# TCS measurements at JLab Hall D

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Towards improved hadron femtography with hard exclusive reactions 2023

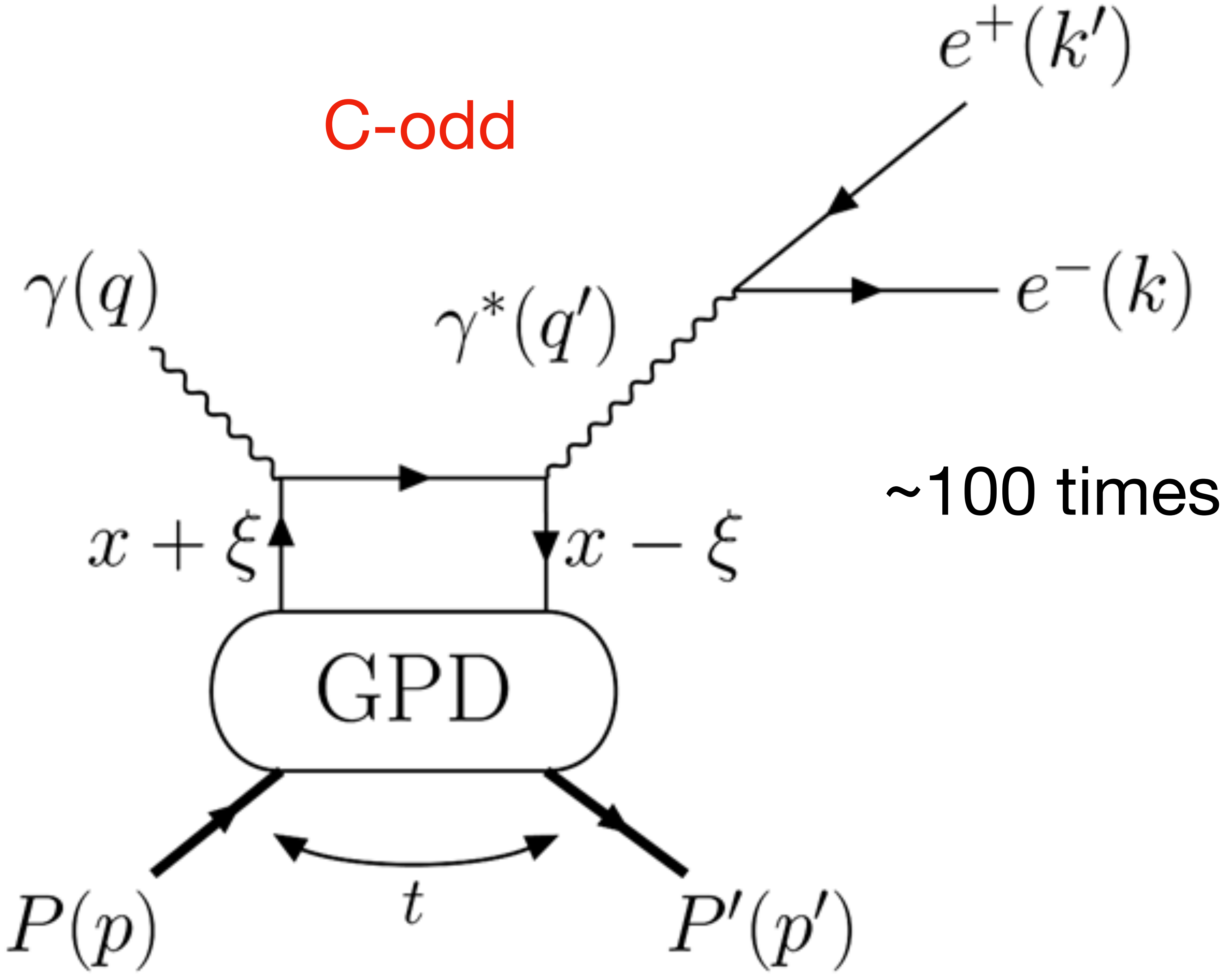
9-Aug-2023

# 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

C-odd

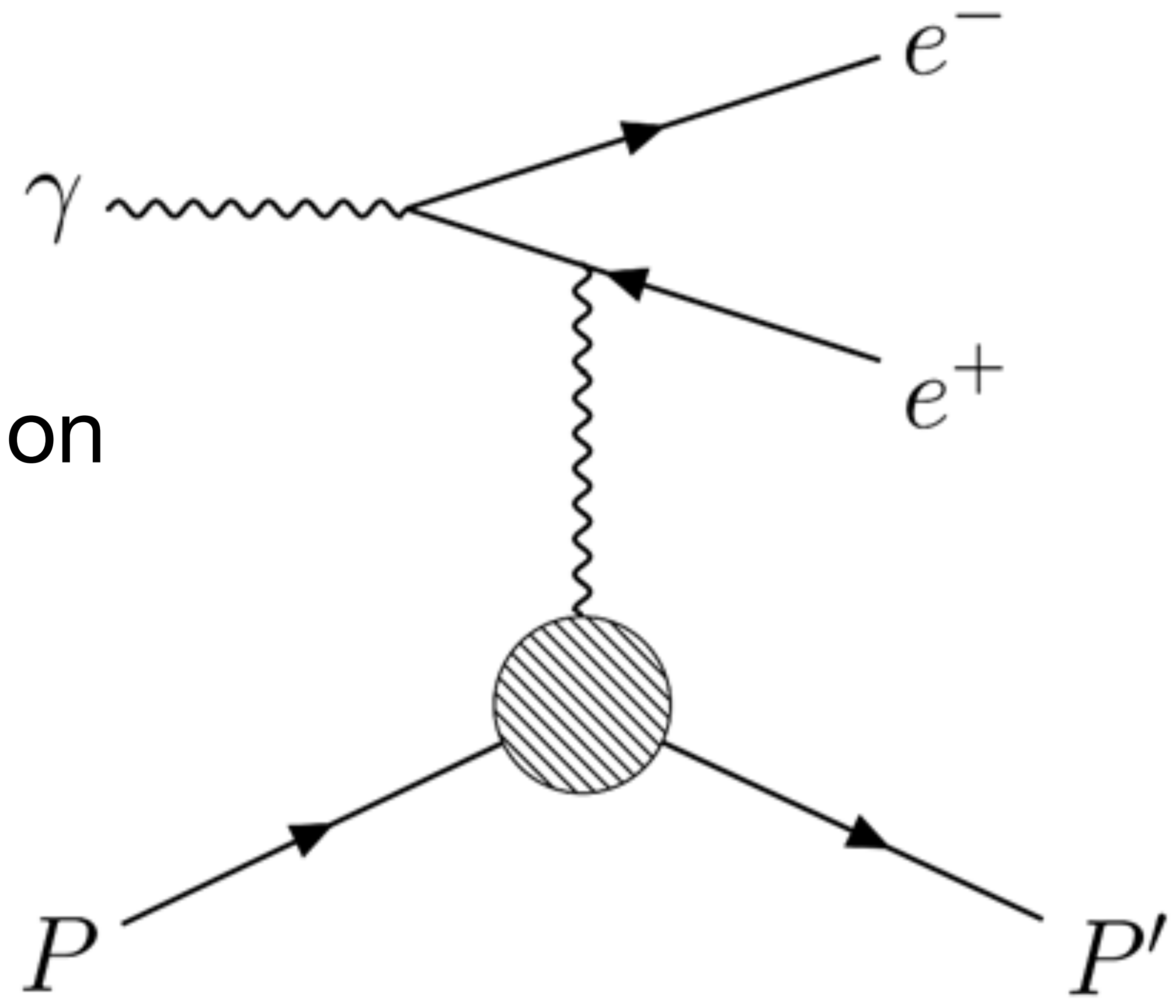



TCS process

~100 times smaller cross section

$\ll$

C-even



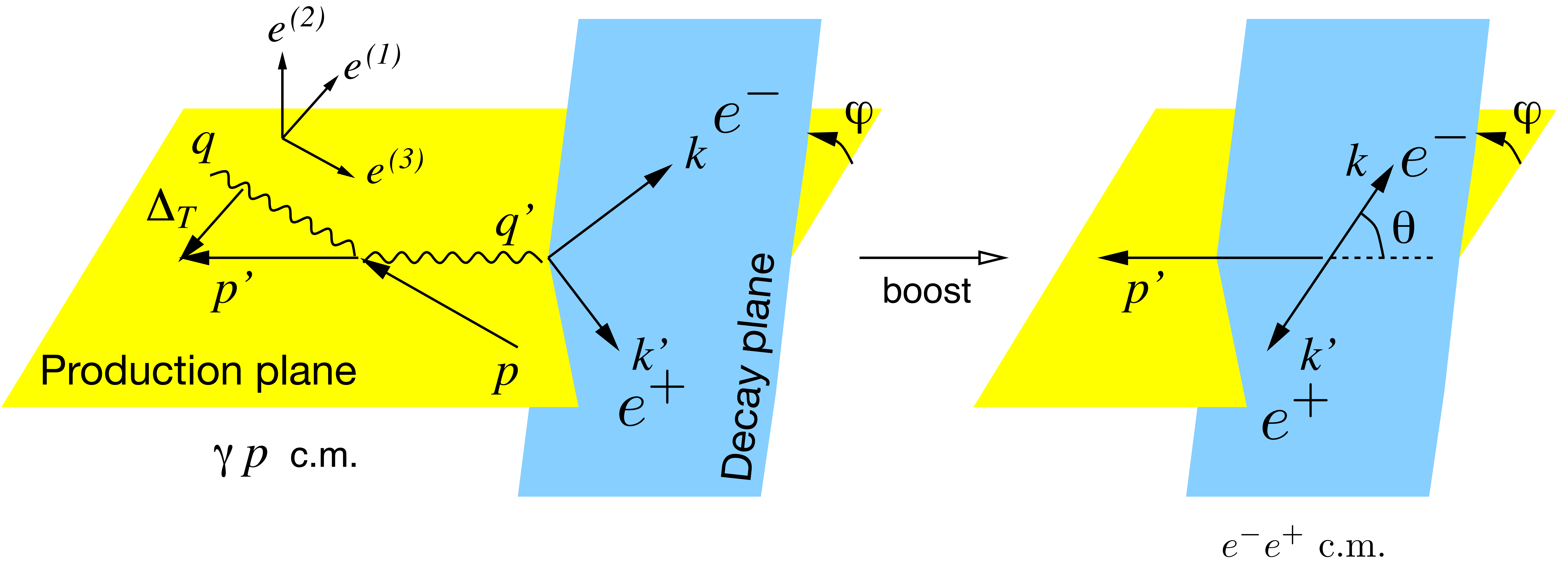

BH process

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

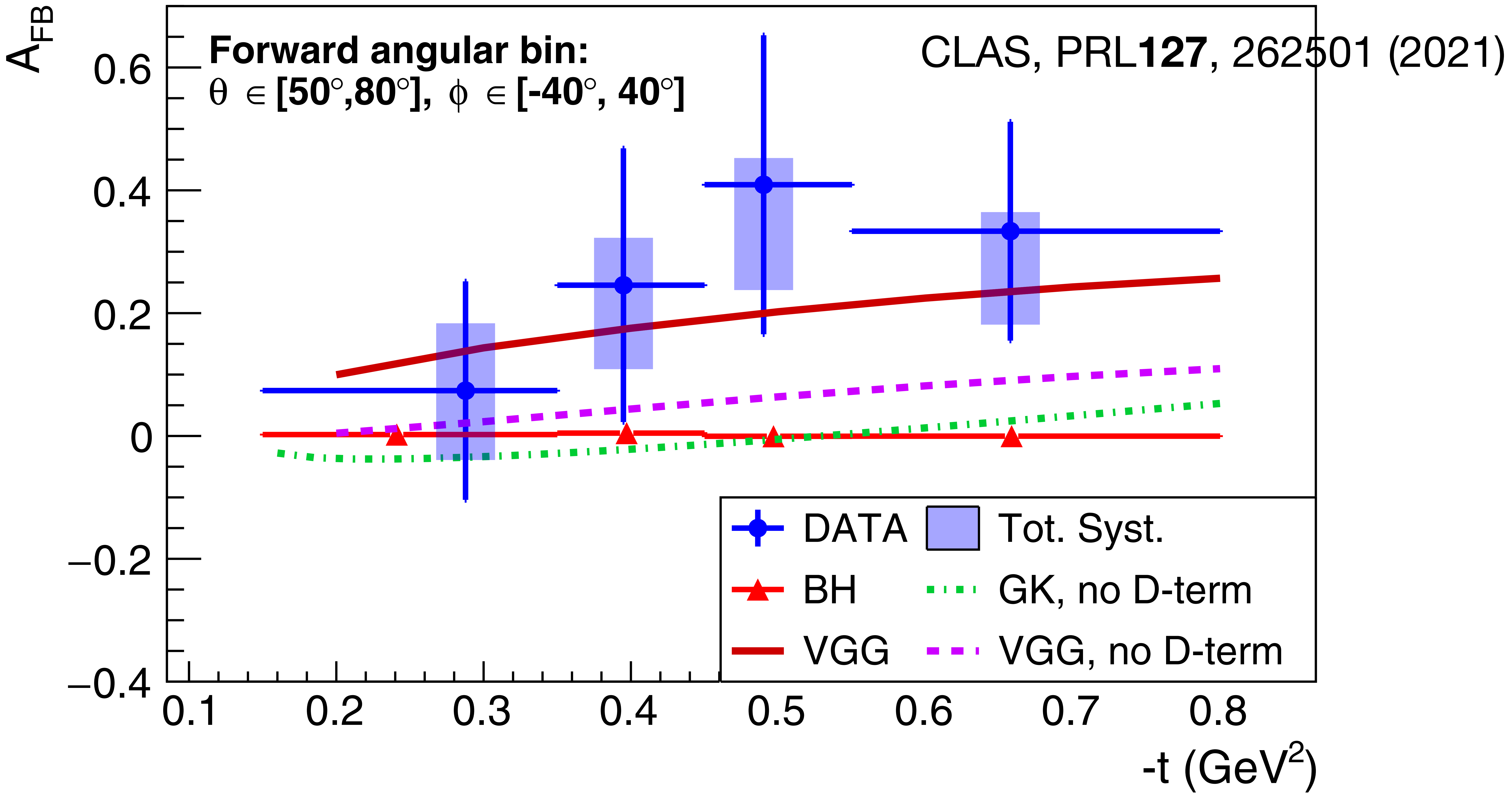



BH-TCS interference term is projected out

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

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

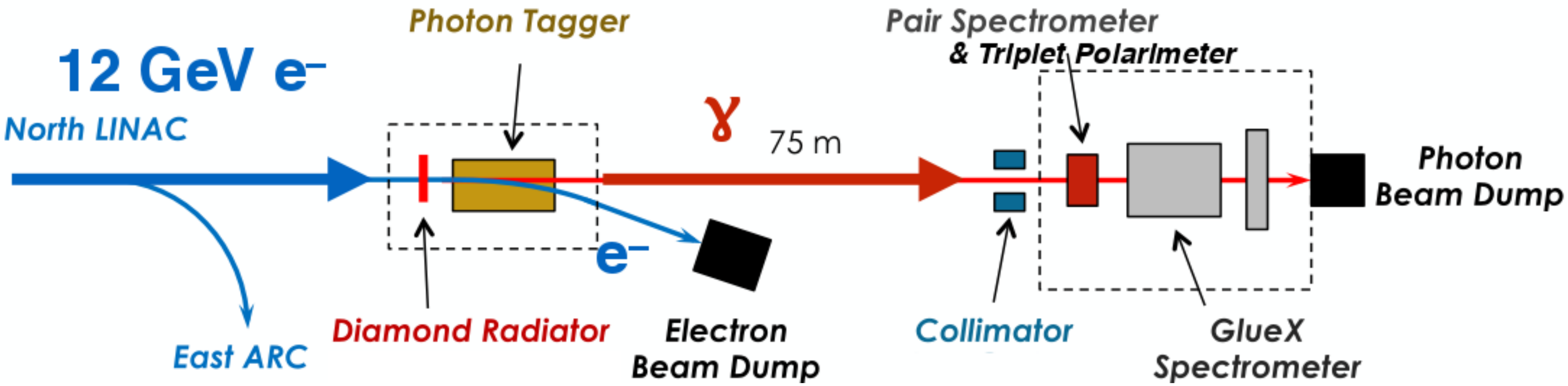
# Forward-Backward Asymmetry ($A_{FB}$)



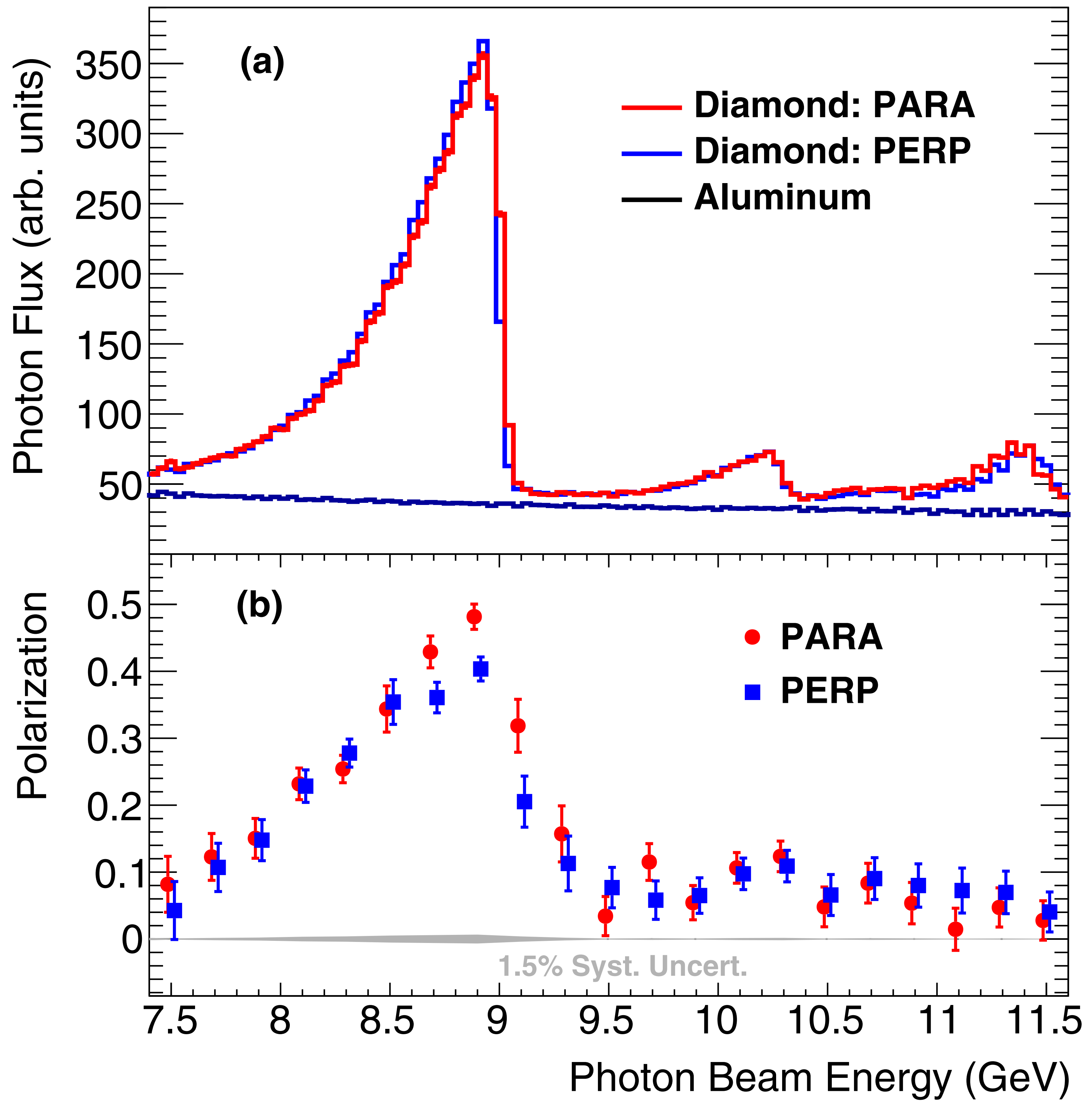

$$A_{\mathrm{FB}}(E_\gamma, t, Q'^2, \theta, \phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi+\pi)} = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi) + d\sigma_{\mathrm{TCS}}(\theta,\phi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\ph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

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

# Hall D Apparatus at JLab

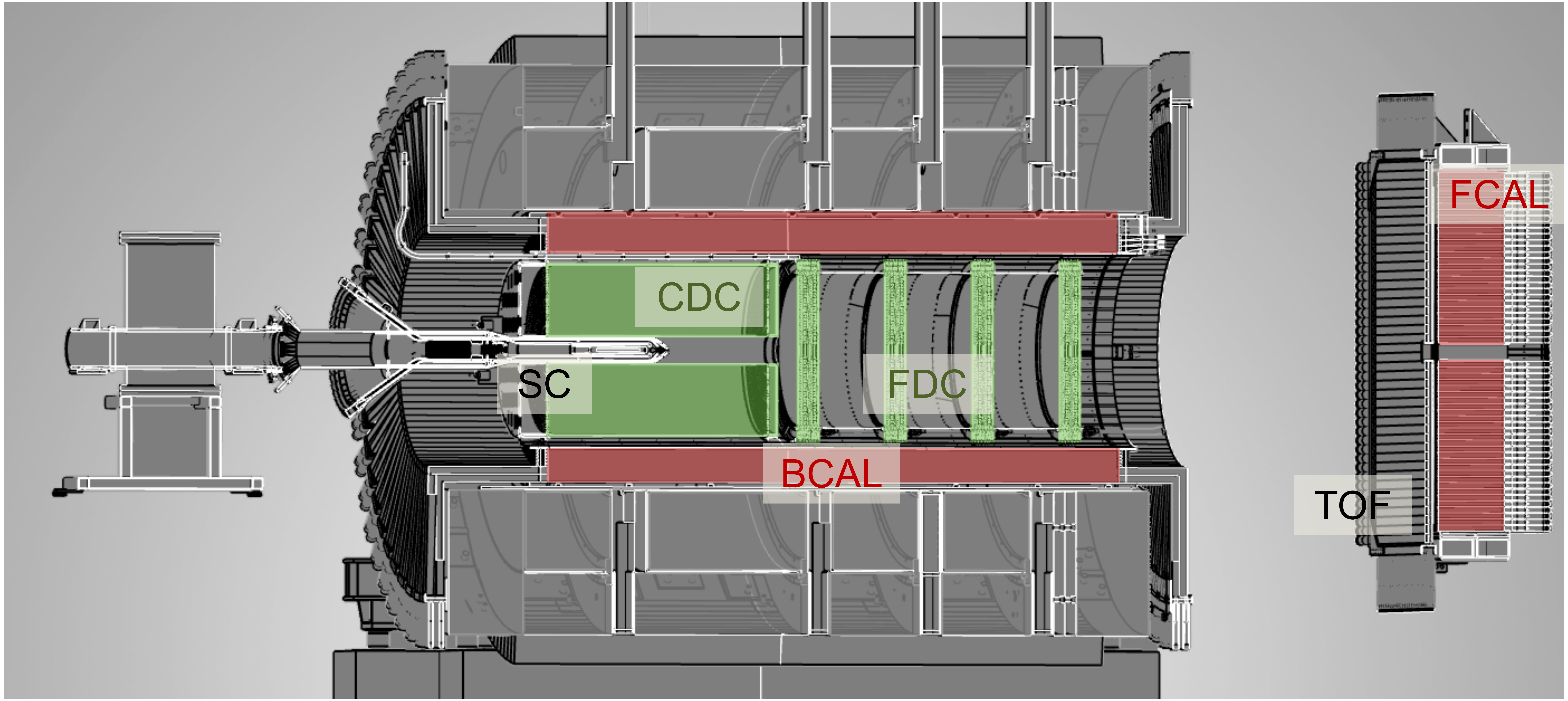



- Photon beam from coherent bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75 m, <35μrad
- Intensity: ~$5\times10^7$-$10^8$ γ/sec
- Data sets: GlueX-I + 2020 (part of GlueX-II)




- 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)

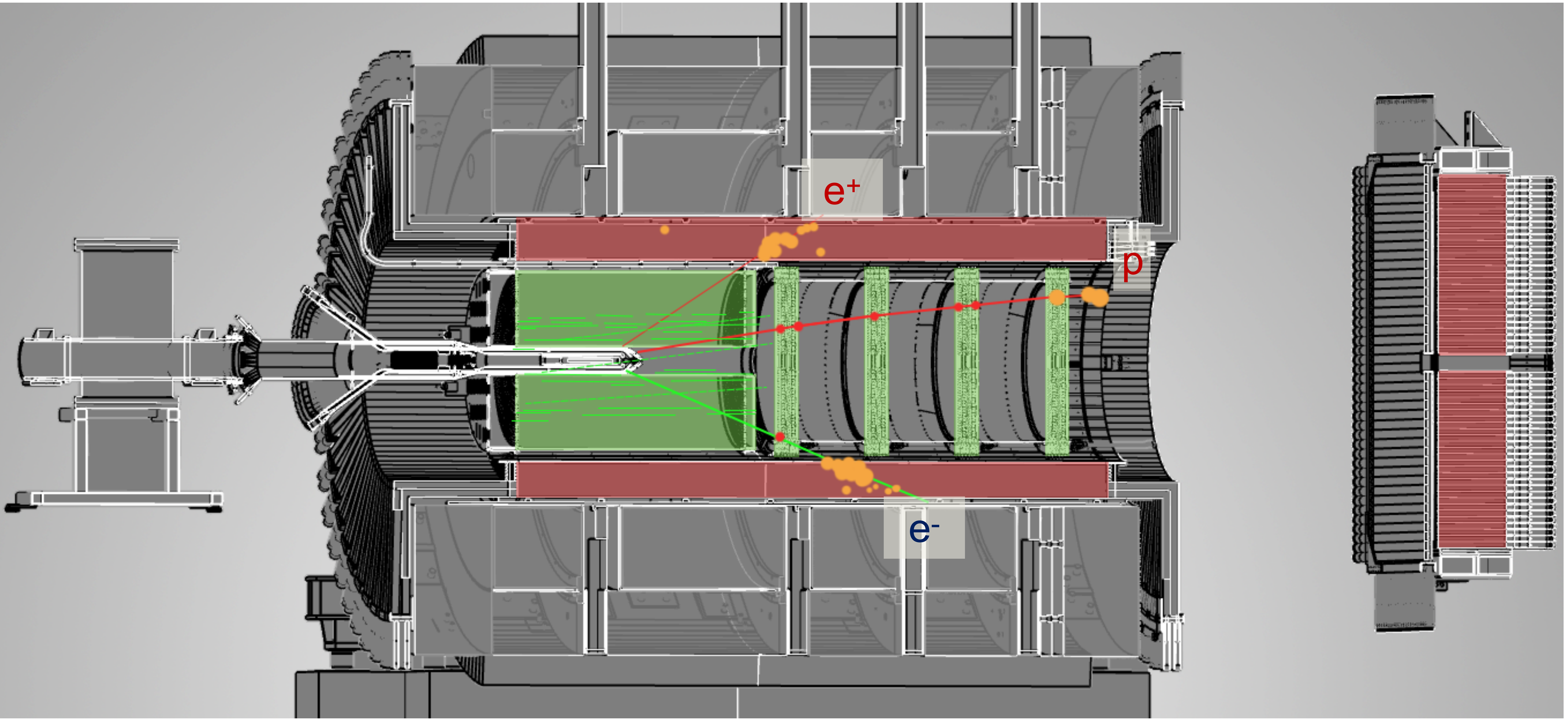
# GlueX spectrometer

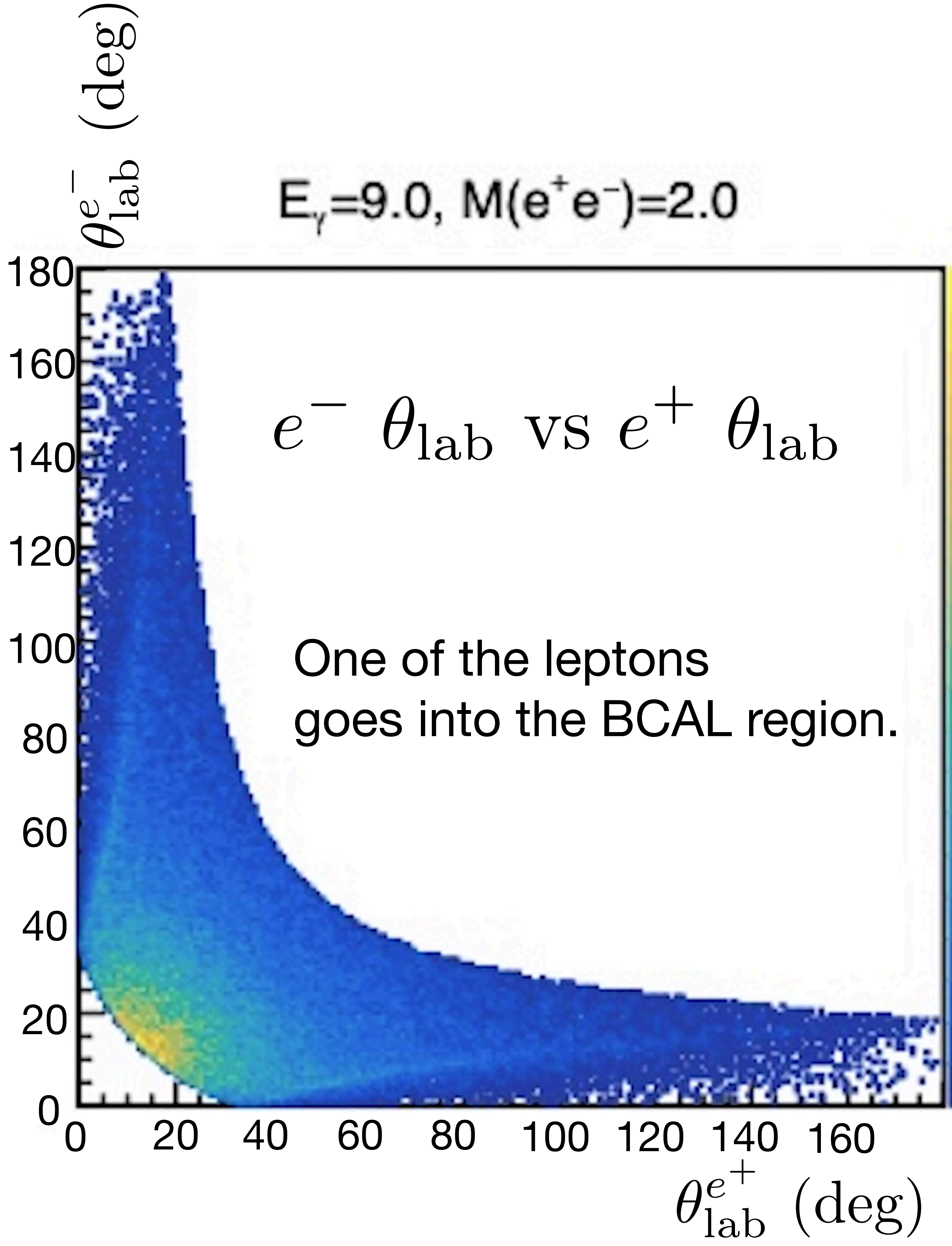



- 2T-Solenoid, $LH_2$ target
- Hermetic Detector: $1° < \theta_{lab} < 120°$, all $\phi_{lab}$
  - Tracking by FDC ($\theta_{lab} < 11°$) and CDC ($\theta_{lab} > 11°$): $\sigma_p/p \sim 1\text{-}5\%$
  - Calorimetry by FCAL ($\theta_{lab} < 11°$) and BCAL ($\theta_{lab} > 11°$): $\sigma_E/E \sim 6\%/\sqrt{E}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

# Exclusive reaction $\gamma p \to e^- e^+ p$

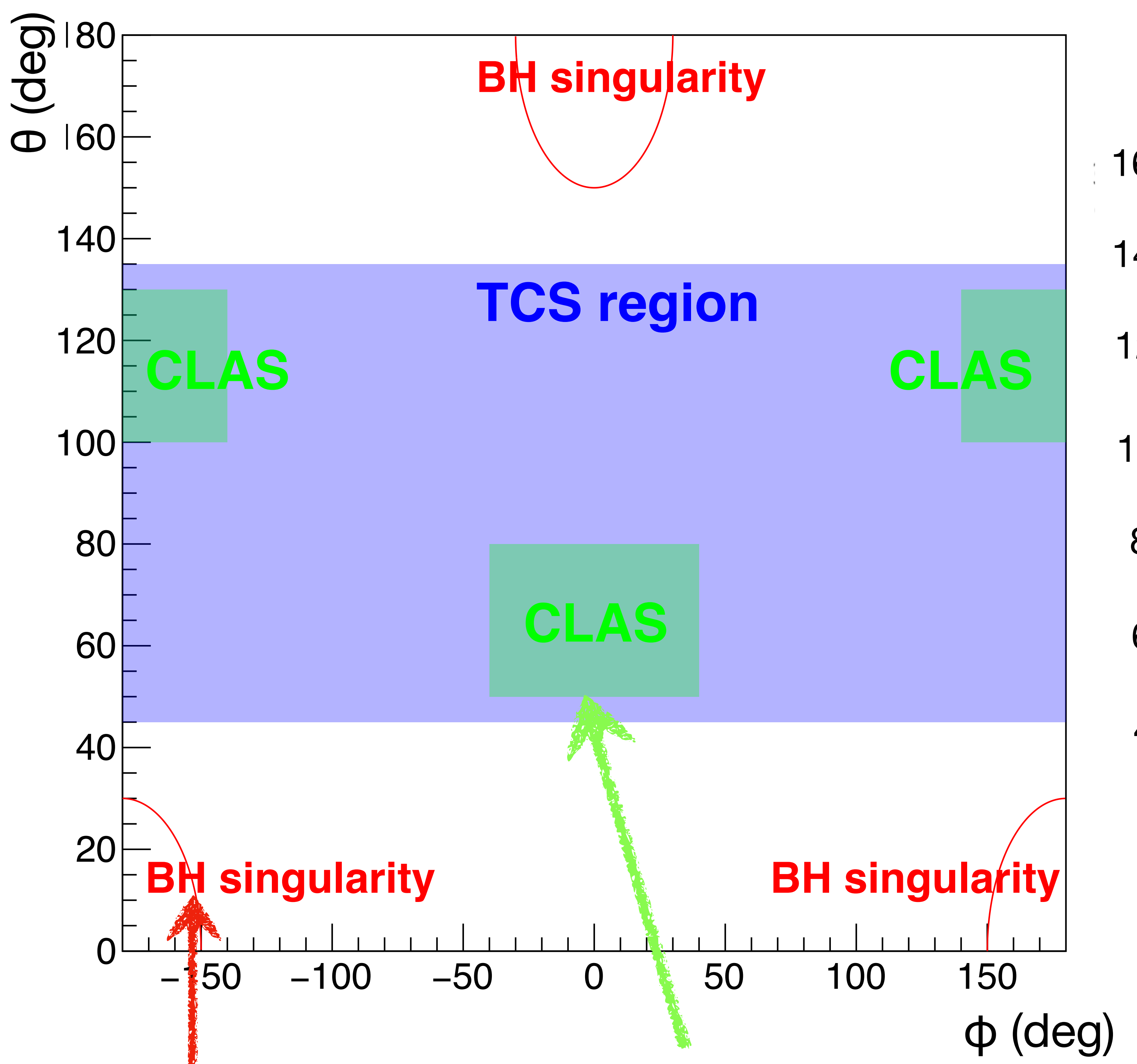


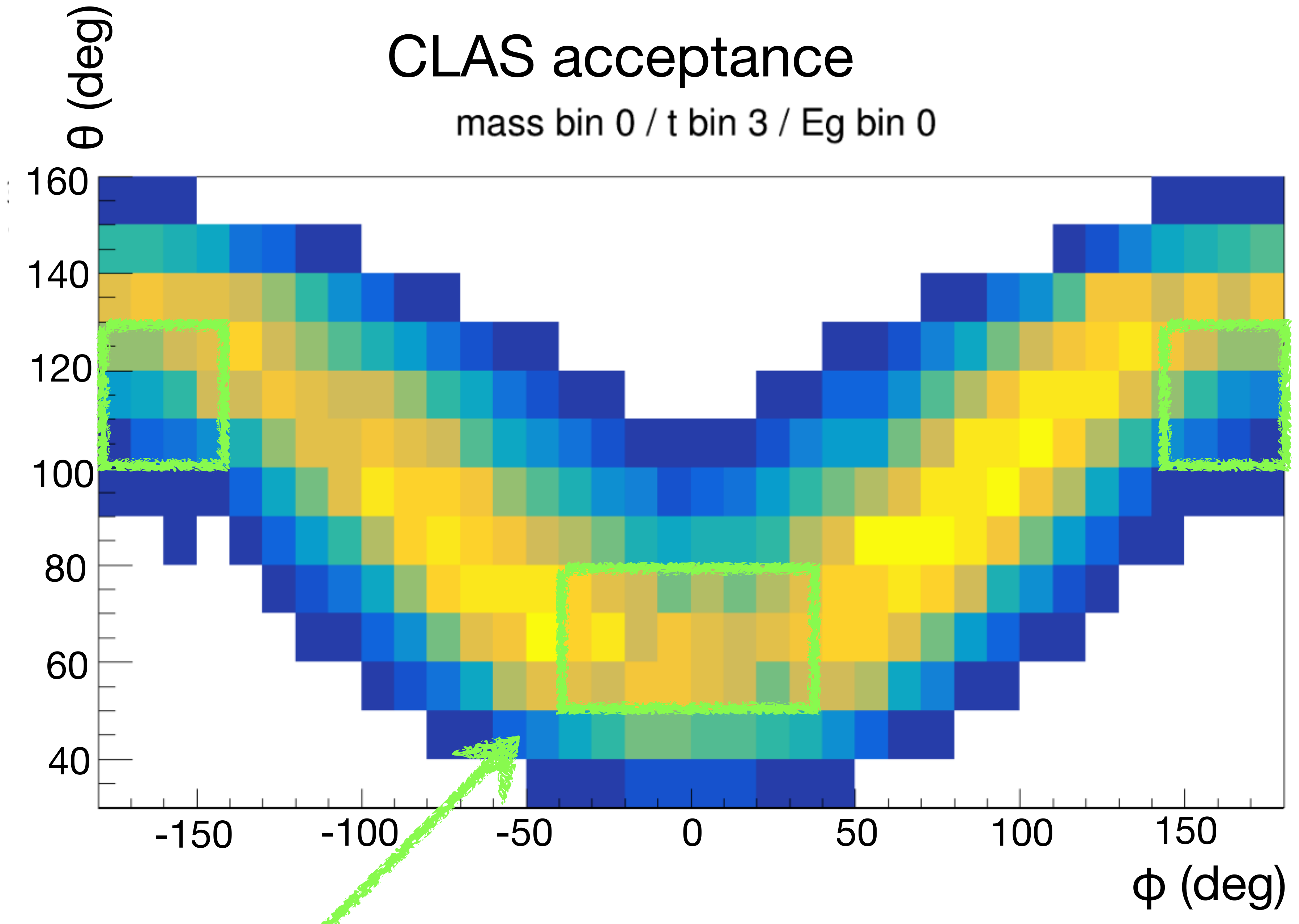


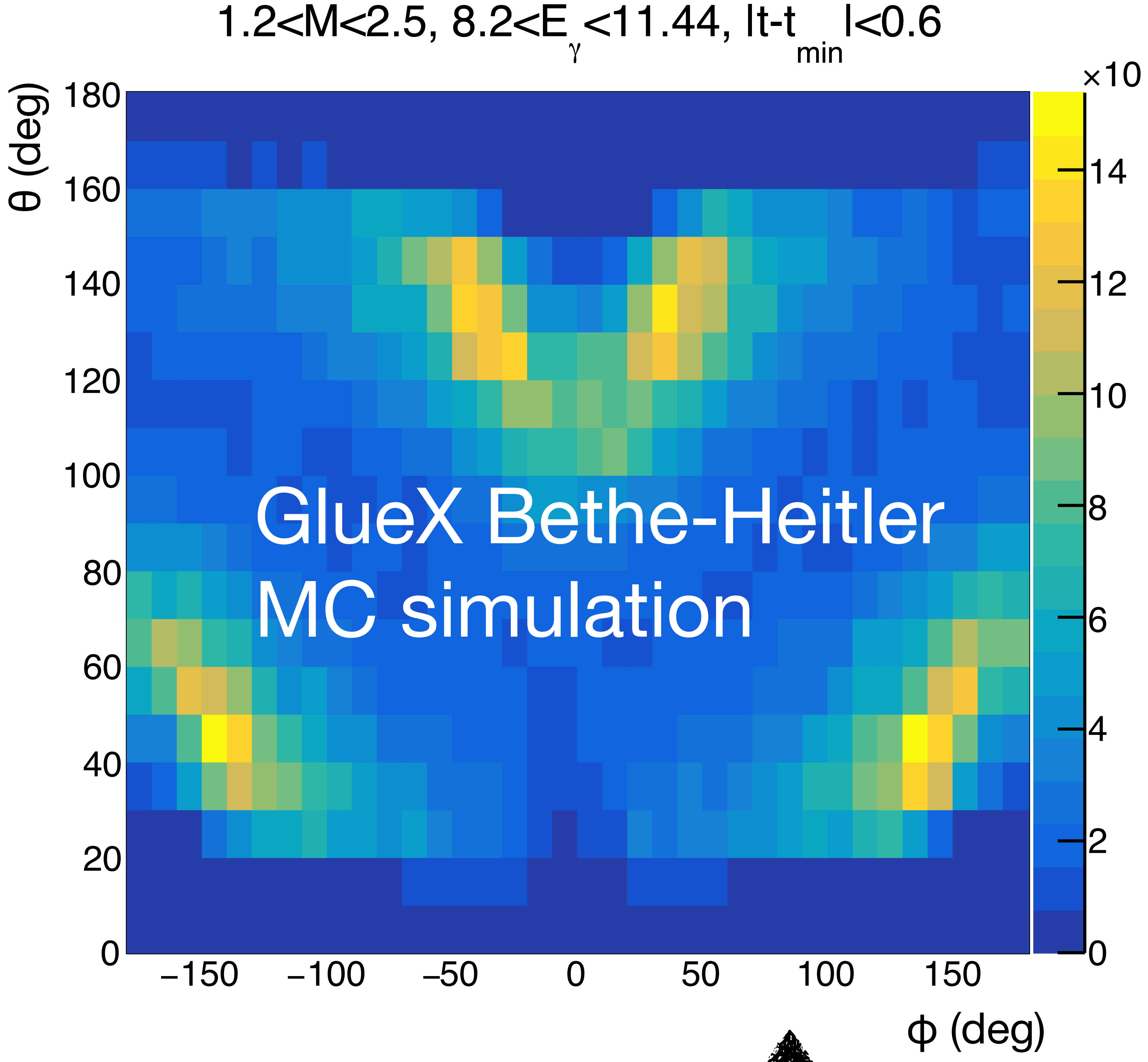

- Large acceptance .. we can access (θ, ϕ) dependence of the FB asymmetry
- e/π separation by p/E (Momentum over energy deposition in the calorimeters)

# Experimental Acceptance




PRL 127, 262501 (2021) supplemental material




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.

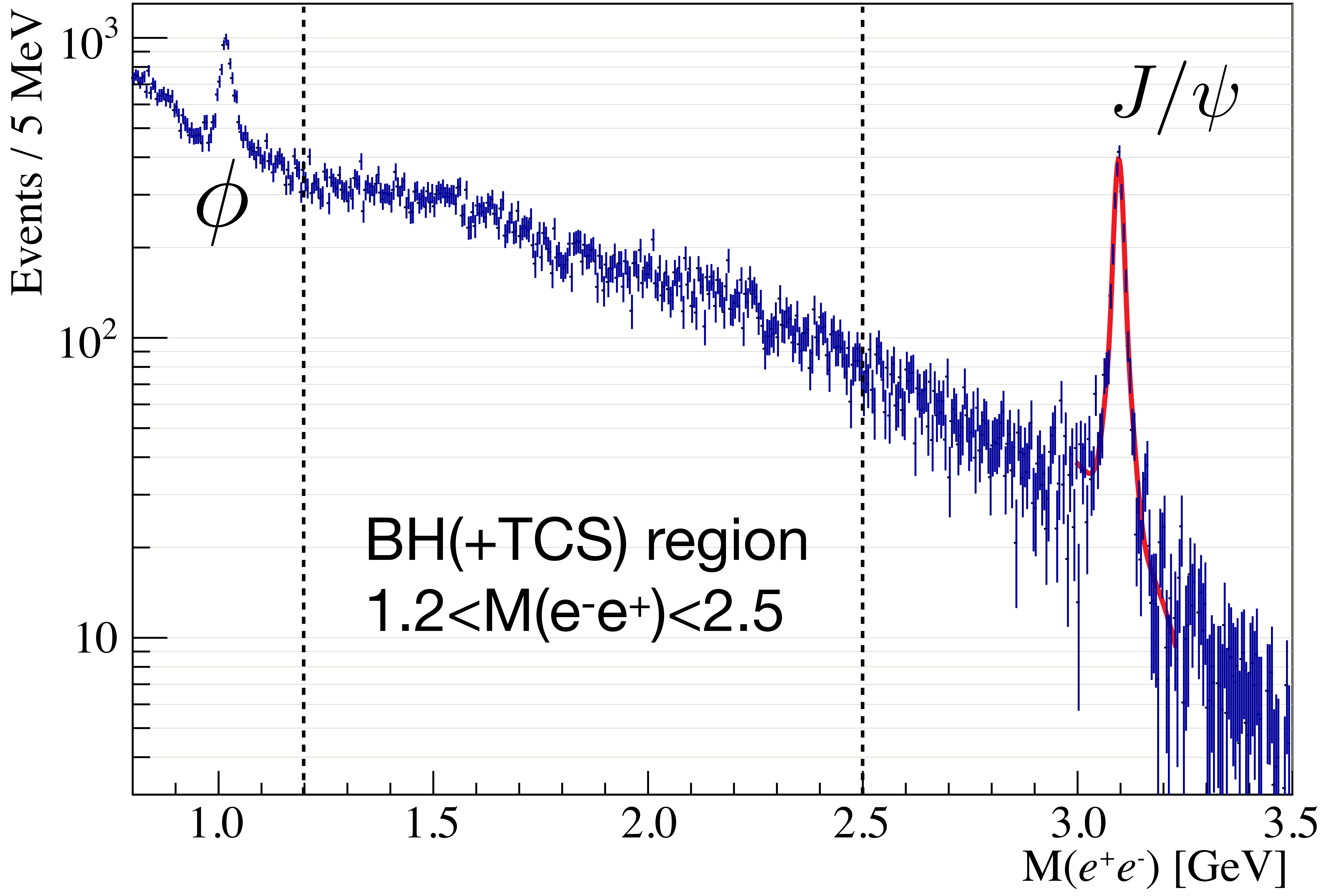
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)} = 0 \quad (d\sigma_{\mathrm{BH}} = \infty)$$

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

# e/π separation by p/E

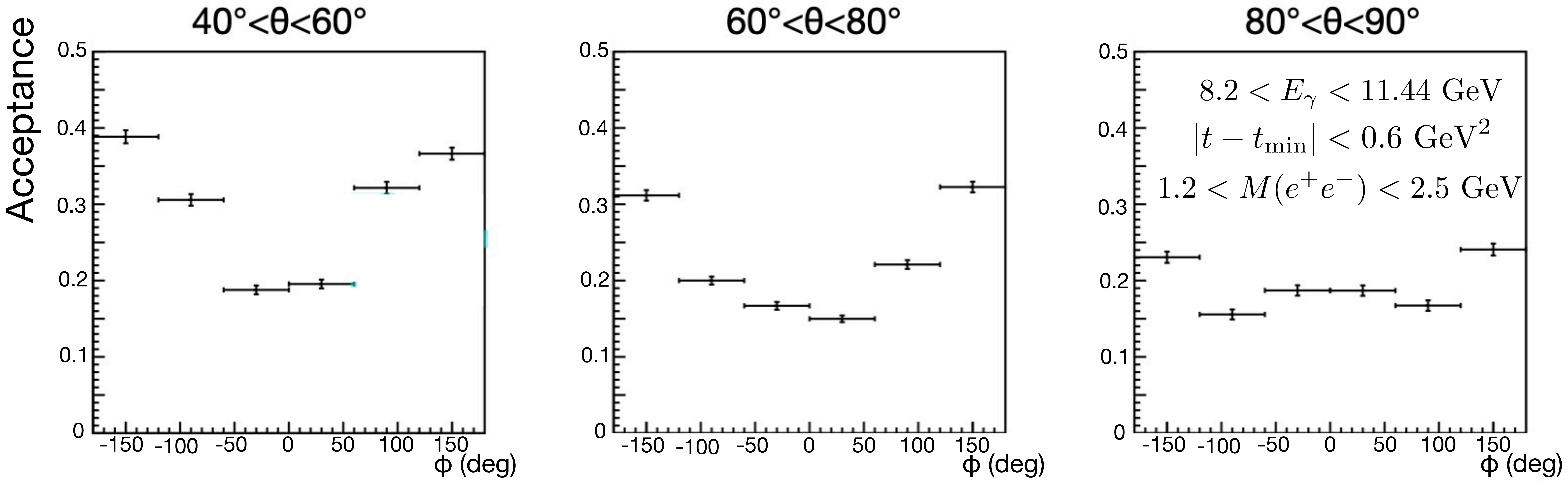

π BG sample is created by "anti-electron" cut (<p/E>+3.5σ < p/E < <p/E>+4.5σ).
Its scale is a fitting parameter.

# $e^-e^+$ 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)

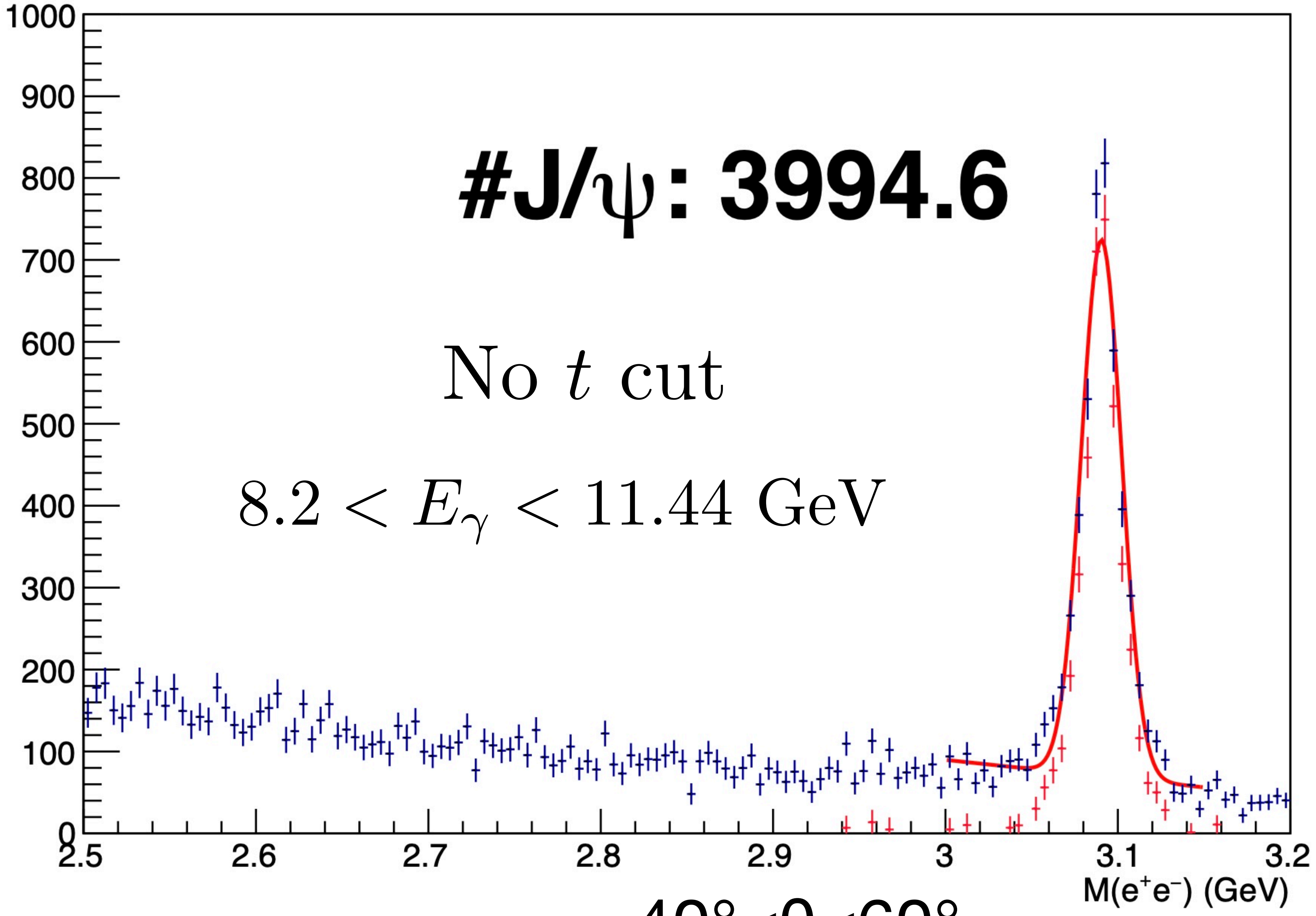
# Acceptance correction by MC simulation




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

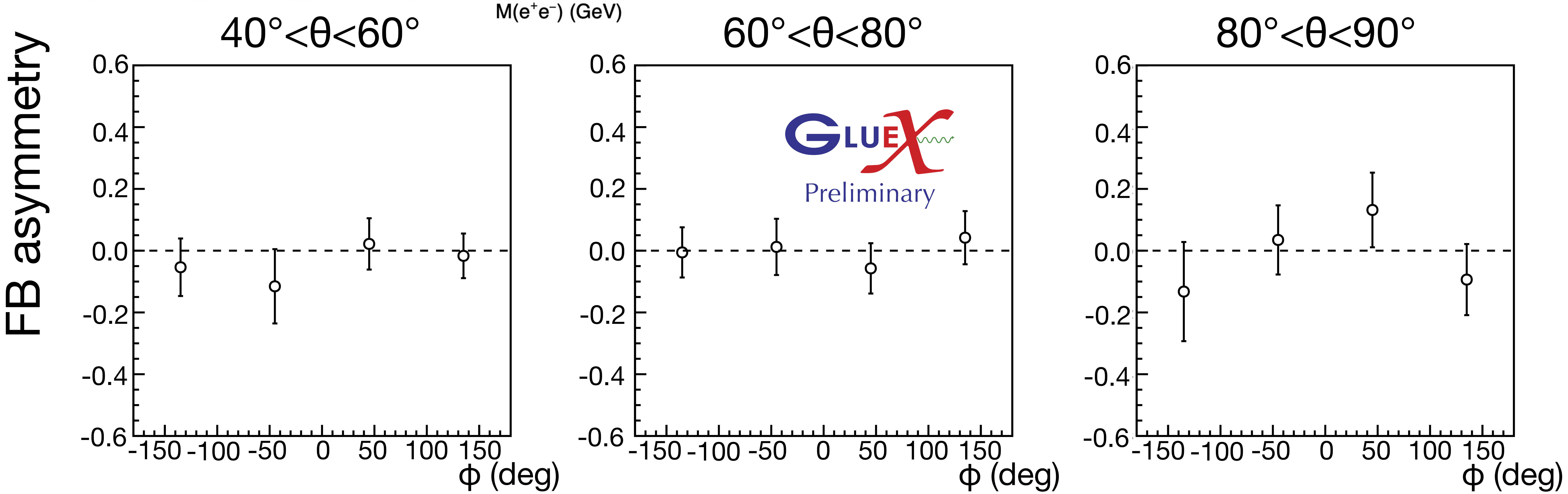
1. FB asymmetry for J/ψ should be zero consistent for any (θ, ϕ).
2. Acceptance is corrected by π sample (assuming $A_{FB}$ for $\gamma p \to \pi^+\pi^- p$ is zero).
3. FB asymmetry for BH singularity regions should be zero consistent.

# 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).



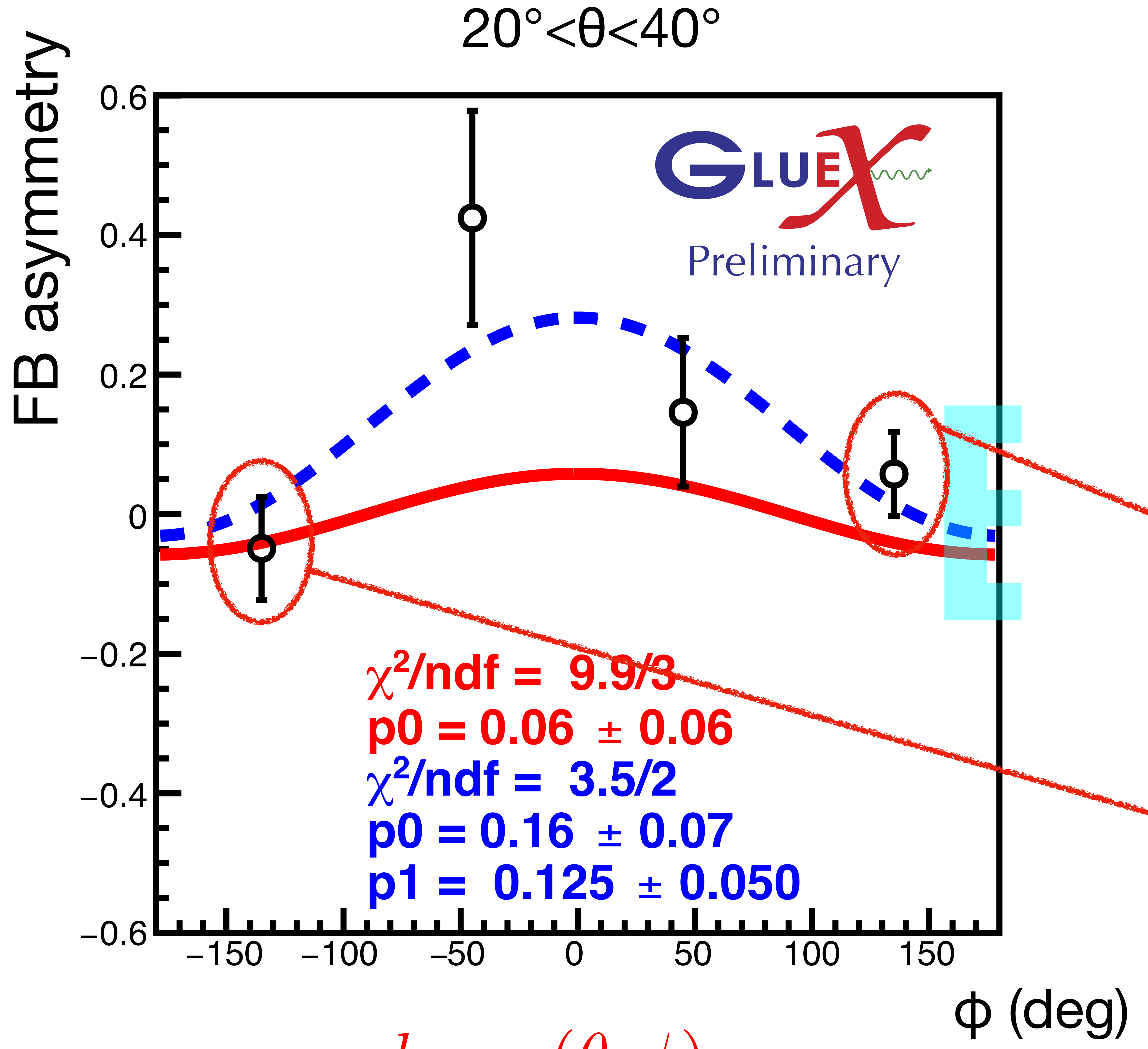
# Cross-check 2. Correction with π events (w/o MC)

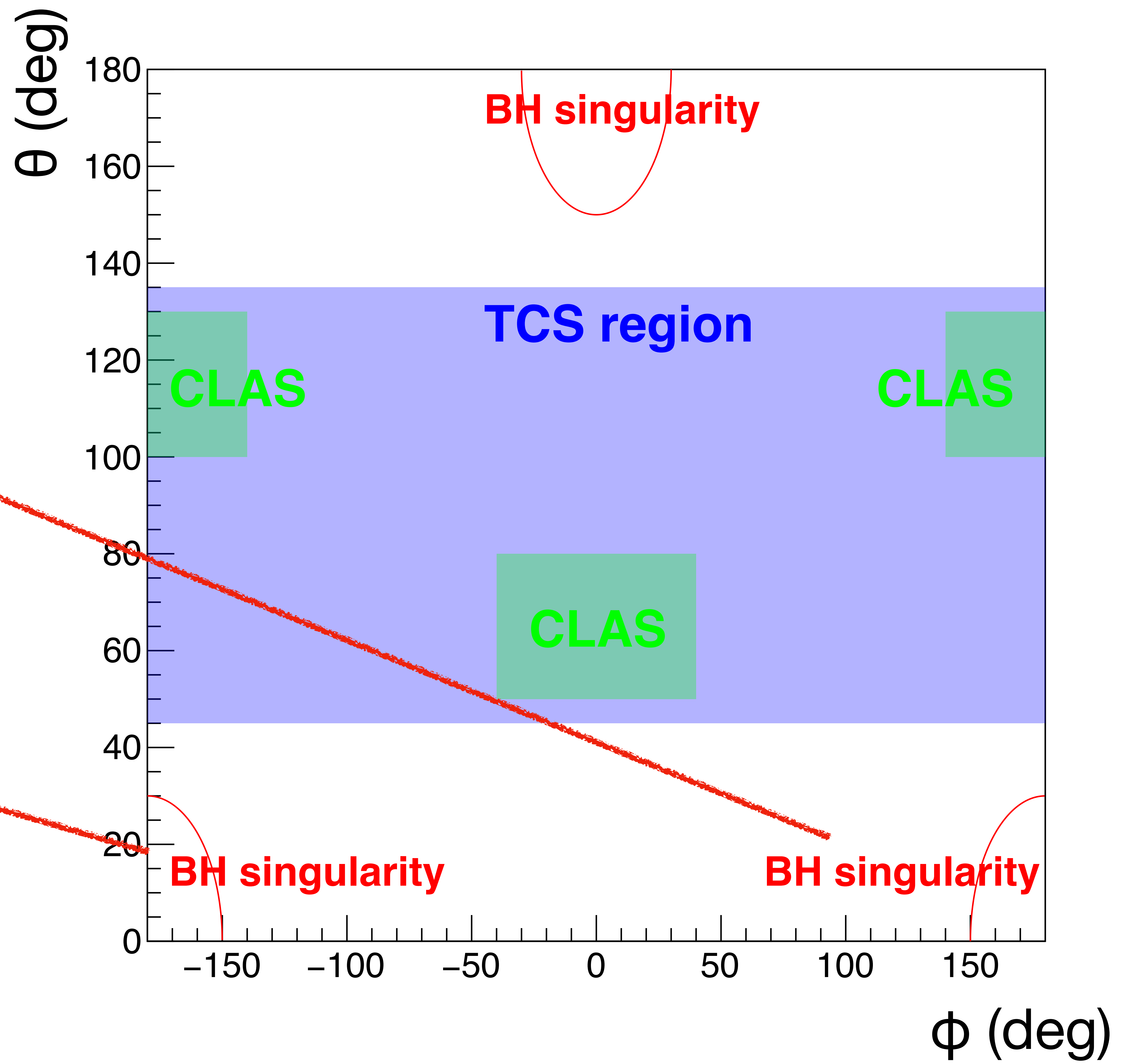
Assuming pion $A_{FB}$=0, efficiencies can be corrected using pion events.

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


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

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



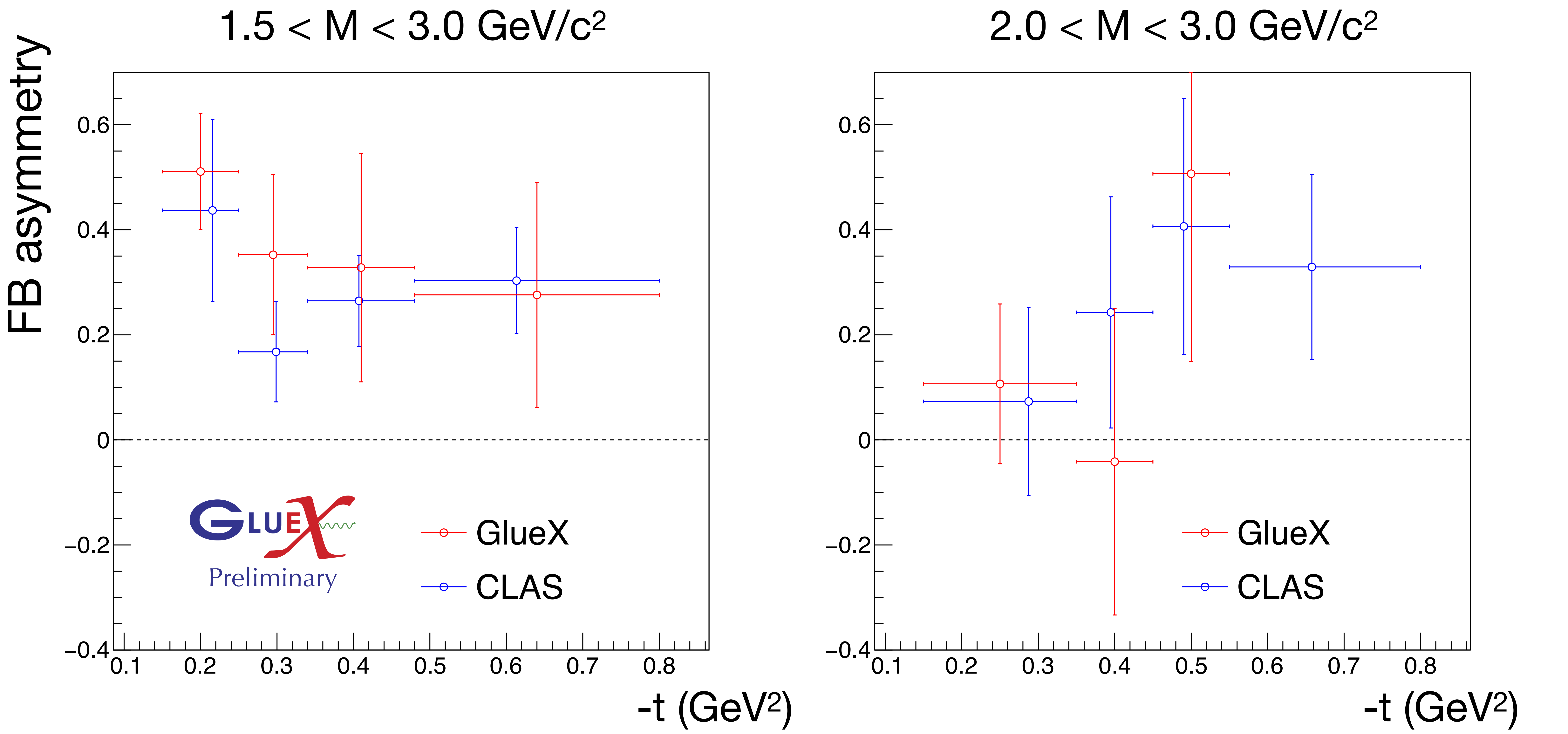

$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)} = 0 \quad (d\sigma_{\mathrm{BH}} = \infty)$$

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.

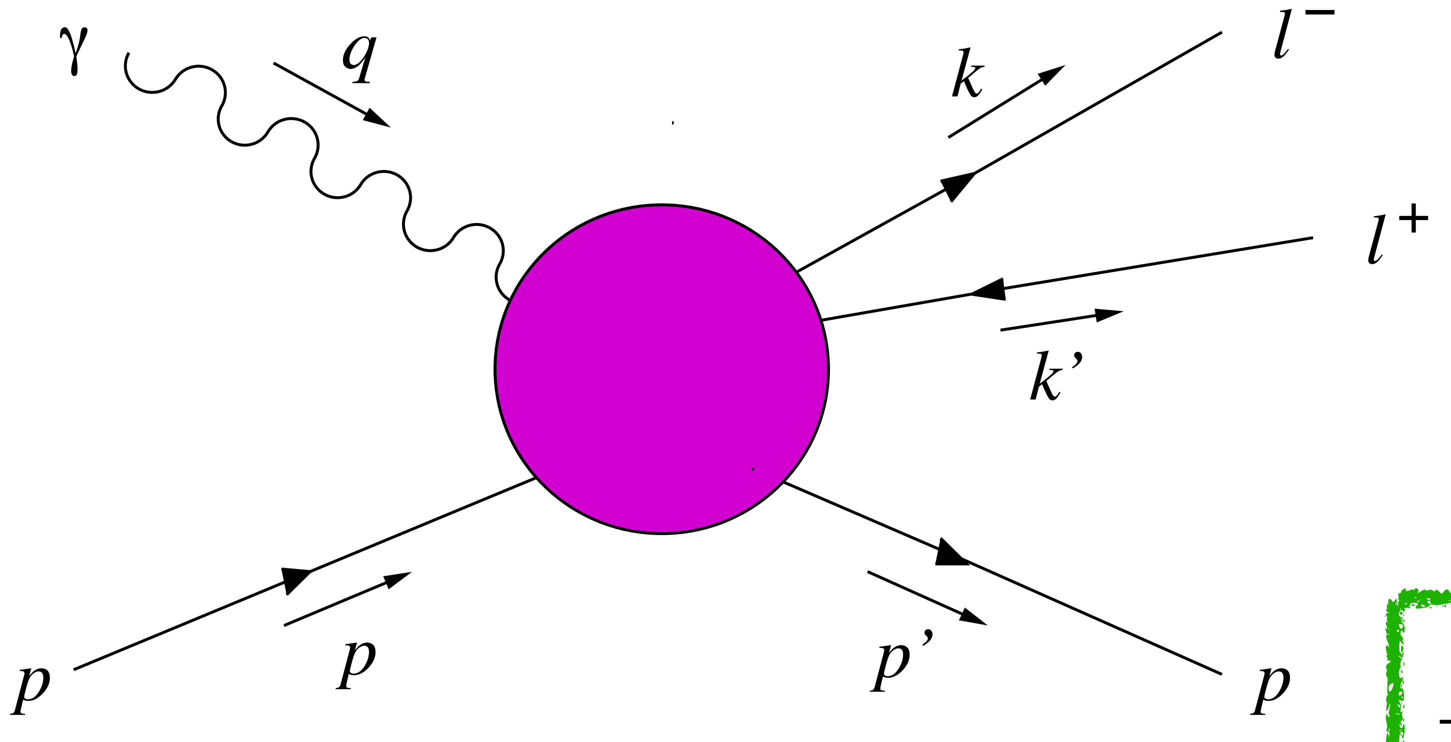
# (θ, ϕ)-dependence of the FB asymmetry


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°).

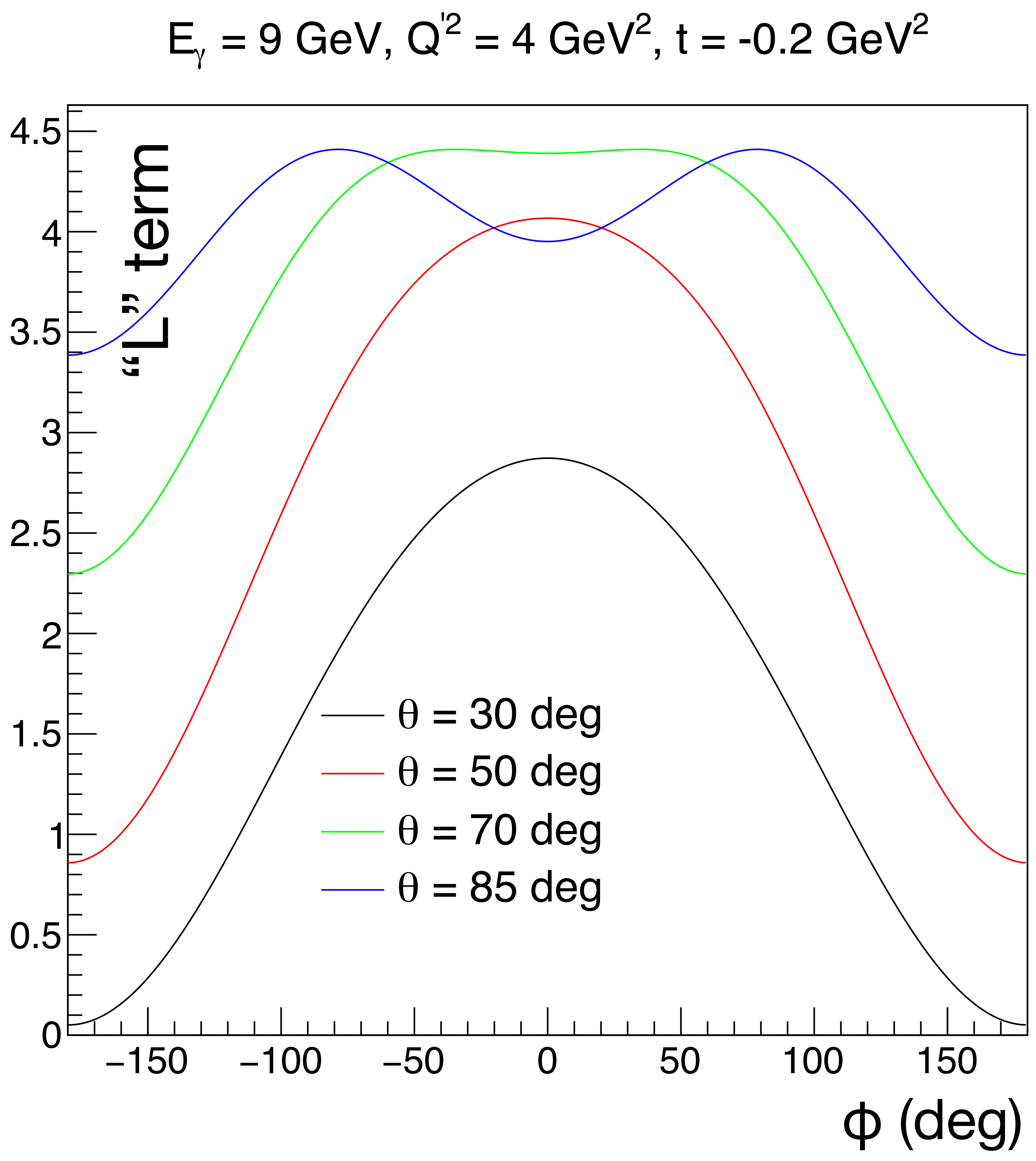
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi) + d\sigma_{\mathrm{TCS}}(\theta,\phi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$




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

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

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




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

→ $A_{\mathrm{FB}} \sim \cos\phi$ at the leading order

# Theoretical prediction

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

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

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

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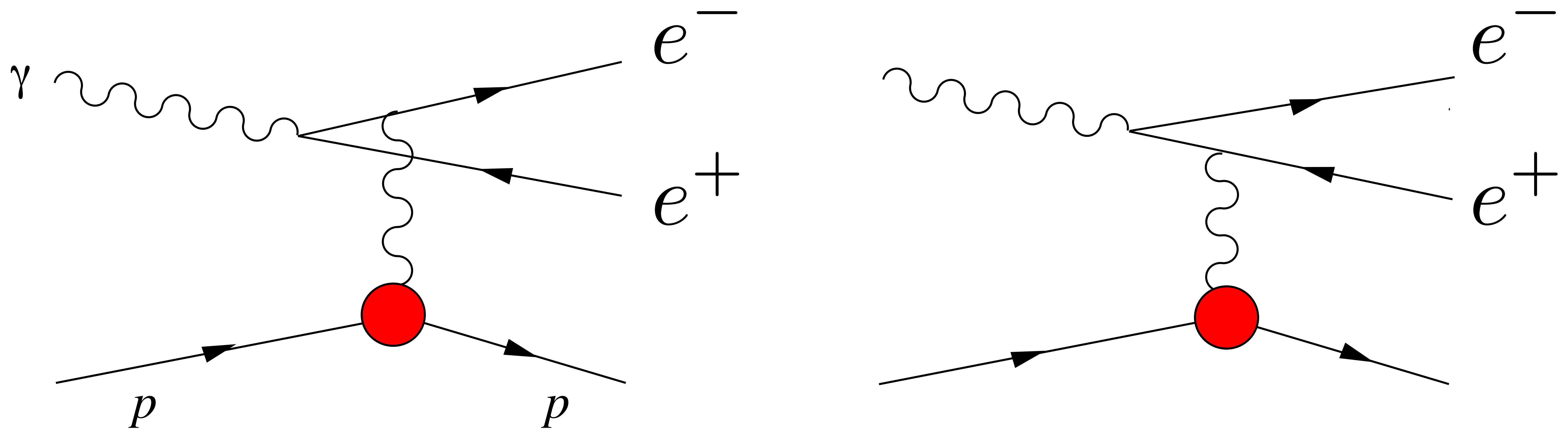



- L comes from the interference b/w 2 BH diagrams.
  - L in dσ$_{\mathrm{BH}}$ is reasonable
  - L in dσ$_{\mathrm{INT}}$ is not straightforward

# 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.
- Following items were checked:
  - Zero-consistent asymmetries for J/ψ
  - Acceptance correction by π gives consistent results
  - Zero-consistent asymmetries at BH singularity regions
- Consistent results with CLAS at $50° < \theta < 80°$, $-40° < \phi < 40°$
- To understand (θ, ϕ)-dependence, theoretical supports are essential.

- Marie Boër suggested linearly polarized observables are also useful to extract GPD information. (cf. M. Boër *et al.*, PoS(DIS2015)028, Future work)

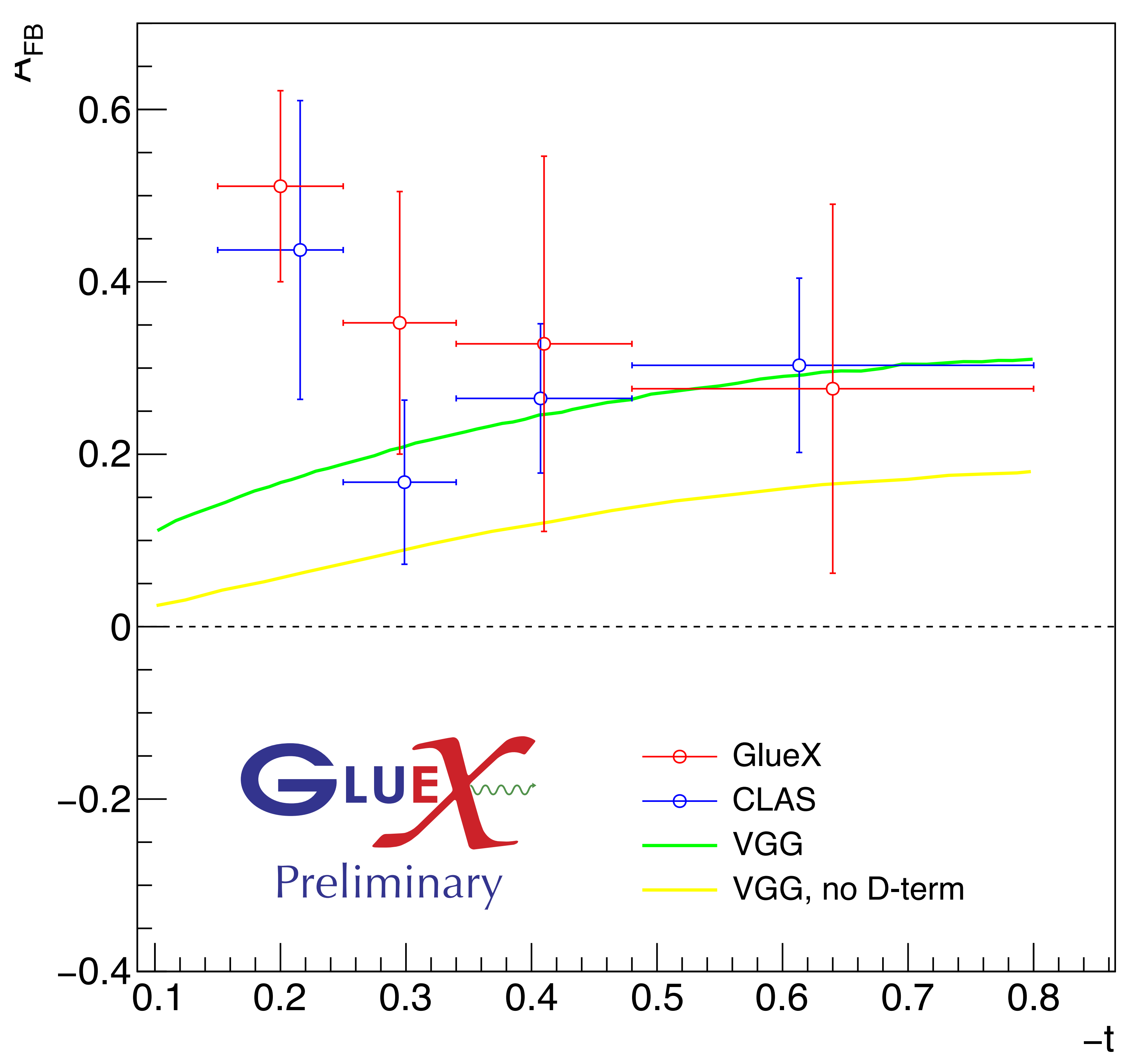
# Comparison with CLAS results



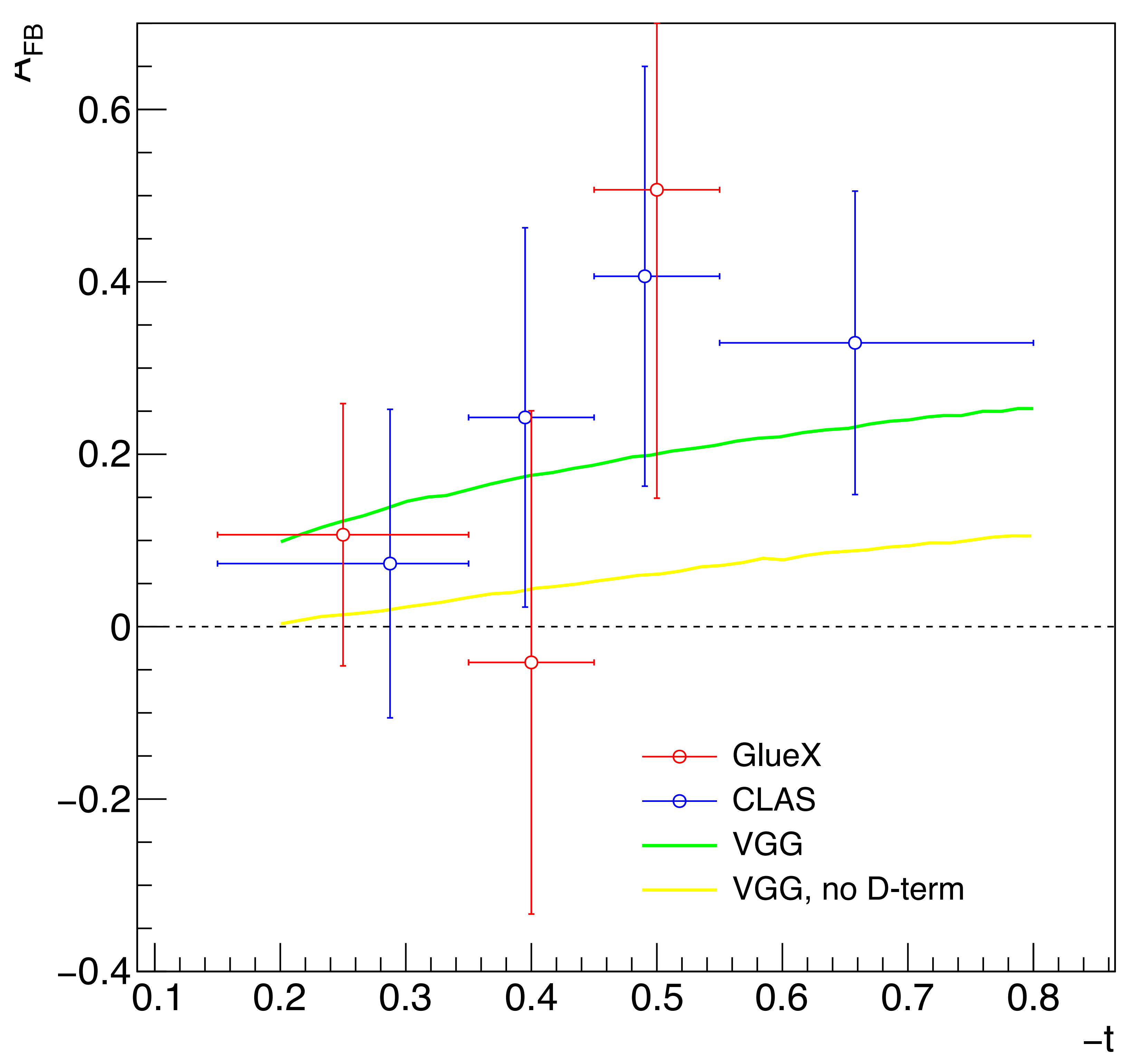
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi+\pi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi+\pi)} \sim \frac{d\sigma_{\mathrm{INT}}(\theta,\phi)}{d\sigma_{\mathrm{BH}}(\theta,\phi)}$$

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

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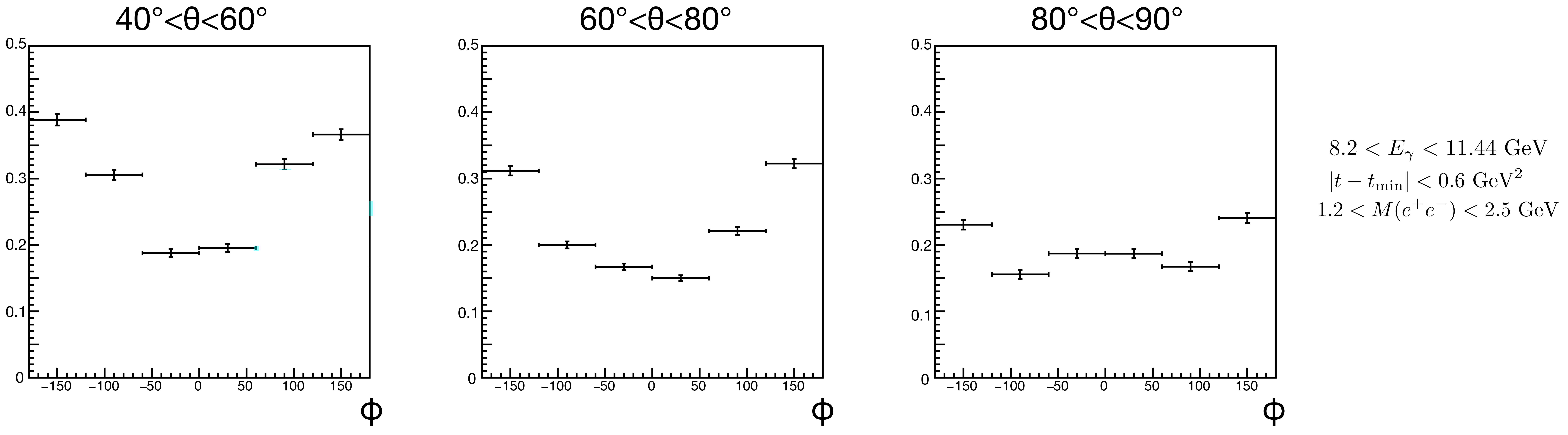
# Acceptance correction by MC simulation

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