Time-like Electromagnetic form factors at PANDA

Yue Ma,

Helmholtz Institute Mainz

Nucleon form factor related talks from Erice2011 program

- Diego Bettoni (Ferrara)

  Antiproton physics (timelike processes at PANDA)

- Nikolay Kivel (Mainz)

  Nucleon FF in space- and time-like regions

- Dmitry Khaneft (Mainz)

  Feasibility Study on the extraction of the time-like form factors via the process pbar p -> e+e- with PANDA-Experiment at FAIRT using the PandaRoot frame work.

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Outline

Theoretical preparation

- Definition & interpretation of form factors (FFs)
- Time-like FFs & spin observables

Experimental aspect

- pbar p -> e+ e-
- eppi0 with TDA simulation
- Polarized target R&D

Definition of form factors

- Dirac equation with external field

$$(\gamma_\mu p_\mu - m)\psi = 0 \quad \gamma_\mu p_\mu \rightarrow \gamma_\mu p_\mu + e\gamma_\mu A_\mu$$

- Pauli equation (non-relativistic limit of Dirac equation)

$$[\frac{1}{2m}(\vec{p} - \frac{e}{c}\vec{A})^2 + e\phi + \mu_B \hat{\sigma} \cdot \vec{B}]\psi = i\hbar\frac{\partial \psi}{\partial t}$$

- W. Pauli Rev. Mod. Phys. 13, 203 (1941)

$$-i\kappa\gamma_\mu\gamma_\nu(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})$$

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Dirac term already includes e and g

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$$-i\kappa\gamma_\mu\gamma_\nu(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})$$

Pauli term contributes to anomalous magnetic moment

Extension

- Relativistic covariance & gauge invariance
- Linear in electromagnetic potential
- Doesn't vanish in static case
- L.I. Foldy, Phys. Rev. 87 688 (1952)

$e\gamma_\mu A_\mu$	$e\gamma_\mu \Box^n A_\mu$	$e\gamma_\mu \sum_{n=0}^{\infty} \Box^n A_\mu$
$-i\kappa\gamma_\mu\gamma_\nu(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})$	$-i\kappa\gamma_\nu\gamma_\mu\Box^n(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})$	$-i\kappa\gamma_\nu\gamma_\mu \sum_{n=0}^{\infty} \Box^n(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})$

Scattering matrix

$$S_{fi} = -i \int dx e^{-iqx} \bar{u_2}(-i)(F_{Dirac}\gamma_\mu A_\mu + \frac{1}{2}\kappa F_{Pauli}\gamma_\mu\gamma_\nu(\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu}))u_1$$

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- By inserting the summation of Dirac and Pauli term, each D'Alembert operator contributes a q^2
- Form factors as a function of q^2 instead of constant

Scattering matrix

Dirac term Pauli term

$$S_{fi} = -i \int dx e^{-iqx} \bar{u_2}(-i)(F_{Dirac} \boxed{\gamma_\mu A_\mu} + \frac{1}{2}\kappa F_{Pauli} \boxed{\gamma_\mu \gamma_\nu (\frac{\partial A_\mu}{\partial x_\nu} - \frac{\partial A_\nu}{\partial x_\mu})}) u_1$$

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Dirac & Pauli FFs

- By inserting the summation of Dirac and Pauli term, each D'Alembert operator contributes a q^2
- Form factors as a function of q^2 instead of constant

Sachs form factor

- Physics interpretation of F_{Dirac} and F_{Pauli} :
  - F_{Dirac} containing both charge and magnetic terms
  - F_{Pauli} only for anomalous magnetic momentum
  - interference expression in cross section
- Non-relativistic limit
  J.D. Walecka Nuovo Cimento 11 821 (1959)
- Breit frame (one value for each q)
  R.G. Sachs, Phys. Rev. 126, 2256(1962)

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$$\bar{u}(\frac{1}{2}\vec{q})\vec{F}(\vec{q},0)u(-\frac{1}{2}\vec{q}) \propto (\vec{\sigma}\times\vec{q})G_M(\vec{q}^2) \qquad G_M(q^2) = F_1(q^2) + \kappa F_2(q^2)$$

$$\bar{u}(\frac{1}{2}\vec{q})F_4(\vec{q},0)u(-\frac{1}{2}\vec{q}) \propto G_E(\vec{q}^2) \qquad G_E(q^2) = F_1(q^2) + \frac{q^2}{4M^2}\kappa F_2(q^2)$$

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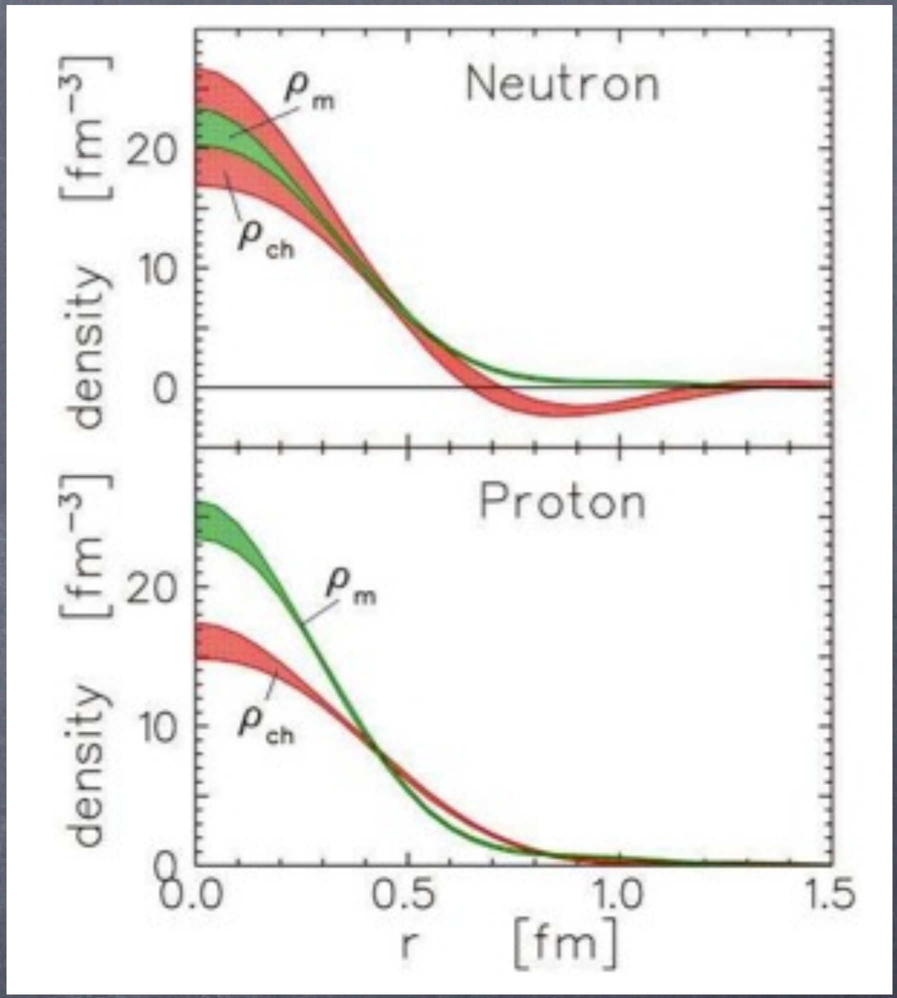

J.J. Kelly Phsy. Rev. C 66 065203 (2002)

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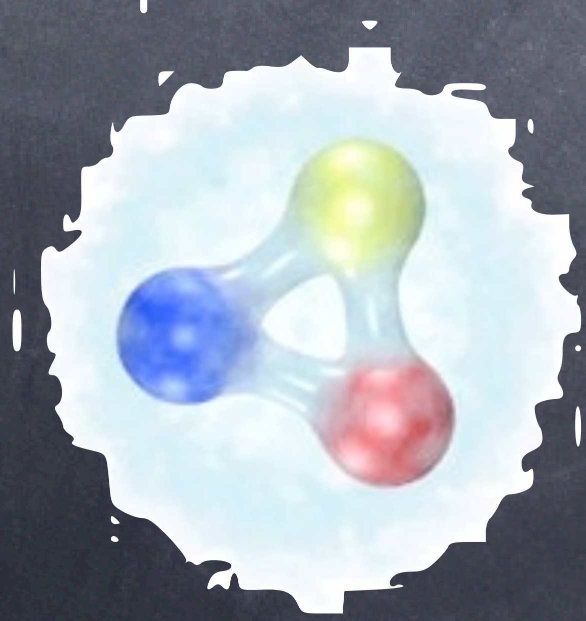
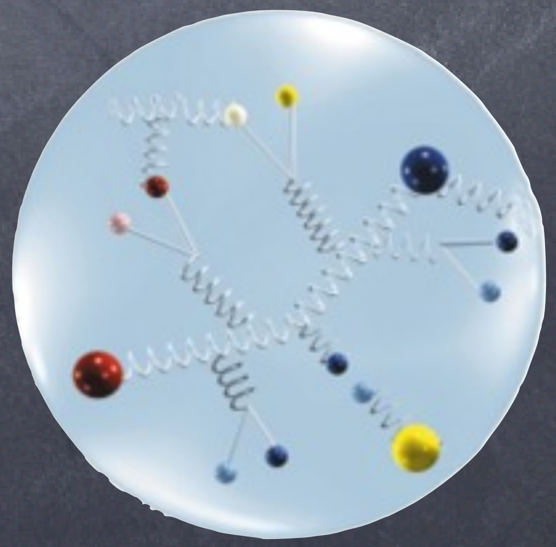
Dirac equation vs. nucleon

- Anomalous magnetic moment occurs
- Form factors as a function of q^2 instead of constant
- Accommodate complicated meson clouds/quarks within Dirac equation
- By requiring T&P invariance, 2s+1 form factors for spin s particles





Picture taken from PANDA website

Time-like vs. space-like

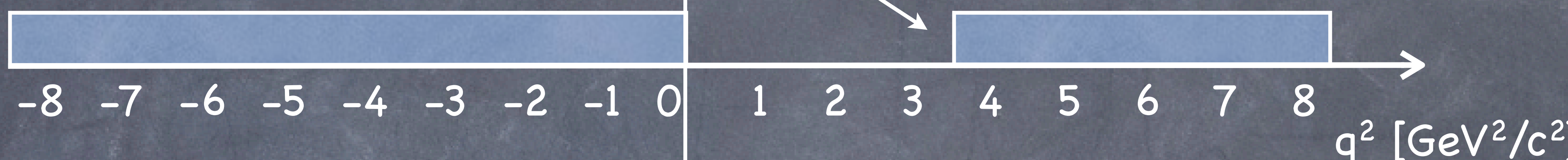
$q^2 < 0$

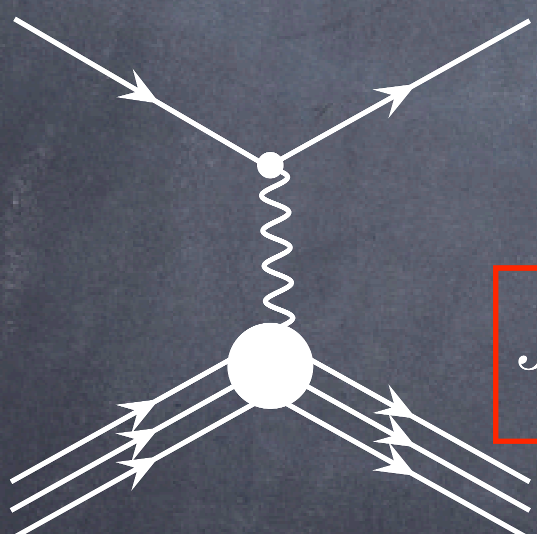
space-like region

$q^2 > 0$

time-like region

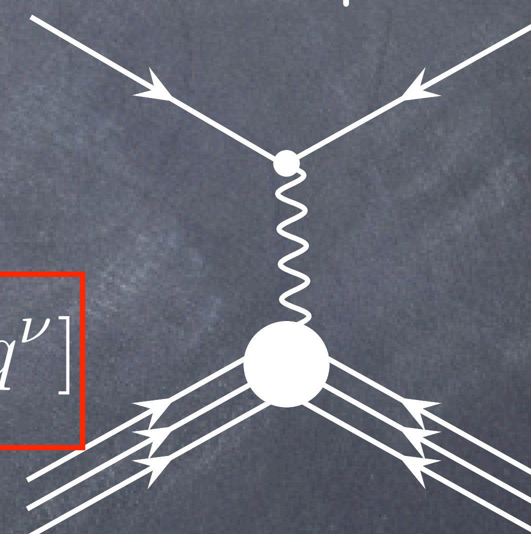
$4M_p{}^2$





$$\boxed{j_\mu = ie\gamma_\mu}$$

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



crossing symmetry

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

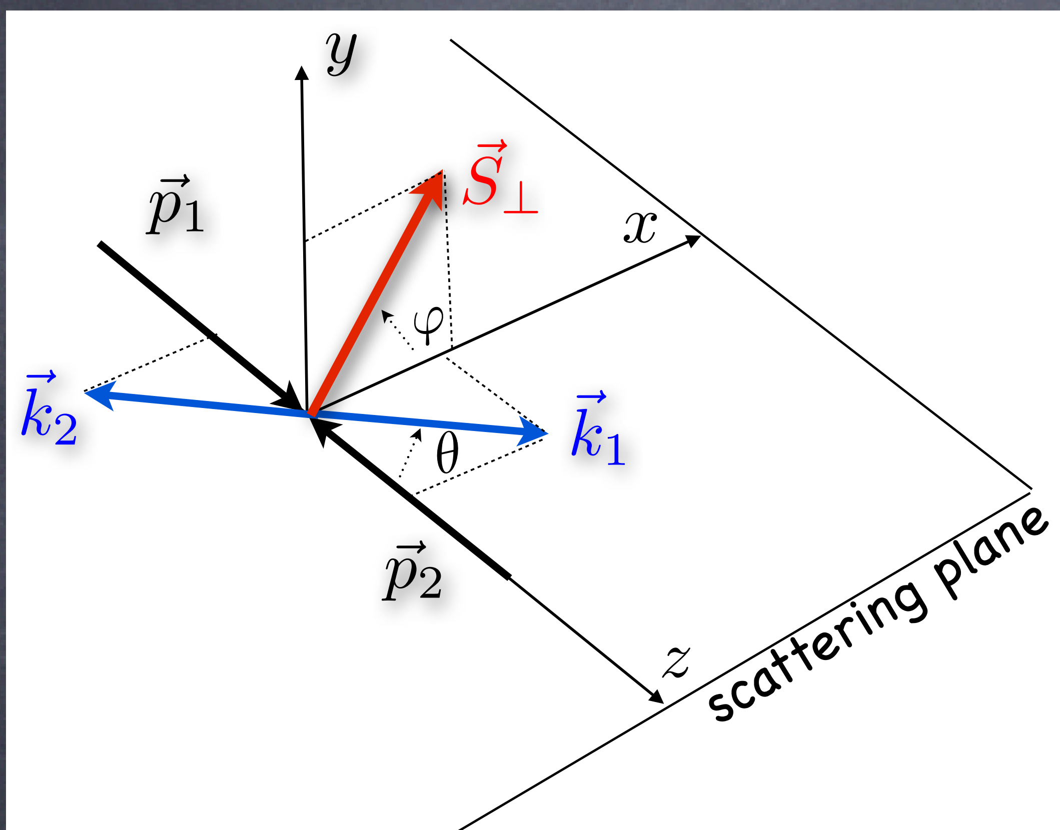
Dispersion relation

Dispersion relation

- Causality: effect cannot exceed cause (Titchmarsh theorem)
- analyticity of G_E and G_M over complex q^2 plane (application of Cauchy integral with multiple cuts)
- Causality vs. analyticity
- c.f. Simone Pacetti recent talk

Picture from S. Pacetti

Polarization: complete measurement of time-like FFs



Px: perpendicular to beam
(inside scattering plane)

Py: normal to scattering plane

Pz: beam direction

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

perpendicular to scattering plane, either target or outgoing baryon

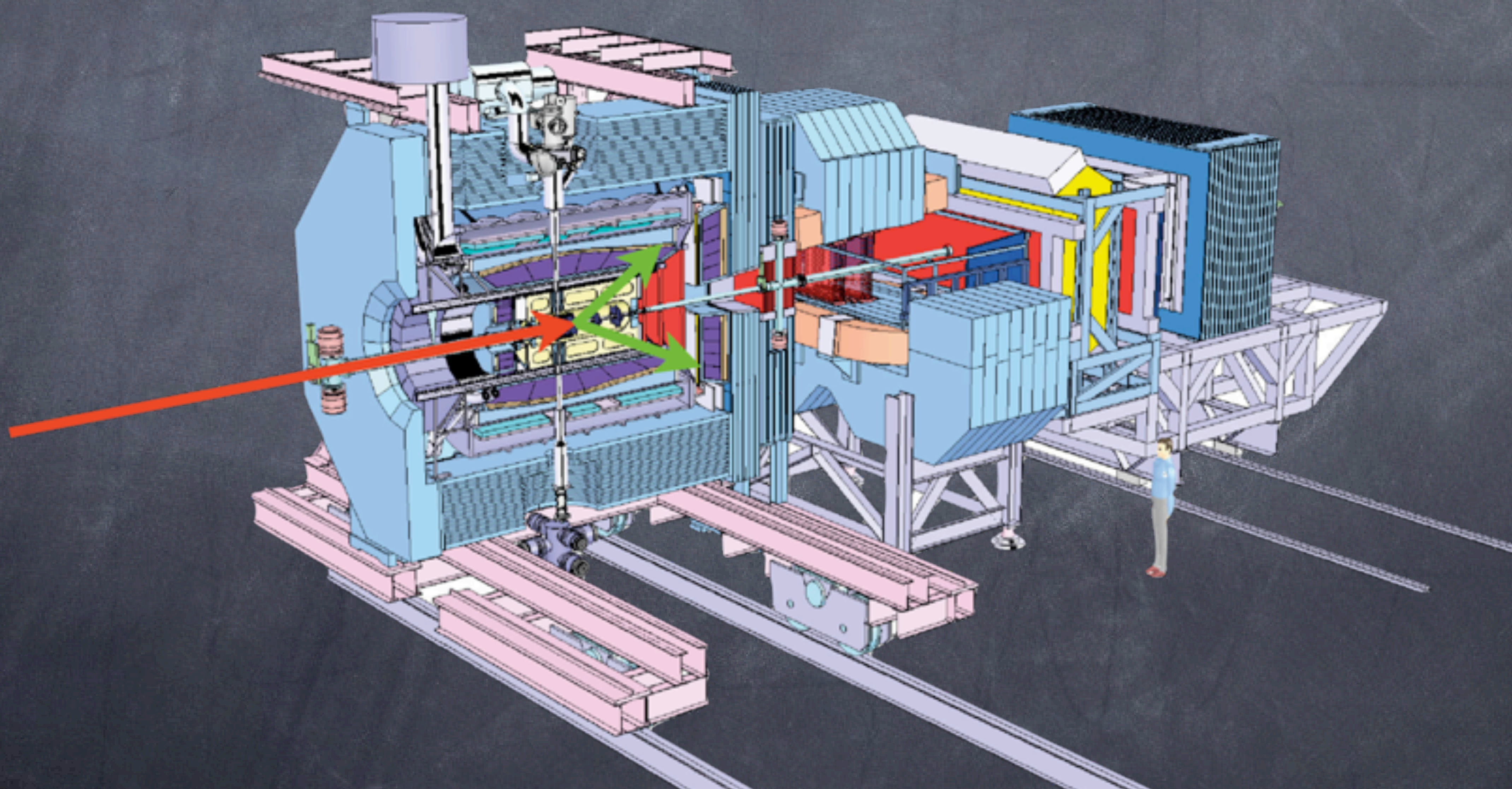
$$P_{zx} = P_{xz} \propto \frac{1}{\sqrt{\tau}} sin 2\theta Re G_E G_M^*$$

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)

Experimental aspects

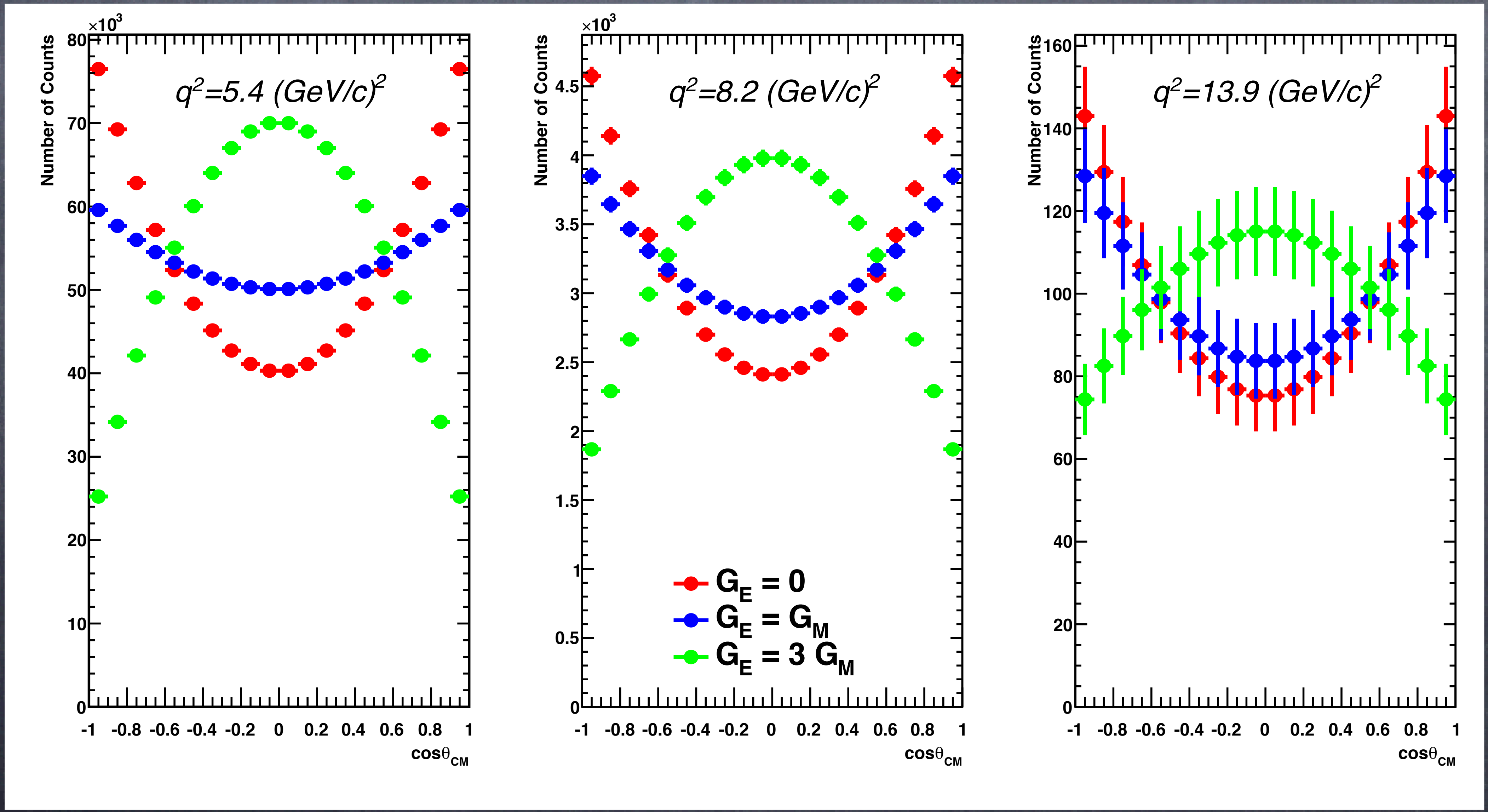
- Good tracking capability;
- High luminosity $L=1.6\times10^{32}cm^{-2}s^{-1}$;
- Wide momentum range: 1.5 GeV/c ~ 15 GeV/c



pbar p -> e+ e-

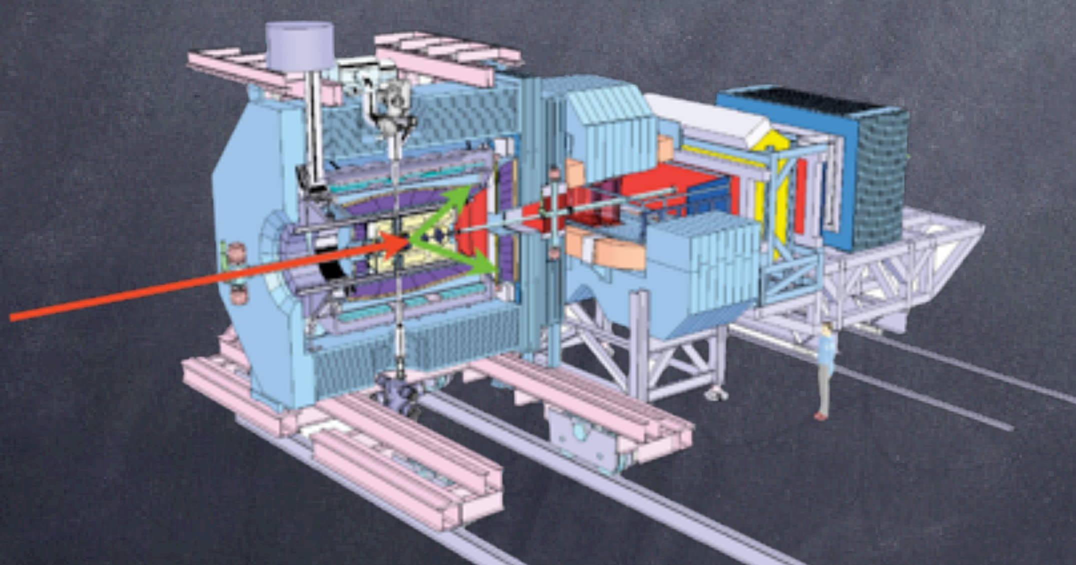
Rosenbluth cross section

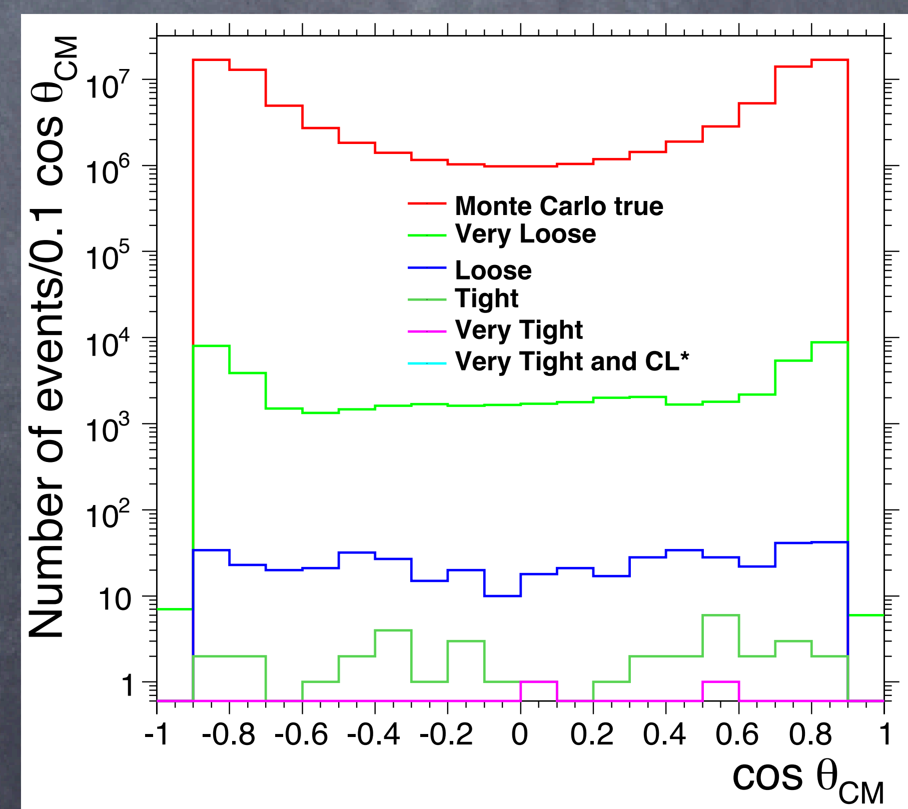
$$\frac{d\sigma}{dcos\theta} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[|G_M|^2\left(1+cos^2\theta\right) + \frac{|G_E|^2}{\tau}(1-cos^2\theta)\right], \quad \tau = \frac{-q^2}{4M^2}$$



pbar p -> e+ e-

- Simulation done by Mainz and Orsay groups:
  - 100 CPUs in Orsay,
  - 300 CPUs Lyon
  - 200 CPUs at GSI
- event generator (M. Zambrana)
- pi+pi- background suppression (D. Khaneft)





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

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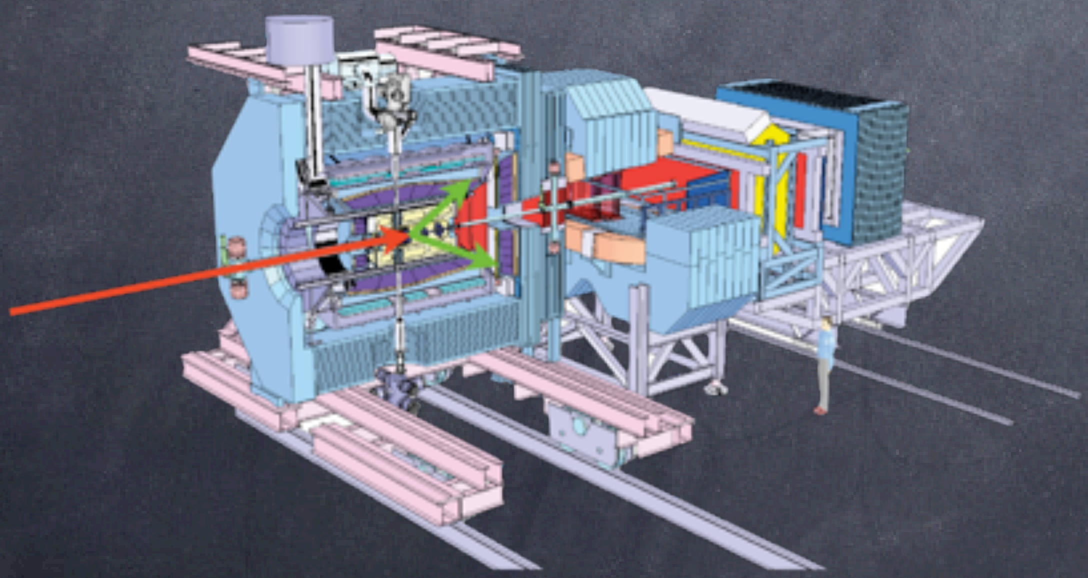

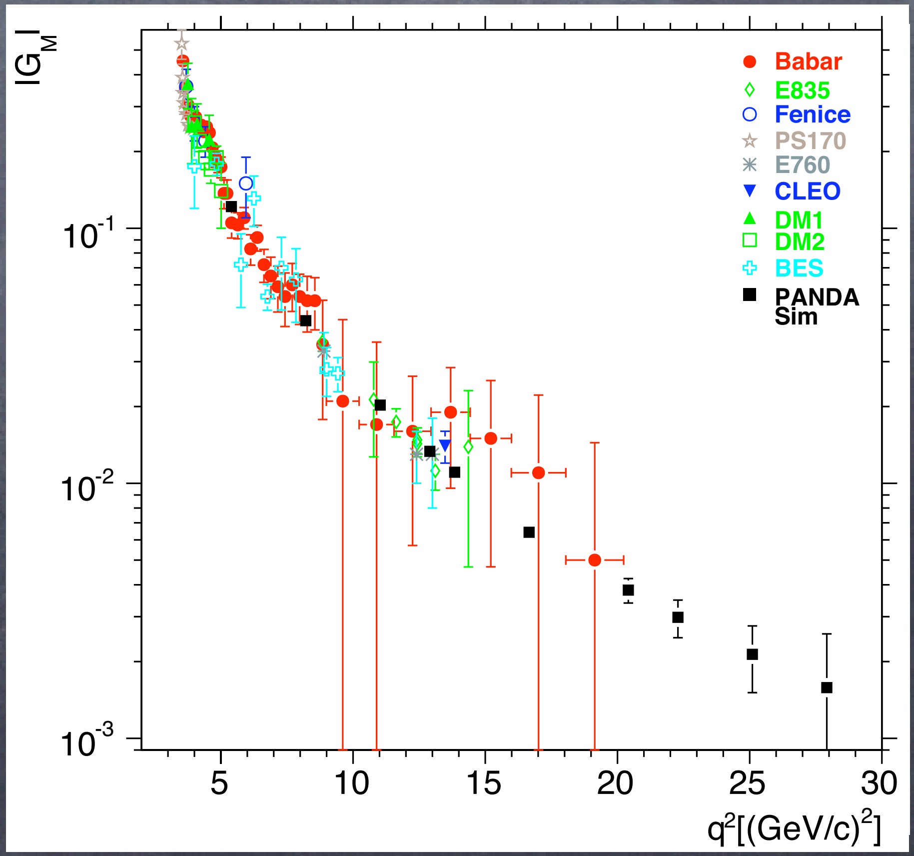

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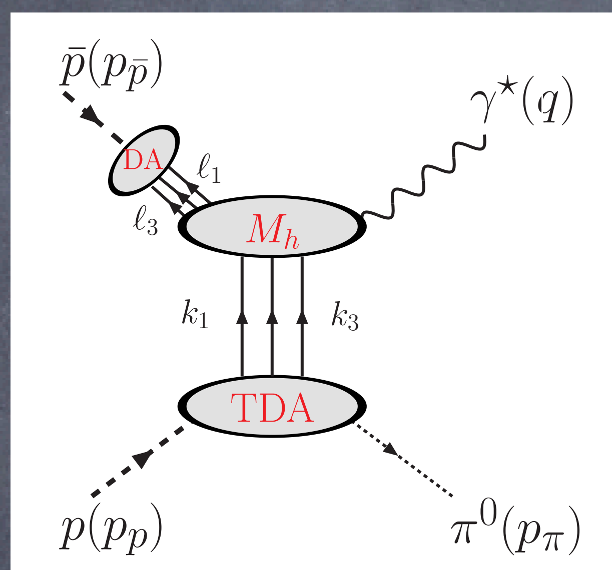
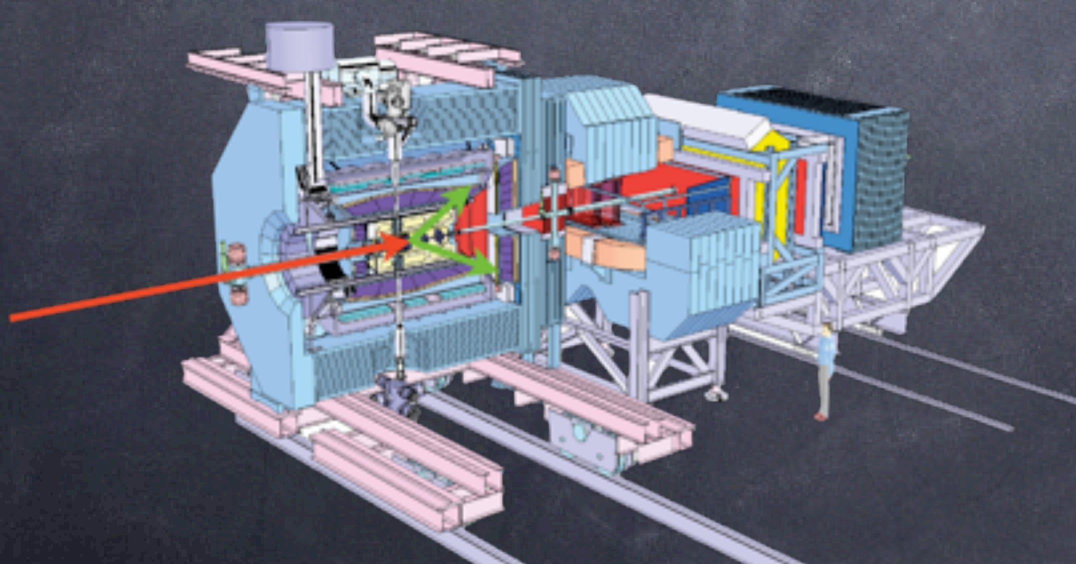
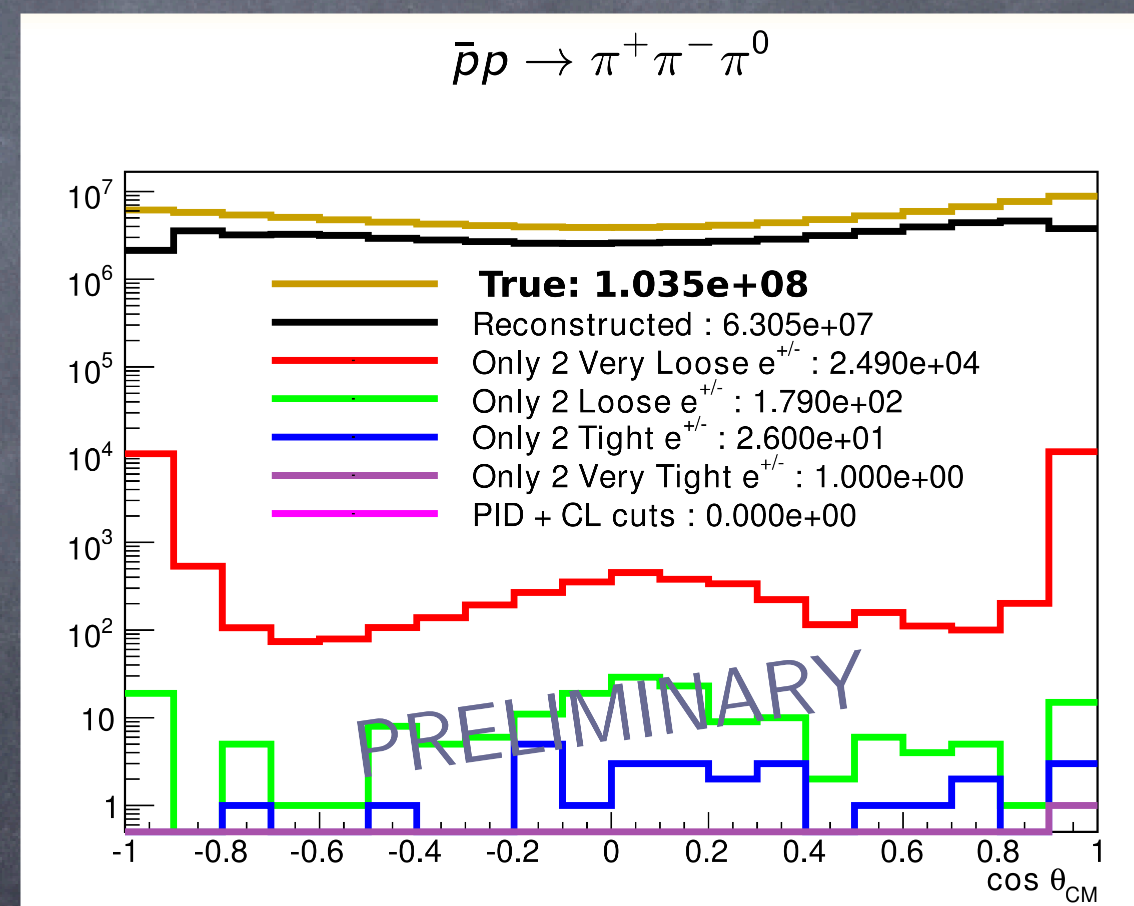
Transition Distribution Amplitude

- Feasibility study by M. Mora Espi (PhD candidate)

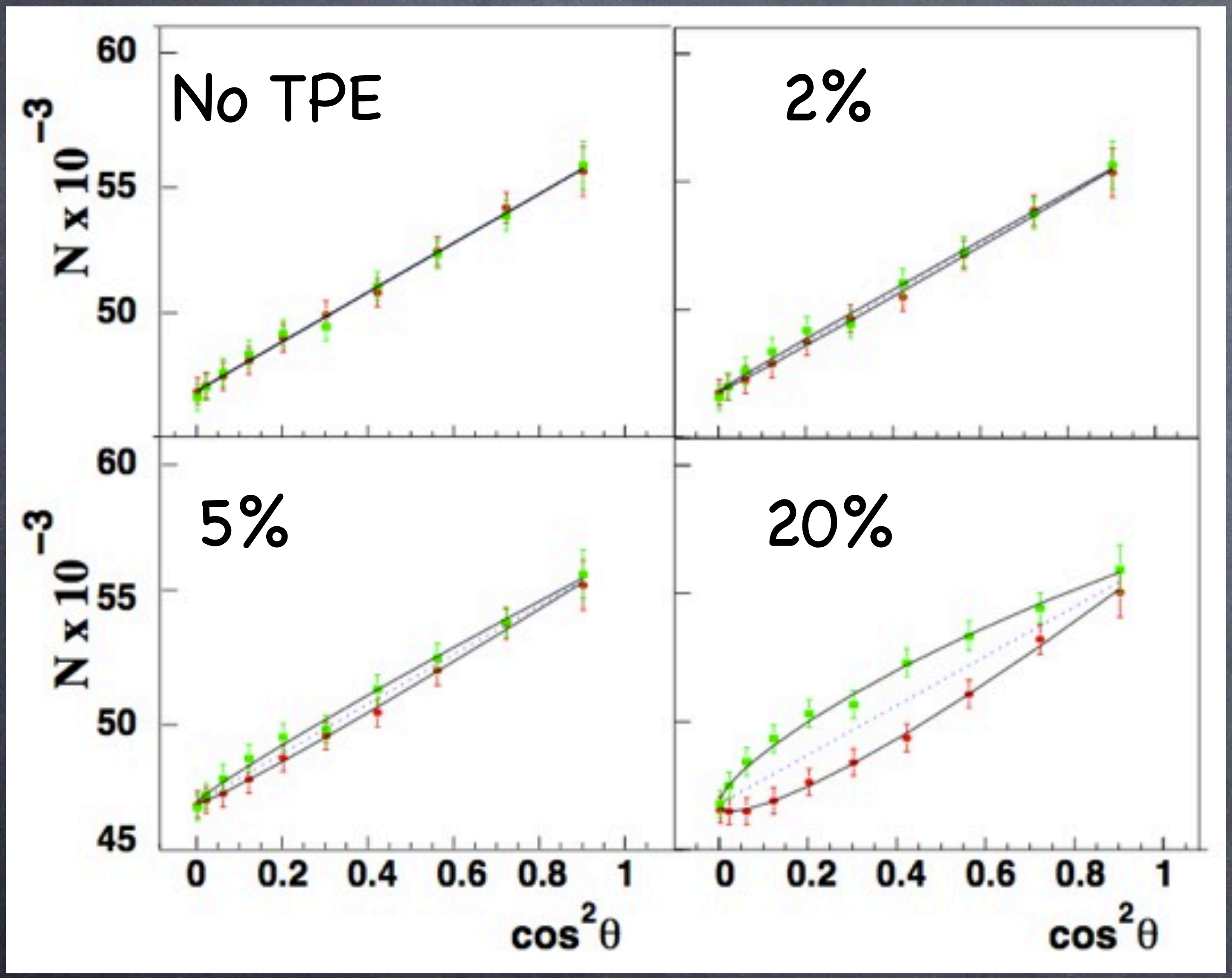






PANDA experiment at FAIR:

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

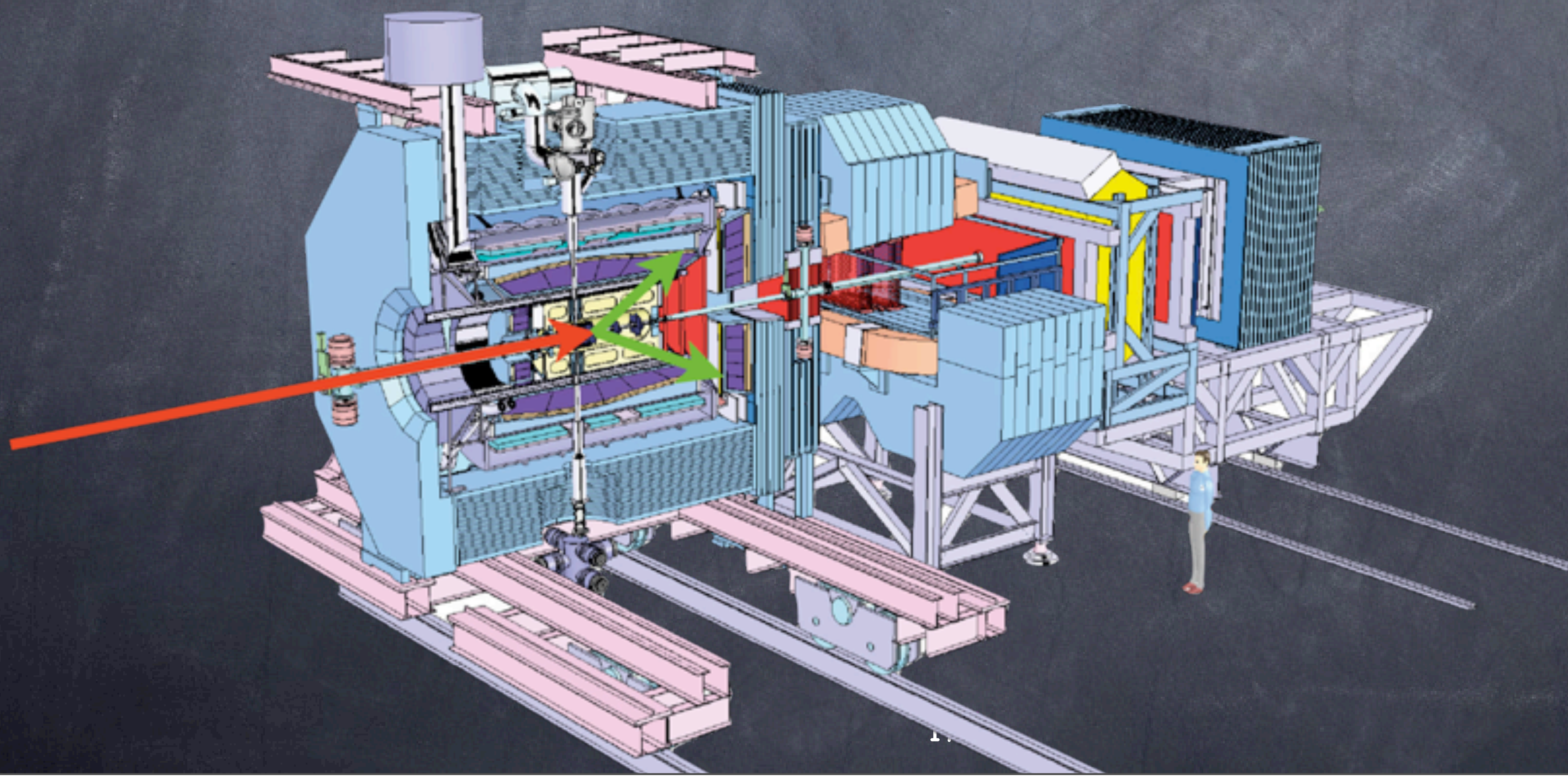
backward lepton

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

Is PANDA polarizable?

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

- Innovative R&D by B. Feher (PhD candidate)
- Close collaboration with experts from Mainz and IHEP.



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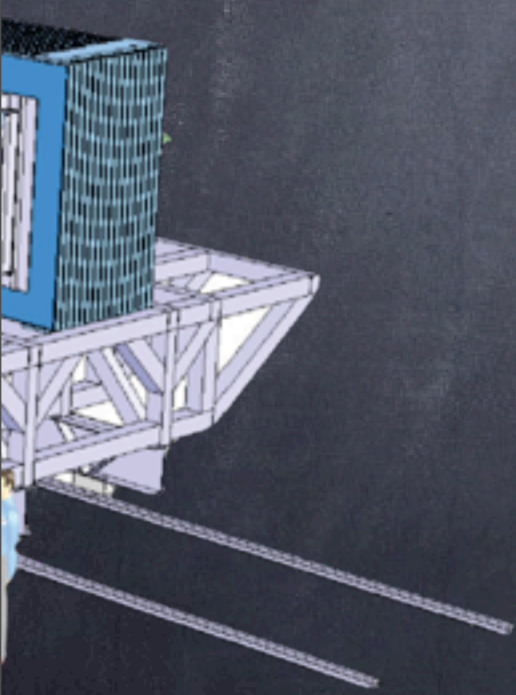

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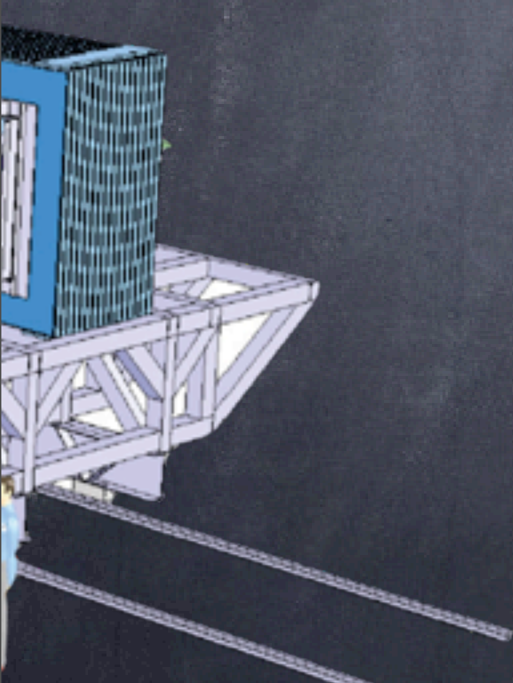
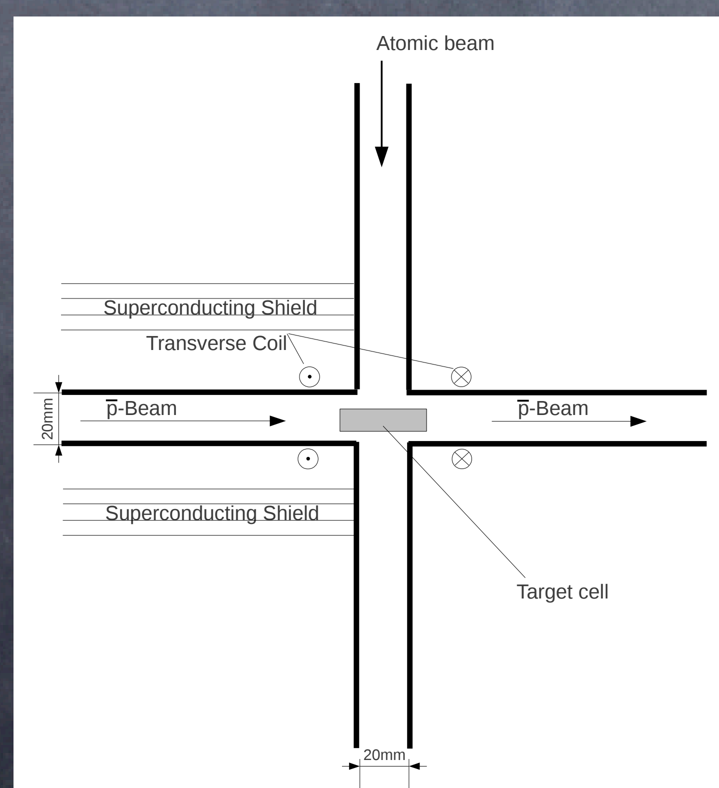
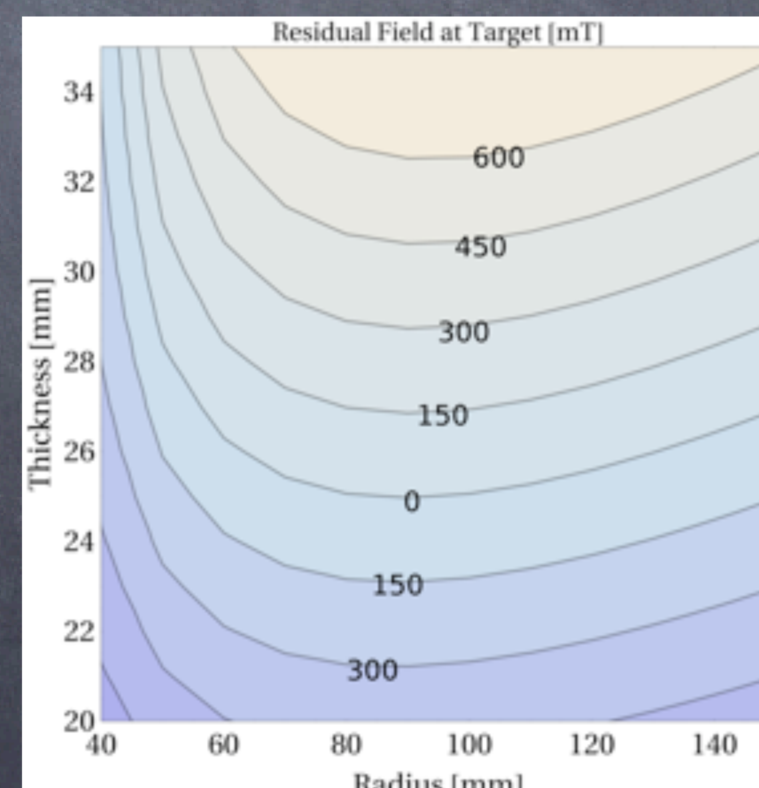
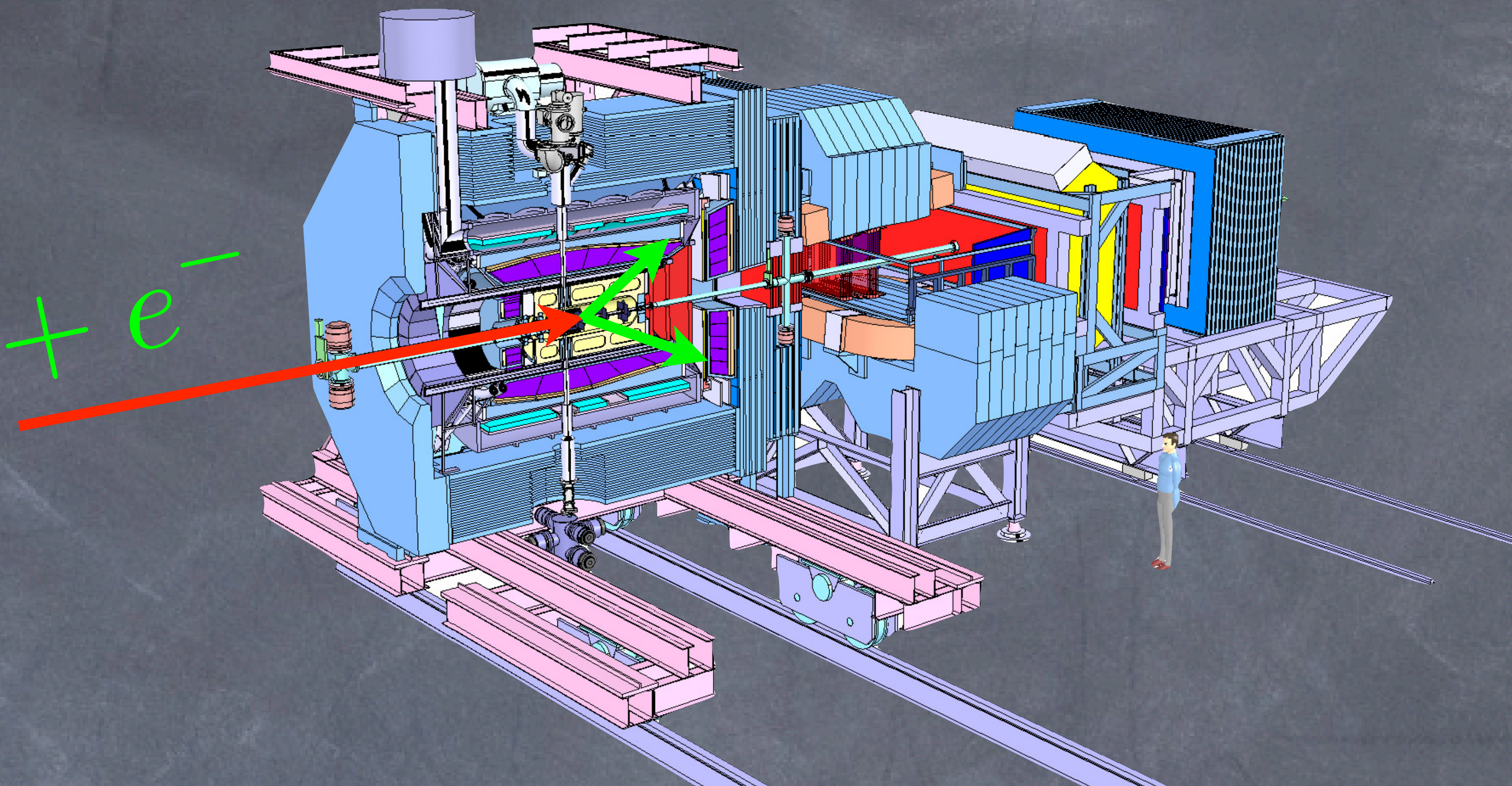




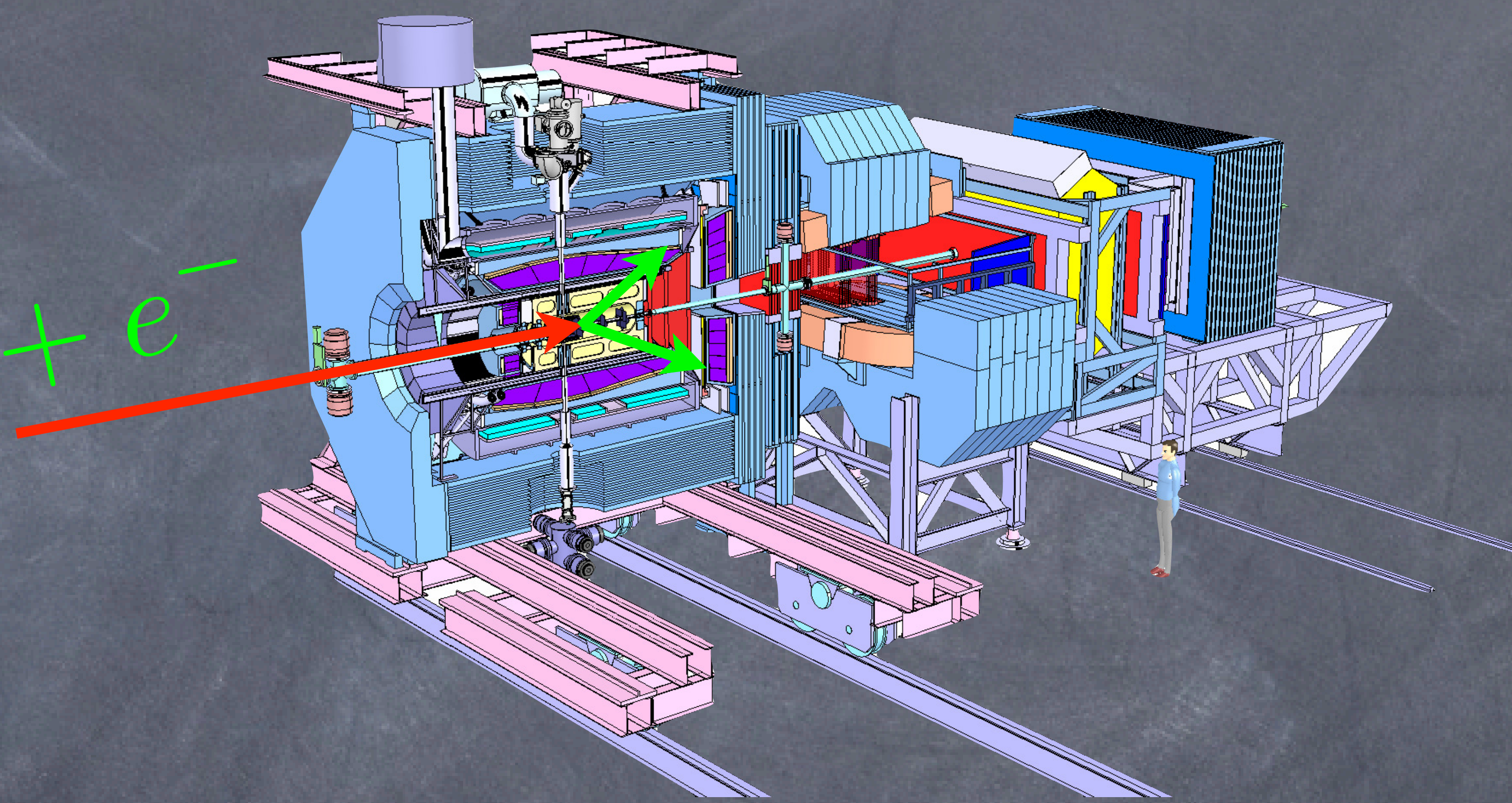


$$\bar{p} + p \rightarrow e^+ + e^-$$



- Essentially improve data in TL region
- Possibility to measure relative phase (G_E, G_M)
- Determine contribution of TPE
- Other interesting EM processes

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



The end

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