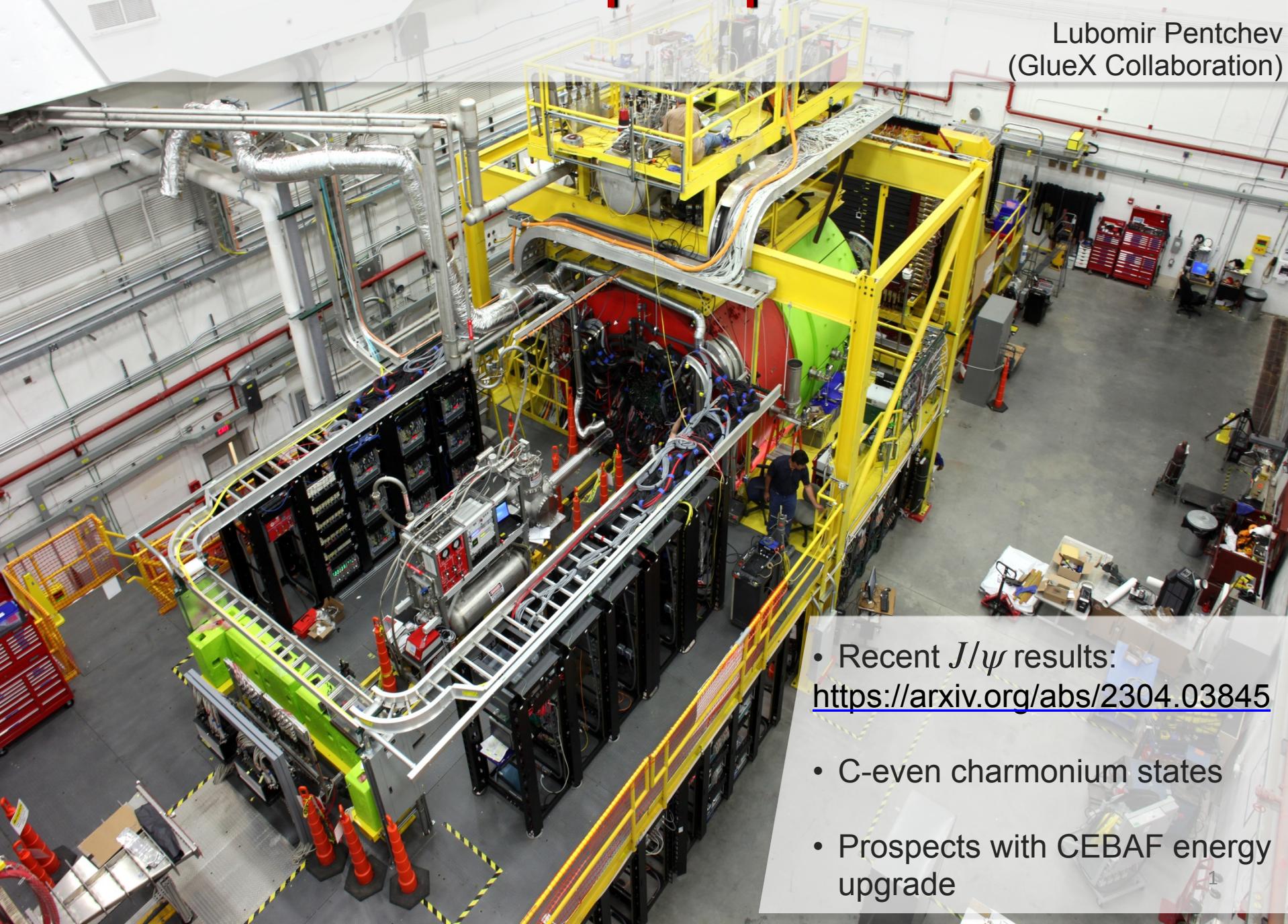


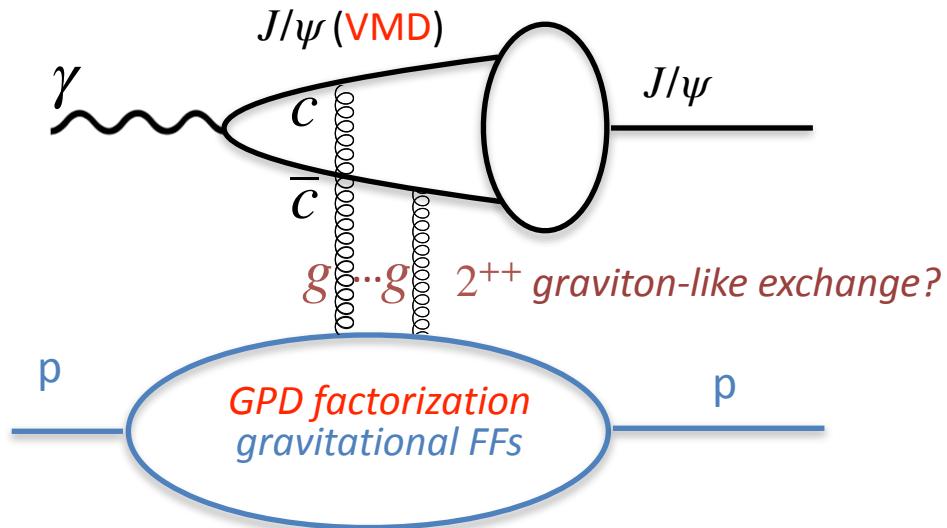
# Threshold charmonium photoproduction with GlueX

Lubomir Pentchev  
(GlueX Collaboration)



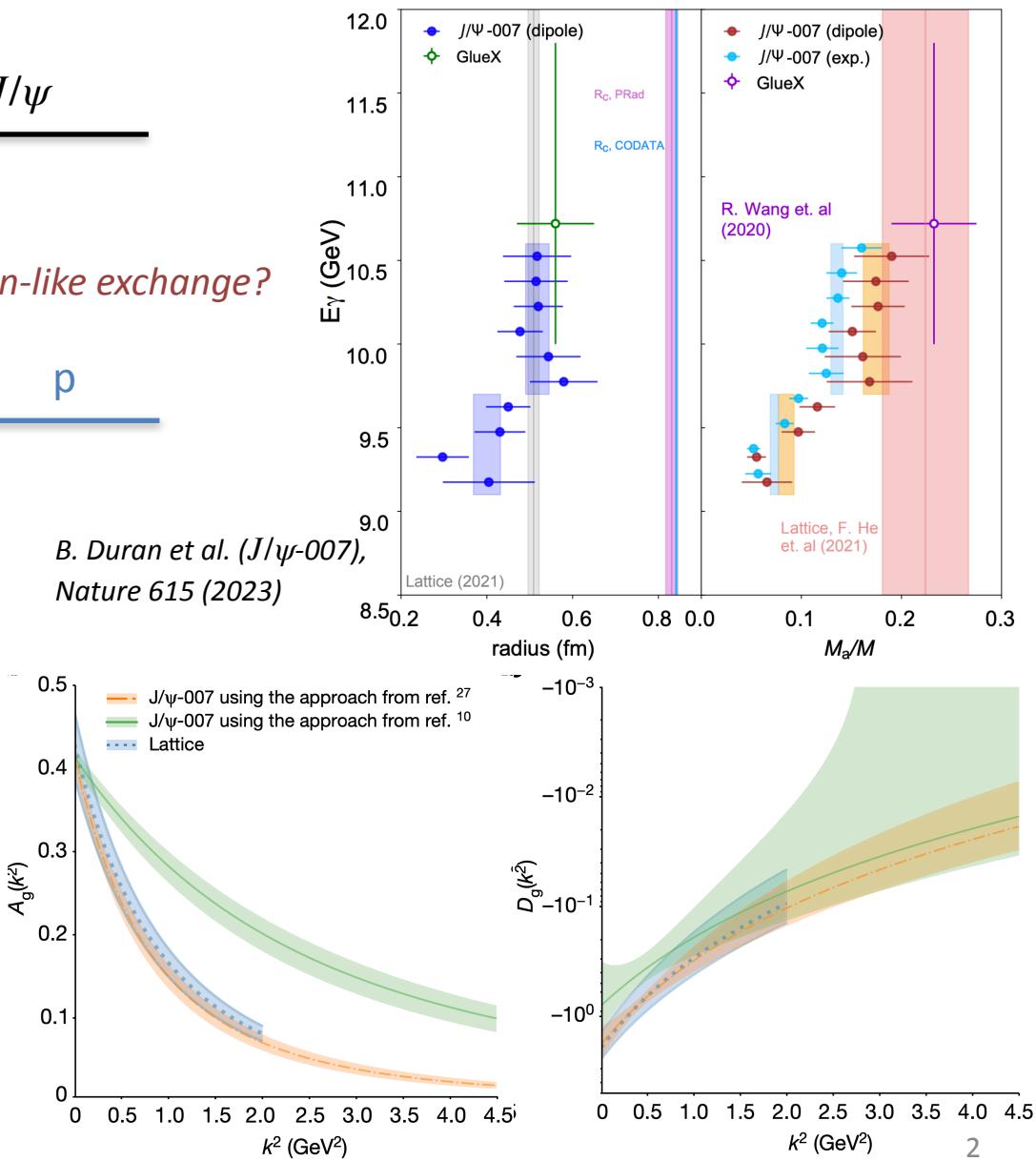
- Recent  $J/\psi$  results:  
<https://arxiv.org/abs/2304.03845>
- C-even charmonium states
- Prospects with CEBAF energy upgrade

# Uniqueness of exclusive threshold charmonium photoproduction - relation to gluonic/mass properties of proton

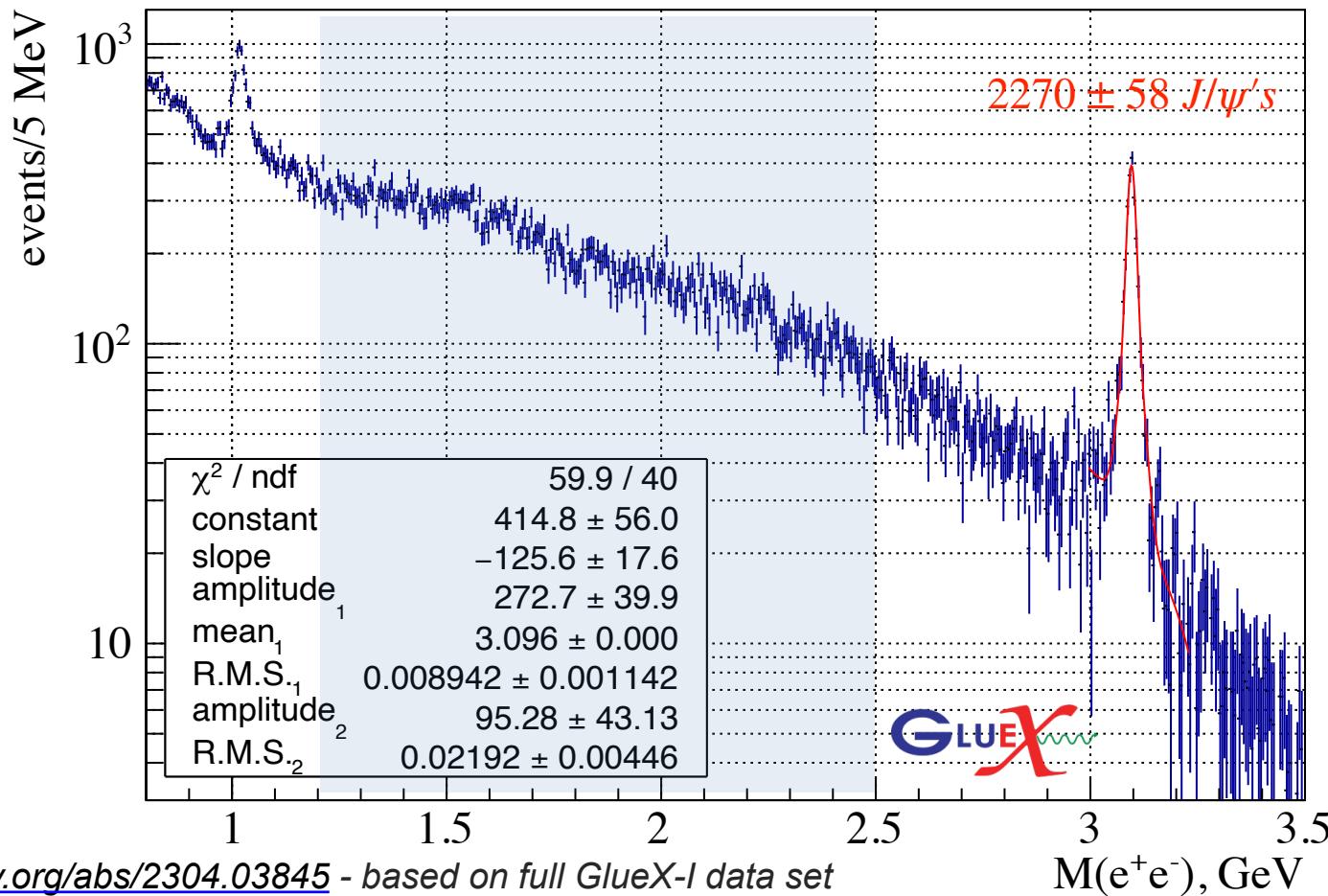


- Assuming gluon exchange/factorization:
- VMD, GPD, or holographic models
- GPD factorization valid for  $m_q \rightarrow \infty$  at threshold (*Gun, Ji, Liu 2021, Hatta, Strikman 2021*)
- $d\sigma/dt(t)$  related to gravitational FF (*Hatta, Kharzeev, Ji et al. 2018-2021*) - extraction of  $r_m, M_a$

Such ambitious program requires detailed studies of the reaction mechanism to justify these assumptions.



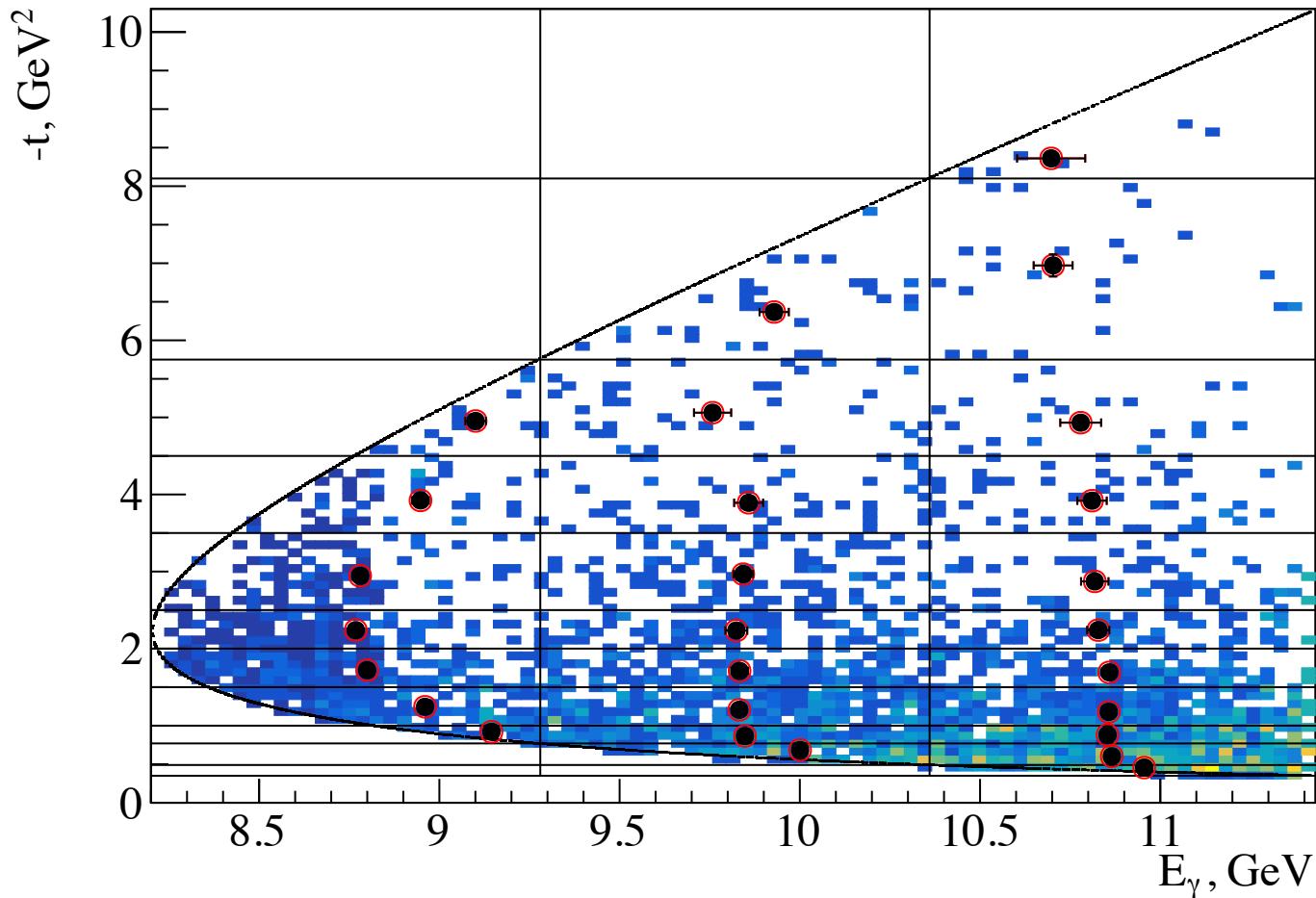
# GlueX results - exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$



<https://arxiv.org/abs/2304.03845> - based on full GlueX-I data set

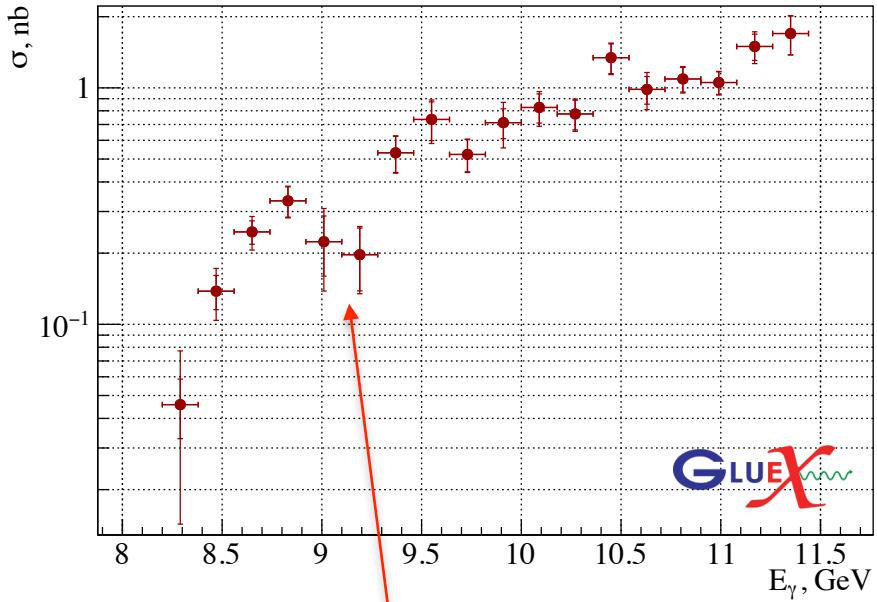
- GlueX uses tagged polarized photon beam (0.2% energy resolution) from coherent Bremsstrahlung (of 12 GeV electron beam) off thin diamond
- +exclusivity of the reaction: kinematic fit 13 MeV mass resolution;
- $J/\psi$  yields extracted from fits of  $M(e^+e^-)$  distributions
- BH(1.2 – 2.5 GeV) used for normalization

# Threshold region coverage



- Event-by-event weighting by luminosity
- Dots - mean energy and  $t$ -value for the corresponding bin
- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors

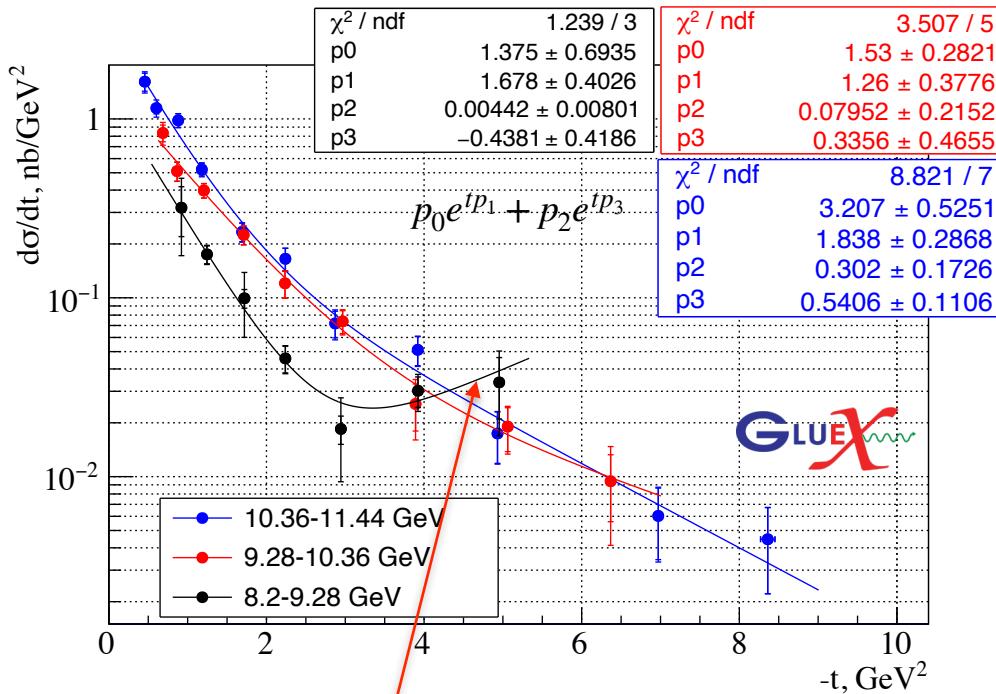
# GlueX results: total and differential cross-sections



- $\sigma_{tot}$  increasing with energy approximately following the phase space

however:

- Possible structure in  $\sigma(8.6 - 9.6 \text{ GeV})$ , the statistical significance of the two “dip” points is  $2.6\sigma$ ; if include look-elsewhere effect -  $1.3\sigma$

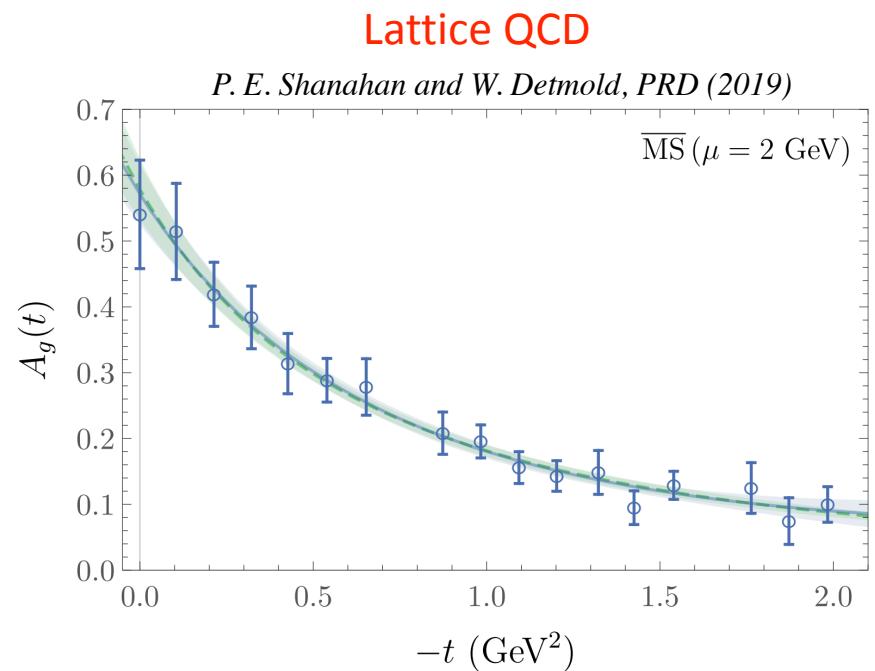
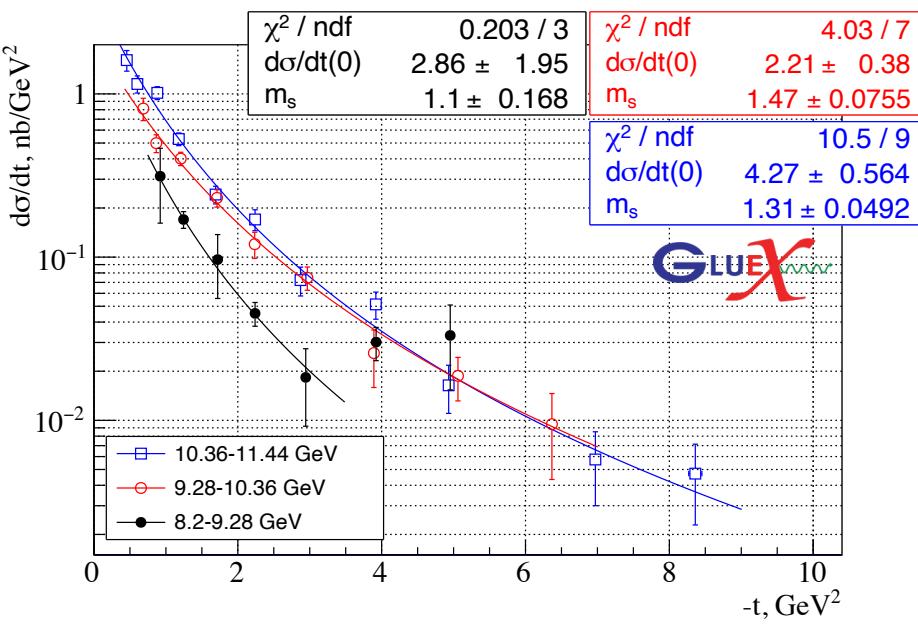


- Exponentially falling  $t$ -dependence

however:

- Enhancement of  $d\sigma/dt$  at high  $t$  (for the lowest energy slice), indicates contribution beyond gluon exchange

# Differential cross-sections vs Lattice QCD



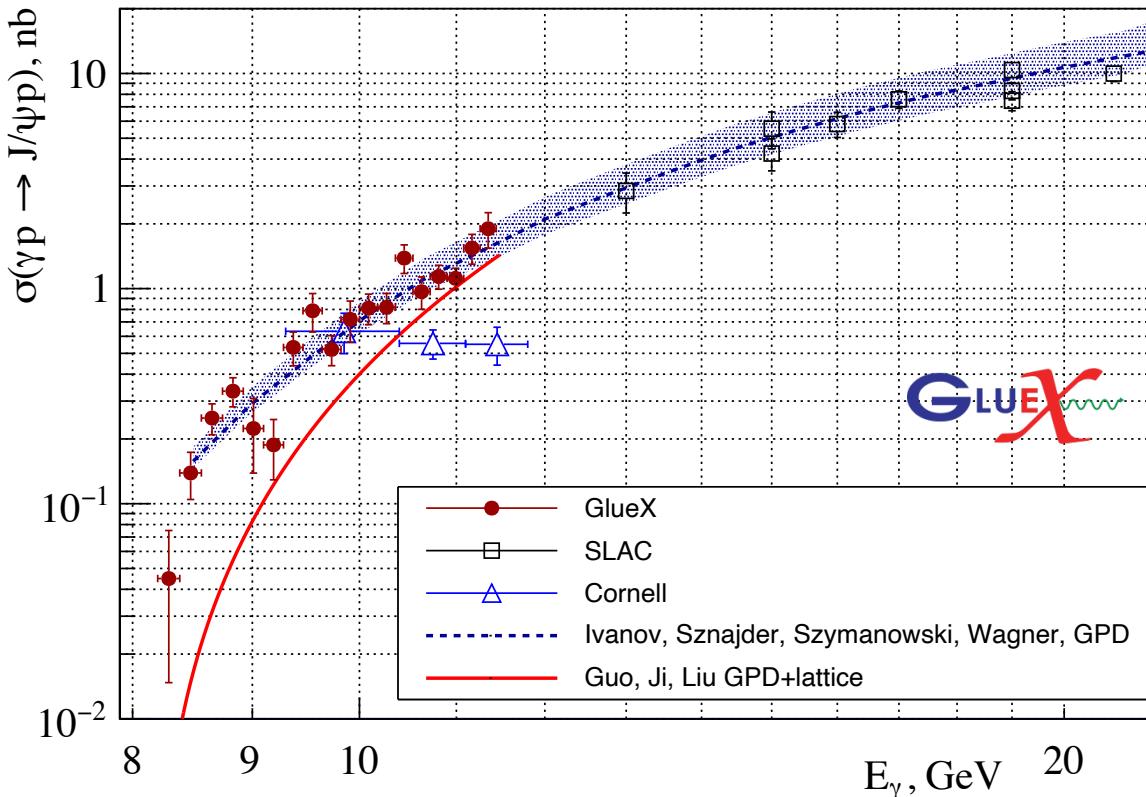
Dipole fits: 
$$\frac{d\sigma/dt(0)}{(1 - t/m_s^2)^4}$$

$q_{c.m.}, \text{GeV}$ (J/ψ p.c.m.)	0.499	0.767	0.978
$d\sigma/dt(0), \text{nb}/\text{GeV}^2$	$2.863 \pm 1.95$	$2.205 \pm 0.380$	$4.268 \pm 0.564$
$m_s, \text{GeV}$	$1.105 \pm 0.168$	$1.472 \pm 0.075$	$1.313 \pm 0.049$

$m_s$  of  $A_g(t)$ , GeV Lattice QCD  $1.13 \pm 0.06$

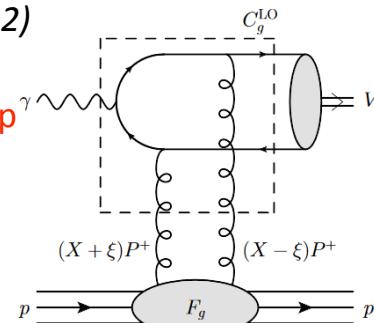
$d\sigma/dt(t)$  generally consistent with gluon exchange mechanism

# GPD factorization models



Ivanov, Sznajder, Szymanowski, Wagner (2022)

- GPD LO calculations
- Big uncertainties in NLO, **data can help to constrain gluon GPDs**

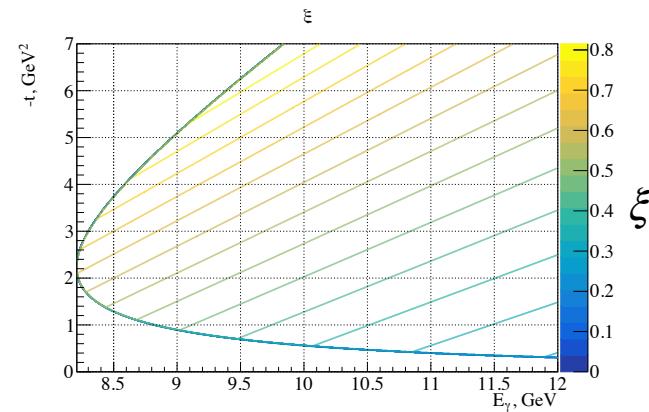


Guo, Ji, Liu, Yang arxiv:2305.06992 (2023),

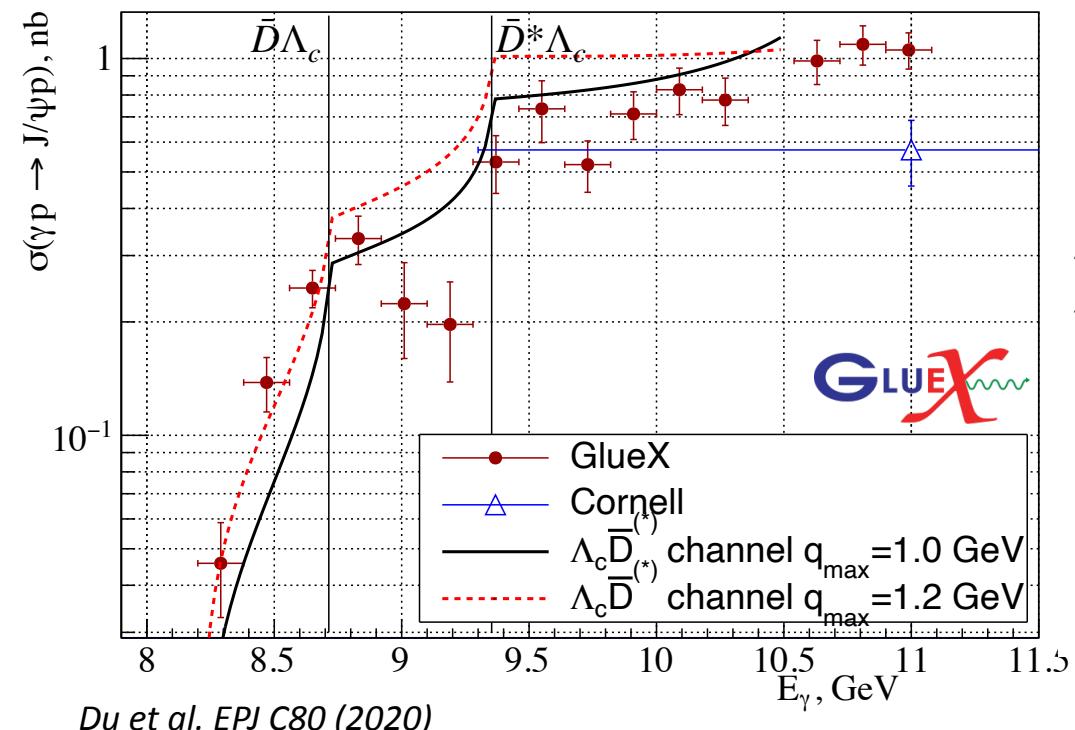
in  $m_c \rightarrow \infty$  limit,  $\xi \rightarrow 1$  expansion

(Hatta, Strikman 2021):

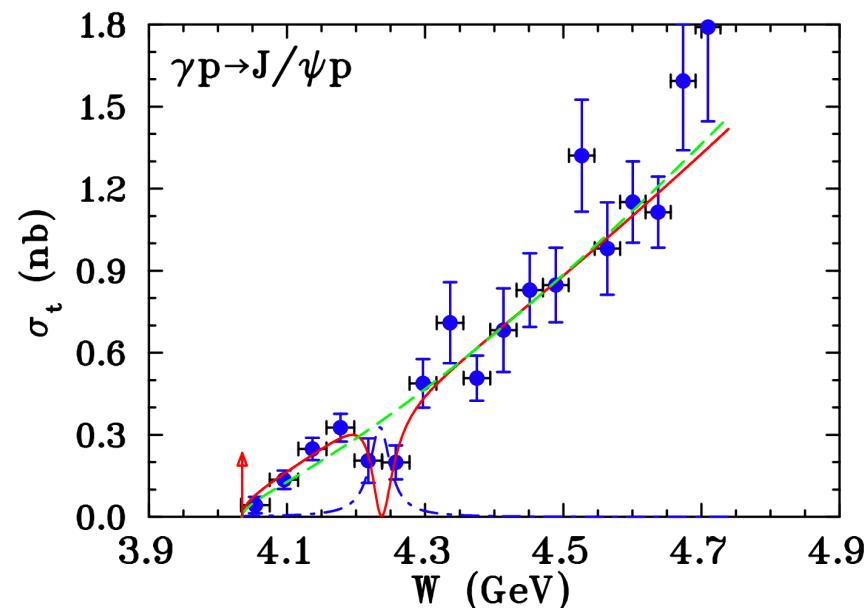
- factorization valid near threshold
- connection to gravitational FFs



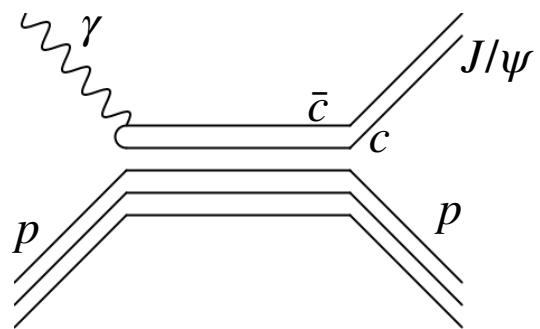
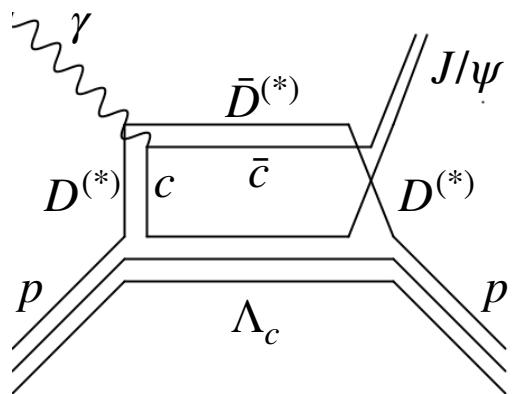
# Other reaction mechanisms: open-charm, 5q exchange



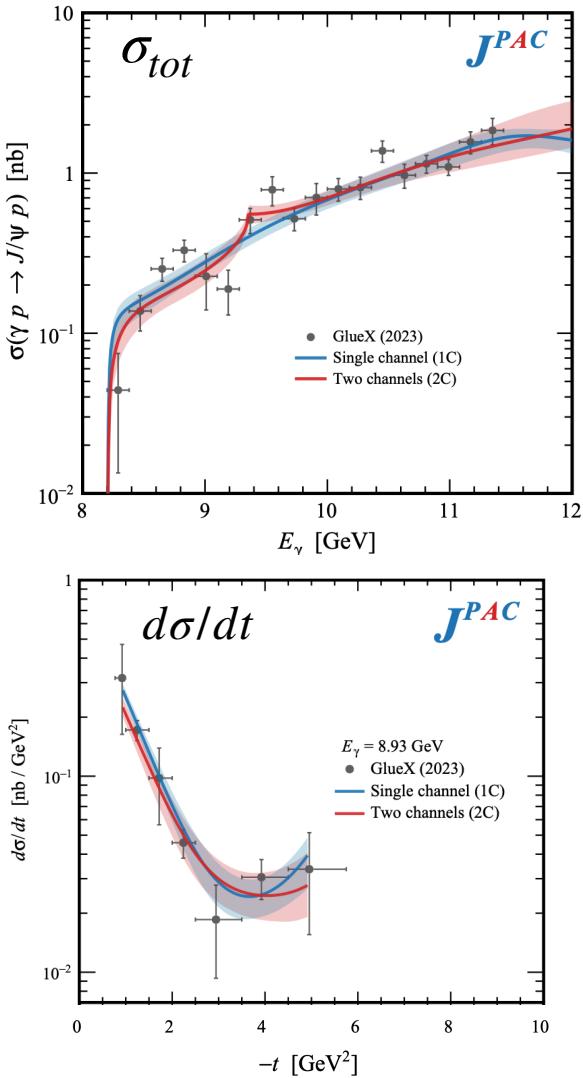
Du et al. EPJ C80 (2020)



Strakovsky et al. arxiv:2304.04924 (2023)



# Gluon or charm exchange: JPAC interpretation



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 maybe due to proximity to threshold (s-wave only)

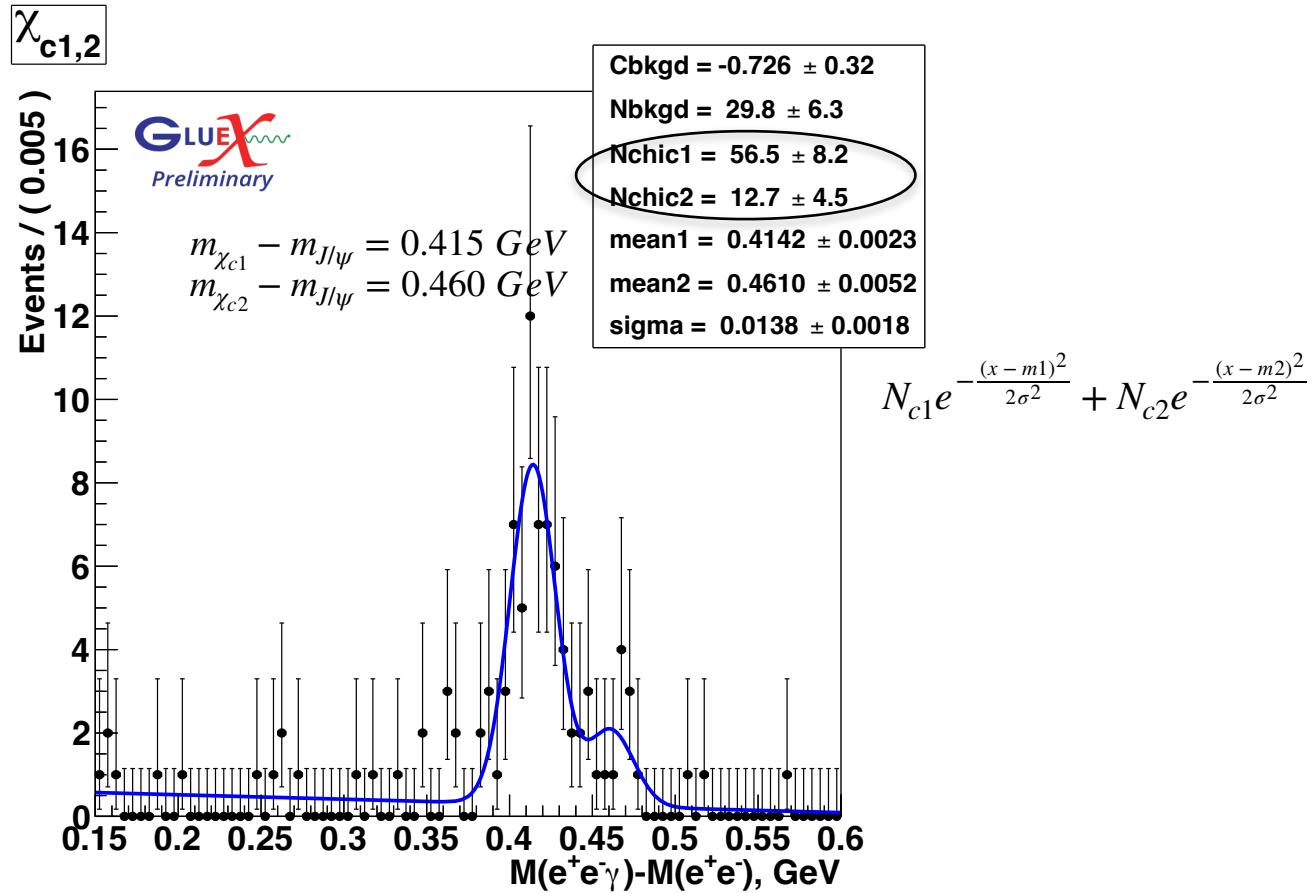
# Threshold $J/\psi$ photoproduction - summary

- Differential cross sections for  $|t| < 3 \text{ GeV}^2$  generally consistent with gluon exchange, however enhancement at higher  $|t|$  indicates contribution beyond t-channel
- Total cross section is consistent with some GPD models assuming factorization, however the structure at 9 GeV, if statistically significant, require sizable contribution from open-charm exchange (or s-channel resonance), that will obscure the relation to the proton gluonic properties.

Precise measurements are critically important to disentangle reaction mechanism and study mass properties of proton:

- GlueX:
  - has on tape and started already analysis with x2 more statistics
  - assuming same running conditions expect another x2 for the rest of phase-II
  - test running with x3 higher intensity, submitted LOI (requires tagger modification)
- Hall B: projections with existing data show similar statistics as with GlueX-I, expect much more assuming CLAS12 luminosity upgrade
- SoLID: the ultimate  $J/\psi$  factory, including electroproduction ( $2\pi$  acceptance, may not have full near-threshold coverage with all final state particles detected, limited by 11GeV beam energy).

# C-event charmonium states at threshold with GlueX

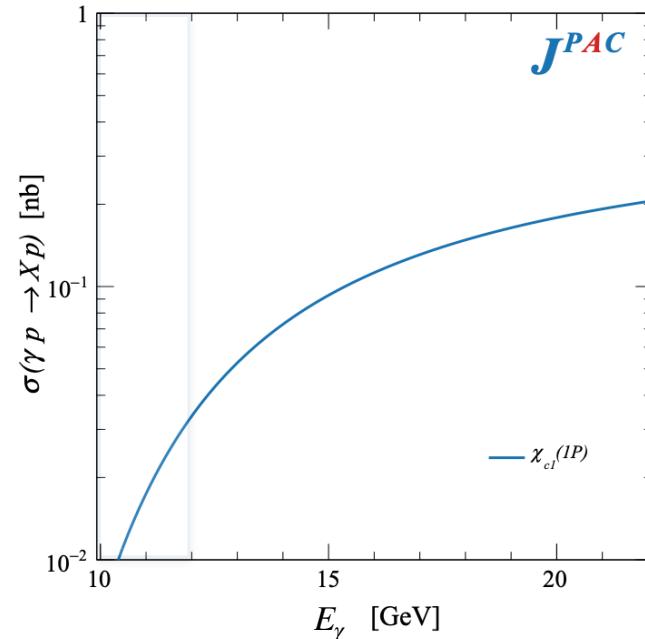
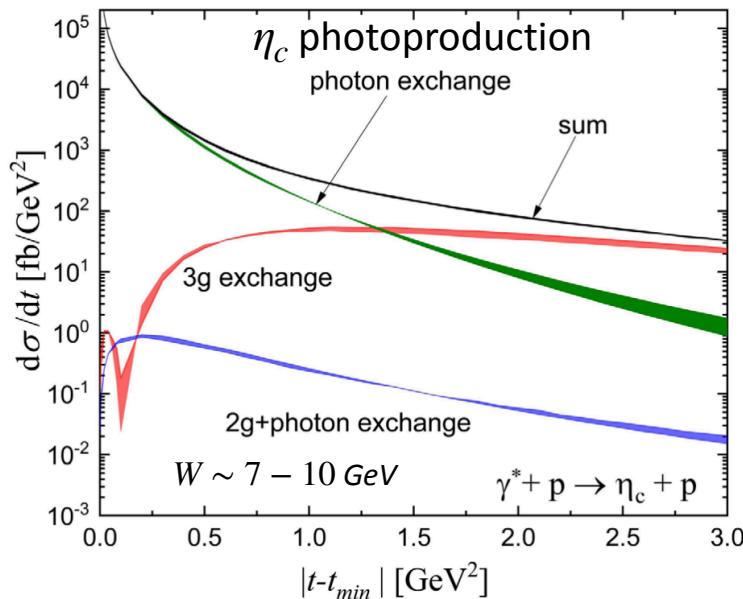


- $\chi_{c1}(3511)$  and  $\chi_{c2}(3556)$ ,  $1^{++}$  and  $2^{++}$  ( $1P$ ),  
 $E_\gamma^{thr} = 10.1 \text{ GeV}$

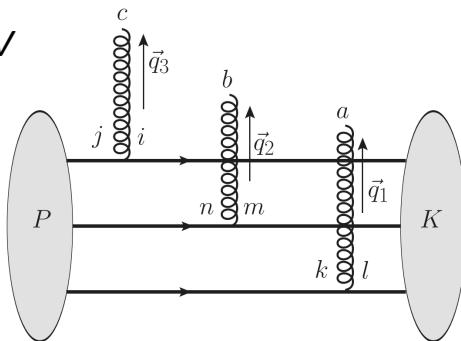
First ever evidence for photoproduction of C-even charmonium

# C-even charmonium states with GlueX

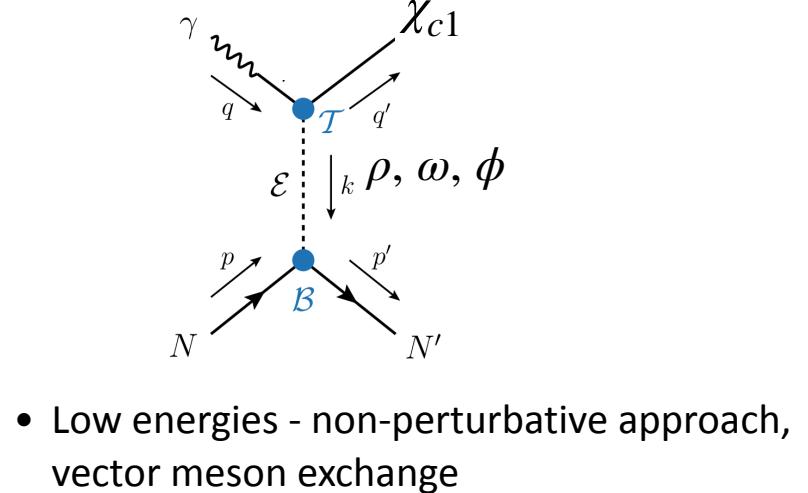
C-odd ( $J/\psi, \psi'$ ) vs C-even ( $\eta_c, \chi_c$ ) production



JPAC, PRD 102 (2020)



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

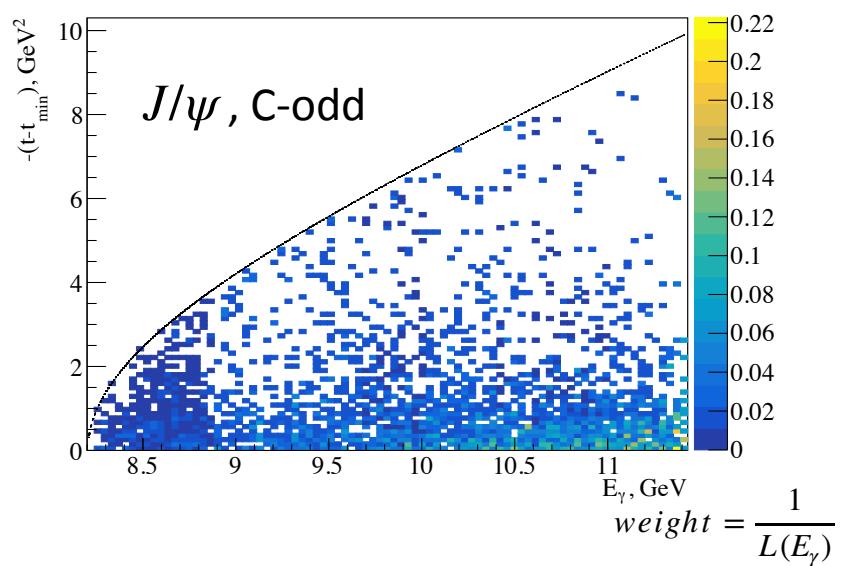
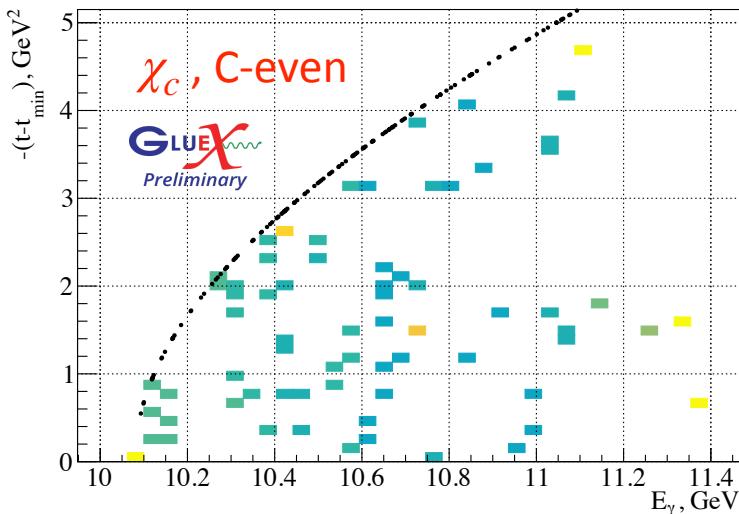


- Low energies - non-perturbative approach, vector meson exchange

# C-even charmonium states with GlueX

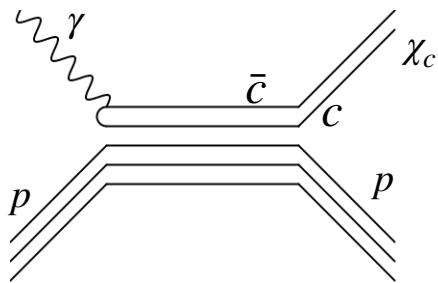
C-odd ( $J/\psi, \psi'$ ) vs C-even ( $\eta_c, \chi_c$ ) production

- Dramatic difference:  $\chi_c$  distribution in  $(E_\gamma, t)$  w.r.t.  $J/\psi$

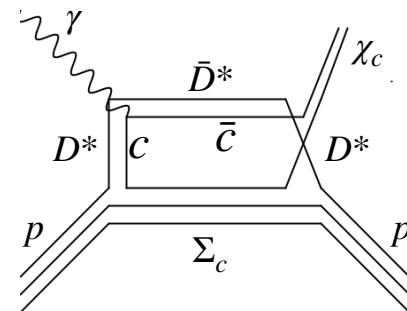


- At threshold other possible mechanisms may dominate:

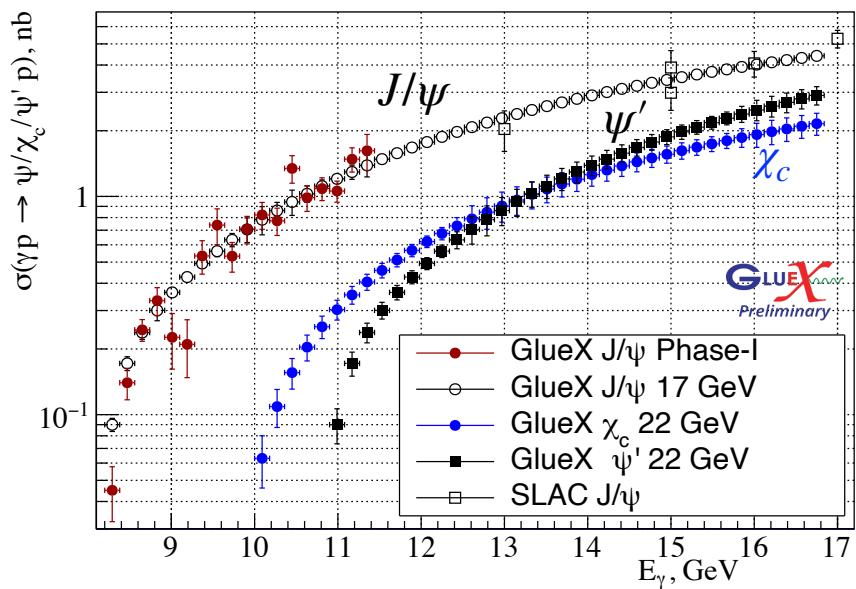
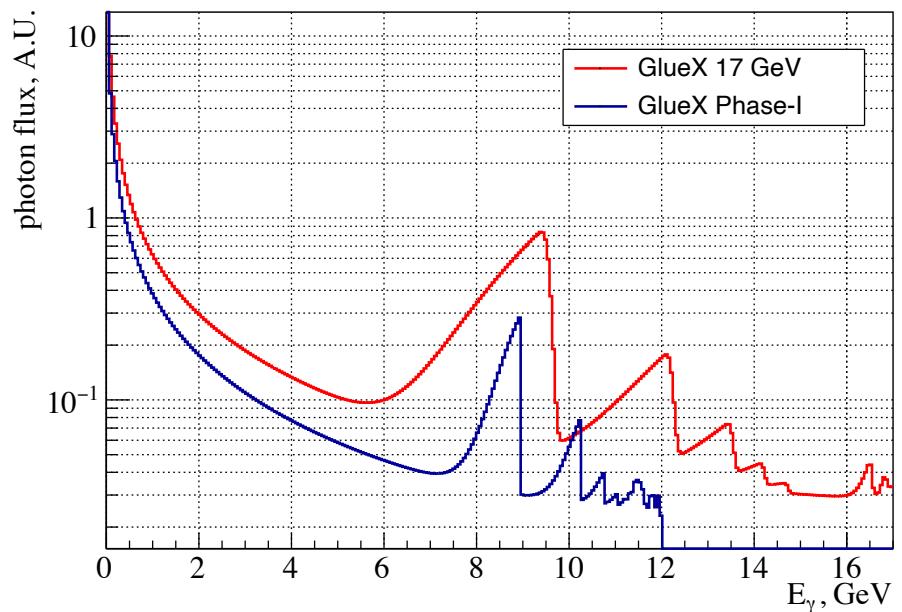
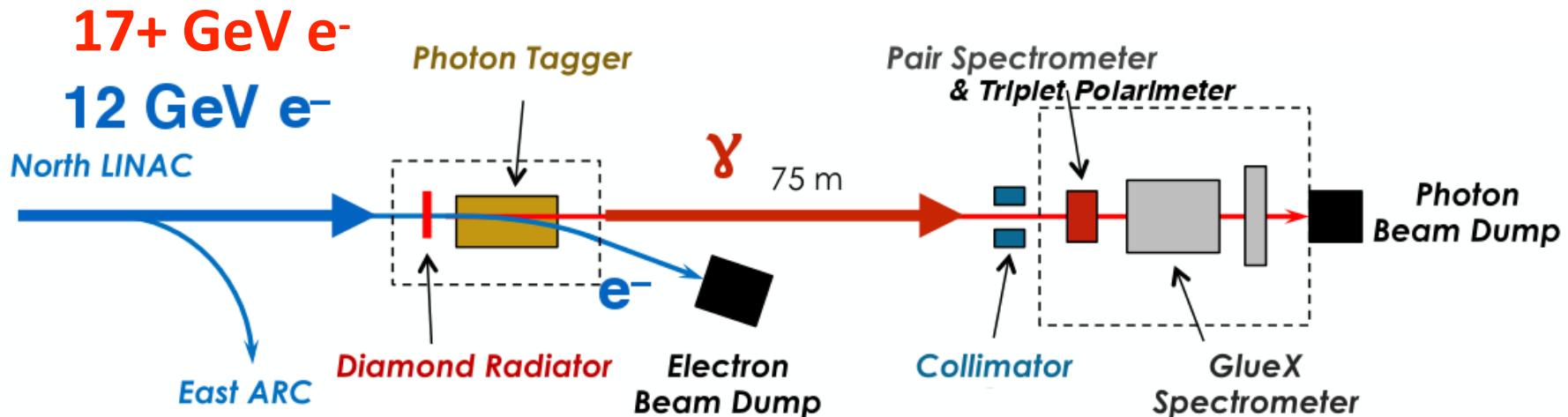
S-channel exchange of 5q



Open-charm exchange



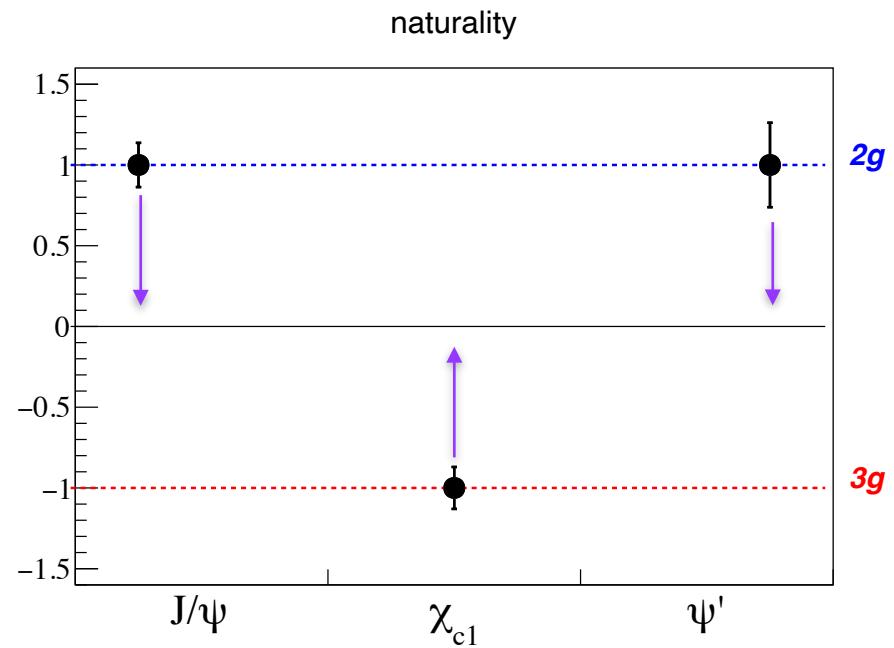
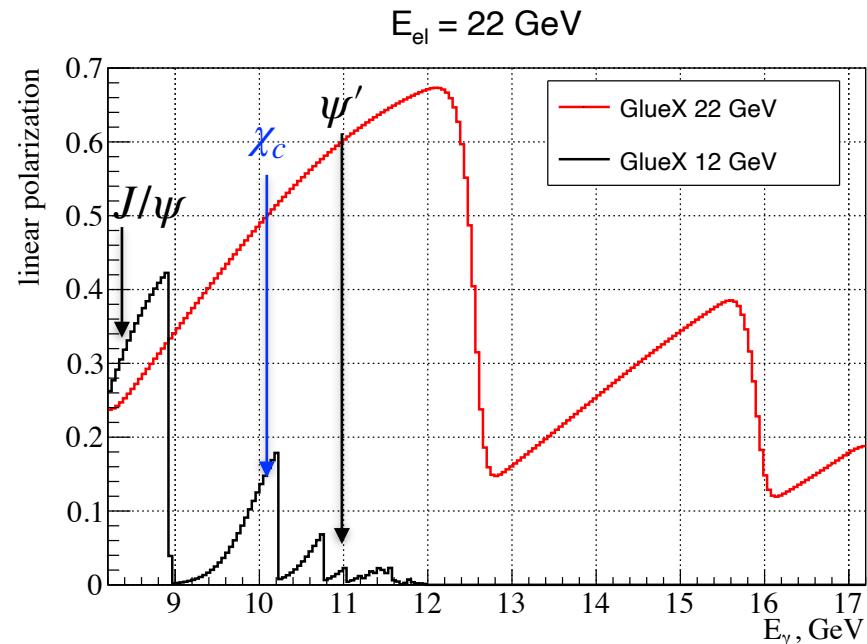
# Hall D Apparatus with 17+ GeV electron beam



- 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

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



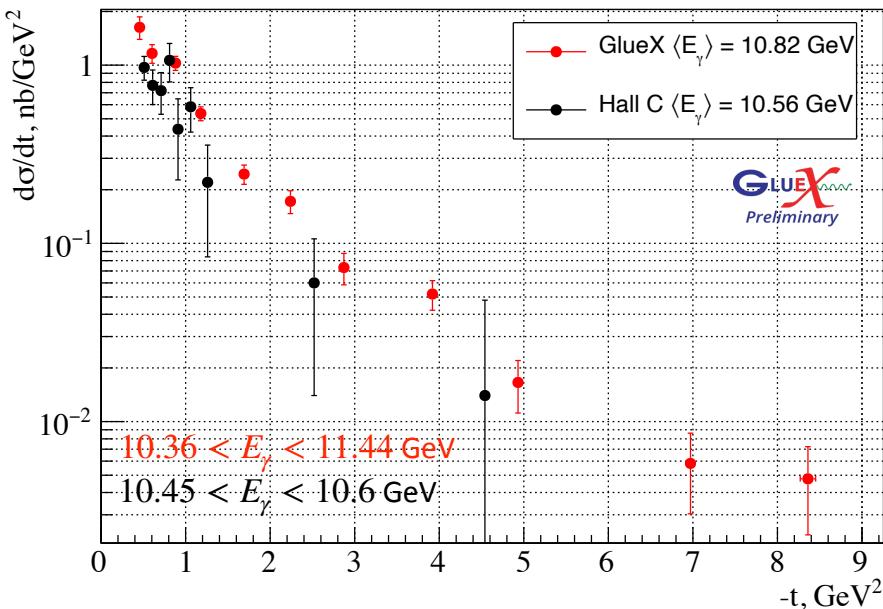
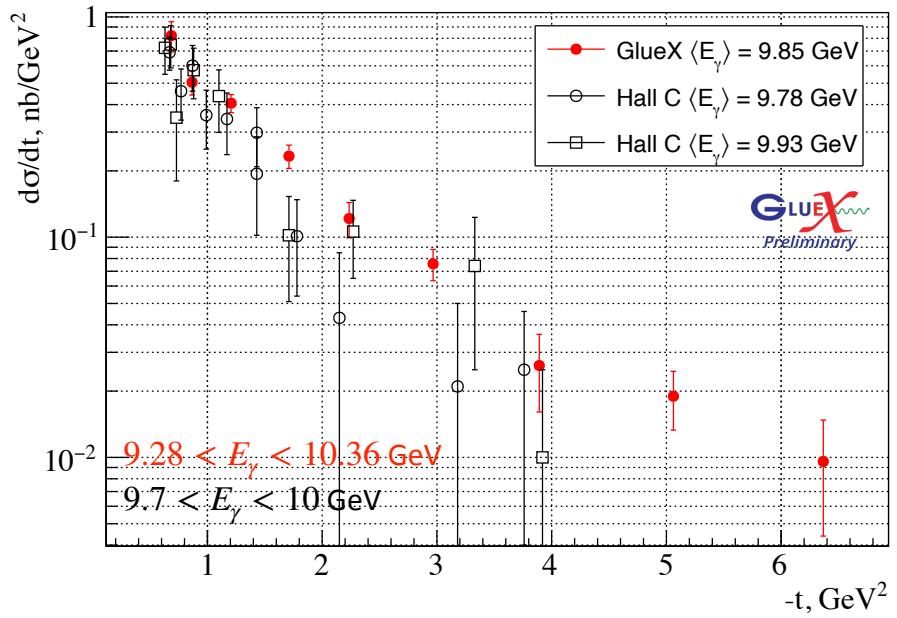
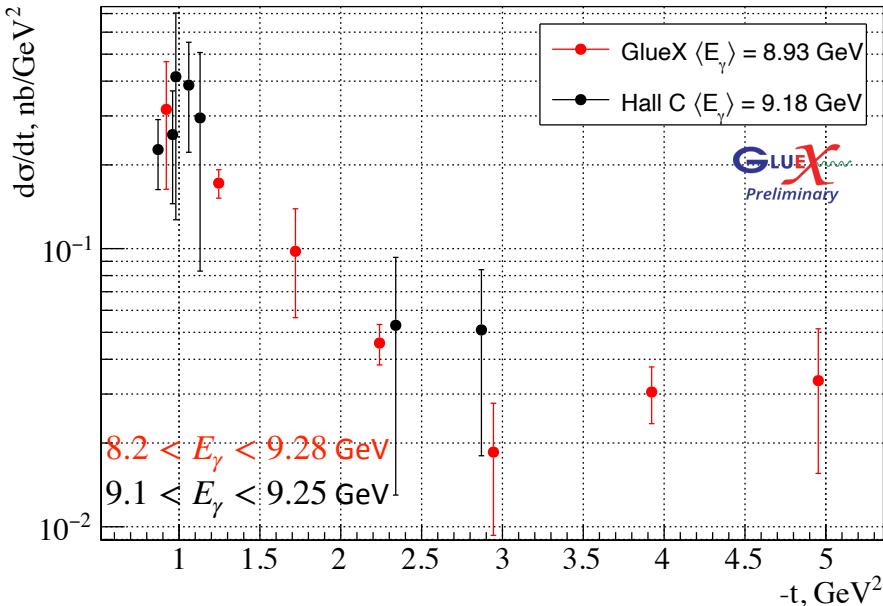
Any deviation from the expected (via gluon exchange) naturality indicates contribution of mechanism different from what is needed to study mass properties of the proton

# Conclusions

- The reported total and differential cross sections of  $J/\psi$  photoproduction near threshold are generally consistent with gluon exchange (t-slope, GPD factorization), except some features consistent with open charm exchange.
- It is important to separate between the gluon exchange, open-charm exchange, or any other contribution (resonances ( $P_c$ 's), u-channel) and possibly find a kinematic region that can be used to constrain gGPDs, extract proton gravitational form factors and study mass properties of proton. Need precise data!
- First ever evidence for C-even charmonium photoproduction - important tool to understand reaction mechanism, complementary to  $J/\psi$  (C-odd charmonium) studies
- JLab energy increase would be critical in understanding the charmonium photoproduction near threshold and justify this reaction as a method to study mass properties of the proton

# Back-ups

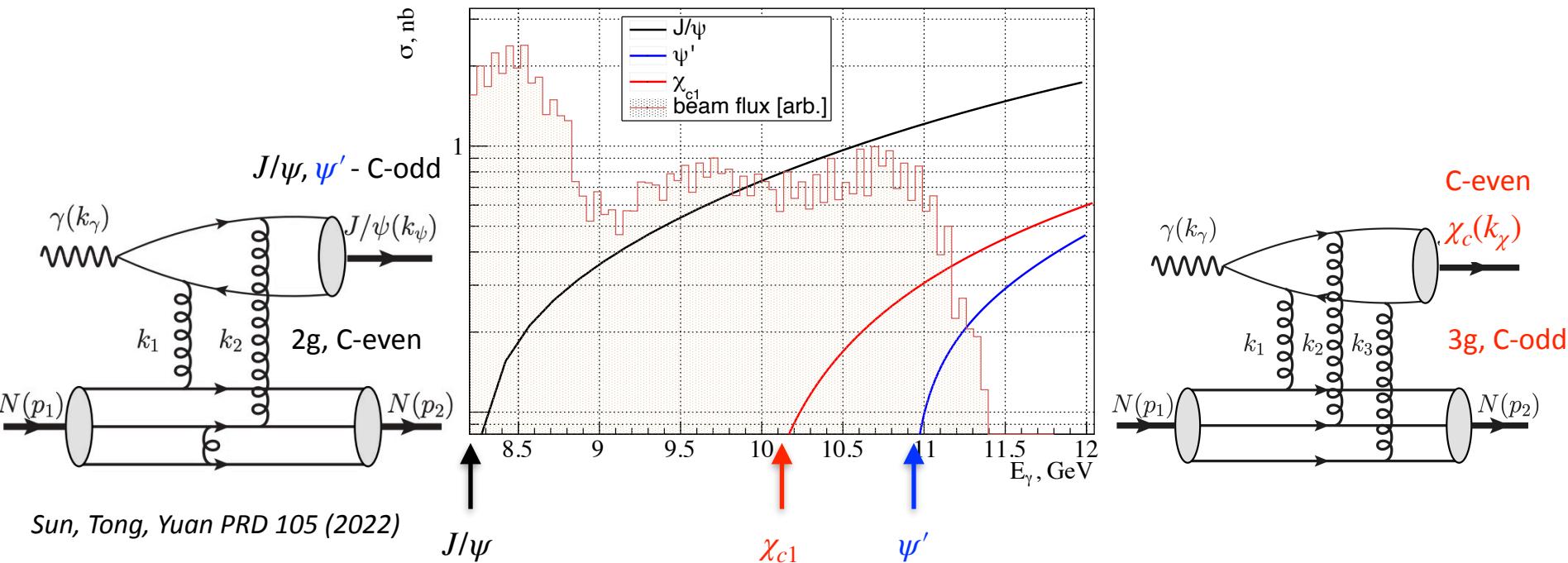
# GlueX results: comparison to Hall C ( $J/\psi$ -007)



- Three GlueX energies compared to closest Hall C ( $J/\psi$ -007) energies
- Shown only 4 out 10 energies for Hall C - common fit of all 10 used to disentangle contributions from  $A_g(t)$  and  $C_g(t)$  (B.Duran <https://arxiv.org/abs/2207.05212>)
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors;** note also differences in average energies

# C-event charmonium states at threshold with GlueX

## C-odd ( $J/\psi, \psi'$ ) vs C-even ( $\chi_c$ ) production



- $\chi_{c1}(3511)$  and  $\chi_{c2}(3556)$ ,  $1^{++}$  and  $2^{++}$  ( $1P$ ),  $E_\gamma^{thr} = 10.1$  GeV
- C-even charmonium states require 3g-exchange
- GlueX has observed also a small number of  $\psi'(3686)$  ( $2S$ ) states in  $\gamma p \rightarrow \psi' p \rightarrow (e^+e^-) p$ ,  $E_\gamma^{thr} = 10.9$  GeV

# Proposed GEM-TRD detector

