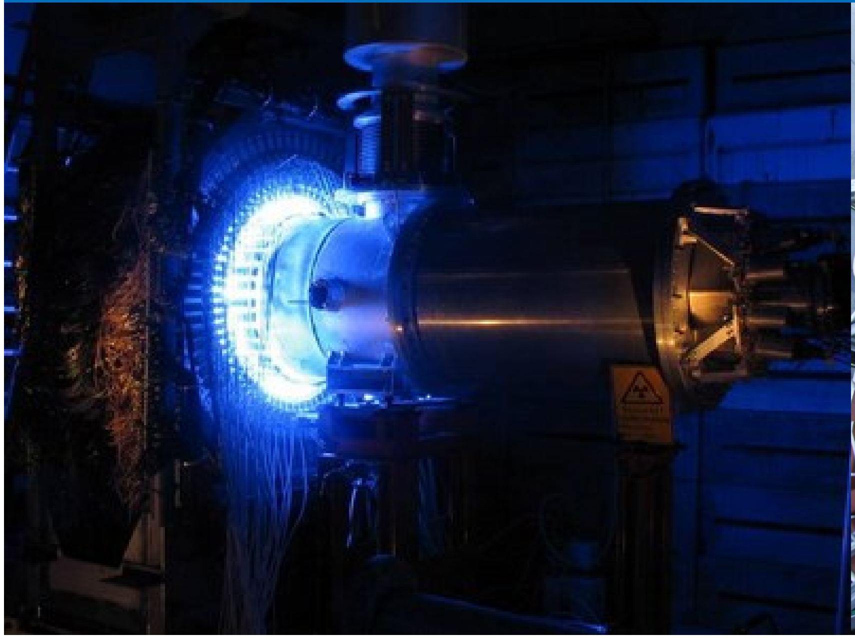
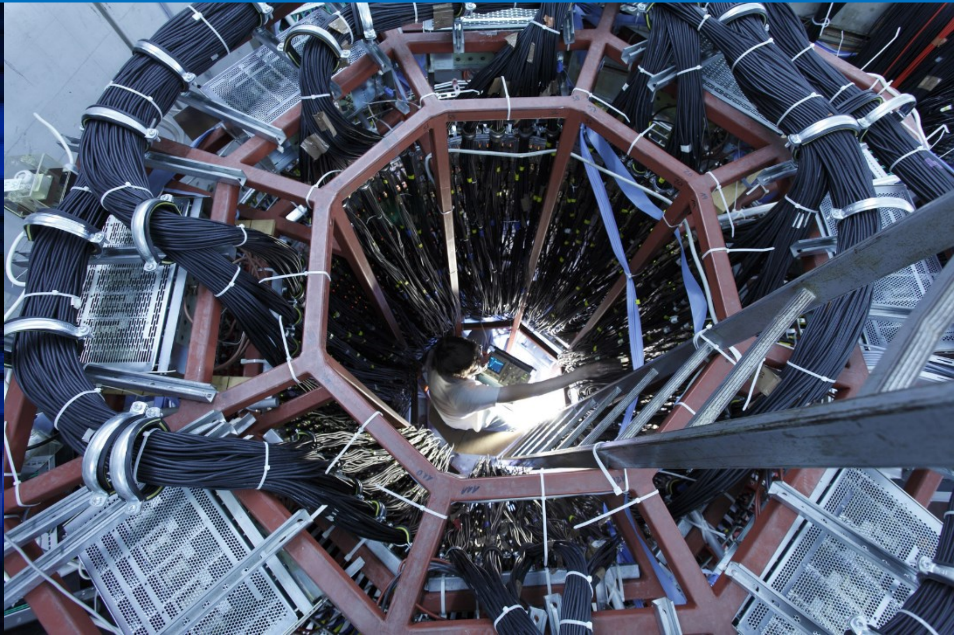
Study of two-photon exchange with polarized electron beam at A4

Boxing Gou for the A4 Collaboration

The 11th Workshop on Hadron Physics in China and Opportunities Worldwide, Tianjin, August 26, 2019



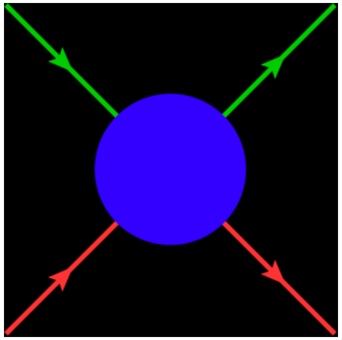


Outline

- Proton form factor puzzle and two-photon exchange
- Two-photon exchange study at MAMI-A4
- Published data and latest results

Proton form factors

Generalized form factors

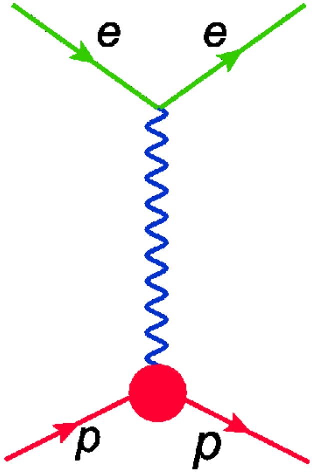


Elastic scattering of two spin-1/2 particles can be described by 6 amplitudes (form factors).

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

- 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 represents the helicity conserving and flip processes respectively
- Sachs form factors (G_E, G_M) describe the charge and magnetization distribution

Methods for form factor measurement

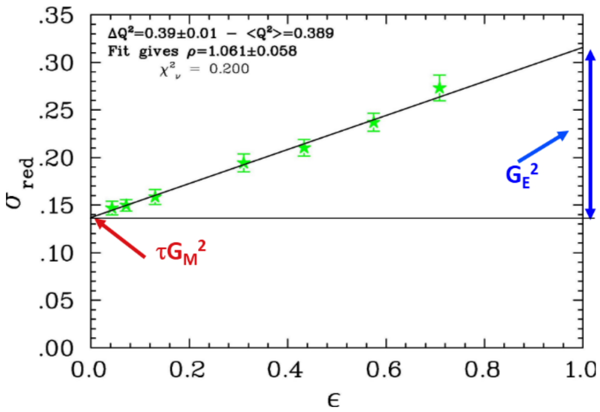
Rosenbluth separation

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

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

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

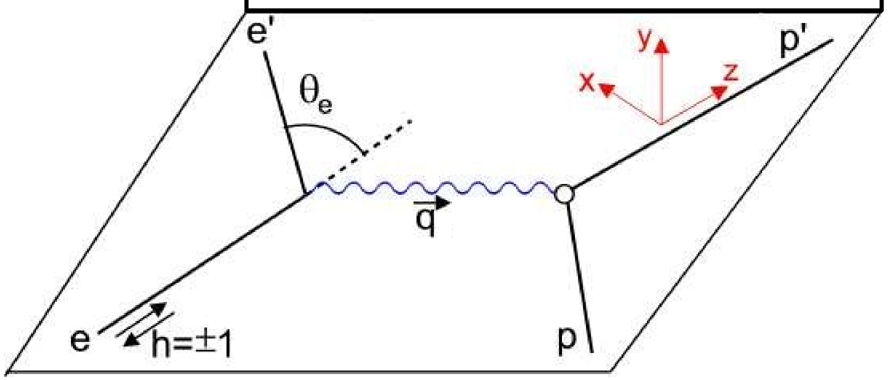
$$\sigma_R=\varepsilon G_E^2(Q^2)+\tau G_M^2(Q^2)$$



- 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: $\vec{e}p \rightarrow e\vec{p}$



Phys. Rev. C 23, 363 (1981)

$$I_0 P_x=-2\sqrt{\tau(1+\tau)}G_E G_M\tan\frac{\theta_e}{2}$$

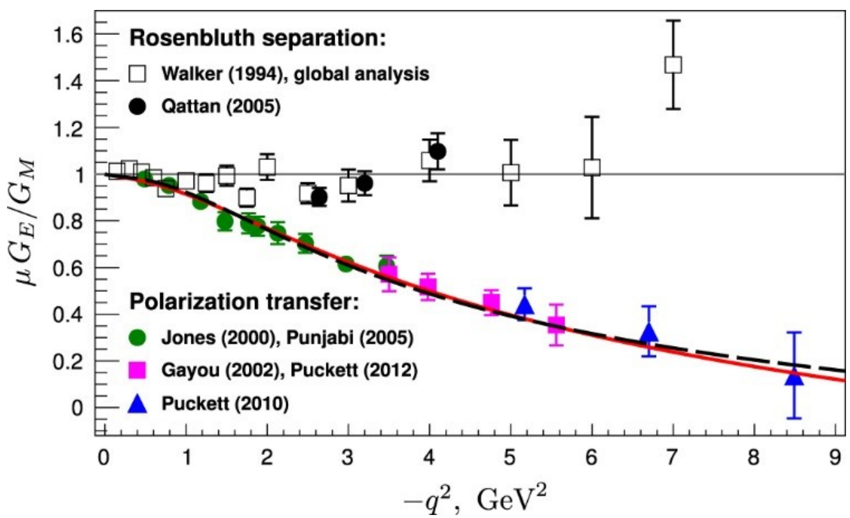
$$P_y=0$$

$$I_0 P_z=\frac{E_0+E'}{M}\sqrt{\tau(1+\tau)}G_M^2\tan\frac{\theta_e}{2}$$

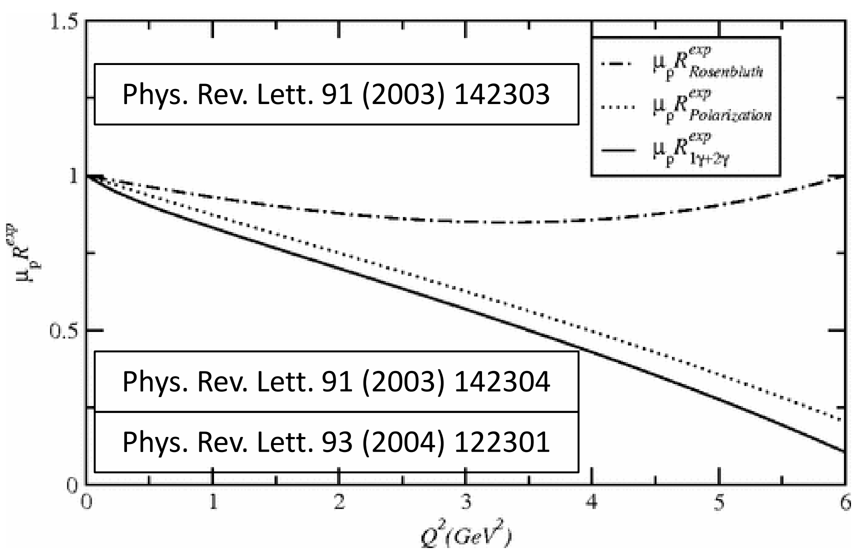
$$I_0=G_E^2(Q^2)+\frac{\tau}{\varepsilon}G_M^2(Q^2)$$

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

Proton form factor puzzle

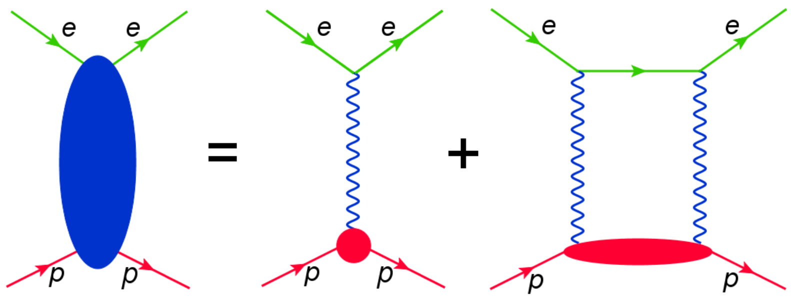


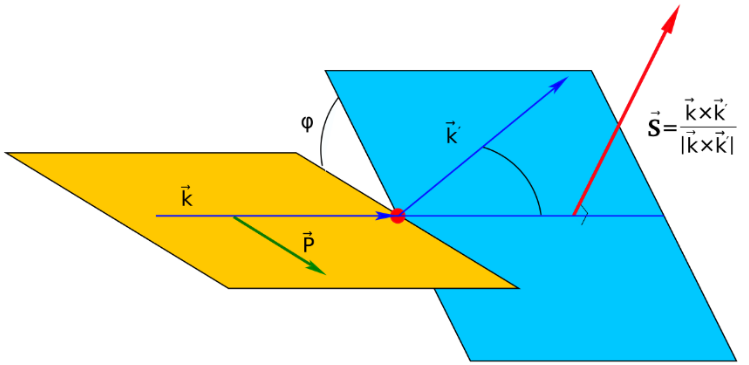
- Discrepancy between Rosenbluth separation and spin transfer experiments.
- Failure of the Born approximation in electron scattering .



- A two-photon exchange (TPE) correction could explain the discrepancy.
- Two-photon exchange mechanism needs to be understood systematicly.
- Both theoretical and experimental investigations are needed.

TPE accessible via transverse spin asymmetry





Azimuthal asymmetry

$$A_{exp} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = A_\perp \frac{\vec{s}\cdot\vec{p}}{|\vec{s}||\vec{p}|} = -A_\perp \cos\varphi$$

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

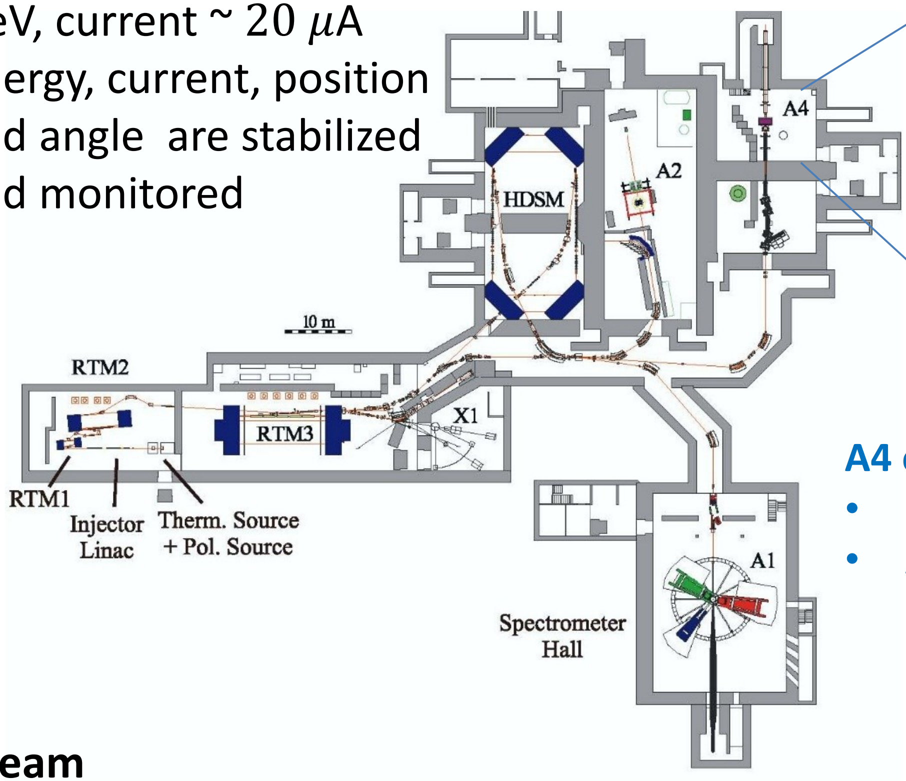
Nucl. Phys. B 35 (1971) 365.

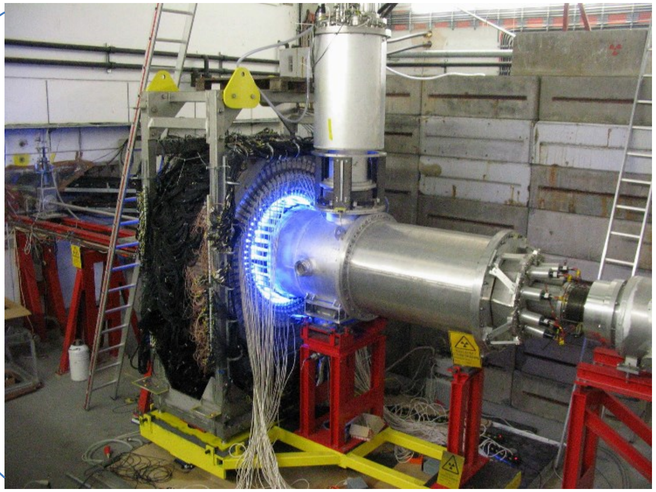
Target Spin Asymmetry in $e\vec{p} \to ep$	Beam Spin Asymmetry in $\vec{e}p \to ep$
• Imaginary parts of $\tilde{F}_1, \tilde{F}_2, \tilde{F}_3$ • $A_\perp \sim\alpha \sim 10^{-2}$ • No experiments	• Imaginary parts of $\tilde{F}_3, \tilde{F}_4, \tilde{F}_5$ • $A_\perp \sim\alpha \cdot \frac{m_e}{E} \sim 10^{-5}-10^{-6}$ • SAMPLE@MIT-Bates • HAPPEX, G0, Q_{weak} @JLab • A4@MAMI

MAMI

Mainz Microtron (MAMI)

- Electron beam: 0.2 – 1.5 GeV, current ~ 20 μA
- Energy, current, position and angle are stabilized and monitored





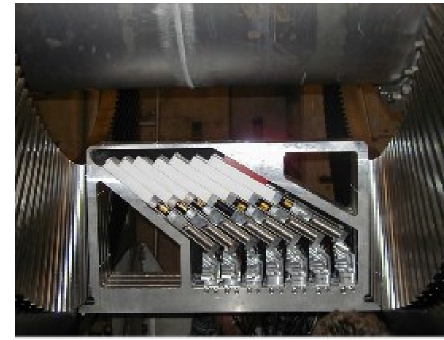
A4 experiment

- Parity violation asymmetry: Strange form factor
- Azimuthal asymmetry: Two-photon exchange

Pol. beam

- Photoelectric effect on GaAs with circularly polarized laser: **longitudinally** polarized electrons
- Wien filter **+** procession in micrtrons → **longitudinal / transverse**
- Solenoid: transverse → **vertical**
- Beam polarization ~ 80%
- Pol. state reverses every 20 ms, flip pattern follows either ↑↓↓↑ or ↓↑↑↓

A4 experiment

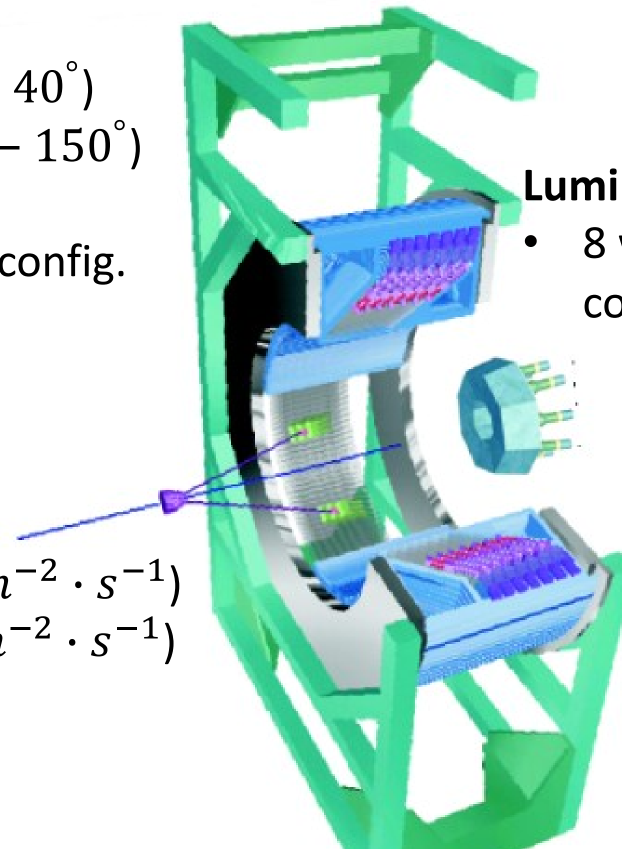


Electromagnetic calorimeter

- PbF_2 crystals, pure Cherenkov → fast response (20 ns)
- 1022 crystals: 7 rings x 146 frames → φ: $(0,\ 2\pi)$
- Read out: sum of 3x3 crystals. $\Delta E/E \approx 3.9\%/\sqrt{E[GeV]}$
- Rotatable platform: both forward $(30^{\circ} - 40^{\circ})$
  and backward $(140^{\circ} - 150^{\circ})$
- Plastic scintillator to veto γ in backward config.

High power liquid target

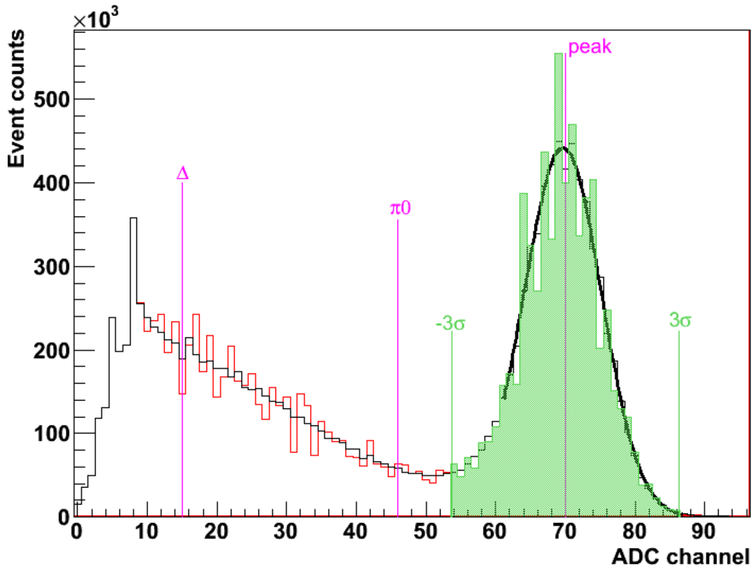
- Hydrogen
- Deuterium
- Forward (L = 10 cm, $\mathcal{L} = 0.5 \times 10^{38} cm^{-2} \cdot s^{-1}$)
- Backward (L = 23 cm, $\mathcal{L} = 1.2 \times 10^{38} cm^{-2} \cdot s^{-1}$)

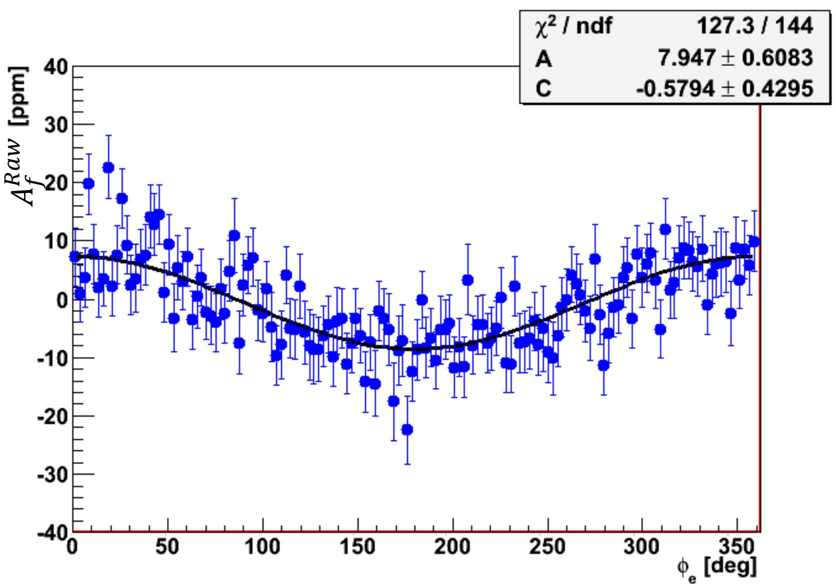


Luminosity monitor

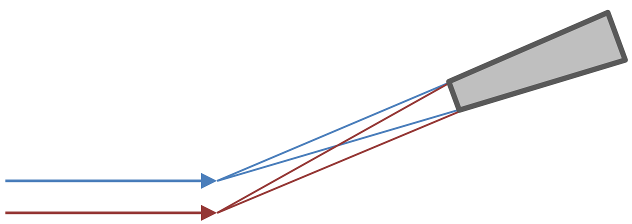
- 8 water Cherenkov counters $(4.4^{\circ} - 10^{\circ})$

Asymmetry extraction





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



False asymmetry caused by difference in

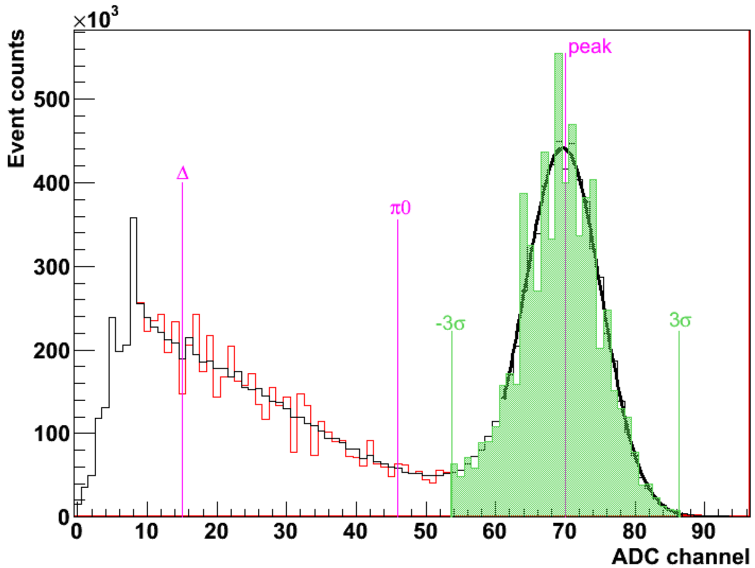
- Beam position $(\Delta X, \quad \Delta Y)$
- Beam angle $(\Delta X', \Delta Y')$
- Beam current ΔI
- Beam energy ΔE

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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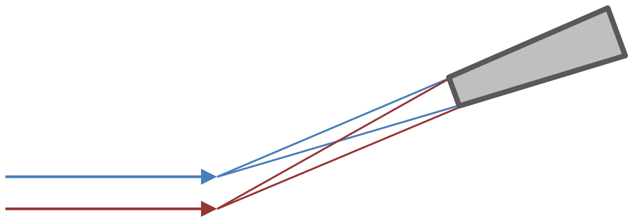

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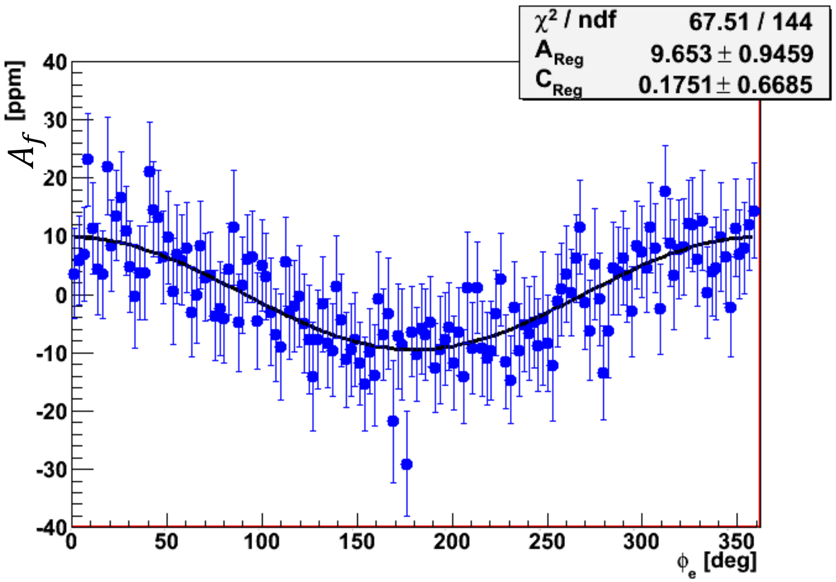
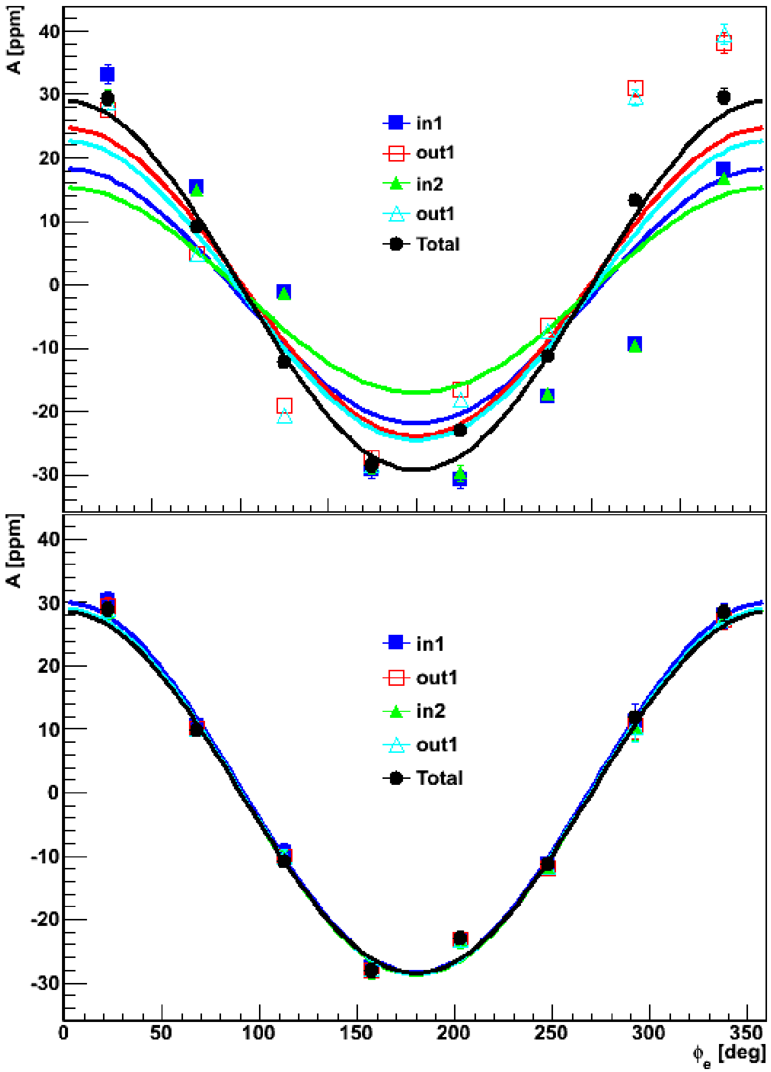
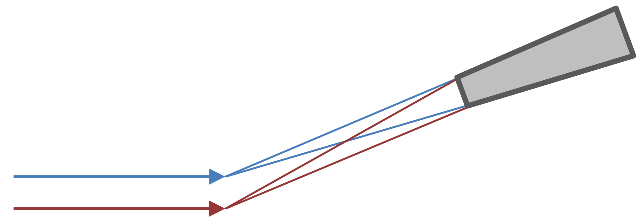


- Fit A_f by $A_f = A\cos\left[\frac{2\pi}{146} \cdot (f - 0.5)\right] + C$

Asymmetry in luminosity monitor



- Large statistics
- Large asymmetry
- Serve as polarization monitor



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

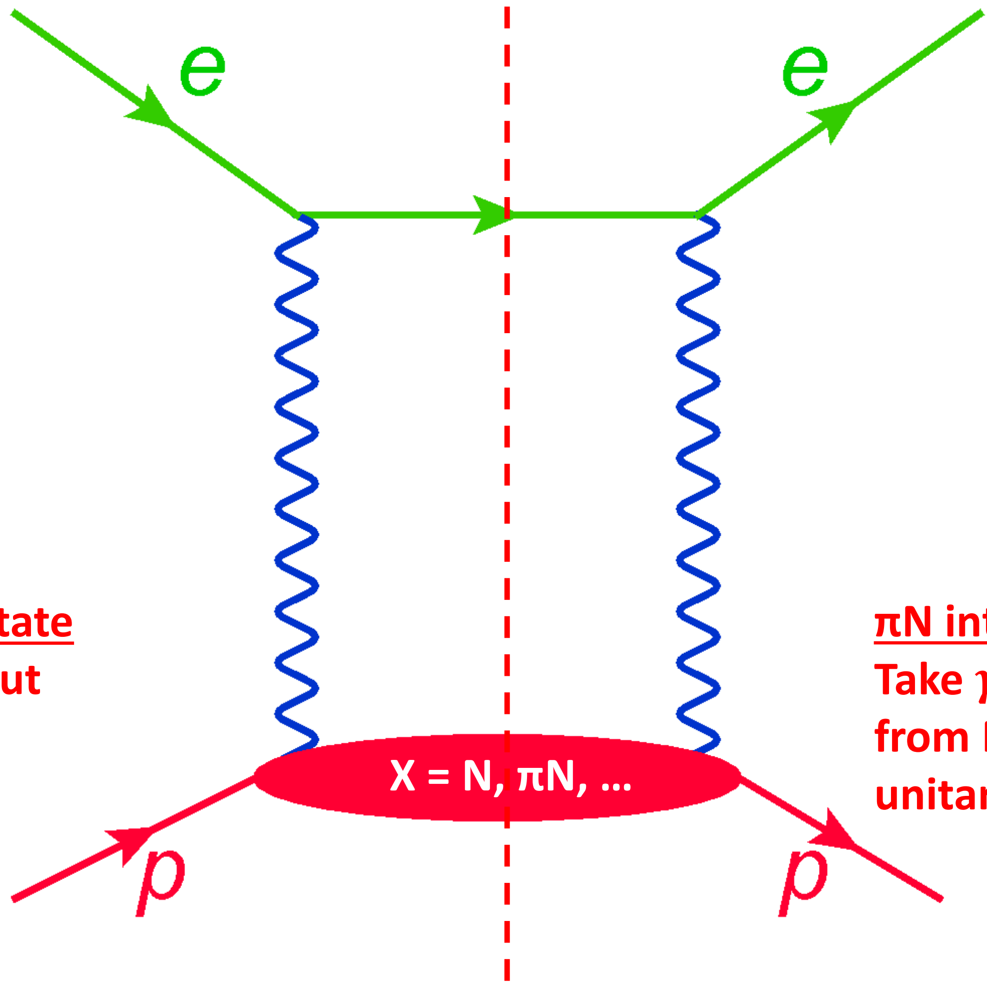
Corrected via regression analyses

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

Asymmetry calculation

Theory by B. Pasquini and M. Vanderhaeghen
Phy. Rev. C 70, 045206(2004)

QED

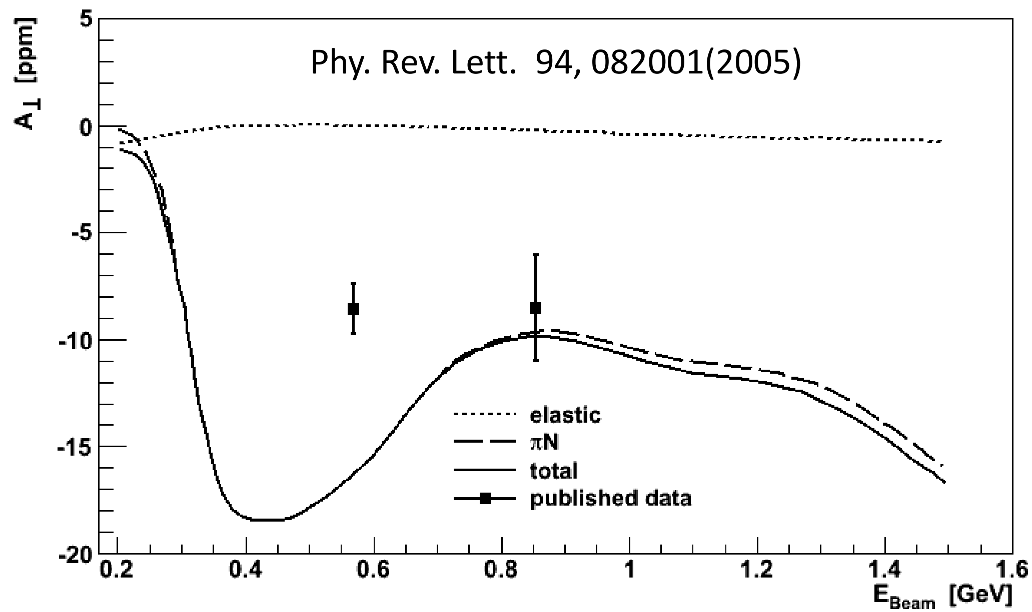


Ground proton state
G_E and G_M as input

πN intermediate states
Take $\gamma N \rightarrow \pi N$ amplitudes from MAID as input using unitary

A4 results: 2005

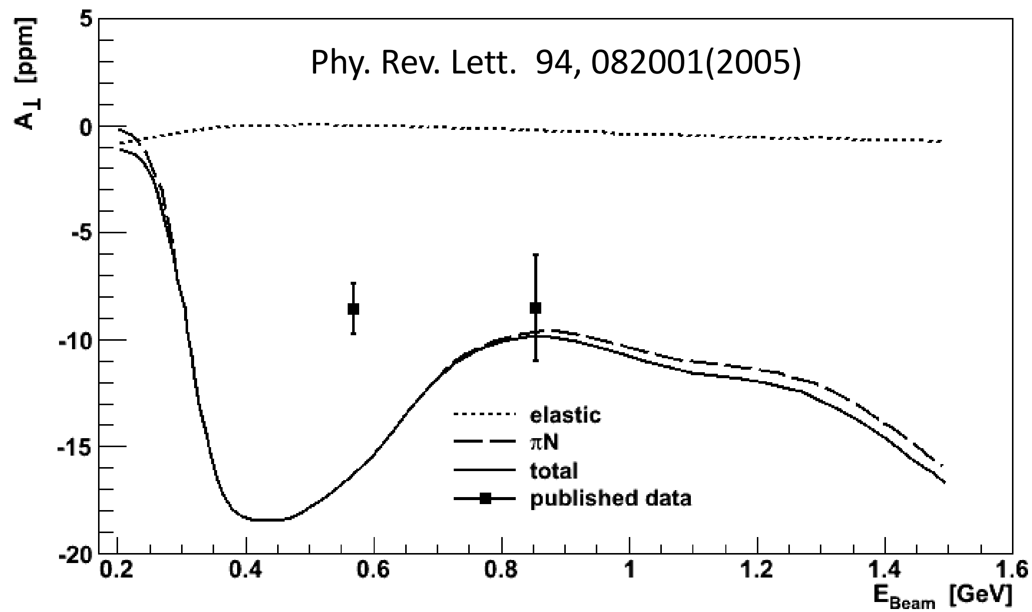
Kinematics	Energy & Target
Forward	Hydrogen
	570
	855



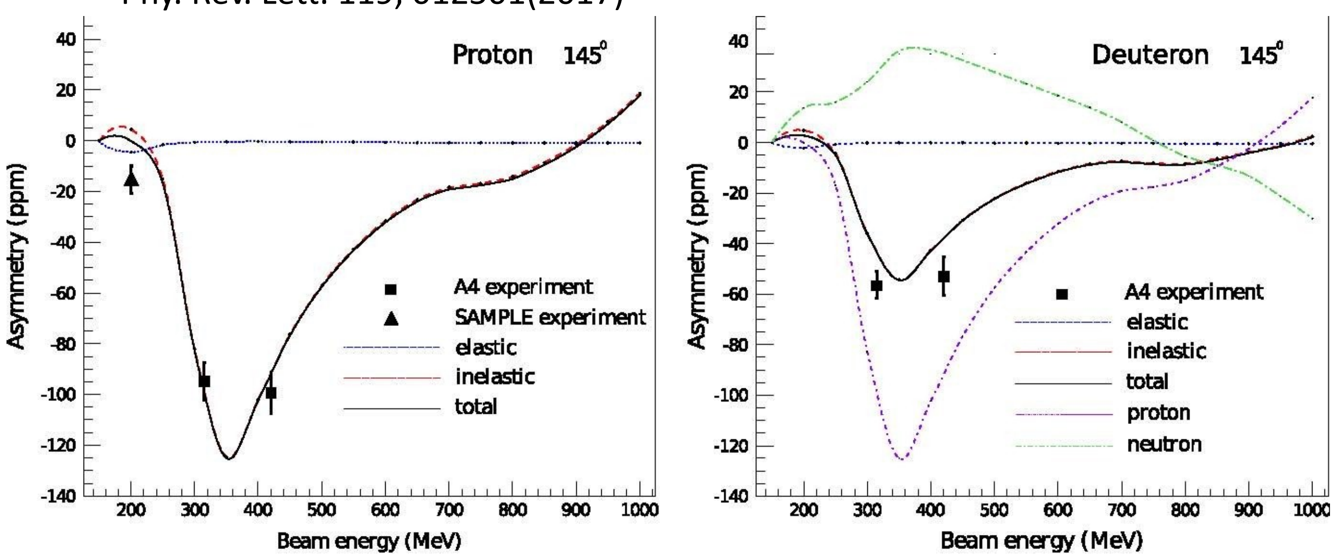
- Significant inelastic contribution

A4 results: 2005 ---> 2017

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



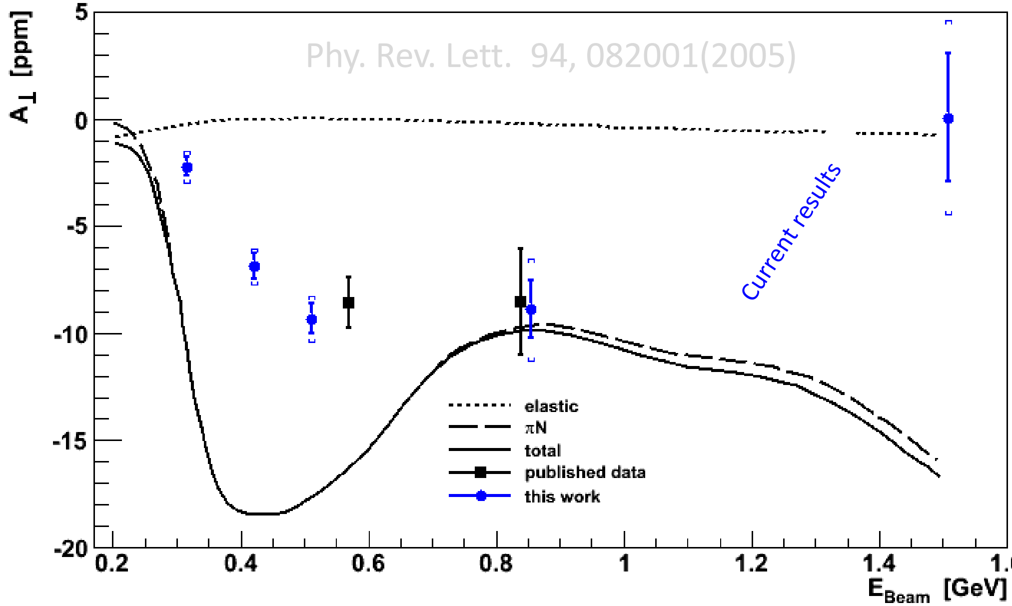
Phy. Rev. Lett. 119, 012501(2017)



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

A4 results: 2005 ---> 2017 ---> 2019

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



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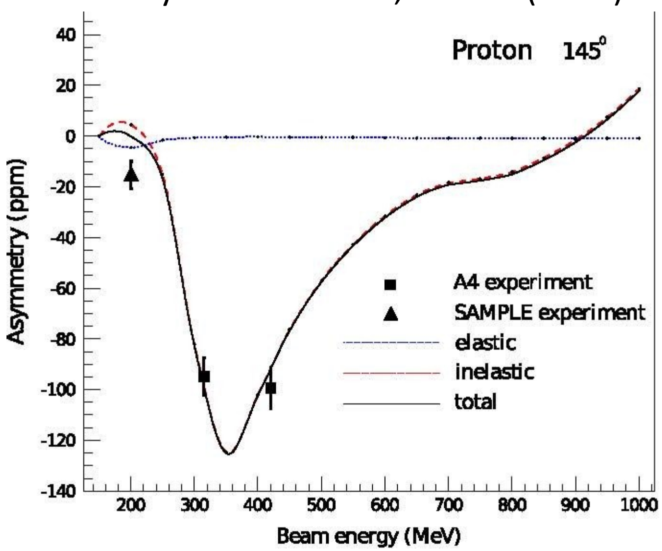
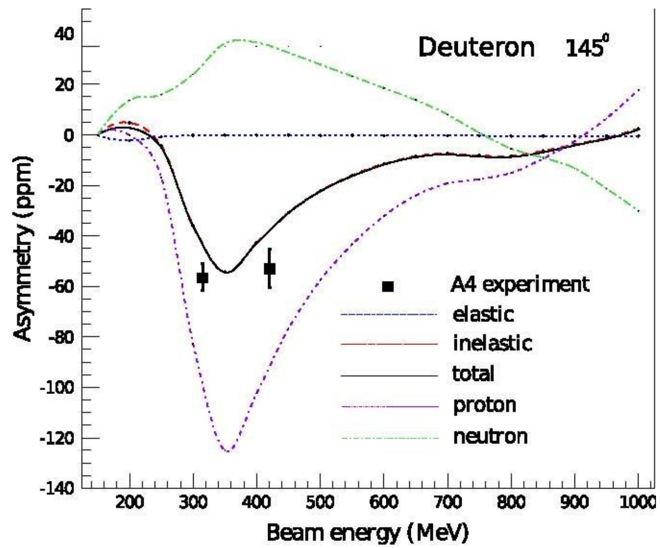
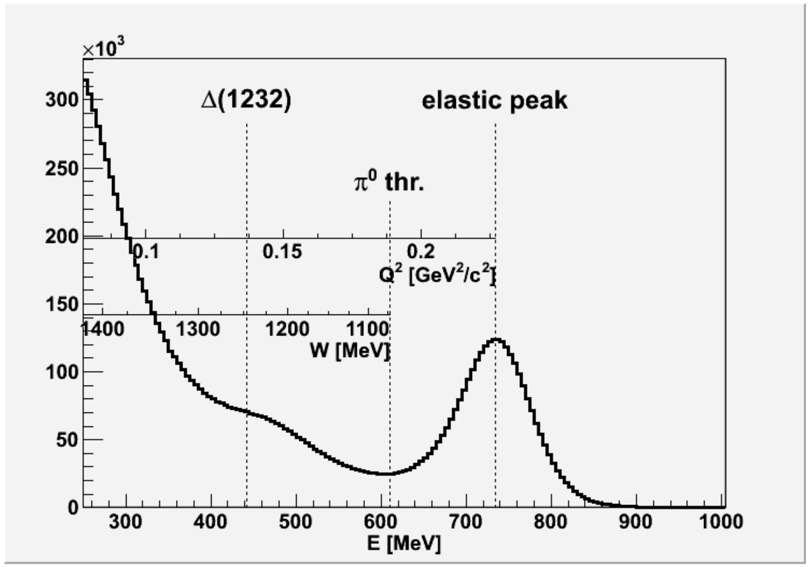
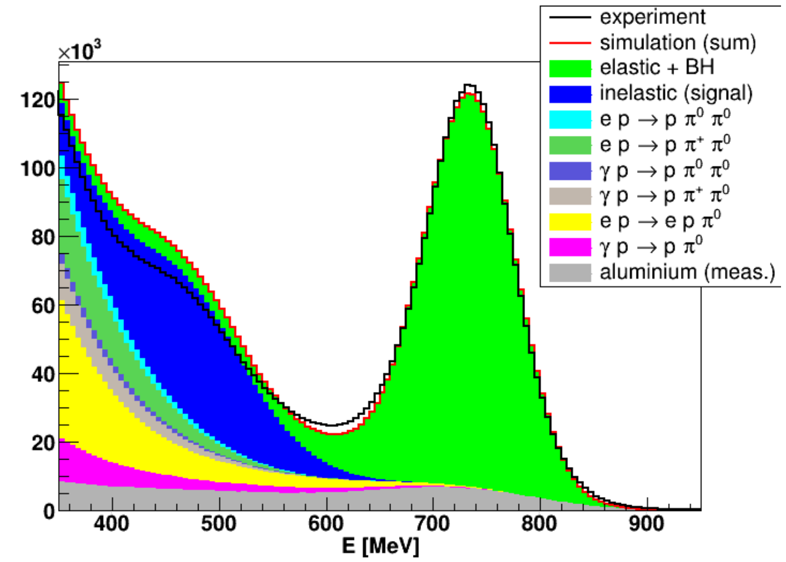




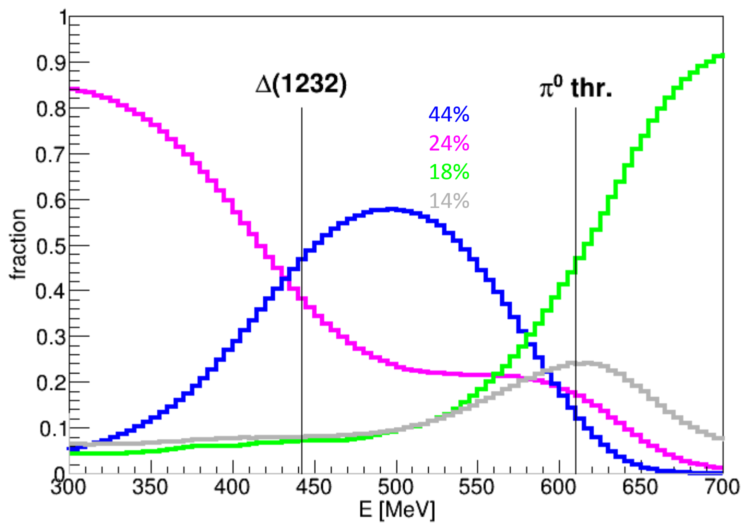
- Significant inelastic contribution
- Backward data agree well with the theory
- Tension between forward data and theory.
- **ππN intermediate states?**

Asymmetry in resonance region





- Large asymmetry in inelastic region.
- Test models describling $N \to \Delta$ transations beyond one-photon exchange.
- Background understood by Monte-Carlo simulation.



Summary

- Discrepancy between Rosenbluth separation and polarization transfer triggered the two-photon exchange (TPE) study.
- Transverse spin asymmetry ($A_{\perp}$) provides an ideal test bed to study TPE.
- A4 has completed the $A_{\perp}$ measurement in elastic scattering.
- A4 is still delivering new results ($A_{\perp}$ and PVA in inelastic region).

Thanks for your attention !