Search for T-odd mechanisms beyond the standard model in transversely polarized p$\vec{e}$ scattering?

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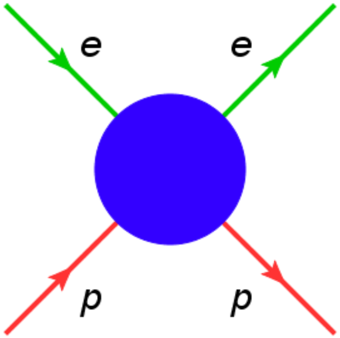
December 15-19, 2023

Outline

- Proton form factor puzzle → two-photon exchange
- Probe two-photon exchange with $A_{\perp}^{\vec{e}p}$
- World data and puzzle in $A_{\perp}^{\vec{e}p}/A_{\perp}^{\vec{e}A}$
- New T-odd mechanisms search via $A_{\perp}^{p\vec{e}}$?
- Opportunities in China

Proton form factors

Generalized form factors

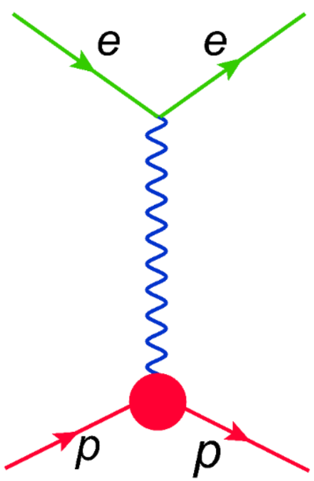


Elastic scattering of two spin-1/2 particles can be described by 6 amplitudes (form factors).

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

- 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

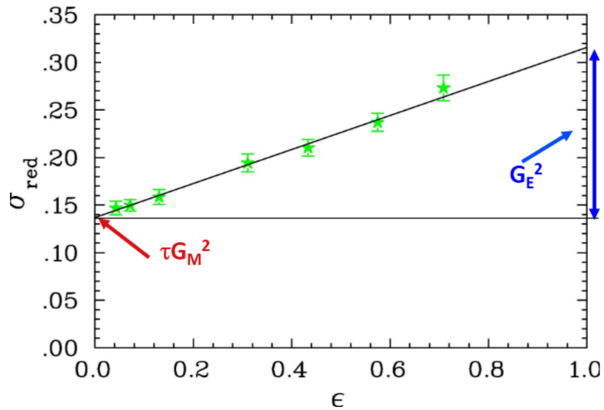
Rosenbluth separation

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

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

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

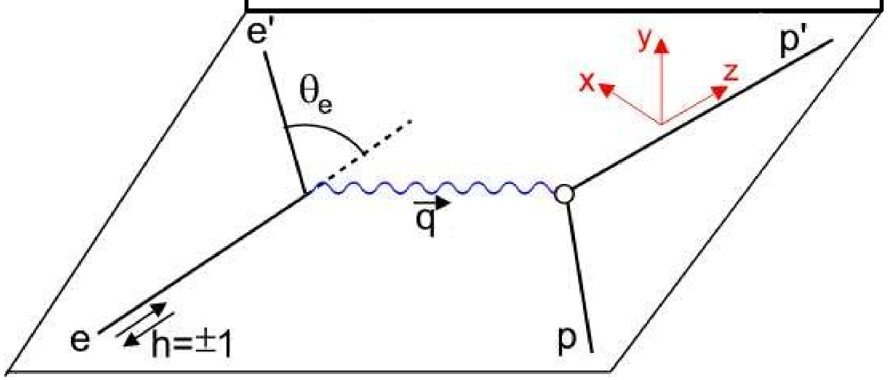
$$\sigma_R=\varepsilon G_E^2(Q^2)+\tau G_M^2(Q^2)$$



- 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)

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

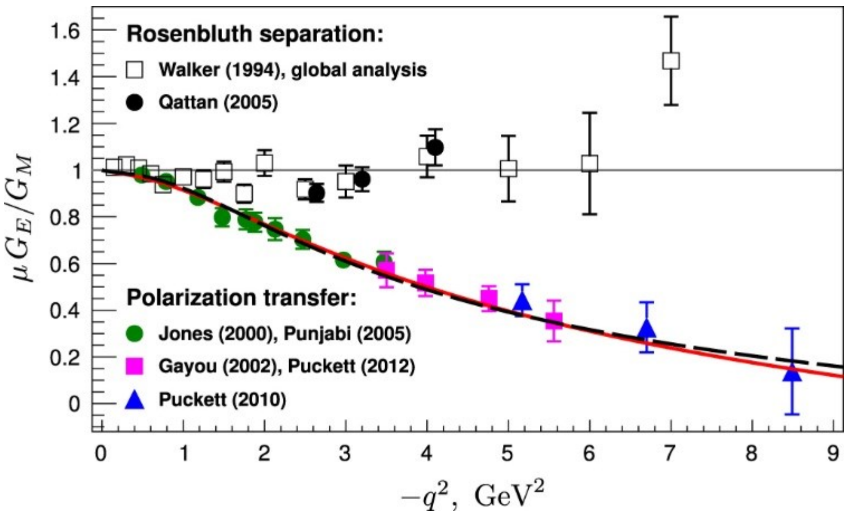
$$P_y=0$$

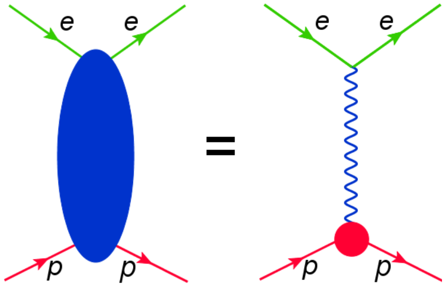
$$I_0P_z=\frac{E_0+E'}{M}\sqrt{\tau(1+\tau)}G_M^2\tan\frac{\theta_e}{2}$$

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

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

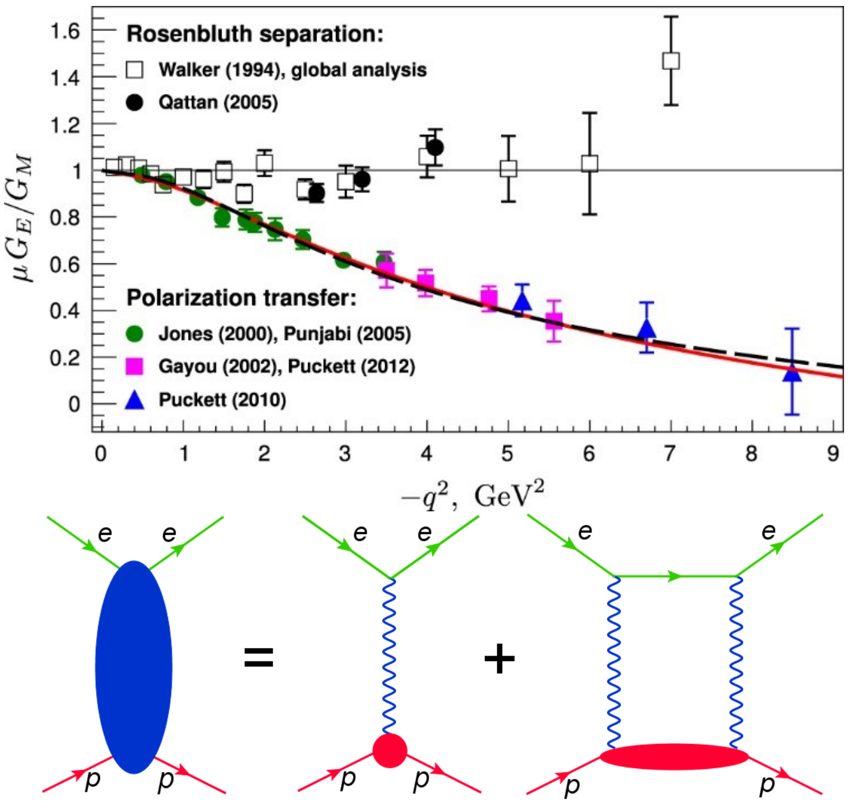
Proton form factor puzzle





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

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.

  Phys. Rev. Lett. 91 (2003) 142303
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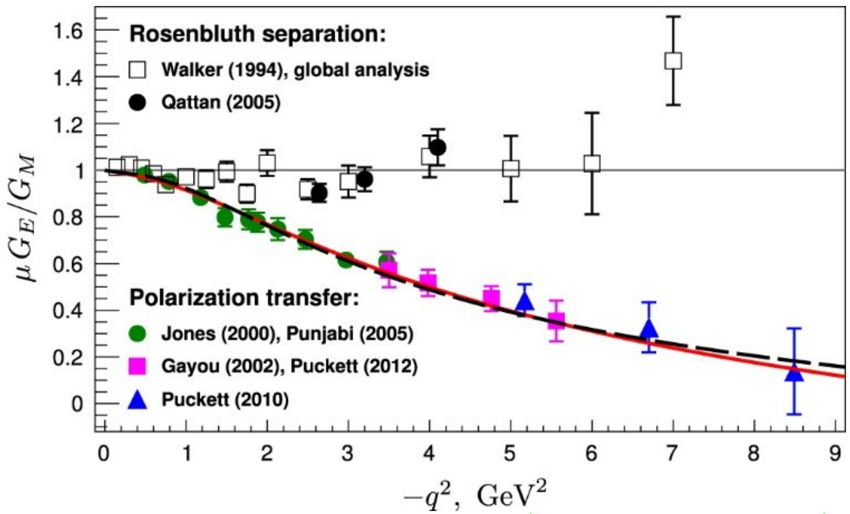
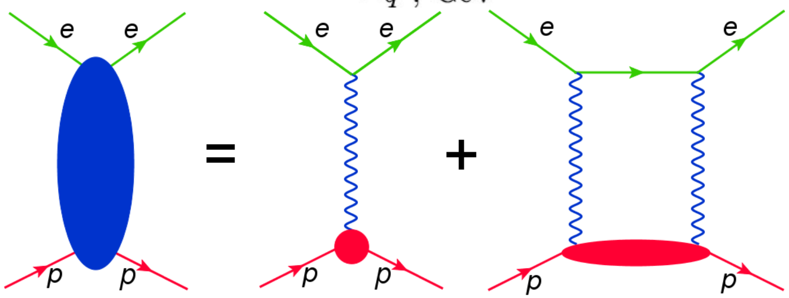
Proton form factor puzzle





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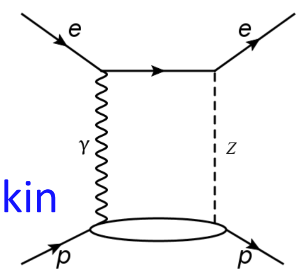
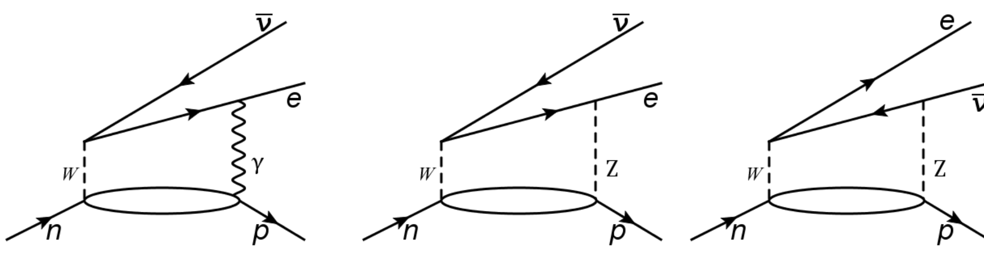
An understanding of TBE exchange is essential to other high-precision measurements

θ_w

Neutron skin



V_{ud}



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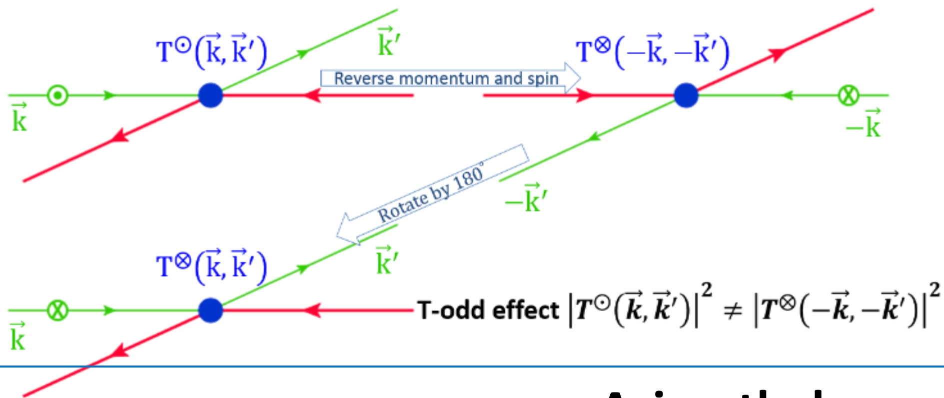
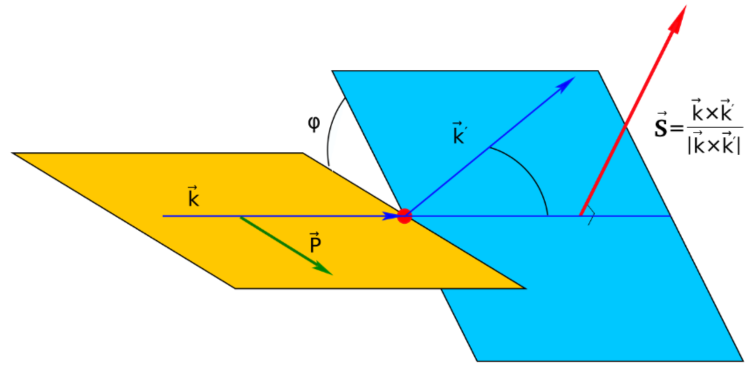
How to study TPE? Transverse spin asymmetry





Azimuthal asymmetry

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

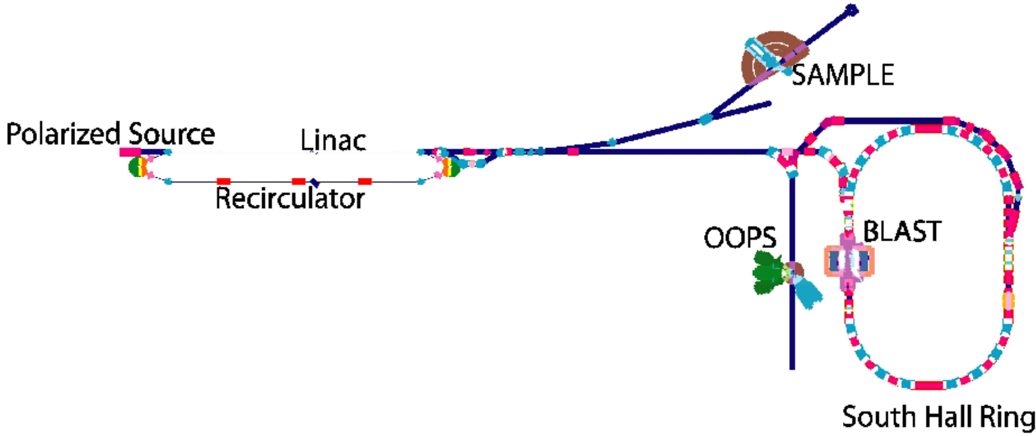
$$A_{\perp} \propto \frac{Im(\mathcal{M}_{\gamma}^{*}\mathcal{M}_{2\gamma})}{|\mathcal{M}_{\gamma}|^2}$$

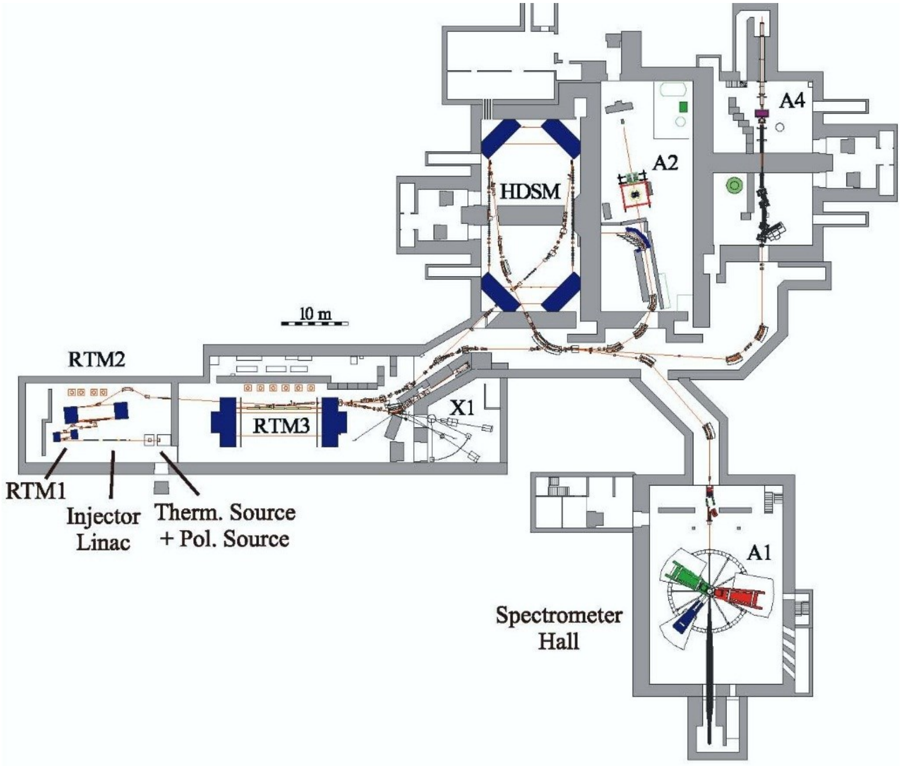
Nucl. Phys. B 35 (1971) 365.

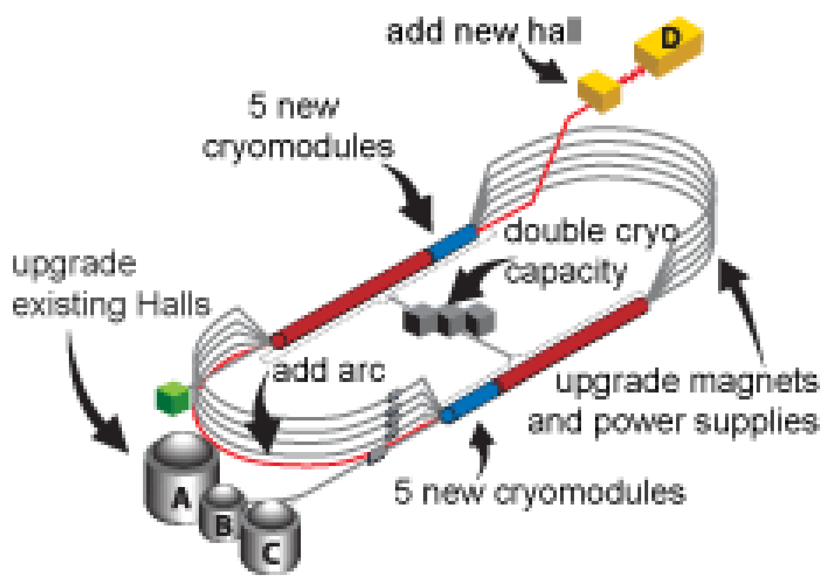
Target Spin Asymmetry in $e\vec{N} \to eN$	Beam Spin Asymmetry in $\vec{e}N \to eN$
• Imaginary parts of $\tilde{F}_1, \tilde{F}_2, \tilde{F}_3$ • $A_{\perp} \sim \alpha \sim 10^{-2}$ • HallA@JLab (pol. ^{3}He target)	• Imaginary parts of $\tilde{F}_3, \tilde{F}_4, \tilde{F}_5$ • $A_{\perp} \sim \alpha \cdot \frac{m_e}{E} \sim 10^{-5} - 10^{-6}$ • SAMPLE@MIT-Bates • HAPPEX, G0, Q_{weak} @JLab • A4@MAMI

World facilities

- SAMPLE @ MIT-Bates
- HAPPEX, G0 and Qweak @ JLAB
- A4 @ MAMI







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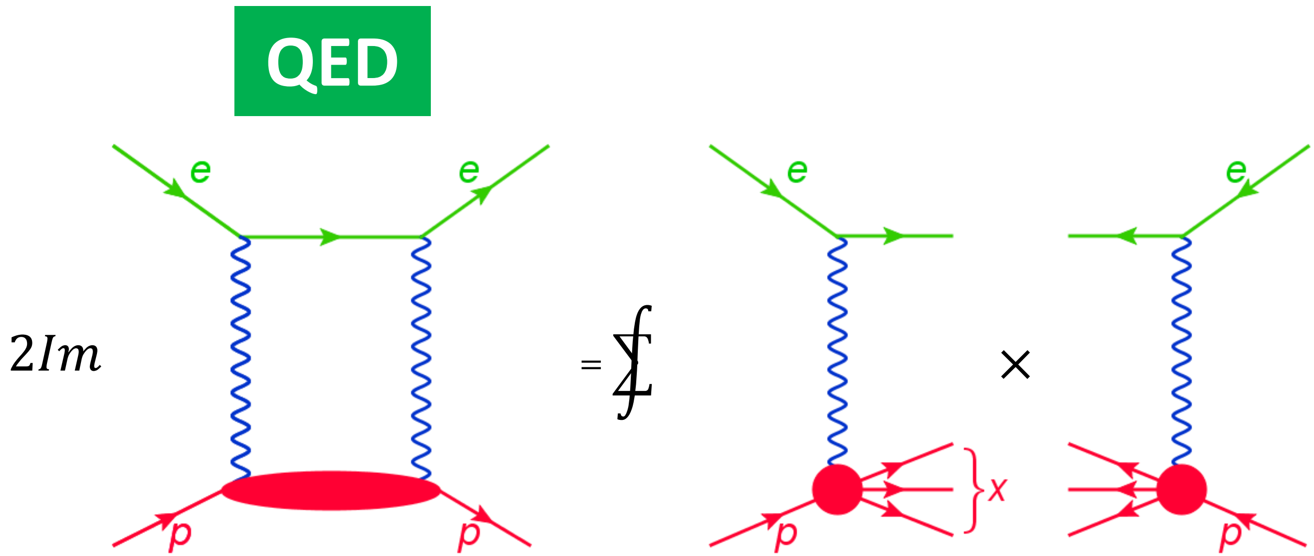
Calculation based on unitarity



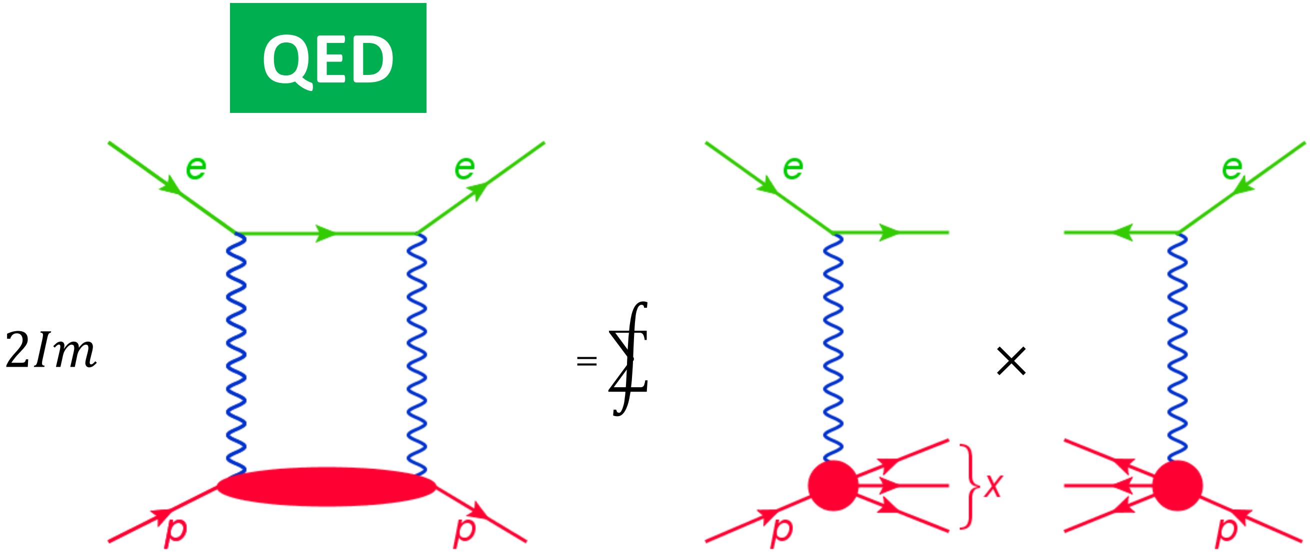
Calculation 1

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

Ground proton state
G_E and G_M as input

All πN intermediate states (both resonant and nonresonant)
$\gamma N \to \pi N$ amplitudes from MAID 2007

Calculation based on unitarity



Calculation 2

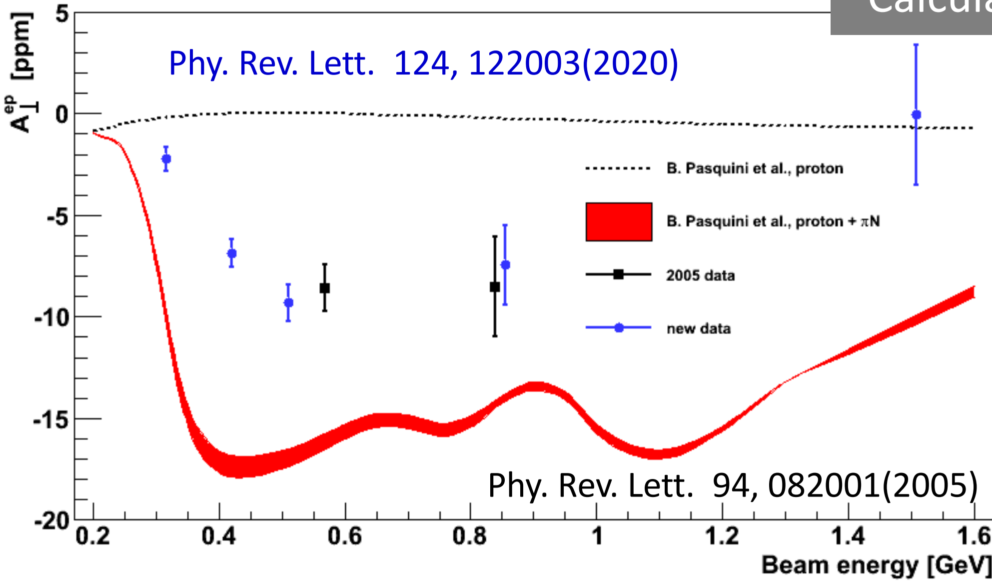
Theory by Jaseer Ahmed, P. G. Blunden, and W. Melnitchouk
Phy. Rev. C 108, 055202(2023)

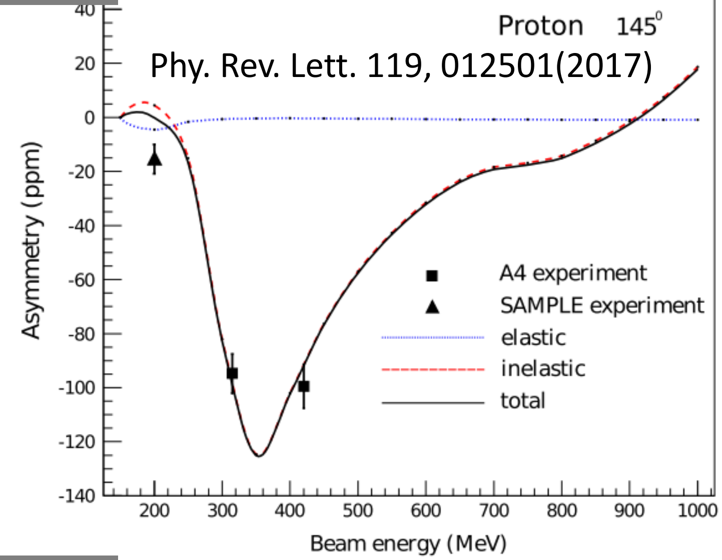
Ground proton state
G_E and G_M as input

Resonant states of spin-parity $1/2^{\pm}$ and $3/2^{\pm}$ ($W \leq 1.8$ GeV)
$\gamma N \rightarrow X$ amplitudes from the latest CLAS exclusive meson production

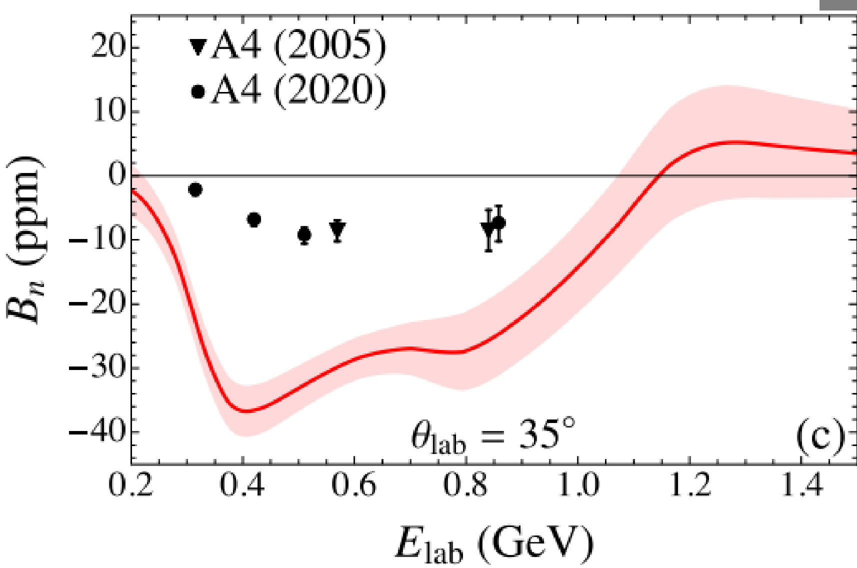
Theory-experiment comparison ($A_\perp^{\vec{e}p}$)

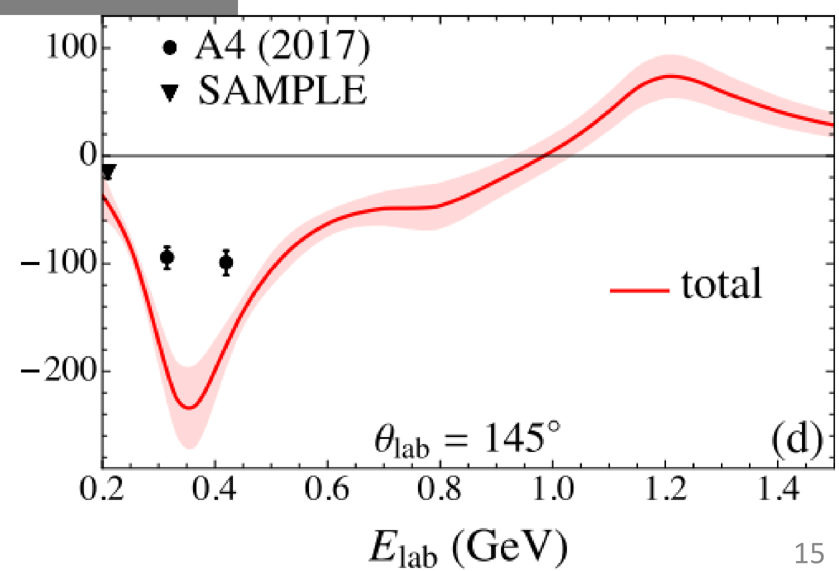
Calculation 1





Calculation 2





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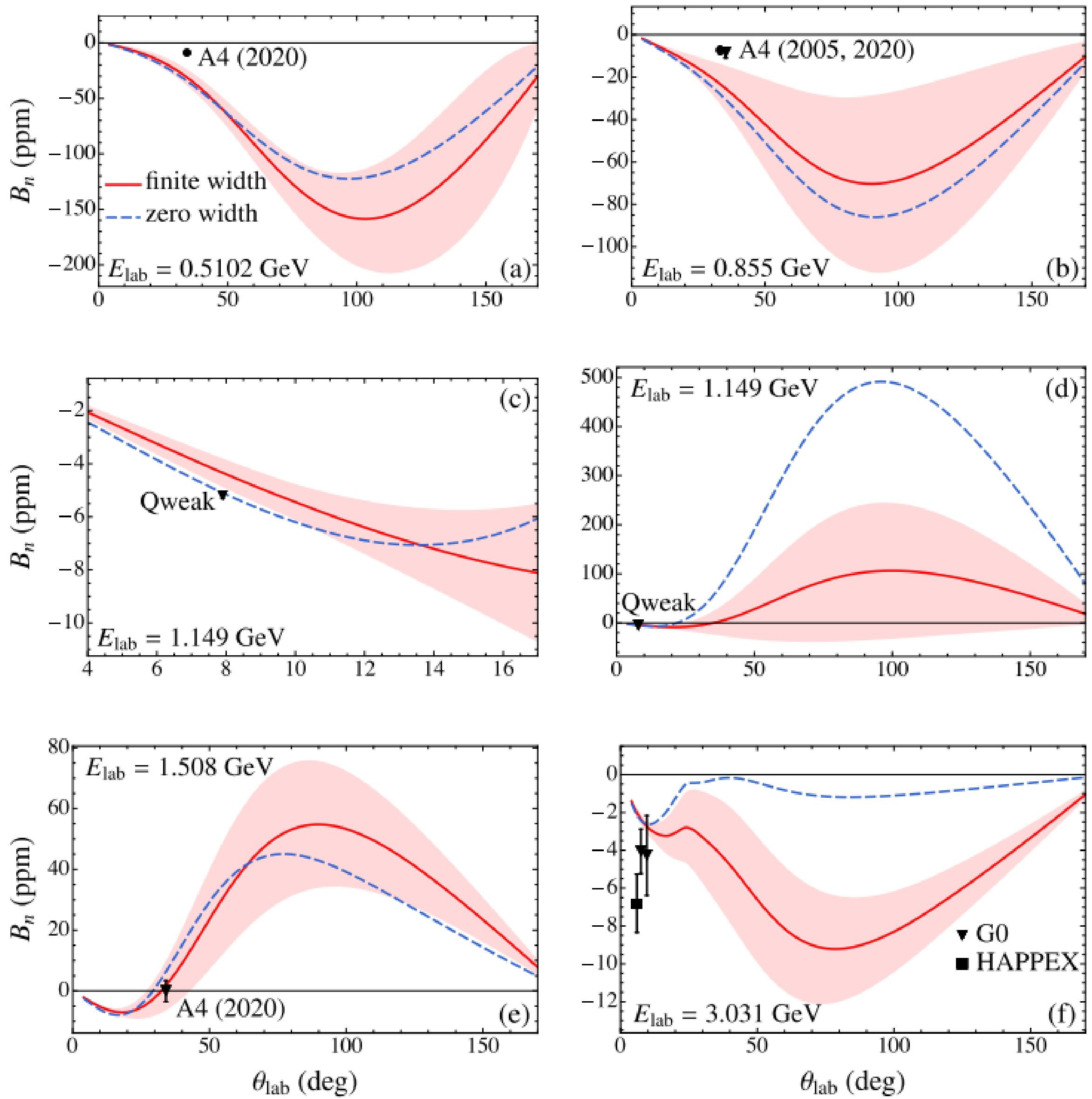


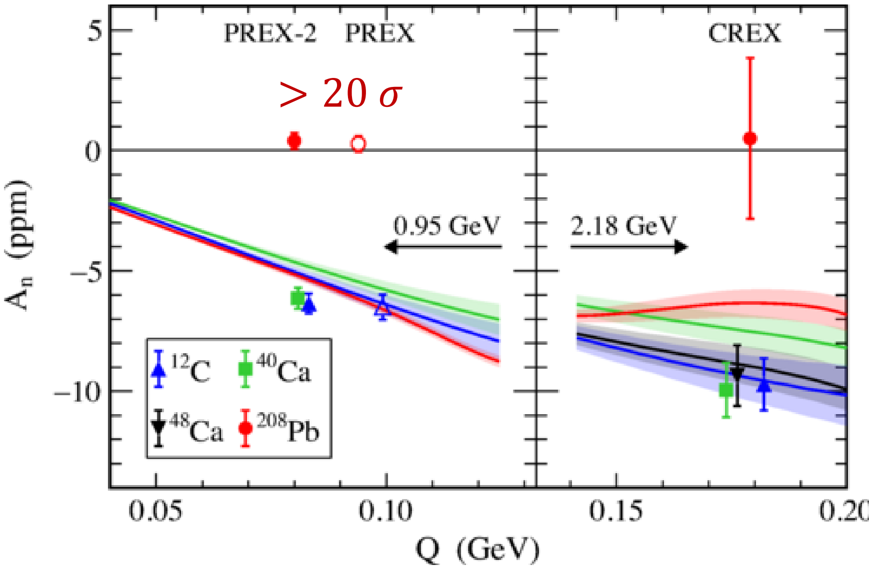
Theory-experiment comparison ($A_{\perp}^{\vec{e}A}$)

Optical Theorem: $\sigma_{tot} = \frac{4\pi}{k} Im(0)$

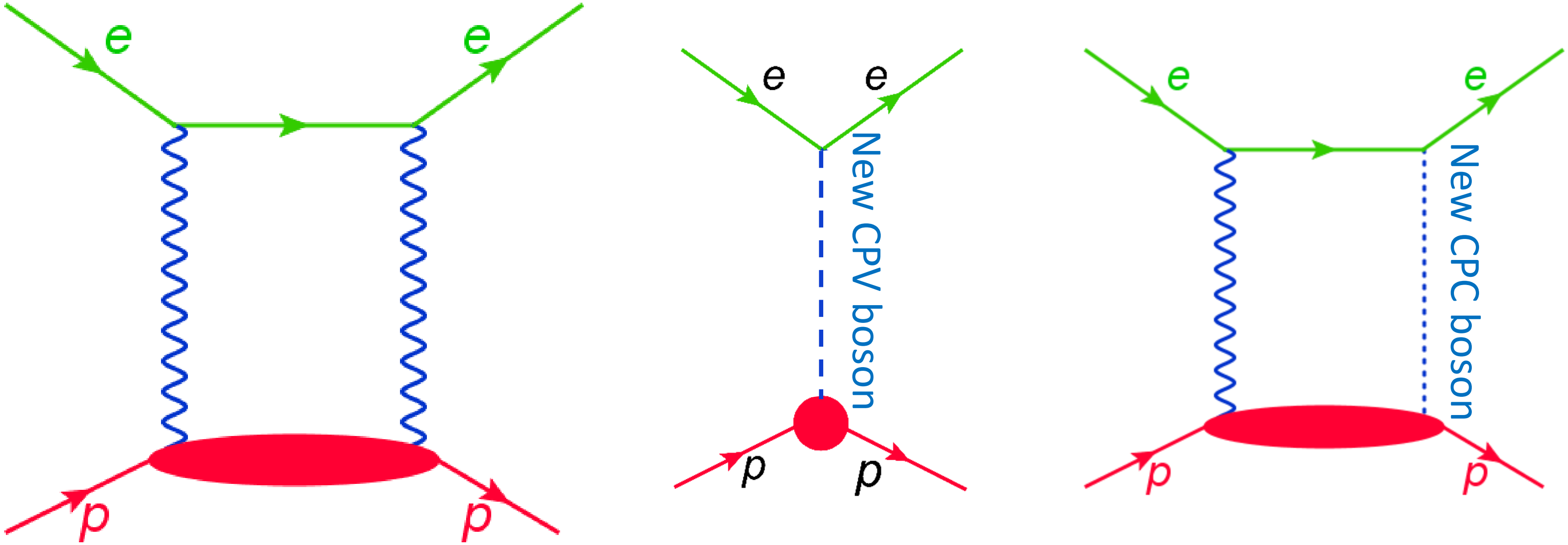
Phy. Rev. C 103, 064316(2021) by
O. Koshchii, M. Gorchtein, X. Roca-Maza, and H. Spiesberger

PREX, PREXII, CREX @ JLab
Phy. Rev. Lett. 109, 192501(2012), Phy. Rev. Lett. 128, 142501(2022)

E_{beam} (GeV)	Target	$\langle\theta_{lab}\rangle$ (deg)	$\langle Q^2\rangle$ (GeV^2)	$\langle\cos\phi\rangle$
0.95	^{12}C	4.87	0.0066	0.967
0.95	^{40}Ca	4.81	0.0065	0.964
0.95	^{208}Pb	4.69	0.0062	0.966
2.18	^{12}C	4.77	0.033	0.969
2.18	^{40}Ca	4.55	0.030	0.970
2.18	^{48}Ca	4.53	0.030	0.970
2.18	^{208}Pb	4.60	0.031	0.969



How to understand the discrepancy?



- We respect unitarity.
- MAID database and CLAS data need improvement? **(hadronic uncertanity)**
- New unknown boson?
- Uncertainty in theoretical calculation in electron scattering
- Small asymmetry signal due the Lorentz effect
- Hard to test new-physics hypothesis in $\vec{e}\text{p} \rightarrow \text{ep}$

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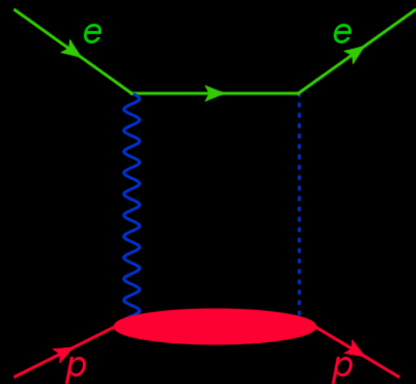
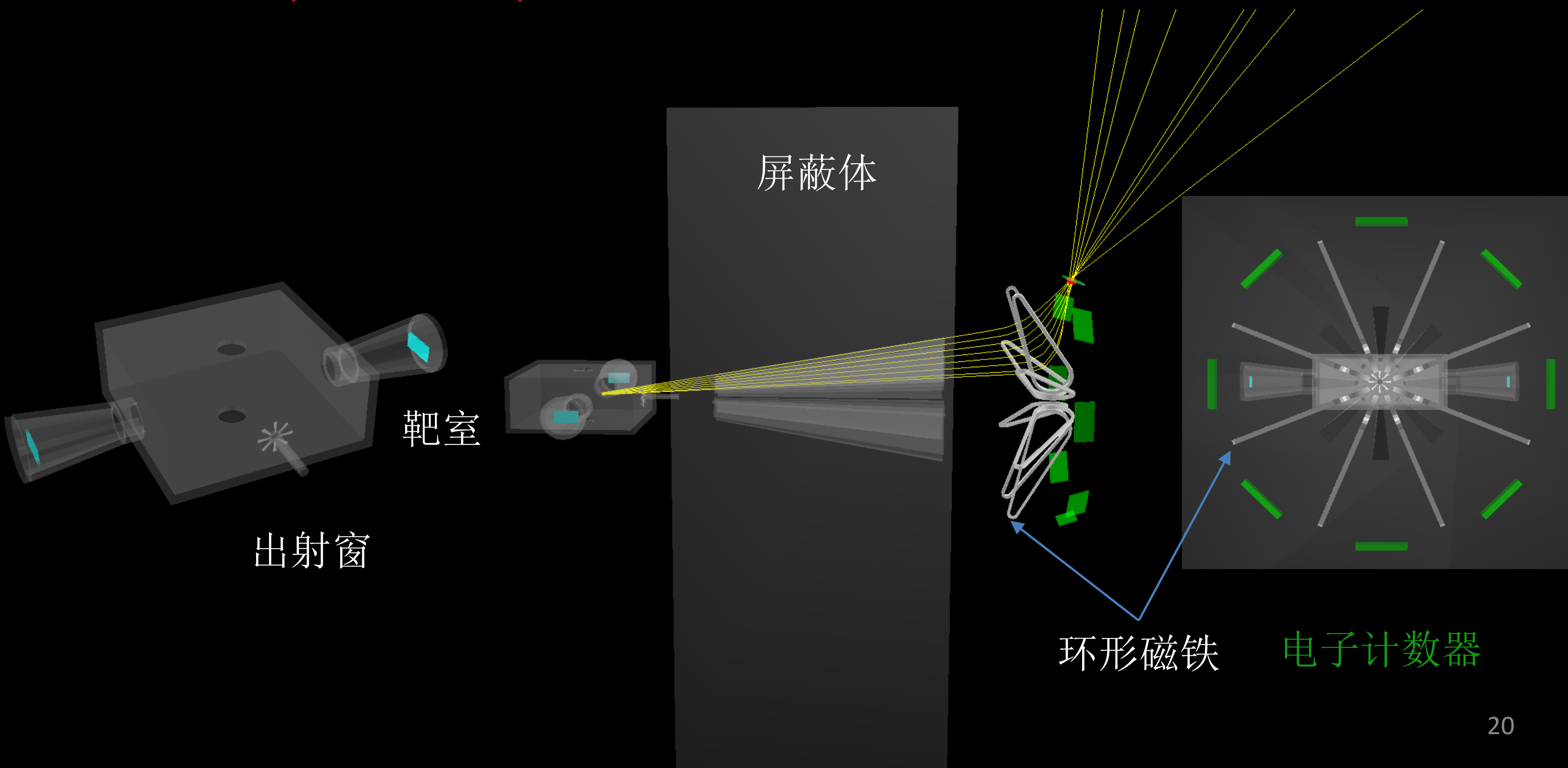
New physics search in $p\vec{e} \rightarrow pe$

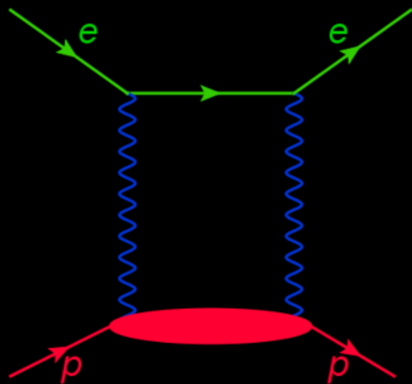


Advantages：

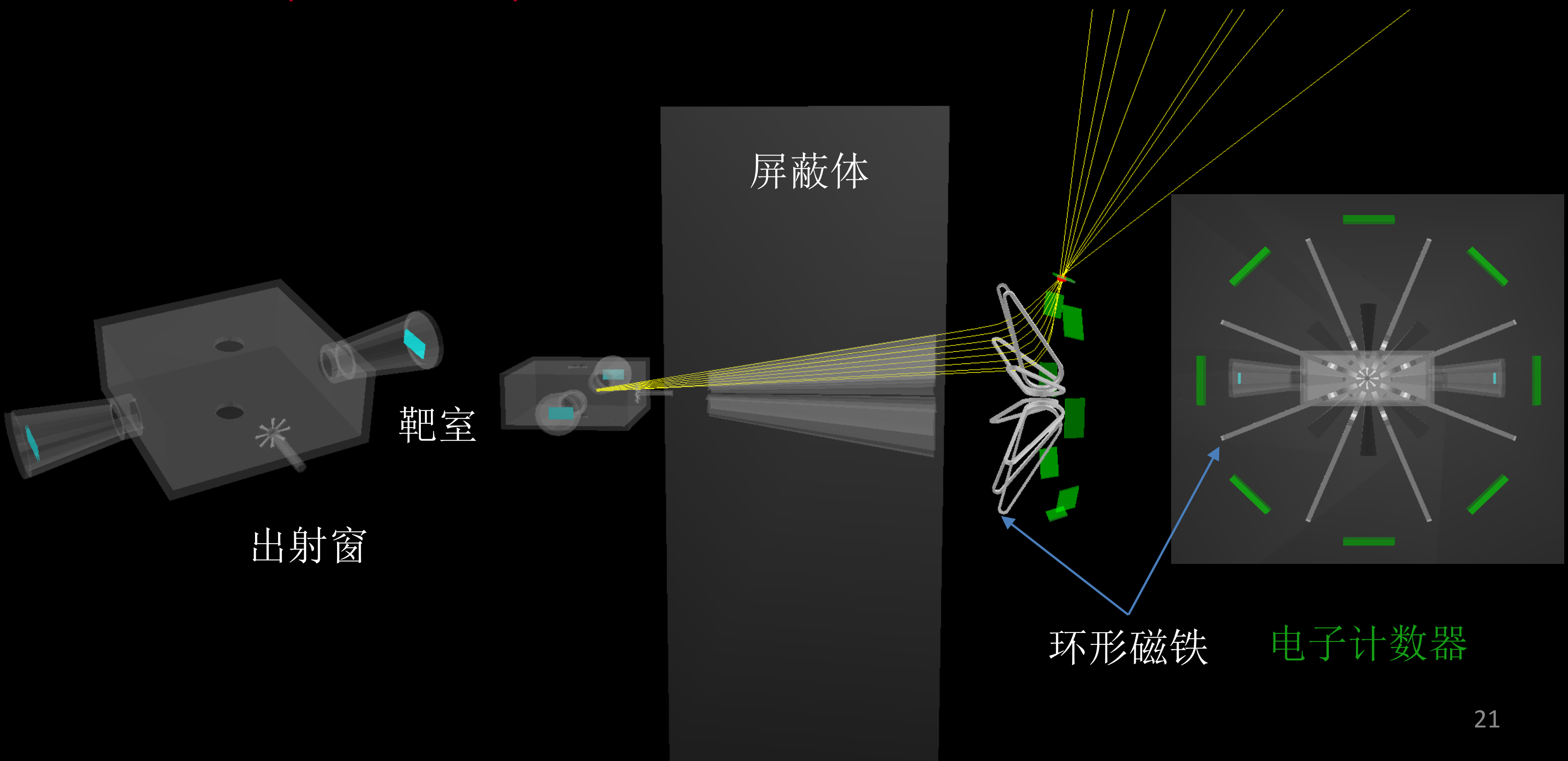
1. Low Q2 ➡ almost no background
2. Polarized target ➡ Large asymmetry



Proton from factor check at very low Q^2



- At very low Q^2: only G_E and G_M within SM
- New approach to constrain proton FFs



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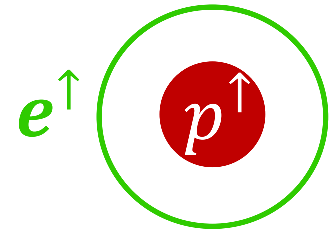
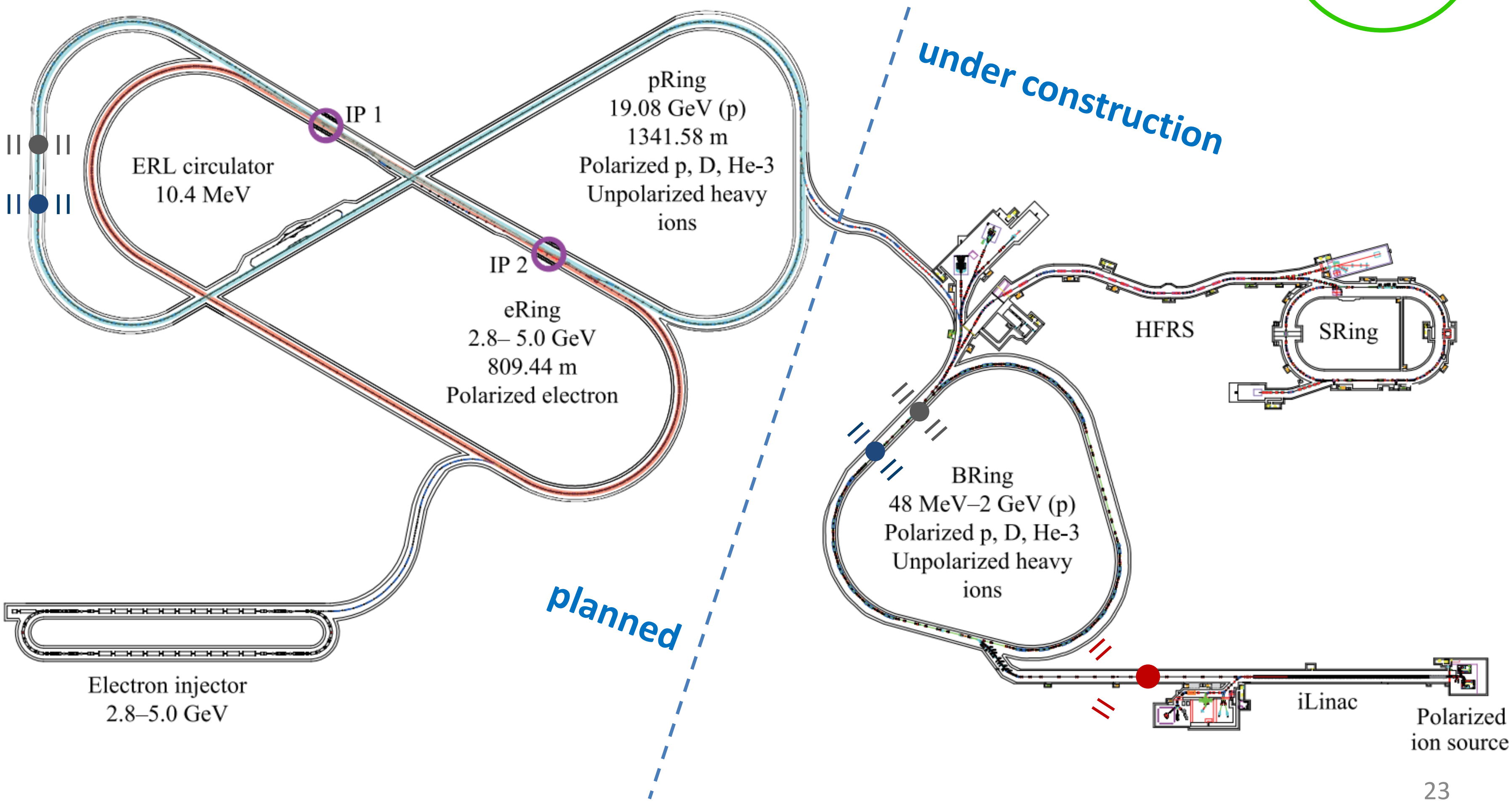
Opportunities in China

- HIAF is under construction
- EicC is being proposed
- **National Key R&D Program** received from MOST for polarized ion source and **polarized hydrogen target → pol. e^- target**





Summary

- Discrepancy between Rosenbluth separation and polarization transfer triggered the two-photon exchange (TPE) study.
- Transverse spin asymmetry ($A_\perp$) provide test ground to study TPE.
- Surprising theory-experiment discrepancies in both $A_\perp^{\vec{e}p}$ and $A_\perp^{\vec{e}A}$
- $A_\perp^{p\vec{e}}$ with polarized electron target is a clean observable to search new T-odd mechanisms ?
- Nice opportunities at proton machines (HIAF and EicC)
- Collaborations are more than welcome

Thanks for your attention !