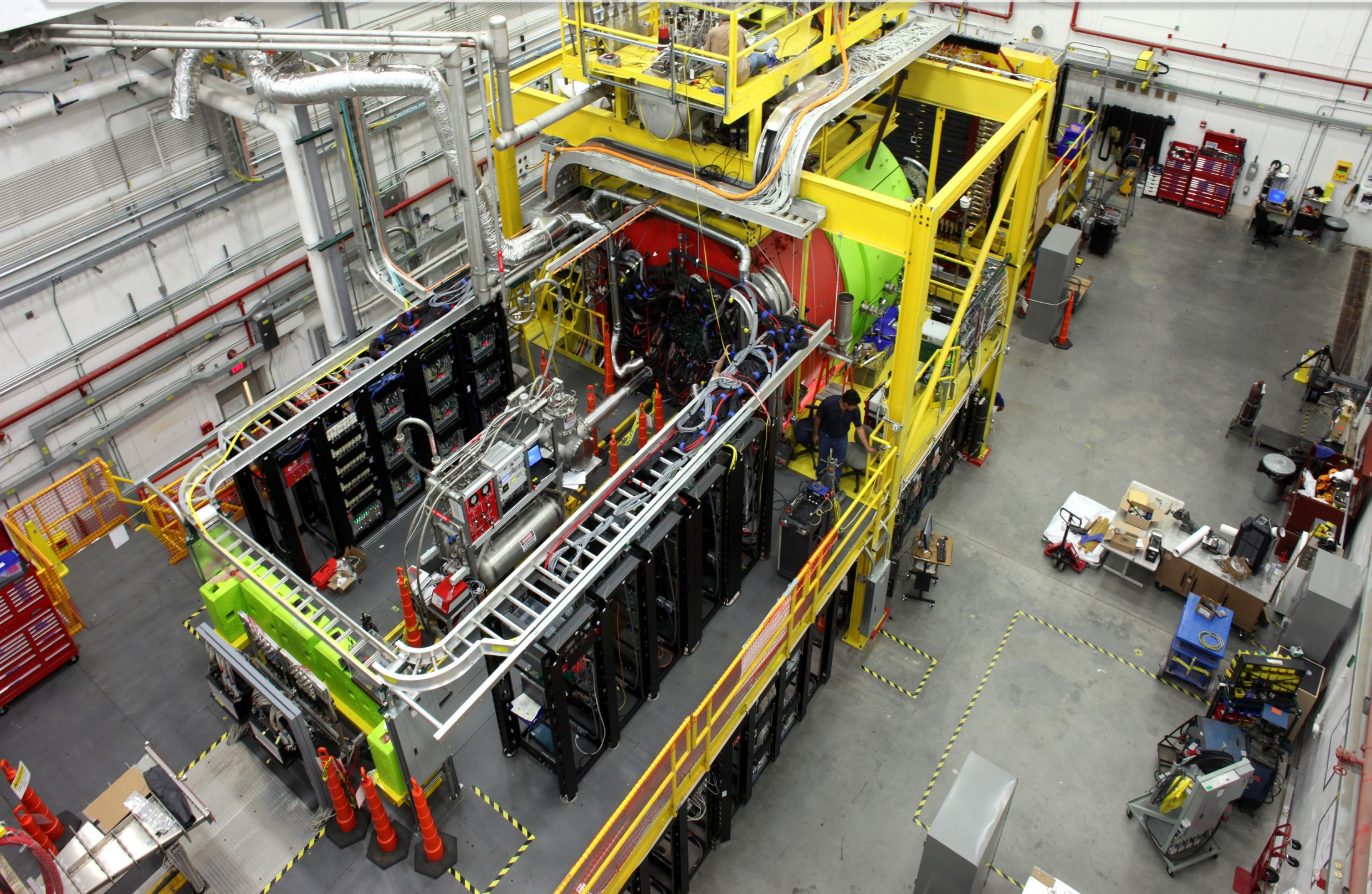
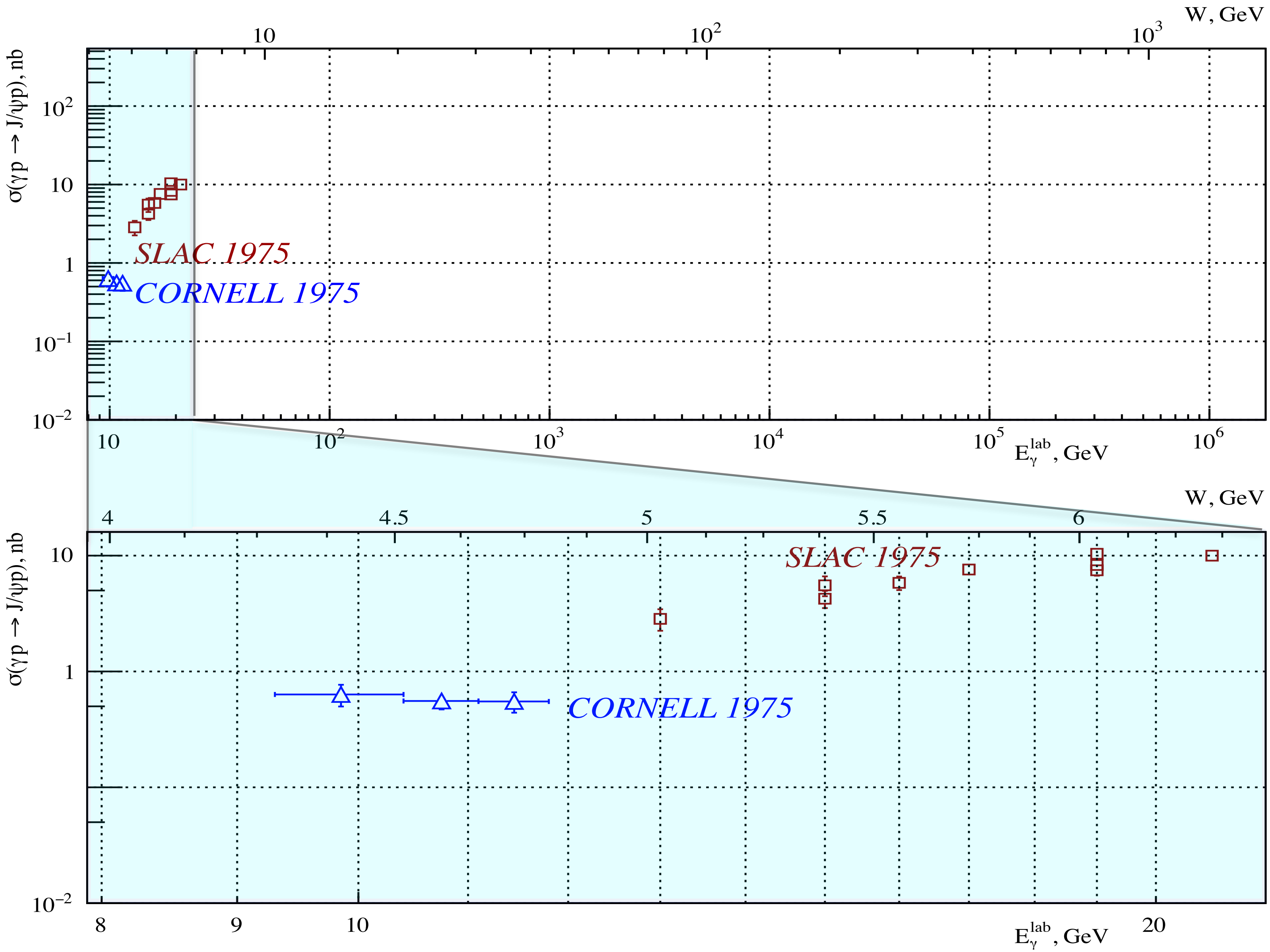
Threshold charmonium photoproduction at JLab

Lubomir Pentchev
Jefferson Lab (GlueX Collaboration)

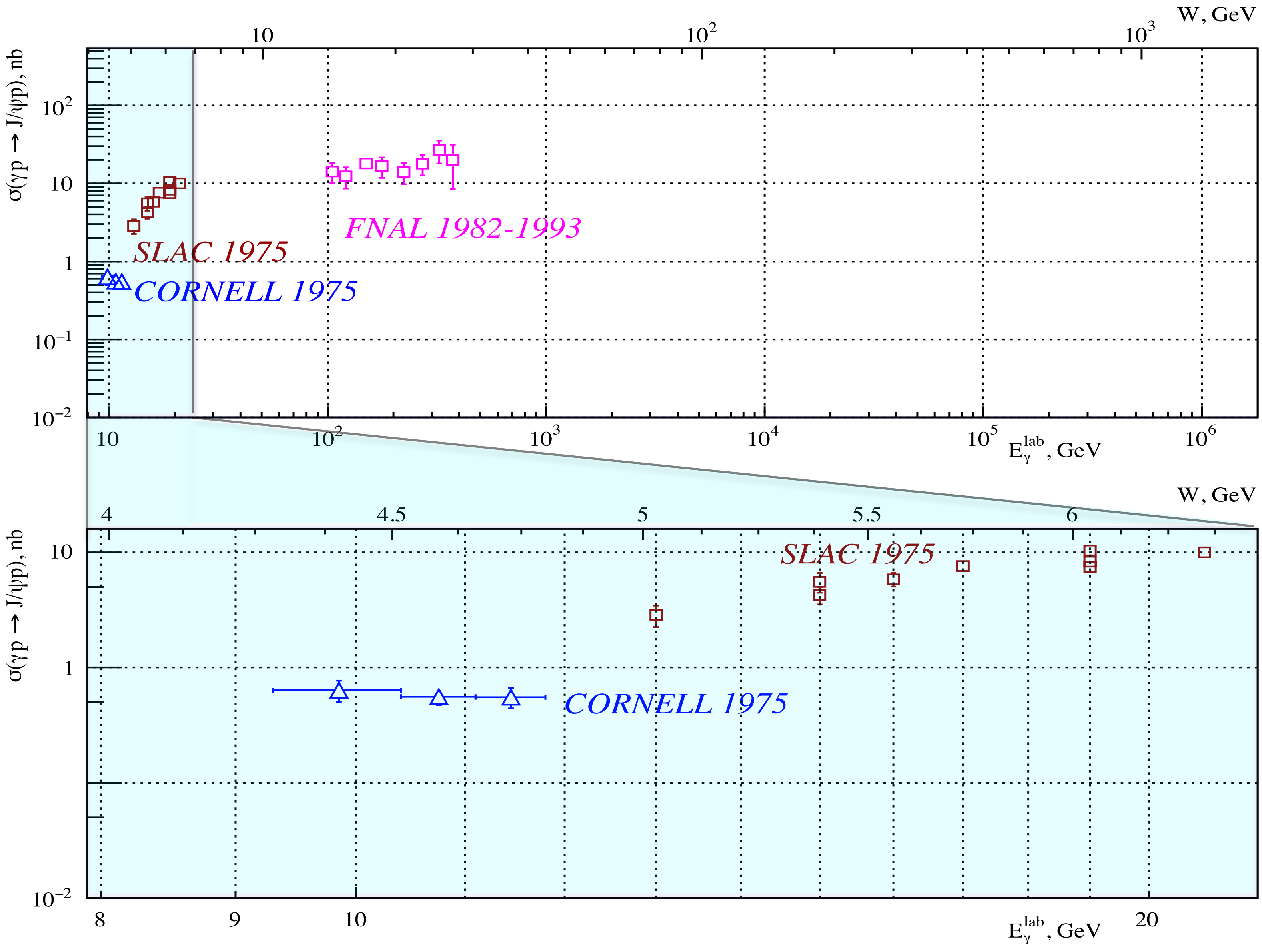


~50 years J/ψ photoproduction

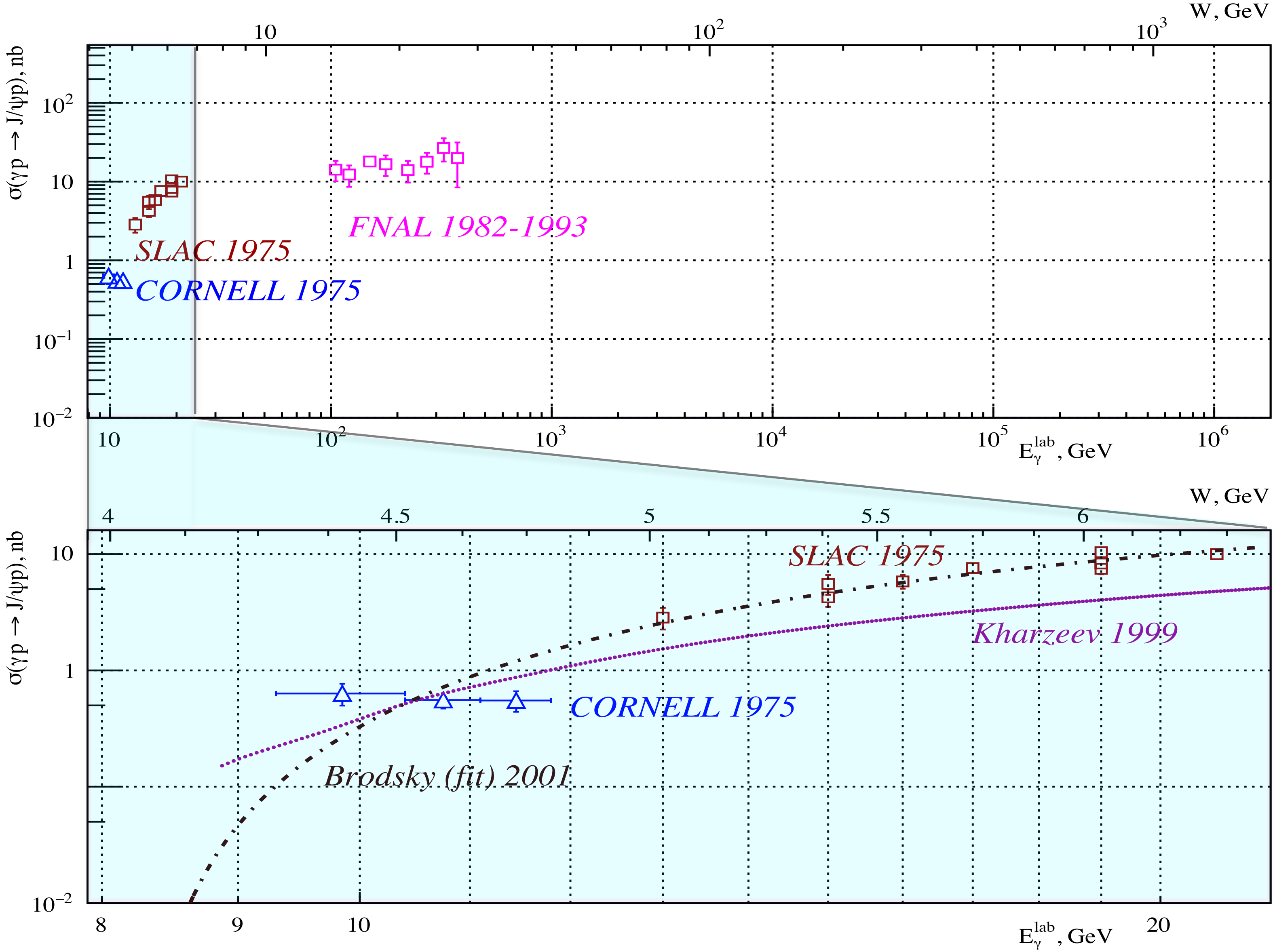


- FNAL: Knapp et al., Phys. Rev. Lett. **34**, 1040 – 3 February 1975 (no explicit cross-sections given)
- SLAC: Camerini, Learned, Prepost, Spencer, Wiser, Ash, Anderson, Ritson, Sherden, and Sinclair, Phys. Rev. Lett. **35**, 2 June 1975
- Cornell: Gittelman, Hanson, Larson, Loh, Silverman, Theodosiou, Phys. Rev. Lett. **35**, 11 August 1975

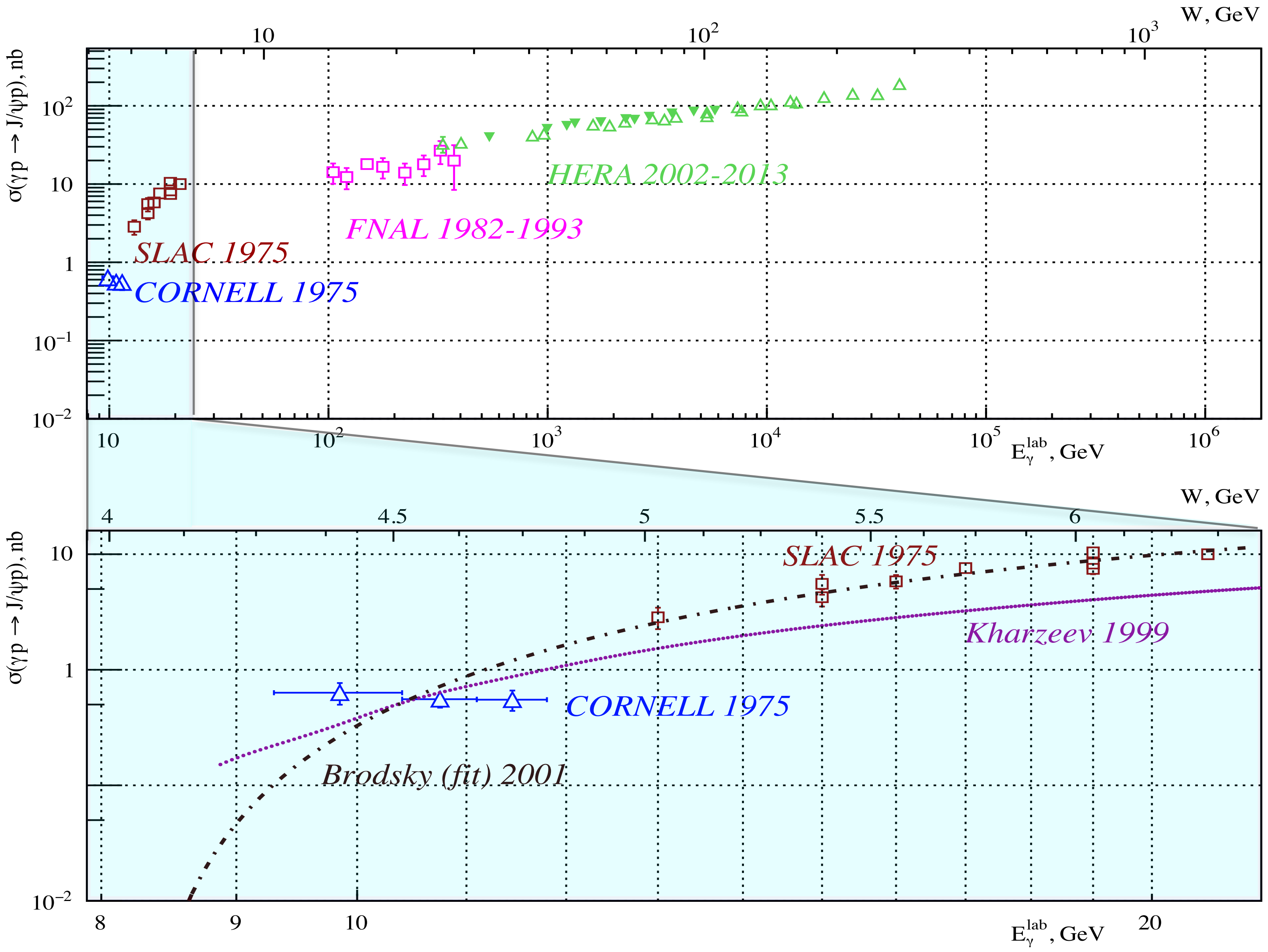
~50 years J/ψ photoproduction



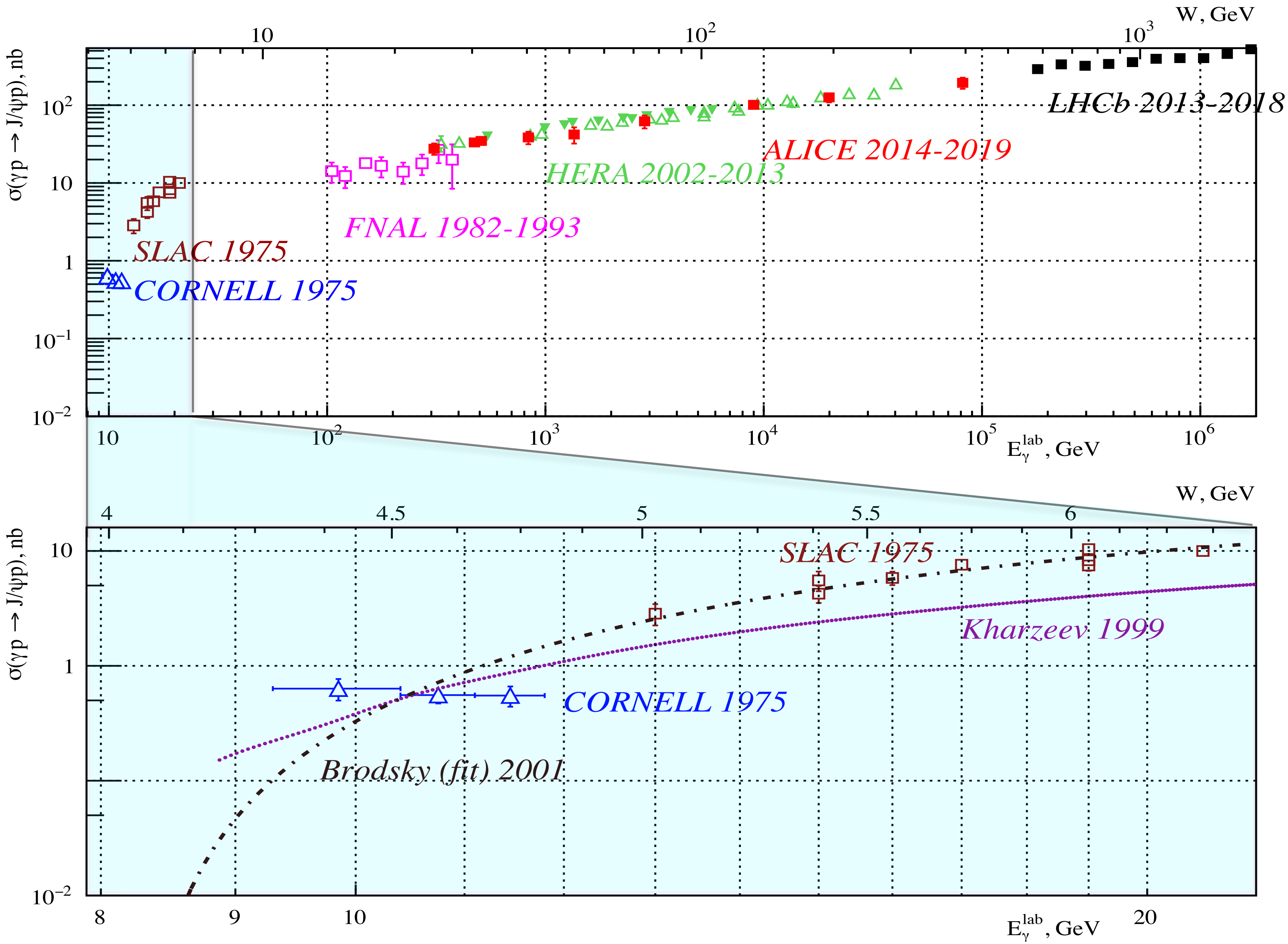
~50 years J/ψ photoproduction



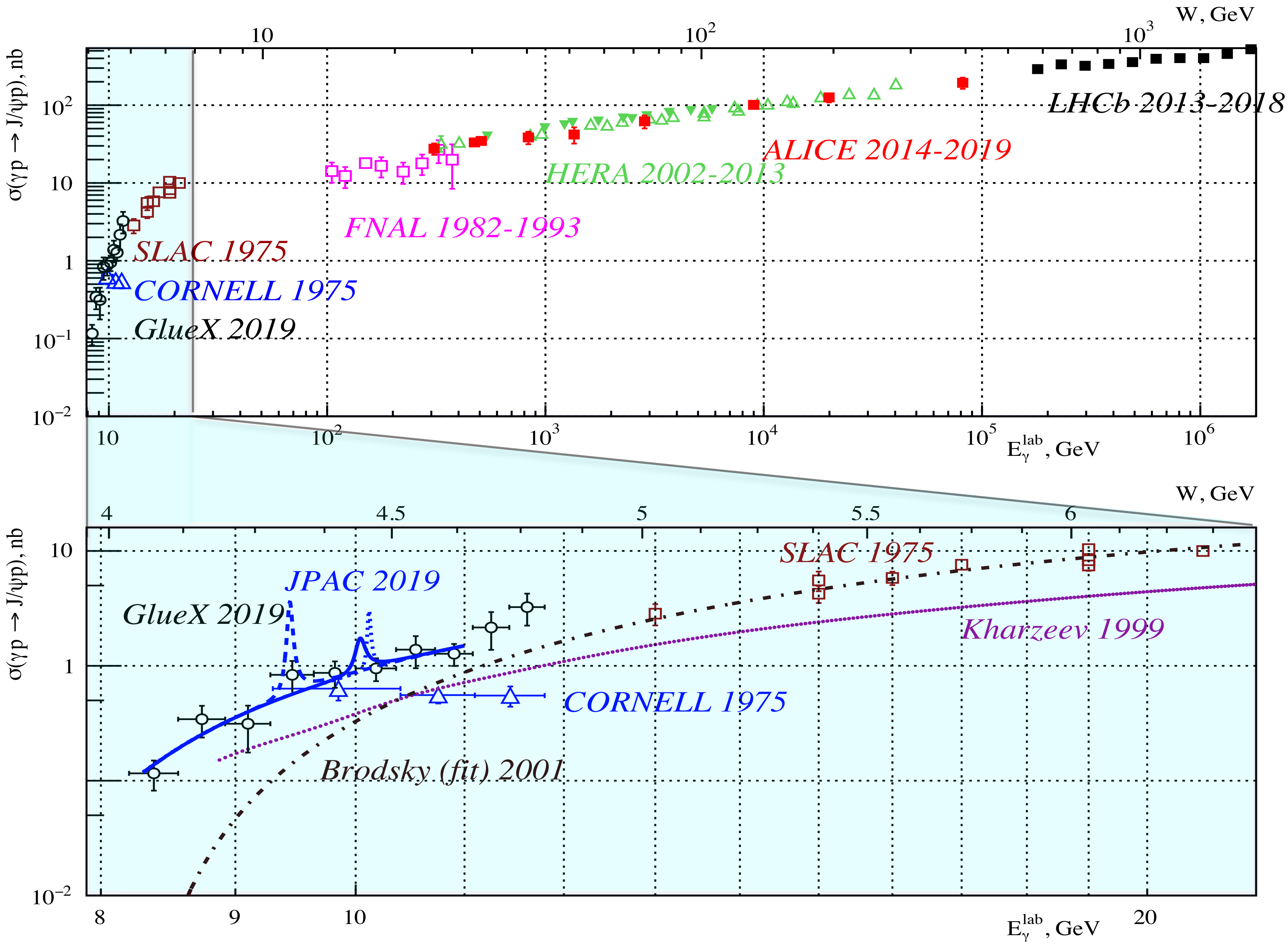
~50 years J/ψ photoproduction



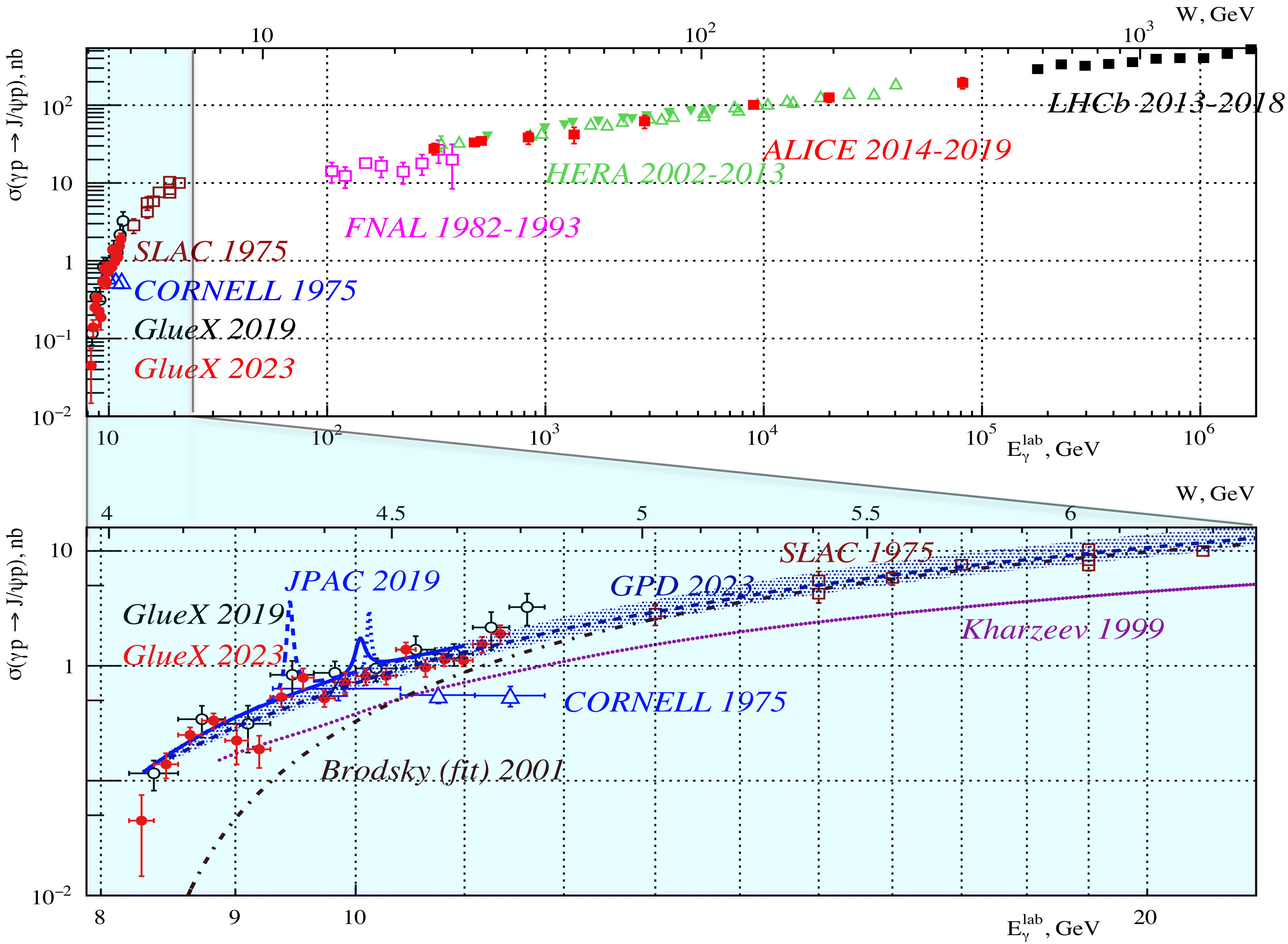
~50 years J/ψ photoproduction



~50 years J/ψ photoproduction

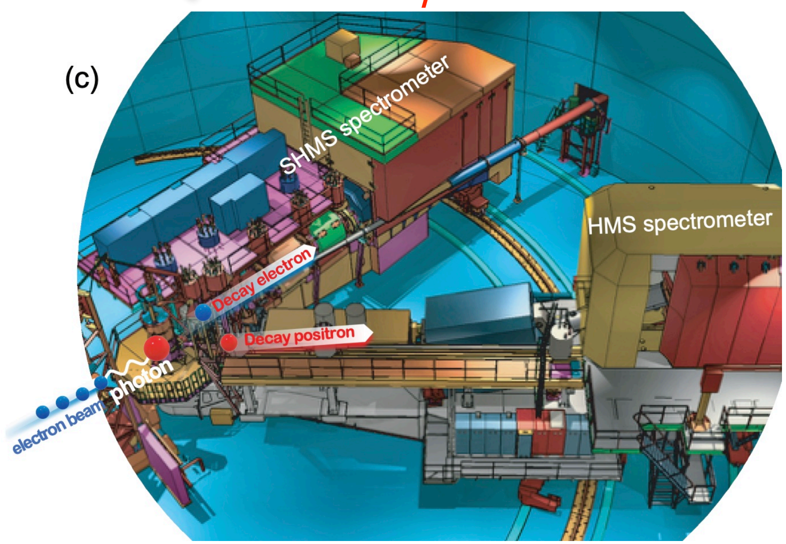


~50 years J/ψ photoproduction



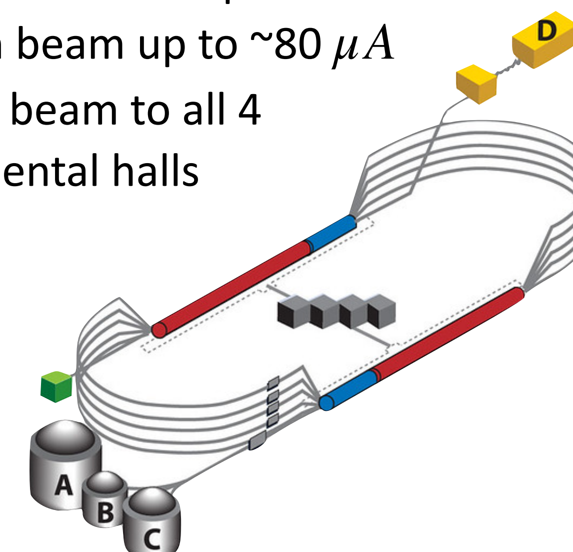
Continuous Electron Beam Facility (CEBAF) at JLab

Hall C J/ψ-007

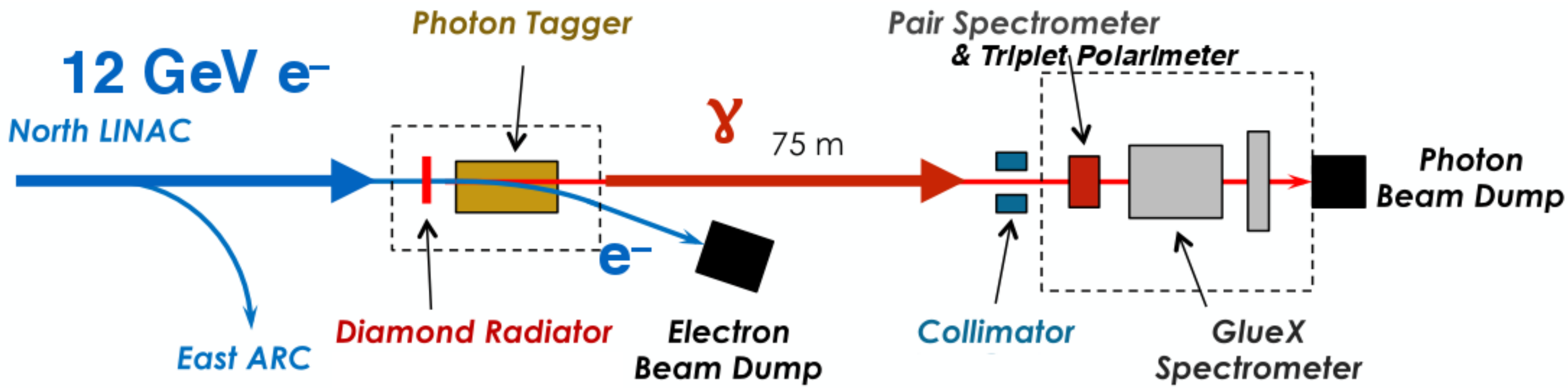


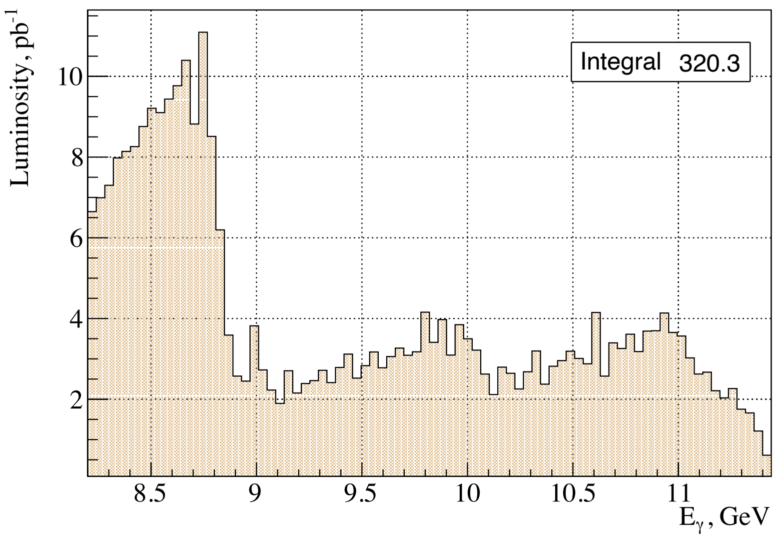
$$(\gamma)p \rightarrow J/\psi(p) \rightarrow e^+e^-(p)$$

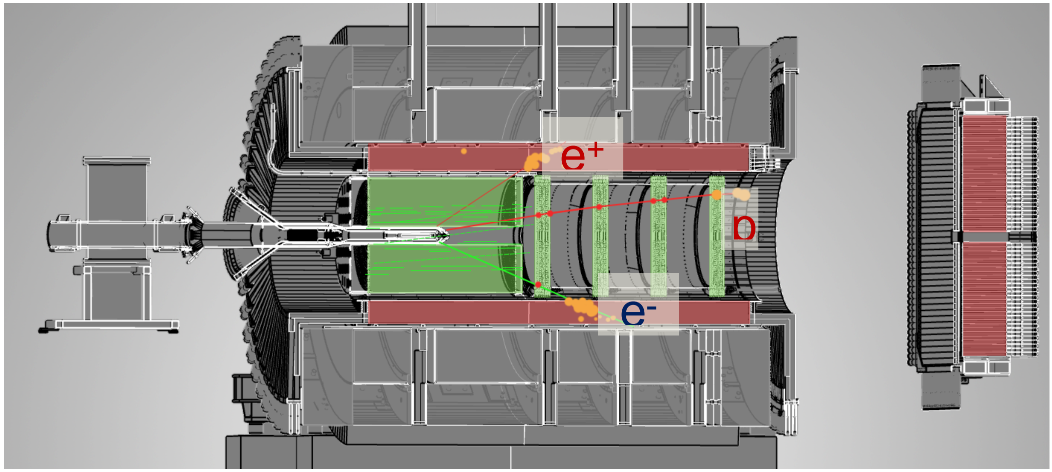
- 12 GeV continuous polarized electron beam up to ~80 μA
- Delivers beam to all 4 experimental halls



Hall D beam line and detector



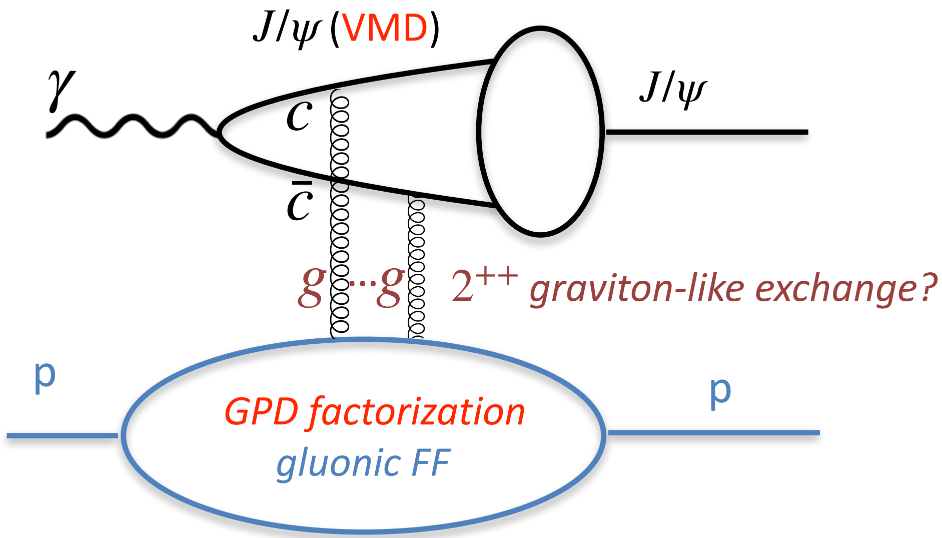


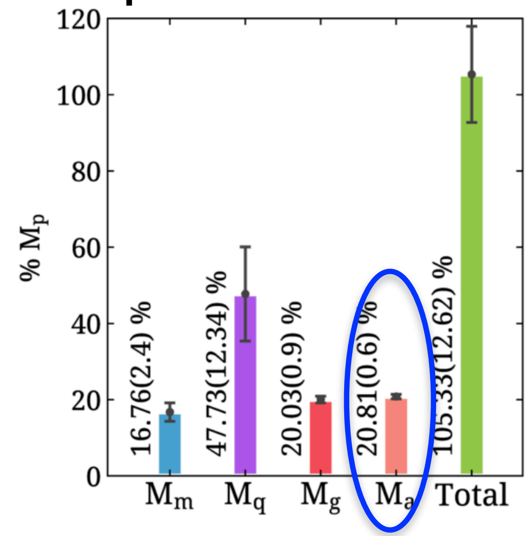


Hall D GlueX $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$

- Linearly-polarized photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Intensity: $\sim 2\ 10^7 - 5\ 10^7\ \gamma/sec$ above J/ψ threshold (8.2 GeV)

Uniqueness of threshold J/ψ photoproduction - relation to gluonic properties of proton

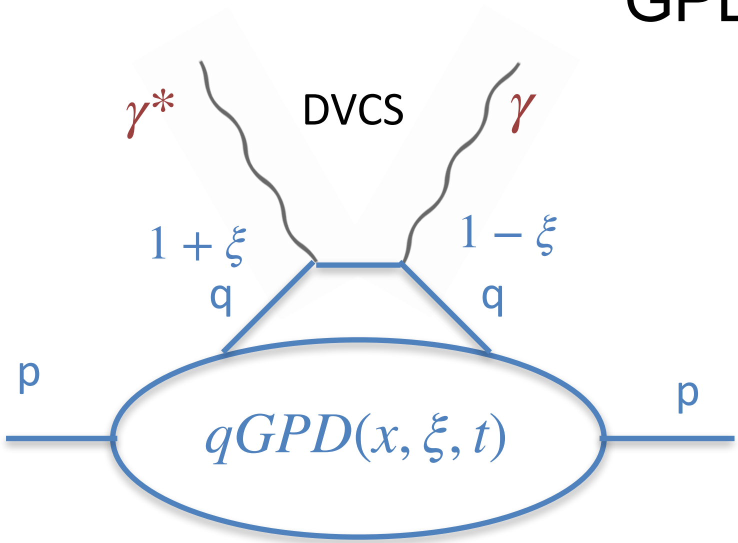


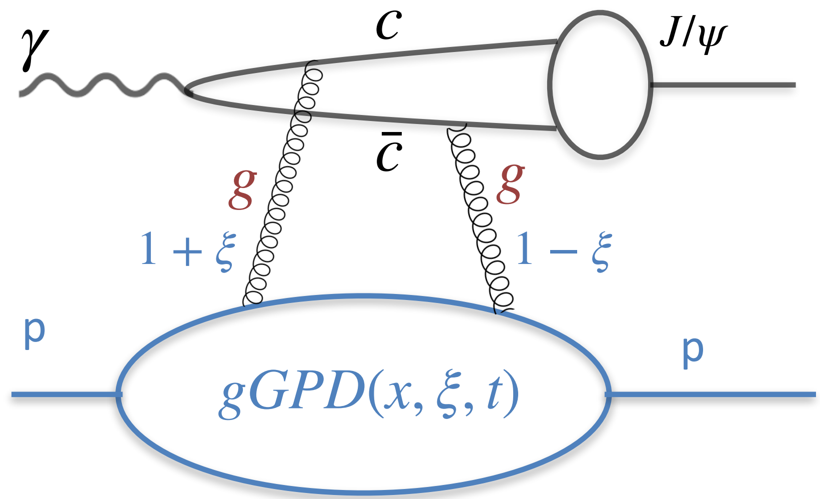


C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

- No common quarks with proton target - interaction via gluon exchange
- Close to threshold J/ψ is produced ~ at rest, amplitude dominated by real part (at high energy Pomeron exchange gives imaginary amplitude), therefore sensitive to trace anomaly (*Kharzeev, Satz, Syamtomov, Zinovjev 1996-1999*) contribution to proton mass (*Ji 1995*), important information about p-J/ψ interaction at low energies
- GPD factorization valid for skewness $\xi \to 1$ (*Guo, Ji at al. 2021-2024),* 2g dominated by 2^{++}exchange (graviton) allows to study mass properties of the proton: gravitational form factors → mass radius of the proton (*Hatta, Kharzeev, Ji et al. 2018-2021*)

Uniqueness of threshold charmonium photoproduction - GPD approach





- Compton-like amplitudes, form-factors $\mathscr{A}_g(t)$, $\mathscr{B}_g(t)$, $\mathscr{C}_g(t)$, as in Deeply Virtual Compton scattering (DVCS)

However:

- gluon (not photon) probe
- Threshold kinematics is very different: high momentum transfer t and skewness ξ
- In heavy-quark limit: $t \to \infty$ $\xi \to 1$

For $\xi \to 1$ expansion in x/ξ:

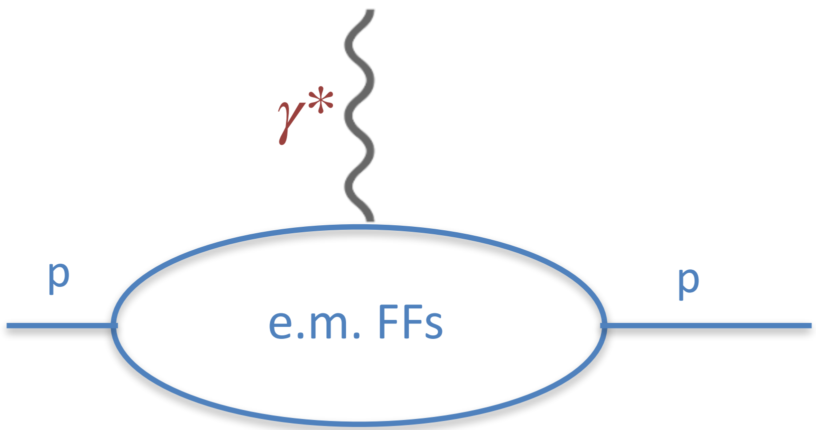
$d\sigma/dt = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)] + \ldots,$ $G_i(t)$ functions of $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$

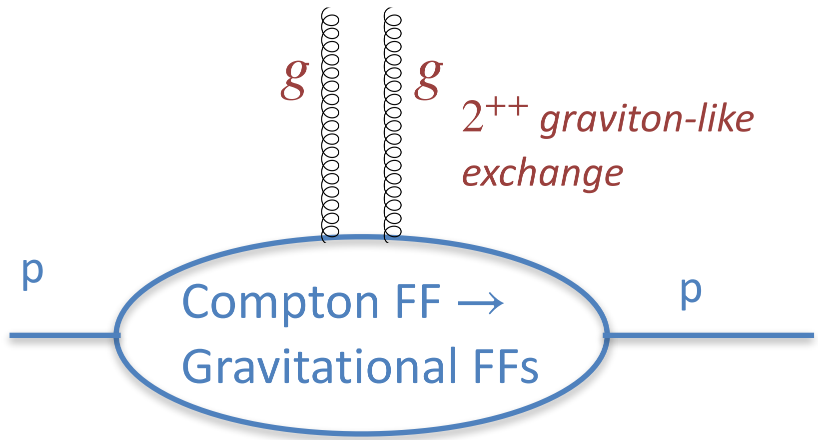
In leading-moment approximation:

gluon Gravitational Form Factors $A_g(t)$, $B_g(t)$, $C_g(t)$ are leading terms of $\mathscr{A}_g^{(2)}(t)$, $\mathscr{B}_g^{(2)}(t)$, $\mathscr{C}_g(t)$

GPD analysis by Guo, Ji, Liu, Yuan PRD 109 (2024)

Gluon Gravitational Form Factors





$$\left(\frac{d\sigma}{d\Omega}\right)_{ep\to ep} = \left(\frac{d\sigma}{d\Omega}\right)_M \frac{1}{(1+\tau)}\left[G_E^2(t) + \frac{\tau}{\epsilon}G_M^2(t)\right]$$

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)]$$

Model approach - fit dipole/tripole FFs (within some model) to data

$$G_E(t), G_M(t) \sim G_D(t) = \frac{1}{(1+t/0.71GeV^2)^2}$$

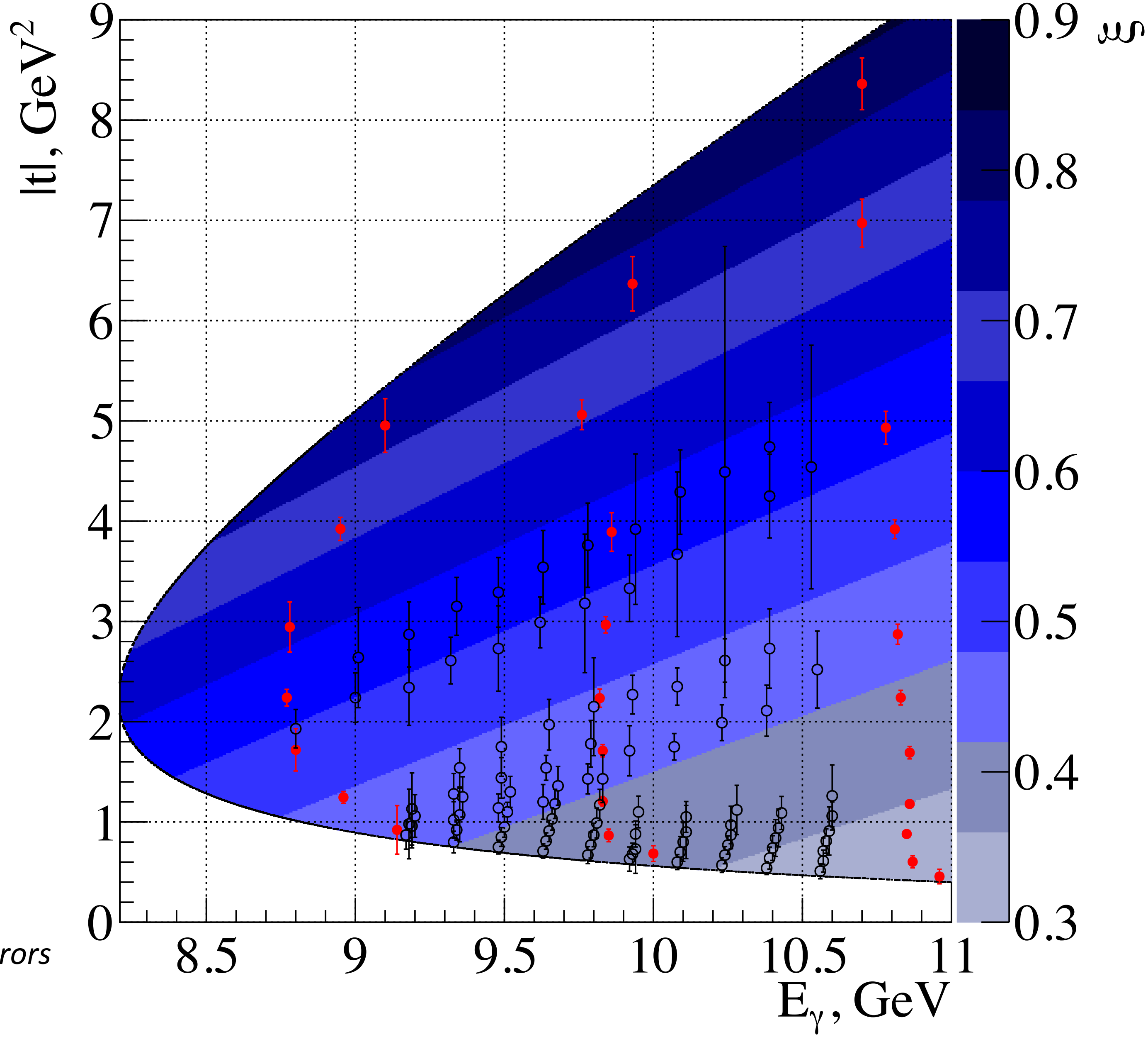
$$A_g(t), B_g(t), C_g(t) \sim \frac{1}{(1+t/m_i^2)^{2(3)}}$$

Rosenbluth separation

$$\sigma_R = \frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega}\right)_M \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau}G_E^2(t) + G_M^2(t),$$

$$\sigma_{R0} = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t) + \xi^2 G_4(t)$$

Near-threshold $d\sigma/dt$ measurements

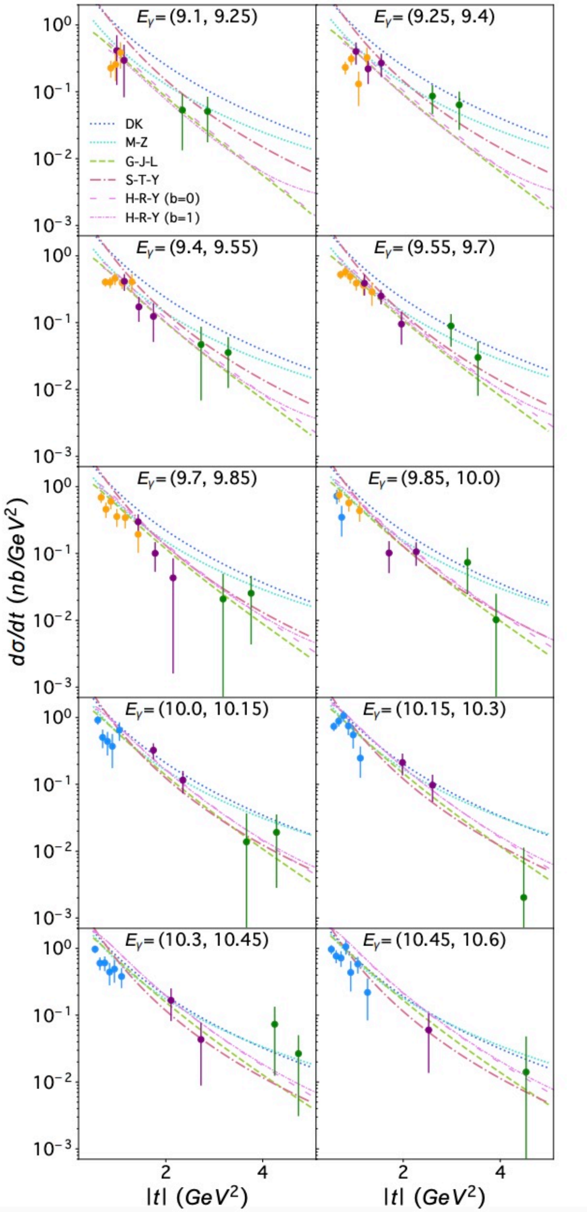


Hall C $J/\psi - 007$

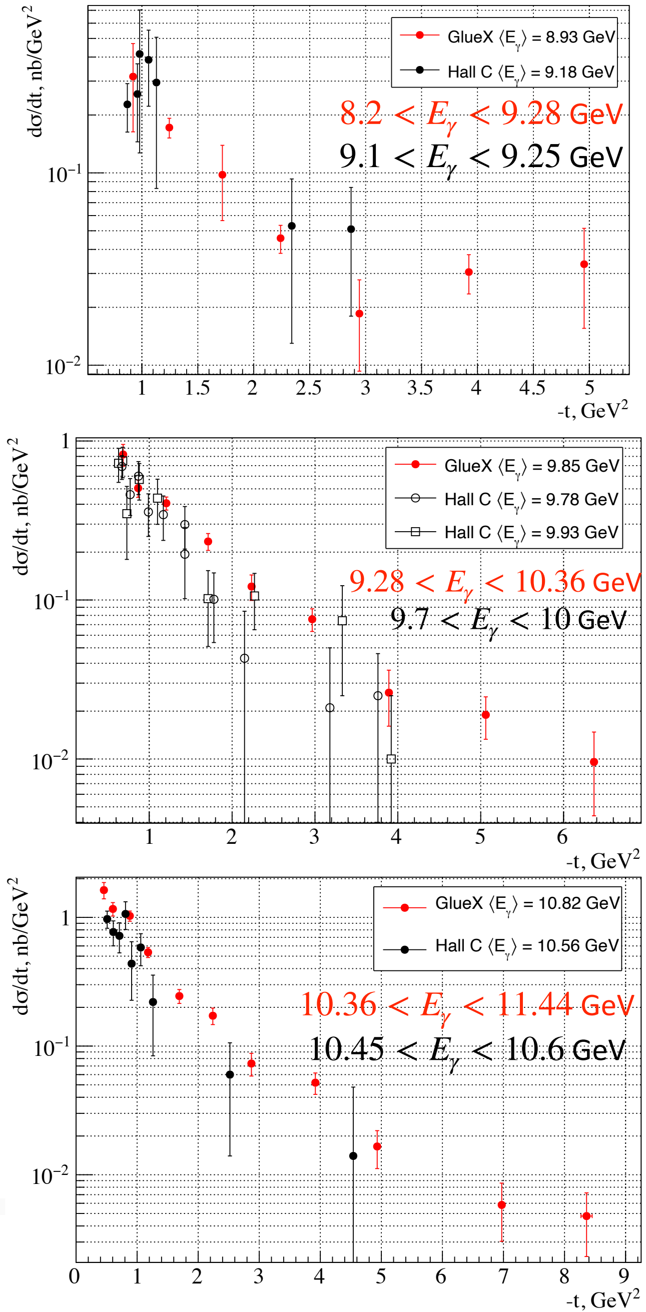
Hall D GlueX

Error bars: relative errors (not related to y-axis)

Differential cross sections from J/ψ-007 and GlueX



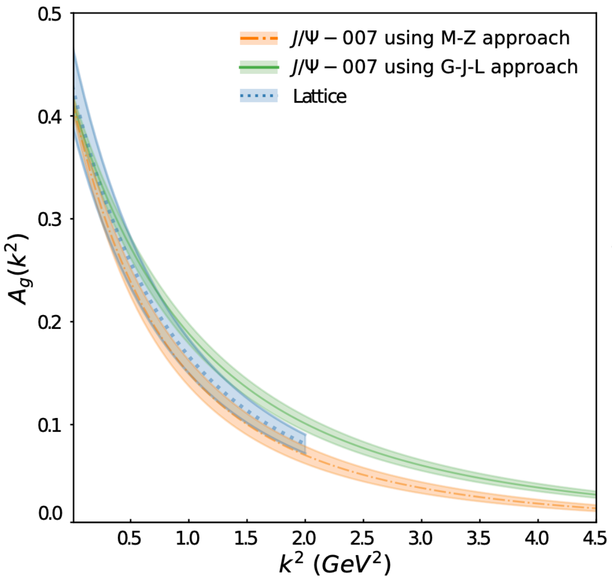
B. Duran et al. (J/ψ-007), Nature 615 (2023)

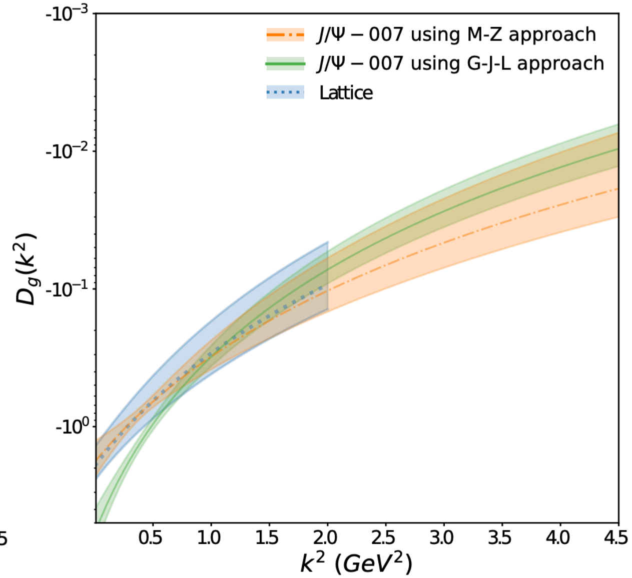


- 10 energy bins in J/ψ-007
- Results for the three **GlueX energy bins** compared to closest **Hall C (J/ψ-007) energies**
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies

S.Adhikari et al. (GlueX), Phys. Rev. C 108 (2023)

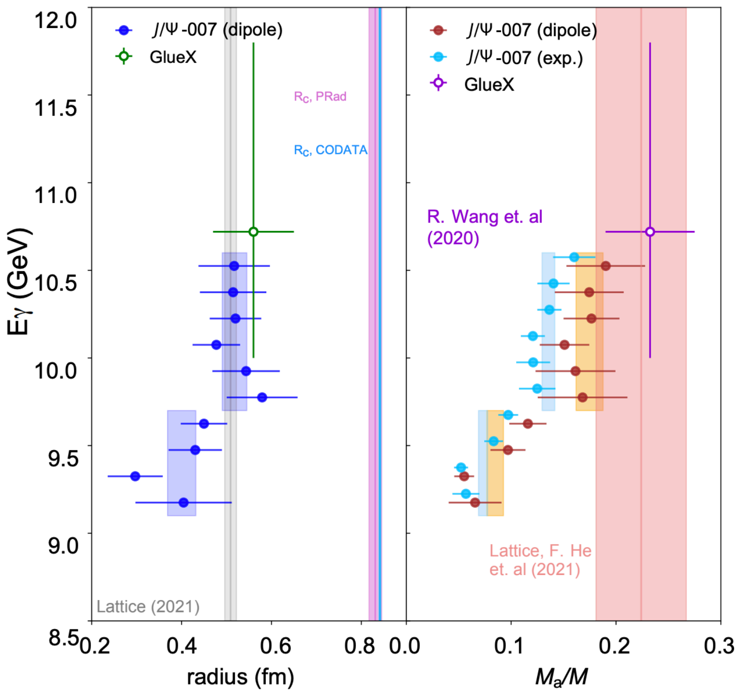
Gravitational Form Factors (model approach) - J/ψ-007





B. Duran et al. (J/ψ-007), Nature 615 (2023)

$k^2 = -t$



Global fit of all Hall C $d\sigma/dt$ data with 3 parameters, m_A, m_C, $C(0)$:

$$A_g(t) = \frac{A_g(0)}{(1 - t/m_A{}^2)^3}, \quad C_g(t) = \frac{C_g(0)}{(1 - t/m_C{}^2)^3}, \quad D_g(t) = 4C_g(t)$$

($A_g(0)$ fixed from global DIS analysis) using two theoretical models:

1) Guo, Ji, Liu PRD103 (2023), using GPD factorization

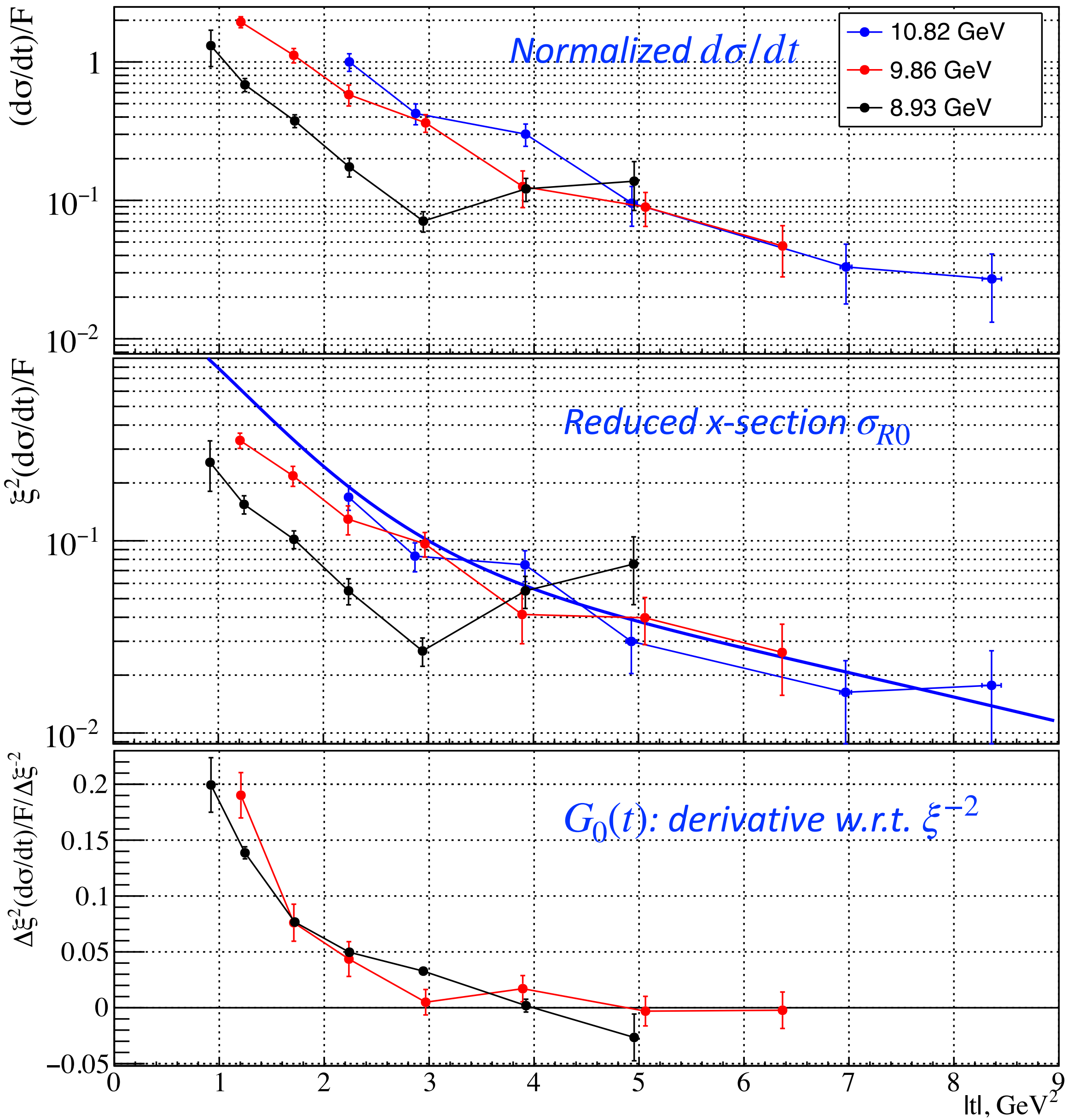
2) Mamo, Zahed PRD101 (2020), holographic QCD, $d\sigma/dt(t)$ directly related to GFF

Lattice calculations of GFF: Pefkou, Hackett, Shanahan PRD105 (2022)

Mass radius and anomalous contribution to proton mass:

Kharzeev et al. NPA 661 (1999), Kharzeev PRD 104 (2021), Guo at al. PRD 103 (2021)

Gluon Form Factors (Rosenbluth separation) - GlueX data



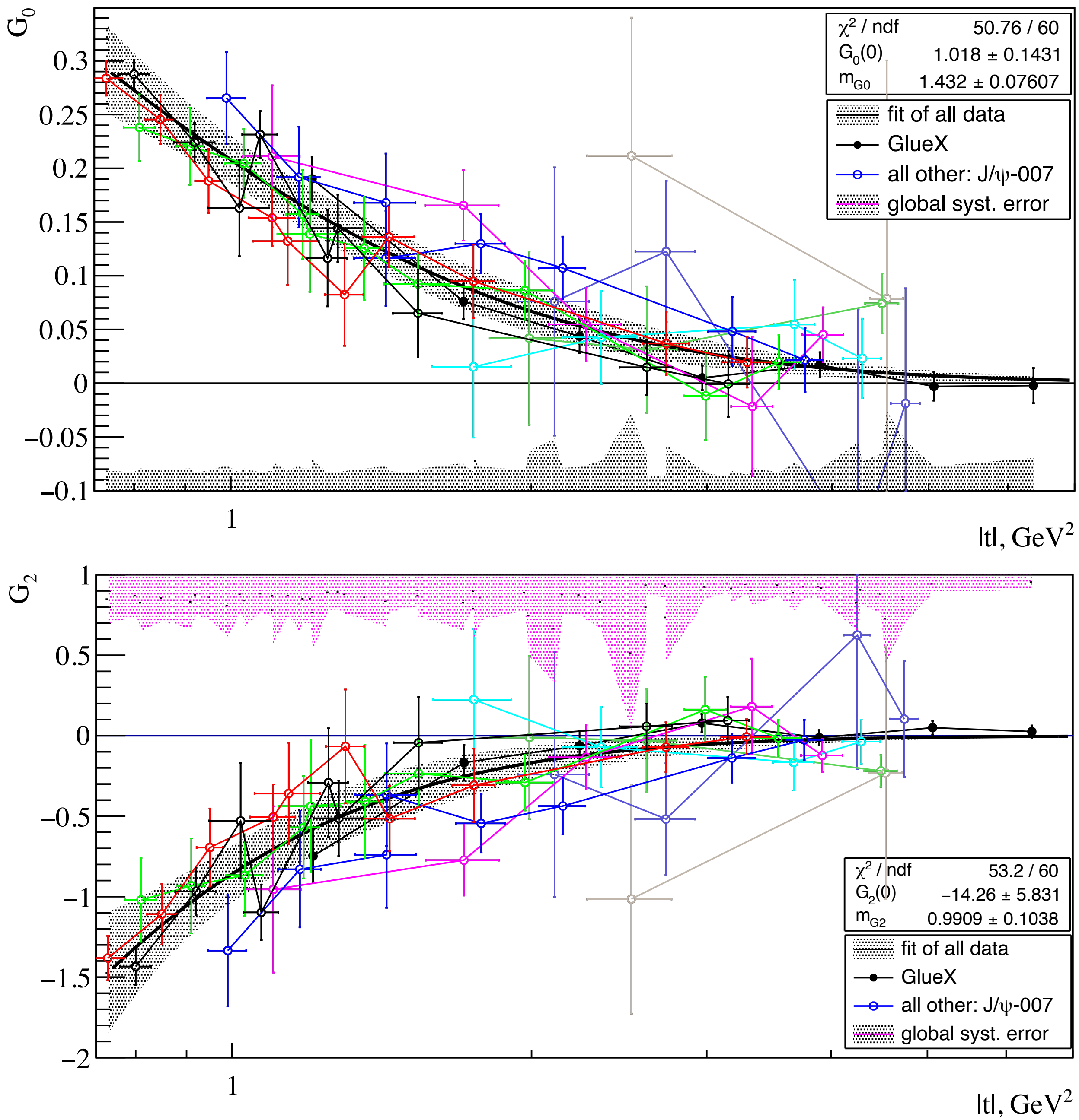
Testing energy independence of the gluon Form Factors

$$\sigma_{R0} = \frac{d\sigma}{dt}\frac{\xi^2}{F(E_\gamma)} = \xi^{-2}G_0(t) + G_2(t)$$

$$G_0(t) = \left[\sigma_{R0}(E_i, t) - \sigma_{R0}(E_j, t)\right] / \left[\xi^{-2}(E_i, t) - \xi^{-2}(E_j, t)\right]$$

$\xi > 0.4$

Gluon Form Factors (Rosenbluth separation) - all data



Testing energy independence of the gluon Form Factors

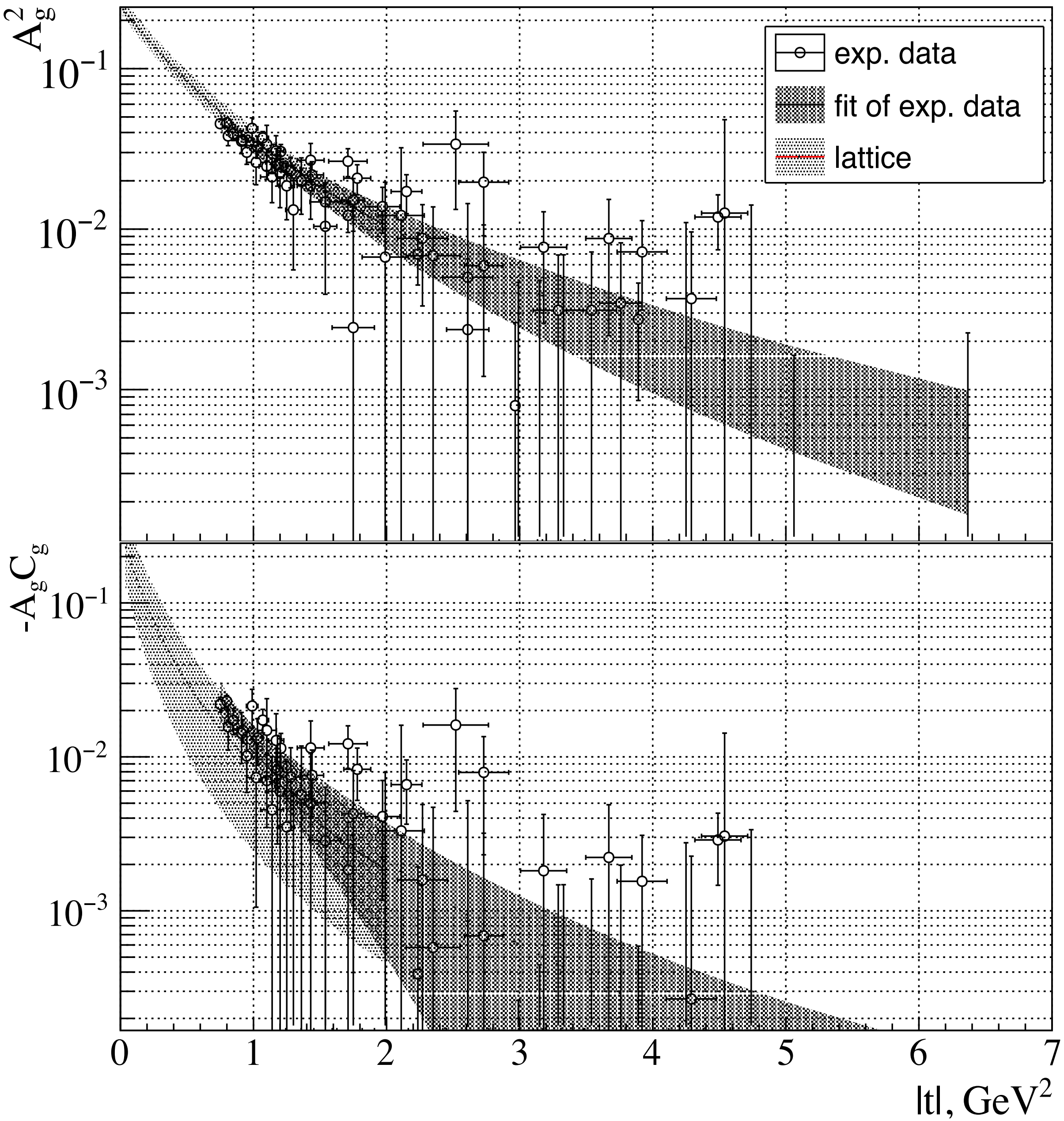
Fits with:

$$\frac{G(0)}{(1+t/m^2)^4}$$

$$\xi > 0.4,$$
$$E_\gamma > 9.3 \text{ GeV}$$

LP and E.Chudakov
arXiv:2404.18776

Gluon Gravitational Form Factors - all data



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

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

In leading-moment approximation access to gluon GFFs $A_g(t)$, $C_g(t)$ (neglecting $B_g(t)$):

$$G_0(t) \sim A_g^2(t)$$
$$G_0(t) + G_2(t) \sim A_g(t)C_g(t)$$

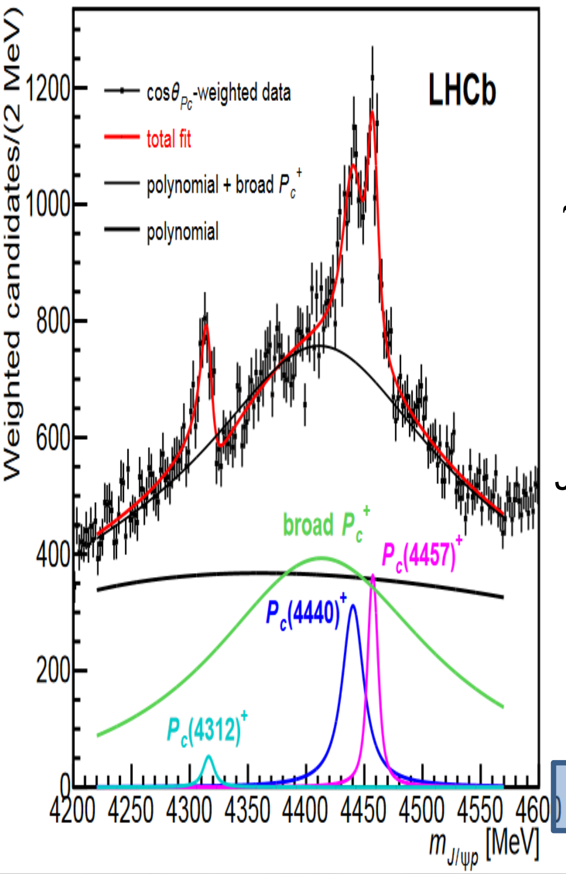
also calculated on lattice:

Pefkou, Hackett, Shanahan PRD105 (2022), Hackett, Pefkou, Shanahan arxiv:2310.08484 (2023)

LP and E.Chudakov arXiv:2404.18776

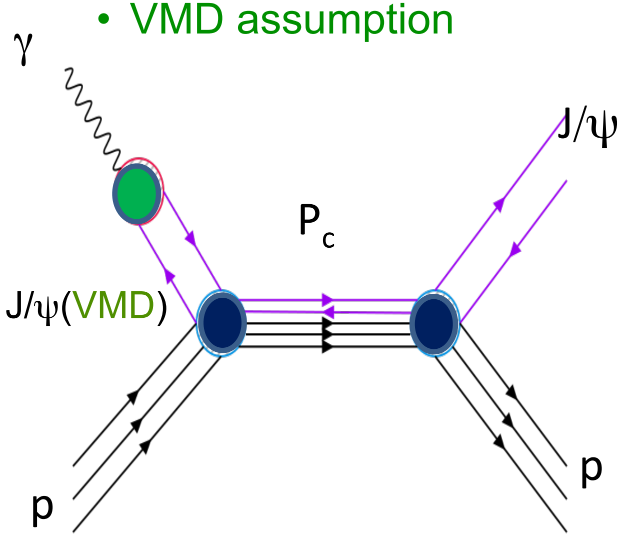
LHCb pentaquarks and J/ψ photo-production

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

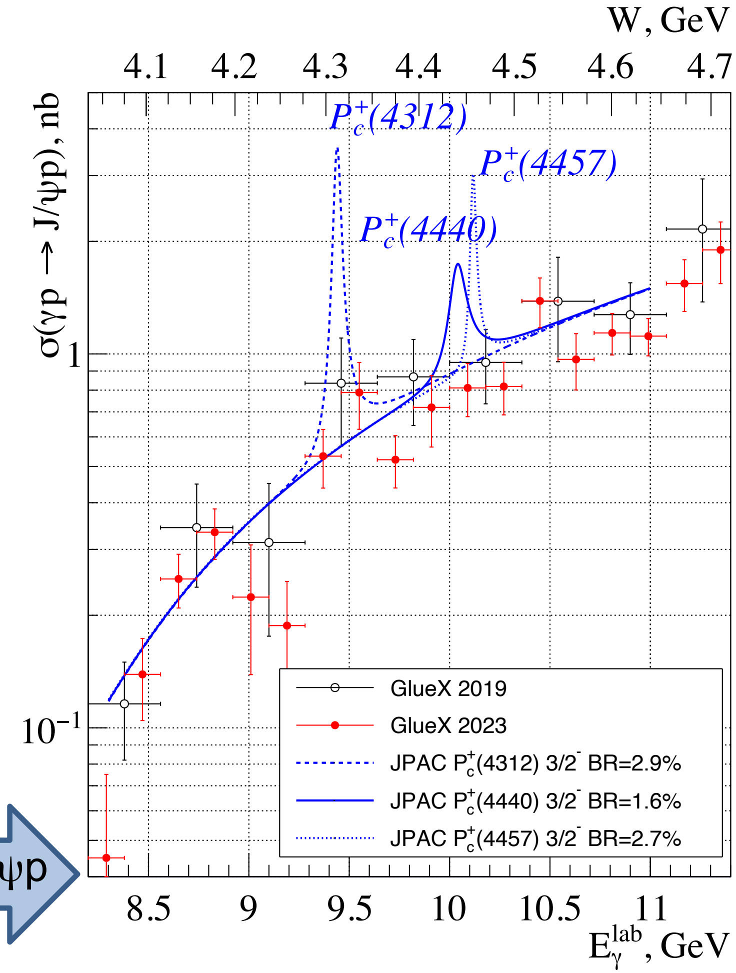


Main uncertainty:

- Br. ratio $P_c \to J/\psi p$
  $\sigma \sim \mathscr{B}^2(P_c \to J/\psi p)$
- VMD assumption



LHCb P_c related to $\gamma p \to P_c \to J/\psi p$

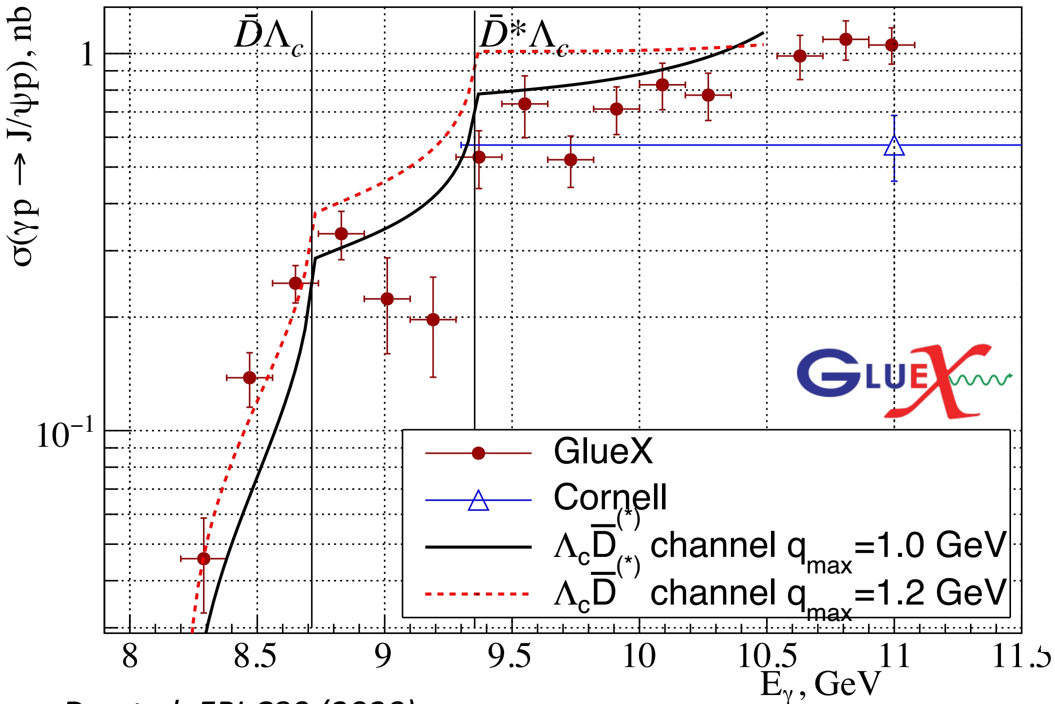


V.Kubarovsky and M.B.Voloshin, PRD 92.031502 (2015).
M.Karliner and J.Rosner, arXiv: PLB 752, 329 (2016).
A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).

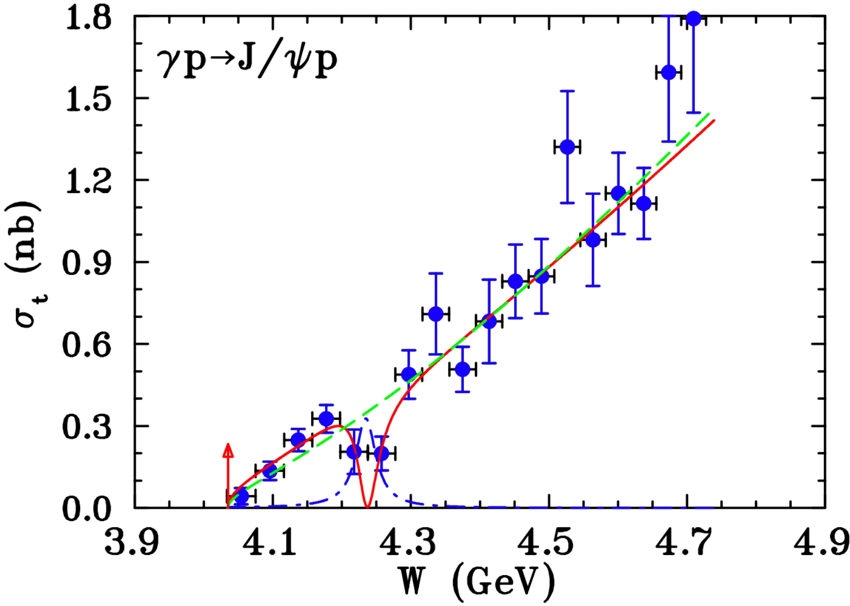
J/ψ-007: much lower upper limits based on modeling t-dependance of P_c^+ production

B.Dran, Ph.D. thesis, TU(2021)

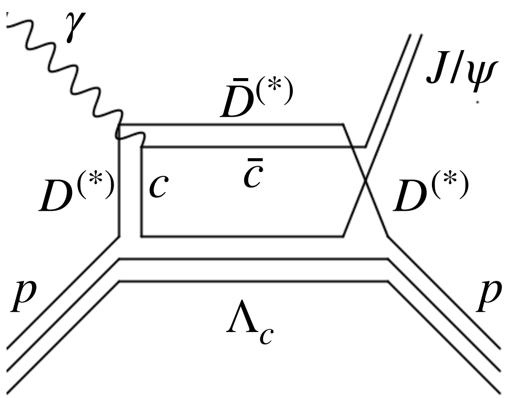
Other reaction mechanisms: open-charm, 5q exchange

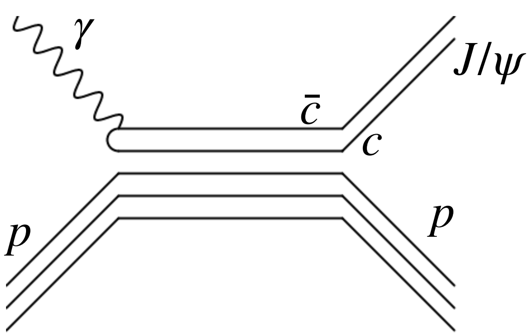


Du et al. EPJ C80 (2020)



Strakovsky et al. PRC 108 (2023)



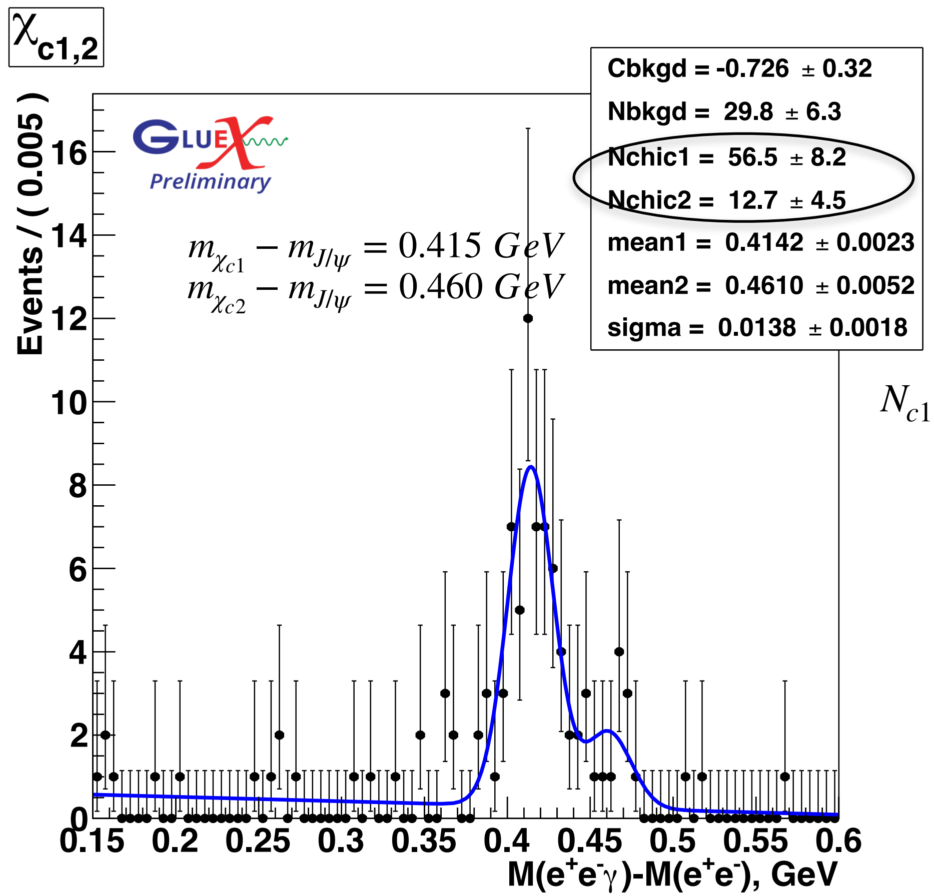


JPAC PRD 108 (2023)

Threshold photoproduction of higher-mass charmonium states

C-event charmonium states at threshold with GlueX

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



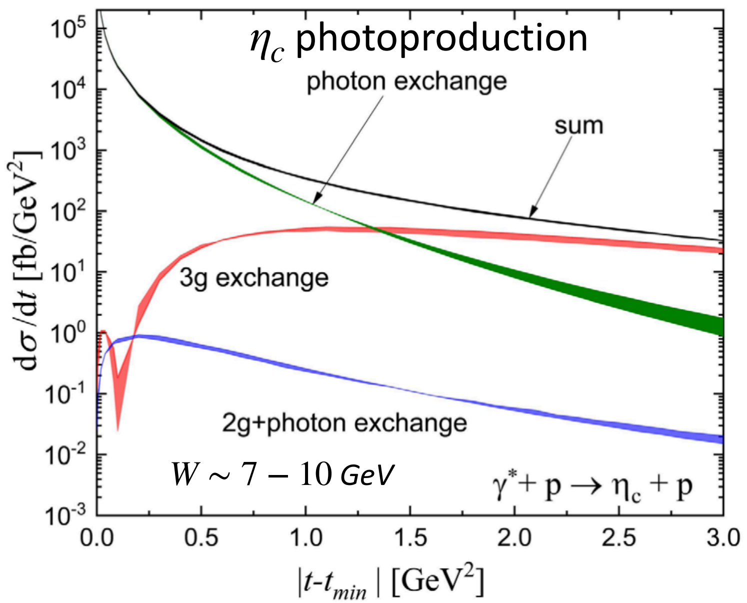
$$N_{c1}e^{-\frac{(x-m1)^2}{2\sigma^2}} + N_{c2}e^{-\frac{(x-m2)^2}{2\sigma^2}}$$

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

First ever evidence for photoproduction of C-even charmonium

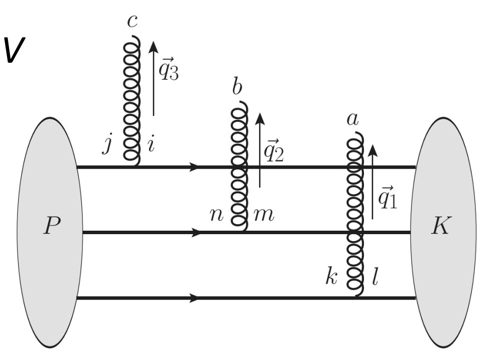
C-even charmonium states with GlueX

C-odd (J/ψ, ψ') vs C-even (χ_c) production

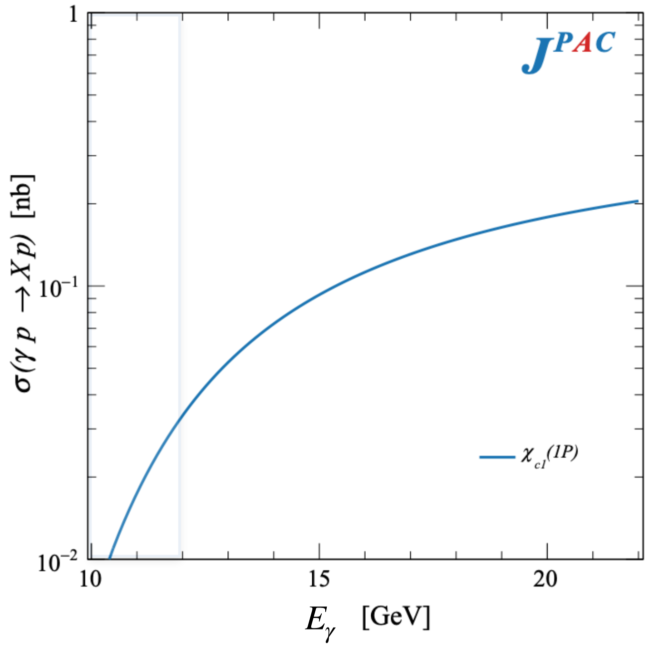


Dumitru, Skokov, Stebel, PRD 101 (2020), Dumitru, Stebel, PRD 99 (2019)

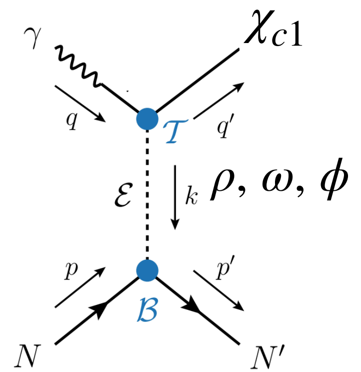
$W \sim 7 - 10$ GeV



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



JPAC, PRD 102 (2020)

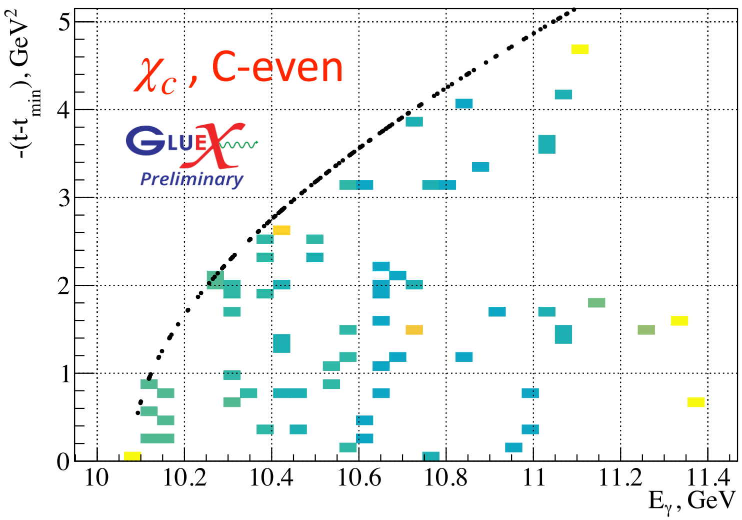


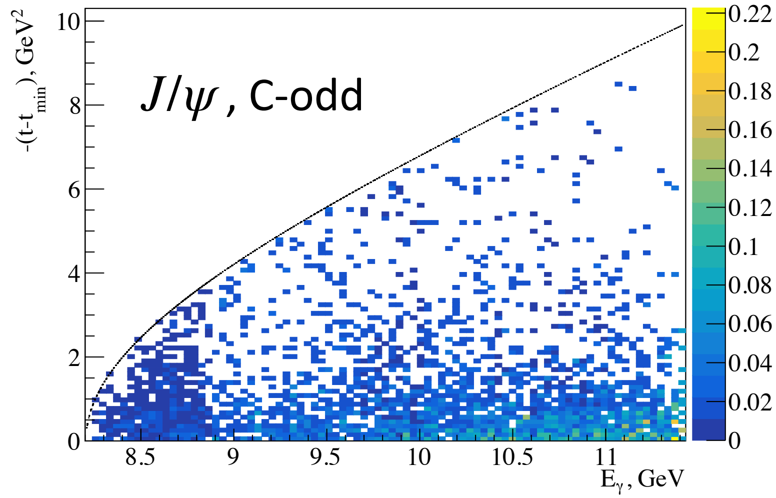
- Low energies - non-perturbative approach, vector meson exchange

C-even charmonium states with GlueX

C-odd (J/ψ, ψ') vs C-even (χ_c) production

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

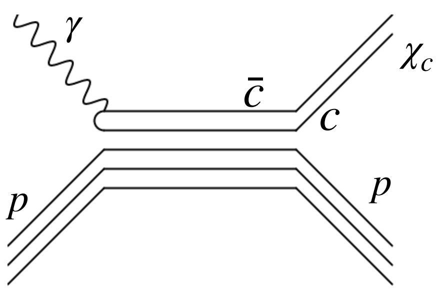




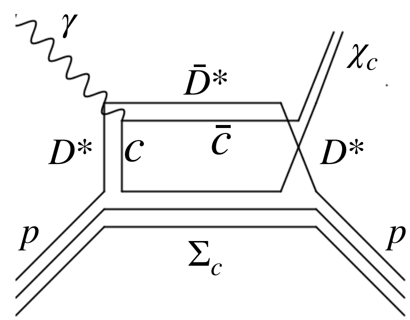
$$weight = \frac{1}{L(E_\gamma)}$$

- At threshold other possible mechanisms may dominate:

S-channel exchange of 5q



Open-charm exchange

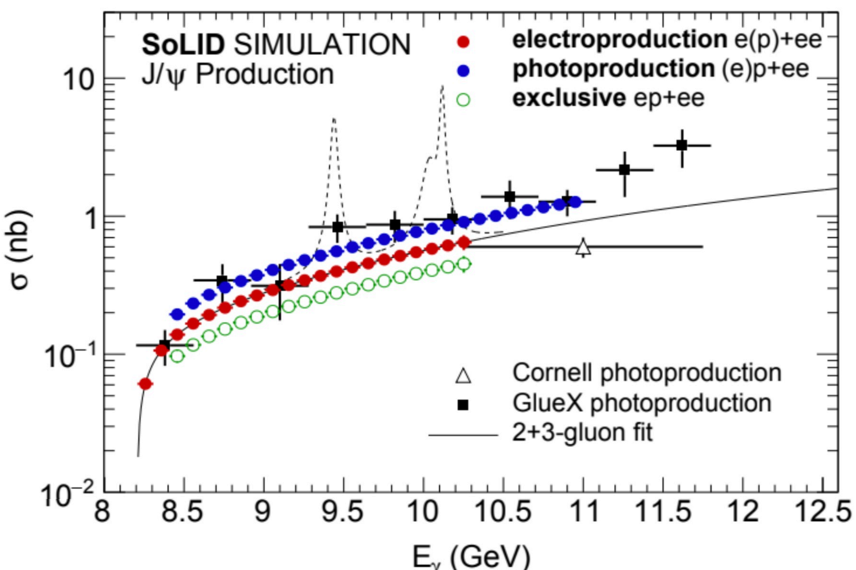


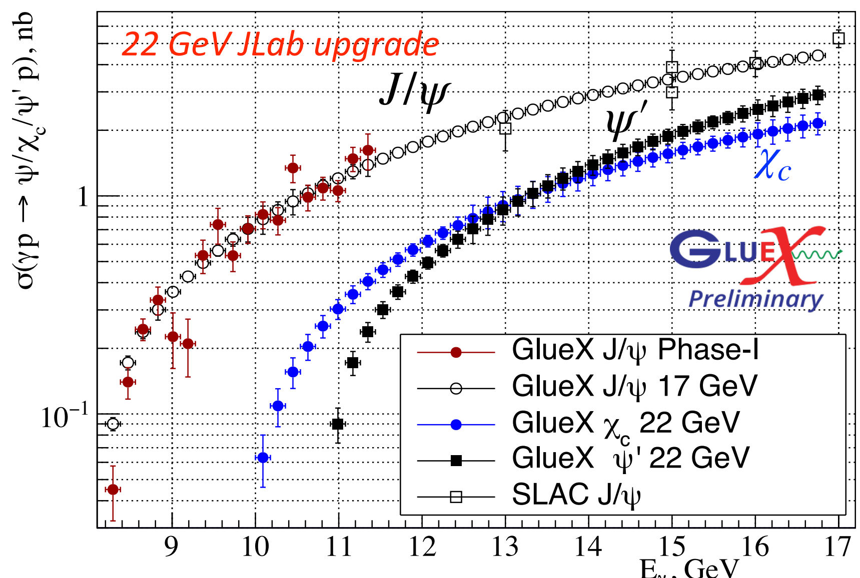
Prospect for charmonium threshold production at JLab

- GlueX has planned running till 2025 (phase-II) and proposal for phase-III (double intensity):

Run Period	J/ψ	χ_{c1}	$\psi(2S)$
2016-2020 Phase I-II	3,960	55	12
2023-2025 Phase II (planned)	*3,615*	*48*	*11*
Phase III (proposal)	*11,271*	*364*	*178*
Projected Total	18,846	467	201

- Results from from Hall B expected soon
- SoLID detector (in Hall A) would be the ultimate J/ψ factory at threshold (*800k*) , including electroproduction (*20k*) - mentioned in the recommendations of 2023 Long Range Plan for nuclear science, under reviewing process
- JLab energy increase up to 22 GeV (white paper - arXiv:2306.09360) critical in justifying charmonium photoproduction near threshold as a method to study mass properties of the proton; also passing thresholds of $X(3872)$, $Z_c^+(3900)$ photoproduction (~12 GeV)





Summary

- After ~50 years, thanks to 12 GeV CEBAF, precise measurements of J/ψ photoproduction in full near-threshold kinematic region

- Near-threshold cross sections contain important information about gluonic (mass) properties of proton target and p-J/ψ interaction at low energies

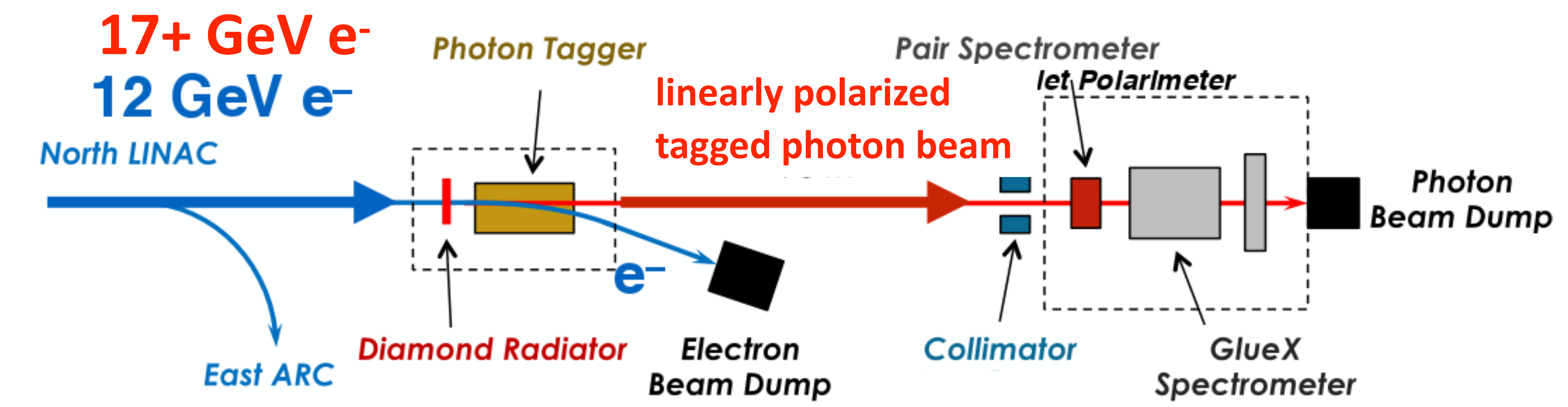
- Gluon Form Factors extracted from JLab data are energy independent in agreement with GPD factorization and within some models can be related to Gravitational Form Factors, showing general agreement with lattice, however more data and theoretical efforts are needed

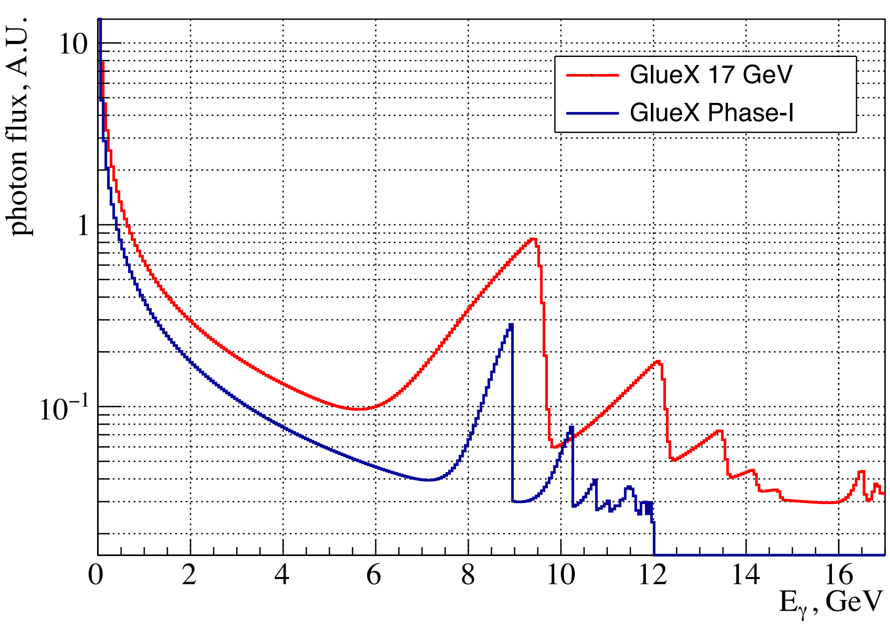
- No evidence for LHCb pentaquarks in the s-channel found

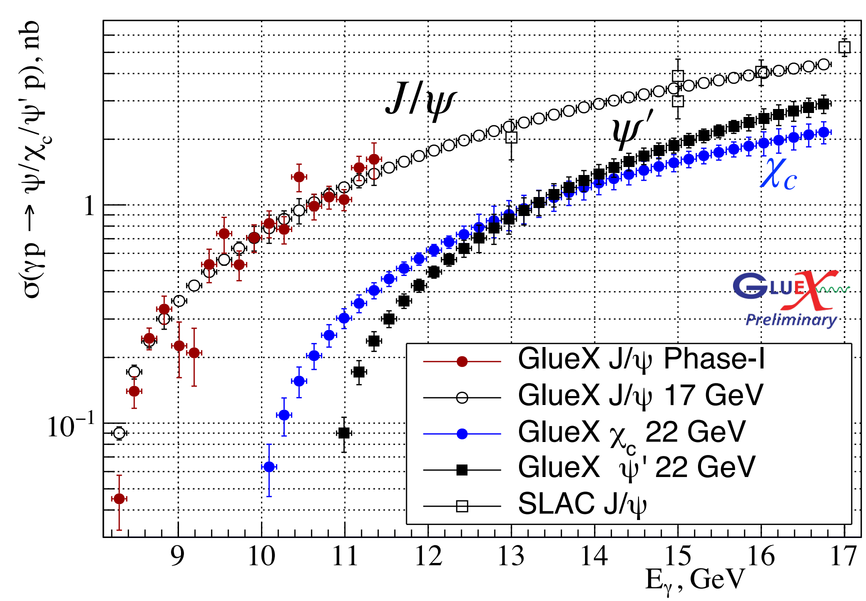
- First ever evidence for C-even charmonium photoproduction - important to understand reaction mechanism, complementary to J/ψ (C-odd charmonium) studies

- Future planned and proposed experiments at JLab will increase significantly the statistics, critical for justifying threshold charmonium production as a tool to study gluonic structure of the nucleon

Hall D Apparatus with 17+ GeV electron beam



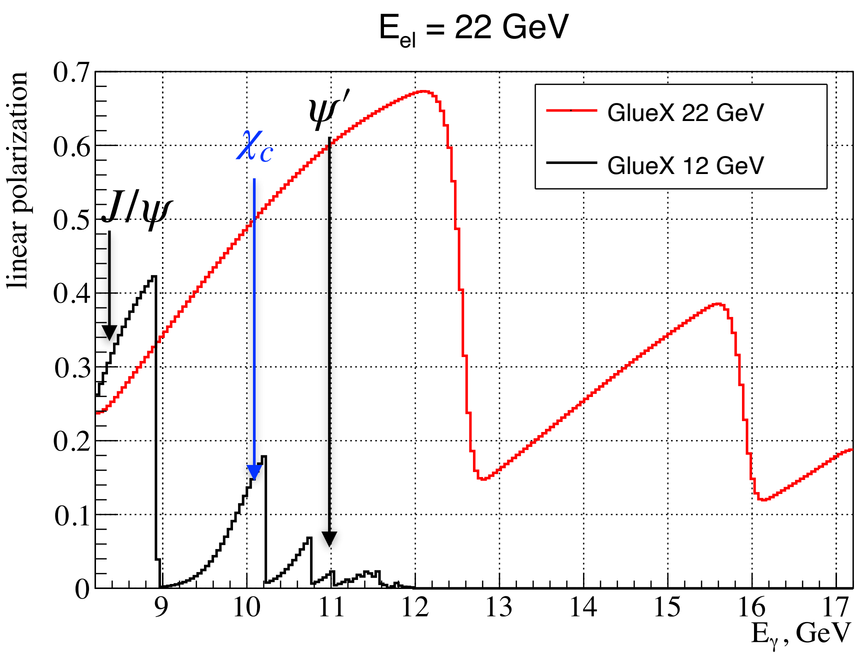


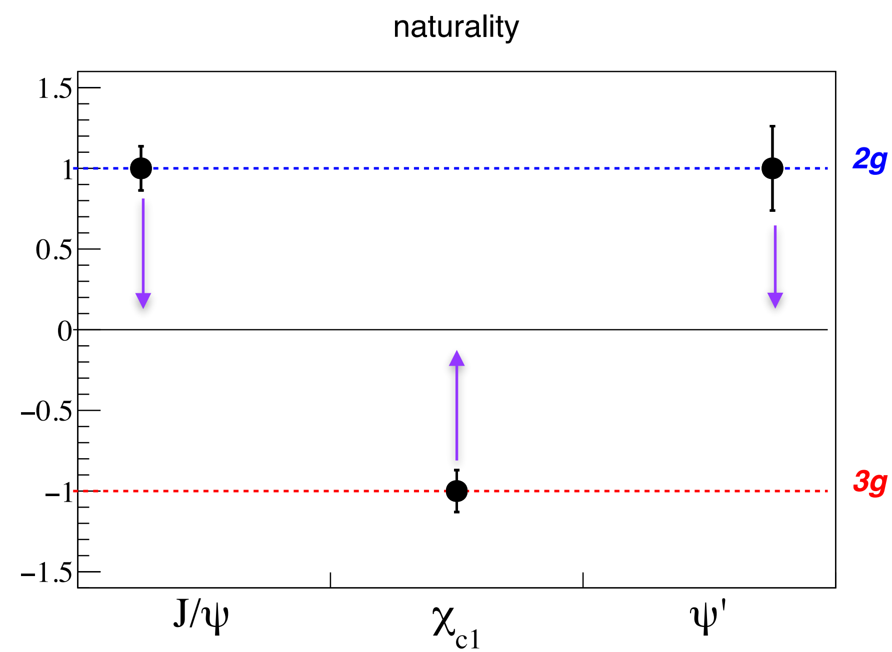


- Moving end point from 12 GeV to 17+ GeV:
  - higher flux (and polarization) toward higher energies, while low energies less affected (no load on detectors)

Charmonium polarization measurements at 22 GeV

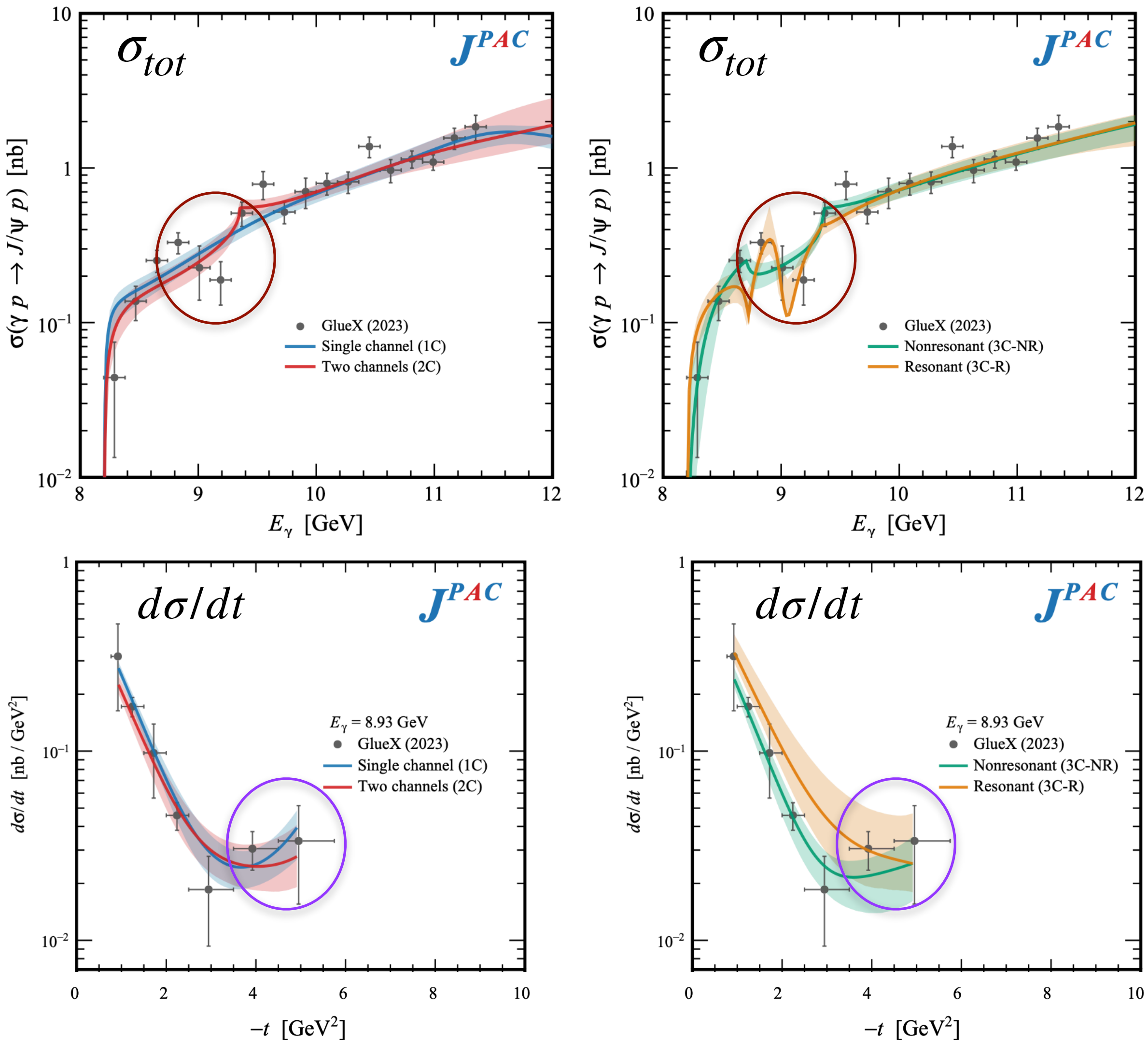
$naturality \times (-1)^J = P$





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

Phenomenological approach: JPAC results



JPAC arxiv:2305.01449 (2023)

Global fit of both Hall C & D $d\sigma/dt(t)$ and Hall D $\sigma_{tot}(E_\gamma)$

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 indicates s-channel contribution: due to proximity to threshold or open-charm exchange