Threshold charmonium photoproduction with Gluex

Lubomir Pentchev

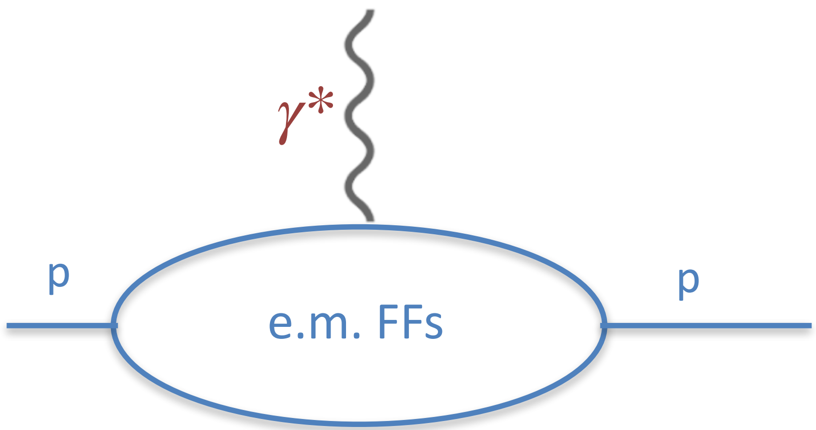
- J/ψ photoproduction as a probe of gluonic content of proton - GFF from experimental point of view
- Open questions:
  - GPD factorization?
  - Reaction mechanisms - open charm, …

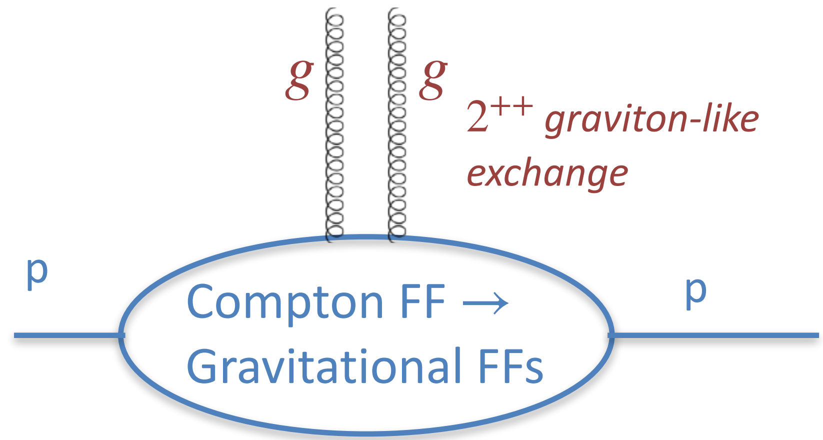
- Observation of $\chi_{c1,2}$ photoproduction with GlueX

- Photoproduction of charmonia with opposite-to-photon parity
  - what does it mean?
  - complementarity to C-odd charmonium (J/ψ) photoproduction

Gluon Gravitational Form Factors from experimental point of view

Test the main general property of Form Factors - they depend ONLY on t





$$\left(\frac{d\sigma}{d\Omega}\right)_{ep\to ep} = \left(\frac{d\sigma}{d\Omega}\right)_M \frac{1}{(1+\tau)}\left[G_E^2(t) + \frac{\tau}{\epsilon}G_M^2(t)\right] \qquad \left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)] + \ldots$$

Guo, Ji, Yuan PRD 109 (2024)

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

$$G_E(t), G_M(t) \sim G_D(t) = \frac{1}{(1+t/0.71GeV^2)^2} \qquad A_g(t), B_g(t), C_g(t) \sim \frac{1}{(1+t/m_i^2)^{2(3)}}$$

Rosenbluth separation - data-driven kinematic FF extraction

$$\sigma_R = \frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega}\right)_M \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau}G_E^2(t) + G_M^2(t), \qquad \sigma_{R0} = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t) + \xi^2 G_4(t) + \ldots$$

Gluon Form Factors - energy independence

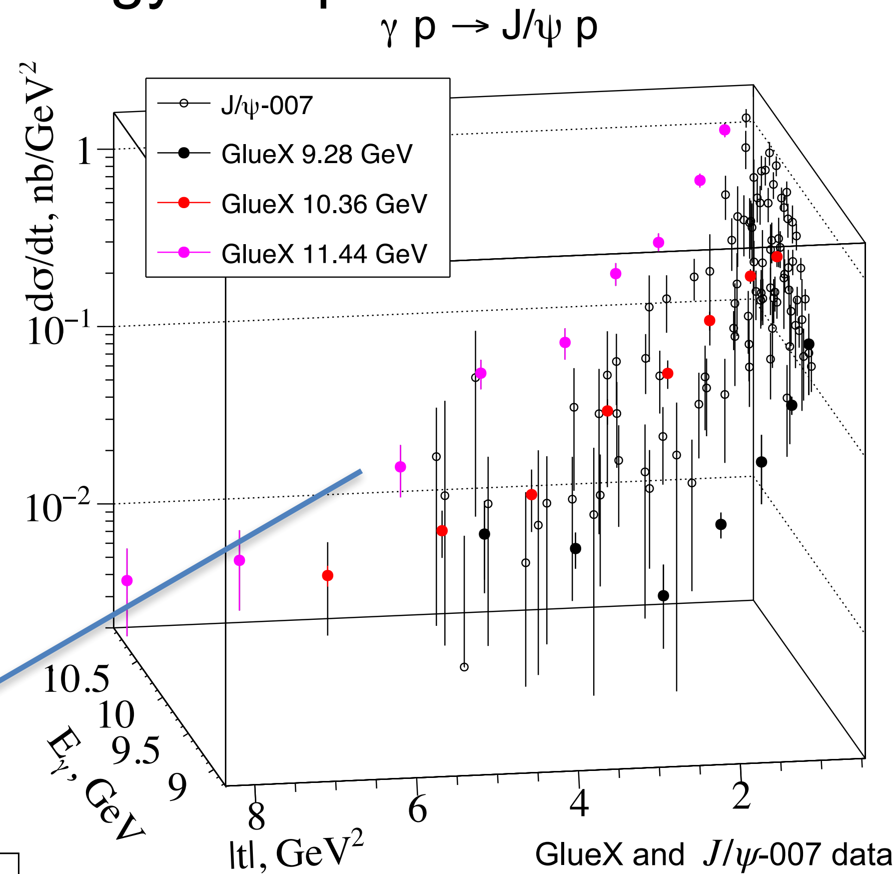
Energy independence of the $G_0(t)$ FF function (within errors)

No theory/lattice constraints used,
No theoretical assumptions,

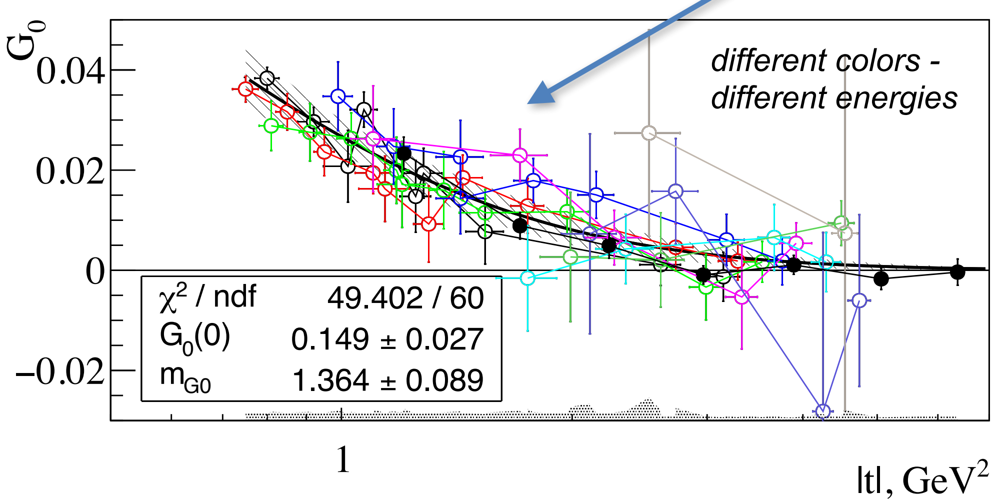
GPD approach used as a guidance:

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

$$\xi(E_\gamma, t) = \frac{M^2_{J/\psi} - t}{4E_\gamma m - M^2_{J/\psi} + t}$$



GlueX and J/ψ-007 data
Phys.Rev.C 108 (2023)
Nature 615 (2023)

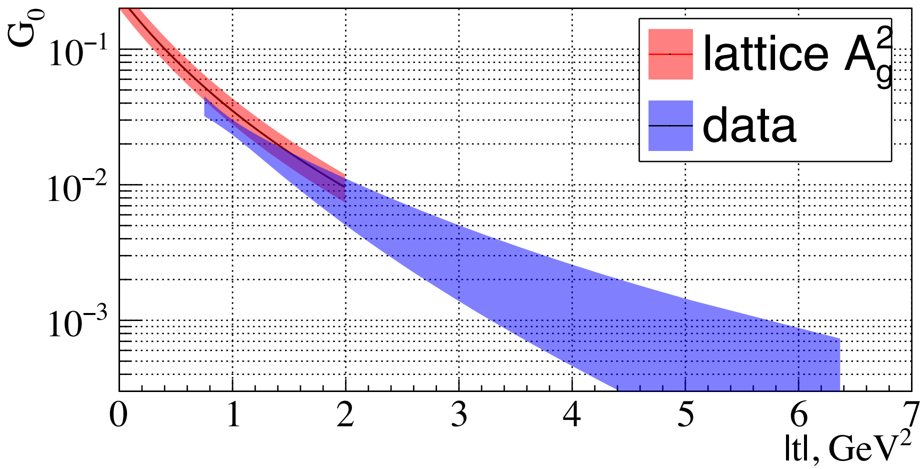


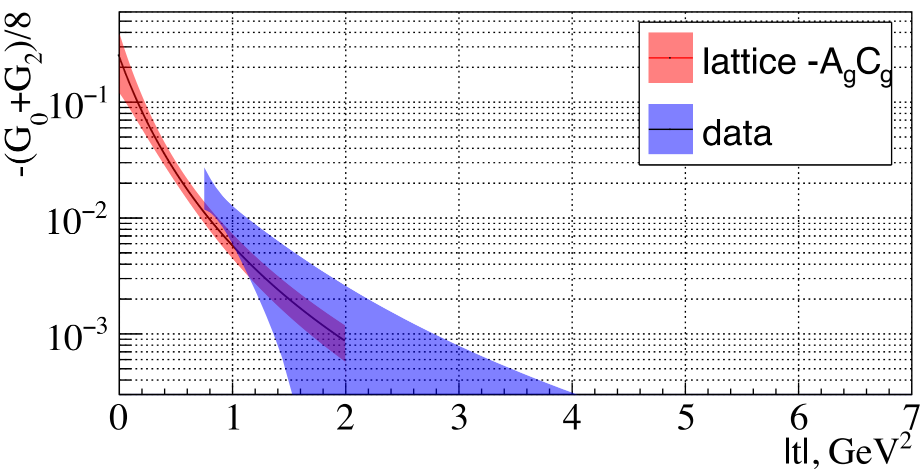
Fit with $\dfrac{G_0(0)}{(1 - t/m^2_{G0})^4}$

LP and E.Chudakov
*Phys. Rev. D **112**, 052009 (2025)*

Relation to Gluon Gravitational Form Factors

now using theory





Features in data consistent with the GPD model:

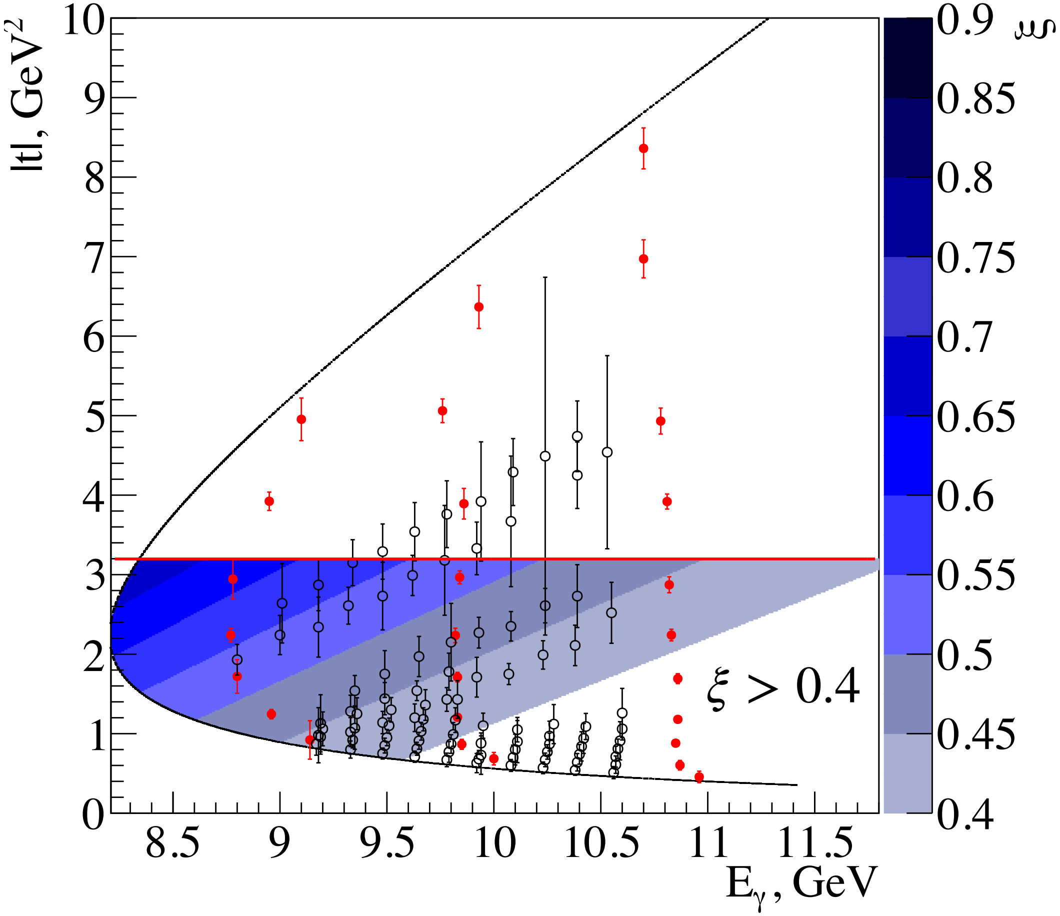
- $d\sigma/dt(E_\gamma, t \to fixed)$ increases with energy
- $G(t)$ form factor functions are energy independent (within the experimental errors)

- In leading-moment approximation valid at high ξ (and neglecting B_g):

$$G_0(t) = A_g^2(t) \text{ and}$$
$$G_0(t) + G_2(t) = 8C_g(t)A_g(t)$$

→ agreement with lattice

Open questions: GPD factorization - kinematic limits

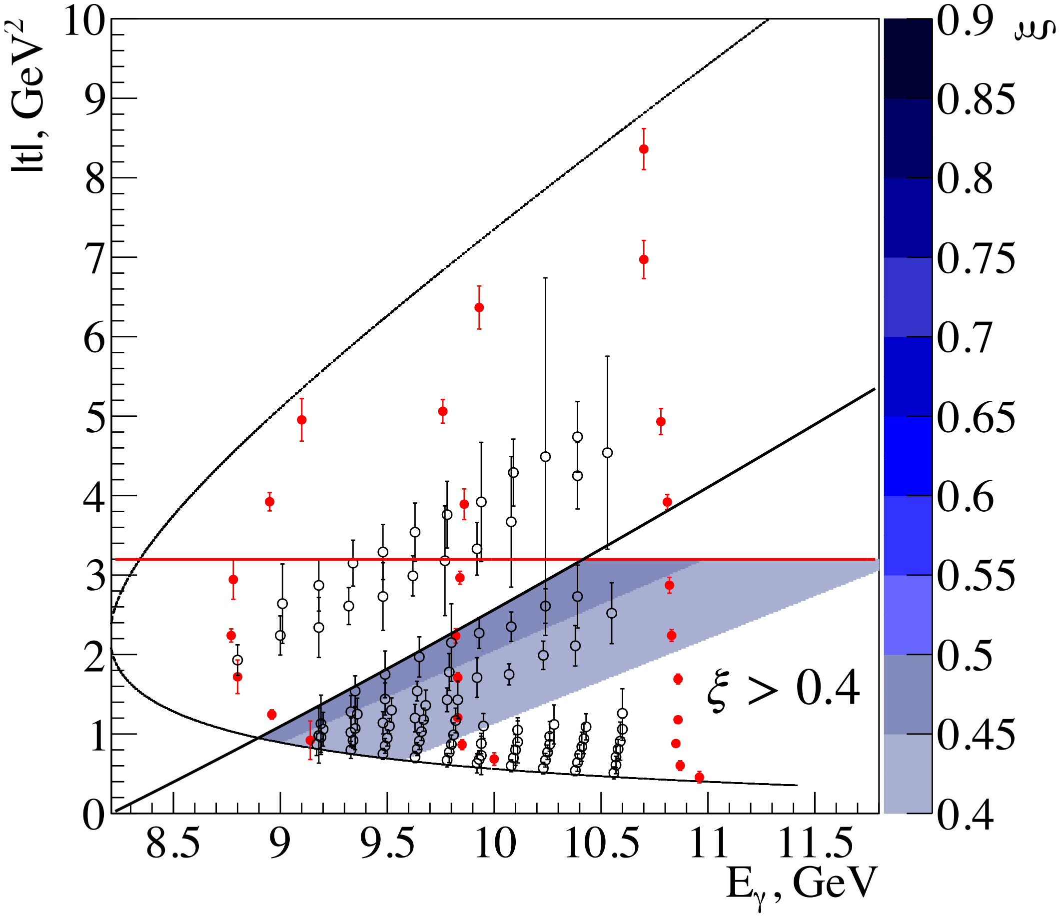


High ξ needed for leading-moment approximation

- $|t| < M_{J/\psi}^2/3$ - to reduce contributions from higher-twist; corrections $\sim |t|/M_{J/\psi}^2$

Y. Hatta et al., PTEP 076 (2025)

Open questions: GPD factorization - kinematic limits

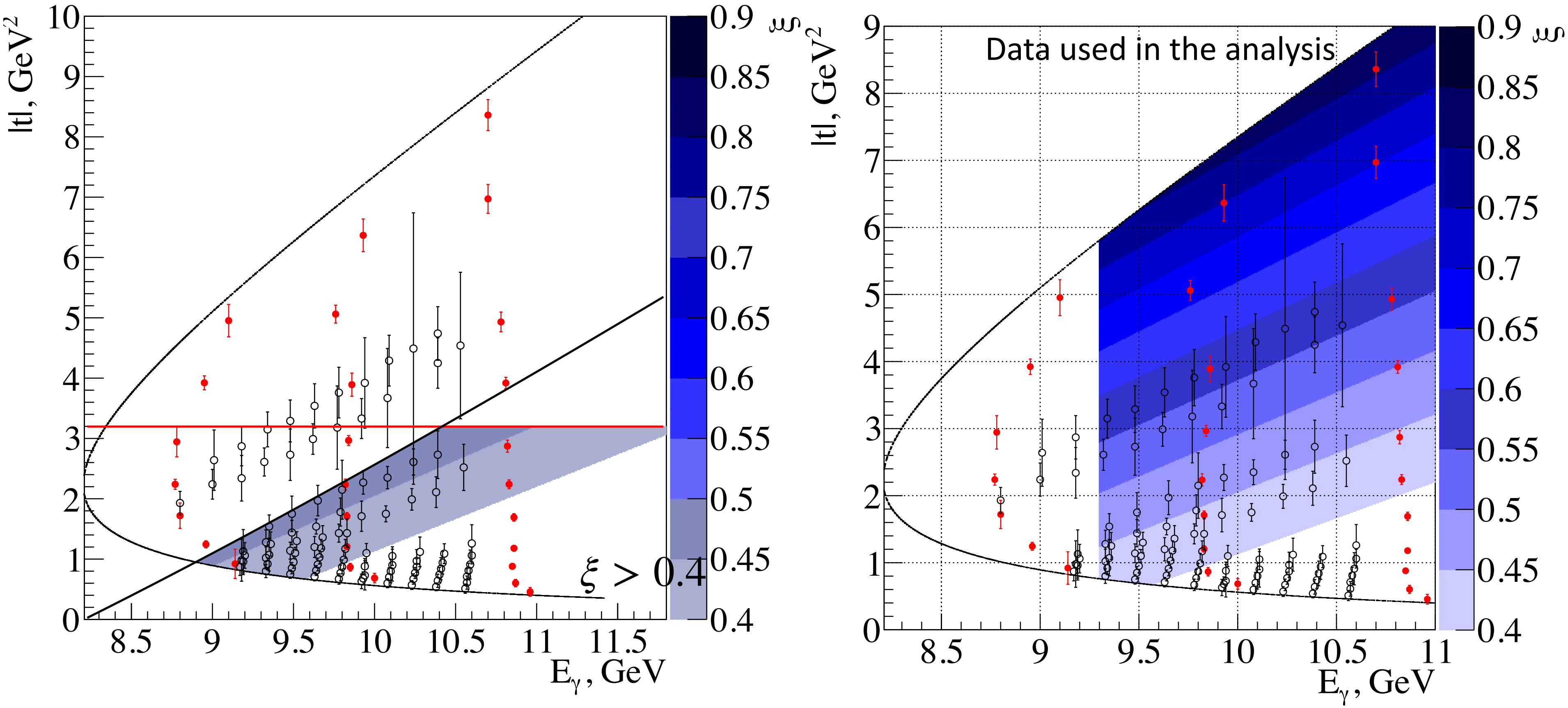


High ξ needed for leading-moment approximation

- $|t| < M_{J/\psi}^2/3$ - to reduce contributions from higher-twist; corrections $\sim |t|/M_{J/\psi}^2$
- $|t| < (2k_{cm})^2$ - relative velocity between final state particles $> \sqrt{|t|}$ to avoid FSI

Y. Hatta et al., PTEP 076 (2025)

Open questions: GPD factorization - kinematic limits

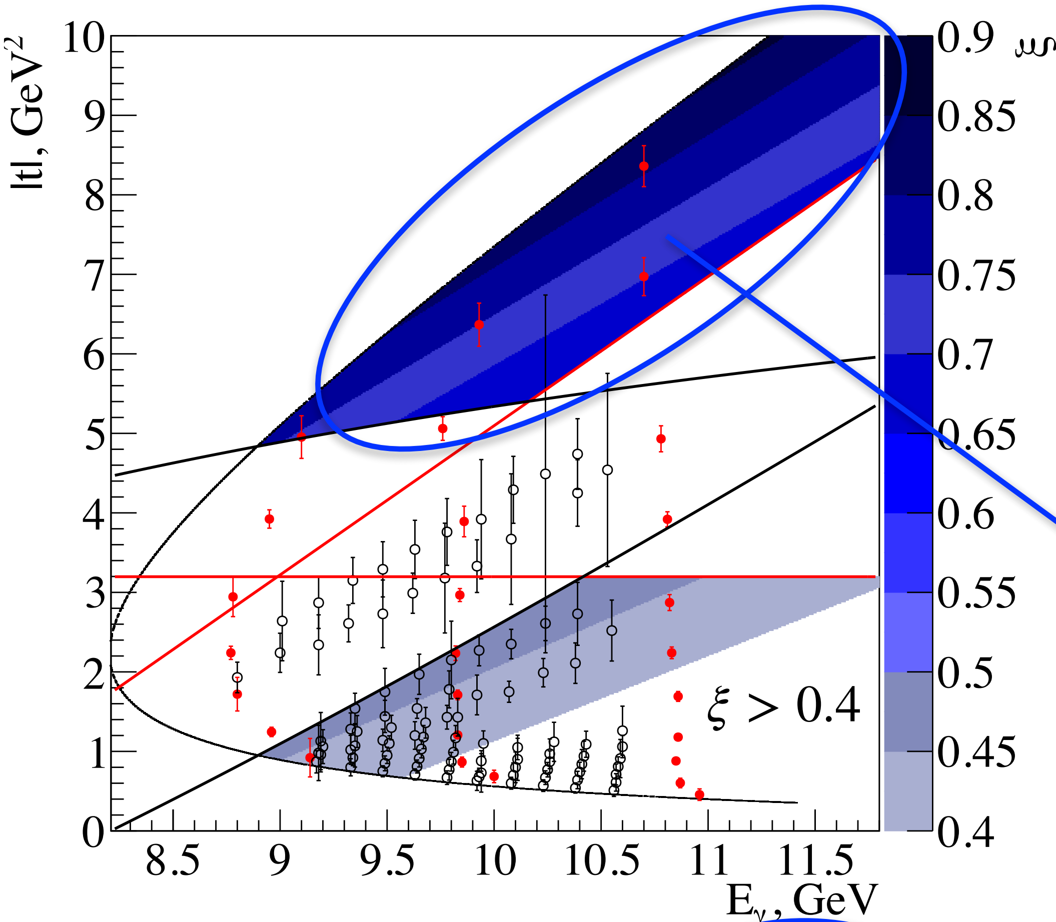


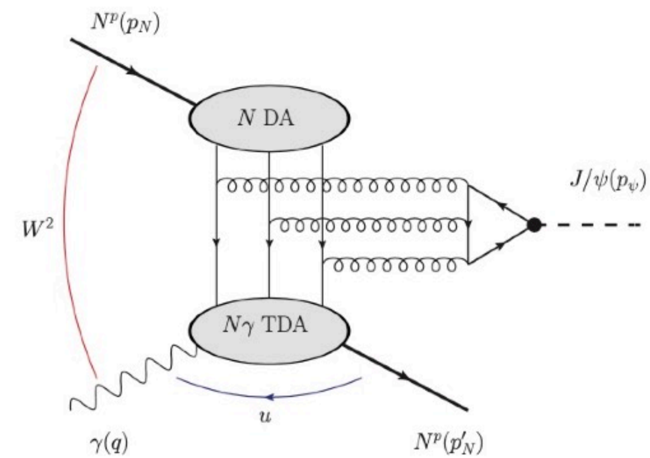
- $|t| < M_{J/\psi}^2/3$
- $|t| < (2k_{cm})^2$

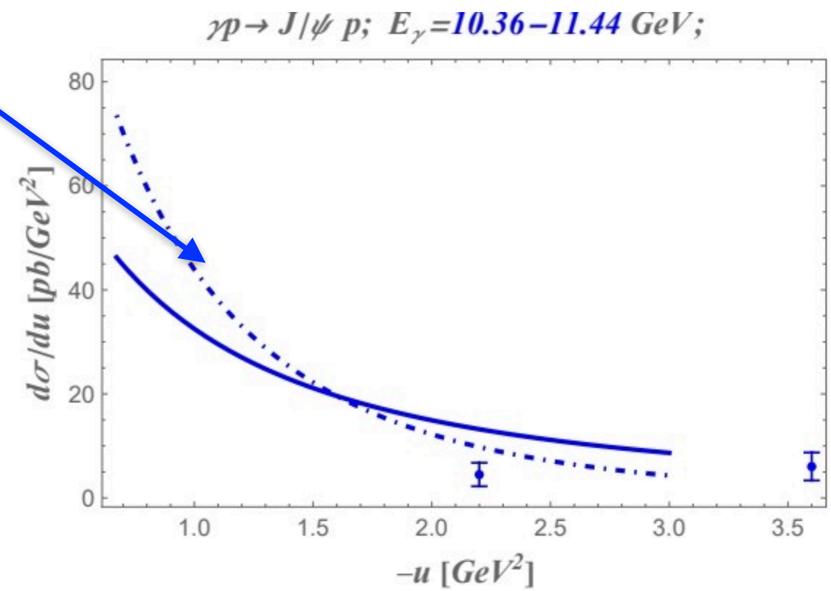
Y. Hatta et al., PTEP 076 (2025)

- Data-driven extraction of $G(t)$ FFs demonstrates validity in the above region (higher $|t|$)
- Need to study higher-twist corrections!

Open questions: GPD factorization - u-channel







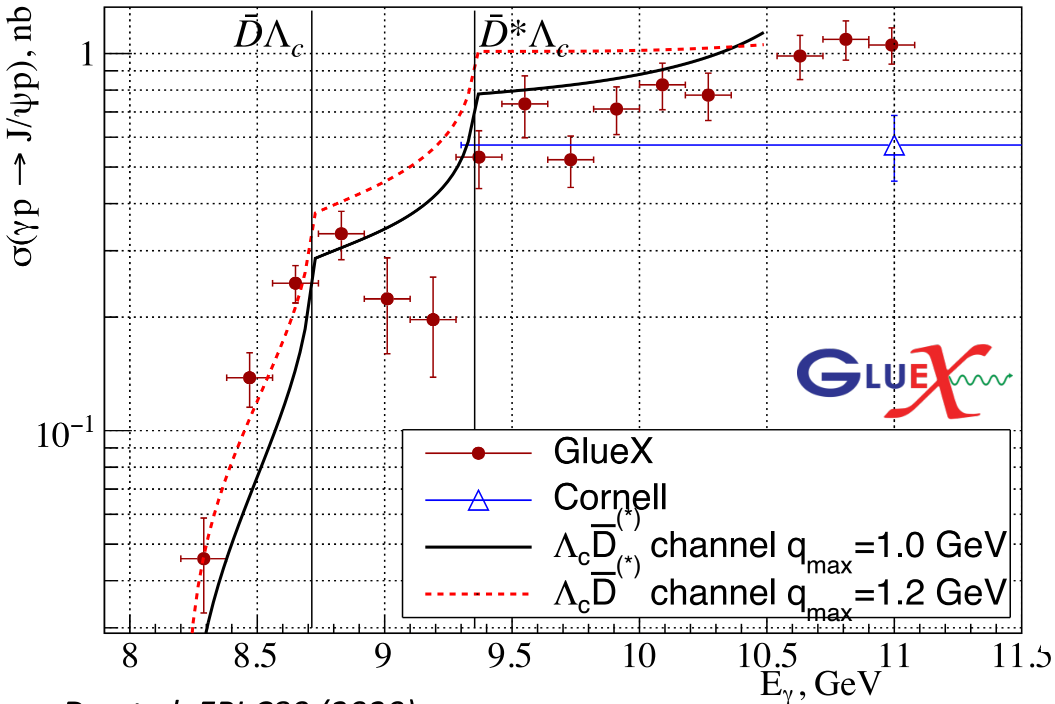
- $|t| < M^2_{J/\psi}/3$
- $|t| < (2k_{cm})^2$

Y. Hatta et al., PTEP 076 (2025)

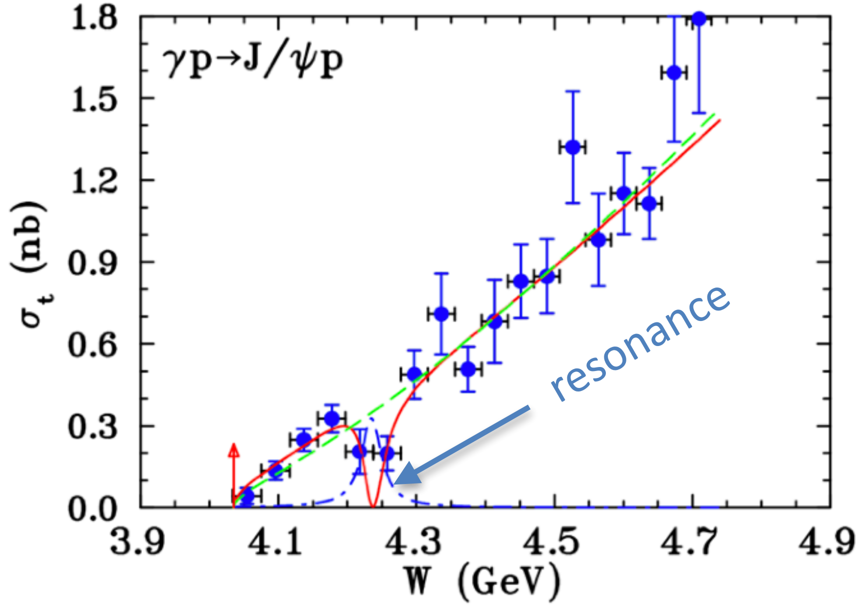
- $|u| < M^2_{J/\psi}/3$
- $|u| < (2k_{cm})^2$

Pire et al. AAPPS Bull. 33 (2023) 1

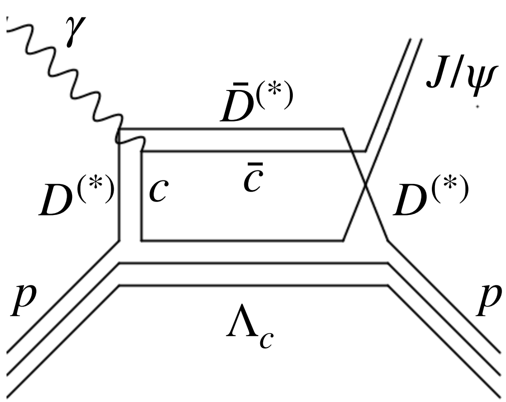
Open questions: reaction mechanisms: open-charm, resonance

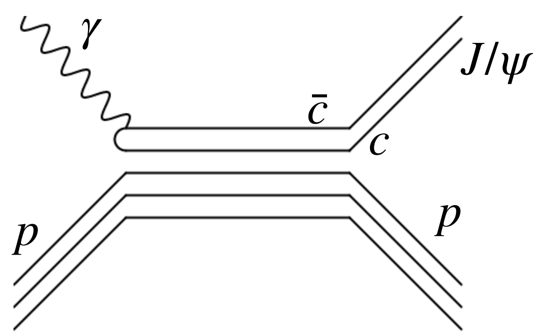


Du et al. EPJ C80 (2020)



Strakovsky et al. PRC 108 (2023)





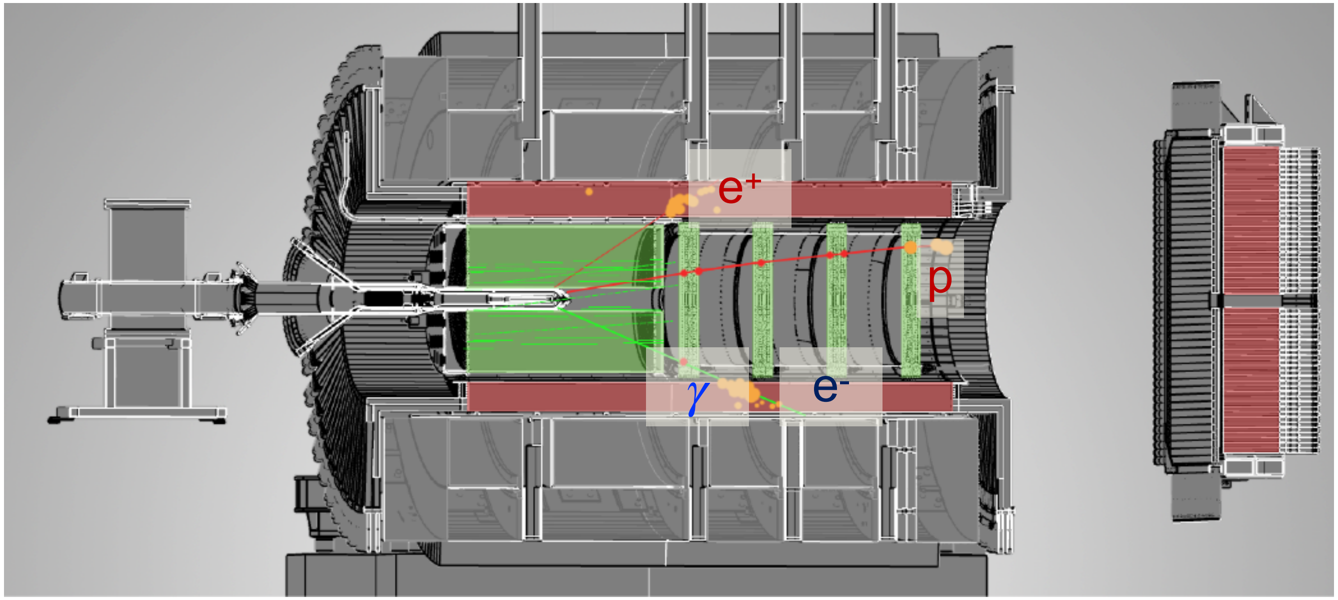
What GlueX can contribute addressing these questions:

- *GPD factorization*
- *Reaction mechanisms - open charm, other s-channel mechanisms*

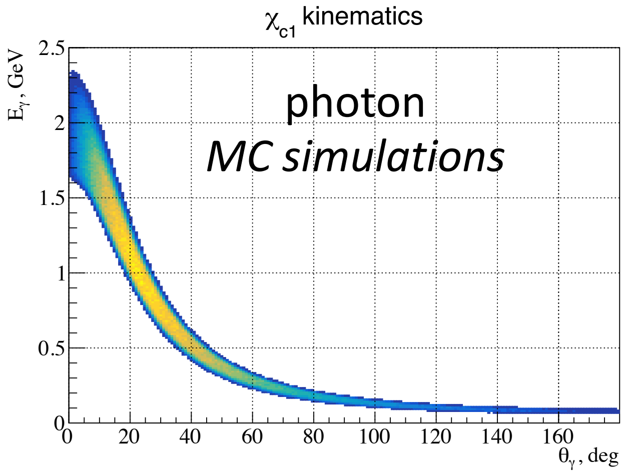
- Higher statistics: *GlueX-III - x5 statistics from what we have now - see last slide*
- Amplitude analysis (including using polarized photon beam): *SDMEs - next talk by Josh Jackson*
- Photoproduction of higher-mass charmonia: χ_c states - next slides

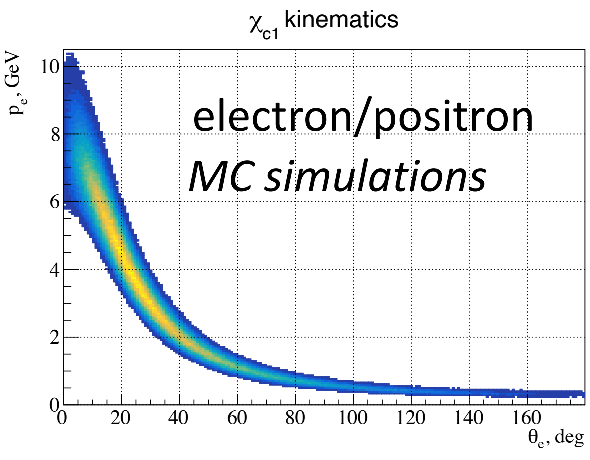
χ_c detection with GlueX

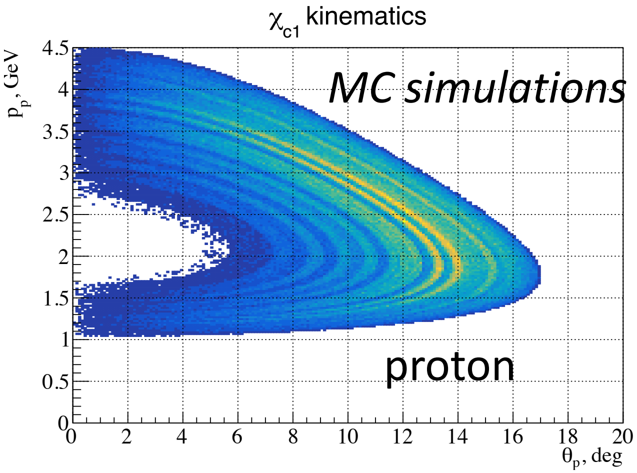
$$\gamma p \to \chi_c p \to J/\psi \gamma\, p \to e^+ e^- \gamma\, p \quad \textit{exclusive}$$



- Requires photon detections
- GlueX has almost full coverage of all final state particles:

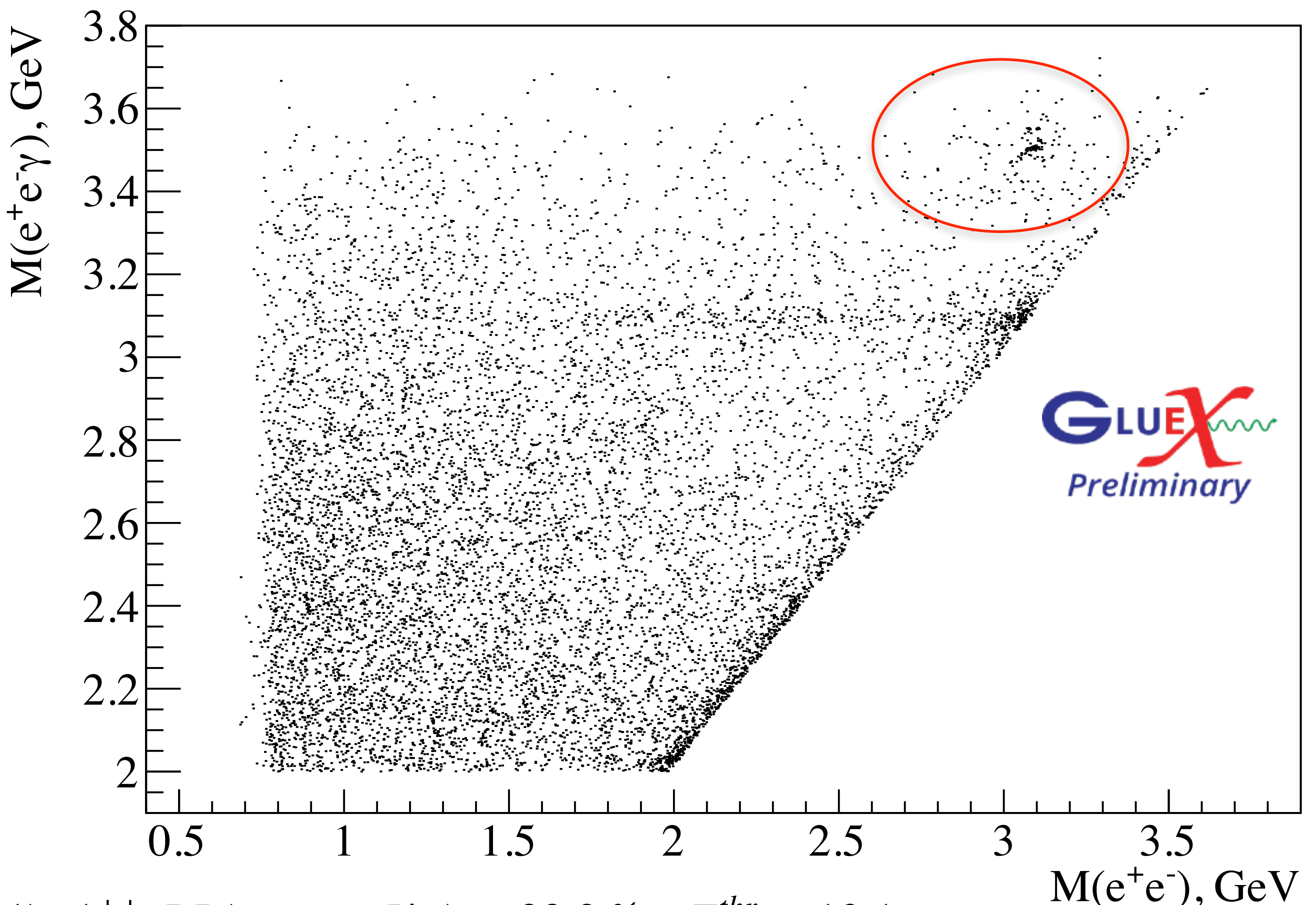






C-event charmonium states at threshold with GlueX

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

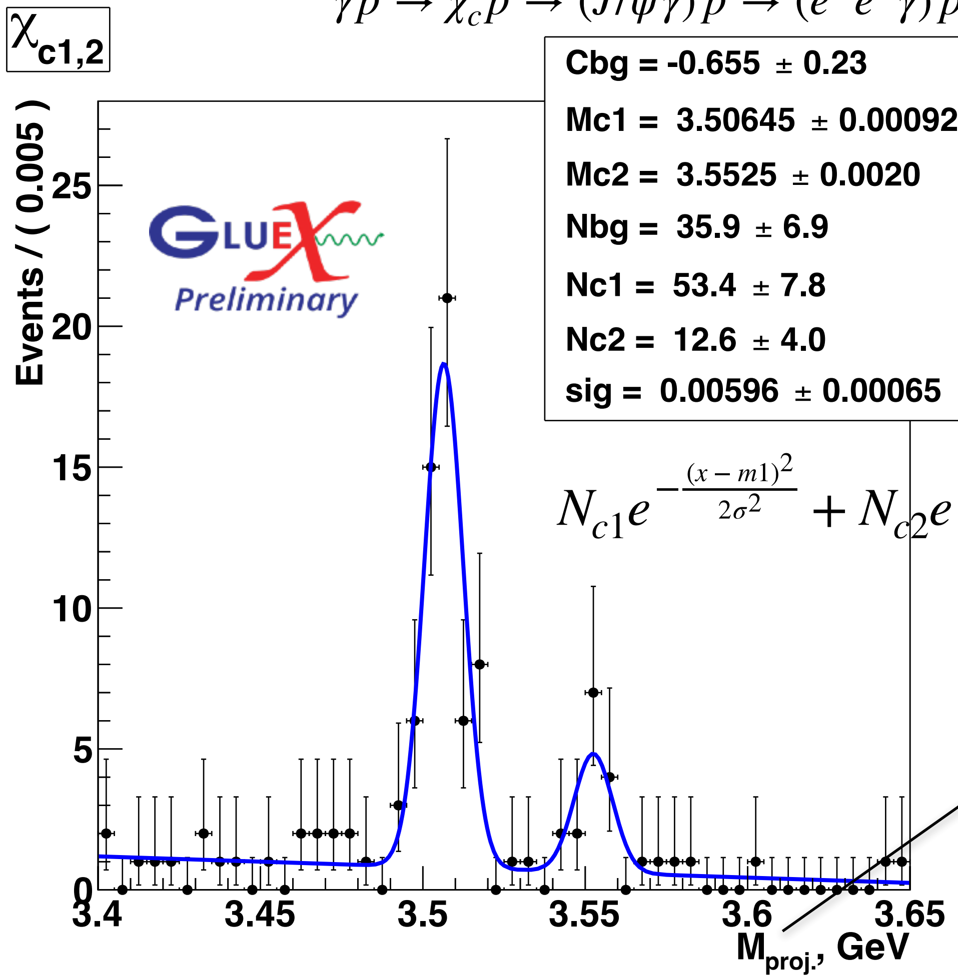


- $\chi_{c1}(3511)$, 1^{++} $BR(\chi_{c1} \to \gamma J/\psi) = 33.9\,\%$ $E_\gamma^{thr} = 10.1$ GeV
- $\chi_{c2}(3556)$, 2^{++} $BR(\chi_{c2} \to \gamma J/\psi) = 19.0\,\%$ $E_\gamma^{thr} = 10.2$ GeV
- $\chi_{c0}(3415)$, 0^{++} $BR(\chi_{c0} \to \gamma J/\psi) = 1.35\,\%$ - not visible yet in our data

First ever evidence for photoproduction of C-even charmonium

C-event charmonium states at threshold with GlueX

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



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

$M_{proj.}$ is $M(e^+e^-\gamma)$, corrected by $M(e^+e^-)$, based on correlation between invariant masses

- $\chi_{c1}(3511)$, 1^{++} $BR(\chi_{c1} \to \gamma J/\psi) = 33.9\,\%$ $E_\gamma^{thr} = 10.1$ GeV
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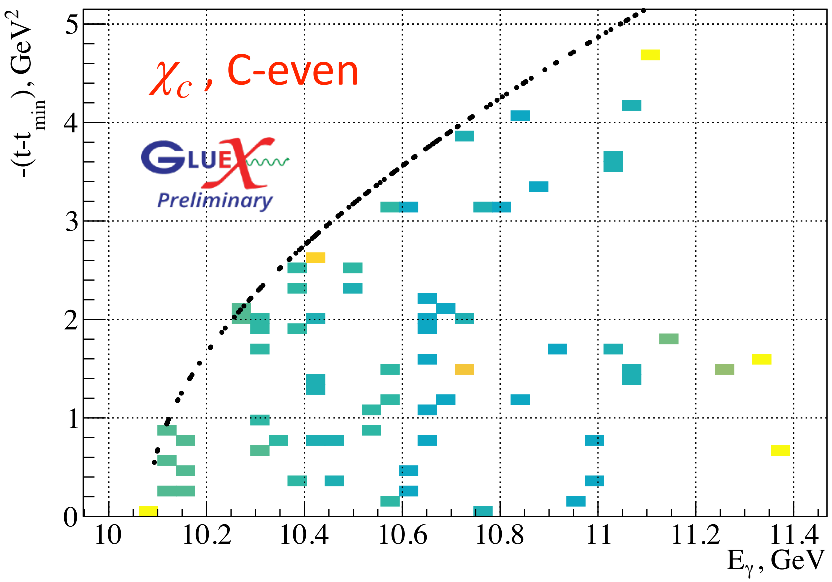
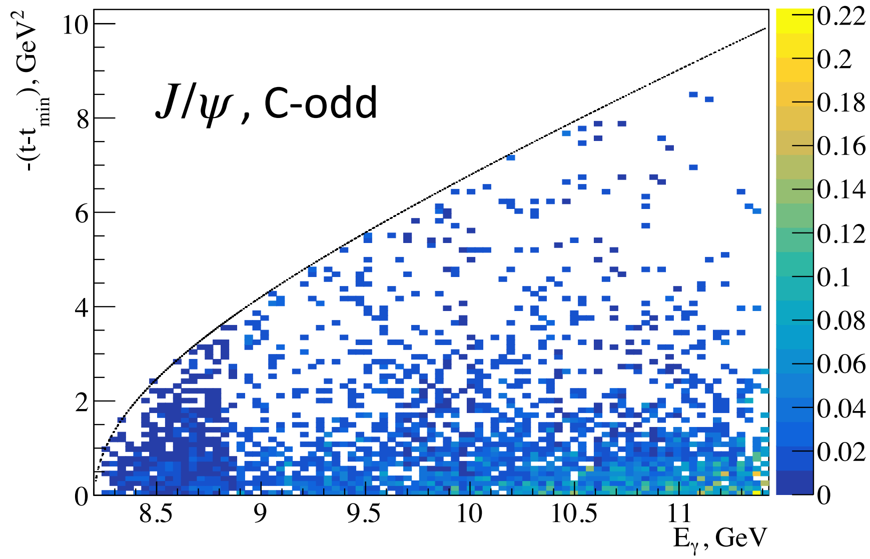
First ever evidence for photoproduction of C-even charmonium

C-event charmonium states at threshold with GlueX

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

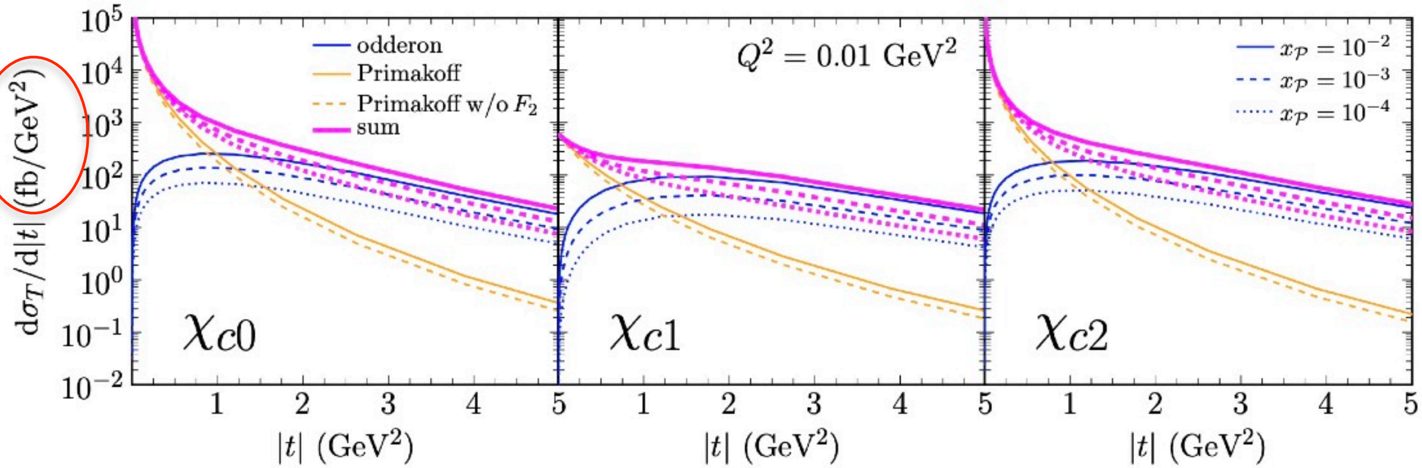




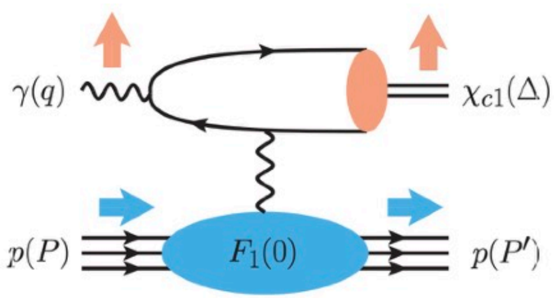
$$weight = \frac{1}{L(E_\gamma)}$$

t-channel production - perturbative calculations

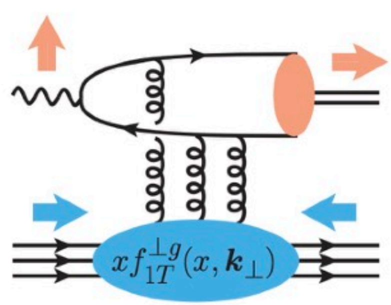
Note units -highly suppressed



Benic, Dumitru, Kaushik, Motyka, Stebel, PRD 110 (2024) -
perturbative calculations (high energies)

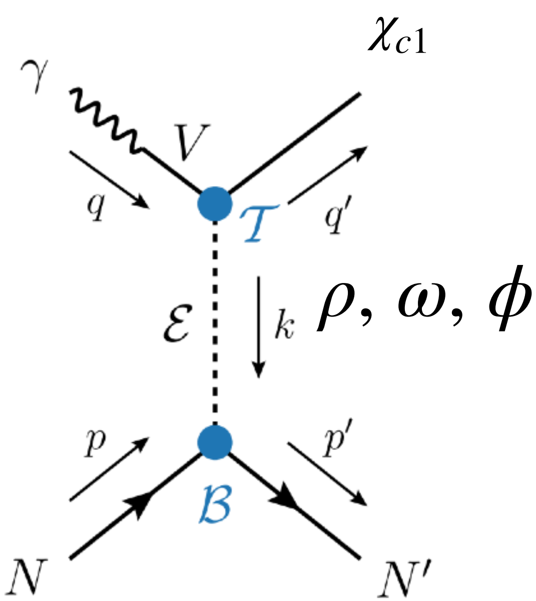


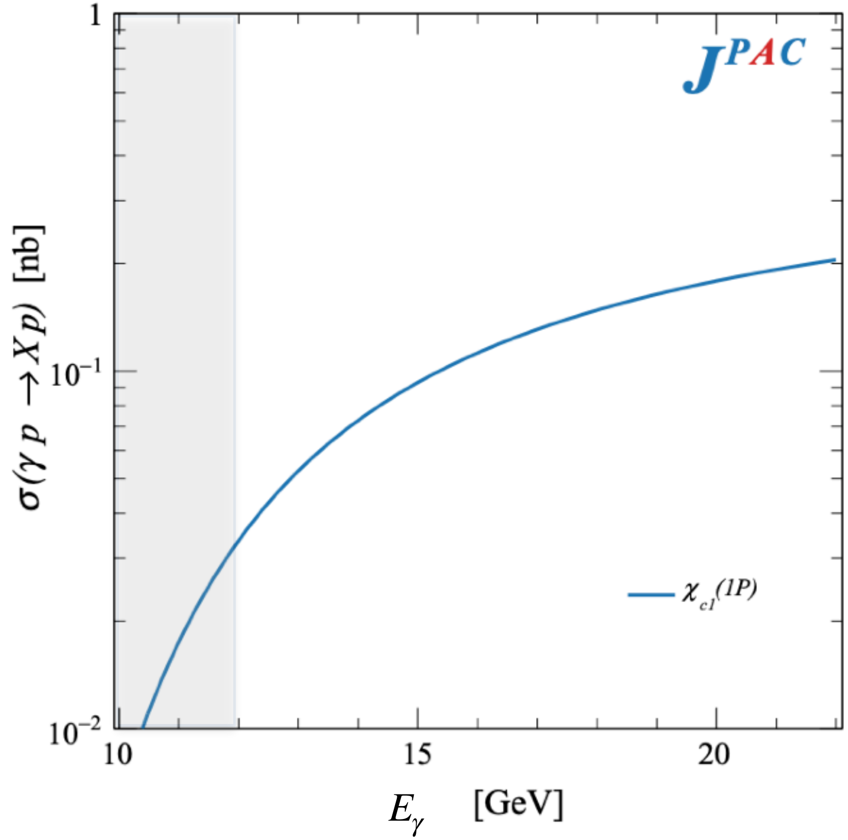
- Primakoff - suppressed for χ_{c1} due to Landau-Yang theorem:
  $\chi_{c1}(J=1) \rightarrow \gamma\gamma$ suppressed for $t \rightarrow 0$



- Odderon (odd-parity Pomeron) 3g exchange - suppressed by $1/\alpha_s^6$ still dominates at higher $|t|$ due to $n_s = 0$ ($n_s = 2$ for Primakoff)

t-channel production - VM exchange





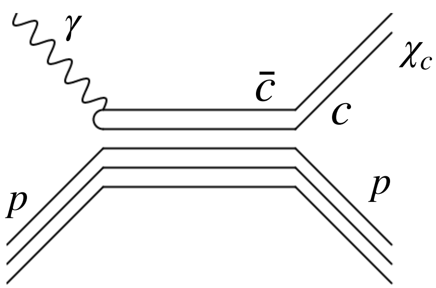
JPAC, PRD 102 (2020)

- Low energies - non-perturbative approach, vector meson exchange
- $\chi_{c1} \to \gamma V(\rho, \omega, \phi)$ is suppressed: *BR* $\sim 10^{-4} - 10^{-5}$, due to OZI rule

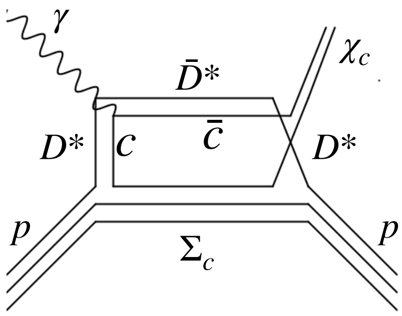
s-channel mechanisms

- t-channel is suppressed (requires C-odd exchange), allows us to study other possible mechanisms that may dominate:

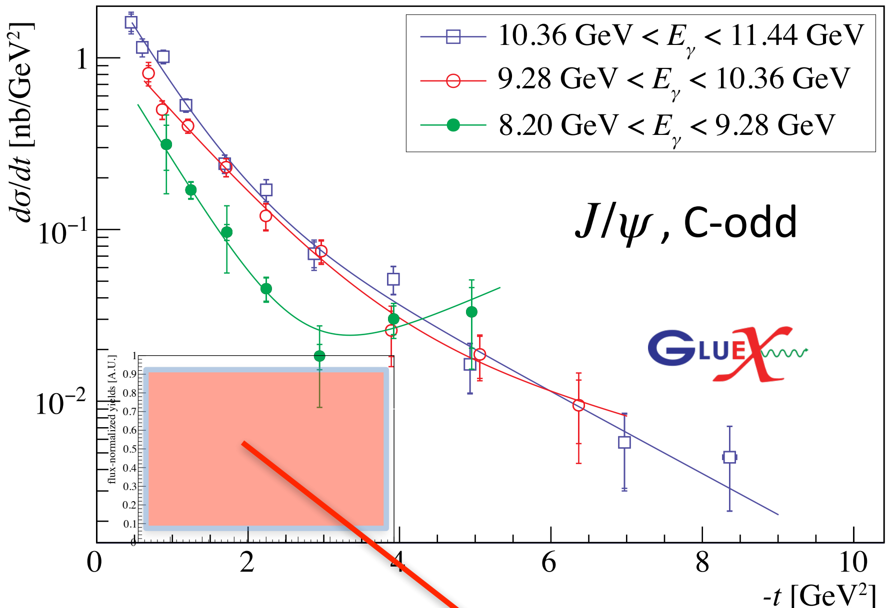
S-channel exchange of 5q

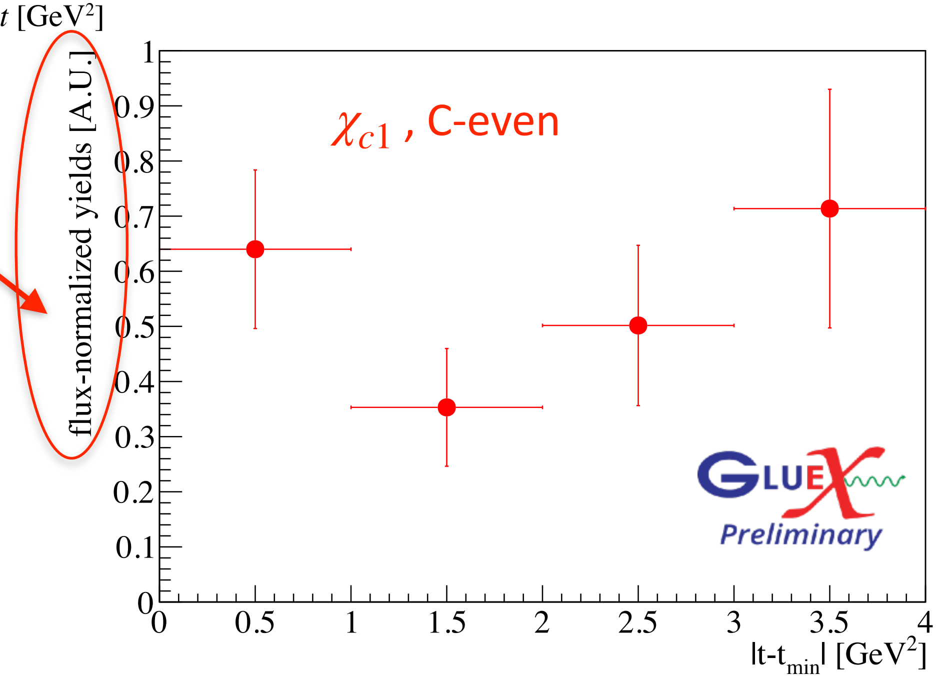


Open-charm exchange

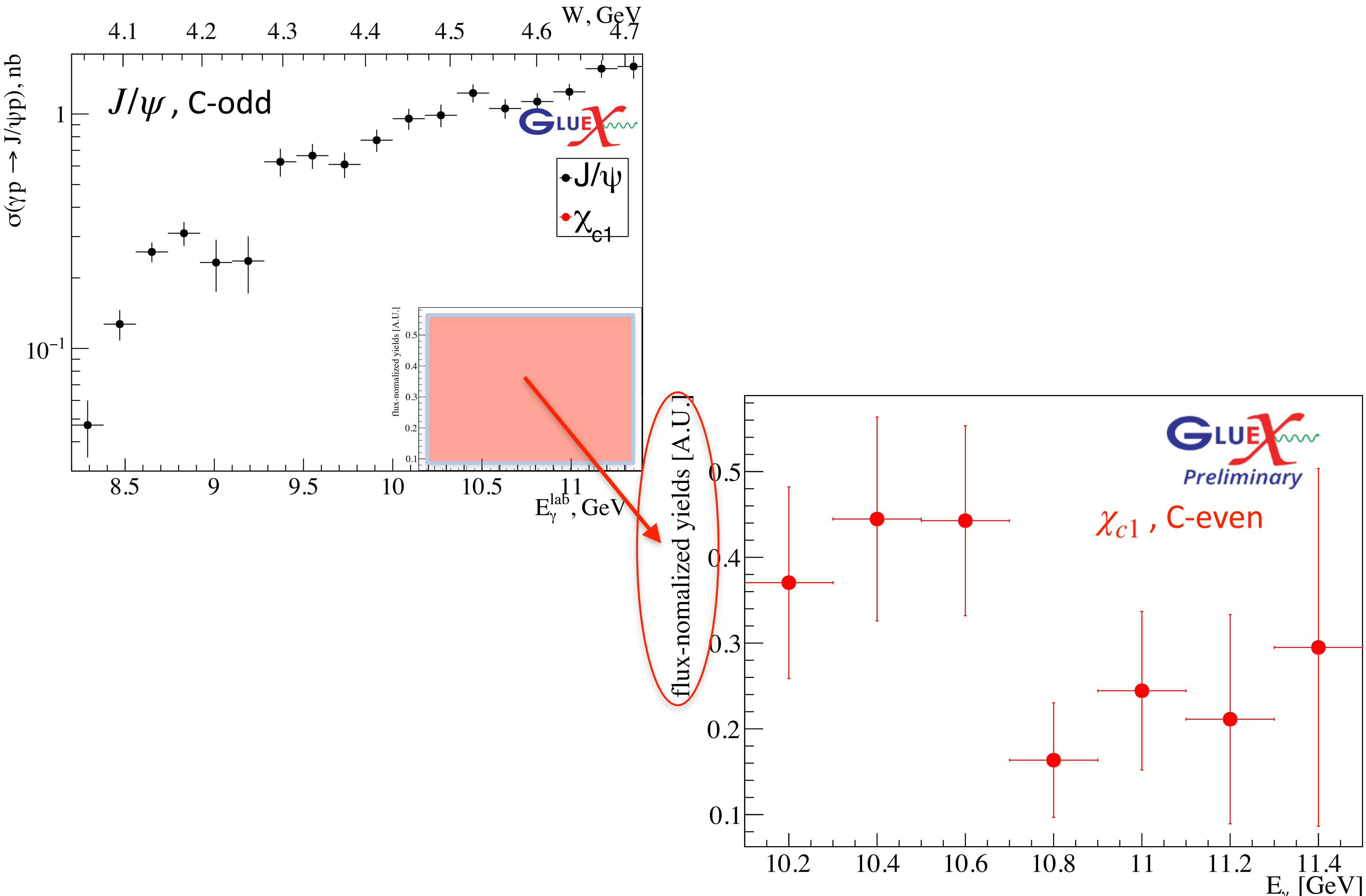


C-event charmonium photoproduction - $d\sigma/dt$





C-event charmonium states at threshold with GlueX



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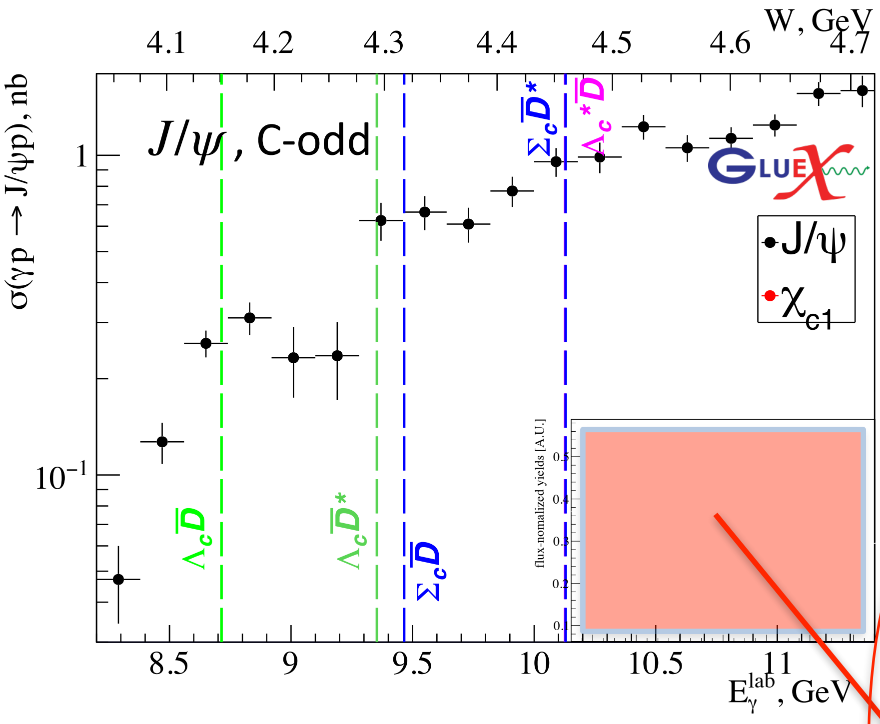

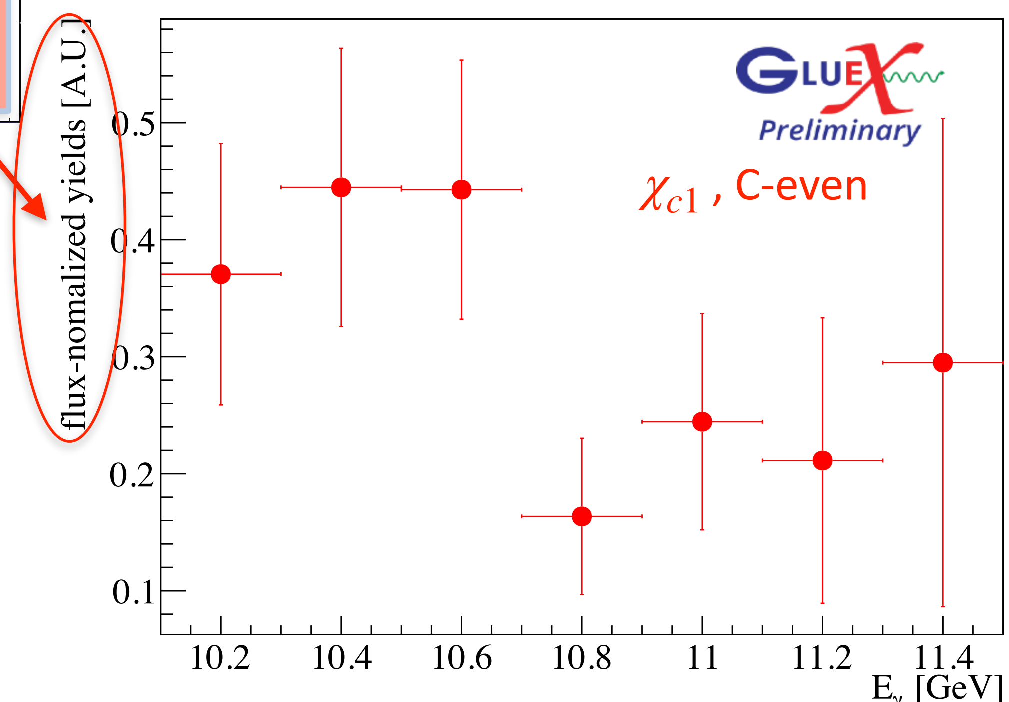

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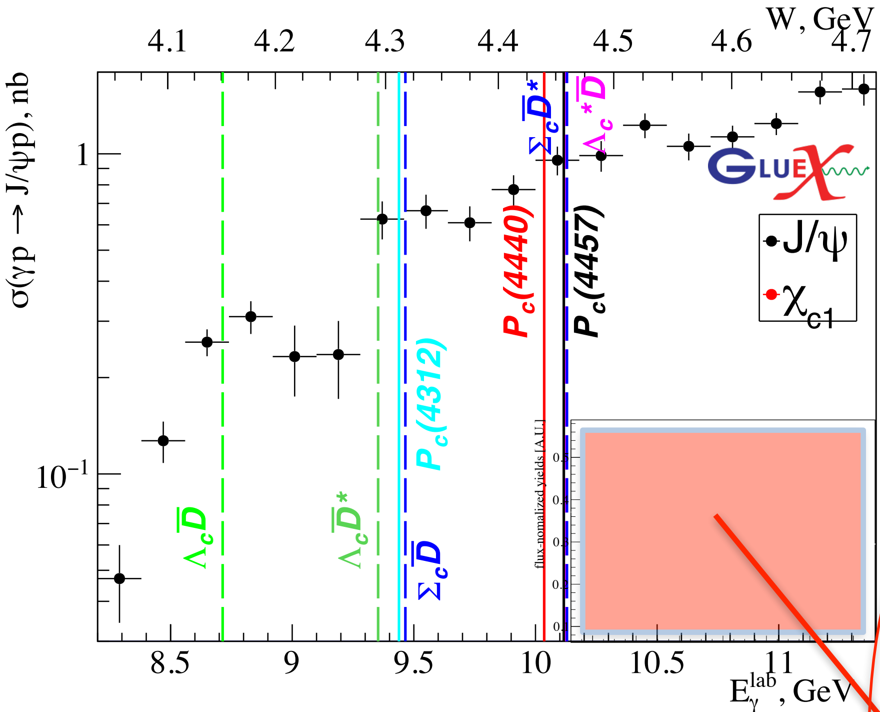
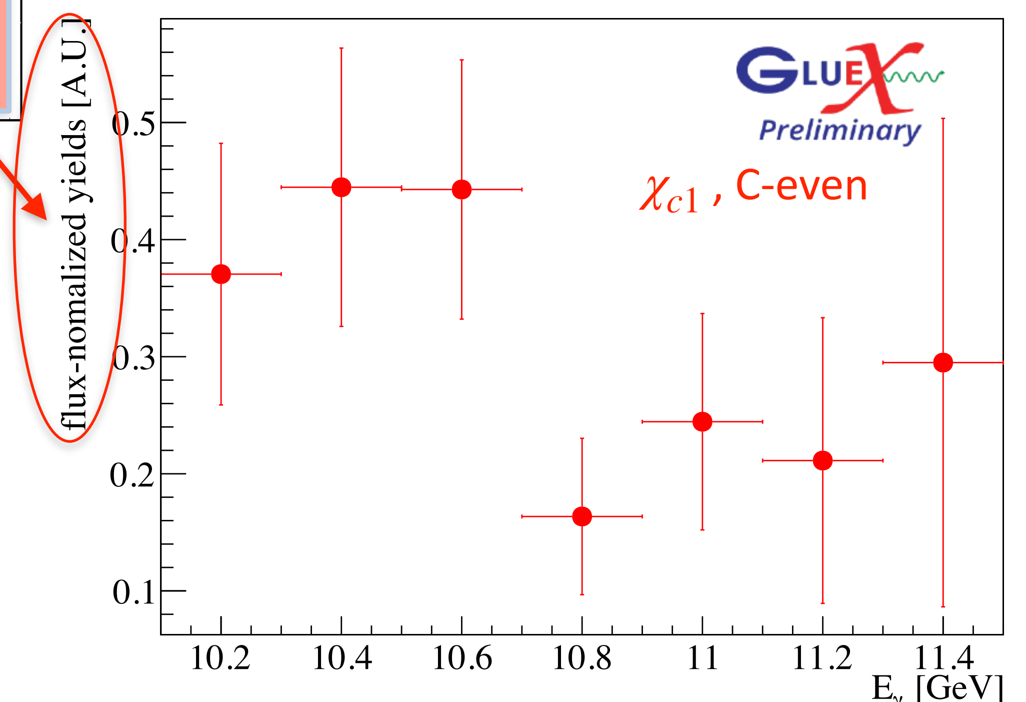
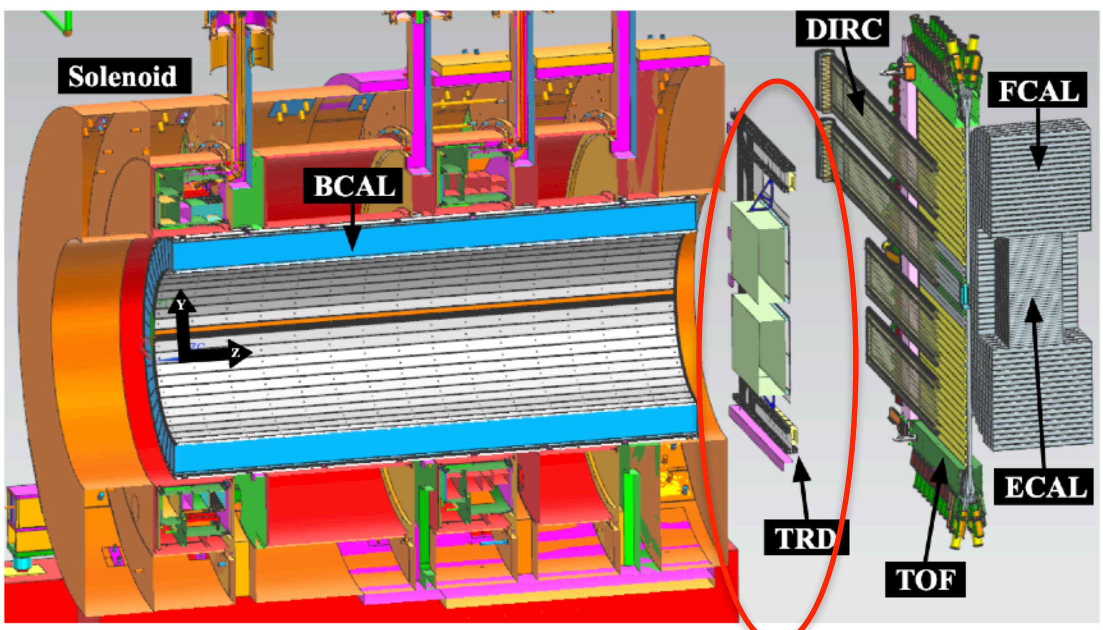


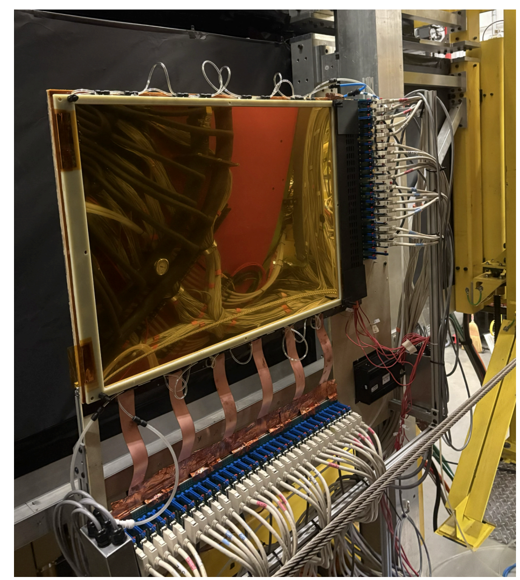


GlueX phase III - charmonium program

- Significant increase in J/ψ statistics and purity - GEM-based Transition Radiation Detector (TRD)
- Reaching high-mass charmonia

Run Period	PAC Days	J/ψ Yield	In coh. peak	χ_{c1} Yield	$\psi(2S)$ Yield
All Phase I	120	2,180	326	$\downarrow$	$\downarrow$
2020 Phase II	67.5	1,780	162	52	12
2023 Phase II	28.1	*741*	*67*	$\downarrow$	$\downarrow$
2024-2026 Phase II	109	*2,874*	*262*	*48*	*11*
2027-2028 Phase III	200	*11,271*	*1,795*	*364*	*178*
Projected Total		18,846	2612	464	201





Conclusions

- Kinematic extraction of $G(t)$ form factors in agreement with GPD predictions (within errors), even outside of the kinematic domain of the validity of GPD factorization - further theoretical and experimental studies are needed

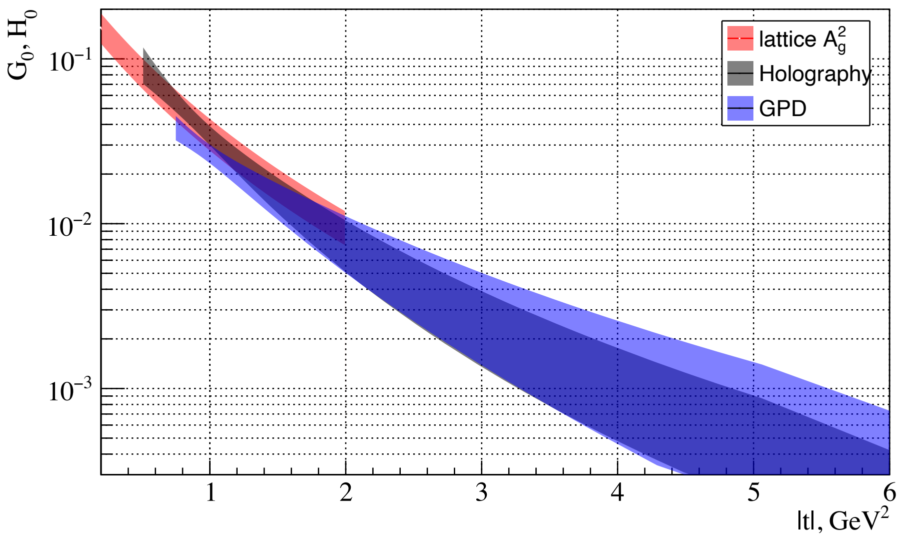
- First-time observation of charmonium photoproduction with opposite-to-photon parities

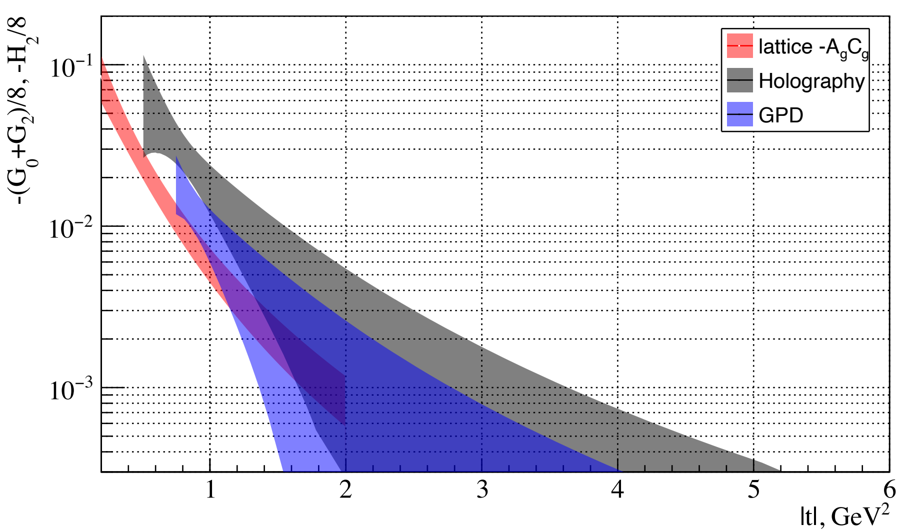
- Photoproduction of χ_c in t-channels is suppressed due to C-parity flip - dramatic difference of χ_c distributions in (E_γ, t) vs J/ψ

- This allows us to study s-channel reaction mechanisms that would help understanding their contributions in J/ψ photoproduction

- GlueX -III: threshold production of higher-mass charmonia (with different J^{PC}) adds a new dimension in studying gluonic content of the proton

Relation to Gluon Gravitational Form Factors





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- $G(t)$ 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