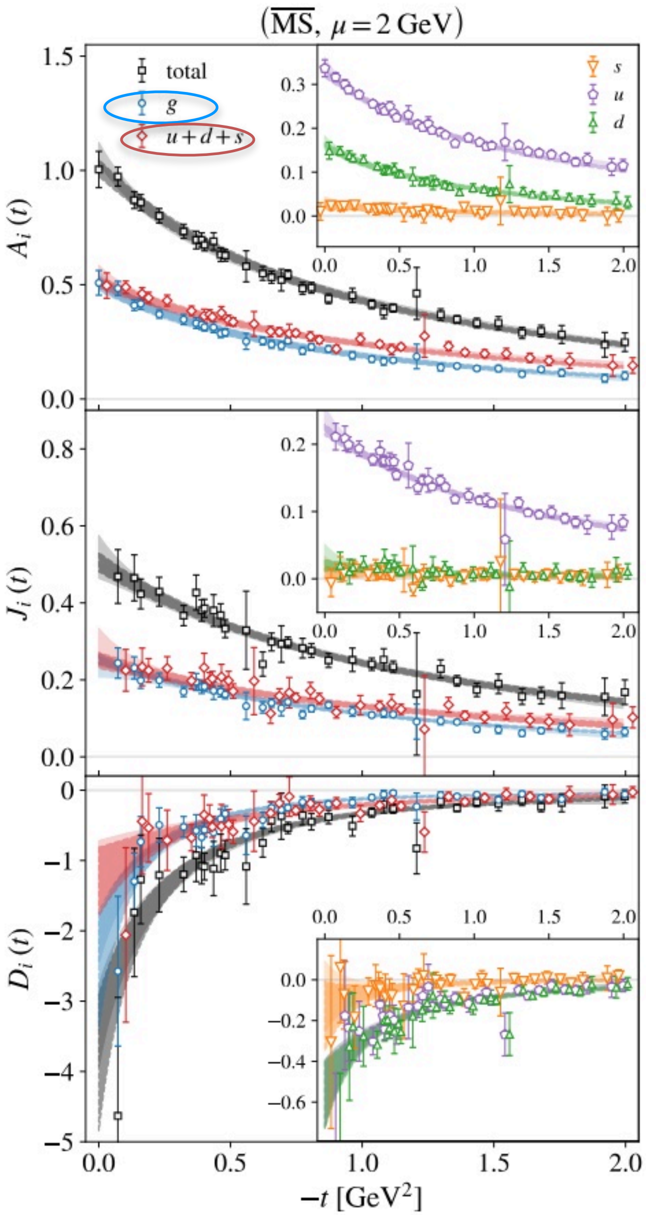
Threshold charmonium production at JLab22 - an access to gluon structure of the proton

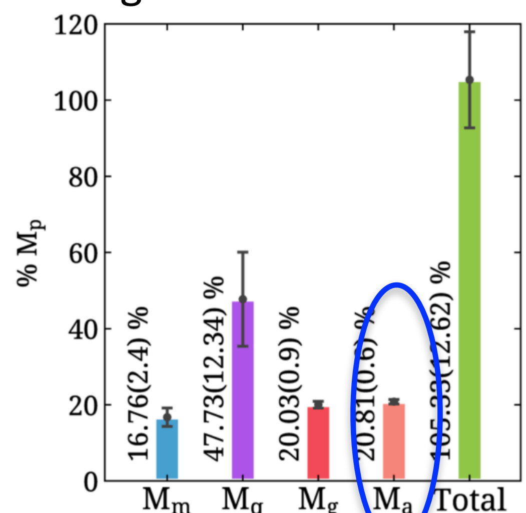
Lubomir Pentchev



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

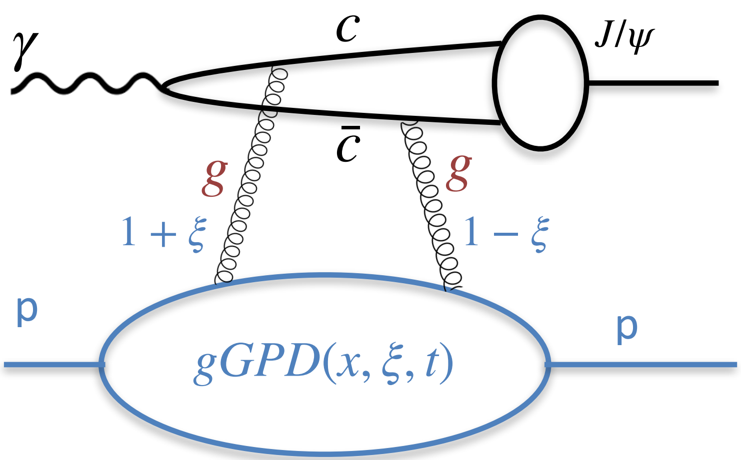
Lattice calculations of Gravitational Form Factors (GFFs) show similar contributions from gluons (g) and quarks (u+d+s).
Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)

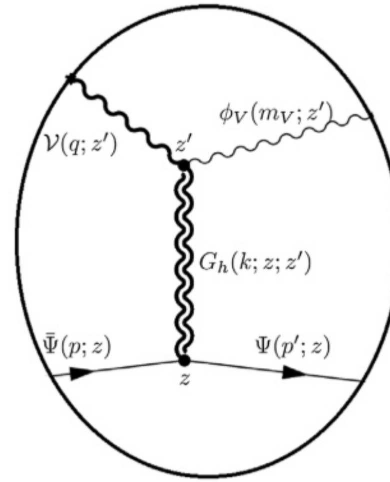
- Quark masses and kinetic energies of quarks and gluons are not enough to explain the mass of the proton: gluon condensate, or anomalous contribution to the mass of the proton is significant:



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

Threshold charmonium photoproduction - GPD and holographic approaches





Witten diagram representation

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

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

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

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

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

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

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

leading moments for high ξ values

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

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

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

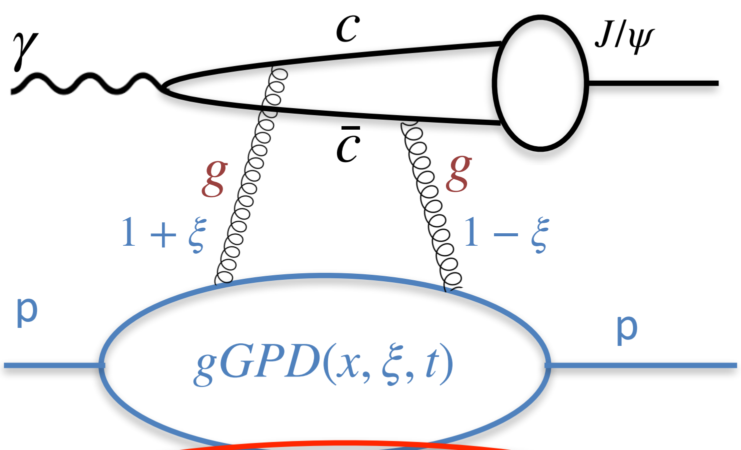
$$H_2(t) = 8A_g(t)C_g(t)$$

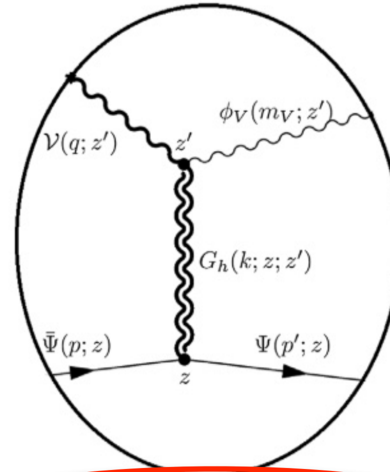
$$\eta = \frac{M_{J/\psi}^2}{2(s-m^2) - M_{J/\psi}^2 + t}$$

for large N_c and strong α_s

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

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

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

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

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

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

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

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

leading moments for high ξ values

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

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

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

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

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

for large N_c and strong α_s

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

Form Factor Functions

$G_0(t)$ - GPD

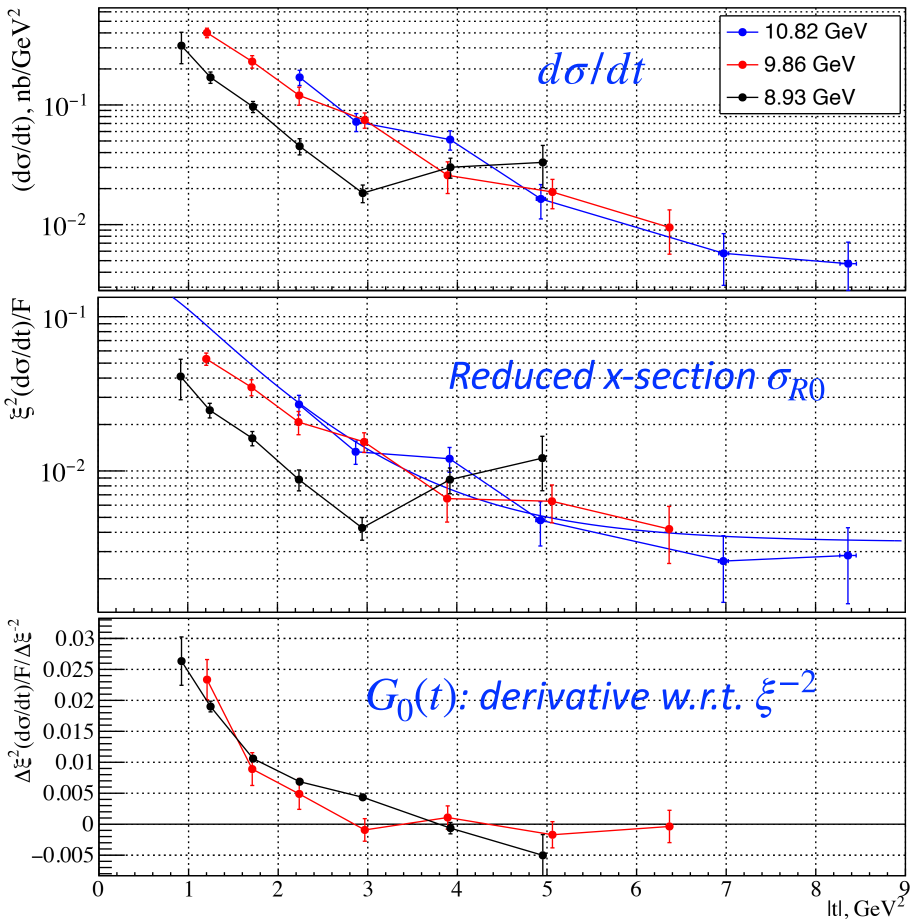
$$\sigma_{R0} = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t)$$

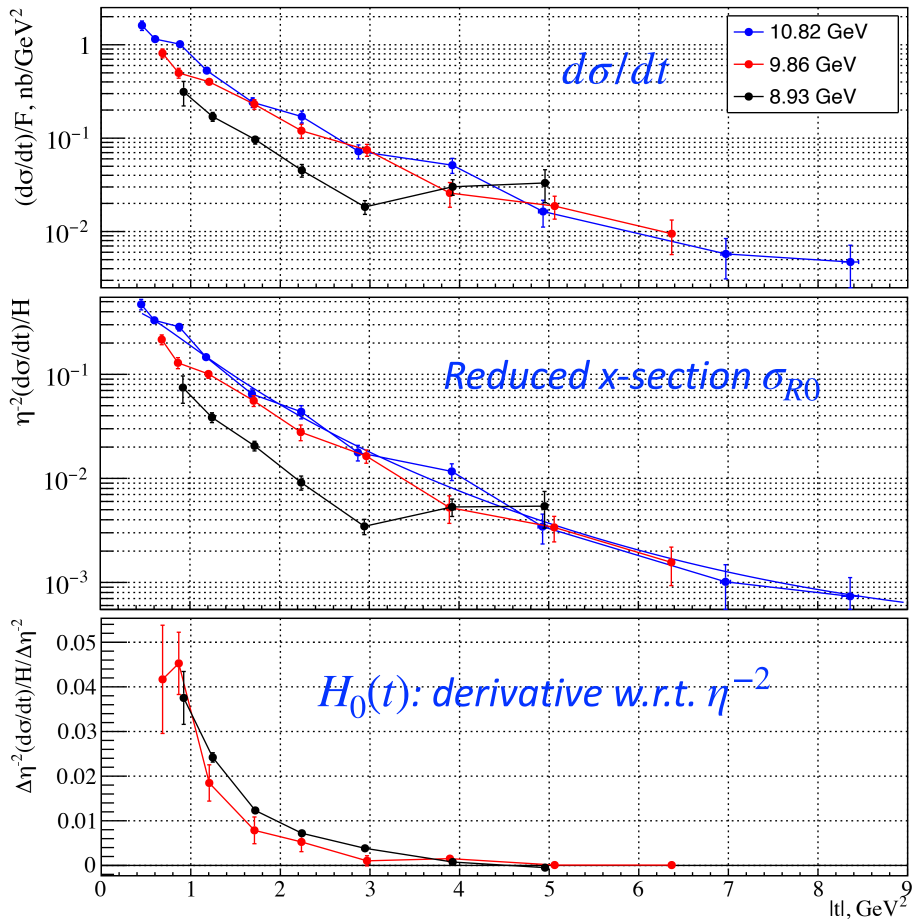
$$G_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\xi^{-2}(E_i,t) - \xi^{-2}(E_j,t)\right]$$

$H_0(t)$ - Holography

$$\sigma_{R0} = \frac{d\sigma}{dt}\frac{\eta^{-2}}{H(E_\gamma)} = \eta^{-2}H_0(t) + 4H_2(t)$$

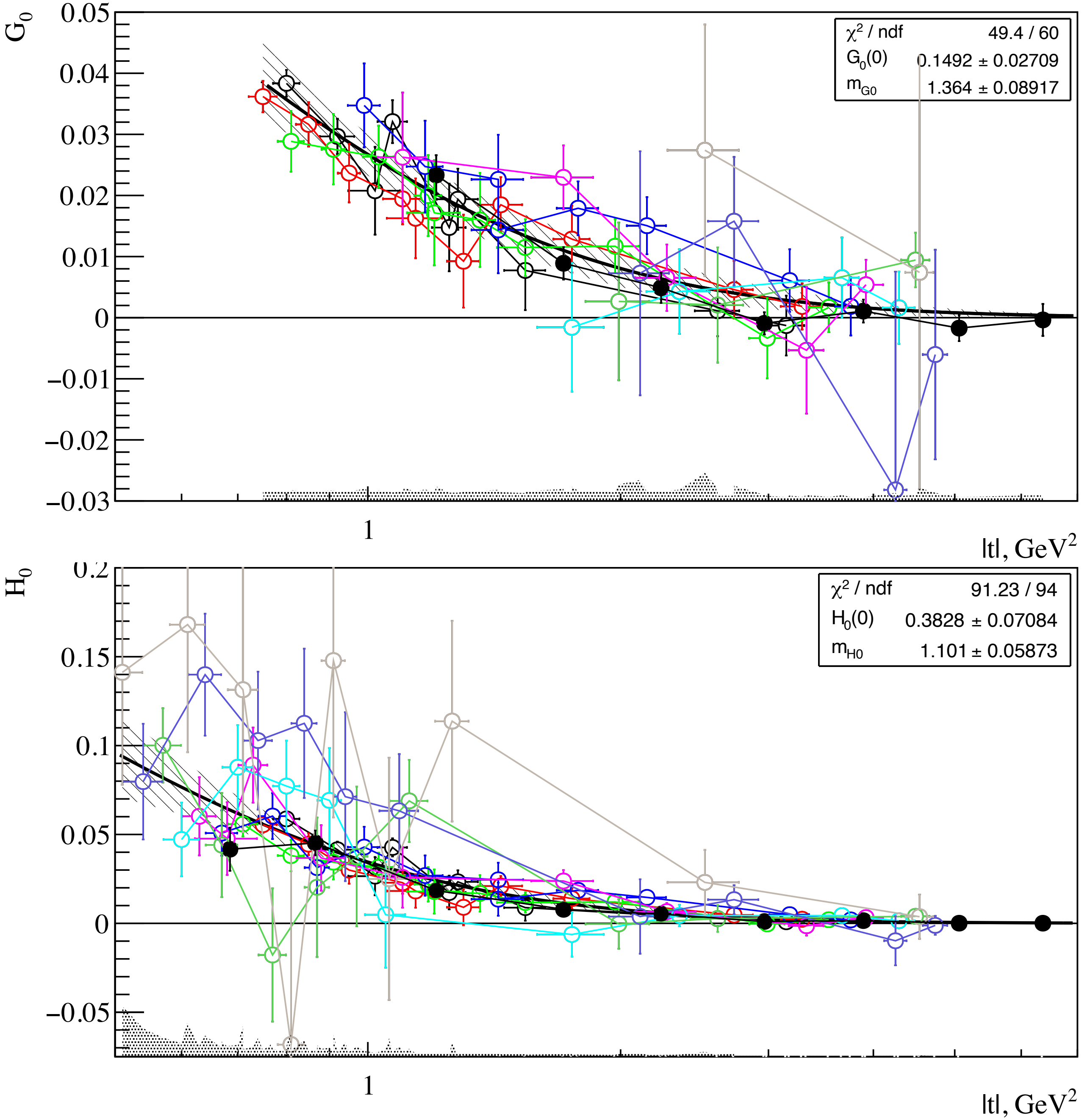
$$H_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\eta^{-2}(E_i,t) - \eta^{-2}(E_j,t)\right]$$





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

Gluon Form Factors - energy independence



Energy independence of the $G(t)/H(t)$ functions (within errors) in agreement with the ξ/η-scaling

Fits with:

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

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

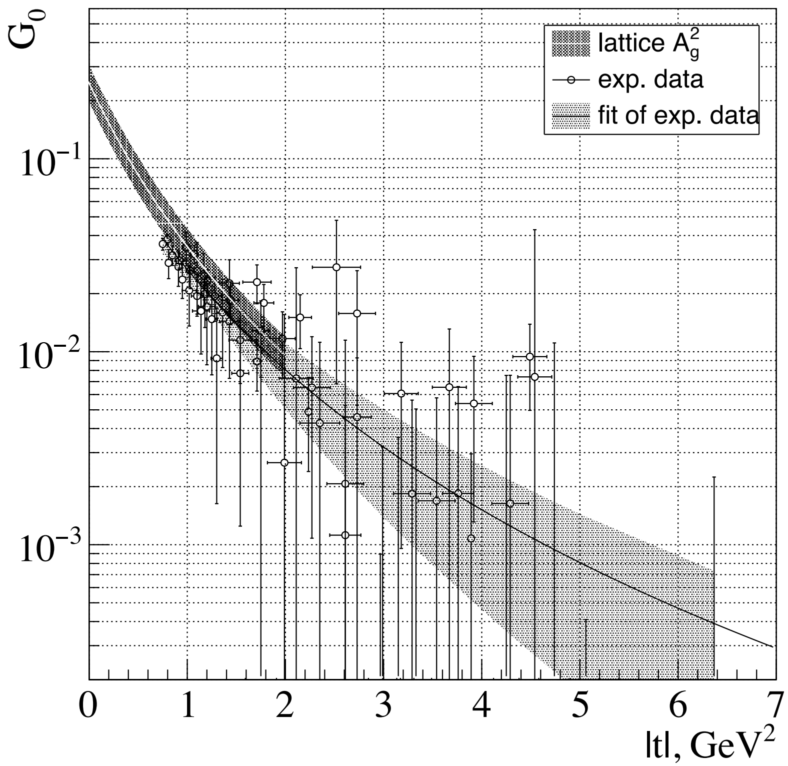
Using GlueX and J/ψ-007 data - different colors - different energies

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

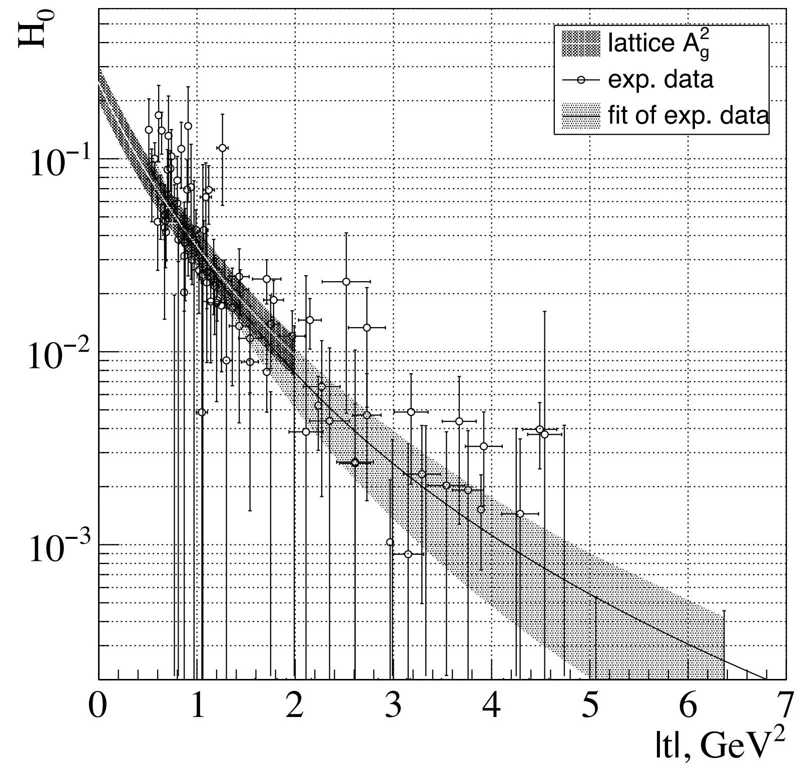
LP and E.Chudakov
arXiv:2404.18776

Assuming leading-term approximation - data vs lattice

GPD



Holographic



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

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

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

leading-moment approximation

neglecting $B_g(t)$

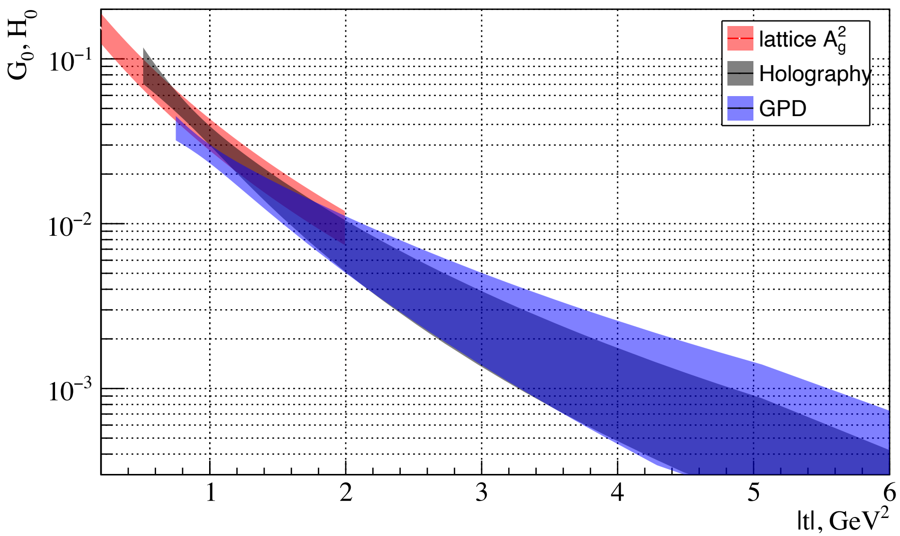
$G_0(t) = A_g^2(t)$

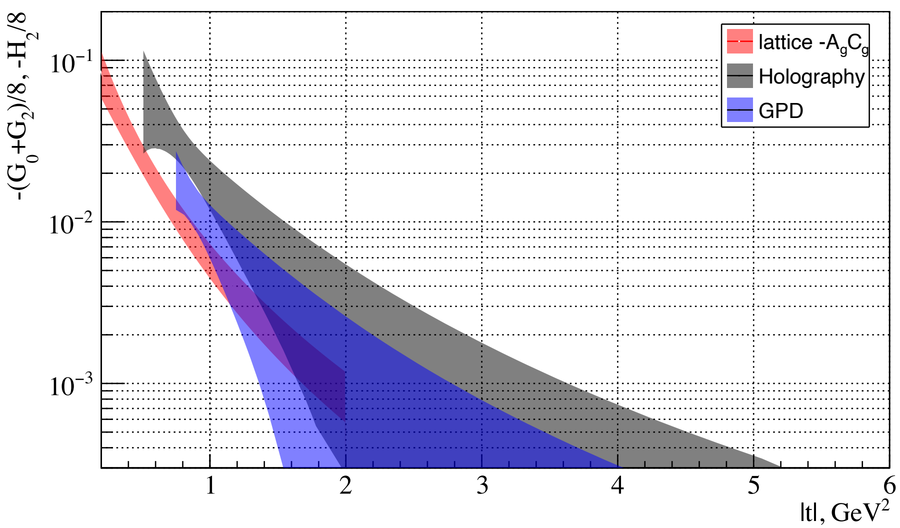
$B_g(t)$=0

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

for large N_c and strong α_s

Gluon Gravitational Form Factors - summary





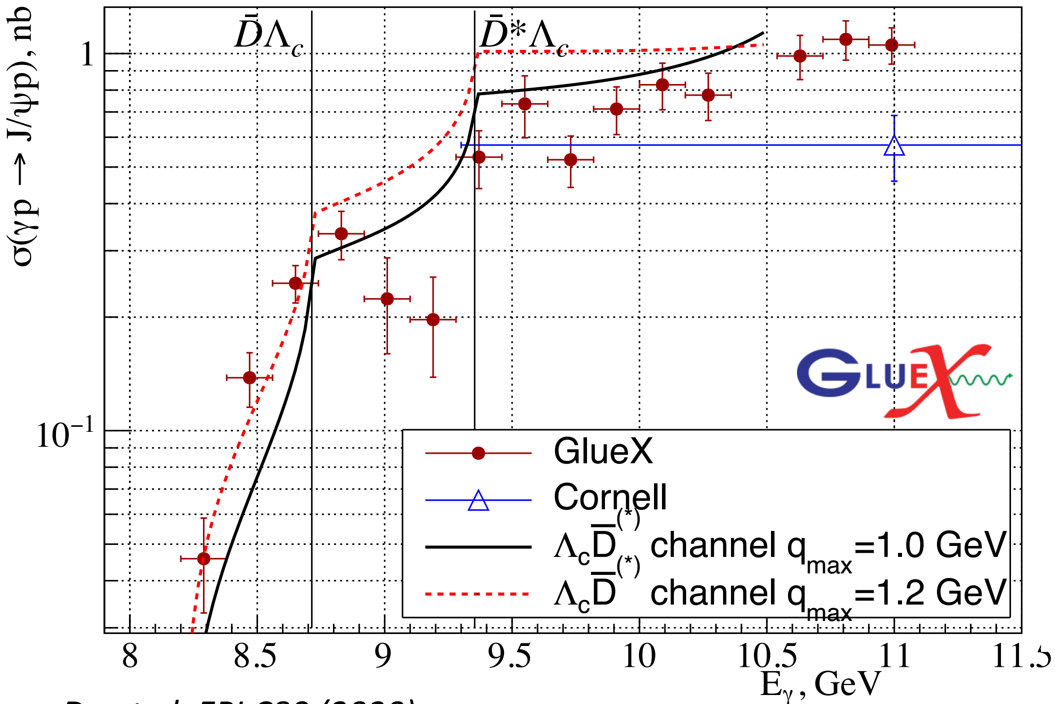
- Assuming $d\sigma/dt \sim \xi^{-4}[G_0(t)+\xi^2 G_2(t)]$ (GPD) or $d\sigma/dt \sim H_0(t)+\eta^2 H_2(t)$ (Holography), we extracted the FF functions kinematically from the data and found they are indeed energy independent (within the experimental errors)
- In leading-term approximation (and neglecting B_g):

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

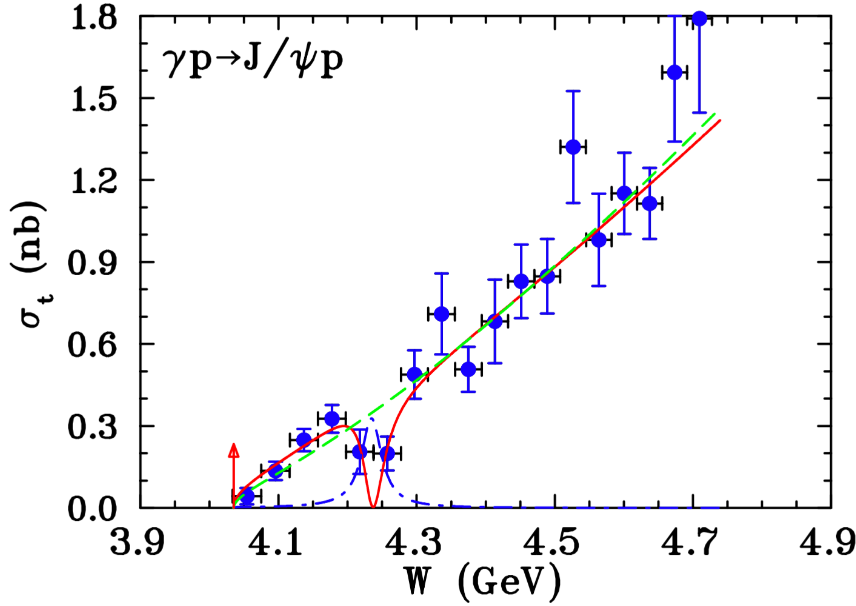
  $G_0(t) + G_2(t) = H_2(t) = 8C_g(t)A_g(t)$
- General agreement b/n extracted FFs using two diametric theories, each with specific corrections very different in nature (higher moments, $1/N_c$, …) and agreement with lattice - possible conclusion: the corrections to the theories are not dominant

- The above results should not be considered as a proof of the validity of the two theories, just that the data are consistent with them; in fact the observed ξ/η-scaling may come from more general considerations

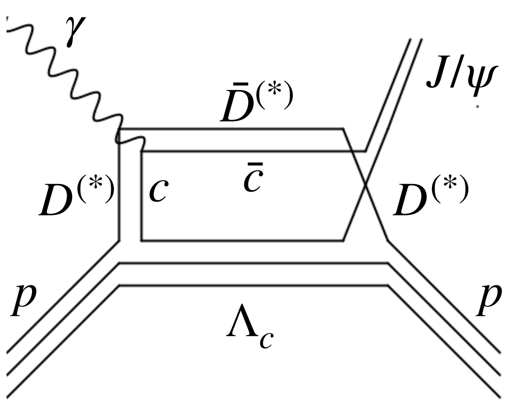
Other reaction mechanisms: open-charm, resonance

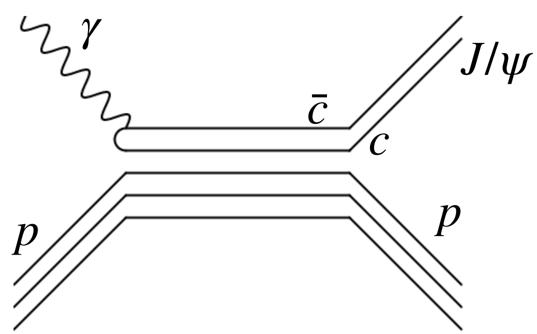


Du et al. EPJ C80 (2020)



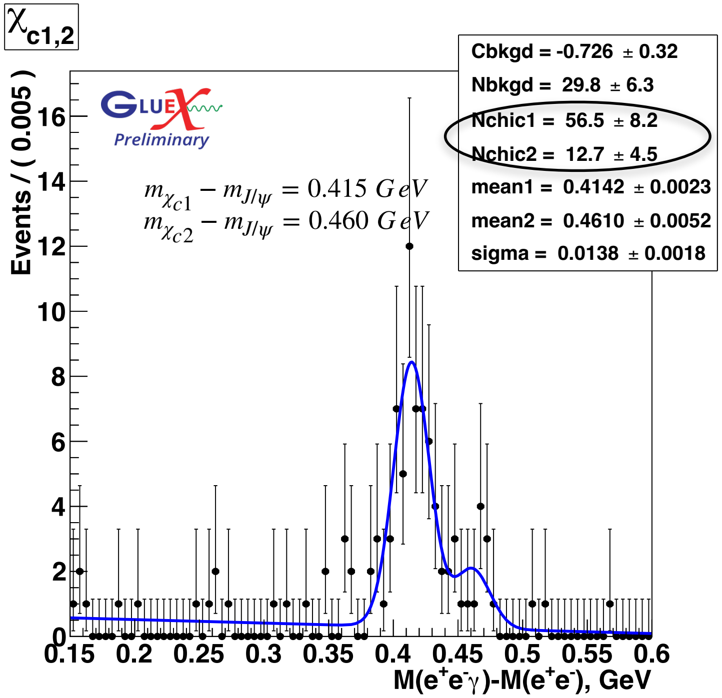
Strakovsky et al. PRC 108 (2023)





JPAC Phys.Rev.D 108 (2023)

Higher-mass charmonium states at threshold



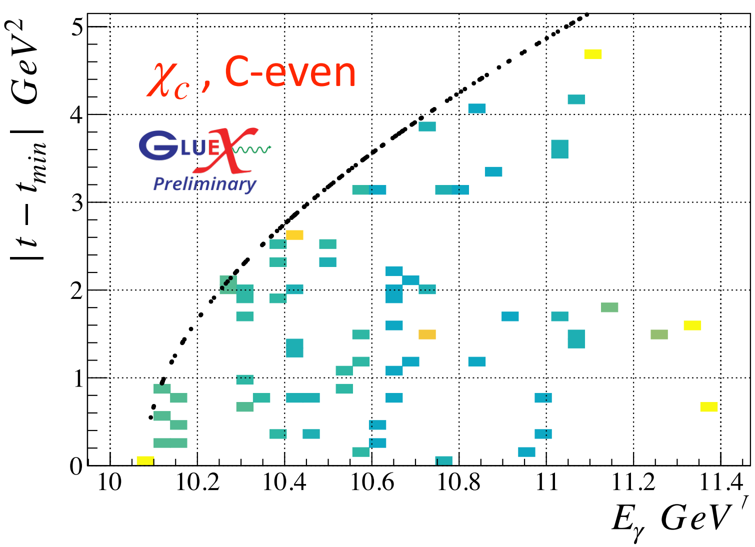
$$\gamma p \to \chi_c p \to (J/\psi\gamma)p \to (e^+e^-\gamma)p$$

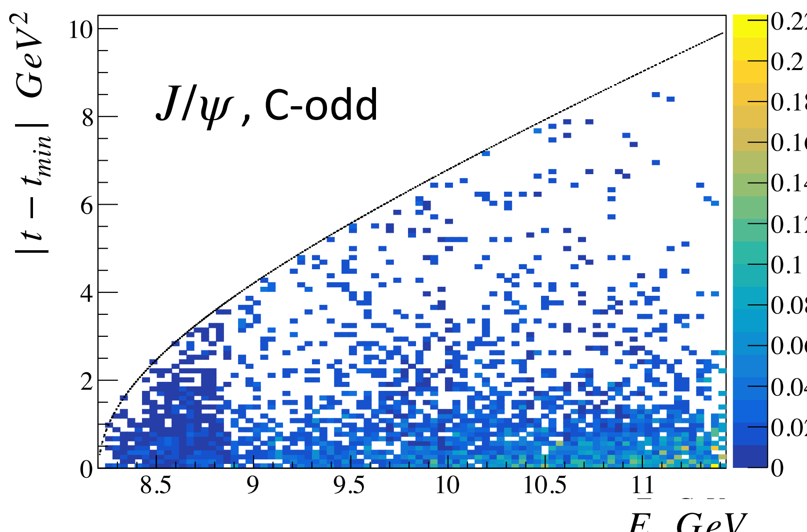
$\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++},

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

- First ever evidence for photoproduction of C-even charmonium
- Studying χ_c states - complementary to J/ψ in understanding reaction mechanism near threshold

Dramatic difference: χ_c distribution in (E_γ, t) vs J/ψ



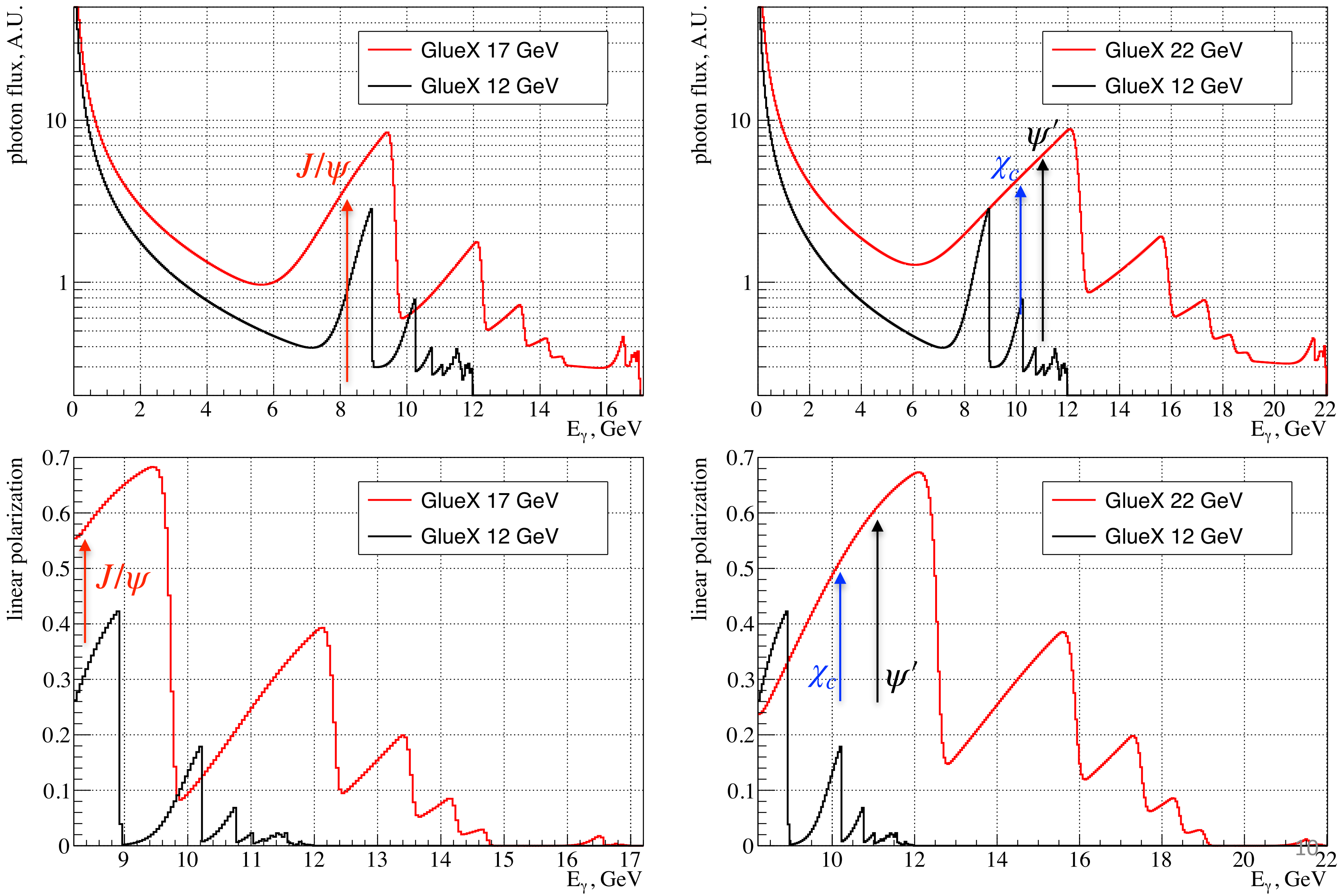


Studying χ_c can help to understand $X(3872)$ production mechanism

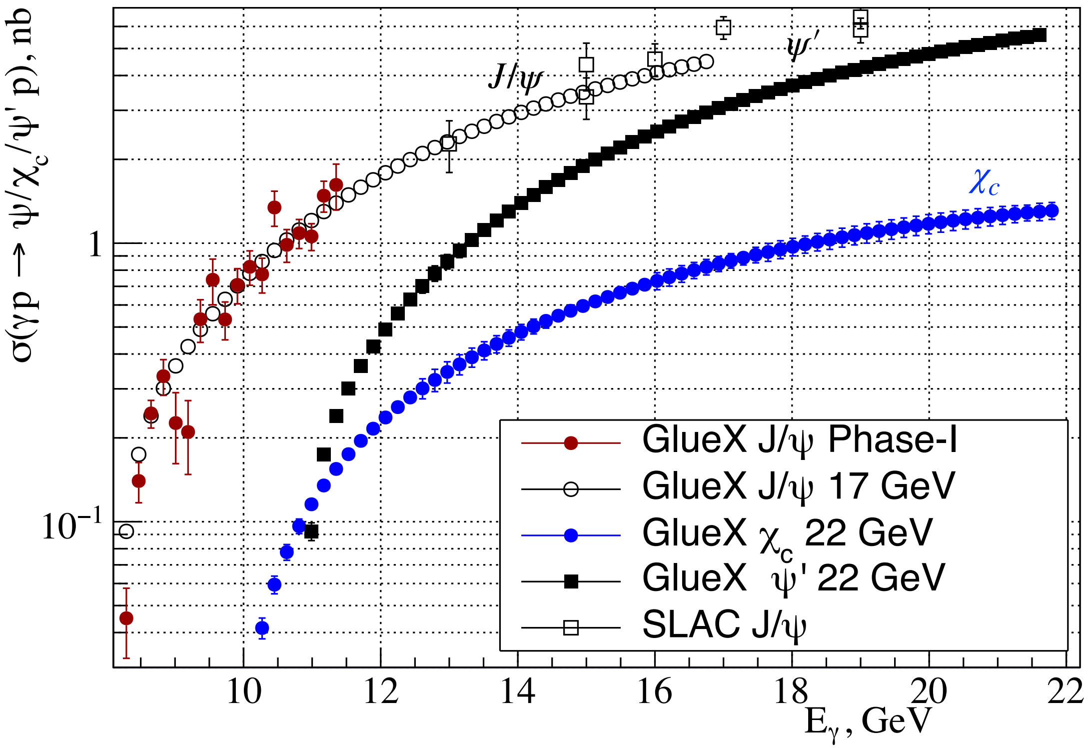
Threshold charmonium photoproduction at JLab22 with GlueX

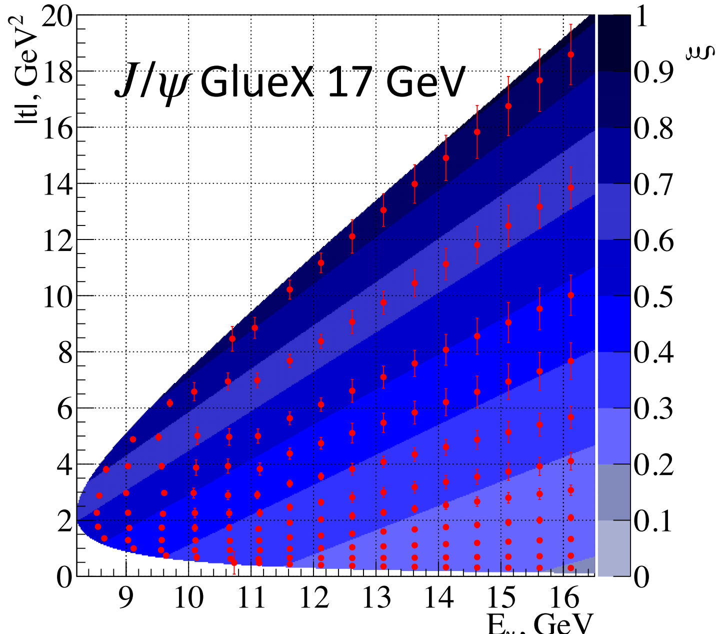
GlueX uses polarized photon beam from coherent Bremsstrahlung

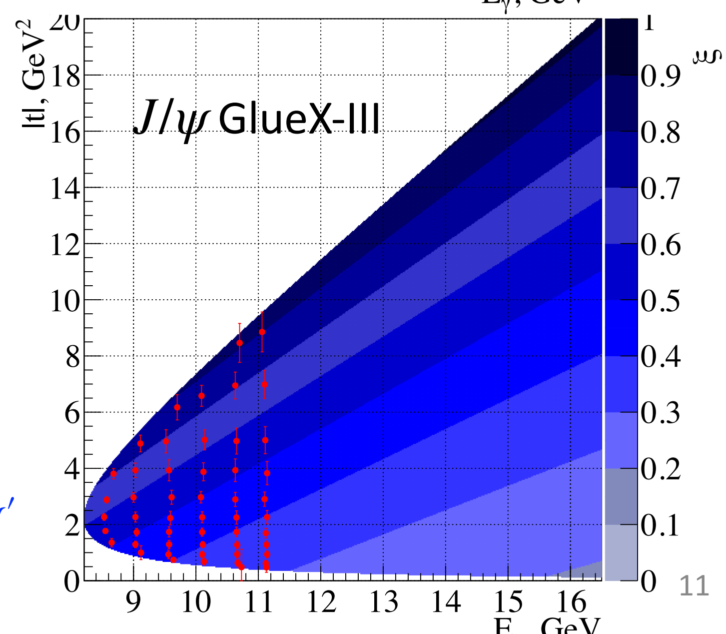
Taking advantage of increased end-point (electron beam energy):



Threshold charmonium photoproduction at JLab22 with GlueX

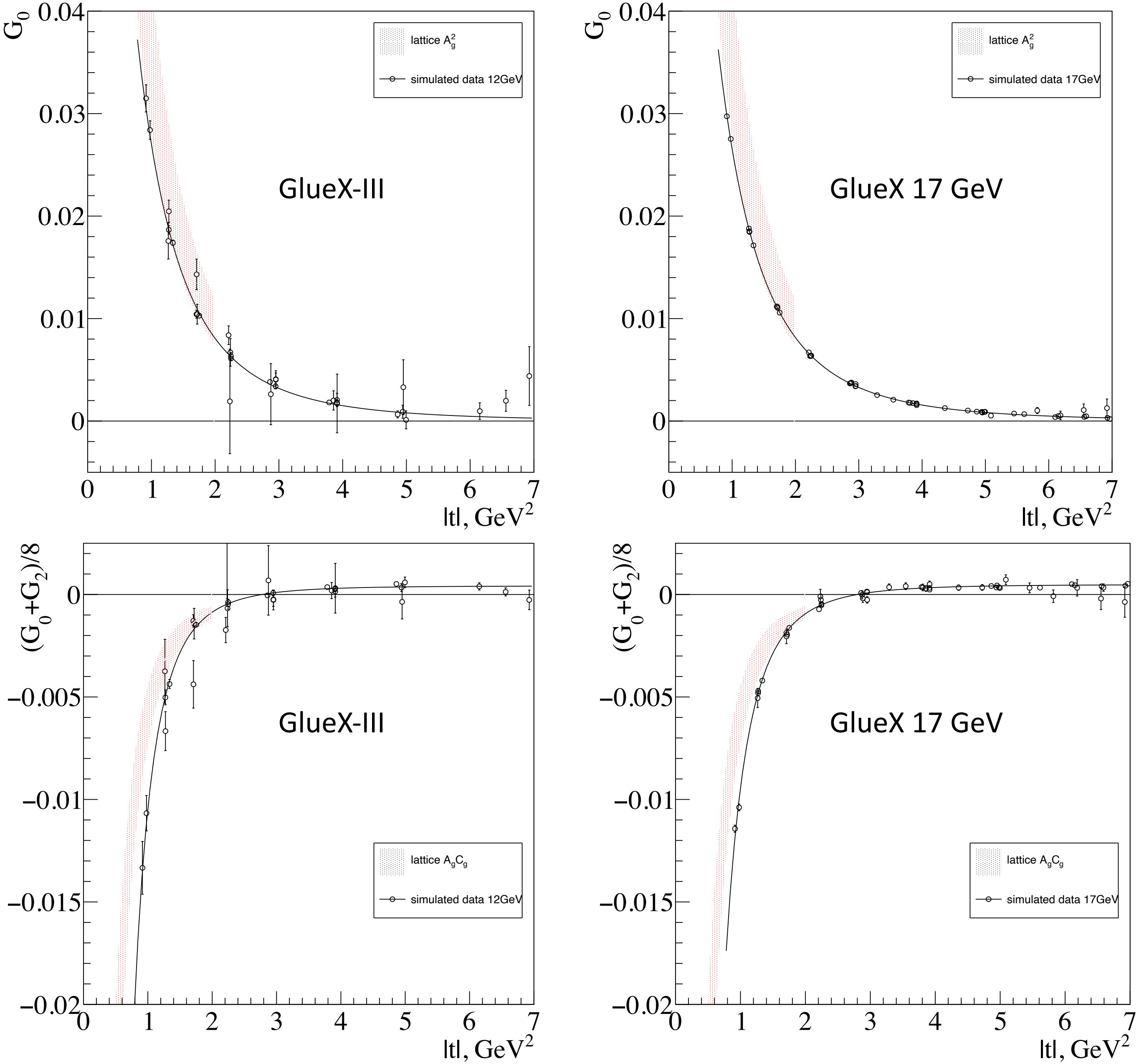






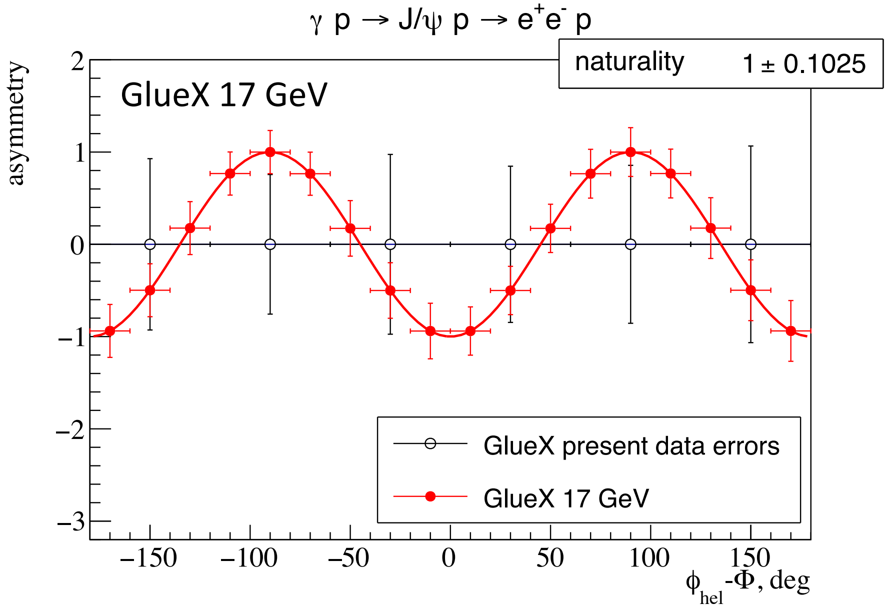
- Absolute normalization and error estimation: scaling existing measurements (<12 GeV) by anticipated luminosity increase
- Energy dependence extrapolation: using fits of J/ψ data for J/ψ and ψ', for χ_c based on VM exchange model (*JPAC, Phys.Rev.D 102 (2020)*)
- Efficiencies estimated with MC
- All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

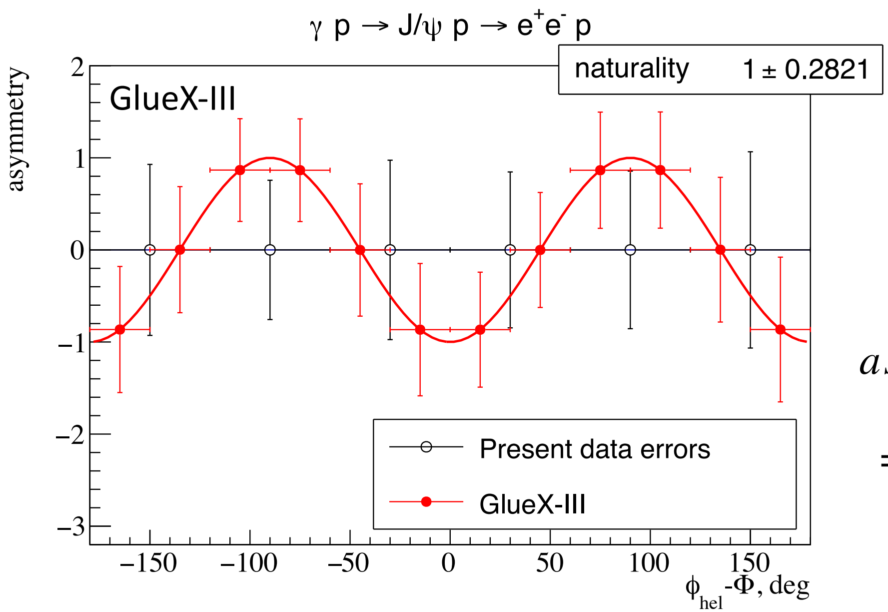
Threshold charmonium photoproduction at JLab22 with GlueX



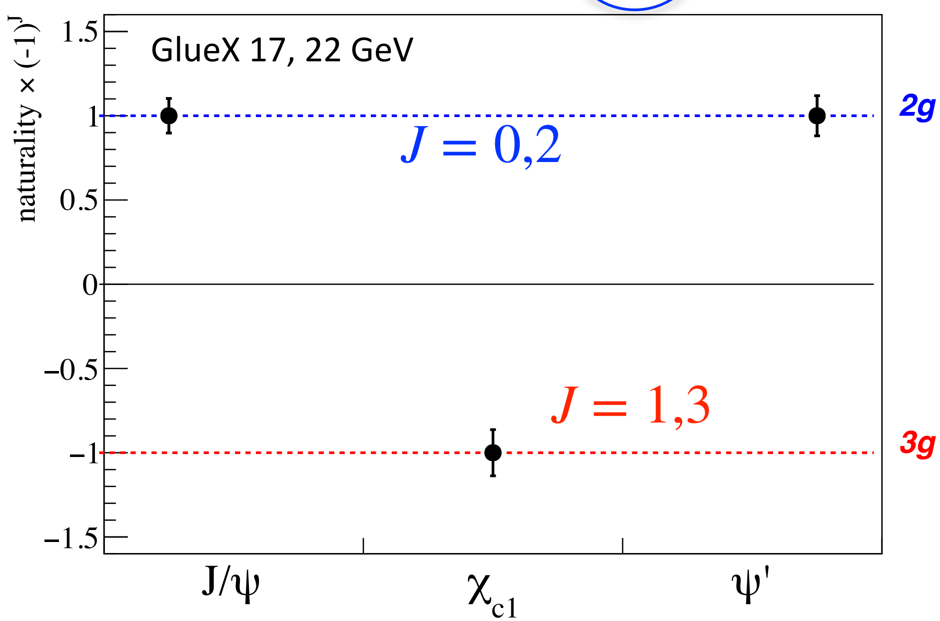
- Anticipated results for the extracted gluon Form Factors, assuming skewness scaling is valid
- Data randomized around a fit of the current data

Threshold charmonium photoproduction at JLab22 with GlueX





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

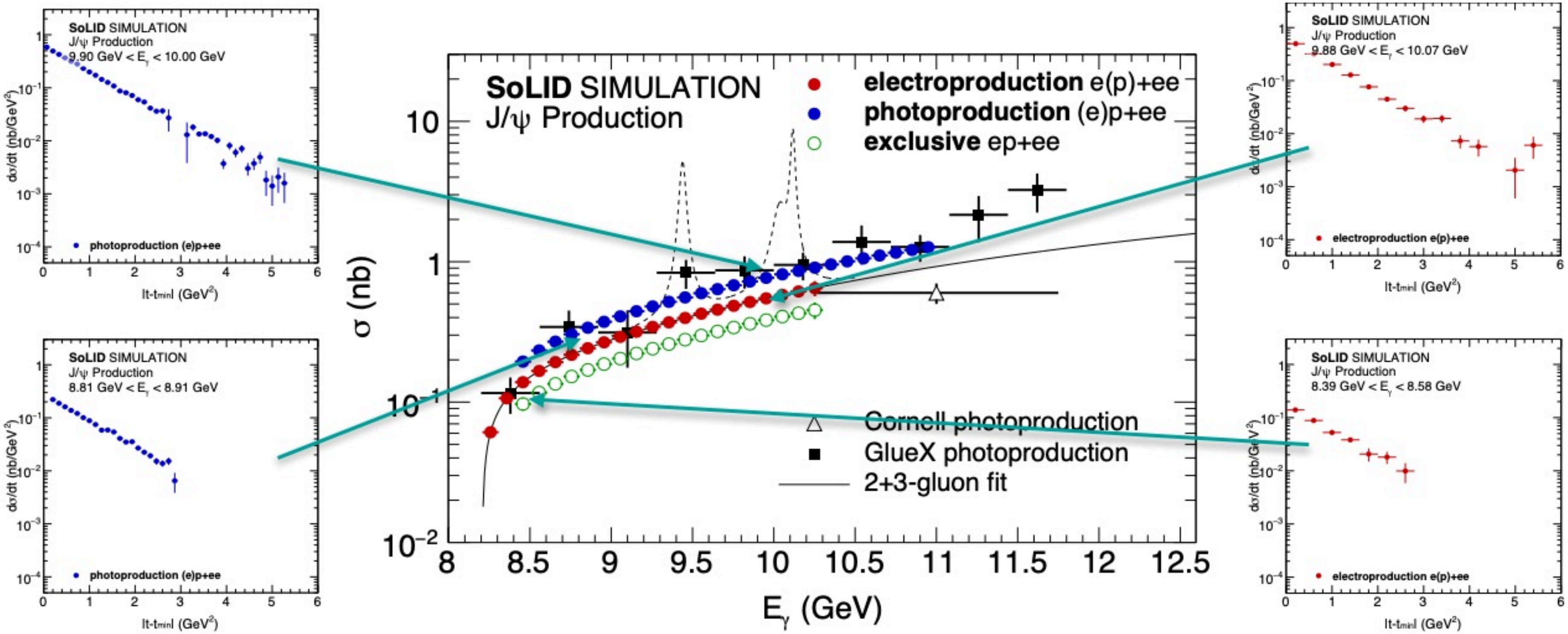


$$asymmetry = \frac{2}{P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} =$$

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

$naturality = (-1)^J P$

SoLID at JLab12

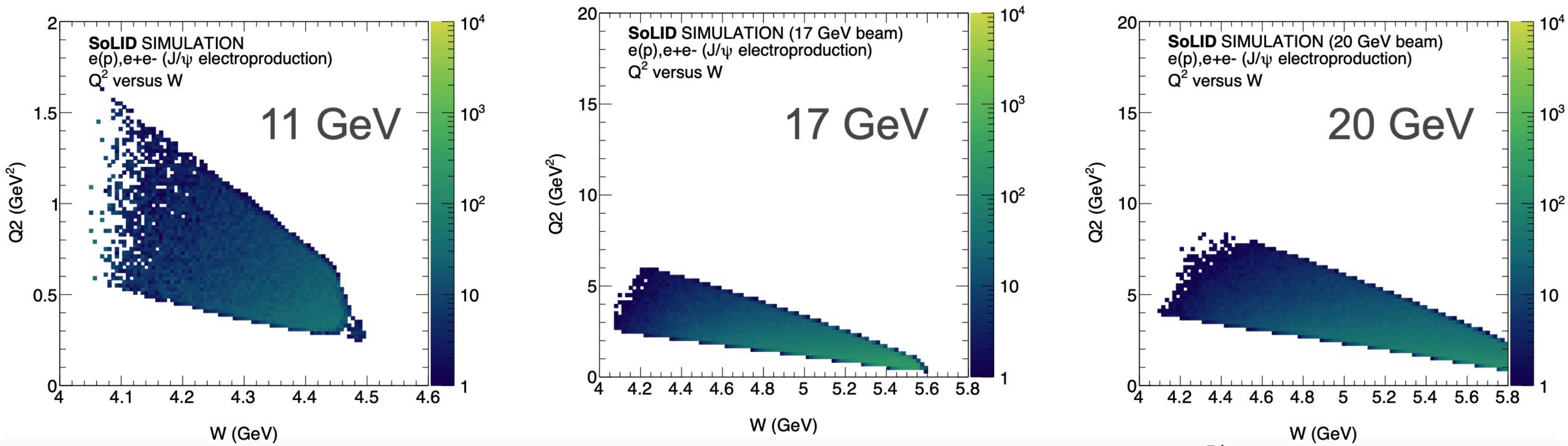


From S.Joosten talk at "J/ψ and Beyond" workshop

- SoLID at 12 GeV would give $\sim 1M\ J/\psi$'s per year in photo-production covering practically full t-region
- … and $\sim 20k\ J/\psi$'s in electro-production with $Q^2 < 1.5\ GeV^2$, which however is not enough to study mass dependance of the charmonium production, as $Q^2 \ll M^2_{J/\psi}$

see Boussarie and Hatta, Phys. Rev. D 101 (2020)

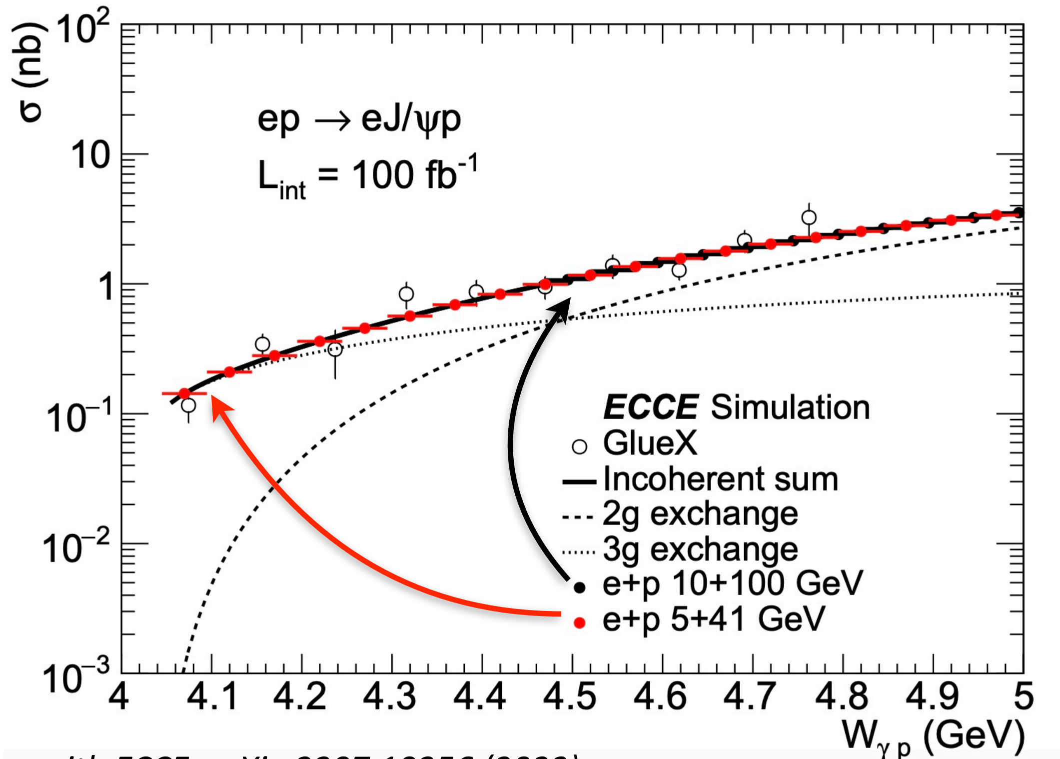
SoLID at JLAB22



From S.Joosten talk at "J/ψ and Beyond" workshop

- However SoLID at 22 GeV in J/ψ electroproduction can reach $Q^2 \sim 8\ GeV^2 \approx M^2_{J/\psi}$, effectively increasing the mass of charmonium
- SoLID angular acceptance is in the range $7-28^{\circ}$, limiting in J/ψ photoproduction medium t-region for $E_\gamma > 12$ GeV
- Good coverage for $\psi(2S)$ with acceptance limitations for $E_\gamma > 16$ GeV in photoproduction

J/ψ production close to threshold at EIC



Exclusive J/ψ detection with ECCE: arXiv:2207.10356 (2022)

- 5+41 GeV beam configuration needed to reach threshold, however it has very low luminosity (4.4 fb^{-1} annually)
- Difficult to detect scattered electron with energy close to electron beam energy - bad $W_{\gamma p}$ resolution
- Using the detected J/ψ and proton to calculate $W_{\gamma p}$ also leads to a bad resolution (*Sylvester Joosten*)

Heavy quarkonium production close to threshold

	GlueX 22GeV	Solid 22GeV	EIC
J/ψ photoproduction	✓	✓ Aceptance limitations for E_γ>12 GeV	?
J/ψ electroproduction	✗	✓ unique up to Q^2 = 8 GeV^2	?
χ_c photoproduction	✓ unique	✗	?
$\psi(2S)$ photoproduction	✓	✓ Acceptance limitations for E_γ>16 GeV	?
$\psi(2S)$ electroproduction	✗	✓ up to Q^2 = 1.5 GeV^2	?
J/ψ, χ_c, $\psi(2S)$ linear polarization	✓ unique	✗	✗
Υ	✗	✗	✓ unique

- GlueX has linear polarization and almost full acceptance for multi-particle final states (including photons) - unique in polarization measurements and χ_c states
- SoLID has very high luminosity, relatively wide acceptance, capable of reaching high Q^2 values in electroproduction (unique)
- EIC energies much above charmonia thresholds, detection is questionable, however very suitable for studying Υ production at threshold

Conclusions

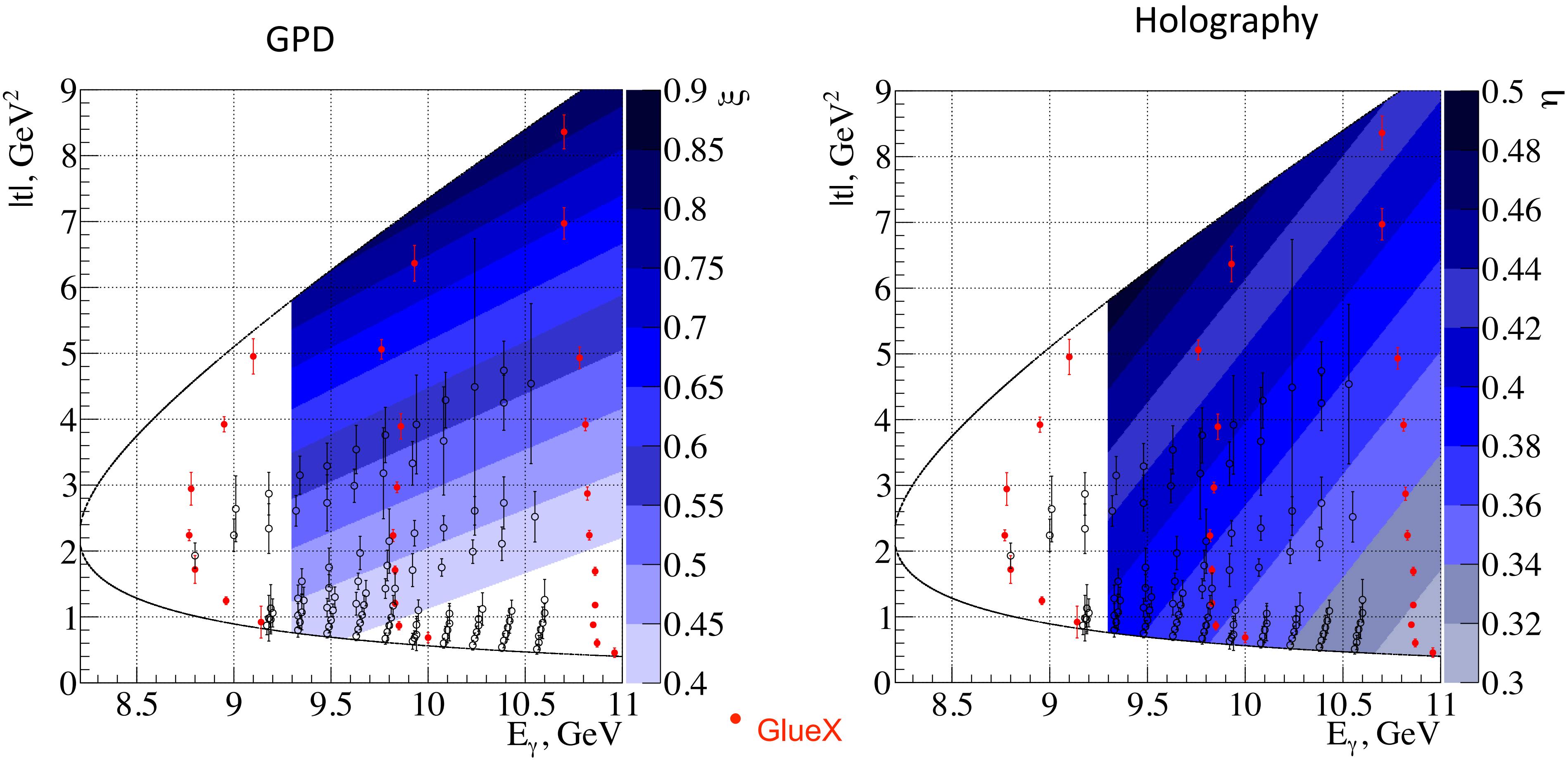
- It is remarkable to see the gluon GFFs extracted from J/ψ data using two diametric approaches (without any external constraints) on the same scale with the lattice calculations. However, more precise relation to the gluon properties of the proton requires comprehensive experimental and theoretical studies to better understand the reaction mechanism.
- CEBAF energy upgrade adds three new dimensions to these studies:

  - Threshold production of higher-mass charmonium states (with different quantum numbers) - $\psi(2S)$ (SoLID, GlueX), χ_c (GlueX)
  - Threshold charmonium electroproduction at high Q^2 (SoLID)
  - Polarization measurements with high FOM (GlueX)
  - What about open-charm production, that is supposed to dominate with increasing the energy

- EIC would extend the charmonium studies at JLab to the bottomonium sector

Back up slides

Data used in gluon Form Factor extraction



$\circ$ J/ψ-007
Nature 615 (2023)

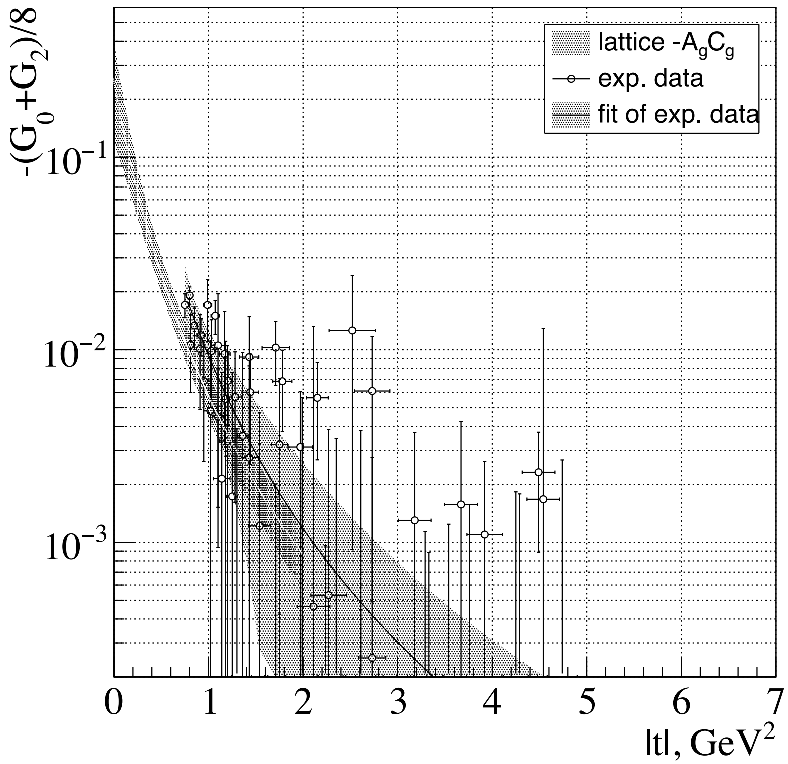
$\xi > 0.4$
$E_\gamma > 9.3$ GeV (away from $\bar{D}\Lambda_C$ and $\bar{D}^*\Lambda_C$ thresholds)

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

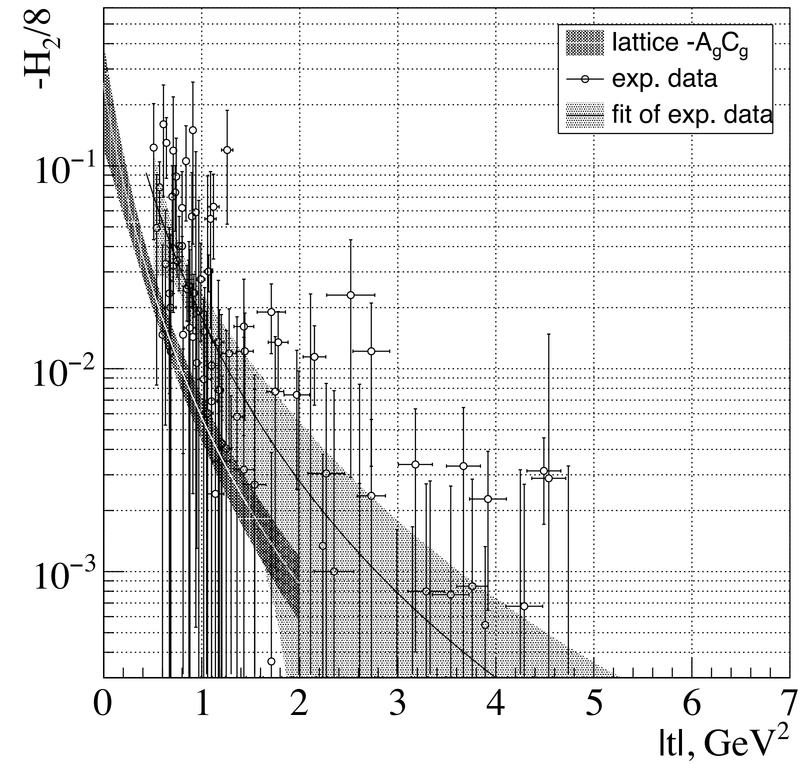
Error bars: relative errors in A.U. (not related to y-axis)

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 ξ values

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

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

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

leading-moment approximation

neglecting $B_g(t)$

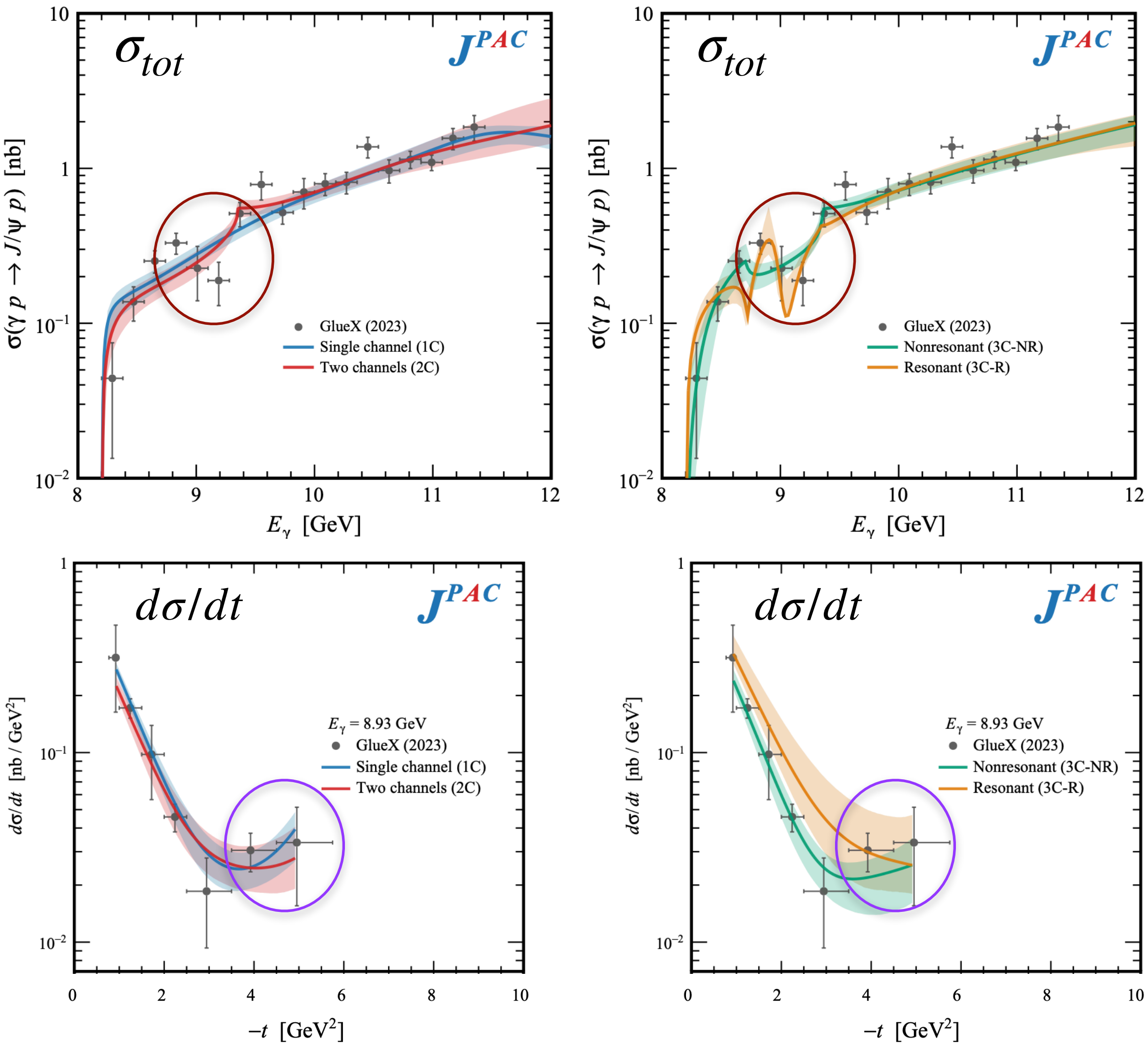
$$G_0(t) + G_2(t) = 8A_g(t)C_g(t)$$

$B_g(t)=0$

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

for large N_c and strong α_s

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)

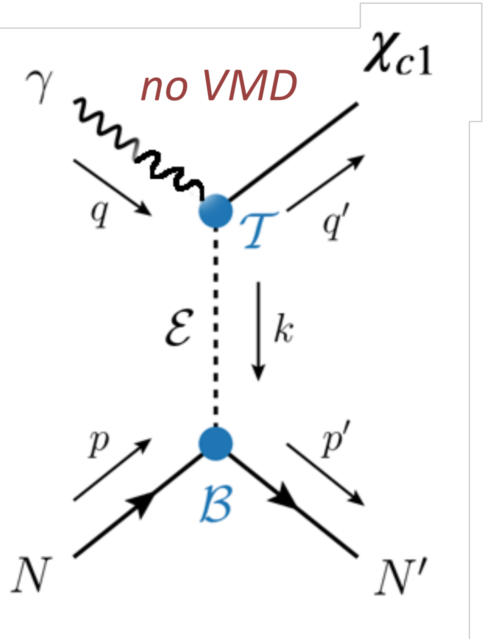
No stat. significant preference:

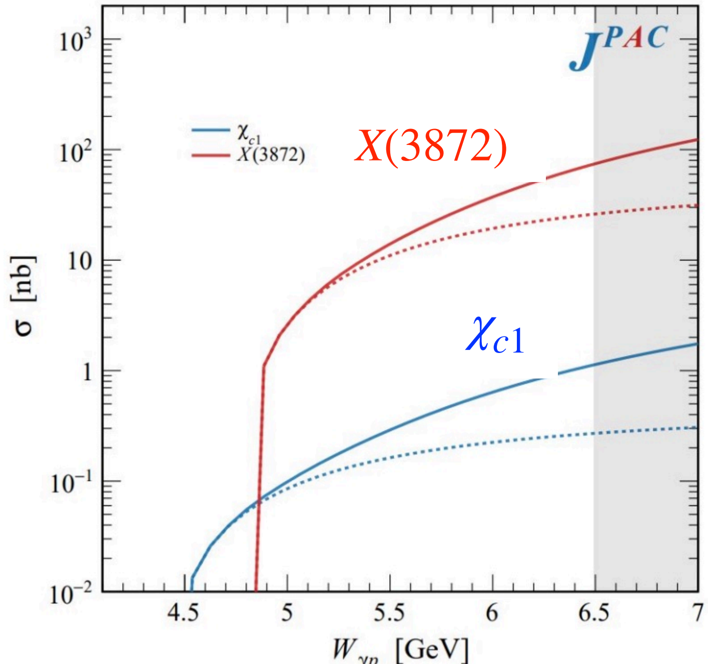
- 9 GeV structure requires sizable contribution from open charm
- Severe violation of VMD and factorization not excluded
- s-channel resonance not excluded
- t-enhancement indicates s-channel contribution: due to proximity to threshold or open-charm exchange

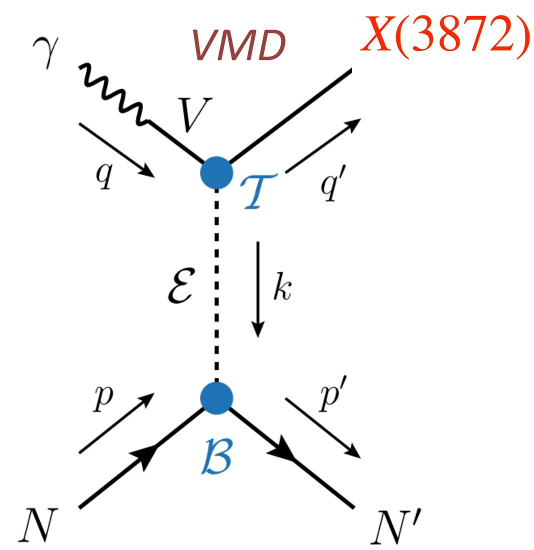
JPAC Phys.Rev.D 108 (2023)

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

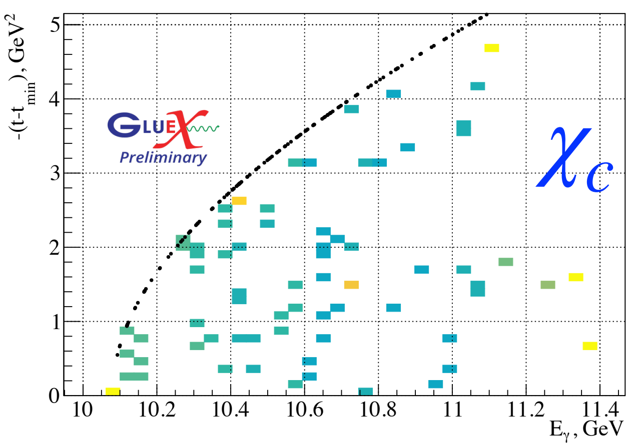
χ_c vs $X(3872)$ production

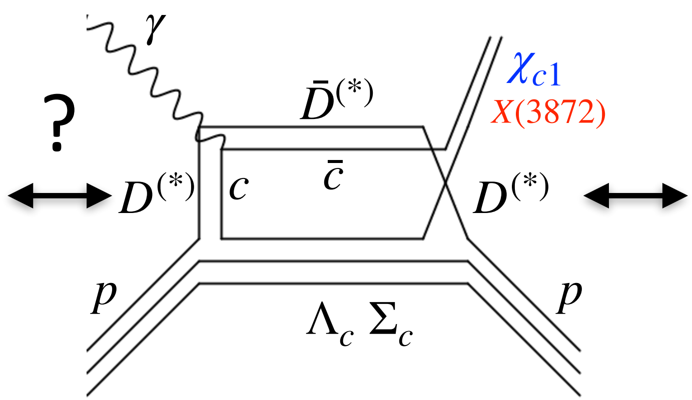






JPAC, PRD 102 (2020). *t*-channel production





$X(3872)$

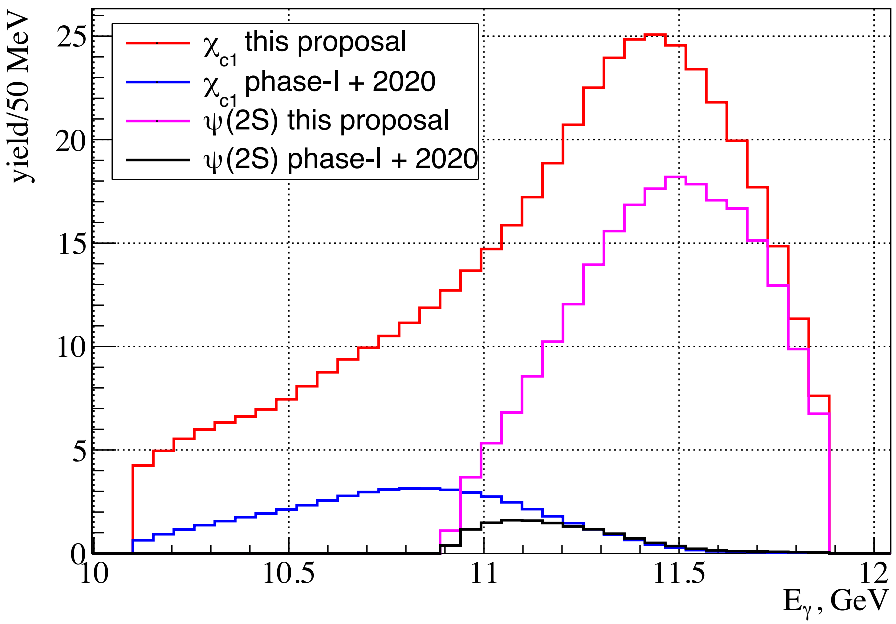
?

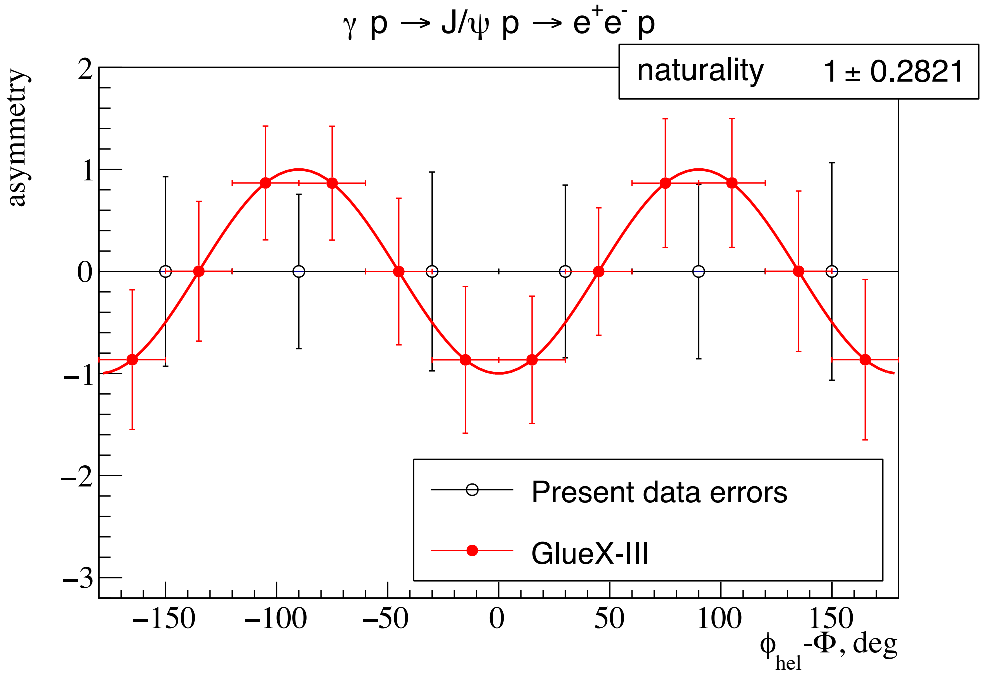
Recall discussions on Monday - Daniel's talk p.9

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

Prospect for charmonium threshold production with GlueX-III

Run Period	J/ψ	χ_{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