J/ψ SDMEs with GlueX at 17 GeV

Keigo Mizutani

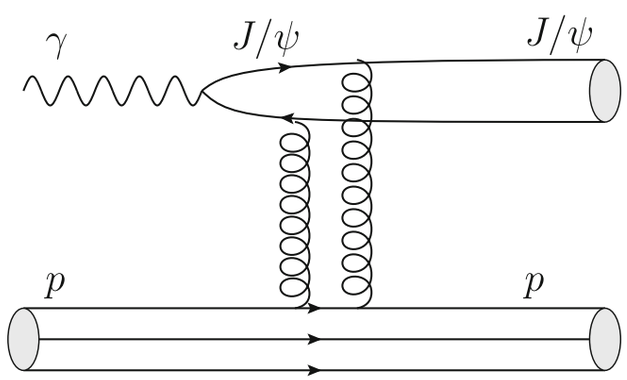
Opportunities with JLab Energy and Luminosity Upgrade

27 September 2022

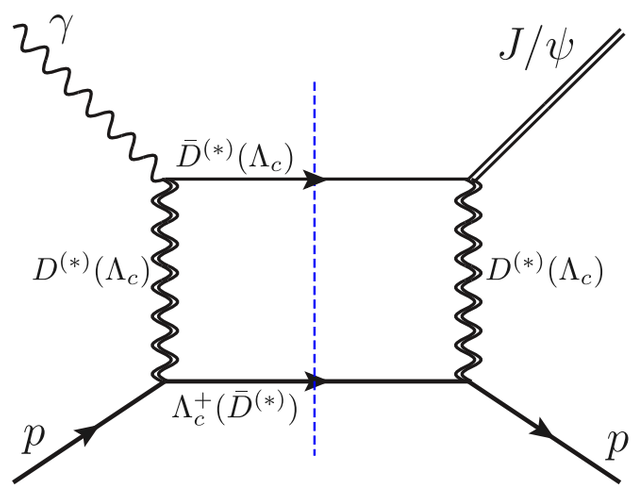
Why measure J/ψ SDMEs?

- Threshold J/ψ photoproduction → properties of proton mass?
- High E_γ region is well explained by Pomeron model.
- Understanding of production mechanism near threshold is desired.

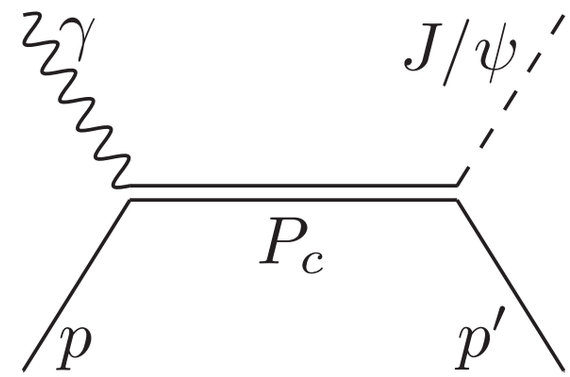
M. Du *et al.*, EPJ C80 (2020)



Gluon exchange?



Open-charm?

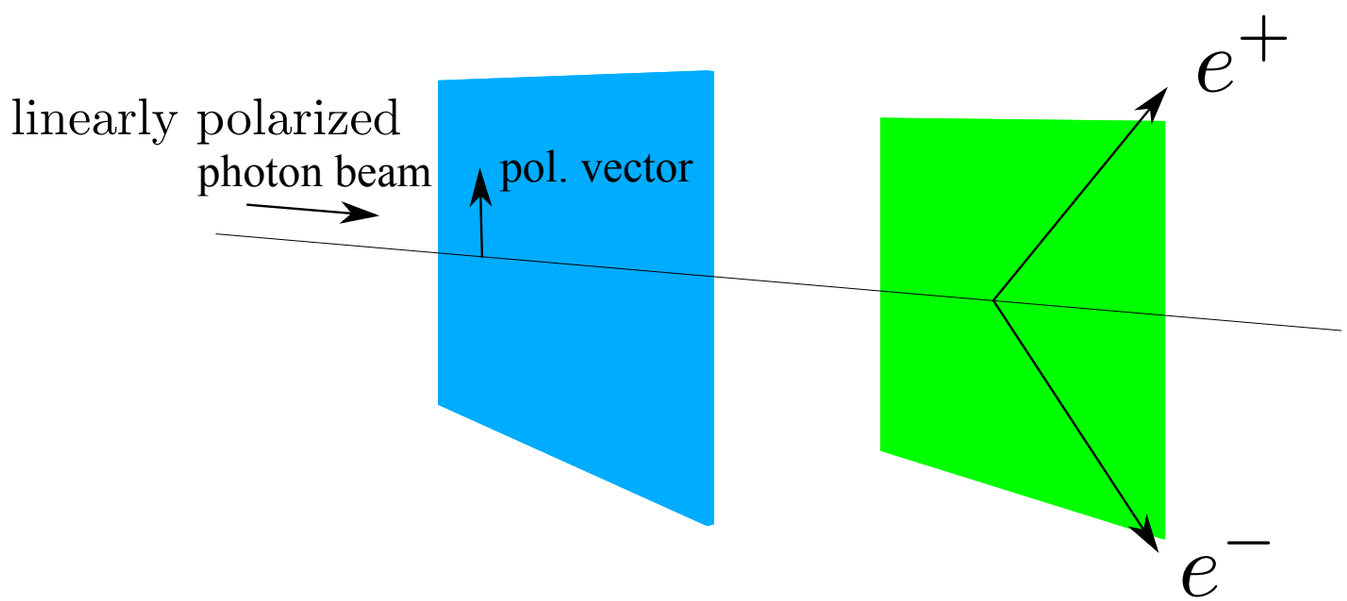


Pentaquark?

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

Polarization measurements: Naturality

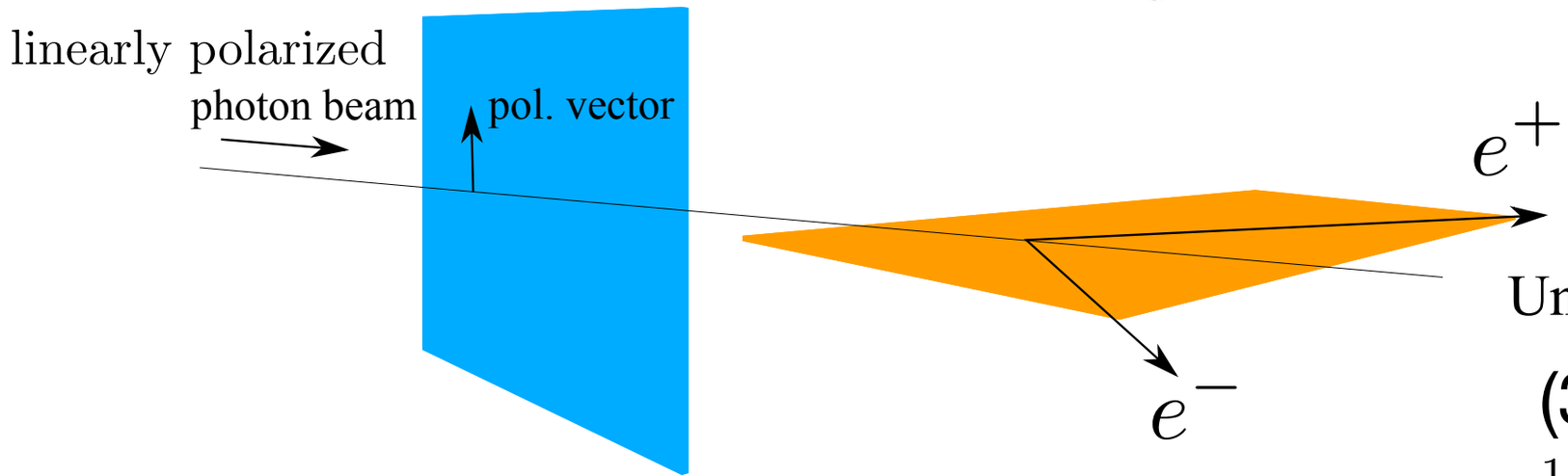
Decay angle wrt polarization plane is sensitive to naturality $P(-1)^J$ of the t-channel exchanged particle.



Natural parity exchange

(2 gluons, Pomeron, f_0, …)

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



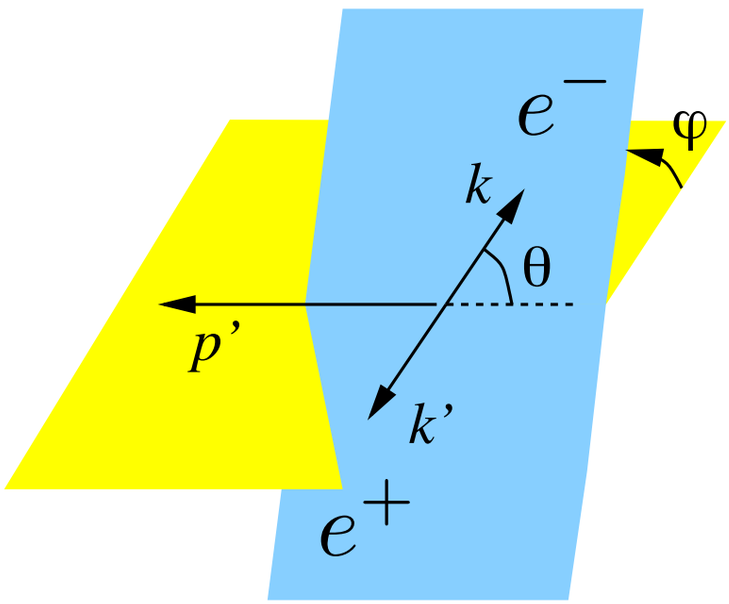
Unnatural parity exchange

(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

$$\begin{cases} W(\cos\theta) = \dfrac{3}{8}\left(1 + \rho^0_{00} + (1 - 3\rho^0_{00})\cos^2\theta\right), \\ W(\phi) = \dfrac{1}{2\pi}\left(1 + \text{Re}\rho^0_{1-1}\cos 2\phi\right), \end{cases}$$

Naturality

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

Helicity conservation

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

Beam Asym. ($\sum$)

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

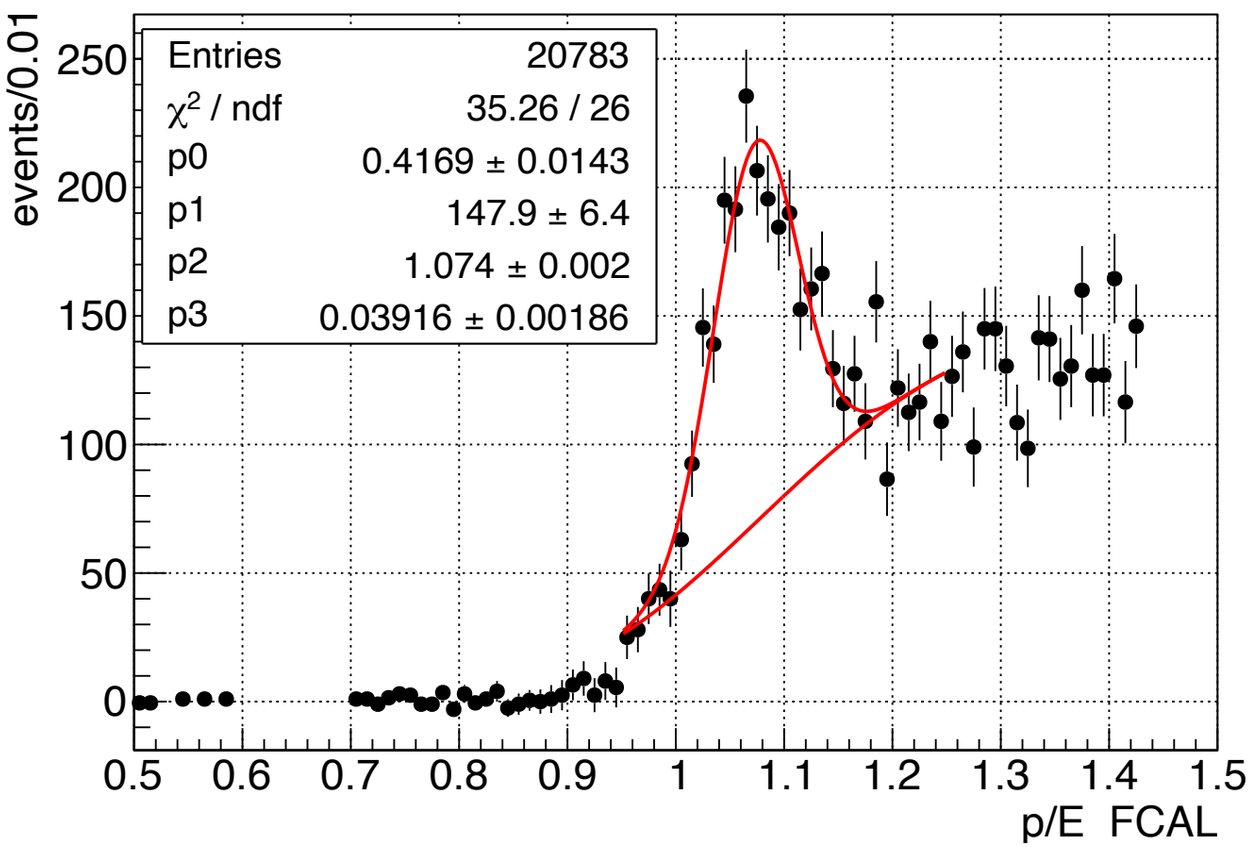
What we expect about J/ψ SDMEs?

- 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 $\sum \sim 0$ is observed for light vector mesons. $\sum \sim 0$ for J/ψ as well?

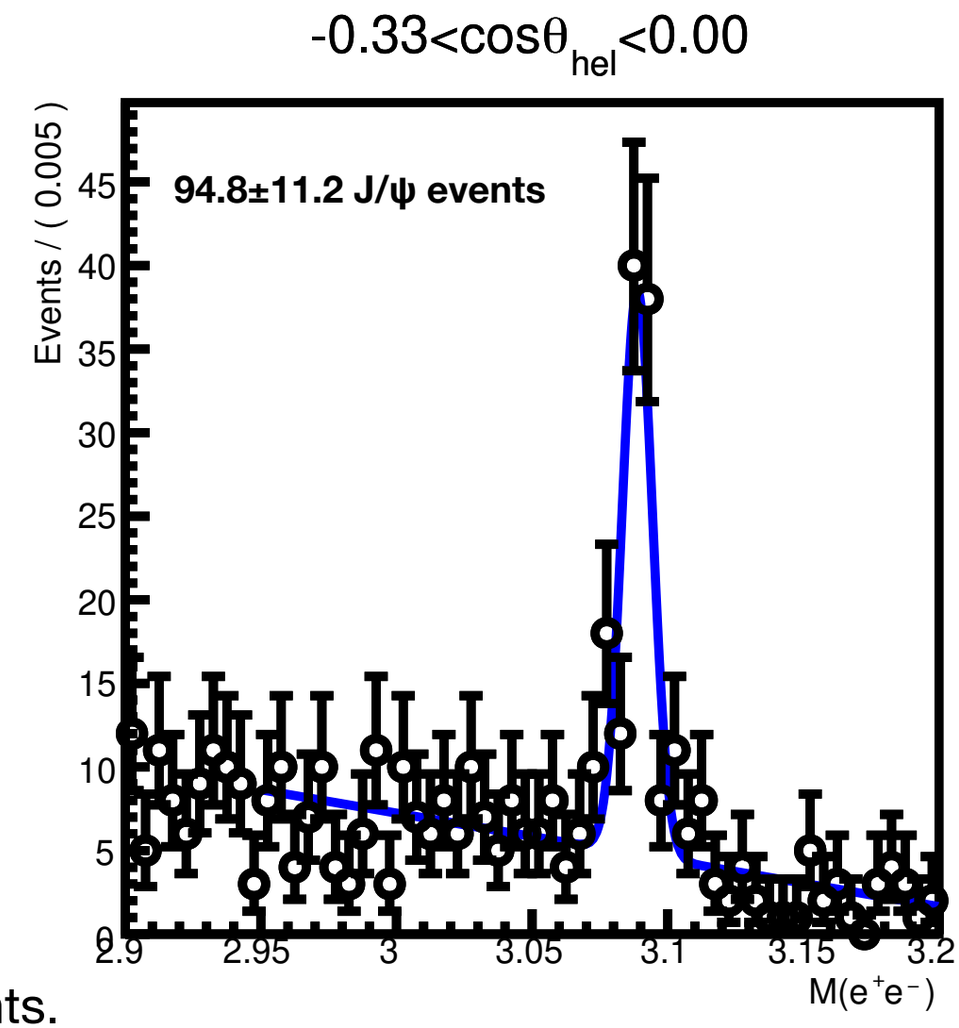
Basically, we have no knowledge about J/ψ SDMEs near thr.
That's why we measure them.
GlueX can do unique measurements of naturality.

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

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.

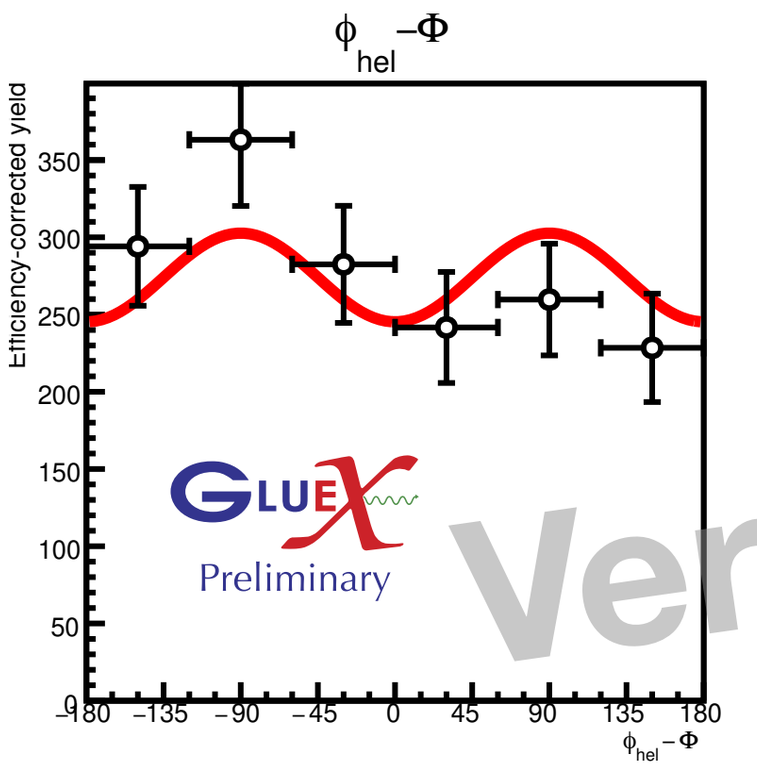


Clean J/ψ peak is observed in e^+ e^- mass distribution.

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

Polarized measurements

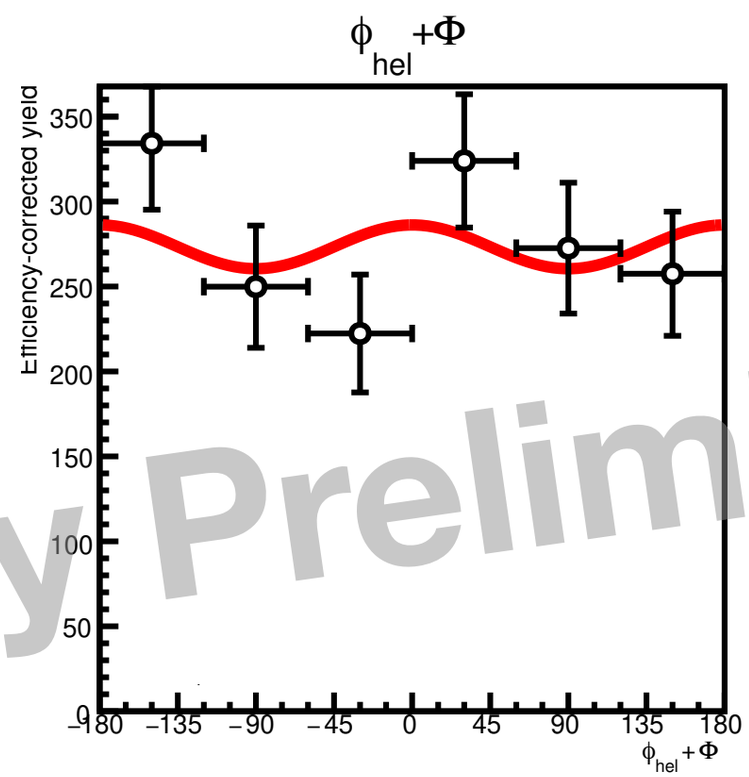
Naturality



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

Stat. error: 0.23

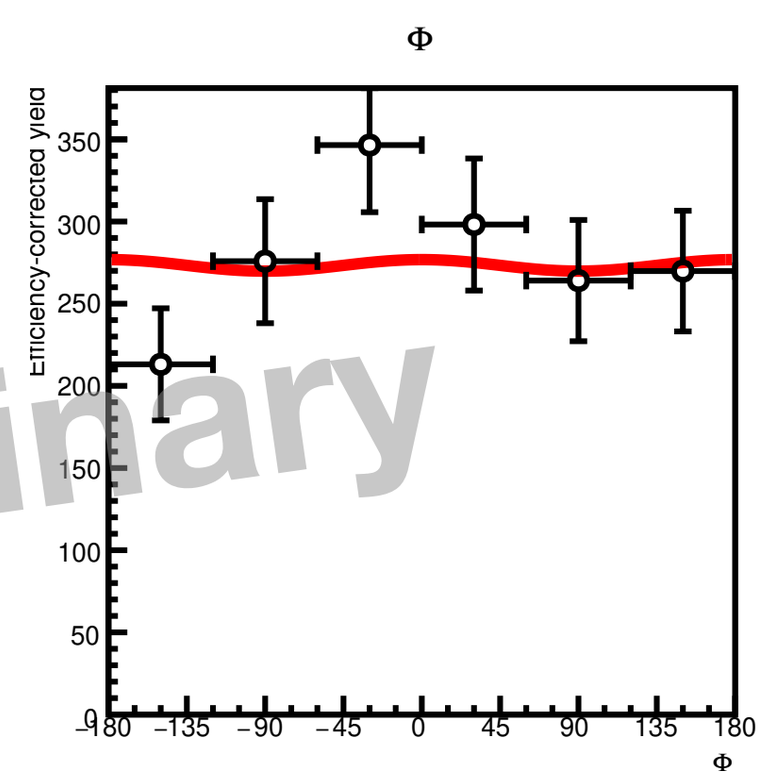
Helicity conservation



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

Stat. error: 0.22

Beam Asym.



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

Stat. error: 0.22

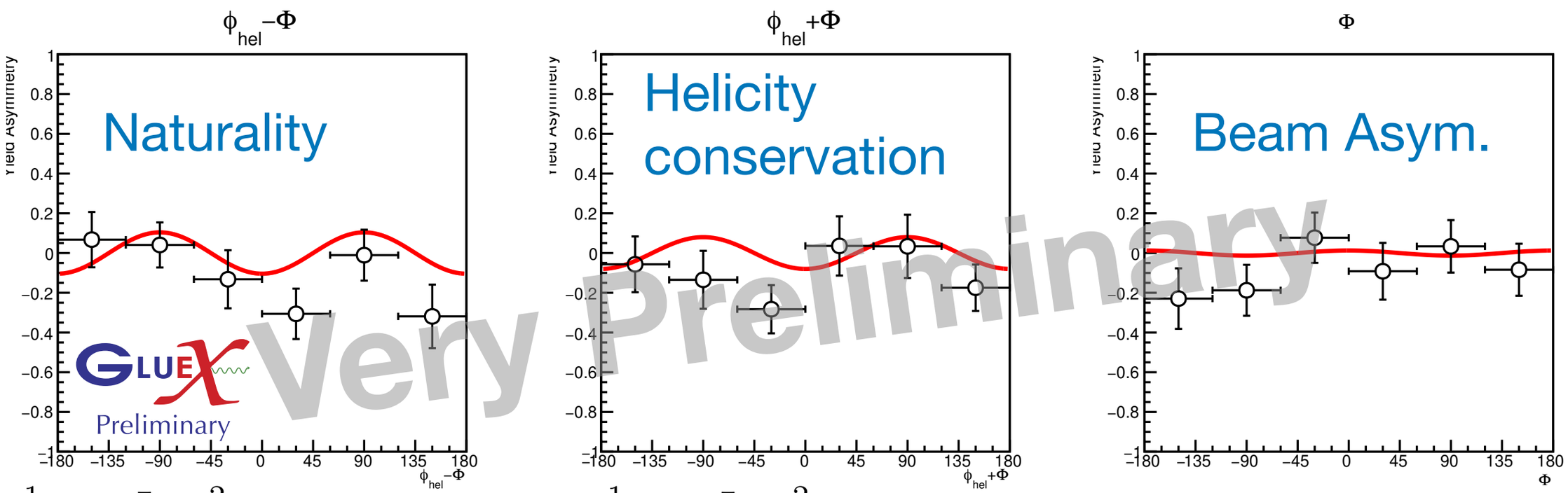
Large uncertainty for naturality, but enough to distinguish
“fully unnatural-parity exchange (-0.5)” and “fully natural-party exchange(+0.5)”.

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

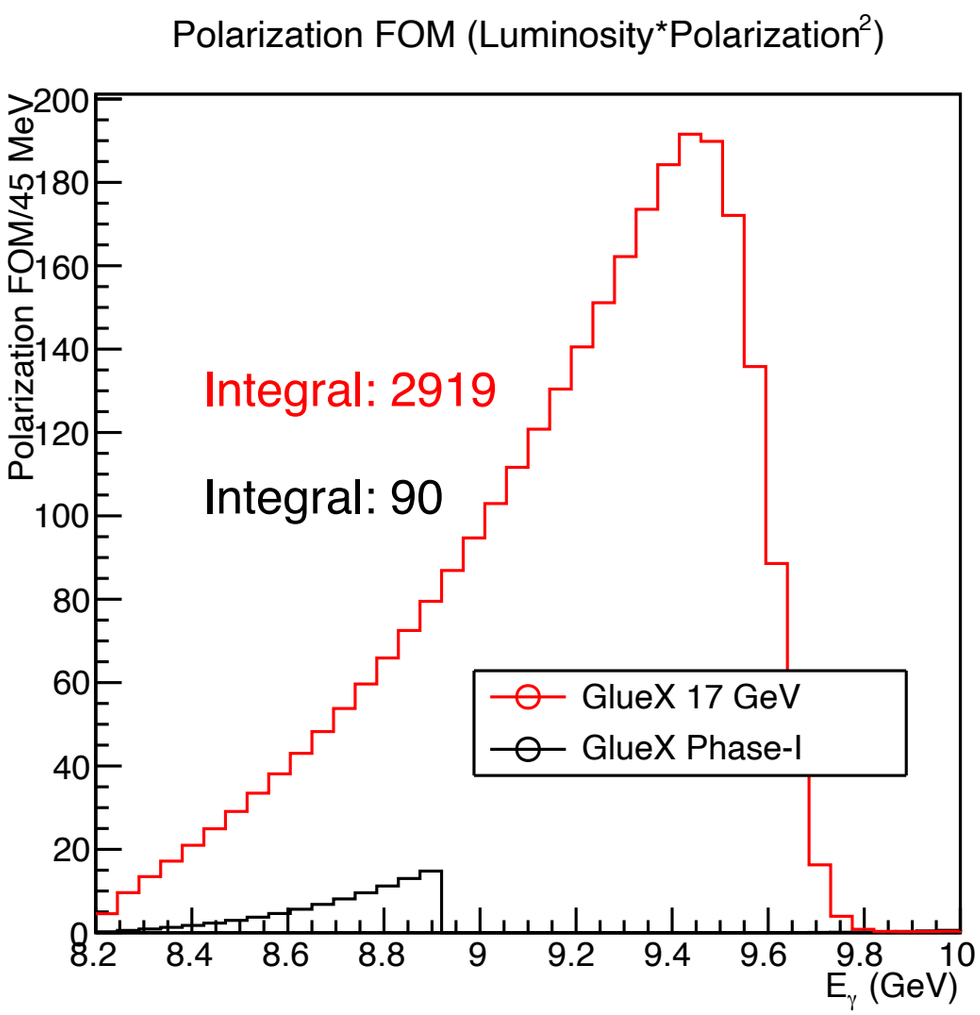
Stat. error: 0.22

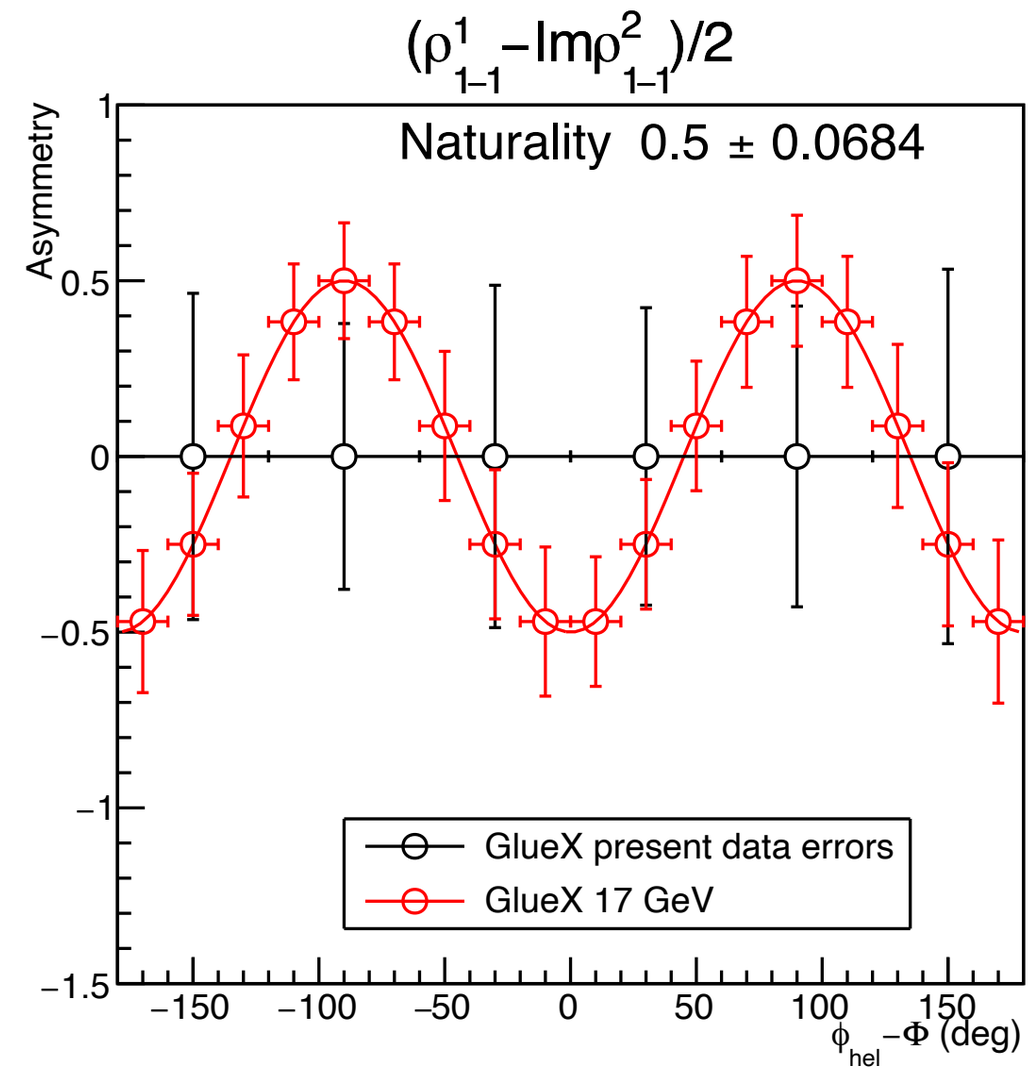
Stat. error: 0.21

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

Naturality at 17 GeV

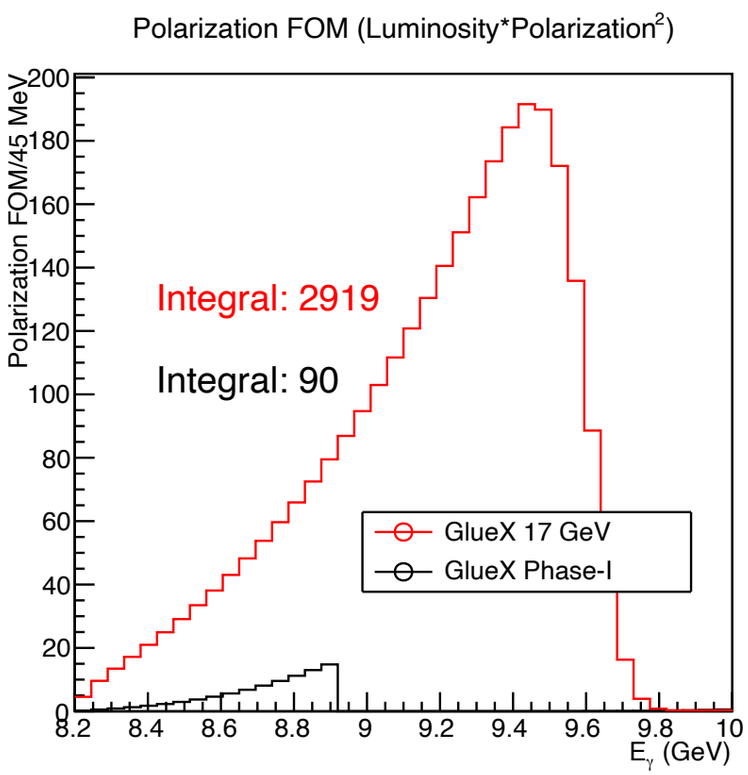
The same assumption as Lubomir's talk.

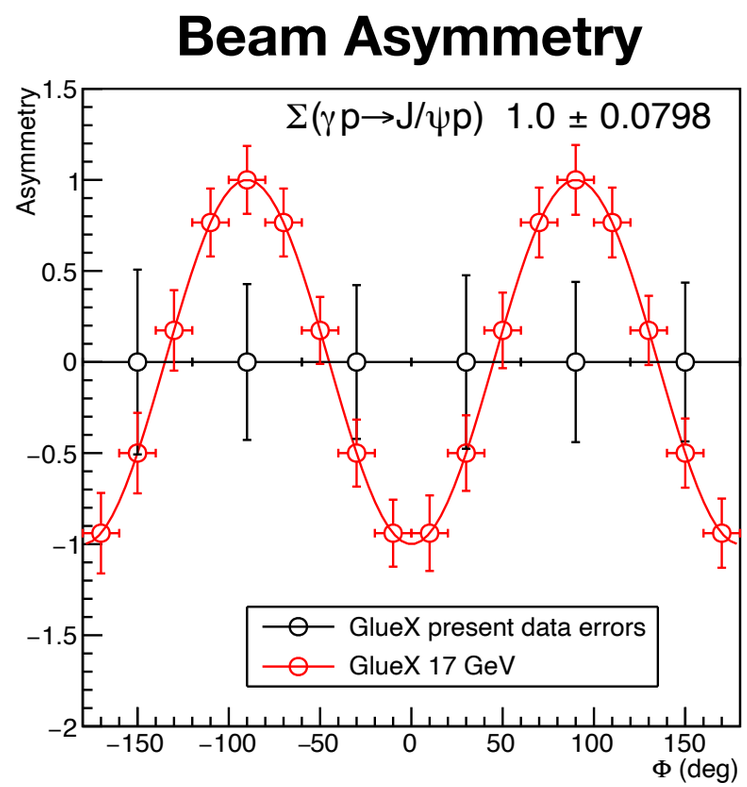


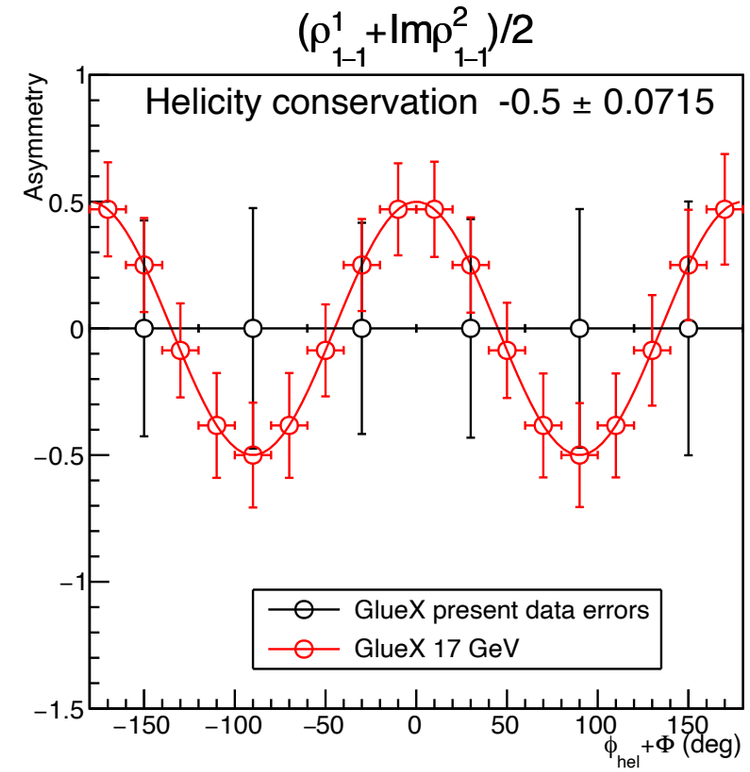


Polarization FOM increases ~30 times in the coherent peak region.
Precise measurement of naturality is possible with 17 GeV data.

Polarized SDMEs at 17 GeV



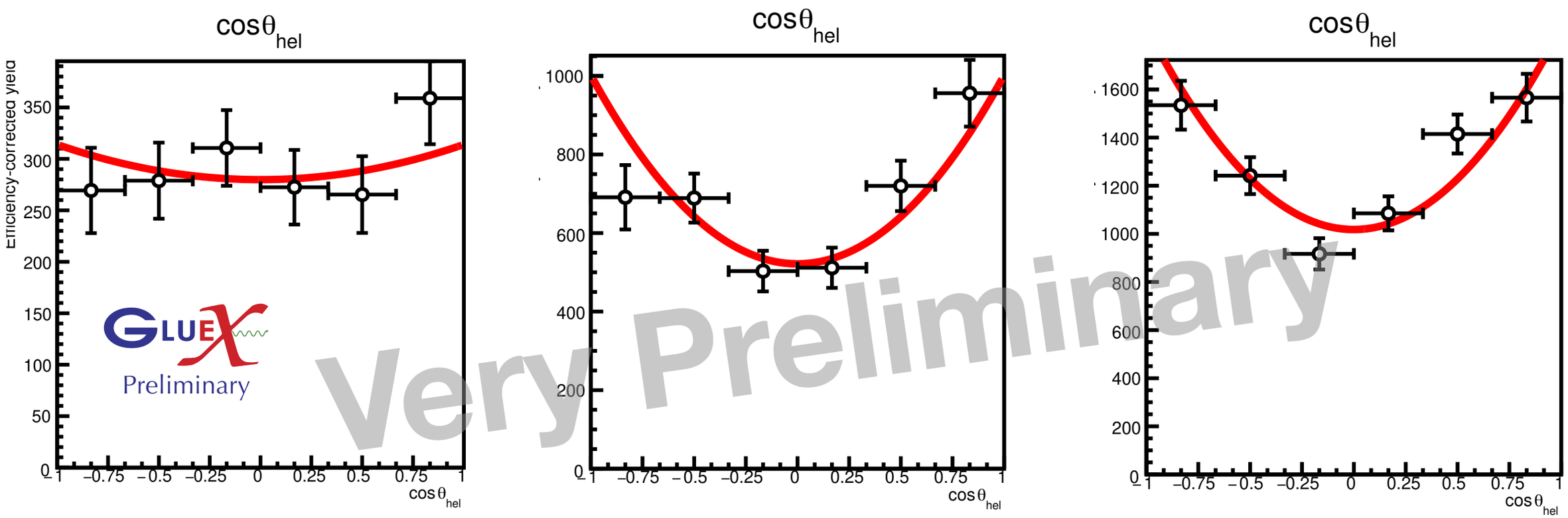




Also, other SDMEs provide strong constraints on the production mechanism.

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

Low E_γ ⟷ High E_γ



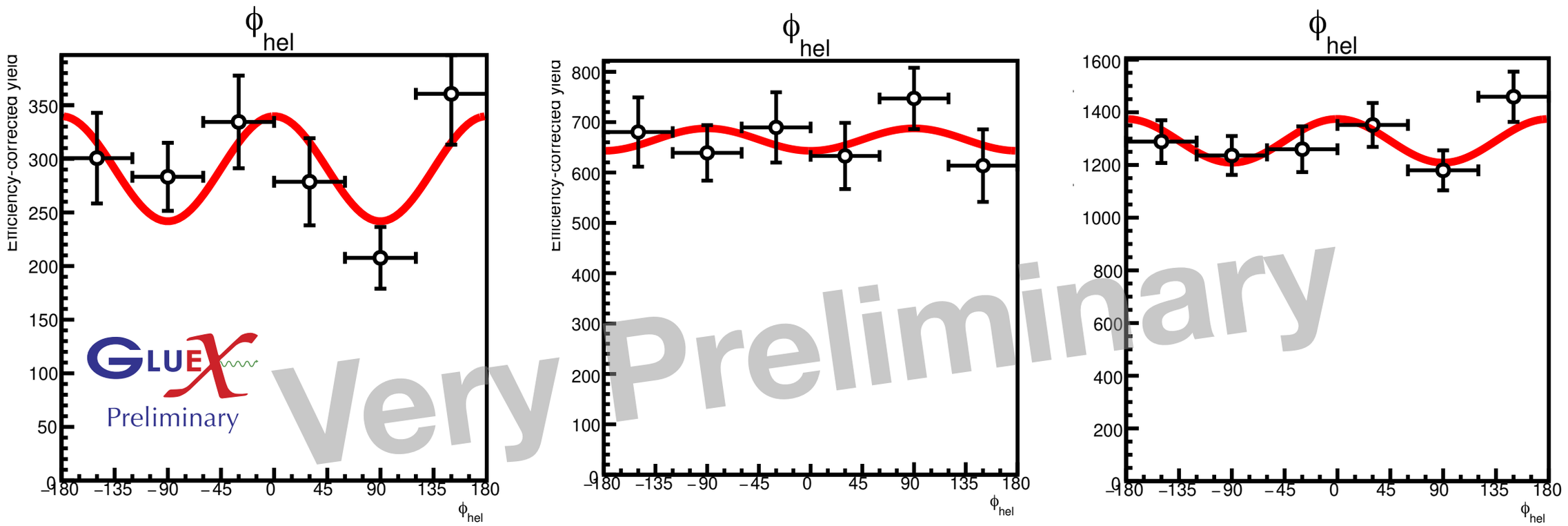
Stat. error: 0.09 Stat. error: 0.06 Stat. error: 0.04

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

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



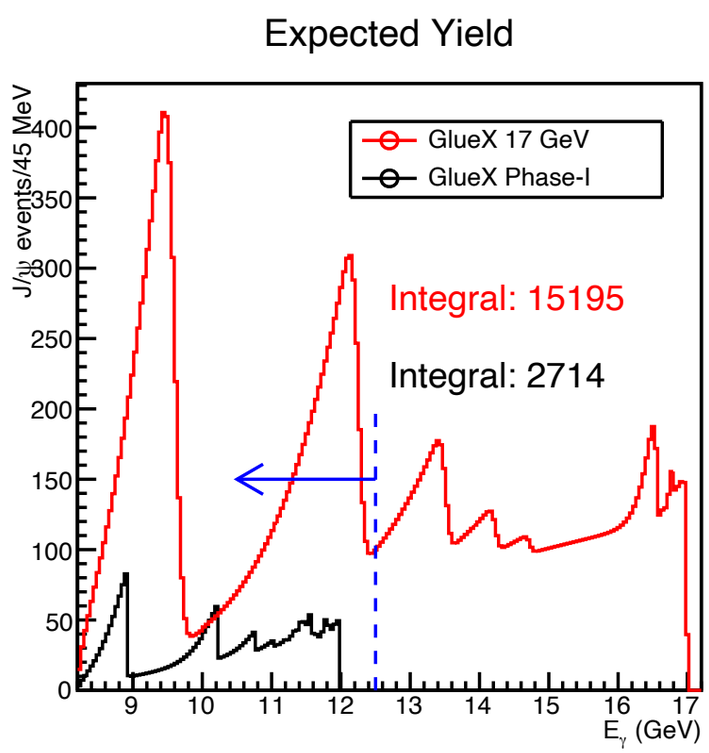
Stat. error: 0.07 Stat. error: 0.06 Stat. error: 0.04

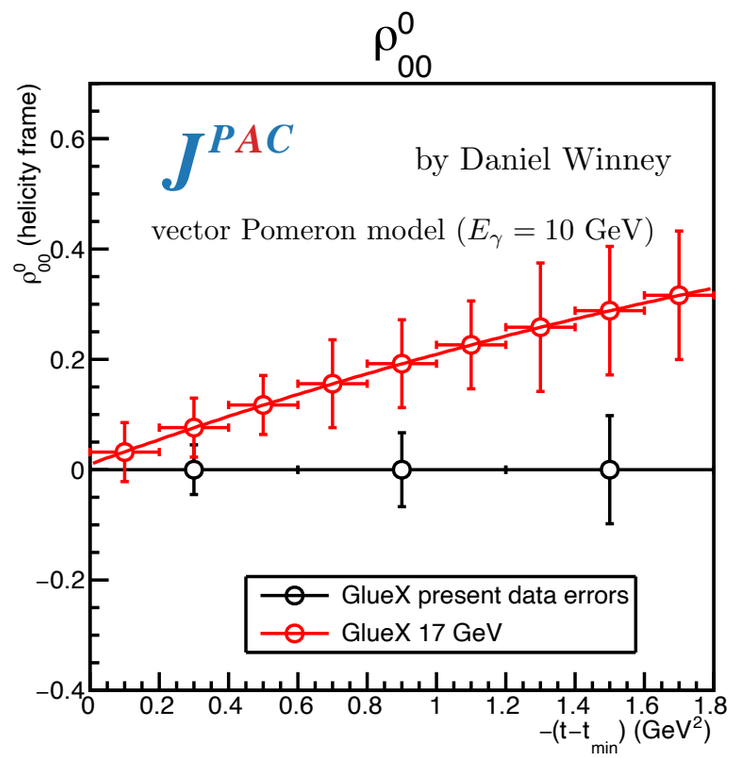
$$W(\phi) = \text{flat} \quad (\text{Re}\rho^0_{1-1} = 0)$$

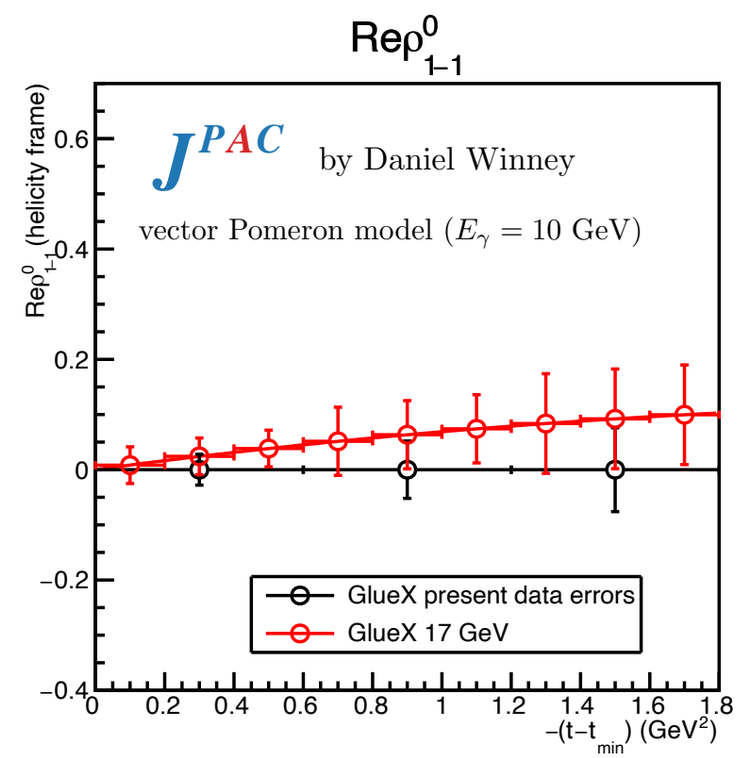
Non-zero Re $\rho^1_{1\text{-}1}$ means photon helicity is not fully transferred to J/ψ.
The curves are suggesting helicity is not conserved near threshold.

Helicity conservation at 17 GeV

Non-zero values mean the helicity is not conserved.



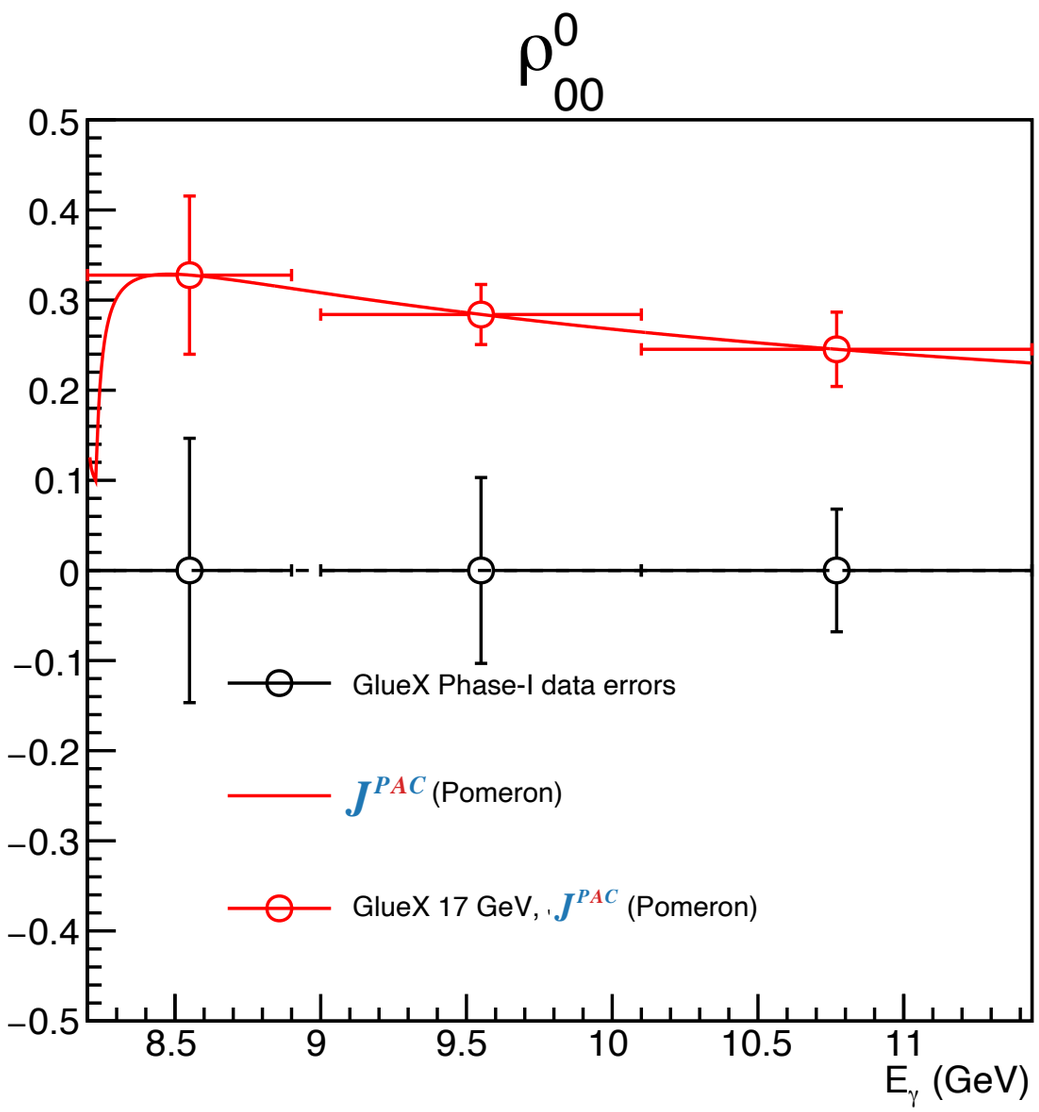


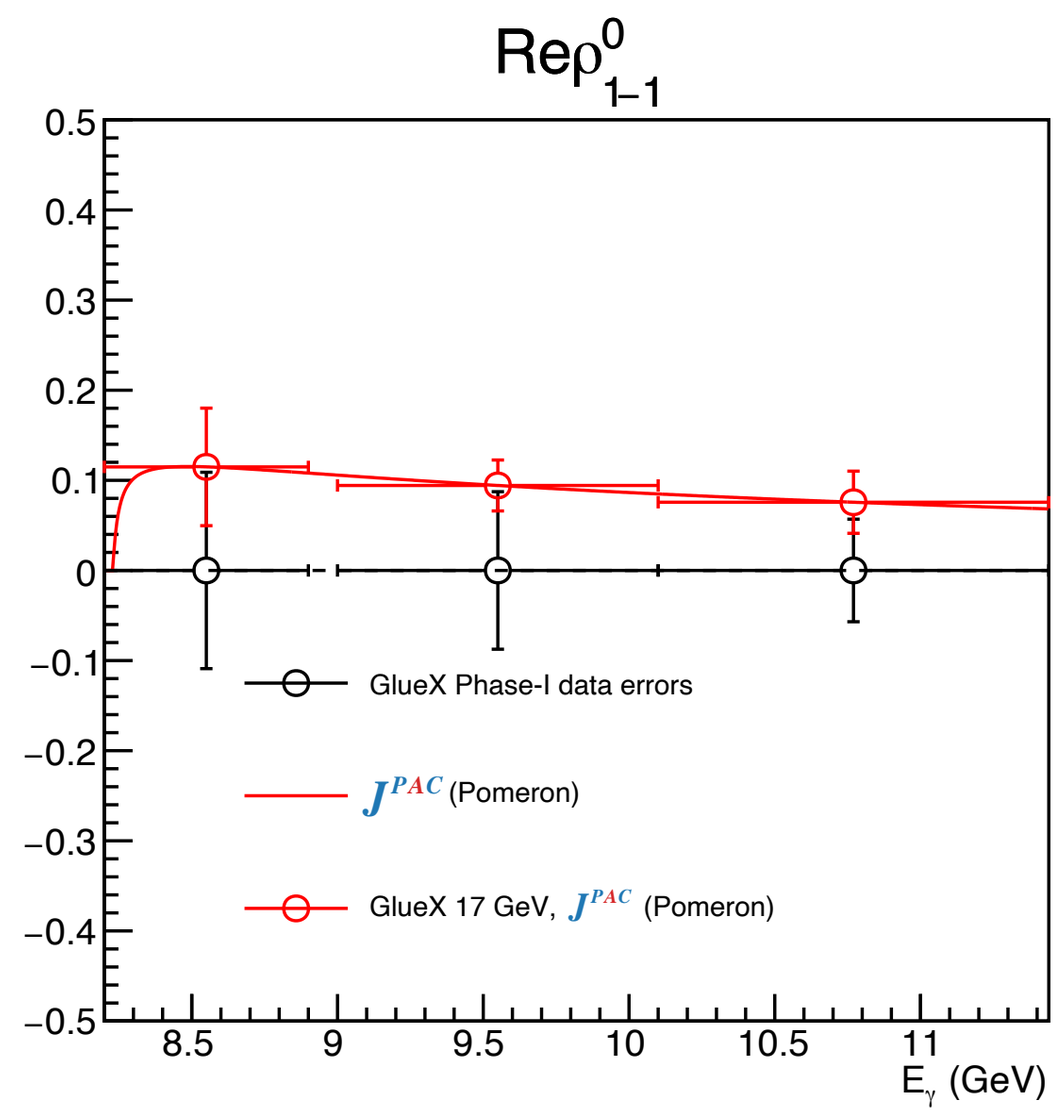


Luminosity near threshold region (E_γ < 12.5 GeV) is 5.5 times larger with 17 GeV beam.

Precise check of helicity conservation is possible with 17 GeV beam.

E_γ dep. of Unpolarized SDMEs





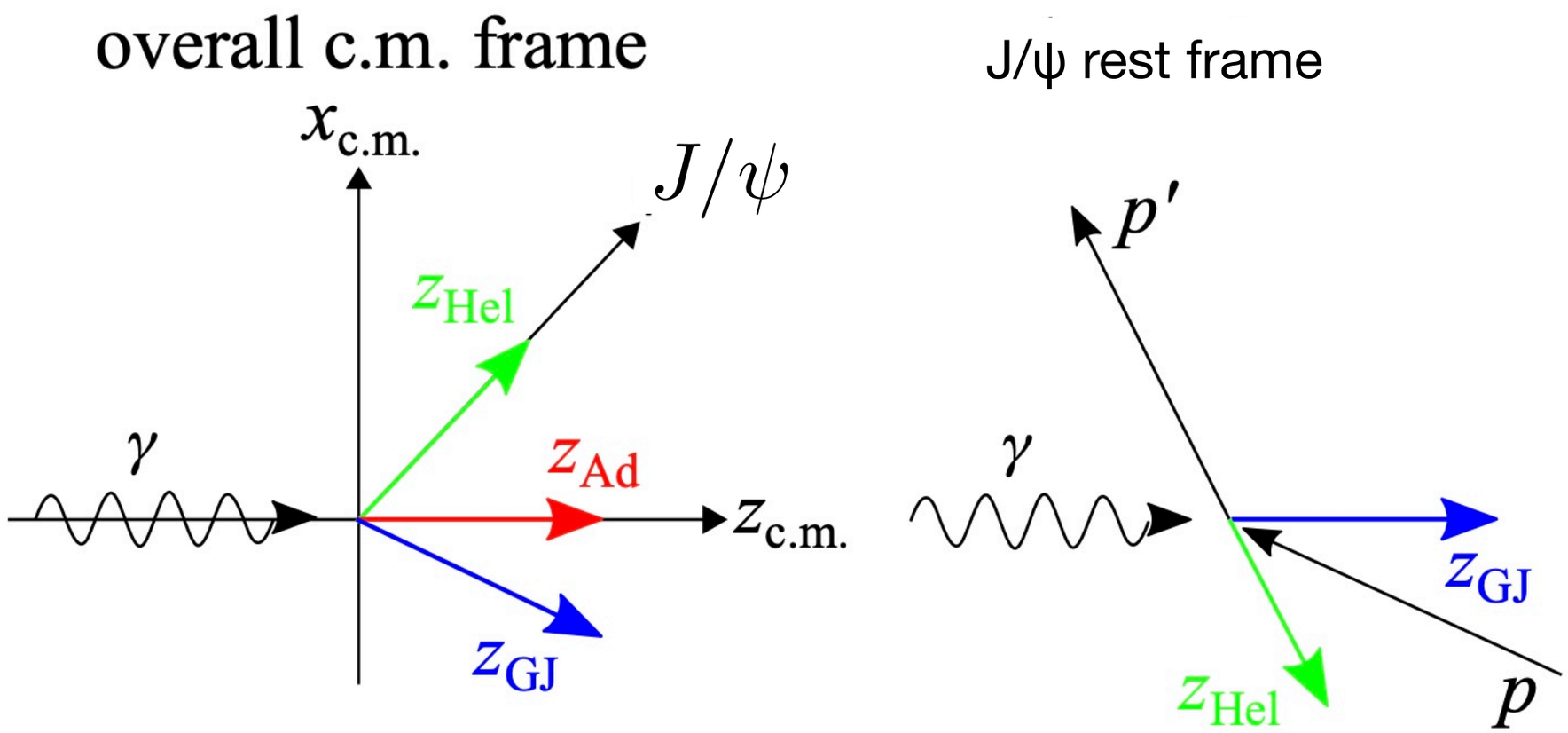
Measurements of E_γ dep. of helicity conservation will be improved with 17 GeV beam as seen above.

Summary

- J/ψ SDMEs are measured to help determine the production mechanism near threshold.
- We have no SDME data so far. No reliable predictions either.
  - GlueX can provide unique polarized SDME measurements.
- 17 GeV energy upgrade gives 30 times larger polarization FOM, and significantly increase the precision of polarized measurements.
  - Precise measurements of naturality.
- For unpolarized measurements, 17 GeV upgrade gives 5.5 times larger yields near threshold region. Helicity conservation can be checked precisely.

Backup

GJ frame to check helicity conservation



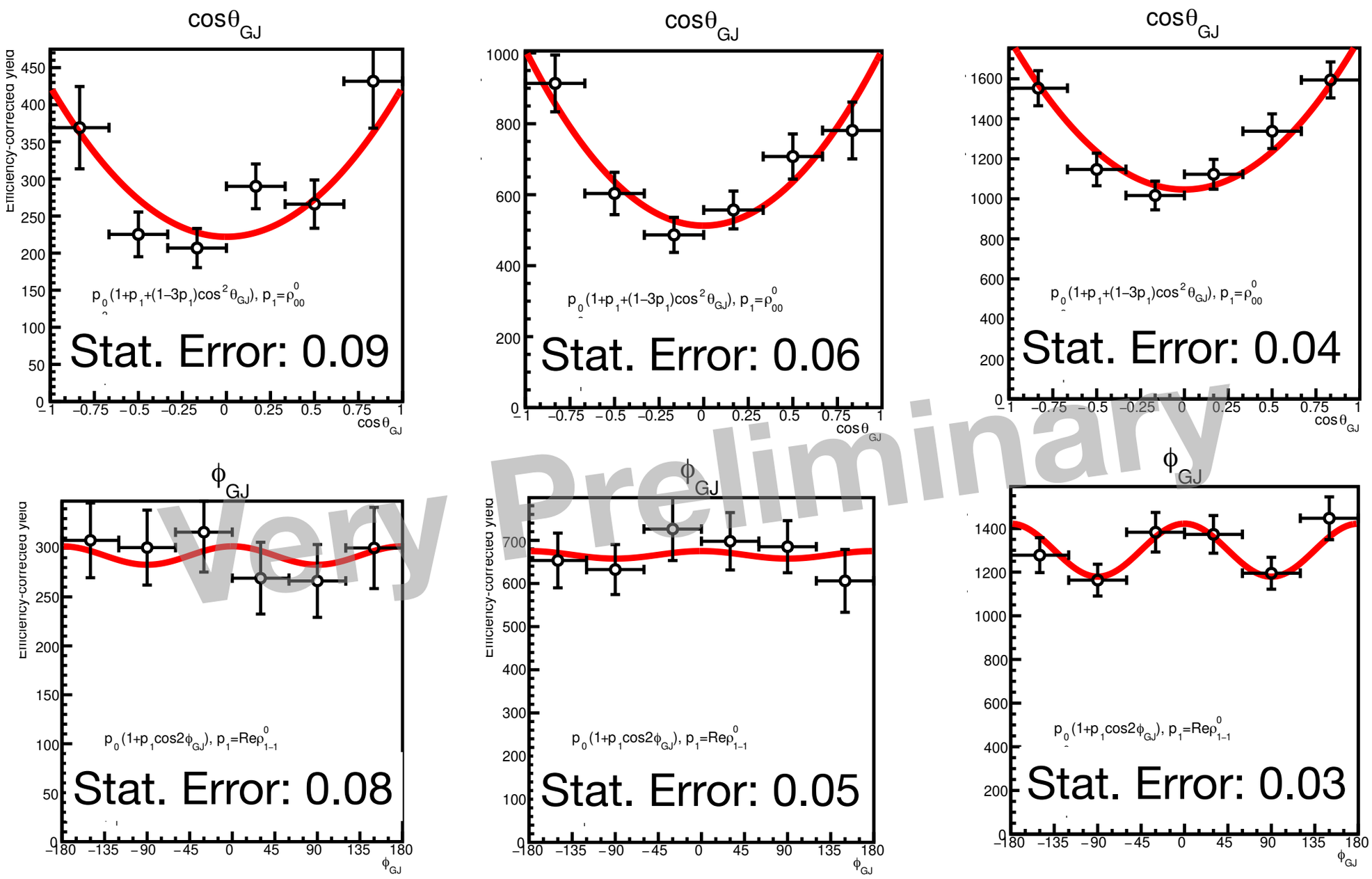
Decay asymmetry measurements in the helicity frame are used to check “helicity conservation” where incoming photon helicity is fully transferred to J/ψ.

GJ frame allows us to check “helicity conservation in $\gamma J/\psi \to \bar{p}p$”.

For light vector mesons (ρ, ω, ϕ), it is known that helicity conservation in $\gamma V \to \bar{p}p$ is badly broken.

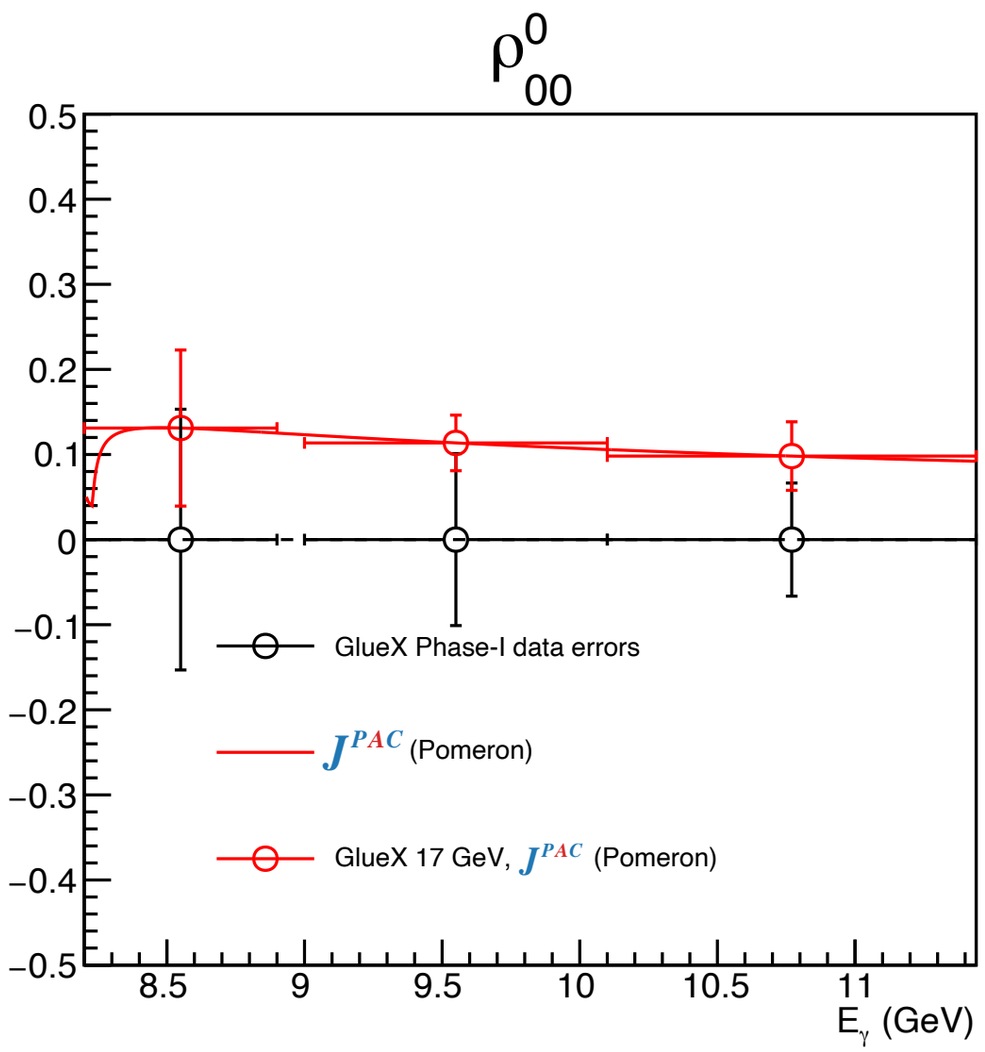
Unpolarized SDME in GJ frame

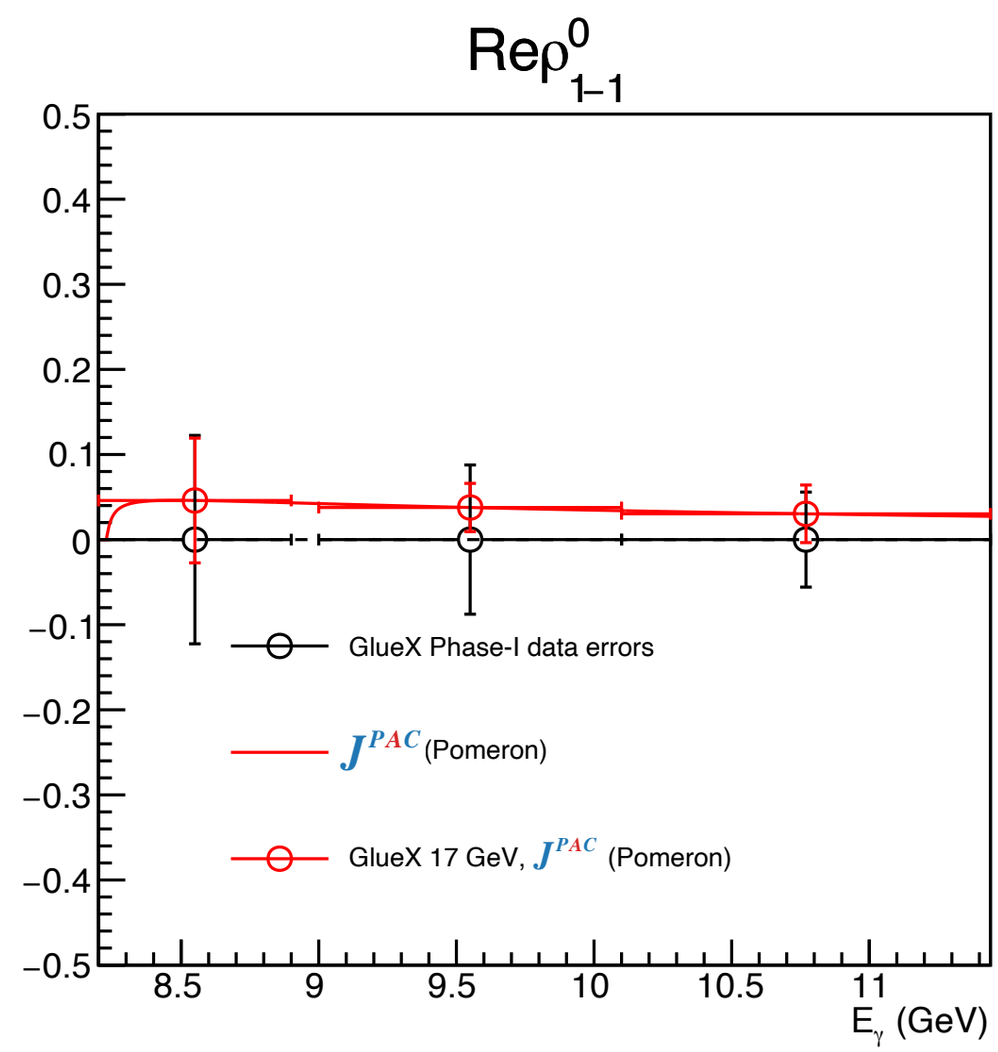
Low E_γ ⟷ High E_γ



The curves are suggesting helicity conservation in $\gamma J/\psi \to \bar{p}p$, at low E_γ.

E_γ dep. of Unpolarized SDMEs (GJ)

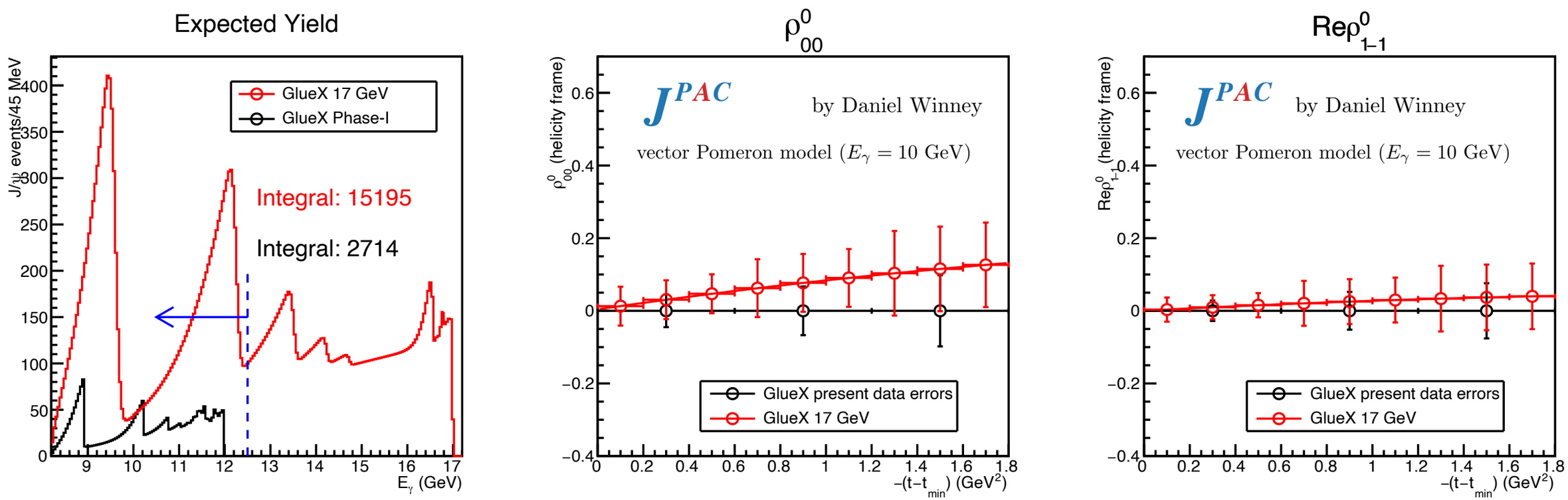




E_γ dep. of helicity conservation in $\gamma J/\psi \to \bar{p}p$ will be more precisely measured with 17 GeV beam, which place strict constraints on models.

GJ frame analysis at 17 GeV

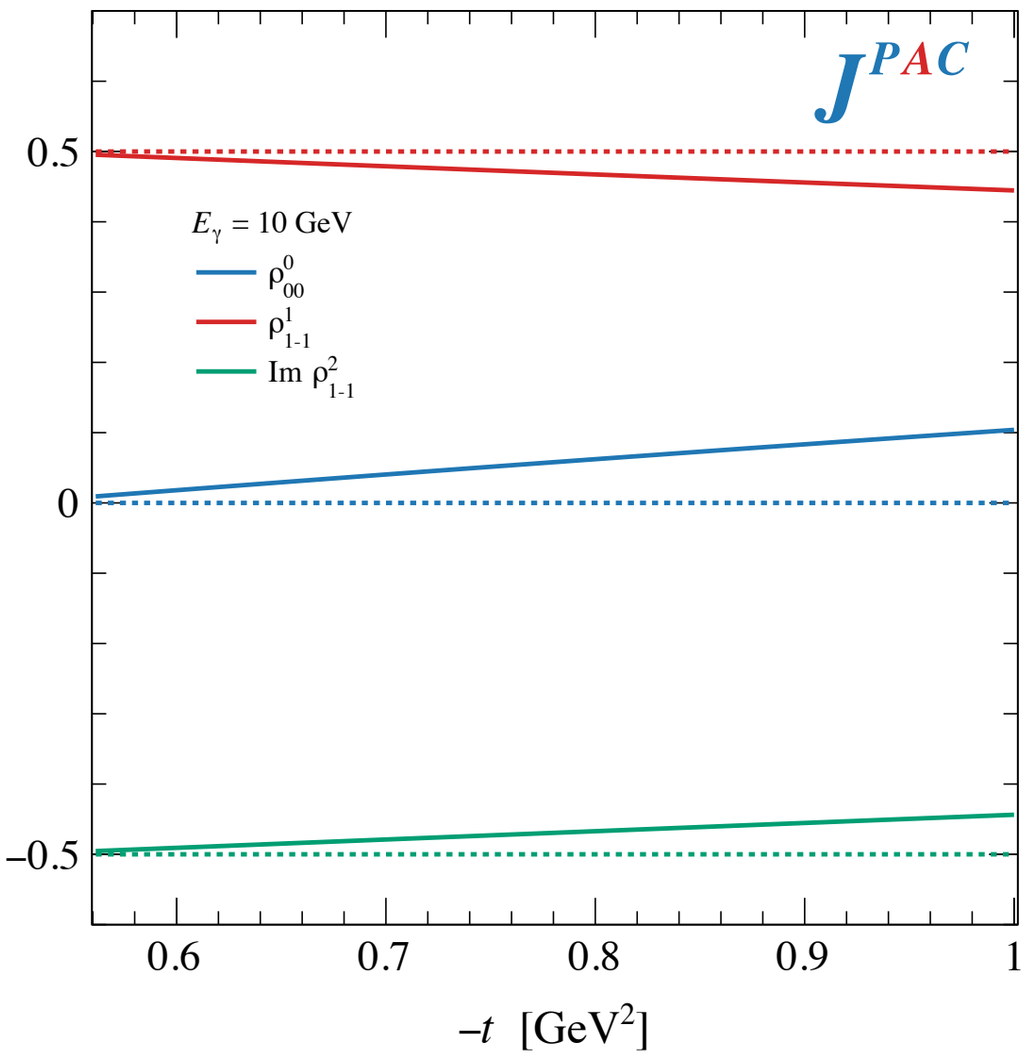
Non-zero values mean helicity conservation in $\gamma J/\psi \to \bar{p}p$ is broken.



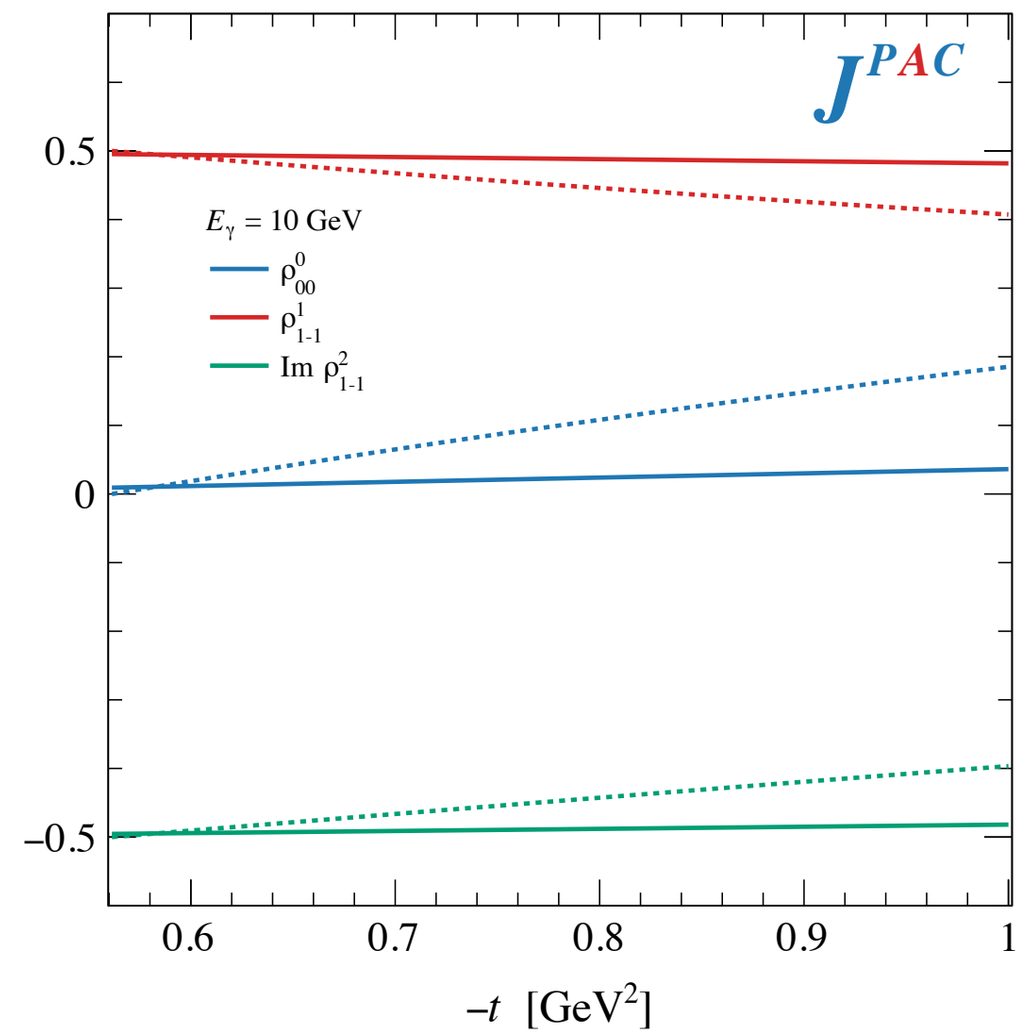
5.5 times larger luminosity (17 GeV beam) allows us more precise study about helicity conservation in $\gamma J/\psi \to \bar{p}p$.

JPAC Pomeron model by Daniel Winney

Helicity frame
Solid: vector Pomeron
Dashed: Pomeron with Helicity conserved



GJ frame
Solid: vector Pomeron
Dashed: Pomeron with Helicity conserved



Unpolarized distributions

Ref.) A. I. Titov et al., PRC60,035205 (1999)

In the case of $\phi \to K^+K^-$ ($a = K^+$), we obtain:

$$W(\cos\theta,\phi) = \frac{3}{4\pi}\left(\frac{\rho_{11}+\rho_{-1-1}}{2}\sin^2\theta + \rho_{00}\cos^2\theta - \frac{\mathrm{Re}\rho_{10}-\mathrm{Re}\rho_{-10}}{\sqrt{2}}\sin 2\theta\cos\phi \right.$$
$$\left. + \frac{\mathrm{Im}\rho_{10}+\mathrm{Im}\rho_{-10}}{\sqrt{2}}\sin 2\theta\sin\phi - \mathrm{Re}\rho_{1-1}\sin^2\theta\cos 2\phi + \mathrm{Im}\rho_{1-1}\sin^2\theta\sin 2\phi\right), \quad (2)$$

In the case of $J/\psi \to e^-e^+$ ($a = e^-$), we obtain:

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

Linearly polarized distributions

For K^+K^- case,

$$W^0(\cos\theta,\phi) = \frac{3}{4\pi}\left(\frac{1-\rho^0_{00}}{2} + \frac{3\rho^0_{00}-1}{2}\cos^2\theta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\theta\cos\phi - \mathrm{Re}\rho^0_{1-1}\sin^2\theta\cos 2\phi\right), \tag{4}$$

$$W^1(\cos\theta,\phi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\theta\cos\phi - \mathrm{Re}\rho^1_{1-1}\sin^2\theta\cos 2\phi\right), \tag{5}$$

$$W^\alpha(\cos\theta,\phi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^\alpha_{10}\sin 2\theta\sin\phi + \mathrm{Im}\rho^\alpha_{1-1}\sin^2\theta\sin 2\phi\right) \qquad (\alpha = 2,3). \tag{6}$$

For e^-e^+ case,

$$W^0(\cos\theta,\phi) = \frac{3}{8\pi}\left(\frac{1+\rho^0_{00}}{2} - \frac{3\rho^0_{00}-1}{2}\cos^2\theta + \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\theta\cos\phi + \mathrm{Re}\rho^0_{1-1}\sin^2\theta\cos 2\phi\right), \tag{7}$$

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

$$W^\alpha(\cos\theta,\phi) = \frac{3}{8\pi}\left(-\sqrt{2}\mathrm{Im}\rho^\alpha_{10}\sin 2\theta\sin\phi - \mathrm{Im}\rho^\alpha_{1-1}\sin^2\theta\sin 2\phi\right) \qquad (\alpha = 2,3). \tag{9}$$

Averaged one-dimensional distributions

For $V \to 2$ spinless particles,

$$W(\cos\theta) = \frac{3}{2}\left(\frac{1-\rho^0_{00}}{2}\sin^2\theta + \rho^0_{00}\cos^2\theta\right), \tag{10}$$

$$W(\phi) = \frac{1}{2\pi}\left(1 - 2\mathrm{Re}\rho^0_{1-1}\cos 2\phi\right), \tag{11}$$

$$W(\phi-\Phi) = \frac{1}{2\pi}\left(1 + 2P_\gamma\frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2}\cos\left[2\left(\phi-\Phi\right)\right]\right), \tag{12}$$

$$W(\phi+\Phi) = \frac{1}{2\pi}\left(1 + 2P_\gamma\frac{\rho^1_{1-1} + \mathrm{Im}\rho^2_{1-1}}{2}\cos\left[2\left(\phi+\Phi\right)\right]\right), \tag{13}$$

$$W(\Phi) = 1 - P_\gamma\left(2\rho^1_{11} + \rho^1_{00}\right)\cos 2\Phi. \tag{14}$$

For $J/\psi \to e^-e^+$,

$$W(\cos\theta) = \frac{3}{8}\left(1 + \rho^0_{00} + (1 - 3\rho^0_{00})\cos^2\theta\right), \tag{15}$$

$$W(\phi) = \frac{1}{2\pi}\left(1 + \mathrm{Re}\rho^0_{1-1}\cos 2\phi\right), \tag{16}$$

} SCHC

$$W(\phi-\Phi) = \frac{1}{2\pi}\left(1 - P_\gamma\frac{\rho^1_{1-1} - \mathrm{Im}\rho^2_{1-1}}{2}\cos\left[2\left(\phi-\Phi\right)\right]\right), \tag{17}$$

Naturality

$$W(\phi+\Phi) = \frac{1}{2\pi}\left(1 - P_\gamma\frac{\rho^1_{1-1} + \mathrm{Im}\rho^2_{1-1}}{2}\cos\left[2\left(\phi+\Phi\right)\right]\right), \tag{18}$$

$$W(\Phi) = 1 - P_\gamma\left(2\rho^1_{11} + \rho^1_{00}\right)\cos 2\Phi. \tag{19}$$

Beam Asym. ($\sum$)