

Charmonium in Hall D

Open questions in charmonium threshold production and what GlueX can do

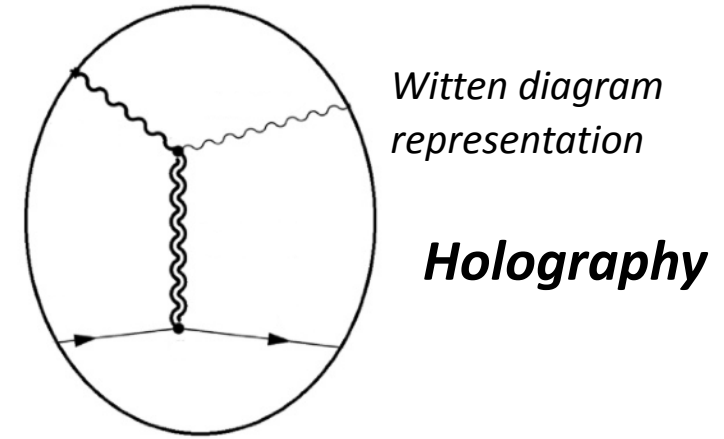
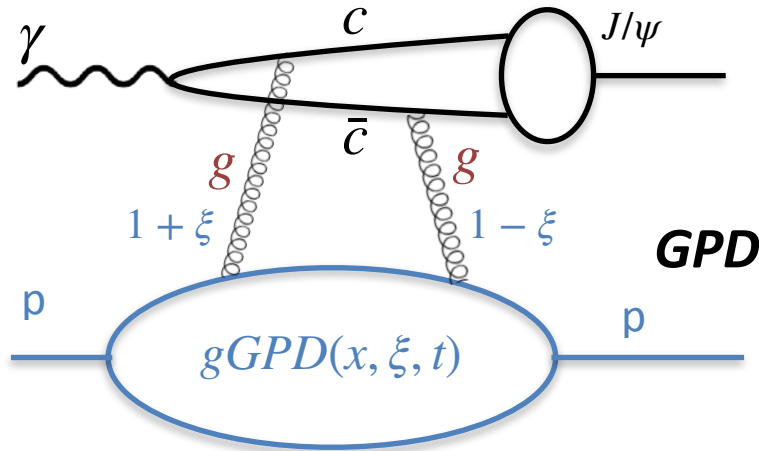
Lubomir Pentchev

- Reaction mechanism of J/ψ threshold production
 - two-gluon exchange, open charm, s -channel resonance, u -channel contribution?
- If two-gluon exchange is dominating, can we access gluonic content of proton?
 - is QCD factorization justified, estimates of corrections to leading-moment, -twist?
- Exotic states
 - LHCb P_c^+ , can we reach some of XYZ states?
- Higher statistics with GlueX-III
 - doubled intensity, improved PID (GEM-based Transition Radiation Detector)
- Amplitude analysis using linearly-polarized photons
 - polarized SDMEs, ...
- Photoproduction of charmonia with opposite-to-photon parity (χ_c states)
 - unique access to reaction mechanisms beneath gluon-, t -channel exchange
- $X(3872)$ or $\chi_{c1}(3872)$ photoproduction with GlueX ($E_\gamma^{thresh} = 11.9$ GeV)?



Gluon EMT Form Factors from experimental point of view

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



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

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

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

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

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

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

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

for high ξ
values
leading moments

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

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

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

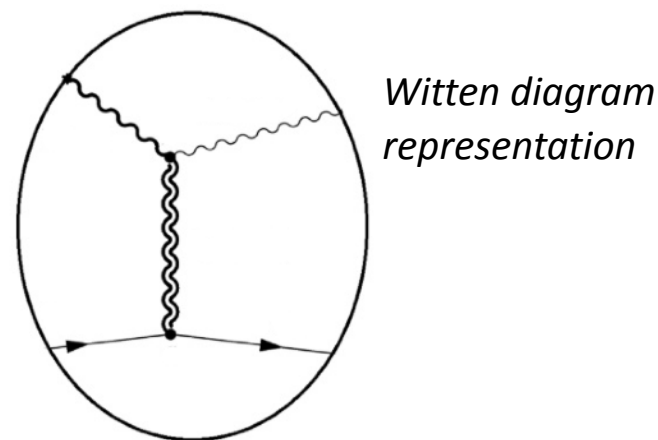
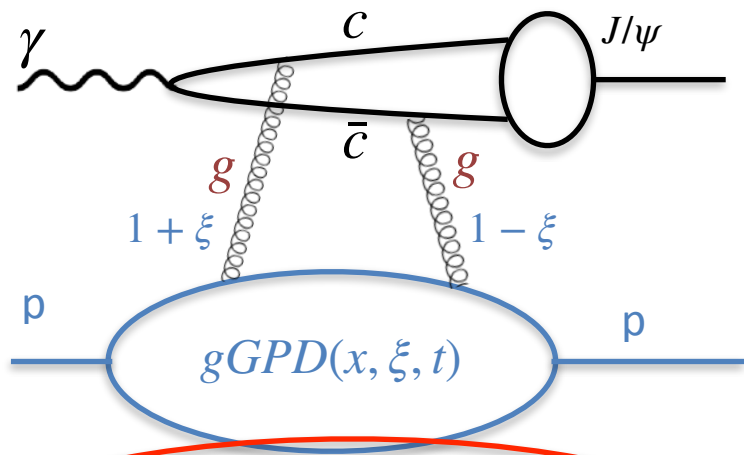
for large N_c and
strong α_s

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

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

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Gluon Form Factors - energy independence

$\gamma p \rightarrow J/\psi p$

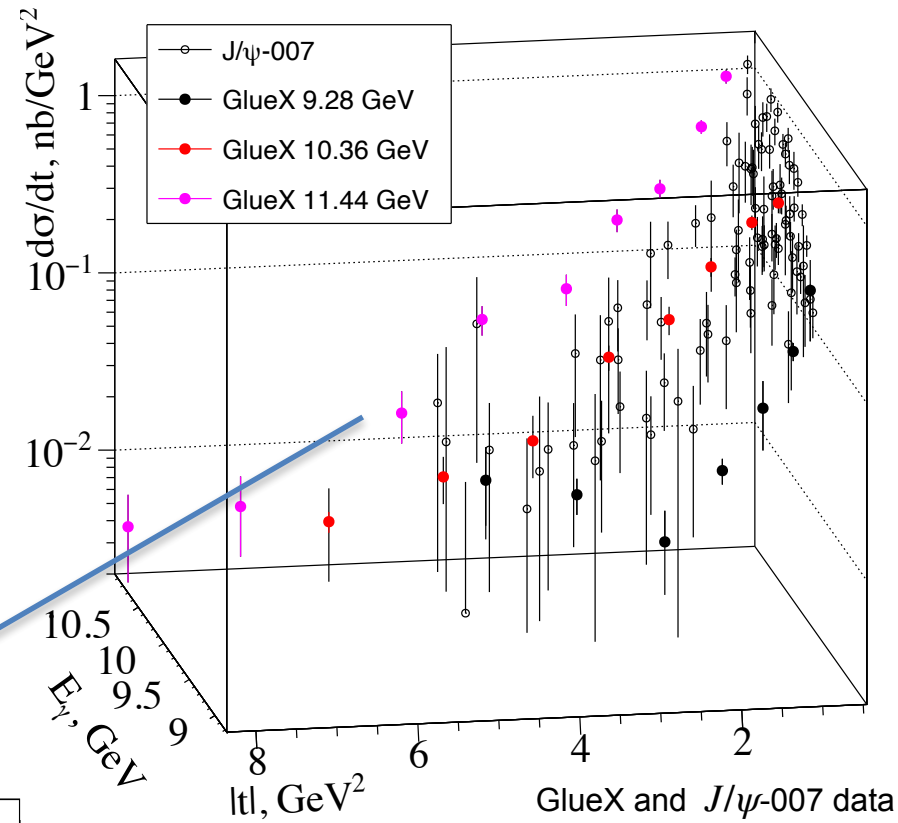
Energy independence of the
 $G_0(t)$ FF function (within errors)

No theory/lattice constraints used,
No theoretical assumptions,

GPD approach used as a guidance:

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

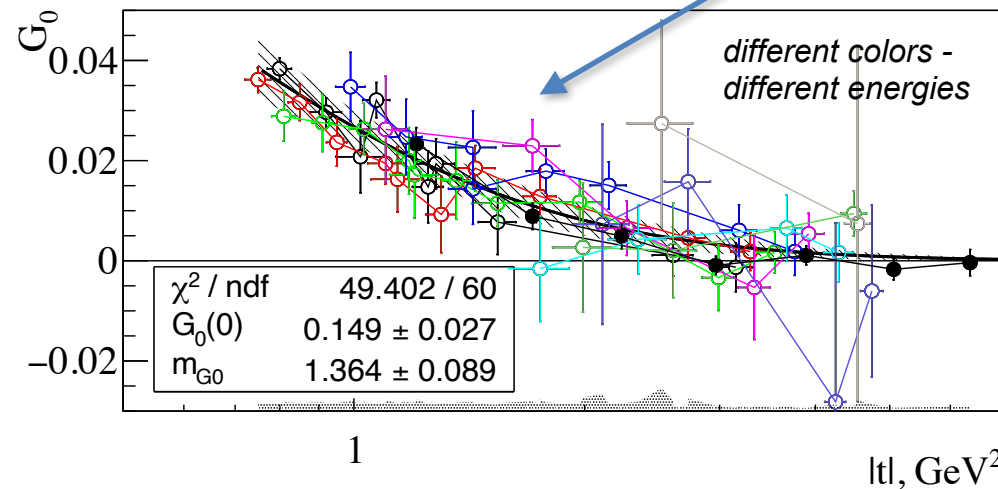
$$\xi(E_\gamma, t) = \frac{M_{J/\psi}^2 - t}{4E_\gamma m - M_{J/\psi}^2 + t}$$



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

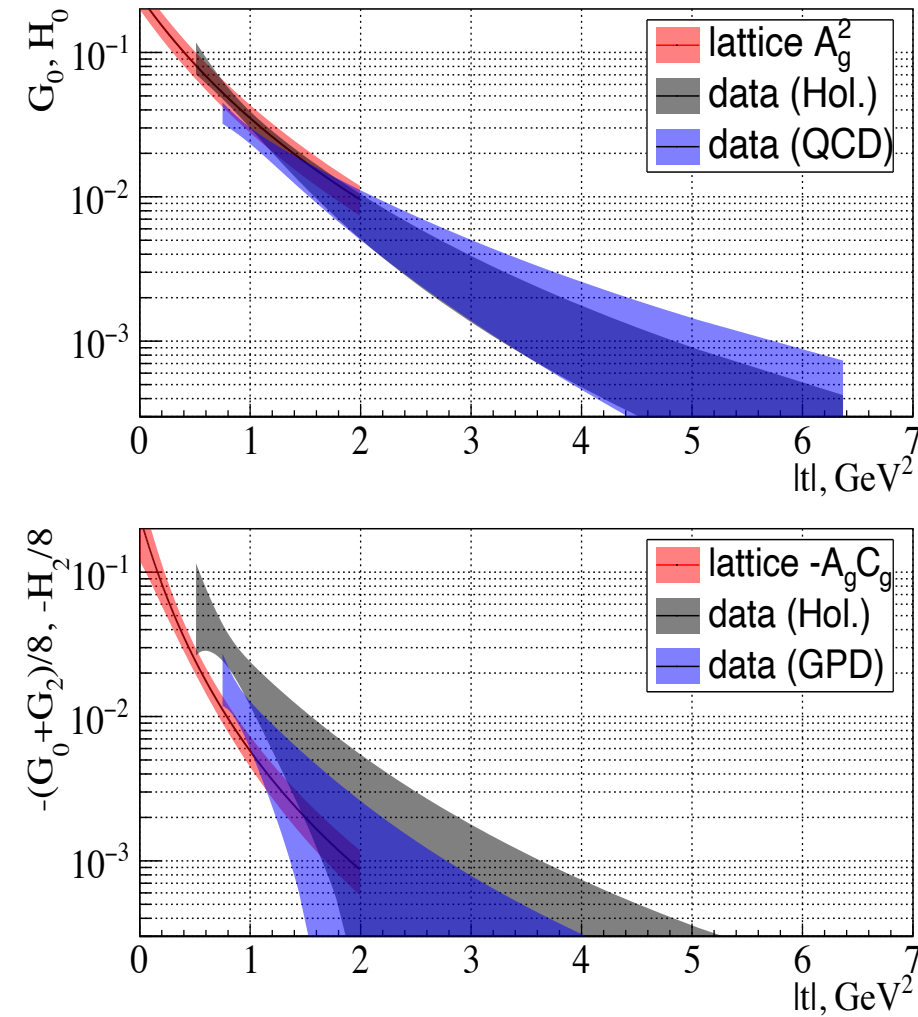
Fit with $\frac{G_0(0)}{(1 - t/m_{G_0}^2)^4}$

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



Relation to Gluon EMT Form Factors

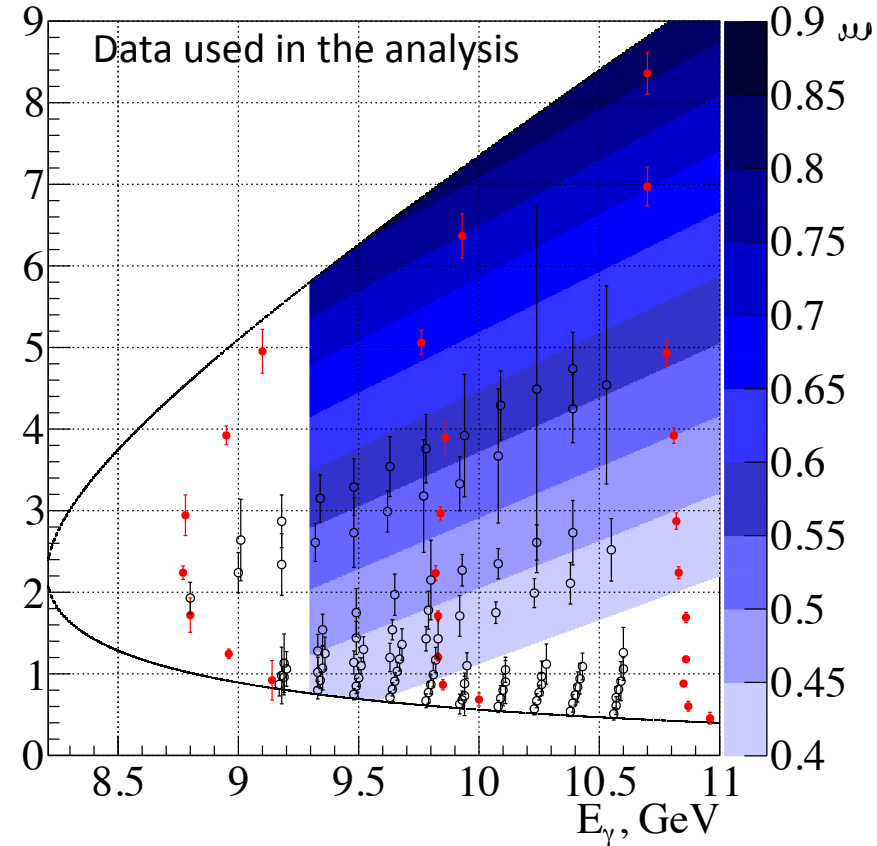
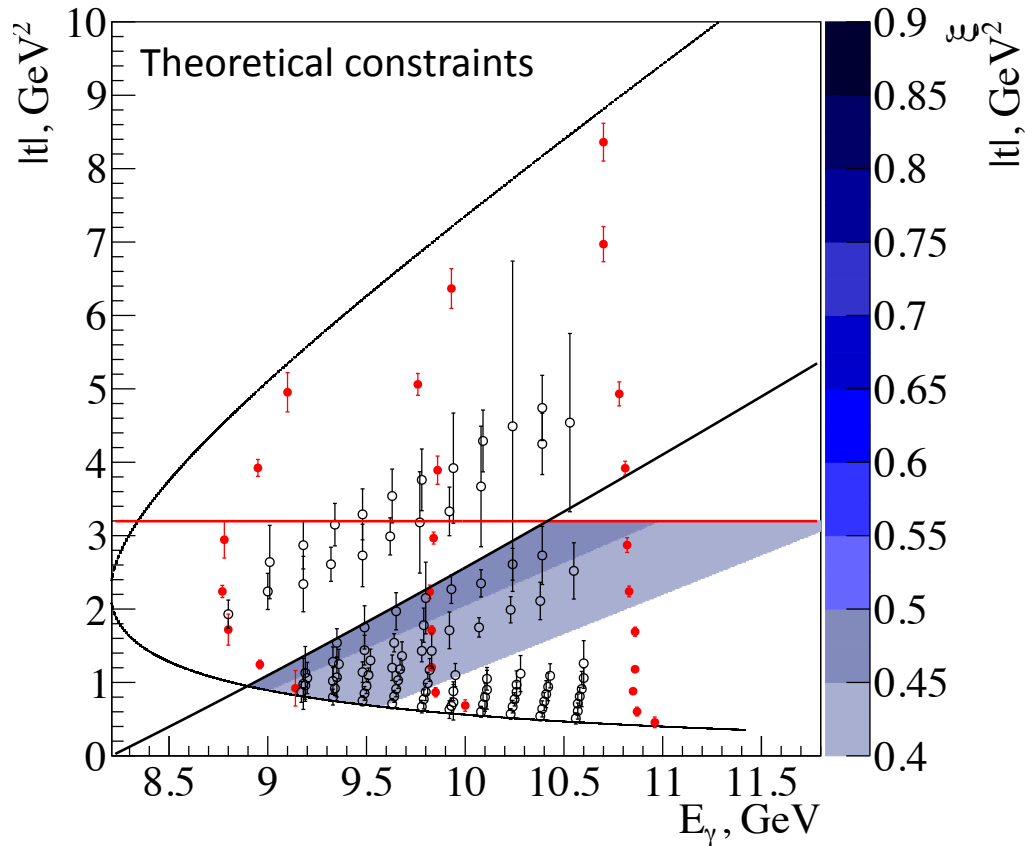
now using theory



Features in data consistent with the GFF models:

- $d\sigma/dt(E_\gamma, t \rightarrow \text{fixed})$ 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

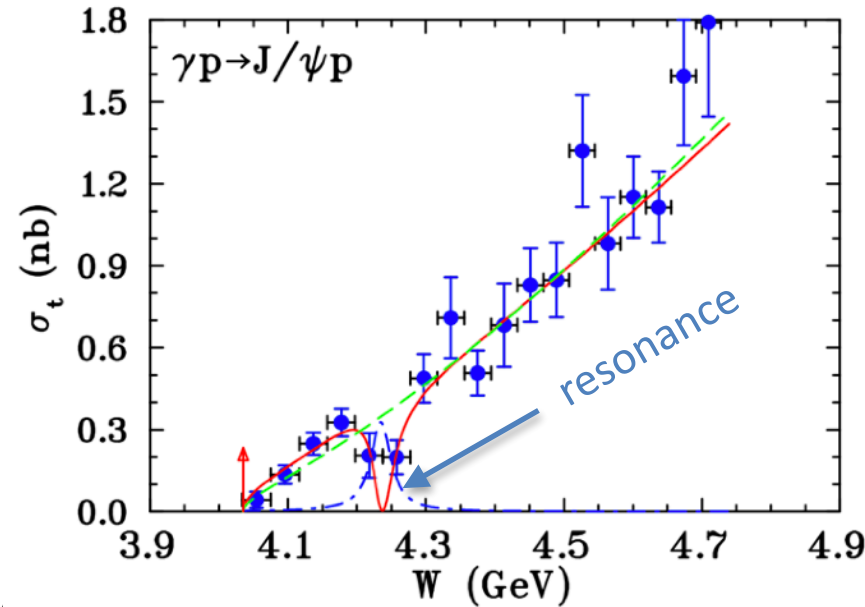
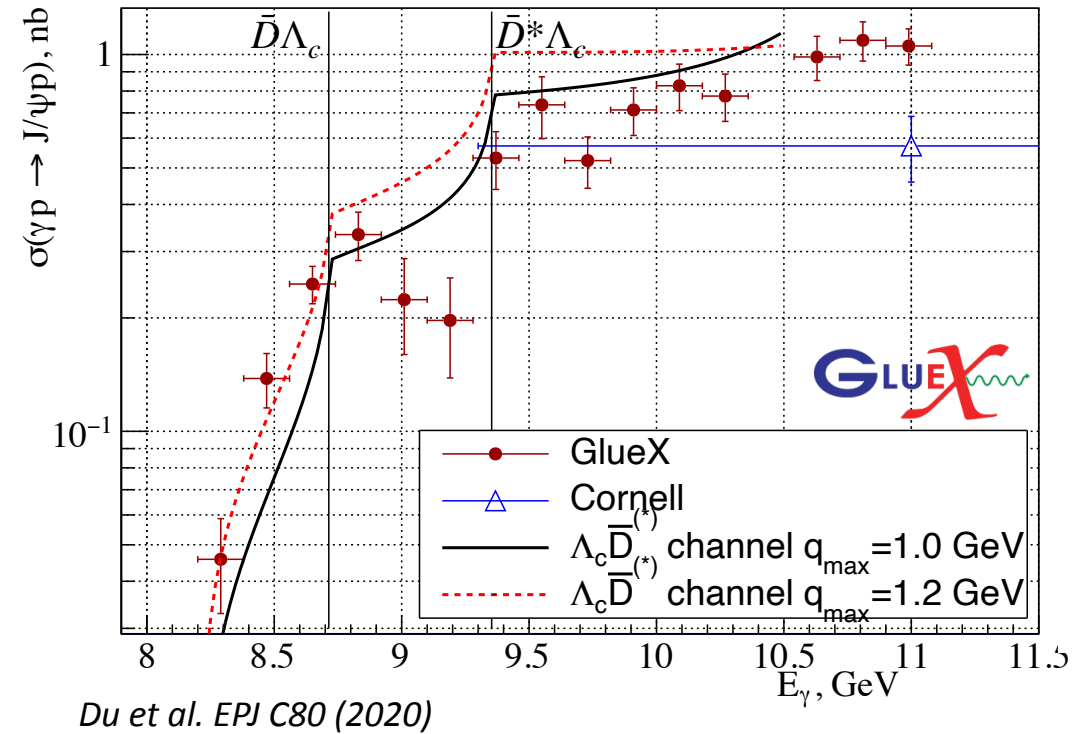
Open questions: GPD factorization - kinematic limits



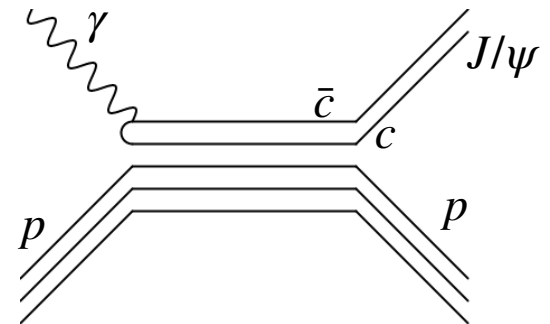
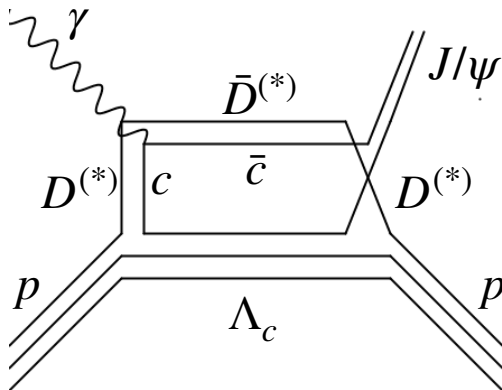
- $\xi > 0.4$ - needed for leading-moment approximation
- $|t| < M_{J/\psi}^2/3$ - higher-twist corrections $\sim |t|/M_{J/\psi}^2$
- $|t| < (2k_{cm})^2$ - relative velocity between final state particles $> \sqrt{|t|}$ to avoid FSI

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

Open questions: reaction mechanisms: open-charm, resonance

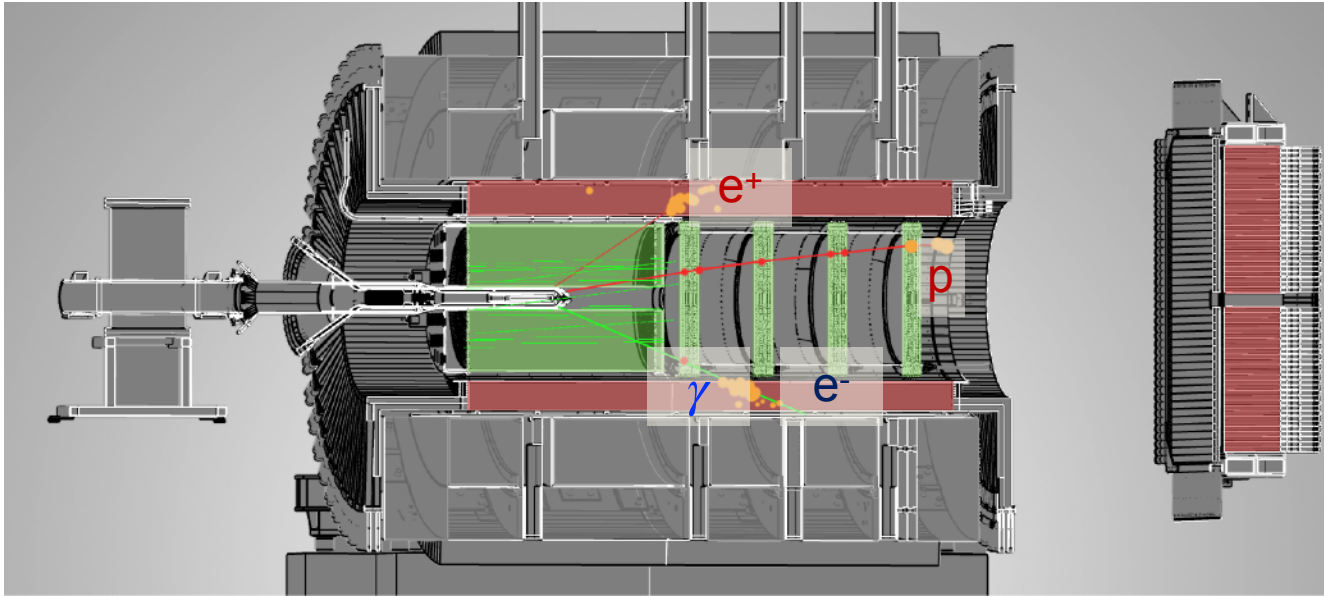


Strakovsky et al. PRC 108 (2023)

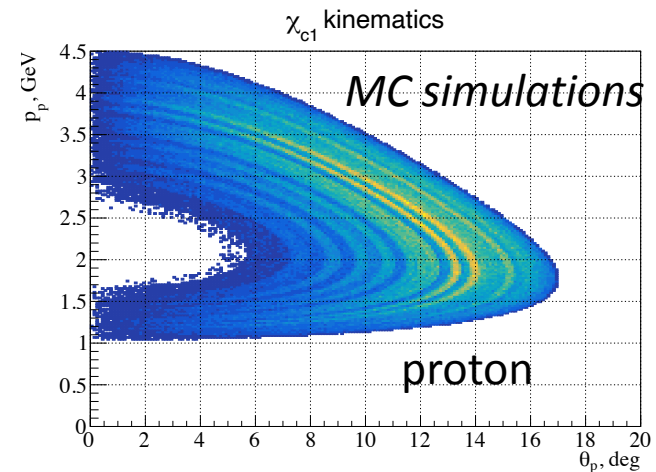
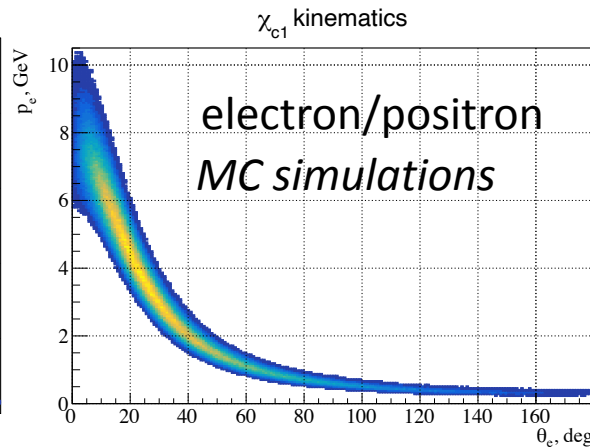
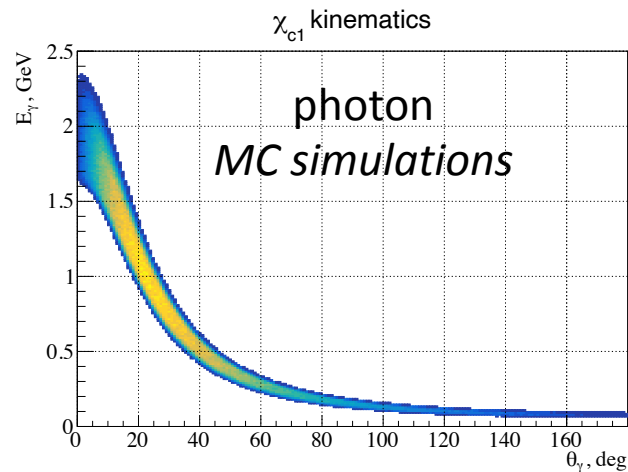


χ_c detection with GlueX

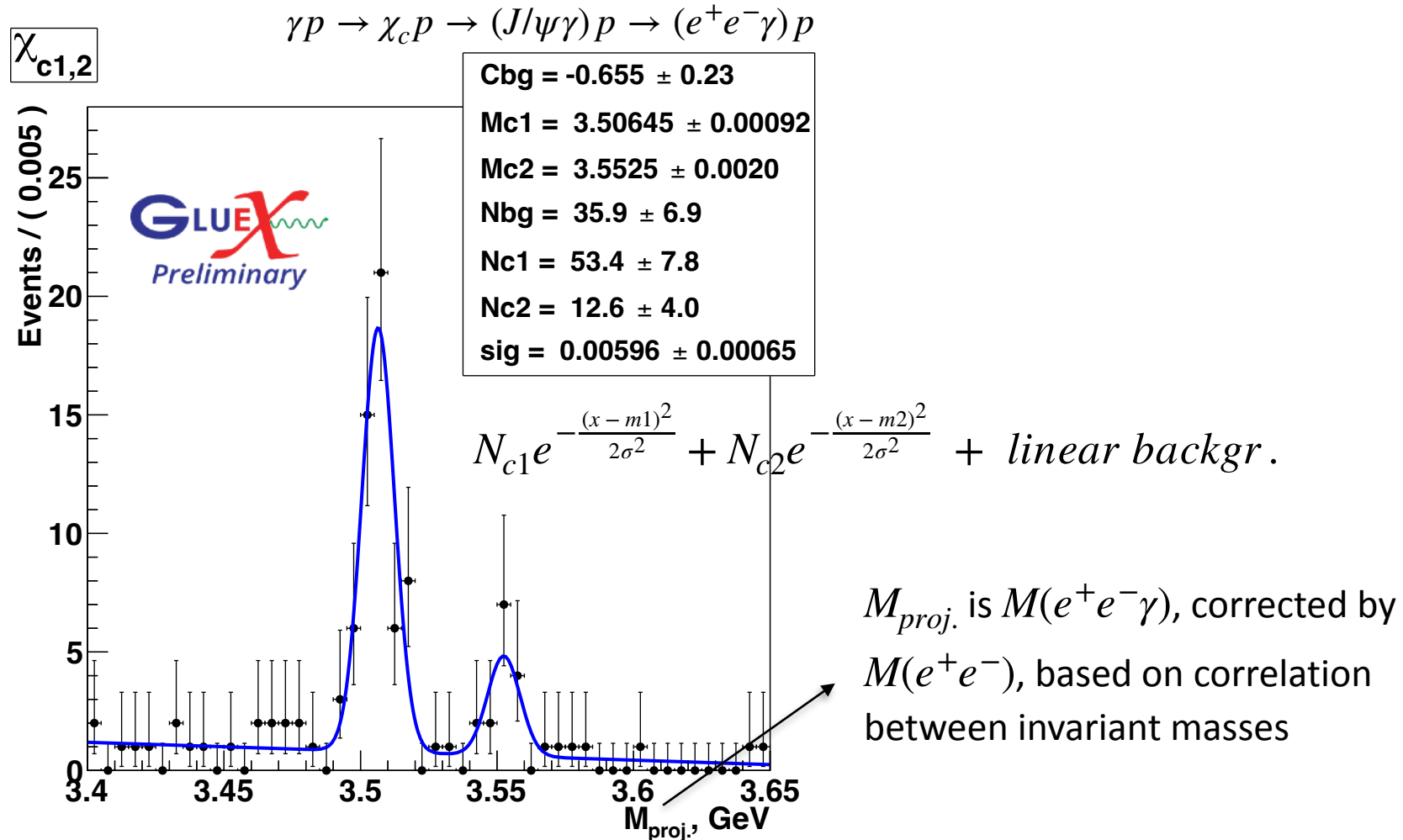
$$\gamma p \rightarrow \chi_c p \rightarrow J/\psi \gamma p \rightarrow e^+ e^- \gamma p \text{ exclusive}$$



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



C-event charmonium states at threshold with GlueX

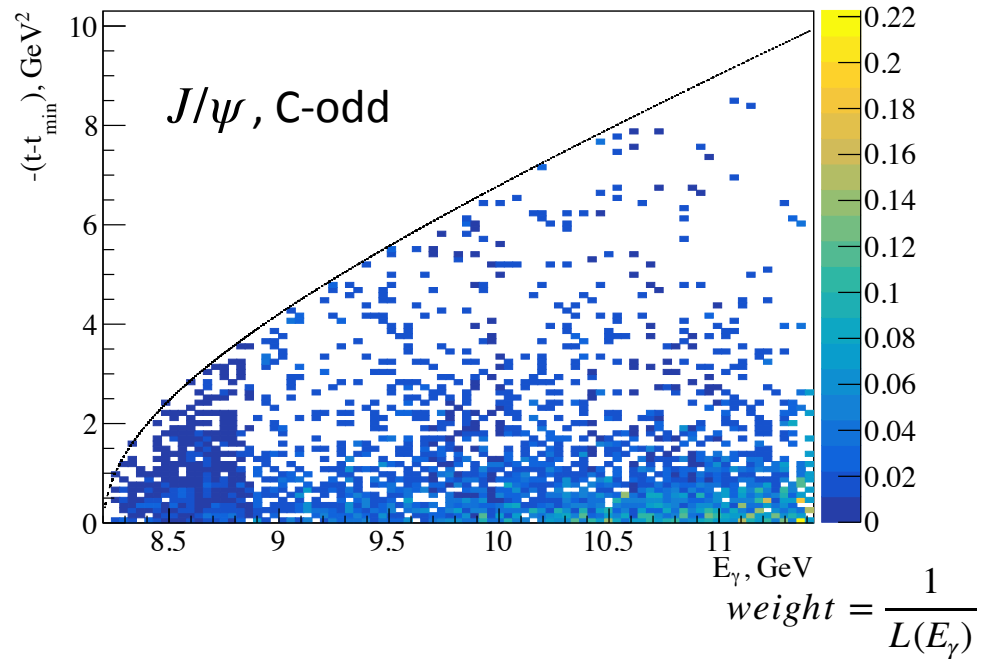
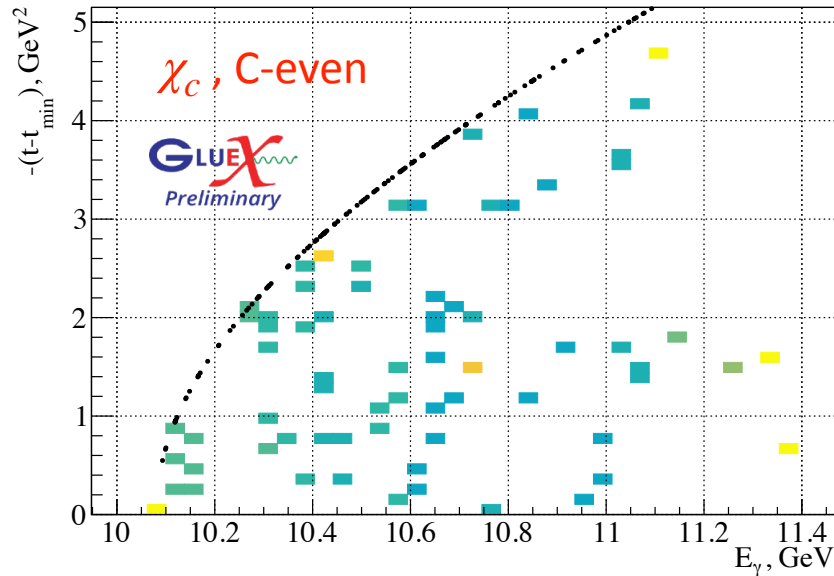


- $\chi_{c1}(3511), 1^{++}$ $BR(\chi_{c1} \rightarrow \gamma J/\psi) = 33.9 \%$ $E_{\gamma}^{thr} = 10.1 \text{ GeV}$
- $\chi_{c2}(3556), 2^{++}$ $BR(\chi_{c2} \rightarrow \gamma J/\psi) = 19.0 \%$ $E_{\gamma}^{thr} = 10.2 \text{ GeV}$
- $\chi_{c0}(3415), 0^{++}$ $BR(\chi_{c0} \rightarrow \gamma J/\psi)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

First ever evidence for photoproduction of C-even charmonium

C-event charmonium states at threshold with GlueX

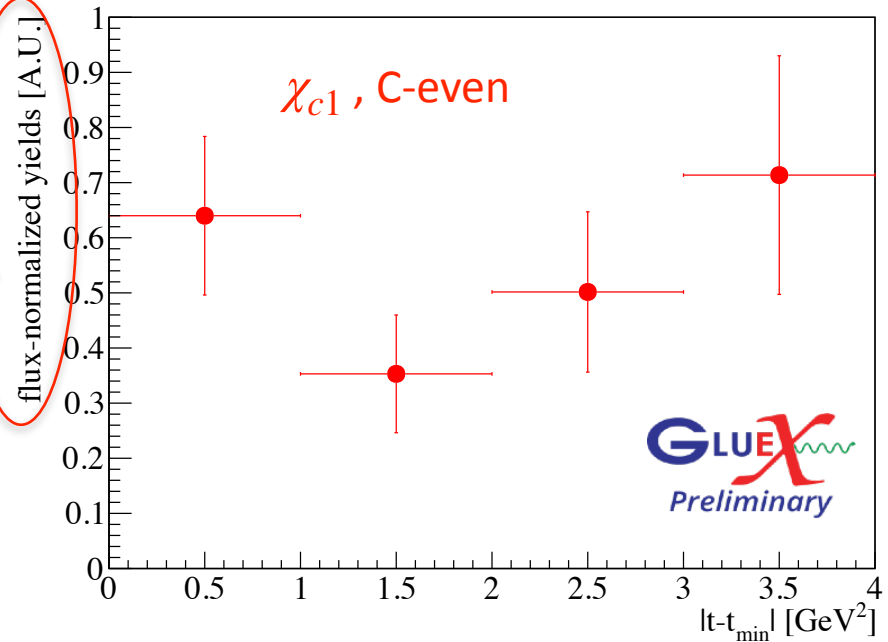
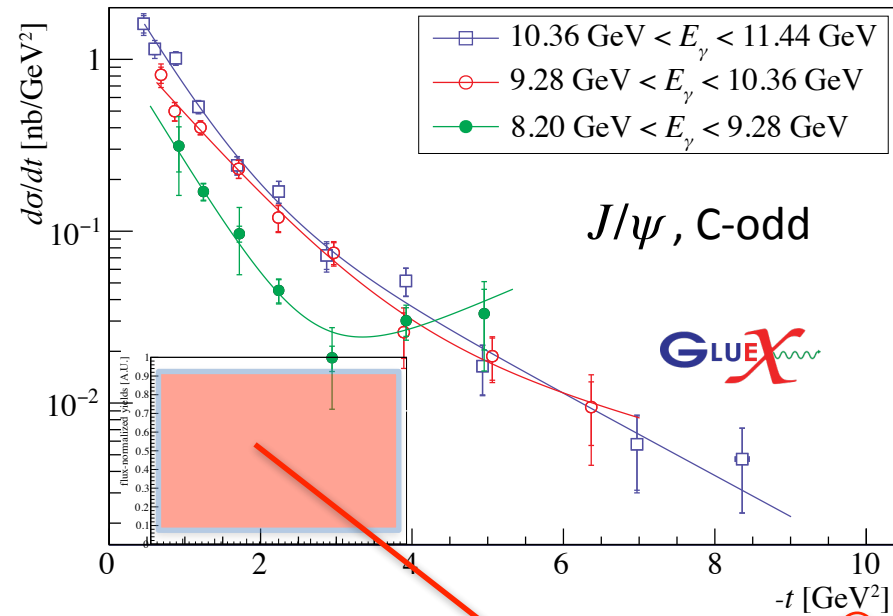
- Dramatic difference: χ_c distribution in (E_γ, t) vs J/ψ



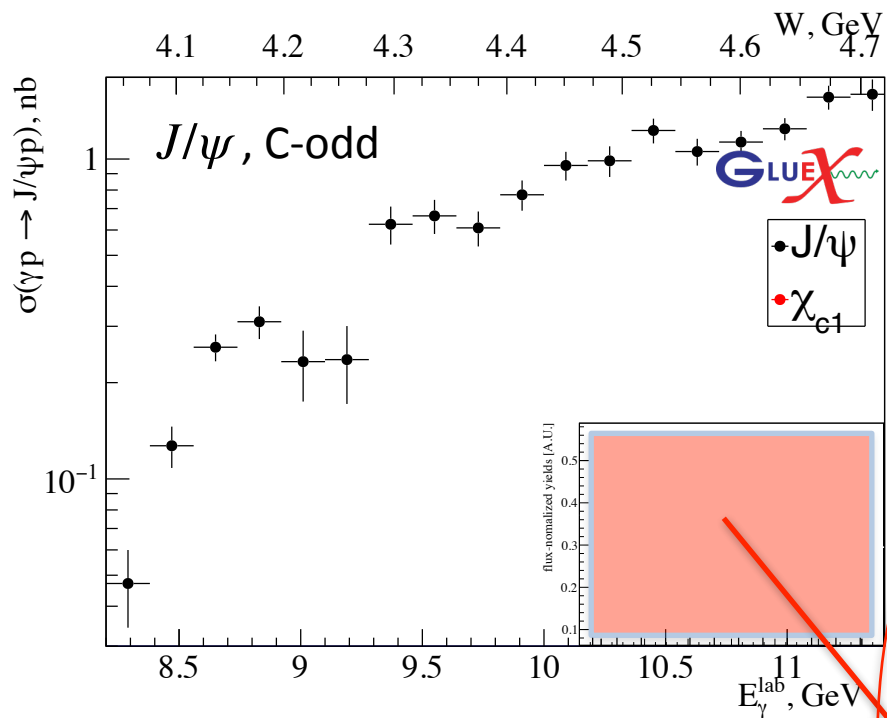
t -channel exchange mechanism is suppressed for χ_{c1} (requires C -odd exchange)

- C -odd gluon exchange (odderon!)
- vector meson (quark) exchange is suppressed (OZI rule)
- photon exchange suppressed (Landau-Yang theorem)

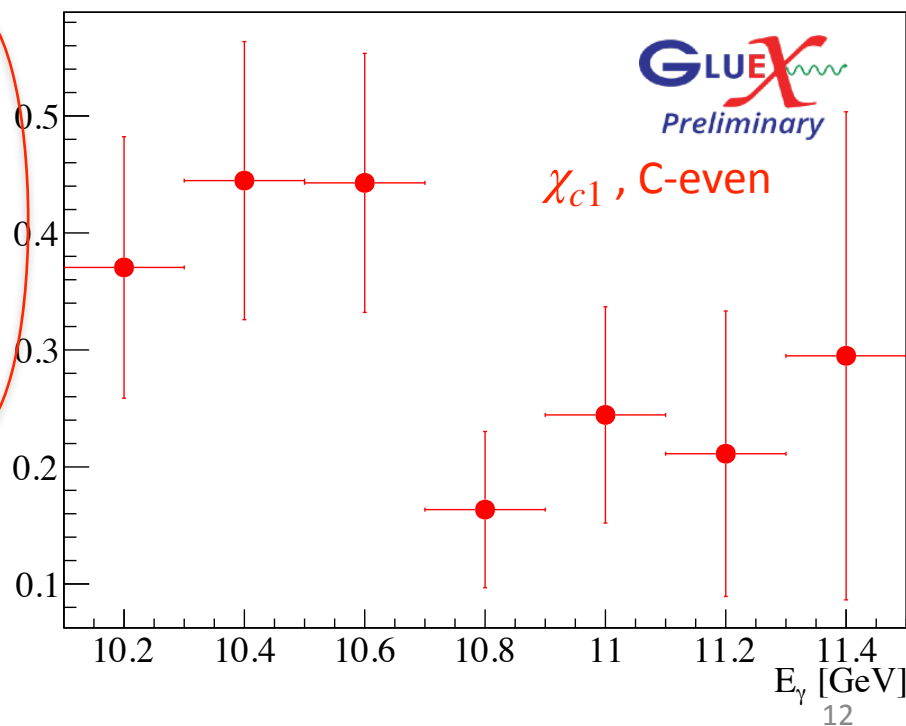
C-event charmonium photoproduction - $d\sigma/dt$



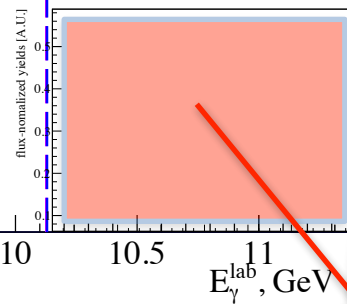
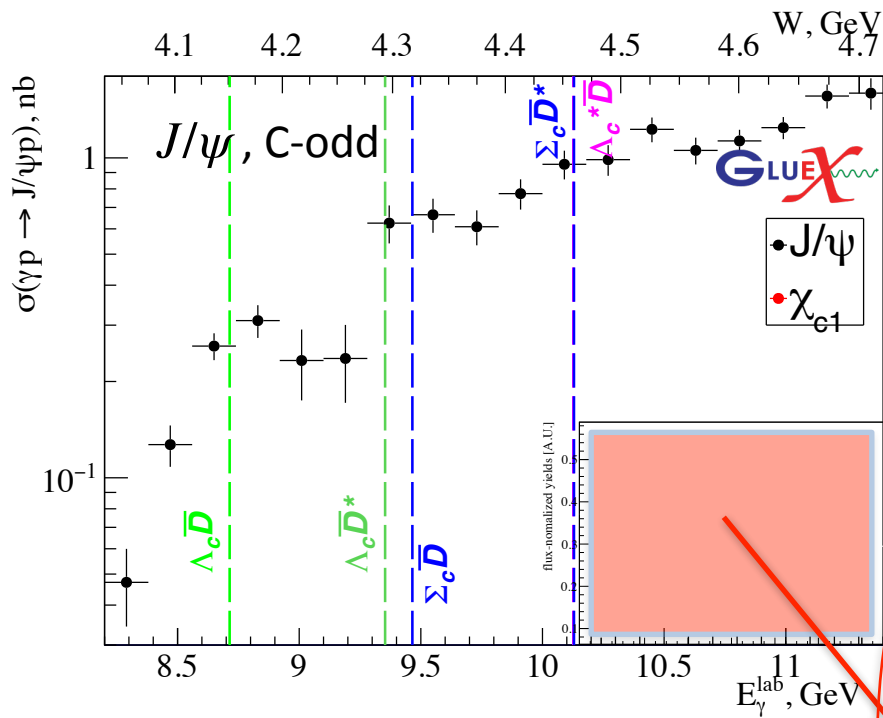
C-event charmonium states at threshold with GlueX



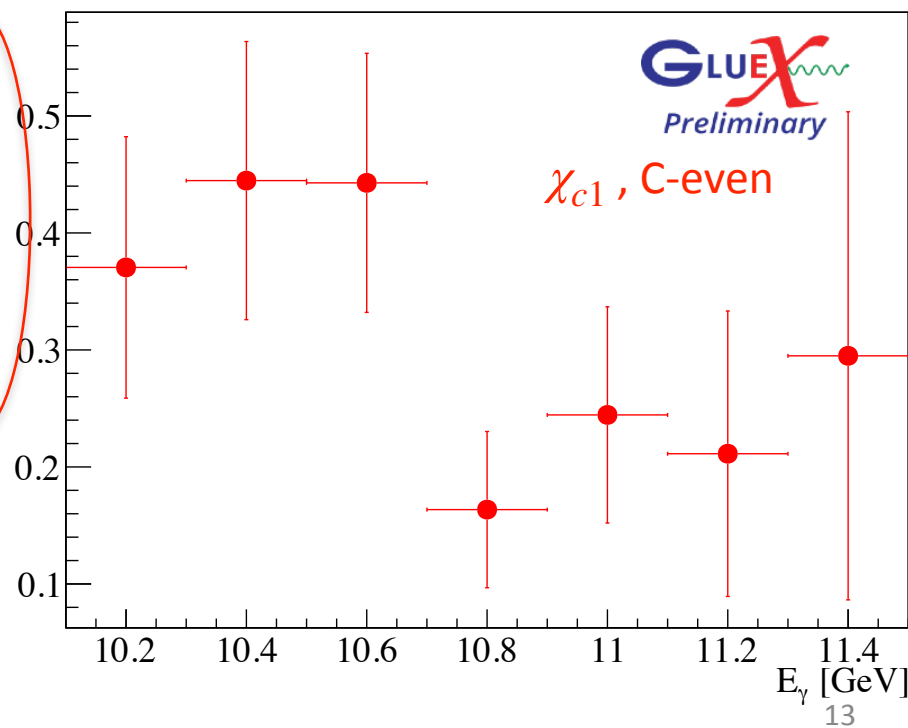
flux-normalized yields [A.U.]



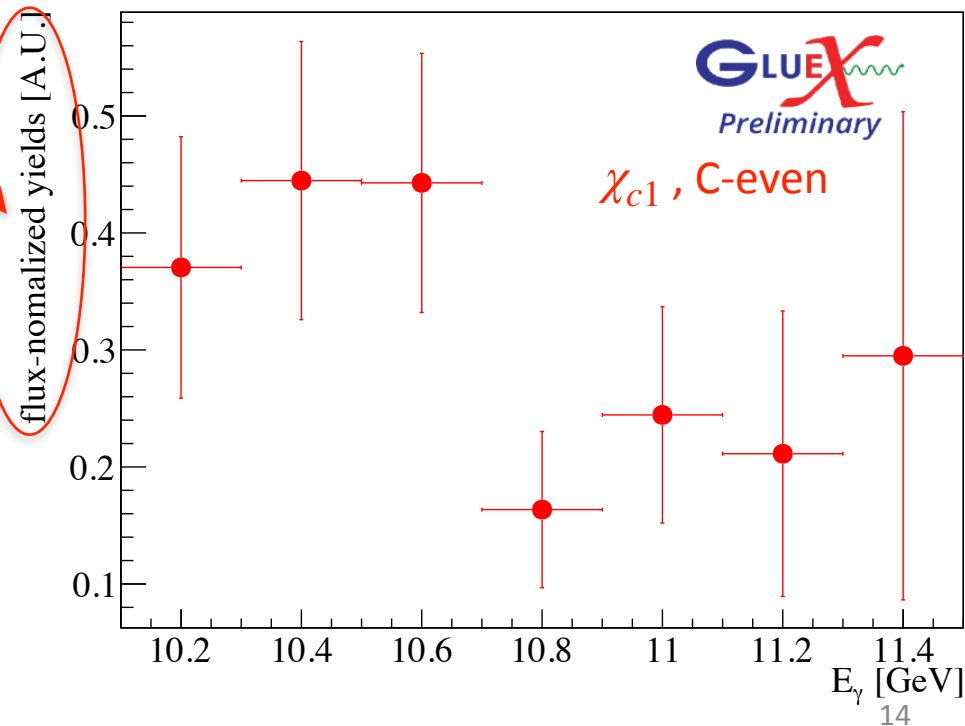
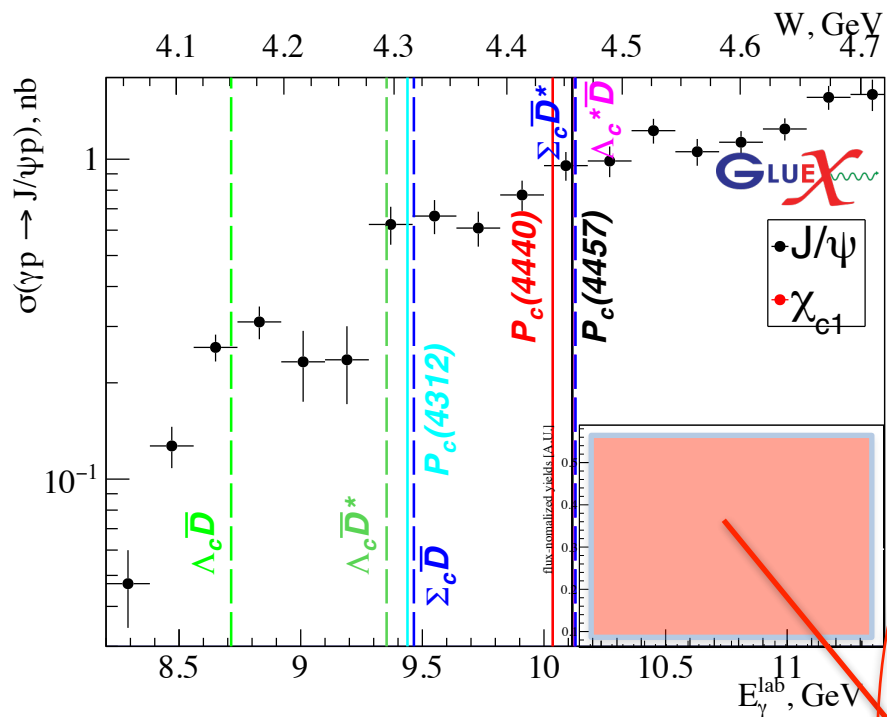
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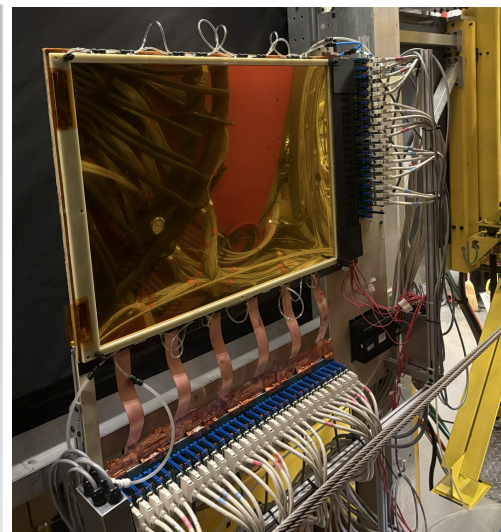
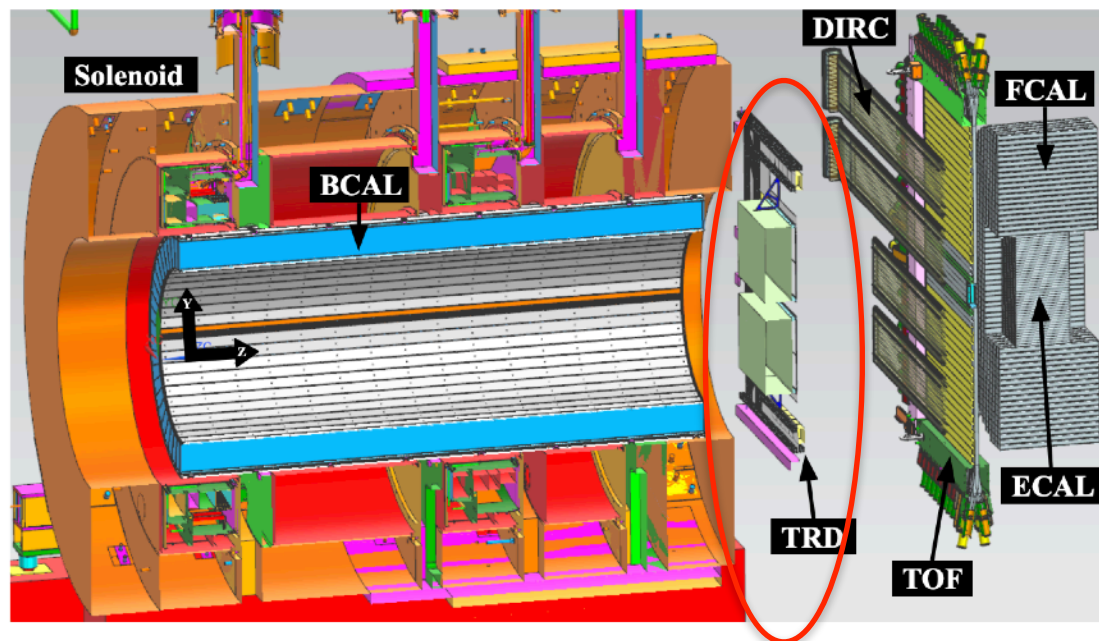
C-event charmonium states at threshold with GlueX



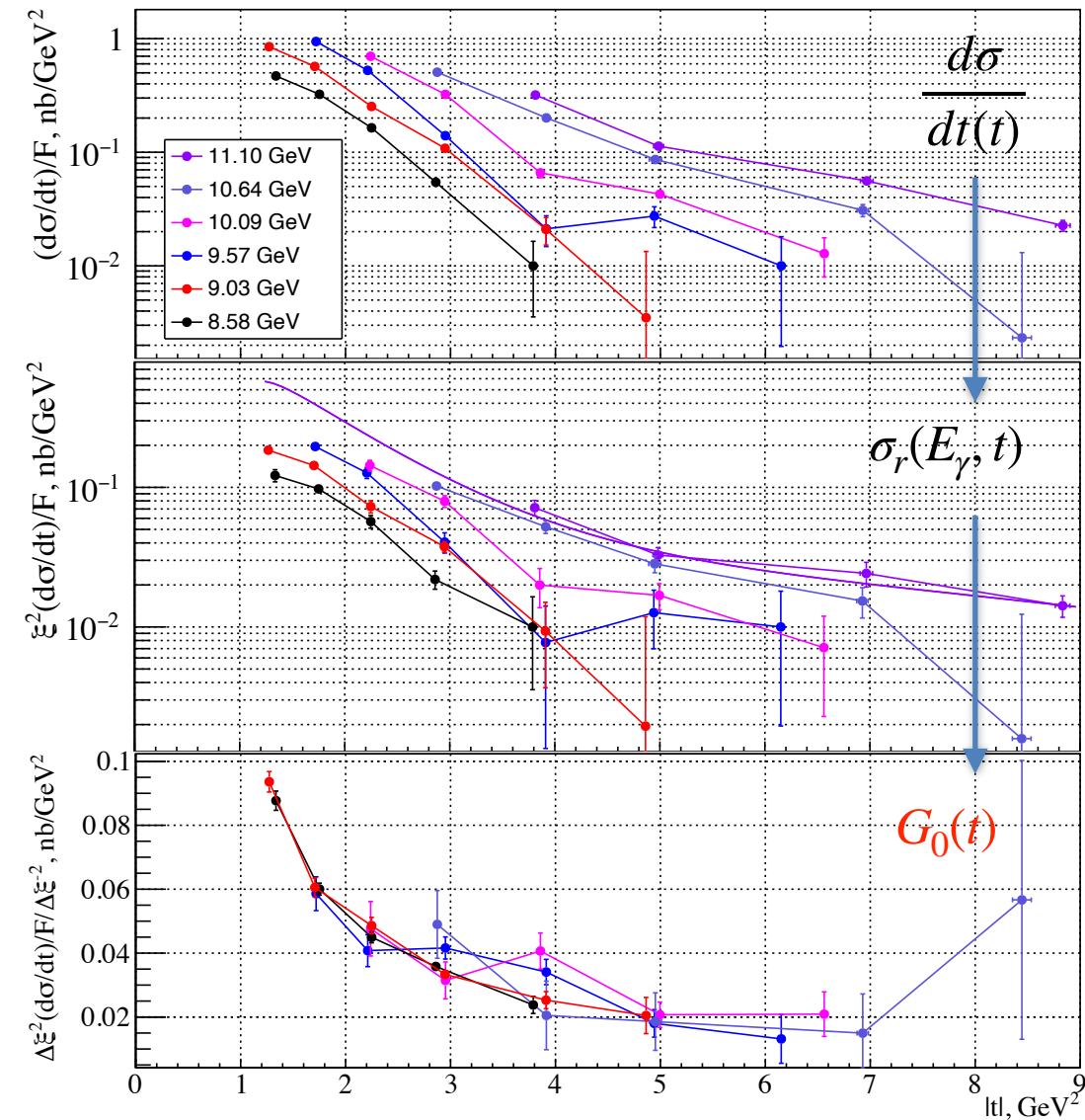
GlueX phase III - charmonium program

- 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	↓	↓
2020 Phase II	67.5	1,780	162	52	12
2023 Phase II	28.1	741	67	↓	↓
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



GlueX phase III - J/ψ “Rosenbluth” separation



Anticipated $d\sigma/dt(t)$

Reduced cross section

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

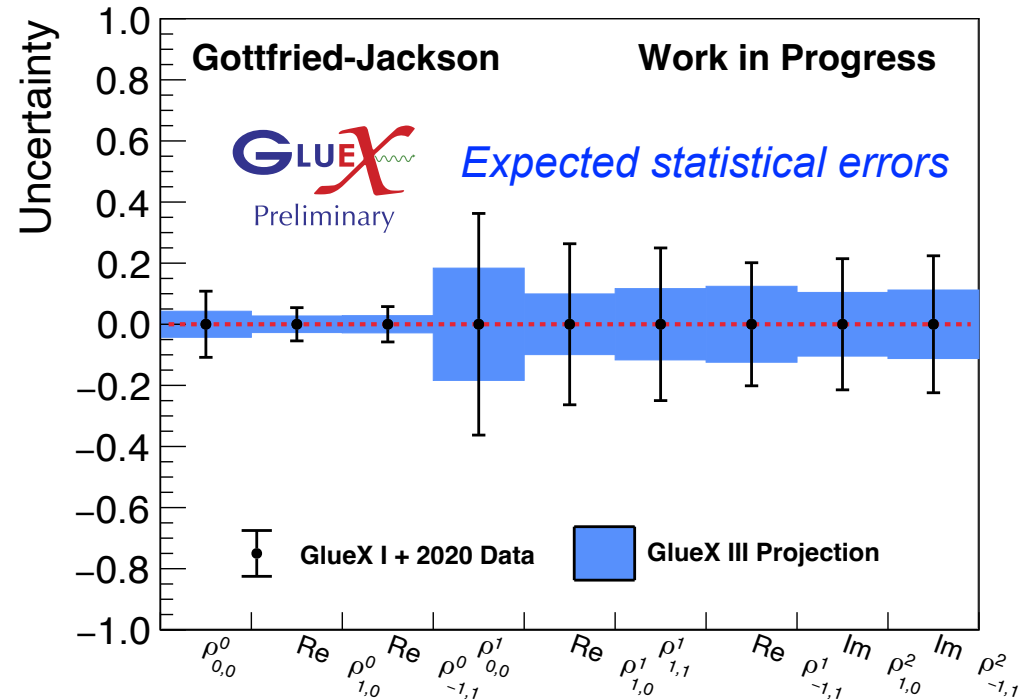
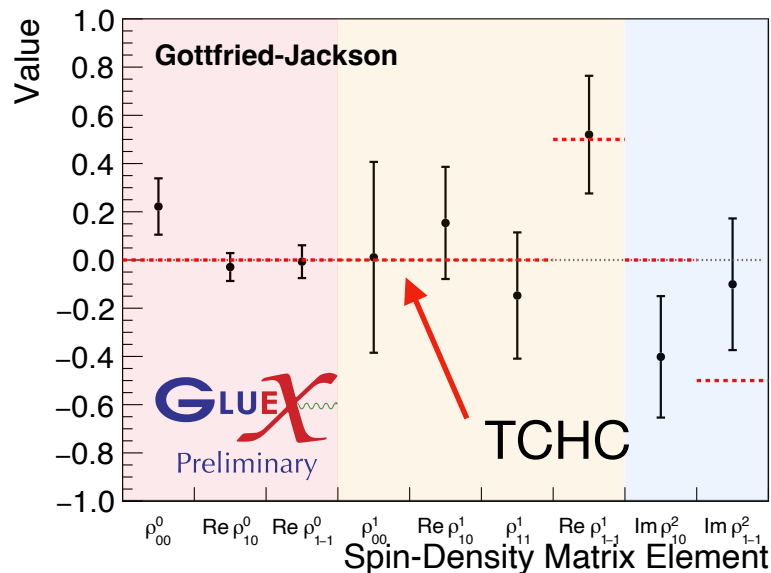
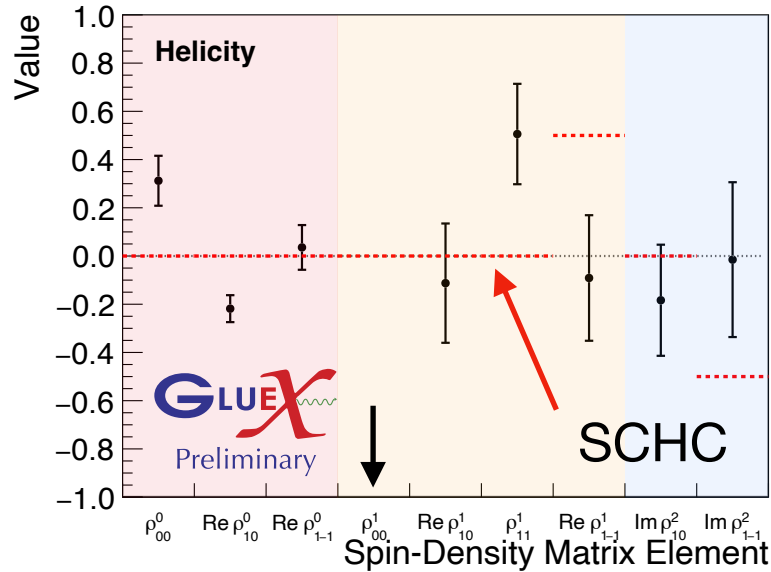
$$\xi(E_\gamma, t) = \frac{M_{J/\psi}^2 - t}{4E_\gamma m - M_{J/\psi}^2 + t}$$

Extracted $G_0(t)$ form factor

$G_0(t) = A_g^2(t)$ in leading moment approximation

GlueX phase III - J/ψ SDMEs

Slide from Joshua Jackson



- Polarized SDMEs extracted in coherent peak where average $P_\gamma \approx 35 - 40 \%$
 - Polarized SDMEs not well constrained with just GlueX-I and 30% of GlueX-II
- Estimate GlueX-III error bars (stat. only) by performing analysis on toy data with expected statistics

Lessons learned from χ_{c1} photoproduction $\rightarrow \chi_{c1}(3872)$

Due to C -parity flip, t -channel exchange mechanism is suppressed for χ_{c1} - flat distributions w.r.t energy and t

Allows to study other reaction mechanisms beneath t -channel

- Open charm exchange
- ...

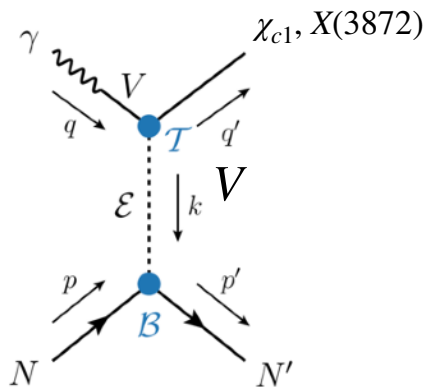
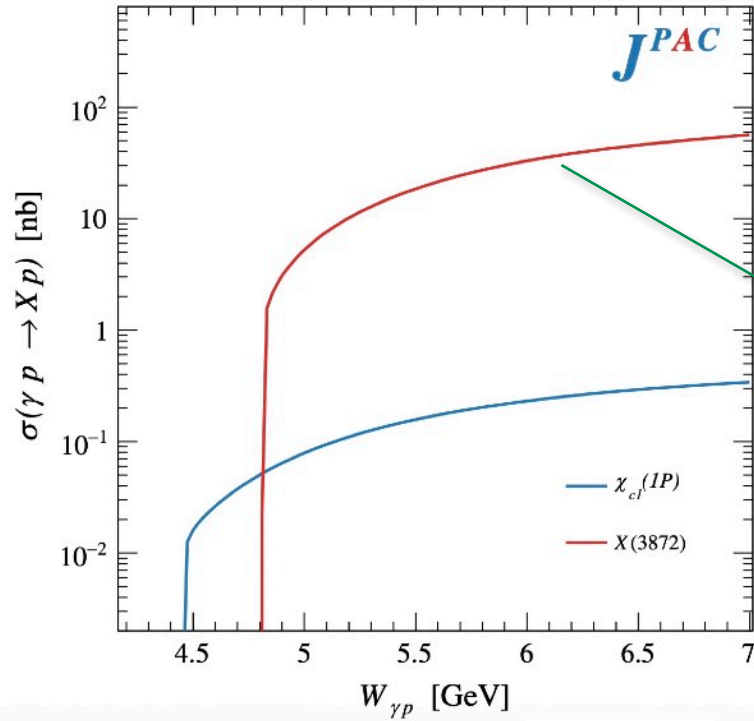
What if the same is true for exotic state $\chi_{c1}(3872)$ - same 1^{++} quantum numbers

- cross sections might be high near threshold
- but threshold is $E_\gamma = 11.9 \text{ GeV} !!!$

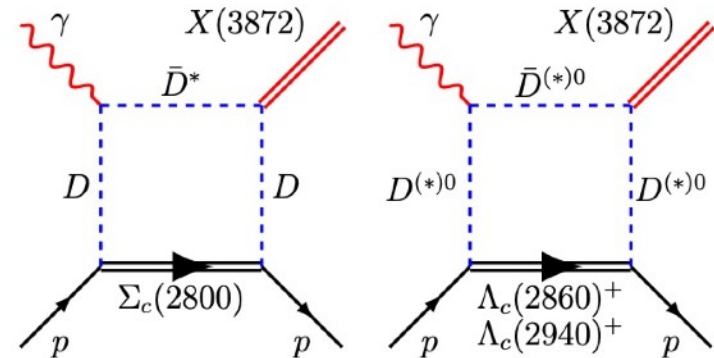
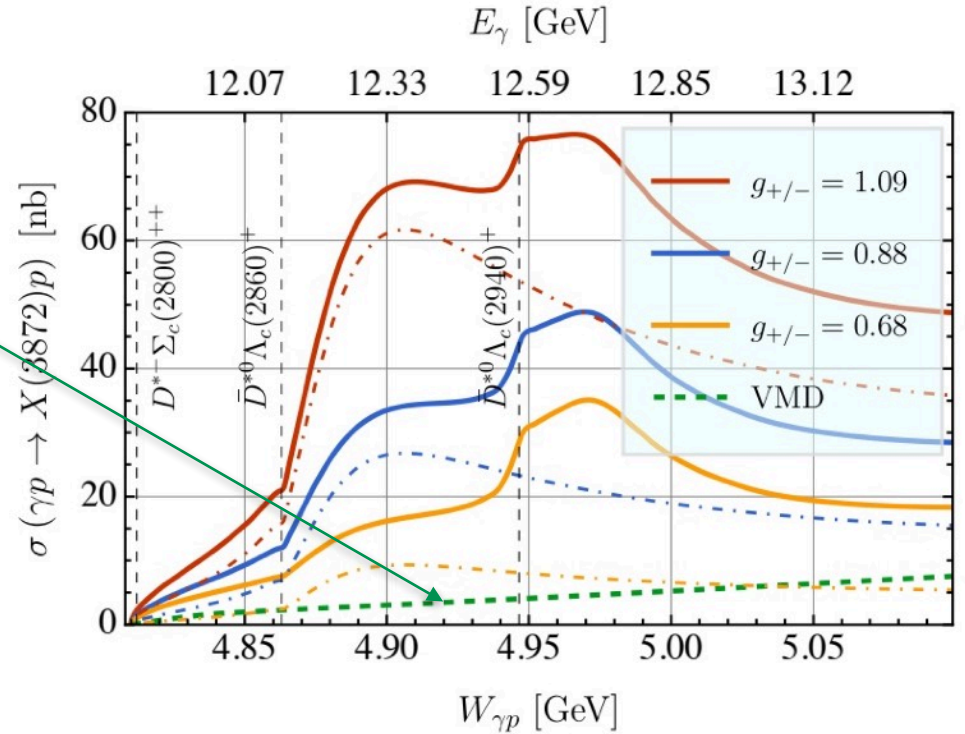
$X(3872)$ now $\chi_{c1}(3872)$ Tetraquark or Mesonic Molecule (D^0 and $\bar{D}^{*0}$) ?

- found in 2003 by Belle
- seen by BaBar, BESIII, CDF, LHCb (1^{++}), CMS, ATLAS, GlueX???

$\chi_{c1}(3872)$ - cross sections



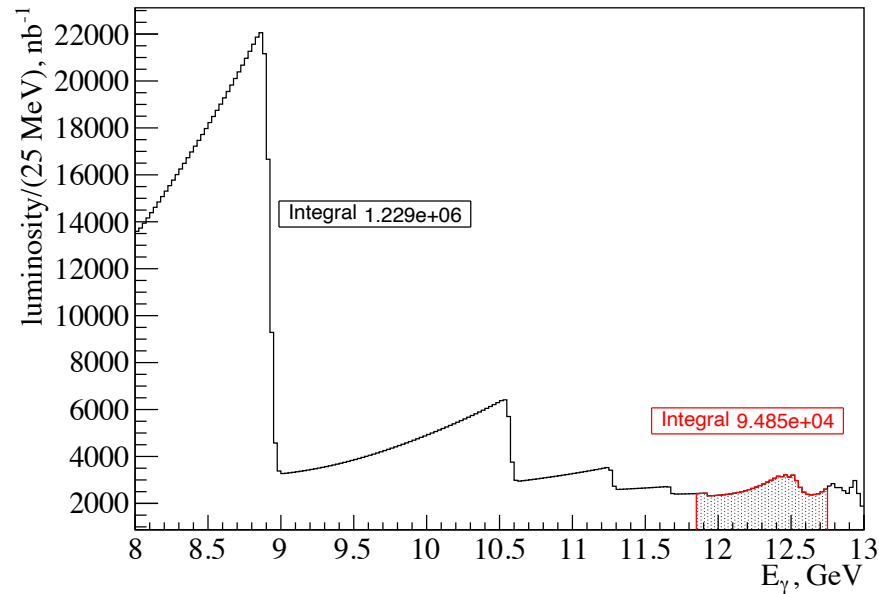
JPAC, PRD **102** (2020)



Xiong-Hui Cao et al, J. Phys. G **51** (2024)

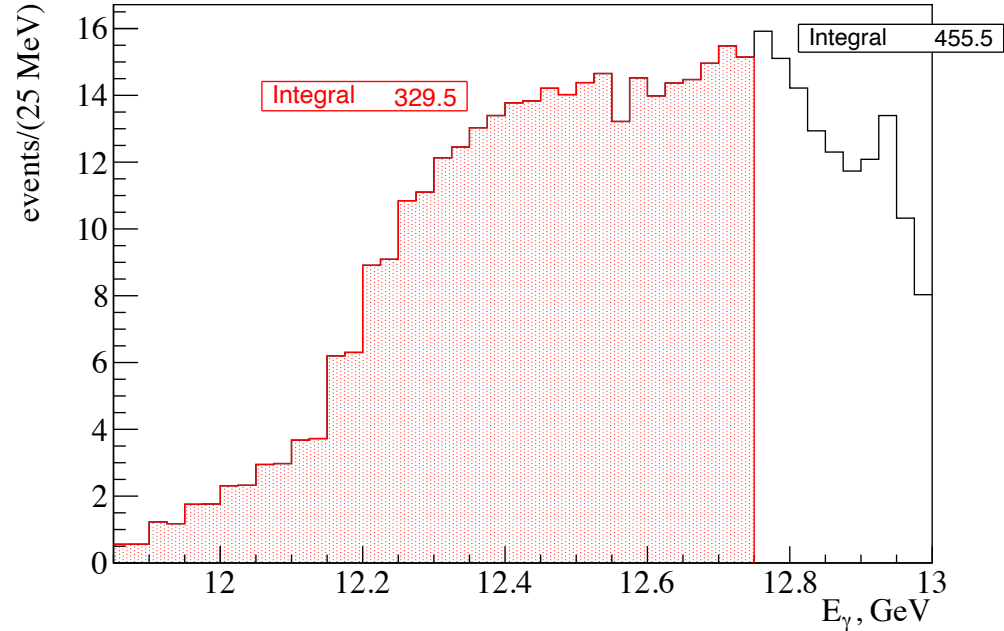
$\chi_{c1}(3872)$ with 12+1 GeV

luminosity with 13 GeV electron beam



Assuming luminosity of 2020 GlueX-II
running (67 PAC days)

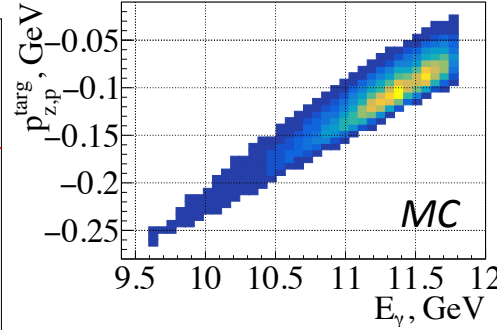
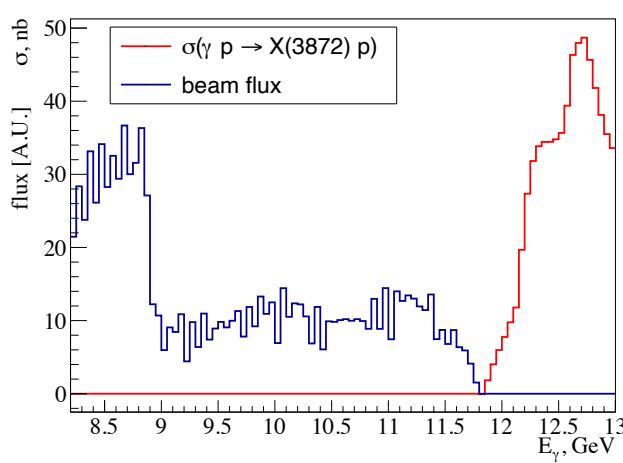
$\gamma p \rightarrow X(3872) p \quad X(3872) \rightarrow \pi^+ \pi^- J/\psi$



$$\gamma p \rightarrow X(3872) p \rightarrow \pi^+ \pi^- J/\psi p \rightarrow \pi^+ \pi^- e^+ e^- p$$

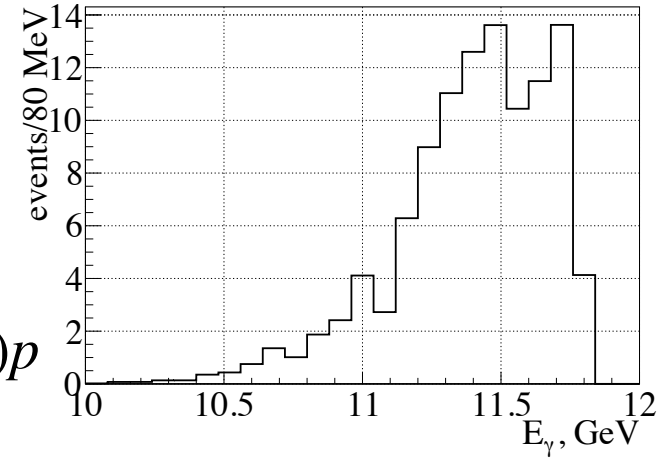
$$\mathcal{B}(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 4.3 \pm 1.4 \%$$

$\chi_{c1}(3872)$ production off ${}^4\text{He}$ with 12 GeV

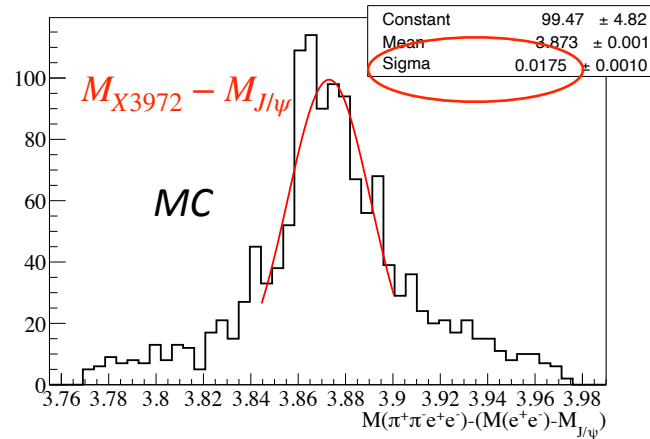
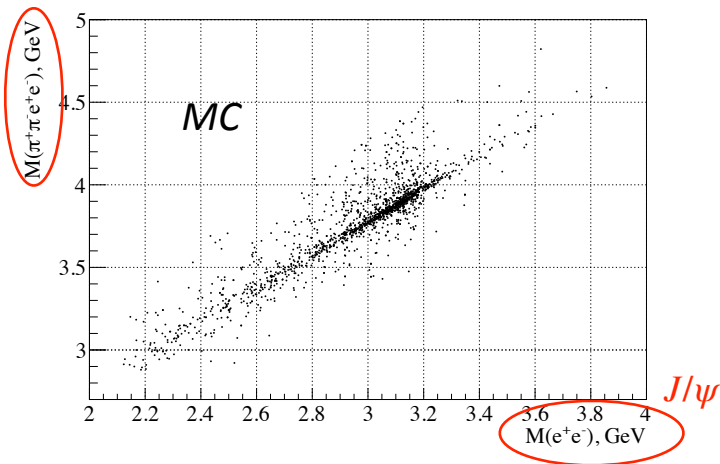


$$\gamma p({}^4\text{He}) \rightarrow X(3872)p$$

$$\sigma(E_\gamma) = \sigma(W)$$



$\chi_{c1}(3872)$



Assuming same luminosity
(67 PAC days) and 12 GeV
electron beam

Expect 50-100 $\chi_{c1}(3872)$
events

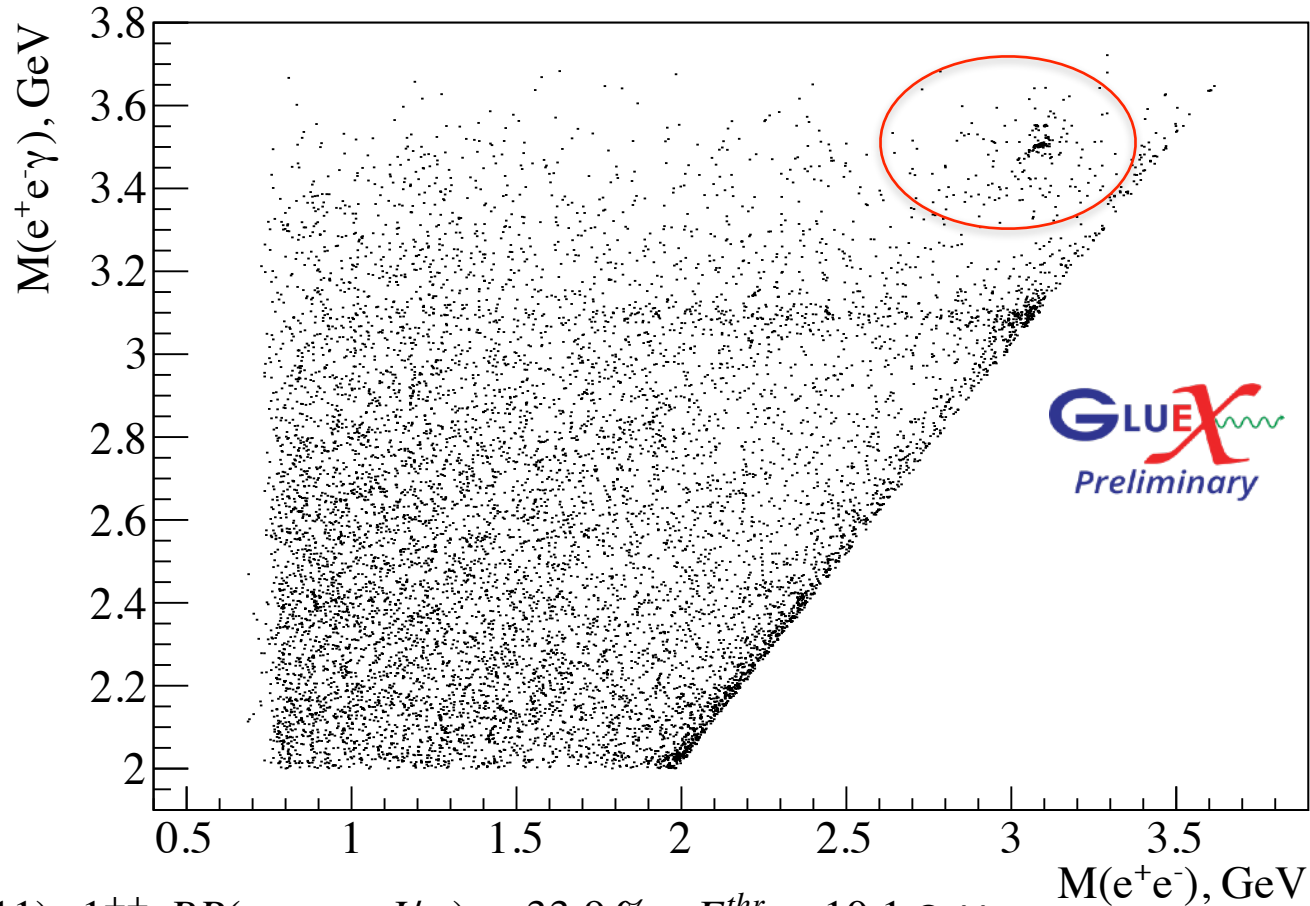
$$\gamma p({}^4\text{He}) \rightarrow X(3872) p + X \rightarrow \pi^+\pi^-J/\psi p + X \rightarrow \pi^+\pi^-e^+e^-p + X \text{ inclusive}$$

Conclusions

- GlueX -III:
 - higher statistics and purity (GEM-TRD for pion suppression) of J/ψ photo-production
 - threshold production of higher-mass charmonia (with different J^{PC}) adds a new dimension in studying gluonic content of the proton
- Thus, GlueX is in unique position to contribute to the future charmonium program at JLab addressing the open questions:
 - **Reaction mechanism:** photoproduction of C-even charmonia via t -channel is suppressed (C-parity flip) $\rightarrow$ measurements of χ_c states reveals what's beneath gluon-exchange contribution, dominating J/ψ photoproduction
 - **QCD factorization:** ξ -scaling to be tested with higher statistics, linearly-polarized photons in the full near-threshold kinematic region
 - **Exotic charmonium states:** $X(3872)$ with 12+1 GeV electron beam/ off nuclei with 12 GeV
 - $\rightarrow$ Everybody will benefit from increasing power of cavities - higher stability at high currents, or/and higher energy
 - $\rightarrow$ Need to make the physics case (12 GeV $X(3872)$ production off ^4He Lol coming)
- This experimental program should be combined with **further theoretical studies:**
 - higher-twist contributions to QCD factorization model
 - calculations of open-charm exchange in χ_c photoproduction (have it for $X(3872)$)

C-event charmonium states at threshold with GlueX

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

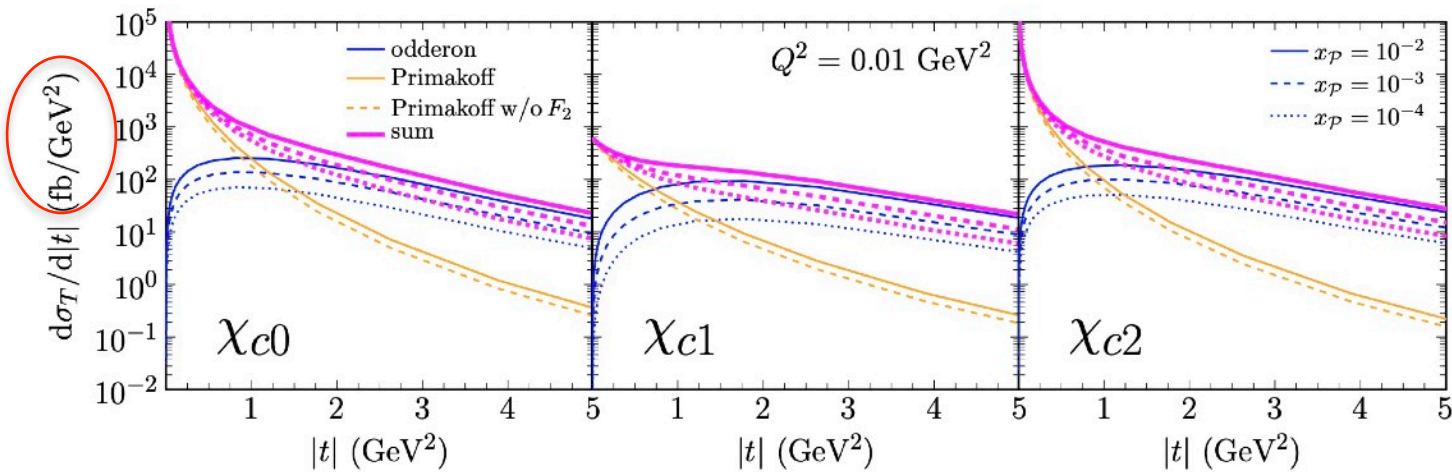


- $\chi_{c1}(3511)$, 1^{++} $BR(\chi_{c1} \rightarrow \gamma J/\psi) = 33.9\%$ $E_\gamma^{thr} = 10.1$ GeV
- $\chi_{c2}(3556)$, 2^{++} $BR(\chi_{c2} \rightarrow \gamma J/\psi) = 19.0\%$ $E_\gamma^{thr} = 10.2$ GeV
- $\chi_{c0}(3415)$, 0^{++} $BR(\chi_{c0} \rightarrow \gamma J/\psi) = 1.35\%$ - not visible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

First ever evidence for photoproduction of C-even charmonium

χ_c t-channel production suppressed - perturbative calculations

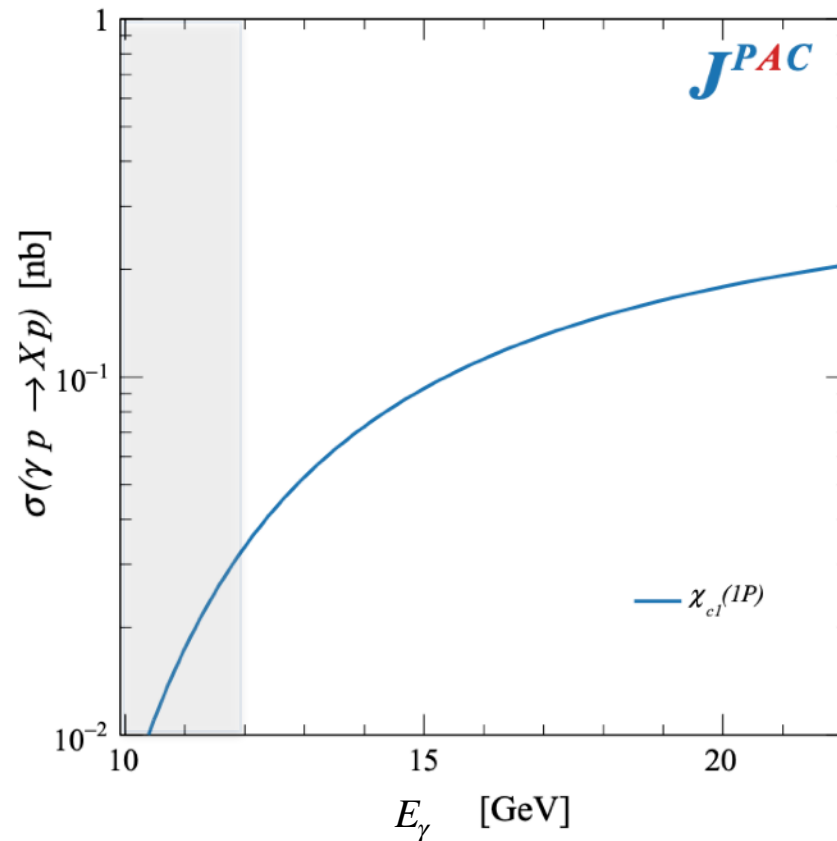
Note units - highly suppressed



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)

χ_c t-channel production suppressed - VM exchange



JPAC, PRD 102 (2020)

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

