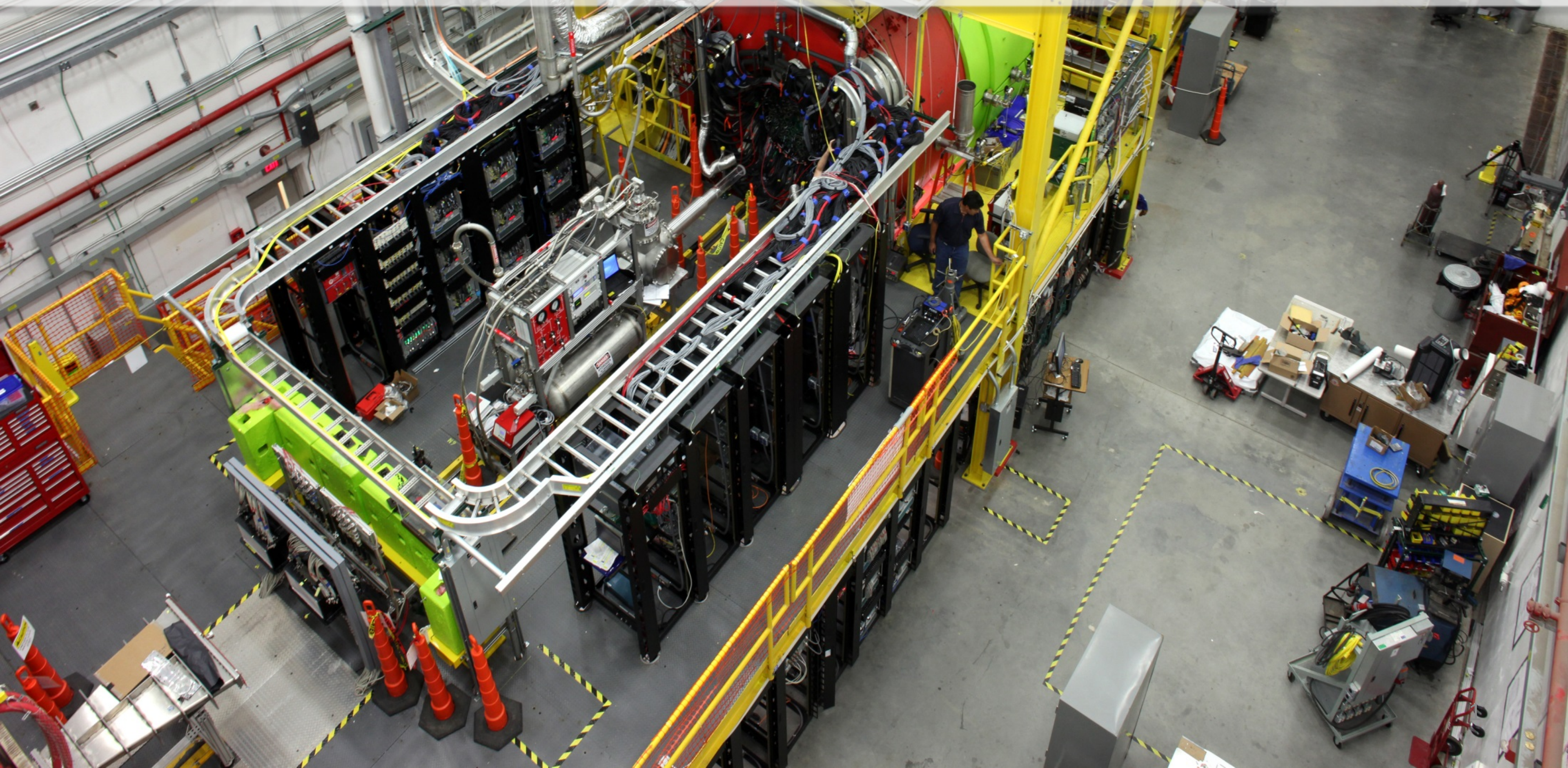
New physics opportunities with conventional charmonium production at 22 GeV

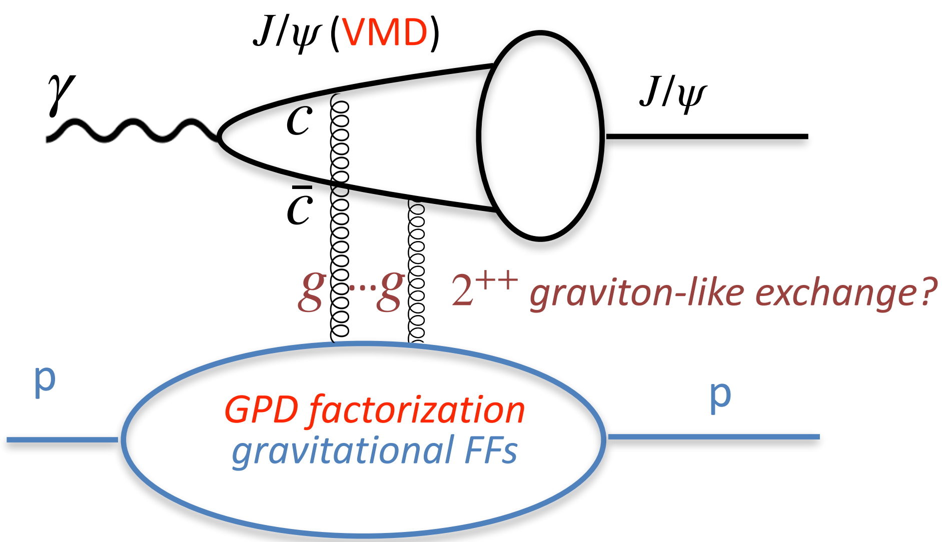
- Defining the problem: The physics case for the exclusive threshold charmonium production and what are the experimental/theoretical challenges to be solved?
- Solution: How CEBAF energy upgrade is critical in solving these problems using existing GlueX detector?

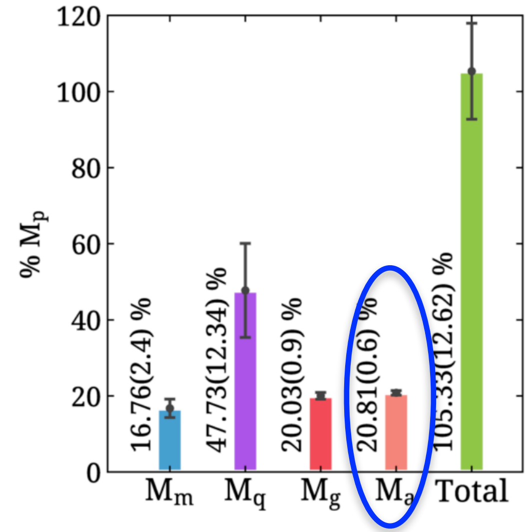
Lubomir Pentchev
(GlueX Collaboration)

Will try to make realistic projections based on existing measurements



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





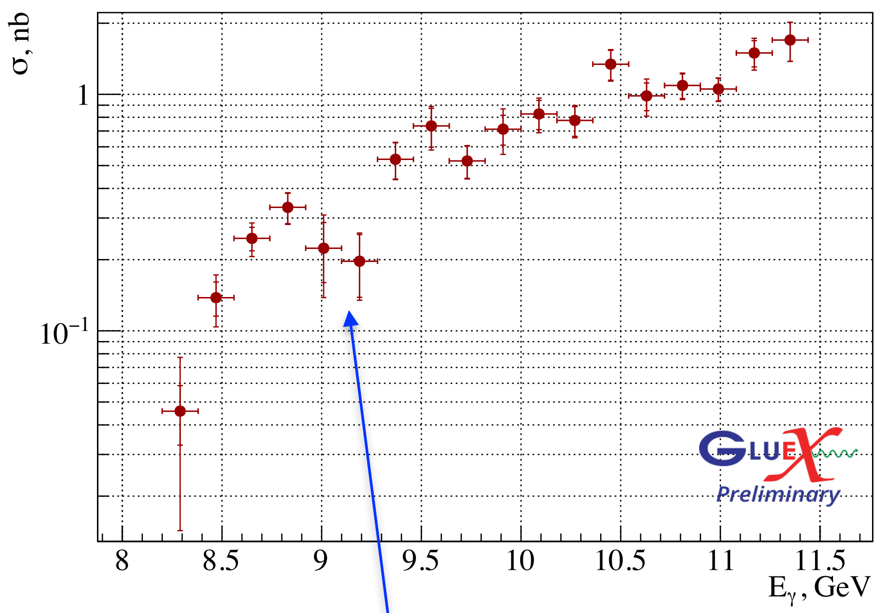
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

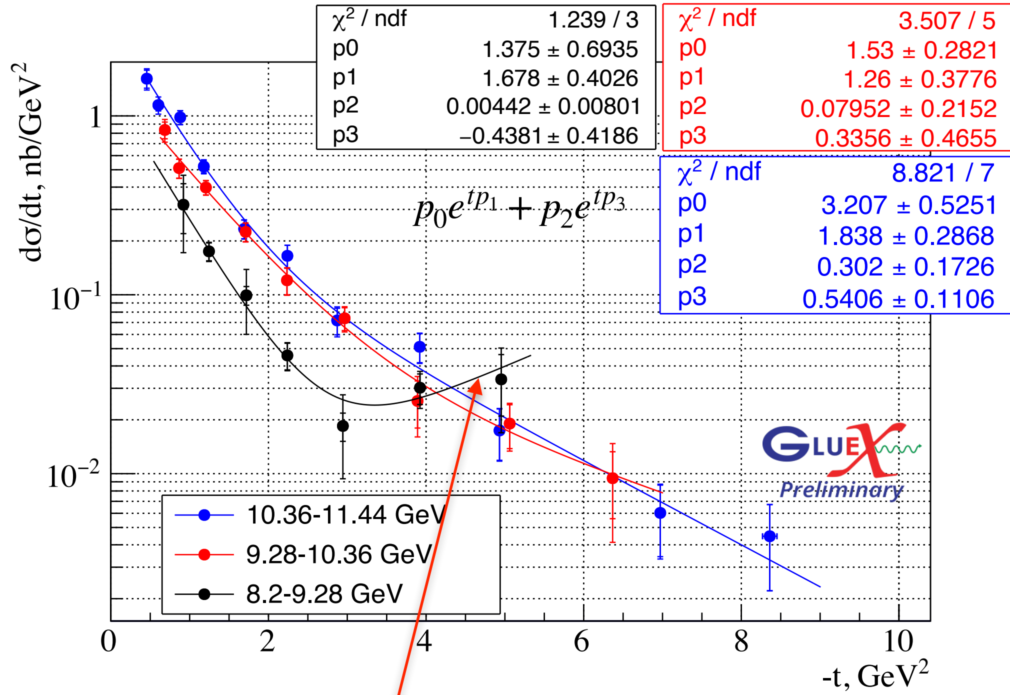
- VMD reduces $\gamma p \to J/\psi p$ to $J/\psi p \to J/\psi p$
- If $m_c \to \infty$ interaction via gluon exchange, at threshold sensitive to trace of EMT (*Kharzeev, Satz, Syamtomov, Zinovjev 1996-1999*) and its contribution to proton mass (*Ji 1995*)
- GPD factorization valid for $m_c \to \infty$ at threshold (*Gun, Ji, Liu 2021*)
- t-dependance of the amplitudes related to gluon gravitational form factors, $A_g(t), B_g(t), C_g(t), \bar{C}_g(t)$
  $\to$ mass radius of the proton, D-term (*Hatta, Kharzeev, Ji et al. 2018-2021*)

Will demonstrate the challenges to justify these assumptions using latest JLab results (from GlueX and Hall C) and what important measurements can be done with the CEBAF energy upgrade in solving the problems.

Preliminary GlueX results: total and differential cross-sections

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





- σ_{tot} increasing with energy approximately following the phase space,

however:

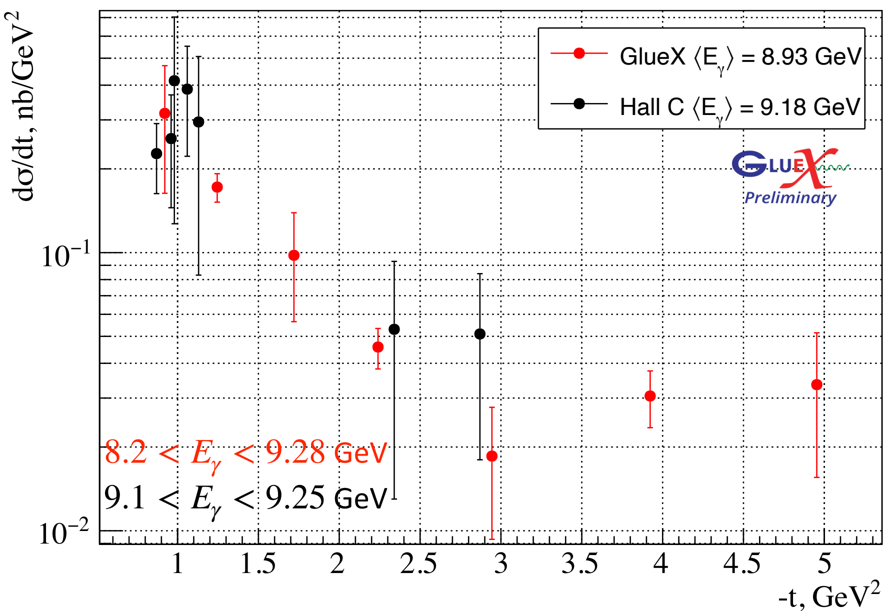
- Possible structure in $\sigma(8.6 - 9.6 GeV)$, the statistical significance of the two "dip" points is 2.6σ; if include look-elsewhere effect - 1.3σ

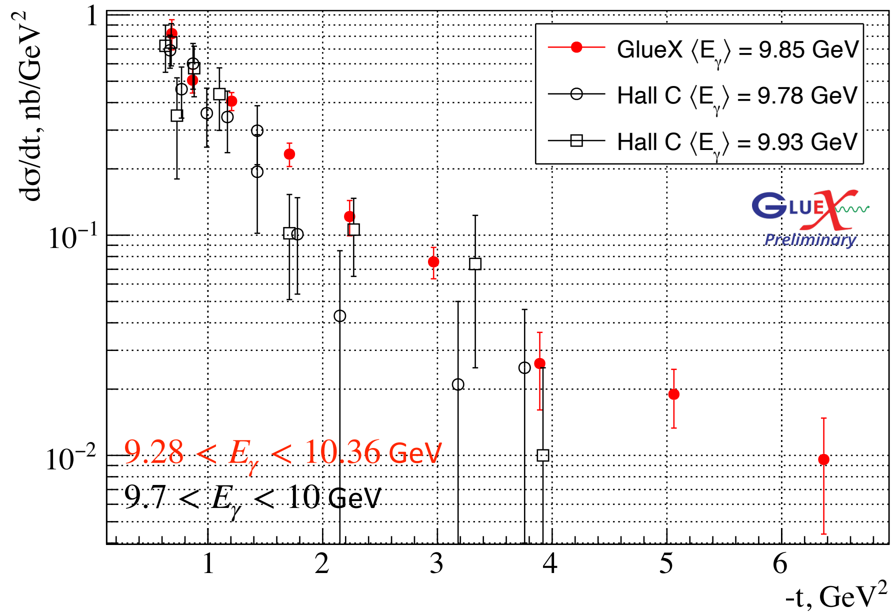
- t-slopes close to lattice predictions for the $A_g(t)$ gravitational form factor,

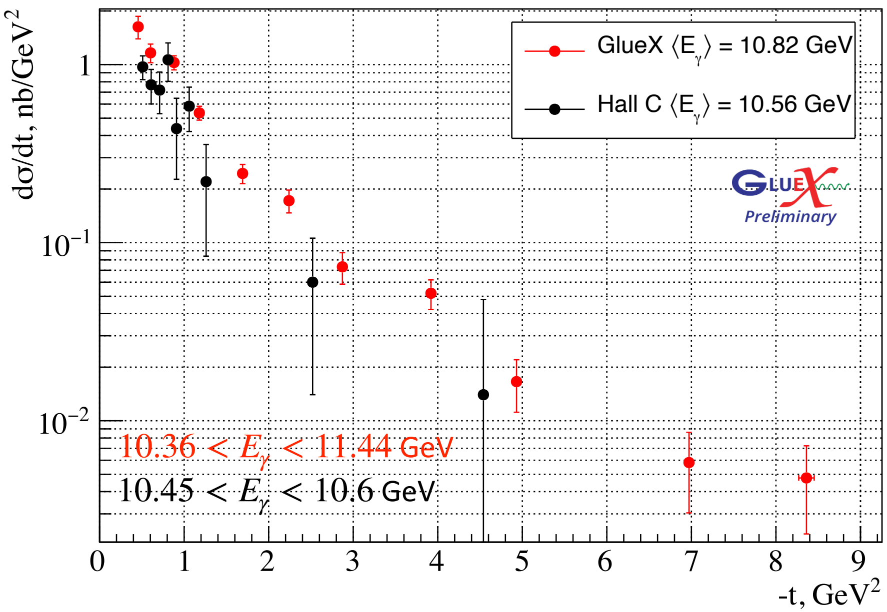
however:

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

Preliminary GlueX results: comparison to Hall C (J/ψ-007)



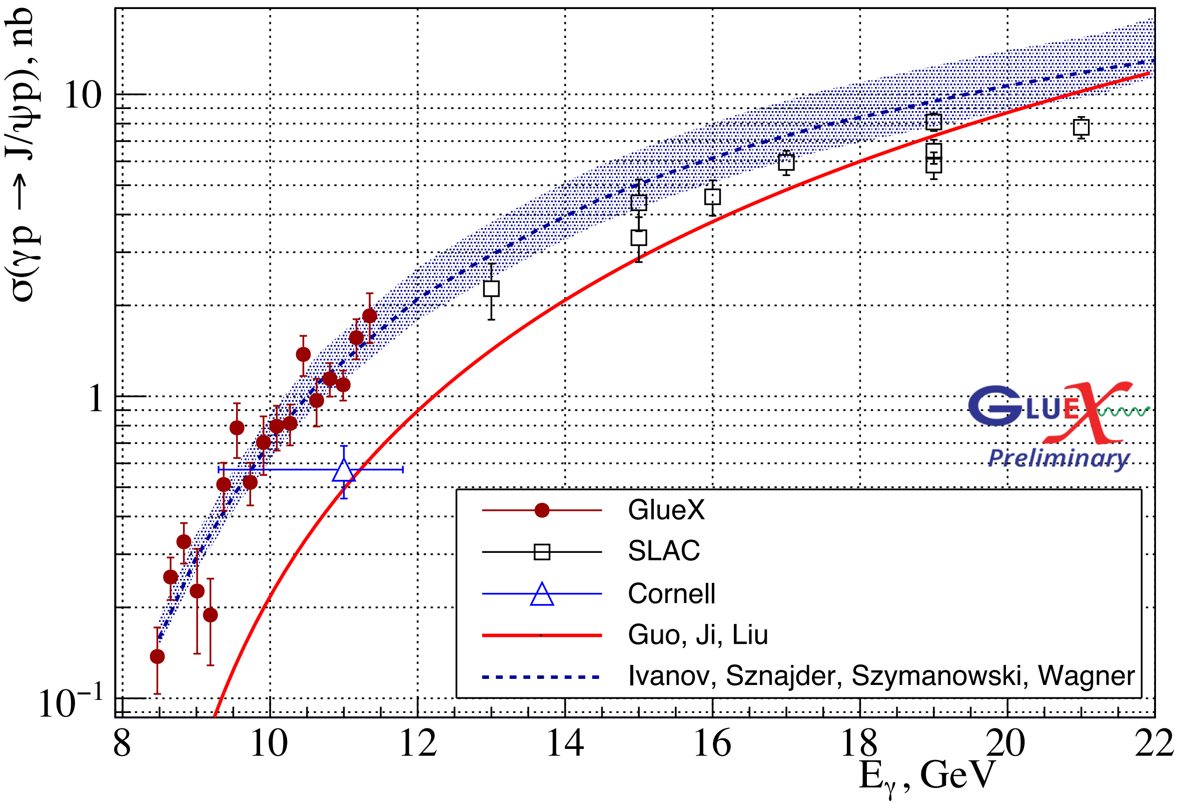




- Three GlueX energies compared to closest Hall C (J/ψ-007) energies
- Shown only 4 out 10 energies for Hall C - common fit of all 10 used to disentangle contributions from $A_g(t)$ and $C_g(t)$ (B.Duran https://arxiv.org/abs/2207.05212)

- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies

QCD factorization models



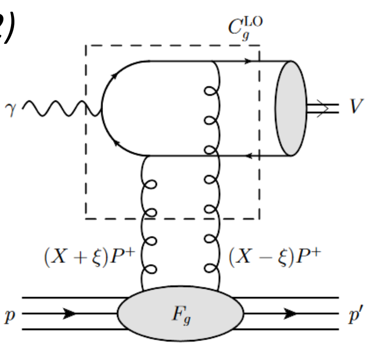
Ivanov, Sznajder, Szymanowski, Wagner (2022)

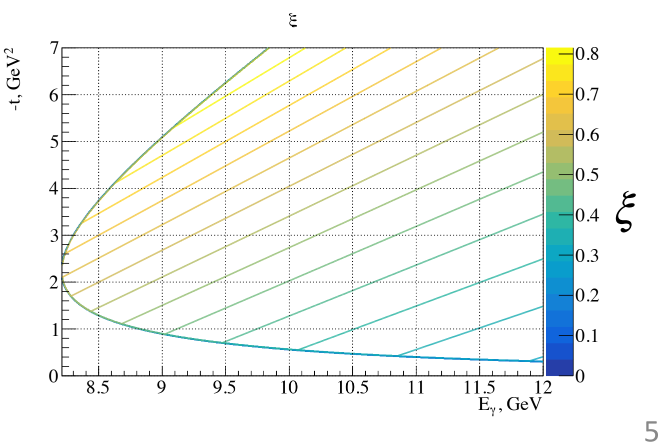
- GPD LO calculations

Guo, Ji, Liu PRD103 (2021),

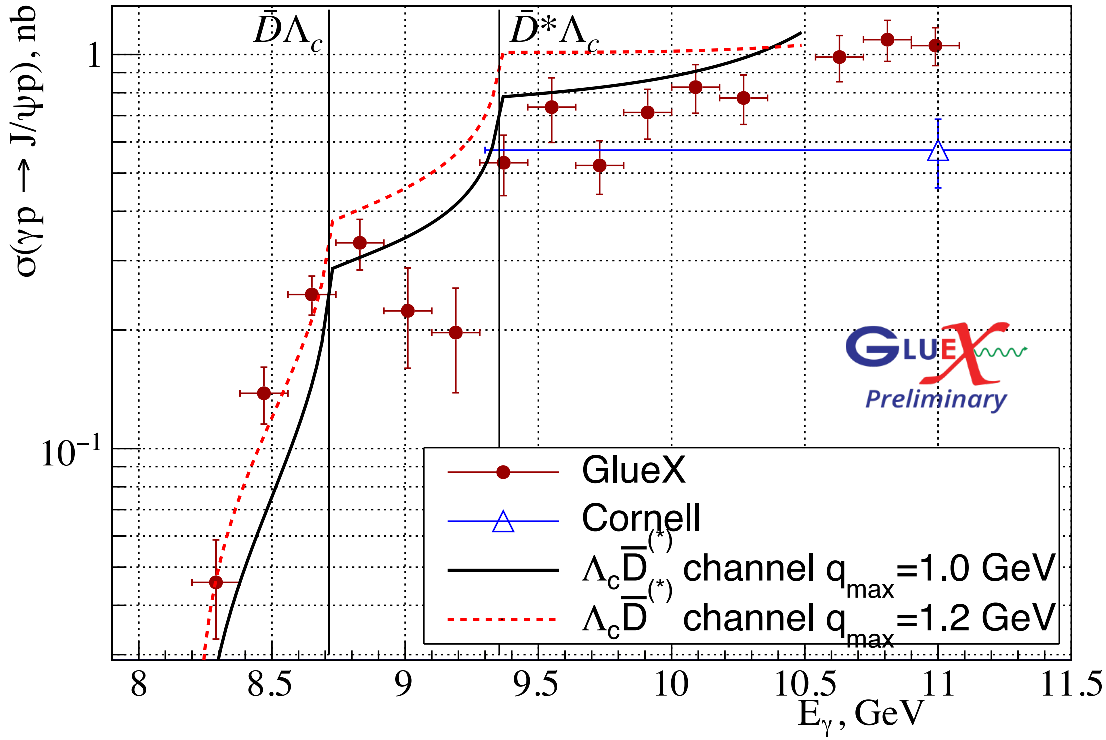
in $m_c \to \infty$ limit, $\xi \to 1$ expansion:

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





Open-charm exchange



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

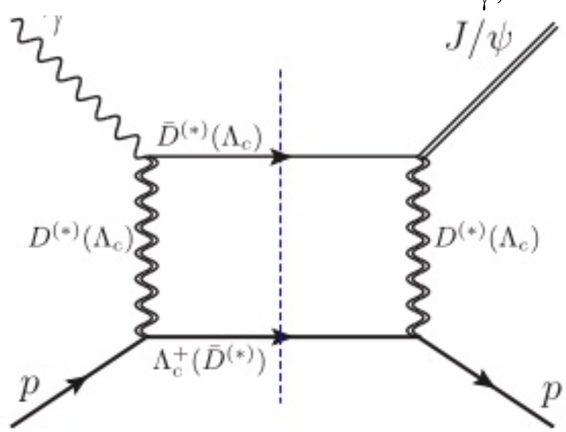
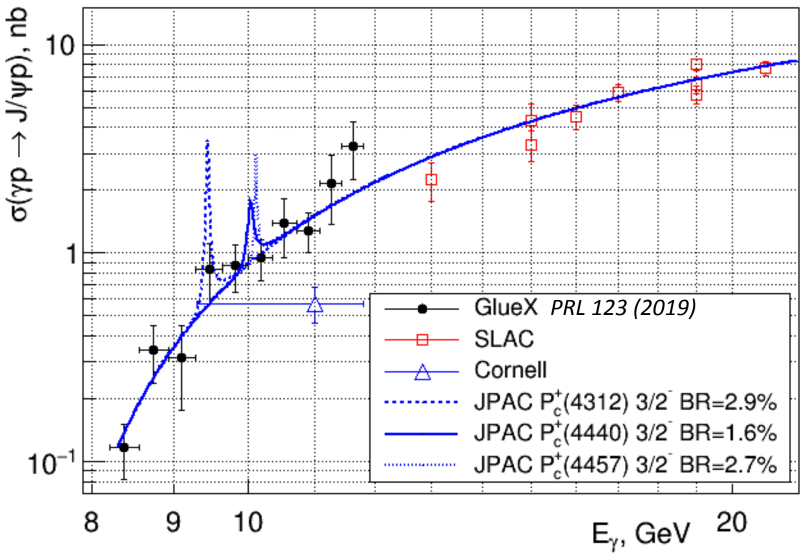
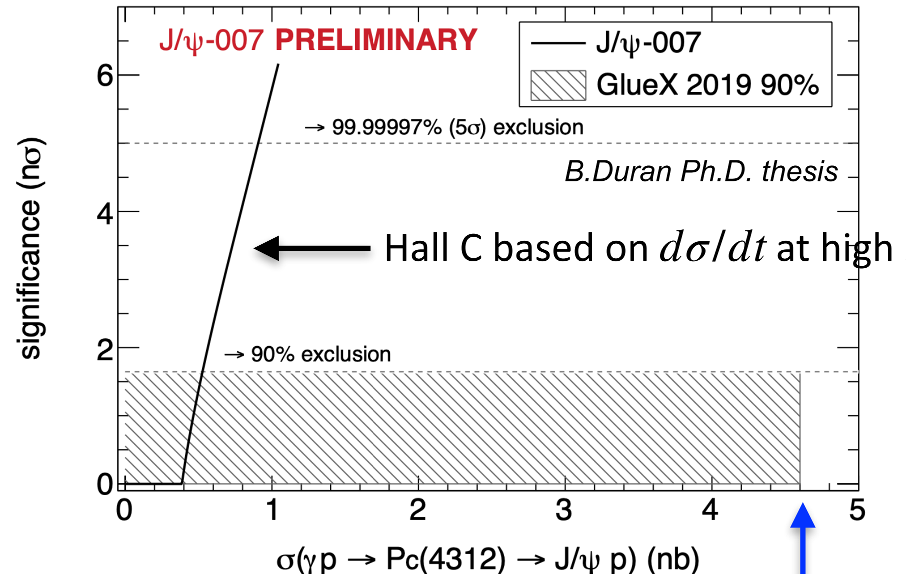


FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

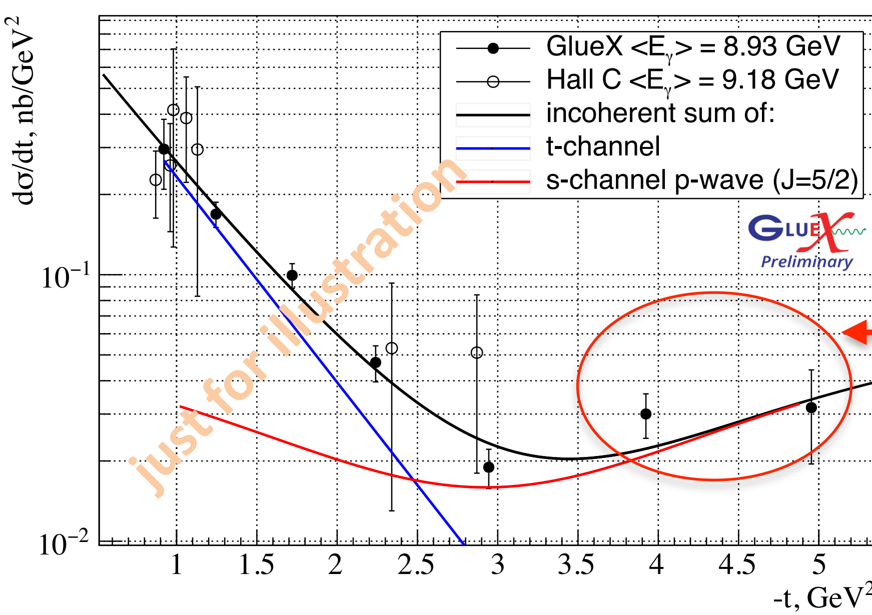
LHCb pentaquarks: model-dependent upper limits





GlueX based on σ_{tot}

All estimates based on JPAC model (VMD s-channel + Pomeron): A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).

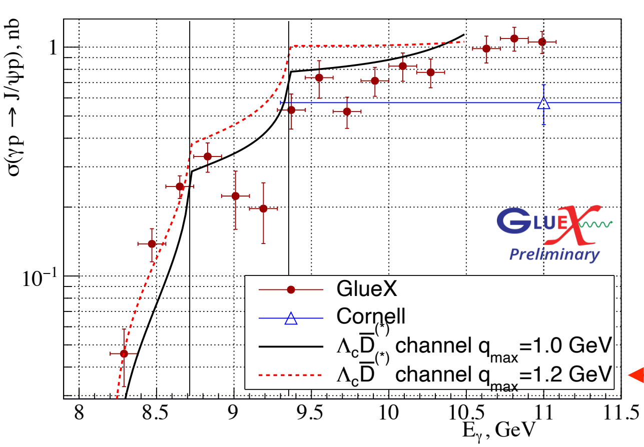


Can we interpret this as a possible evidence for a s-channel resonance (P_c?)

Open-charm, or gluon exchange, or resonances?

Experimental observations	open-charm exchange	gluon exchange	Resonance states (Pc ?)
possible structures in total cross section	cusp-like structures at $\bar{D}^{(*)}\Lambda_c$ thresholds ✓	no structures ✗	structures, but not at LHCb Pc masses ✗
$d\sigma/dt$ enhancement at high t	s,u -channel contribution? ✓	Not likely in t-channel ✗	s-channel contribution ✓
sharp t-slope	expect shallow t-dependance due to high mass exchange ✗	consistent with gluon FFs as predicted on lattice ✓	s+t channel contributions ✓
helicity conservation	?	yes?	?
beam asymmetry	?	small	?
naturality	unnatural D exchange ?	2g - natural parity exchange 3g - unnatural (C-parity violation)	?

SDME measurements to be performed



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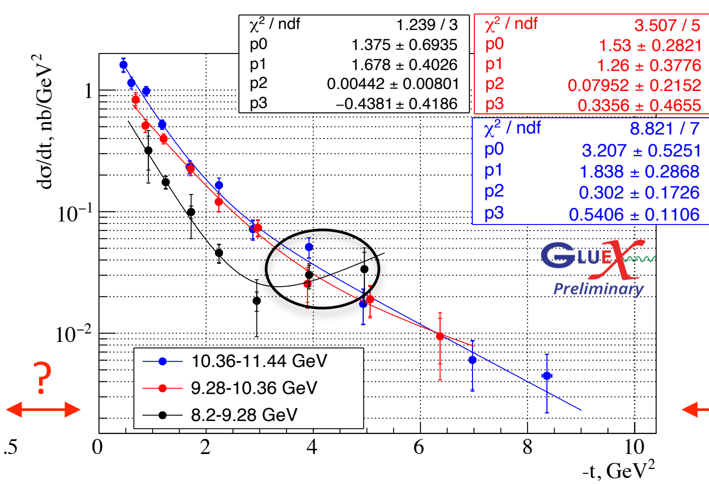
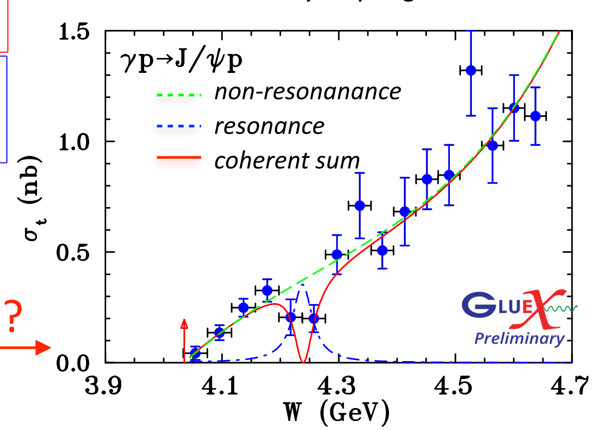


?

I.Strakovsky in progress



Need to understand the reaction mechanism

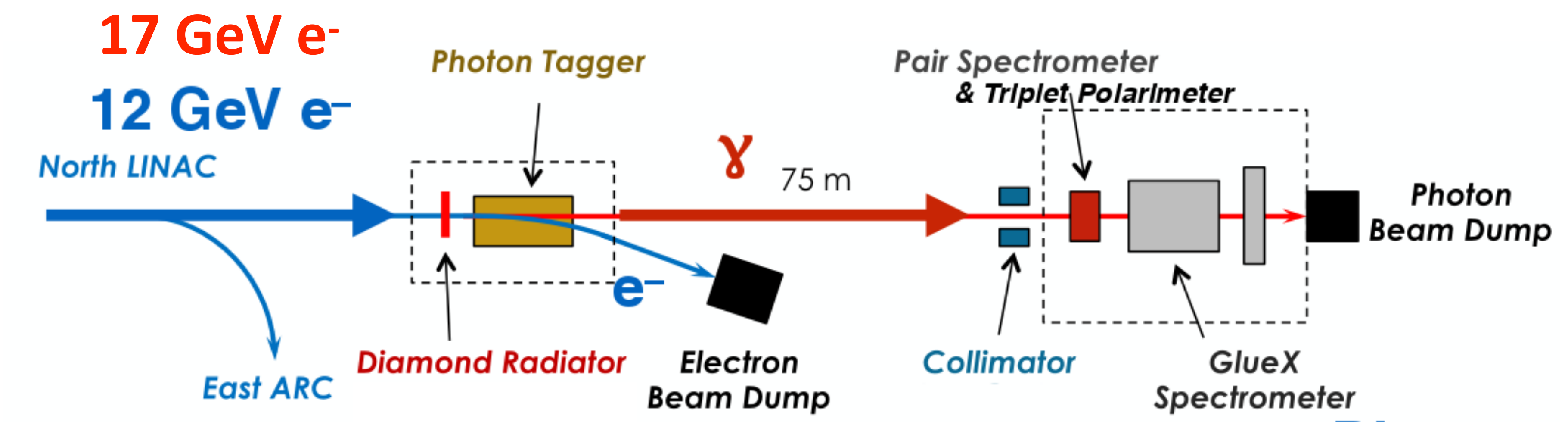
Based on current theoretical description of the threshold charmonium production, to study mass properties of the proton we need:

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

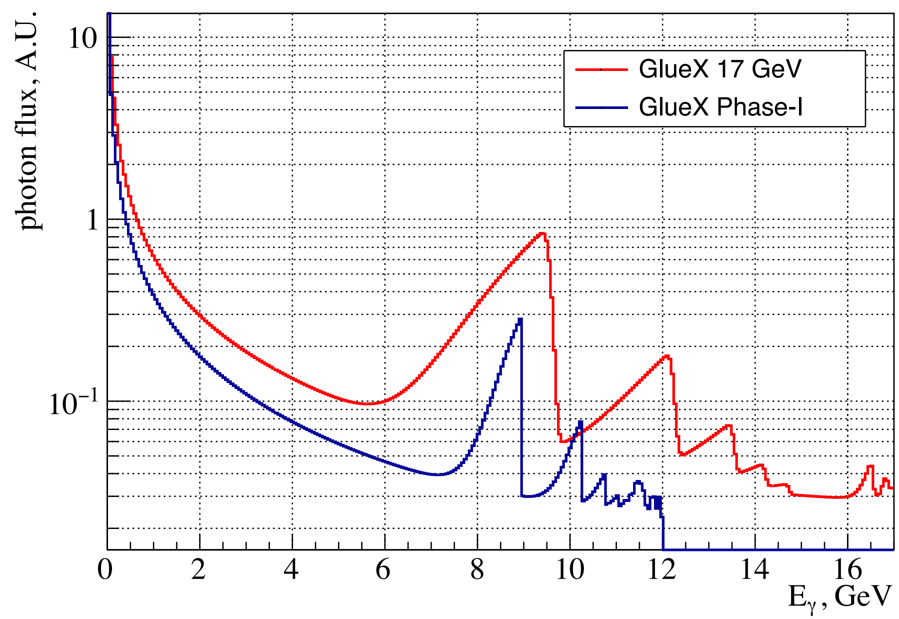
To extract possible resonance states (P_c's), or set limits on them, first we need to understand not only the t-channel (gluon exchange), but also all other processes (such as open-charm exchange, u-channel mechanisms) that can contribute.

What we can do with higher electron beam energies (17 and 22 GeV):
- higher statistics, finer binning in energy and t
- unique polarization (SDME) measurements using GlueX linear polarization with much higher FOM
- reaching higher masses
- all this without modification of the GlueX detector

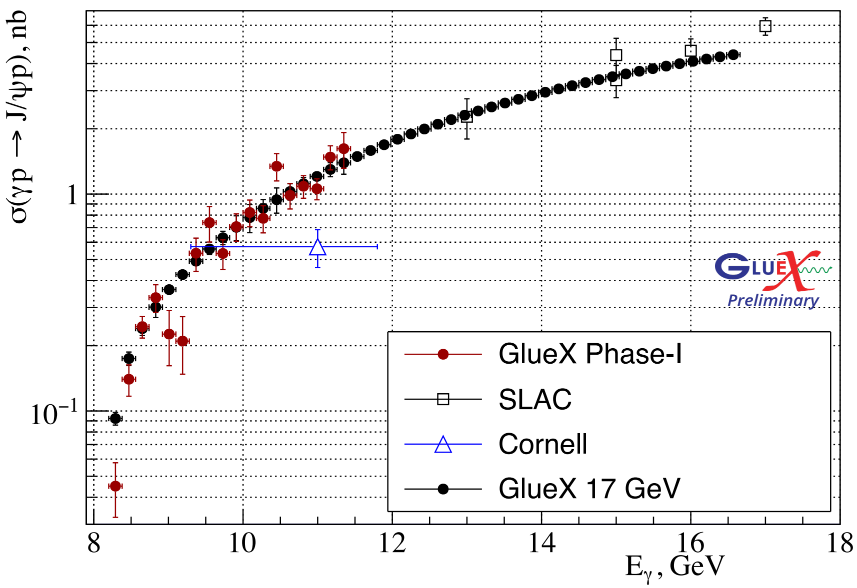
Hall D Apparatus with 17 GeV electron beam

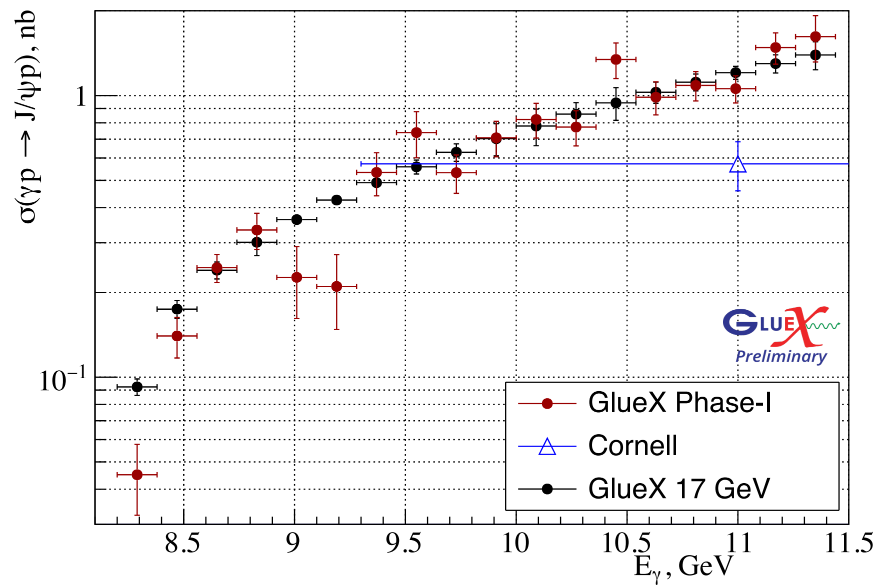


- Linearly polarized photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Moving end point from 12 GeV to 17 GeV:
  - higher flux toward higher energies, while low energies less affected (similar load on detectors)
  - wider coherent peaks
  - coherent edge at higher energy
  - much higher linear polarization
- The only significant modification: tagger magnet field increase by 17/12



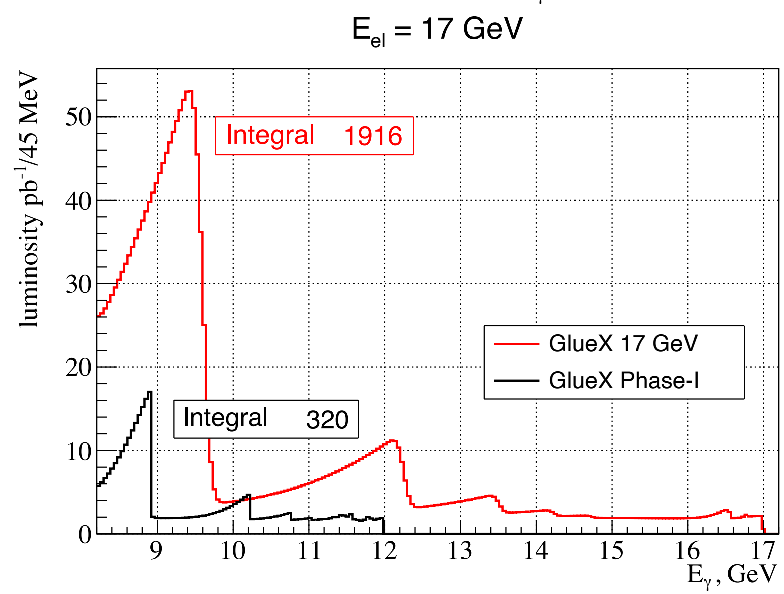
J/ψ at 17 GeV - cross section projections



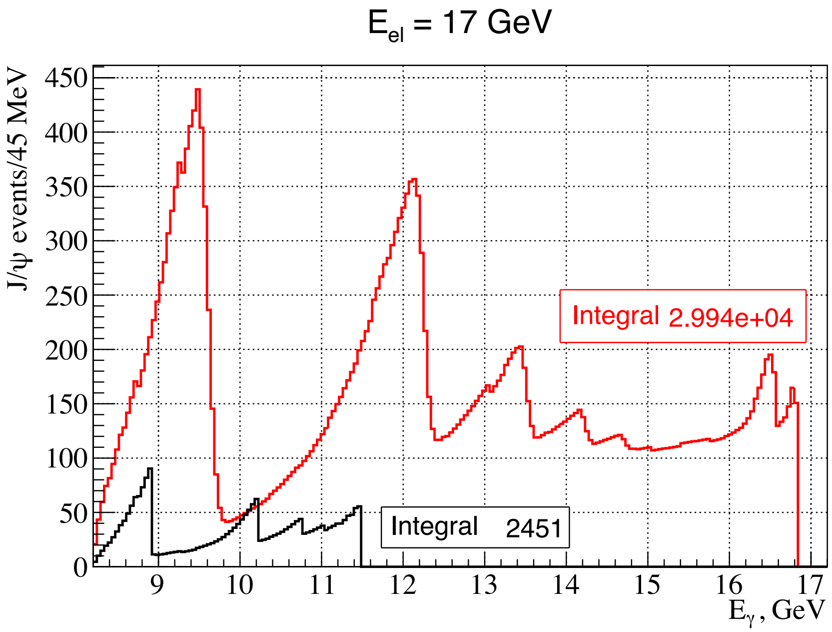


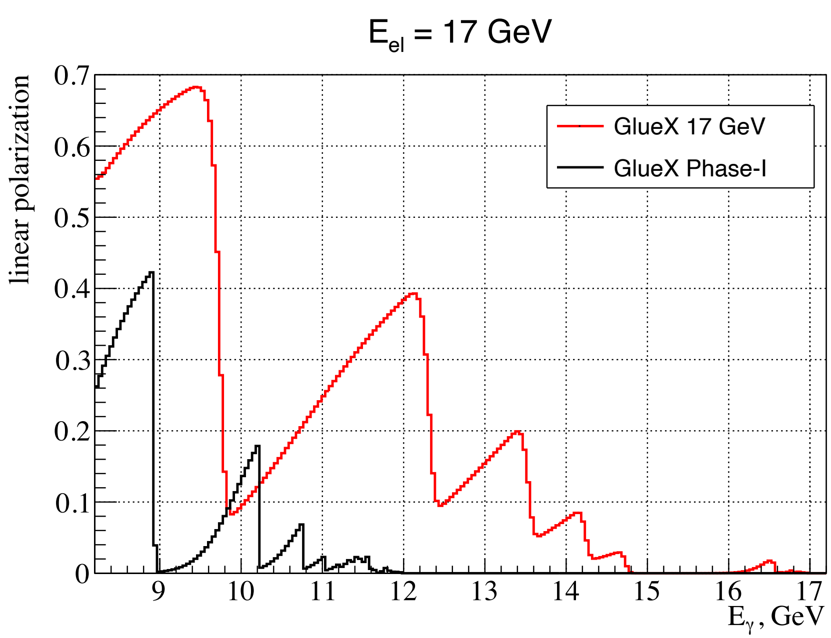
All projections based on scaling the GlueX Phase-I real data:

- Assuming same parameters (time, beam current, radiator) as for Phase-I (~1.5 years)
- Tagger accidental analysis based on existing data
- Performing realistic simulations at higher energies to estimate the detector efficiency - no variations with energy due to the full acceptance of the GlueX detector

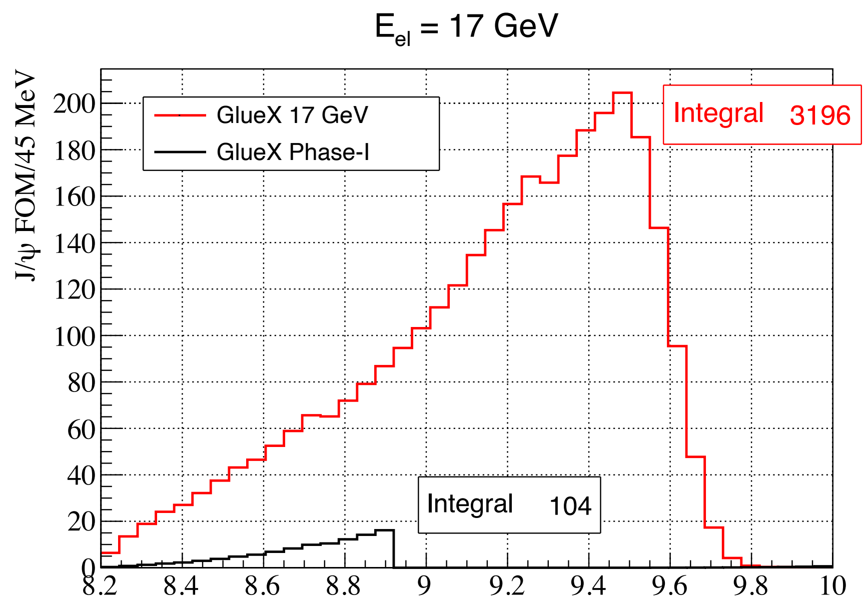


J/ψ at 17 GeV - polarization measurements



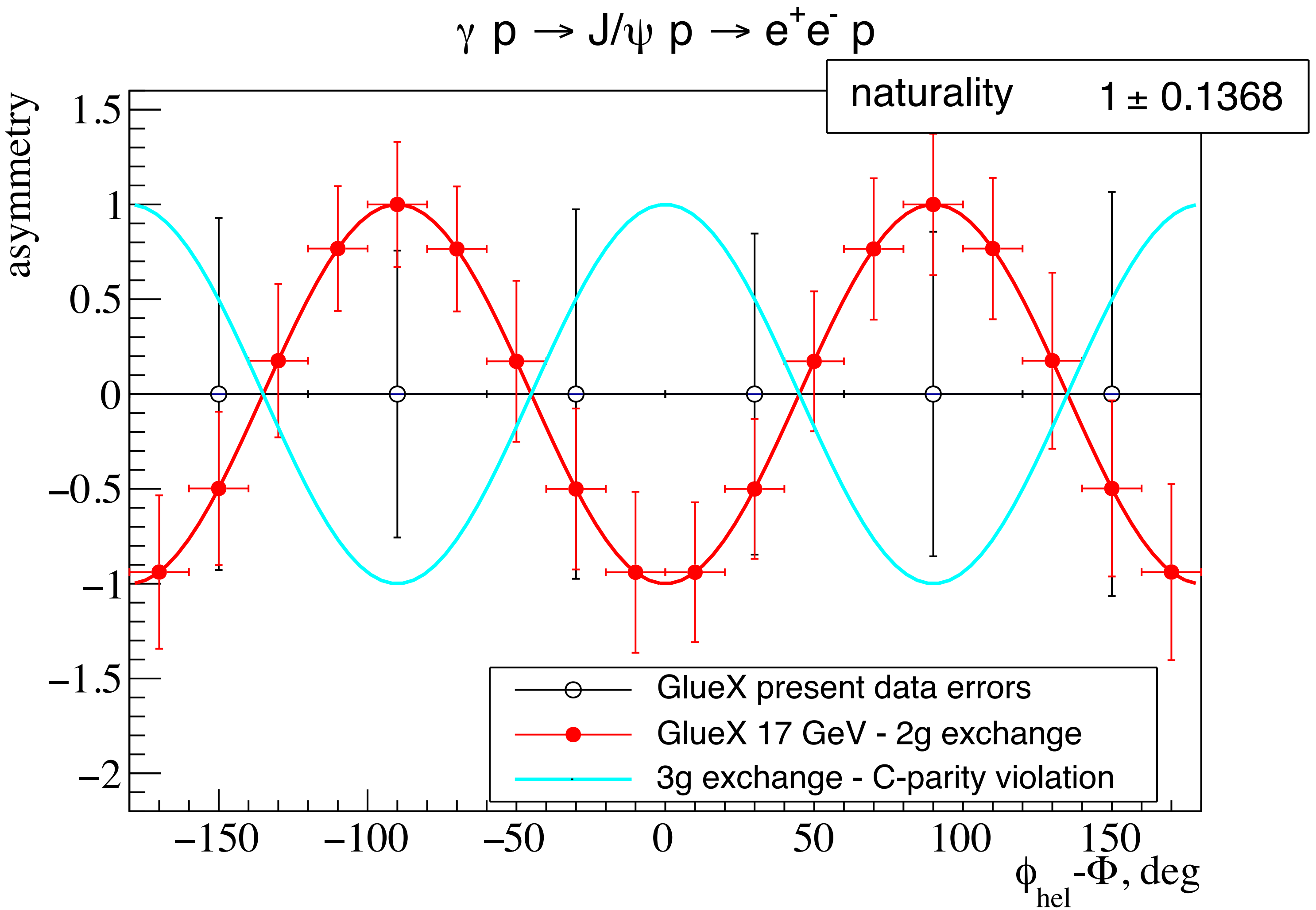


- Projections using the measured errors and scaling them based on the Figure Of Merit, FOM:



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

J/ψ at 17 GeV - naturality



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

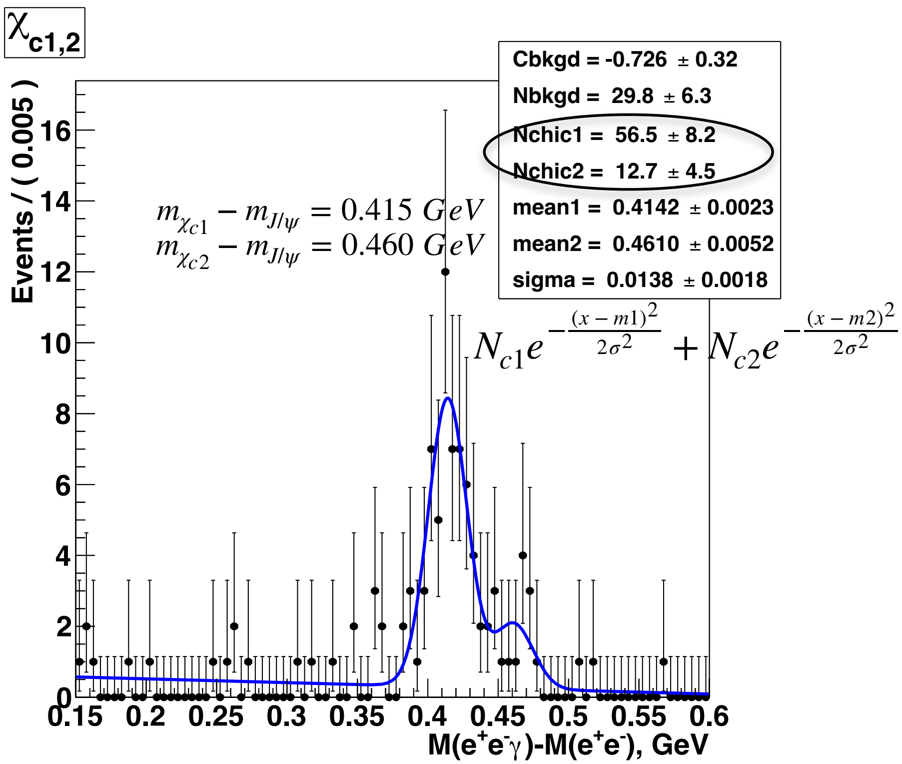
naturality $=(-1)^J P$

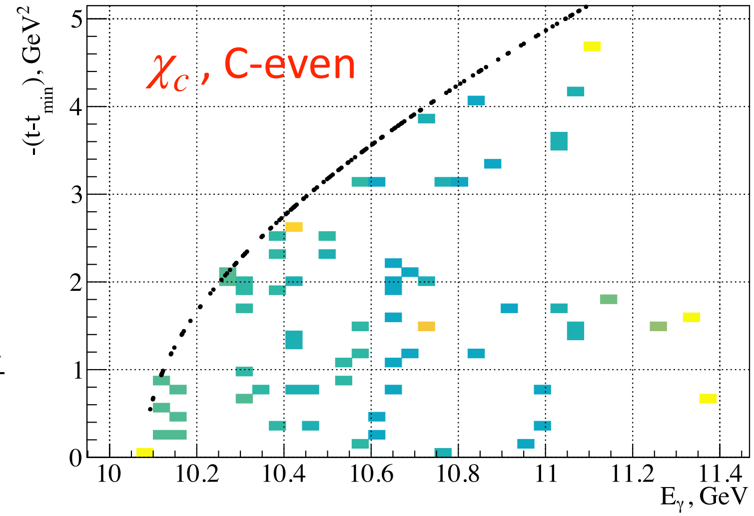
Keigo Mizutani's SDME's calculations

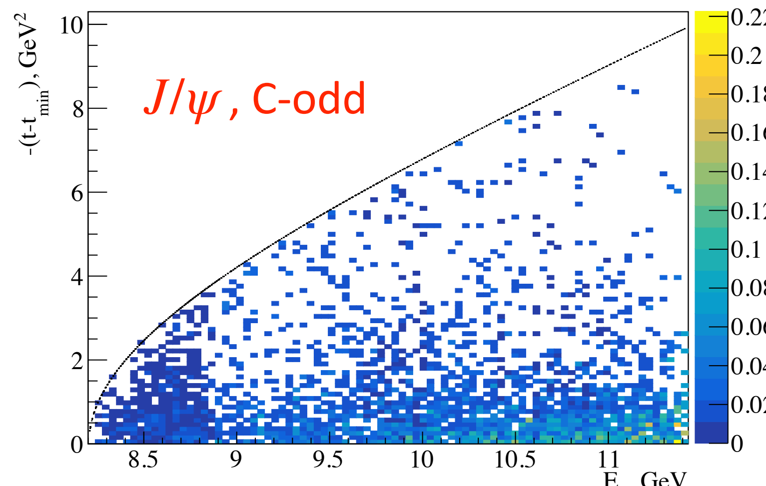
$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi')]\right)$$

Higher charmonium sates, χ_c and ψ' with GlueX

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







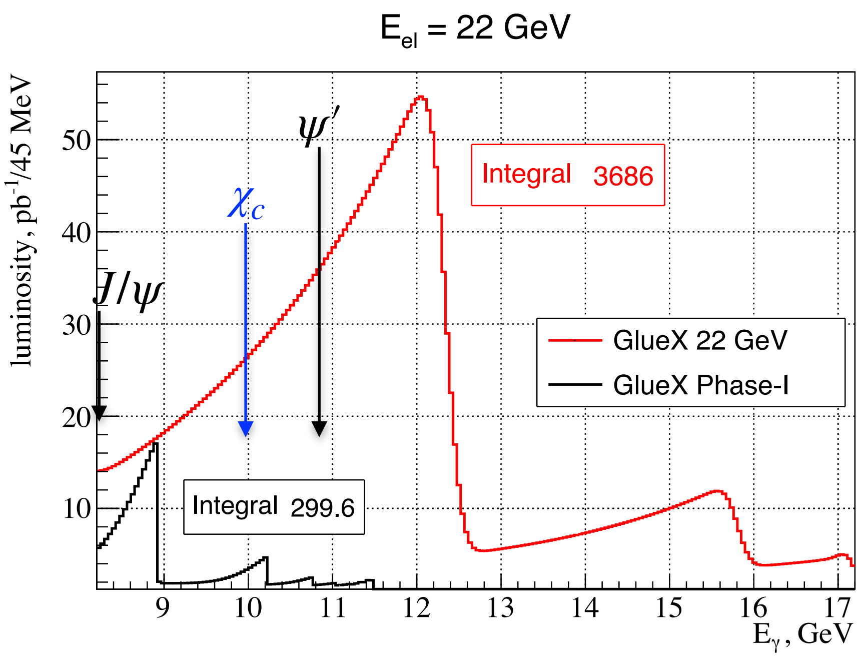
$$weight = \frac{1}{L(E_\gamma)}$$

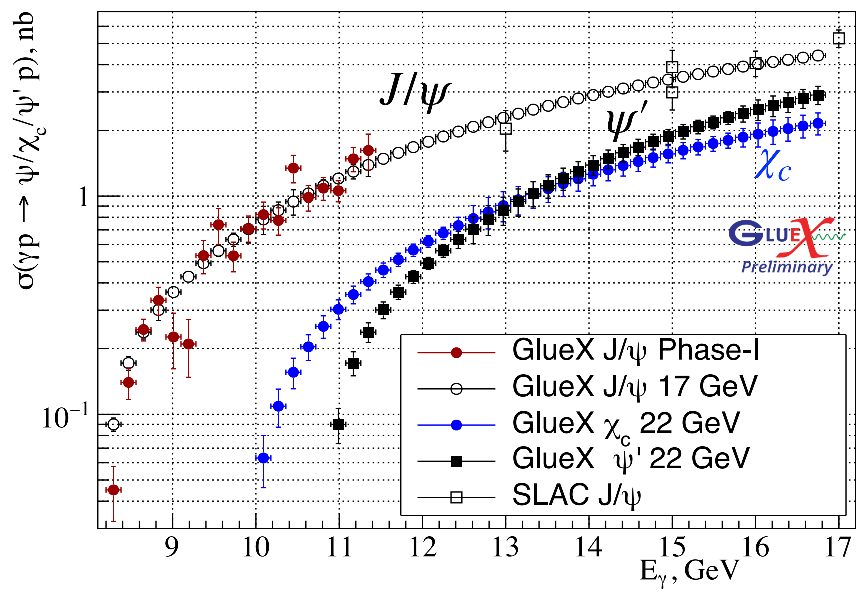
- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV
- C-even charmonium states require 3g-exchange
- Dramatic difference in (E_γ, t) distribution w.r.t J/ψ

- GlueX has observed also a small number of $\psi'(3686)$ $(2S)$ states in $\gamma p \to \psi' p \to (e^+e^-)p, \quad E_\gamma^{thr} = 10.9$ GeV

χ_c and ψ' states with 22 GeV - cross sections

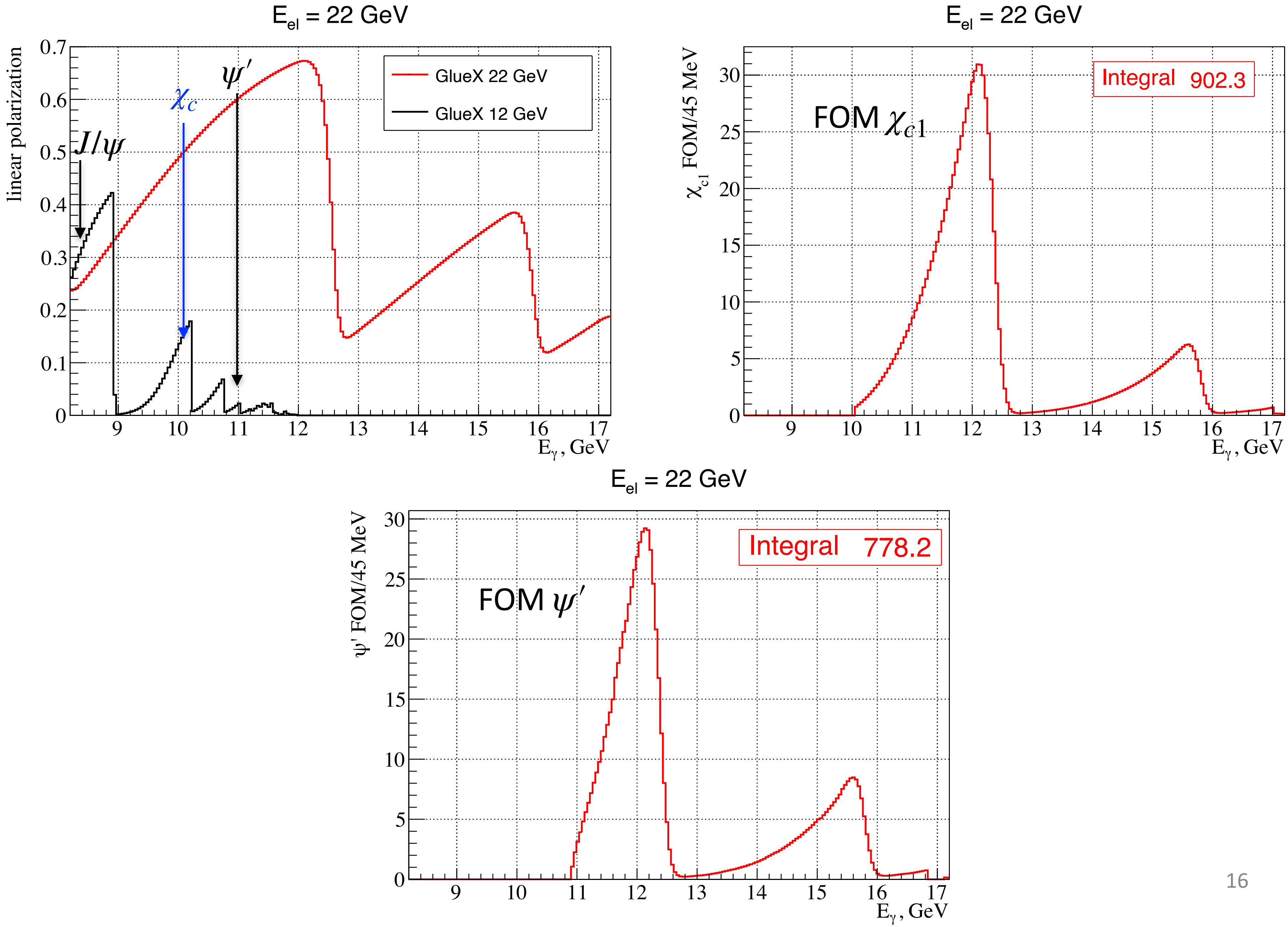
- 22 GeV needed to reach these higher charmonium states
- Measured χ_c and ψ' yields and MC simulations used to make projections for 22 GeV beam.
- Assuming energy dependance: for ψ' same as measured for J/ψ; for χ_{c1} as calculated by JPAC





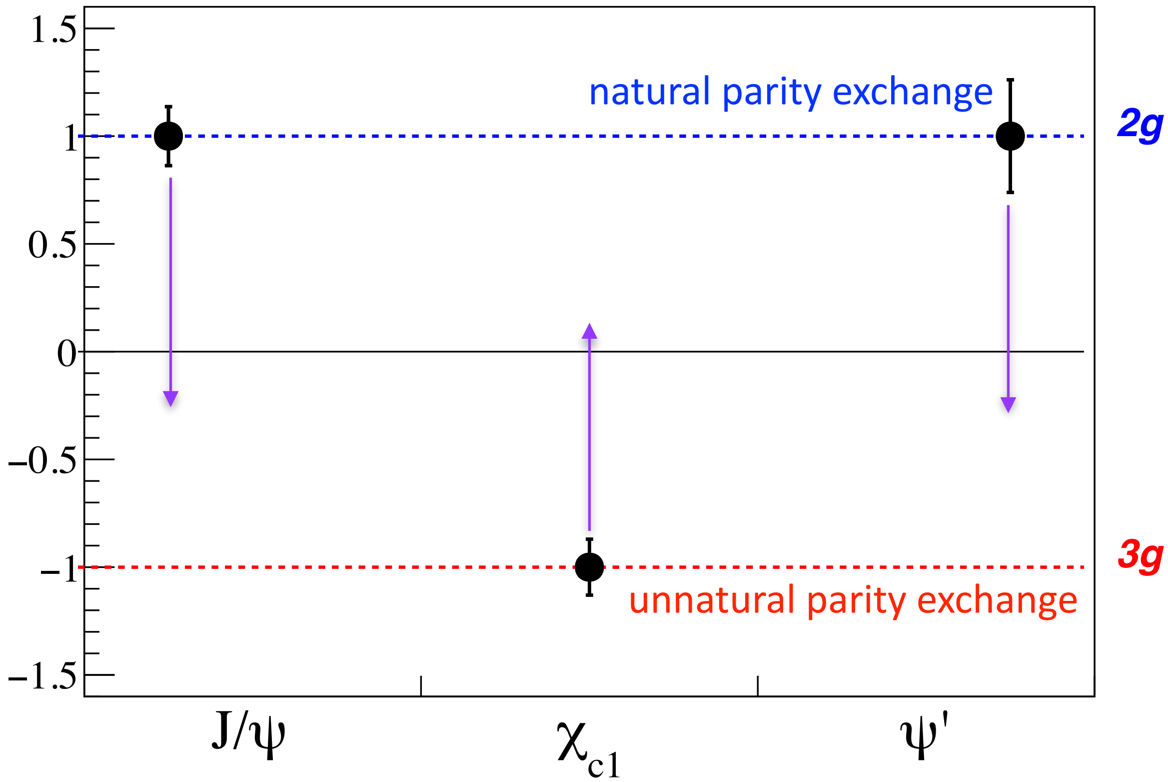
- C-even charmonium production - very important to understand the gluon-exchange (2g vs 3g) and possibly additional mechanisms that may dominate
- The $m_c \to \infty$ limit gives: (1) factorization, (2) access to gravitational form factors, strictly valid for $\xi \to 1$ at threshold (*Gun, Ji, Liu 2021*), therefore we want to study also quarkonium with higher masses like $\Upsilon(9460)$ at EIC.
- ψ' photoproduction will be a complementary step b/n J/ψ and Υ to justify the above assumptions

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



J/ψ, χ_{c1}, ψ' naturality studies

naturality = $(-1)^J P$



Any deviation from the expected naturality ($+$ or -1) indicates contribution of mechanism different from what is needed to study mass properties of the proton

Conclusions

- Charmonium threshold photoproduction has potential to access very important physics - mass properties of the proton - however:

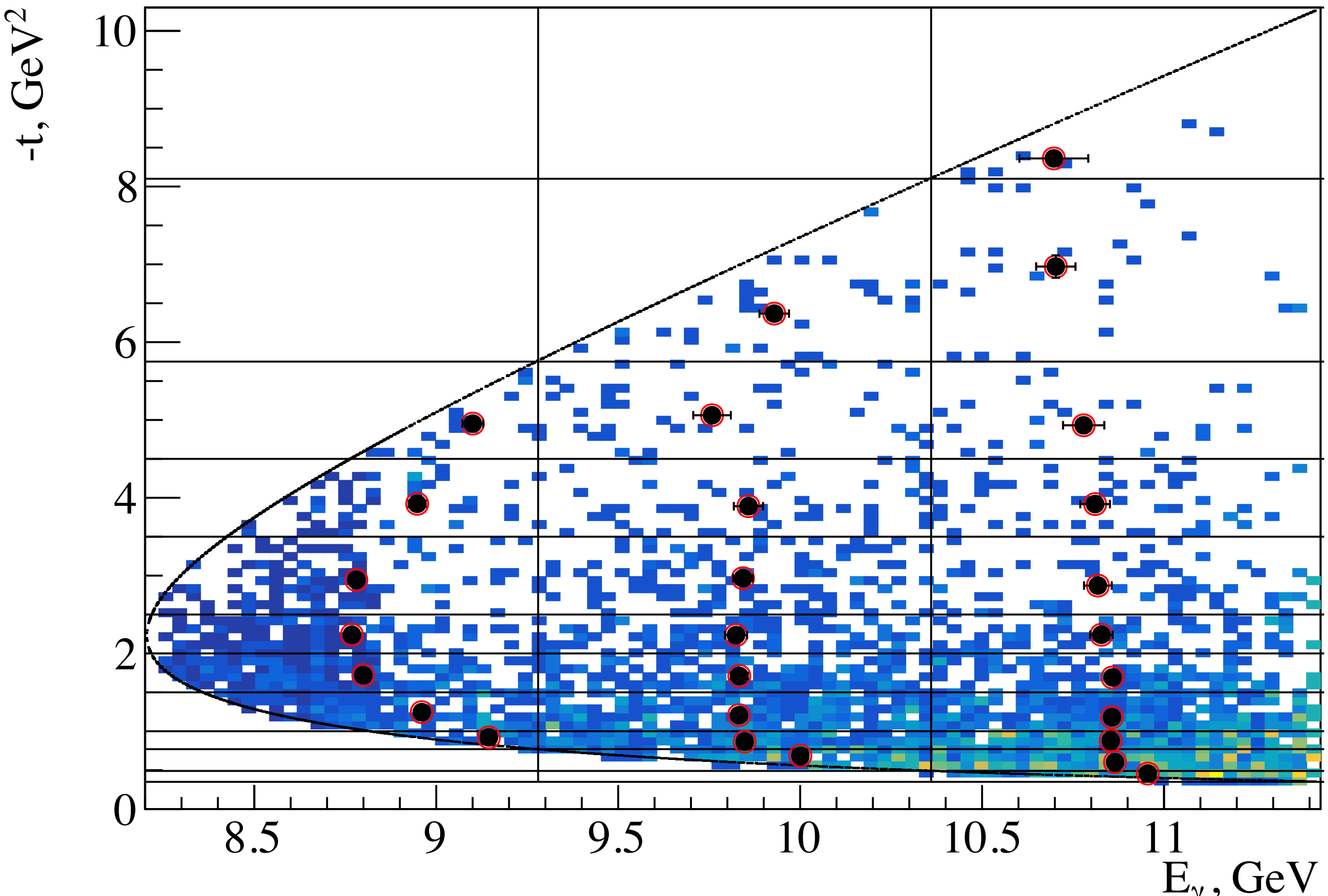
  … assuming VMD, or QCD factorization, or using holographic approach

  … assuming gluon exchange over open-charm exchange mechanism

  … assuming relation of the reaction amplitudes to the gravitational FFs
- Need to understand the reaction mechanism - open questions for both experimentalists and theorists
- With the energy upgrade in GlueX we can have significant increase in luminosity and polarization, reaching higher masses:
  - 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 mass dependance of the above assumptions
  - Comparing C-odd (J/ψ, ψ') and C-even charmonium states (χ_c) allows to study the gluon exchange (2g, 3g) mechanism
- All this with the existing GlueX detector

Back-ups

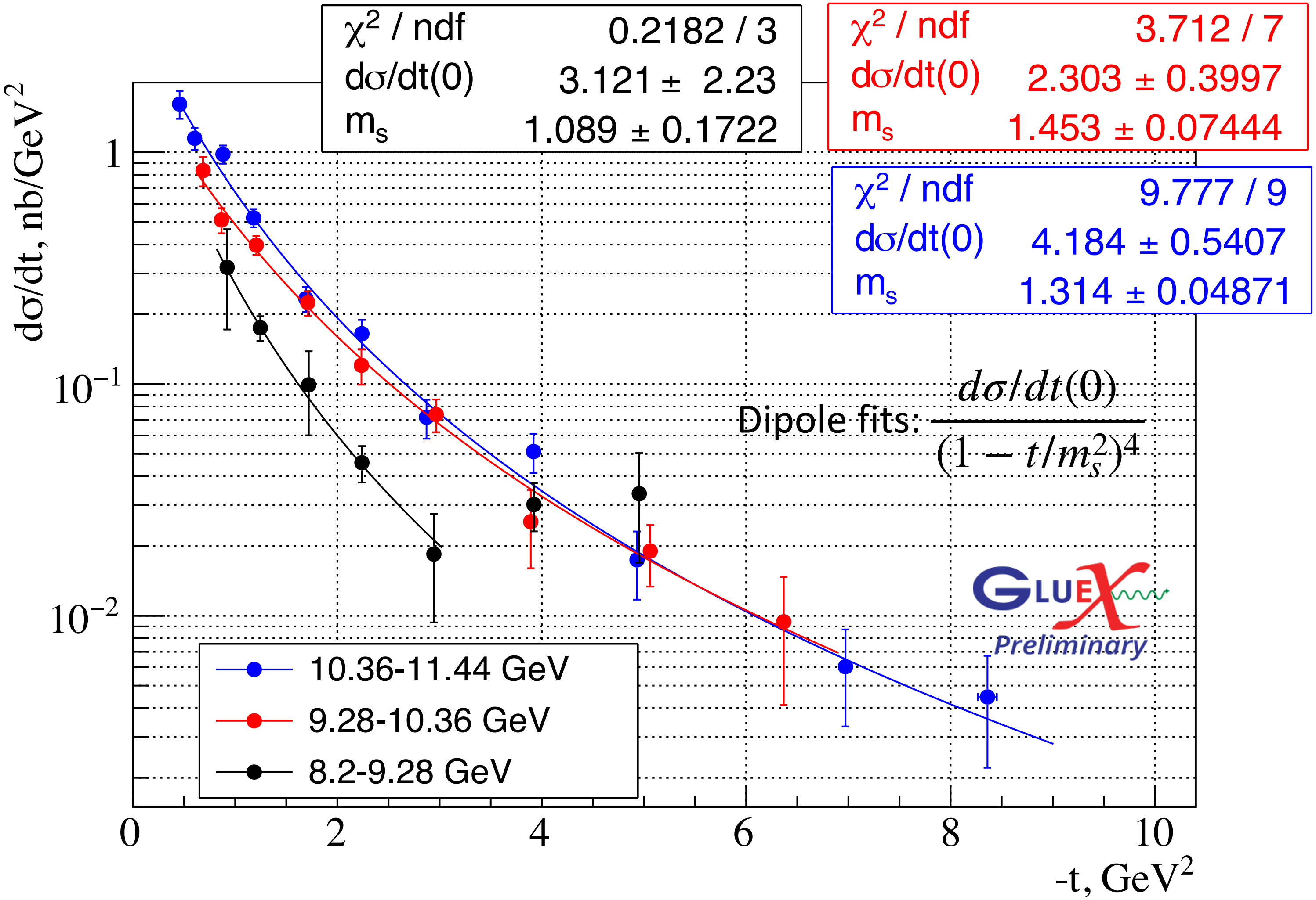
Differential cross-sections



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

- 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

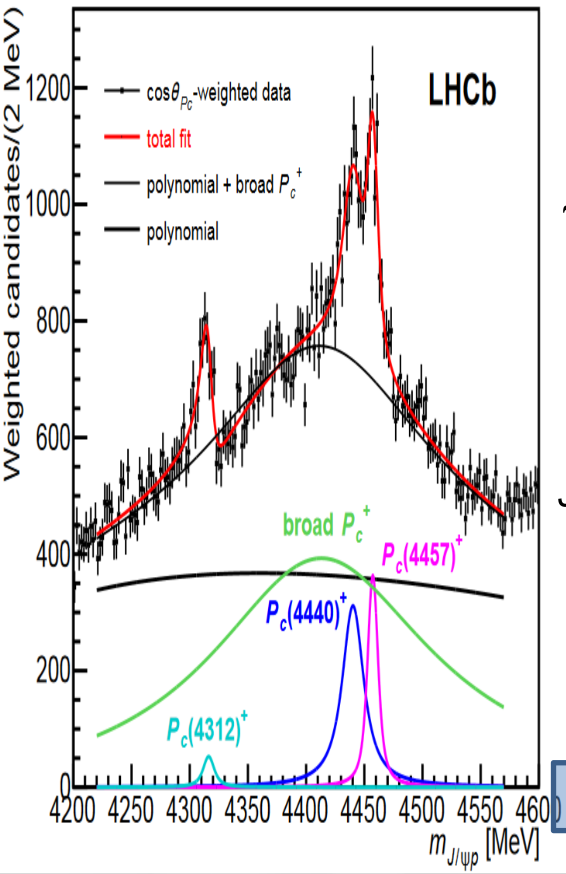
Differential cross-sections - forward extrapolation

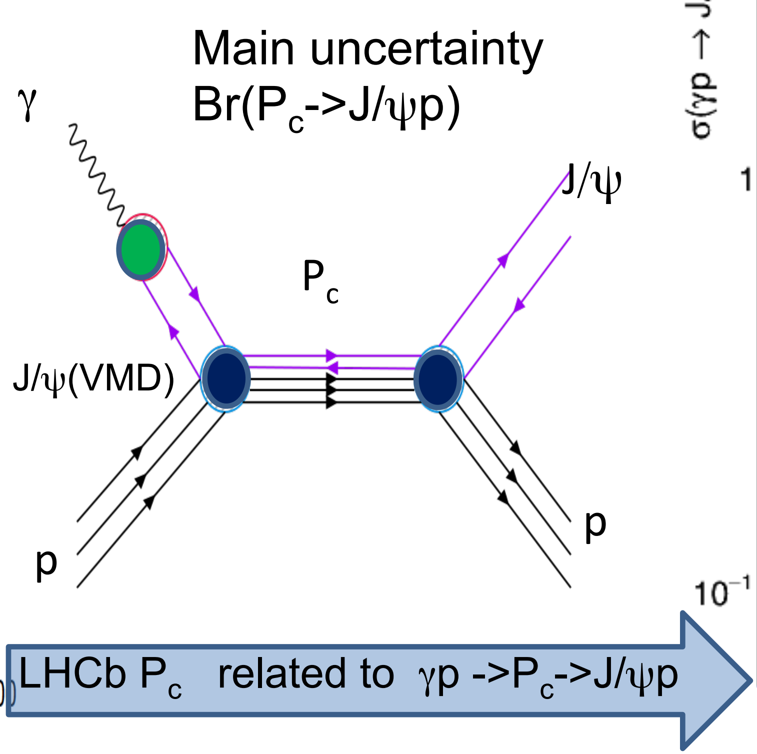


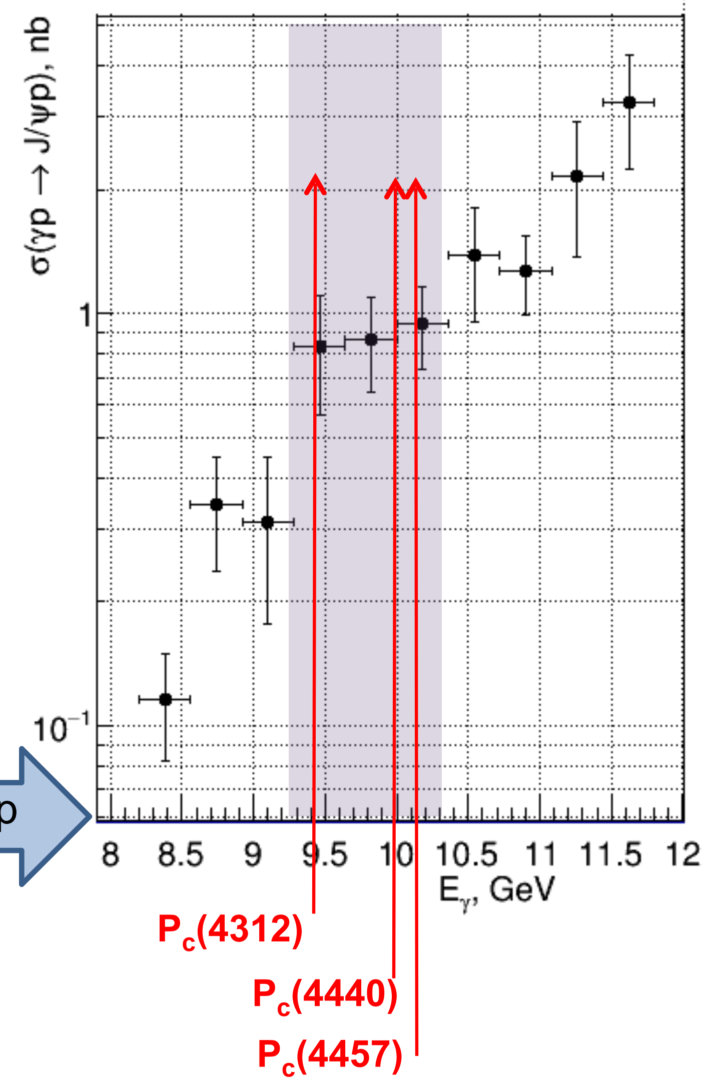
E_γ, GeV	8.93	9.86	10.82
$q_{c.m.}$, GeV (J/ψp c.m.)	0.499	0.767	0.978
$d\sigma/dt(0)$, nb/GeV^2	3.121 ± 2.23	2.303 ± 0.400	4.184 ± 0.541
m_s, GeV	1.089 ± 0.172	1.453 ± 0.074	1.314 ± 0.049

LHCb pentaquarks and J/ψ photo-production

- If LHCb pentaquarks exist they should be seen in s-channel photoproduction (free of rescattering effects in the final state):

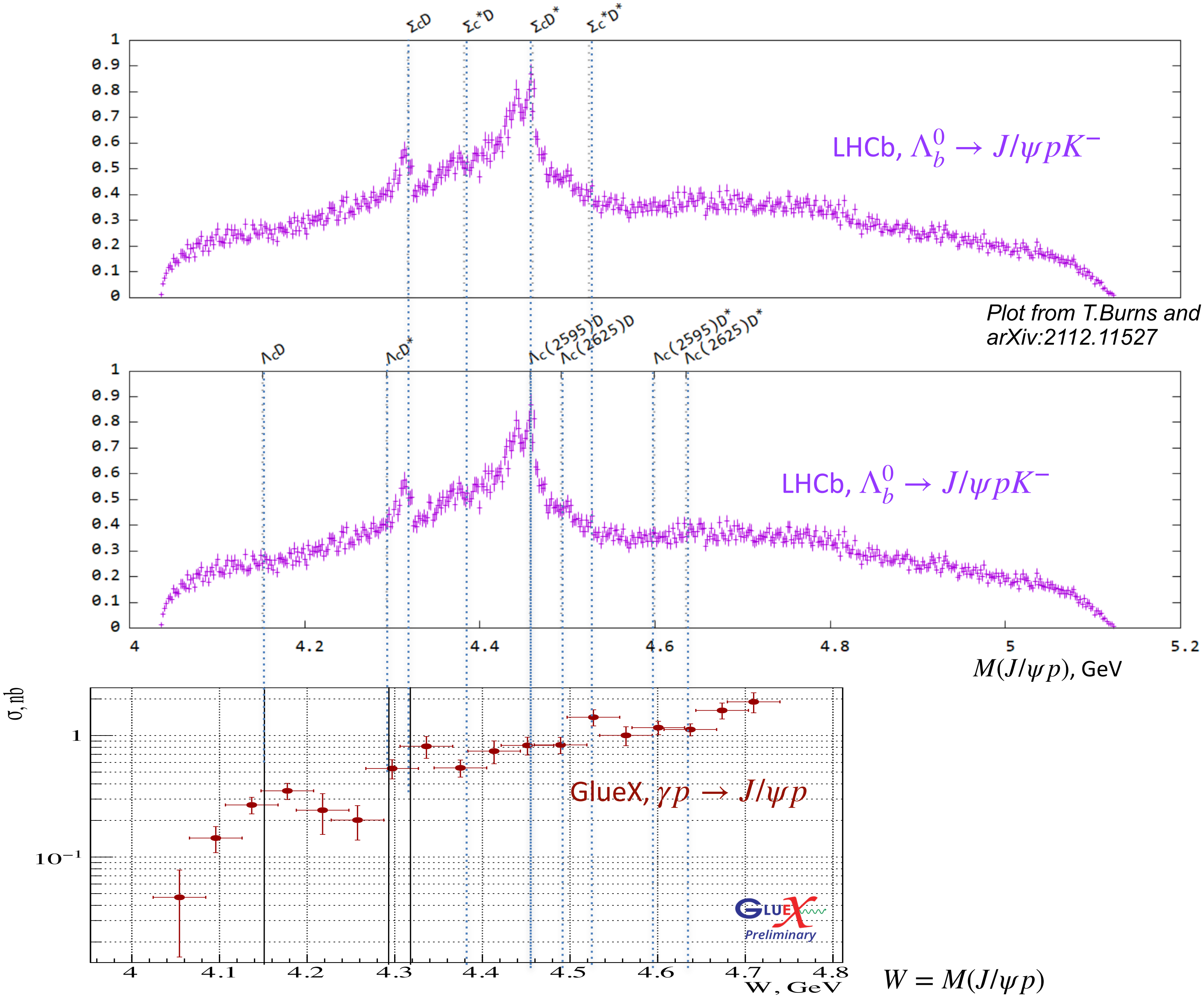






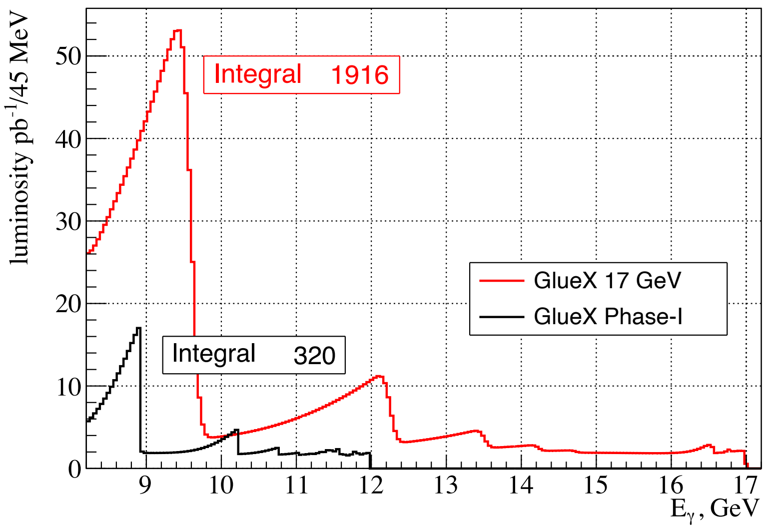
- *V.Kubarovsky and M.B.Voloshin, PRD 92.031502 (2015).*
- *M.Karliner and J.Rosner, arXiv: PLB 752, 329 (2016).*
- *A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).*

Pentaquarks and open-charm thresholds



Plot from T.Burns and E.Swanson, arXiv:2112.11527

J/ψ at 17 GeV - cross sections and yields



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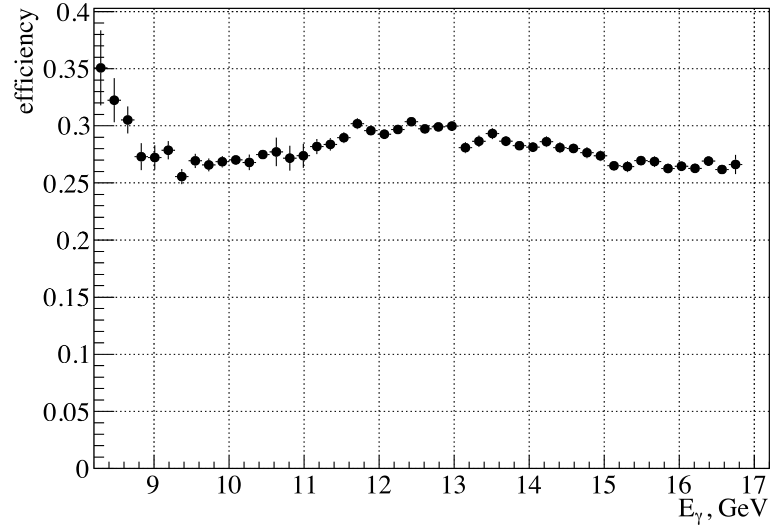

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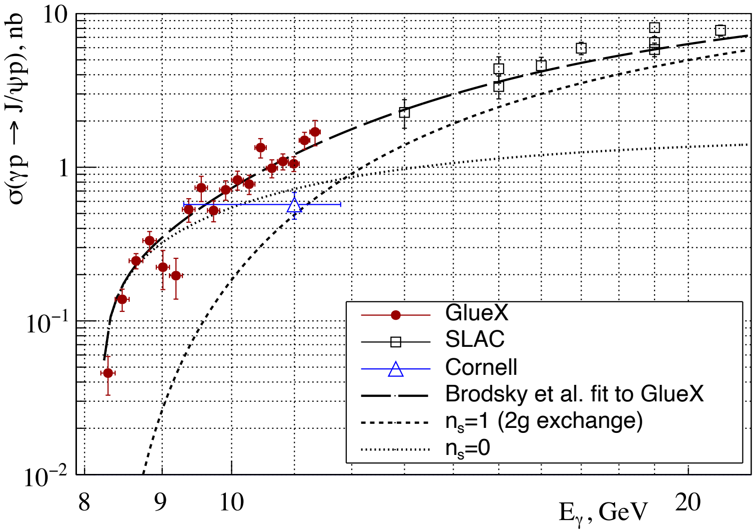
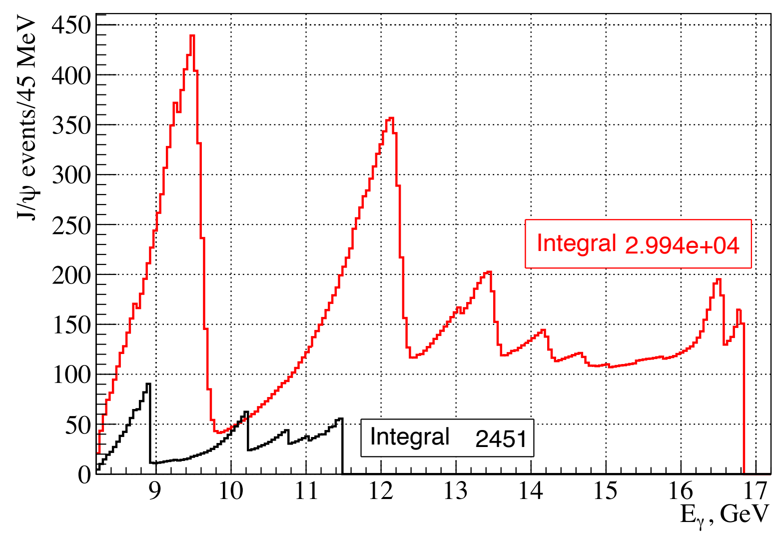
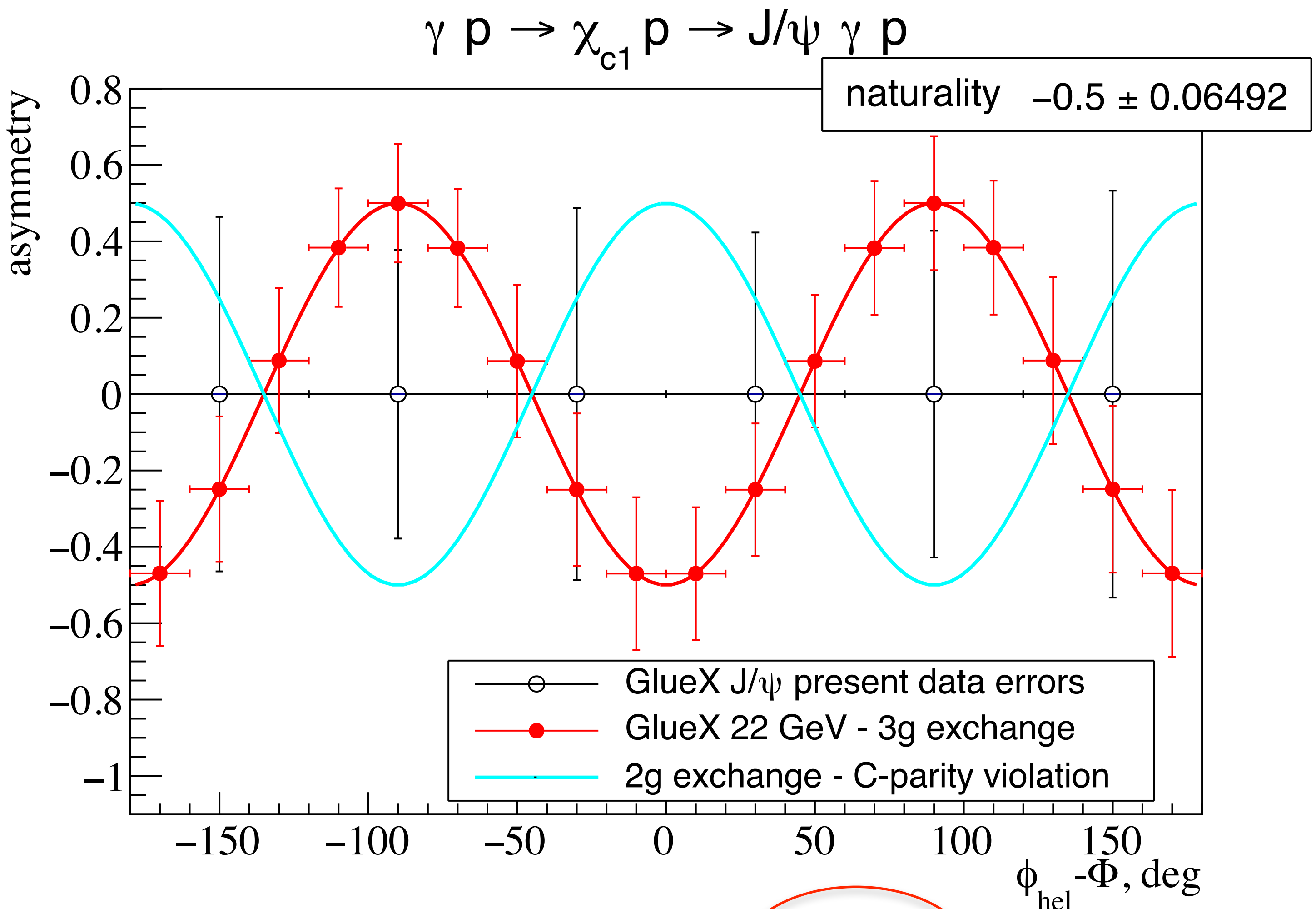
$$Y_{J/\psi}(E_\gamma) = L(E_\gamma)\sigma_{J/\psi}(E_\gamma)\varepsilon(E_\gamma)\mathscr{B}(J/\psi \to e^+e^-)$$





χ_{c1} with 22 GeV - naturality



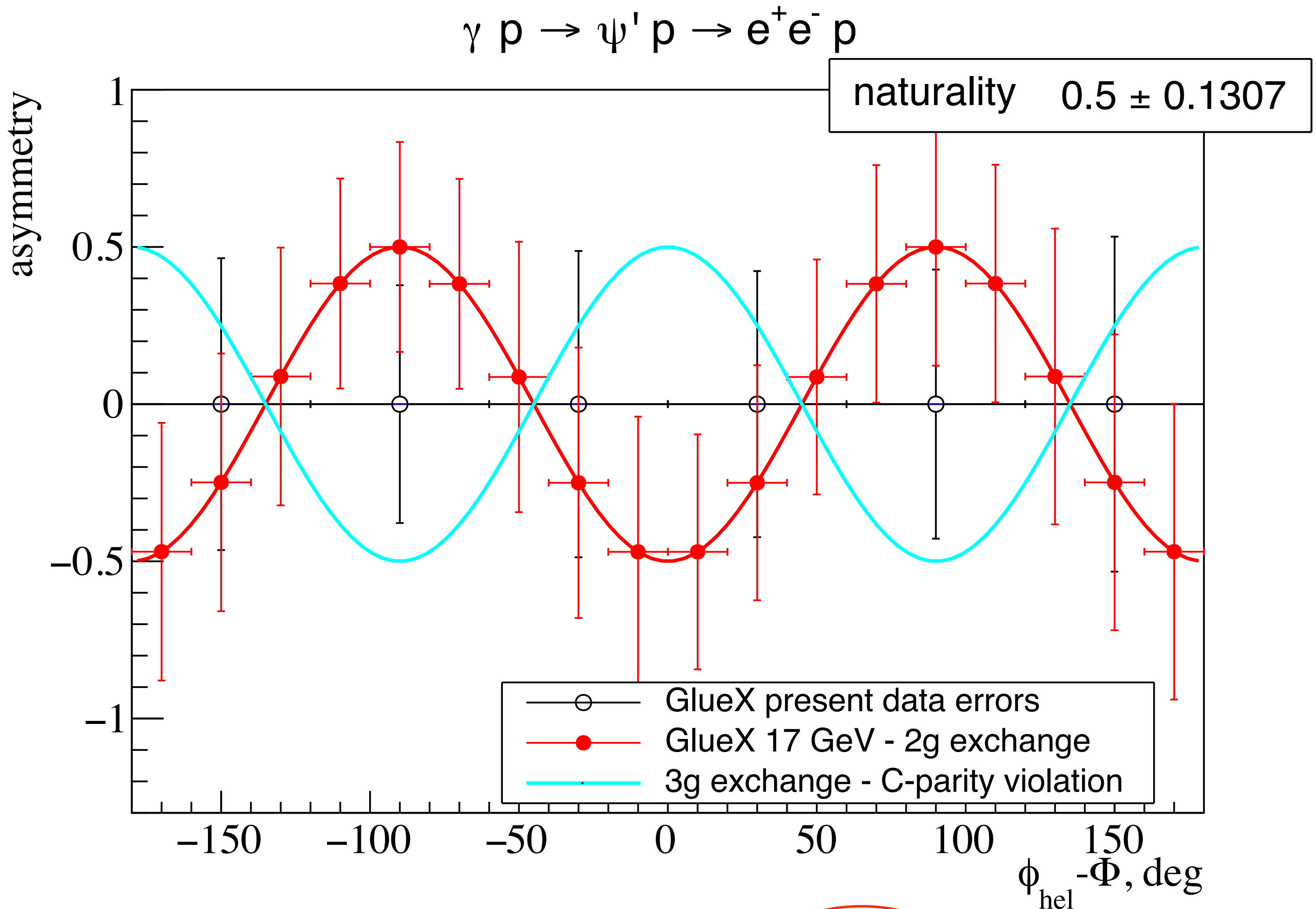
$$asymmetry = \frac{1}{2P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = \frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi)]$$

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

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

…assuming equal helicity couplings

ψ' at 22 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 $= 0.5(-1)^J P$

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