Exclusive e^+e^- production at GlueX

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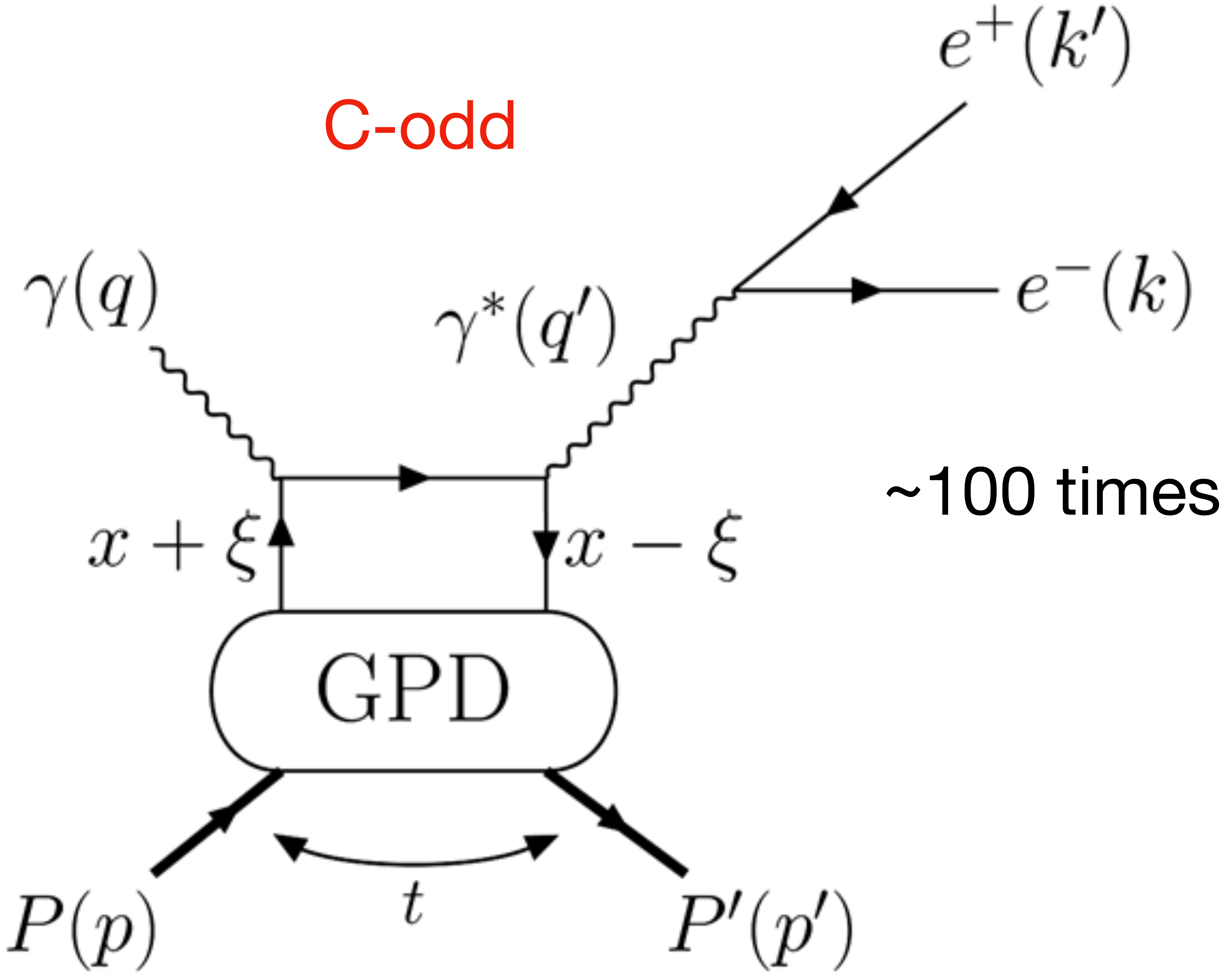
$$\gamma p \to e^+e^-p \text{ (TCS)}$$

$$\gamma p \to J/\psi p \to e^+e^-p$$

Timelike Compton Scattering (TCS)

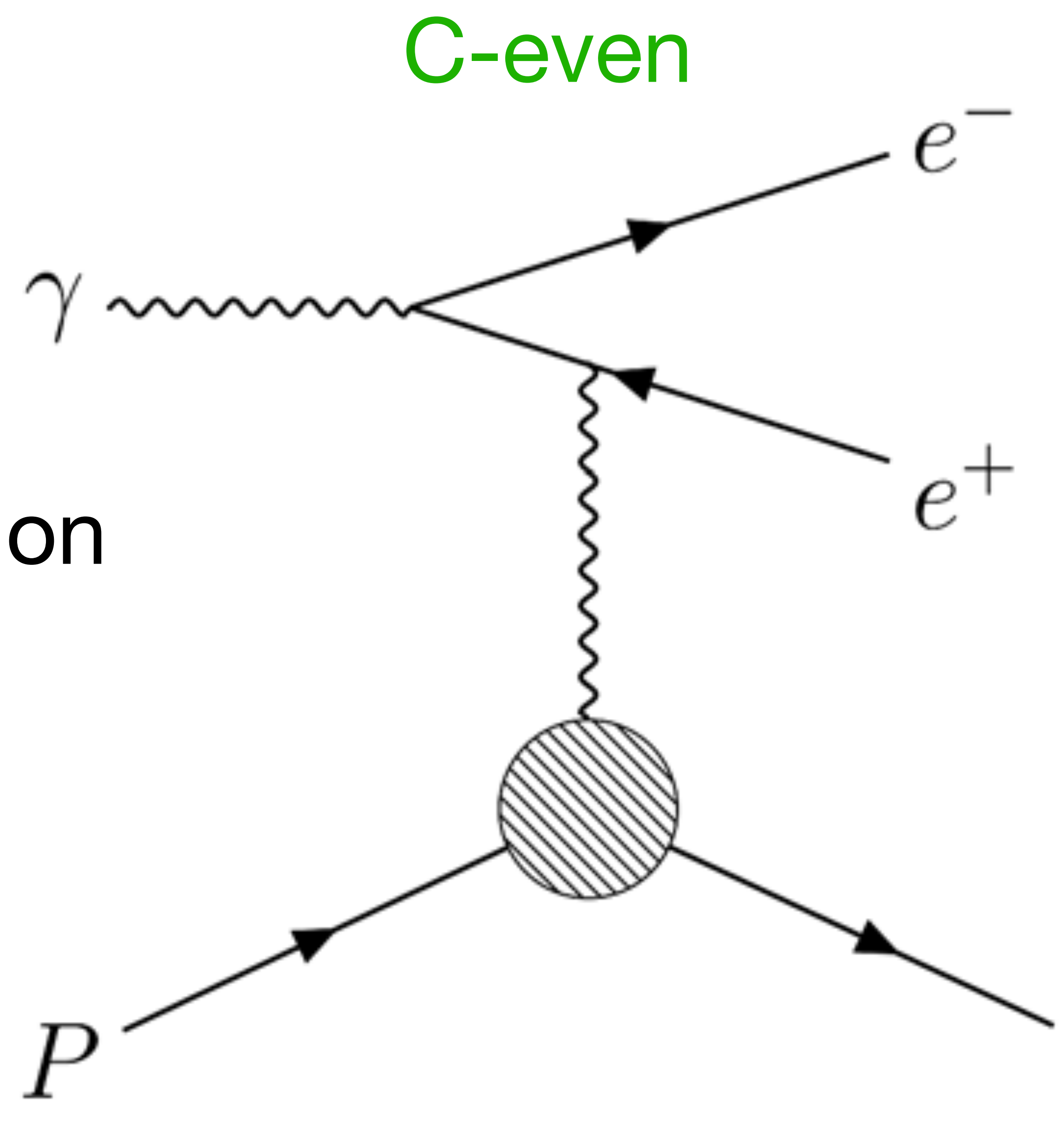
- $\gamma p \to p'\gamma^*$ with a high timelike virtuality
- Time-reversal symmetric process to DVCS ($\gamma^* p \to p'\gamma$)
- Gives access to the real part of Compton amplitude, and provides constraints for modeling the GPDs



TCS process

~100 times smaller cross section

$\ll$

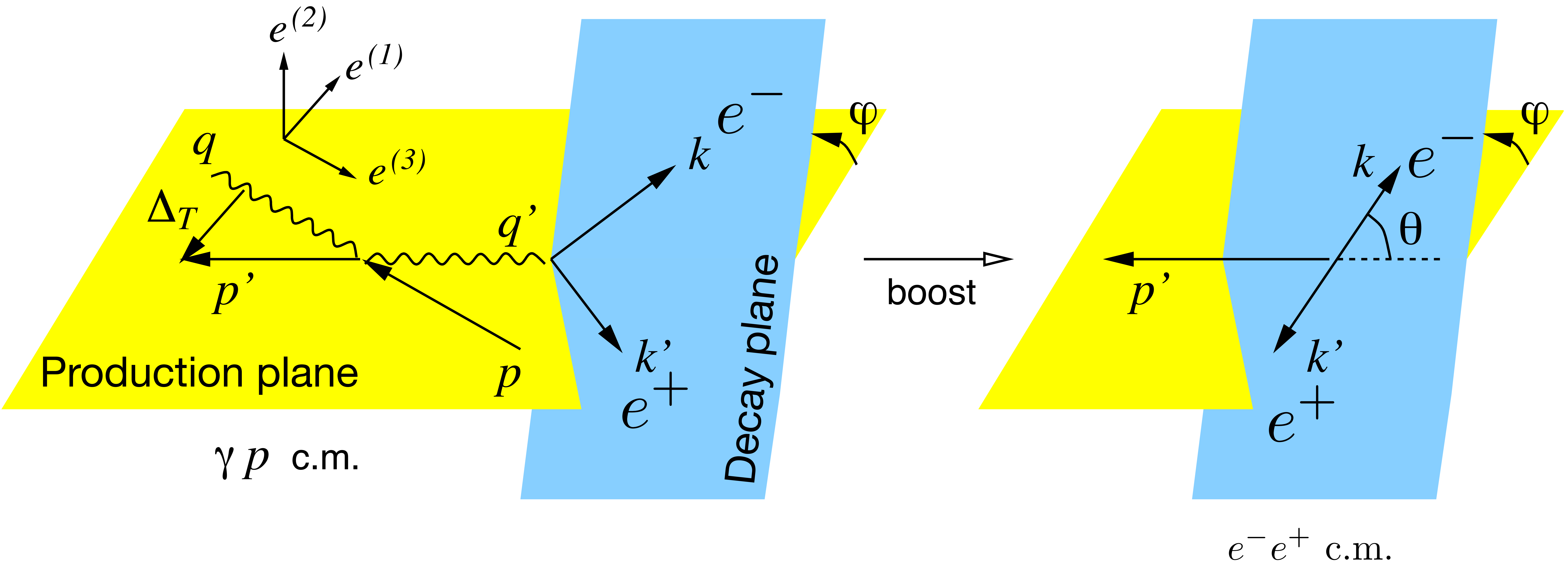


BH process

BH-TCS interference is projected out by measuring the asymmetry arising from the exchange of e^-e^+.

Forward-Backward Asymmetry (A_{FB})

Decay angles (θ, ϕ) of $\gamma^* \to e^- e^+$ in the helicity system

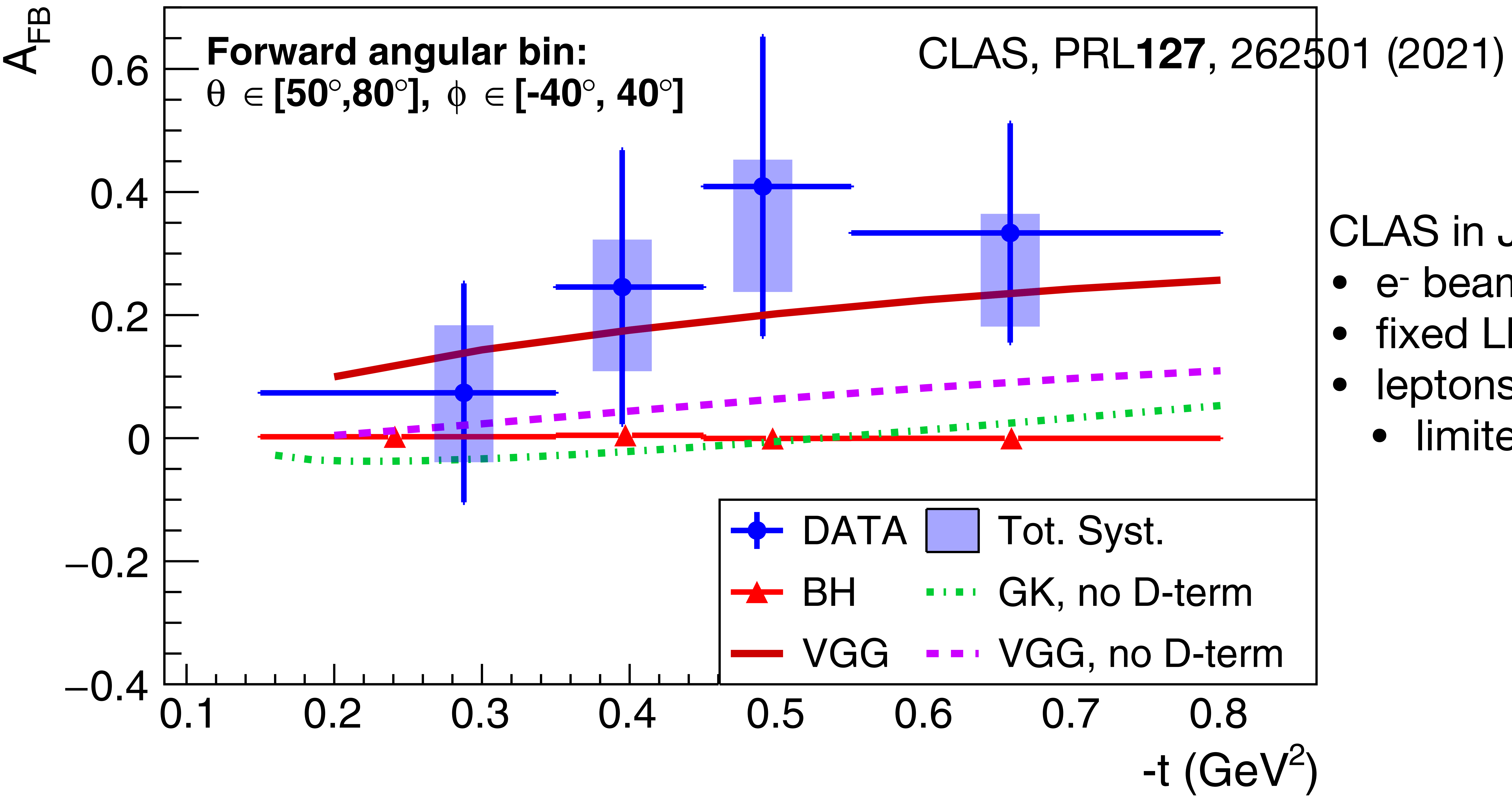


BH-TCS interference term is projected out

FB asymmetry .. asymmetry arising from the exchange of $e^- e^+$

$$A_{\mathrm{FB}}(E_\gamma, t, Q'^2, \theta, \phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi+\pi)} = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi) + d\sigma_{\mathrm{TCS}}(\theta,\phi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$

Forward-Backward Asymmetry (A_{FB})



CLAS in JLab/Hall B

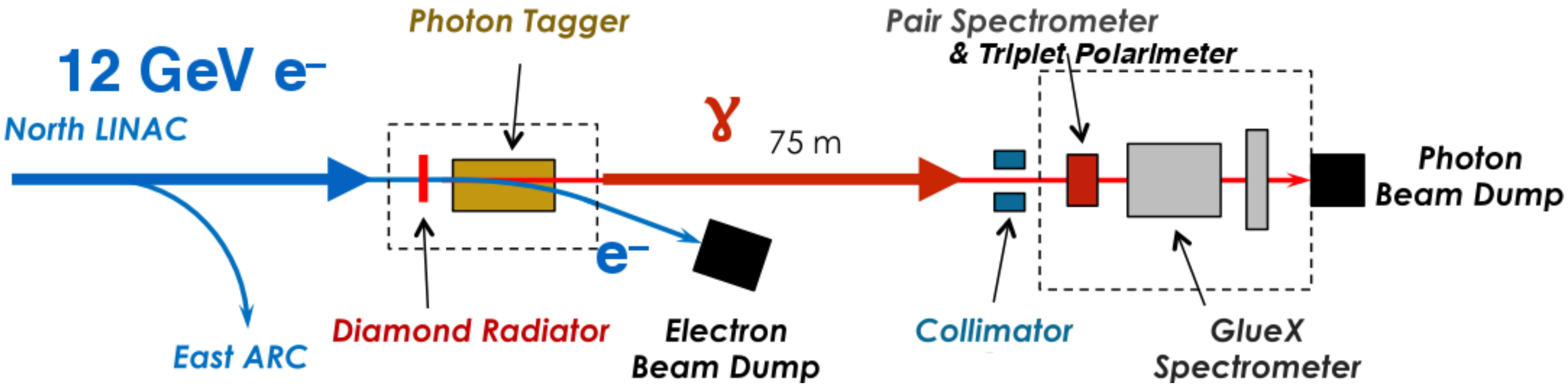
- e^- beam ($Q^2 < 0.15$ GeV^2 for this analysis)
- fixed LH_2 target
- leptons are detected at forward region
  - limited (θ, ϕ) acceptance

$$A_{\mathrm{FB}}(E_\gamma, t, Q'^2, \theta, \phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta, \phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta, \phi+\pi)} = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi) + d\sigma_{\mathrm{TCS}}(\theta,\phi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$

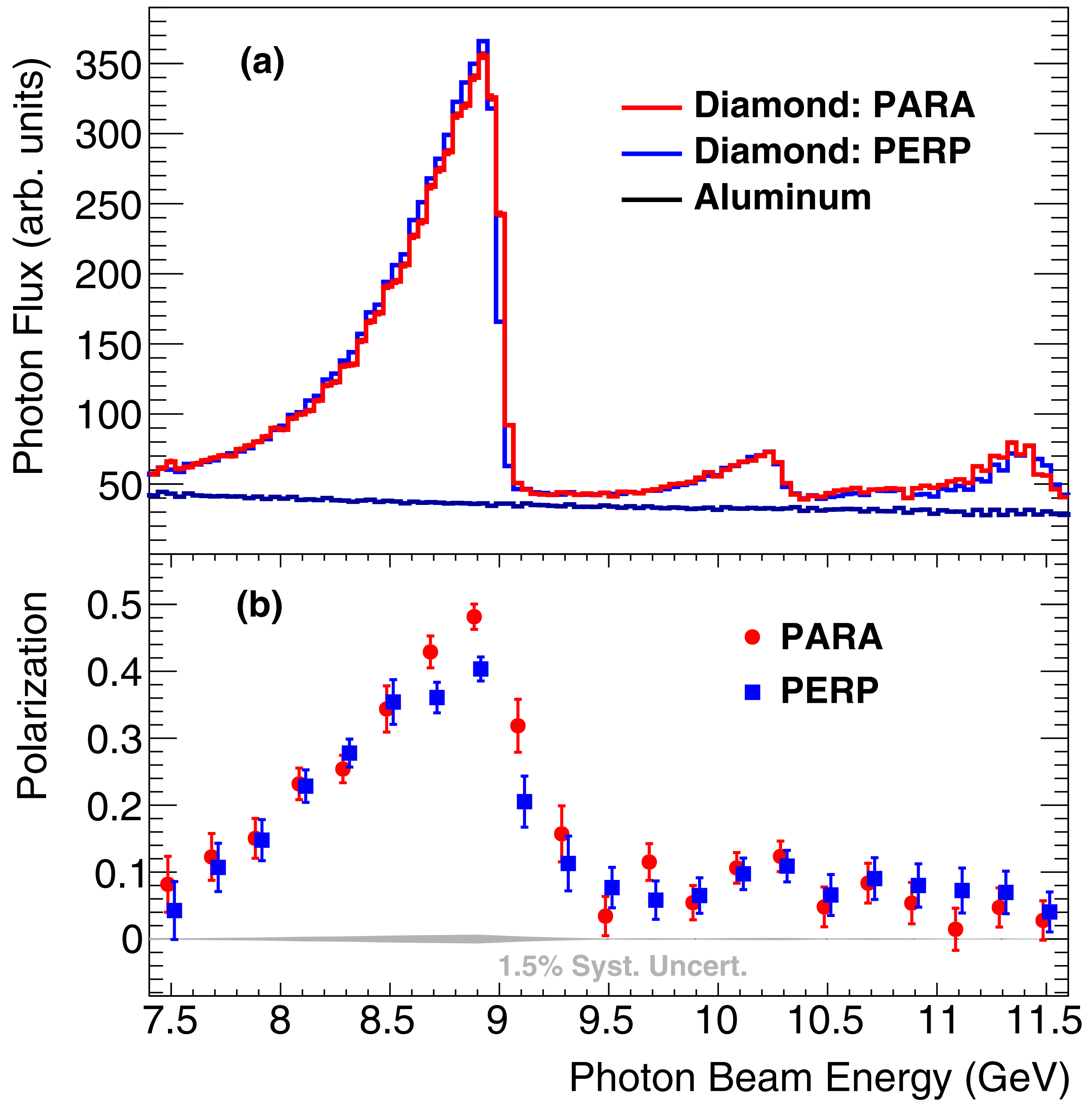
Non-zero asymmetries are expected due to the interference b/w BH and TCS.
→ confirmed by CLAS measurements in 2021.

GlueX can access wider (θ, ϕ) region.

JLab Hall D Apparatus

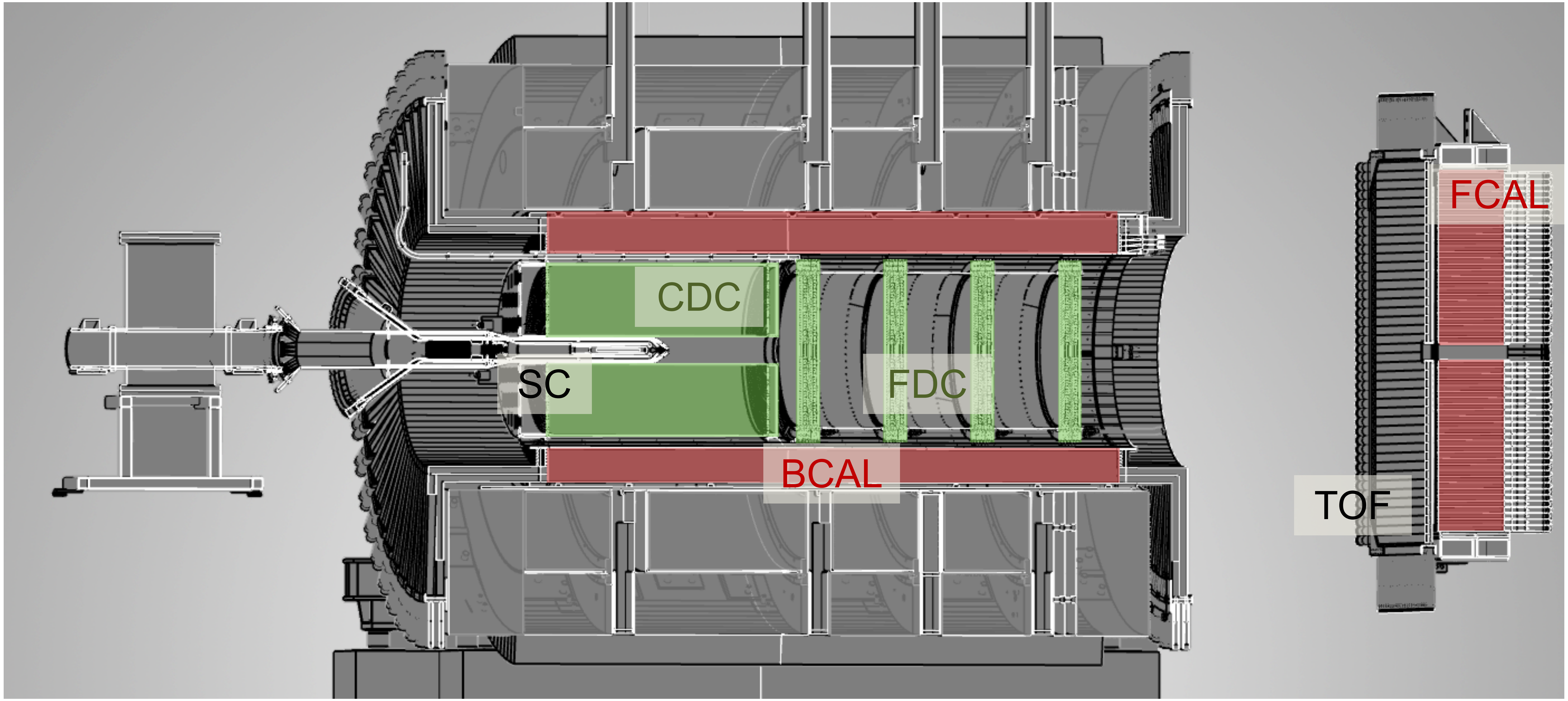


- Photon beam from coherent bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75 m, <35μrad
- Intensity: ~5×10^7 γ/sec ($8.4<E_\gamma<9.0$ GeV)
- Data sets: GlueX-I + 2020 (part of GlueX-II)



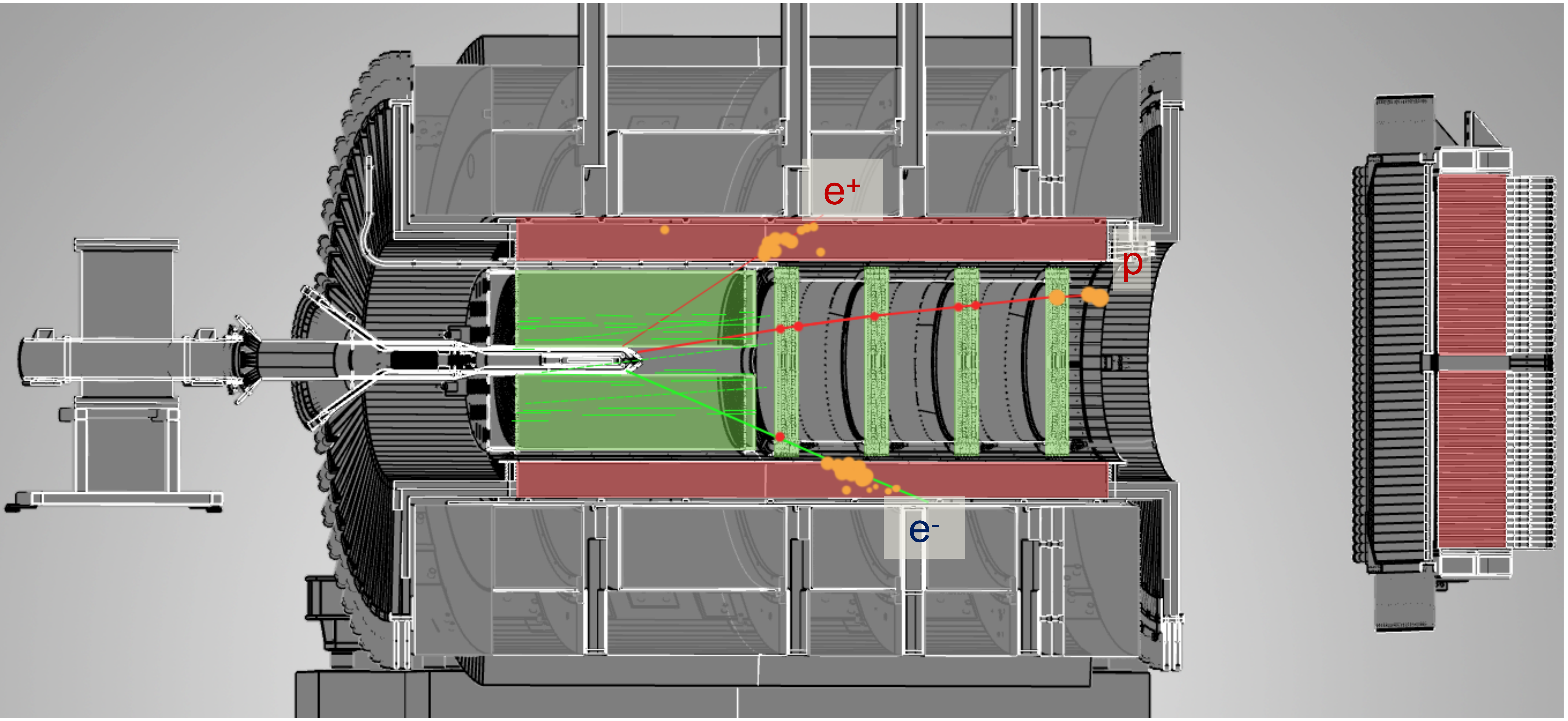
- FB asymmetry: Unpolarized asymmetry
  - Photon polarization is not required
  - Other polarized observables are useful to extract GPD info. (cf. M. Boër *et al.*, PoS(DIS2015)028, Future work)

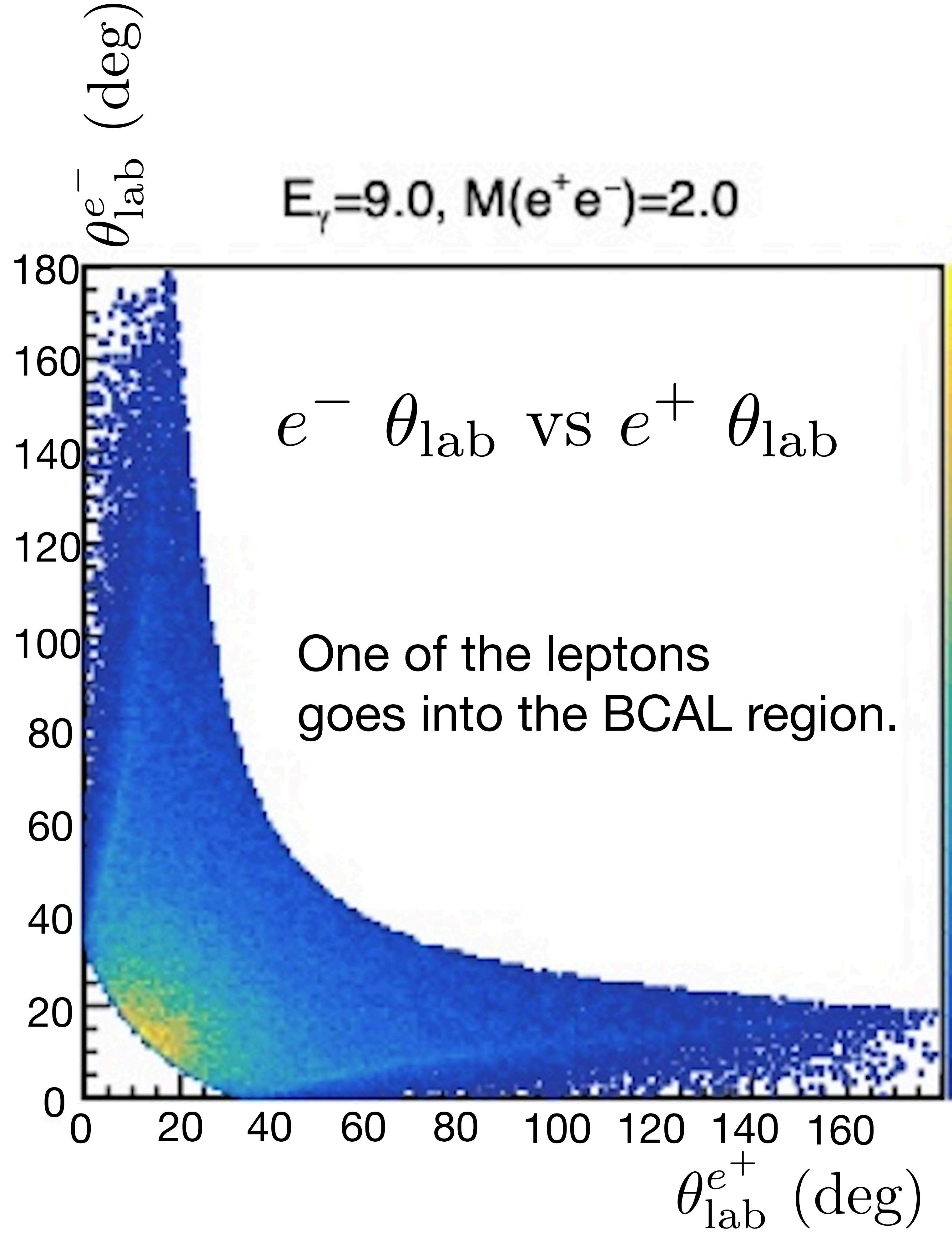
GlueX spectrometer



- 2T-Solenoid, LH_2 target
- Hermetic Detector: $1° < \theta_{lab} < 120°$, all ϕ_{lab}
  - Tracking by FDC ($\theta_{lab} < 11°$) and CDC ($\theta_{lab} > 11°$): $\sigma_p/p \sim 1\text{-}5\%$
  - Calorimetry by FCAL ($\theta_{lab} < 11°$) and BCAL ($\theta_{lab} > 11°$): $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$

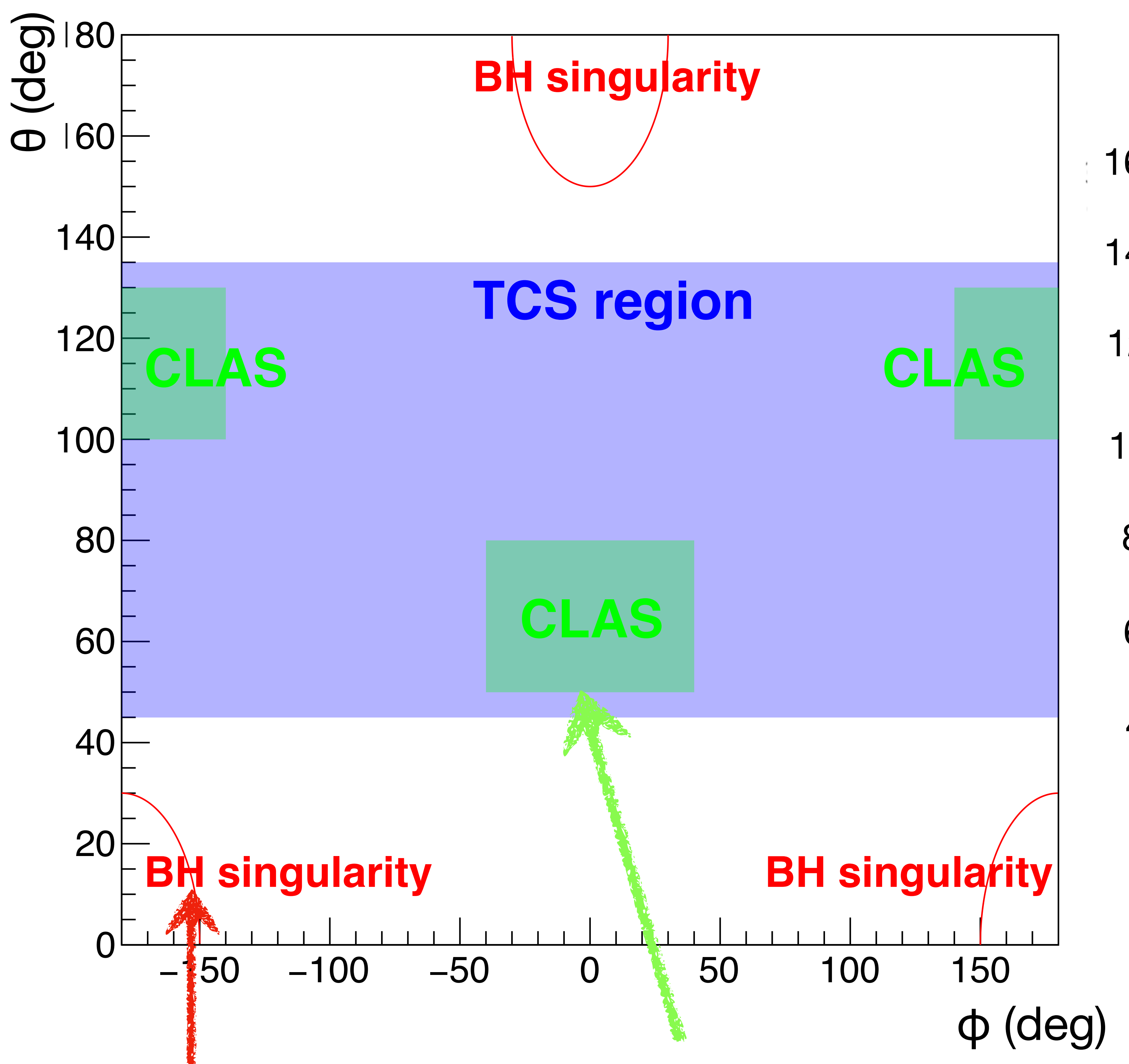
Exclusive reaction γp→e⁻e⁺p

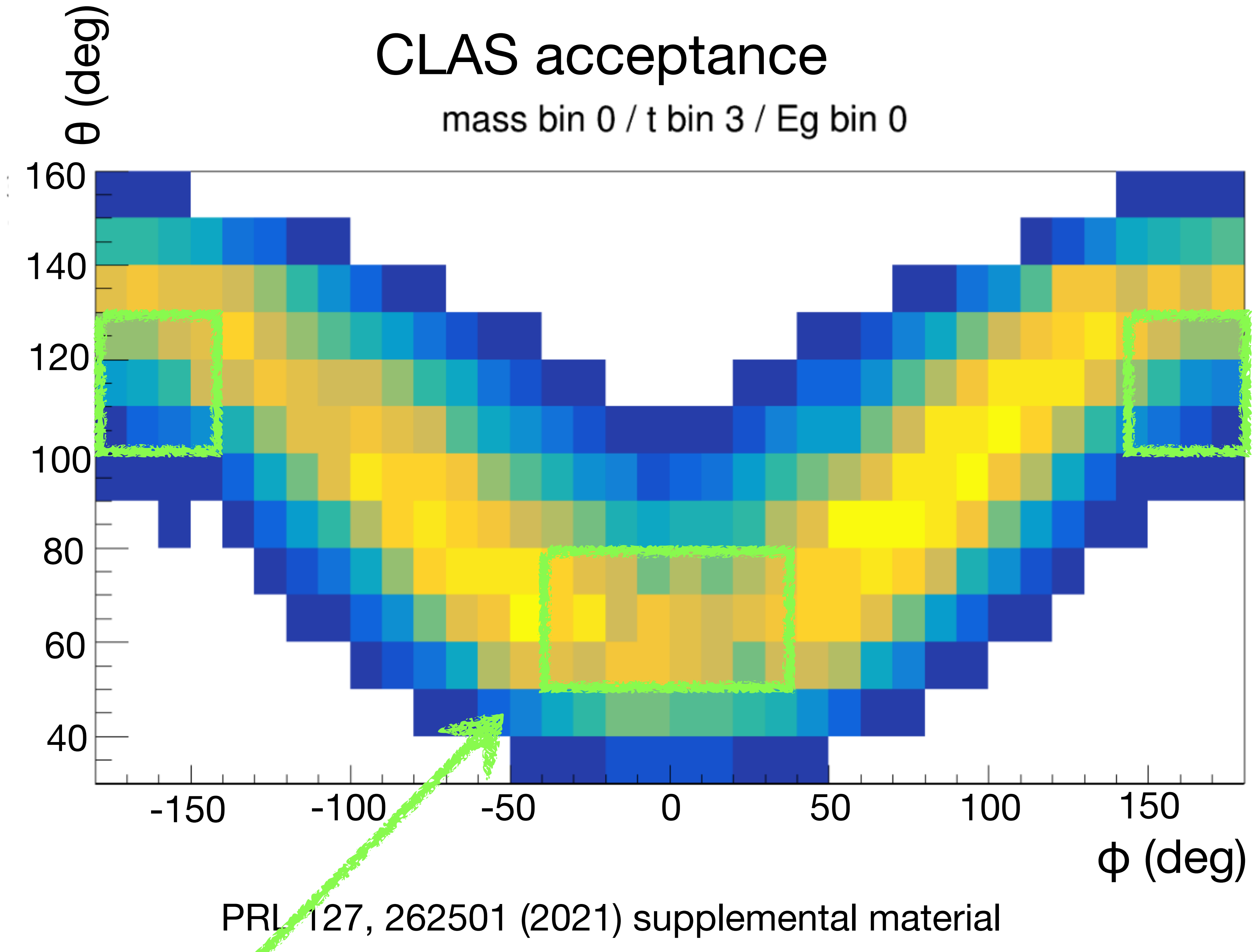


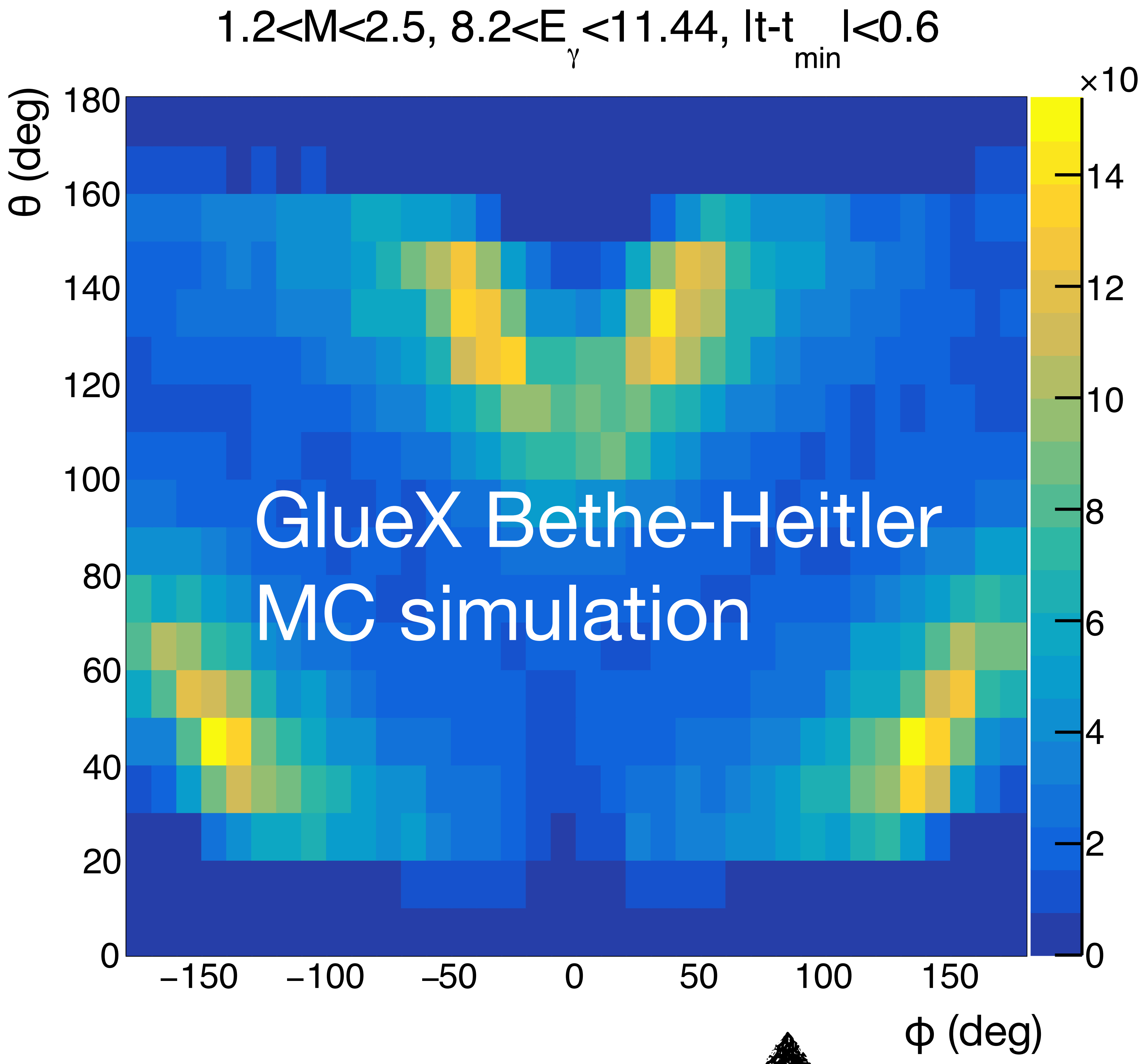


- Large acceptance .. we can access (θ, ϕ) dependence of the FB asymmetry
- e/π separation by p/E (Momentum over energy deposition in the calorimeters)

Experimental Acceptance







CLAS measured A_{FB} at 50°<θ<80°,-40°<ϕ<40°.
GlueX can access (θ, ϕ)-dependence.

At these BH singularity regions ($d\sigma_{BH}=\infty$), TCS information cannot be extracted. Instead, A_{FB} at these regions can be used for a cross-check of the acceptance calculations.

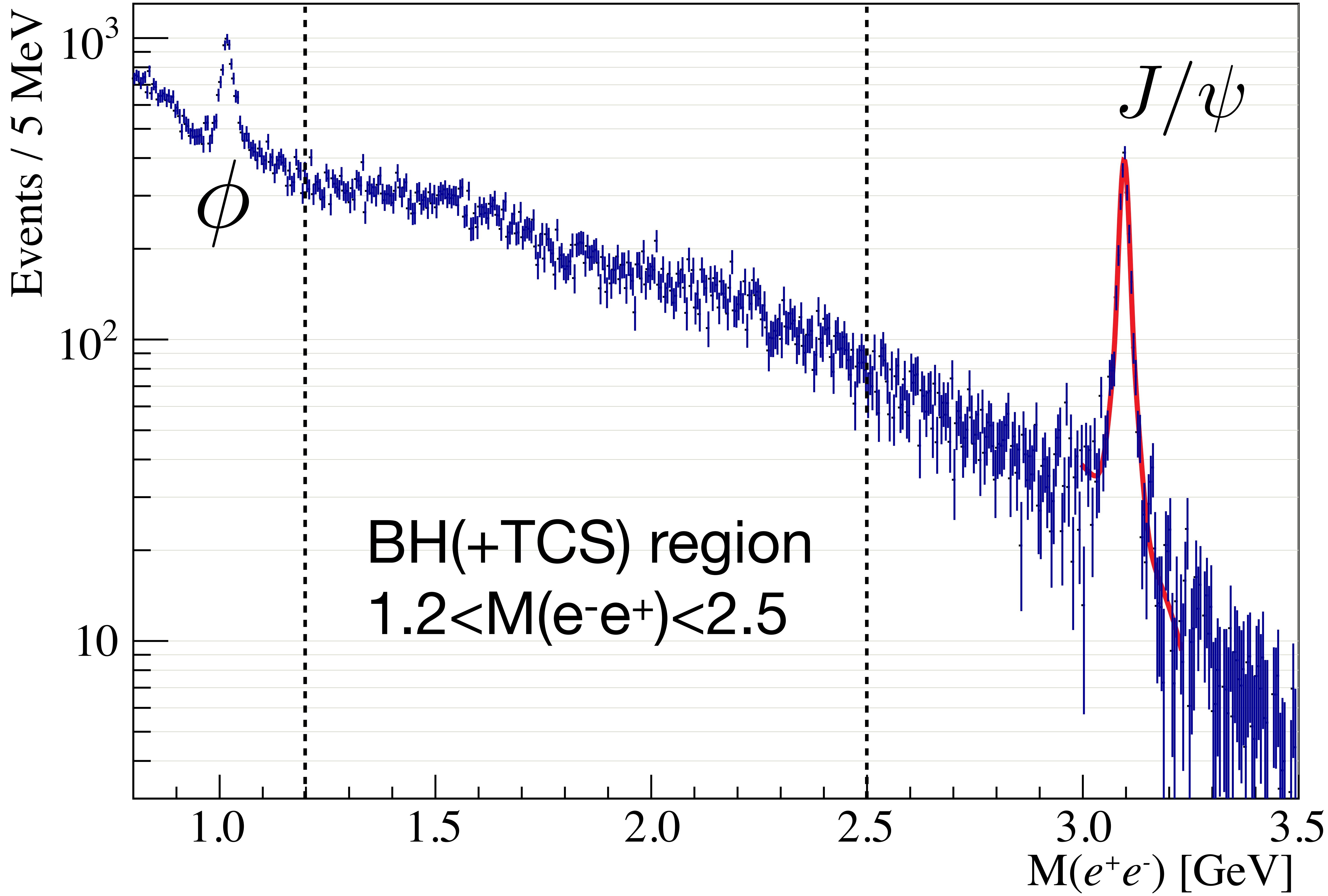
$$A_{\mathrm{FB}}(\theta,\phi)=\frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}=0\quad(d\sigma_{\mathrm{BH}}=\infty)$$

Thanks to hermeticity, GlueX has the large acceptance, and (θ, ϕ)-dependence of A_{FB} is accessible.

e/π separation by p/E

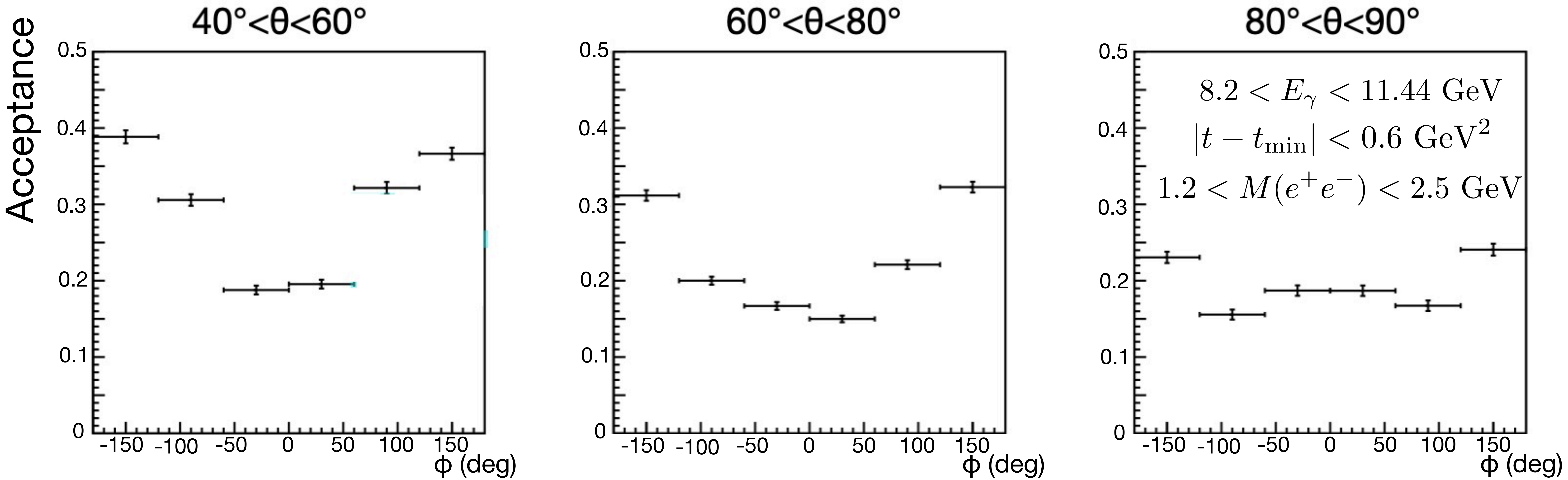
π BG sample is created by “anti-electron” cut ($\langle p/E\rangle+3.5\sigma < p/E < \langle p/E\rangle+4.5\sigma$).
Its scale is a fitting parameter.

e^-e^+ invariant mass spectrum



- Kinematic fitting (constrained mostly by the recoil proton)
- BH region (1.2-2.5 GeV) is used to obtain FB asymmetry
- J/ψ region can be used for a cross-check (J/ψ FB asym. = 0)

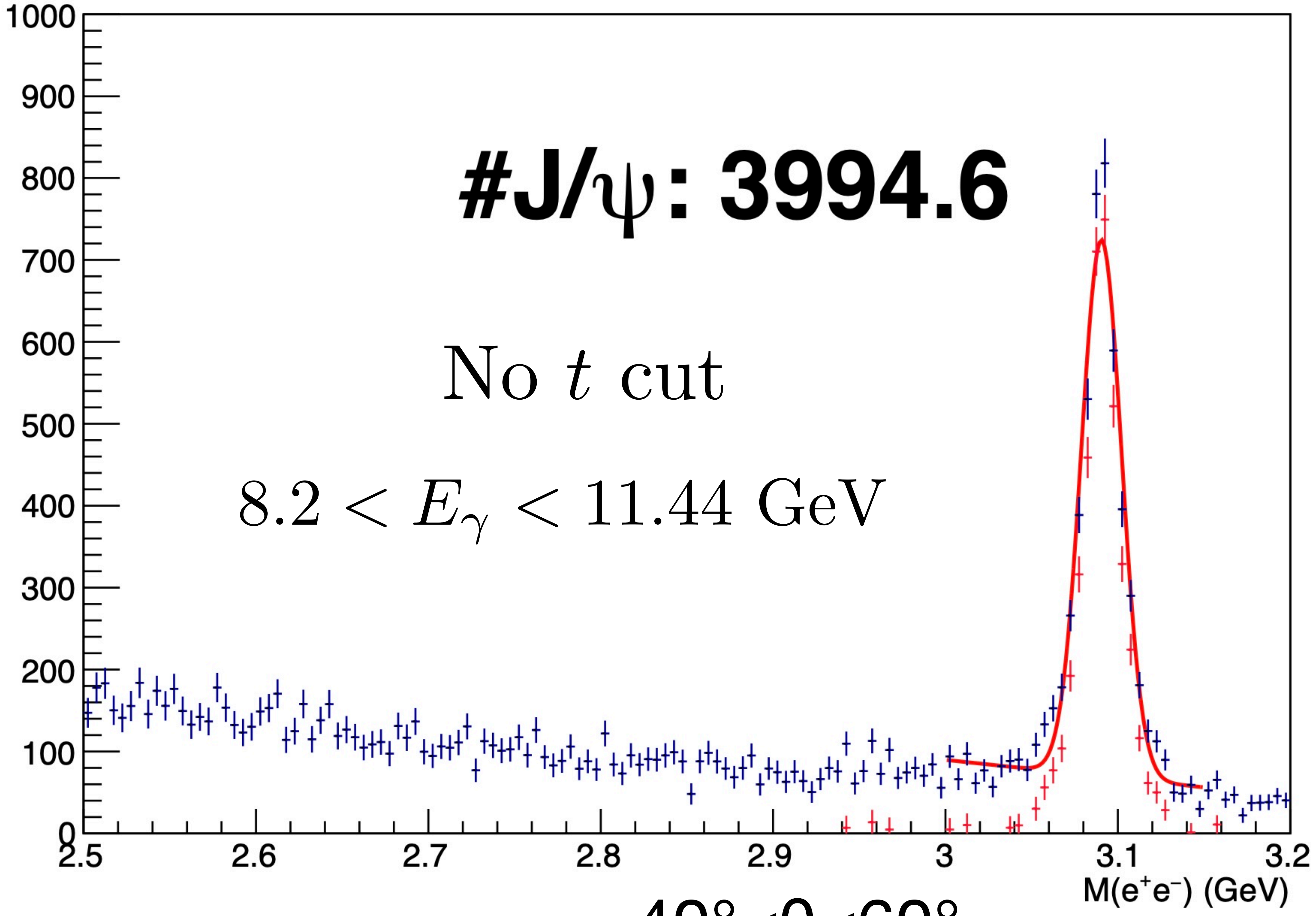
Acceptance correction by MC simulation



Acceptance correction is carried out by using MC samples.
To check the validity of this correction, following items are checked:

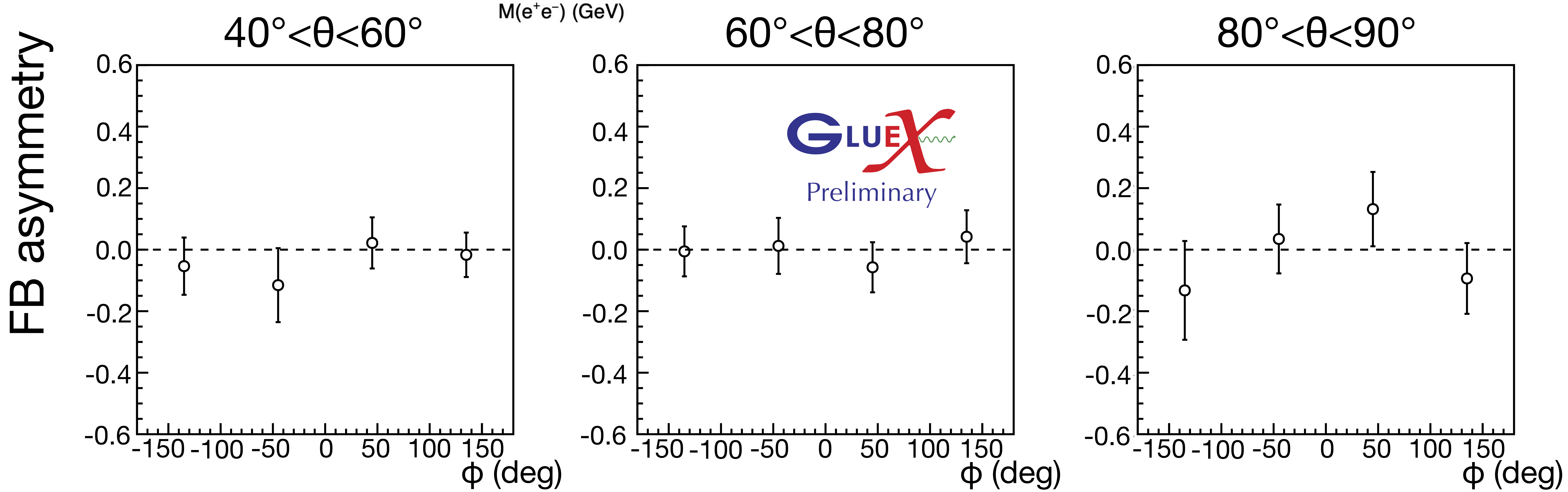
1. FB asymmetry for J/ψ should be zero consistent for any (θ, ϕ).
2. Acceptance is corrected by π sample (assuming A_{FB} for $\gamma p \rightarrow \pi^+\pi^- p$ is zero).
3. FB asymmetry for BH singularity regions should be zero consistent.

Cross-check 1. FB-asymmetry for J/ψ



$A_{FB}(\theta, \phi) = 0$ for J/ψ since J/ψ doesn't care about the charge exchange of daughter particles (e^+e^-).

Obtained Zero-consistent $A_{FB}(\theta, \phi)$ for J/ψ at any angle (θ, ϕ).



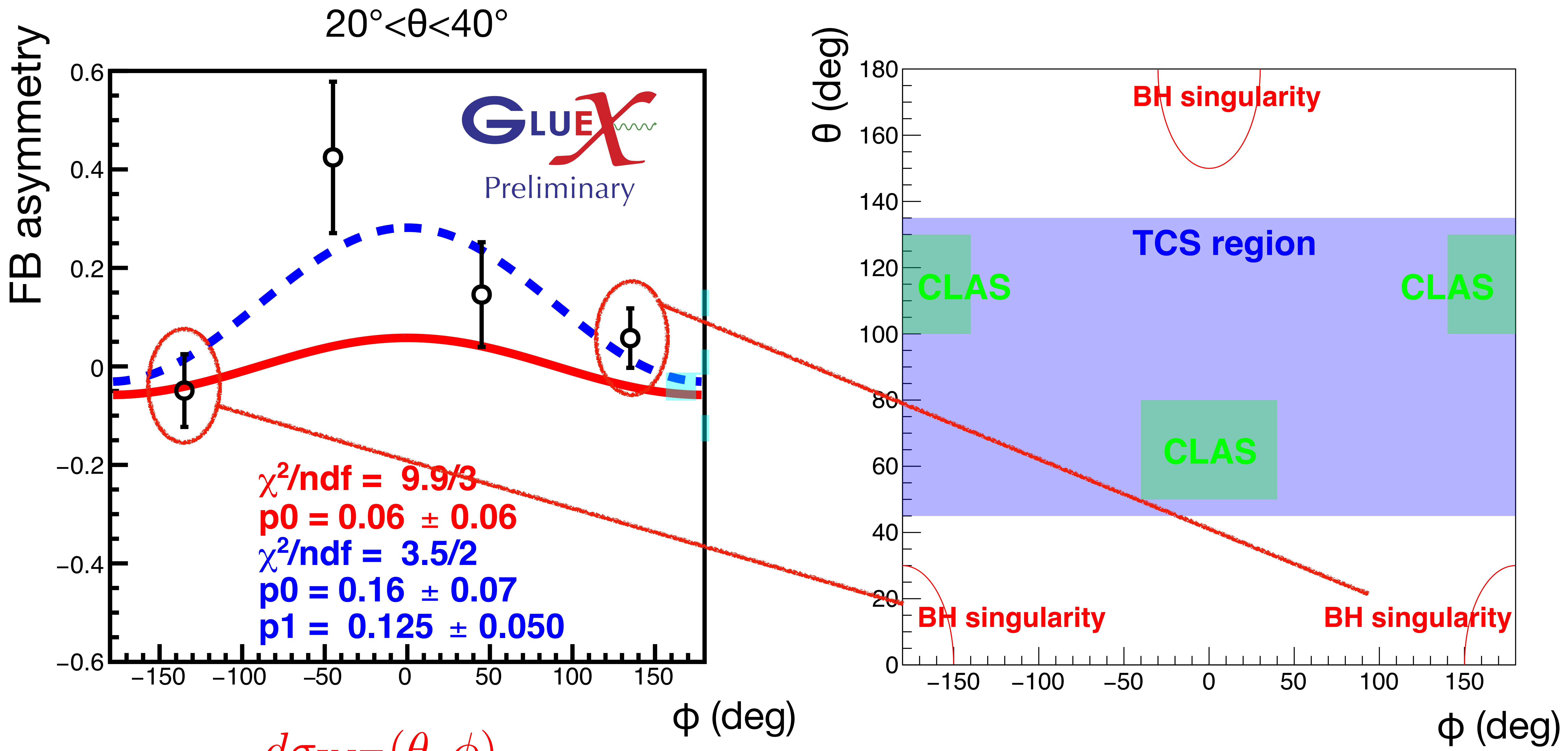
Cross-check 2. Correction with π events (w/o MC)

Assuming pion A_{FB}=0, efficiencies can be corrected using pion events.

$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)} \approx \frac{\frac{\mathrm{yield}_{e^+e^-}(\theta,\phi)}{\mathrm{yield}_{\pi^+\pi^-}(\theta,\phi)} - \frac{\mathrm{yield}_{e^+e^-}(180^\circ-\theta,180^\circ+\phi)}{\mathrm{yield}_{\pi^+\pi^-}(180^\circ-\theta,180^\circ+\phi)}}{\frac{\mathrm{yield}_{e^+e^-}(\theta,\phi)}{\mathrm{yield}_{\pi^+\pi^-}(\theta,\phi)} + \frac{\mathrm{yield}_{e^+e^-}(180^\circ-\theta,180^\circ+\phi)}{\mathrm{yield}_{\pi^+\pi^-}(180^\circ-\theta,180^\circ+\phi)}}$$

Overall, the results are consistent with MC-based efficiency calculations.

Cross-check 3. A_{FB} at BH singularity regions



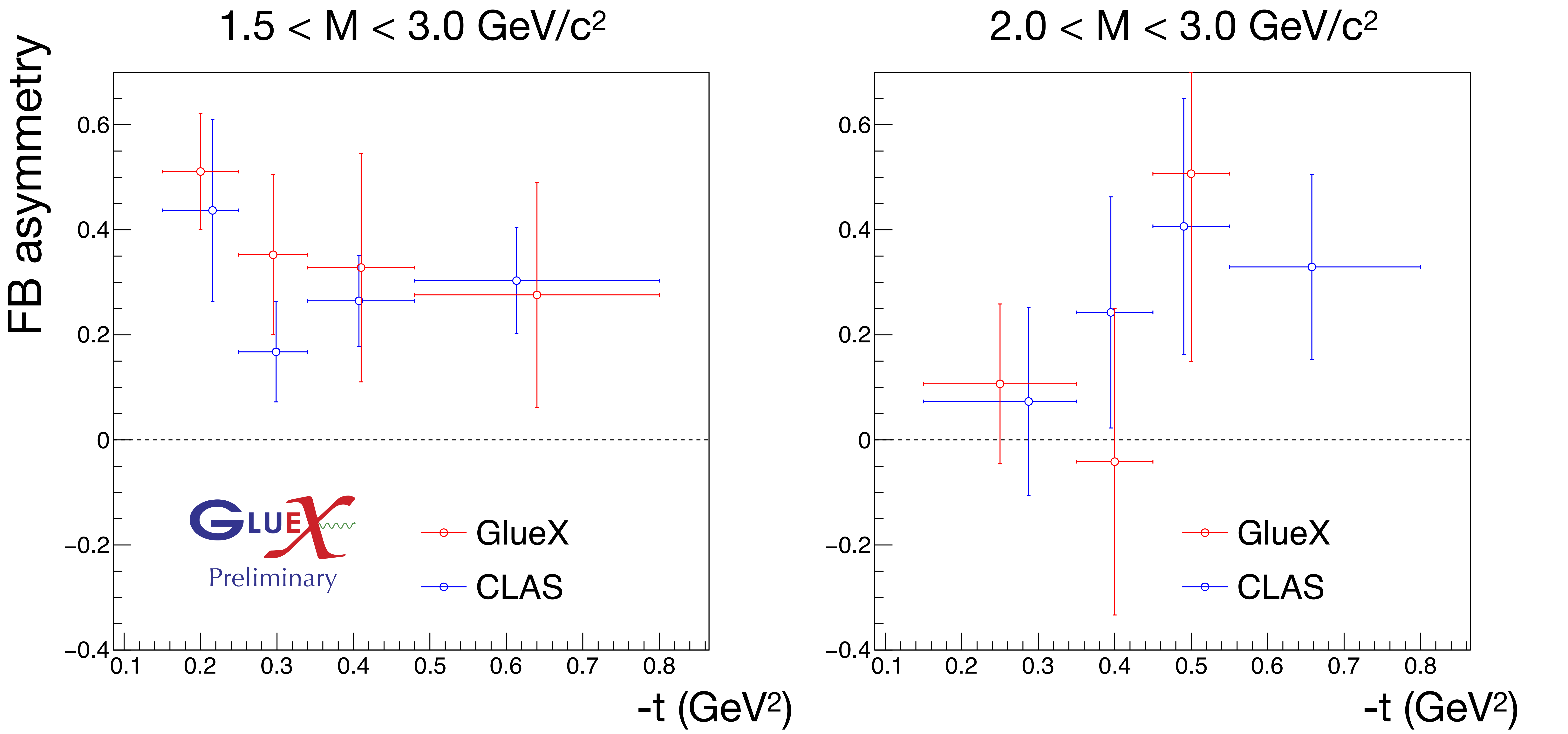
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)} = 0 \quad (d\sigma_{\mathrm{BH}} = \infty)$$

At BH singularity regions, A_{FB} is reasonably zero-consistent.

Comparison with CLAS results

$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi+\pi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$

at 50°<θ<80°, -40°<ϕ<40° (CLAS region)



GlueX shows consistent results with CLAS at their (50°<θ<80°, -40°<ϕ<40°) region.

(θ, ϕ)-dependence of the FB asymmetry

Red: cosϕ (w/o offset term)
Blue: cosϕ + constant term

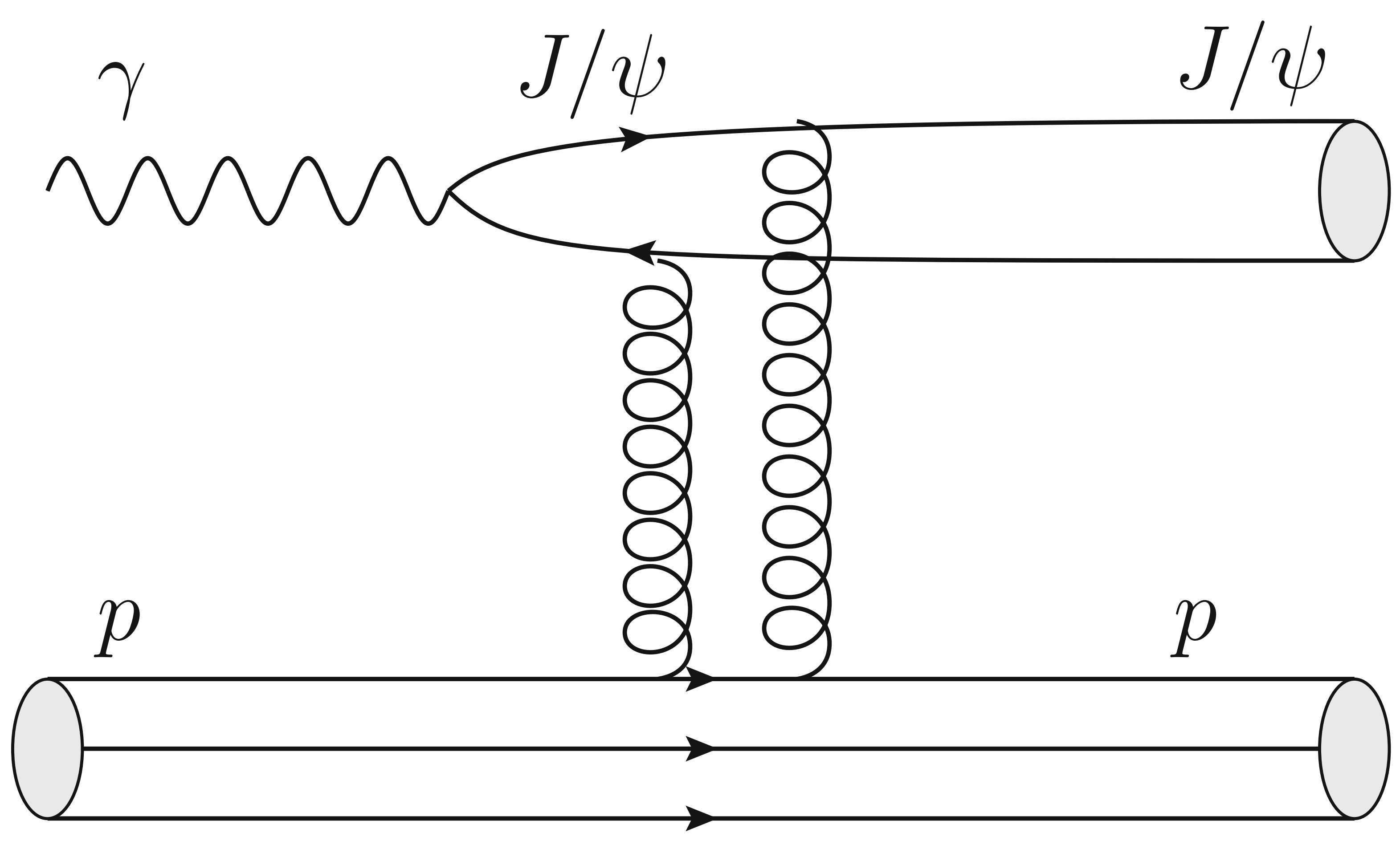
At small θ, ϕ-dependence of $A_{FB}(\theta,\phi)$ cannot be explained by the simple cosϕ shape w/o constant term.

Theory papers predict ~cosϕ shape w/o constant term at TCS region (45°<θ<135°).

Berger *et al.*, EPJC**23**, 675 (2002)

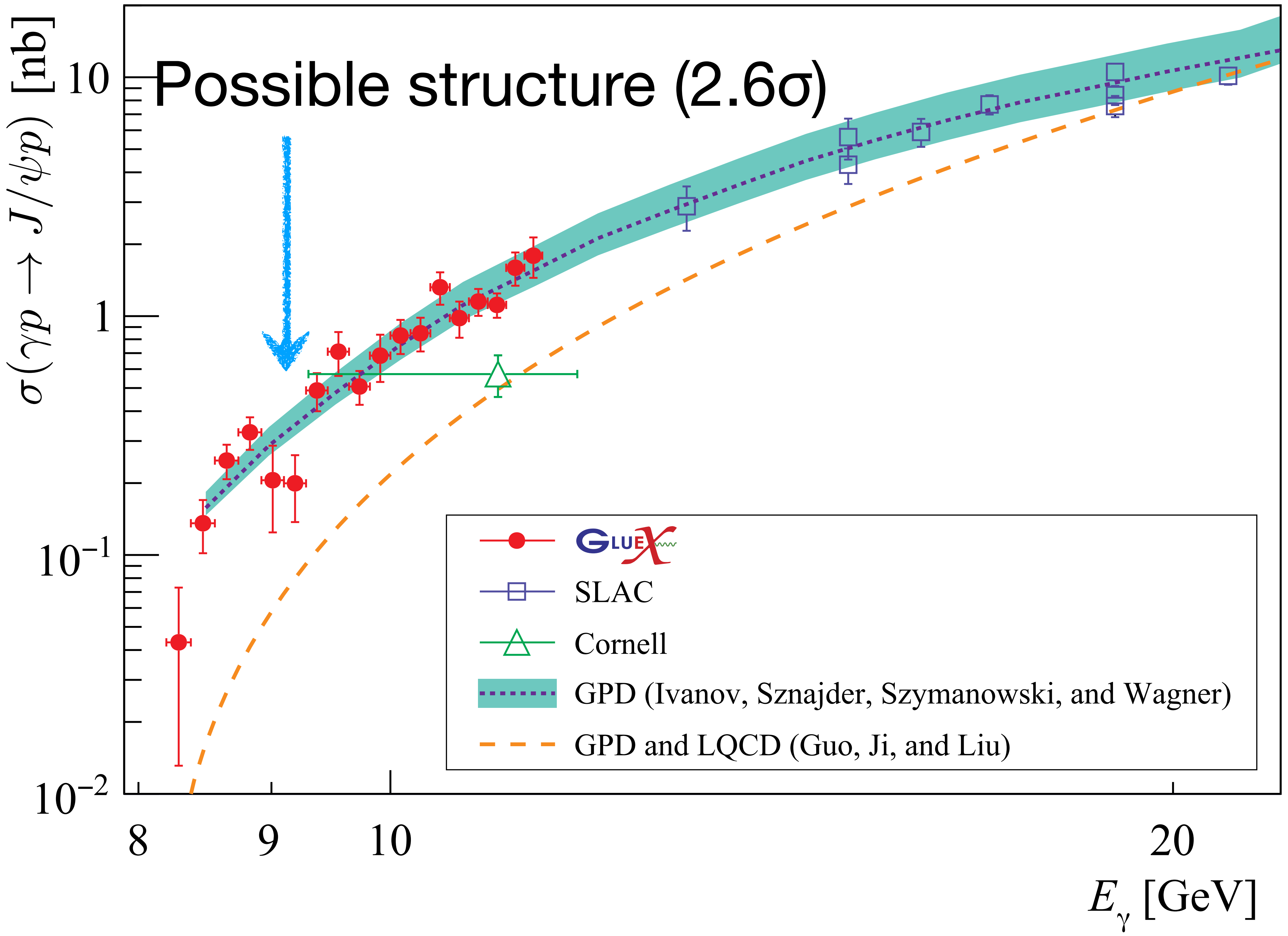
Simonetta Liuti reported a problem in the calculations. Needs more discussions with theorists.

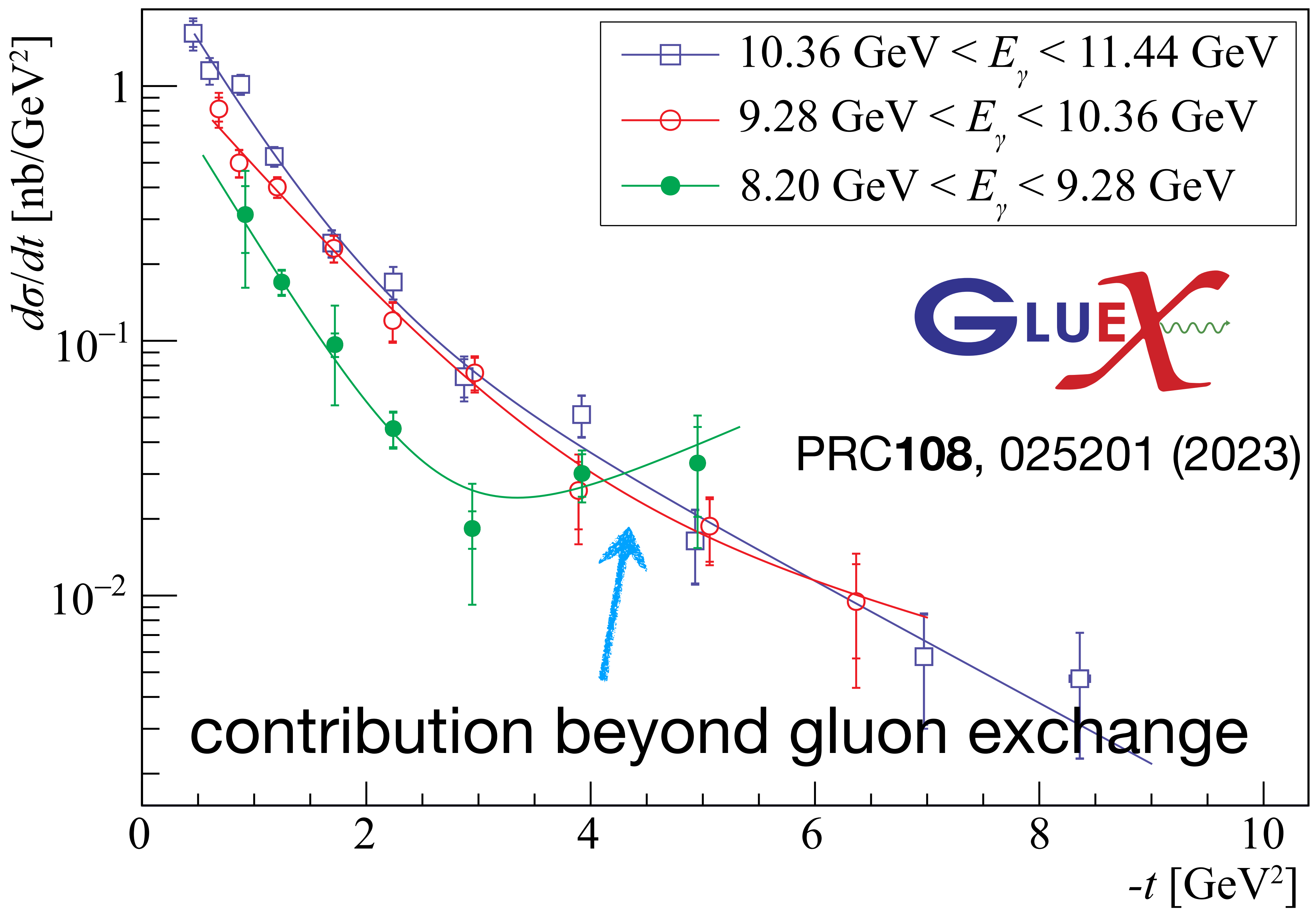
$\gamma p \to J/\psi p \to e^+e^-p$ near threshold



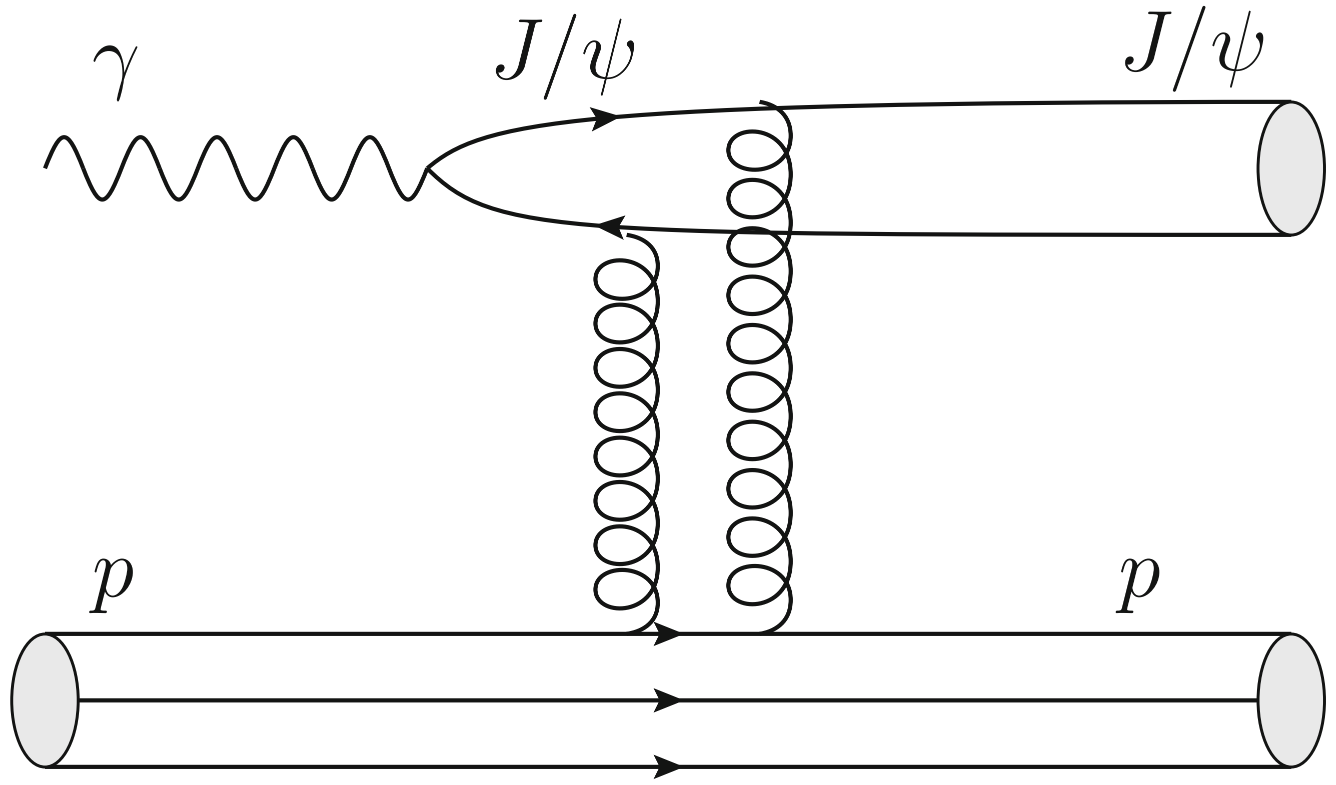
J/ψ production as a probe of the gluon distribution of the proton
→ mass radius of the proton & D-term can be accessible

“If” the gluon exchange process is dominant

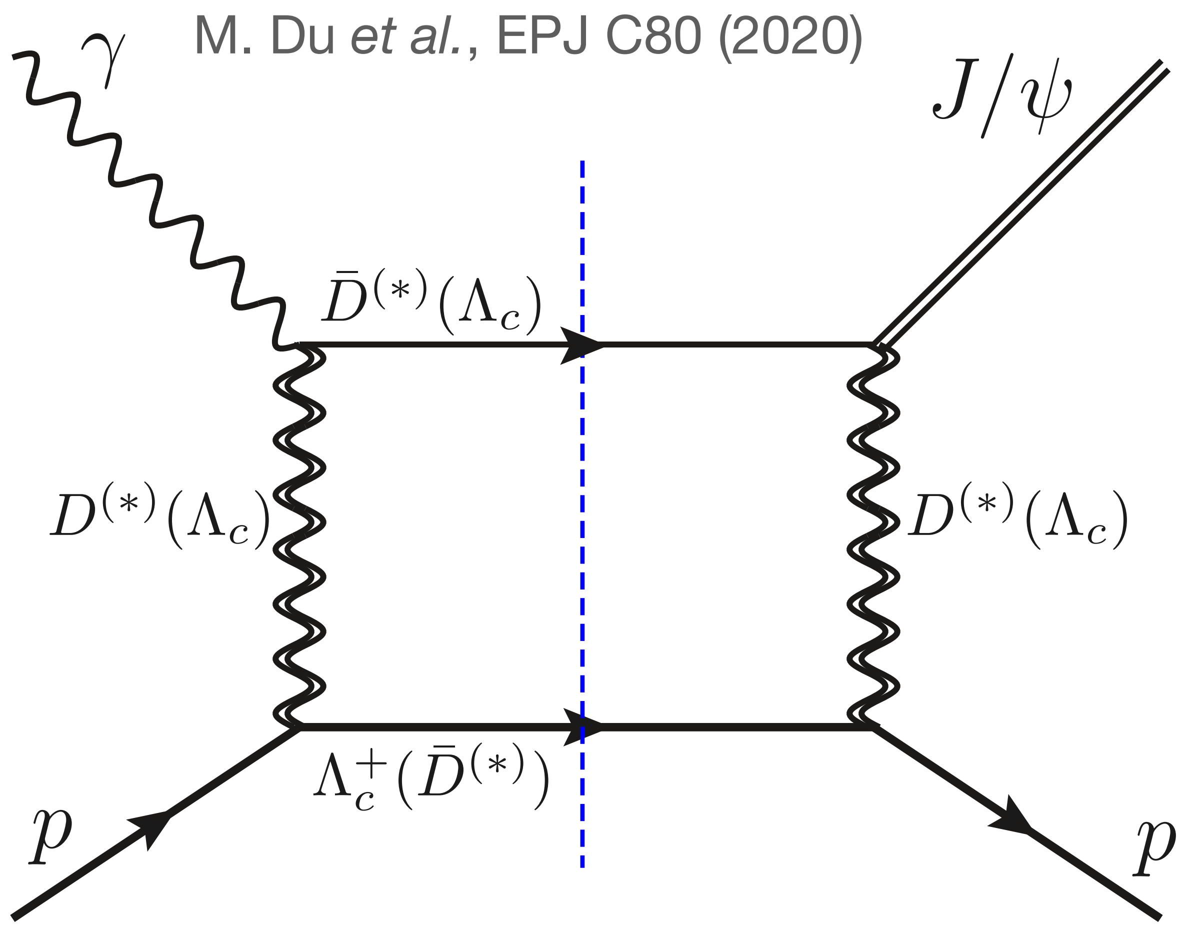




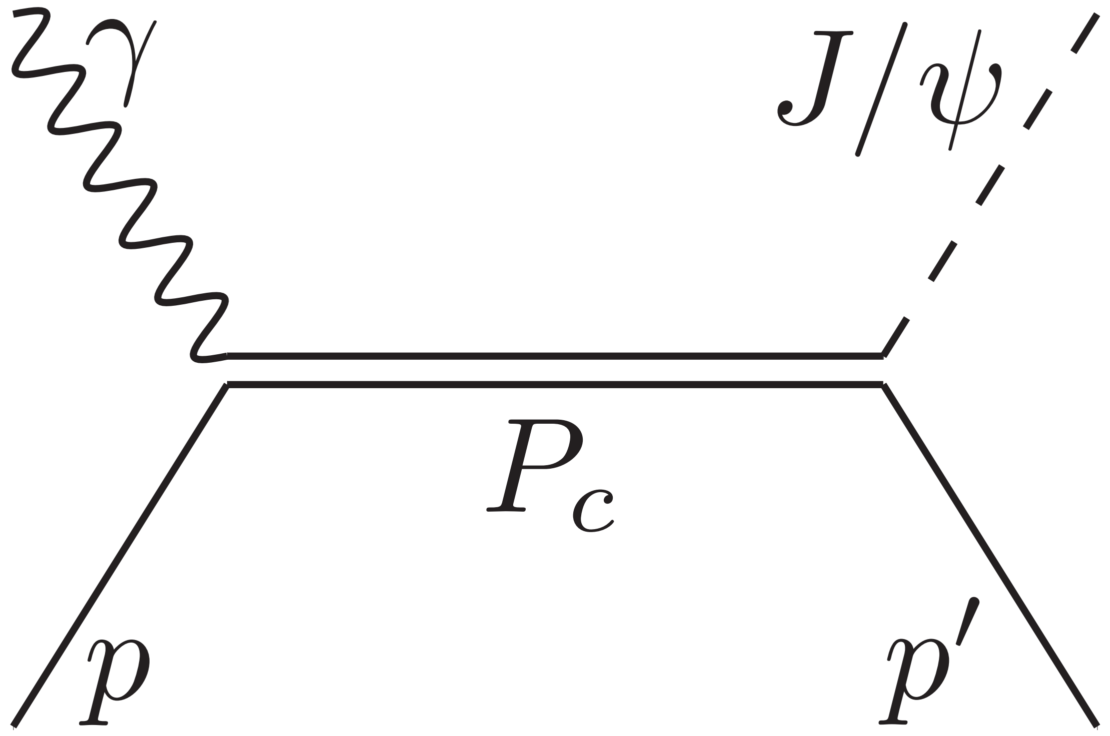
- High E_γ region is well explained by Pomeron model.
- Production mechanism near threshold has to be pinned down before extracting gluonic properties of the proton.



Gluon exchange?



Open-charm?



Pentaquark?

In addition to σ_{total} and $d\sigma/dt$ measurements,
Spin observables (SDME) place stringent constraints on models!

9 SDMEs ($\rho^{\alpha}_{\lambda\lambda'}$) describes the decay angular distribution with the linear polarization.

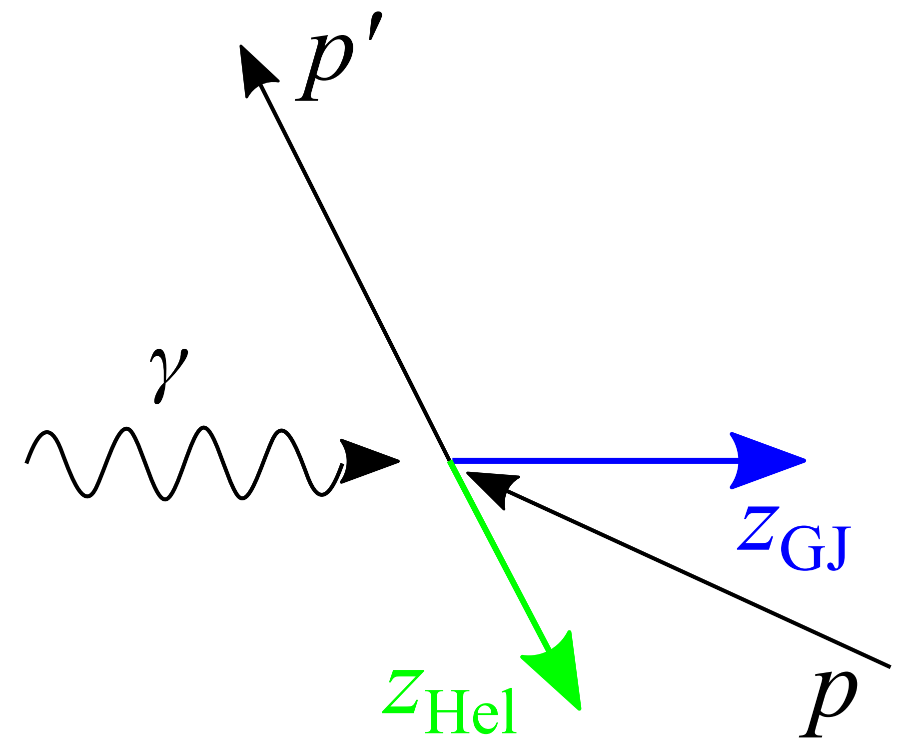
$$W = W^0(\cos\theta,\phi) - W^1(\cos\theta,\phi)P_\gamma \cos 2\Phi - W^2(\cos\theta,\phi)P_\gamma \sin 2\Phi$$

$$W^0(\cos\theta,\phi) = \frac{3}{8\pi}\left(\frac{1+\rho^0_{00}}{2} - \frac{3\rho^0_{00}-1}{2}\cos^2\theta + \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\theta\cos\phi + \mathrm{Re}\rho^0_{1-1}\sin^2\theta\cos 2\phi\right)$$

$$W^1(\cos\theta,\phi) = \frac{3}{8\pi}\left(\rho^1_{11}\left(1+\cos^2\theta\right) + \rho^1_{00}\sin^2\theta + \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\theta\cos\phi + \mathrm{Re}\rho^1_{1-1}\sin^2\theta\cos 2\phi\right)$$

$$W^2(\cos\theta,\phi) = \frac{3}{8\pi}\left(-\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\theta\sin\phi - \mathrm{Im}\rho^2_{1-1}\sin^2\theta\sin 2\phi\right)$$

J/ψ rest frame



Φ .. angle between the photon polarization plane and production plane

P_γ .. degree of the linear polarization

(θ,ϕ) .. polar and azimuthal angles of e⁻ in the J/ψ rest frame
depends on the choice of z-axis (Helicity frame and Gottfried-Jackson frame)

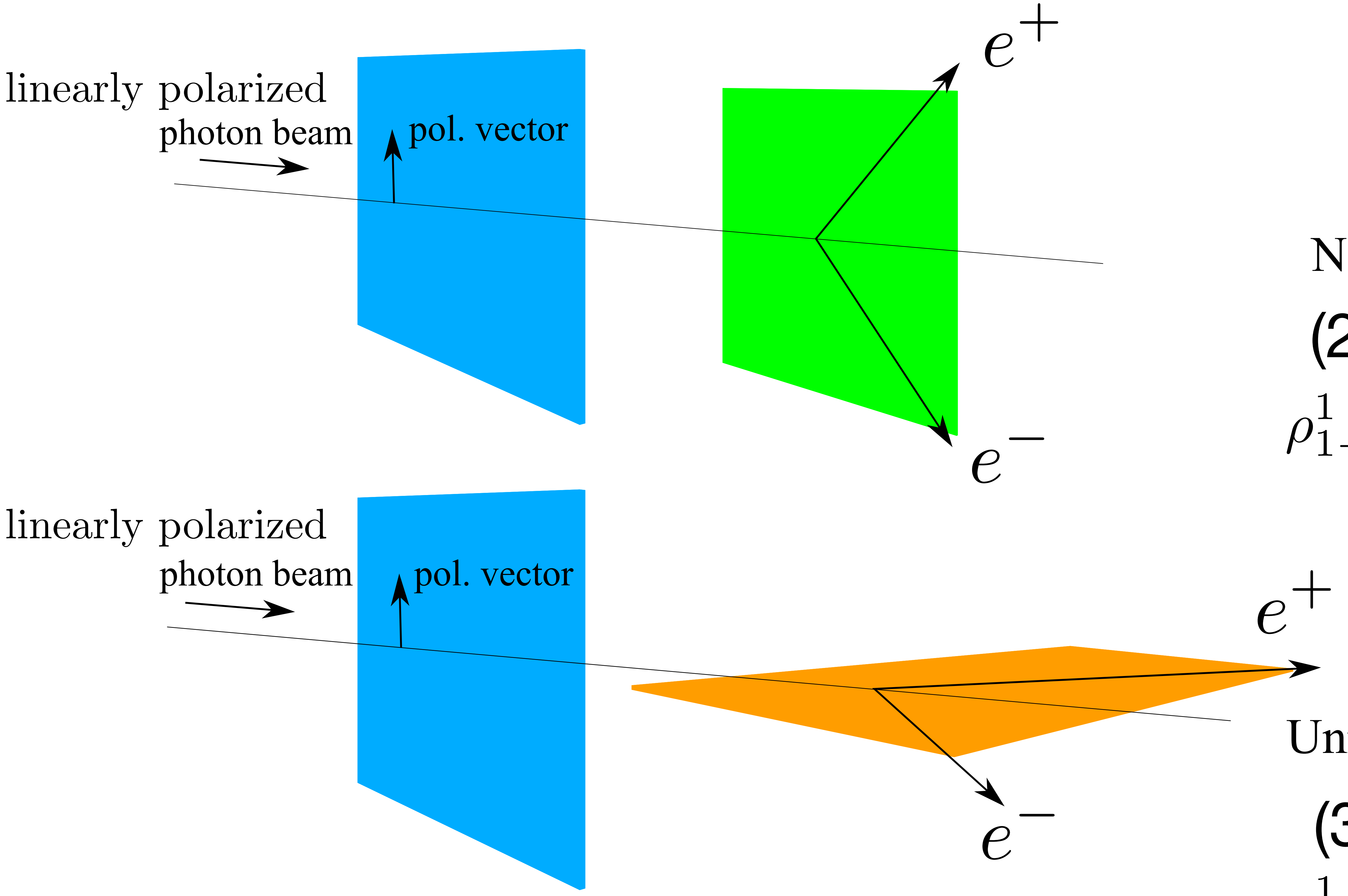
$$\lambda_\theta = \frac{1-3\rho^0_{00}}{1+\rho^0_{00}},$$

$$\lambda_\phi = \frac{2\rho^0_{1-1}}{1+\rho^0_{00}},$$

$$\lambda_{\theta\phi} = \frac{2\sqrt{2}\mathrm{Re}\rho^0_{10}}{1+\rho^0_{00}}.$$

Polarization measurements: Naturality

Decay angle wrt polarization plane is sensitive to naturality $P(-1)^J$ of the t-channel exchanged particle.



Natural parity exchange

(2 gluons, Pomeron, f_0, …)

$$\rho^1_{1-1} = -\mathrm{Im}\rho^2_{1-1} = +0.5$$

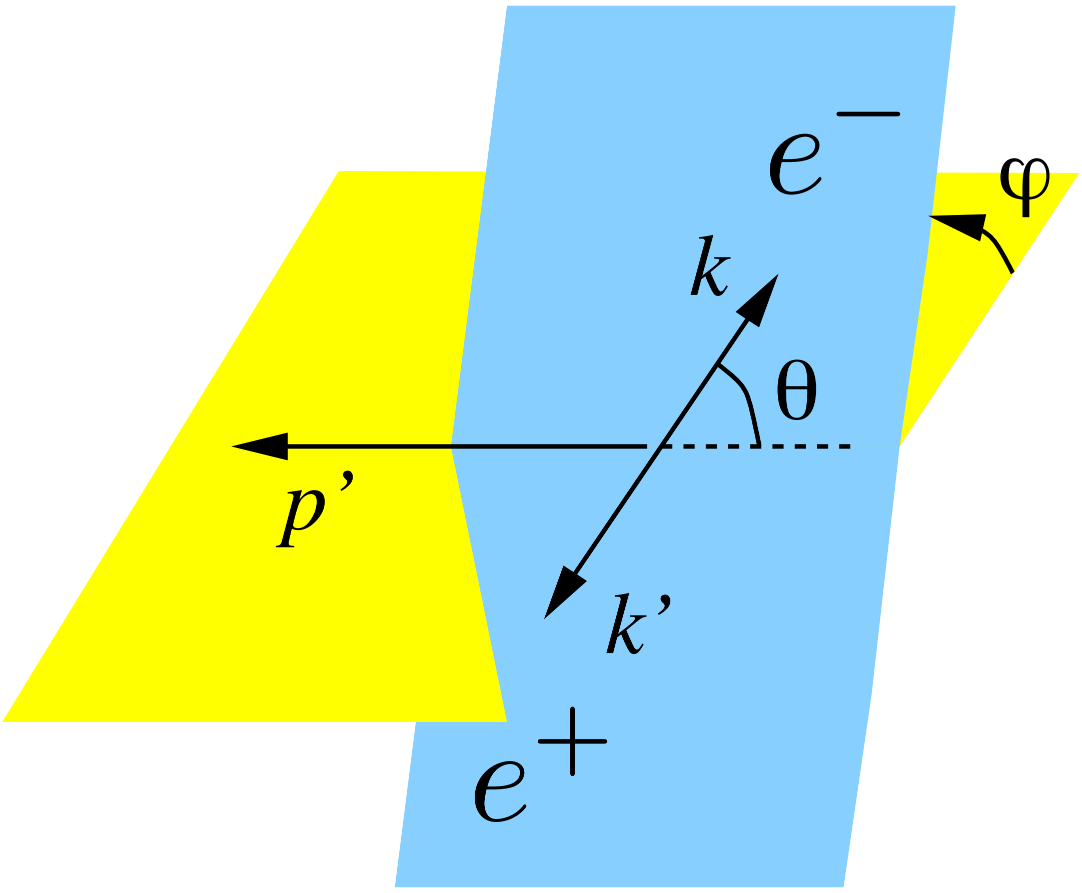
Unnatural parity exchange

(3 gluons, π, η, …)

$$\rho^1_{1-1} = -\mathrm{Im}\rho^2_{1-1} = -0.5$$

Naturality $\frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2}$ is +0.5 when Pomeron exchange is dominant.
Deviation from +0.5 implies unnatural parity exchanges.

Angular distributions of $J/\psi \to e^+e^-$



Decay angles (θ, ϕ) in helicity frame is sensitive to helicity conservation.

When helicity of the photon is fully transferred to J/ψ,

$$W(\cos\theta) \sim 1 + \cos^2\theta \quad (\rho^0_{00} = 0)$$

$$W(\phi) = \text{flat} \quad (\text{Re}\rho^0_{1-1} = 0)$$

Φ .. angle btw polarization & production plane

Helicity conservation

$$W(\cos\theta) = \frac{3}{8}\left(1 + \rho^0_{00} + (1 - 3\rho^0_{00})\cos^2\theta\right),$$

$$W(\phi) = \frac{1}{2\pi}\left(1 + \text{Re}\rho^0_{1-1}\cos 2\phi\right),$$

Naturality

$$W(\phi - \Phi) = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} - \text{Im}\rho^2_{1-1}}{2}\cos\left[2(\phi - \Phi)\right]\right),$$

Helicity conservation

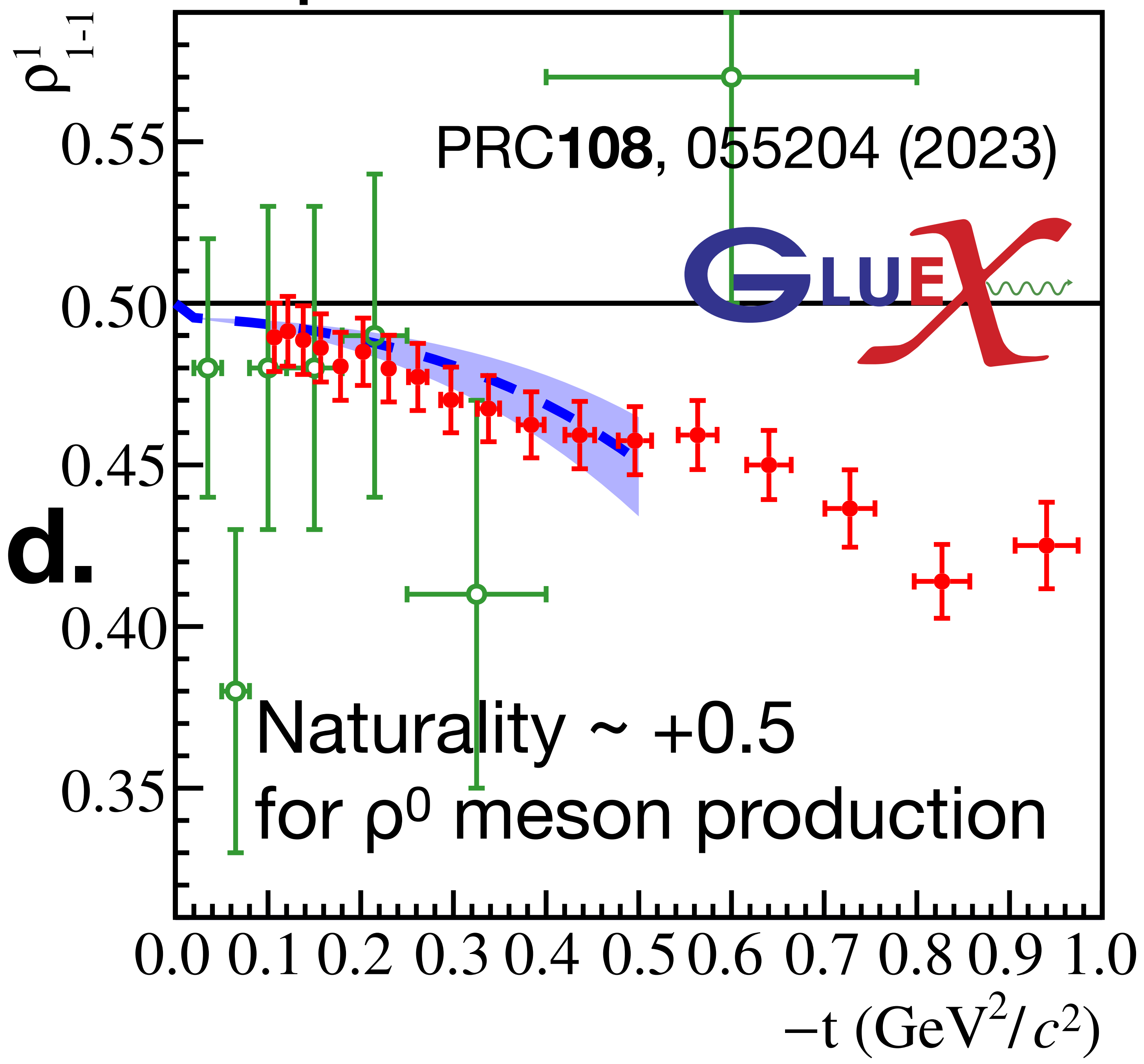
$$W(\phi + \Phi) = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} + \text{Im}\rho^2_{1-1}}{2}\cos\left[2(\phi + \Phi)\right]\right),$$

Beam Asym. (Σ)

$$W(\Phi) = 1 - P_\gamma\left(2\rho^1_{11} + \rho^1_{00}\right)\cos 2\Phi.$$

What we expect about J/ψ SDMEs?

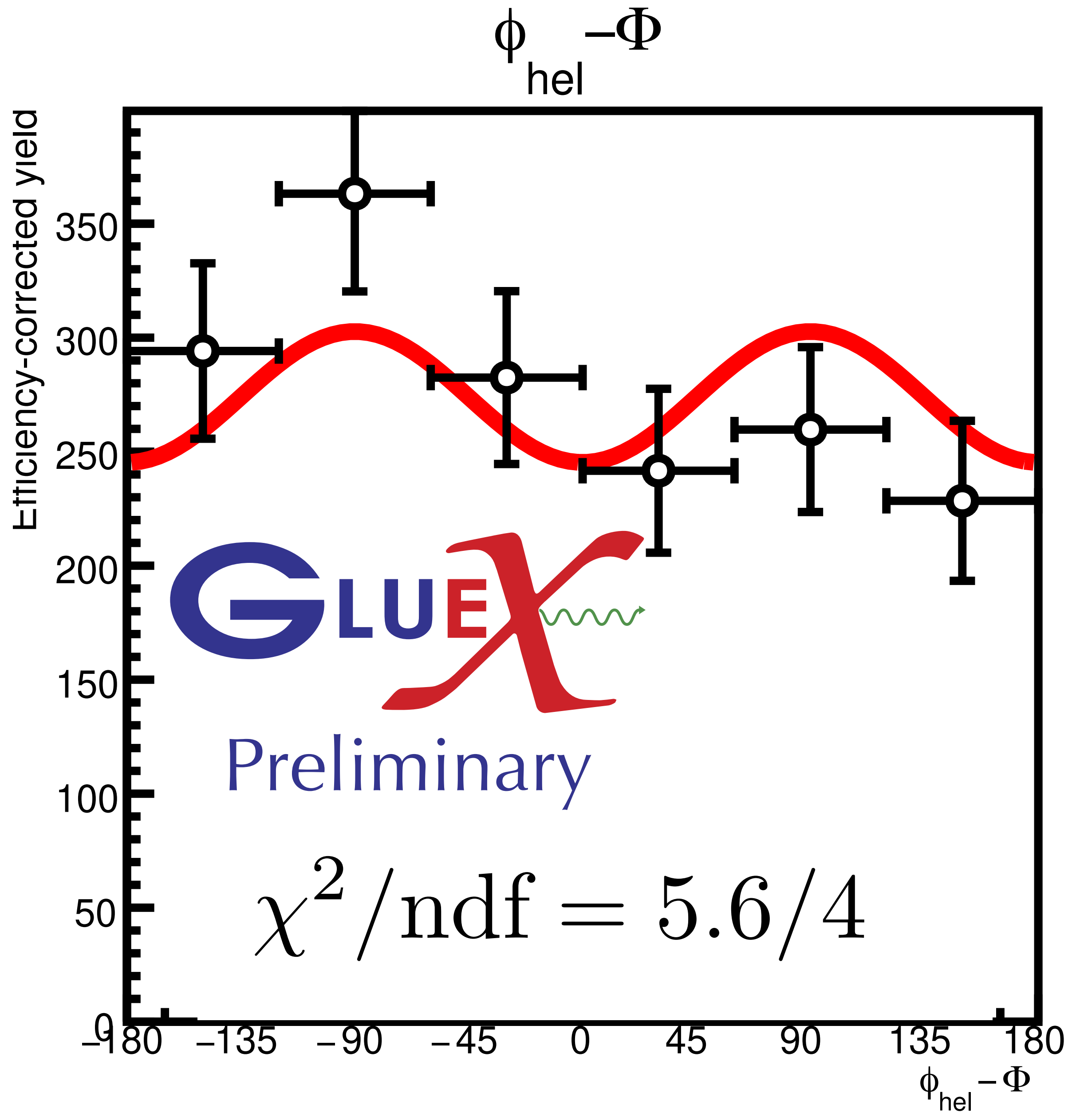
- No SDME measurements for threshold J/ψ photoproduction so far.
- Helicity conservation is known to be broken for light vector mesons. The same for J/ψ or not?
- In high E_γ region, naturality close to +0.5 is observed for light vector mesons, corresponding to t-channel Pomeron exchange.
  - How about threshold J/ψ production?
  - Close to +0.5 because of 2 gluon exchange?
  - Or close to -0.5 because of 3 gluon exchange?
- Beam asymmetry ∑ ~ 0 is observed for light vector mesons. ∑ ~ 0 for J/ψ as well?



Very limited knowledge about J/ψ SDMEs near threshold.
GlueX can do unique measurements of naturality.

Polarized measurements

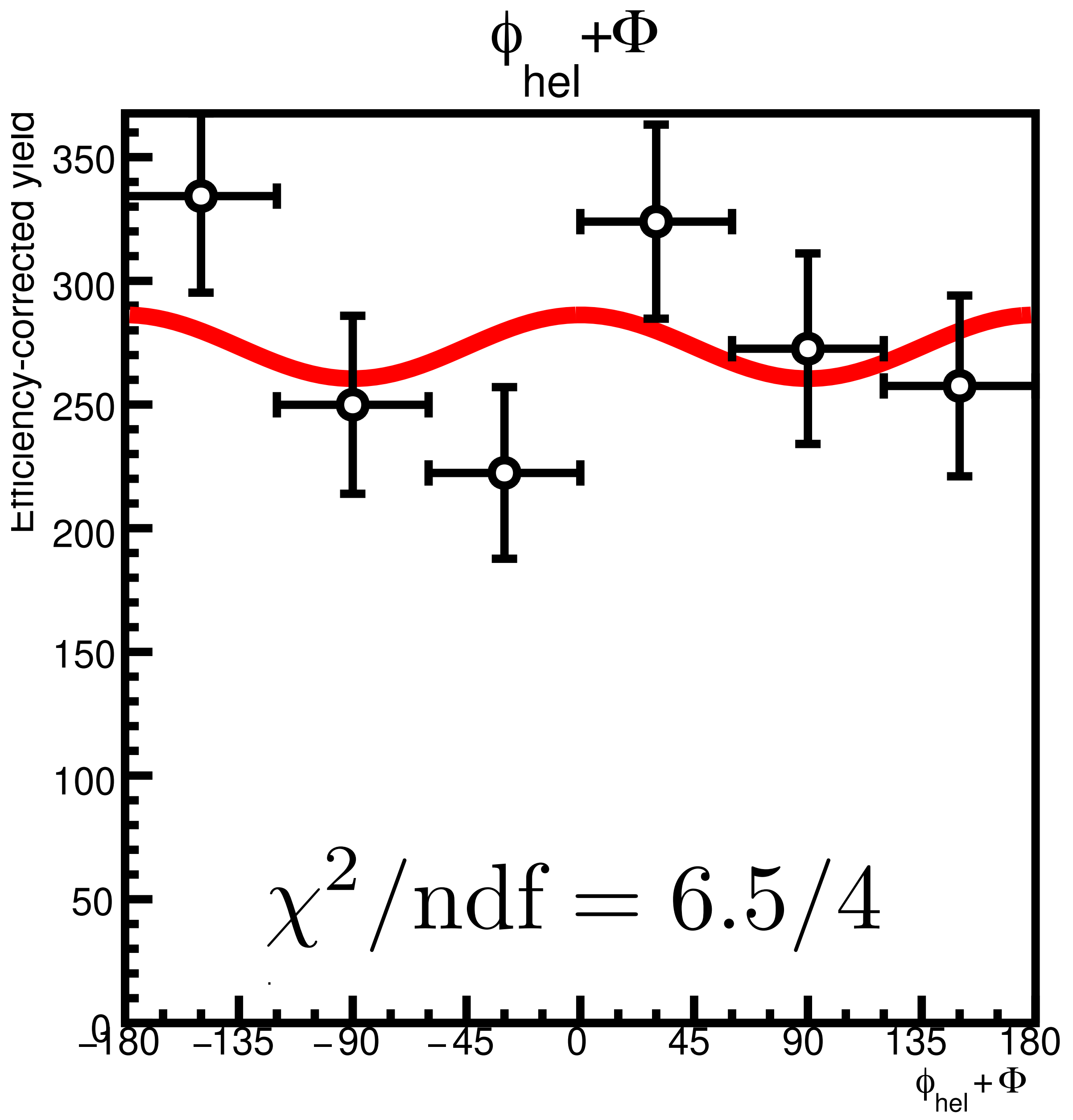
Naturality



$$\frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2} \in [-0.5, 0.5]$$

Stat. error: 0.23

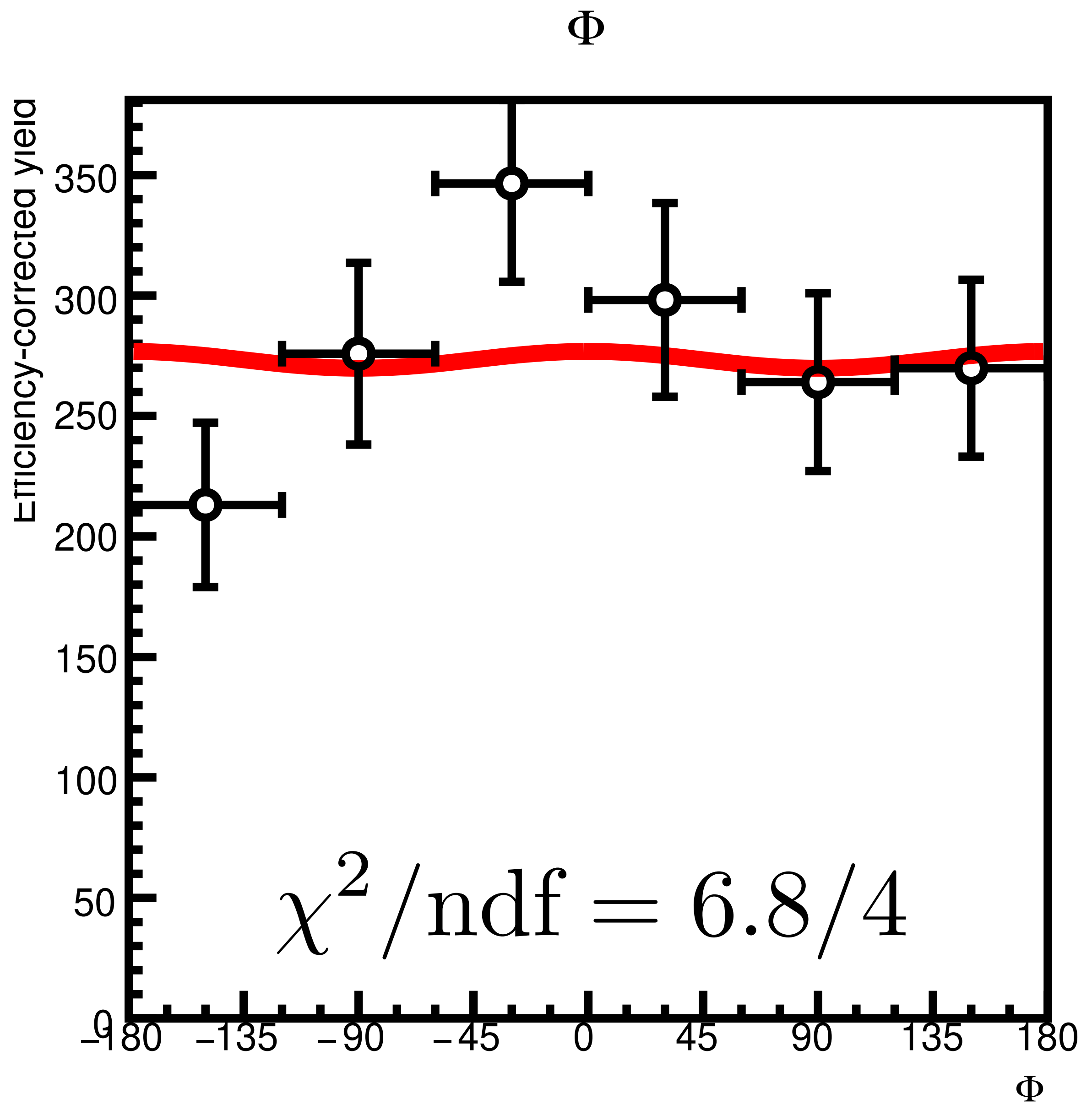
Helicity conservation



$$\frac{\rho^1_{1-1} + \mathrm{Im}\rho^2_{1-1}}{2} \in [-0.5, 0.5]$$

Stat. error: 0.22

Beam Asym.



$$\Sigma \in [-1, 1]$$

Stat. error: 0.22

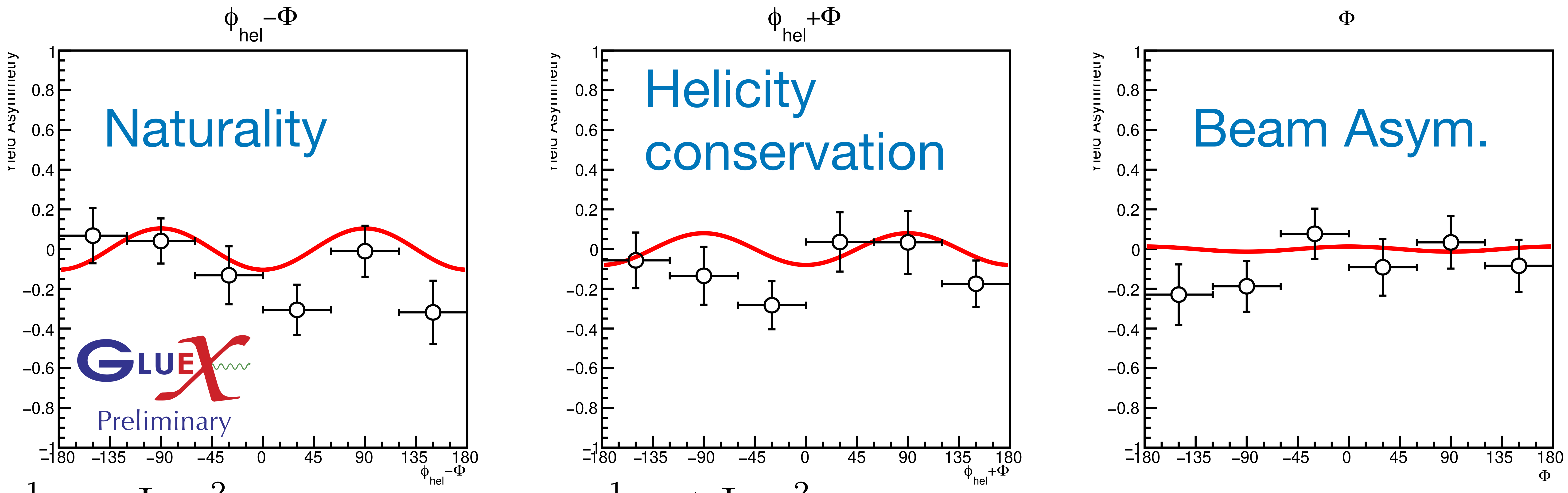
Uncertainty for naturality is not small, but enough to distinguish
"fully unnatural-parity exchange (-0.5)" and "fully natural-party exchange(+0.5)".

Cross-check: Yield Asymmetry

Detector efficiencies are canceled in the 1st order by constructing following Yield Asymmetry.

$$\text{Asymmetry for Naturality} = \frac{1}{P_\gamma}\frac{Y^{0^\circ}(\phi-\Phi) - Y^{90^\circ}(\phi-\Phi)}{Y^{0^\circ}(\phi-\Phi) + Y^{90^\circ}(\phi-\Phi)} = \frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2}\cos 2(\phi-\Phi)$$

Naturality

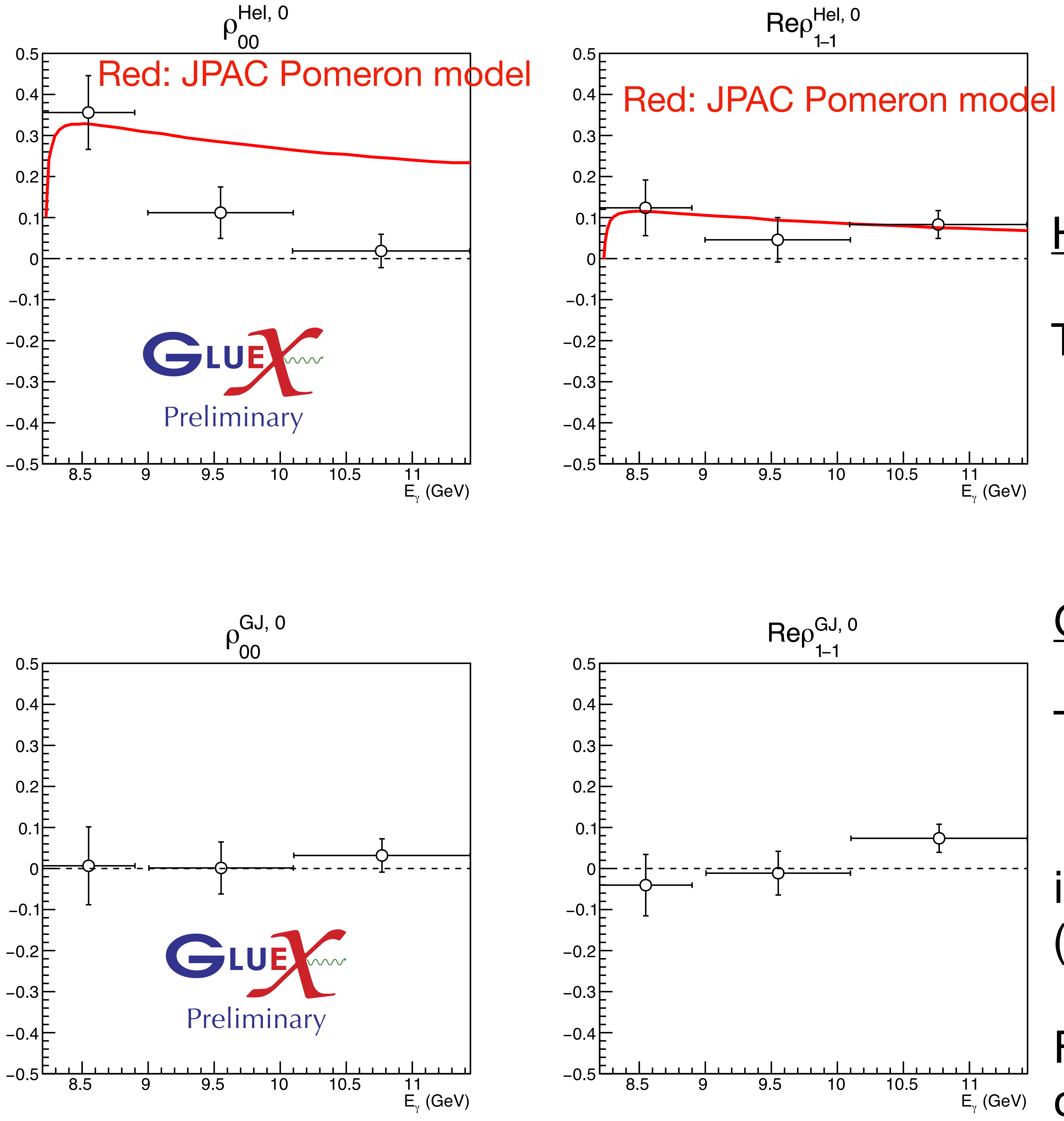


$\frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2} \in [-0.5, 0.5]$ | $\frac{\rho^1_{1-1} + \mathrm{Im}\rho^2_{1-1}}{2} \in [-0.5, 0.5]$ | $\Sigma \in [-1, 1]$

Stat. error: 0.21 | Stat. error: 0.22 | Stat. error: 0.21

Both analyses (efficiency-corrected yield & yield asymmetry) give consistent results.

Helicity conservation



<u>Helicity frame</u> (z-axis: opposite of out-going proton)

The photon helicity is not fully transferred to J/ψ at low E_γ.

<u>Gottfried-Jackson frame</u> (z-axis: photon direction)

The photon helicity for the t-channel cross reaction:

$$\gamma J/\psi \to p\bar{p}$$

is almost conserved.
(photon helicity) = -(J/ψ helicity), otherwise amplitudes = 0

For light vector mesons (ρ, ω, ϕ), this "t-channel helicity conservation" is known to be badly broken.

Summary and prospects

- Timelike Compton scattering can be accessible with GlueX detector
- Thanks to the large acceptance, (θ, ϕ)-dependence of FB asymmetry can be accessed.
- Consistent results with CLAS at 50°<θ<80°, -40°<ϕ<40°
- To understand (θ, ϕ)-dependence, theoretical supports are essential.

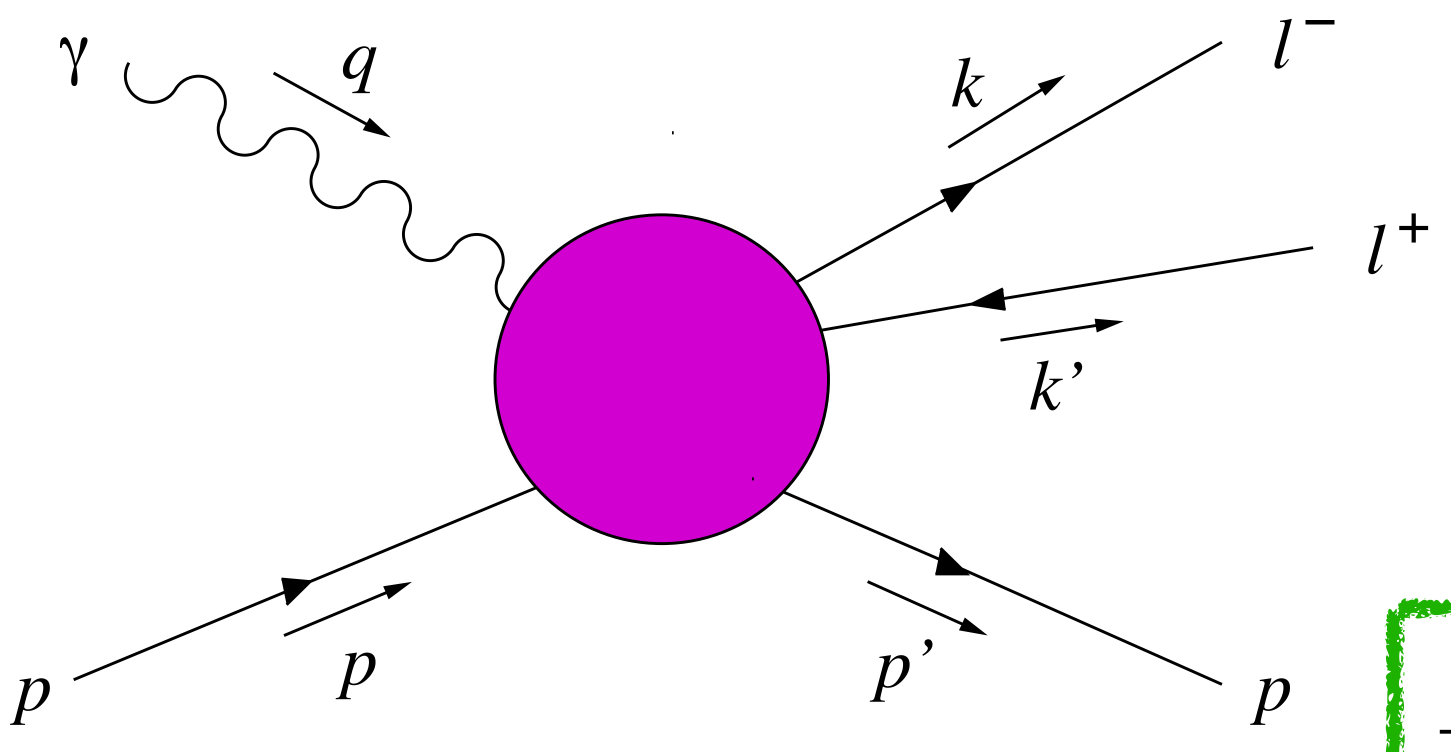
- Exclusive J/ψ photophotoproduction near threshold might give us the gluonic properties of the proton, but first we have to understand the production mechanism.
- GlueX cross section data is indicating the contribution beyond the gluon exchange.
- To help determine the production mechanism, GlueX can provide unique (especially polarized) SDME measurements.
- We're planning to collect additional data, and expect a few times more J/ψ events.

Theoretical prediction

Berger *et al.*, Eur. Phys. J. C 23, 675 (2002)

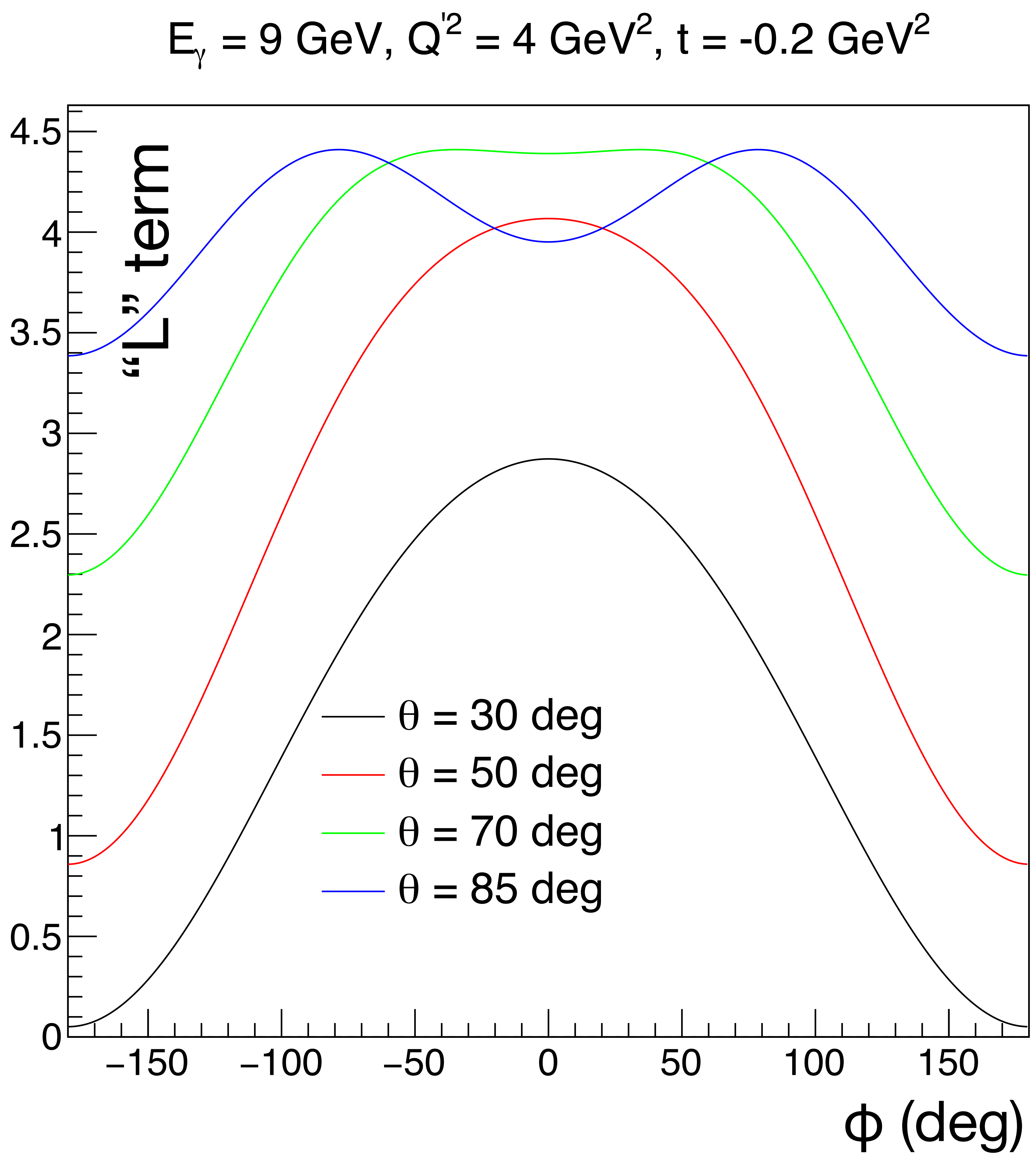
$$A_{\rm FB}(\theta,\phi) = \frac{d\sigma_{\rm INT}(\theta,\phi)}{d\sigma_{\rm BH}(\theta,\phi) + d\sigma_{\rm TCS}(\theta,\phi)} \sim \frac{d\sigma_{\rm INT}(\theta,\phi)}{d\sigma_{\rm BH}(\theta,\phi)}$$

$$\frac{d\sigma_{\rm INT}}{dQ'^2 dt\, d(\cos\theta) d\varphi} = -\frac{\alpha_{\rm em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L} \times \left[\cos\varphi \frac{1+\cos^2\theta}{\sin\theta}{\rm Re}\tilde{M}^{--} - \cos 2\varphi\sqrt{2}\cos\theta{\rm Re}\tilde{M}^{0-} + \cos 3\varphi \sin\theta {\rm Re}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right],$$



$$L = [(q-k)^2 - m_\ell^2][(q-k')^2 - m_\ell^2]$$

$$\frac{d\sigma_{\rm BH}}{dQ'^2 dt\, d(\cos\theta) d\varphi} = \frac{\alpha_{\rm em}^3}{4\pi(s-M^2)^2}\frac{\beta}{-tL} \times \left[\left(F_1^2 - \frac{t}{4M^2}F_2^2\right)\frac{A}{-t} + (F_1+F_2)^2\frac{B}{2}\right]$$



Kinematic factor "L" strongly depends on ϕ, but canceled out by taking the ratio.

→ $A_{\rm FB}$ ~ cosϕ at the leading order

Theoretical prediction

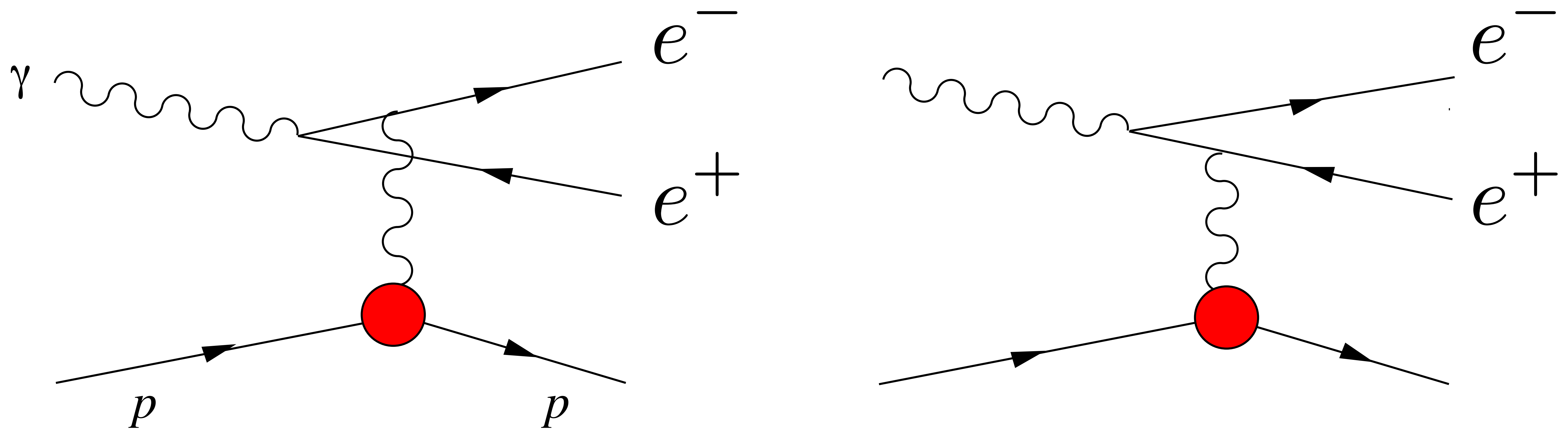
Berger *et al.*, Eur. Phys. J. C 23, 675 (2002)

$$A_{\rm FB}(\theta,\phi) = \frac{d\sigma_{\rm INT}(\theta,\phi)}{d\sigma_{\rm BH}(\theta,\phi) + d\sigma_{\rm TCS}(\theta,\phi)} \sim \frac{d\sigma_{\rm INT}(\theta,\phi)}{d\sigma_{\rm BH}(\theta,\phi)}$$

$$\frac{d\sigma_{\rm INT}}{dQ'^2 dt d(\cos\theta) d\varphi} = -\frac{\alpha_{\rm em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L} \times \left[\cos\varphi \frac{1+\cos^2\theta}{\sin\theta}{\rm Re}\tilde{M}^{--} - \cos 2\varphi\sqrt{2}\cos\theta{\rm Re}\tilde{M}^{0-} + \cos 3\varphi \sin\theta {\rm Re}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right],$$

$$L = [(q-k)^2 - m_\ell^2][(q-k')^2 - m_\ell^2]$$

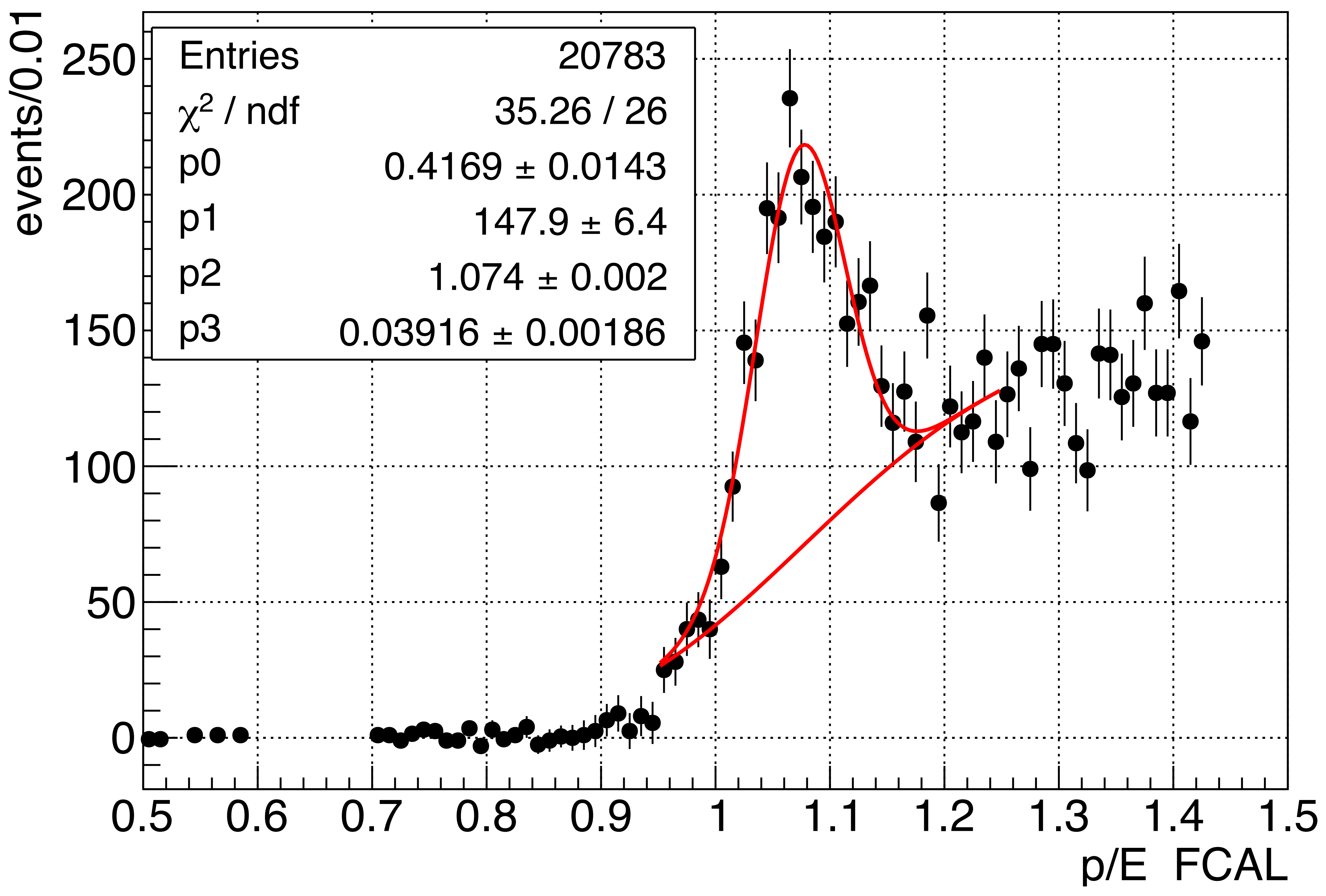
$$\frac{d\sigma_{\rm BH}}{dQ'^2 dt d(\cos\theta) d\varphi} = \frac{\alpha_{\rm em}^3}{4\pi(s-M^2)^2}\frac{\beta}{-tL} \times \left[\left(F_1^2 - \frac{t}{4M^2}F_2^2\right)\frac{A}{-t} + (F_1+F_2)^2\frac{B}{2}\right]$$



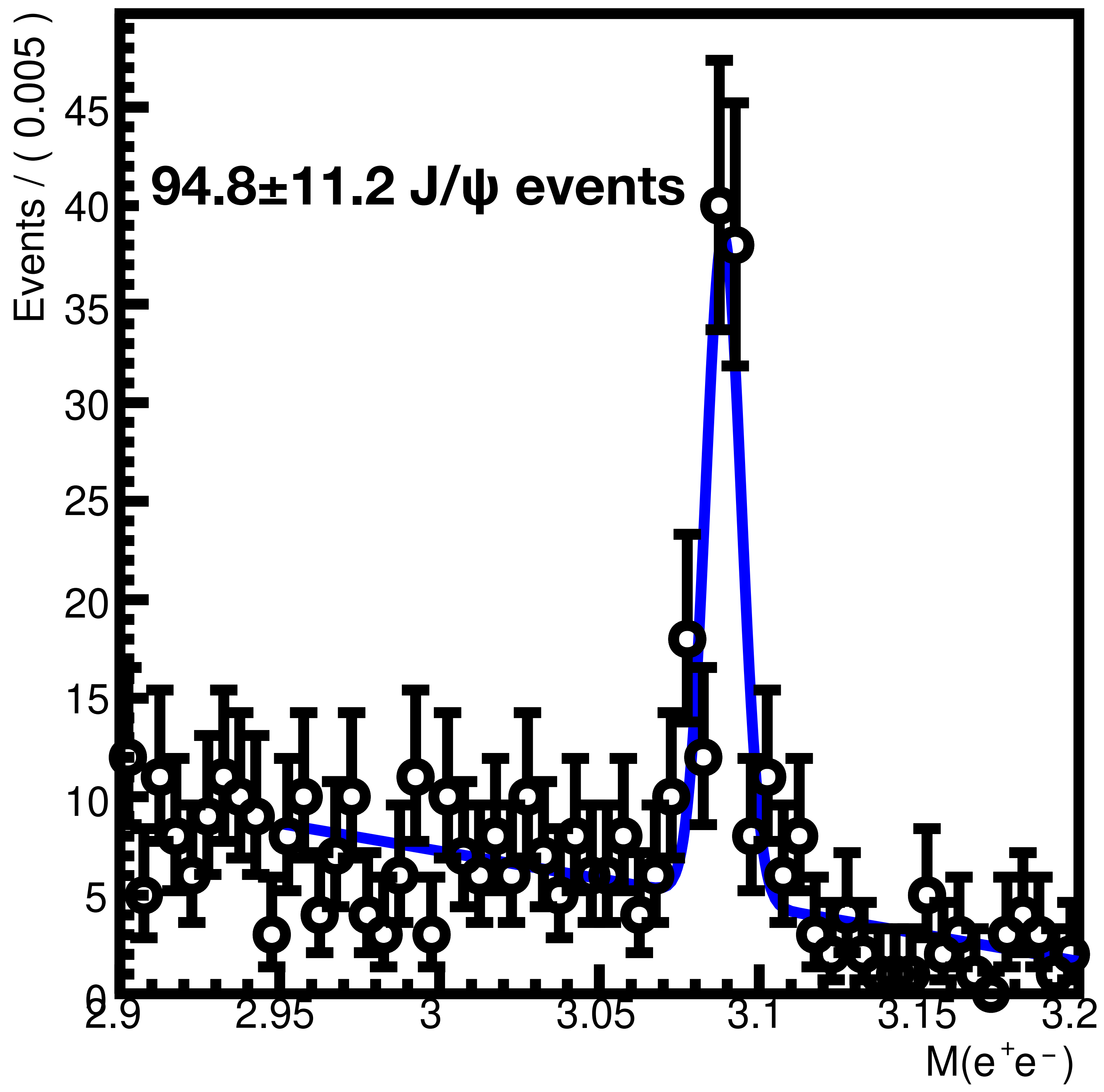
- L comes from the interference b/w 2 BH diagrams.
  - L in $d\sigma_{\rm BH}$ is reasonable
  - L in $d\sigma_{\rm INT}$ is not straightforward

Simonetta Liuti reported a problem in the calculations of DVCS (directly related to TCS).

GlueX-I + 30% GlueX-II data are used for this analysis.
J/ψ is identified using $M(e^+e^-)$ distribution (10-20% background).
Calorimeter response (p/E) is used to subtract π misidentification background.



p/E for lepton events is close to 1 on top of broad π events.

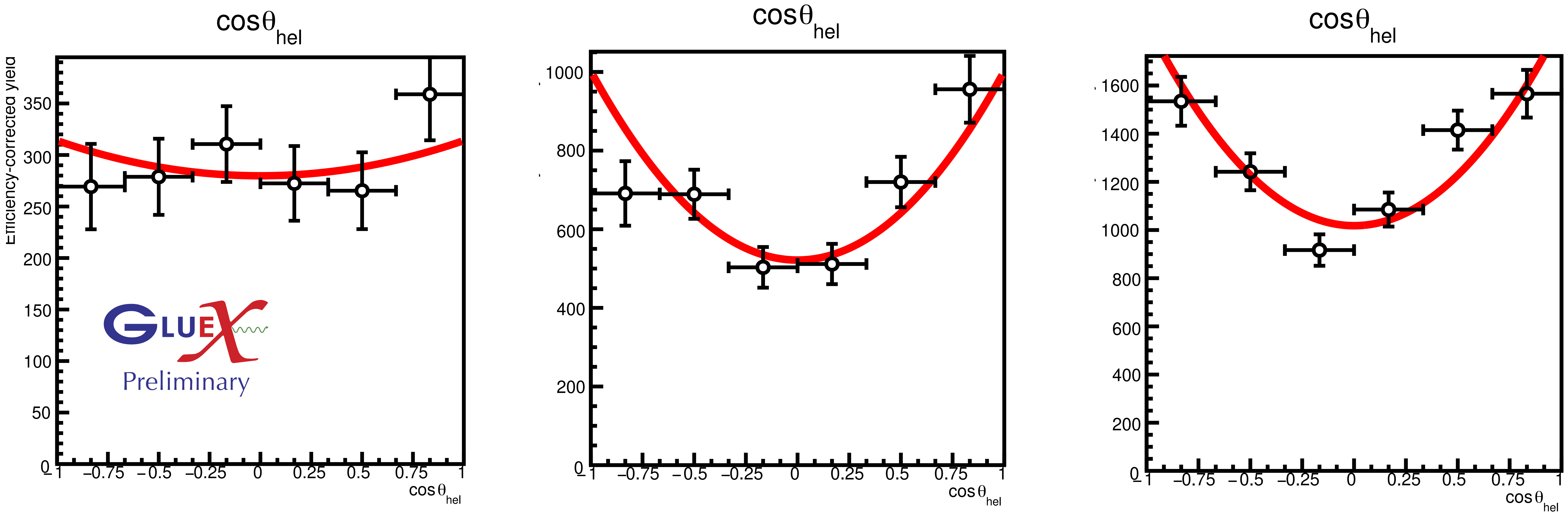


Clean J/ψ peak is observed in e+ e- mass distribution.

Realistic MC samples are generated and analyzed to correct detector efficiency effects.

Unpolarized SDME ($\cos\theta_{hel}$)

Low E_γ ⟷ High E_γ



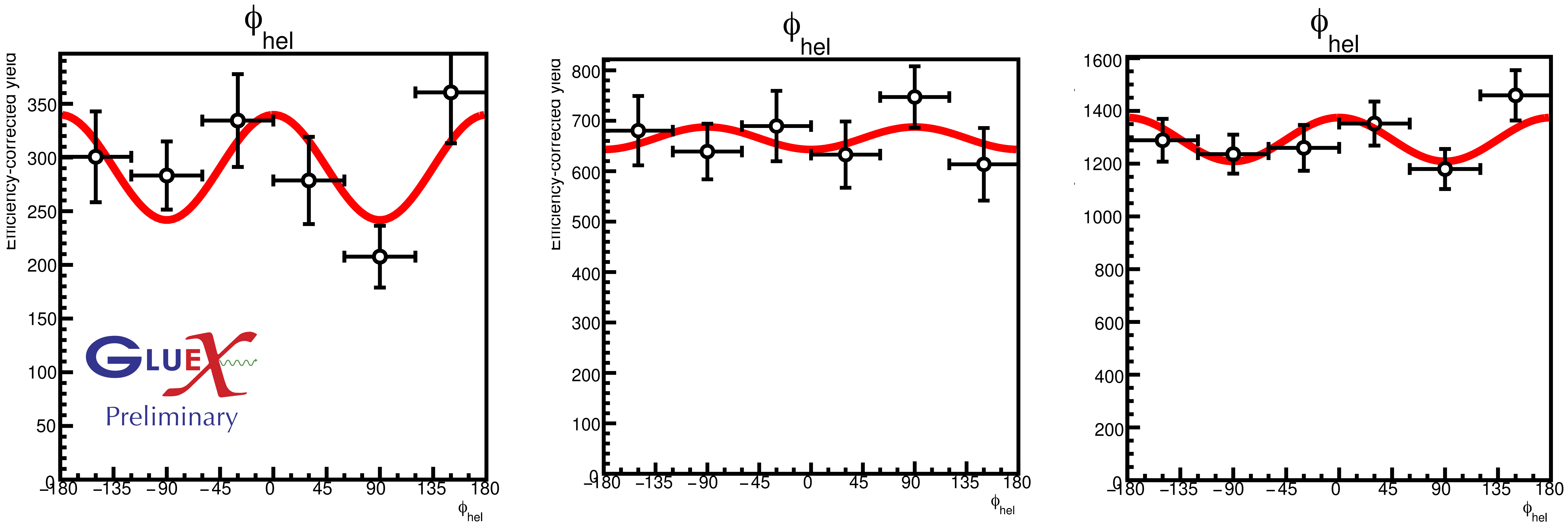
Stat. error: 0.09 Stat. error: 0.06 Stat. error: 0.04

$$W(\cos\theta) \sim 1 + \cos^2\theta \quad (\rho^0_{00} = 0)$$

Non-zero ρ^0_{00} means photon helicity is not fully transferred to J/ψ.
The curves are suggesting helicity is not conserved near threshold.

Unpolarized SDME (ϕ_{hel})

Low E_γ ⟷ High E_γ



Stat. error: 0.07 | Stat. error: 0.06 | Stat. error: 0.04

$$W(\phi) = \text{flat} \quad (\text{Re}\rho^0_{1-1} = 0)$$

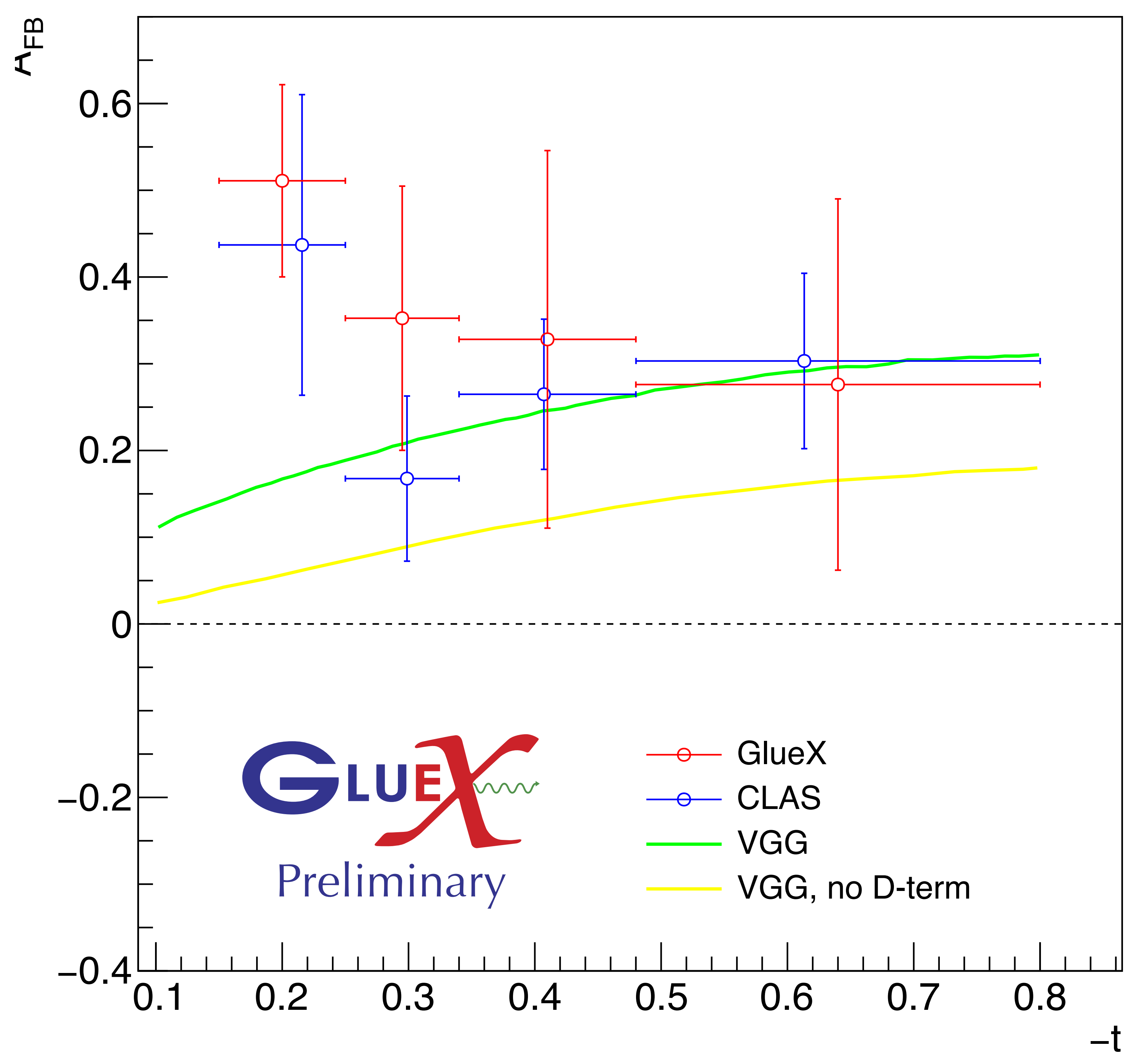
Non-zero Re ρ^1_{1-1} means photon helicity is not fully transferred to J/ψ.
The curves are suggesting helicity is not conserved near threshold.

Comparison with CLAS results

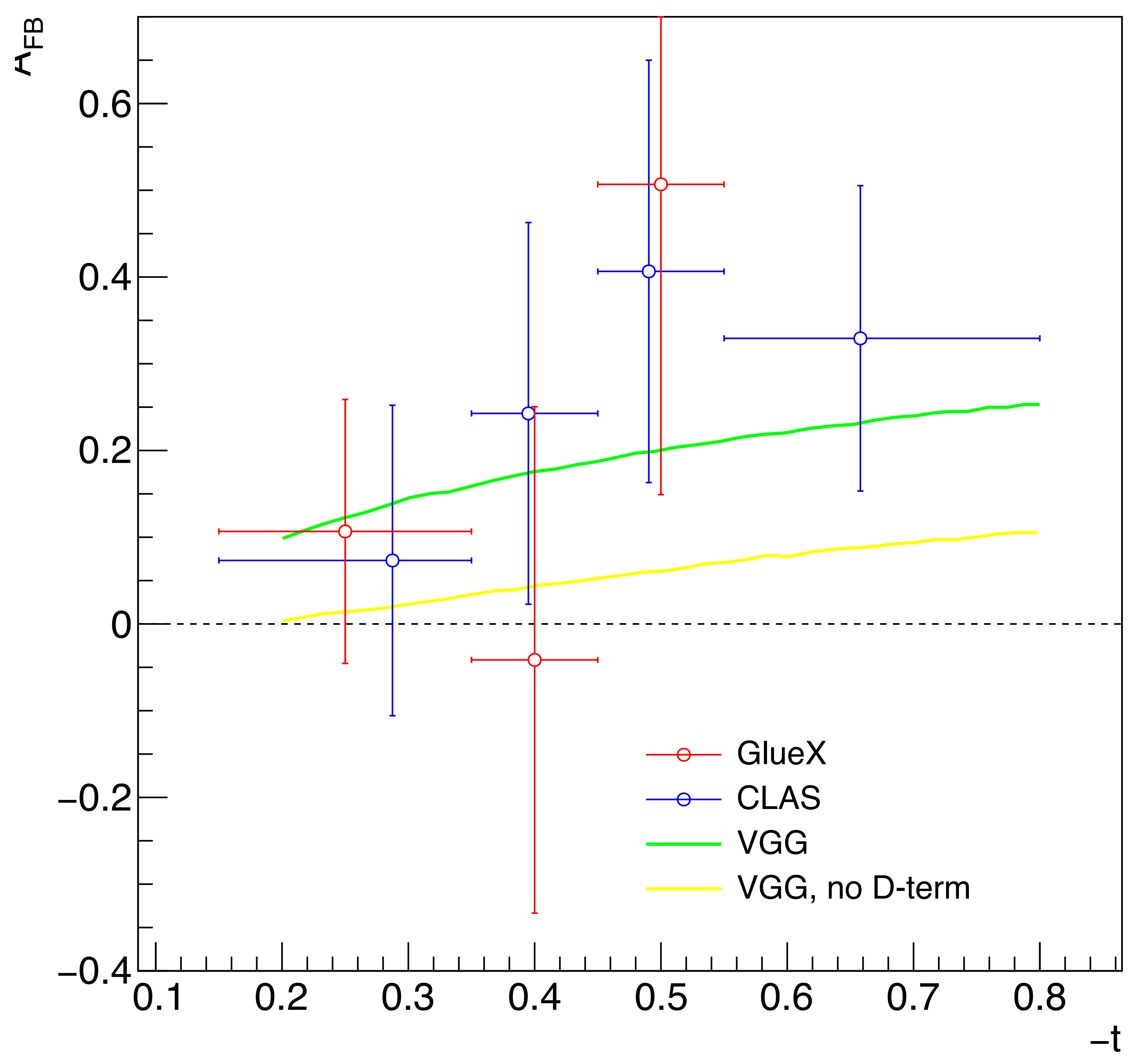
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi+\pi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$

at 50°<θ<80°, -40°<ϕ<40° (CLAS region)

1.5<M<3.0, 50<θ<80, -40<ϕ<40

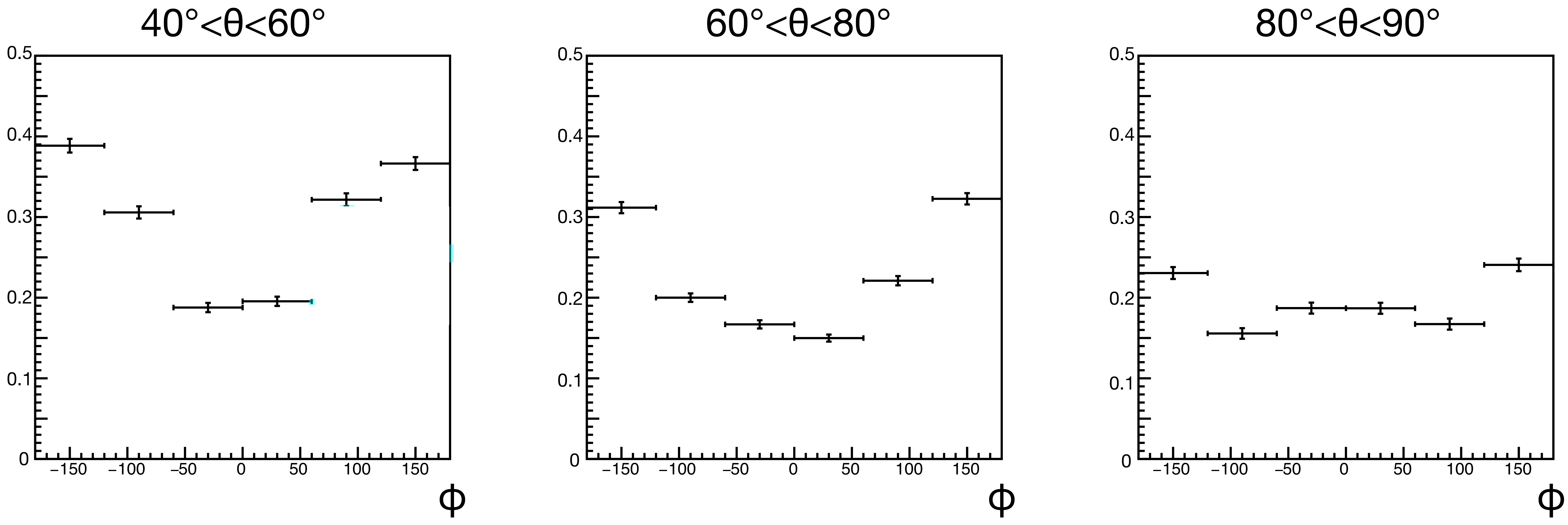


2.0<M<3.0, 50<θ<80, -40<ϕ<40



GlueX shows consistent results with CLAS at their (50°<θ<80°, -40°<ϕ<40°) region.

Acceptance correction by MC simulation



$8.2 < E_\gamma < 11.44$ GeV
$|t - t_{min}| < 0.6$ GeV^2
$1.2 < M(e^+e^-) < 2.5$ GeV

Acceptance correction is carried out by using MC samples.
To check the validity of this correction, following items are checked:

1. FB asymmetry for J/ψ should be zero consistent for any (θ, ϕ).
2. Acceptance is corrected by π sample (assuming A_{FB} for $\gamma p \to \pi^+\pi^- p$ is zero).
3. FB asymmetry for BH singularity regions should be zero consistent.