$\gamma\gamma$ exchange from $e^+e^- \to p\bar{p}\gamma$ BABAR data

PLB659, 197

$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$



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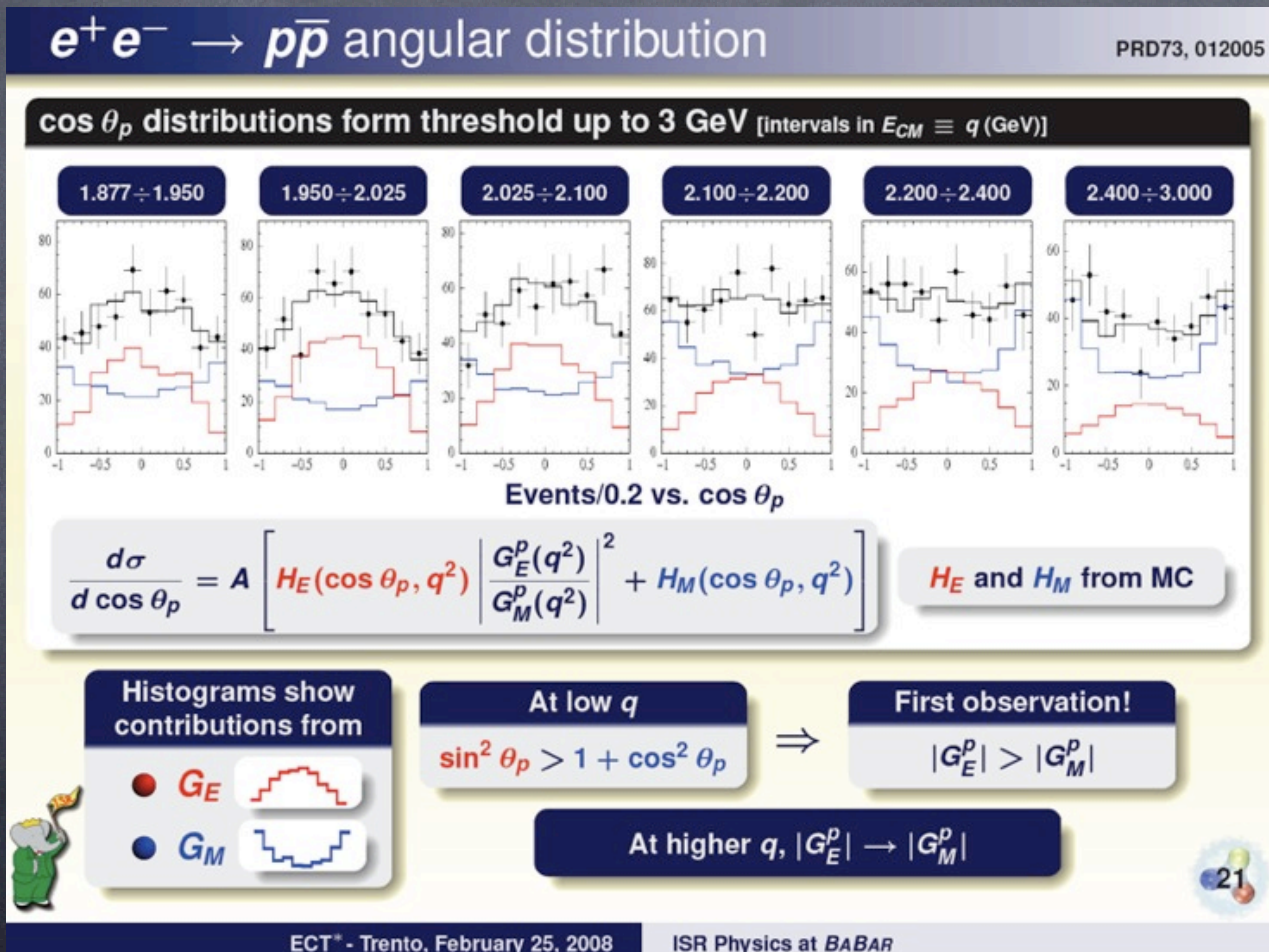
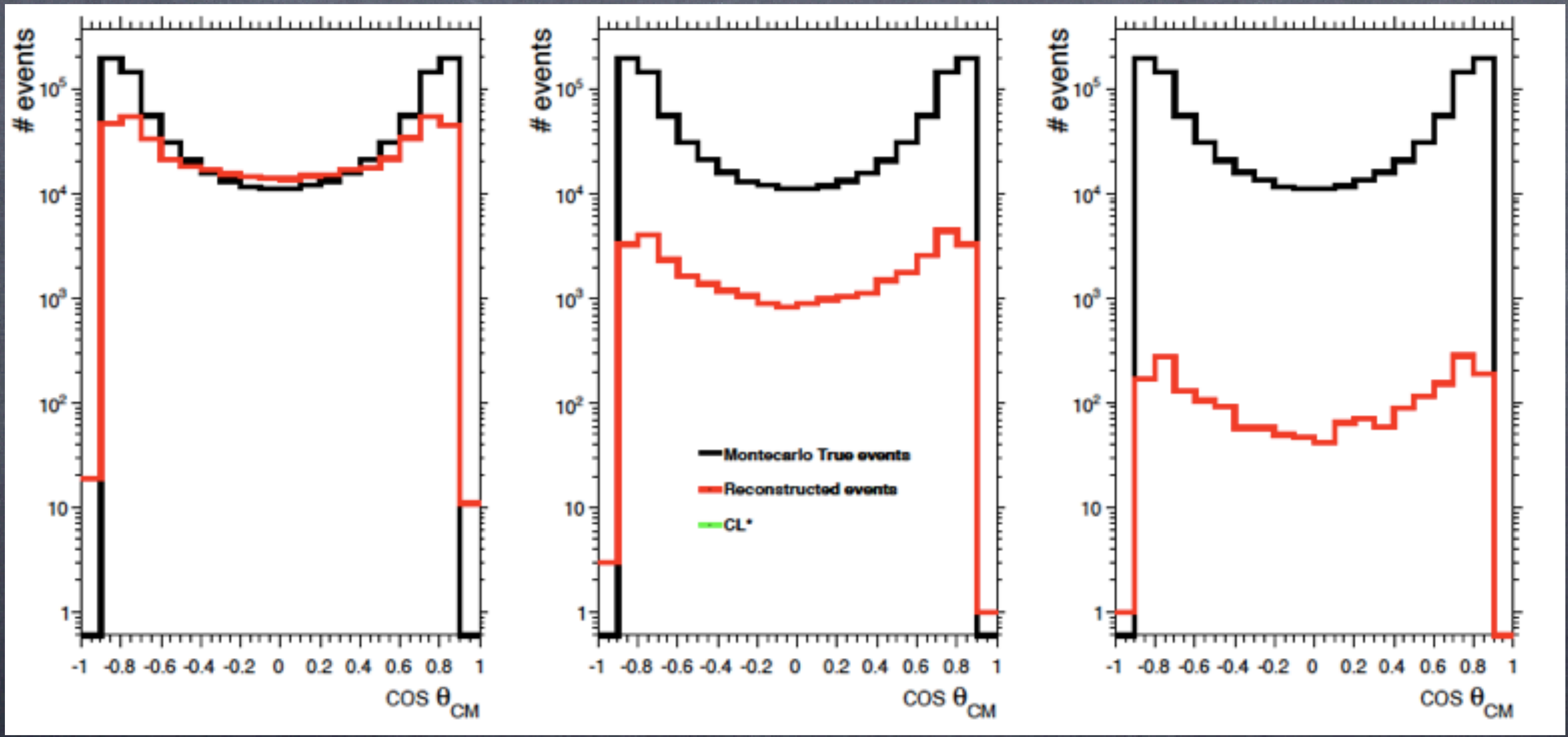
Time-like EM form factors:

existing data



PANDA experiment at FAIR:

simulation



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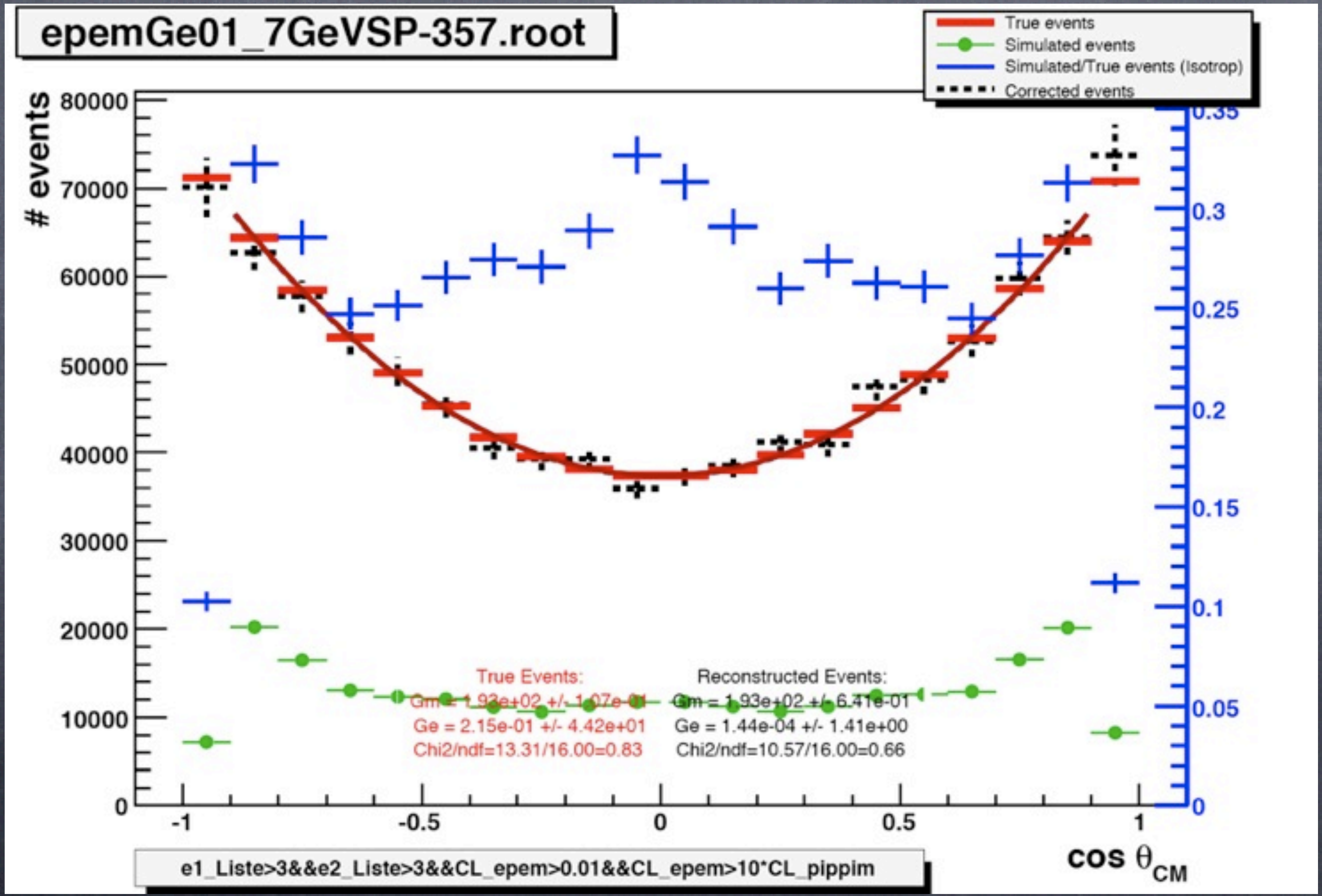

PANDA experiment at FAIR:

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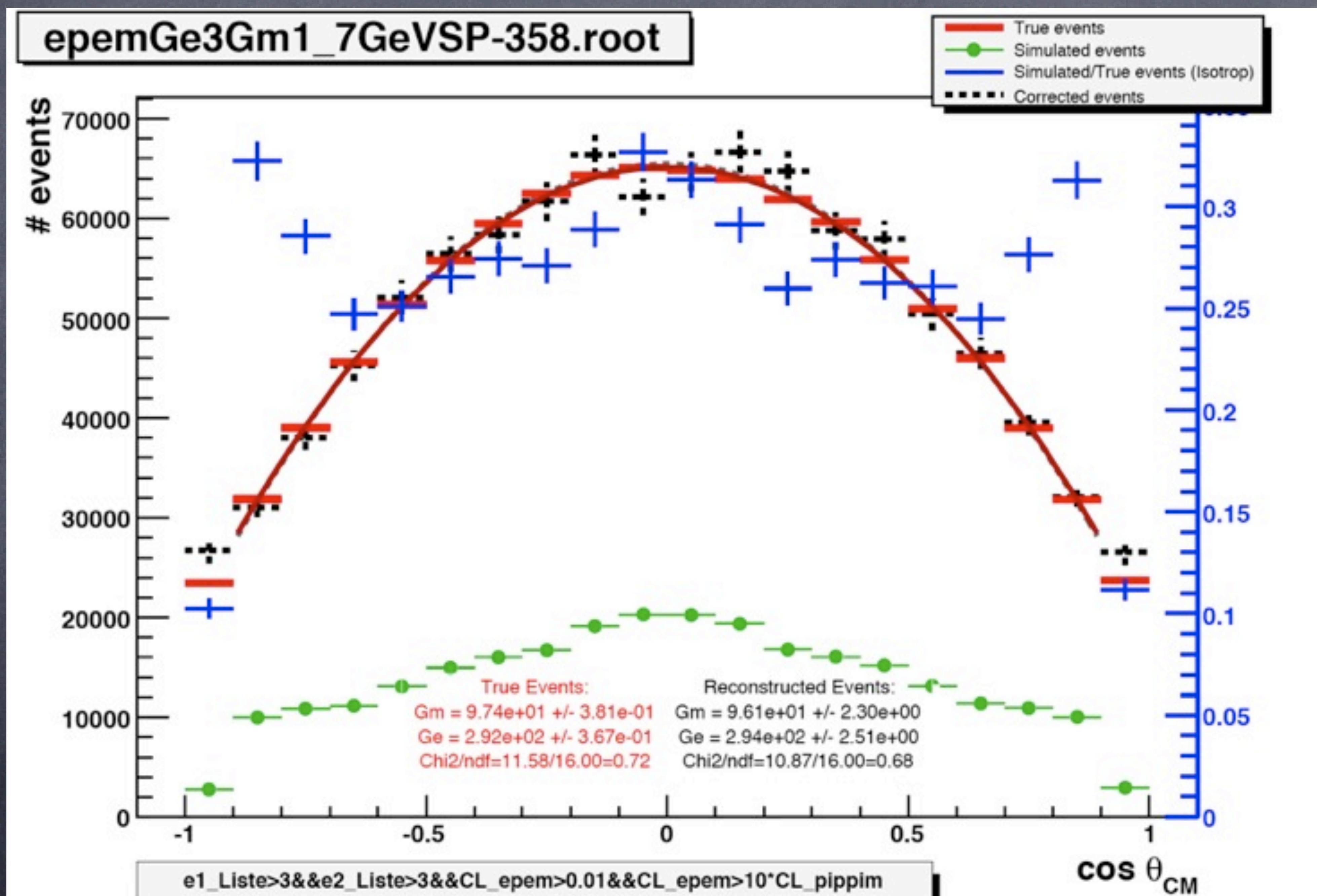
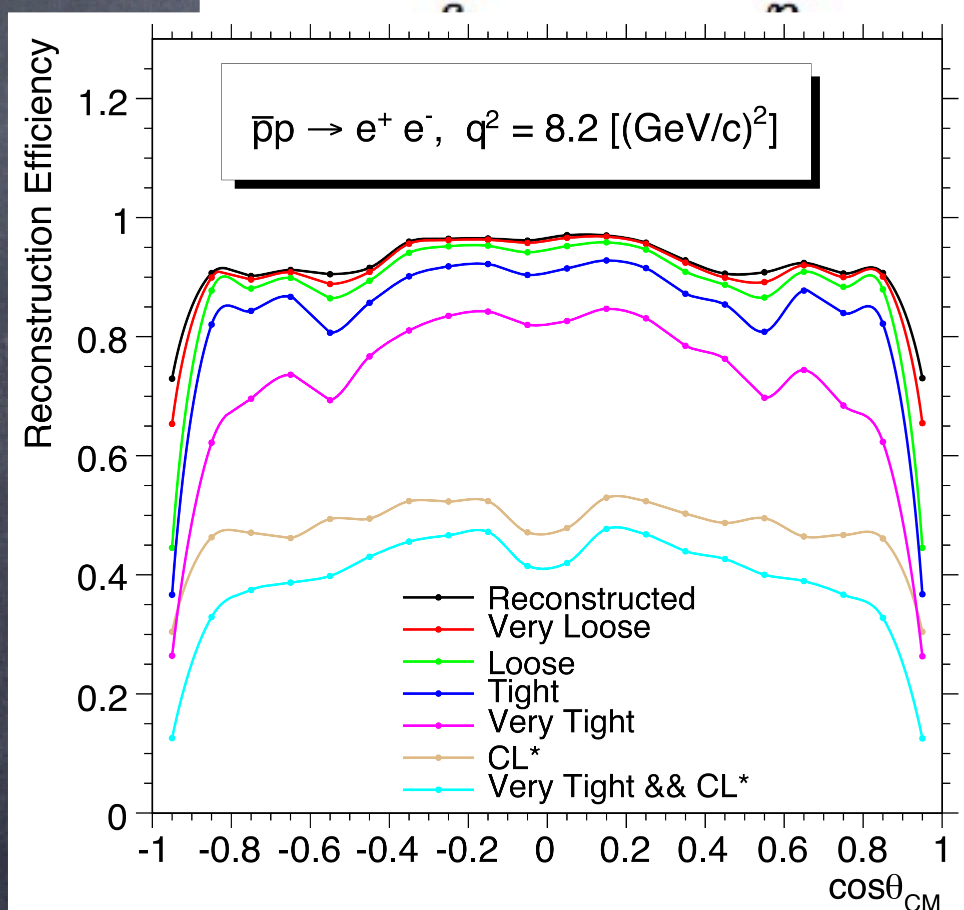
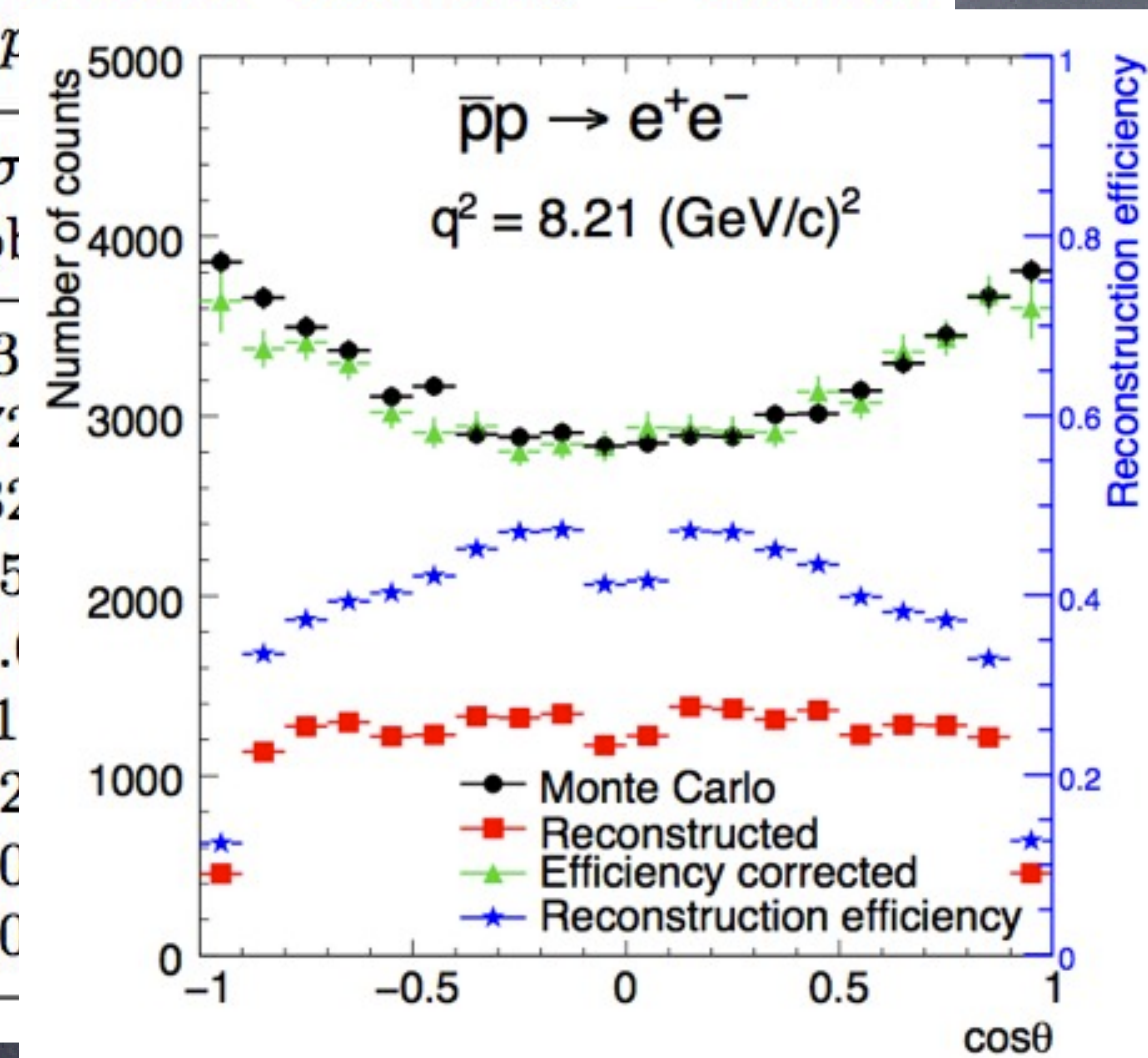


Table 1. Cross section σ (σ_{QCD}) and number of counts, N (N_{QCD}) from eq. 7 (eq. 8) corresponding to an integrated luminosity of $\mathcal{L} = 2\ \text{fb}^{-1}$, for different values of $q^2 = s$ and of the antiproton momentum, p

σ [pb
53
72
32
4.5
1.(
1
0.2
0.0
0.0



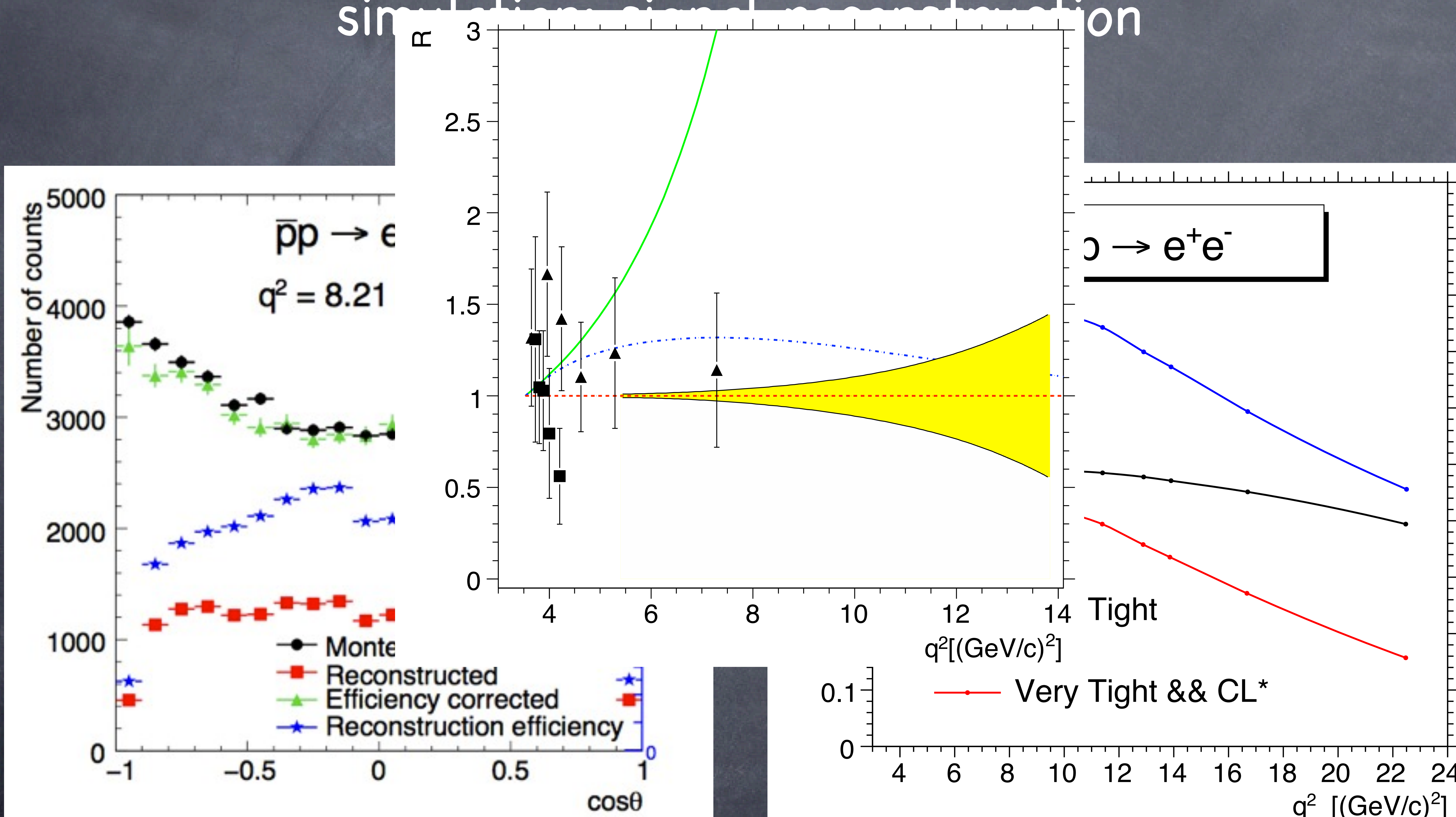


EM form factors: basic facts

- Assuming P, T invariance, a particle with spin S has 2S+1 form factors: Dirac (F1) & Pauli (F2)
  W.R. Theis IL NUOVO CIMENTO 45A, (1966), 124
- EM form factors: G_E & G_M
  space-like ($q^2<0$), distribution of EM field, **real value**;
  time-like ($q^2>0$), particle annihilation, **complex value**
  V.Wataghin, IL NUOVO CIMENTO 54A, (1967), 840
- Space-like region and time-like region are connected by dispersion relations
- Constraints from QCD power counting

PANDA experiment at FAIR:

si… ion



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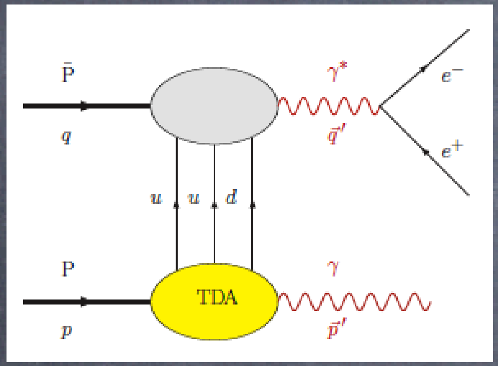
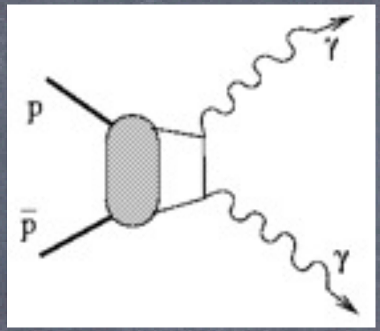
PANDA experiment at FAIR:

other interesting EM processes

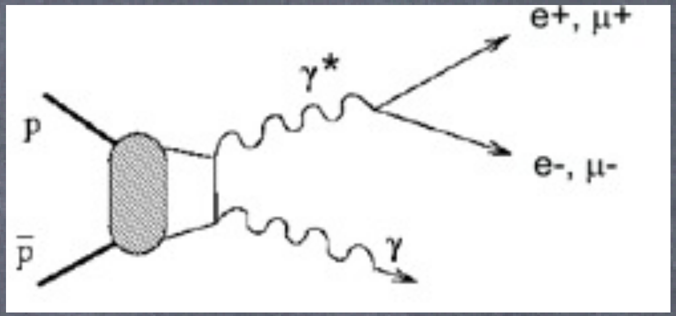
Transition Distribution Amplitudes



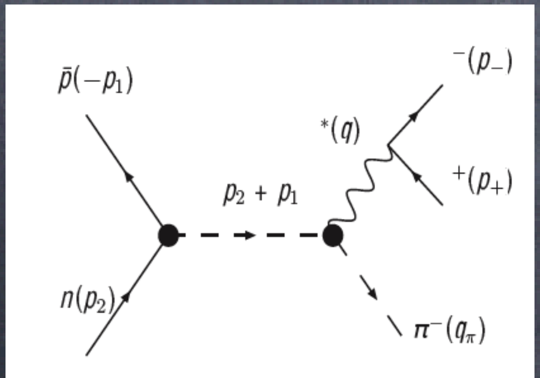
Wide angle TL Compton scattering



Deeply Virtual TL Compton Scattering



Timelike Axial Formfactor



Drell Yan Process

Transverse spin structure