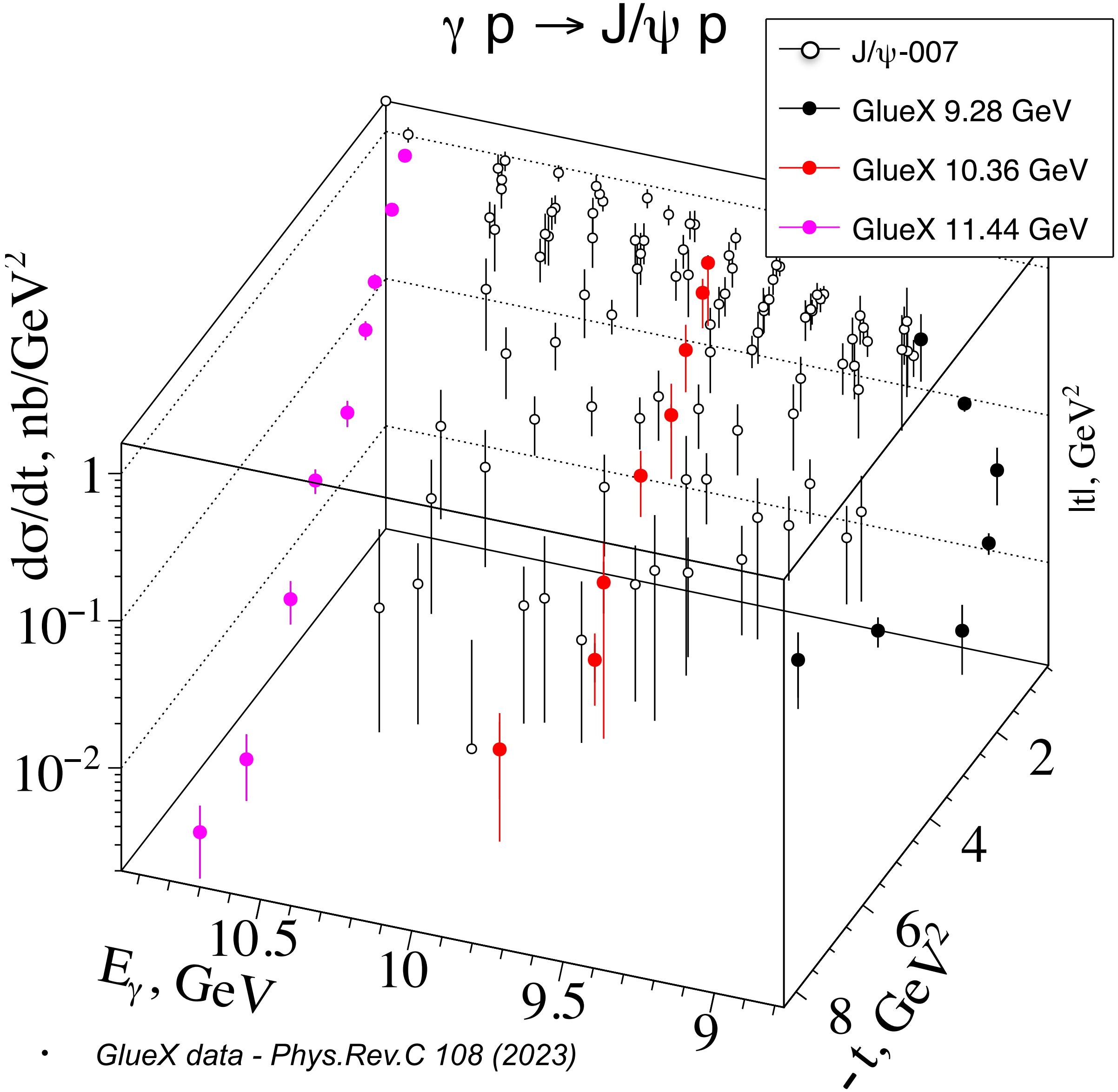
# Data-driven gluon GFF extraction

## What can we learn from threshold charmonium production?

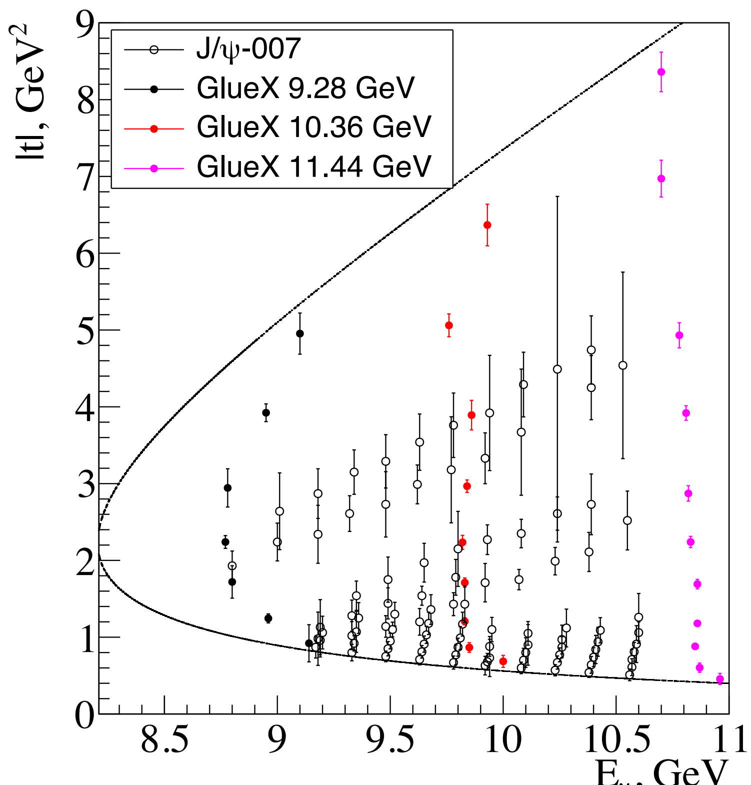
*Lubomir Pentchev*

- Test GFF models using data from threshold $J/\psi$ photoproduction
  - find features in the data consistent with some general model predictions
- Then we will attempt to extract the gluon GFFs from the data only, without any additional theoretical/lattice constraints
- How the extracted gGFFs compare to lattice results
- Comparing $J/\psi$ and $\chi_c$ photoproduction near threshold
  - Why they are different?
  - What can we learn about the production mechanism?
- Why do we need 22 GeV accelerator?

# Threshold $J/\psi$ photoproduction - the data



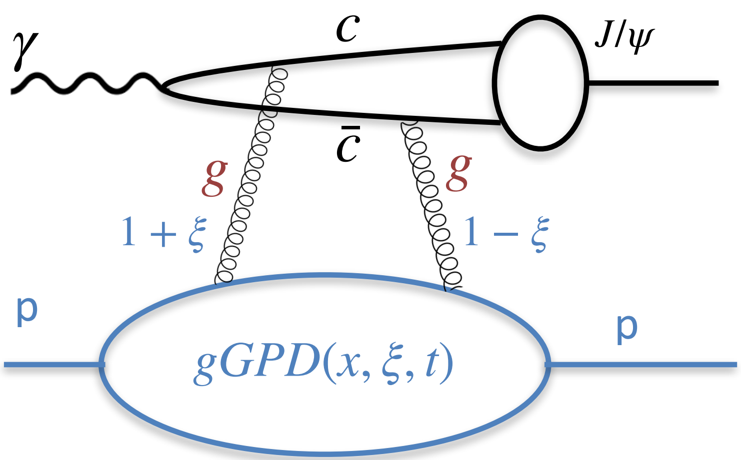

*find features in the data consistent with some general model predictions*

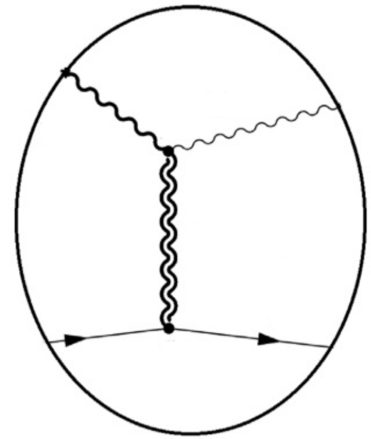



- *GlueX data - Phys.Rev.C 108 (2023)*

*J/ψ-007 data - Nature 615 (2023)*

# Threshold charmonium photoproduction - GPD and holographic approaches



*Witten diagram representation*

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p \to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t)+\xi^2 G_2(t)] + \ldots$$

$$G_0(t) = \left(\mathscr{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathscr{B}_g^{(2)}(t)\right)^2$$

$$G_2(t) = 2\mathscr{A}_g^{(2)}(t)\mathscr{C}_g(t) + 2\frac{t}{4m^2}\mathscr{B}_g^{(2)}(t)\mathscr{C}_g(t) - \left(\mathscr{A}_g^{(2)}(t) + \mathscr{B}_g^{(2)}(t)\right)^2$$

for high $\xi$ values

$$\mathscr{A}_g^{(2)}(t) = A_g(t)$$

$$\mathscr{B}_g^{(2)}(t) = B_g(t)$$

$$\mathscr{C}_g(t) = 4C_g(t)$$

leading moments

$$\xi = \frac{M_{J/\psi}^2 - t}{2(s - m^2) - M_{J/\psi}^2 + t}$$

*GPD analysis by Guo, Ji, Yuan PRD 109 (2024)*

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p \to J/\psi p} = N(E_\gamma)[H_0(t)+\eta^2 H_2(t)] + \ldots$$

$$H_0(t) = A_g^2(t)$$

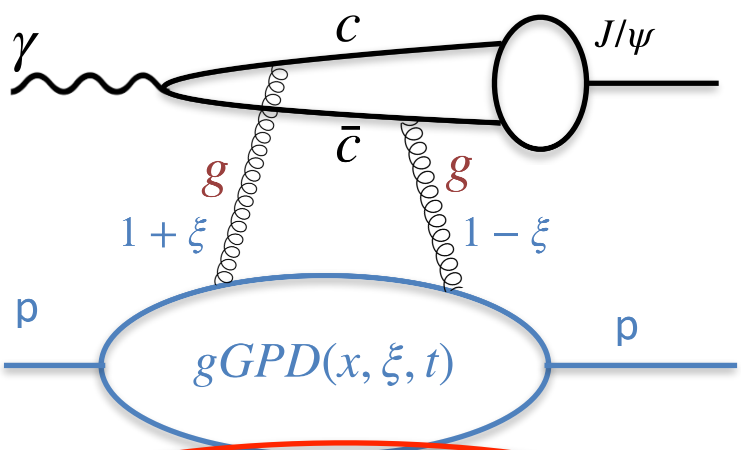
$$H_2(t) = 8A_g(t)C_g(t)$$

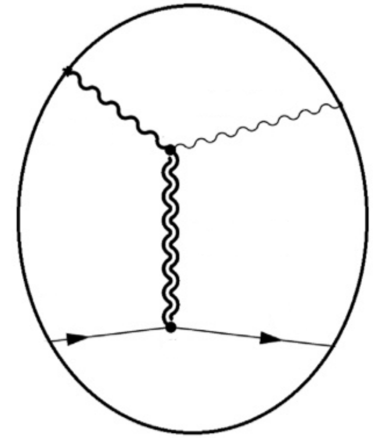
for large $N_c$ and strong $\alpha_s$

$$\eta = \frac{M_{J/\psi}^2}{2(s - m^2) - M_{J/\psi}^2 + t}$$

*Holographic analysis by Mamo and Zahed PRD 106 (2022), PRD, PRD 101 (2020), Hatta and Yang PRD 98 (2018)*

# Threshold charmonium photoproduction - GPD and holographic approaches



*Witten diagram representation*

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p \to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t)+\xi^2 G_2(t)] + \dots$$

*for high ξ values*

$$G_0(t) = \left(\mathscr{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathscr{B}_g^{(2)}(t)\right)^2$$

$$G_2(t) = 2\mathscr{A}_g^{(2)}(t)\mathscr{C}_g(t)+2\frac{t}{4m^2}\mathscr{B}_g^{(2)}(t)\mathscr{C}_g(t)-\left(\mathscr{A}_g^{(2)}(t)+\mathscr{B}_g^{(2)}(t)\right)^2$$

$$\mathscr{A}_g^{(2)}(t) = A_g(t)$$

$$\mathscr{B}_g^{(2)}(t) = B_g(t)$$

$$\mathscr{C}_g(t) = 4C_g(t)$$

*leading moments*

$$\xi = \frac{M_{J/\psi}^2 - t}{2(s-m^2) - M_{J/\psi}^2 + t}$$

*GPD analysis by Guo, Ji, Yuan PRD 109 (2024)*

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p \to J/\psi p} = N(E_\gamma)[H_0(t)+\eta^2 H_2(t)] + \dots$$

*for large $N_c$ and strong $\alpha_s$*

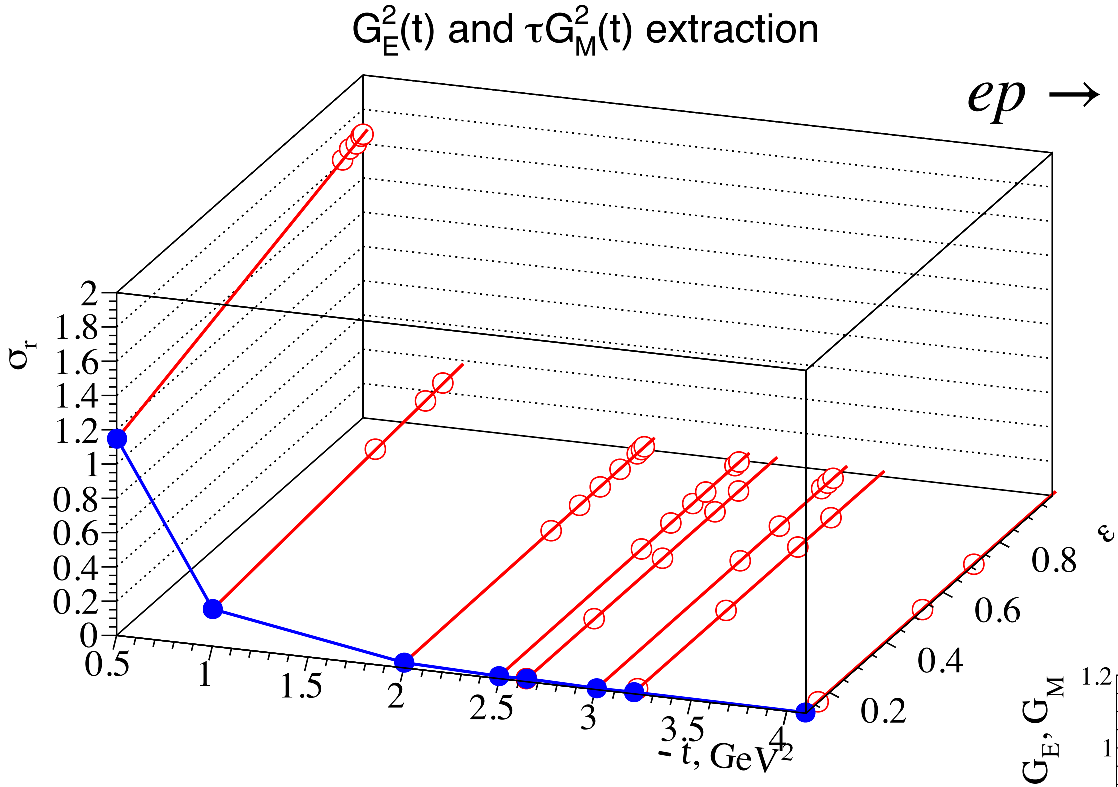
$$H_0(t) = A_g^2(t)$$

$$H_2(t) = 8A_g(t)C_g(t)$$

$$\eta = \frac{M_{J/\psi}^2}{2(s-m^2) - M_{J/\psi}^2 + t}$$

*Holographic analysis by Mamo and Zahed PRD 106 (2022), PRD, PRD 101 (2020), Hatta and Yang PRD 98 (2018)*

# Rosenbluth separation

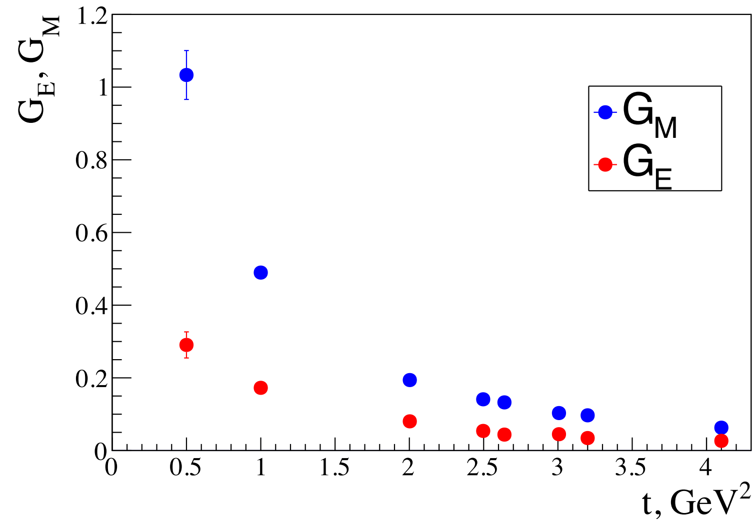



$ep \to ep$

Data from:

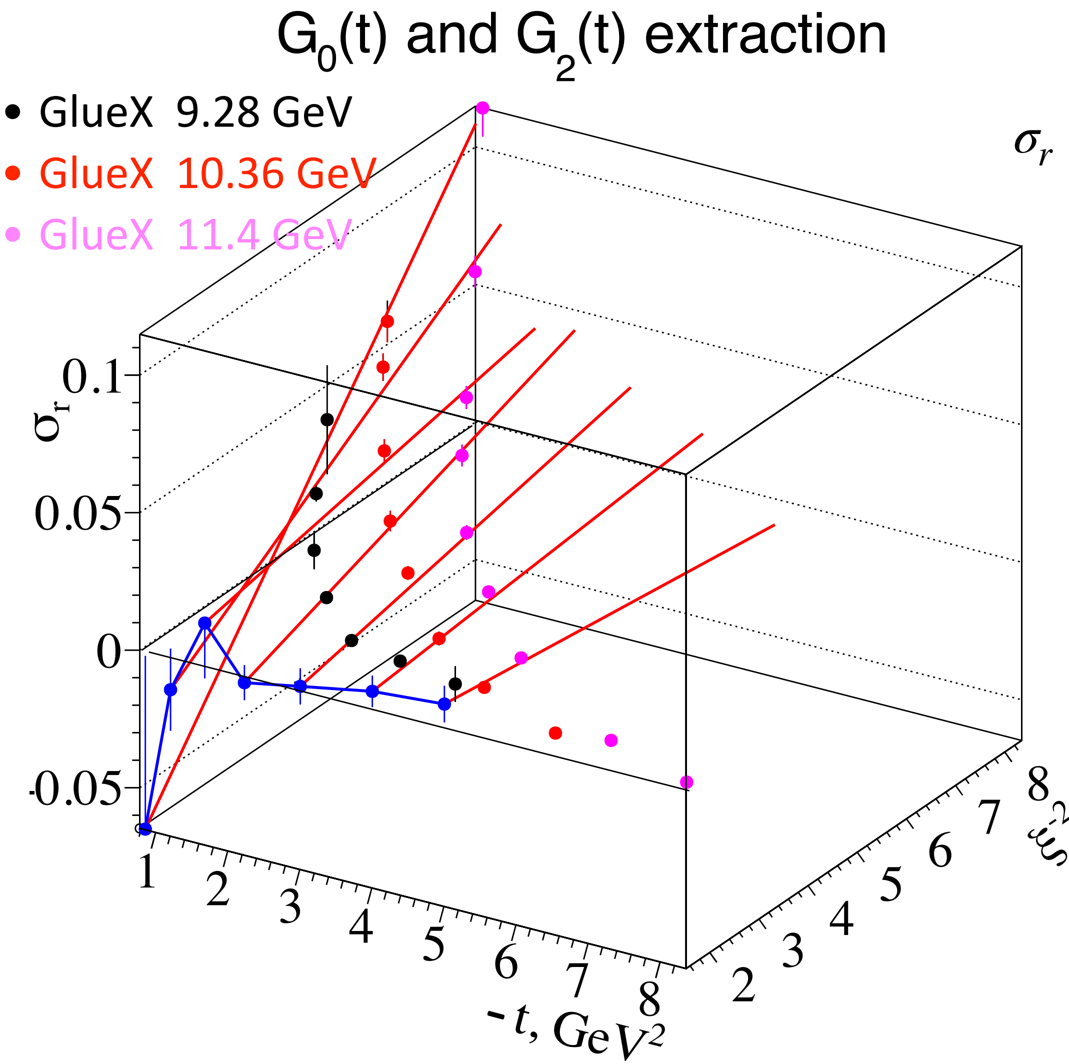
*R.C.Walker et al. Phys.Rev.D 49, 11 (1994) - SLAC*

*I.A.Qattan et al. arXiv 2411.05201 (2024) - JLab*




$$\sigma_R = \frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega}\right)_M \varepsilon(1+\tau) = \varepsilon G_E^2(t) + \tau G_M^2(t)$$

# Threshold $J/\psi$ photoproduction - “Rosenbluth” separation




$$\sigma_r = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t)$$

$$G_0(t) = \left(\mathscr{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathscr{B}_g^{(2)}(t)\right)^2 > 0$$

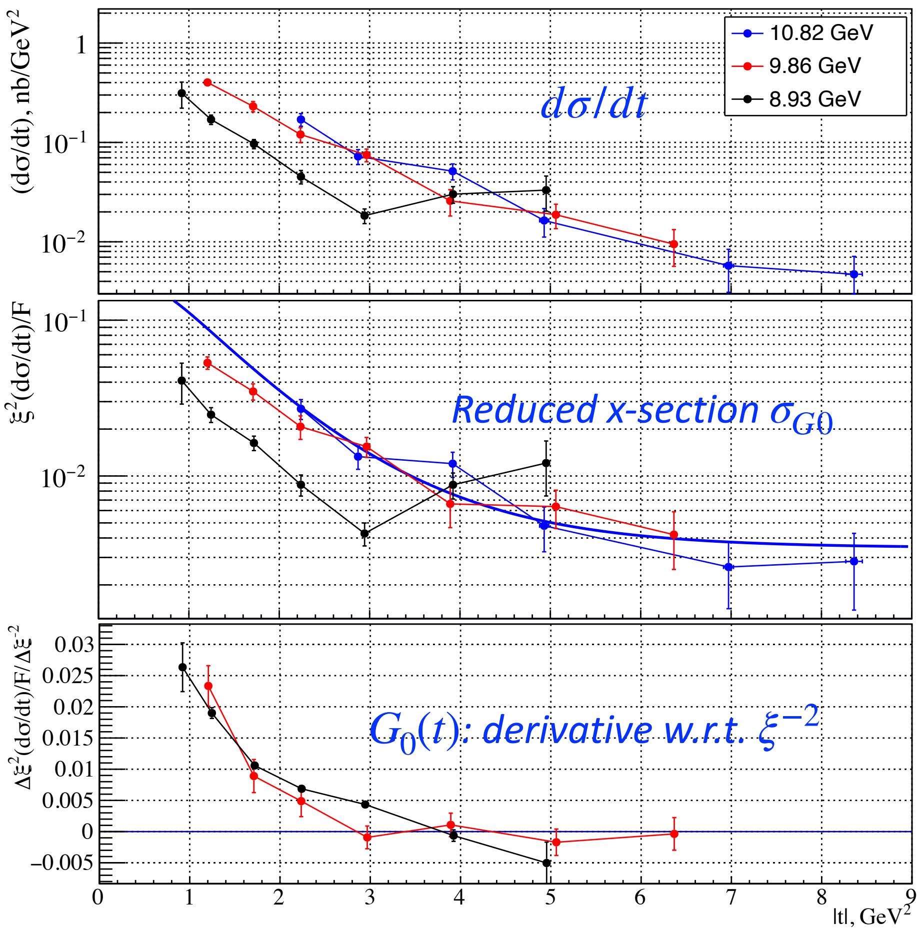
Therefore $d\sigma/dt(E,t)$ at fixed $t$, must increase with energy, consistent with the data!

# Testing Energy Independence of Form Factor Functions

## $G_0(t)$ - GPD

$$\sigma_{G0} = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t) \qquad \xi > 0.4$$

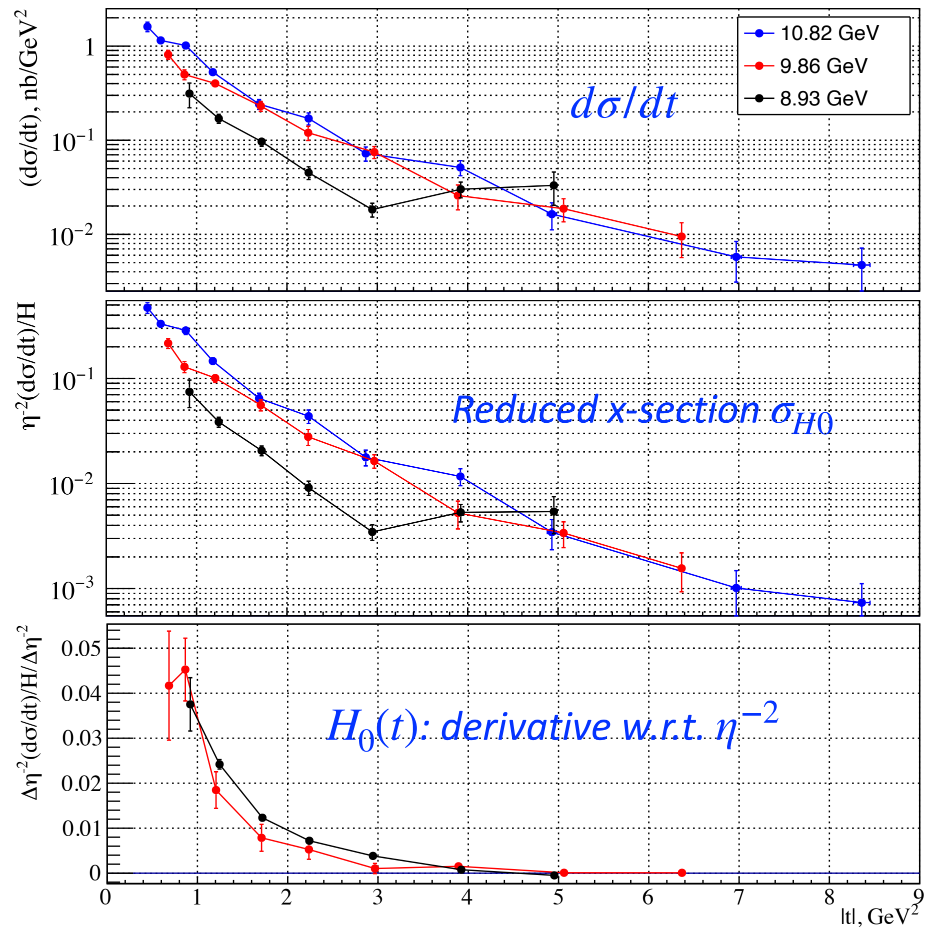
$$G_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\xi^{-2}(E_i,t) - \xi^{-2}(E_j,t)\right]$$




## $H_0(t)$ - Holography

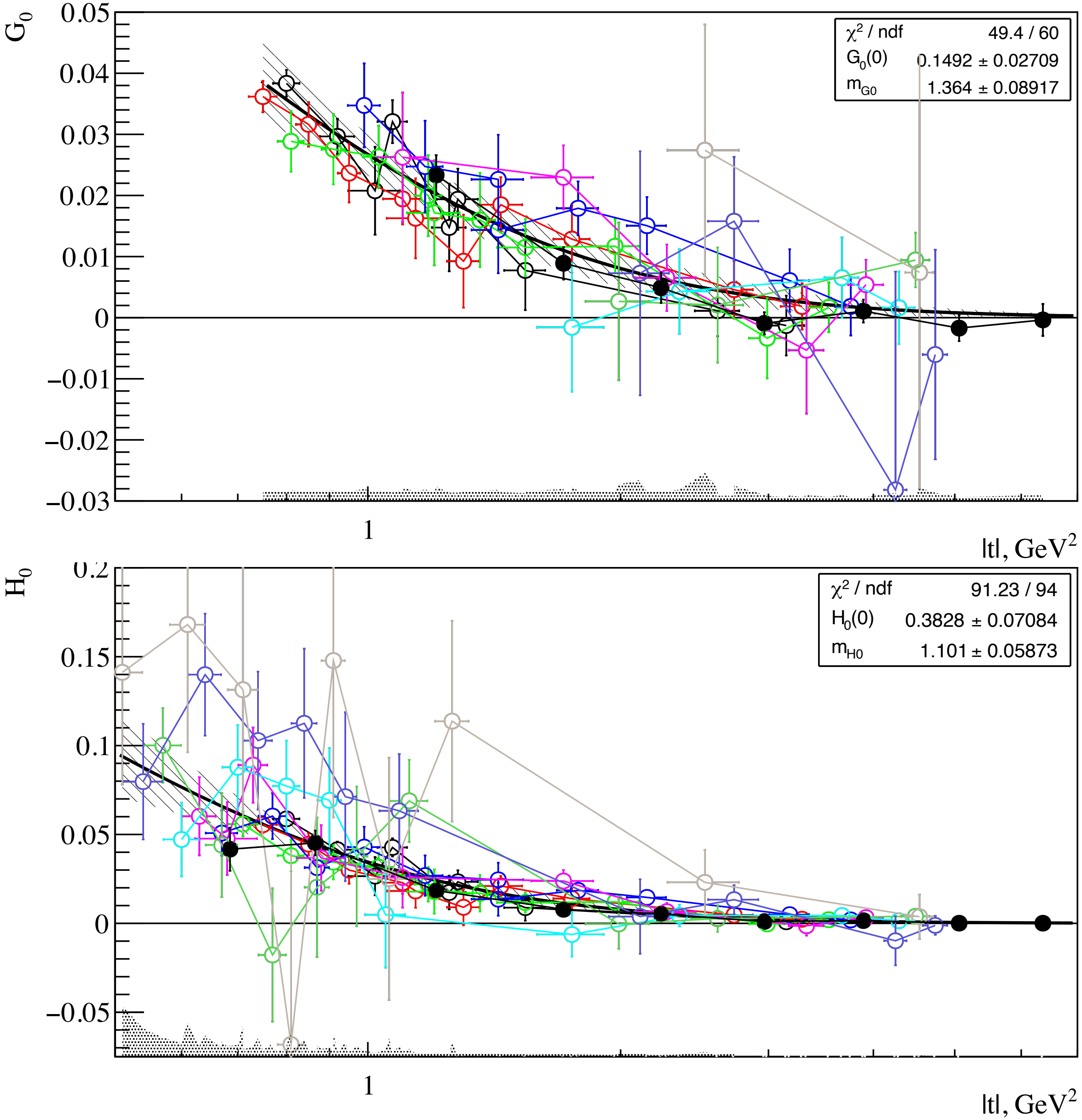
$$\sigma_{H0} = \frac{d\sigma}{dt}\frac{\eta^{-2}}{H(E_\gamma)} = \eta^{-2}H_0(t) + 4H_2(t)$$

$$H_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\eta^{-2}(E_i,t) - \eta^{-2}(E_j,t)\right]$$




*GlueX data - Phys.Rev.C 108 (2023)*

# Gluon Form Factors - energy independence




*Energy independence of the $G(t)/H(t)$ functions (within errors)*

*Fits with:*

$$\frac{G_0(0)}{(1 - t/m_{G0}^2)^4}$$

$$\frac{H_0(0)}{(1 - t/m_{H0}^2)^4}$$

Using GlueX and $J/\psi$-007 data - different colors - different energies

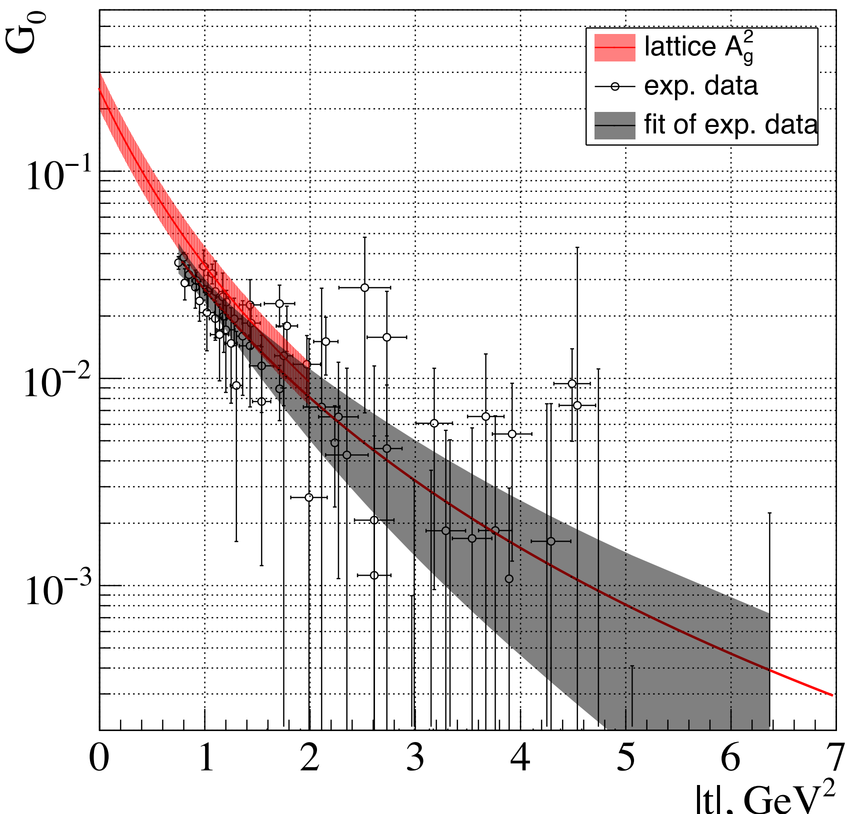
No theory/lattice constraints used!

*Phys.Rev.C 108 (2023)*
*Nature 615 (2023)*

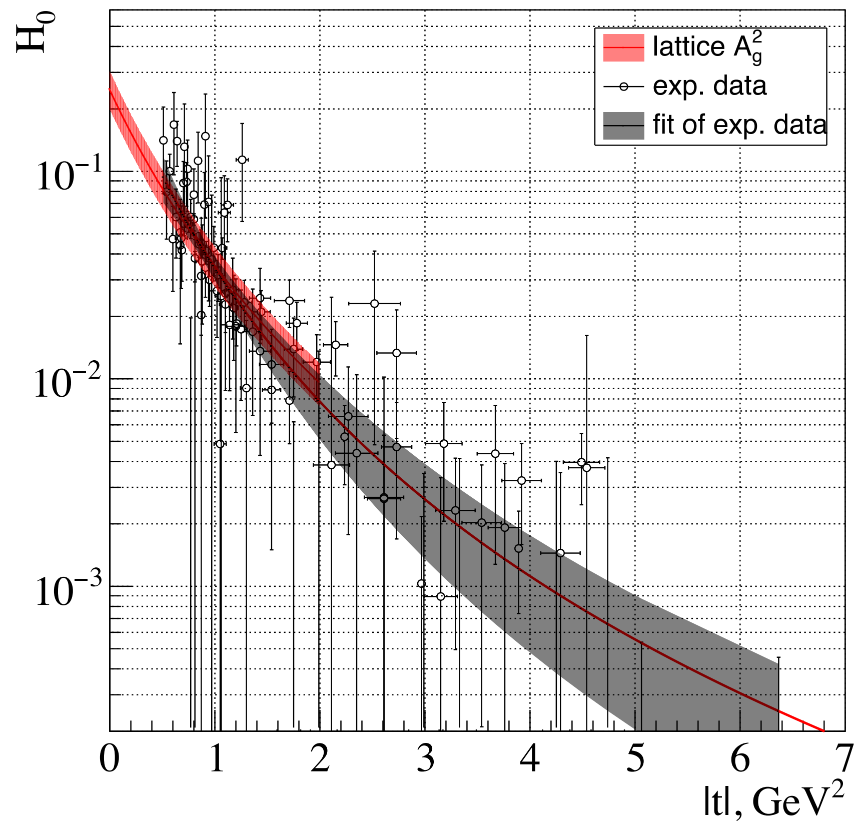
*LP and E.Chudakov*
*arXiv:2404.18776*

# Assuming leading-term approximation - data vs lattice

*GPD*




*Holographic*




$G_0(t) = \left(\mathscr{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathscr{B}_g^{(2)}(t)\right)^2$ *for high $\xi$ values*

$\mathscr{A}_g^{(2)}(t) = A_g(t)$ *leading-moment*

$\mathscr{B}_g^{(2)}(t) = B_g(t)$ *approximation*

neglecting $B_g(t)$

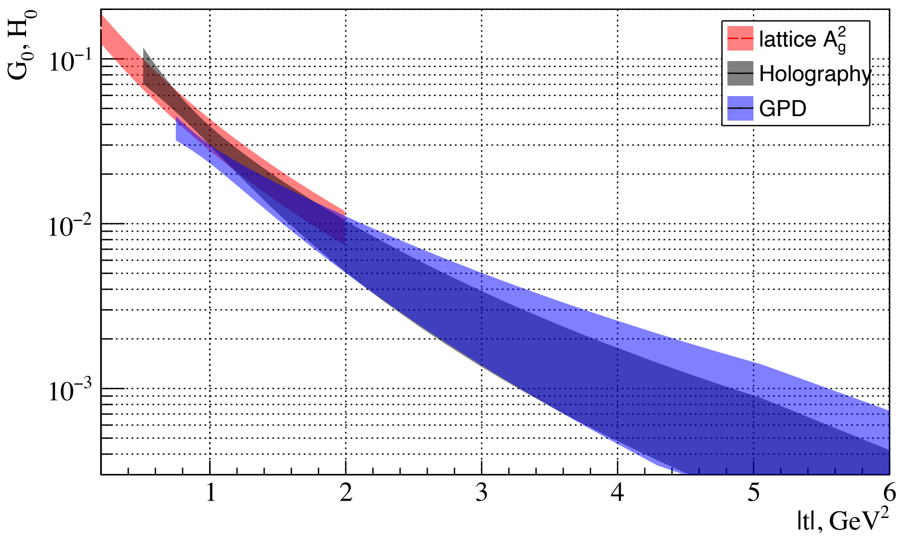
$G_0(t) = A_g^2(t)$

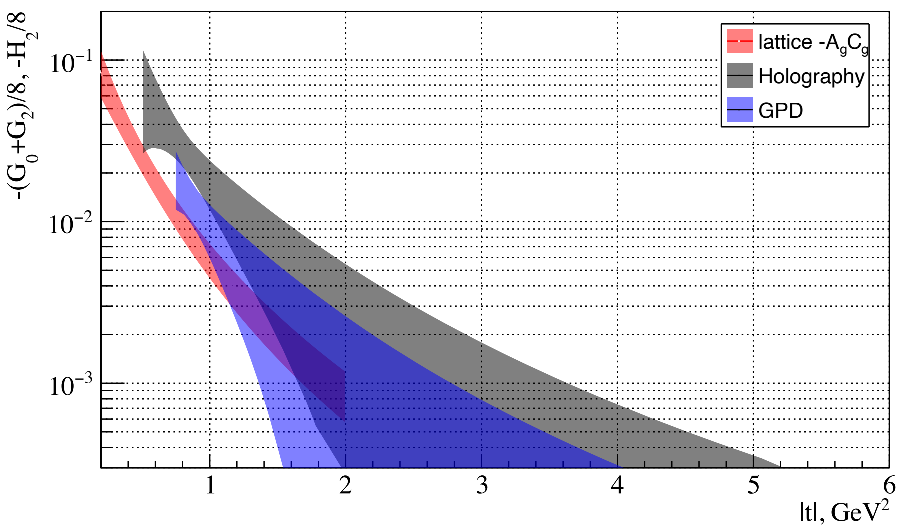
$B_g(t)$=0

$H_0(t) = A_g^2(t)$

*for large $N_c$ and strong $\alpha_s$*

# Gluon Gravitational Form Factors - summary




Features in data consistent with the GFF models:

- $d\sigma/dt(E_\gamma, t \rightarrow fixed)$ increases with energy
- $G(t)$ and $H(t)$ form factor functions are energy independent (within the experimental errors)

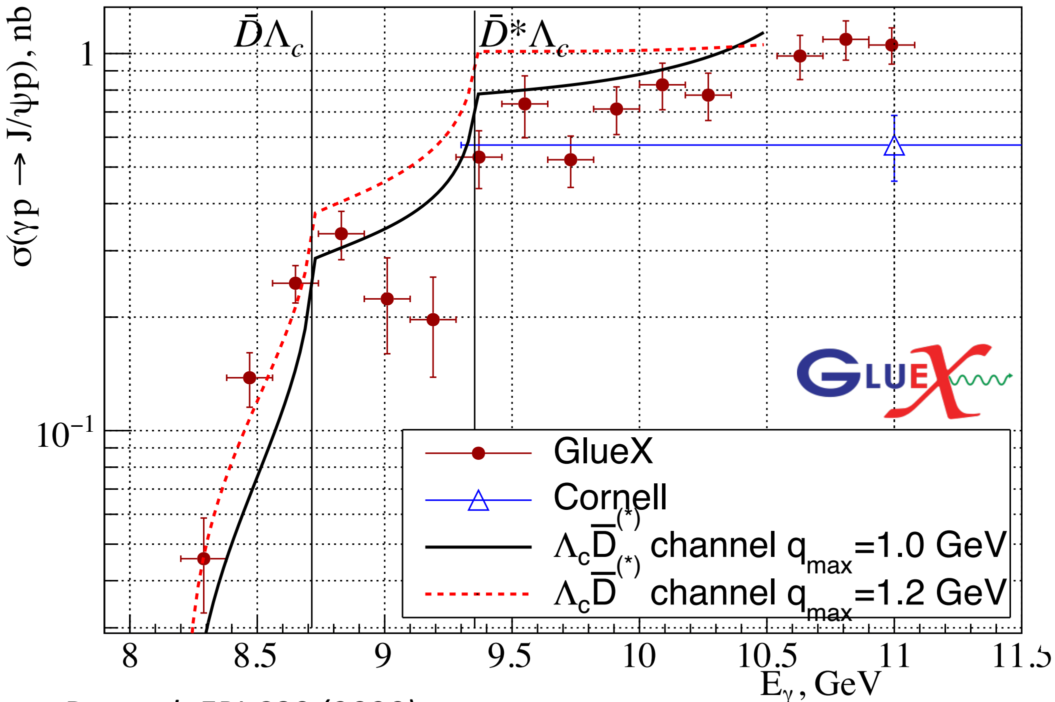
- In leading-term approximation (and neglecting $B_g$):

  $G_0(t) = H_0(t) = A_g^2(t)$ and

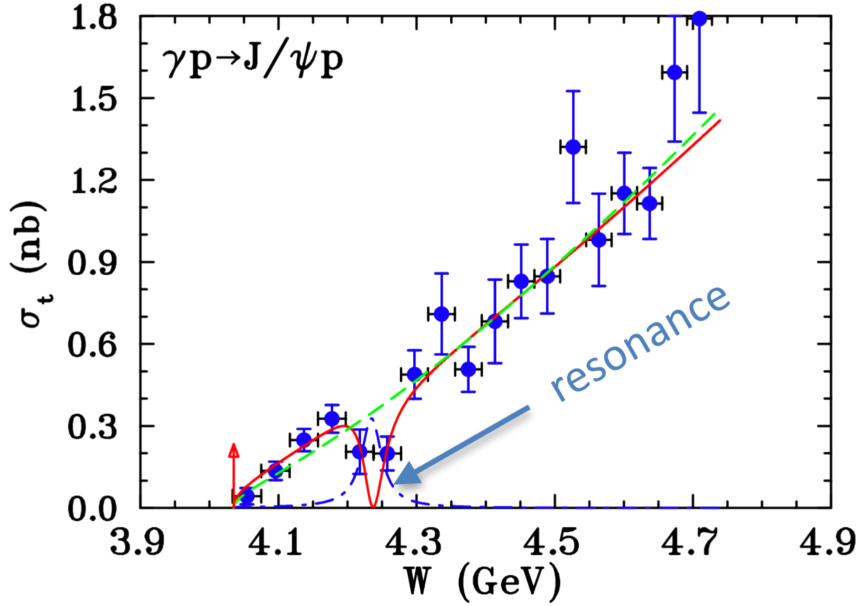
  $G_0(t) + G_2(t) = H_2(t) = 8C_g(t)A_g(t)$

  General agreement b/n extracted FFs using two diametric theories
- agreement with lattice
- possible conclusion: the model corrections are not dominant

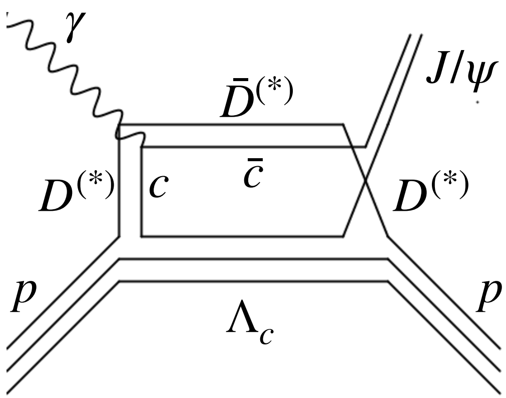
# Other reaction mechanisms: open-charm, resonance

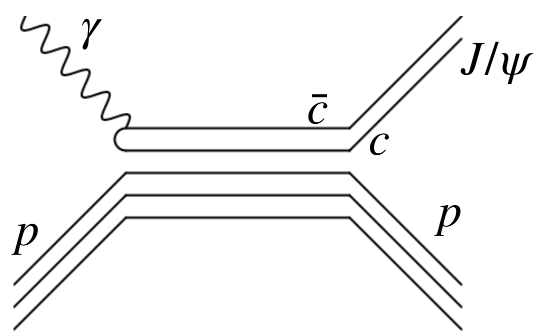



*Du et al. EPJ C80 (2020)*



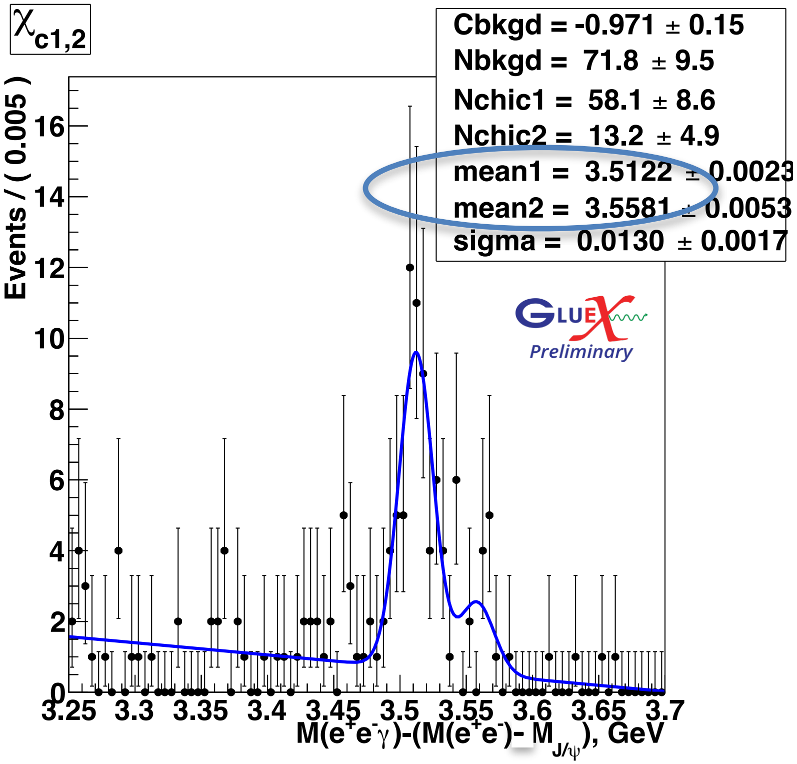

*Strakovsky et al. PRC 108 (2023)*




*JPAC Phys.Rev.D 108 (2023)*

# Higher-mass charmonium states at threshold in GlueX



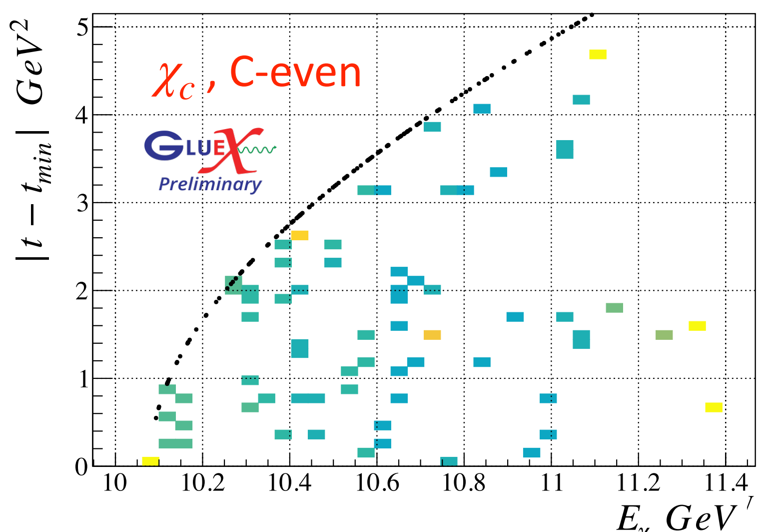

$$\gamma p \to \chi_c p \to (J/\psi\gamma)p \to (e^+e^-\gamma)p$$

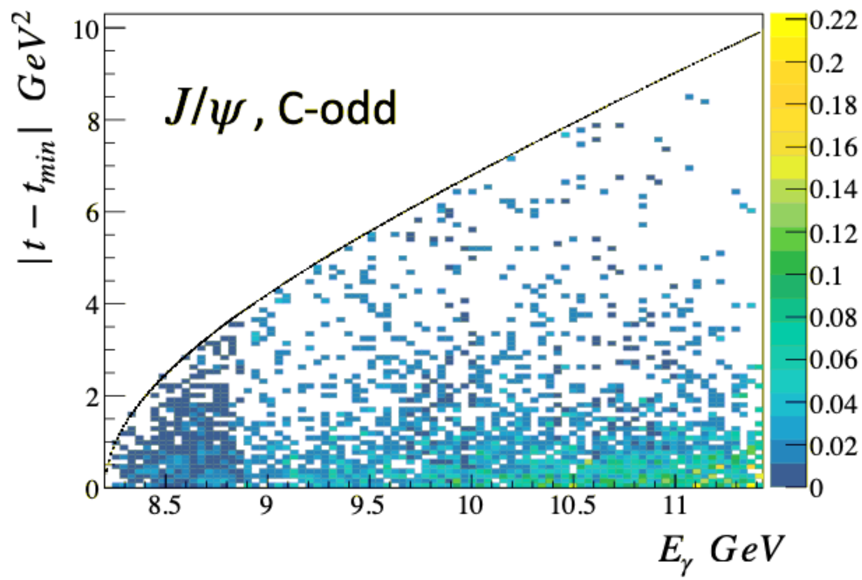
$\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, $1^{++}$ and $2^{++}$,

$E_\gamma^{thr} = 10.1$ GeV

- First ever evidence for photoproduction of C-even charmonium
- $t$-channel is suppressed (requires C-odd exchange), allows to study $s$-channel reaction mechanisms

Dramatic difference: $\chi_c$ distribution in $(E_\gamma, t)$ vs $J/\psi$

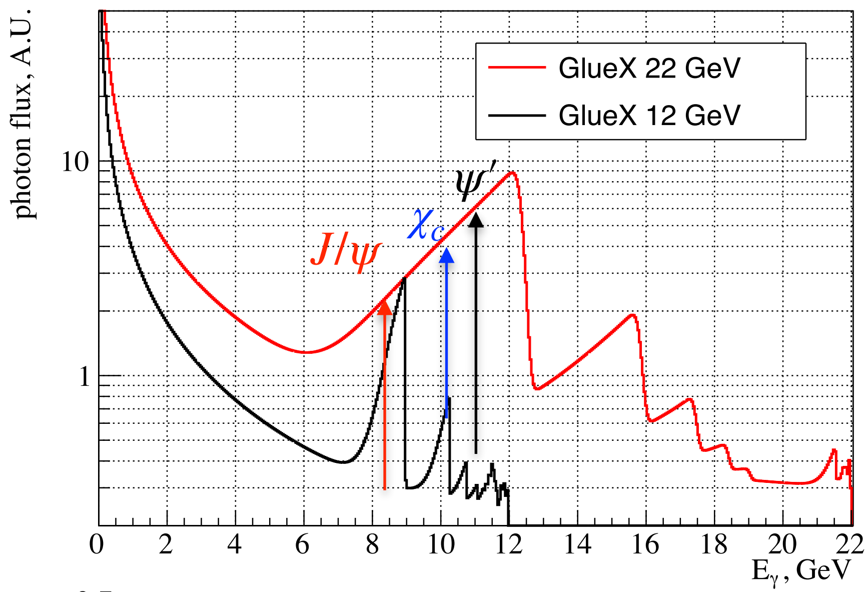


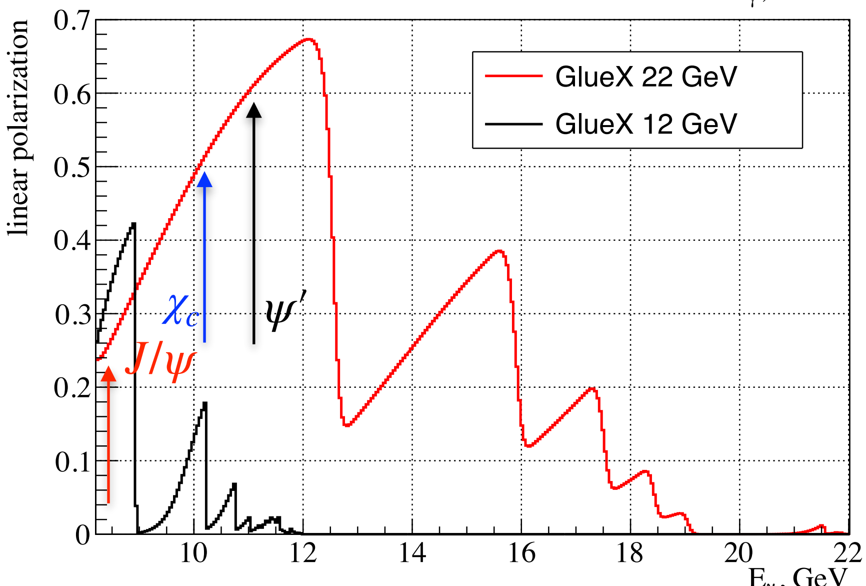



# Threshold charmonium photoproduction at JLab22 with GlueX

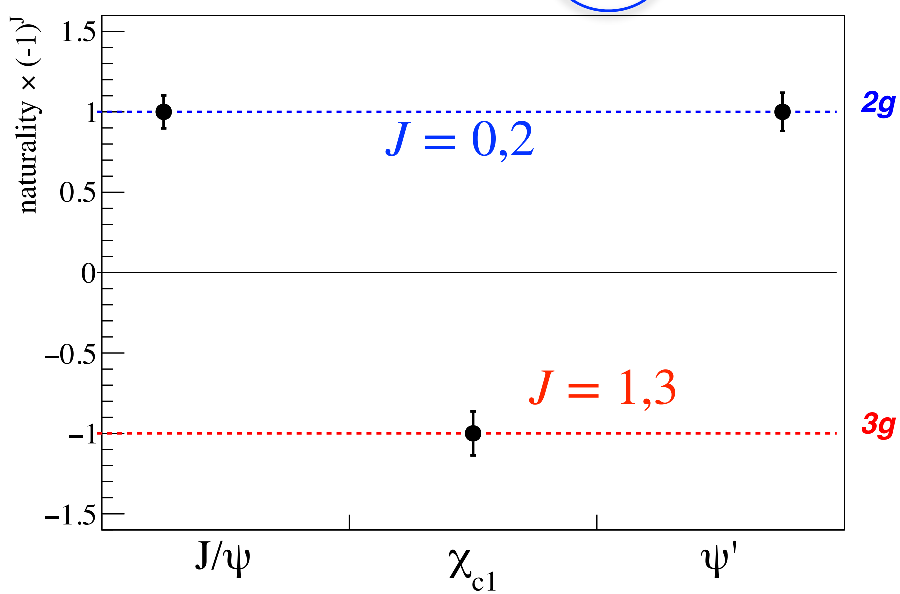
GlueX uses polarized photon beam from coherent Bremsstrahlung

Taking advantage of increased end-point (electron beam energy):




$naturality \times (-1)^J = P$




$$asymmetry = \frac{2}{P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} =$$

$$= -\left(\rho^1_{1-1} - Im\rho^2_{1-1}\right) cos[2(\phi_{hel} - \Phi)]$$

$naturality = (-1)^J P$

# Conclusions

- Features in the $J/\psi$ data consistent with some general predictions of the GFF theoretical models - skewness scaling, $d\sigma/dt(E_\gamma, t \rightarrow fix)$ increases with energy

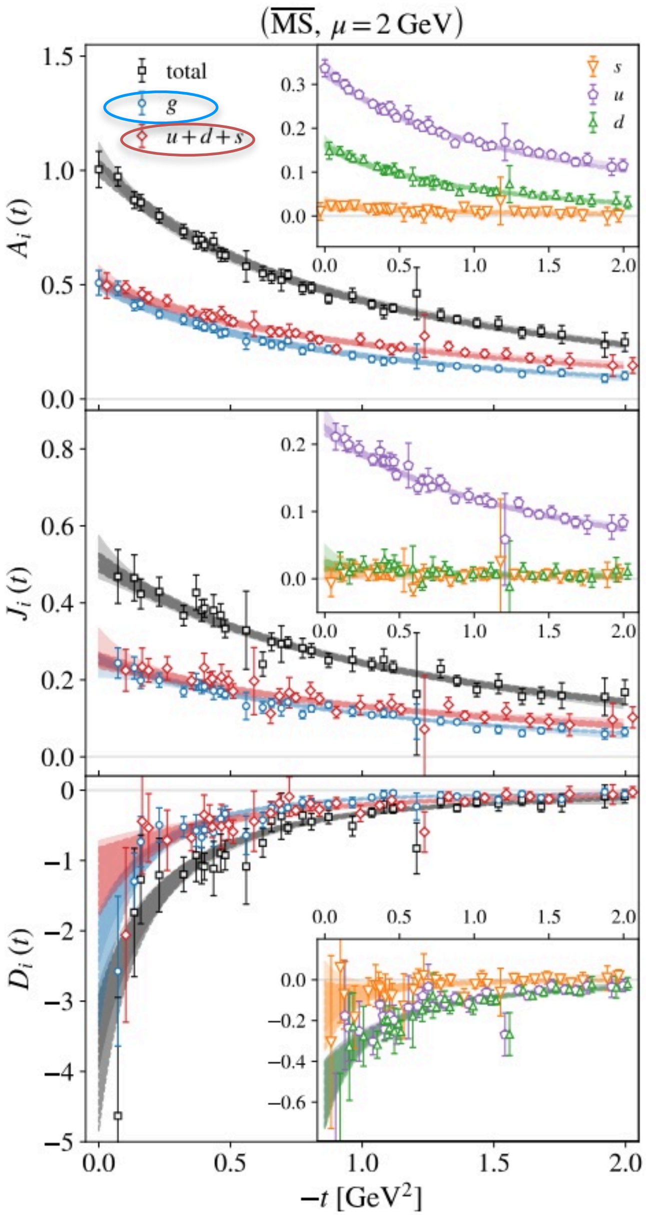
- Gluon GFFs extracted from $J/\psi$ data using two diametric approaches (without any external constraints) on the same scale with the lattice calculations

- Higher mass charmonium states - complementary in understanding the reaction mechanism

- CEBAF energy upgrade adds new dimensions to these studies:
  - Threshold production of higher-mass charmonium states (with different quantum numbers) - $\psi(2S)$, $\chi_c$
  - Polarization measurements with high FOM

Back up slides

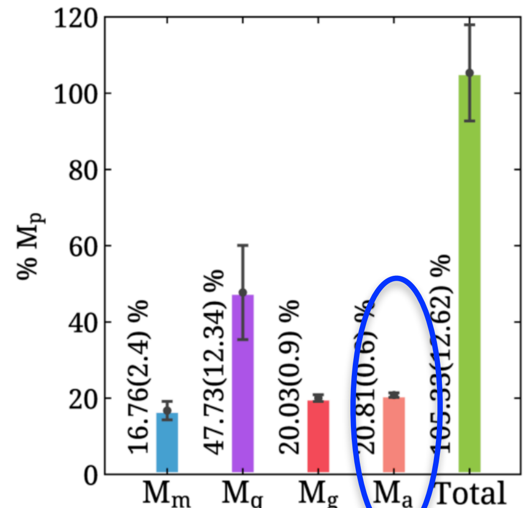
# Gluonic structure of the proton




- Gluon contribution to the mechanical properties of the proton equally important as the quark one:

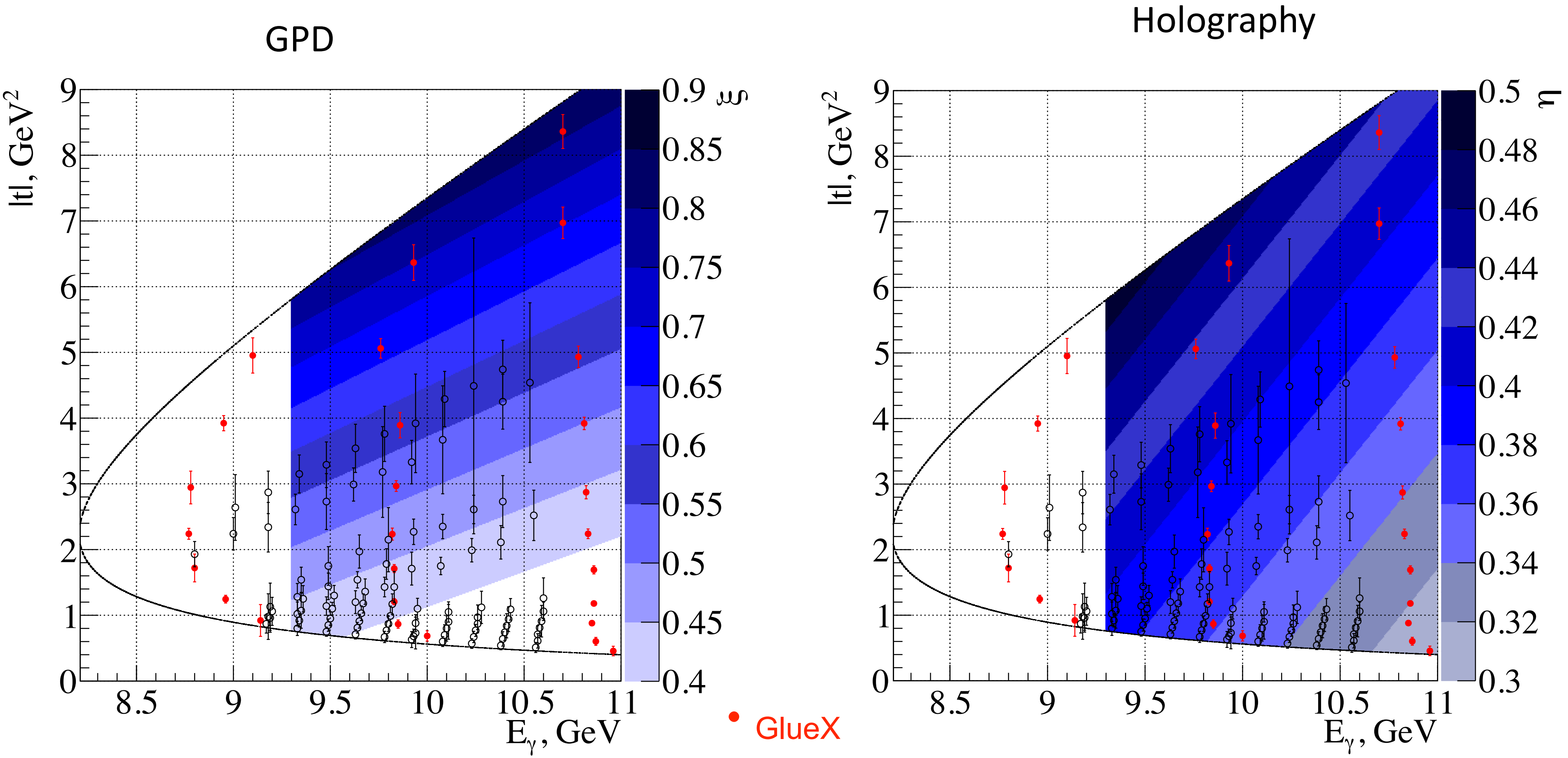
Lattice calculations of Gravitational Form Factors (GFFs) show similar contributions from gluons (g) and quarks (u+d+s).
*Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)*

- Quark masses and kinetic energies of quarks and gluons are not enough to explain the mass of the proton: gluon condensate, or anomalous contribution to the mass of the proton is significant:




C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

# Data used in gluon Form Factor extraction




$\xi > 0.4$
$E_\gamma > 9.3$ GeV (away from $\bar{D}\Lambda_C$ and $\bar{D}^*\Lambda_C$ thresholds)

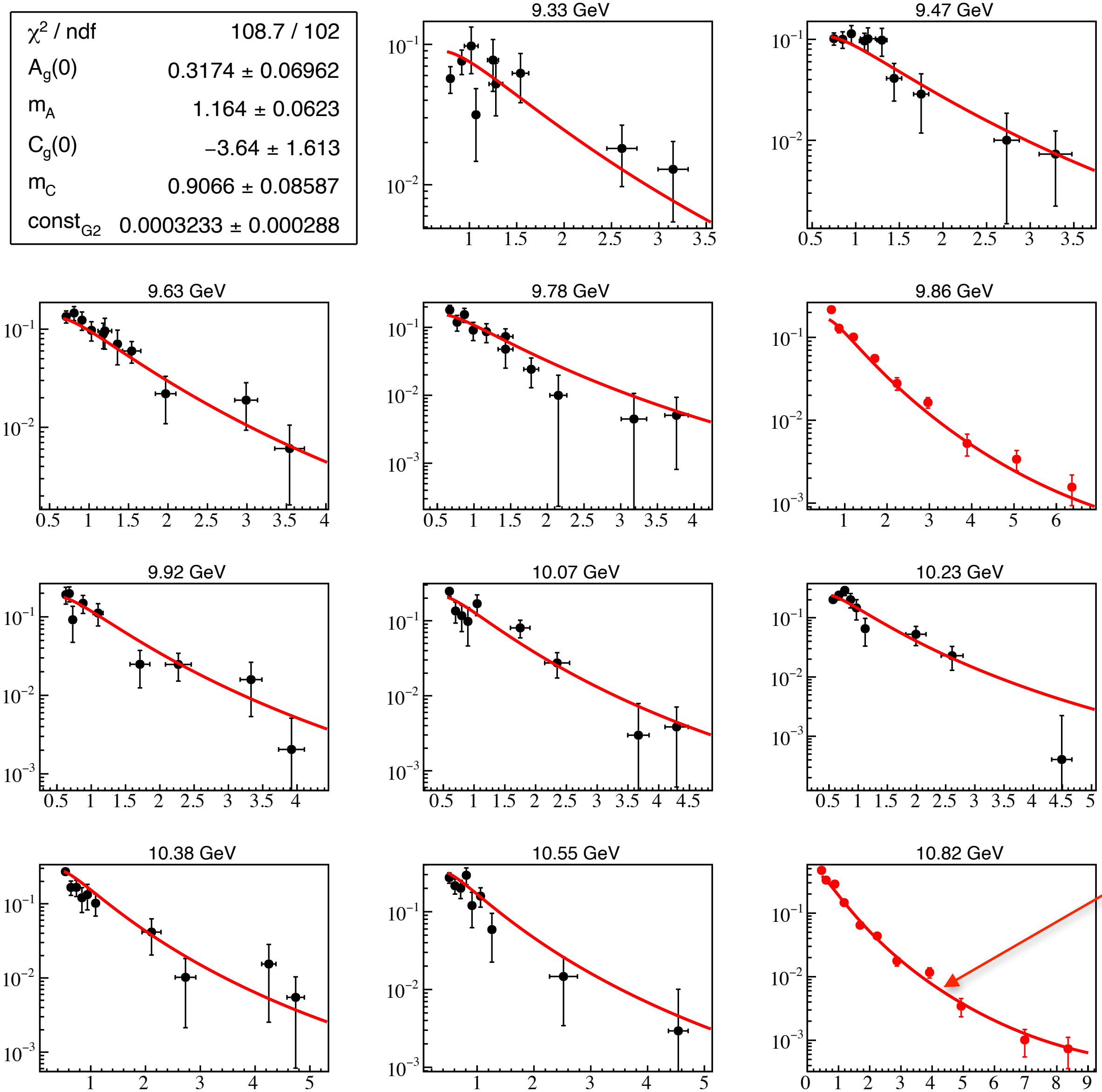
∘ $J/\psi$-007
*Nature 615 (2023)*

no constraints on $\eta$
$E_\gamma > 9.3$ GeV (away from $\bar{D}\Lambda_C$ and $\bar{D}^*\Lambda_C$ thresholds)

*Error bars: relative errors in A.U. (not related to y-axis)*

# Using $\eta$-scaling to describe data (Holographic approach)

$d\sigma/dt \cdot \eta^{-2}/H$ vs $|t|$ $(GeV^2)$




*Fit to all data ($E_\gamma > 9.3$ GeV, all t data points included)*

$$\frac{A_g^2(0)}{(1-t/m_A^2)^4}$$

$$\frac{A_g(0)C_g(0)}{(1-t/m_{AC}^2)^4} + const.$$

$$\left(\frac{d\sigma}{dt}\right)\frac{\eta^{-2}}{H(E_\gamma)} = A_g^2(t)\eta^{-2} + 8A_g(t)C_g(t) + \ldots$$

$$\eta = \frac{M_{J/\psi}^2}{2(s-m_p^2) - M_{J/\psi}^2 + t}$$

- $\chi^2/ndf \sim 1$ in the chosen kinematic region

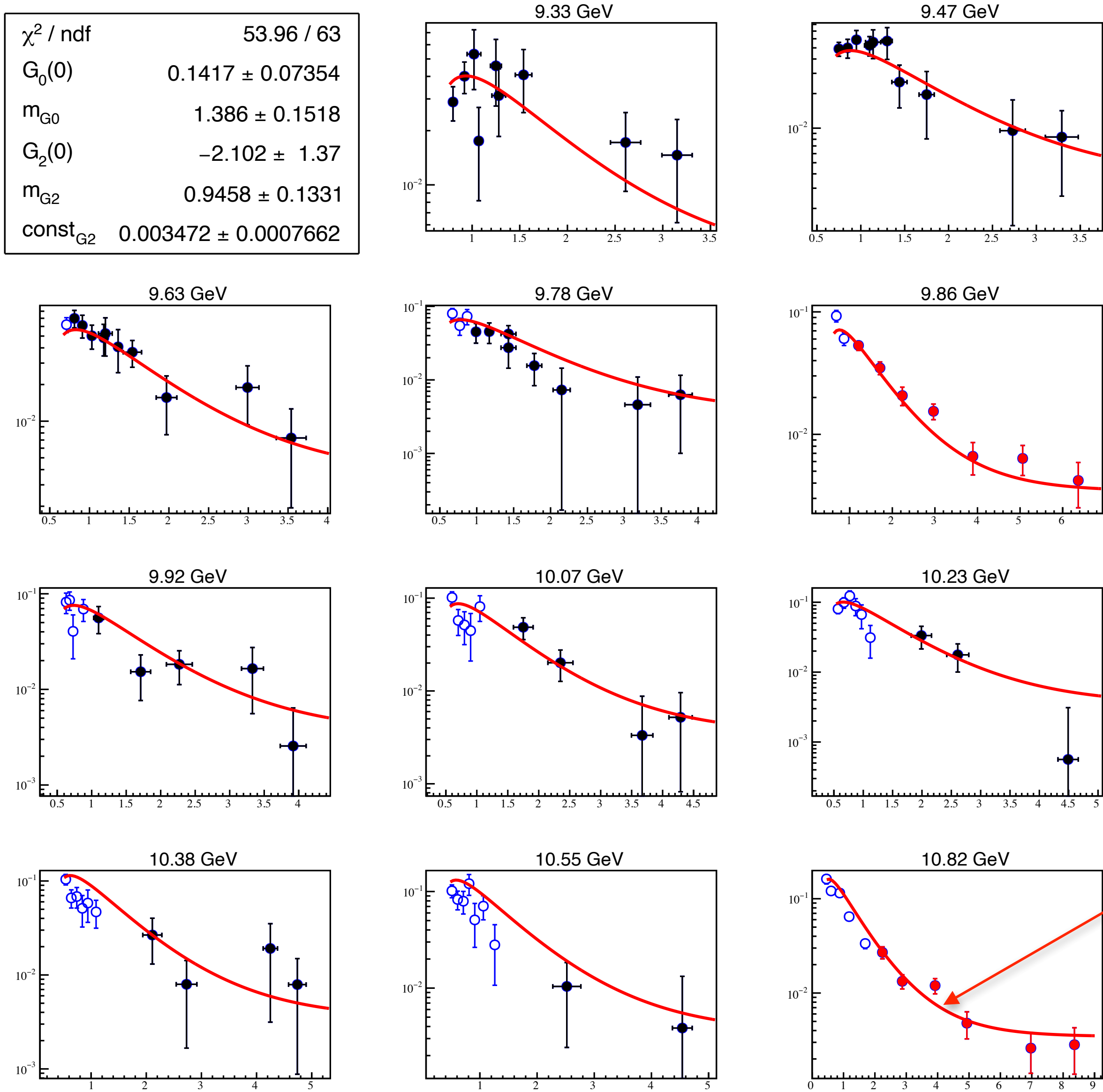
*Only this fitted function used in the analysis*

● GlueX

○ $J/\psi$-007

# Using $\xi$-scaling to describe data (GPD approach)

$d\sigma/dt \cdot \xi^2/F$ vs $|t|$ $(GeV^2)$




*Fit to all data ($E_\gamma > 9.3$ GeV, $\xi > 0.4$)*

$$\frac{G_0(0)}{(1 - t/m_{G0}^2)^4}$$

$$\frac{G_2(0)}{(1 - t/m_{G2}^2)^4} + const.$$

$$\left(\frac{d\sigma}{dt}\right)\frac{\xi^2}{F(E_\gamma)} = G_0(t)\xi^{-2} + G_2(t) + \ldots$$

$$\xi = \frac{M_{J/\psi}^2 - t}{2(s - m_p^2) - M_{J/\psi}^2 + t}$$

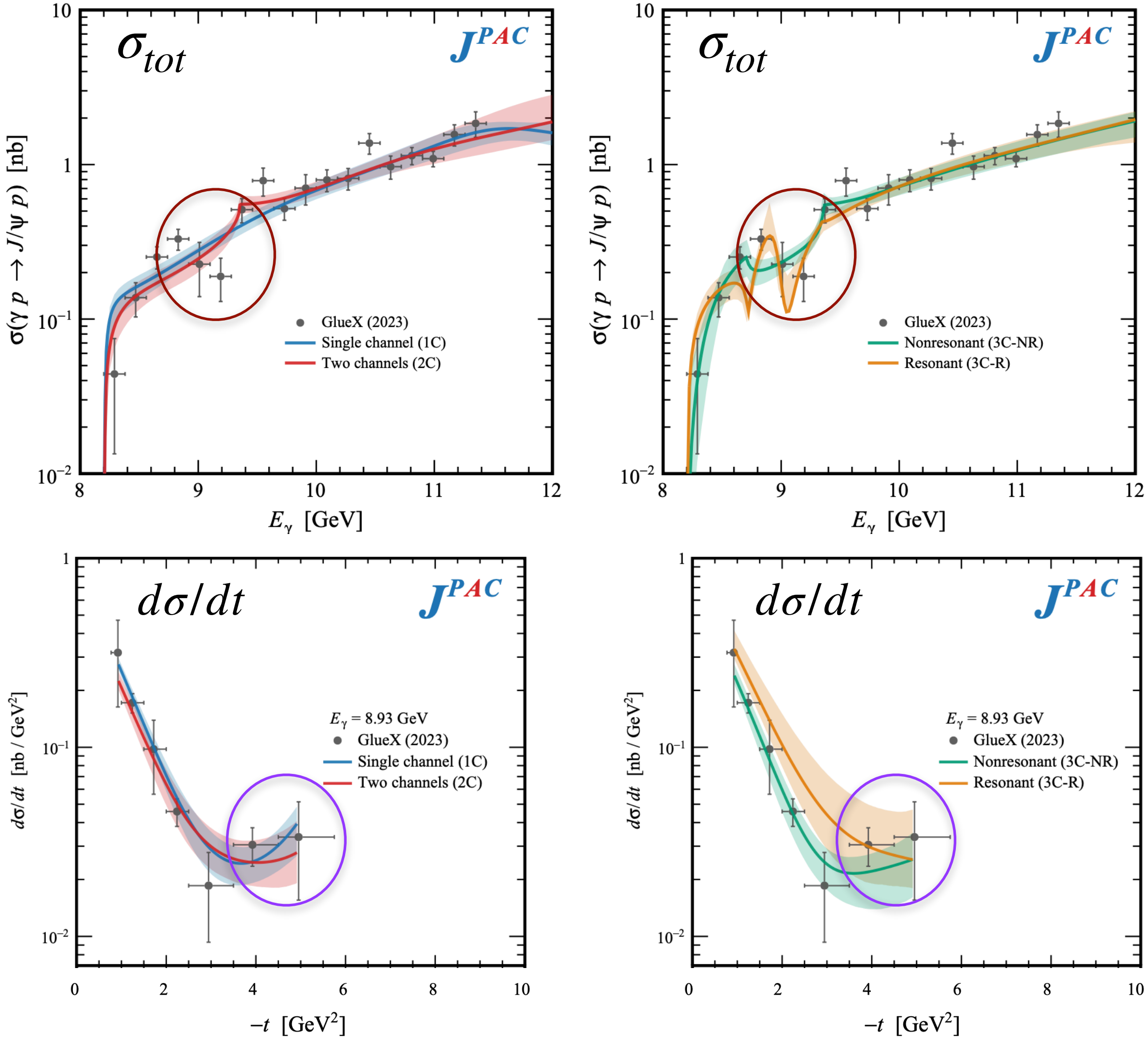
*$\chi^2/ndf \sim 1$ in the chosen kinematic region*

- $\xi < 0.4$ data points (blue) deviate from $\xi$-scaling

*Only this fitted function used in the analysis*

- GlueX
- $J/\psi$-007

# Phenomenological approach: JPAC results




Phenomenological model based on s-channel PW expansion ($l \leq 3$):

- (1C) $J/\psi p$ interaction
- (2C) $J/\psi p$ and $\bar{D}^*\Lambda_C$
- (3C-NR) $J/\psi p$, $\bar{D}\Lambda_C$, $\bar{D}^*\Lambda_C$ (non-resonant solution)
- (3C-NR) $J/\psi p$, $\bar{D}\Lambda_C$, $\bar{D}^*\Lambda_C$ (resonant solution)

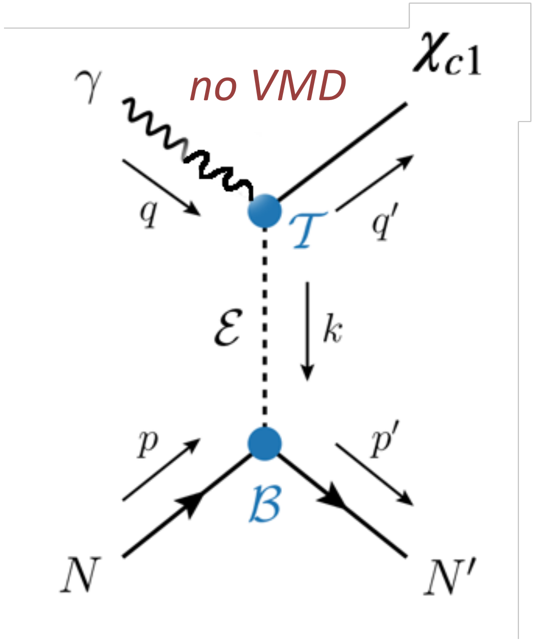
No stat. significant preference:

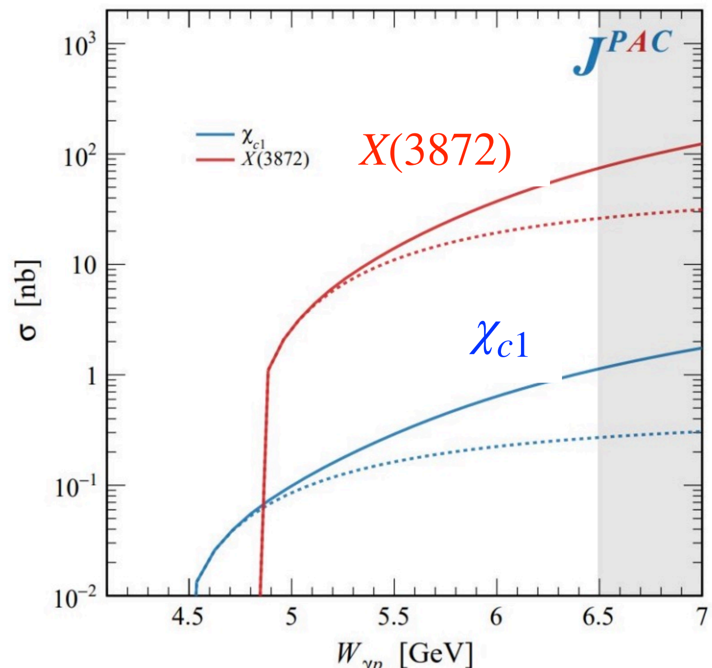
- 9 GeV structure requires sizable contribution from open charm
- Severe violation of VMD and factorization not excluded
- s-channel resonance not excluded
- t-enhancement indicates s-channel contribution: due to proximity to threshold or open-charm exchange

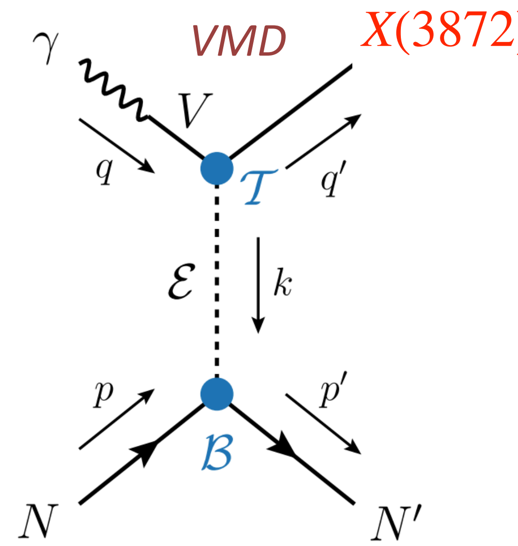
*JPAC Phys.Rev.D 108 (2023)*

*Global fit of both Hall C & D $d\sigma/dt(t)$ and Hall D $\sigma_{tot}(E_\gamma)$*

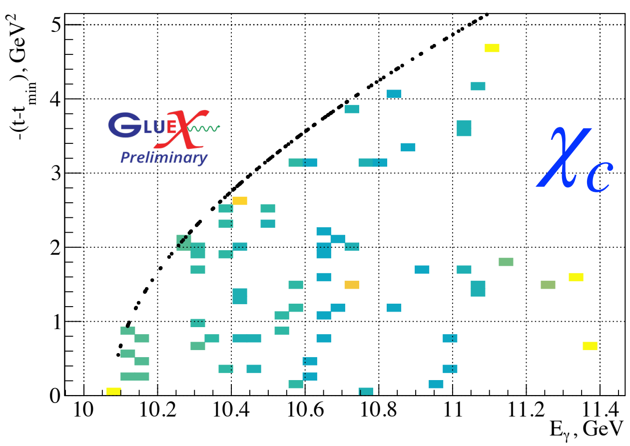
# $\chi_c$ vs $X(3872)$ production

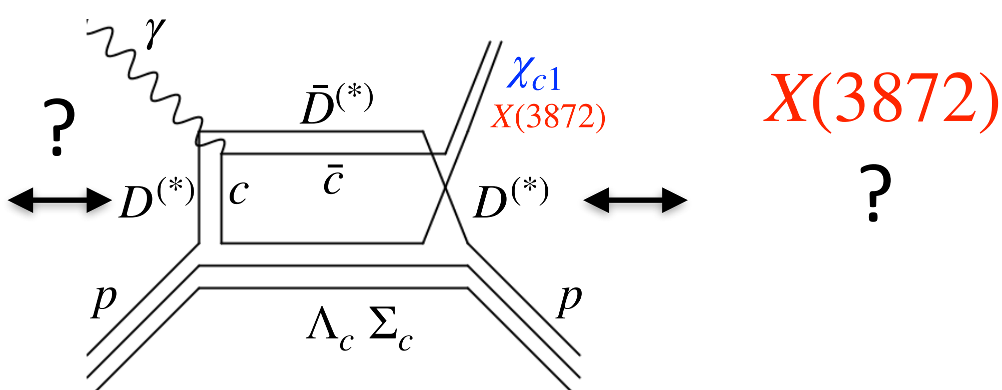



JPAC, PRD 102 (2020). *t*-channel production

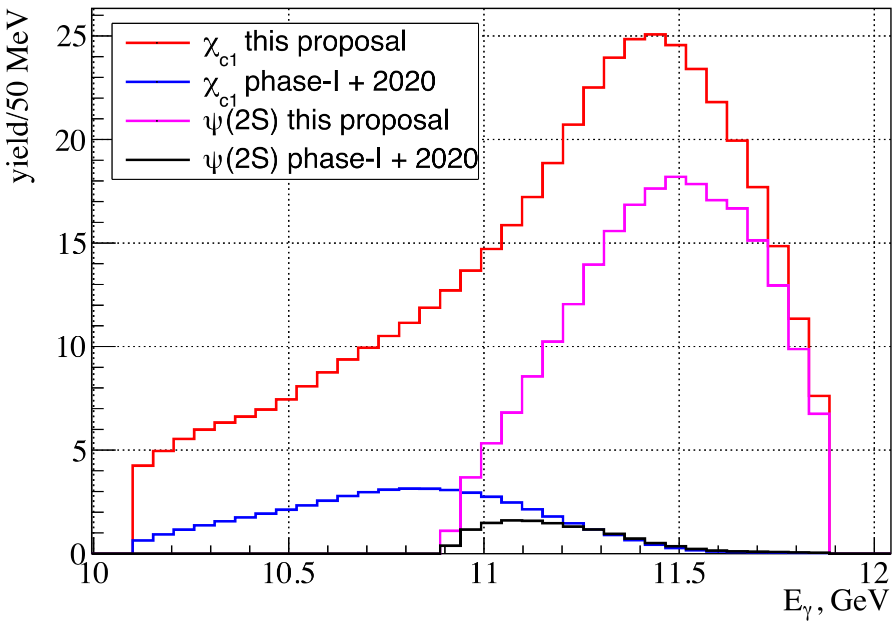


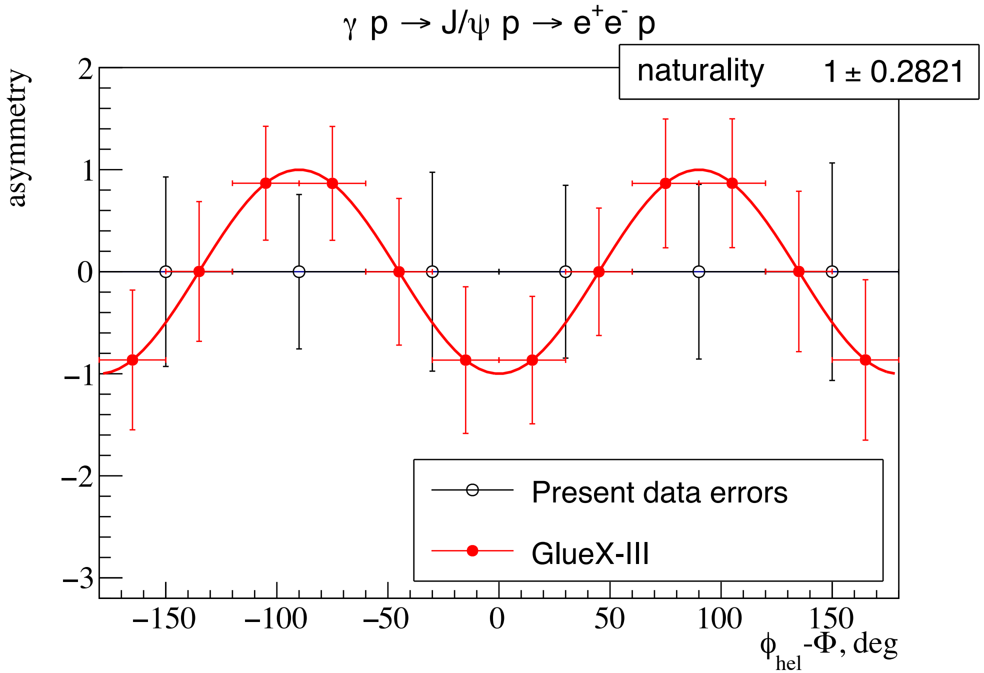




Studying $\chi_c$ can help to understand $X(3872)$ production mechanism

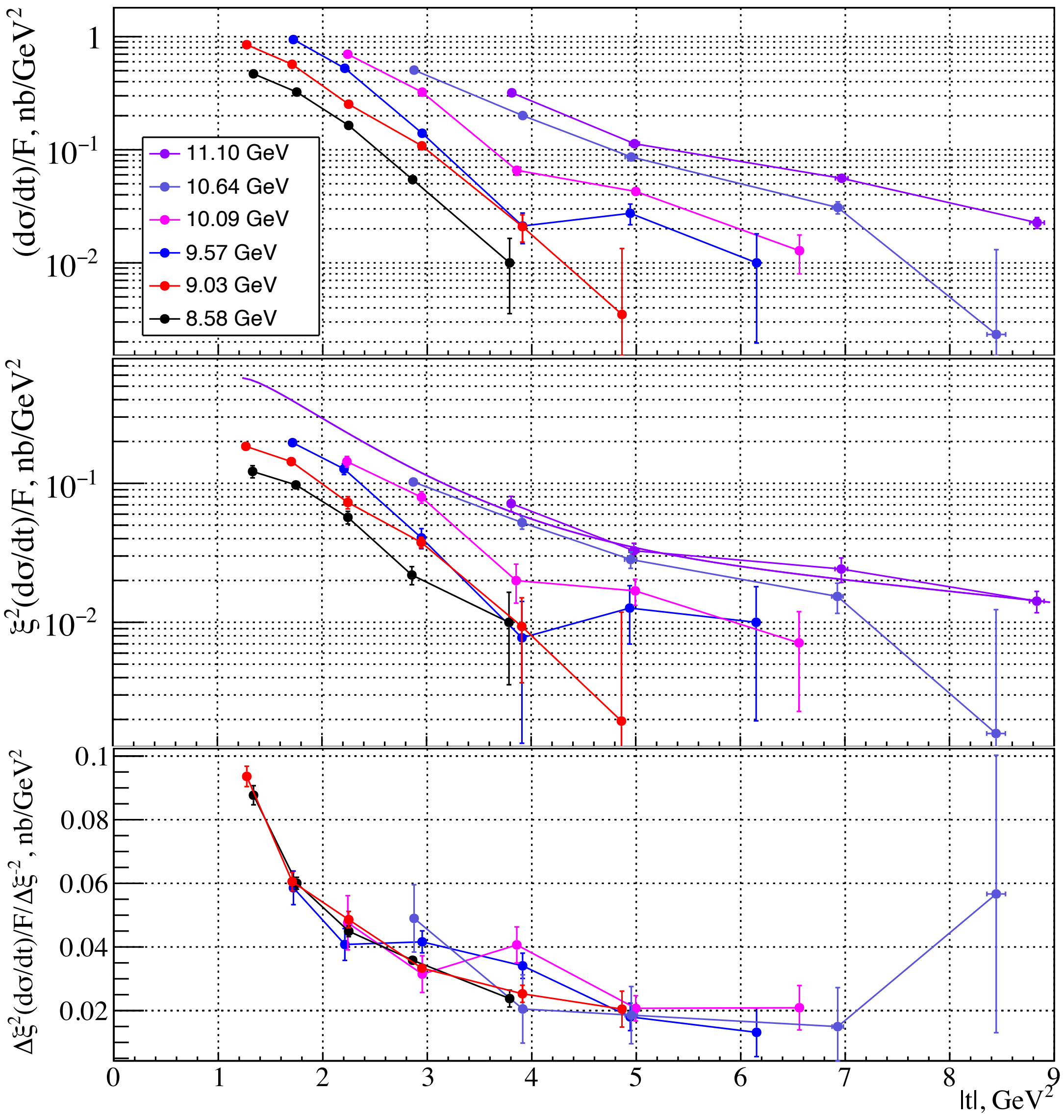
# Prospect for charmonium threshold production with GlueX-III

| Run Period | $J/\psi$ | $\chi_{c1}$ | $\psi(2S)$ |
|---|---|---|---|
| 2016-2020 Phase I-II | 3,960 | 55 | 12 |
| 2023-2025 Phase II (planned) | *3,615* | *48* | *11* |
| Phase III (proposal) | *11,271* | *364* | *178* |
| Projected Total | 18,846 | 467 | 201 |

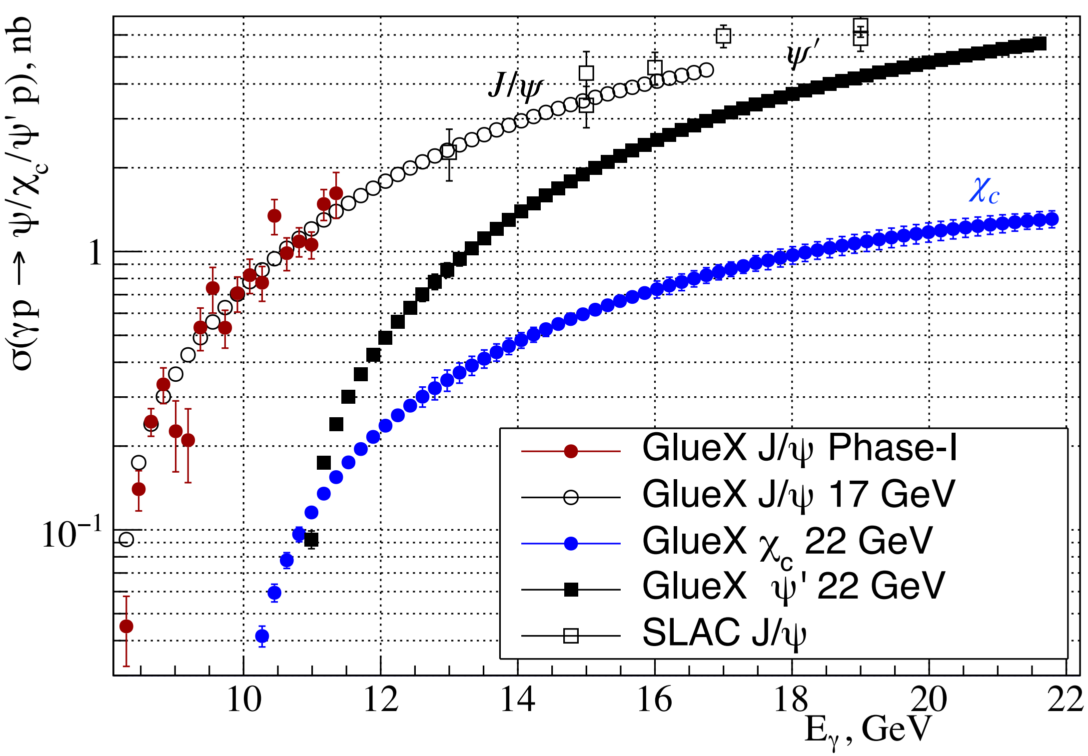


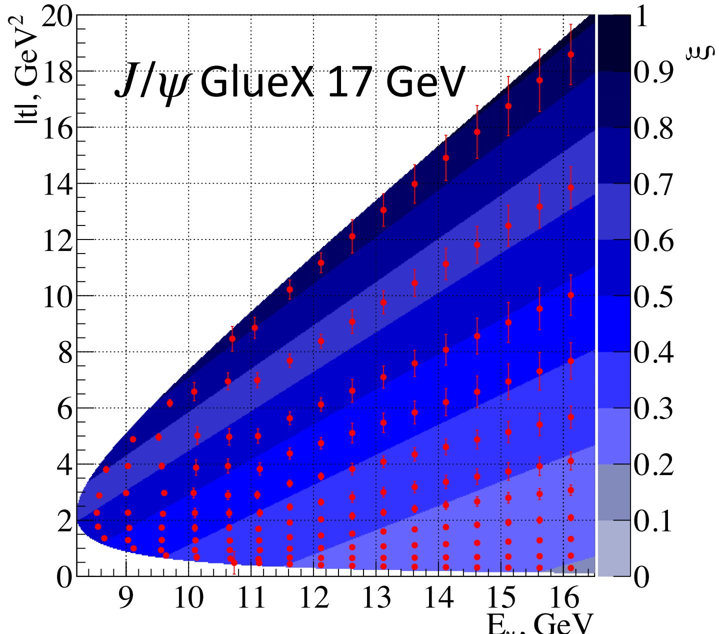



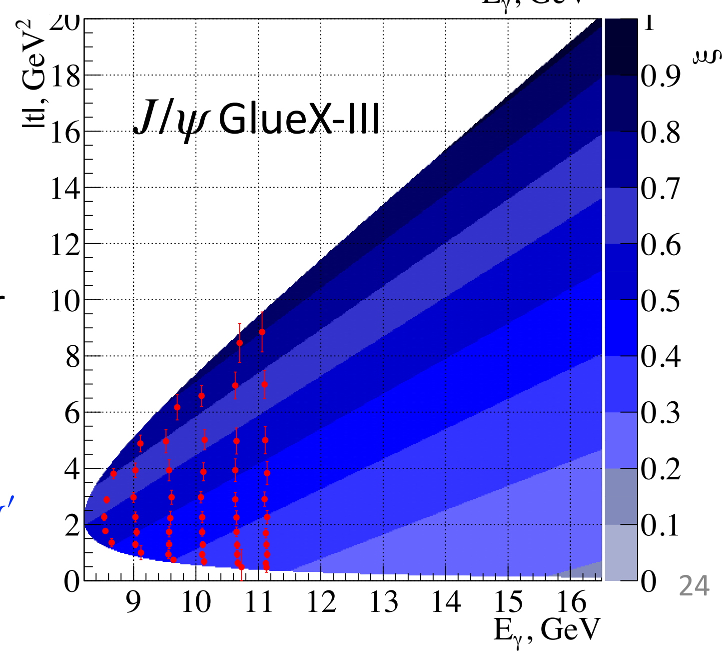
# Prospect for charmonium threshold production with GlueX-III



# Threshold charmonium photoproduction at JLab22 with GlueX

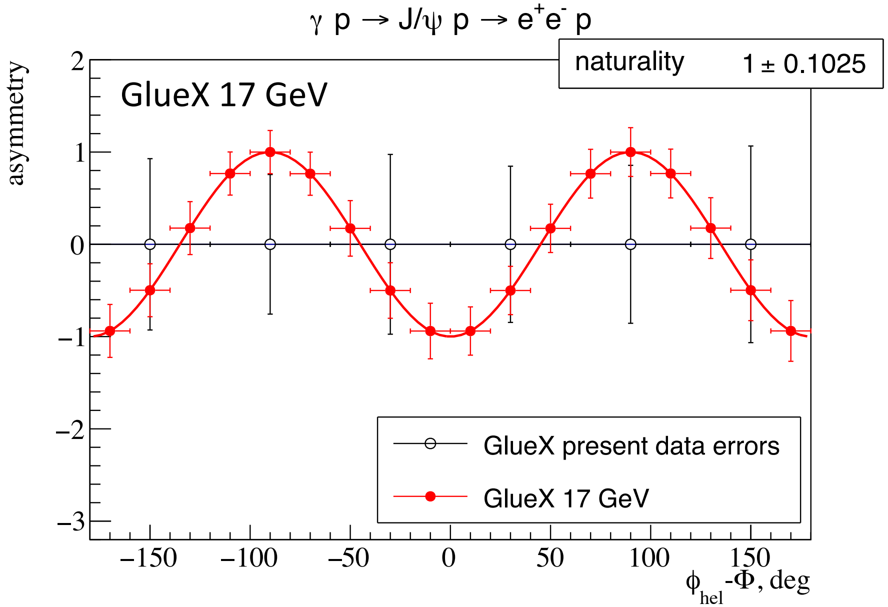


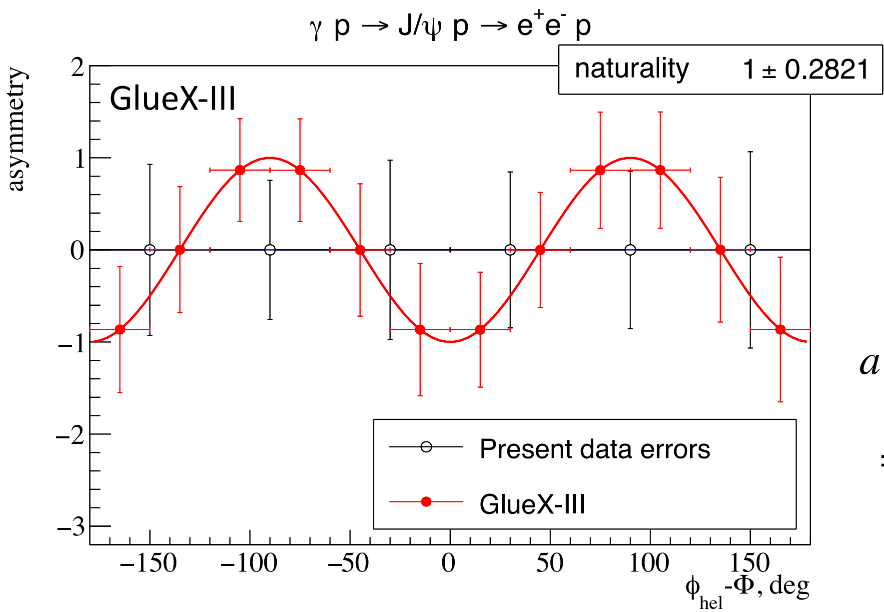



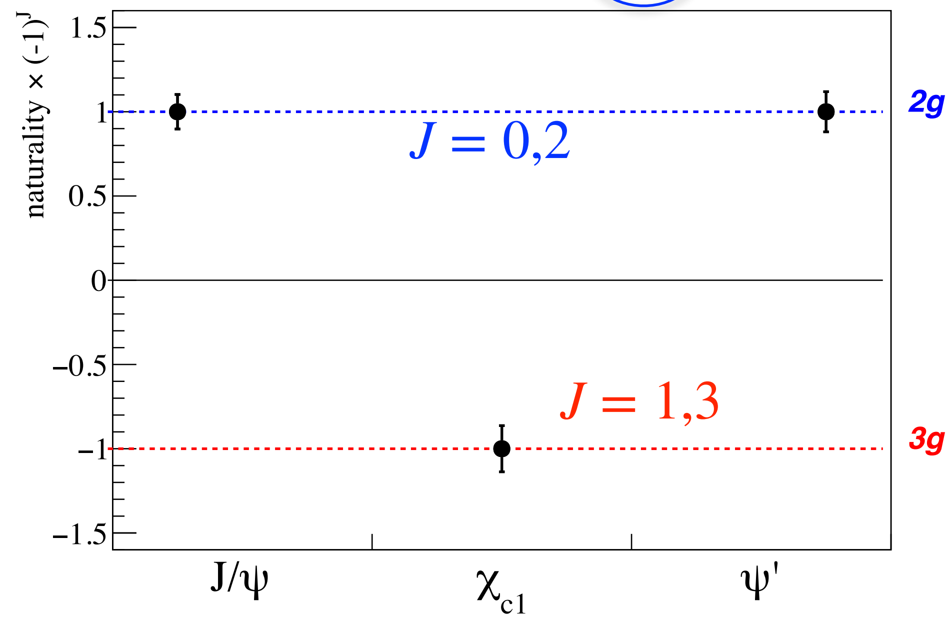

- Absolute normalization and error estimation: scaling existing measurements (<12 GeV) by anticipated flux increase
- Energy extrapolation: using fits of $J/\psi$ data for $J/\psi$ and $\psi'$, for $\chi_c$ based on VM exchange model (*JPAC, Phys.Rev.D 102 (2020)*)
- Efficiencies estimated with MC
- All JLab22 projections for 100 PAC days: 80k $J/\psi$, 8k $\chi_c$, 18k $\psi'$

# Threshold charmonium photoproduction at JLab22 with GlueX




$$naturality \times (-1)^J = P$$

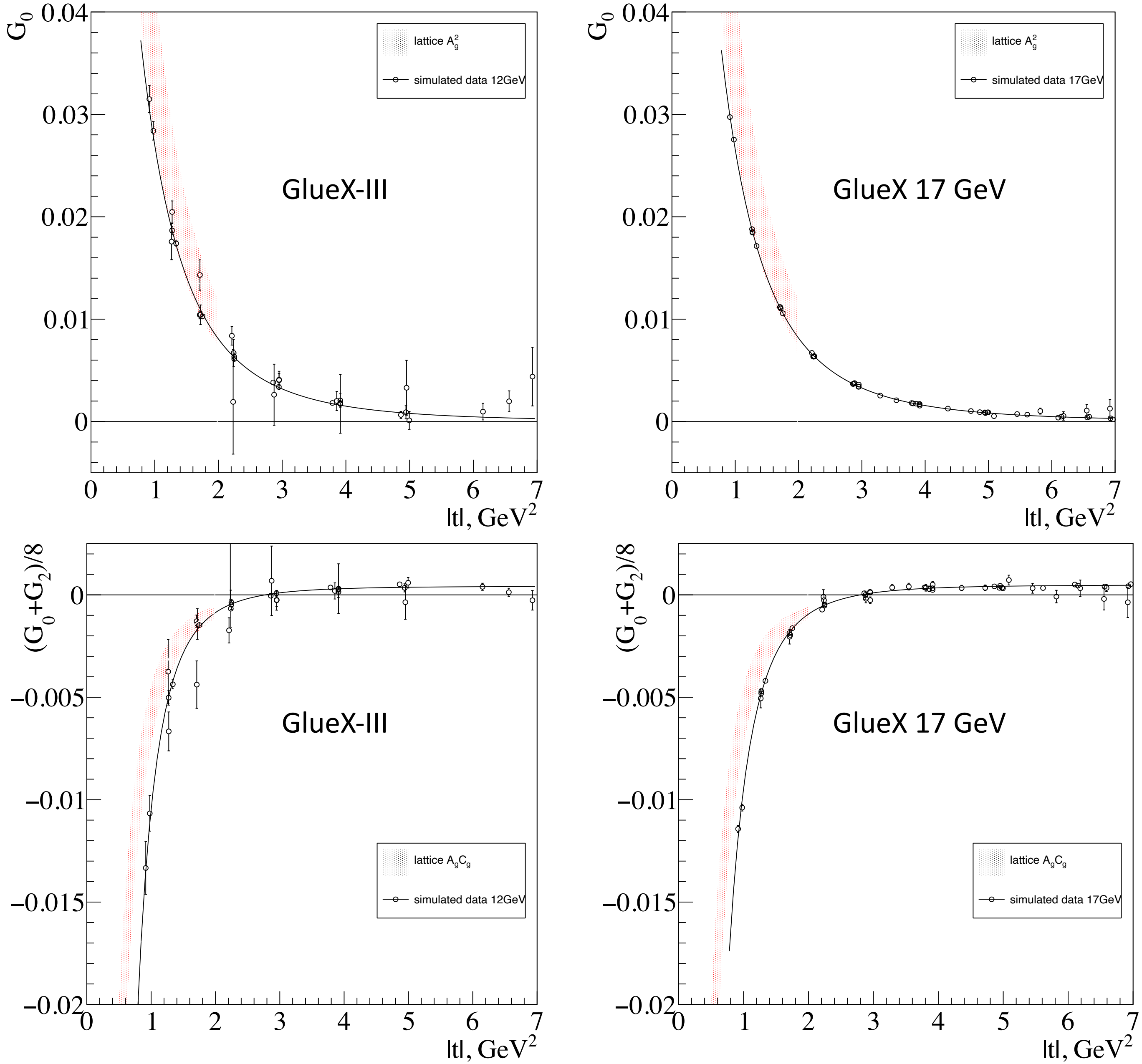



$$asymmetry = \frac{2}{P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} =$$

$$= -\left(\rho^1_{1-1} - Im\rho^2_{1-1}\right) cos[2(\phi_{hel} - \Phi)]$$

$$naturality = (-1)^J P$$

# Threshold charmonium photoproduction at JLab22 with GlueX




- Anticipated results for the extracted gluon Form Factors, assuming skewness scaling is valid
- Data randomized around a fit of the current data