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

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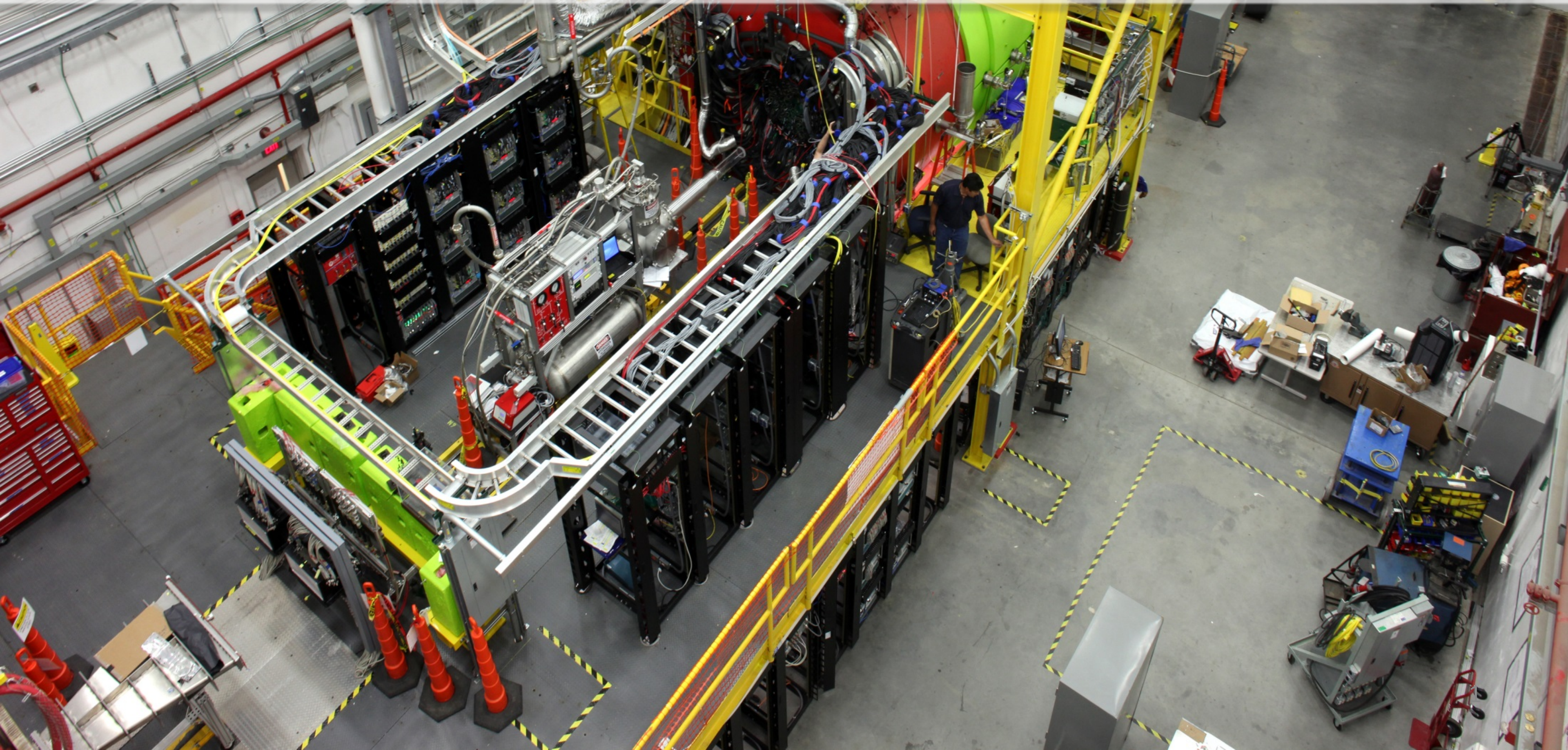
(GlueX Collaboration)

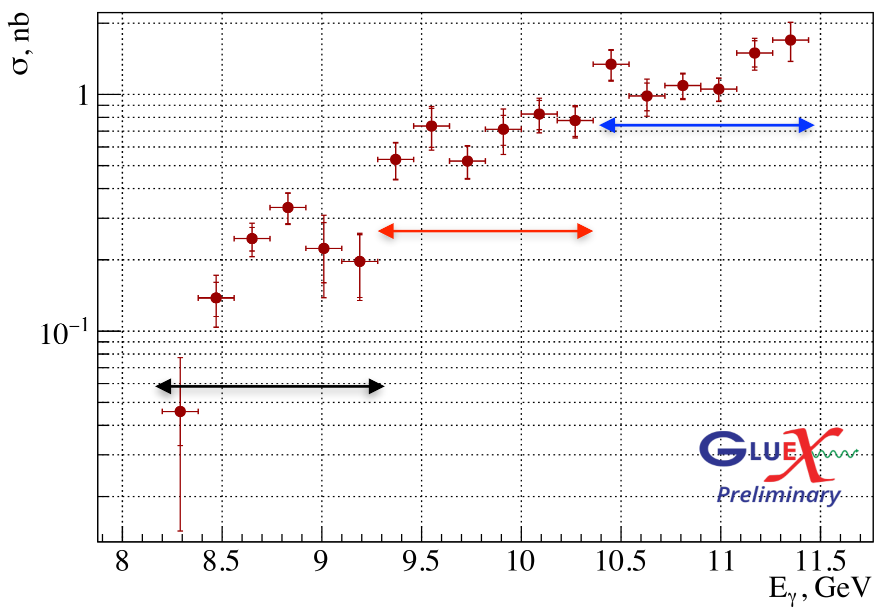
- What are the physics problems related to J/ψ (and beyond) threshold production we need to solve?
- Why CEBAF energy upgrade is important in solving these problems using existing GlueX detector?

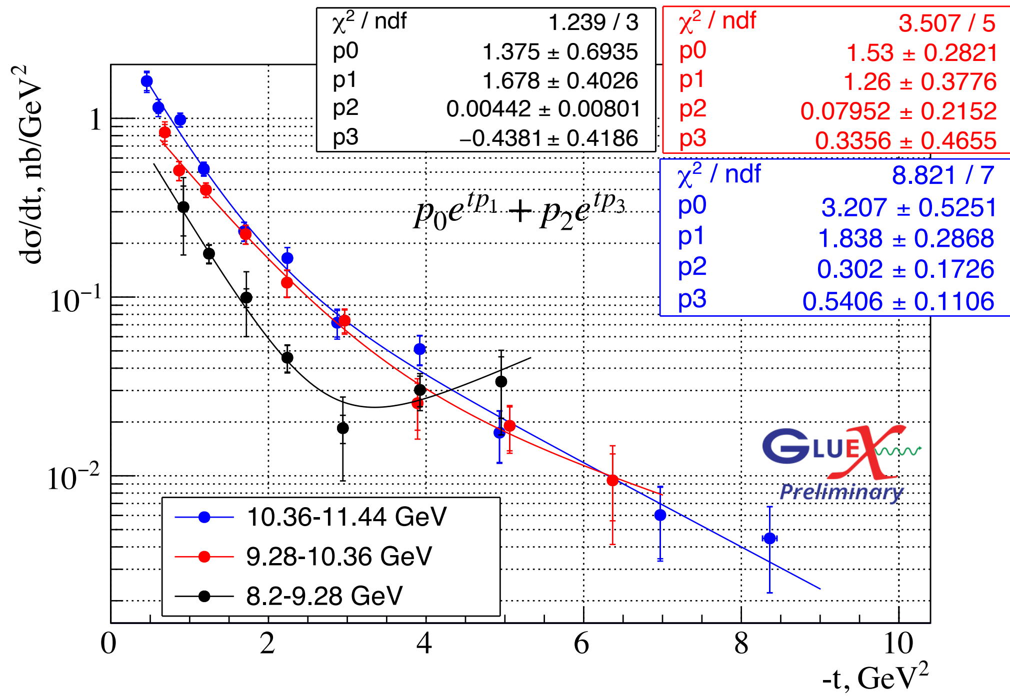
Will try to make realistic projections based on existing measurements



Preliminary GlueX results: total and differential cross-sections

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

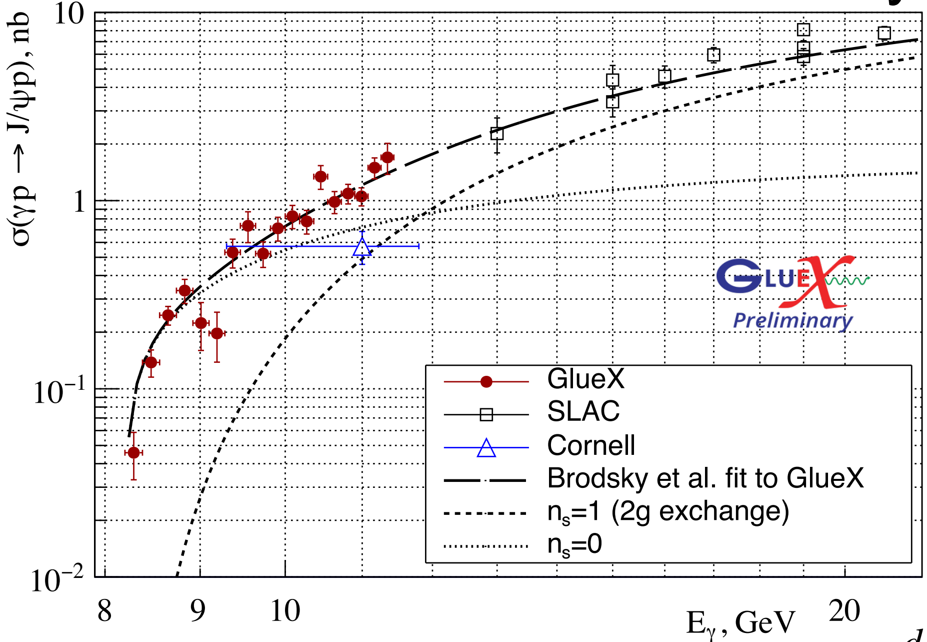


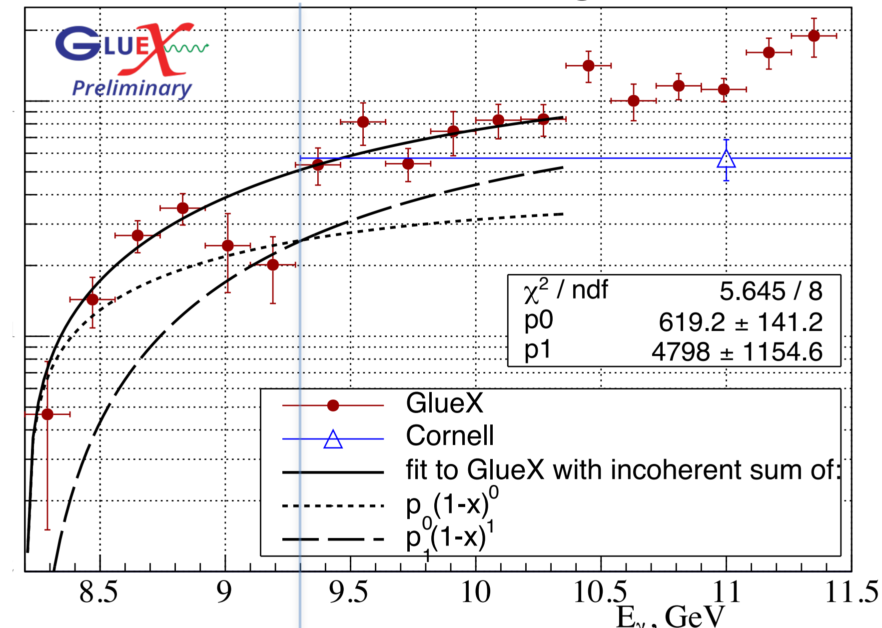


- Possible structure in $\sigma(8.6 - 9.6 GeV)$, however the statistical significance of the two "dip" points is 2.6σ; if include look-elsewhere effect - 1.3σ

- Enhancement of $d\sigma/dt$ at high t (for the lowest energy slice)
- Weak energy dependance 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

Total cross section asymptotic - power counting





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

Sun, Tong, Yuan PRD 105.054032 (2021):

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

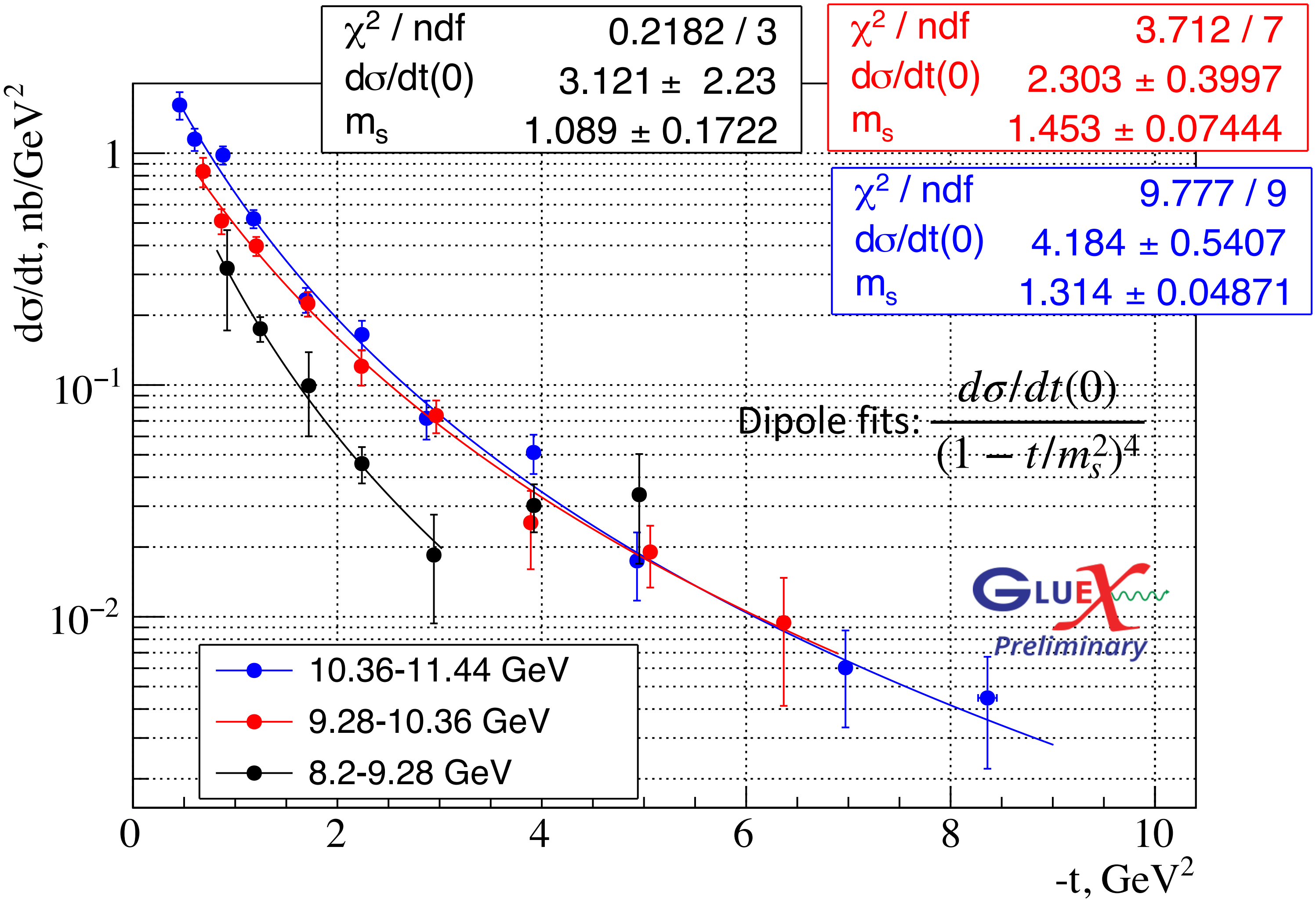
$$\frac{d\sigma^{\gamma p}_{n_s}}{dt} = \mathcal{N}_{n_s}(1-x)^{2n_s} \cdot F^2_{n_s}(t),$$ n_s is *number of spectators in proton;*

$n_s = 0$ *associated with 3g exchange*

Brodsky et al. PLB498 (2001)

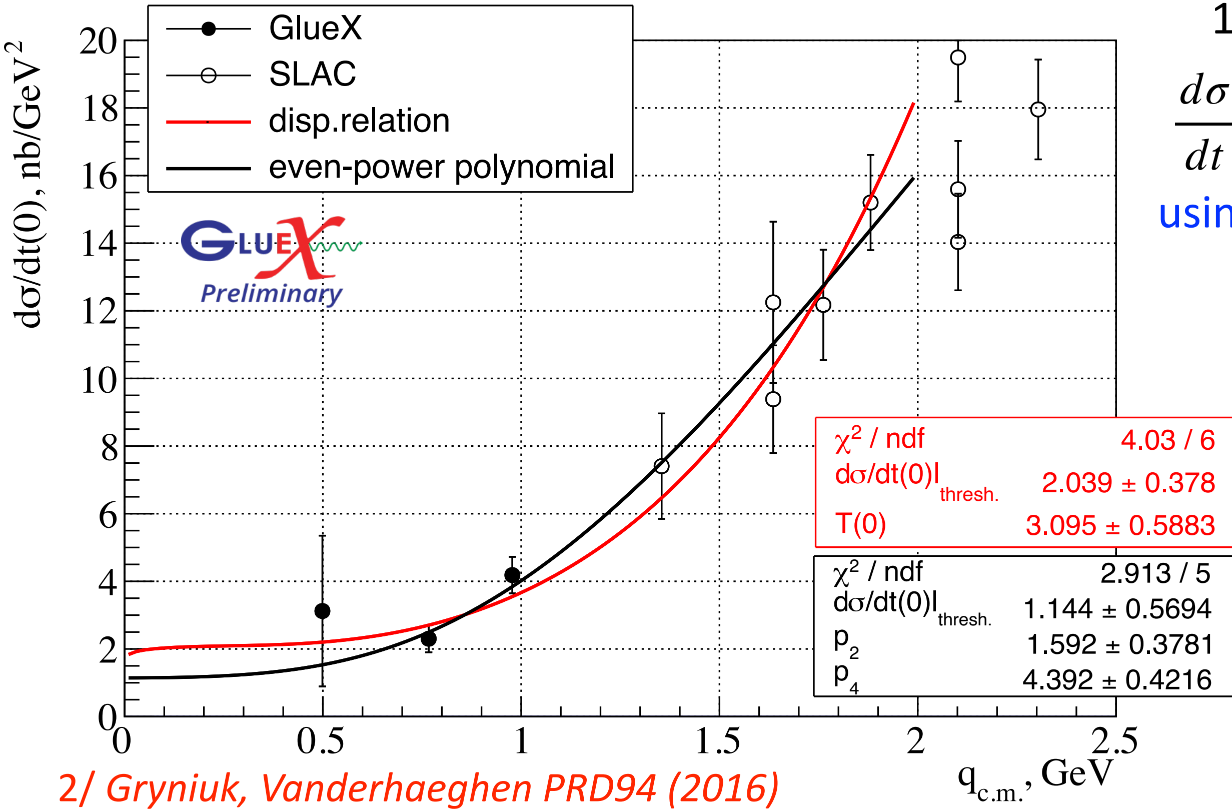
Twist-4	Twist-3
no energy dependance	vanishes at threshold
$1/t^5$	$1/t^4$
proton spin flip	no spin flip
$\sim E_g(t,x,\xi)$	$\sim H_g(t,x,\xi)$

Differential cross-sections - forward extrapolation



E_γ, GeV	8.93	9.86	10.82
$q_{c.m.}$, GeV (J/ψp c.m.)	0.499	0.767	0.978
$d\sigma/dt(0)$, nb/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



1/ Even-power polynomial fit

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

using VMD

$$\downarrow$$

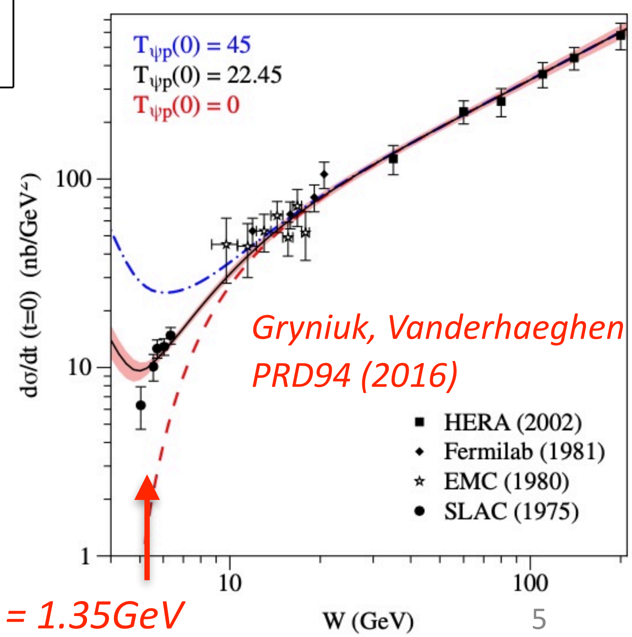
$$\frac{(sk_{\gamma p}^2)_{thr.}}{sk_{\gamma p}^2}[p_0 + p_2 q^2 + p_4 q^4]$$

2/ Gryniuk, Vanderhaeghen PRD94 (2016)

Dispersion relation:

$$ReT^{\psi p}(\nu) = T(0) + \frac{2}{\pi}\nu^2\int_{\nu_{th.}}^{\infty} d\nu' \frac{ImT^{\psi p}(\nu')}{\nu'(\nu'^2 - \nu^2)} \qquad \frac{p_0}{p_1^2}[p_1 + DI(q)]^2\frac{(sk_{\gamma p}^2)_{thr.}}{sk_{\gamma p}^2}$$

p_1 - subtraction constant $T(0)$



$q_{c.m.}$ = 1.35GeV

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

Forward differential cross-sections - model dependent applications

1/ $J/\psi - p$ scattering length:

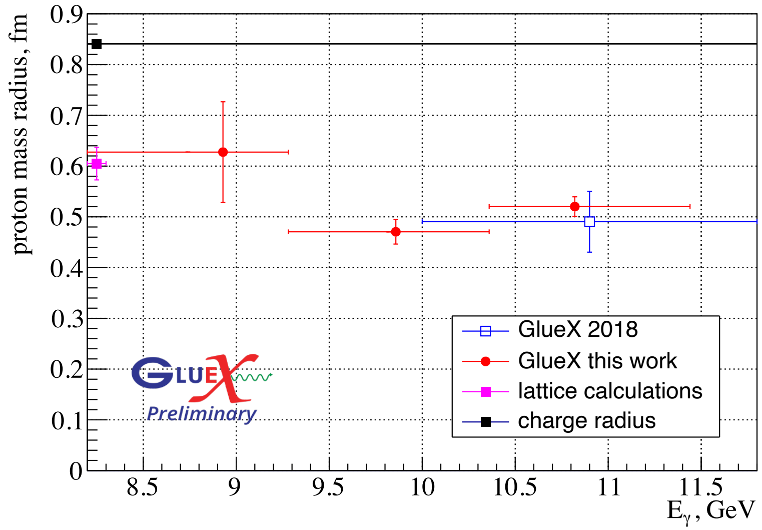
$13.4 \pm 3.8\ mfm$, $17.9 \pm 1.7\ mfm$

very weak $J/\psi - p$ interaction

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

using VMD

2/



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

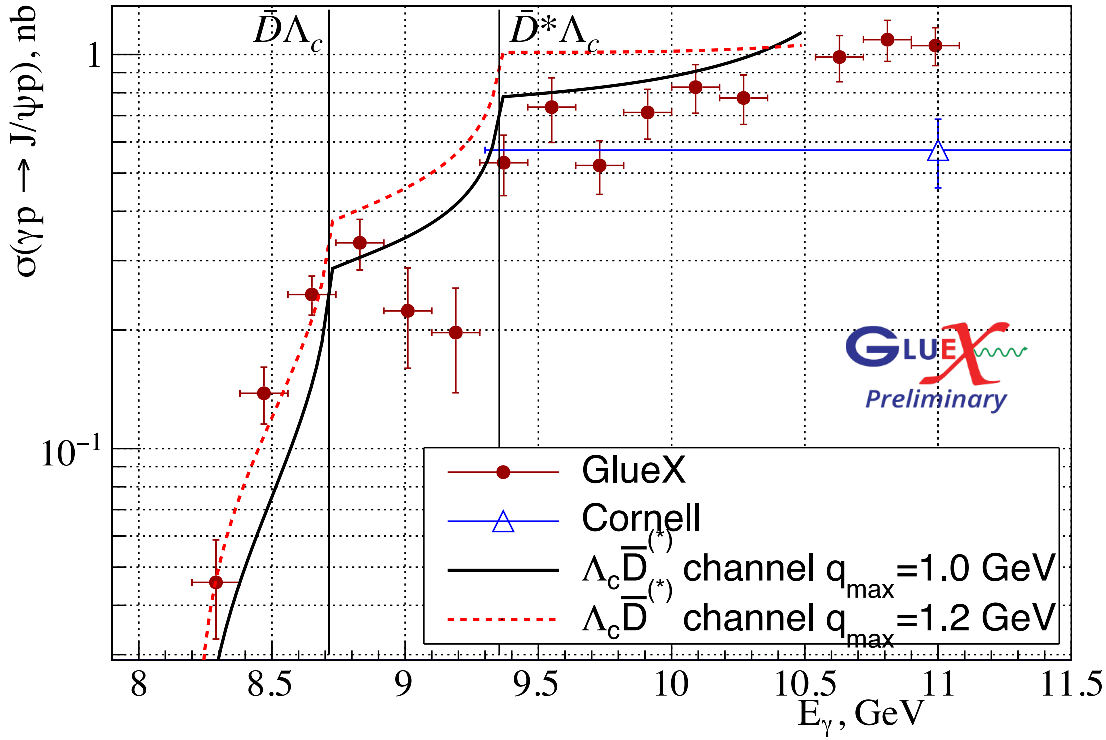
D.Kharzeev PRD104(2021)

3/ Relation to GFFs - QCD: *Guo, Ji, Liu PRD103 (2021)*; holographic: *Mamo, Zahed PRD104 (2021), Hatta, Rajan, Yang PRD100 (2019)*

$$r_s = 6\frac{dA(t)}{dt}\Big|_{t=0} - 18\frac{C(0)}{m_p^2} \qquad r_m = 6\frac{dA(t)}{dt}\Big|_{t=0} - 6\frac{C(0)}{m_p^2}$$

4/ Anomalous contribution to proton mass: M_a/M_N from $d\sigma/dt(0)$, e.g. following: *Wang, Chen, Evelin EPJ C80 (2020),* based on *Kharzeev Proc.ISPF (1996)*

Open-charm exchange



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

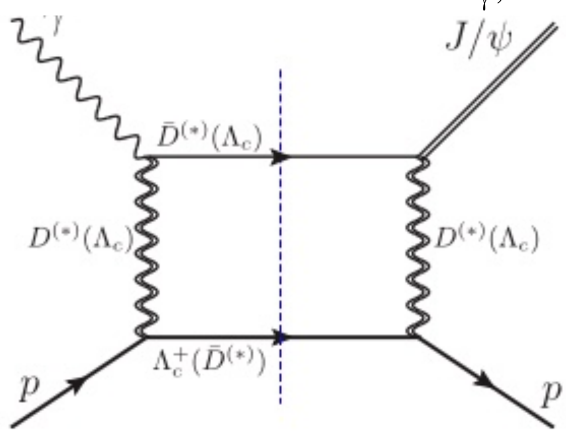


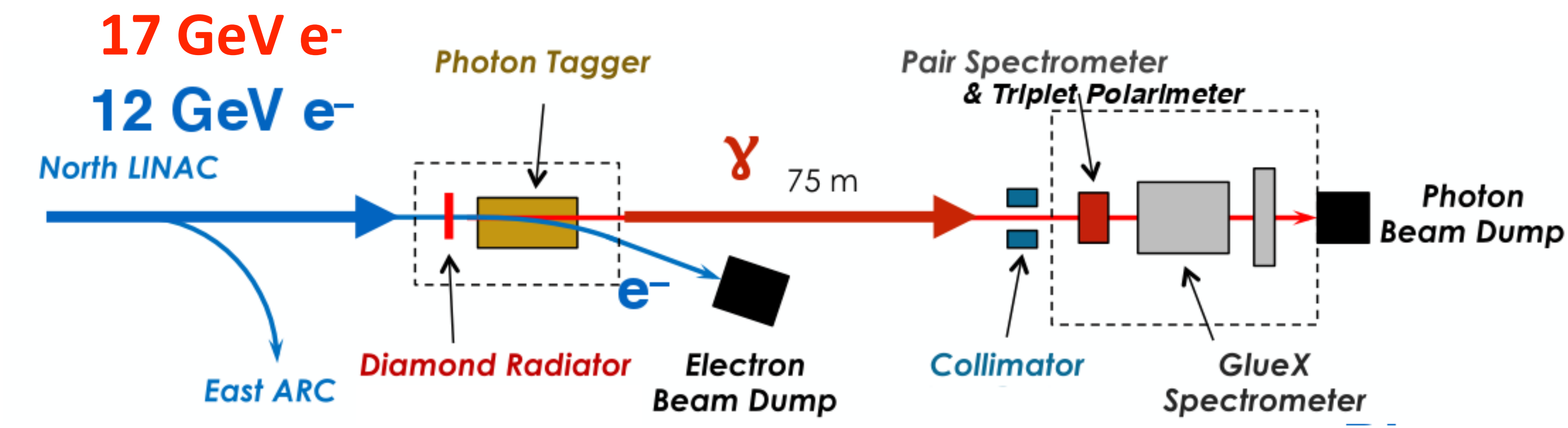
FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

Open-charm or gluon exchange?

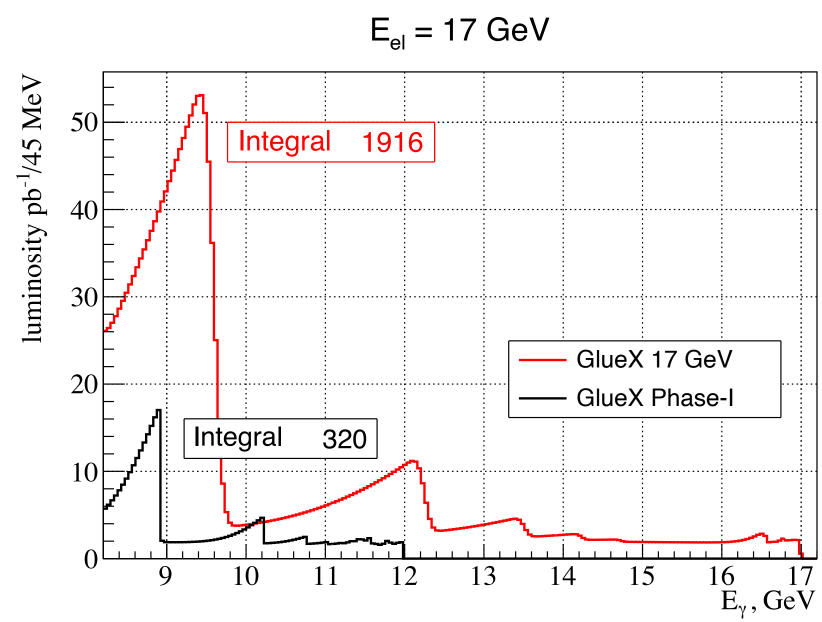
experimental observations	**open-charm exchange**	**2g exchange**	**3g exchange (C-parity violation?)**
possible structures in total cross section	cusp-like structures at $\bar{D}^{(*)}\Lambda_c$ thresholds ✓	no structures ✗	same ✗
$d\sigma/dt$ enhancement at high t	u-channel - charm baryon exchange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

Measurements to be performed

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



J/ψ studies with 17 GeV beam

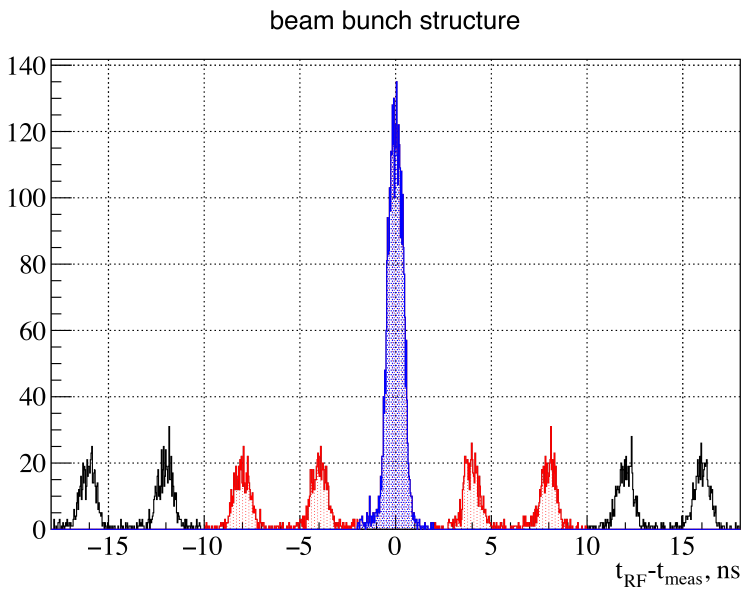
All projections based on scaling the GlueX Phase-I real data:

- 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

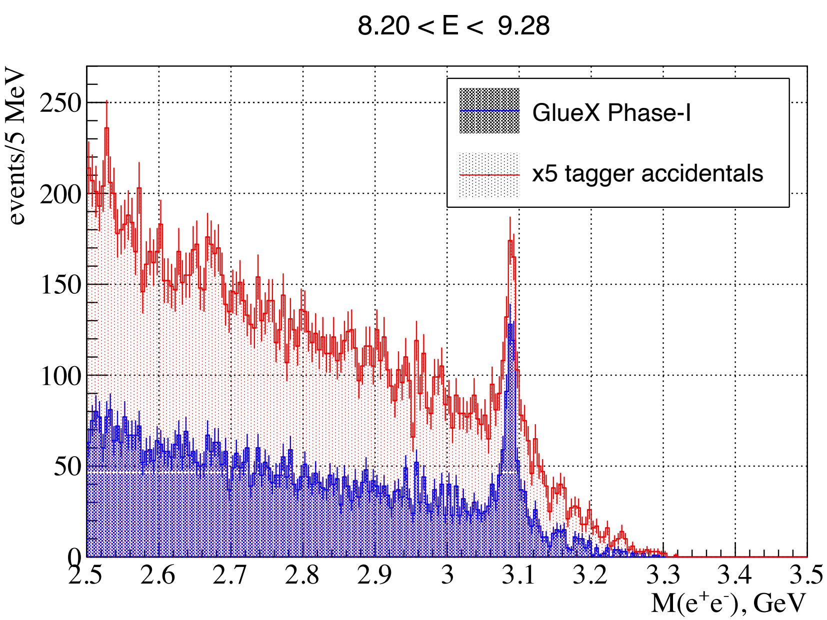
Coherent peak set at 9.7 GeV to cover the whole near threshold region of interest

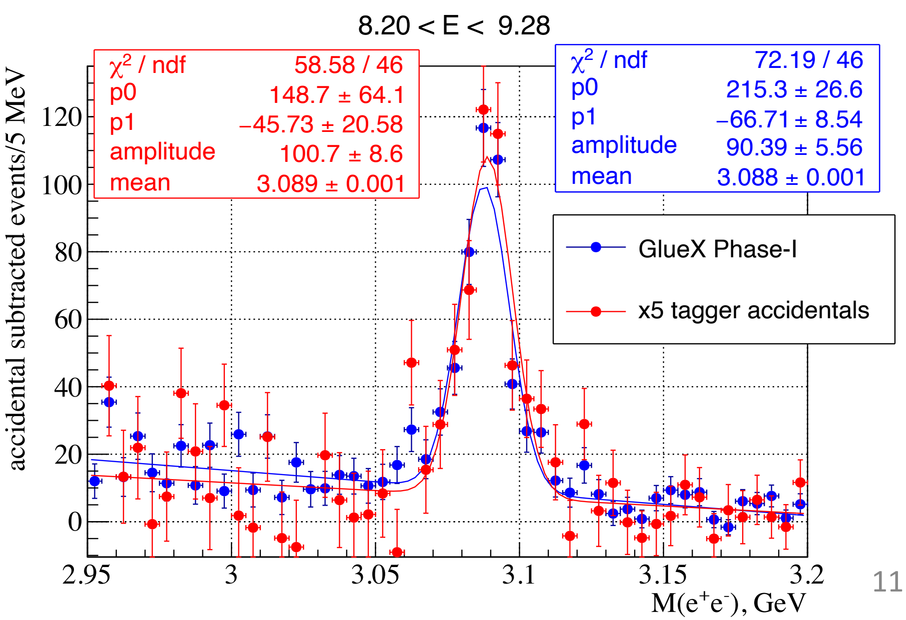
J/ψ with 17 GeV beam - tagger accidentals

Using real data → effect of increasing the tagger accidentals by factor of 5:

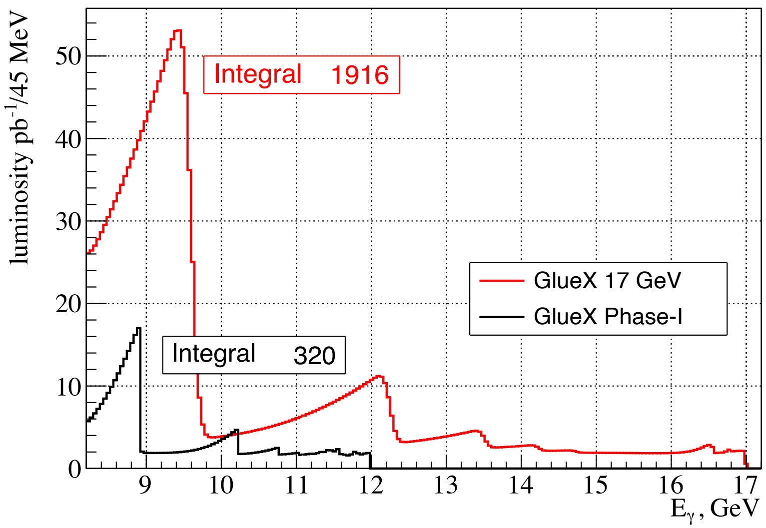


- To simulate higher accidental rates using real data, we add 4 out-of-time peaks to the prompt signal
- In any case the peaks that do not contribute to the signal are used to subtract the tagger accidental background
- Thanks to the narrow J/ψ peak, the effect of the accidental background is not significant:

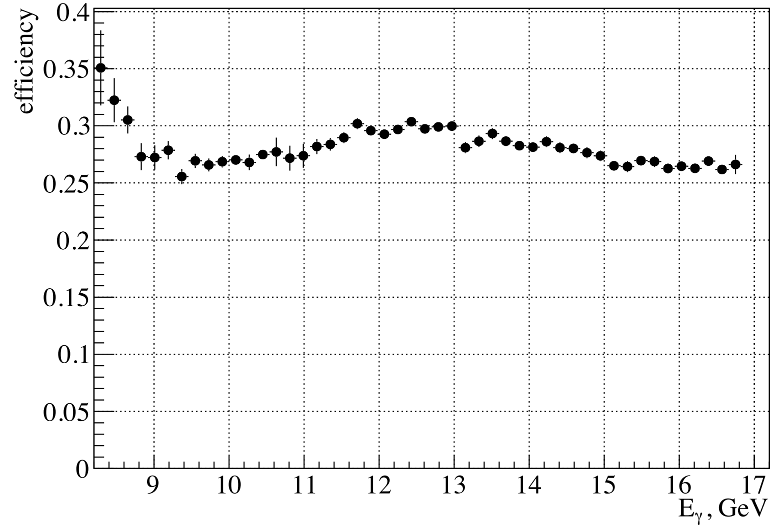




J/ψ at 17 GeV - cross sections and yields



X



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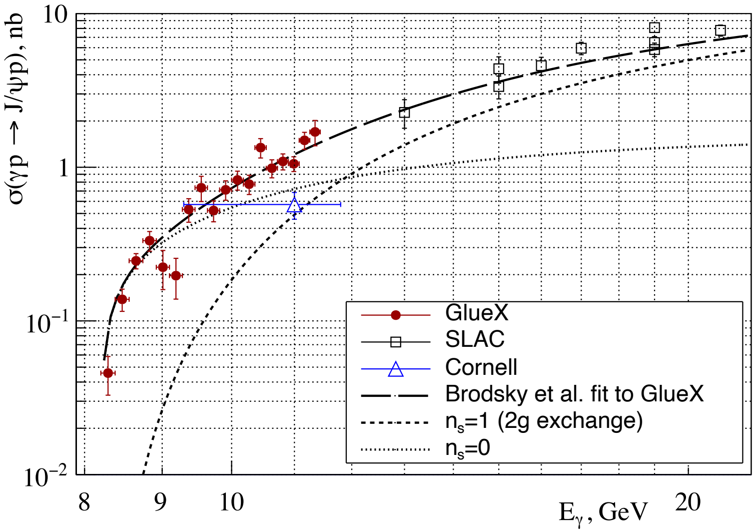
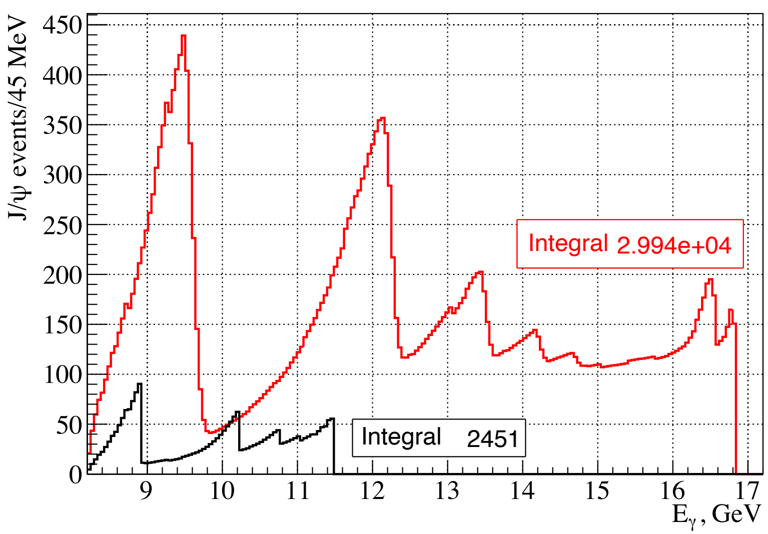
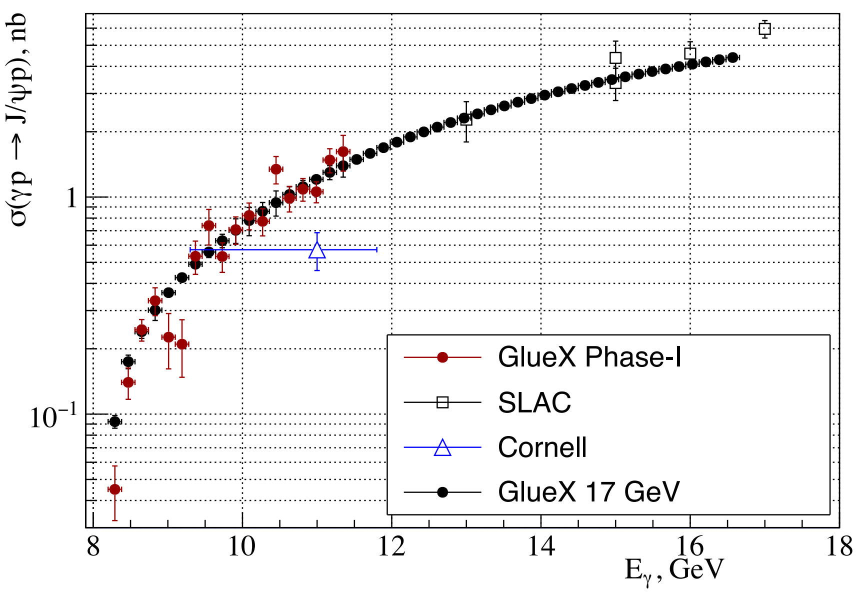
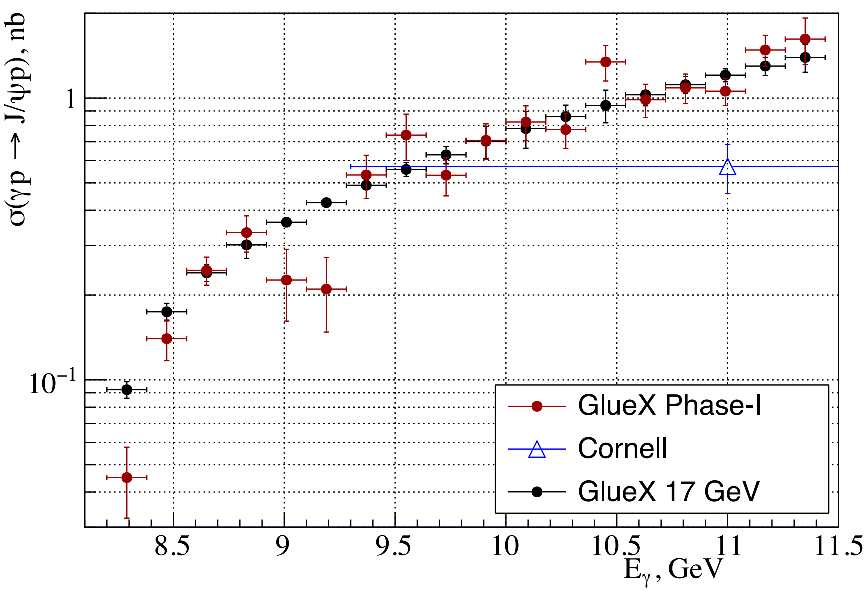


$$Y_{J/\psi}(E_\gamma) = L(E_\gamma)\sigma_{J/\psi}(E_\gamma)\varepsilon(E_\gamma)\mathscr{B}(J/\psi \to e^+e^-)$$

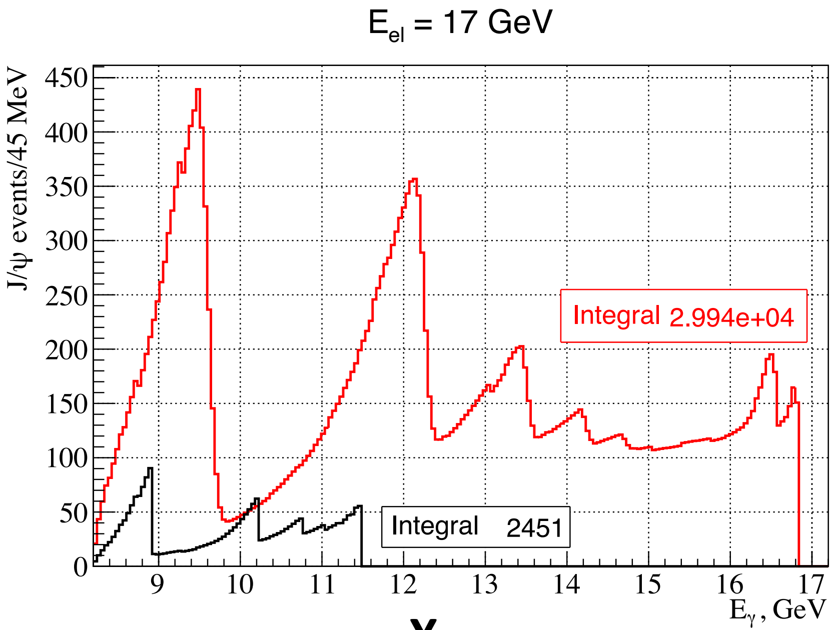


J/ψ at 17 GeV - cross section projections





J/ψ at 17 GeV - polarization measurements



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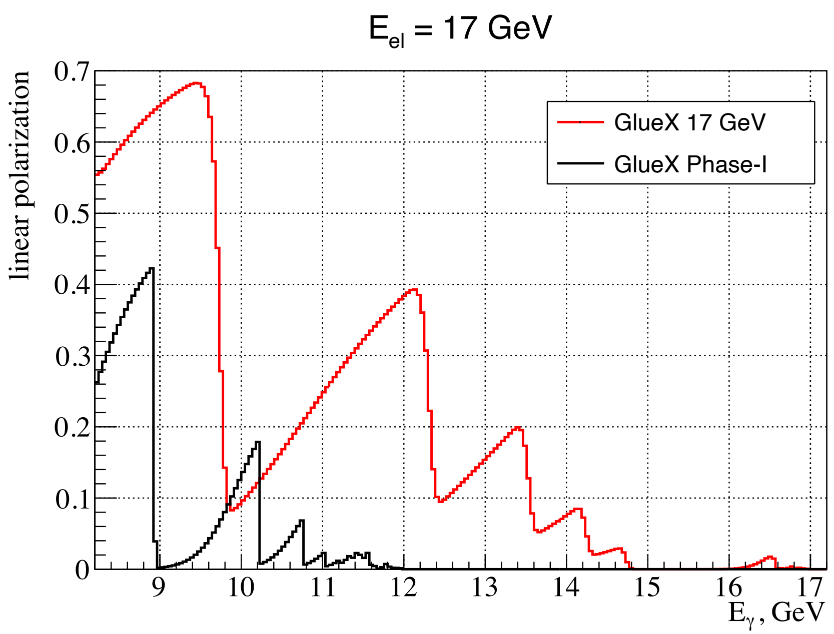

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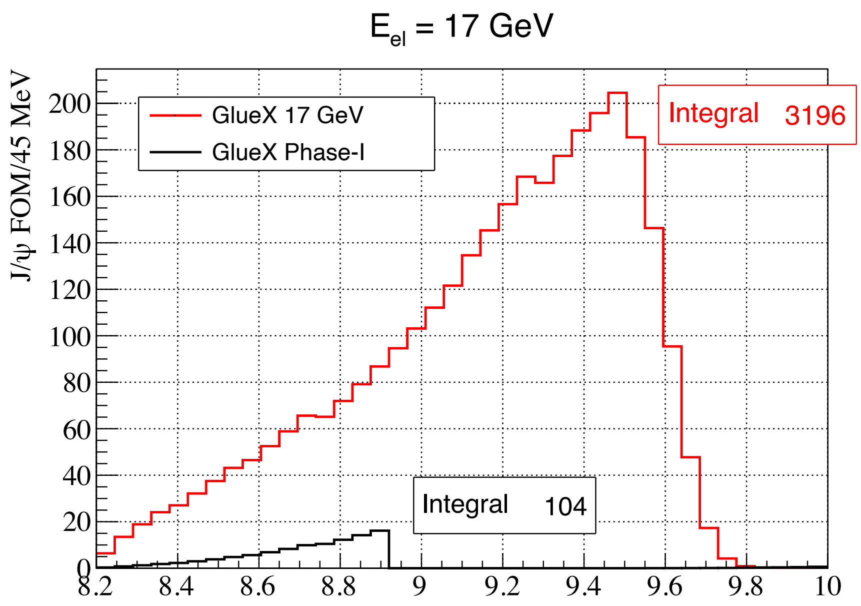
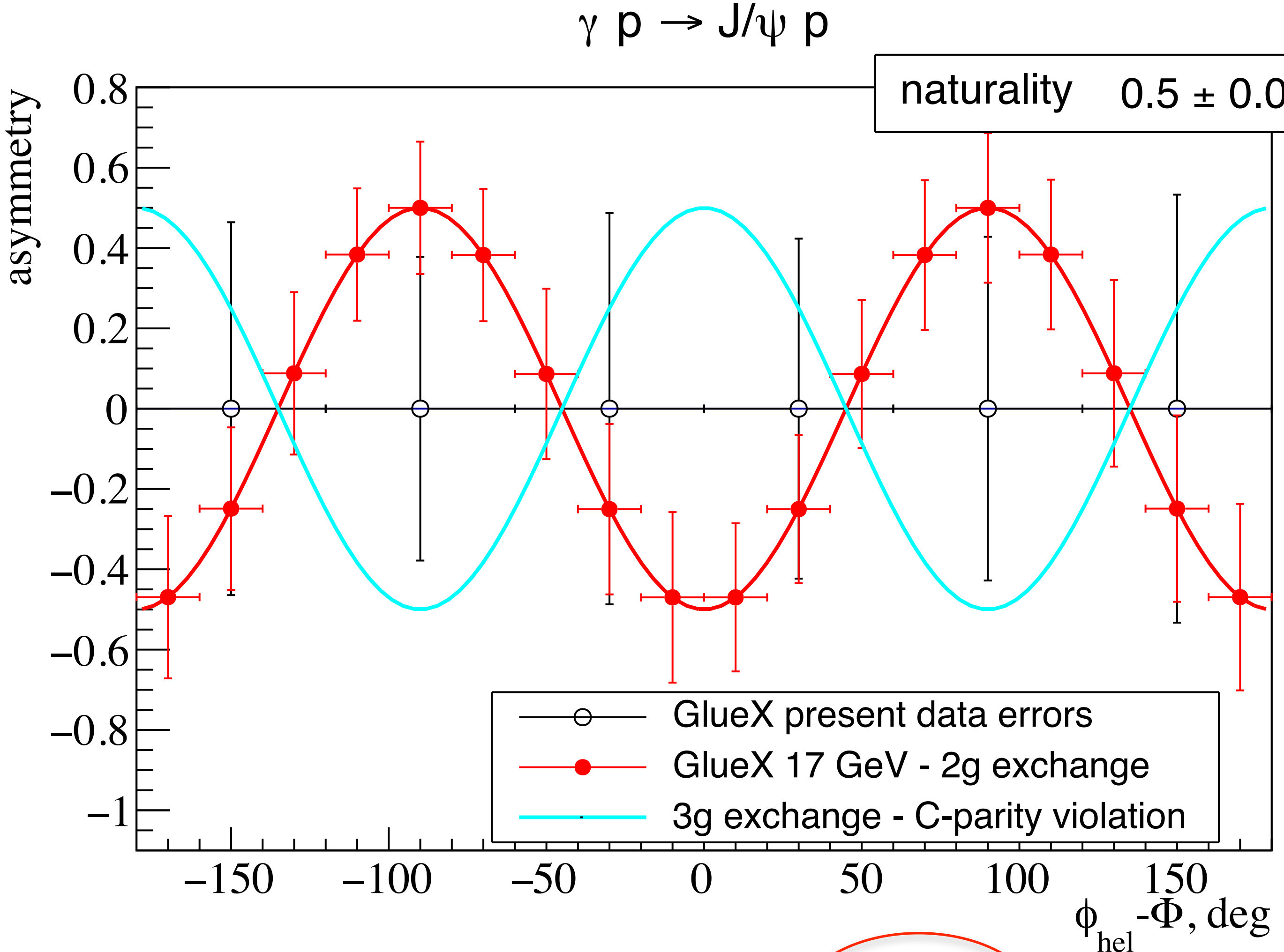


$$FOM(E_\gamma) = Y_{J/\psi}(E_\gamma) \cdot p_\gamma^2(E_\gamma)$$

J/ψ at 17 GeV - naturality



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

naturality

See Keigo Mizutani's slide: more polarization projections

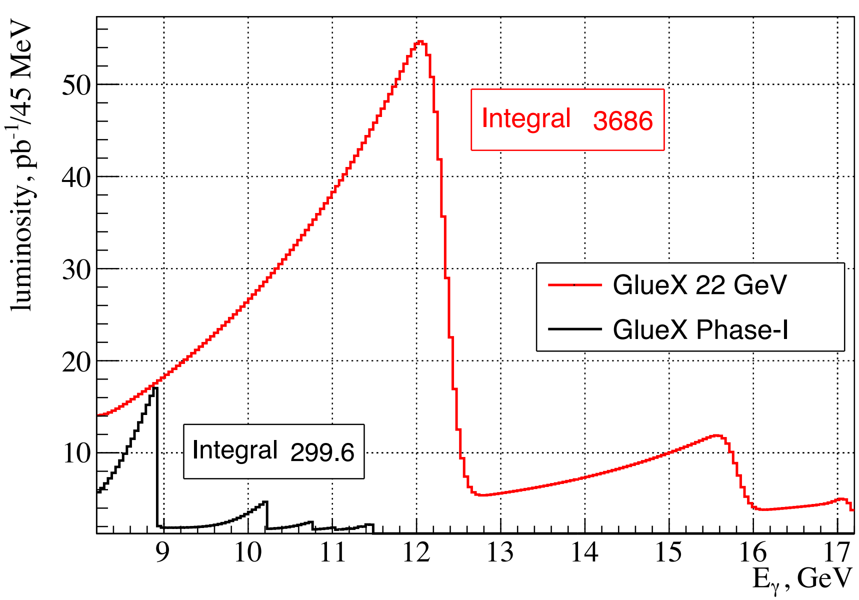
$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi')]\right)$$

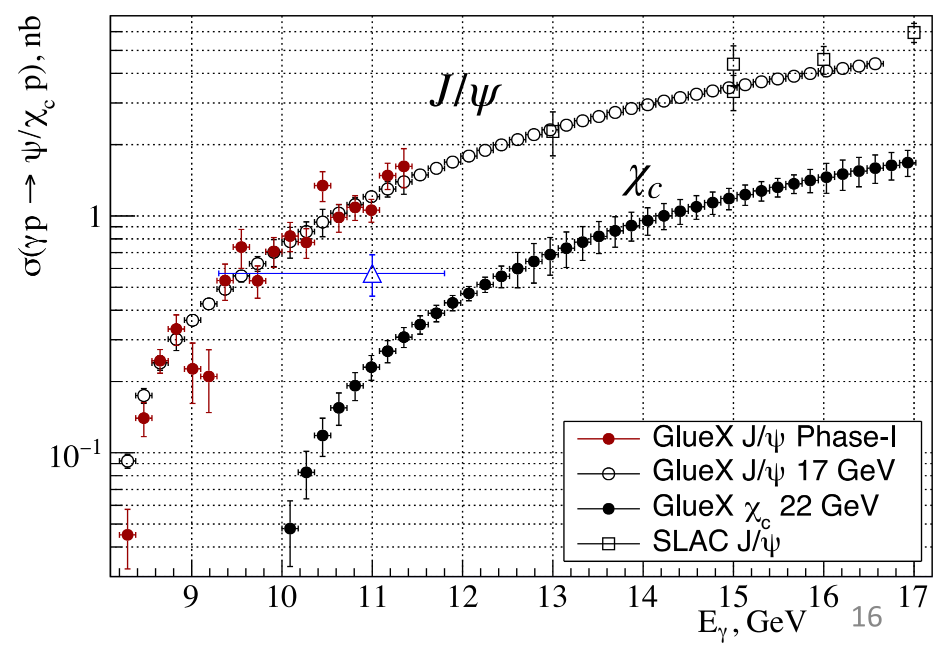
χ_c states with 22 GeV - cross section

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

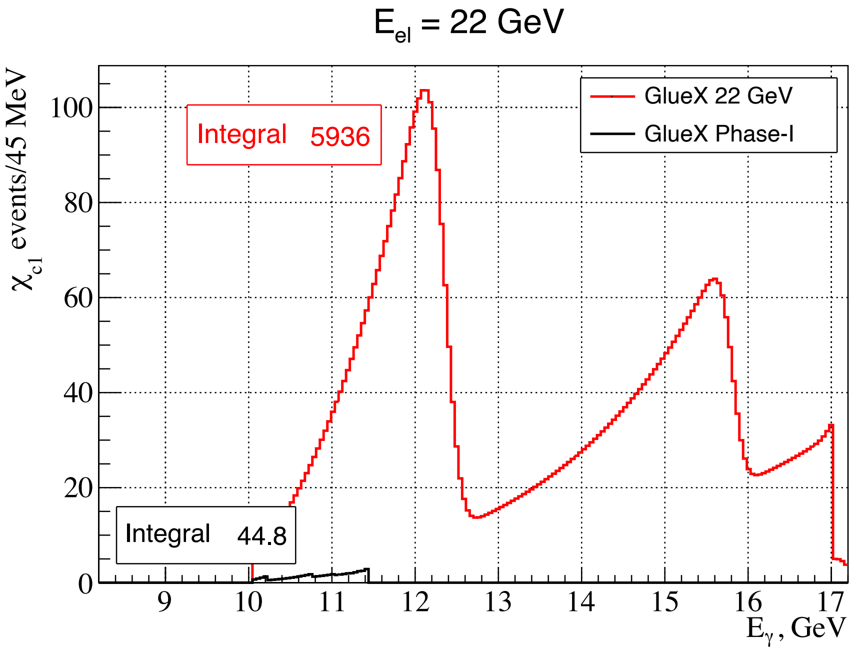
- GlueX has detected charmonium states decaying to $J/\psi\gamma$ in the 3.47-3.58 GeV mass region
- They are consistent with $\chi_{c1}(3511)$ or $\chi_{c2}(3556)$, but the statistics/resolution doesn't allow yet to clearly identify which of the two states (or both) has been detected
- They both are C-even charmonium states, recent interest related to search for odderon (e.g. *Yu Jia et.al arxiv:2207.14171 (2022)*)
- We have used the measured χ_c yields and MC simulations (efficiency ~10%) to scale the JPAC calculations for χ_{c1} photoproduction cross section and make projections for GlueX with 22 GeV beam:

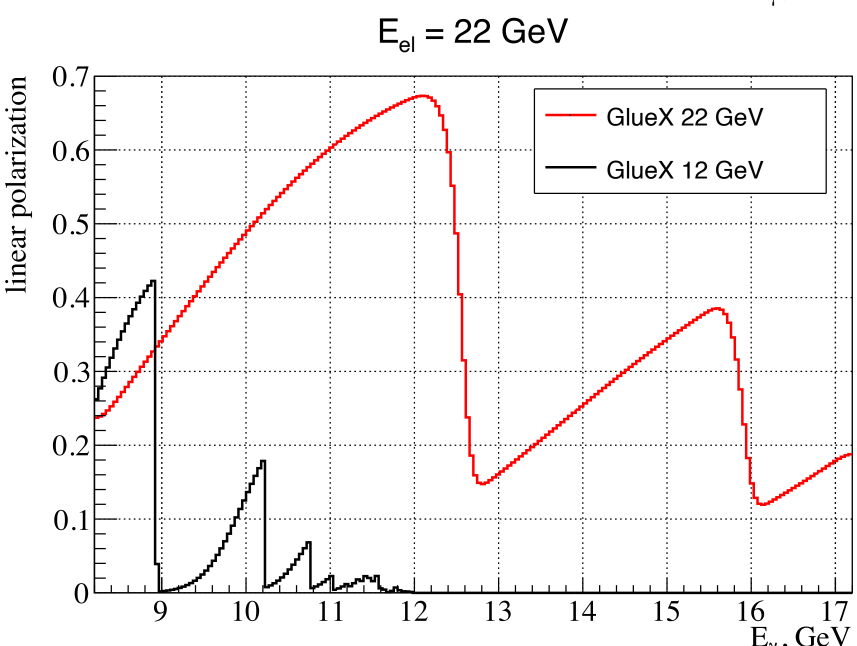
E_{el} = 22 GeV

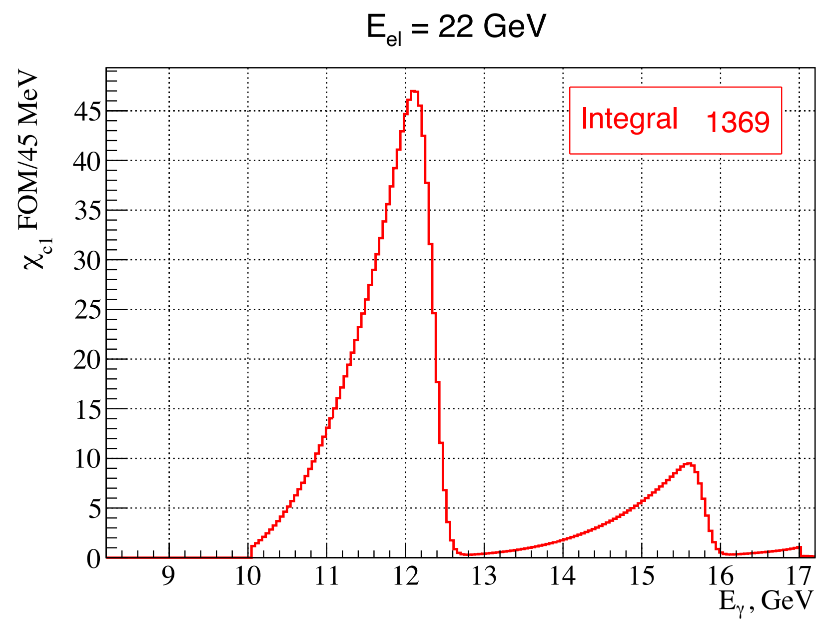




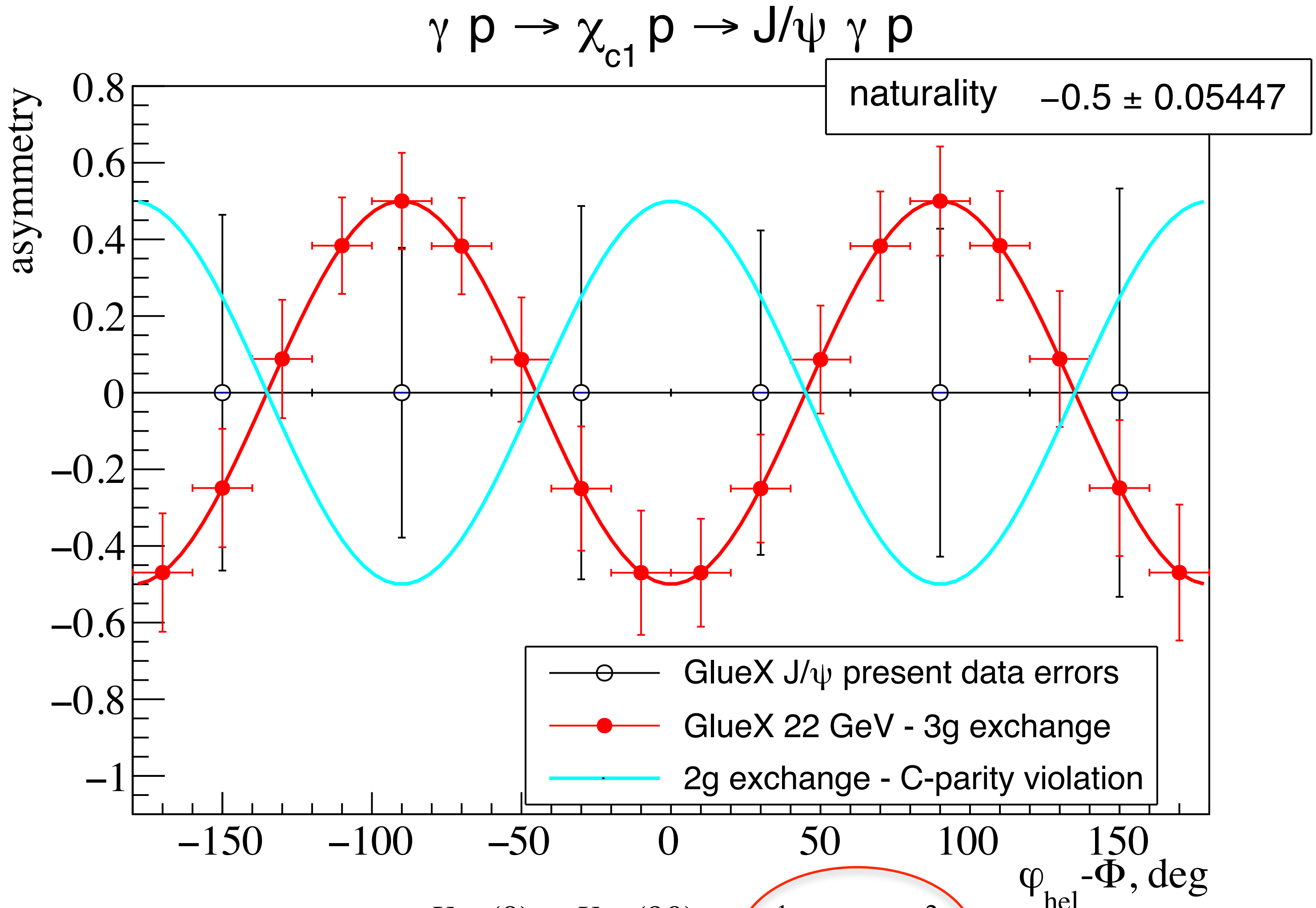
χ_{c1} with 22 GeV - polarization measurements







χ_{c1} with 22 GeV - naturality



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

naturality

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

...assuming equal helicity couplings

Conclusions

- Studies of the J/ψ near-threshold production - in its infancy
- Potential to access to very important physics - gluon properties of the proton - however

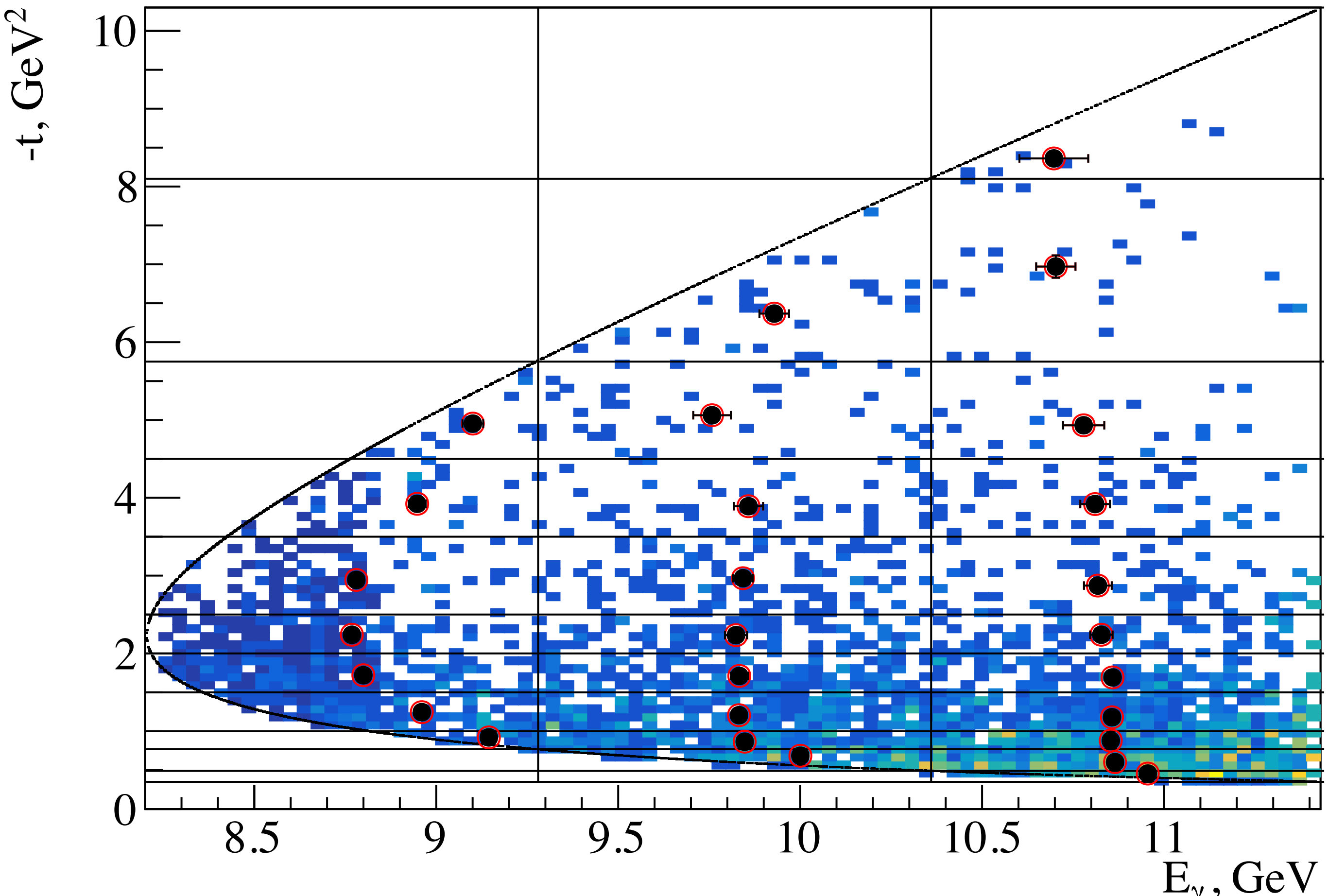
  … assuming VMD, QCD factorization

  … assuming relation of the measured cross sections and the gluon FFs

  … assuming gluon exchange over open-charm exchange mechanism?
- Future cross section measurements at 12 GeV JLab will certainly help to better understand the reaction mechanism
- However, the 17+ GeV energy upgrade will give unique opportunities for GlueX (in addition to cross sections) to measure polarization observables that are critical in separating different contributions to the J/ψ production
- The energy upgrade allows to study C-even charmonium states and search for odderon, including looking at polarization quantities with GlueX
- Important input from theorists is expected
- Note: all projected results in the near threshold region are based on scaling real data results

Back-ups

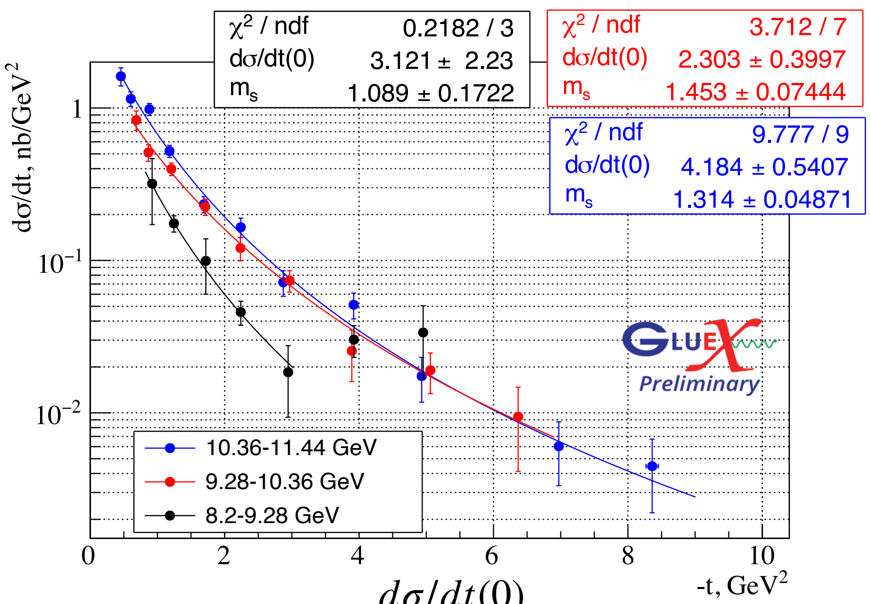
Differential cross-sections



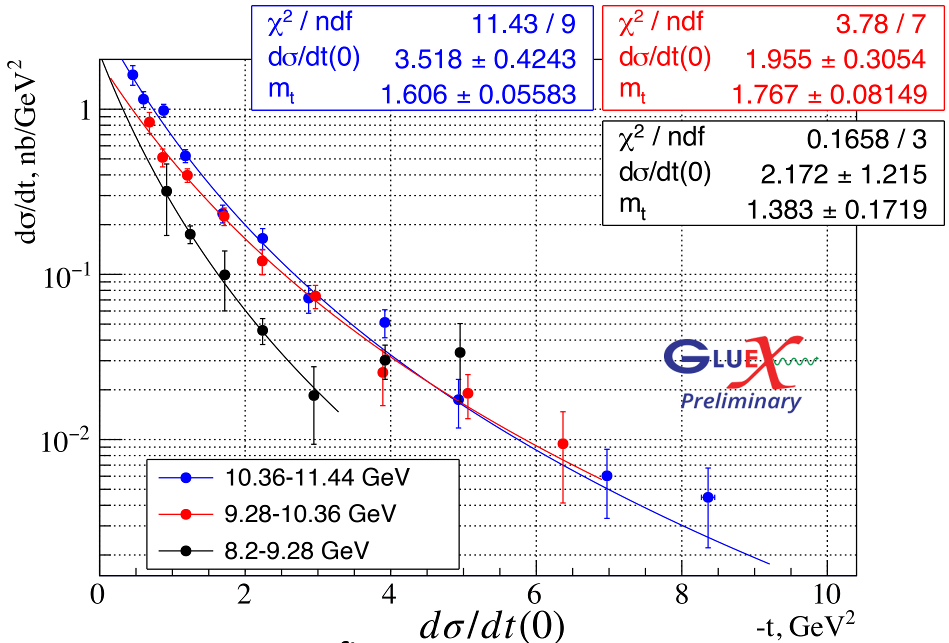
$$\frac{d\sigma}{dt}(E,t) = \frac{N_{J/\psi}}{L(E_\gamma)[nb^{-1}]/0.045GeV} \frac{1}{area(E,t)[GeV \cdot GeV^2]} \frac{1}{\varepsilon(E,t)}$$

- 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



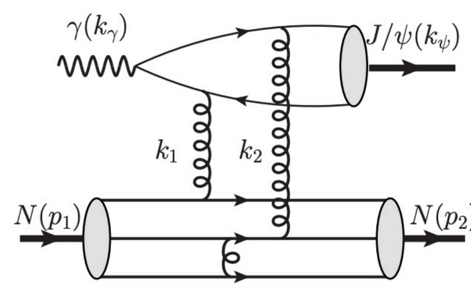
fit: $\dfrac{d\sigma/dt(0)}{(1 - t/m_s^2)^4}$



fit: $\dfrac{d\sigma/dt(0)}{(1 - t/m_t^2)^5}$

Sun, Tong, Yuan PRD105 (2022)

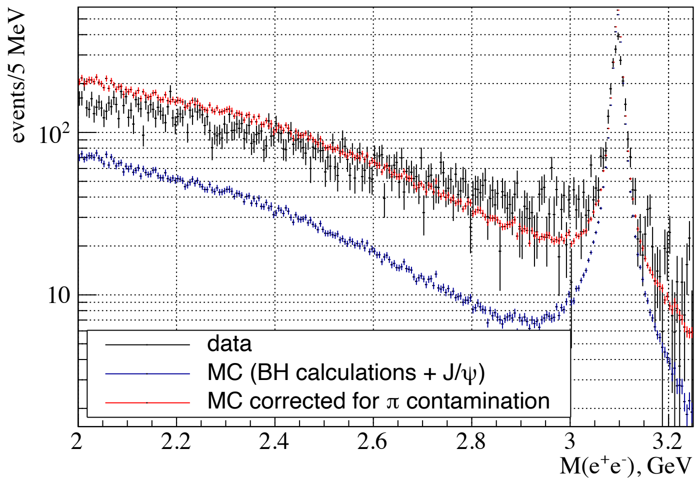
Asymptotic t-dependance $1/t^5$ $(vs\ 1/t^4)$ due to helicity flip

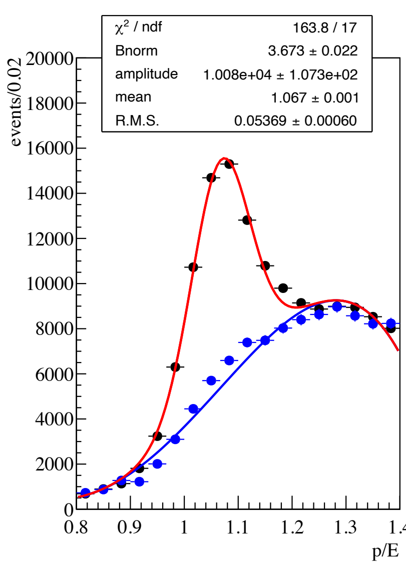


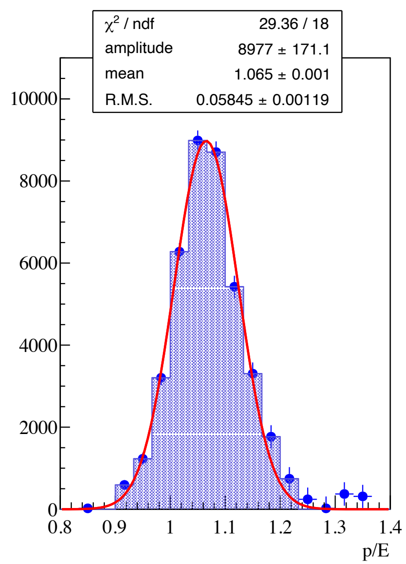
Not enough statistics to test the t-asymptotic

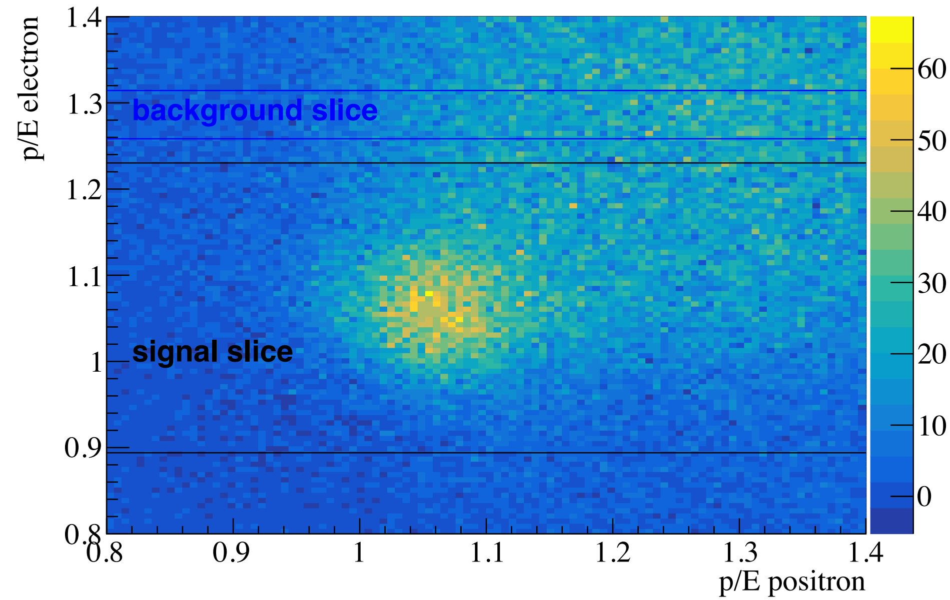
However we can detect proton spin flip, using double polarization measurements?

e/π separation



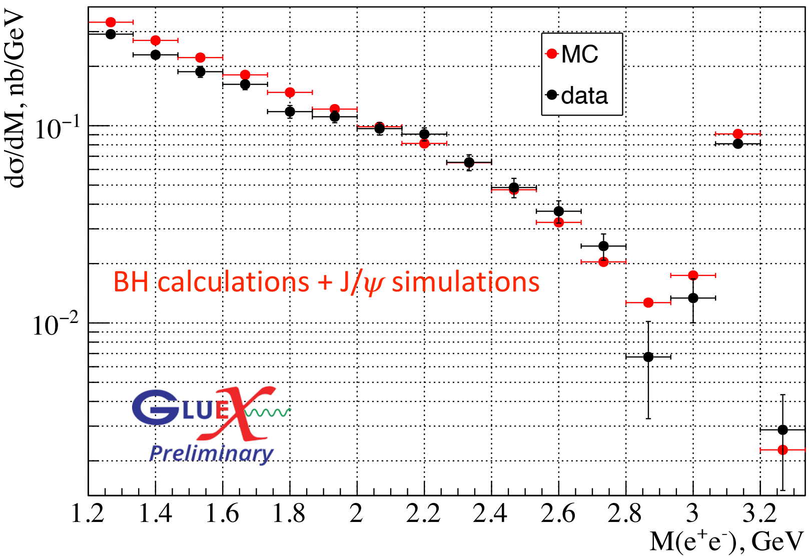


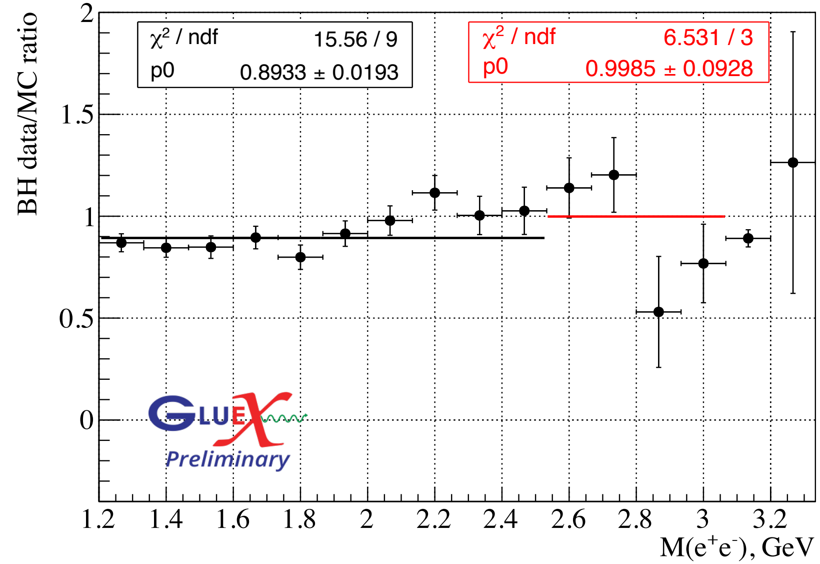


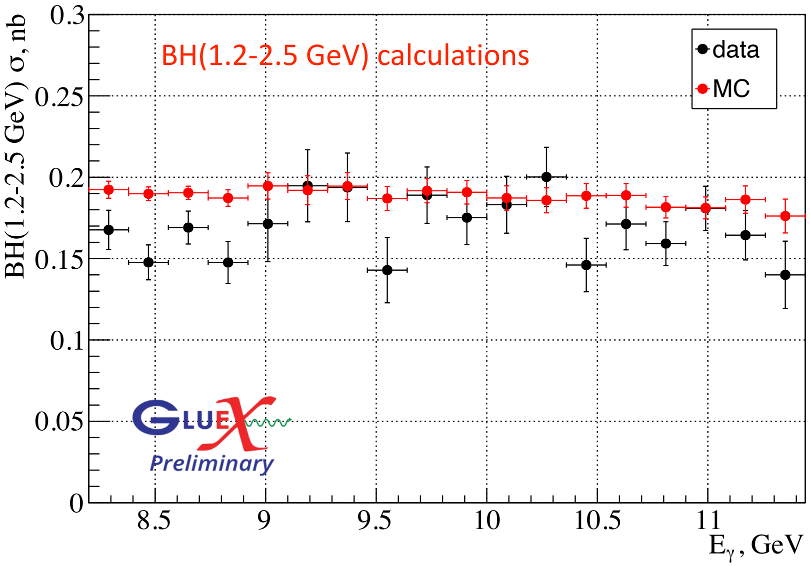


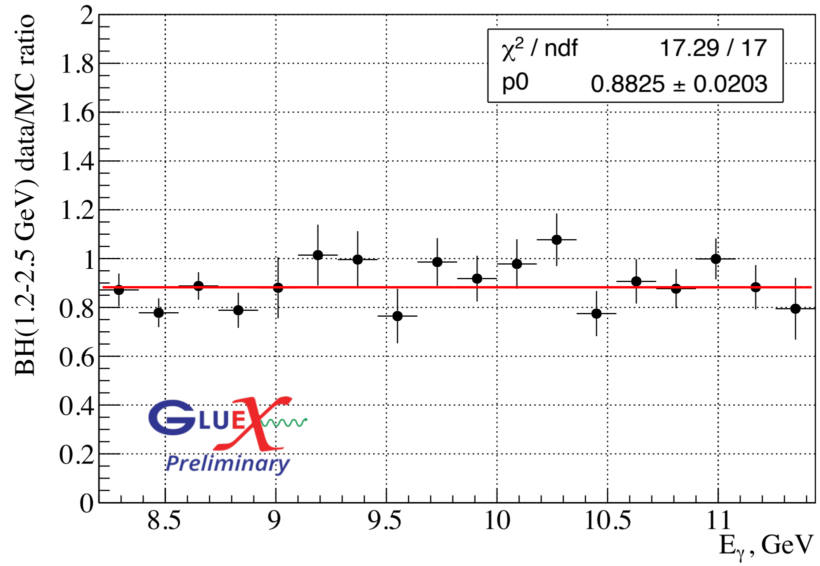
- Pion contamination ~50% in the continuum (using p/E fits to estimate it)

BH e.m. calculations vs data



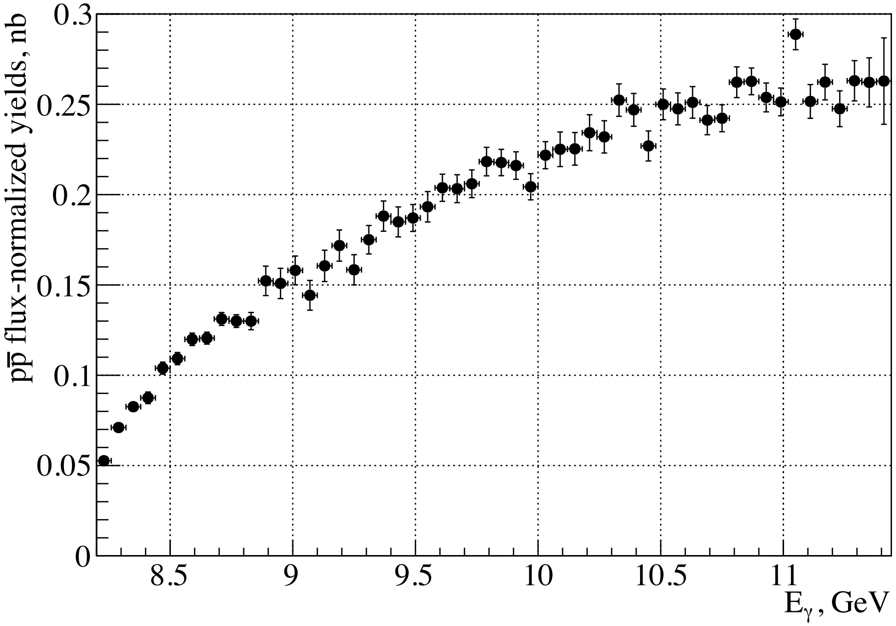


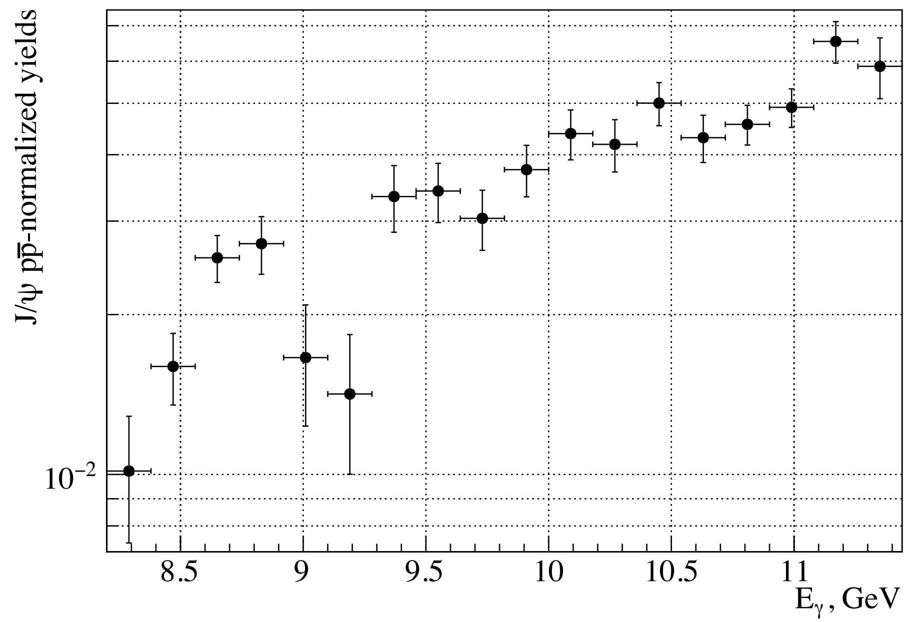




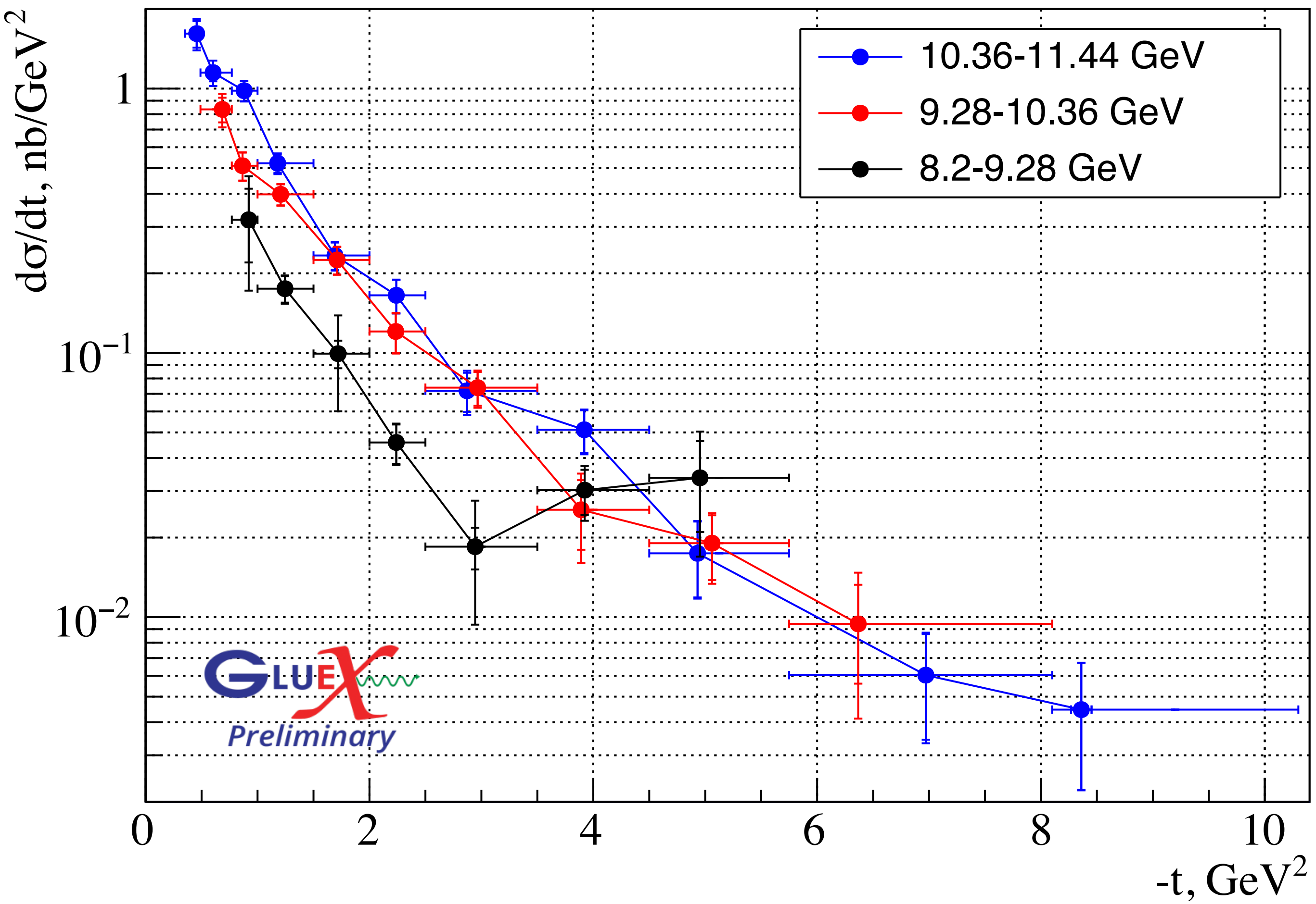
BH yields extracted from fits of E/p distributions

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





Preliminary results: differential cross-sections



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

- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors using data-driven model