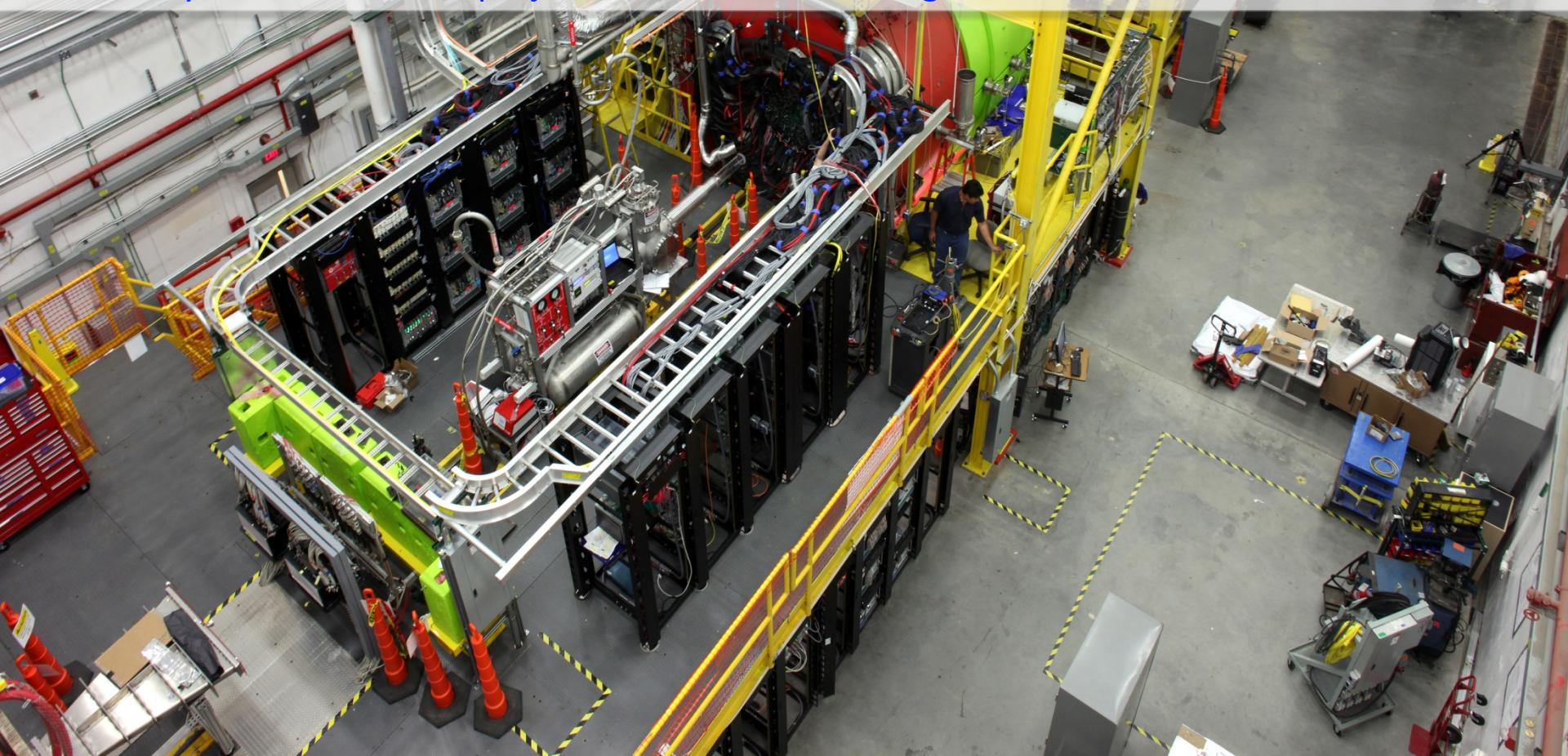


New opportunities for J/ψ (and beyond) photo-production studies in HallD with the CEBAF upgrade

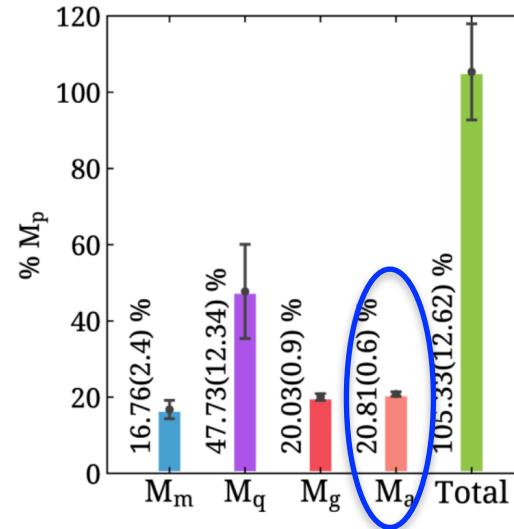
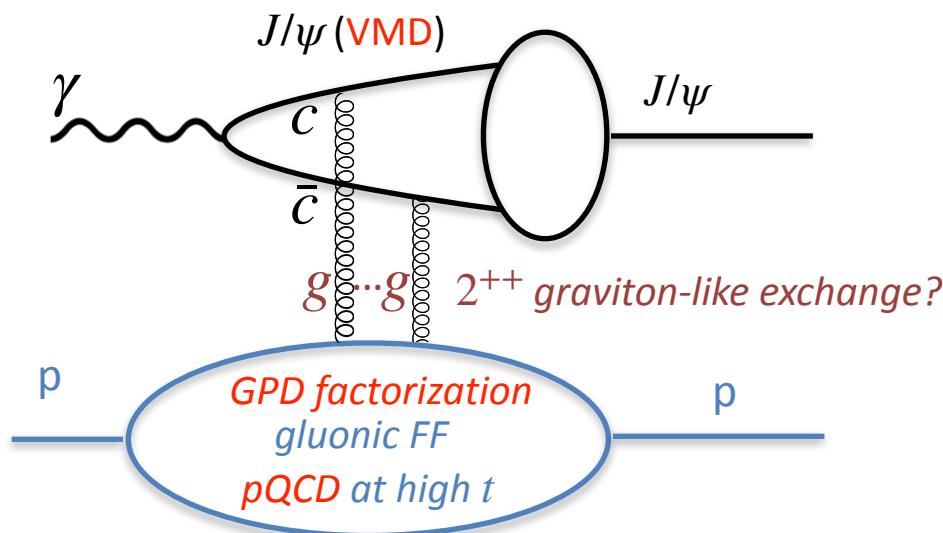
- What are the physics problems related to J/ψ (and beyond) threshold production we need to solve?
- Why CEBAF energy upgrade is important in solving these problems using existing GlueX detector?

Will try to make realistic projections based on existing measurements

Lubomir Pentchev
(GlueX Collaboration)



Threshold J/ψ photoproduction \leftrightarrow mass properties of proton?



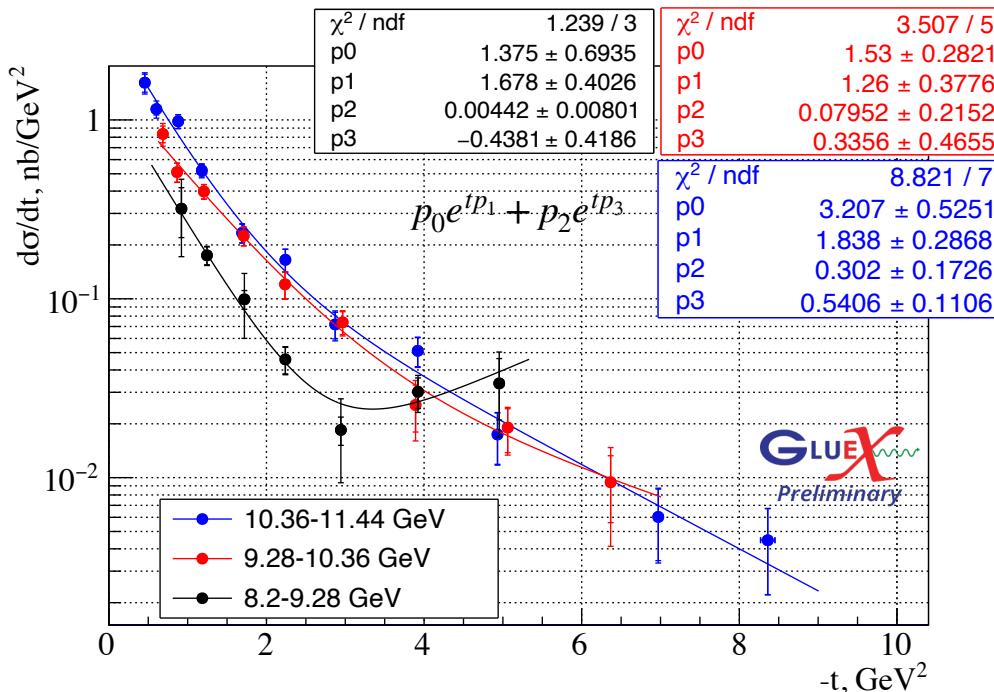
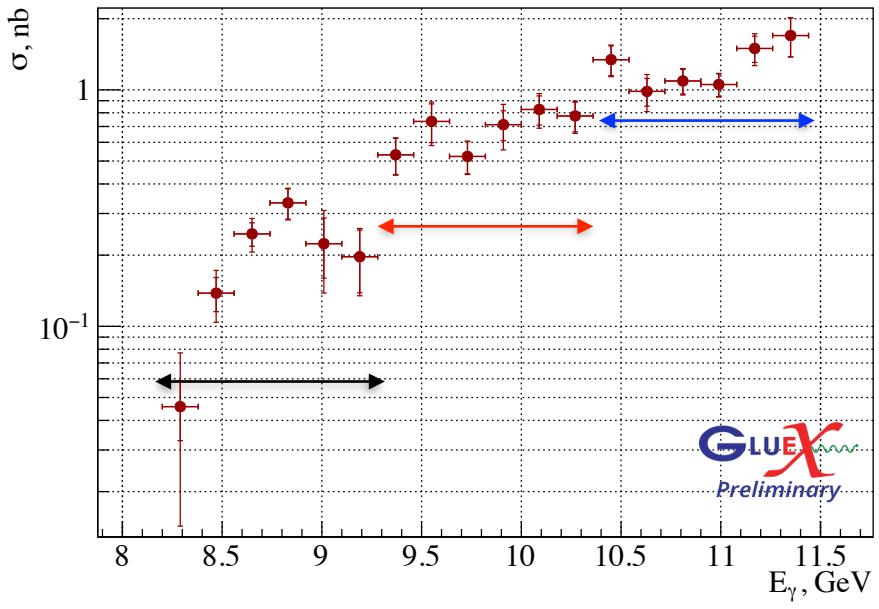
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

- **VMD** reduces $\gamma p \rightarrow J/\psi p$ to $J/\psi p \rightarrow J/\psi p$
- If $m_c \rightarrow \infty$ interaction via gluon exchange, at threshold sensitive to **trace anomaly - quantum fluctuations** (Kharzeev, Satz, Syamtomov, Zinovjev 1996-1999) contributing to proton mass (Ji 1995)
- **GPD factorization** valid for $m_c \rightarrow \infty$ at threshold (Gun, Ji, Liu 2021)
- At threshold large difference in gluon rapidity (skewness ξ), 2g dominated by 2^{++} exchange (graviton) allows to study mass properties of the proton (Hatta, Ji *et al.* 2021)
- t -dependance of the amplitudes - **gravitational form factors** \rightarrow mass radius of the proton, D-term (Hatta, Kharzeev, Ji *et al.* 2018-2021)
- At large t **pQCD** approach - no direct relation to gravitational FF? (Sun, Tong, Yuan 2021,2022)
- Is the J/ψ mass large enough for the above assumptions to be valid?

New results from Jefferson Lab - Hall C (J/psi-007) and **GlueX** - what the data say about this?

Preliminary GlueX results: total and differential cross-sections

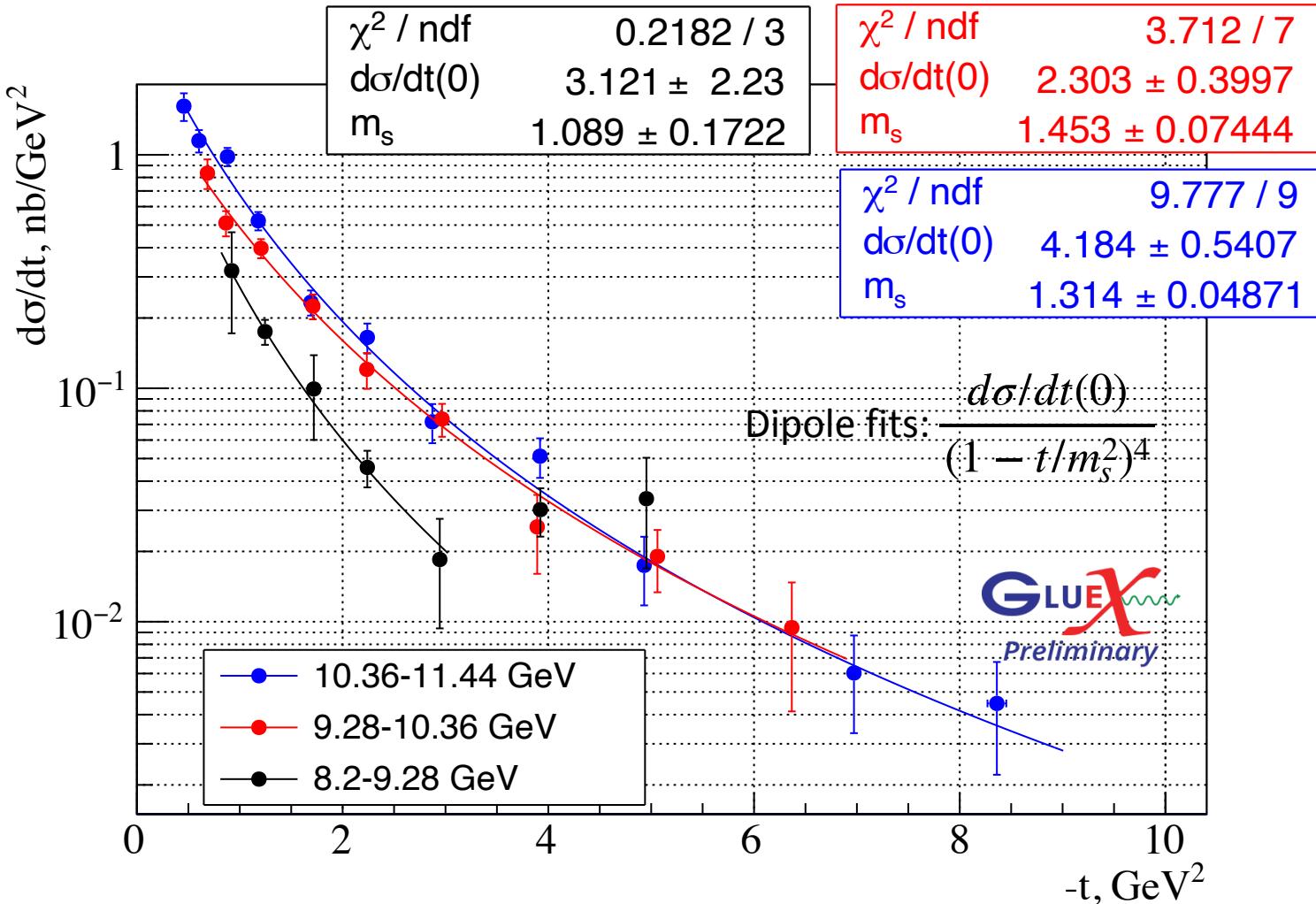
$$\gamma p \rightarrow J/\psi p \rightarrow e^+ e^- p$$



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

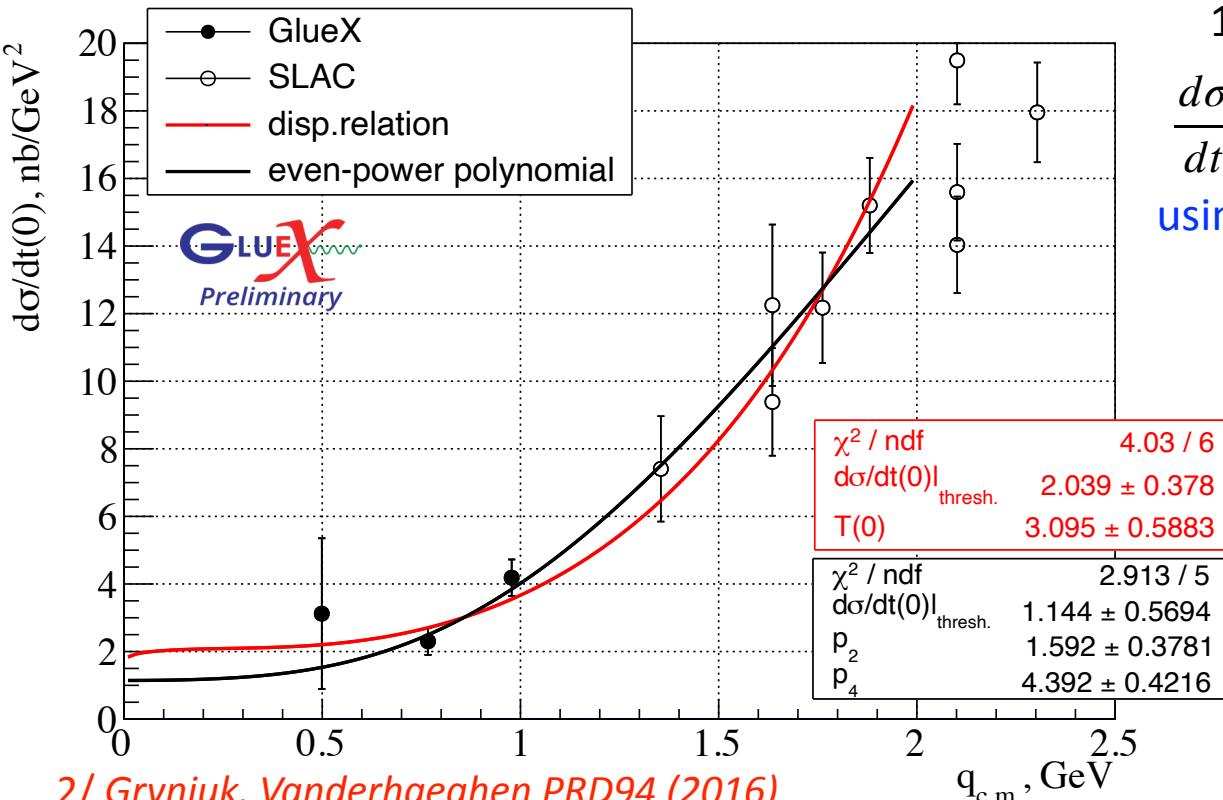
- Enhancement of $d\sigma/dt$ at high t (for the lowest energy slice)
- Weak energy dependence of $d\sigma/dt$ (less so at lower t and energy)
- t -slopes close to lattice predictions for $A_g(t)$
- Possible change of the slope at low energies

Differential cross-sections - forward extrapolation



E_γ, GeV	8.93	9.86	10.82
$q_{c.m.}, \text{GeV}$ (J/ψp c.m.)	0.499	0.767	0.978
$d\sigma/dt(0), \text{nb}/\text{GeV}^2$	3.121 ± 2.23	2.303 ± 0.400	4.184 ± 0.541
m_s, GeV	1.089 ± 0.172	1.453 ± 0.074	1.314 ± 0.049

Forward differential cross-sections - threshold extrapolation



2/ Gryniuk, Vanderhaeghen PRD94 (2016)

Dispersion relation:

$$ReT^{\psi p}(\nu) = T(0) + \frac{2}{\pi} \nu^2 \int_{\nu_{th.}}^{\infty} d\nu' \frac{ImT^{\psi p}(\nu')}{\nu'(\nu'^2 - \nu^2)}$$

$$\frac{p_0}{p_1^2} [p_1 + DI(q)]^2 \frac{(sk_{\gamma p}^2)_{\text{thr.}}}{sk_{\gamma p}^2}$$

p_1 - subtraction constant $T(0)$

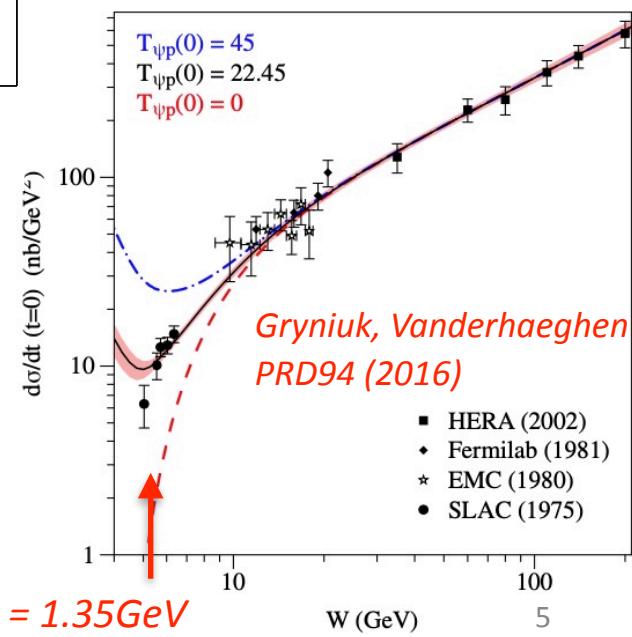
$$d\sigma/dt(0) \Big|_{\text{thr.}} = 1.14 \pm 0.57 \quad 2.04 \pm 0.38 \text{ nb/GeV}^2$$

1/ Even-power polynomial fit

$$\frac{d\sigma}{dt}(q,0) = \frac{\alpha\pi}{\gamma_\psi^2} \frac{1}{64\pi sk_{\gamma p}^2} \cdot |T^{\psi p}(q,0)|^2$$

using VMD

$$\frac{(sk_{\gamma p}^2)_{\text{thr.}}}{sk_{\gamma p}^2} [p_0 + p_2 q^2 + p_4 q^4]$$

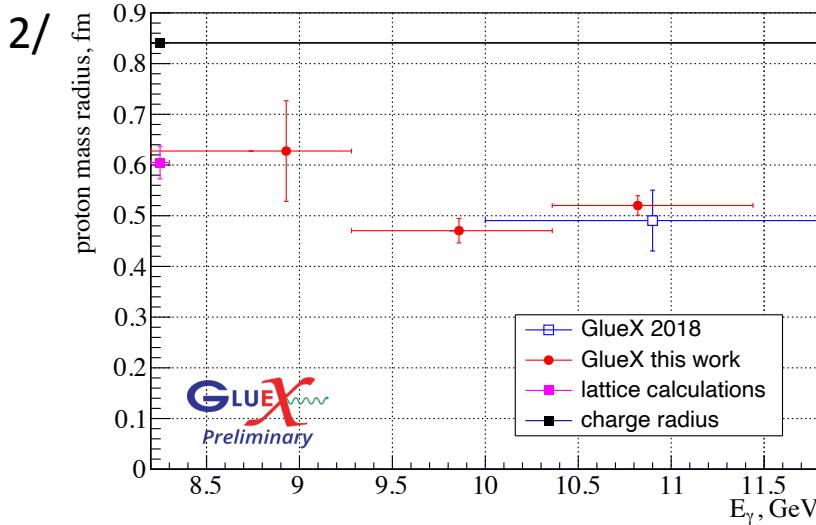


Forward differential cross-sections - model dependent applications

- 1/ $J/\psi - p$ scattering length:
 $13.4 \pm 3.8 \text{ mfm}$, $17.9 \pm 1.7 \text{ mfm}$
 very weak $J/\psi - p$ interaction

$$|\alpha_{J/\psi p}| = \sqrt{\frac{d\sigma}{dt}(0) \Big|_{thr} \frac{\gamma_\psi^2 k_{\gamma p}^2}{\alpha \pi} \frac{k_{\gamma p}^2}{\pi}}$$

using VMD



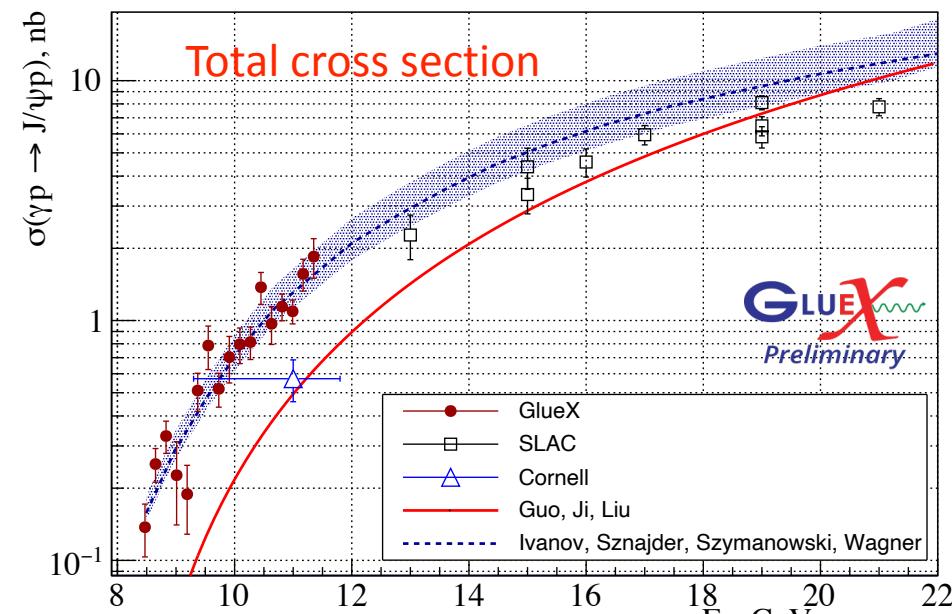
$$r_m = \frac{6}{m_p} \frac{dG}{dt} \Big|_{t=0} = \frac{12}{m_s^2}$$

D.Kharzeev PRD104(2021)



- 3/ Other quantities - trace anomaly, scalar/mass radius of the proton ...

QCD factorization models



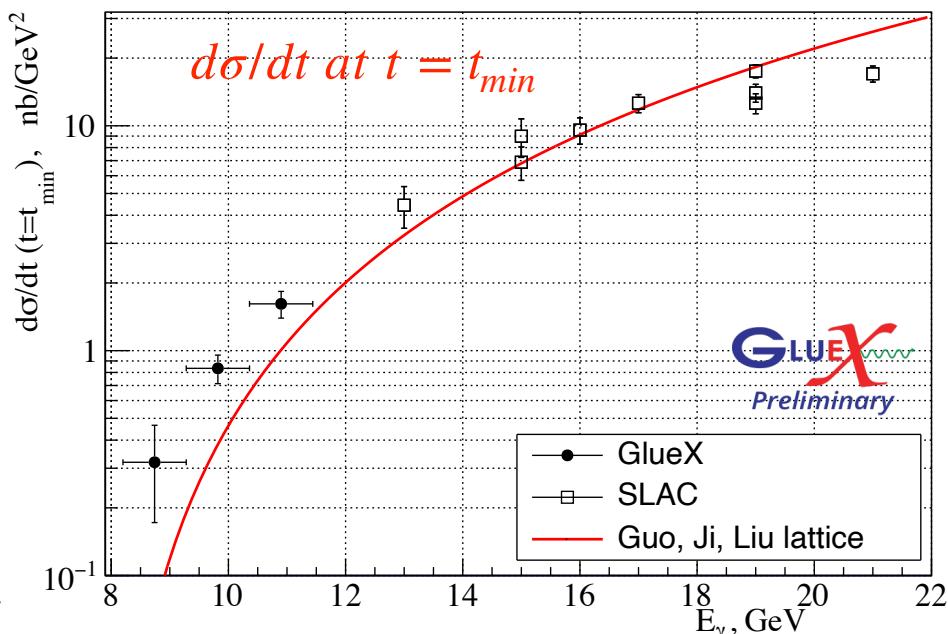
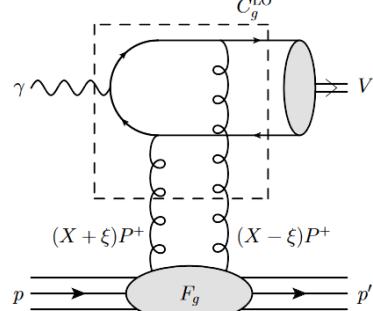
Ivanov, Sznajder, Szymanowski, Wagner (2022)

- GPD LO calculations

Guo, Ji, Liu PRD103 (2021),

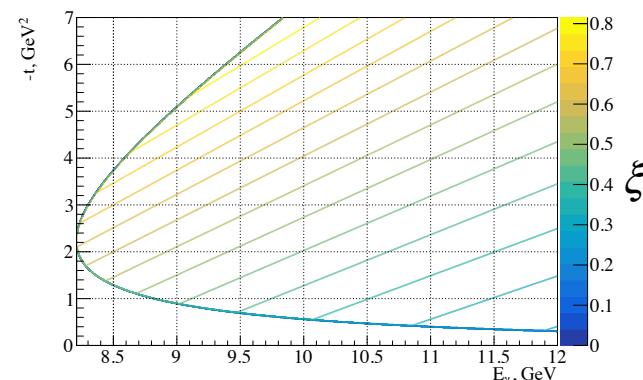
in $m_c \rightarrow \infty$ limit, $\xi \rightarrow 1$ extension:

- factorization valid near threshold
- connection to gravitational FFs: $A_g(t)$ and $C_g(t)$

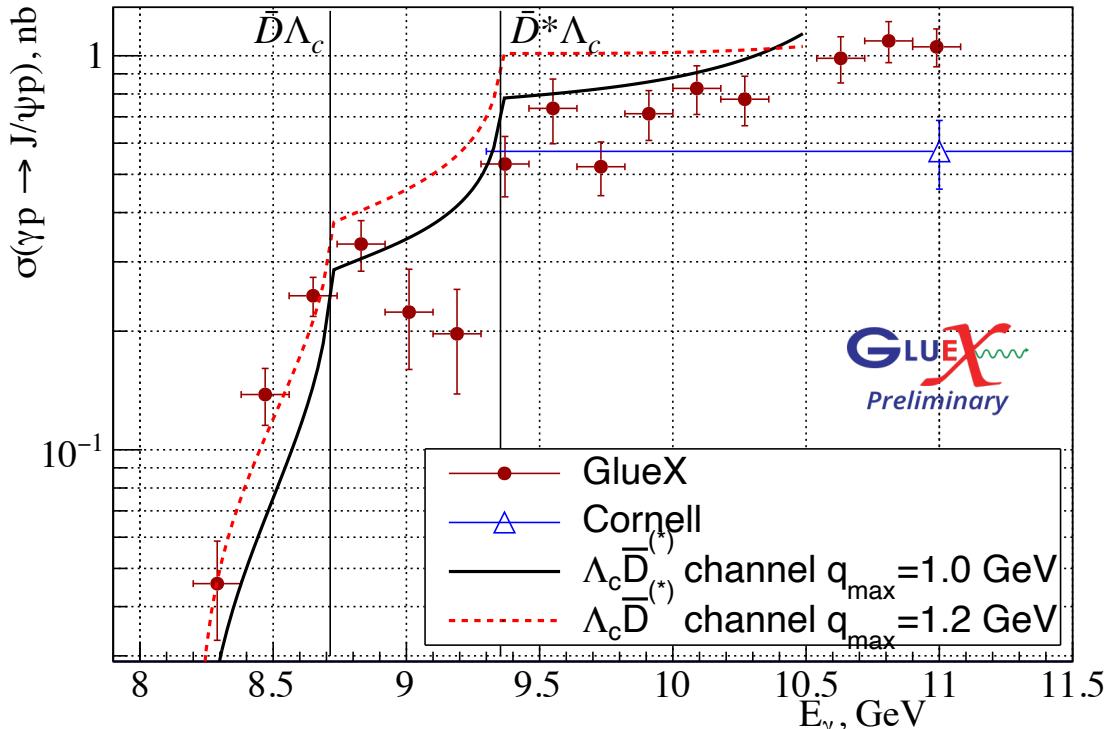


Comparison at $t = t_{min} \rightarrow$ advantages:

- Data: - SLAC measurements done at $t = t_{min}$; -using GlueX $d\sigma/dt(t = t_{min})$
- Theory: less dependence on lattice FF parameters, better factorization, connection to gravitational FF?



Open-charm exchange



Du, Baru, Guo, Hanhart,
Meissner, Nefediev,
Strakovsky EPJ C80 (2020)

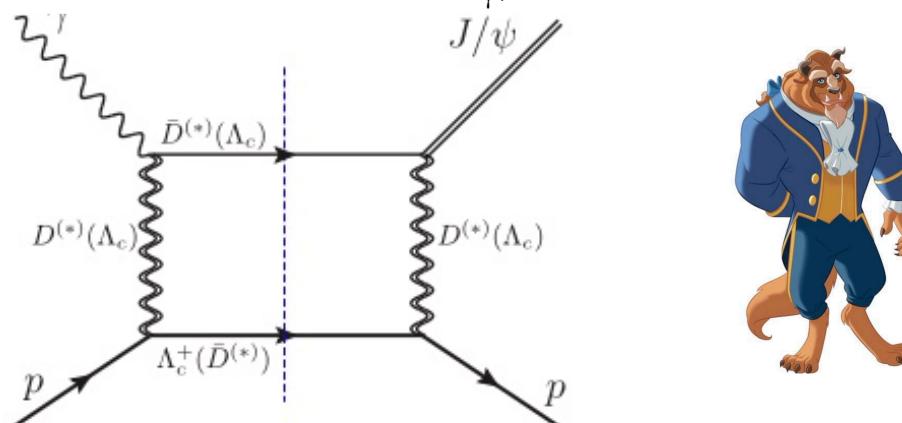
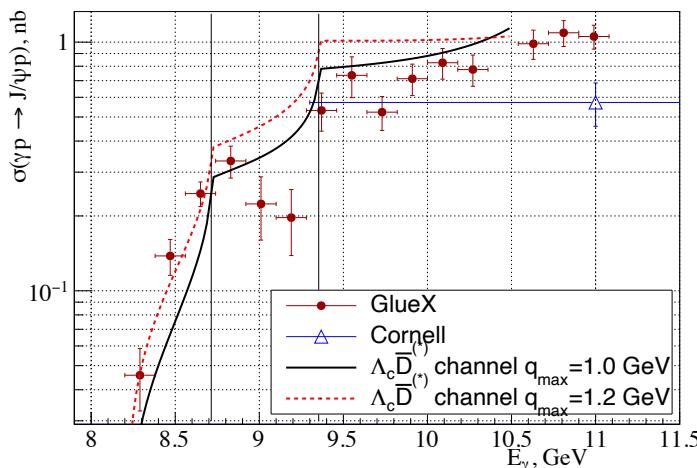


FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

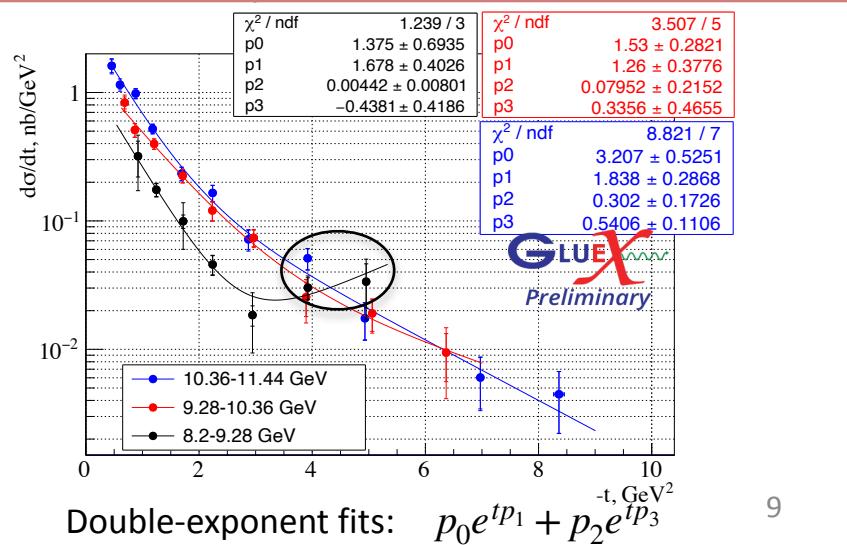
Open-charm or gluon exchange dominates?

Experimental observations	open-charm exchange	gluon exchange
possible structures in total cross section	cusp-like structures at $\bar{D}^{(*)}\Lambda_c$ thresholds ✓	no structures ✗
$d\sigma/dt$ enhancement at high t	s,u -channel contribution? ✓	Not likely in t-channel ✗
sharp t-slope	expect shallow t-dependance due to high mass exchange ✗	consistent with gluon FFs as predicted on lattice ✓
$d\sigma/dt$ - weak energy dependence especially at high t (approx.)	?	expected from power counting rules ✓
helicity conservation ?	?	yes?
beam asymmetry	?	small
naturality ?	unnatural \bar{D} exchange ?	2g - natural parity exchange 3g - unnatural (C-parity violation)

Measurements to be performed



?

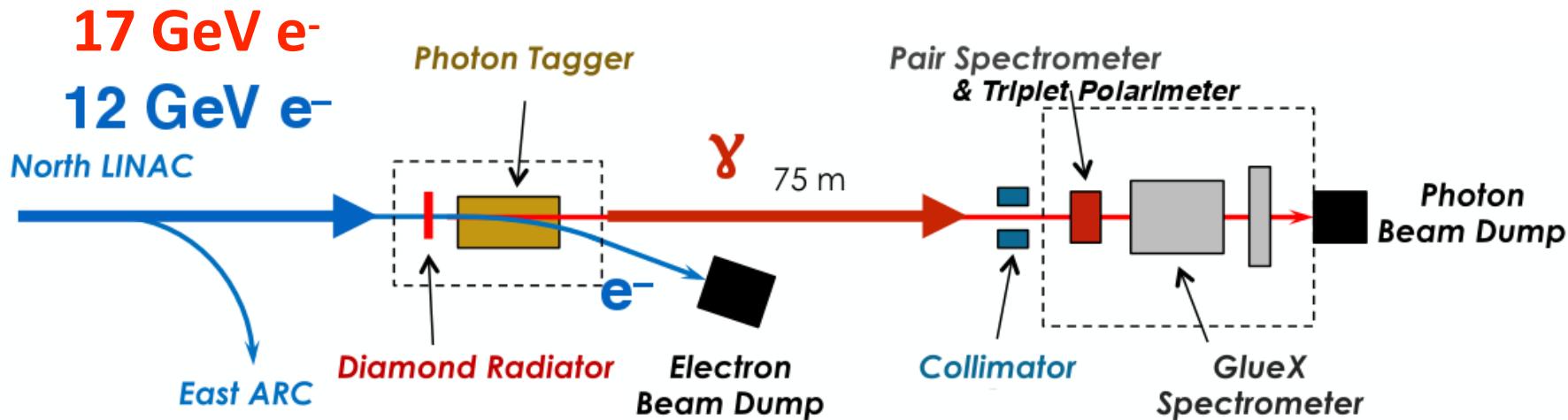


Need to understand the reaction mechanism

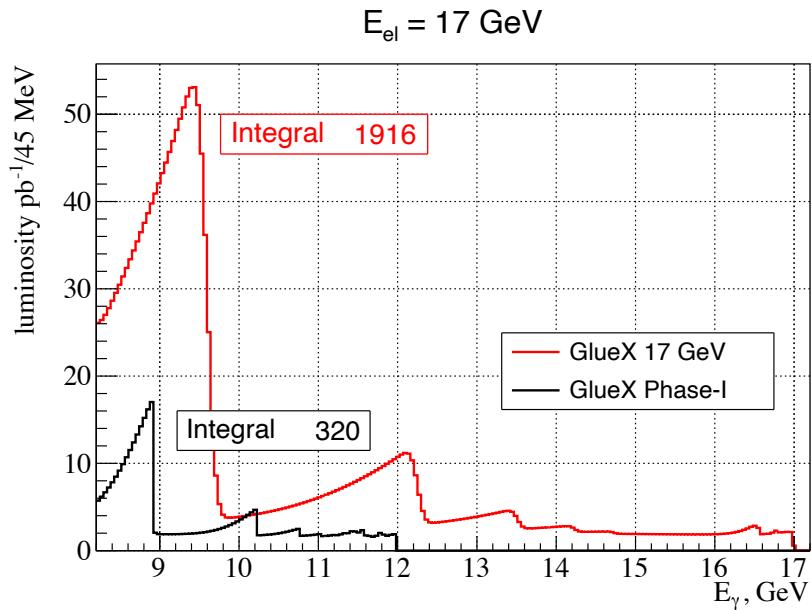
Based on current theoretical description of the threshold charmonium production, to study mass properties of the proton we need:

- Relation between $\gamma p \rightarrow J/\psi p$ and $c\bar{c}(J/\psi)p \rightarrow J/\psi p$ reactions (VMD, GPD factorization)
- Gluon exchange (not open charm)
- The gluon exchange must be dominated by 2^{++} (graviton-like) exchange

Hall D Apparatus with 17 GeV electron beam



- Linearly polarized photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- With 17 GeV beam, coherent edge can be placed at higher energy at the same time giving higher photon flux and higher linear polarization
- The only modification: tagger magnet field increase by 17/12



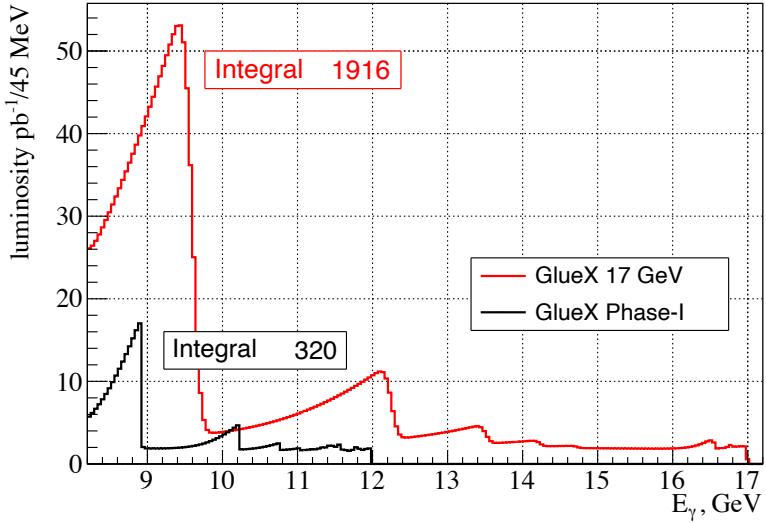
J/ψ studies with 17 GeV beam

All projections based on scaling the GlueX Phase-I real data:

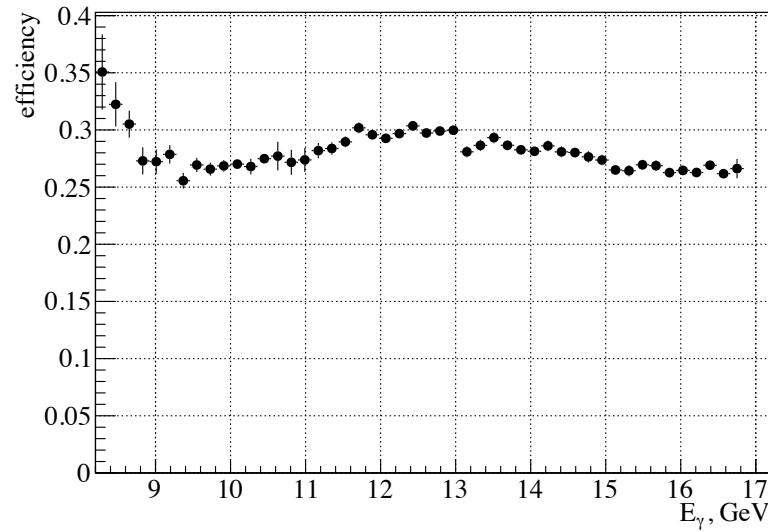
- Assuming same time as for Phase-I (~1.5 years)
- Assuming same average beam current (~200nA) and radiator thickness
- Tagger accidental analysis based on existing data
- Using the measured errors in the near-threshold region (covered by 12 GeV accelerator), and scaling them based on luminosities
- Performing realistic simulations at higher energies to estimate the detector efficiency
- In polarization measurements - using the measured errors and scaling them based on the Figure Of Merit, FOM

Coherent peak set at 9.7 GeV to cover the whole near threshold region of interest

J/ψ at 17 GeV - cross sections and yields

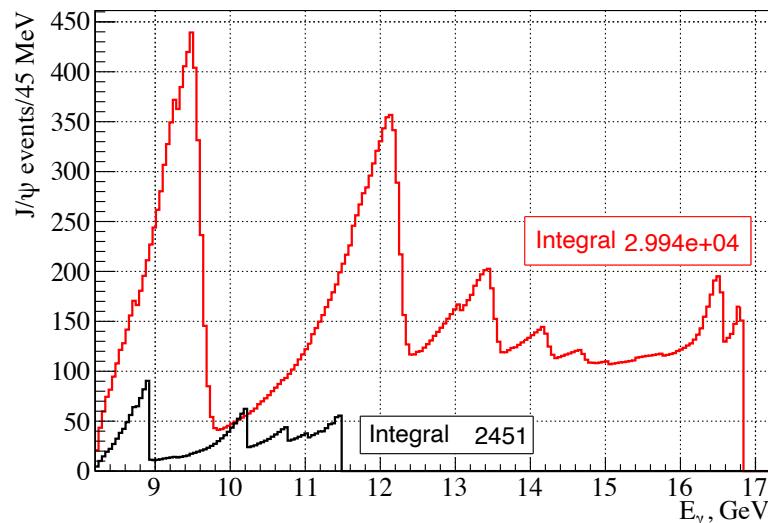
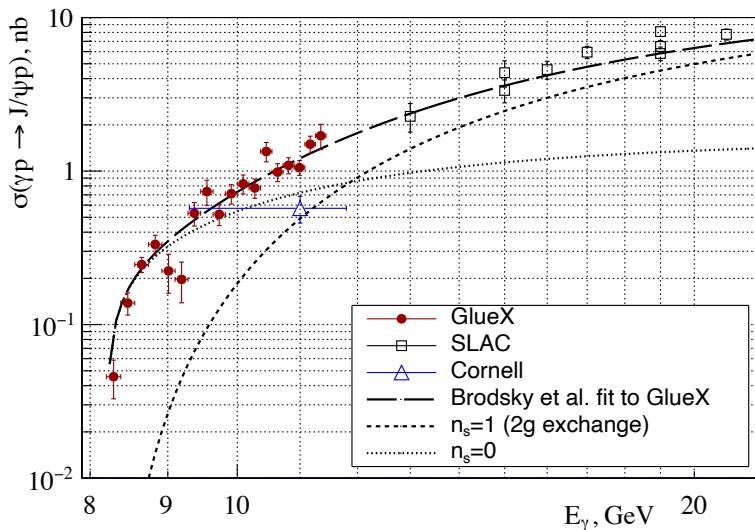


X

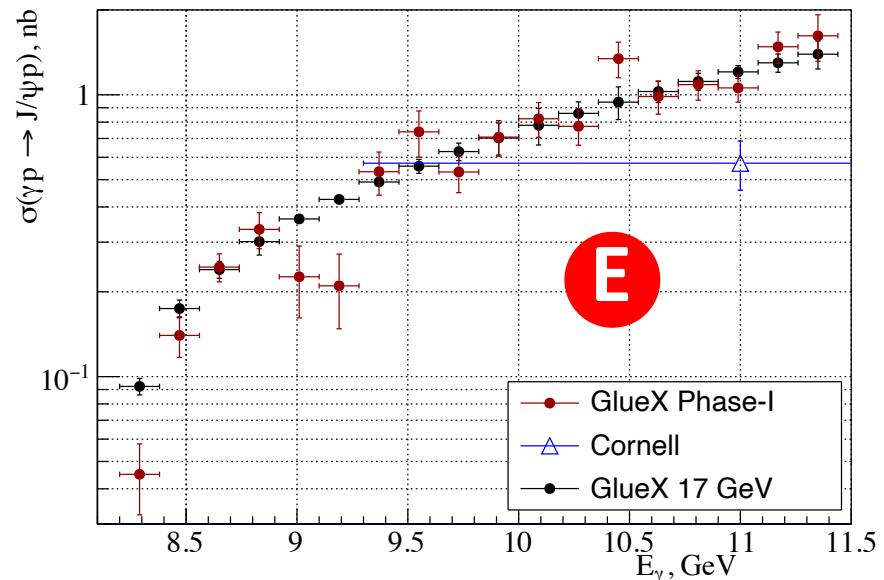
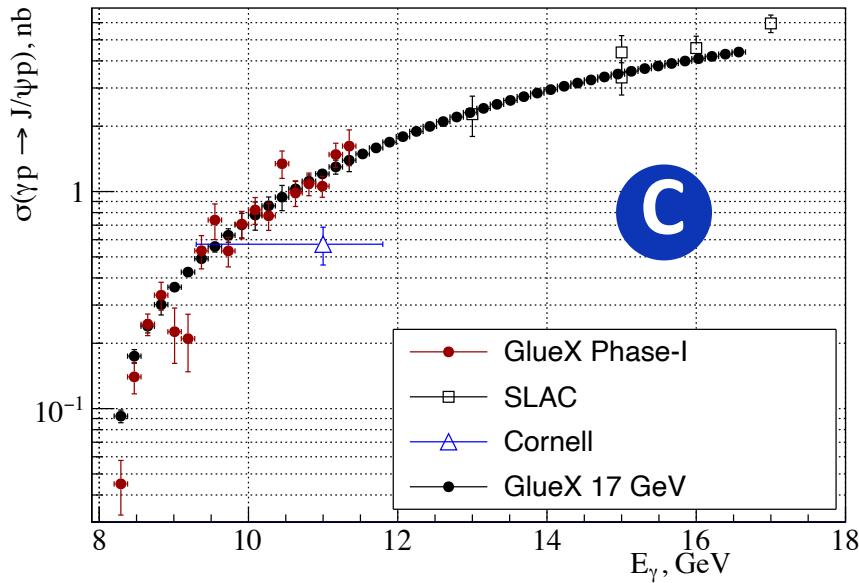


=

$$Y_{J/\psi}(E_\gamma) = L(E_\gamma)\sigma_{J/\psi}(E_\gamma)\epsilon(E_\gamma)\mathcal{B}(J/\psi \rightarrow e^+e^-)$$

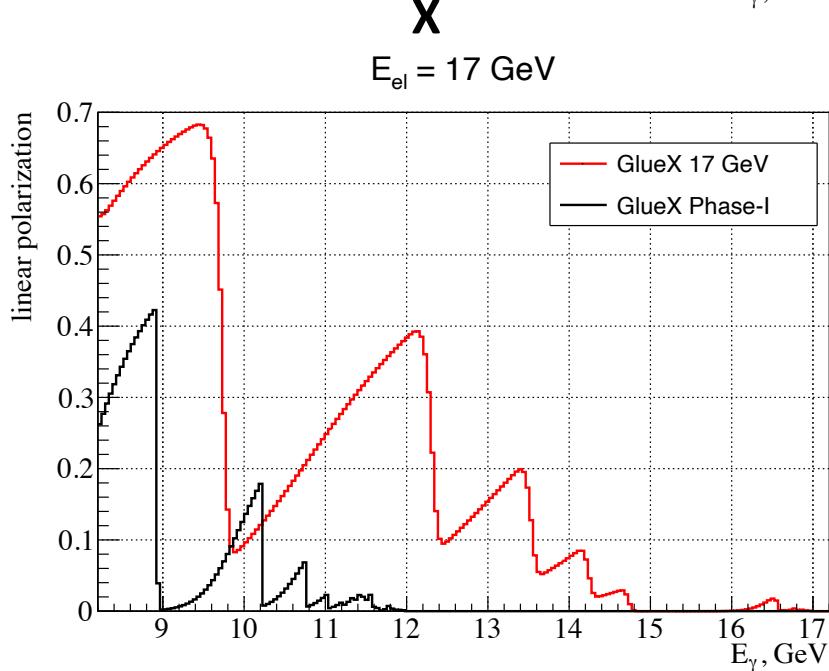
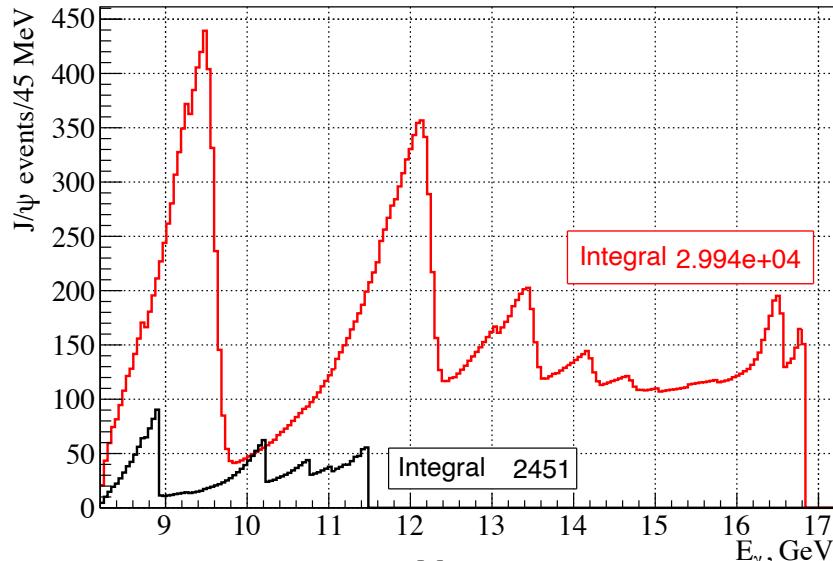


J/ψ at 17 GeV - cross section projections

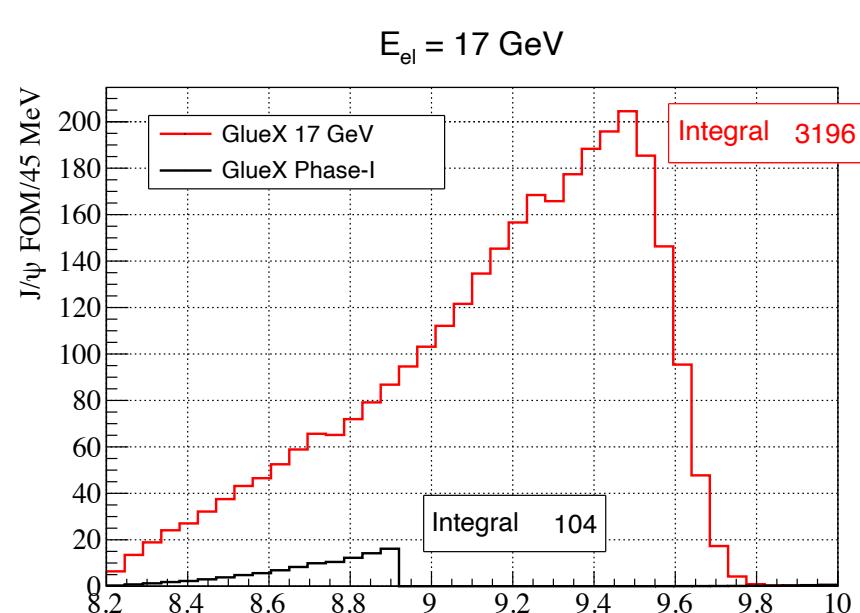


J/ψ at 17 GeV - polarization measurements

$E_{el} = 17 \text{ GeV}$



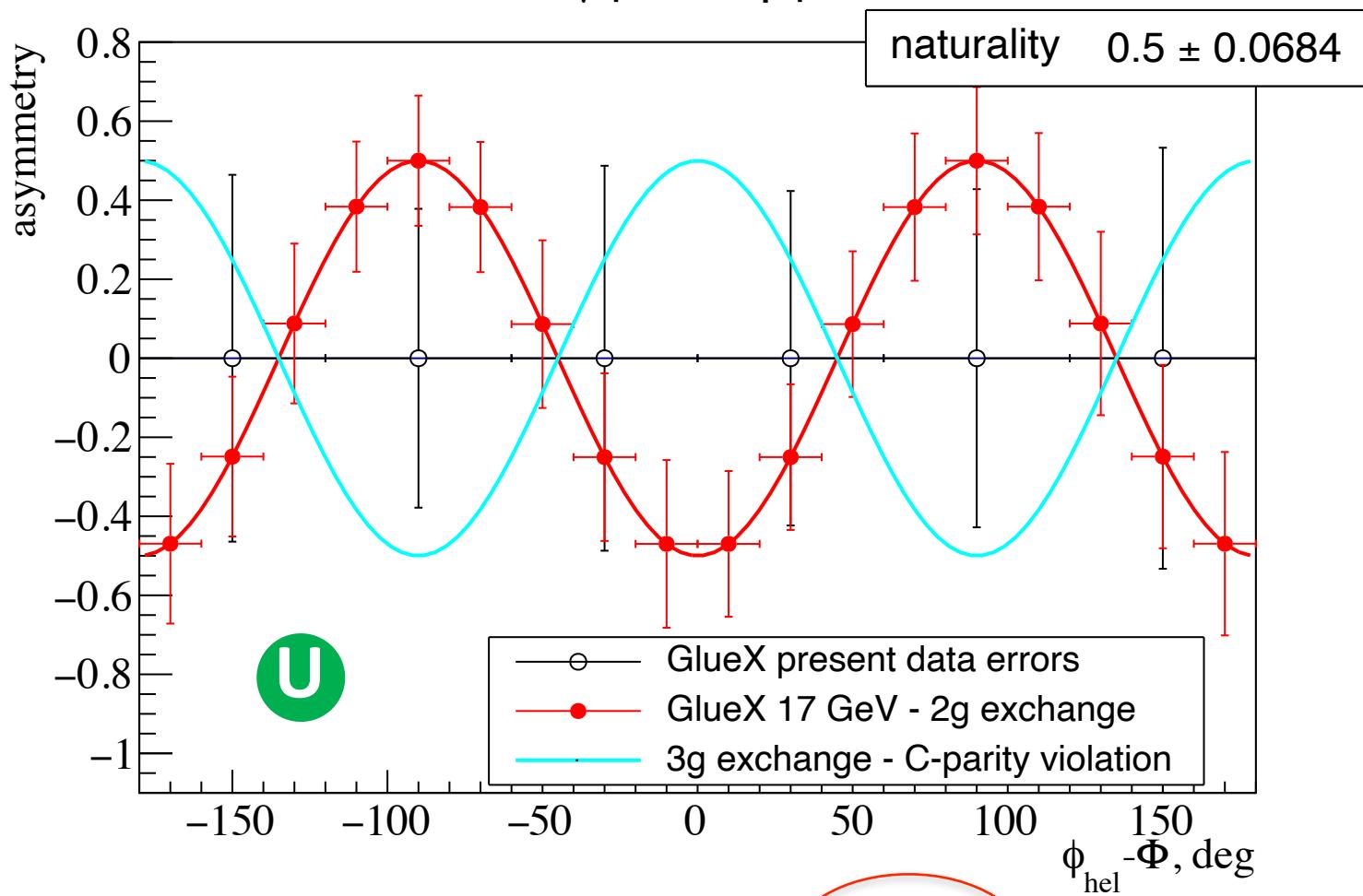
2



$$FOM(E_\gamma) = Y_{J/\psi}(E_\gamma) \cdot p_\gamma^2(E_\gamma)$$

J/ψ at 17 GeV - naturality

γ p → J/ψ p



$$\text{asymmetry} = \frac{1}{P_\gamma} \frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = -\frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi)]$$

naturality $= 0.5(-1)^J P$

See Keigo Mizutani's talk:

more polarization
projections

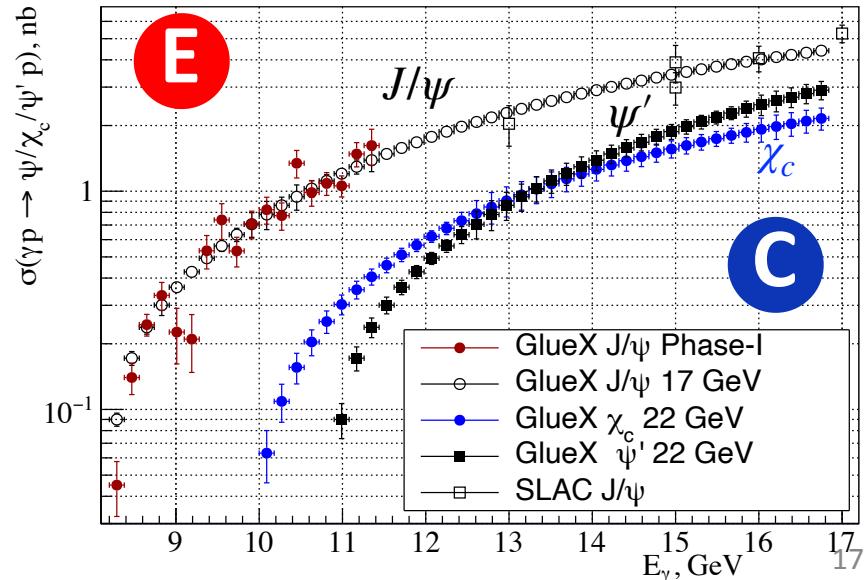
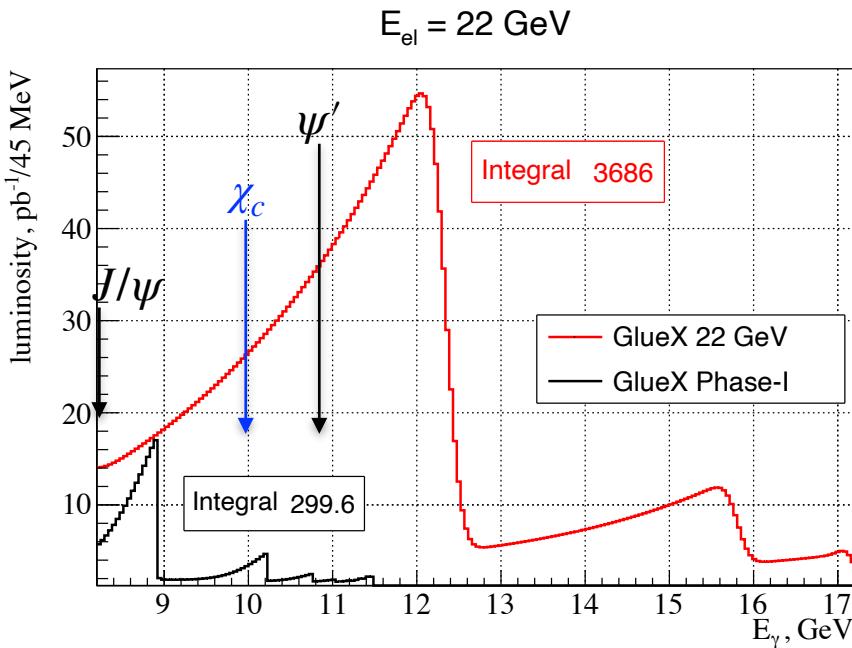
$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi} \left(1 - P_\gamma \frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi')] \right)$$

χ_c and ψ' states with 22 GeV - cross sections

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

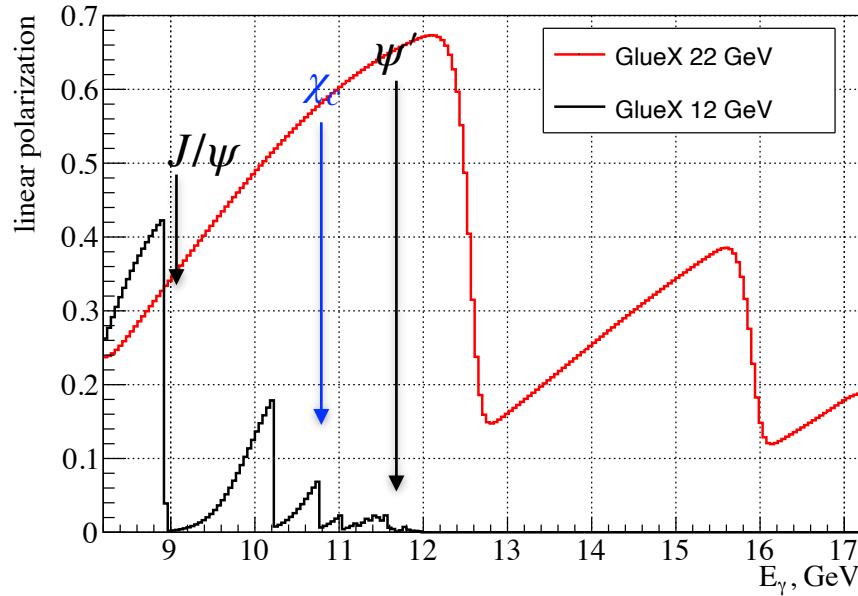
$$\gamma p \rightarrow \psi' p \rightarrow e^+ e^- p$$

- GlueX has detected charmonium states decaying to $J/\psi\gamma$ in the 3.47-3.58 GeV mass region, consistent with $\chi_{c1}(3511)$ or $\chi_{c2}(3556)$, both are C-even charmonium states.
- We have used the measured χ_c yields and MC simulations (efficiency $\sim 10\%$) to scale the JPAC calculations for χ_{c1} photoproduction cross section and make projections for GlueX with 22 GeV beam.
- GlueX has observed ψ' states in e^+e^- decay mode; measured yields used to project the expected yields with 22 GeV beam, assuming same energy dependence as for J/ψ . Note: extrapolations have significant uncertainties due to small number of ψ' observed.

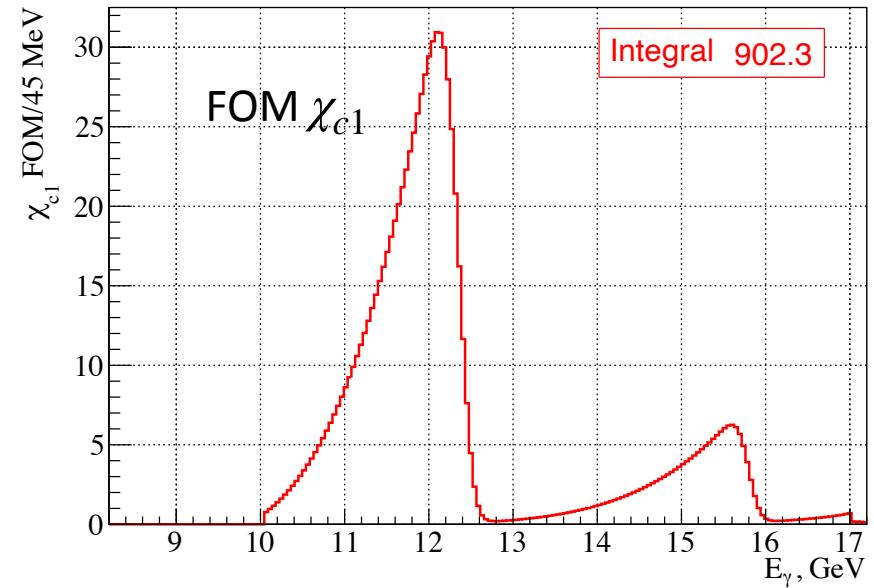


χ_{c1} and ψ' with 22 GeV - polarization measurements

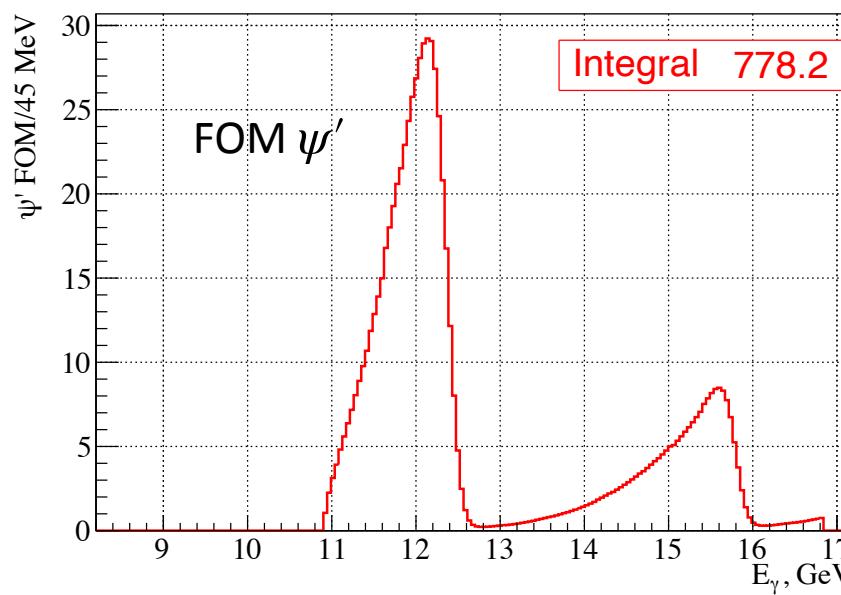
$E_{el} = 22 \text{ GeV}$



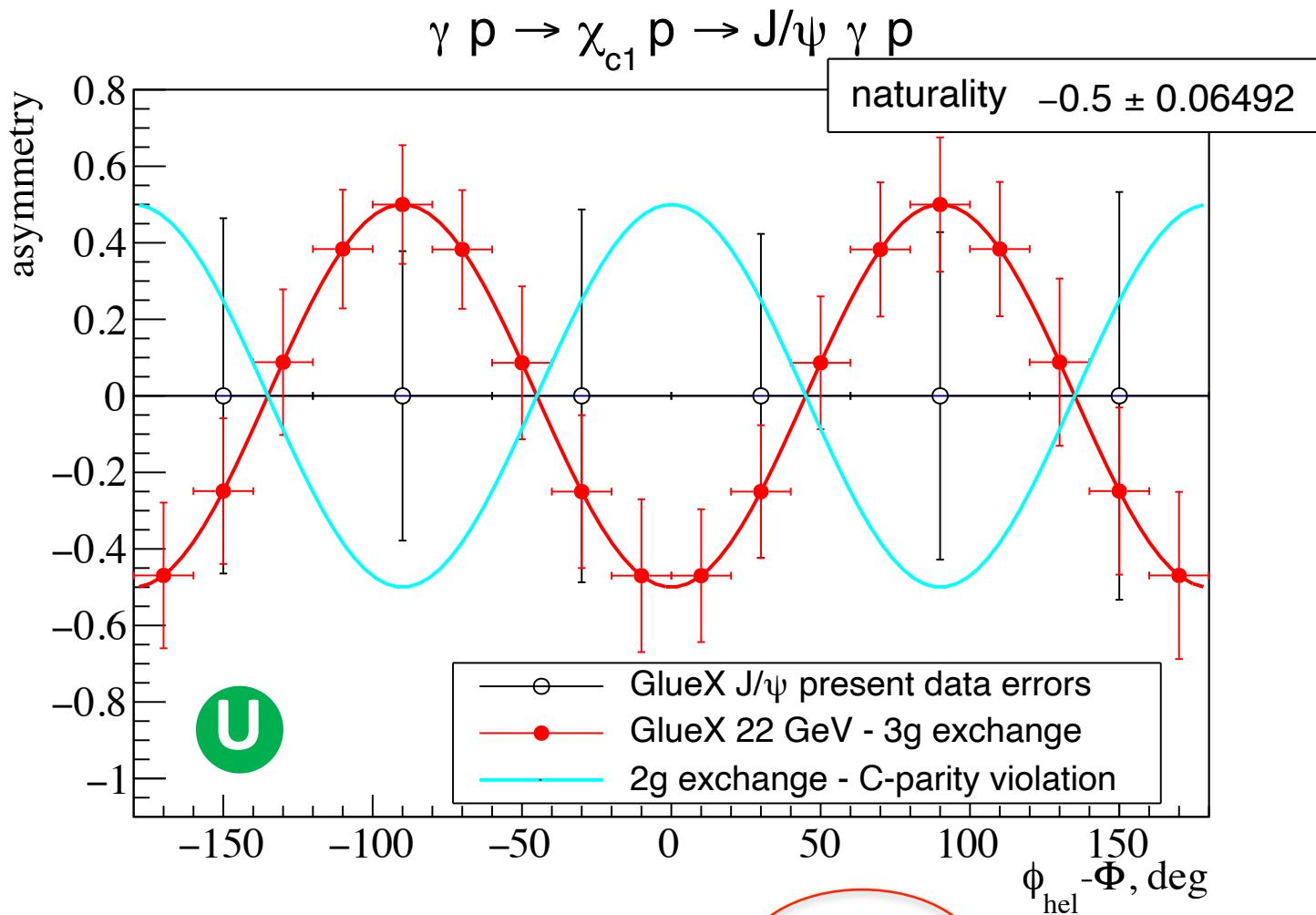
$E_{el} = 22 \text{ GeV}$



$E_{el} = 22 \text{ GeV}$



χ_{c1} with 22 GeV - naturality



$$asymmetry = \frac{1}{2P_\gamma} \frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = \frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi)]$$

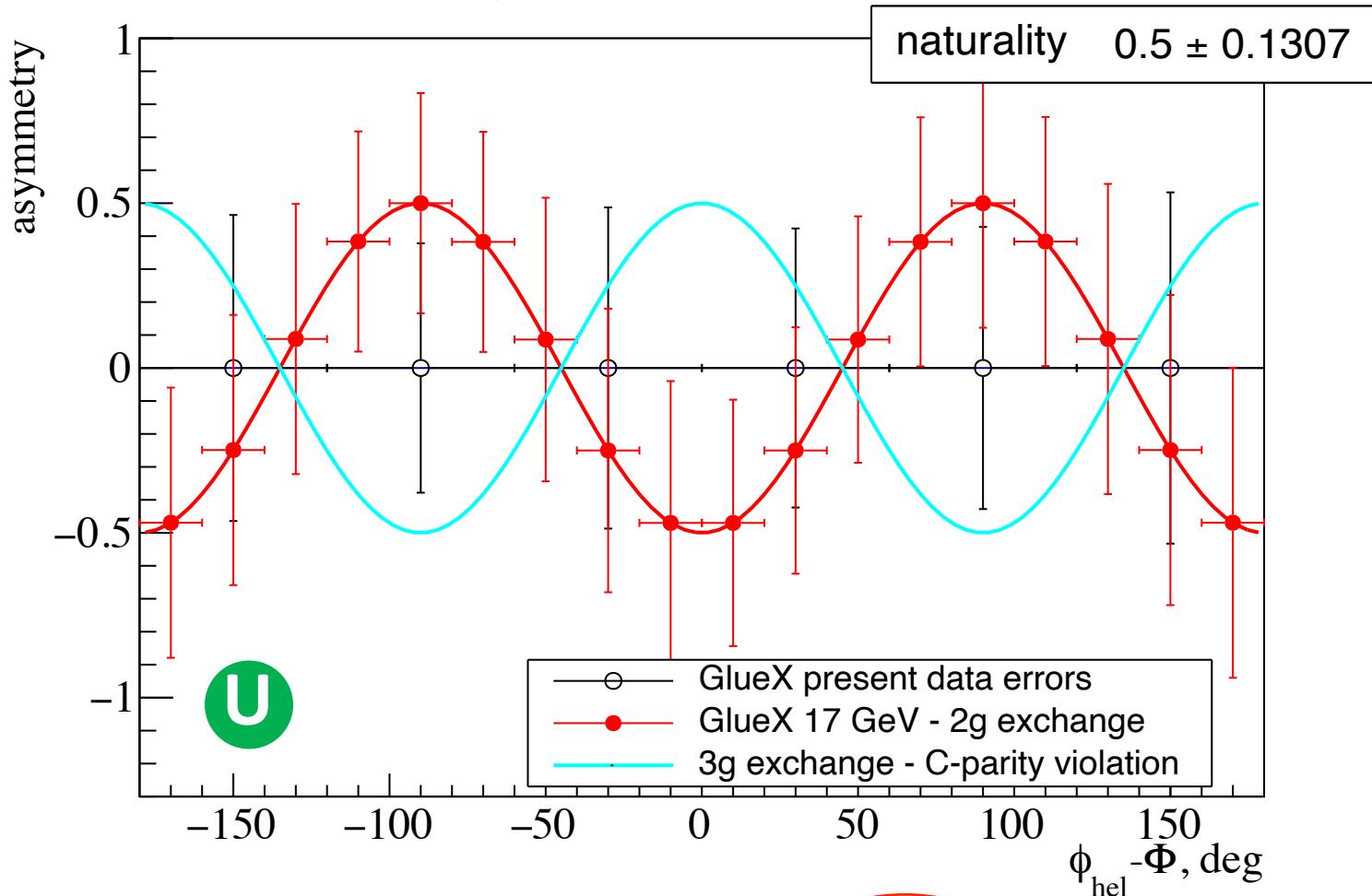
naturality = $0.5(-1)^J P$

$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi} \left(7 + 2P_\gamma \frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi')] \right)$$

...assuming equal helicity couplings

ψ' at 22 GeV - naturality

$\gamma p \rightarrow \psi' p \rightarrow e^+ e^- p$



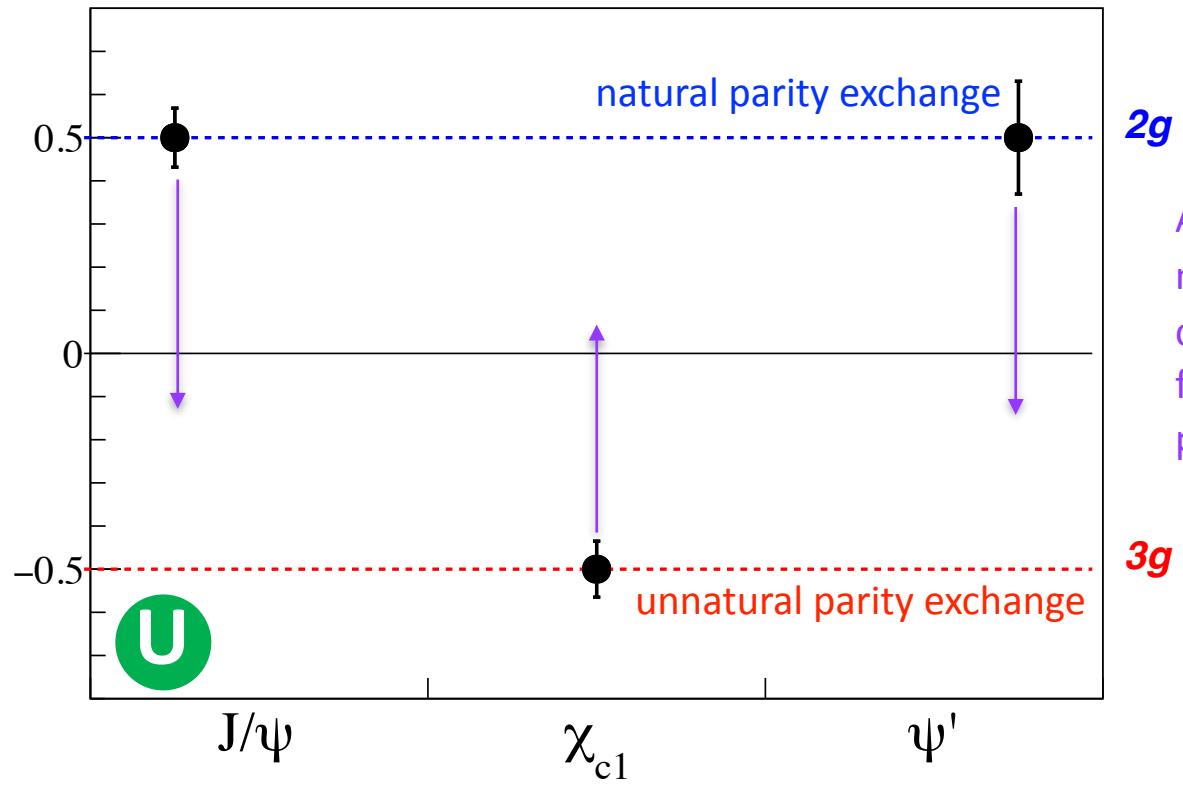
$$asymmetry = \frac{1}{P_\gamma} \frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = -\frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi)]$$

naturality = $0.5(-1)^J P$

$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi} \left(1 - P_\gamma \frac{\rho_{1-1}^1 - Im \rho_{1-1}^2}{2} \cos[2(\phi_{hel} - \Phi')] \right)$$

$J/\psi, \chi_{c1}, \psi'$ naturality studies

$$\text{naturality} = 0.5(-1)^J$$



2g

Any deviation from the expected naturality (+ or -0.5) indicates contribution of mechanism different from what is needed to study mass properties of the proton

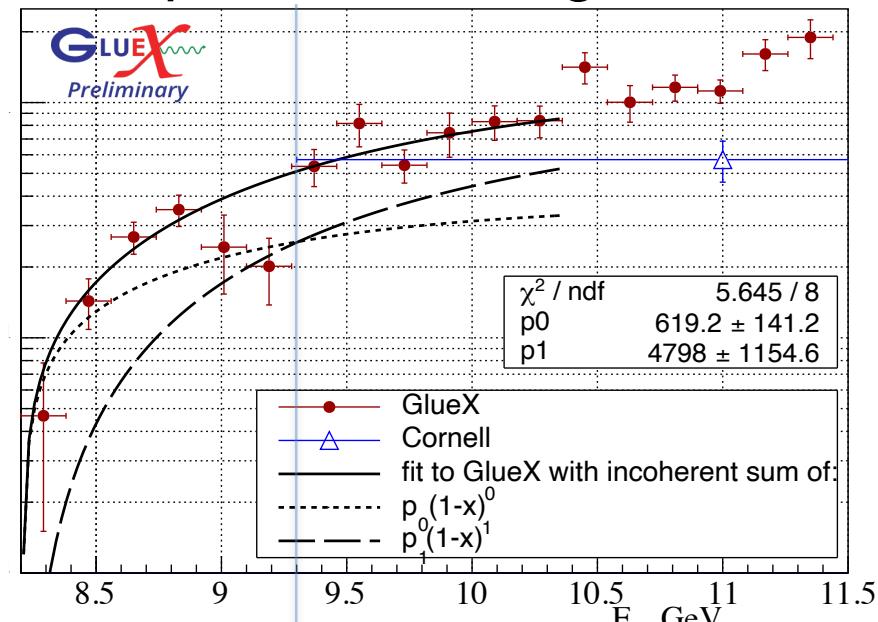
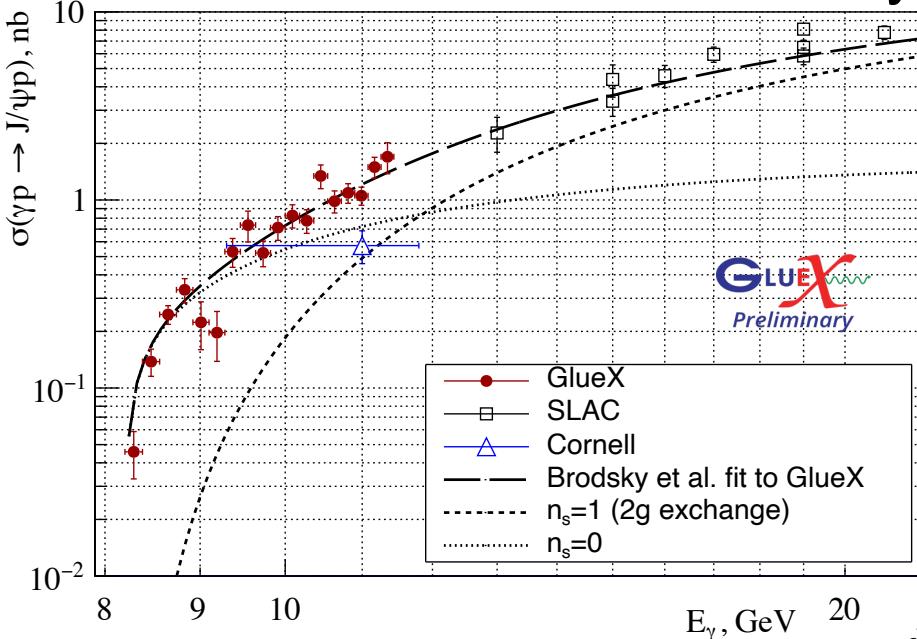
3g

Conclusions

- Charmonium threshold photoproduction has potential to access very important physics - mass properties of the proton - however:
 - ... assuming VMD, QCD factorization
 - ... assuming relation of the measured cross sections and the gravitational FFs
 - ... assuming gluon exchange over open-charm exchange mechanism?
- Need to understand the reaction mechanism:
 - Precise cross section measurements near J/ψ threshold, thanks to higher beam energy increasing the coverage/intensity of the coherent peak
 - The energy upgrade will give unique opportunities for GlueX to measure polarization observables that are critical in separating different contributions to the J/ψ production
 - Studies of higher charmonium states (χ_c, ψ') are very important in understanding the charmonium mass dependence (recall: factorization, graviton exchange assumptions are valid at high mass limit)
 - Comparing C-odd ($J/\psi, \psi'$) and C-even charmonium states (χ_c) allows to study the type of gluon exchange (2g, 3g)
 - Important input from theorists is expected
 - Note: all projected results in the threshold region are based on scaling real data results₂₂

Back-ups

Total cross section asymptotic - power counting



$$\frac{d\sigma_{\gamma p}^{yp}}{dt} = (1-x)^0 N_4 F_4^2(t) + (1-x)^1 N_3 F_3^2(t), t > 1 \text{ GeV}^2$$

Sun, Tong, Yuan PRD 105.054032 (2021):

3g exchange is violating C-parity, all 2g and $n_s = 0$

$$\frac{d\sigma_{n_s}^{yp}}{dt} = \mathcal{N}_{n_s} (1-x)^{2n_s} \cdot F_{n_s}^2(t), n_s \text{ is}$$

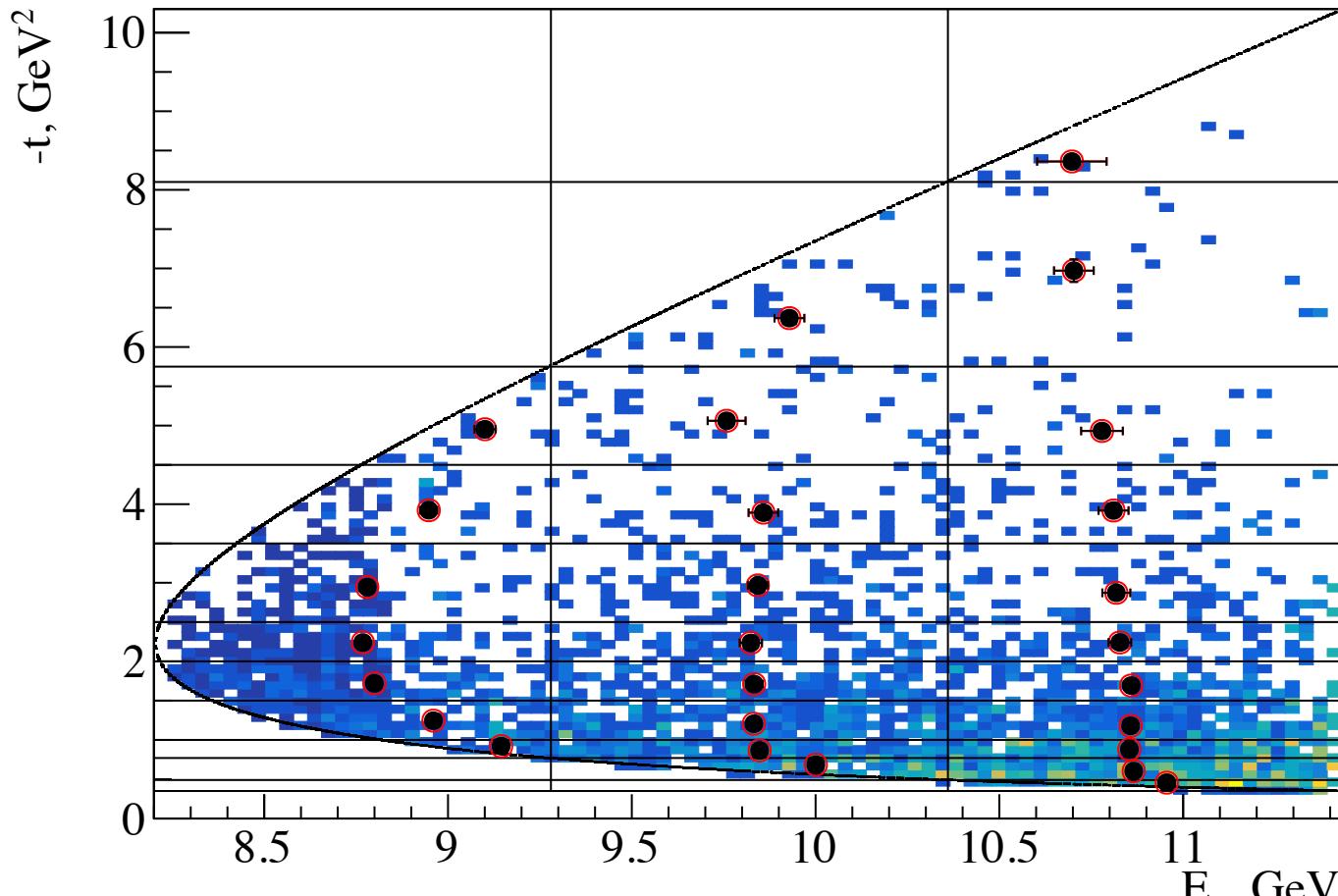
number of spectators in proton;

$n_s = 0$ associated with 3g exchange

Brodsky et al. PLB498 (2001)

Twist-4	Twist-3
no energy dependance	vanishes at threshold
$1/t^5$	$1/t^4$
proton spin flip	no spin flip
$\sim E_g(t, x, \xi)$	$\sim H_g(t, x, \xi)$

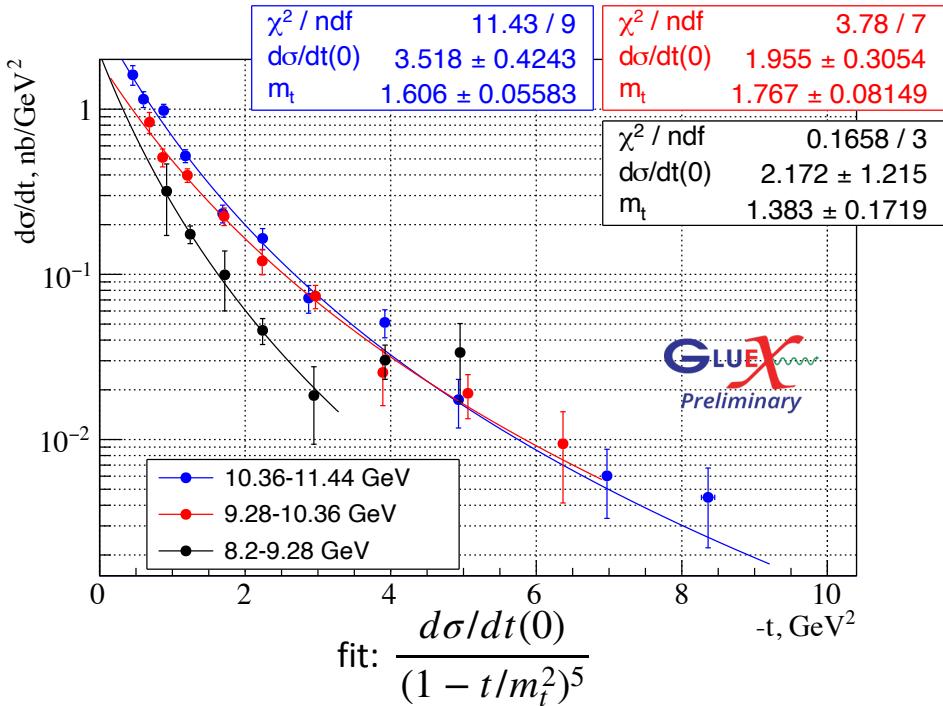
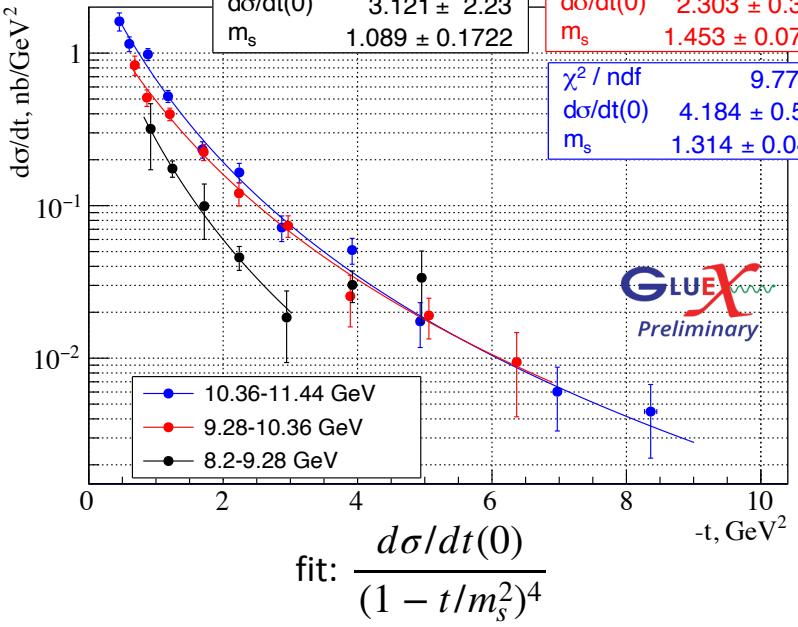
Differential cross-sections



$$\frac{d\sigma}{dt}(E, t) = \frac{N_{J/\psi}}{L(E_\gamma)[nb^{-1}]/0.045\text{GeV}} \frac{1}{\text{area}(E, t)[\text{GeV} \cdot \text{GeV}^2]} \frac{1}{\varepsilon(E, t)}$$

- 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

QCD: high- t asymptotic

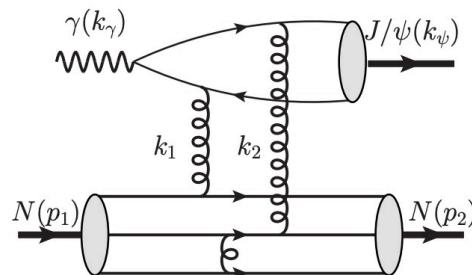


Sun, Tong, Yuan PRD105 (2022)

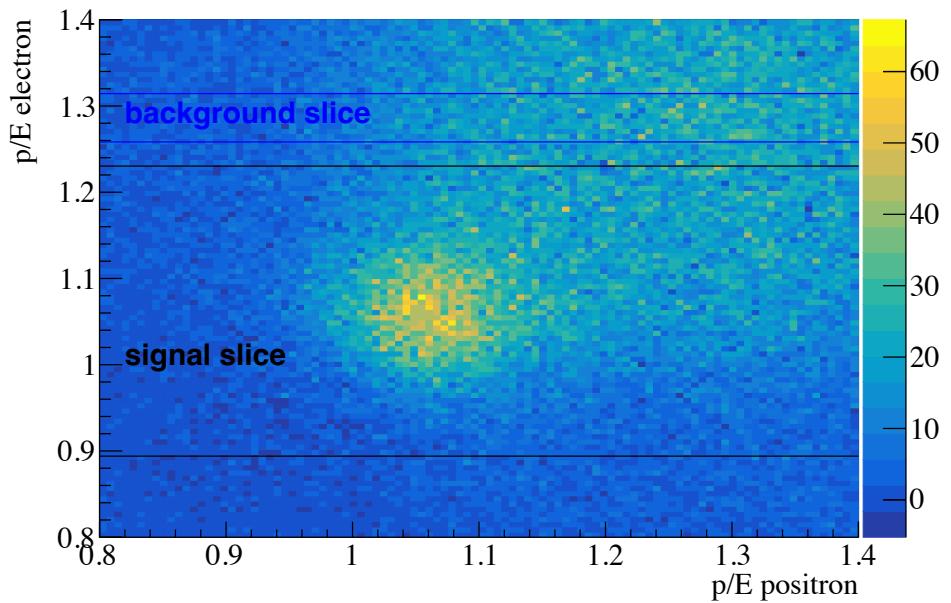
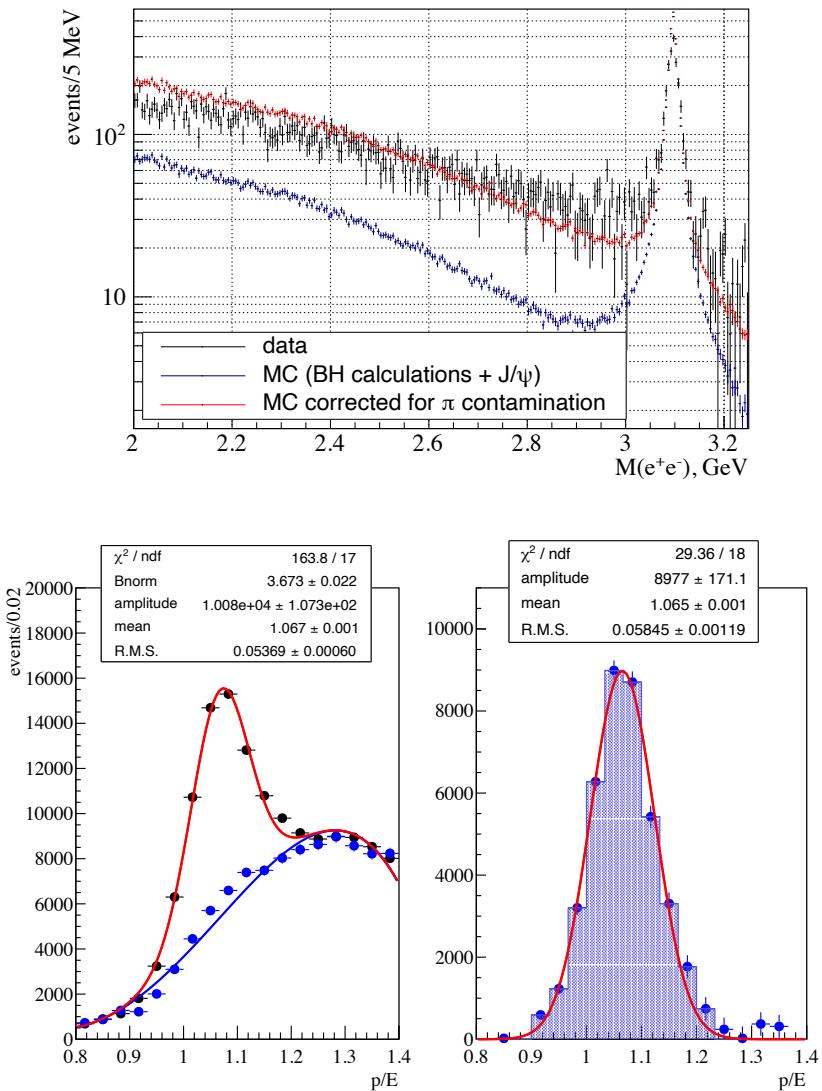
Asymptotic t -dependance $1/t^5$ (vs $1/t^4$)
due to helicity flip

Not enough statistics to test the t -asymptotic

However we can detect proton spin flip,
using double polarization measurements?

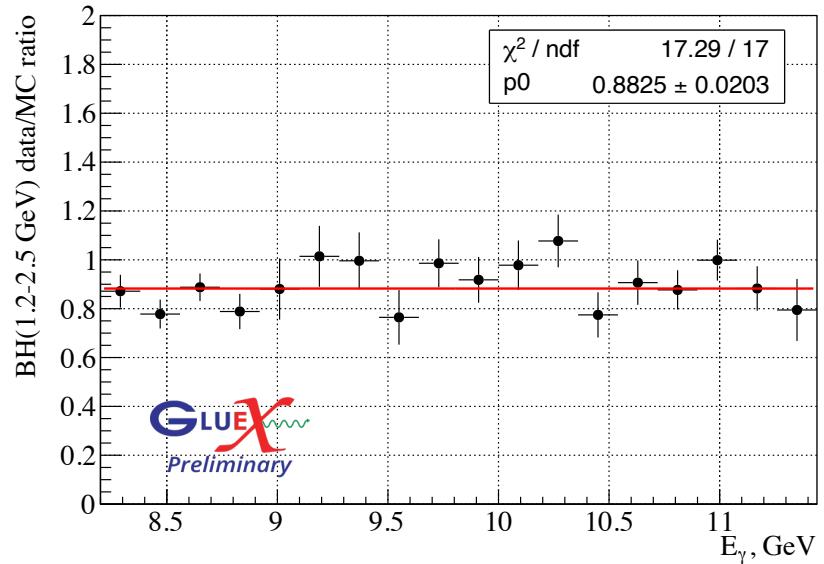
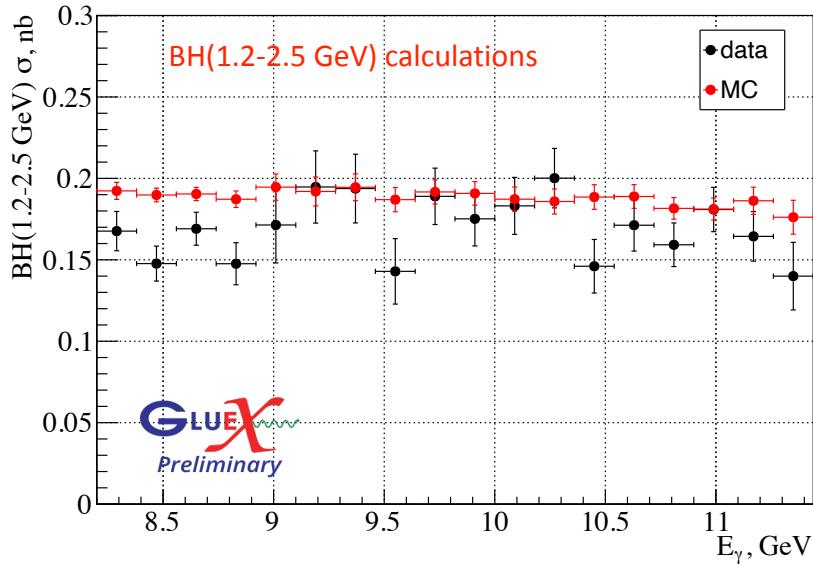
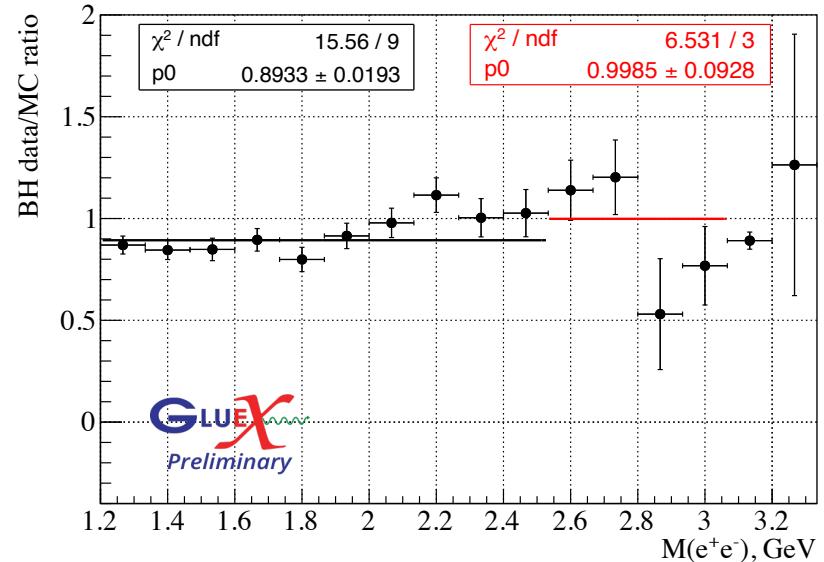
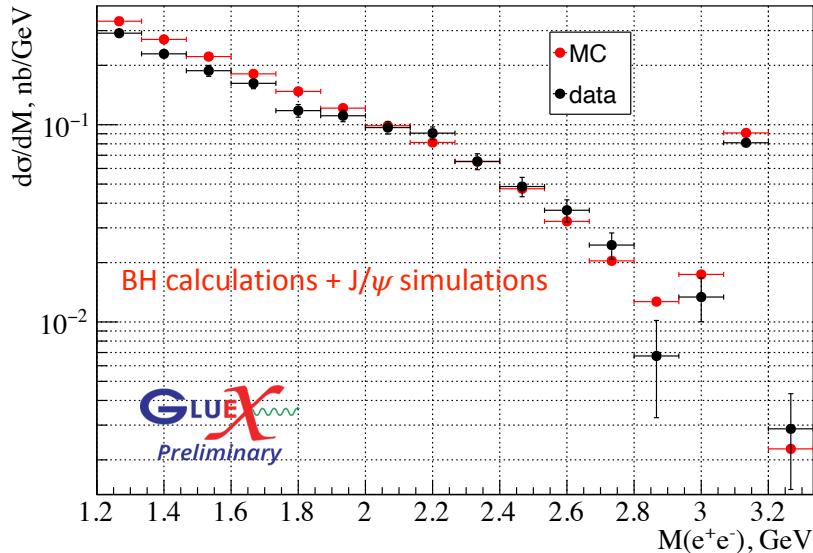


e/π separation



- Pion contamination ~50% in the continuum (using p/E fits to estimate it)

BH e.m. calculations vs data



BH yields extracted from fits of E/p distributions

$\gamma p \rightarrow (p\bar{p})p$ with $M(p\bar{p}) \sim M_{J/\psi}$

