Spin-density matrix elements in J/ψ photoproduction at GlueX

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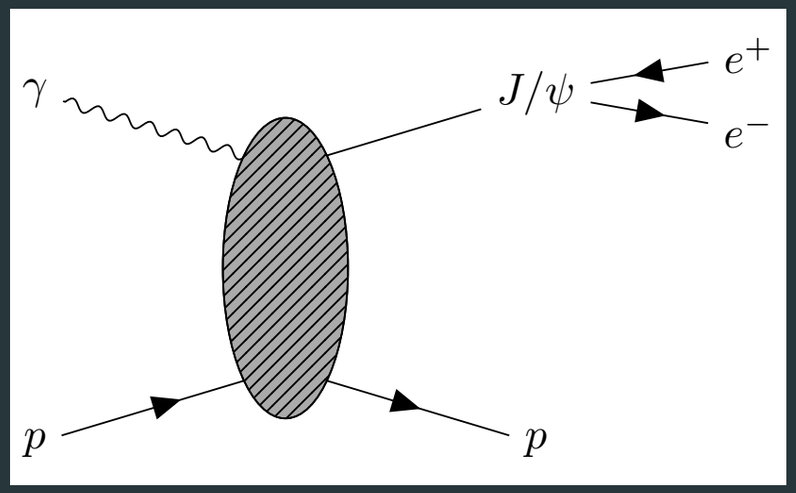
Towards improved hadron femtography with hard exclusive reactions
20 July 2026

Motivation



GlueX seeks to provide a complete description of J/ψ photoproduction.

Cross-section analysis
Phys. Rev. C 108, 025201

SDME extraction
This work

Cross-section analysis demonstrates complexity in t channel near threshold

- Hints of open-charm contributions?

Spin-density matrix elements (SDMEs) characterize the transfer of helicity from the incident photon to the outgoing vector

- Extract from GlueX data in coarse bins of E_γ and, where possible, Mandlestam t

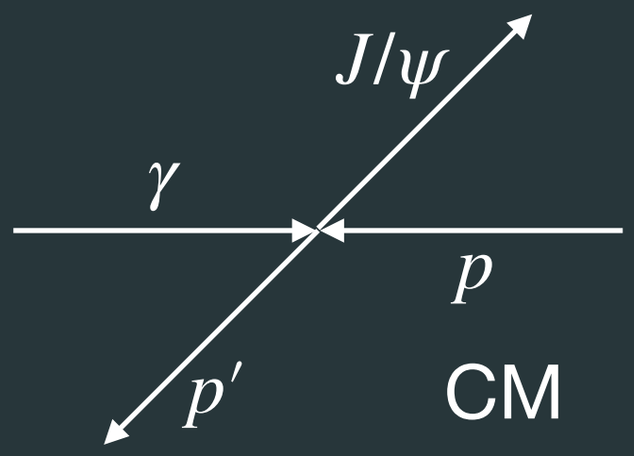
Test

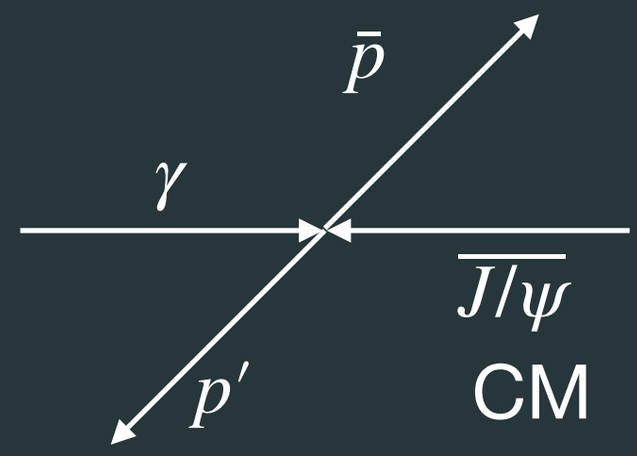
Analytic Pomeron model

Covariant Pomeron model

Factorized GPDs at high skewness

Helicity conservation hypotheses





s-channel Helicity Conservation (SCHC)

$$\gamma p \to J/\psi p'$$

- Helicity of beam photon transferred entirely to J/ψ
- Measured in the J/ψ helicity frame

t-channel Helicity Conservation (TCHC)

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

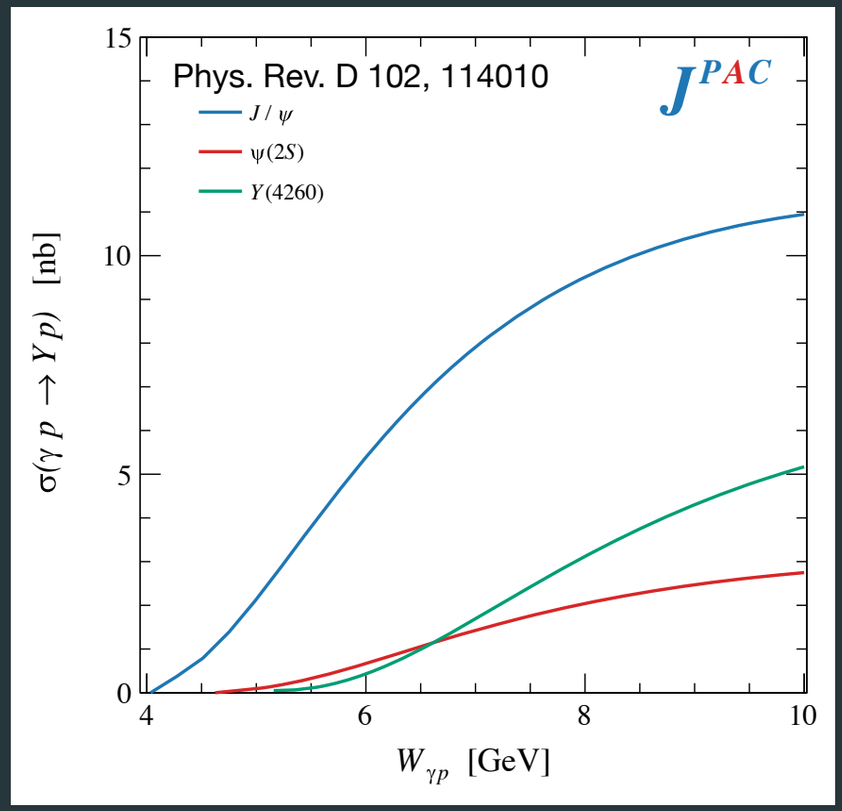
- Helicity preserved across exchange particle
- Measured in the J/ψ Gottfried-Jackson frame

- All independent SDME quantities in the corresponding frame are zero except $\mathfrak{R}\rho^{1}_{1,-1} = -\mathfrak{I}\rho^{1}_{1,-1} = 0.5$ (assuming natural parity exchange)

Pomeron exchange models

From the 2014 CLAS $\gamma p \to \phi p$ paper:[1]

- Naively assign the Pomeron $J^{PC} = 0^{++}$
- Spin-0 exchange implies TCHC
- Expect zero-valued unpolarized SDMEs in Gottfried-Jackson frame



In 2019, JPAC models J/ψ photoproduction near threshold with covariant effective pomeron model.[2]

- More robust Pomeron models not necessarily helicity conserving[3]
  - Expect SDMEs to vary with energy
- More recent 2023 paper uses helicity independent amplitudes
  - Not particularly interesting for this case

[1] Phys. Rev. C 89, 055208
[2] Phys. Rev. D 102, 114010
[3] Phys. Rev. D 97, 094003

GPD factorization at nonzero skewness

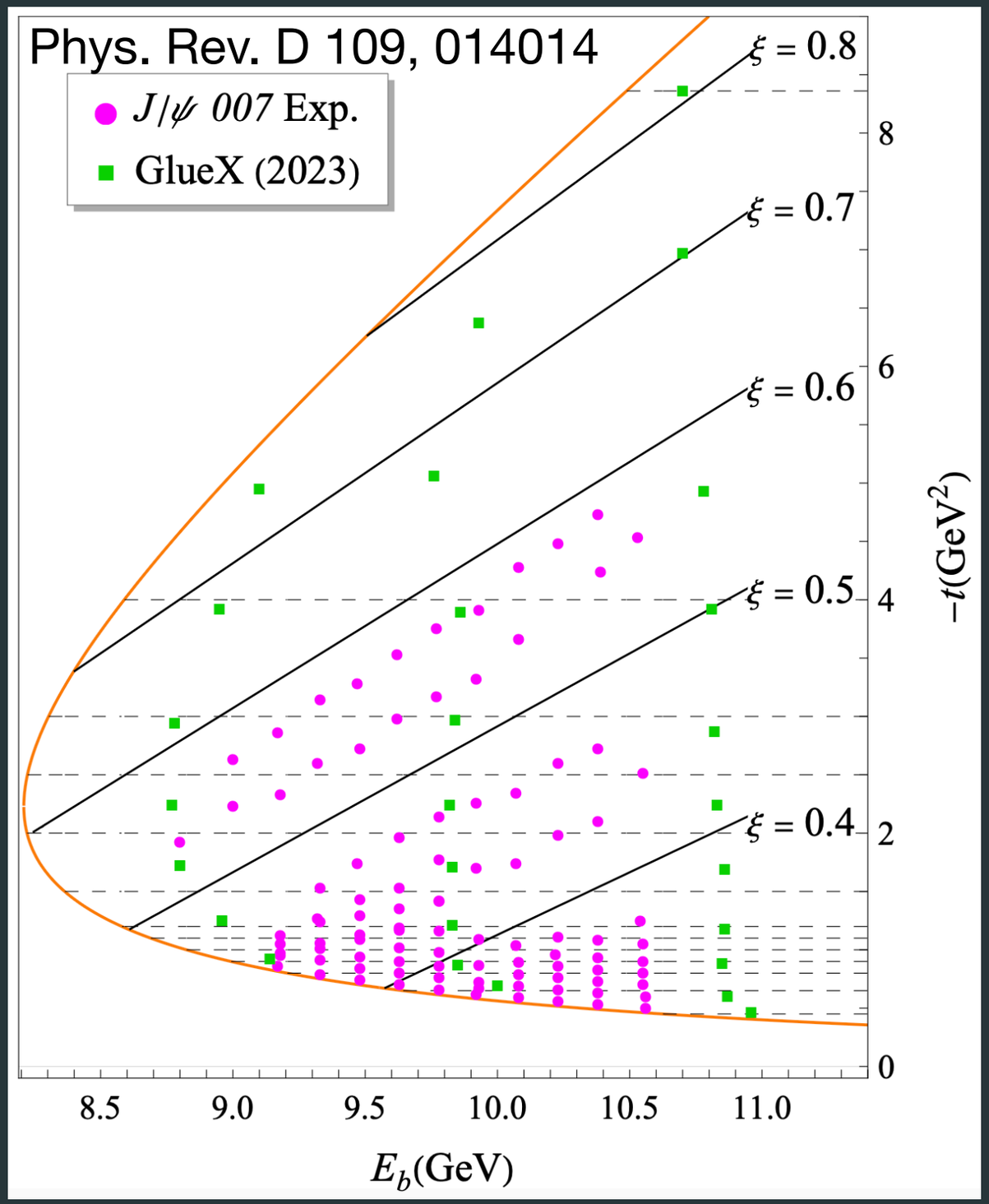
Near threshold J/ψ region has high skewness [4, 5]

- Skewness corresponds to relative quantities of E_γ and t
- $\xi \to 0 \Rightarrow$ GPDs look like PDFs, well-understood
- $\xi \to 1$ region not as well understood

Extract GFFs from GPDs, enabling study of proton structure.

- SCHC is an approximation behind some factorized GPD models?
- By measuring SDMEs, we can test this approximation at high ξ

Seeking further discussions with theorists.



[4] Phys. Rev. D 103, 096010

[5] Phys. Rev. D 109, 014014

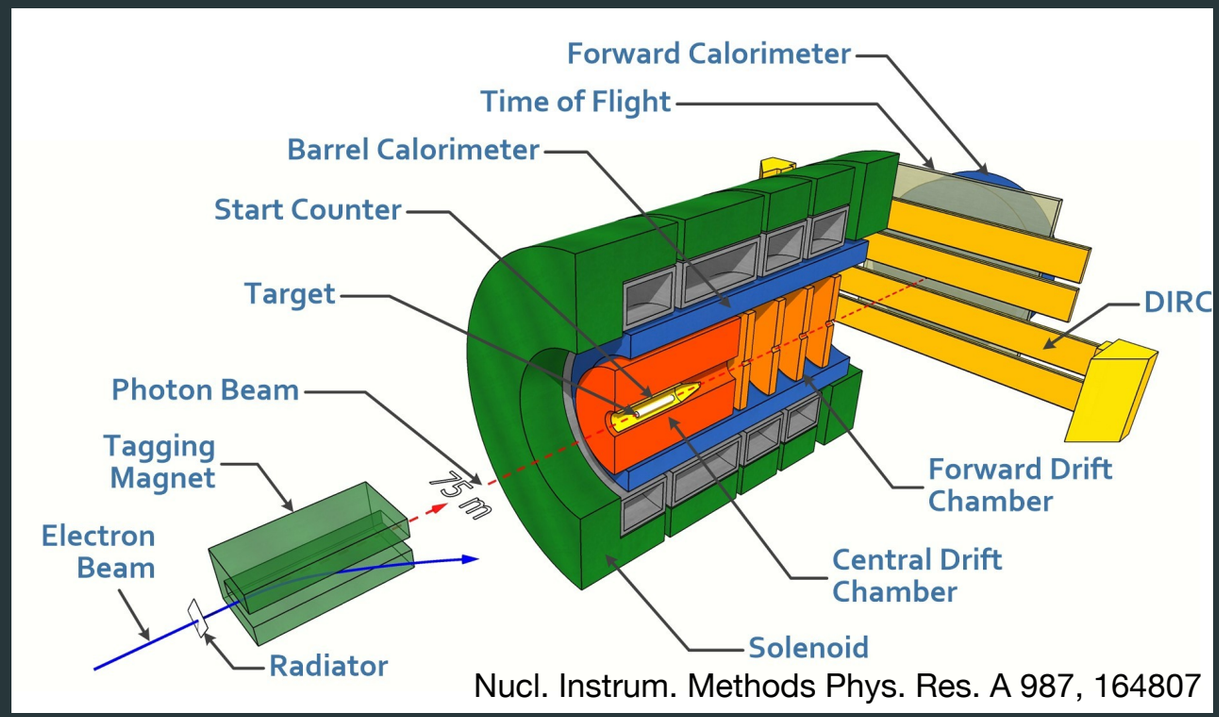
The GlueX Experiment

Located in Hall D at Jefferson Lab in Newport News, VA

CEBAF provides 12 GeV electron beam impinging on diamond radiator

- Produces photon beam through coherent Bremsstrahlung
- Degree of polarization roughly 35% in coherent peak region

Acceptance at nearly 4π solid angle for charged/neutral final states.



Nucl. Instrum. Methods Phys. Res. A 987, 164807


Photo provided by Jefferson Lab

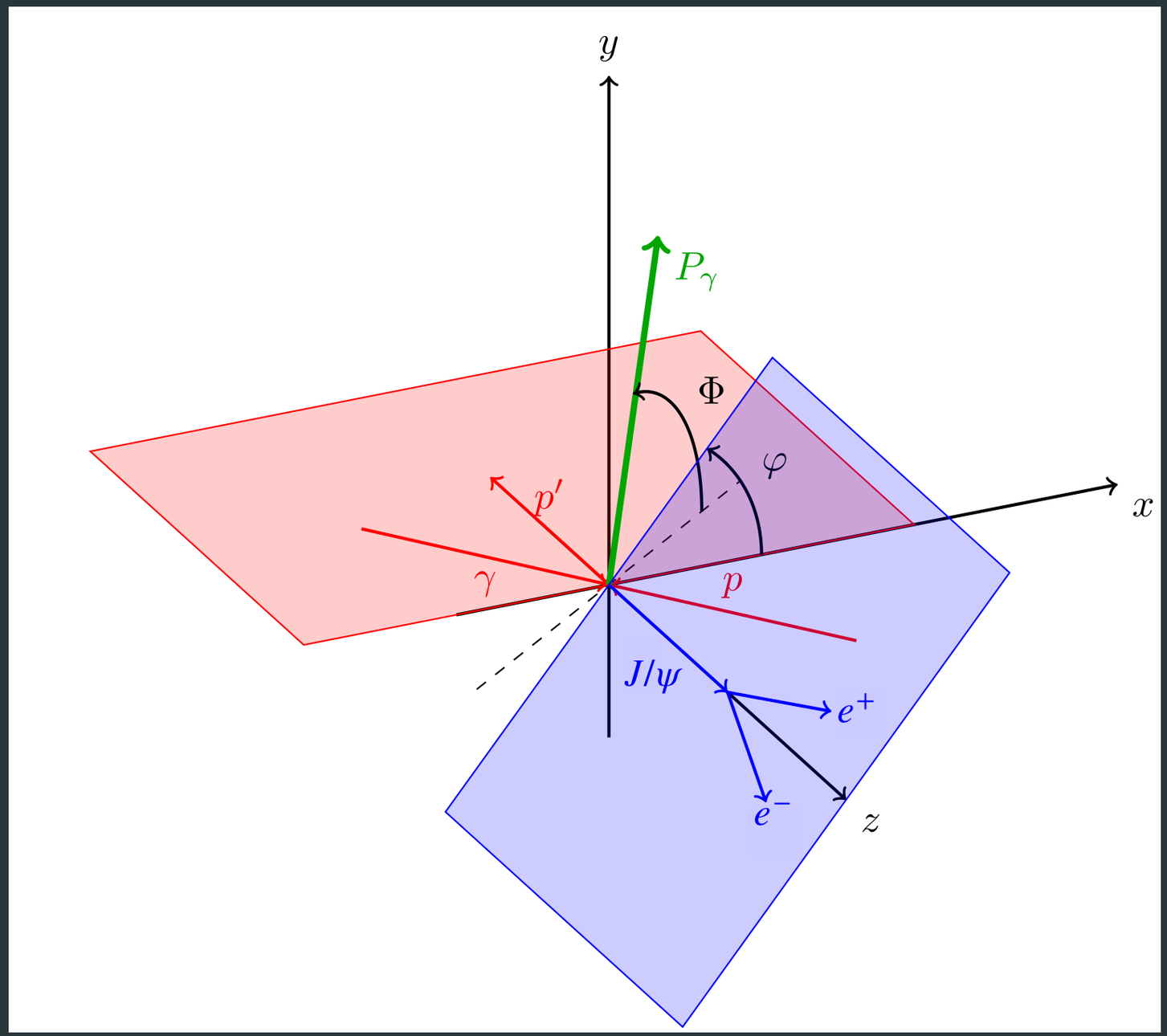
Kinematic frames and physical angles

The J/ψ helicity frame is the center of mass frame of e^+e^- decay products oriented so

$$\hat{z} = -\hat{p}'$$

Three physical angles:

- **Polar helicity angle θ**
  Angle between e and z in J/ψ rest frame
- **Azimuthal helicity angle ϕ**
  Angle between production and decay planes.
- **Polarization angle Φ**
  Angle between γ polarization vector, J/ψ production plane



Gottfried-Jackson frame is largely the same, with $\hat{z} = \hat{\gamma}$

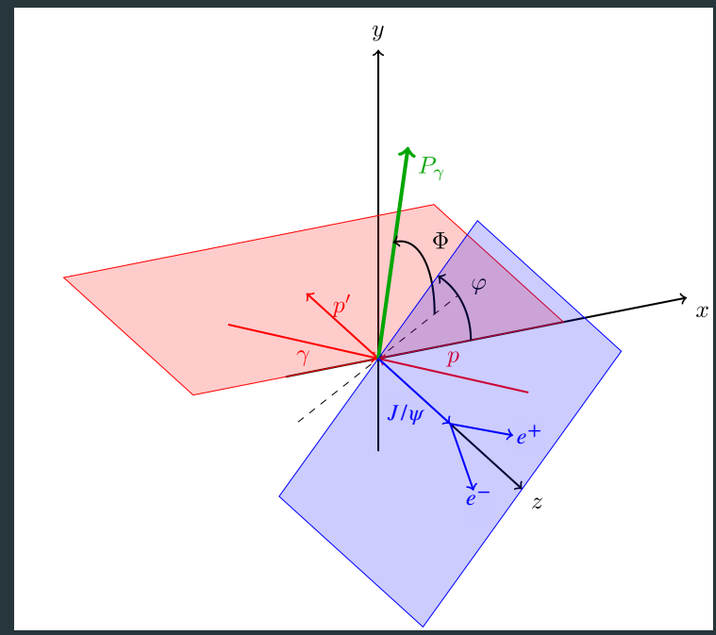
Angular distributions

For linearly polarized beam, reduce to 9 independent SDME quantities: [6]

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

$$W^1(\theta,\phi) \propto \left[\rho^1_{00}\sin^2\theta + \rho^1_{11}(1+\cos^2\theta) + \sqrt{2}\Re\rho^1_{10}\sin 2\theta\cos\phi + \Re\rho^1_{1-1}\sin^2\theta\cos 2\phi\right]$$

$$W^2(\theta,\phi) \propto \left[-\sqrt{2}\Im\rho^2_{10}\sin 2\theta\sin\phi - \Im\rho^2_{1-1}\sin^2\theta\sin 2\phi\right]$$



With the complete angular distribution expressed as

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

Bear in mind:

- $V \to l^+l^-$ angular distribution $\neq V \to PP$ distribution
- W^0 (3 SDMEs) is *unpolarized* and $W^{1,2}$ (6 SDMEs) are *linearly polarized*
  - Only sensitive to polarized SDMEs in the coherent peak $E_\gamma \in (8.2, 8.8)$ GeV

[6] Phys. Rev. C 60, 035205

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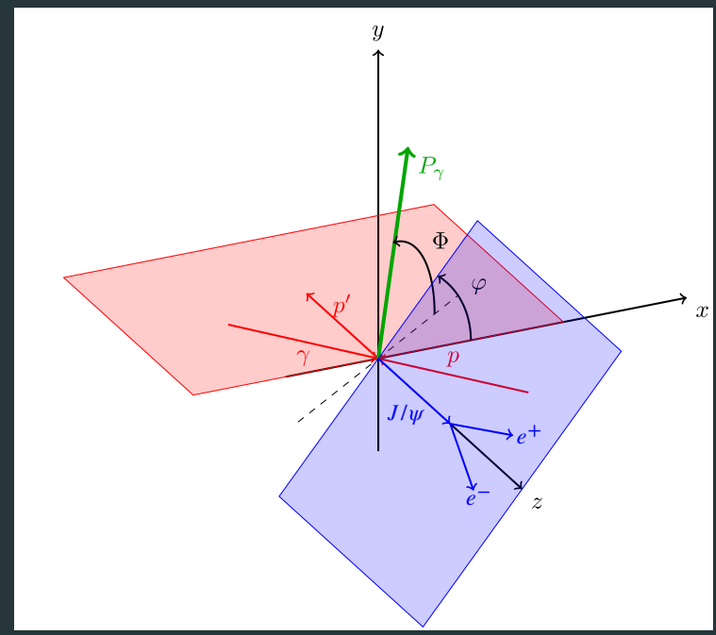

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[6] Phys. Rev. C 60, 035205

Fit strategy

Extract SDMEs with an unbinned, extended maximum-likelihood fit

Evaluate intensity W at each data point

Phase Space MC Integral

$$-2\ln\mathscr{L}(\boldsymbol{\theta}) = -2\left(\sum_{i=1}^{N}\ln W(\boldsymbol{x}_i;\boldsymbol{\theta}) - \int W(\boldsymbol{x};\boldsymbol{\theta})\eta(\boldsymbol{x})d\boldsymbol{x}\right)$$

Acceptance

Fit the angular distributions with SDMEs as free parameters

- Use GlueX-I and 30% of GlueX-II data
- Unpolarized SDMEs: Fix polarized SDMEs to zero
- Polarized SDMEs: All SDMEs float

Normalize sample to phase space MC with simulated detector acceptance

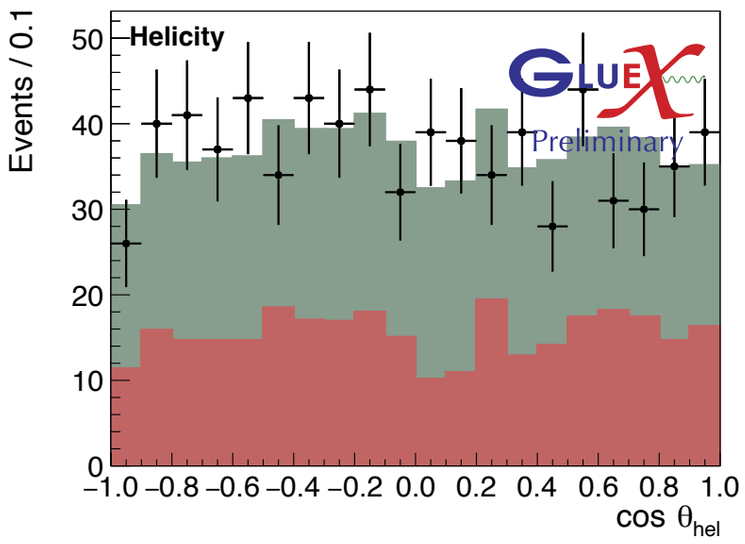
Luminosity (1/pb)	
Coherent Peak	224
Beam Energy > 8.2 GeV	555

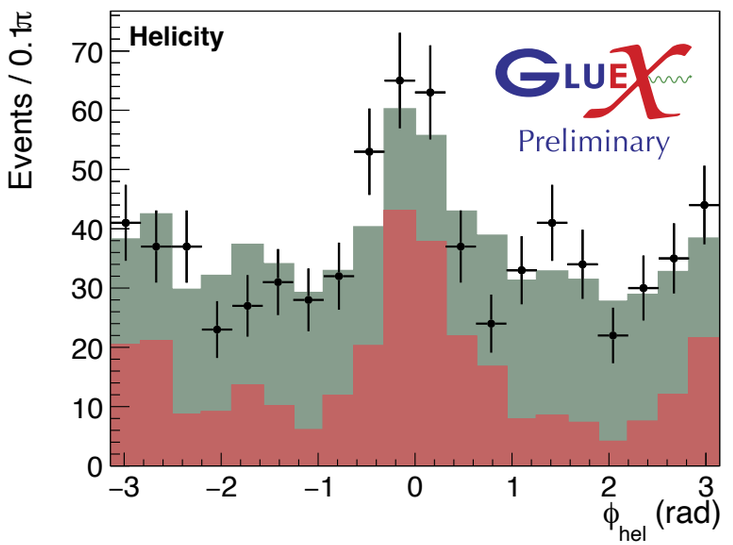
Data

Fit-weighted MC

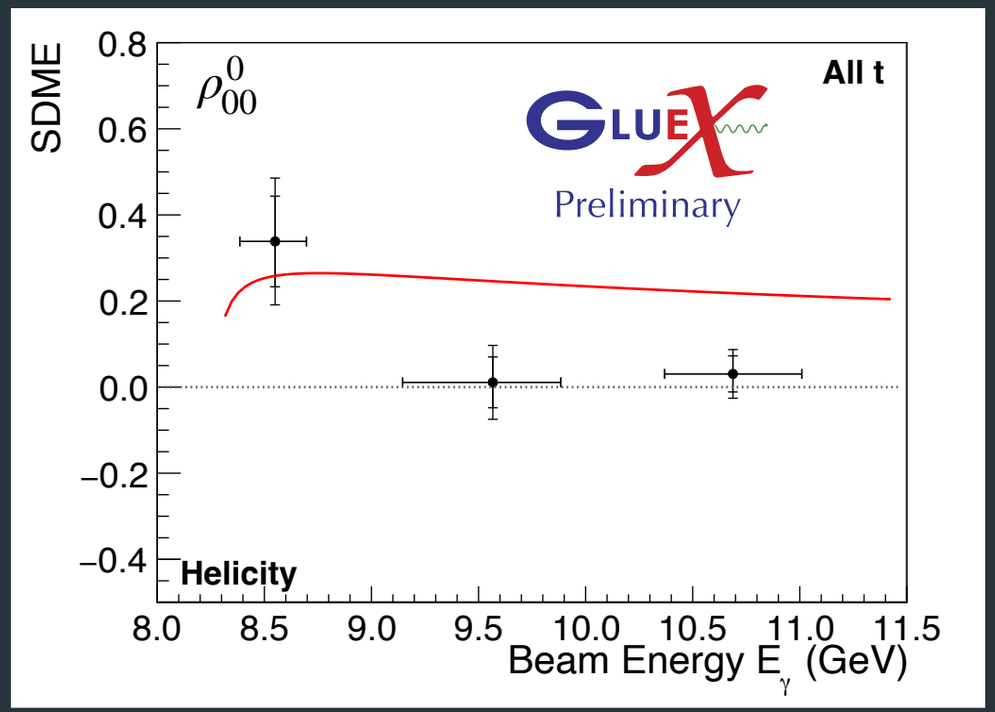
Background

Fit to coherent peak data
Integrate over all t





Preliminary results | Unpolarized



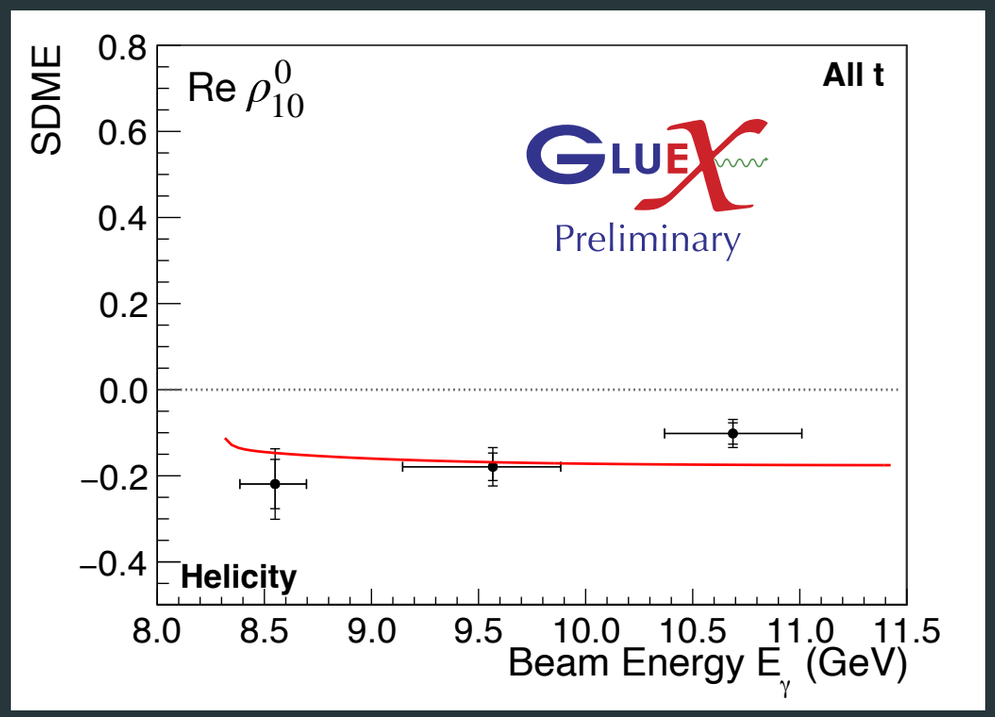
Fit

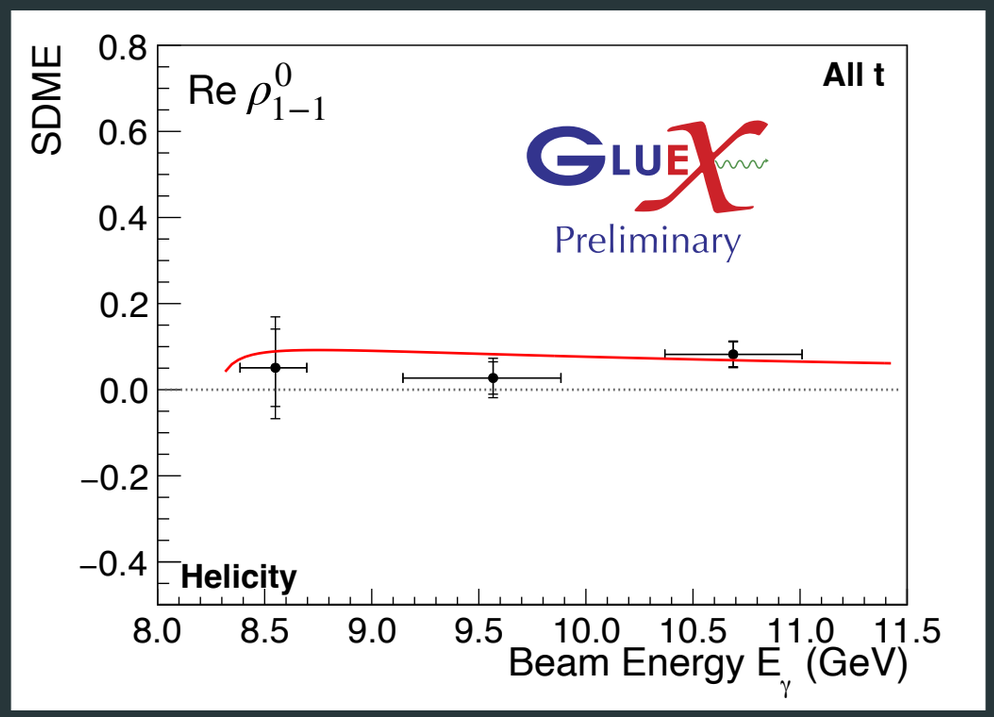
Extract

Compare

$$W^0(\theta,\phi) \propto \frac{1+\rho^0_{00}}{2} - \frac{3\rho^0_{00}-1}{2}\cos^2\theta + \sqrt{2}\Re\rho^0_{10}\sin 2\theta\cos\phi + \Re\rho^0_{1-1}\sin^2\theta\cos 2\phi$$

- POINTS: Fit result w/ error bars
  INNER: stat. uncertainty, bootstrapped
  OUTER: stat.+ sys. uncertainty, quadrature
- SOLID LINE: JPAC covariant Pomeron model
- DASHED LINE: Helicity conservation





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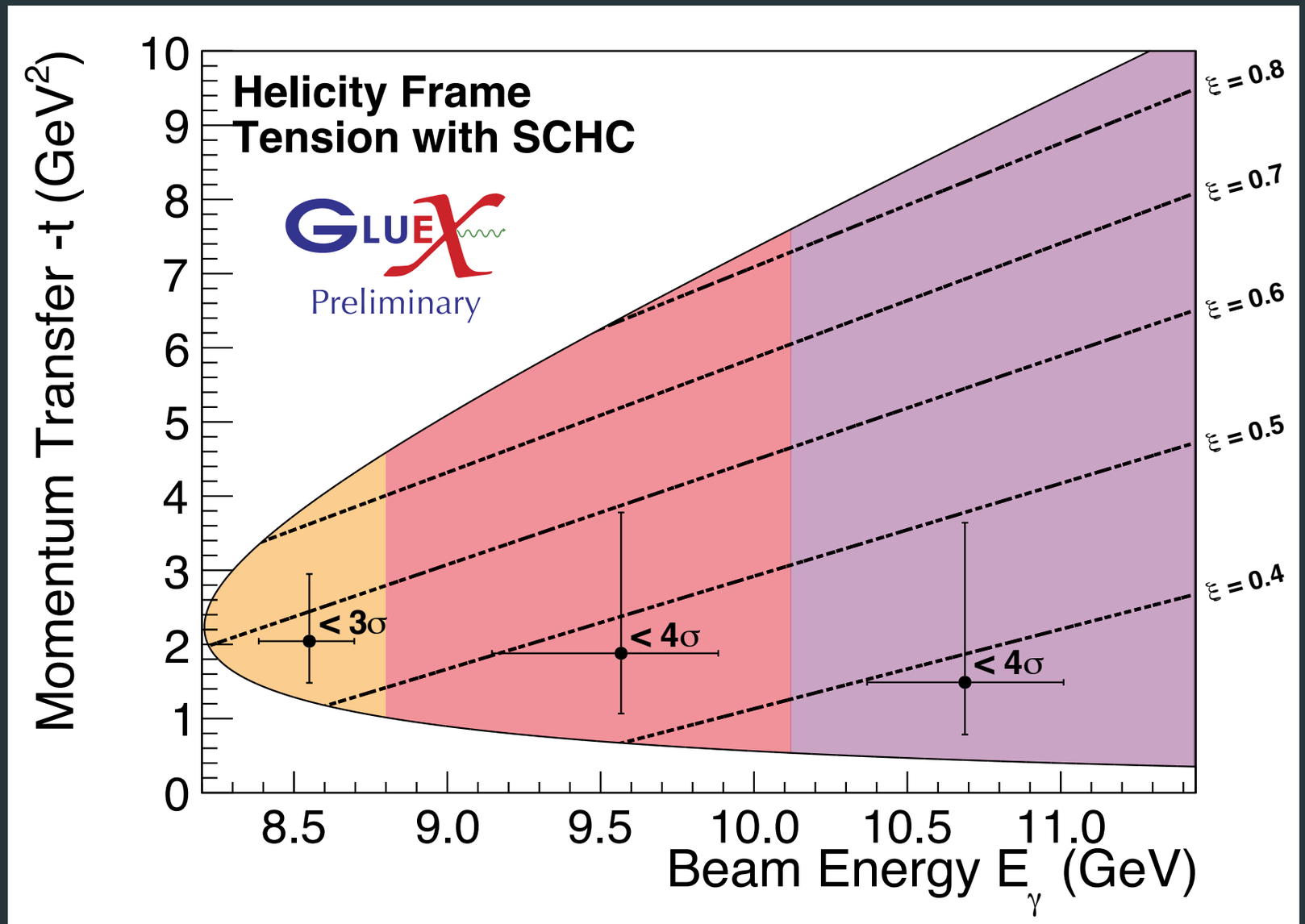
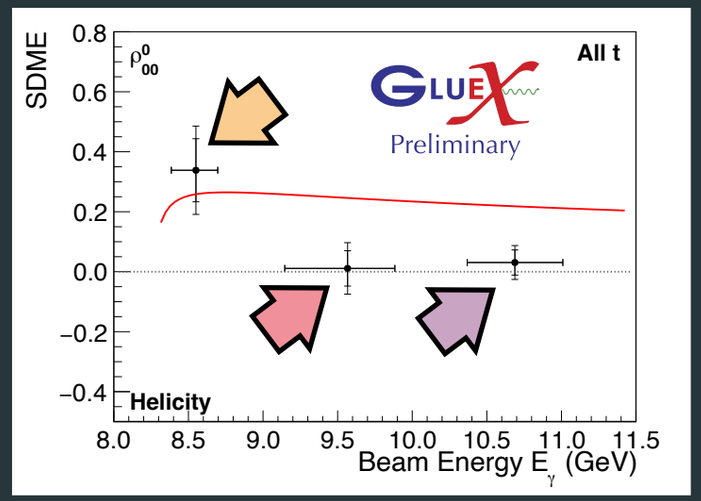
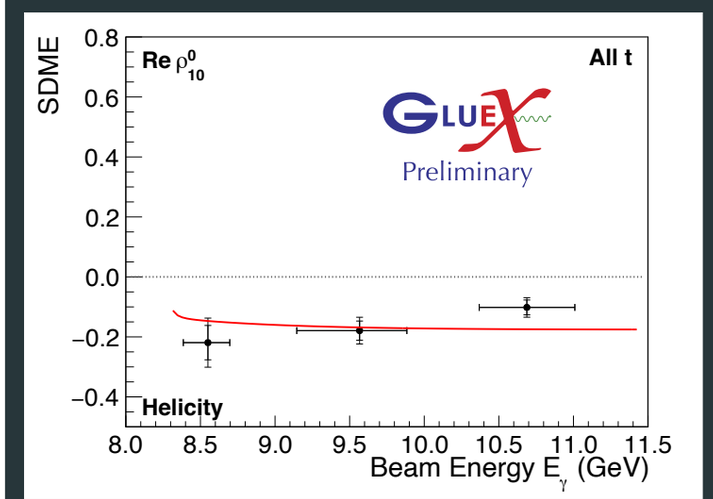
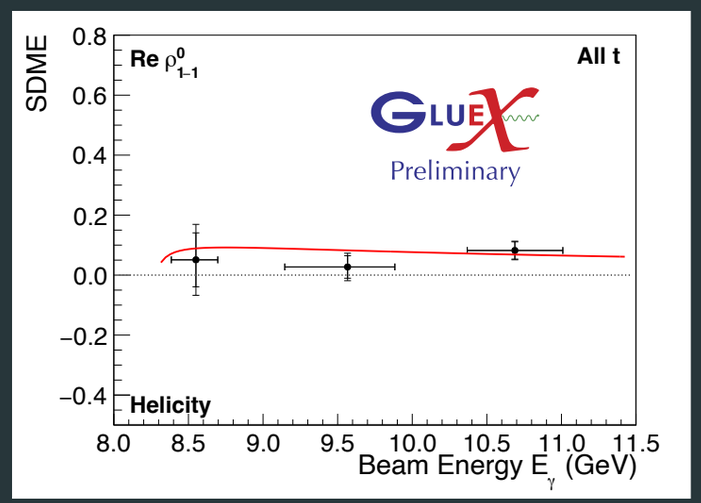








POINTS | Fit results with bootstrap and systematic errors

SOLID LINE | JPAC Pomeron model

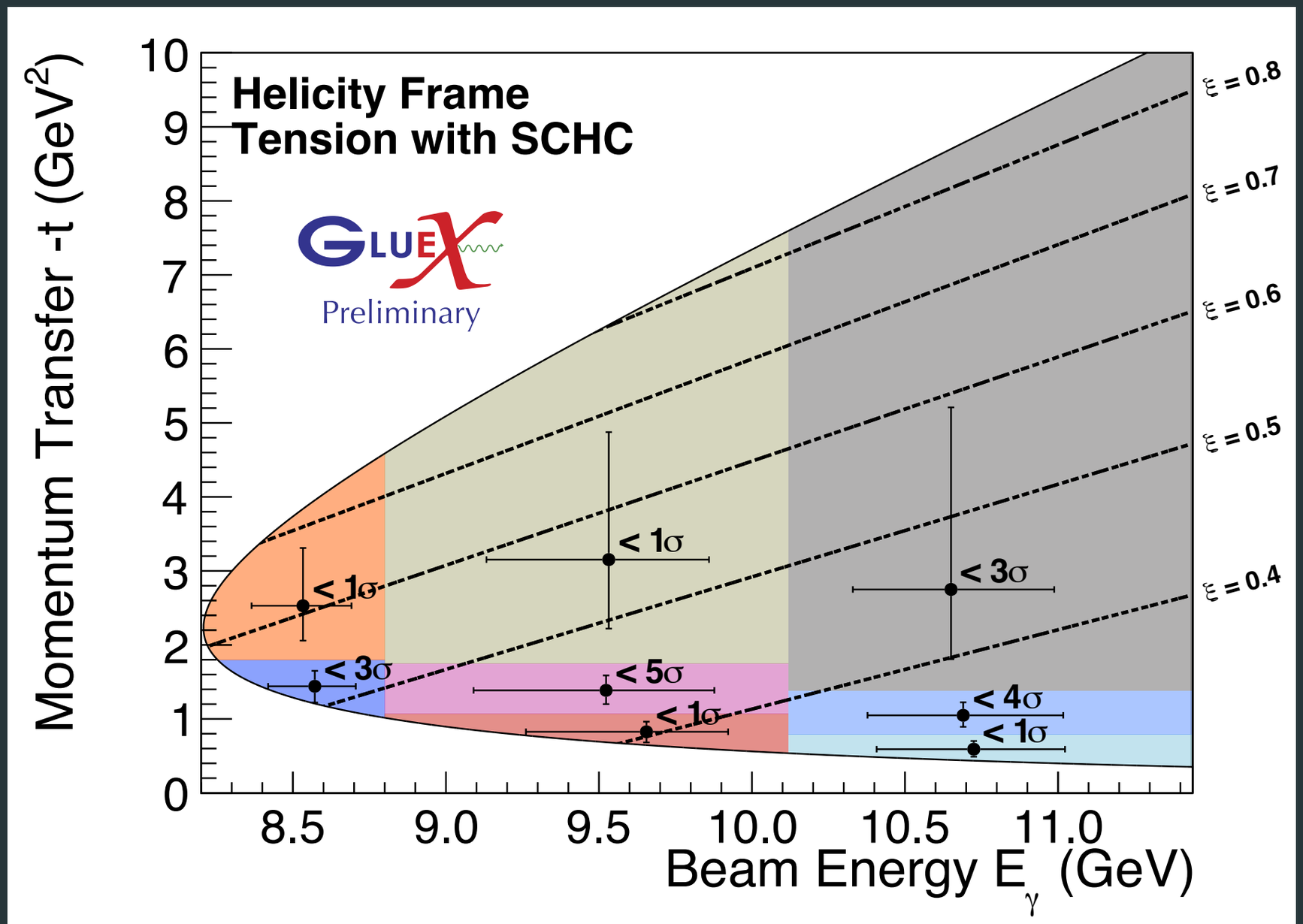
DASHED LINE | s-channel helicity conservation

Significance computed using χ^2 test with 3 d.o.f. and no model uncertainty

Preliminary results | Unpolarized

- Ground results by placing them on the t-E_γ plane.
- Error bars computed separately above and below mean to visualize statistical skew

Bin in E_γ
Bin in t



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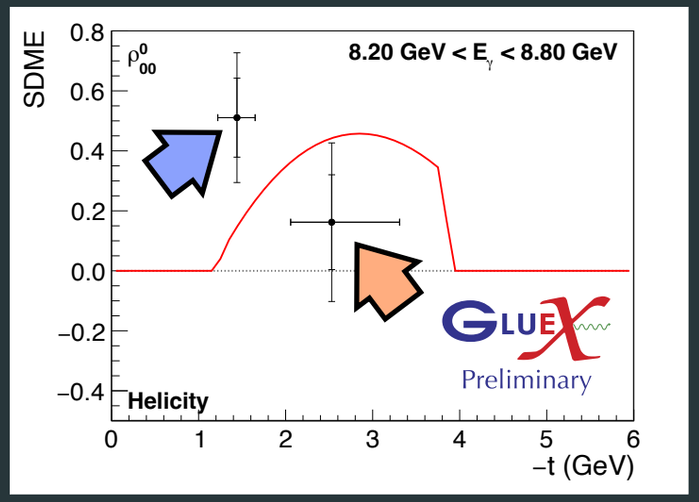

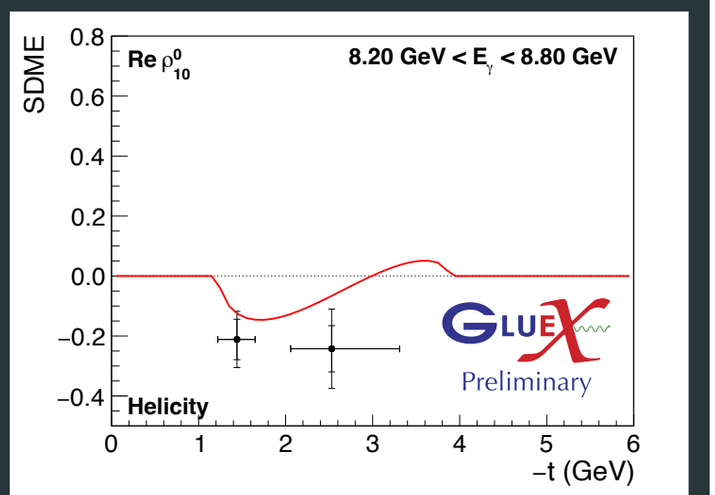

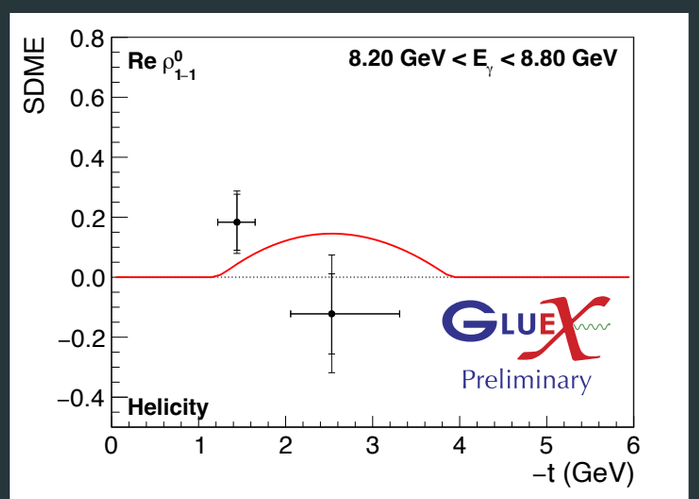

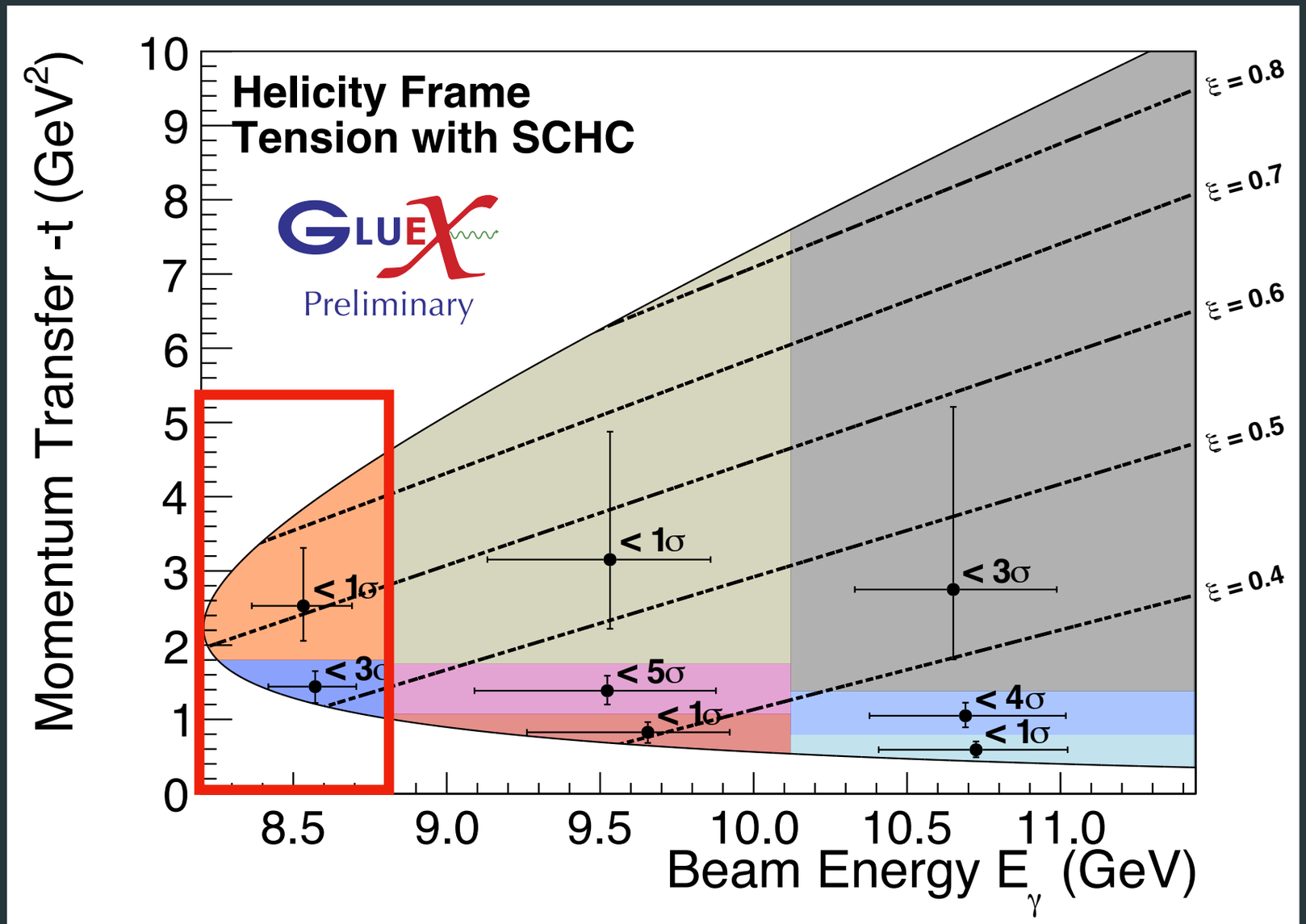

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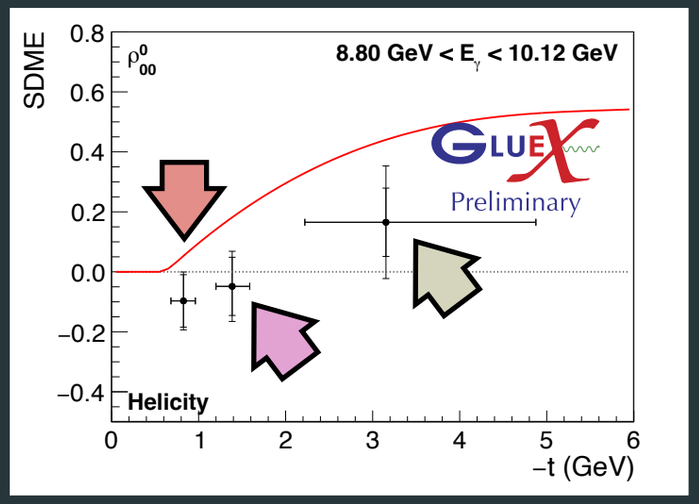

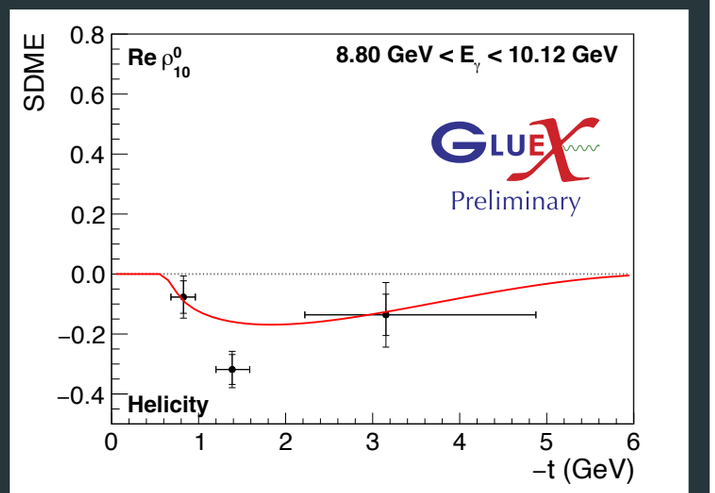

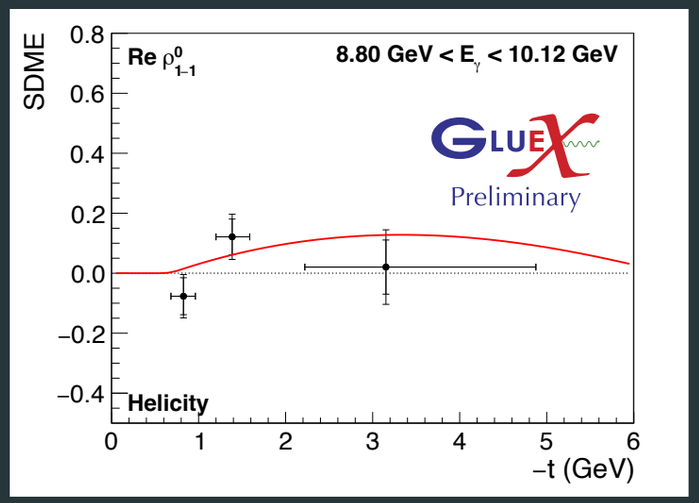

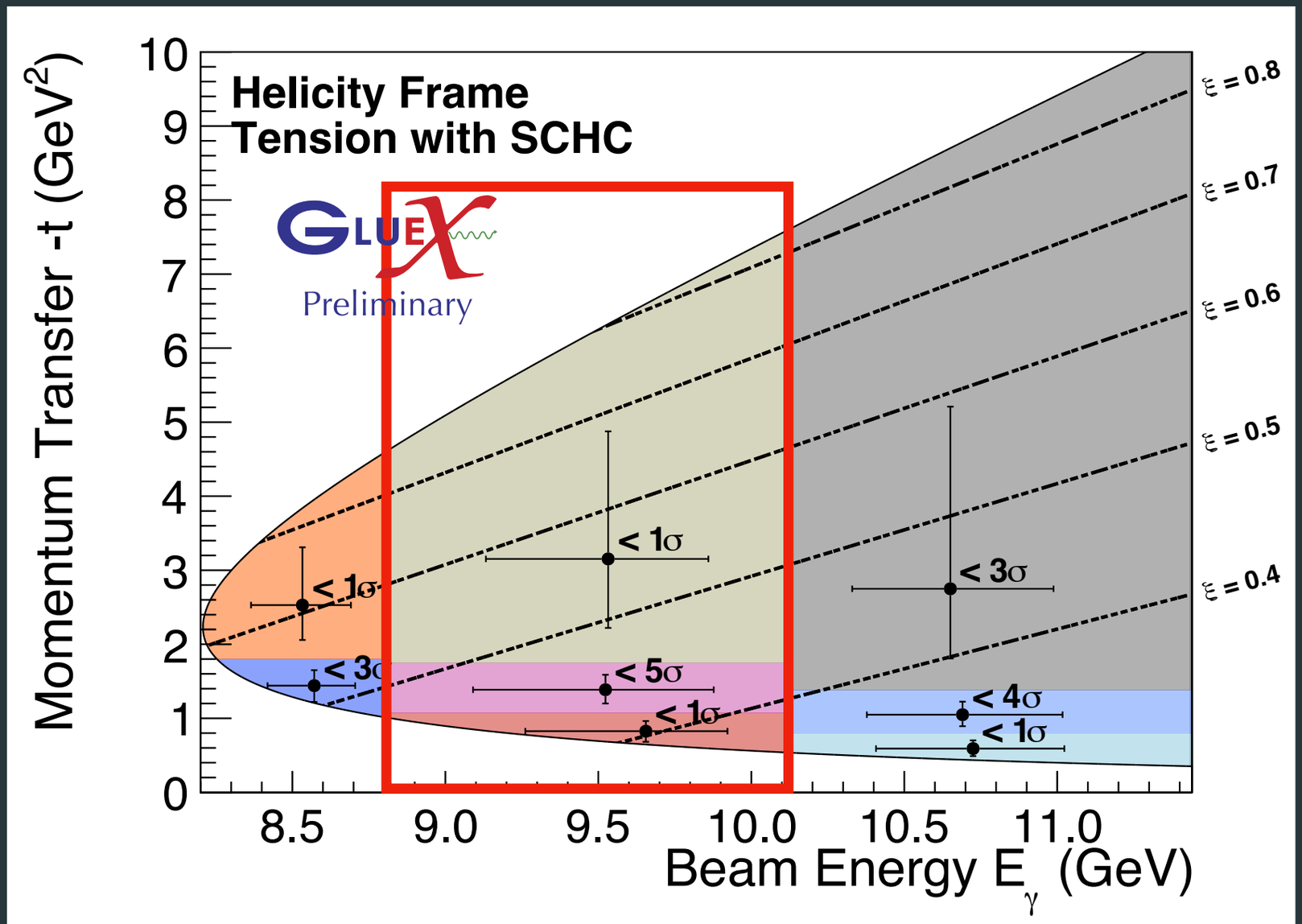

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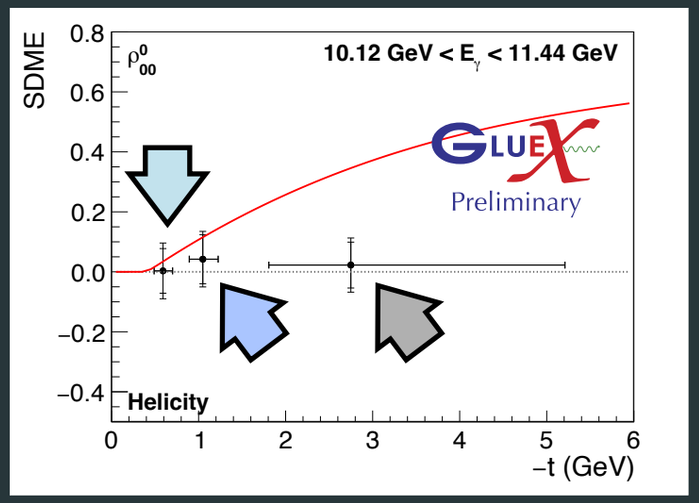

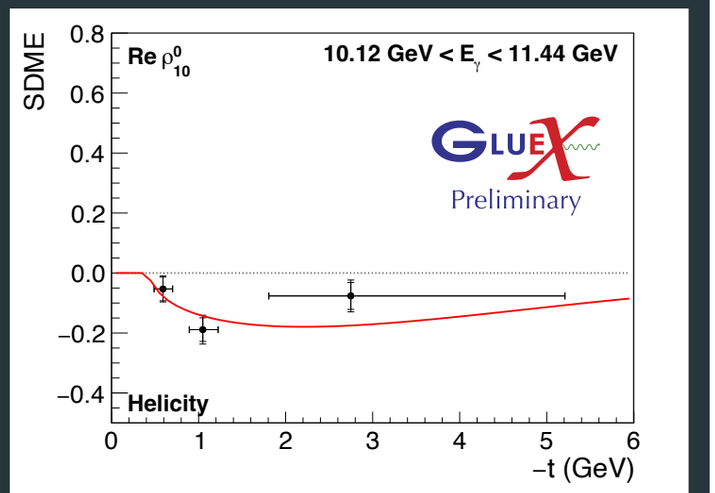

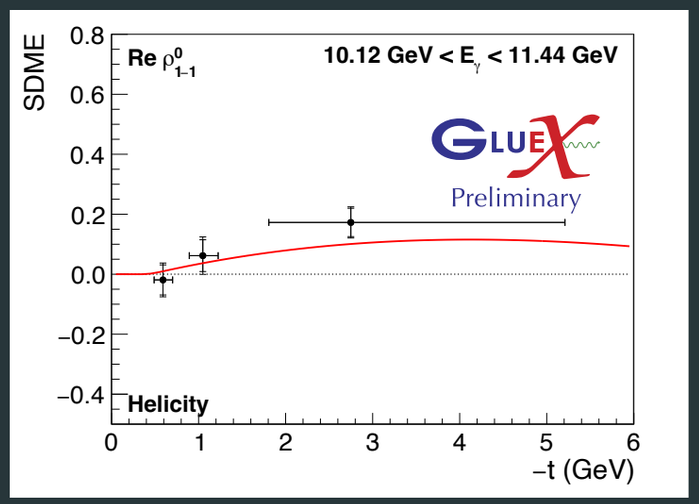

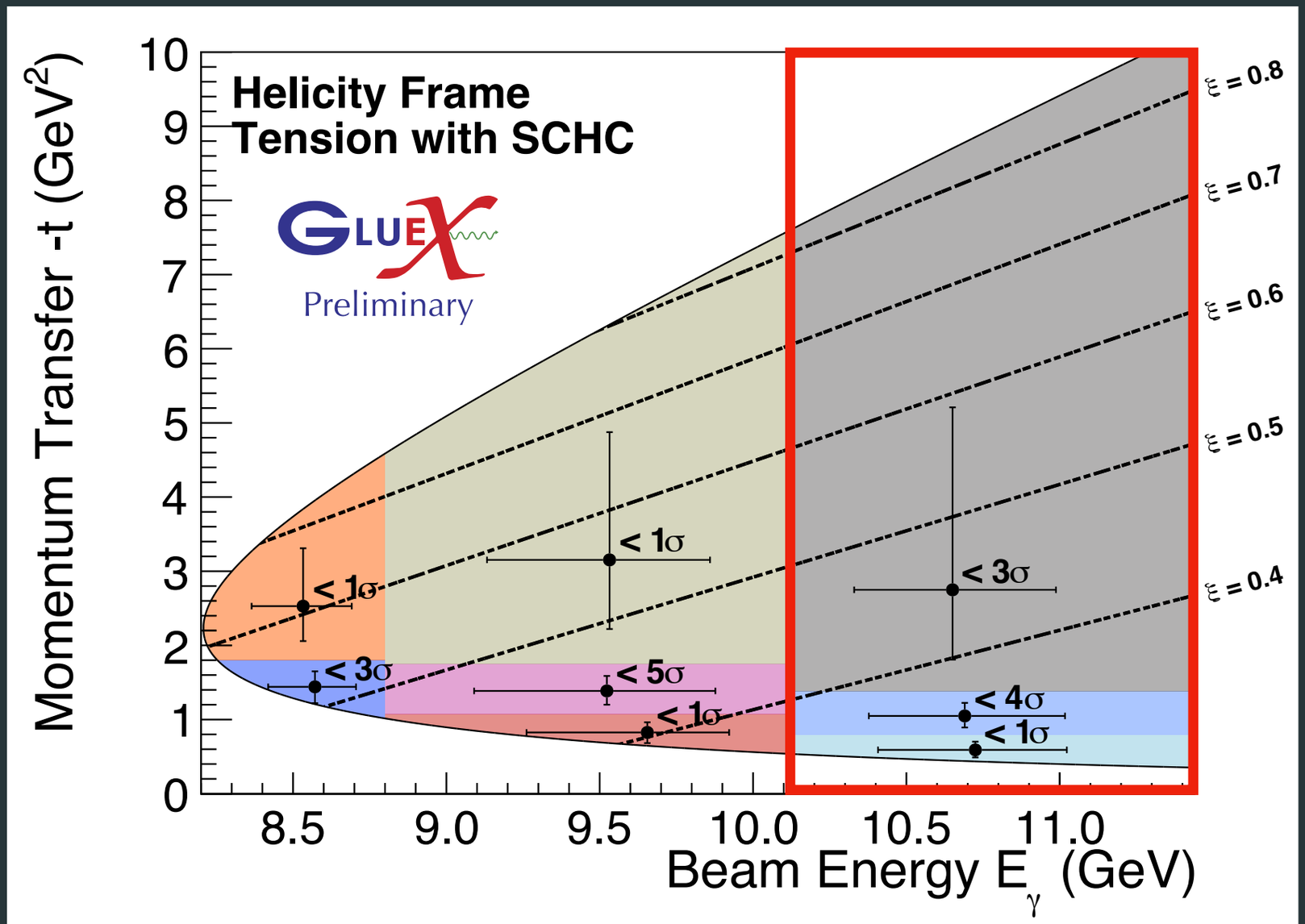

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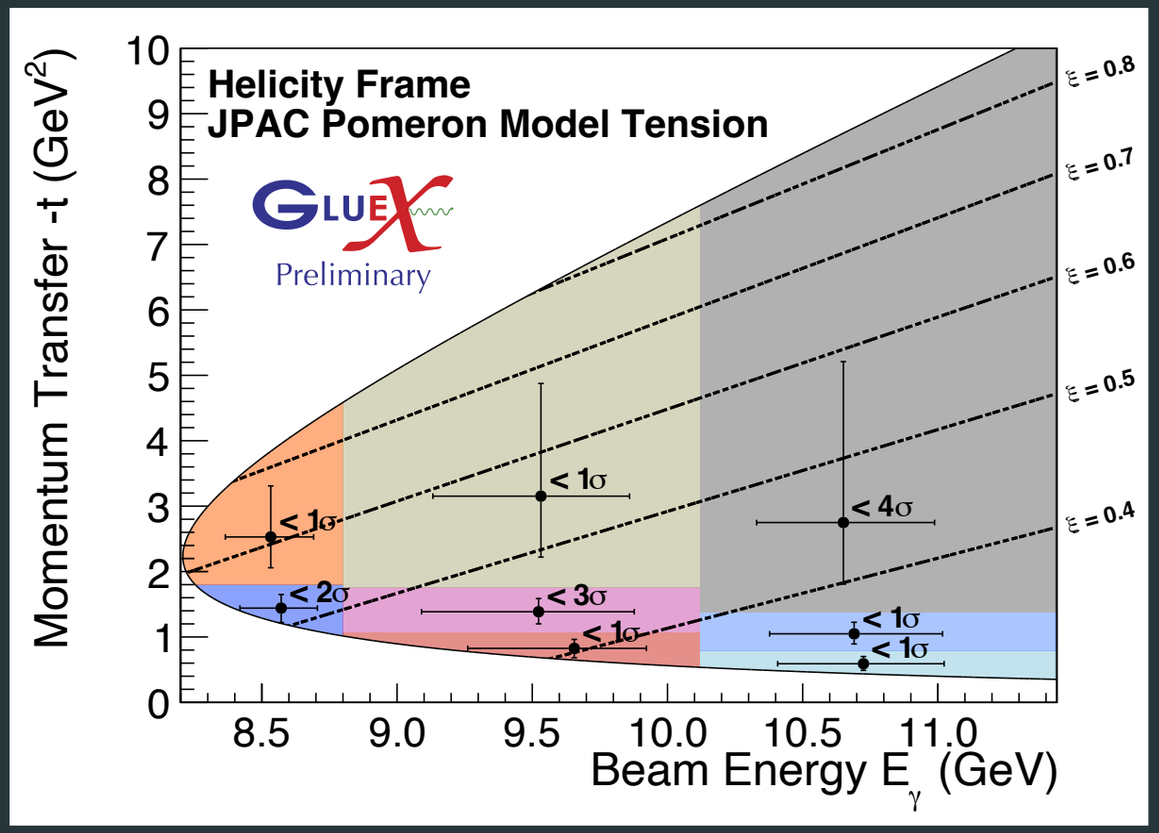
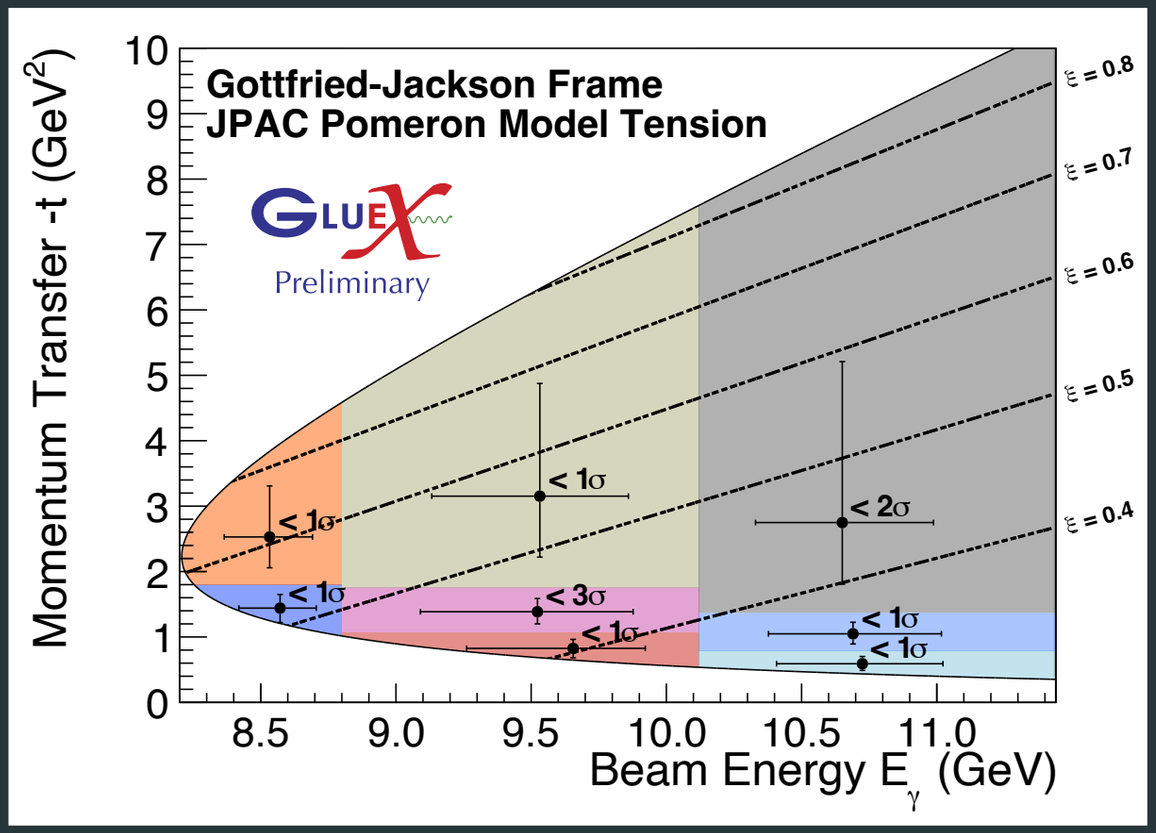
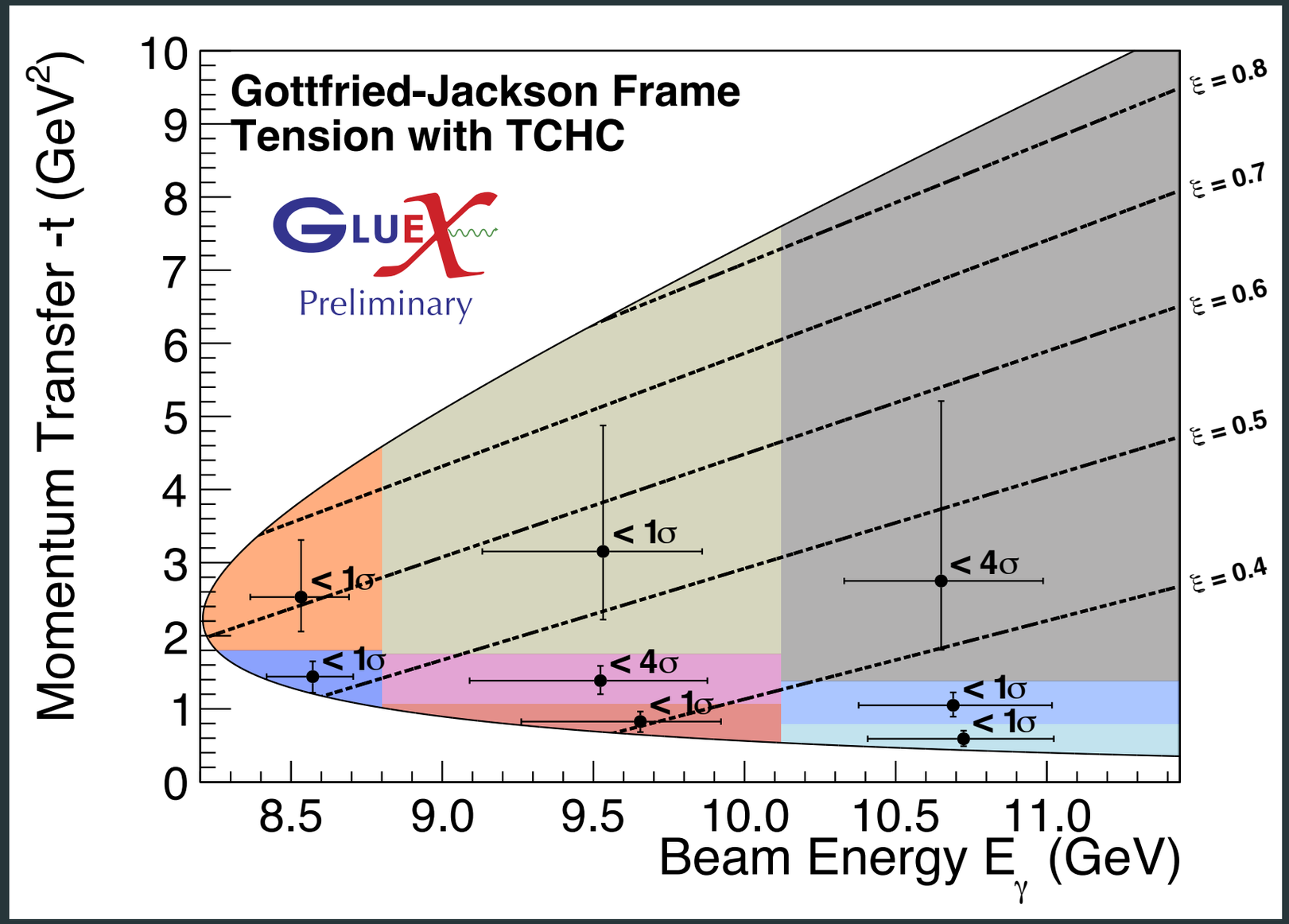
Physics conclusions | JPAC Pomeron model





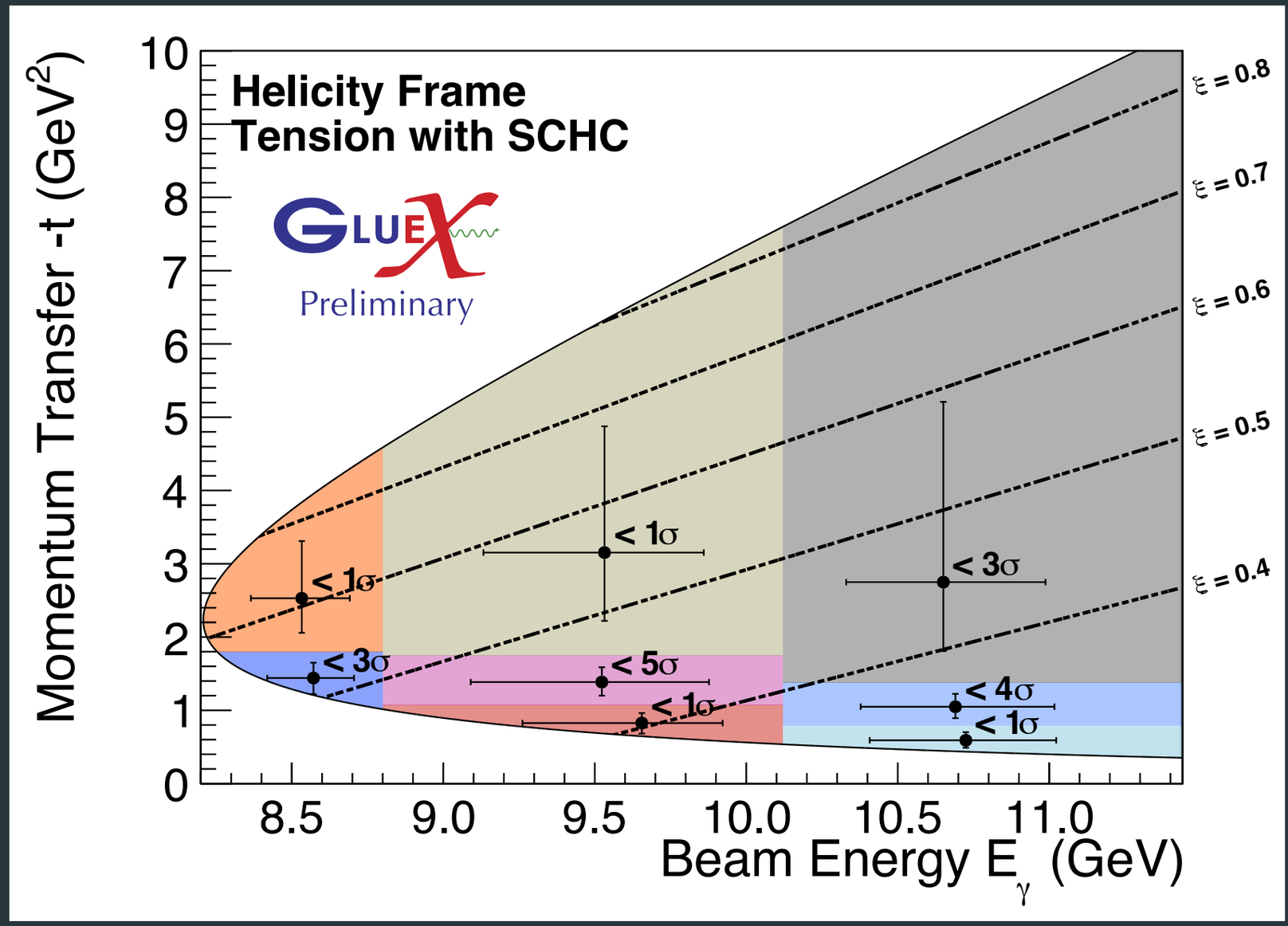
Broad agreement (given large uncertainties) with JPAC's low-energy covariant Pomeron model across helicity and Gottfried-Jackson frames.

Physics conclusions | TCHC



Some evidence of tension with TCHC hypothesis, assuming reaction proceeds in the t-channel.

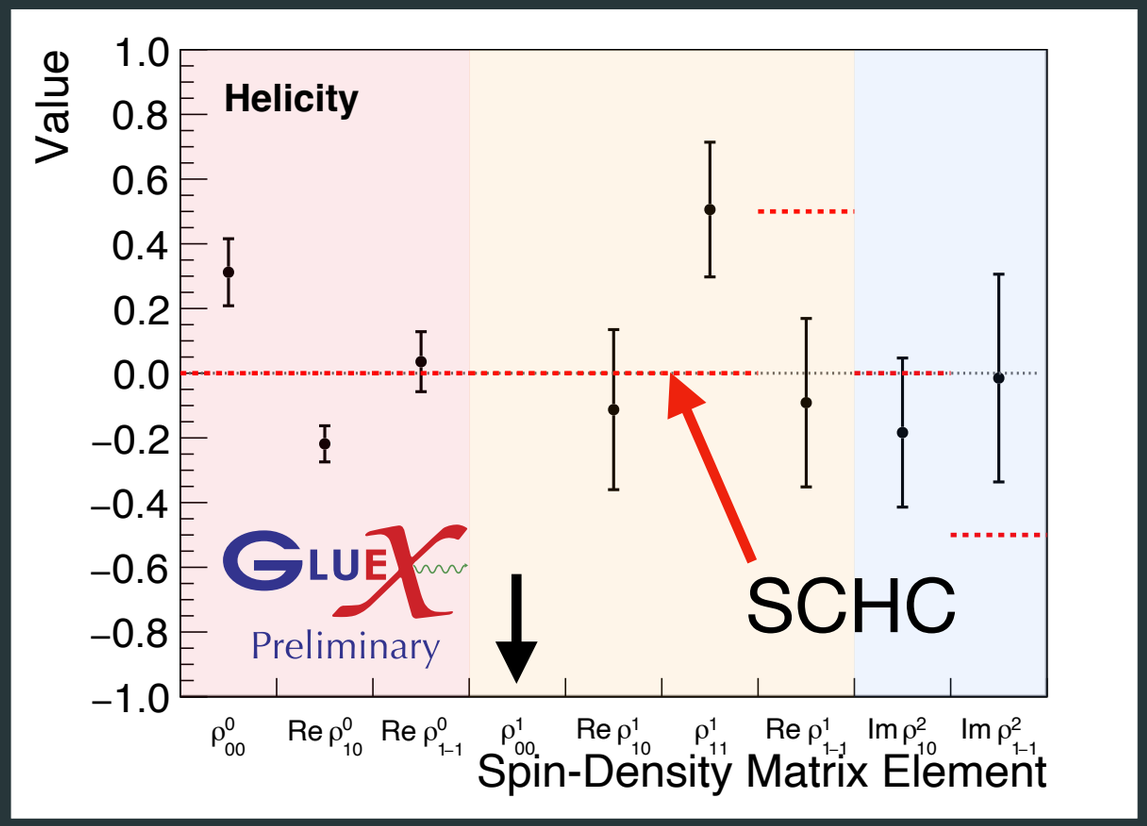
Physics conclusions | SCHC

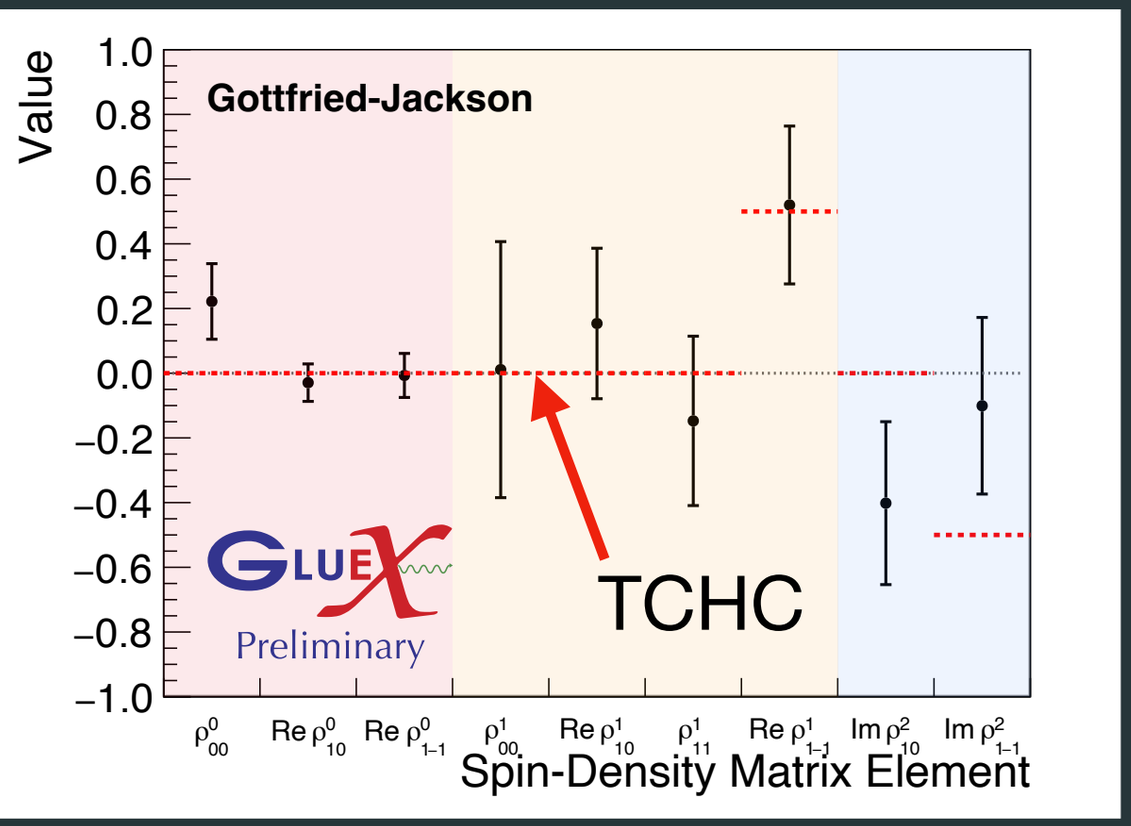


Evidence of tension with SCHC hypothesis across near threshold region driven by SDME deviation at median t.

- May indicate tension with GPD models computed with SCHC?

Extraction of polarized SDMEs





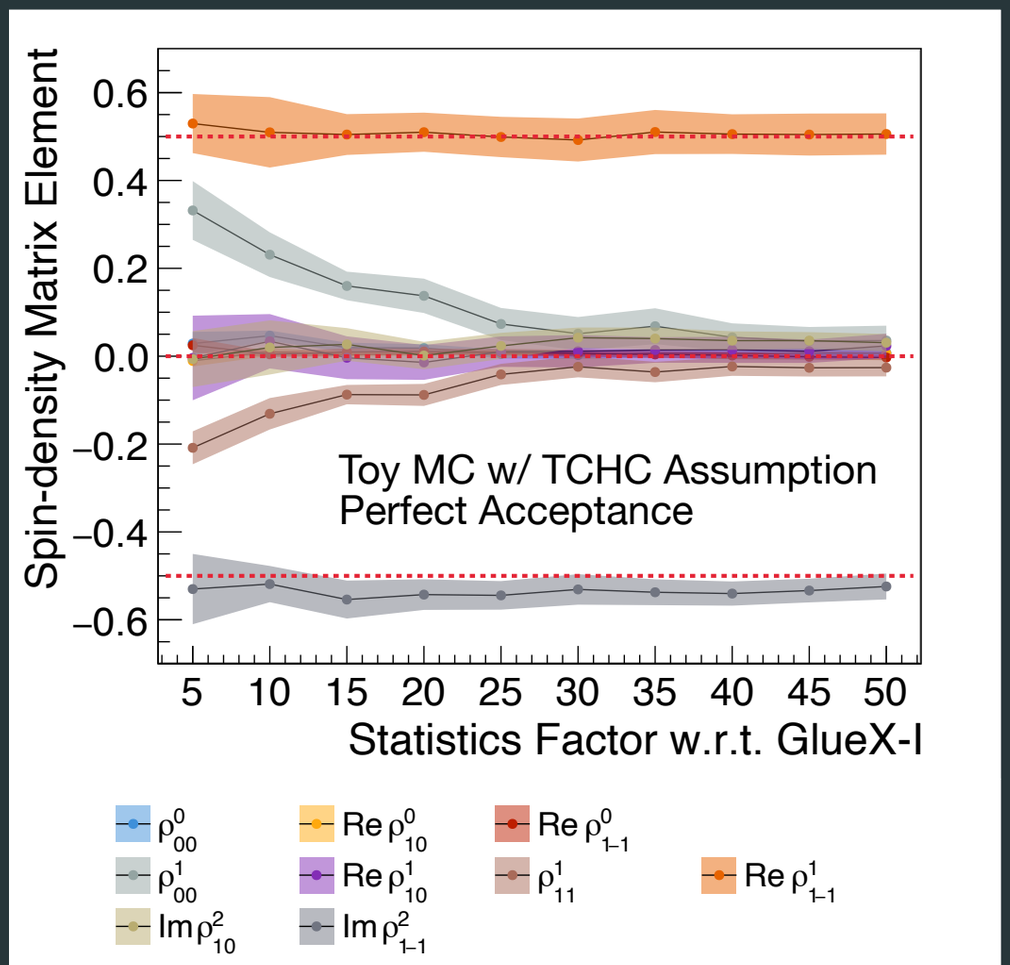
Extract polarized SDMEs in the coherent peak, integrated t

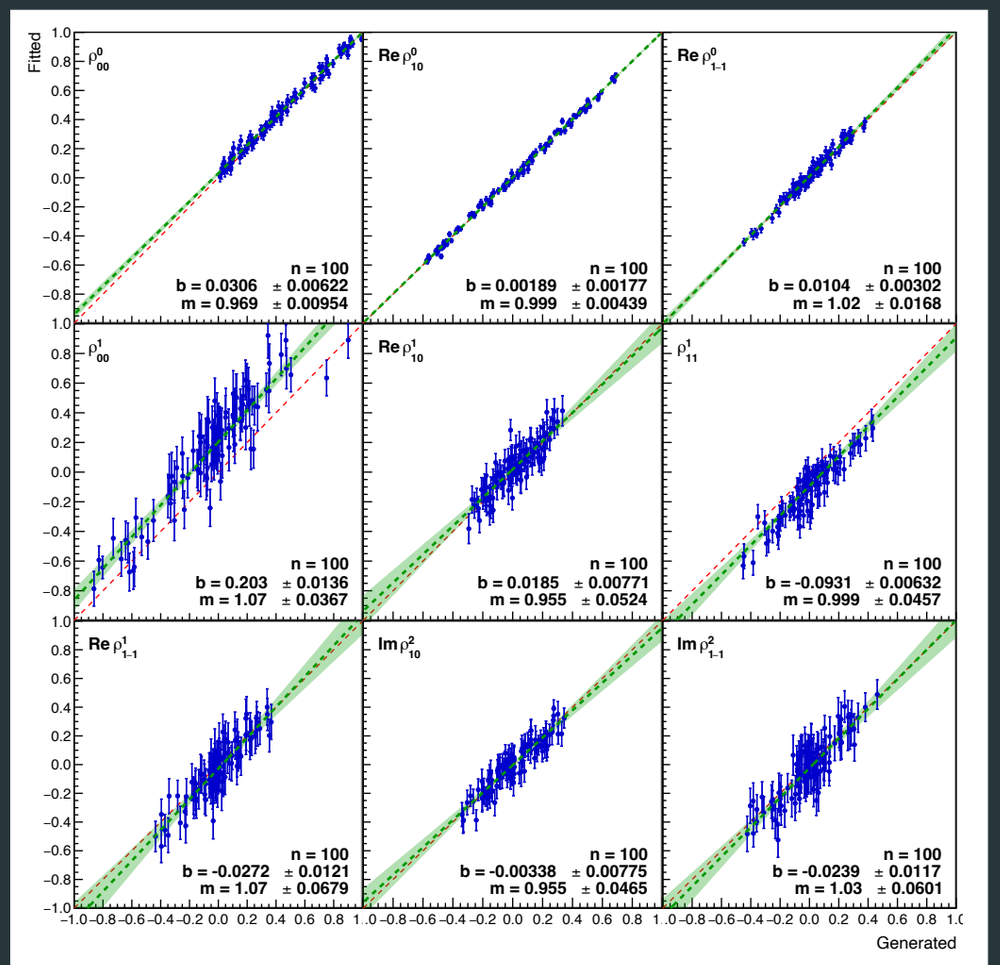
- Statistical errors only
- Broad agreement with TCHC (GJ frame) but disfavors SCHC (helicity frame)
- Expect to reduce error bars further as GlueX III proceeds in 2027

But some challenges remain…

Input-output studies with toy Monte Carlo

- Polarized SDMEs show deviation in the Gottfried-Jackson frame even in case of perfect acceptance
  - Biases diminish with additional statistics
  - Appears correctable, but deeper reason for this is unclear





DASHED LINE | Input-output

SHADED REGION | Linear fit w/ 95% confidence band

Concluding remarks

Extracted polarized and unpolarized SDMEs for J/ψ photoproduction with unbinned, maximum-likelihood fit method

- Broad agreement with JPAC's low-energy covariant Pomeron exchange model
- Some evidence of tension with helicity-conserving hypotheses
- May raise questions about GPD models assuming SCHC near J/ψ threshold?
- Quantified corrections to certain polarized SDMEs

Outlook:

- Aiming to review and publish study as soon as possible
- Seeking input from theory regarding meaningful physics interpretations
- Working to understand why polarized SDMEs biased at low statistics

gluex.org/thanks

GlueX acknowledges the support of several funding agencies and computing facilities.

Backups

Systematics

Systematic	Type	Status
0°/90° vs. -45°/45°	Independent data sets	Consistent
Phase I vs. Phase II-2020	Independent data sets	Consistent
Nominal Polarization Offset Measurement	Inherent	Negligible
TPOL Measurement	Inherent	Polarized SDMEs only
Chi-square selection	Event selection	Significant
J/psi Sideband Selection	Event selection	Significant

Systematic uncertainties displayed on subsequent slides.