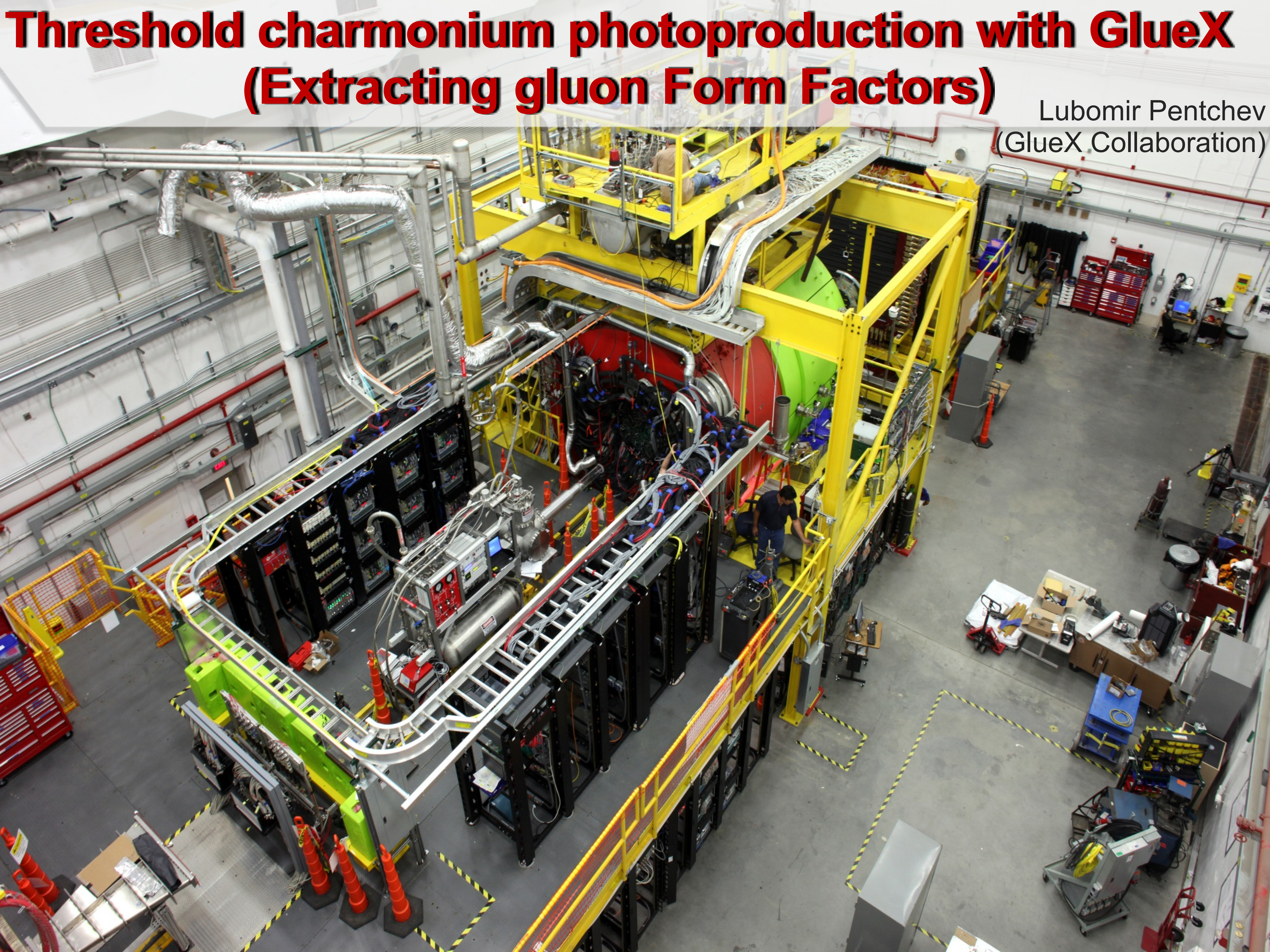
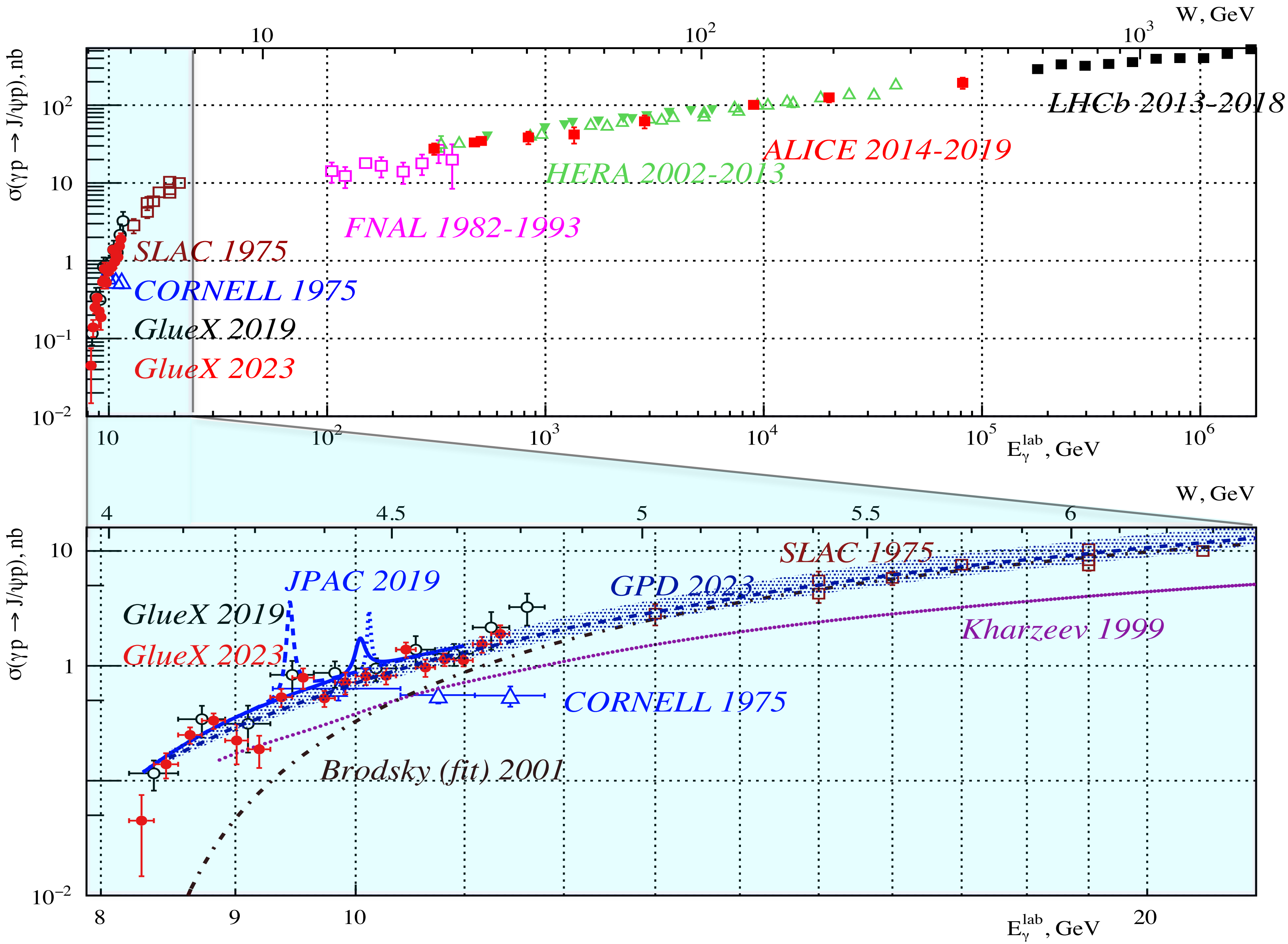
Threshold charmonium photoproduction with GlueX
(Extracting gluon Form Factors)

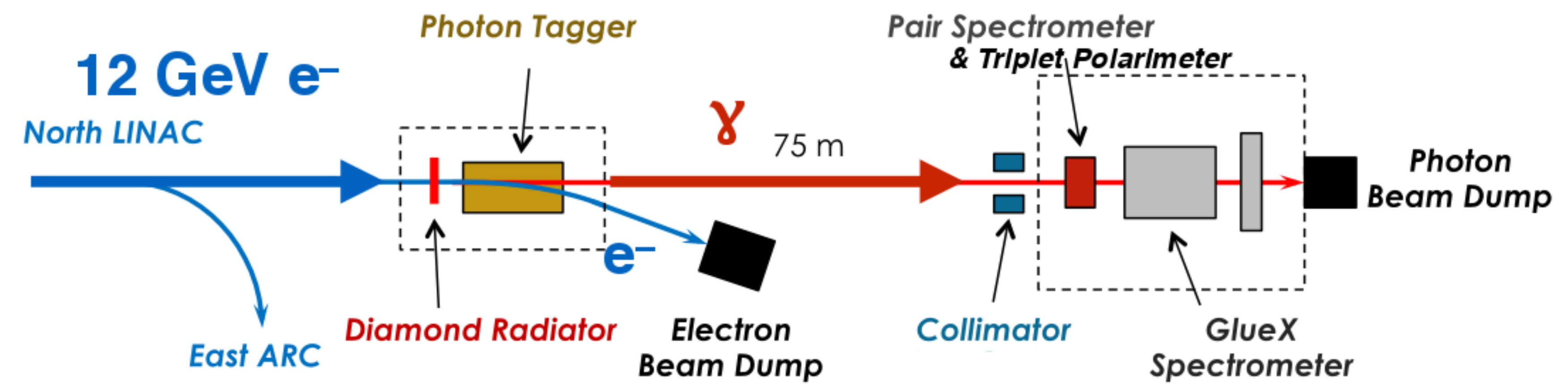
Lubomir Pentchev
(GlueX Collaboration)

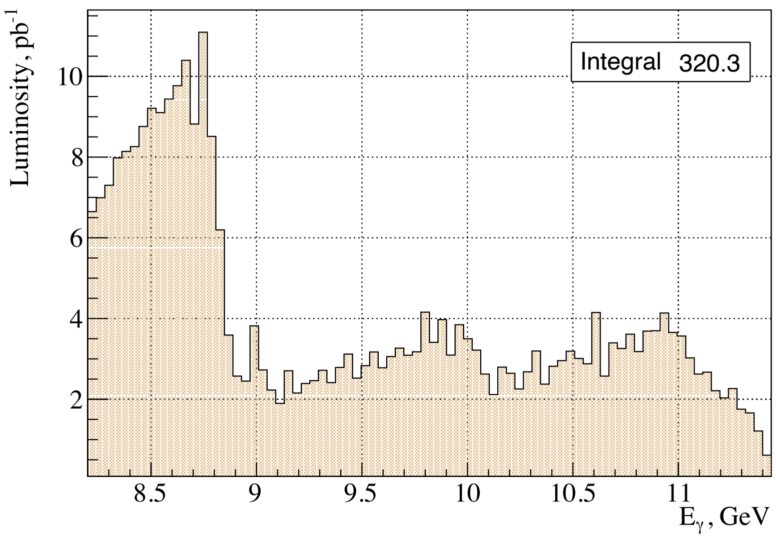


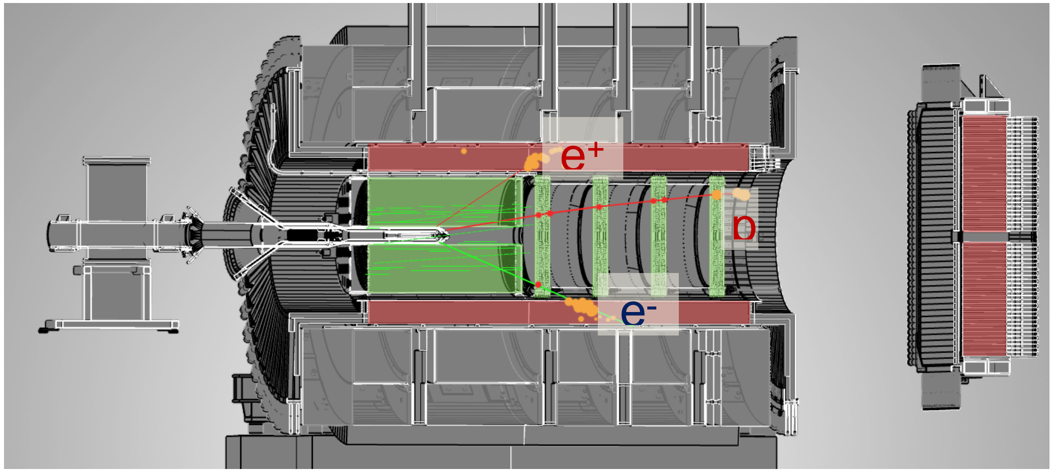
~50 years J/ψ photoproduction



Hall D beam line and detector



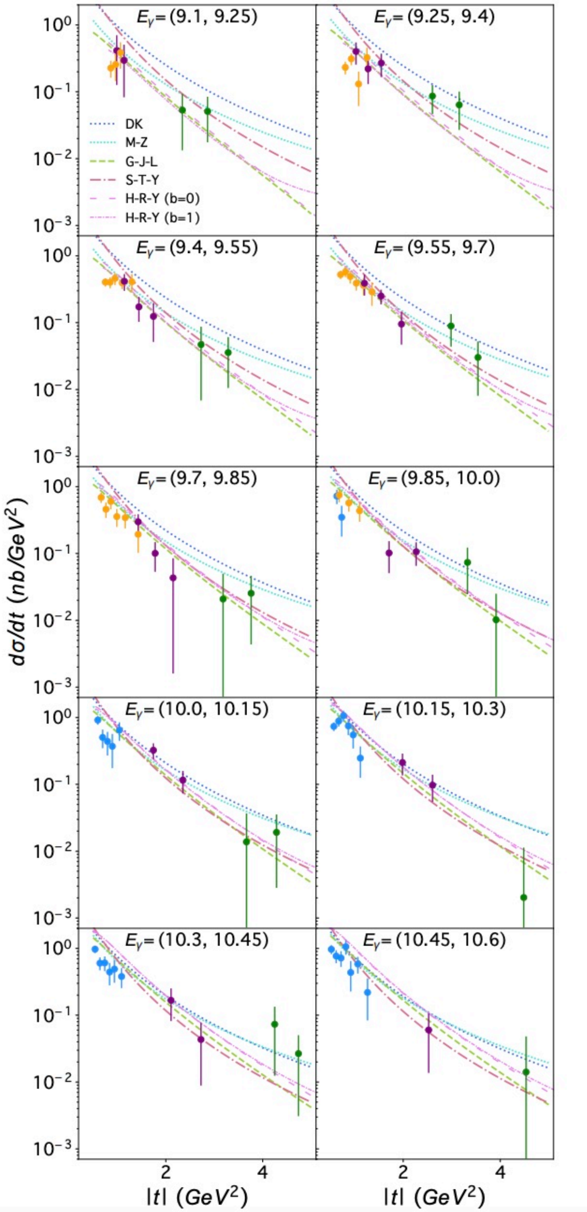




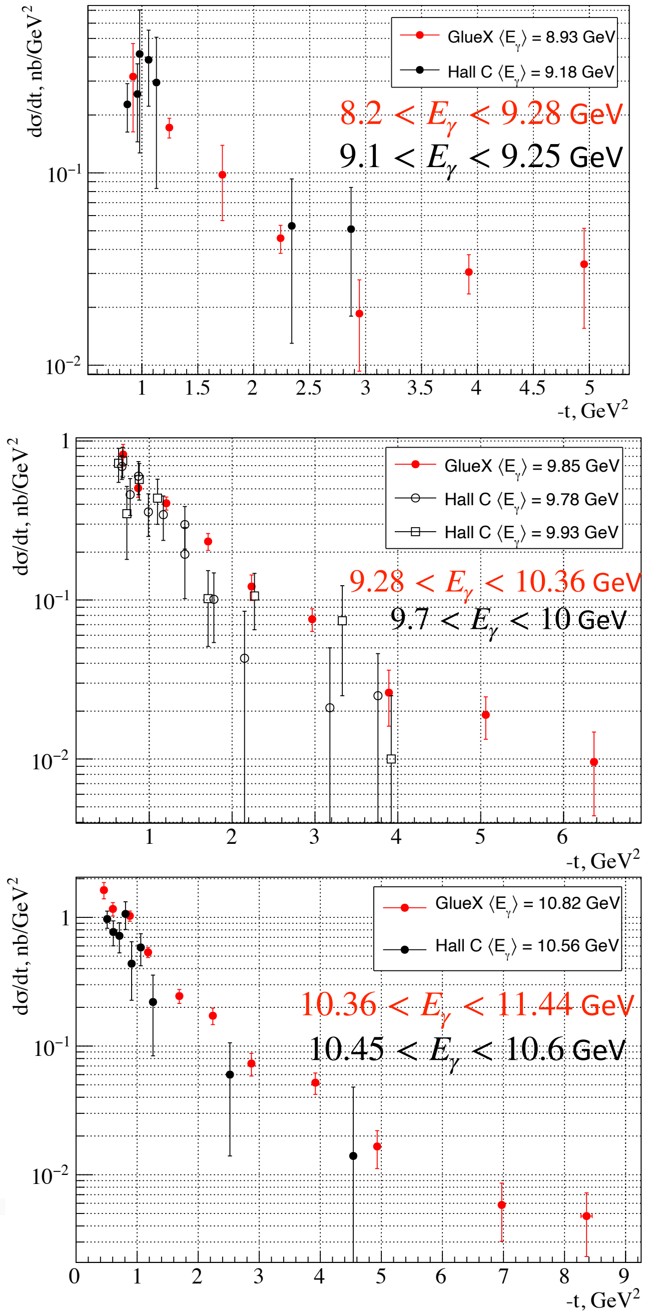
Hall D GlueX $\gamma p \to J/\psi p \to e^+e^-p$

- Linearly-polarized photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Intensity: $\sim 2\ 10^7 - 5\ 10^7\ \gamma/sec$ above J/ψ threshold (8.2 GeV)

Differential cross sections from J/ψ-007 and GlueX



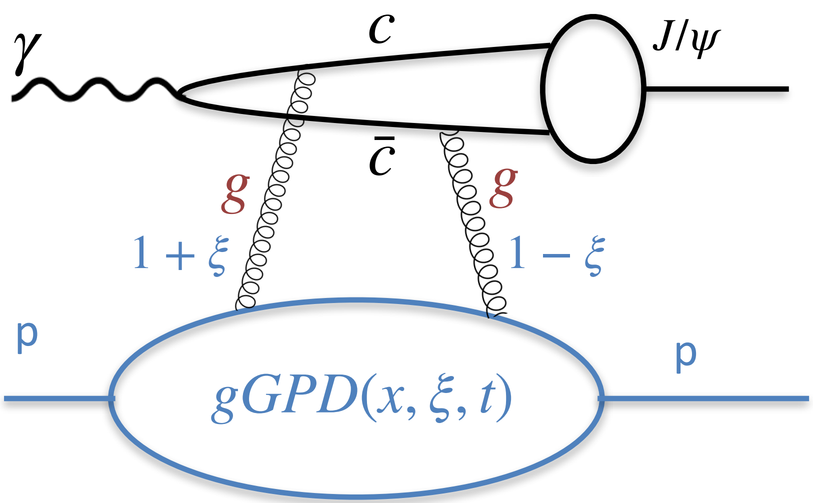
B. Duran et al. (J/ψ-007), Nature 615 (2023)



- 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)

Threshold charmonium photoproduction - GPD approach



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

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

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)

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

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

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

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

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

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

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

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

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

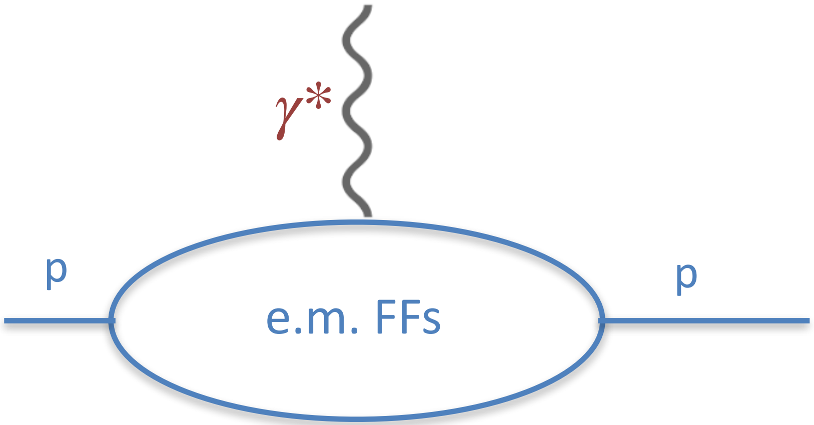
In leading-moment approximation $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$ are proportional to gGFFs $A_g(t)$, $B_g(t)$, $C_g(t)$

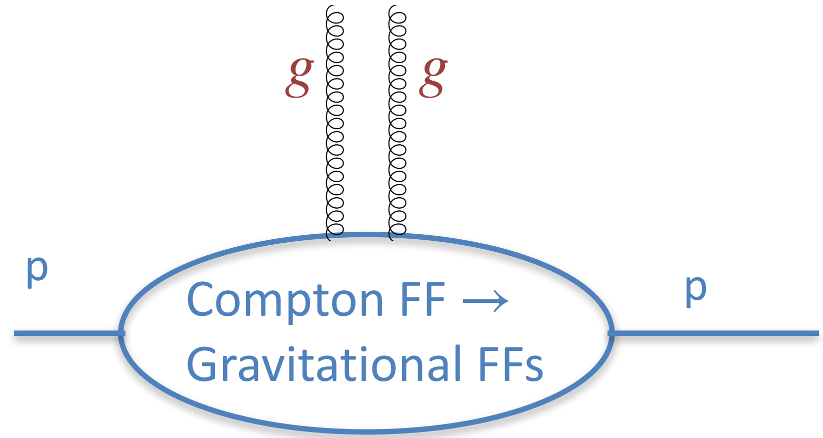
How to check this ξ-asymptotic formula against data:

- 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)

Gluon Form Factors





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

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

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

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

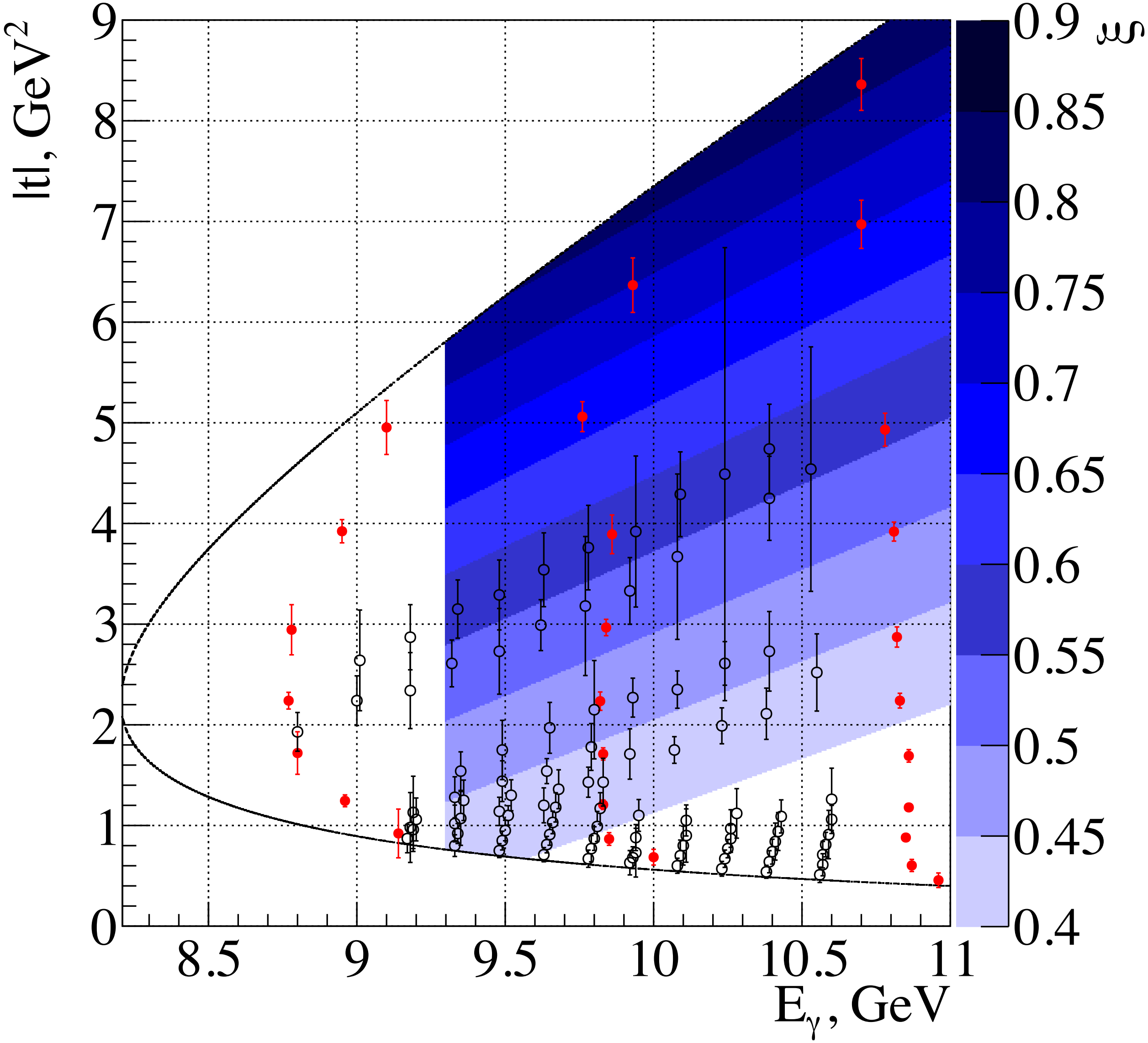
$$A_g(t), B_g(t), C_g(t) \sim \frac{1}{(1 - t/m_i^2)^{2(3)}}$$

Rosenbluth separation

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

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

Data used for extraction of gluon FFs



$\xi > 0.4$

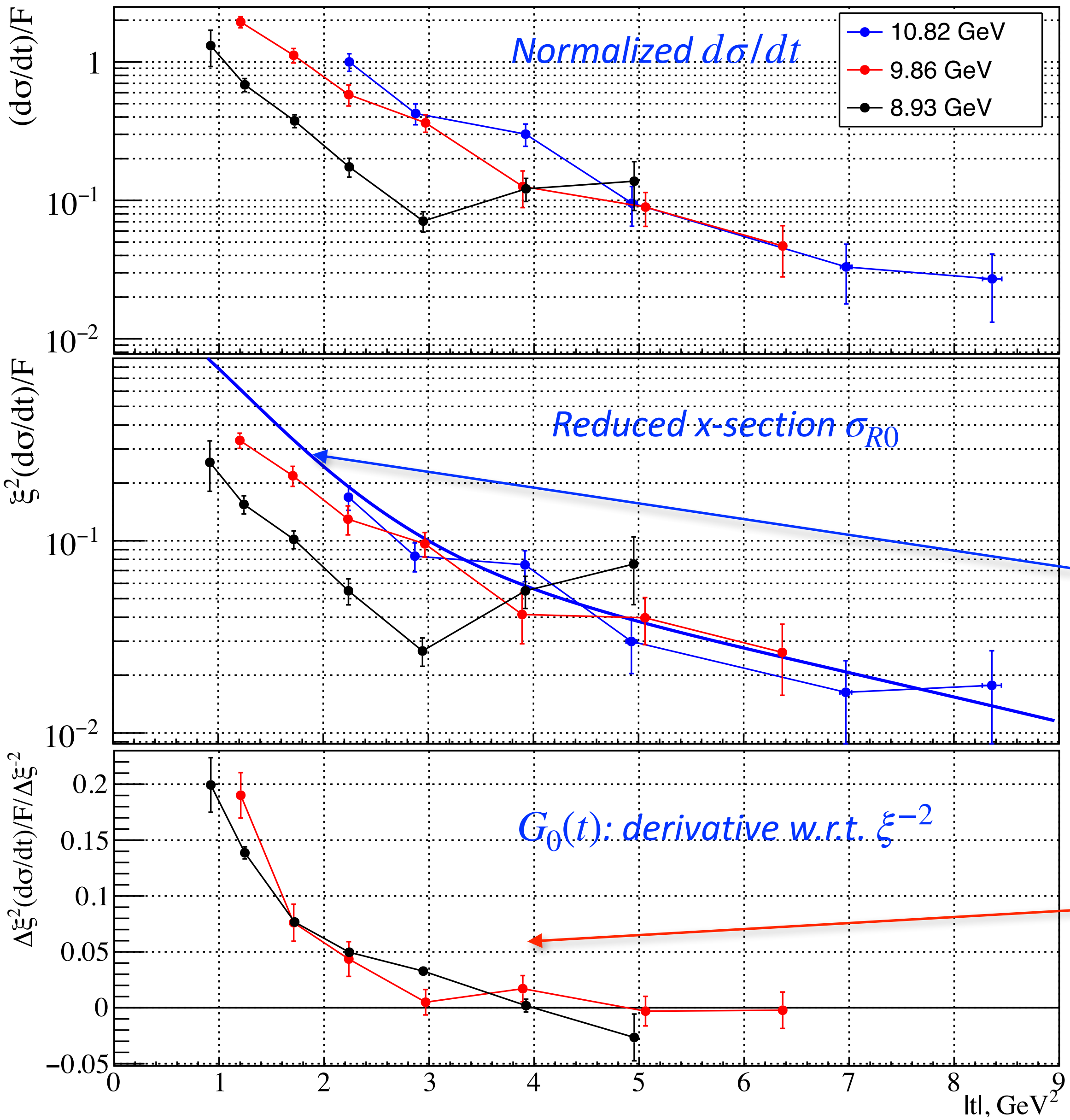
$E_\gamma > 9.3$ GeV (away from $\bar{D}\Lambda_C$ and $\bar{D}^*\Lambda_C$ thresholds)

● GlueX

○ J/ψ-007

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

Gluon Form Factors (Rosenbluth separation) - GlueX data



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

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

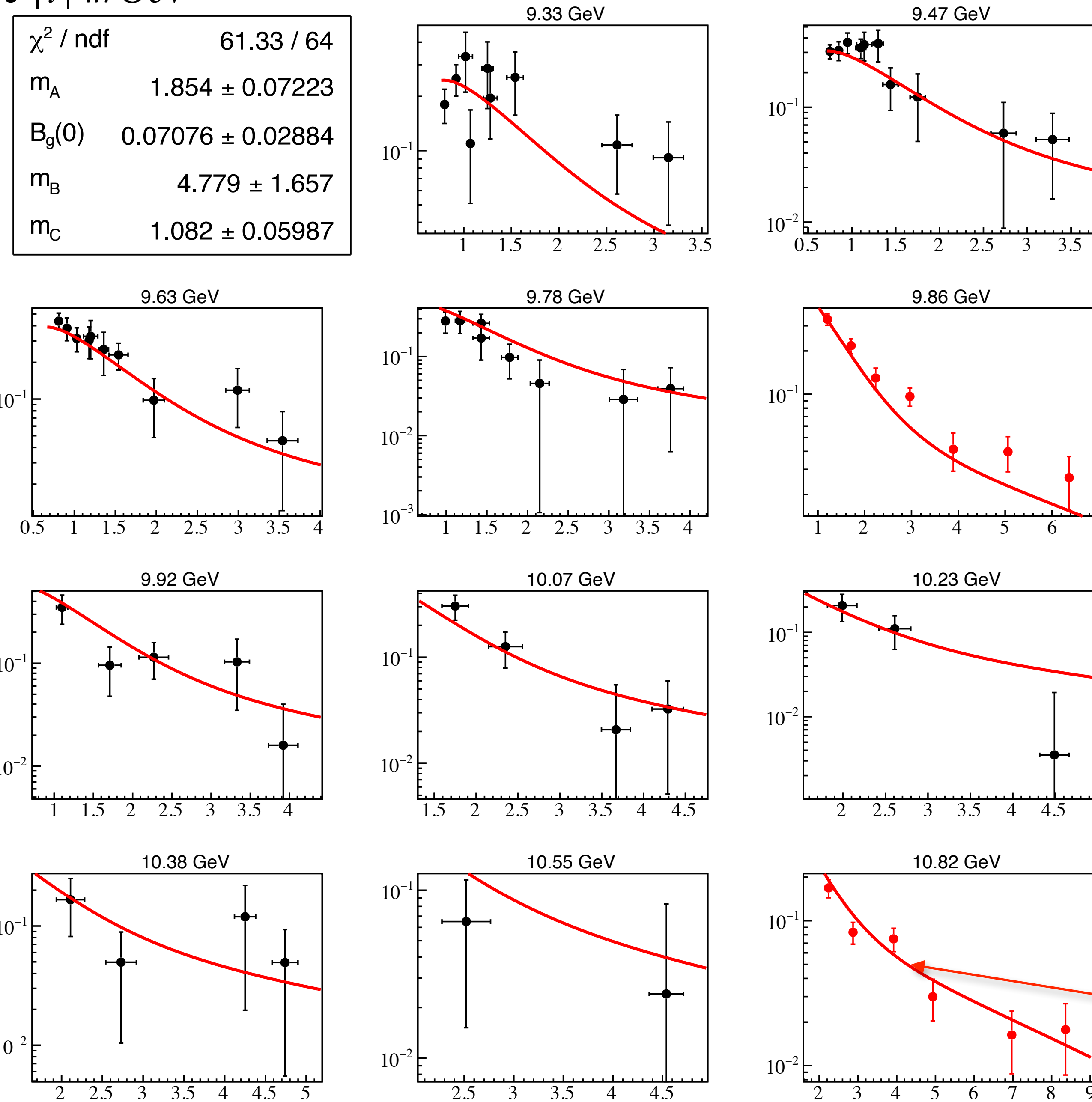
Using highest-energy data at $E_i = 10.82$ GeV as reference and subtract it from all other data at E_j

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

Global fit of JLab data

σ_{R0} *vs* $|t|$ *in* GeV^2



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

- GlueX
- J/ψ-007

Fit in leading-moment approx.

$$A_g(t) = \frac{A_g(0)}{(1 + t/M_A{}^2)^3}$$

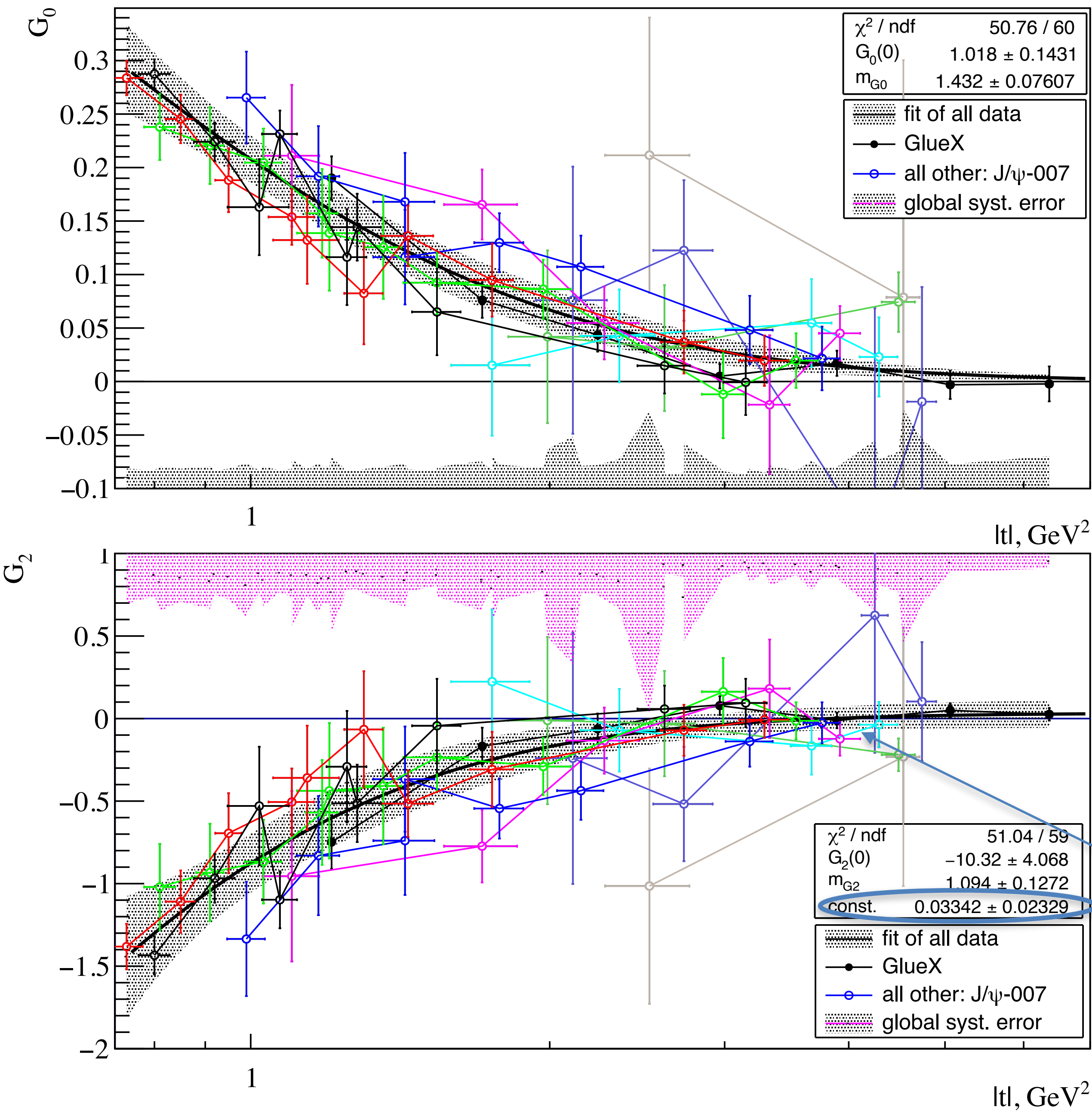
$$B_g(t) = \frac{B_g(0)}{(1 + t/M_B{}^2)^3}$$

$$C_g(t) = \frac{C_g(0)}{(1 + t/M_C{}^2)^3}$$

$A_g(0) = 0.414$, *gluon momentum fraction (CT18)*
$C_g(0) = -0.642$, *lattice Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)*

Only this fitted function used in the analysis

Gluon Form Factors (Rosenbluth separation) - all data



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

Fits with:

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

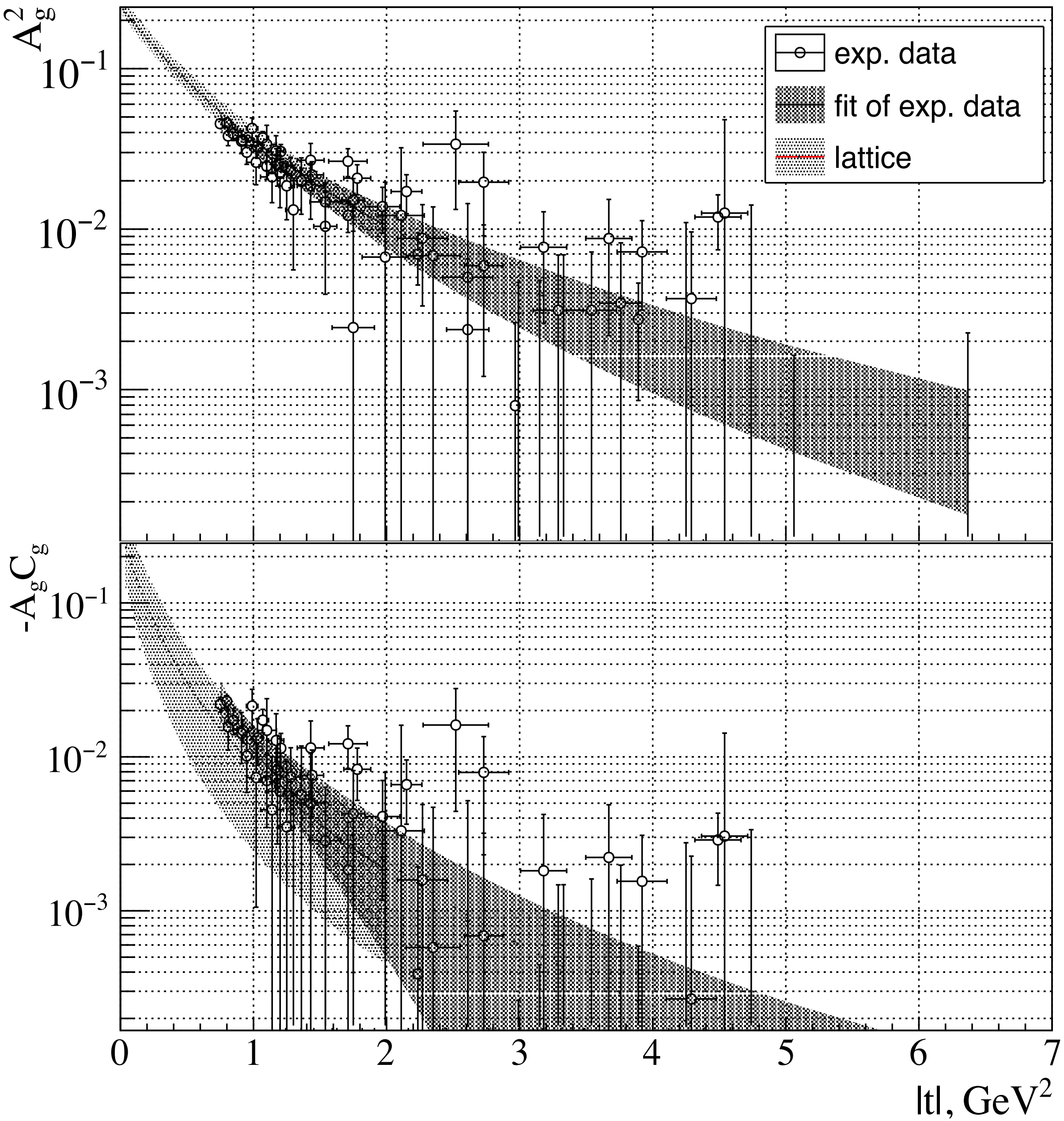
$$\frac{G_2(0)}{(1 - t/m_{G2}^2)^4} + const.$$

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

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

LP and E.Chudakov
arXiv:2404.18776

Gluon Gravitational Form Factors - all data



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

$$G_2(t) = 2\mathcal{A}_g(t)\mathcal{C}_g(t) + $$

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

In leading-moment approximation access to gluon GFFs $A_g(t)$, $C_g(t)$

(neglecting $B_g(t)$):

$$G_0(t) \approx (2A_1^{conf} A_g(t))^2$$

$$G_0(t) + G_2(t) \approx (2A_1^{conf} A_g(t))(8A_1^{conf} C_g(t))$$

$$A_1^{conf} = 5/4$$

also calculated on lattice:

Pefkou, Hackett, Shanahan PRD105 (2022), Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)

Note however, we have used:

$A_g(0) = 0.414$,

$C_g(0) = -0.642$

when extrapolating reference energy data

LP and E.Chudakov arXiv:2404.18776

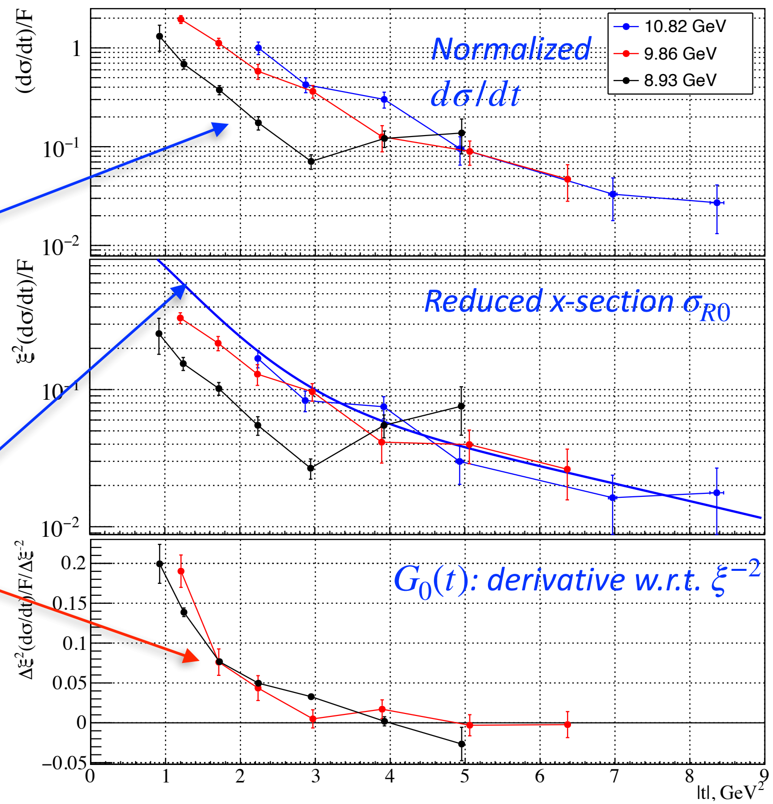
Summary (so far) on Gluon Form Factors

- Check with all JLab data if

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

is valid for ξ above some ξ_{thr}

- We found that for $\xi > 0.4$, despite big differences in $d\sigma/dt$ for different energies, extracted $G_i(t)$ data points are energy independent (within errors)
- $\xi_{thr} = 0.4$ is too low according to GPD analysis?
  - 0.4 should be consider as lower limit, it may go up with improved statistics
  - ξ-scaling might be more general feature
- In leading-moment approximation - agreement with lattice (note: $A_g(0)$, $C_g(0)$ fixed in the extrapolation)



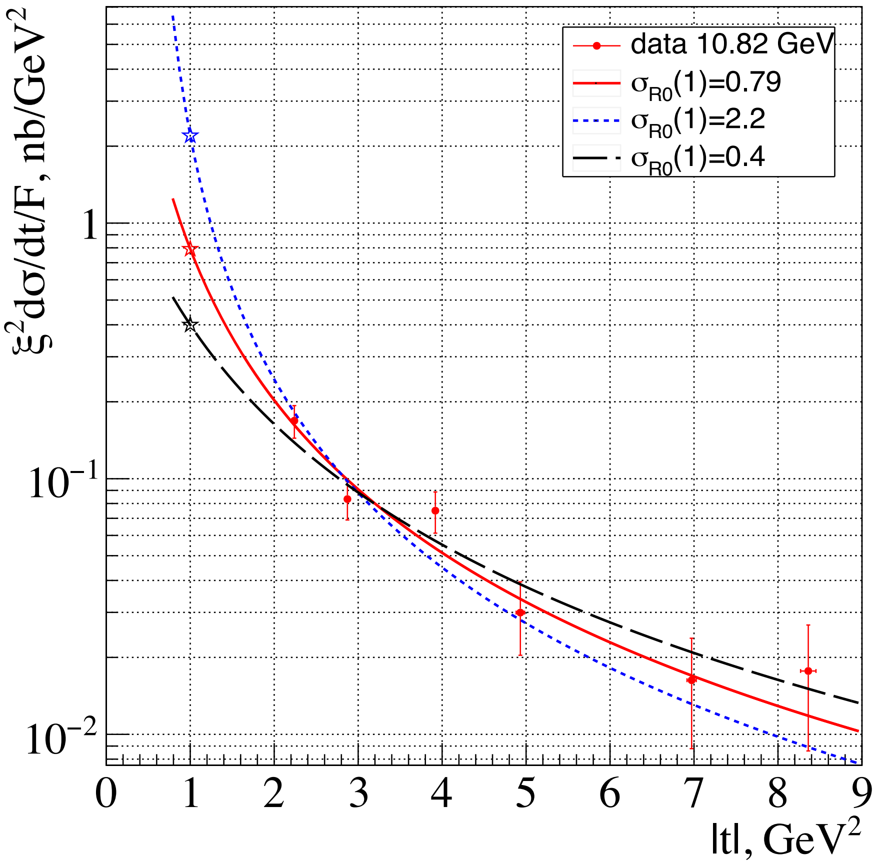
- As $G_0(t) = \left[\sigma_{R0}(E_i,t) - \sigma_{R0}(E_j,t)\right] / \left[\xi^{-2}(E_i,t) - \xi^{-2}(E_j,t)\right] > 0$ $\left(G_0(t) = \left(\mathscr{A}_g^{(2)}(t)\right)^2 - \frac{t}{4m^2}\left(\mathscr{B}_g^{(2)}(t)\right)^2 > 0\right)$

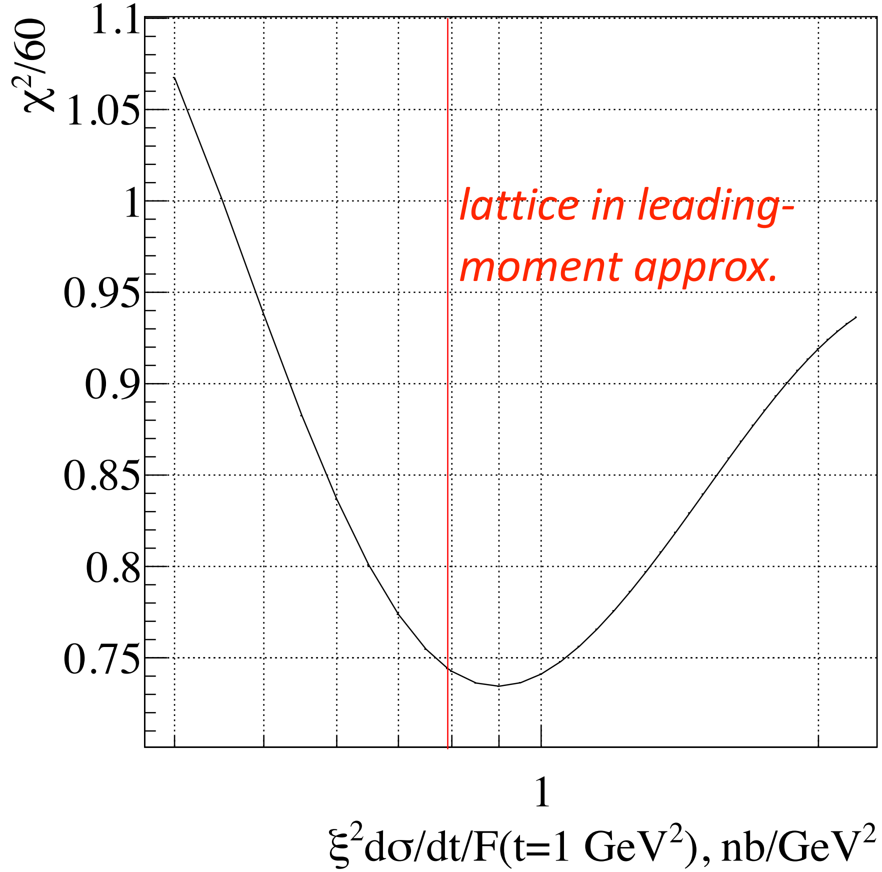
$> 0 \;\; for \;\; E_i > E_j$

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

Example of model-independent extrapolation

Instead of constraining $A_g(0)$ and $C_g(0)$, vary σ_{R0} at $t = 1\ GeV^2$ to minimize the χ^2 of the $G_0(t)$ fit, i.e. requiring energy independence of G_0



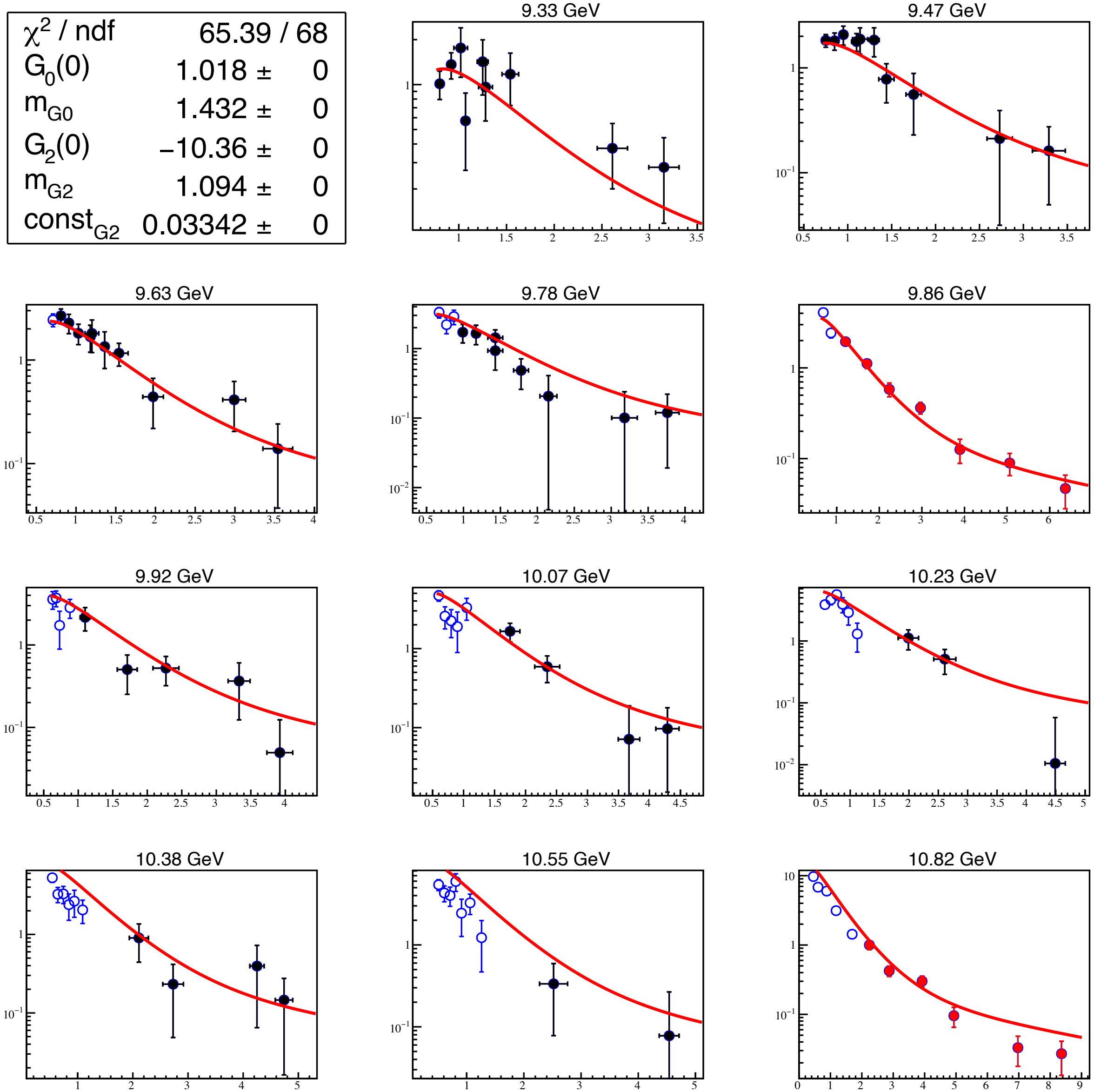


Requires much higher statistics!

Using extracted $G_i(t)$ functions to describe data

$d\sigma/dt\ (nb/GeV^2)$ vs $|t|\ (GeV^2)$

χ^2 / ndf	65.39 / 68
$G_0(0)$	1.018 ± 0
m_{G0}	1.432 ± 0
$G_2(0)$	−10.36 ± 0
m_{G2}	1.094 ± 0
$const_{G2}$	0.03342 ± 0



Upturn the problem:

How the parametrized G_0 and G_2:

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

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

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

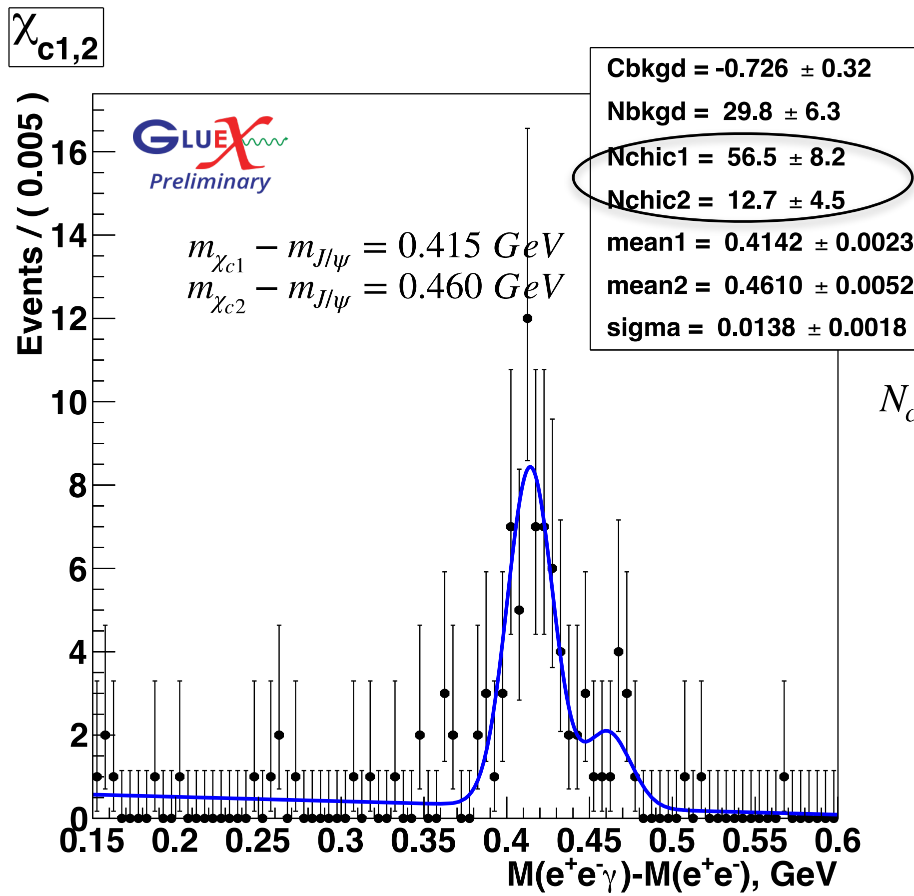
describe the data?

- $\chi^2/ndf \sim 1$ (not a fit) in the chosen kinematic region
- G_2 sign change responsible for describing $t > 4\ GeV^2$ data
- $\xi < 0.4$ data points (blue) deviate from ξ-scaling

Threshold photoproduction of higher-mass charmonium states

C-event charmonium states at threshold with GlueX

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



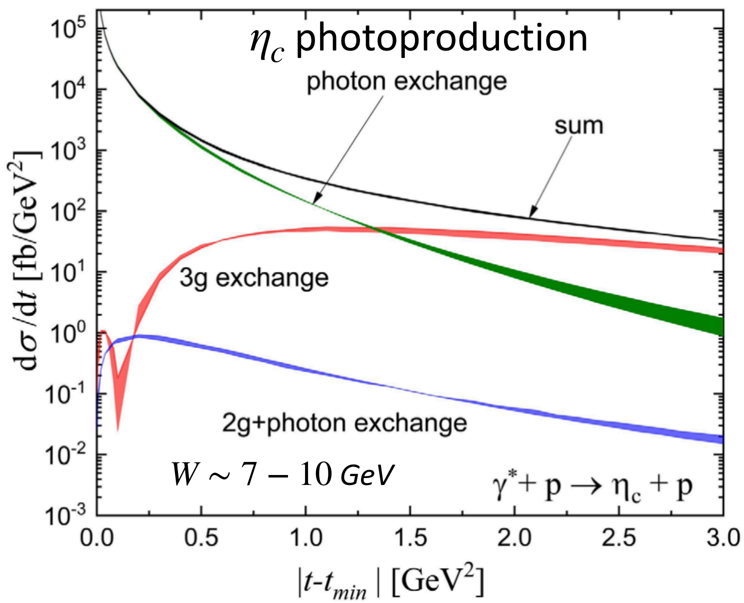
$$N_{c1}e^{-\frac{(x-m1)^2}{2\sigma^2}} + N_{c2}e^{-\frac{(x-m2)^2}{2\sigma^2}}$$

- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV

First ever evidence for photoproduction of C-even charmonium

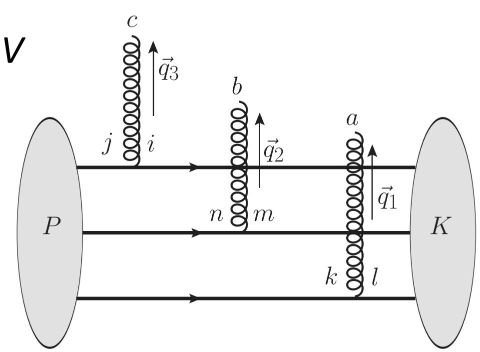
C-even charmonium states with GlueX

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

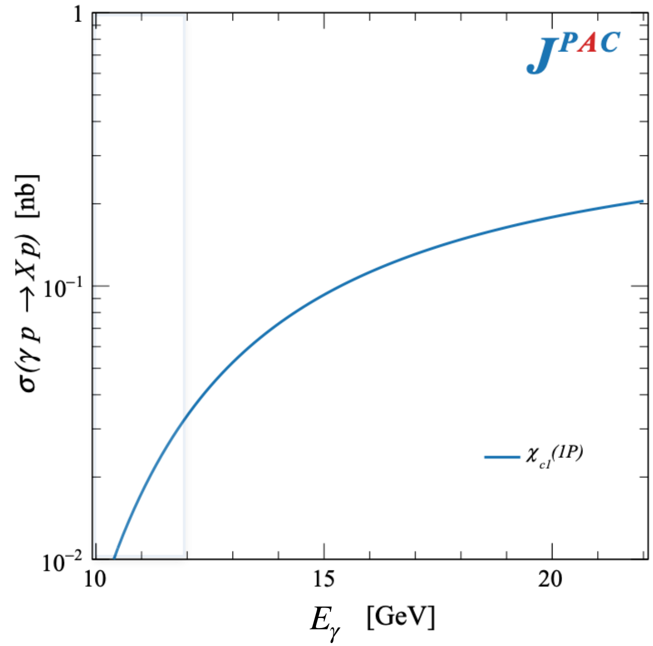


Dumitru, Skokov, Stebel, PRD 101 (2020), Dumitru, Stebel, PRD 99 (2019)

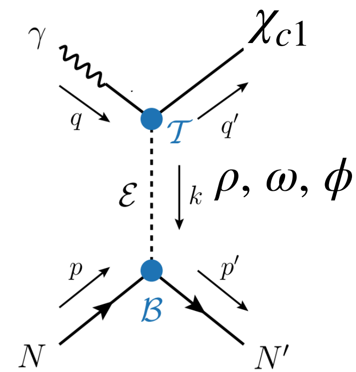
$W \sim 7 - 10$ GeV



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



JPAC, PRD 102 (2020)

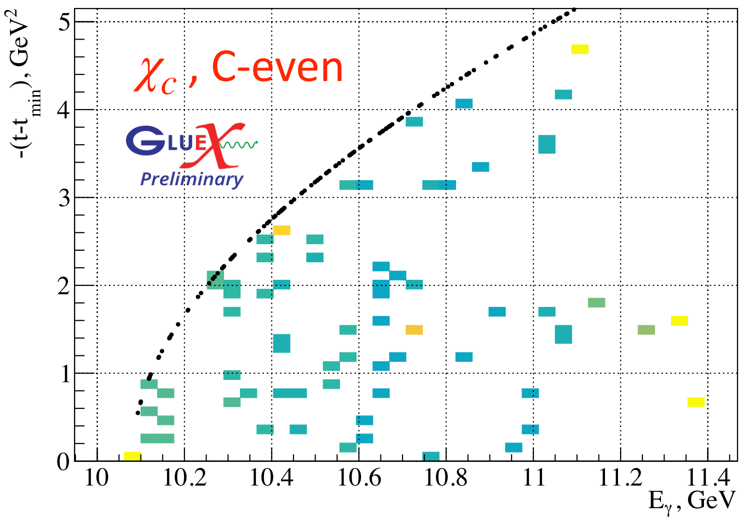


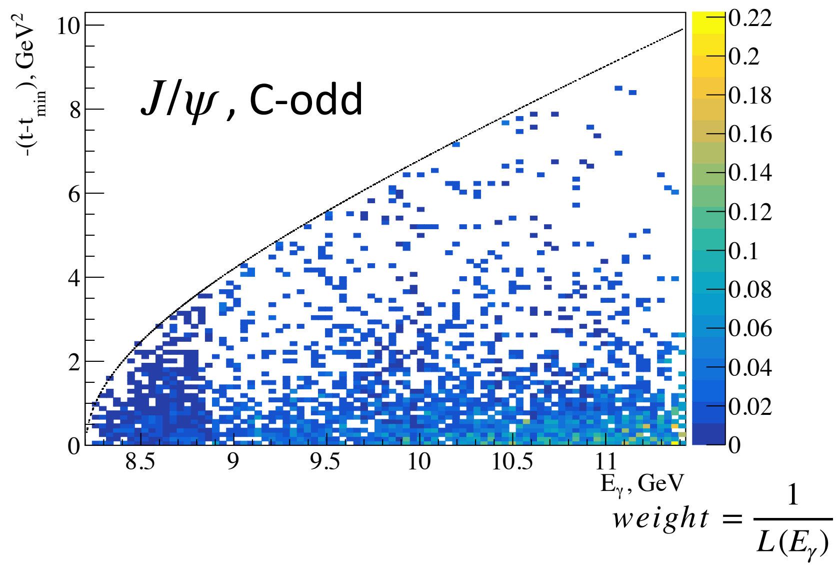
- Low energies - non-perturbative approach, vector meson exchange

C-even charmonium states with GlueX

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

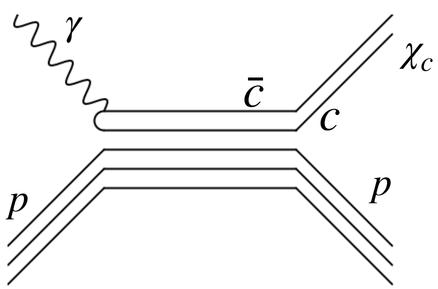
- Dramatic difference: χ_c distribution in (E_γ, t) vs J/ψ



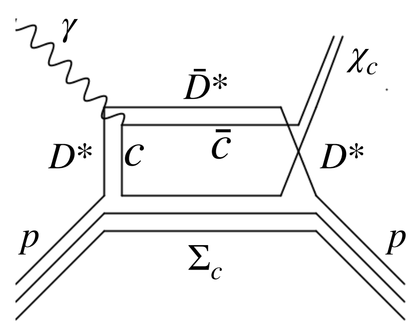


- At threshold other possible mechanisms may dominate:

S-channel exchange of 5q



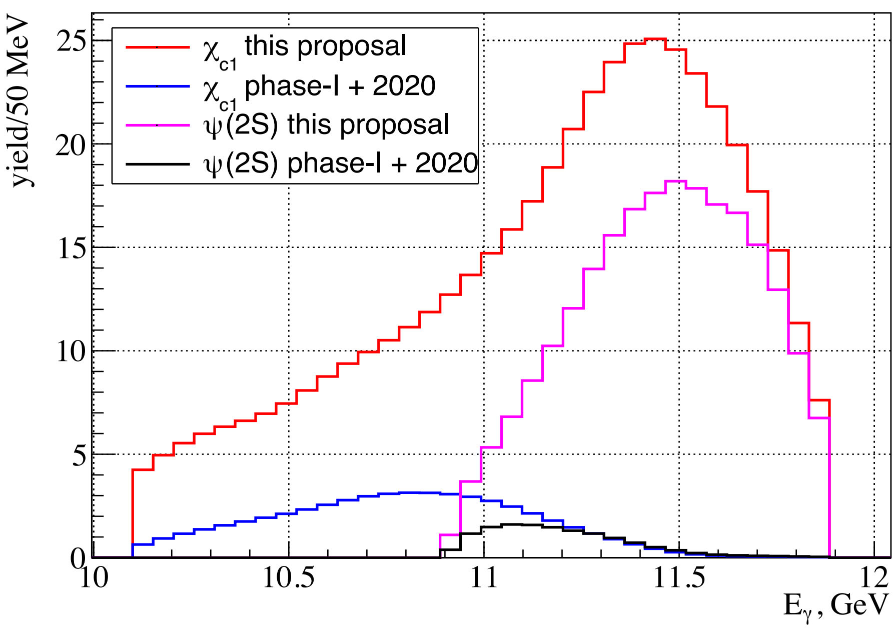
Open-charm exchange

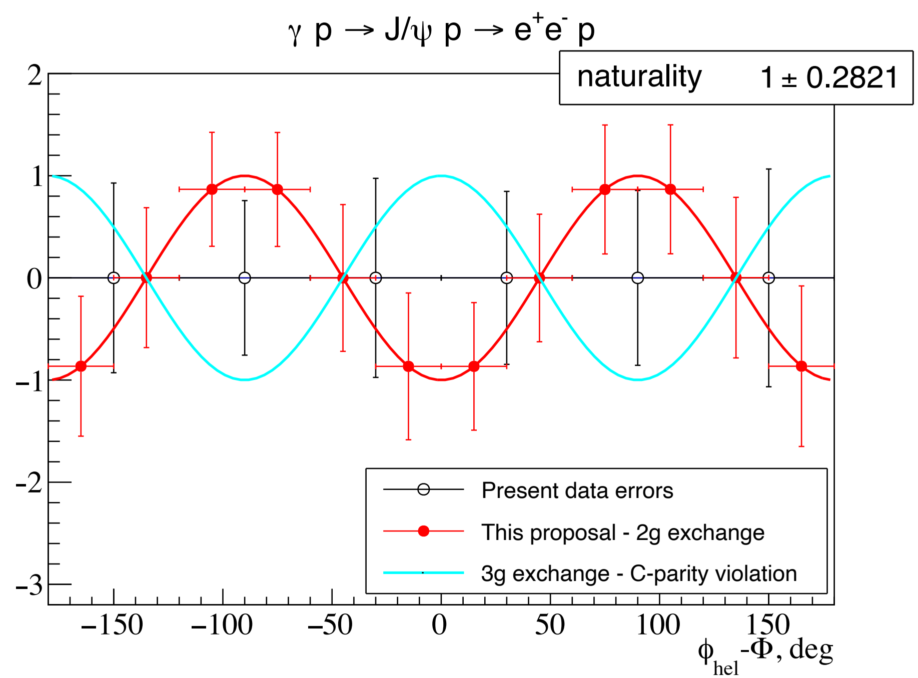


Prospect for charmonium threshold production with GlueX

- 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



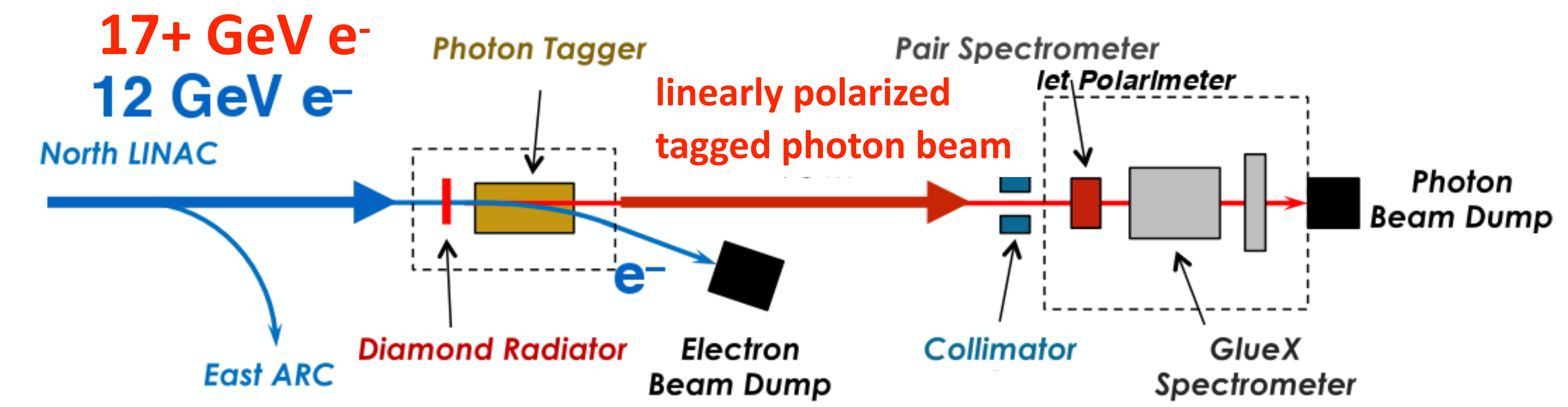


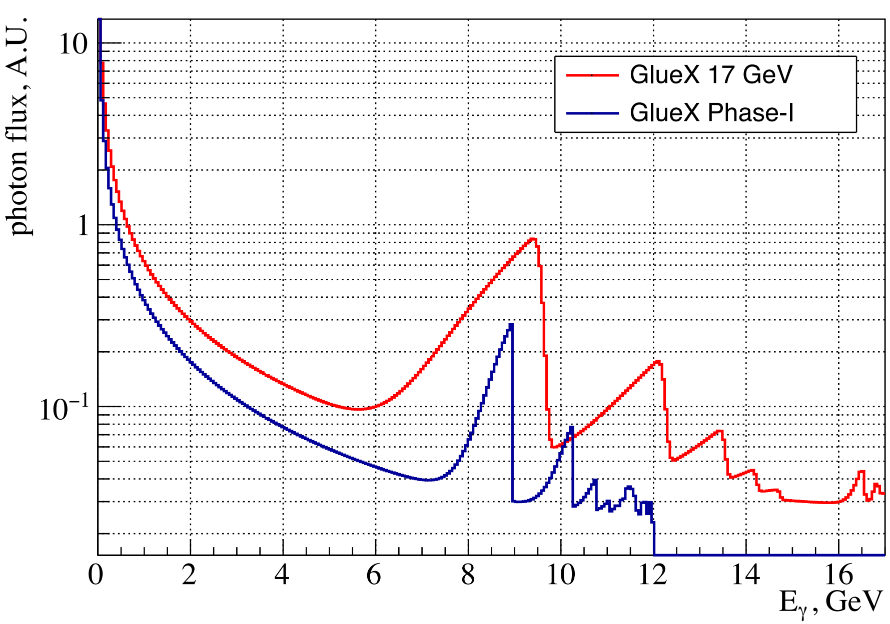
Outlook

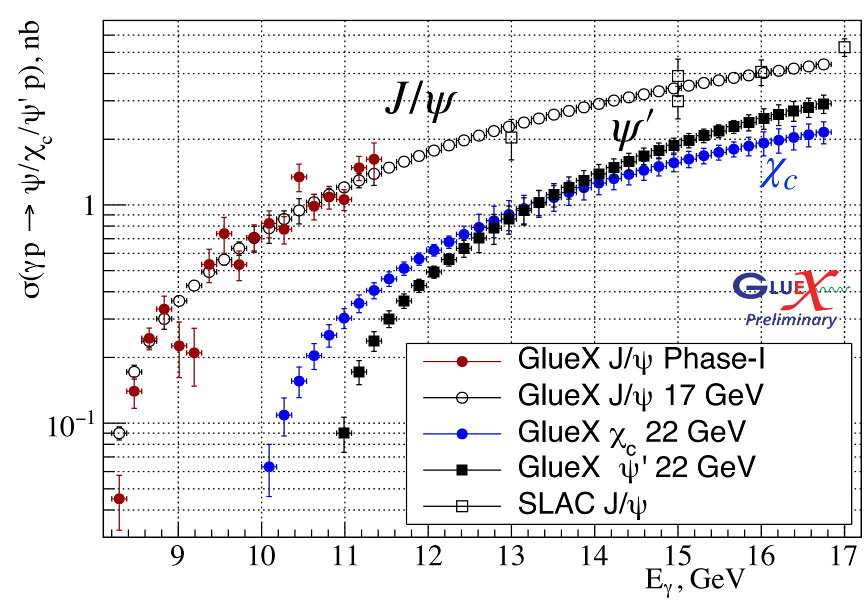
- Procedure for testing the GPD predicted behavior at high ξ was demonstrated, extracting the corresponding form factors as data points using Rosenbluth separation technique
- At the current level of available data, lattice results, and theoretical understanding, the experimental results are generally consistent with the predicted ξ-scaling:
  - Extracted $G_{0,2}(t)$ functions are energy independent (within the errors)
  - Differential/reduced ross-sections at fixed t increase with energy
  - In leading-moment approximation, extracted combinations of gGFFs are consistent with the lattice results, however lattice constraints are used in this procedure; model-independent extraction requires much higher statistics
- Questions:
  - $\xi > 0.4$ too wide region: works by chance due to low statistics or follows from more general theoretical approach?
  - How good is the leading-moment approximation (based on comparison with lattice) ; what is the contribution of the higher moments, imaginary parts of the amplitudes? If leading term dominates, extracted gGFFs would complement lattice for higher t
  - Is $G_2(t)$ sign change indeed needed to describe $t > 4\ GeV^2$ data (may come from $\mathscr{C}_g(t)$ sign change or $\mathscr{B}_g(t)$ contribution at high t)?
- SoLID as ultimate J/ψ factory may answer most of these questions
- Future planned and proposed GlueX running will be complementary to the J/ψ results, studying hight-mass charmonia and also using polarized photon beam

Back up slides

Hall D Apparatus with 17+ GeV electron beam



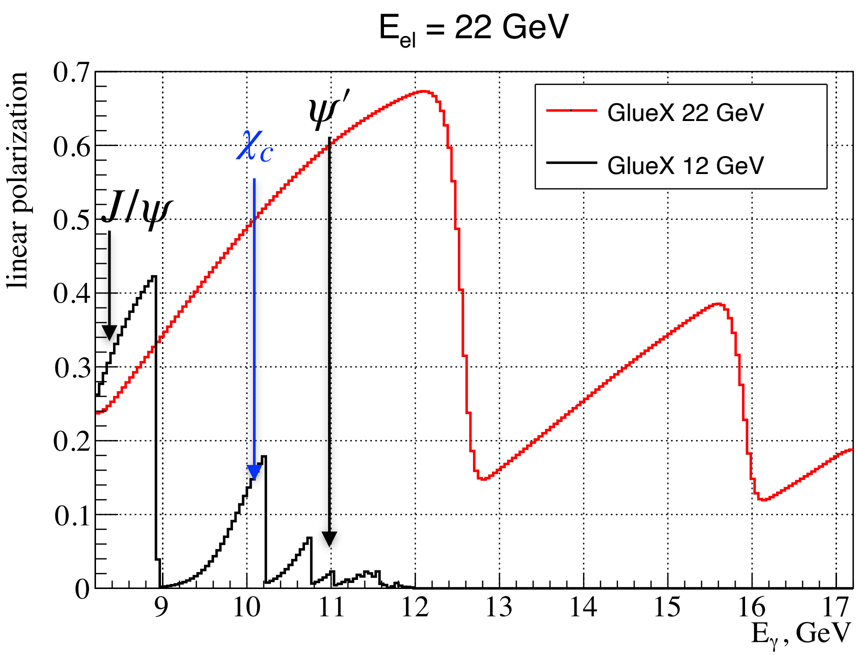


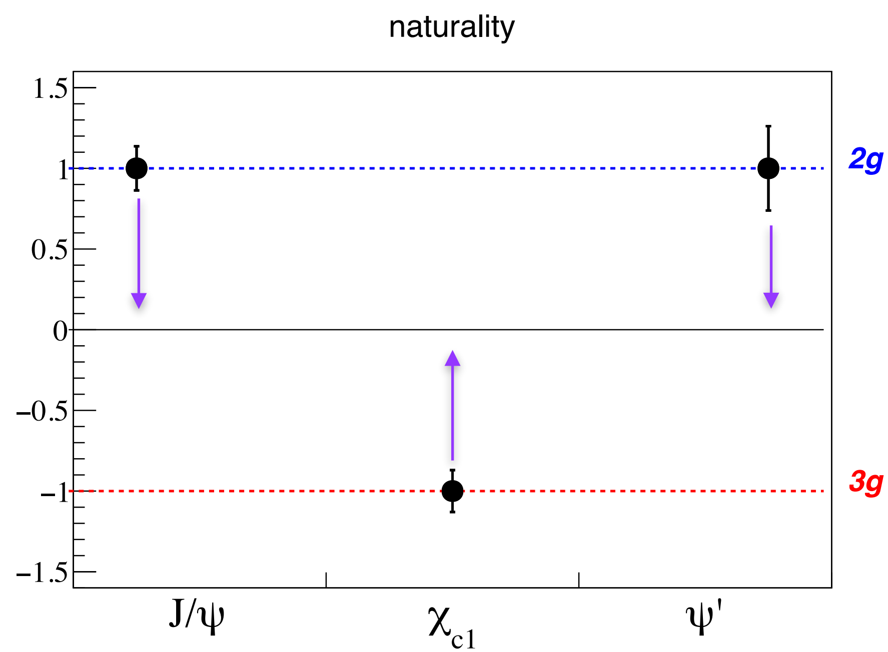


- Moving end point from 12 GeV to 17+ GeV:
  - higher flux (and polarization) toward higher energies, while low energies less affected (no load on detectors)

Charmonium polarization measurements at 22 GeV

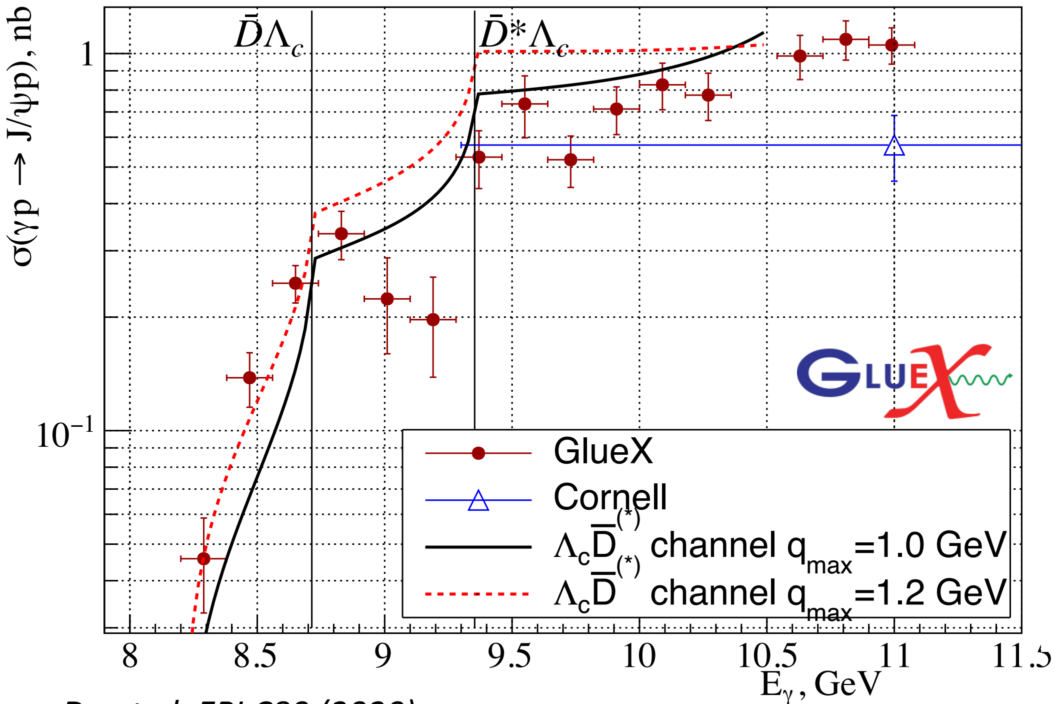
$$\textit{naturality} \times (-1)^J = P$$



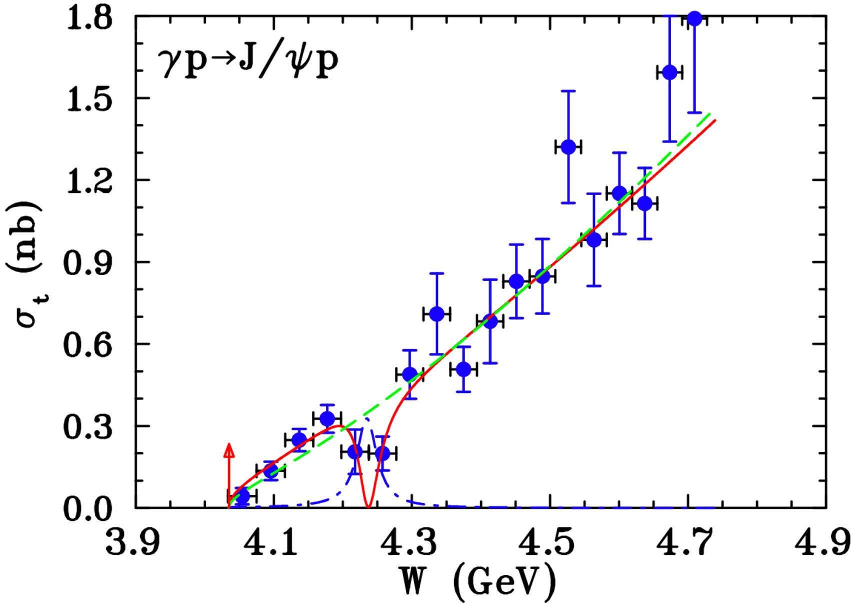


Any deviation from the expected (via gluon exchange) naturality indicates contribution of mechanism different from what is needed to study mass properties of the proton

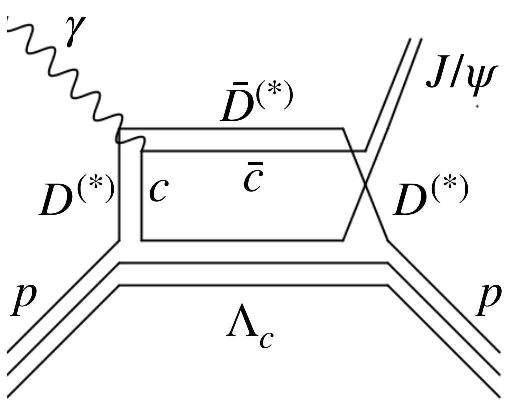
Other reaction mechanisms: open-charm, 5q exchange

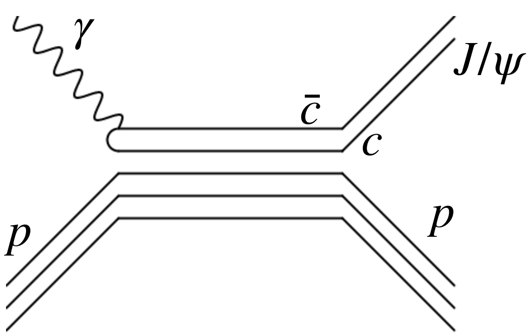


Du et al. EPJ C80 (2020)



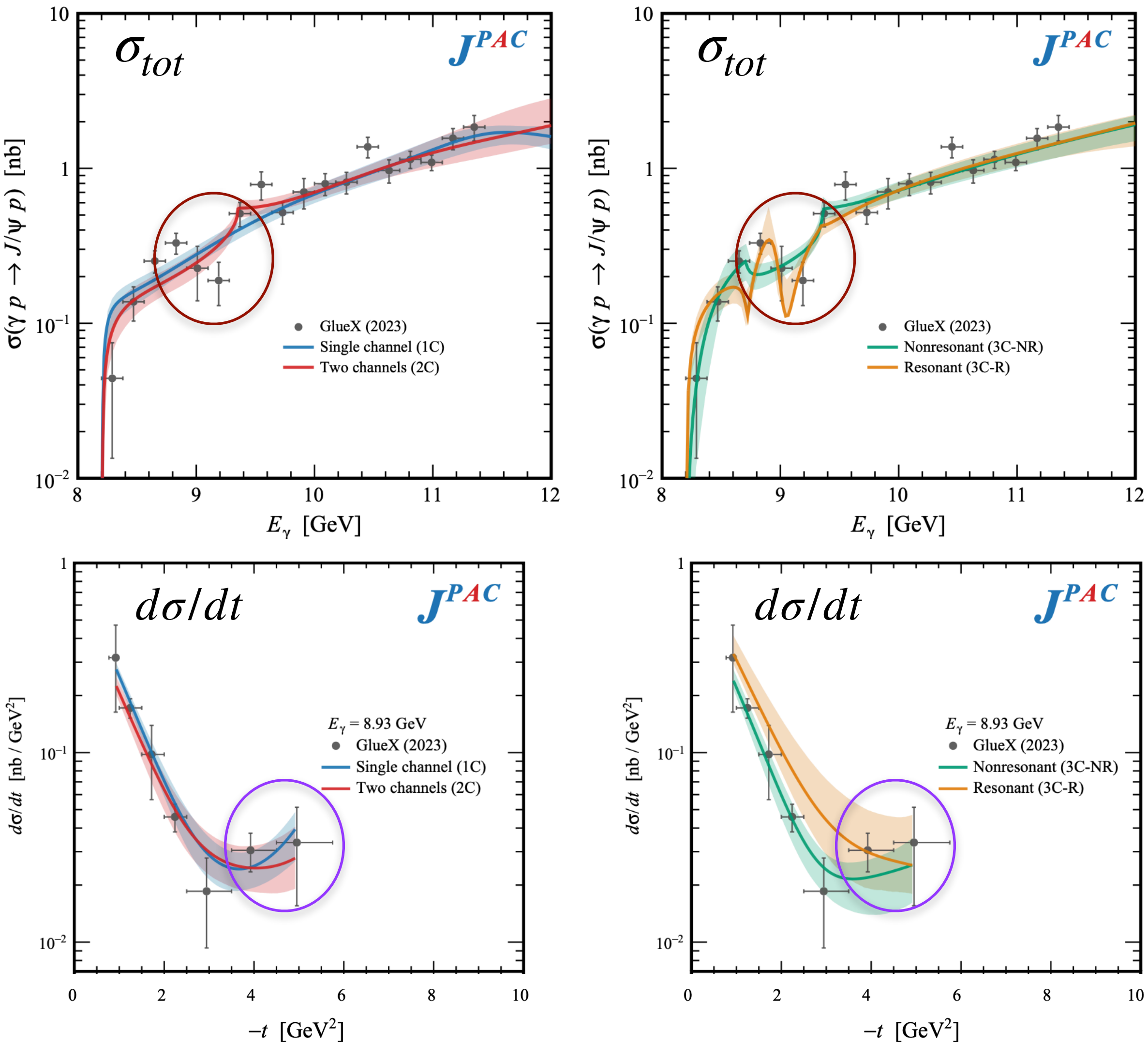
Strakovsky et al. PRC 108 (2023)





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 $\sigma_{tot}(E_\gamma)$

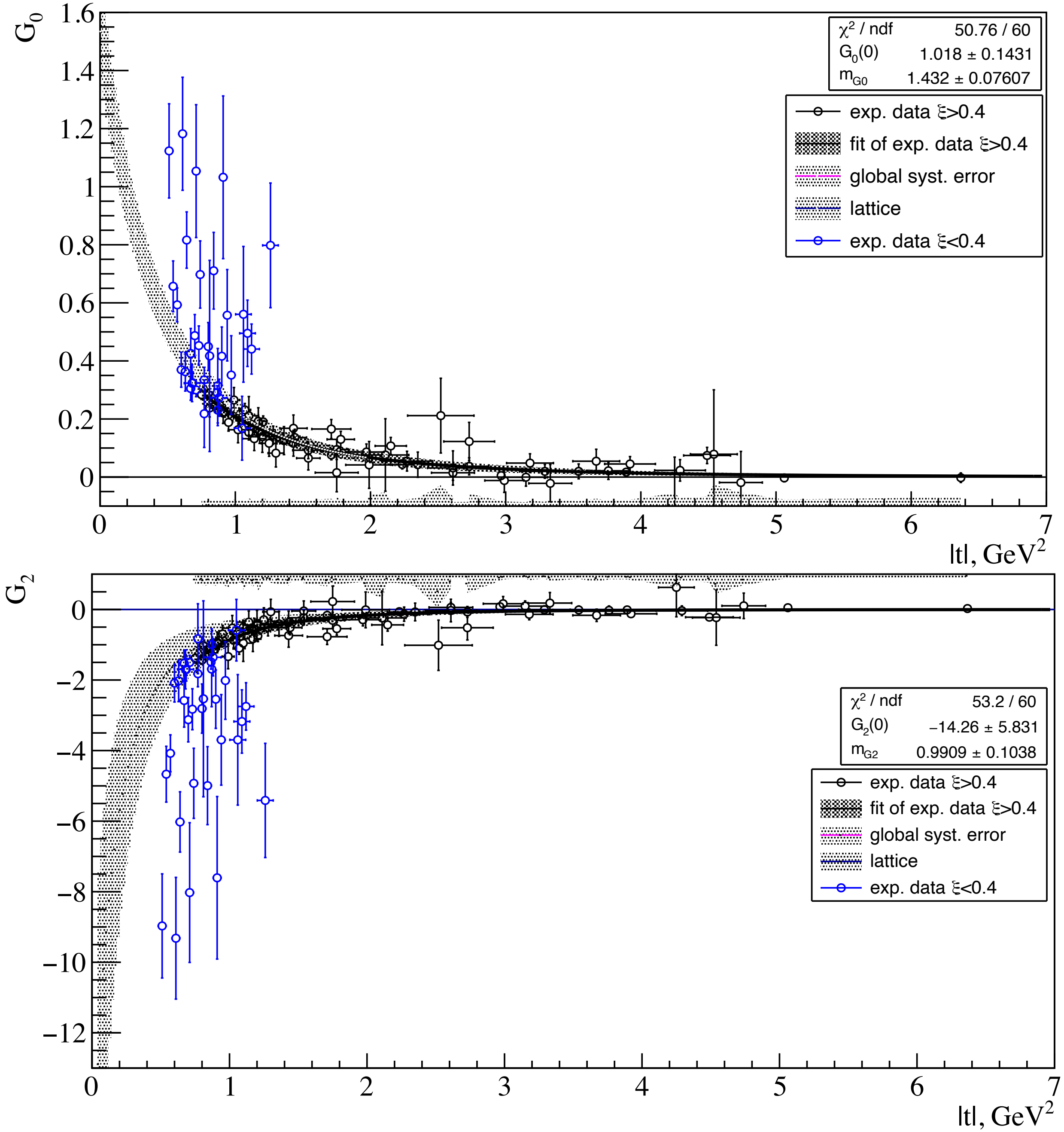
Phenomenological model based on s-channel PW expansion ($l \leq 3$):

- (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

Gluon Form Factors (Rosenbluth separation) - all data



$\xi < 0.4$ *data deviates from ξ-scaling*

Leading-moment calculations using lattice results:
Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)

$\xi > 0.4$
$\xi < 0.4$

$E_\gamma > 9.3$ GeV

Fits with:

$$\frac{G(0)}{(1-t/m^2)^4}$$

LP and E.Chudakov arXiv:2404.18776