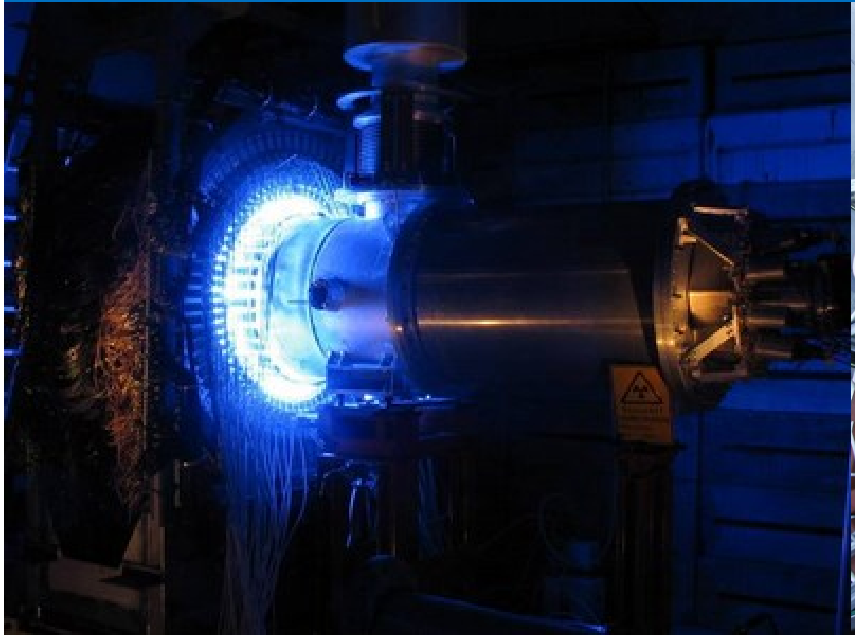
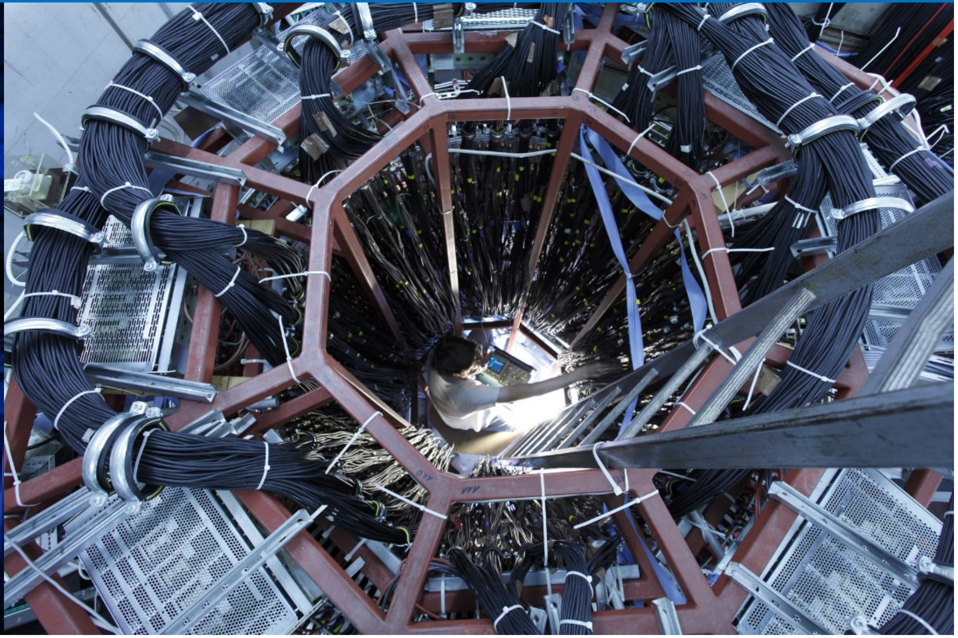
Study of Two-Photon Exchange From MAMI-A4 to PANDA

Boxing Gou for the A4 Collaboration

PANDA Collaboration Meeting 20/1, GSI, Darmstadt, Germany, March 9-13, 2020



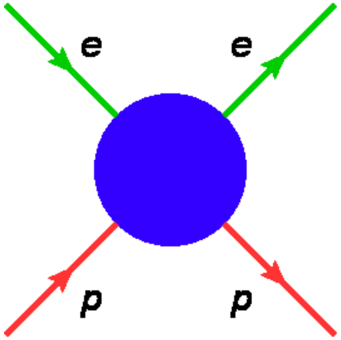


Outline

- Proton form factor puzzle and two-photon exchange (TPE)
- How to investigate TPE
- TPE program at MAMI-A4
- Opportunities to study TPE at PANDA

Proton form factors

Generalized form factors

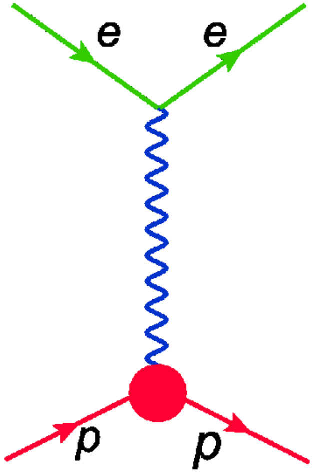


Elastic scattering of two spin-1/2 particles can be described by 6 amplitudes (form factors).

$$\tilde{F}_1, \tilde{F}_2, \tilde{F}_3, \tilde{F}_4, \tilde{F}_5, \tilde{F}_6$$

- Small coupling (1/137) -> small higher order contributions
- One-photon exchange approximation are regareded as sufficient

Form factors in Born approximation



$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

Form factors

- Dirac (F1) and Pauli (F2) form factors represent the helicity conserving and flip processes respectively
- Sachs form factors (G_E, G_M) describe the charge and magnetization distributions

Methods for form factor measurement

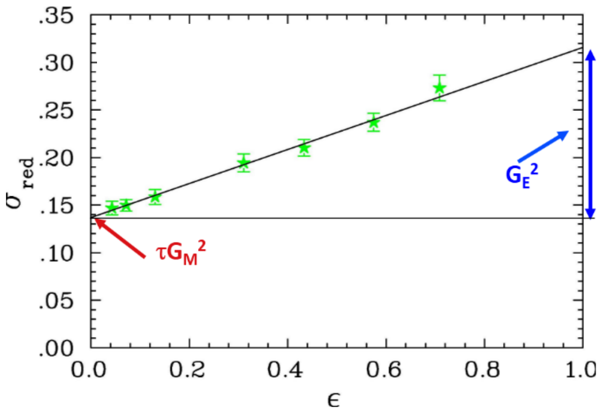
Rosenbluth separation

$$\frac{d\sigma}{d\Omega}=\left(\frac{\alpha}{4MQ^2}\frac{E'}{E}\right)^2|\mathcal{M}_\gamma|^2=\frac{\sigma_{Mott}}{\epsilon(1+\tau)}\sigma_R$$

$$\sigma_{Mott}=\frac{\alpha^2E'\cos^2\frac{\theta_e}{2}}{4E^3\sin^4\frac{\theta_e}{2}}$$ (Point-like)

$$\tau=\frac{Q^2}{4M^2}\qquad \varepsilon=\left[1+2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

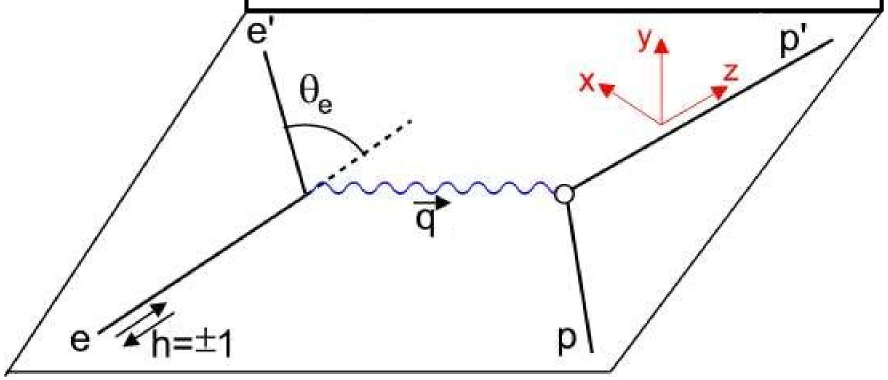
$$\sigma_R=\varepsilon G_E^2(Q^2)+\tau G_M^2(Q^2)$$



- FFs extracted as intercept and slope
- The signs of the FFs can not be determined
- At large Q^2, uncertainty of G_E gets larger

Spin-transfer method

Spin transfer reaction: $\vec{e}p \to e\vec{p}$



Phys. Rev. C 23, 363 (1981)

$$I_0P_x=-2\sqrt{\tau(1+\tau)}G_EG_M\tan\frac{\theta_e}{2}$$

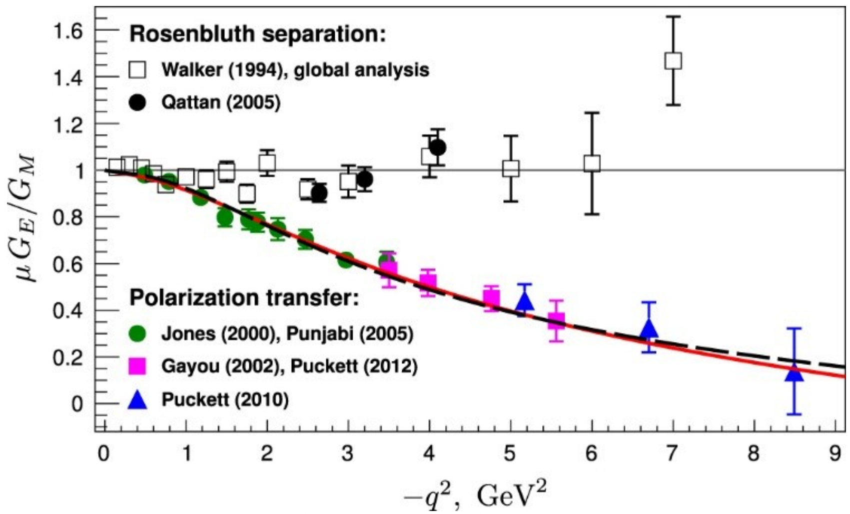
$$P_y=0$$

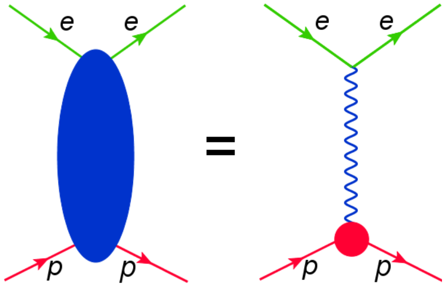
$$I_0P_z=\frac{E_0+E'}{M}\sqrt{\tau(1+\tau)}G_M^2\tan\frac{\theta_e}{2}$$

$$I_0=G_E^2(Q^2)+\frac{\tau}{\varepsilon}G_M^2(Q^2)$$

$$\frac{G_E}{G_M}=-\frac{P_t}{P_l}\frac{E_0+E'}{M}\tan\frac{\theta_e}{2}$$

Proton form factor puzzle





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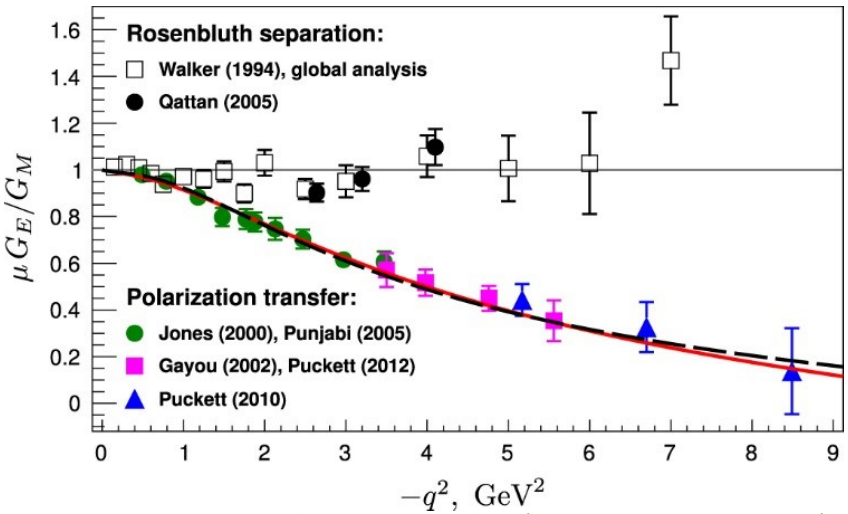
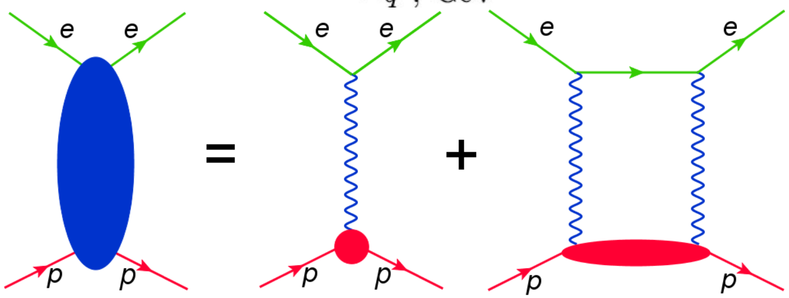
- Failure of the Born approximation in electron scattering .

Proton form factor puzzle





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- A two-photon exchange (TPE) correction could explain the discrepancy.
  Phys. Rev. Lett. 91 (2003) 142303
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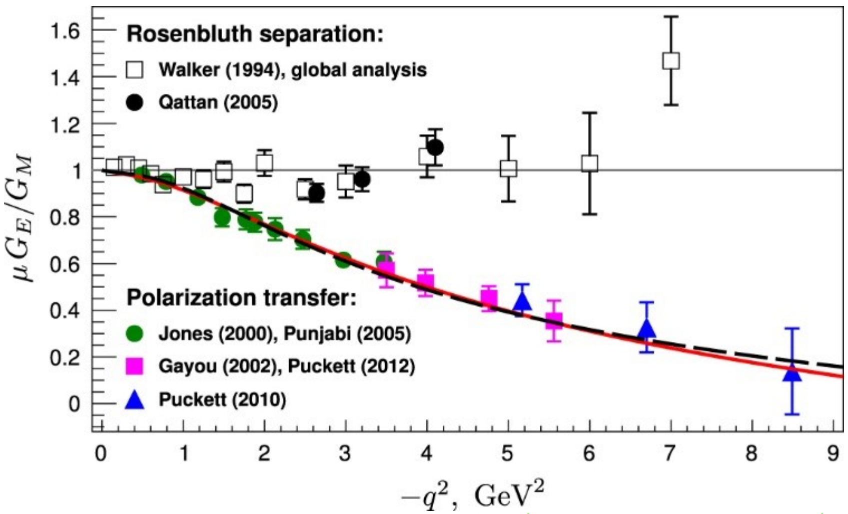
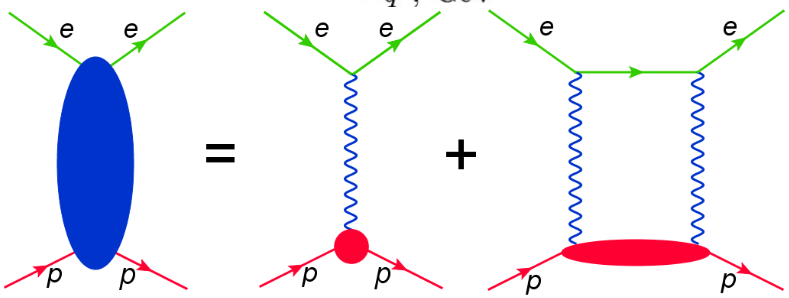
Proton form factor puzzle





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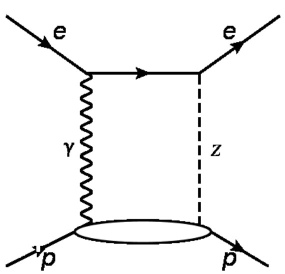
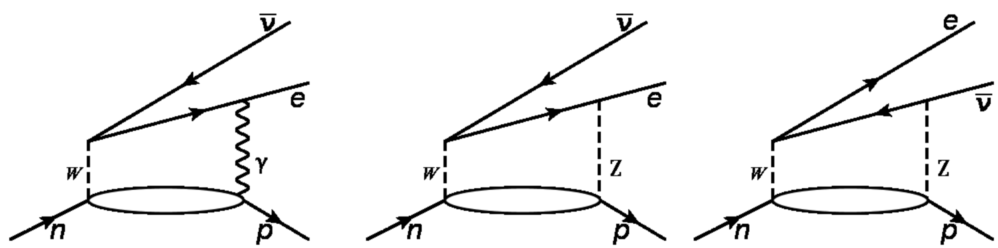
An understanding of TBE exchange is essential for other high-precision measurements

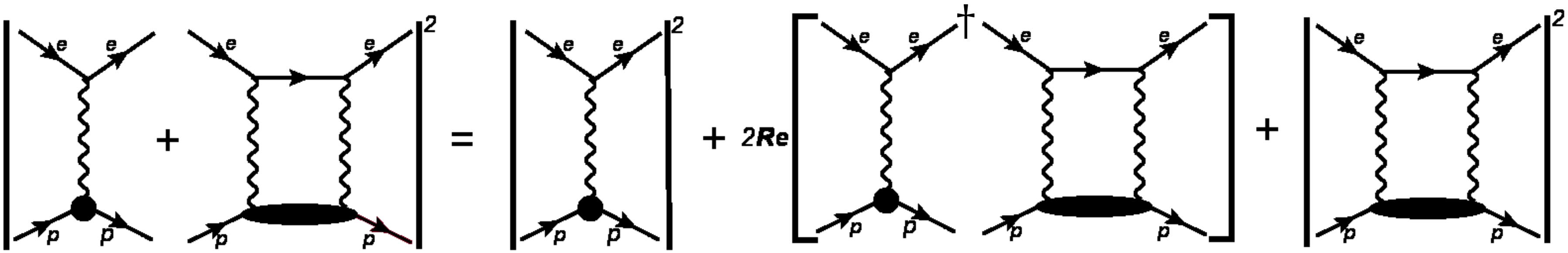
$\boldsymbol{\theta_w}$



V_{ud}



How to study TPE? Charge asymmetry

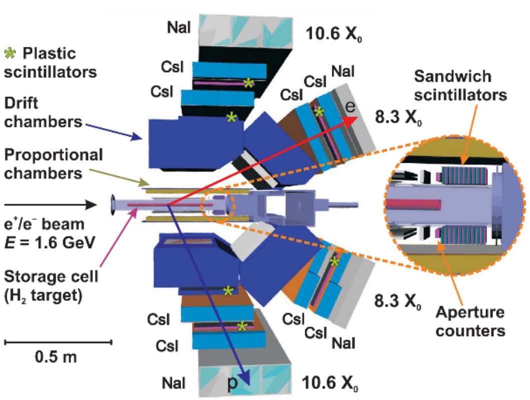


q_e q_e^2 q_e^2 q_e^3 q_e^4

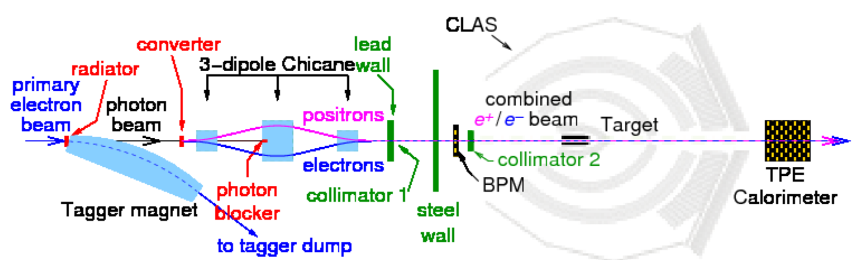
$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + \frac{4Re\left(\mathcal{M}_\gamma^\dagger \mathcal{M}_{2\gamma}\right)}{\left|\mathcal{M}_\gamma\right|^2}$$

Real parts of $\tilde{F}_1, \tilde{F}_2, \tilde{F}_3$

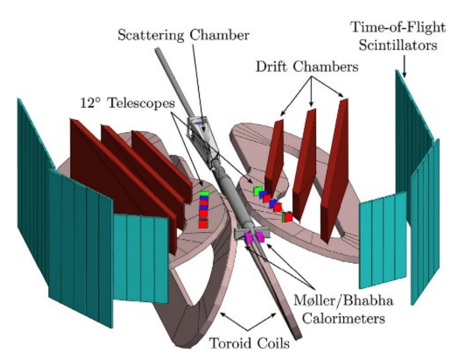
VEPP-3@Novosibirsk



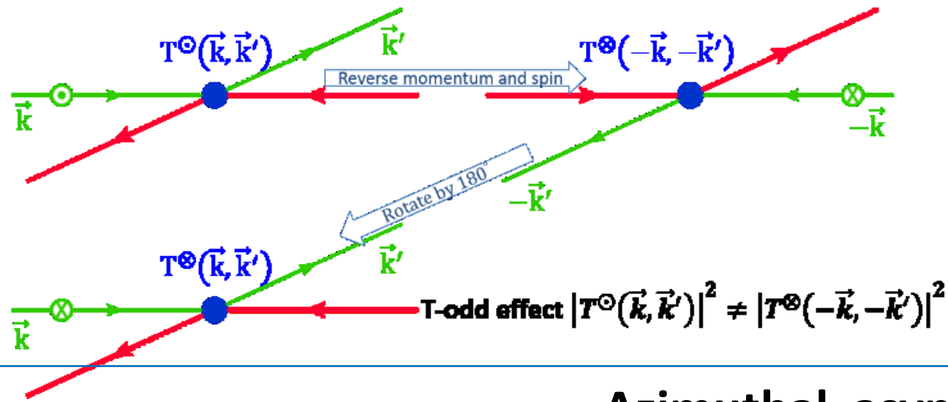
CLAS@JLAB

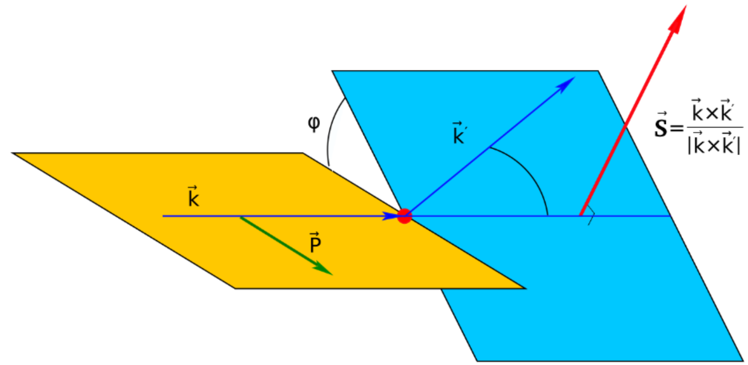


OLYMPUS@DESY



How to study TPE? Transverse spin asymmetry





Azimuthal asymmetry

$$A_{exp} = \frac{\sigma^{\odot} - \sigma^{\otimes}}{\sigma^{\odot} + \sigma^{\otimes}} = A_{\perp} \frac{\vec{s} \cdot \vec{p}}{|\vec{s}||\vec{p}|} = -A_{\perp} \cos\varphi$$

$$A_{\perp} \propto \frac{Im\left(\mathcal{M}_{\gamma}^{*} \mathcal{M}_{2\gamma}\right)}{\left|\mathcal{M}_{\gamma}\right|^{2}}$$

Nucl. Phys. B 35 (1971) 365.

Target Spin Asymmetry in $e\vec{N} \to eN$

- Imaginary parts of $\tilde{F}_1, \tilde{F}_2, \tilde{F}_3$
- $A_{\perp} \sim \alpha \sim 10^{-2}$
- HallA@JLab (pol. ^{3}He target)

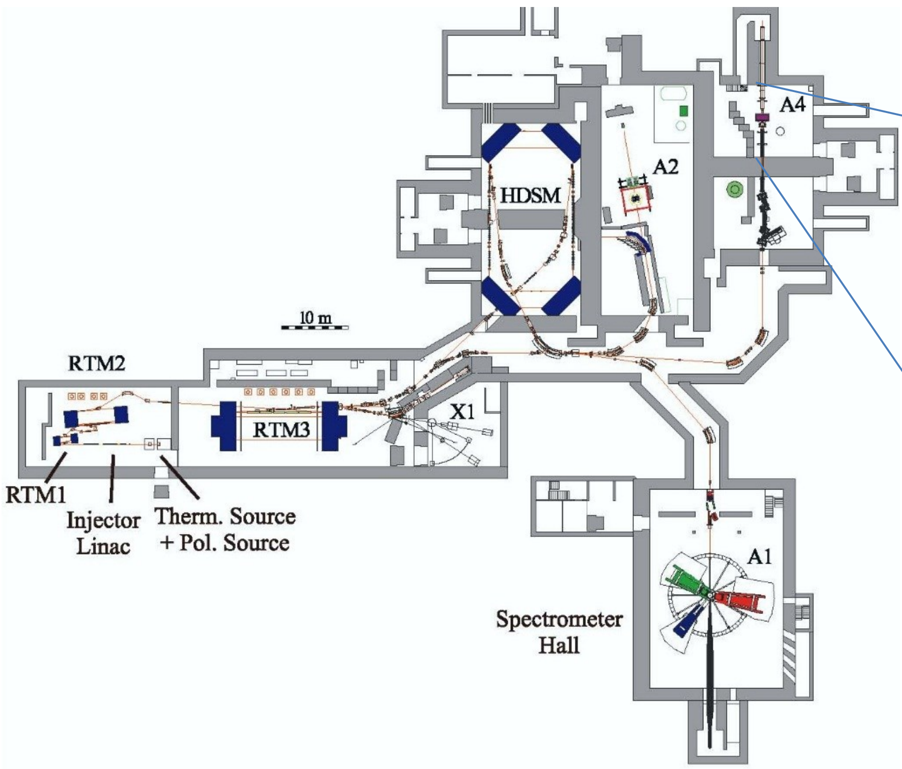
Beam Spin Asymmetry in $\vec{e}N \to eN$

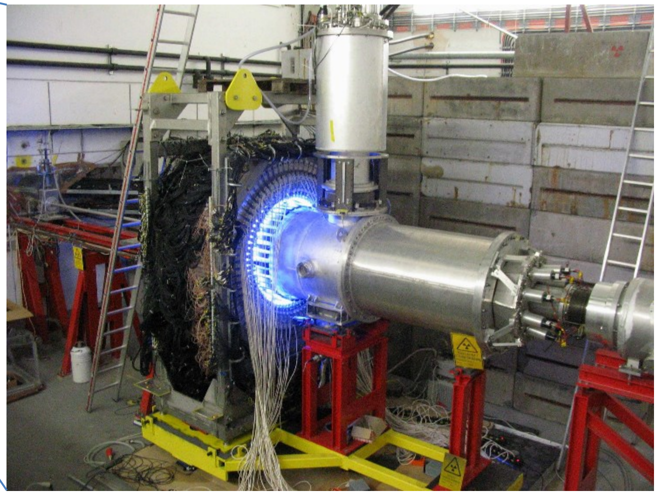
- Imaginary parts of $\tilde{F}_3, \tilde{F}_4, \tilde{F}_5$
- $A_{\perp} \sim \alpha \cdot \frac{m_e}{E} \sim 10^{-5} - 10^{-6}$
- SAMPLE@MIT-Bates
- HAPPEX, G0, Q_{weak} @JLab
- A4@MAMI

MAMI

Mainz Microtron (MAMI)

- Electron beam: 0.2 – 1.5 GeV, current ~ 20 μA
- Circularly polarized laser on GaAs → **longitudinally** polarized electrons
- Wien filter **+** procession in micrtrons → **longitudinal / transverse**
- Pol. state reverses every 20 ms, flip pattern follows either ↑↓↓↑ or ↓↑↑↓
- Energy, current, position and angle are stabilized and monitored

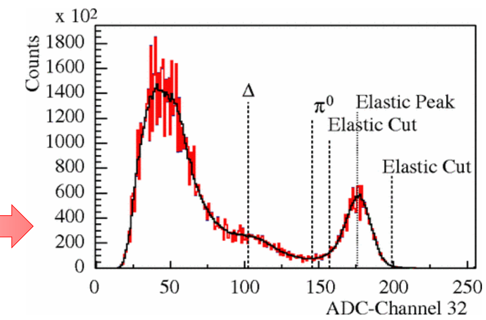




A4 experiment

Electromagnetic calorimeter

- 1022 PbF_2 crystals, 7 rings x 146 frames → φ: $(0,\ 2\pi)$
- Pure Cherenkov → fast response (20 ns)
- Read out: sum of 3x3 crystals. $\Delta E/E \approx 3.9\%/\sqrt{E[GeV]}$

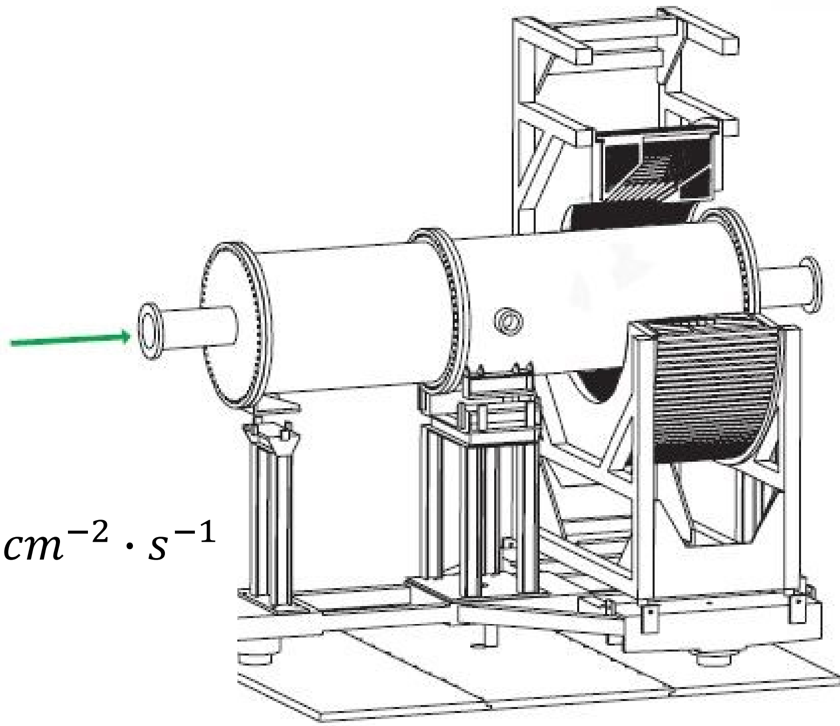


High power liquid target

- Hydrogen
- Deuterium

Rotatable platform

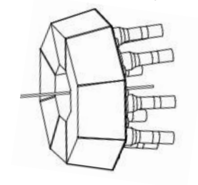
- Forward
  θ: $30^{\circ} - 40^{\circ}$
  L = 10 cm, $\mathcal{L} = 0.5 \times 10^{38} cm^{-2} \cdot s^{-1}$



Luminosity monitor

8 water Cherenkov counters

$(4.4^{\circ} - 10^{\circ})$



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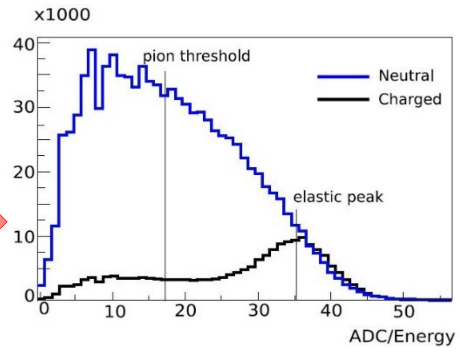

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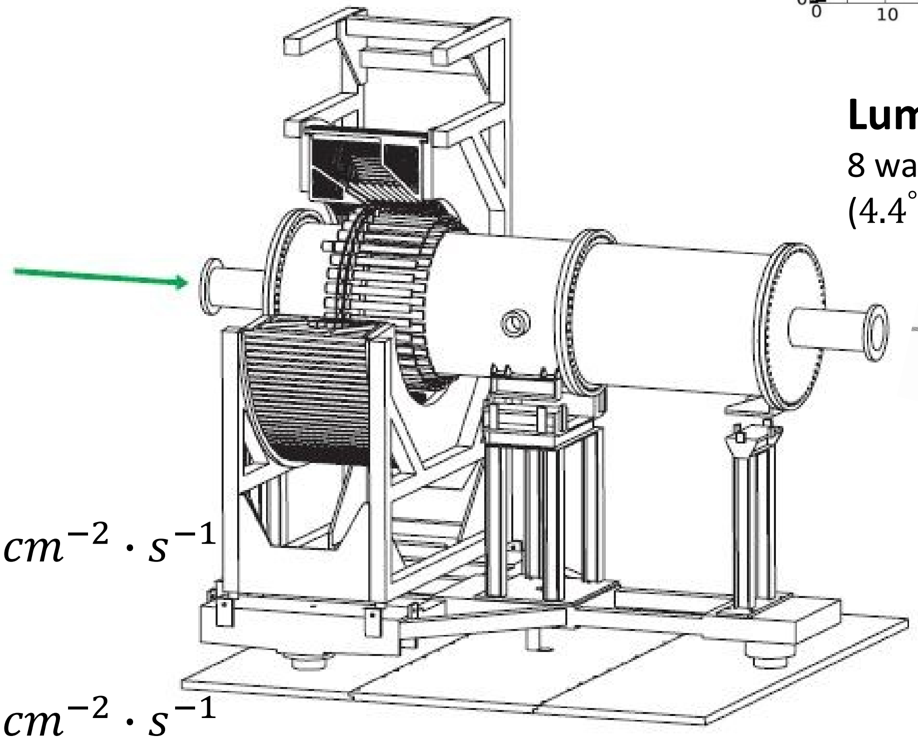

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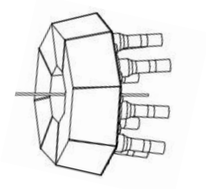

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- Forward

  θ: $30^{\circ} - 40^{\circ}$

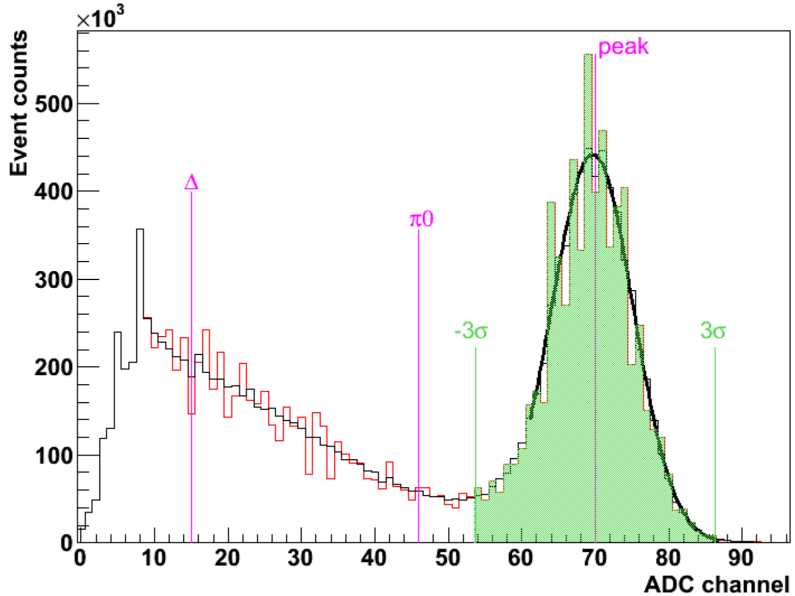
  L = 10 cm, $\mathcal{L} = 0.5 \times 10^{38} cm^{-2} \cdot s^{-1}$
- Backward

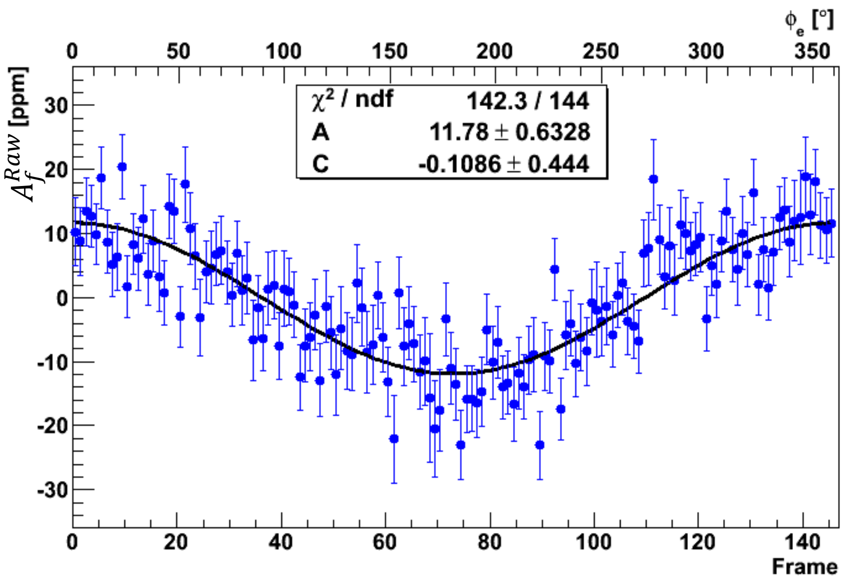
  θ: $140^{\circ} - 150^{\circ}$

  L = 23 cm, $\mathcal{L} = 1.2 \times 10^{38} cm^{-2} \cdot s^{-1}$

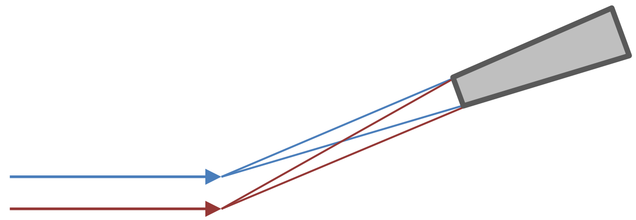
  Plastic scintillator to veto γ

Asymmetry extraction





- Integrate spectra under elastic peak -> $N^{\uparrow}(N^{\downarrow})$
- Raw asymmetry for each frame $A_f^{Raw} = \frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$
- Correct helicity related false aymmetry $A_f^{Raw} \rightarrow A_f$



False asymmetry caused by difference in

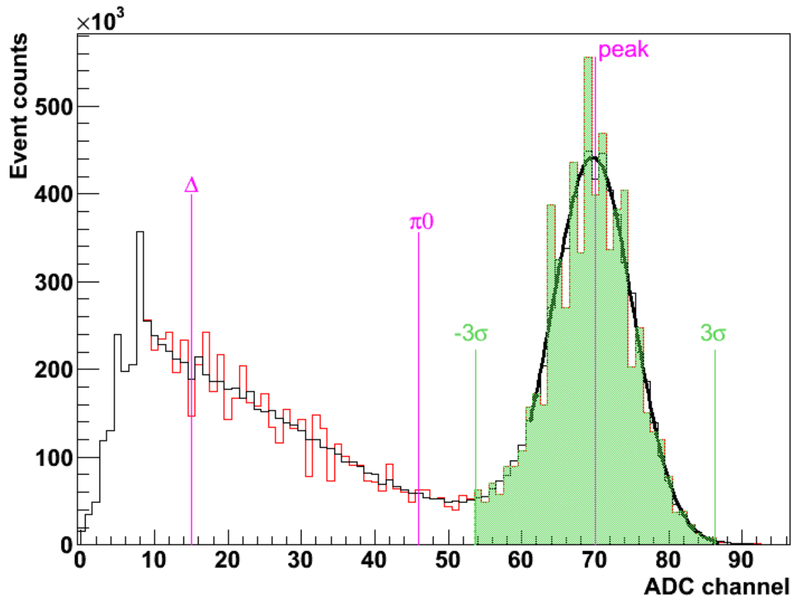
- Beam position $(\Delta X, \quad \Delta Y)$
- Beam angle $(\Delta X', \Delta Y')$
- Beam current ΔI
- Beam energy ΔE

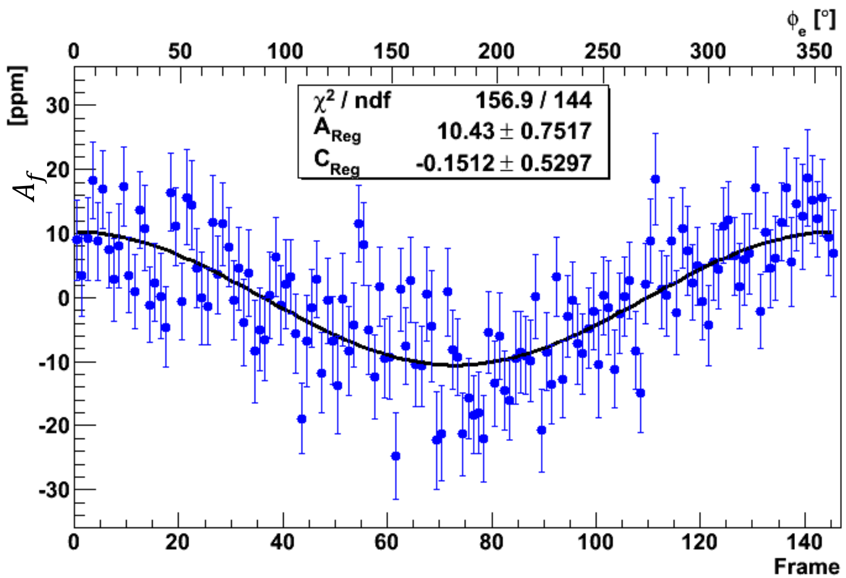
Corrected via regression analyses

$$A_{exp} = P \cdot A_{phy} + \sum_{i=1}^{6} a_i X_i$$

- Fit A_f by $A_f = A \cos\left[\frac{2\pi}{146} \cdot (f - 0.5)\right] + C$

Asymmetry extraction





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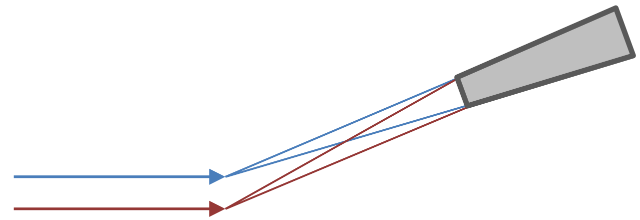

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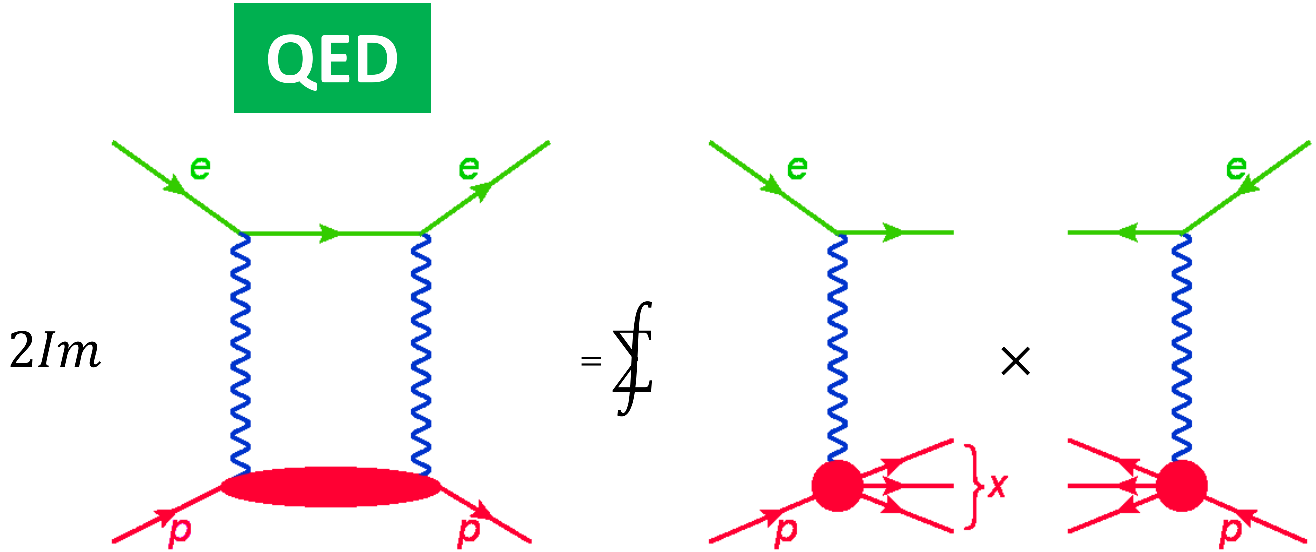
Asymmetry calculation



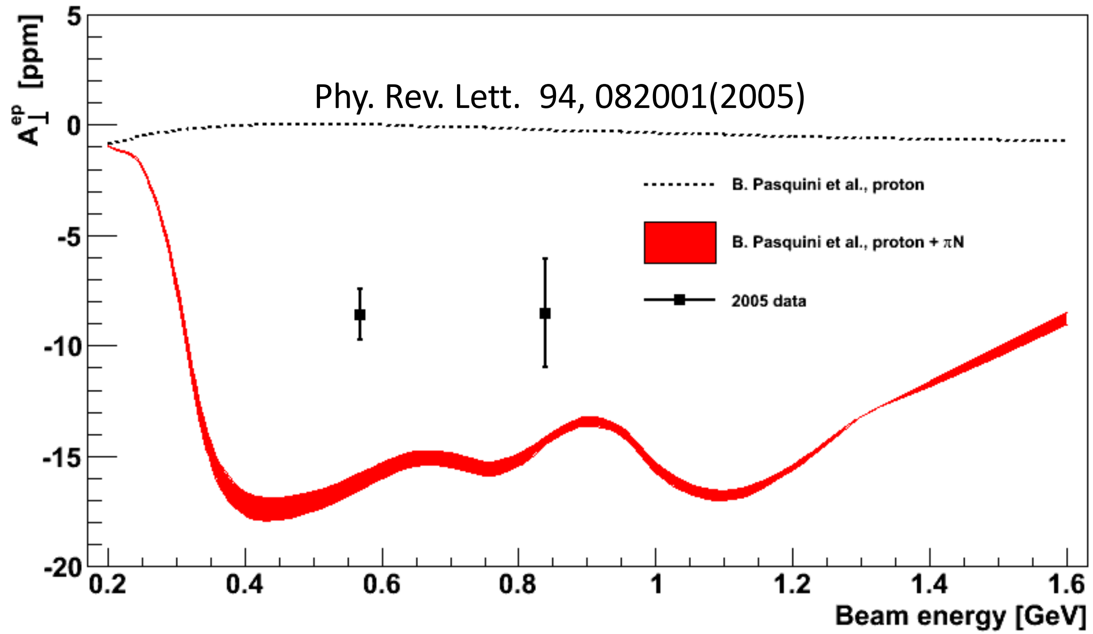
Calculation based on unitarity by B. Pasquini and M. Vanderhaeghen
Phy. Rev. C 70, 045206(2004)

Ground proton state
G_E and G_M as input

πN intermediate states
Take $\gamma^* N \to \pi N$ amplitudes
from MAID 2007 as input

A4 results: 2005

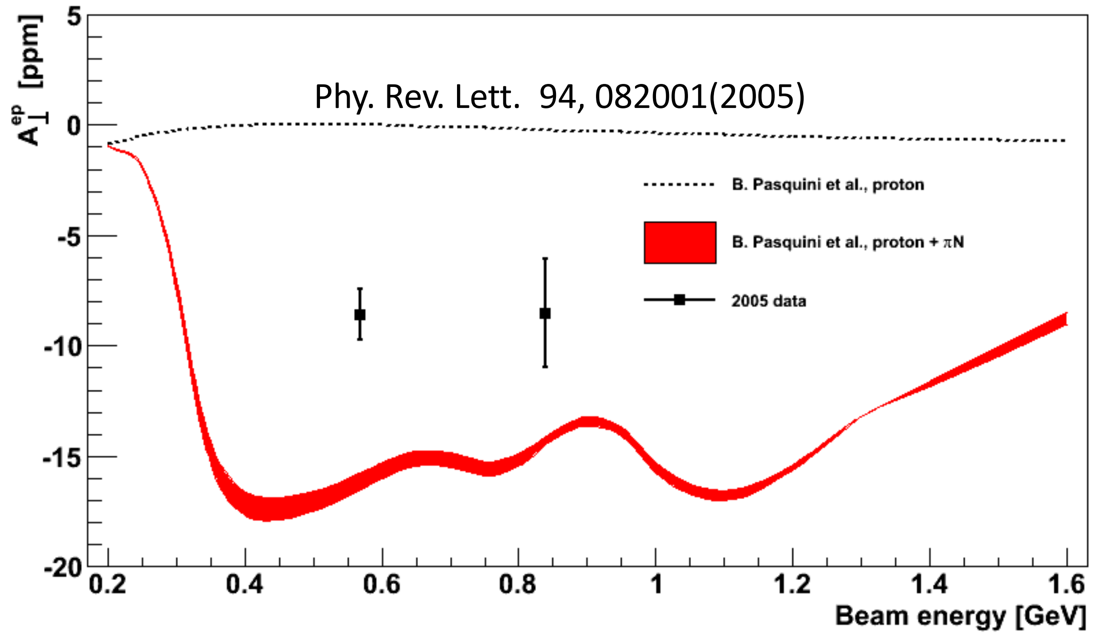
Kinematics	Energy & Target
Forward	Hydrogen
	570
	855



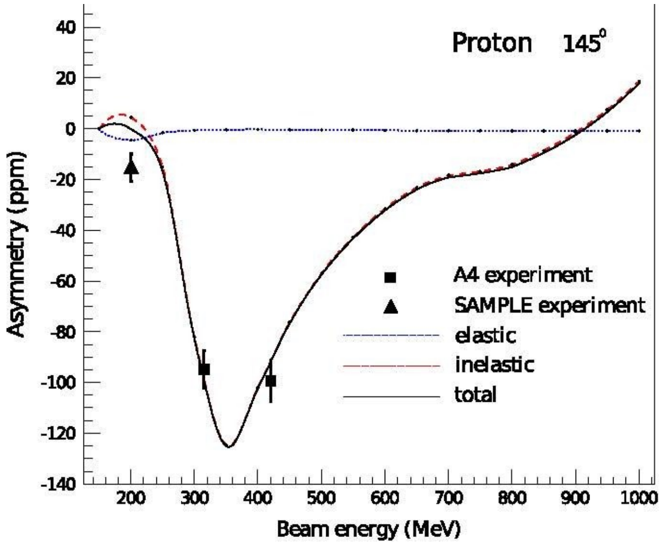
- Significant inelastic contribution

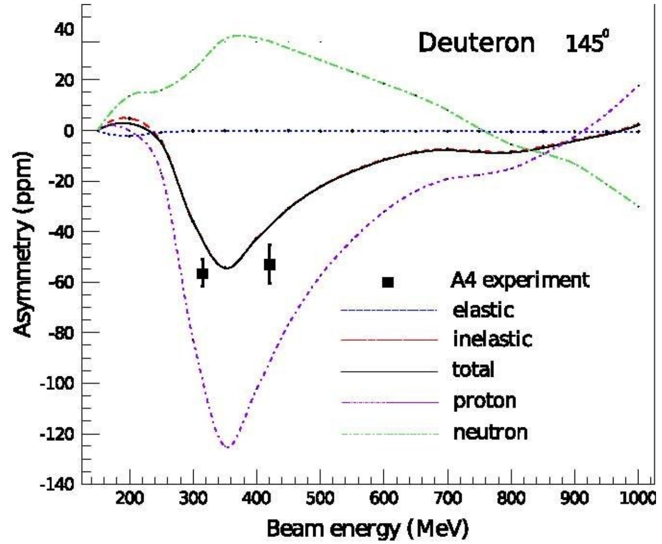
A4 results: 2005 ---> 2017

Kinematics	Energy & Target	
Forward	Hydrogen	
	570	
	855	
Backward	Hydrogen	Deuterium
	315	315
	420	420



Phy. Rev. Lett. 119, 012501(2017)

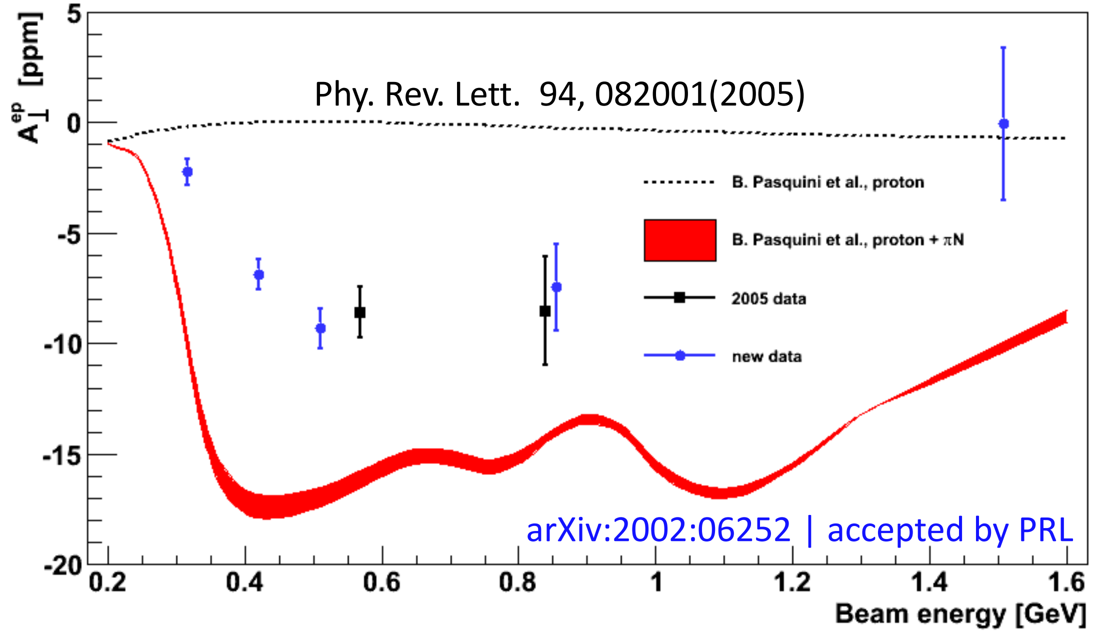




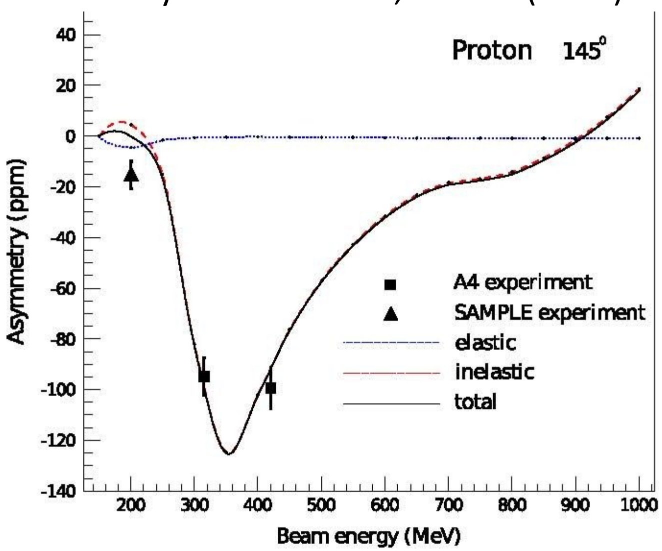
- Significant inelastic contribution
- Backward data agree well with the theory

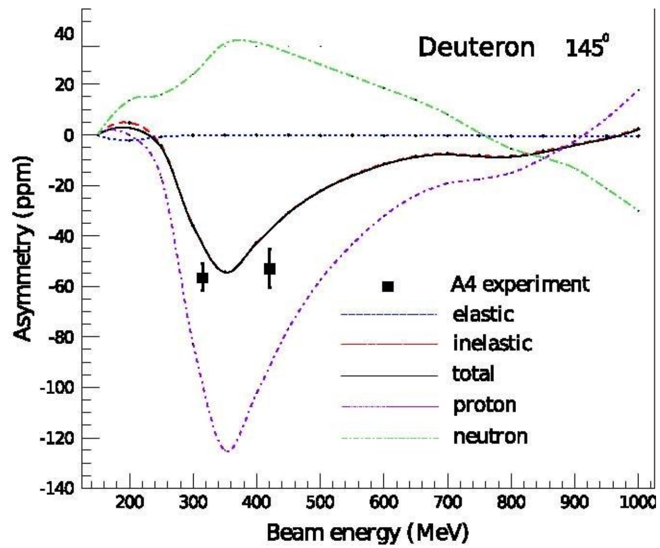
A4 results: 2005 ---> 2017 ---> 2020

Kinematics	Energy & Target	
Forward	Hydrogen	Hydrogen
		315
		420
		510
	570	
	855	855
		1508
Backward	Hydrogen	Deuterium
	315	315
	420	420



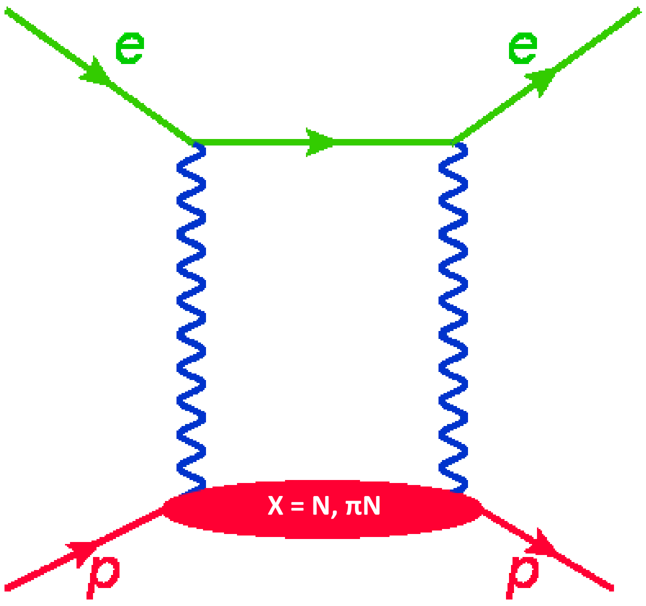
Phy. Rev. Lett. 119, 012501(2017)

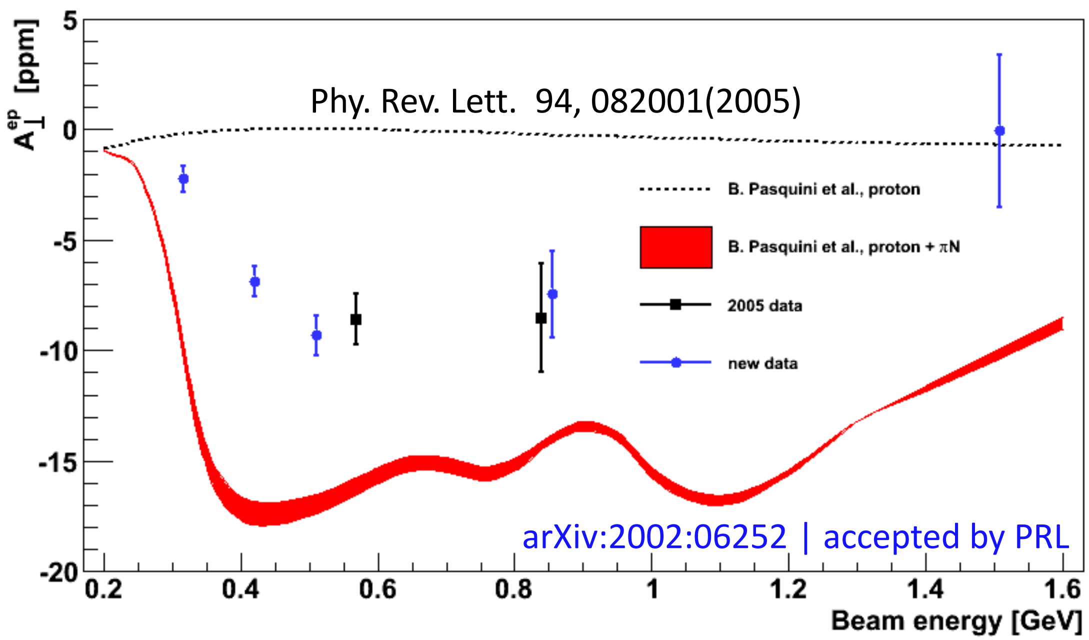




- Significant inelastic contribution
- Backward data agree well with the theory
- Tension between forward data and theory.

How to understand the discrepancy?





- We respect unitarity.
- More intermediate states ($\boldsymbol{\pi\pi}$**N,** $\boldsymbol{K\Lambda}, \boldsymbol{\eta N}$)?
- MAID database needs improvement?

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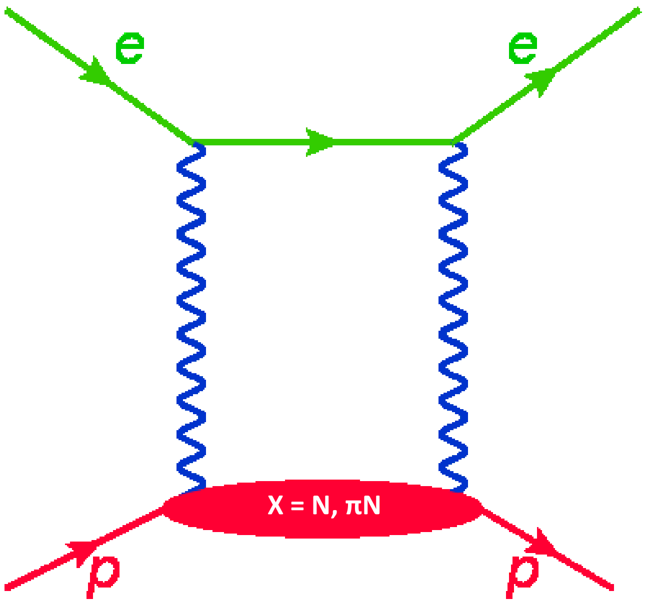
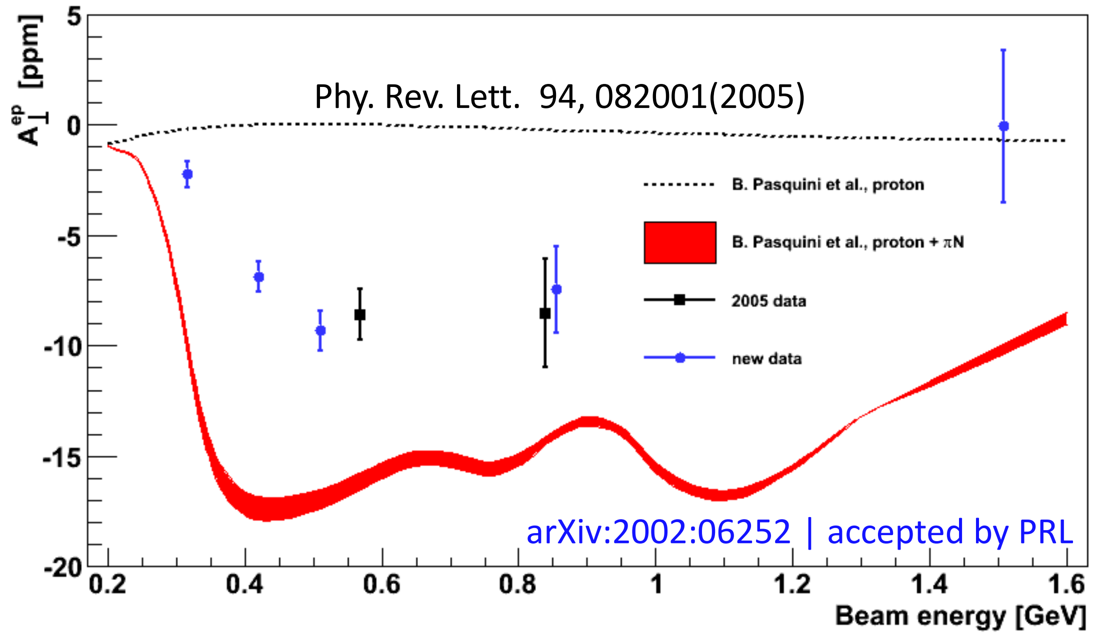
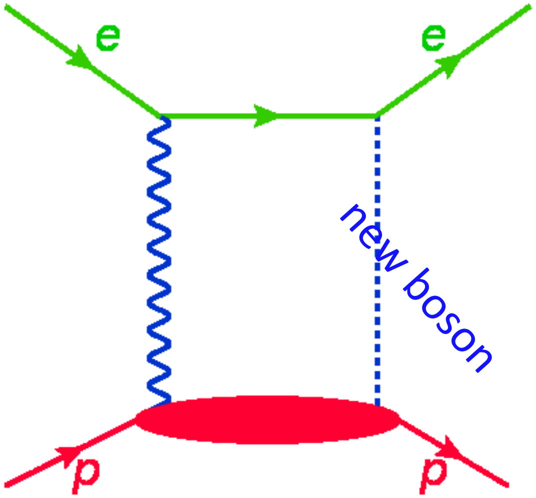


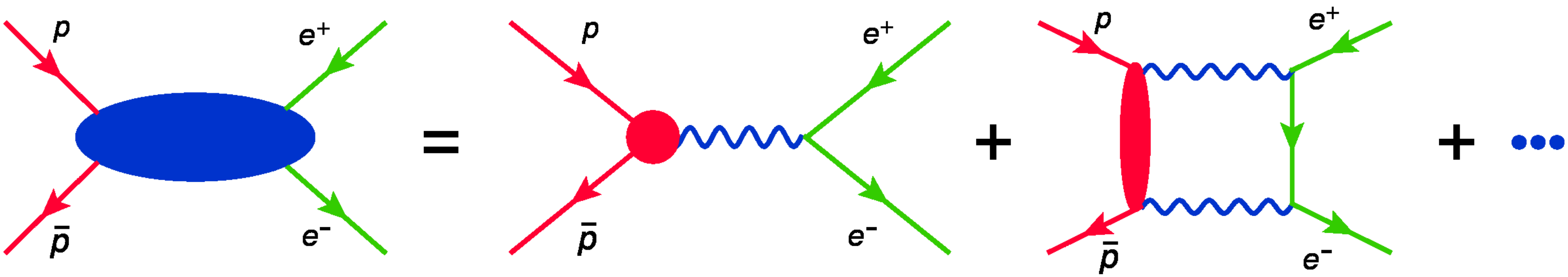


- We respect unitarity.
- More intermediate states ($\boldsymbol{\pi\pi N}, \boldsymbol{K\Lambda}, \boldsymbol{\eta N}$)?
- MAID database needs improvement?
- New parity-conserving boson?



Opportunities at PANDA

In time-like region

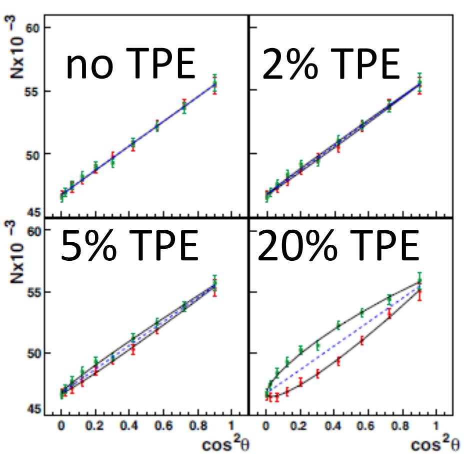


G. I. Gakh and E. T.-Gustafsson, Nucl. Phys. A 761, 120 (2005) | M. P. Rekalo and E. T.-Gustafsson, Eur. Phys. A 22, 331 (2004)

Differential cross-section of $\bar{p} + p \rightarrow e^+ + e^-$ in CM frame

- One-photon-exchange **(OPE)** approximation → even function of $\cos\theta$
- Consider both **OPE** and **TPE** → contains odd terms $(\Delta G_E, \Delta G_M)$ of $\cos\theta$

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}\left[(1+\cos^2\theta)\left(|G_M|^2+2ReG_M\Delta G_M^*\right)+\frac{1}{\tau}\sin^2\theta\left(|G_E|^2+2ReG_E\Delta G_E^*\right)+2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re\left(\frac{1}{\tau}G_E-G_M\right)F_3^*\right]$$



- TPE effects would change angular distrubutions
- Feasibility study has been performed | **Eur. Phys. A44 373 (2010)**
- The TPE contributions induce a deviation from straight line in the angular distribution

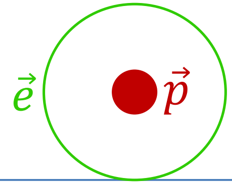
In space-like region

Transverse spin asymmetry

Beam asymmetry $\propto \frac{Im(\mathcal{M}_\gamma^* \mathcal{M}_{2\gamma})}{|\mathcal{M}_\gamma|^2} \cdot \frac{m_e}{E} \sim 10^{-5} - 10^{-6}$ $\quad$ MAMI – A4

Target asymmetry $\propto \frac{Im(\mathcal{M}_\gamma^* \mathcal{M}_{2\gamma})}{|\mathcal{M}_\gamma|^2} \sim \alpha \sim 10^{-2}$ $\quad$ PANDA

With a **polarized hydrogen target**, TPE can be investigated in **inverse kinematics** by measuring transverse asymmetry in $\bar{\mathrm{p}} + \vec{\mathrm{e}} \rightarrow \bar{\mathrm{p}} + \mathrm{e}$



Charge asymmetry

- Compare cross section of $\bar{p} + e^- \rightarrow \bar{p} + e^-$ and $p + e^- \rightarrow p + e^-$
- Need switch between proton beam and antiproton beam in HESR
- Beam can not be switched very frequently → various systematic effects to handle

Summary

- Proton form factor puzzle & two-photon exchange (TPE)

- Approaches to study TPE
  - Charge asymmetry
  - Transverse spin asymmetry

- TPE investigation at MAMI-A4

- Opportunities to study TPE at PANDA

Thanks for your attention !