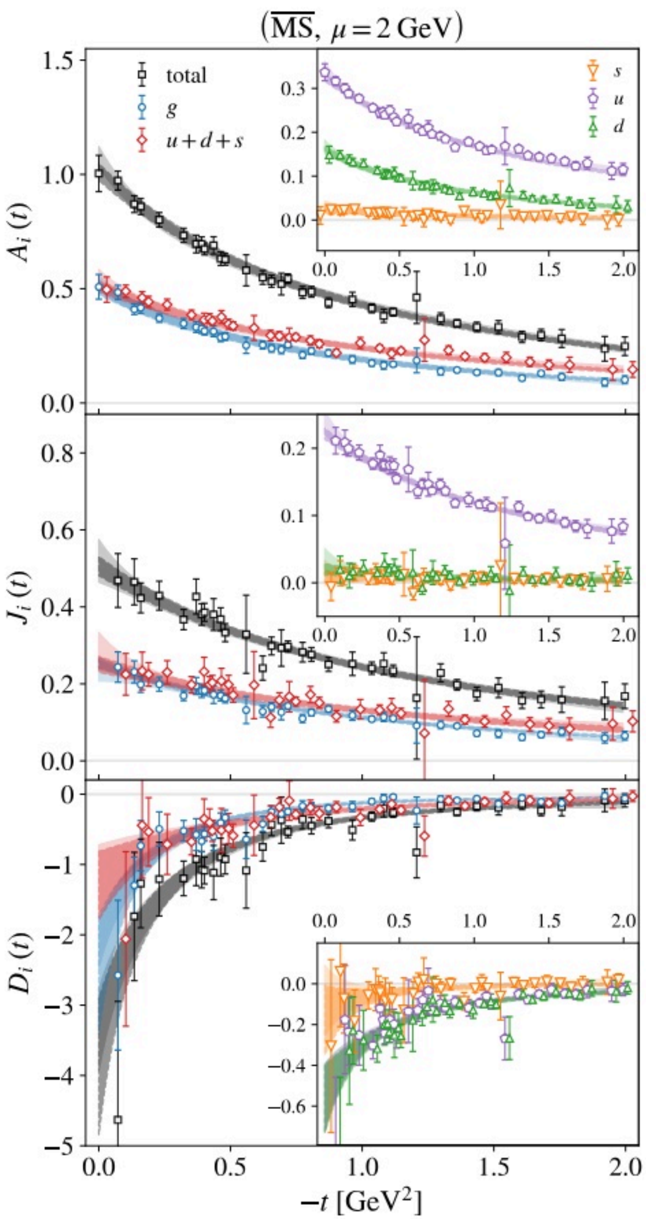
Threshold charmonium photoproduction - an access to gluonic structure of the proton

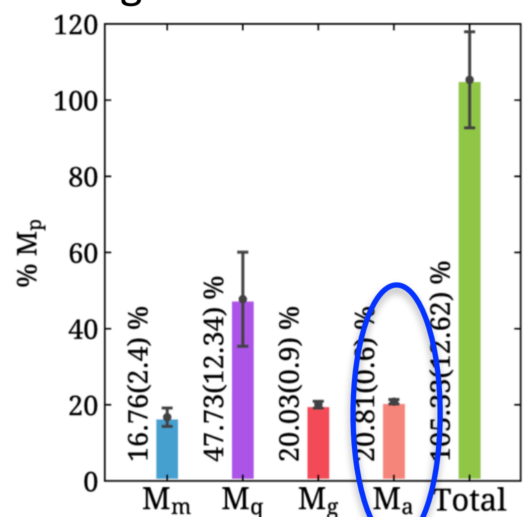
Lubomir Pentchev



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

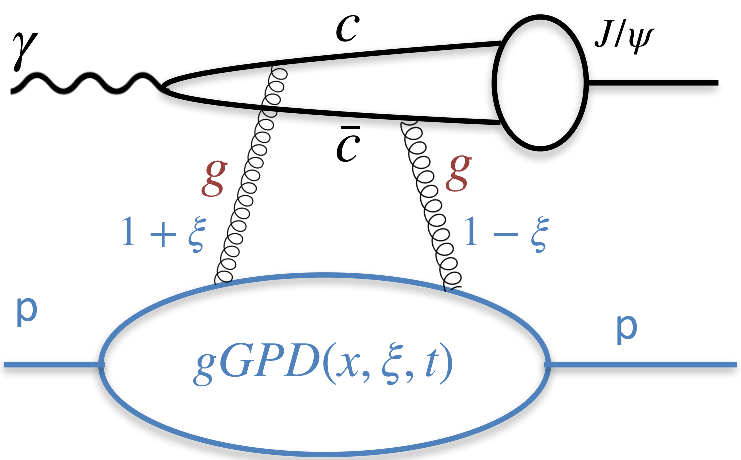
Lattice calculations of Gravitational Form Factors (GFFs) show similar contributions from gluons (g) and quarks (u+d+s).
Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)

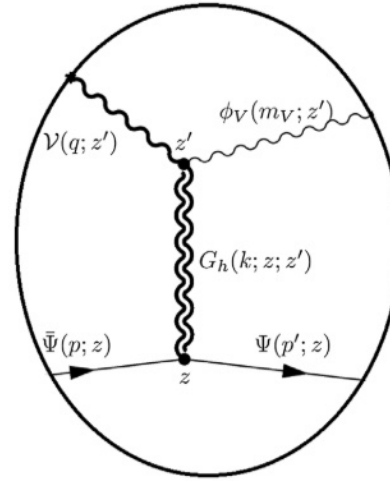
- Quark masses and kinetic energies of quarks and gluons are not enough to explain the mass of the proton: gluon condensate, or anomalous contribution to the mass of the proton is significant:



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

- Compton-like amplitudes $\mathscr{H}_{gC}(\xi,t)$, $\mathscr{E}_{gC}(\xi,t)$ and form-factors as in DVCS
- In contracts: threshold kinematics is very different: at high momentum transfer t and skewness ξ (hard process):

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

- Leading terms in $G_0(t)$ and $G_2(t)$ contain gGFFs $A_g(t), B_g(t), C_g(t)$
- Absolute calculations, but require knowledge of gGFFs

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

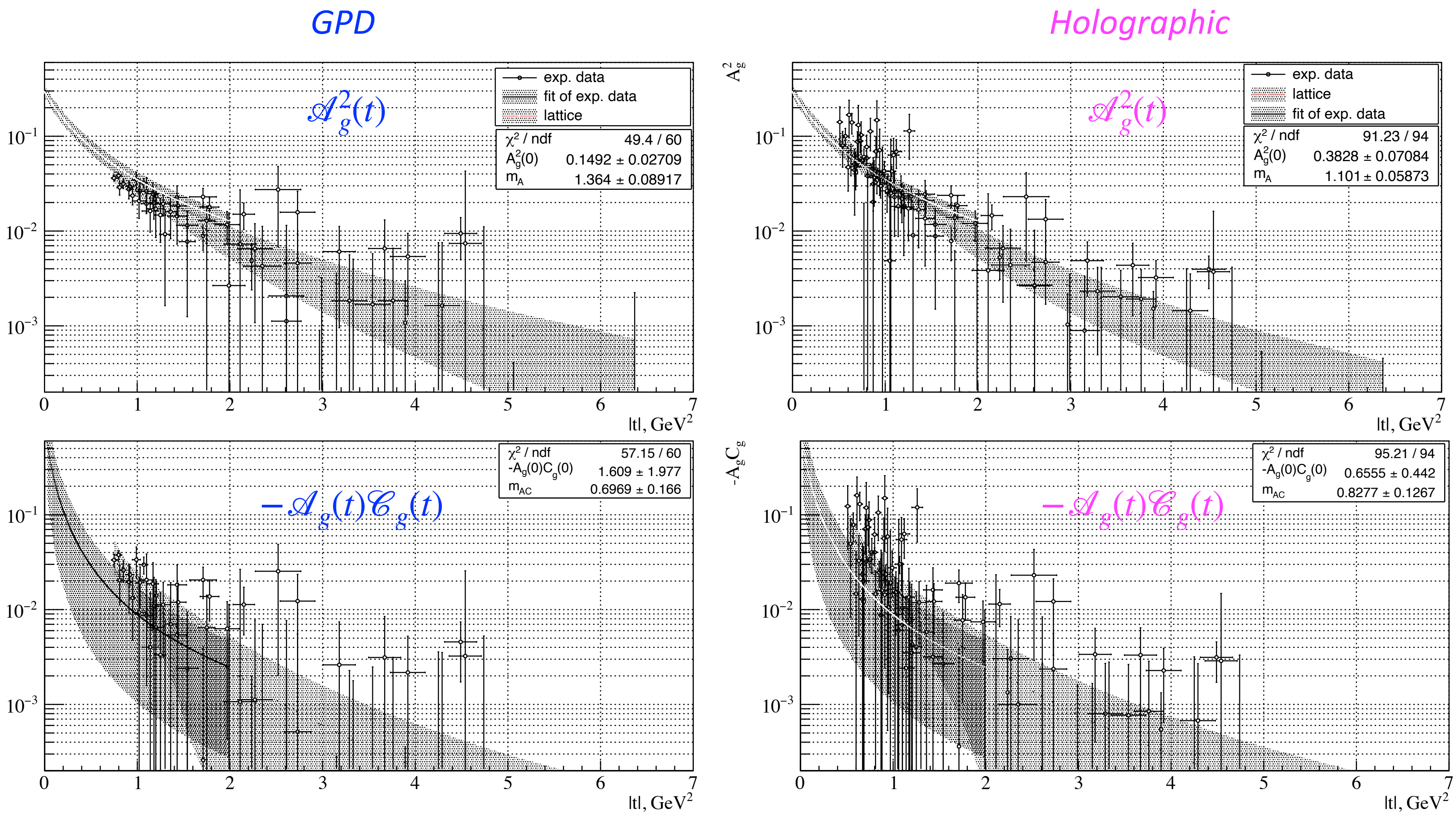
- Using gauge/string correspondence
- In the double limit of large N_c and strong gauge coupling (soft process):

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = H(E_\gamma)[A_g^2(t) + \eta^2 8A_g(t)C_g(t)] + \ldots$$

- Approximate theory, requires $1/N_c$ corrections
- Relative calculations ($H(E_\gamma)$ normalized to GlueX total cross-sections), but predicts $A_g(t)$ and $C_g(t)$ shapes from Regge trajectories

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

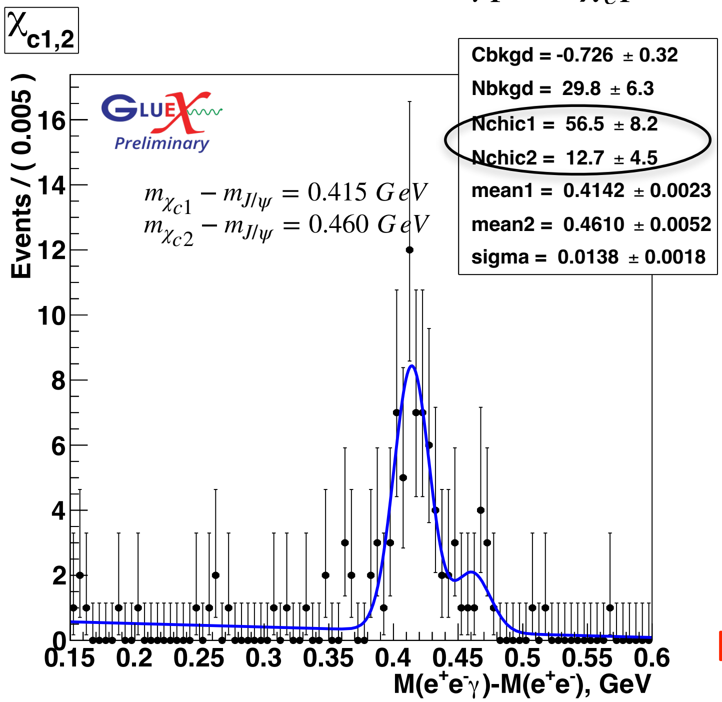
Gluonic Form Factors - data vs lattice



- Kinematic (Rosenbluth-like) separation using only ξ/η-scaling applied to JLab data, $9.3 < E_\gamma < 10.8$ GeV
- Extracted FF combinations do not depend on energy ($\chi^2/dof \approx 1$) - consistent with ξ/η-scaling predictions
- General agreement with lattice, would be the case in leading-term approximation
- General agreement b/n two diametric theories, each with specific corrections (higher moments, $1/N_c$)

Higher-mass charmonium states at threshold

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

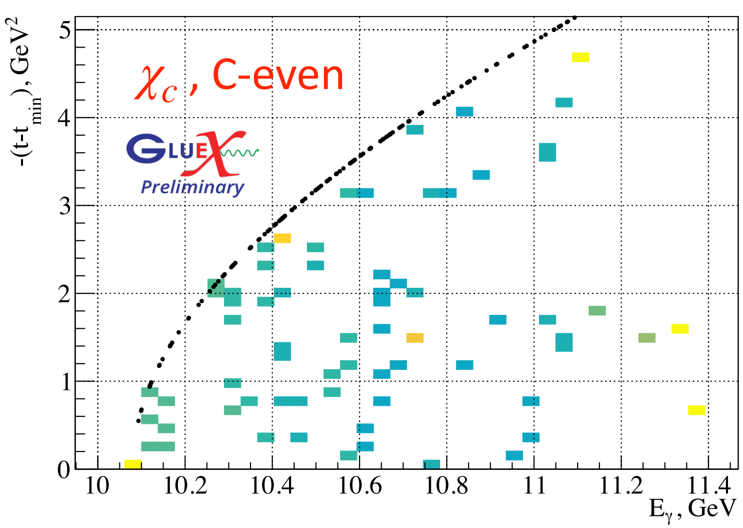


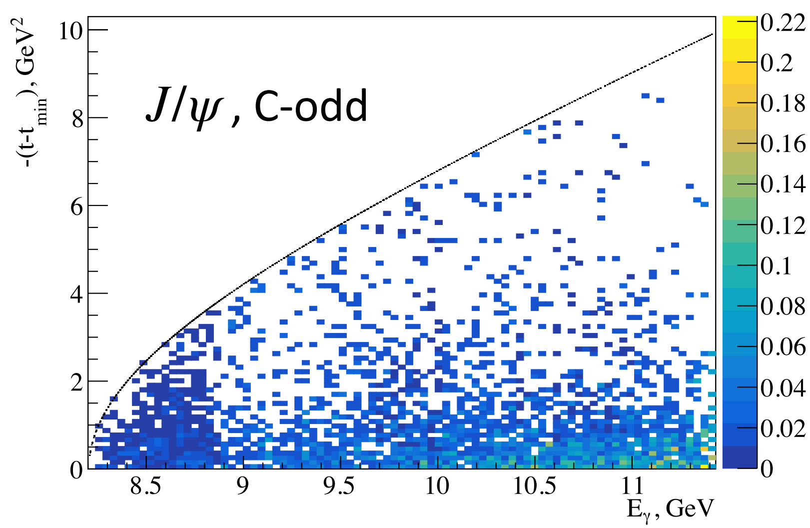
$\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++},

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

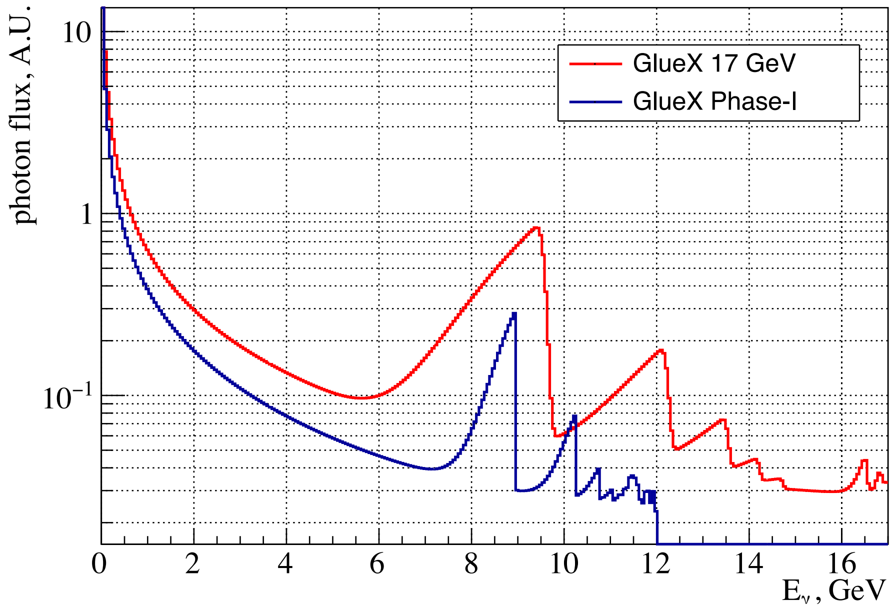
- First ever evidence for photoproduction of C-even charmonium
- Studying χ_c states - complementary to J/ψ in understanding reaction mechanism near threshold

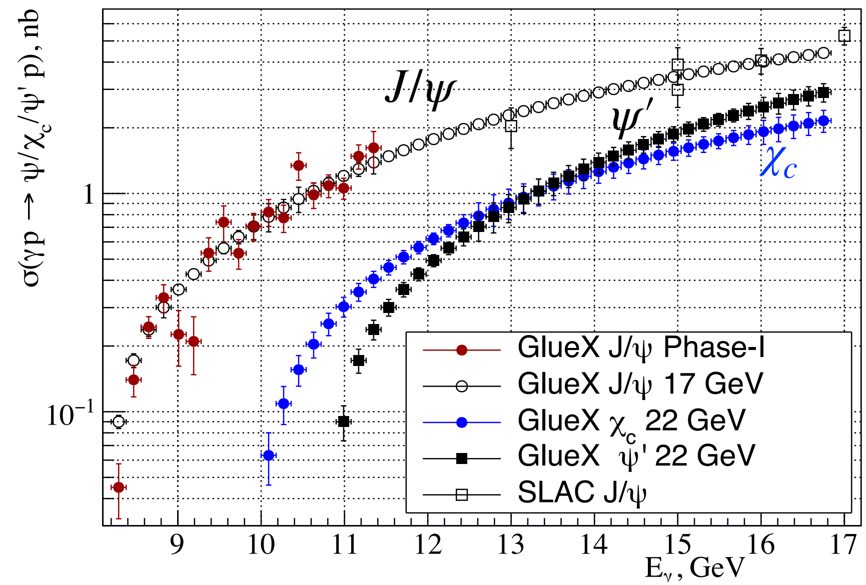
Dramatic difference: χ_c distribution in (E_γ, t) vs J/ψ



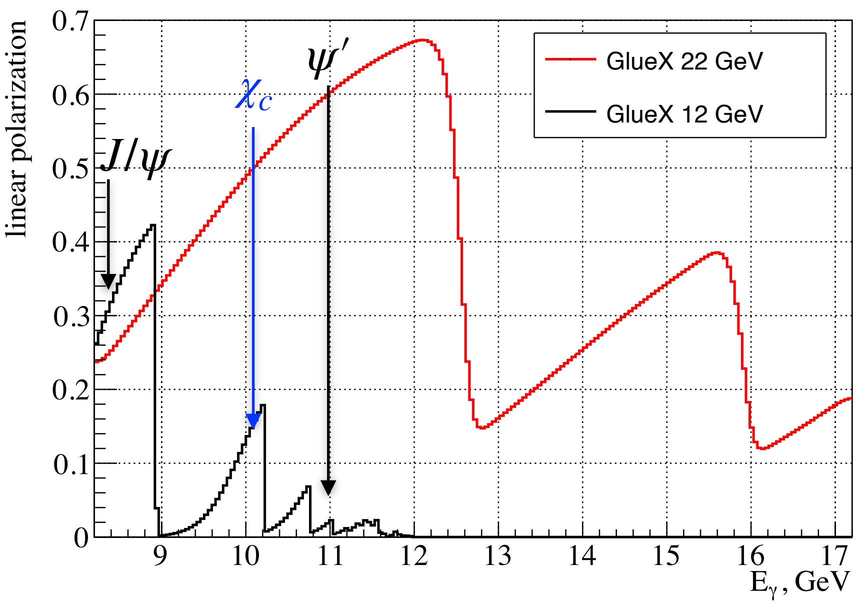


Threshold charmonium photoproduction at 22 GeV era

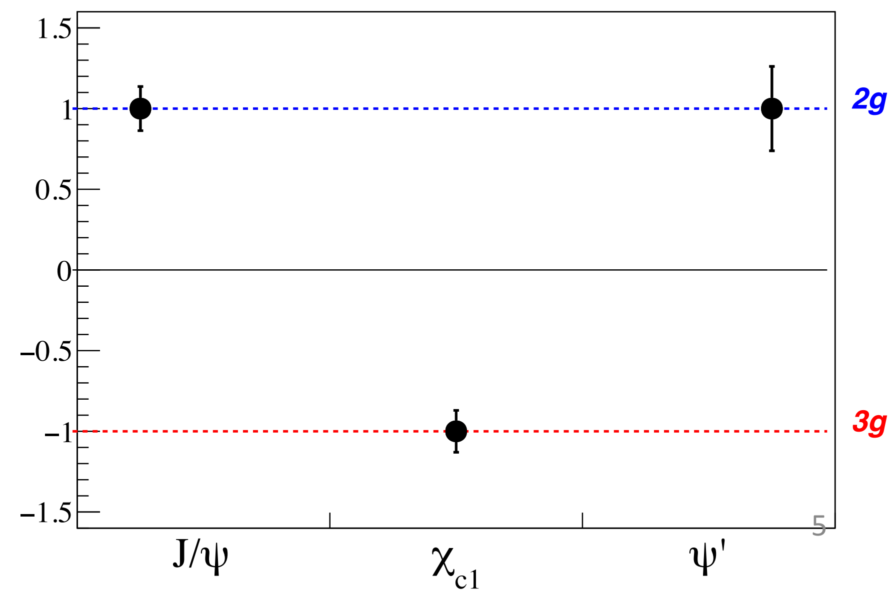




E$_{el}$ = 22 GeV

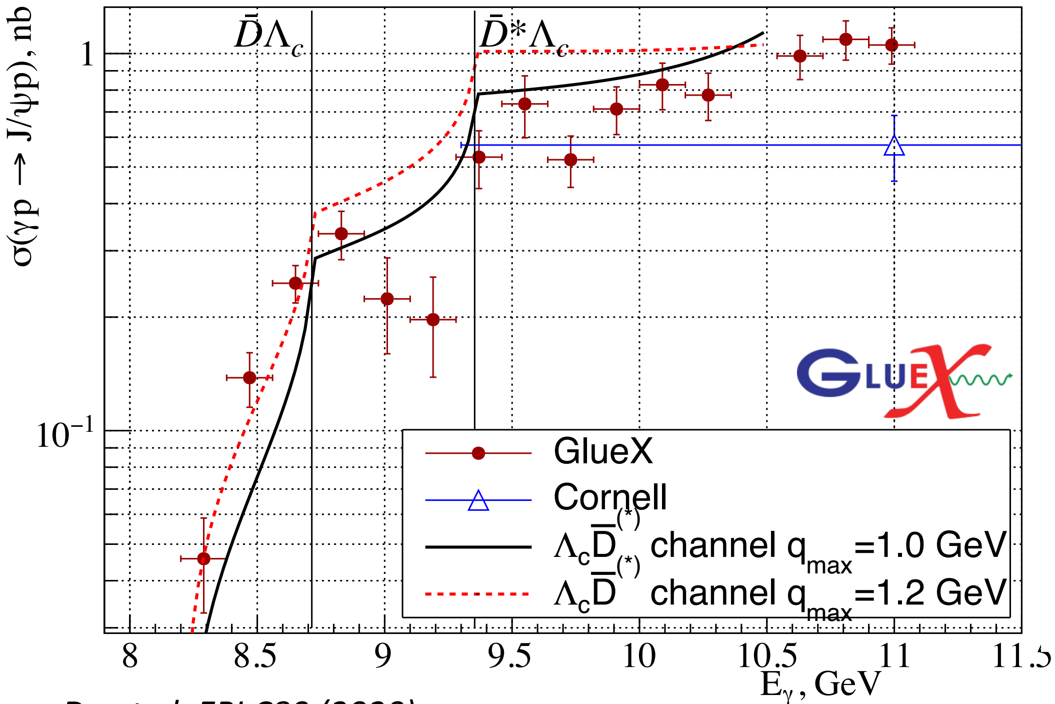


naturality $\times (-1)^J = P$

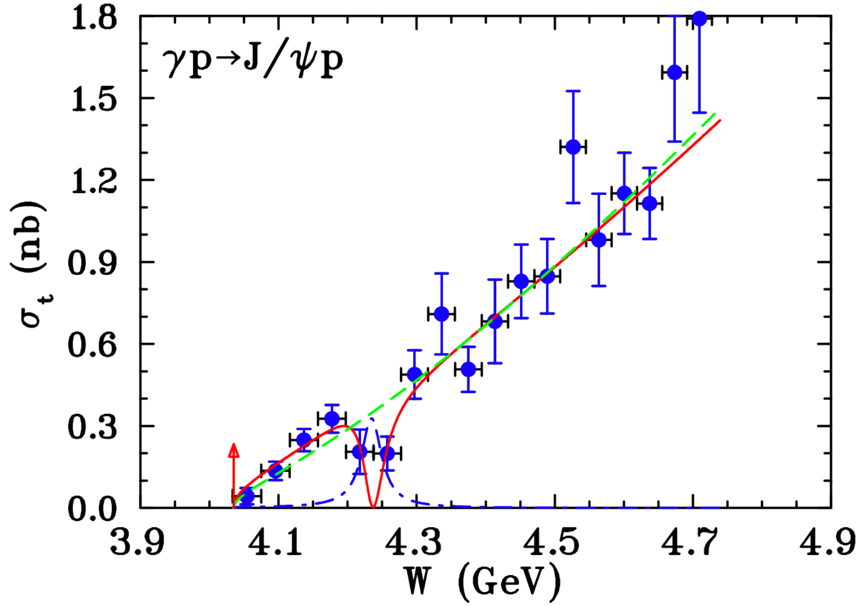


Back up slides

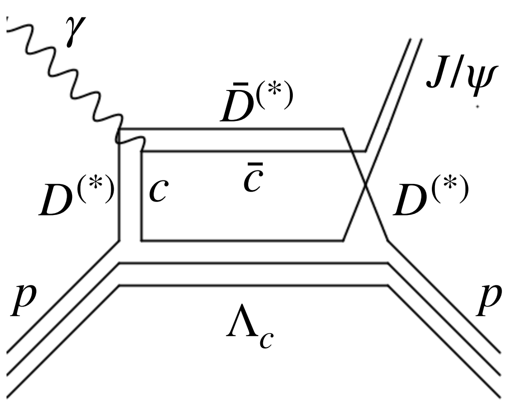
Other reaction mechanisms: open-charm, 5q exchange

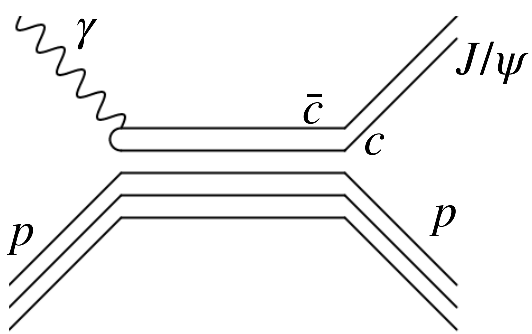


Du et al. EPJ C80 (2020)



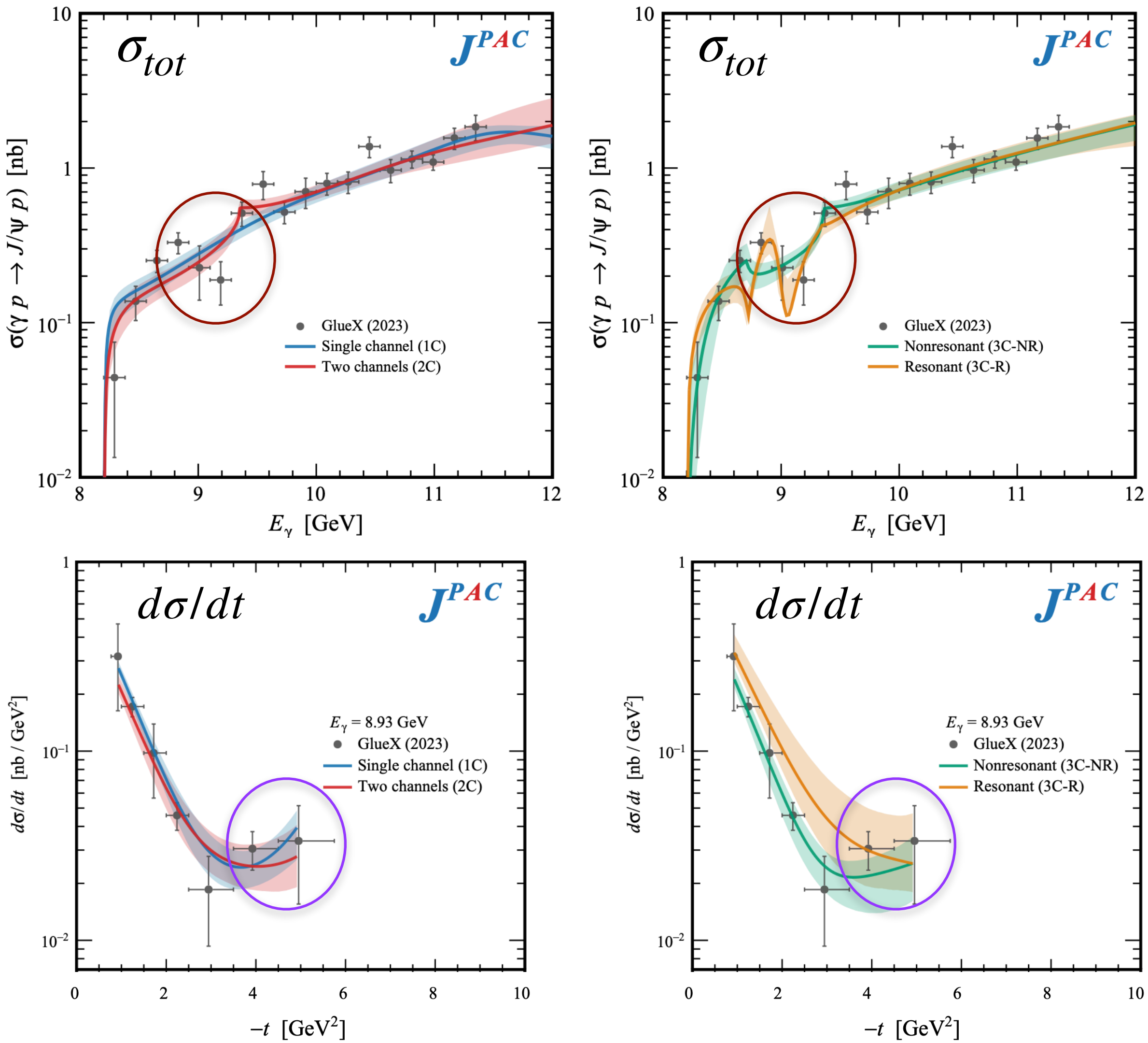
Strakovsky et al. PRC 108 (2023)





JPAC PRD 108 (2023)

Phenomenological approach: JPAC results



JPAC arxiv:2305.01449 (2023)

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

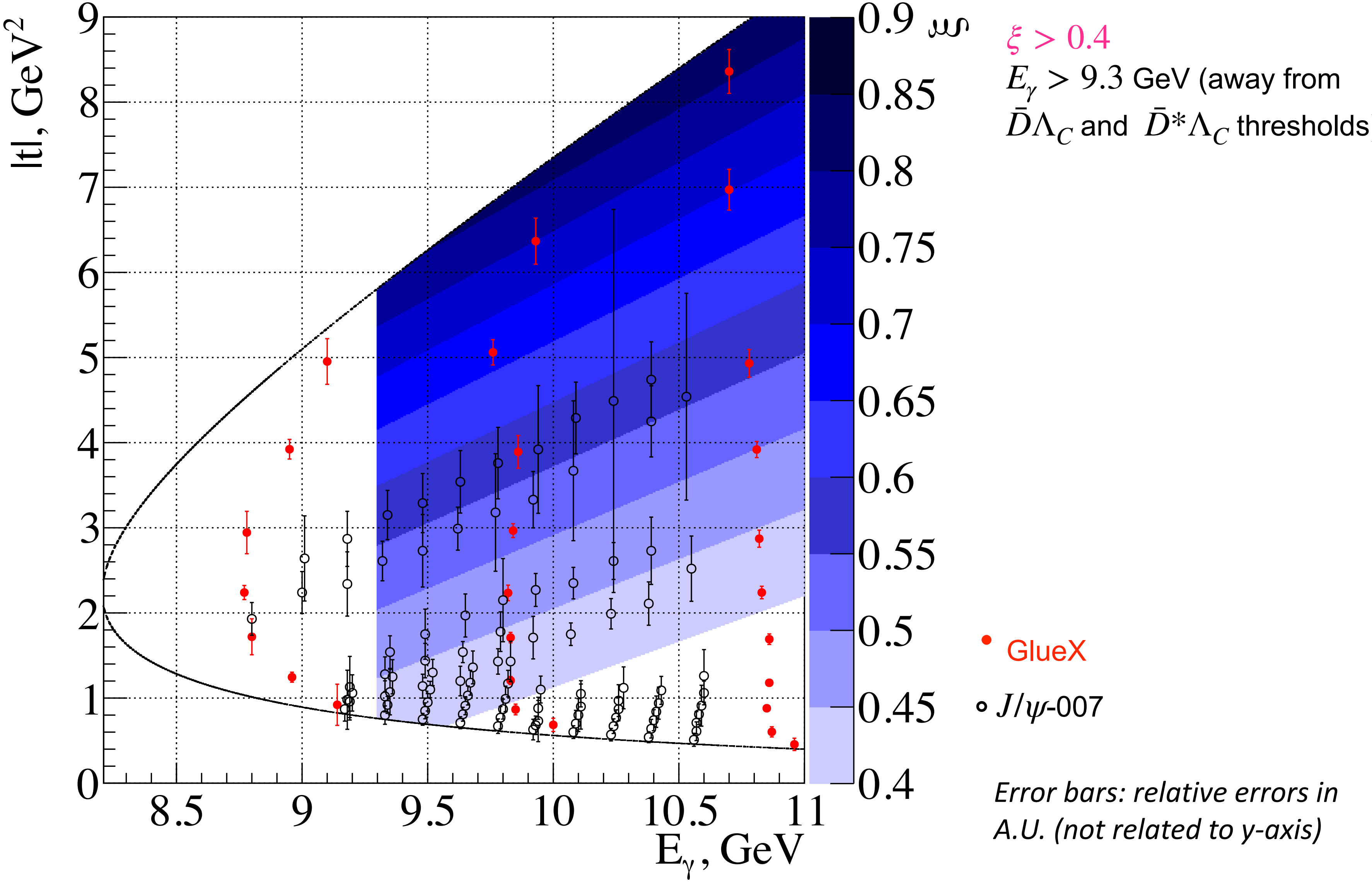
Phenomenological model based on s-channel PW expansion ($l \leq 3$):

- (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)

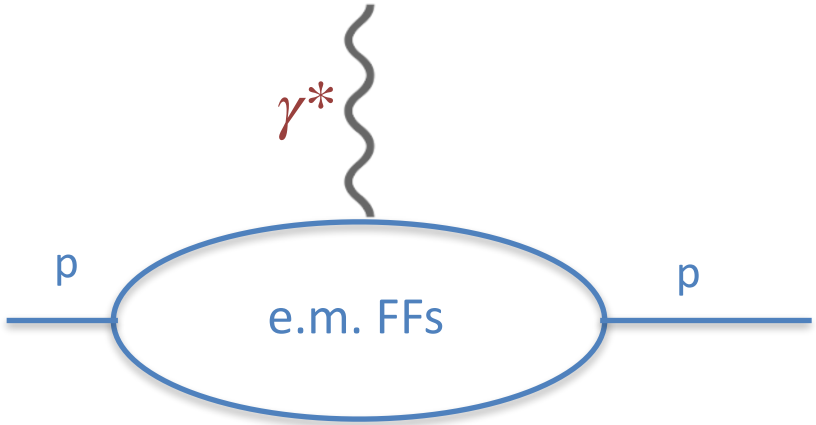
No stat. significant preference:

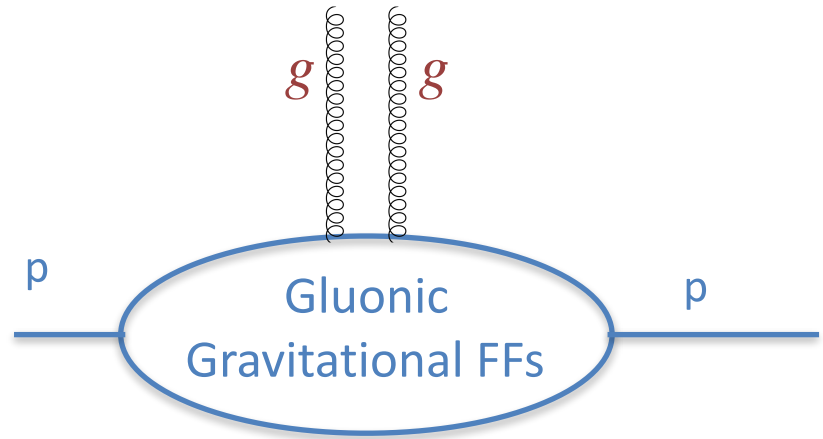
- 9 GeV structure requires sizable contribution from open charm
- Severe violation of VMD and factorization not excluded
- s-channel resonance not excluded
- t-enhancement indicates s-channel contribution: due to proximity to threshold or open-charm exchange

Data used for extraction of gluon FFs in GPD analysis



Gluonic Form Factors





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

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep \to ep} = \left(\frac{d\sigma}{d\Omega}\right)_M \frac{1}{(1+\tau)}\left[G_E^2(t) + \frac{\tau}{\epsilon}G_M^2(t)\right]$$

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

Model approach - fit dipole/tripole FFs (within some model) to data

$$G_E(t), G_M(t) \sim G_D(t) = \frac{1}{(1 - t/0.71GeV^2)^2}$$

$$A_g(t), B_g(t), C_g(t) \sim \frac{1}{(1 - t/m_i^2)^{2(3)}}$$

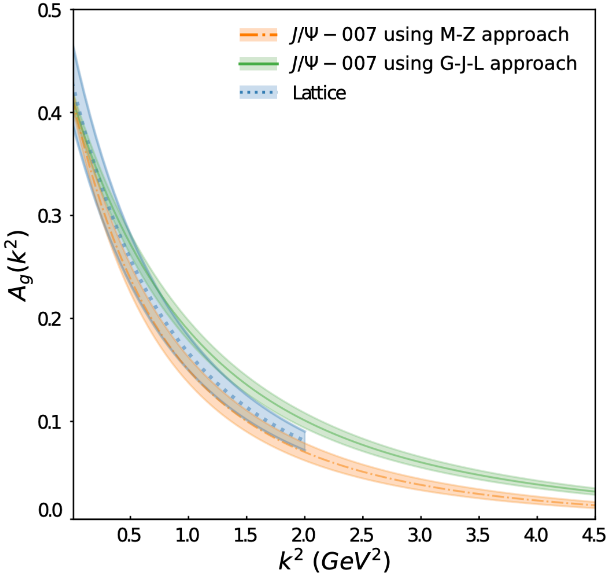
Rosenbluth separation

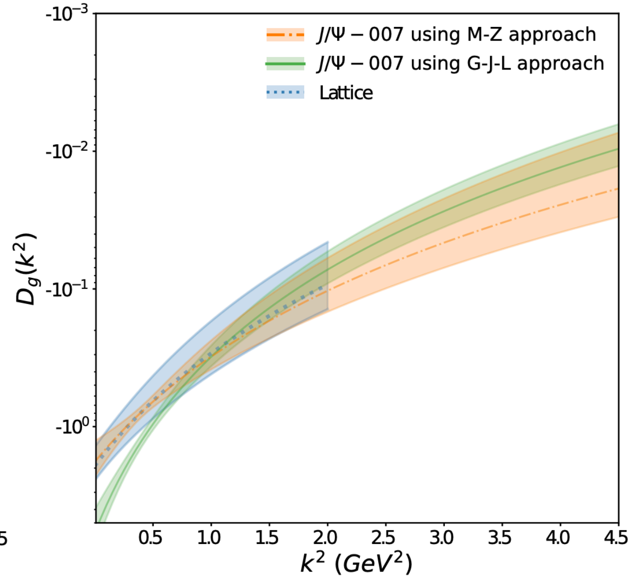
$$\sigma_G = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} \approx \xi^{-2}G_0(t) + G_2(t)$$

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

$$\sigma_H = \frac{d\sigma}{dt}\frac{\eta^{-2}}{F(E_\gamma)} \approx \eta^{-2}\mathscr{A}^2(t) + 8\mathscr{A}(t)\mathscr{C}(t)$$

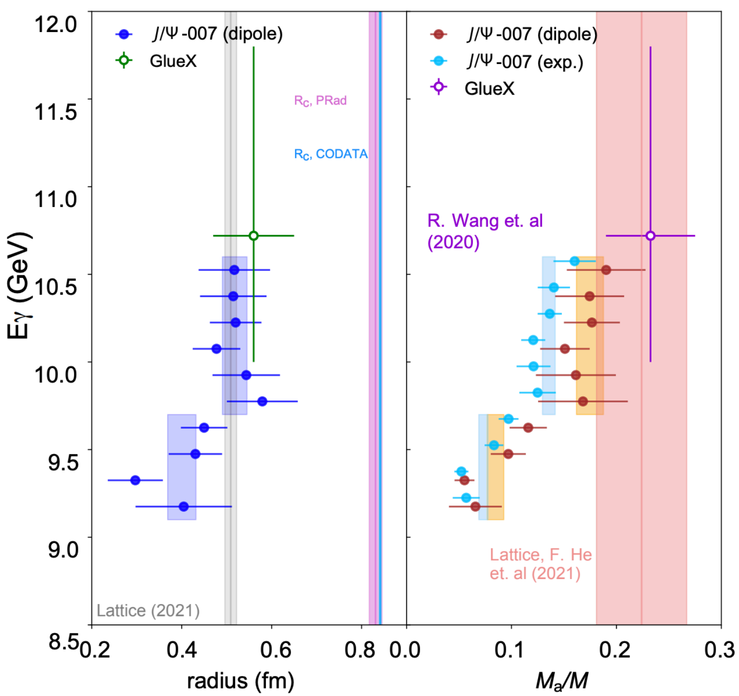
Gravitational Form Factors (model approach) - J/ψ-007





B. Duran et al. (J/ψ-007), Nature 615 (2023)

$k^2 = -t$



Global fit of all Hall C $d\sigma/dt$ data with 3 parameters, m_A, m_C, $C(0)$:

$$A_g(t) = \frac{A_g(0)}{(1 - t/m_A{}^2)^3}, \; C_g(t) = \frac{C_g(0)}{(1 - t/m_C{}^2)^3}, \; D_g(t) = 4C_g(t)$$

($A_g(0)$ fixed from global DIS analysis) using two theoretical models:

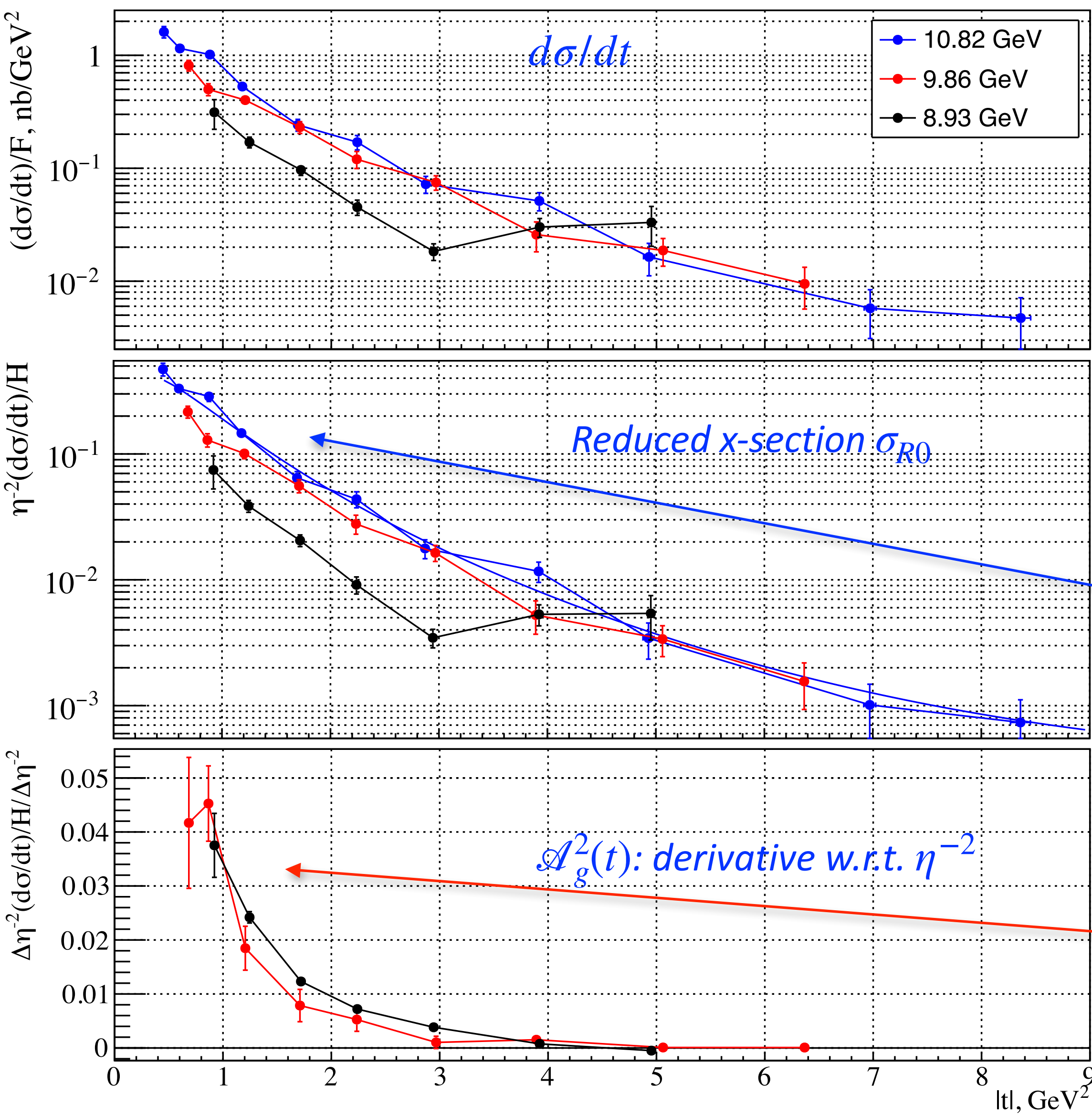
1) Guo, Ji, Liu PRD103 (2023), using GPD factorization

2) Mamo, Zahed PRD101 (2020), holographic QCD, $d\sigma/dt(t)$ directly related to GFF

Lattice calculations of GFF: Pefkou, Hackett, Shanahan PRD105 (2022)

Mass radius and anomalous contribution to proton mass:
Kharzeev et al. NPA 661 (1999), Kharzeev PRD 104 (2021), Guo at al. PRD 103 (2021)

Gluon Form Factors (Holographic Rosenbluth separation) - GlueX data



$$\sigma_{R0} = \frac{d\sigma}{dt}\frac{\eta^{-2}}{H(E_\gamma)} = \eta^{-2}\mathcal{A}_g^2(t) + 8\mathcal{A}_g(t)\mathcal{C}_g(t)$$

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

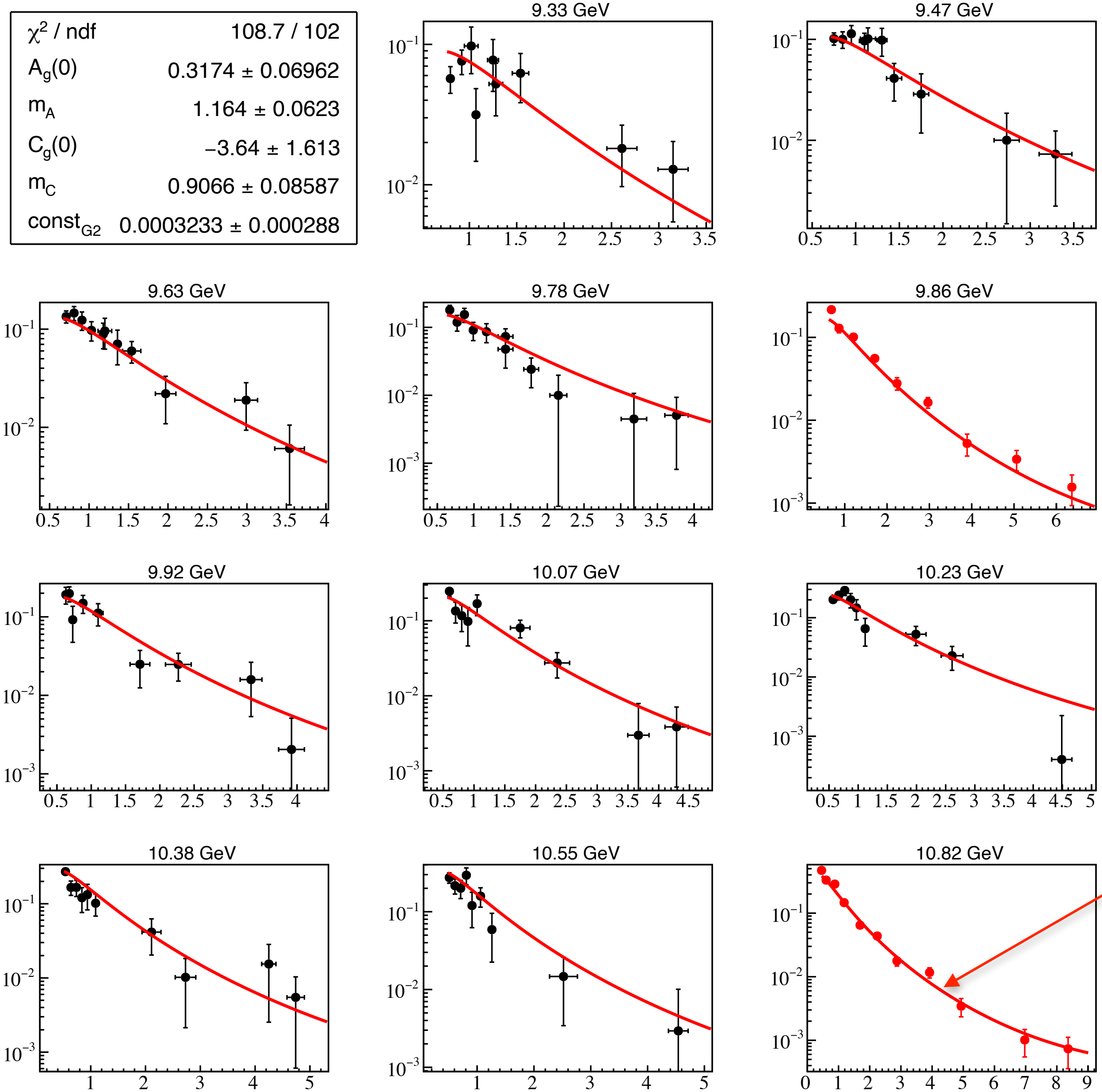
Using highest-energy data at $E_i = 10.82$ GeV as reference and subtract it from all other data at E_j

Requires interpolation of E_i data to match the t-values of the other energies

Energy independence of the $\mathcal{A}_g^2(t)$ functions as a test of the ξ-scaling

Using η-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)

$$\frac{\mathscr{A}_g^2(0)}{(1+t/m_A^2)^4}$$

$$\frac{\mathscr{A}_g(0)\mathscr{C}_g(0)}{(1+t/m_{AC}^2)^4} + const.$$

$$\left(\frac{d\sigma}{dt}\right)\frac{\eta^{-2}}{H(E_\gamma)} = [\mathscr{A}_g^2(t)\eta^{-2} + 8\mathscr{A}_g(t)\mathscr{C}_g(t)]$$

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

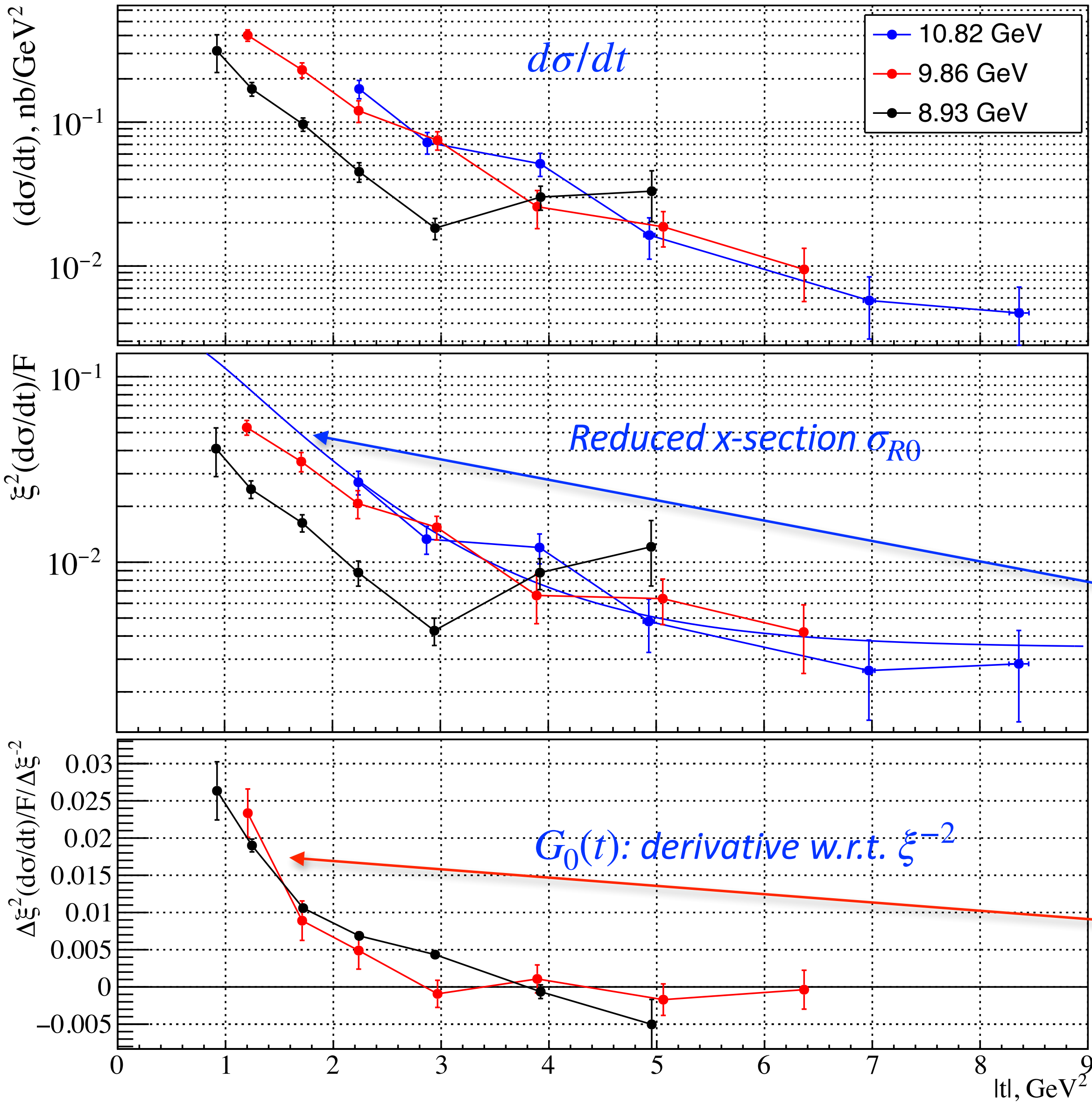
- $\chi^2/ndf \sim 1$ in the chosen kinematic region

Only this fitted function used in the analysis

● GlueX

∘ J/ψ-007

Gluon Form Factors (GPD Rosenbluth separation) - GlueX data



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

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

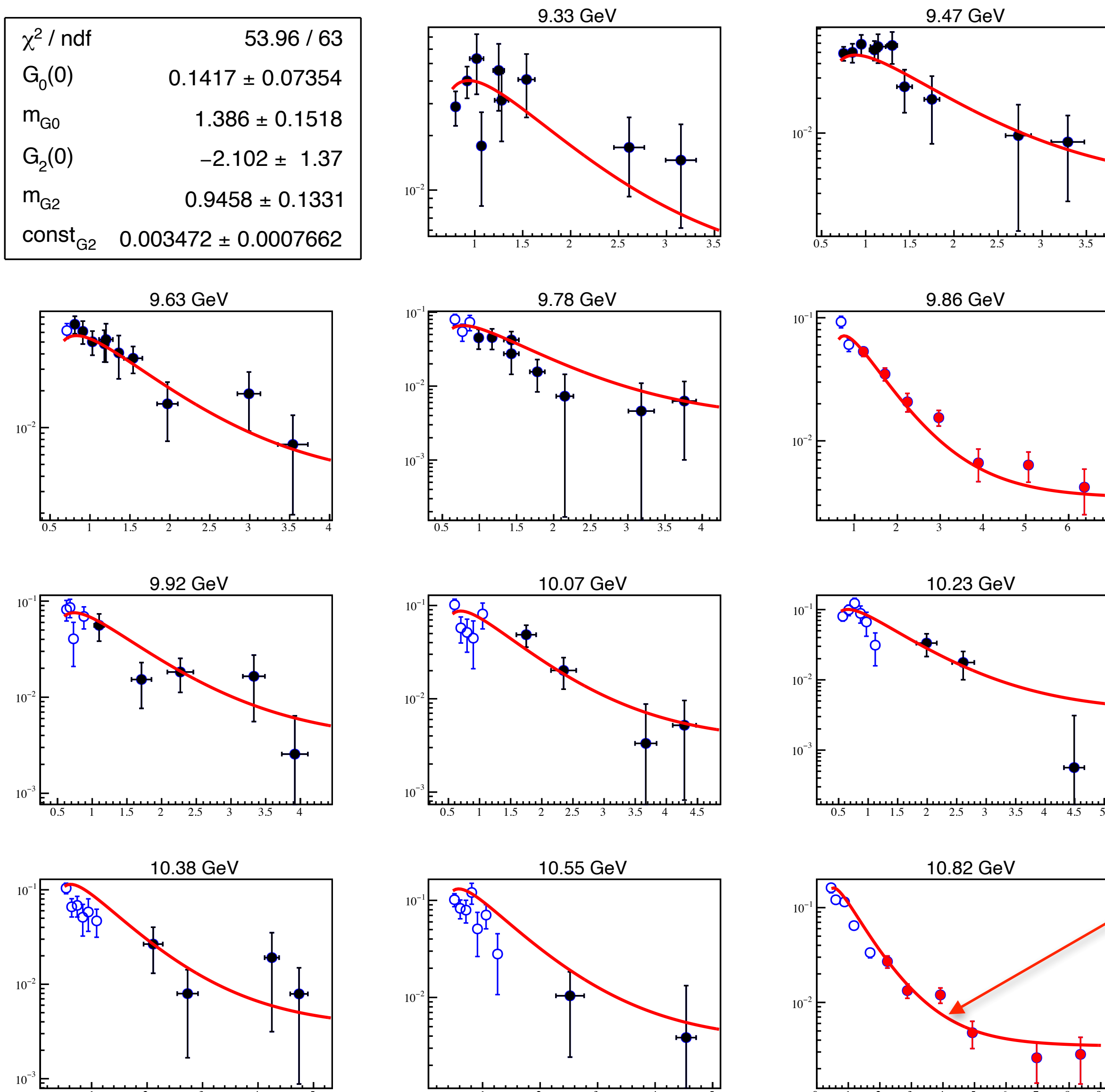
Using highest-energy data at $E_i = 10.82$ GeV as reference and subtract it from all other data at E_j

Requires inter-/extrapolation of E_i data to match the range of the other energies (see next slide)

Energy independence of the $G_i(t)$ functions as a test of the ξ-scaling

Using ξ-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, $\xi > 0.4$)

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

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

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

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

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

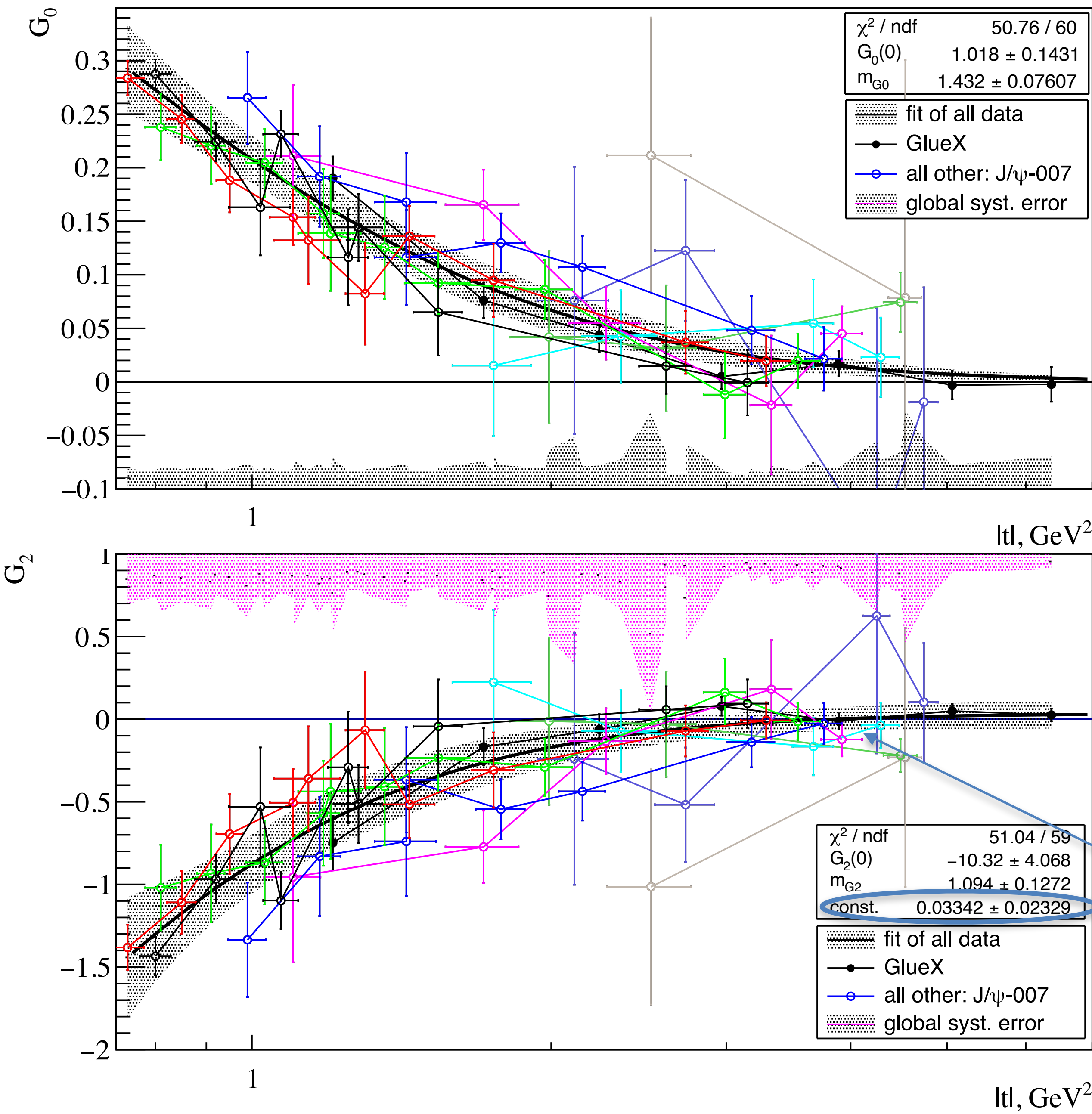
- $\xi < 0.4$ data points (blue) deviate from ξ-scaling

Only this fitted function used in the analysis

- GluEX

∘ J/ψ-007

Gluon Form Factors (GPD Rosenbluth separation) - all data



Energy independence of the $G_i(t)$ functions in agreement with the ξ-scaling

Fits with:

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

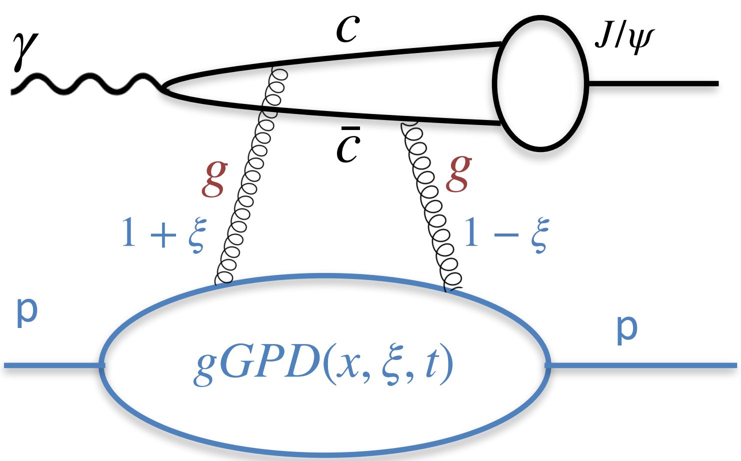
$$\frac{G_2(0)}{(1 - t/m_{G2}^2)^4} + const.$$

$\xi > 0.4$,
$E_\gamma > 9.3$ GeV

G_2 changes sign at high $t > 4\ GeV^2$

LP and E.Chudakov
arXiv:2404.18776

Threshold charmonium photoproduction - GPD approach



- Compton-like amplitudes $\mathscr{H}_{gC}(\xi,t)$, $\mathscr{E}_{gC}(\xi,t)$ and form-factors as in DVCS

However (in contrast to DVCS):

- gluon (not photon) probe
- Threshold kinematics is very different: high momentum transfer t and skewness ξ (in heavy-quark limit: $t \to \infty$ $\xi \to 1$)
- Different expansion of the amplitudes (in x/ξ):

$$Re\mathscr{H}_{gC}(\xi,t) = \sum_{n=0}^{\infty} \frac{2}{\xi^{2n+2}} \mathscr{H}_g^{(2n+1)}(\xi,t) \quad \text{(series in } x/\xi) \qquad \mathscr{H}_g^{(n)}(\xi,t) = \int_0^1 dx\, x^{n-1} H_g(x,\xi,t)$$

$$d\sigma/dt = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)] + \ldots \; (\textit{higher moments} + Im\mathscr{H}_{gC}, Im\mathscr{E}_{gC})$$

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

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

$$G_4(t) = \left(1 - \frac{t}{4m^2}\right)\left(\mathscr{C}_g(t)\right)^2$$

In leading-moment approximation $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$ are proportional to gGFFs $A_g(t)$, $B_g(t)$, $C_g(t)$

GPD analysis by Guo, Ji, Yuan PRD 109 (2024) - absolute calculations, require knowledge of gGFFs

Asymptotic behavior in high ξ region

- To use available data we need expansion in larger $(\xi_{thr}, 1)$ region, ξ_{thr} to be determined from experiment:

$$Re\mathscr{H}_{gC}(\xi,t) = \sum_{n=0}^{\infty} \frac{2}{\xi^{2n+2}} \mathscr{H}_g^{(2n+1)}(\xi,t) \quad \text{(series in } x/\xi\text{)} \qquad \mathscr{H}_g^{(n)}(\xi,t) = \int_0^1 dx\, x^{n-1} H_g(x,\xi,t)$$

$$n=0 \quad \frac{2}{\xi^2} \times \qquad \mathscr{H}_g^{(1)}(\xi,t) = (2\xi)^2 C_g^{(2)}(t) + A_g^{(2)}(t)$$

$$1 \quad \frac{2}{\xi^4} \times \qquad \mathscr{H}_g^{(3)}(\xi,t) = (2\xi)^4 C_g^{(4)}(t) + A_g^{(4,0)}(t) + (2\xi)^2 A_g^{(4,2)}(t)$$

$$2 \quad \frac{2}{\xi^6} \times \qquad \mathscr{H}_g^{(5)}(\xi,t) = (2\xi)^6 C_g^{(6)}(t) + A_g^{(6,0)}(t) + (2\xi)^2 A_g^{(6,2)}(t) + (2\xi)^4 A_g^{(6,4)}(t)$$

....

$$Re\mathscr{H}_{gC}(\xi,t) = \mathscr{C}_g(t) + \xi^{-2}\mathscr{A}_g^{(2)}(t) + \xi^{-4}\mathscr{A}_g^{(4)}(t) + \xi^{-6}\mathscr{A}_g^{(6)}(t) + \ldots$$

$$Re\mathscr{E}_{gC}(\xi,t) = -\mathscr{C}_g(t) + \xi^{-2}\mathscr{B}_g^{(2)}(t) + \xi^{-4}\mathscr{B}_g^{(4)}(t) + \xi^{-6}\mathscr{B}_g^{(6)}(t) + \ldots$$

Leading terms in $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$ are the gGFFs $A_g^{(2)}(t)$, $B_g^{(2)}(t)$, $C_g^{(2)}(t)$

$\mathscr{A}_g^{(2n+2)}(t)$ contain moments of order $\geq 2n+1$

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

Asymptotic behavior in high ξ region

$$\left(d\sigma/dt\right)_{\gamma p\to J/\psi p} = F(E_\gamma)\left[(1-\xi^2)\,|\mathscr{H}_{gC}|^2 - 2\xi^2 Re(\mathscr{H}^*{}_{gC}\mathscr{E}_{gC}) - (\xi^2 + t/4m^2)\,|\mathscr{E}_{gC}|^2\right]$$

$$Re\mathscr{H}_{gC}(\xi,t) = \mathscr{C}_g(t) + \xi^{-2}\mathscr{A}_g^{(2)}(t) + \xi^{-4}\mathscr{A}_g^{(4)}(t) + \xi^{-6}\mathscr{A}_g^{(6)}(t) + \ldots \qquad Im\mathscr{H}_{gC}(\xi,t)\to 0$$

$$Re\mathscr{E}_{gC}(\xi,t) = -\mathscr{C}_g(t) + \xi^{-2}\mathscr{B}_g^{(2)}(t) + \xi^{-4}\mathscr{B}_g^{(4)}(t) + \xi^{-6}\mathscr{B}_g^{(6)}(t) + \ldots \qquad Im\mathscr{E}_{gC}(\xi,t)\to 0$$

$$d\sigma/dt = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)] + \ldots\ (\textit{higher moments} + Im\mathscr{H}_{gC}, Im\mathscr{E}_{gC})$$

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

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

$$G_4(t) = \left(1 - \frac{t}{4m^2}\right)\left(\mathscr{C}_g(t)\right)^2$$

In leading-moment approximation $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$ are proportional to gGFFs $A_g(t)$, $B_g(t)$, $C_g(t)$

How to check this ξ-asymptotic formula against data:

- In which $(\xi_{thr}, 1)$ region it is valid?
- Can we extract $G_i(t)$ as data points, without (with minimal) additional model assumptions?
- Are there qualitative features in the data that correspond to this ξ-behavior?

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

Summary on Gluon Form Factors

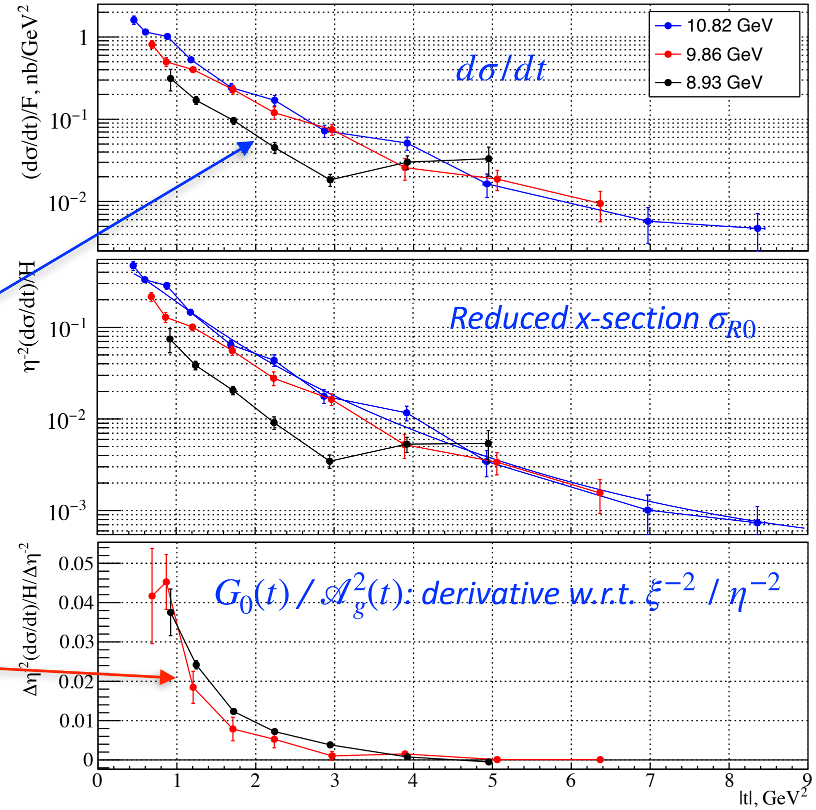
- Check with all JLab data if

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

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = H(E_\gamma)[\mathcal{A}_g^2(t) + \eta^2 8\mathcal{A}_g(t)\mathcal{C}_g(t)] + \dots$$

is valid (for GPD: ξ above some ξ_{thr})

- We found that (for GPD: also $\xi > 0.4$), despite big differences in $d\sigma/dt$ for different energies, extracted $G_i(t)$, $\mathcal{A}_g(t)$, $\mathcal{C}_g(t)$ data points are energy independent (within errors)
- Agreement with lattice - would work in leading-term approximation
- General agreement b/n GPD and Holographic



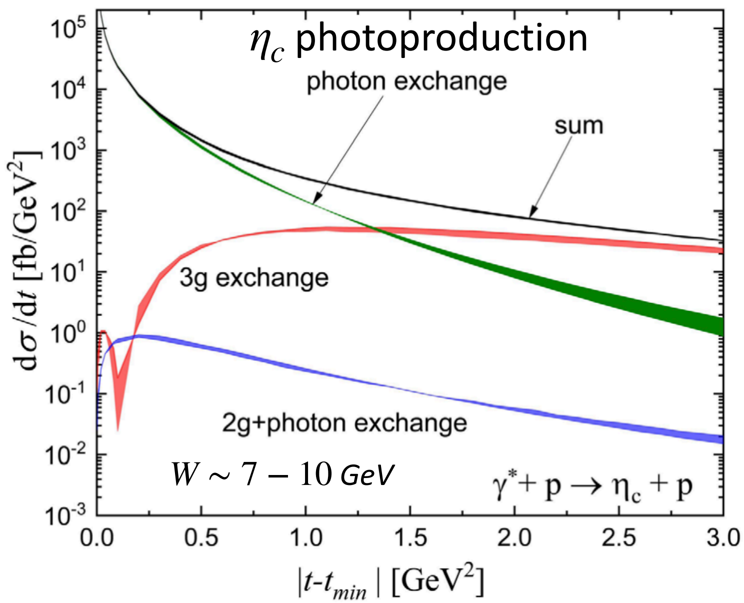
- As $G_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\xi^{-2}(E_i,t) - \xi^{-2}(E_j,t)\right] > 0$ $\left(G_0(t) = \left(\mathcal{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathcal{B}_g^{(2)}(t)\right)^2 > 0\right)$

> 0 *for* $E_i > E_j$

$\frac{d\sigma}{dt}(E_i,t)\frac{\xi^2(E_i,t)}{F(E_i)} > \frac{d\sigma}{dt}(E_j,t)\frac{\xi^2(E_j,t)}{F(E_j)}$, $E_i > E_j$ or in particular $d\sigma/dt(E,t)$ at fixed t increases with E

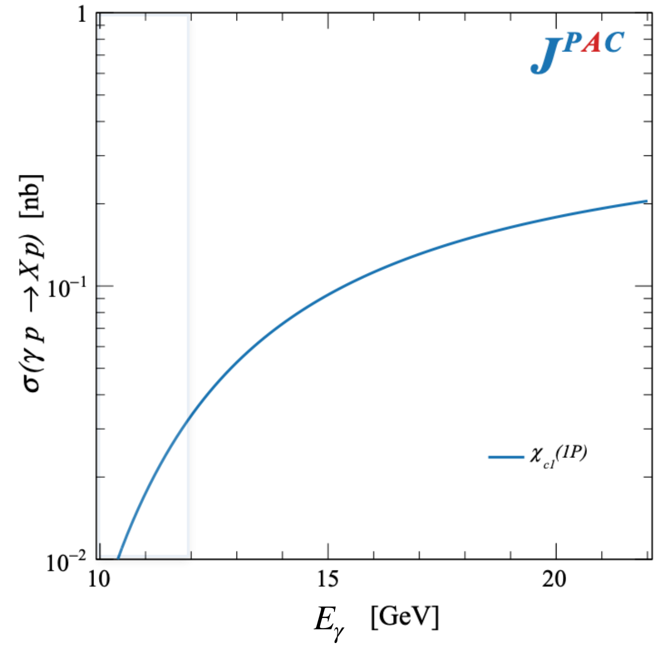
C-even charmonium states with GlueX

C-odd (J/ψ, ψ') vs C-even (χ_c) production

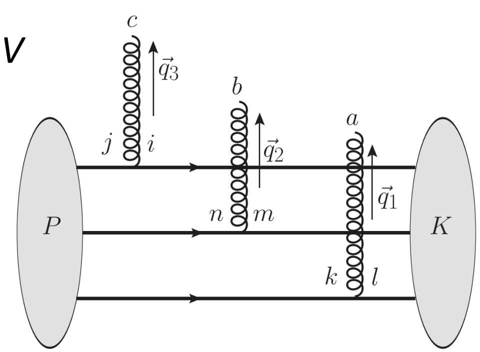


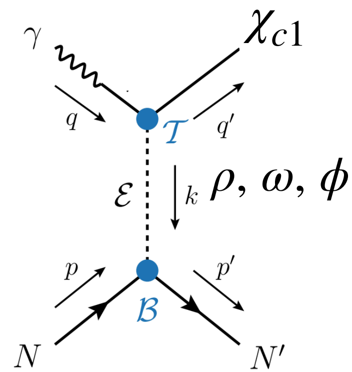
Dumitru, Skokov, Stebel, PRD 101 (2020), Dumitru, Stebel, PRD 99 (2019)

$W \sim 7 - 10$ *GeV*



JPAC, PRD 102 (2020)

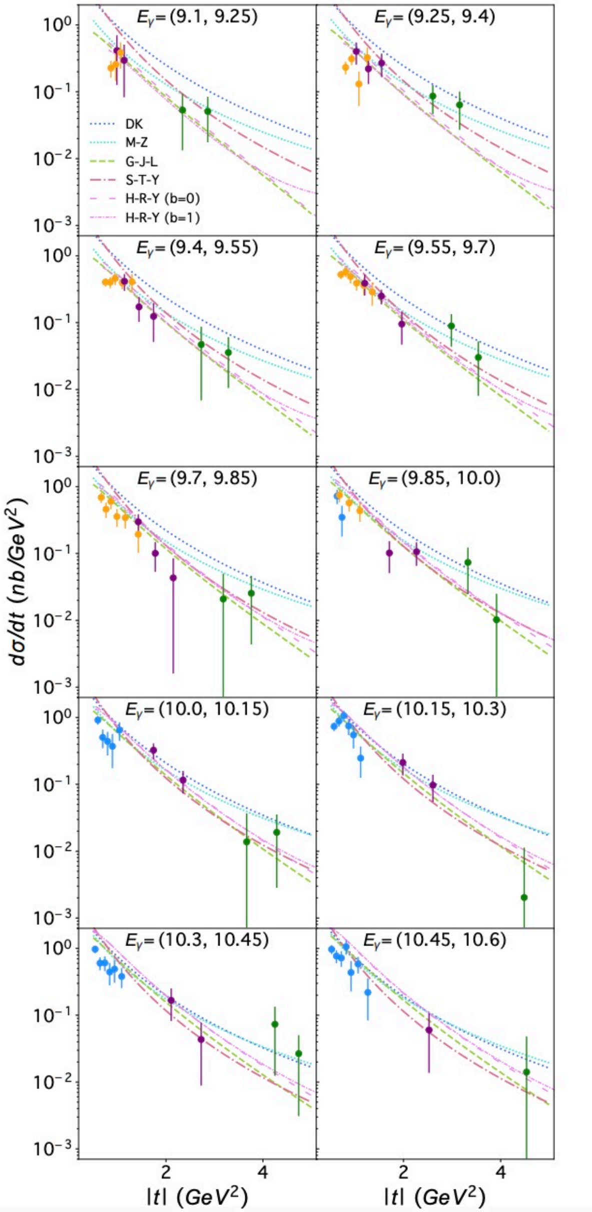




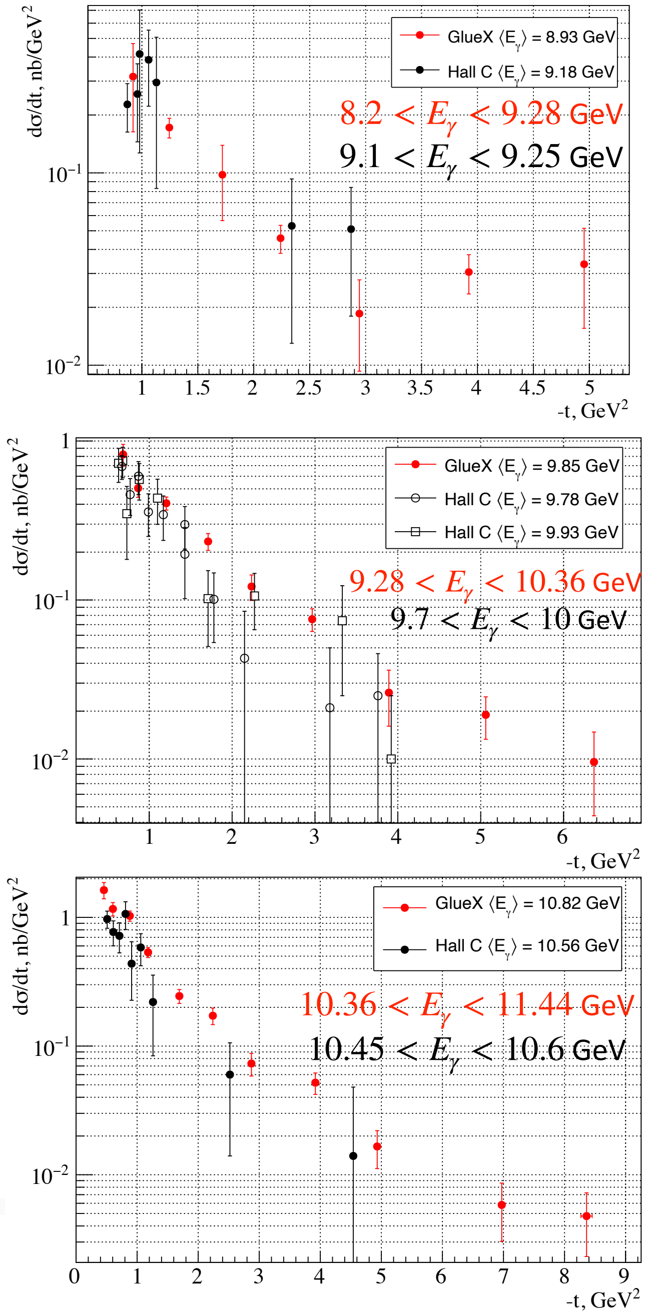
- High energies - perturbative calculation - Odderon (odd-parity Pomeron) 3g exchange

- Low energies - non-perturbative approach, vector meson exchange

Differential cross sections from J/ψ-007 and GlueX



B. Duran et al. (J/ψ-007), Nature 615 (2023)



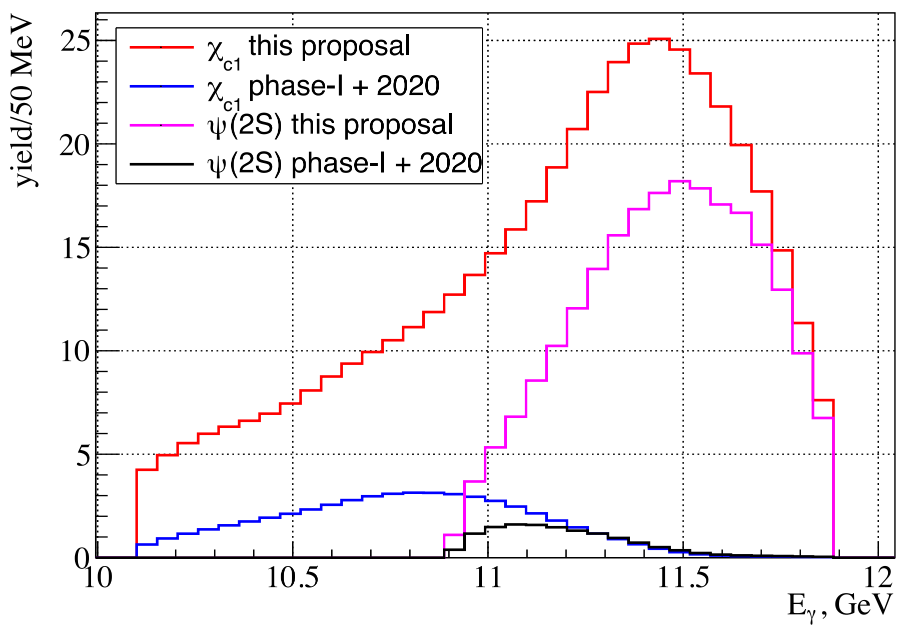
- 10 energy bins in J/ψ-007
- Results for the three **GlueX energy bins** compared to closest **Hall C (J/ψ-007) energies**
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies

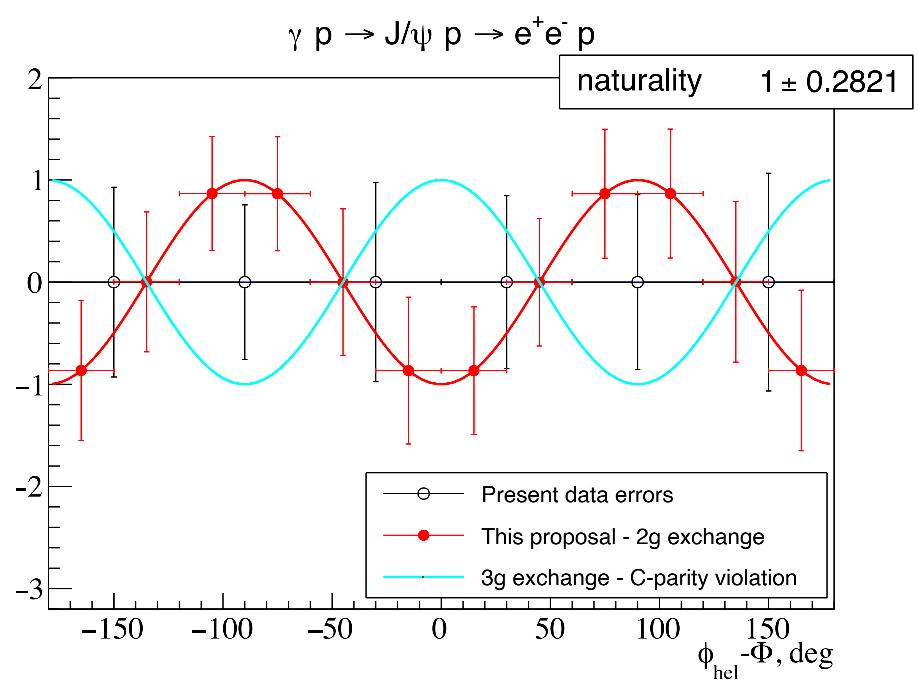
S.Adhikari et al. (GlueX), Phys. Rev. C 108 (2023)

Prospect for charmonium threshold production with GlueX

- GlueX has planned running till 2025 (phase-II) and proposal for phase-III (double intensity and assuming $E_e = 12$ GeV):

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