Near-threshold exclusive J/ψ photoproduction with GlueX

$$\gamma p \to J/\psi p$$

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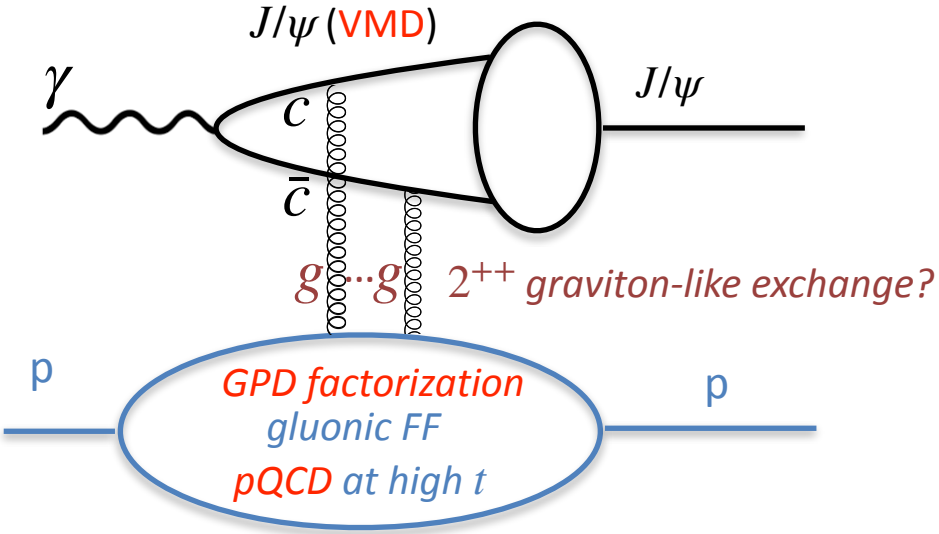
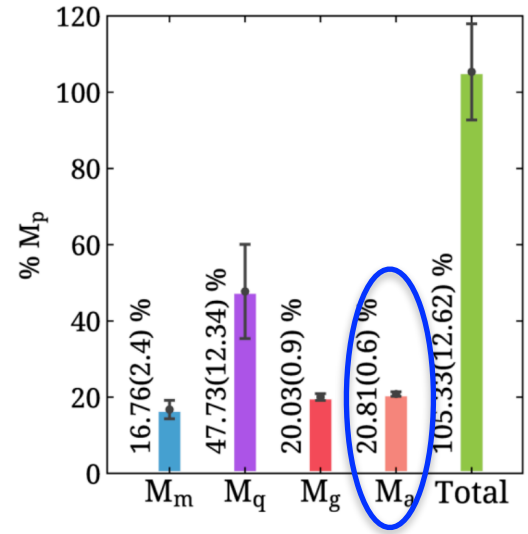
(GlueX Collaboration)

- Why study threshold J/ψ production?
- New results from Jefferson Lab - total and differential cross section in the full near threshold kinematic region - based on full GlueX Phase-I dataset
  - Total cross section (from threshold E_γ=8.2-11.44 GeV)
  - Differential cross sections: three E_γ slices, each $t_{min}(E_\gamma) - t_{max}(E_\gamma)$
- Interpretation of the results
  - Phenomenology - forward cross section at threshold ($t \to 0$, $E_\gamma \to E_{thr.}$)
  - Gluon exchange: VMD, GPD factorization models
  - Open-charm exchange
  - Discussion: relevance to the mass properties of the proton
- Outlook

Threshold J/ψ photoproduction ↔ mass properties of proton?





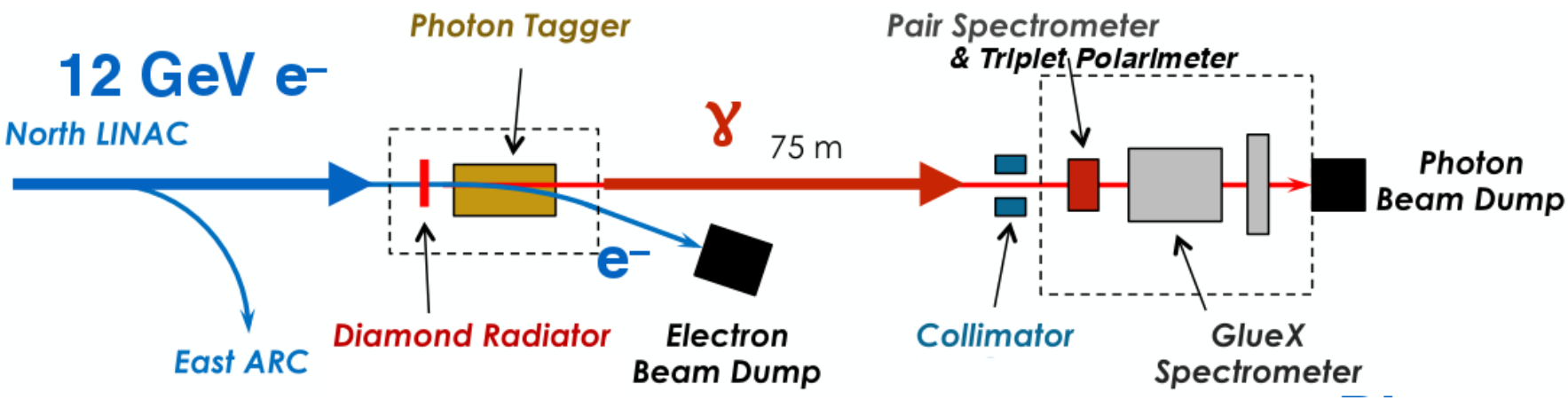
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

- 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 anomaly - quantum fluctuations (*Kharzeev, Satz, Syamtomov, Zinovjev 1996-1999*) contributing to proton mass (*Ji 1995*)
- GPD factorization valid for $m_c \to \infty$ 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 → mass radius of the proton (*Hatta, Kharzeev, Ji et al. 2018-2021*)

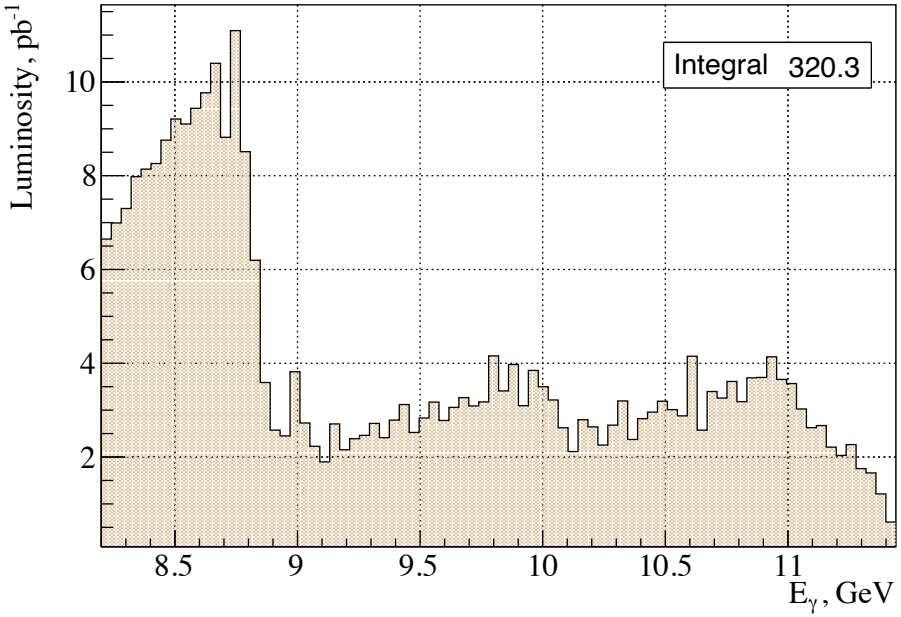
- At large t pQCD approach - no direct relation to gravitational FF? (*Sun, Tong, Yuan 2021,2022*)
- Is the J/ψ mass large enough for the above assumptions to be valid?

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

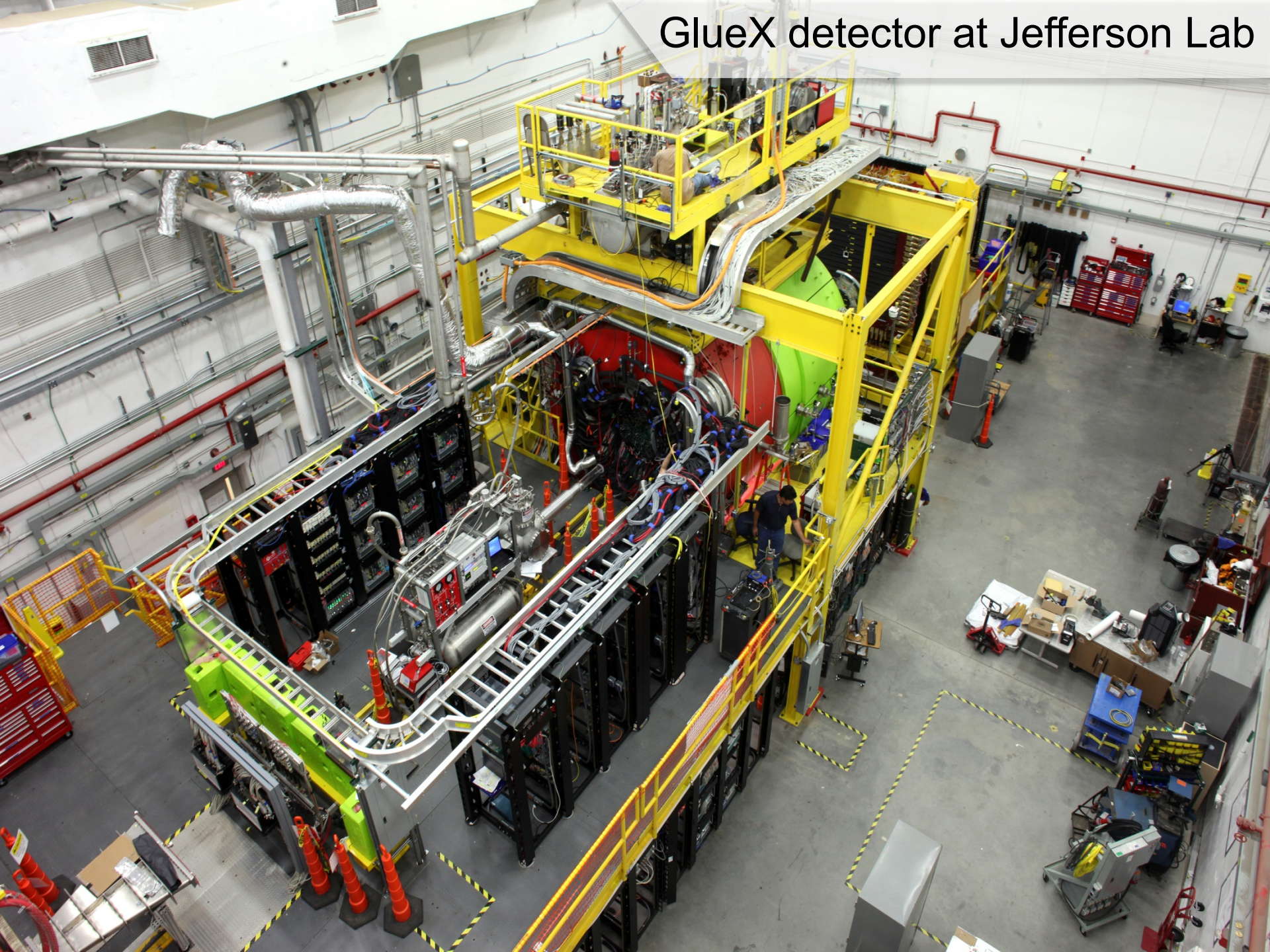
Hall D Apparatus at CEBAF



- Photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75m, <35 μrad
- Intensity: ~ 2 10^7 - 5 10^7 γ/sec above J/ψ threshold (8.2 GeV) – total ~320 pb^{-1} in GlueX phase-I runs



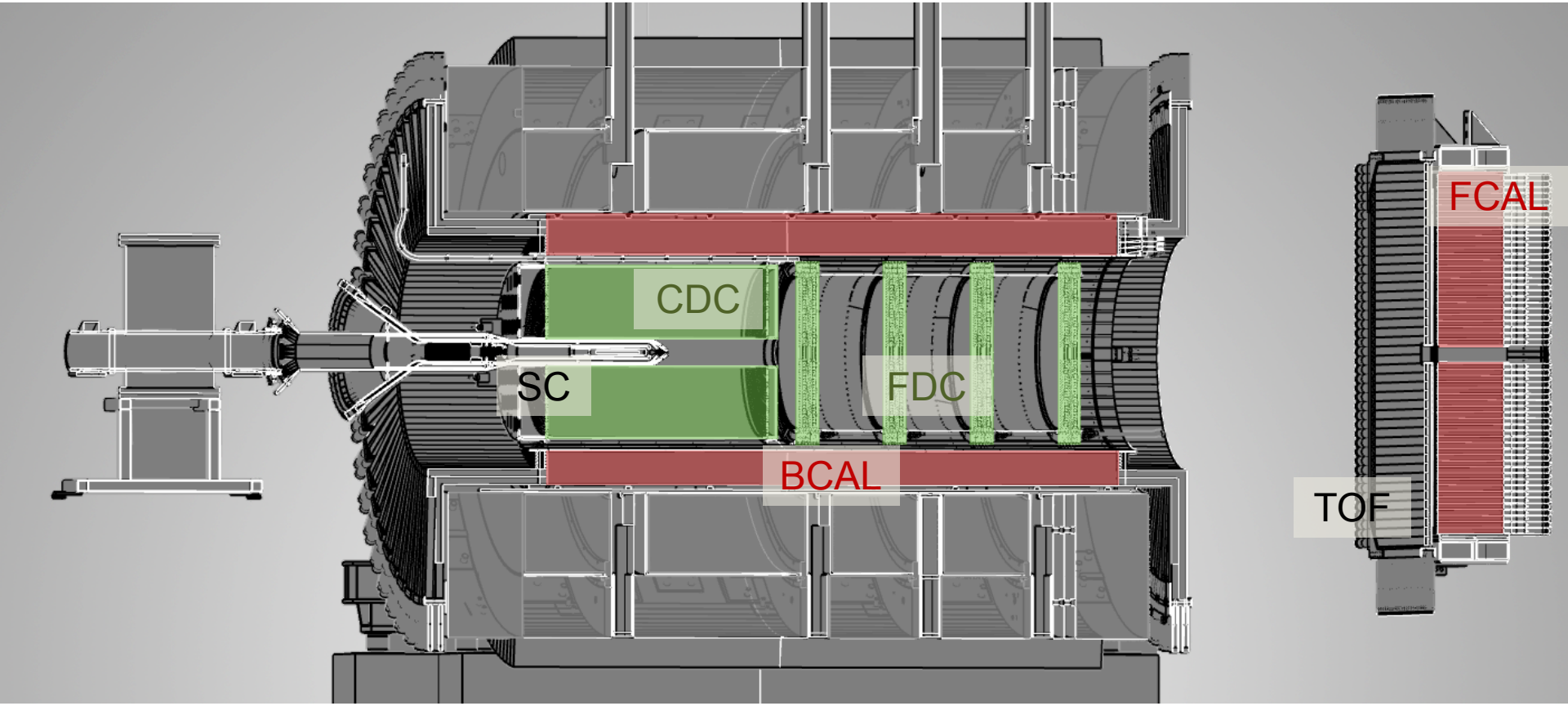
GlueX detector at Jefferson Lab



GlueX detector

2T-solenoid, LH target

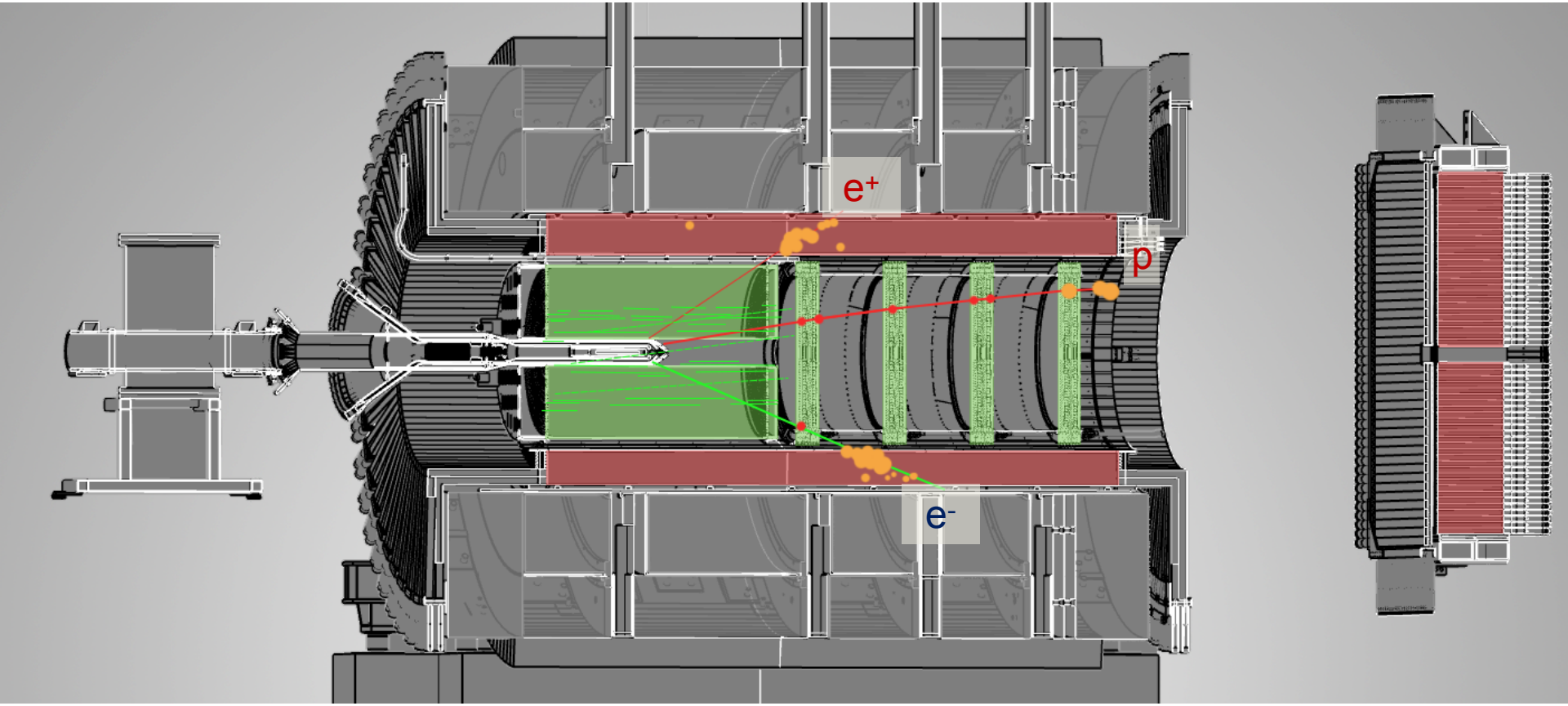
Tracking (FDC,CDC) , Calorimetry (BCAL,FCAL) , Timing (TOF,SC)



- Hermetic detector: $1 - 120^\circ$ polar and full azimuthal acceptance
- Tracking: $\sigma_p/p \sim 1 - 5\,\%$
- Calorimetry: $\sigma_E/E \sim 6\,\%/\sqrt{E} + 2\,\%$

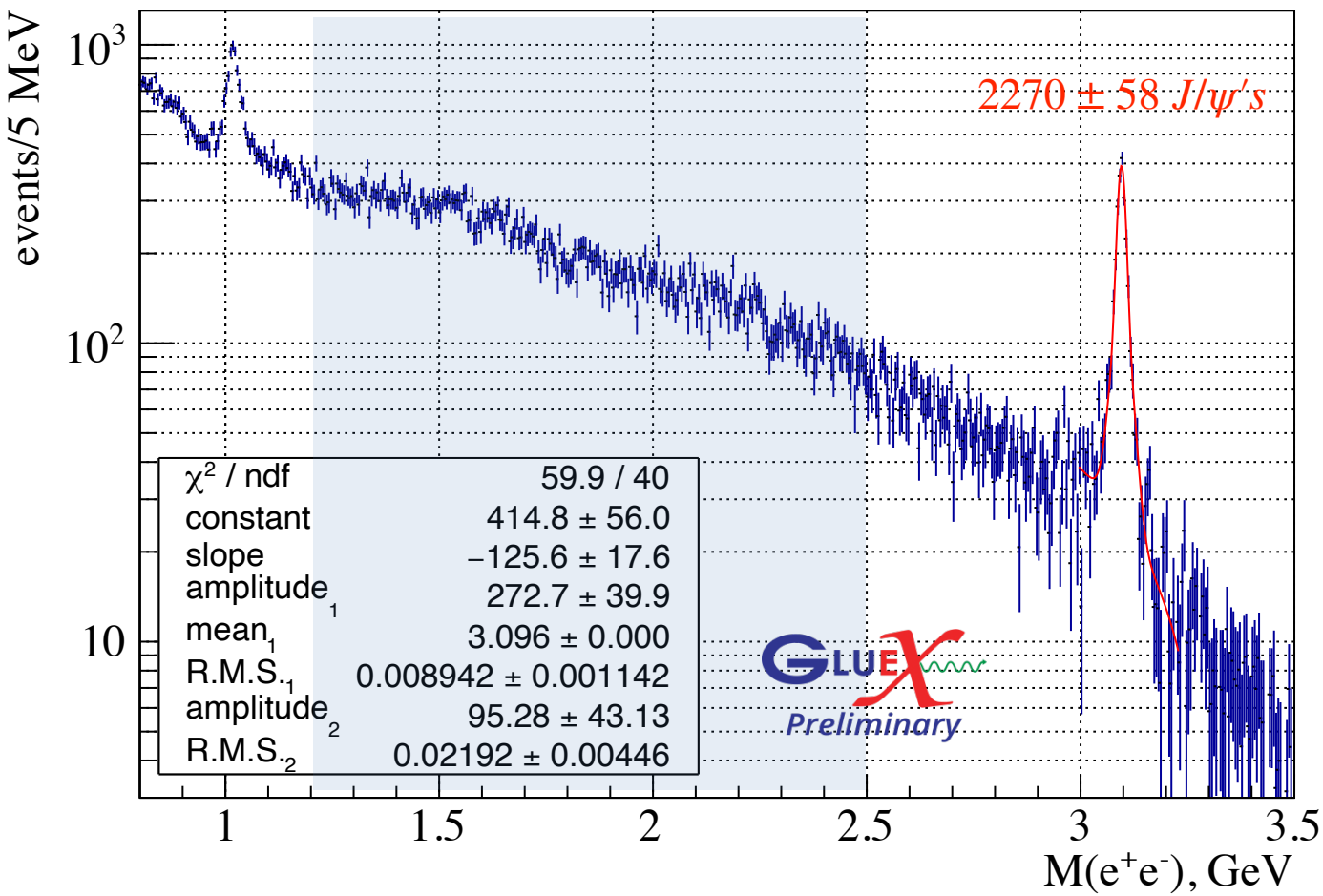
Exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$

- GlueX detector has full acceptance for this reaction - direct measurement of the total cross section - no need to extrapolate to low/high t



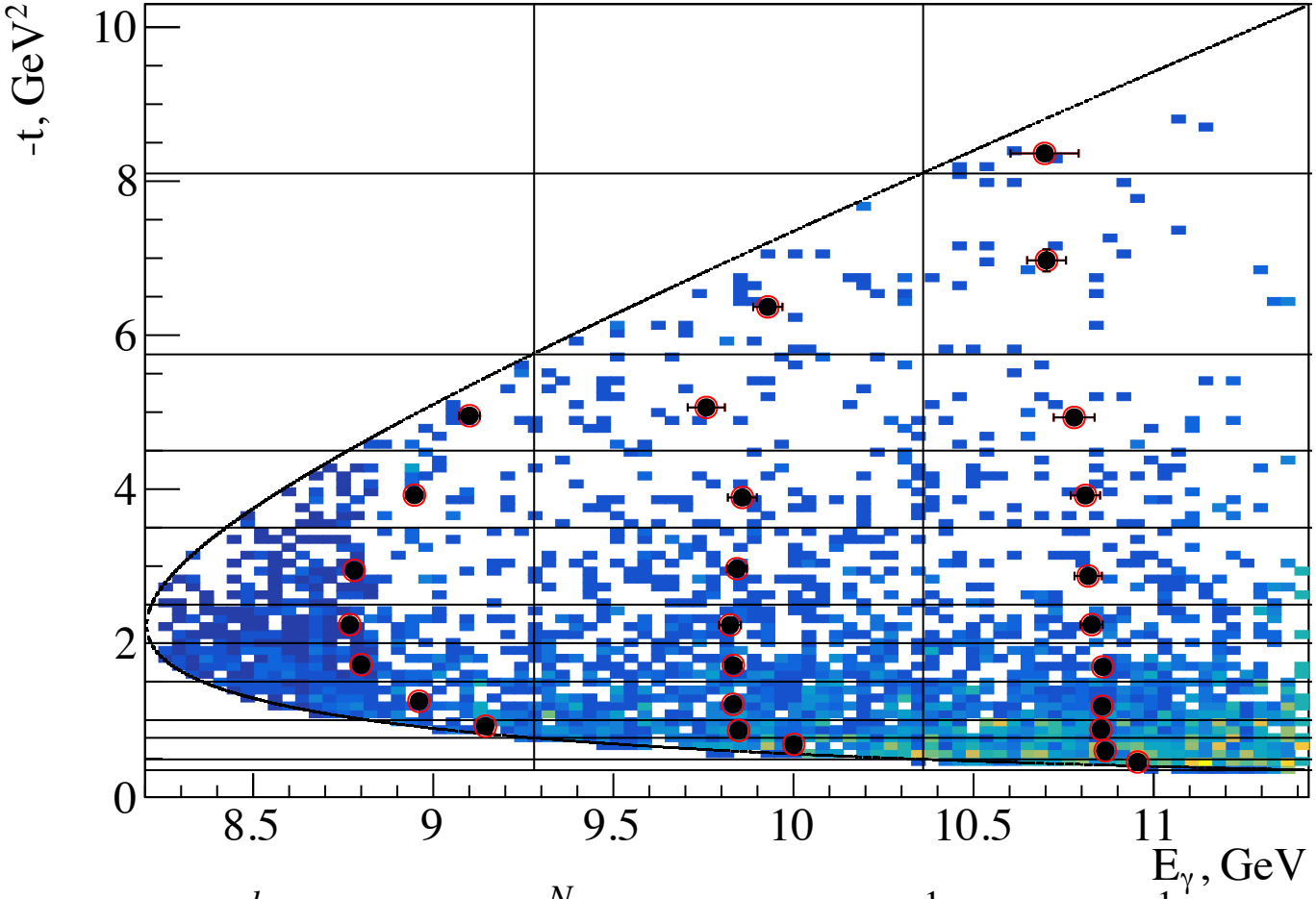
- Electrons separated from pions by E/p – energy deposition in the calorimeters over measured momentum (pions >10^3 times more than electrons)

e^+e^- invariant mass spectrum



- Tagged photon beam (0.2% energy resolution) and exclusivity of the reaction:
- Kinematic fit (constrained mostly by the recoil proton): 13 MeV mass resolution; no radiative tail
- J/ψ yields extracted from fits of $M(e^+e^-)$ distributions
- BH(1.2 – 2.5 GeV) used for normalization

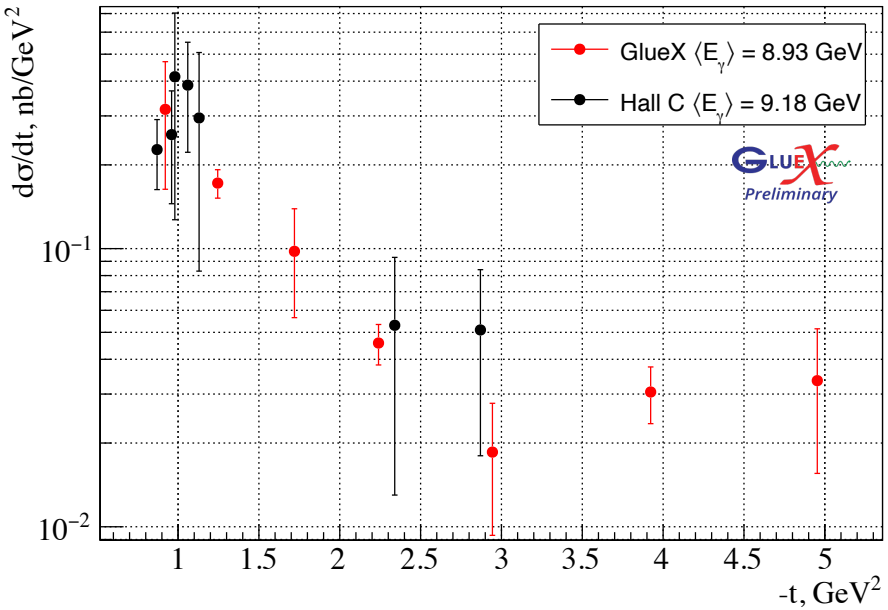
Differential cross-sections

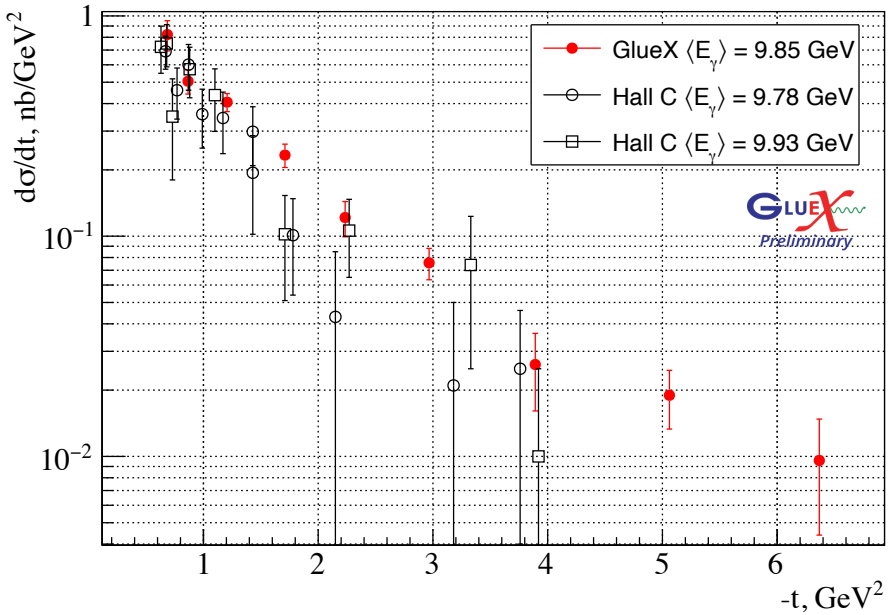


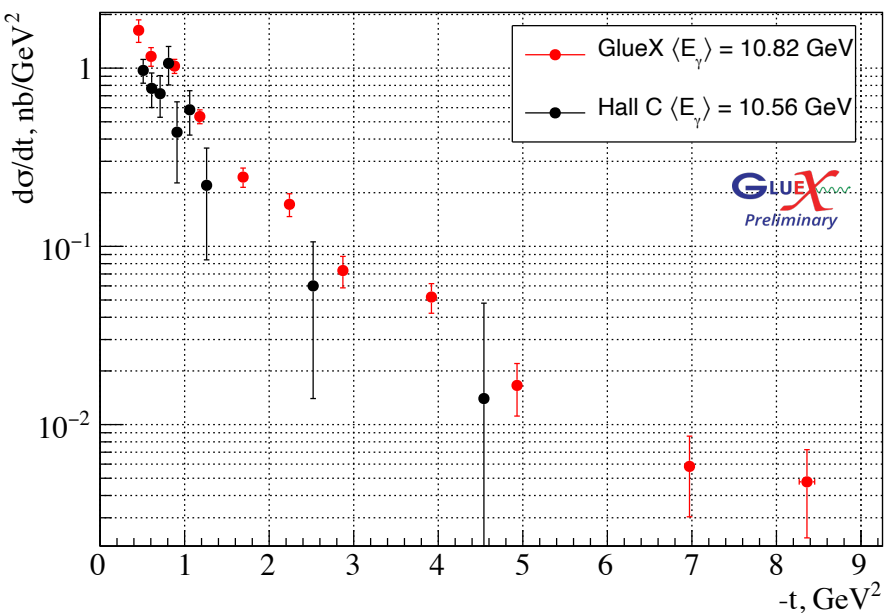
$$\frac{d\sigma}{dt}(E,t) = \frac{N_{J/\psi}}{L(E_\gamma)[nb^{-1}]/0.045GeV} \frac{1}{area(E,t)[GeV \cdot GeV^2]} \frac{1}{\varepsilon(E,t)}$$

- 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

Results: differential cross-sections



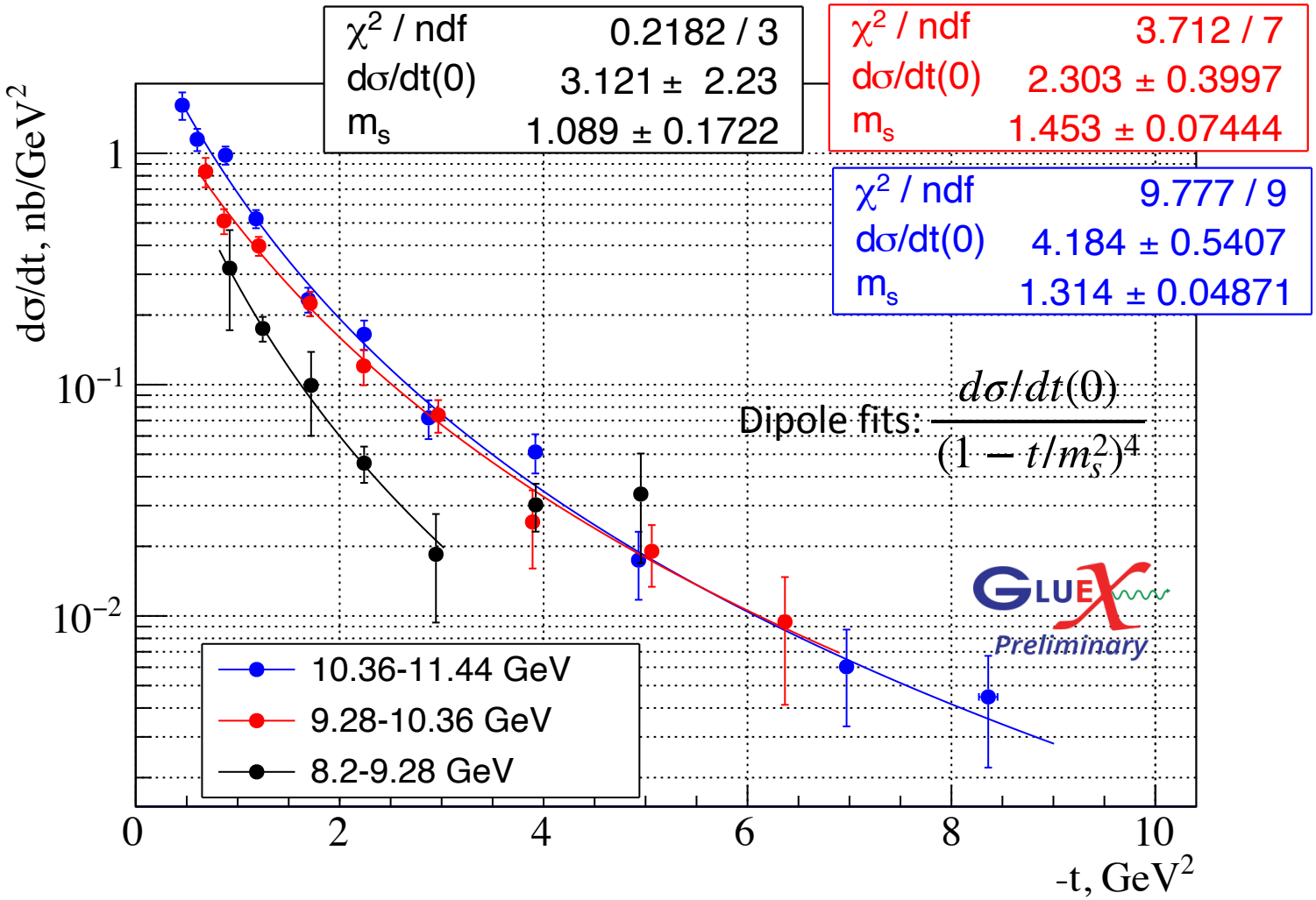




GlueX preliminary results compared to Hall C (J/psi-007):

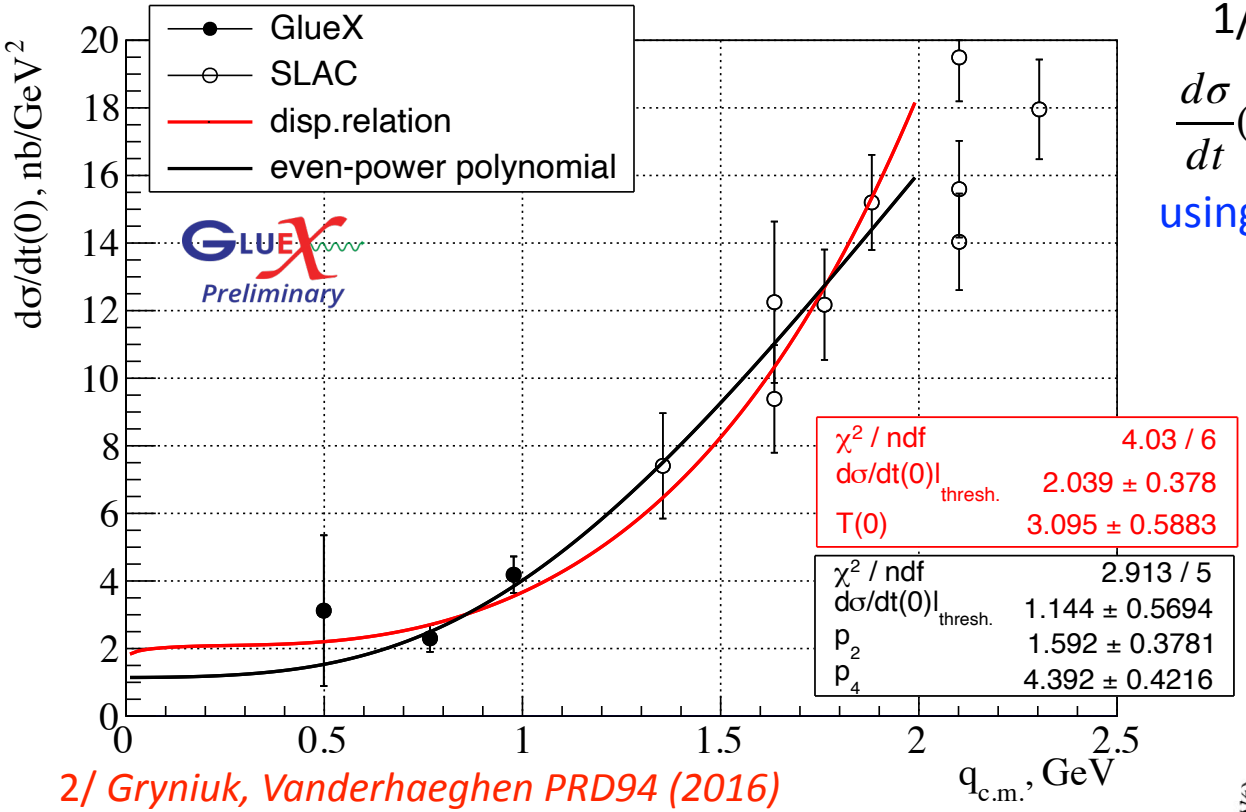
- Three GlueX energies compared to closest Hall C energies (shown only 4 out 10 energies in J/psi-007)
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies

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

$$\downarrow$$

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

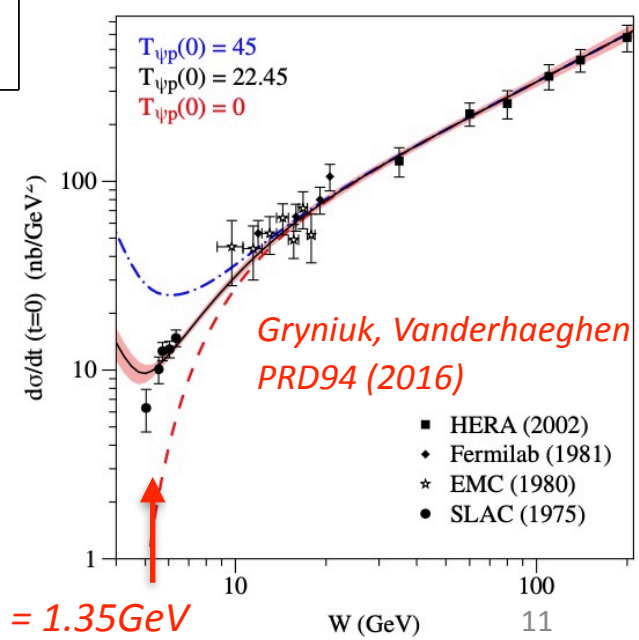
2/ Gryniuk, Vanderhaeghen PRD94 (2016)

dispersive relation:

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

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

p_1 - subtraction constant $T(0)$



Gryniuk, Vanderhaeghen PRD94 (2016)

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

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

Forward differential cross-sections - model dependent applications

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

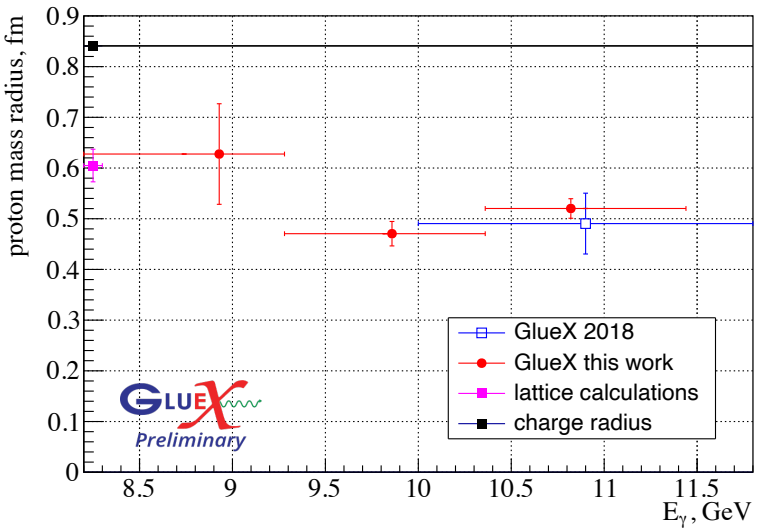
$13.4 \pm 3.8\ mfm$, $17.9 \pm 1.7\ mfm$

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/

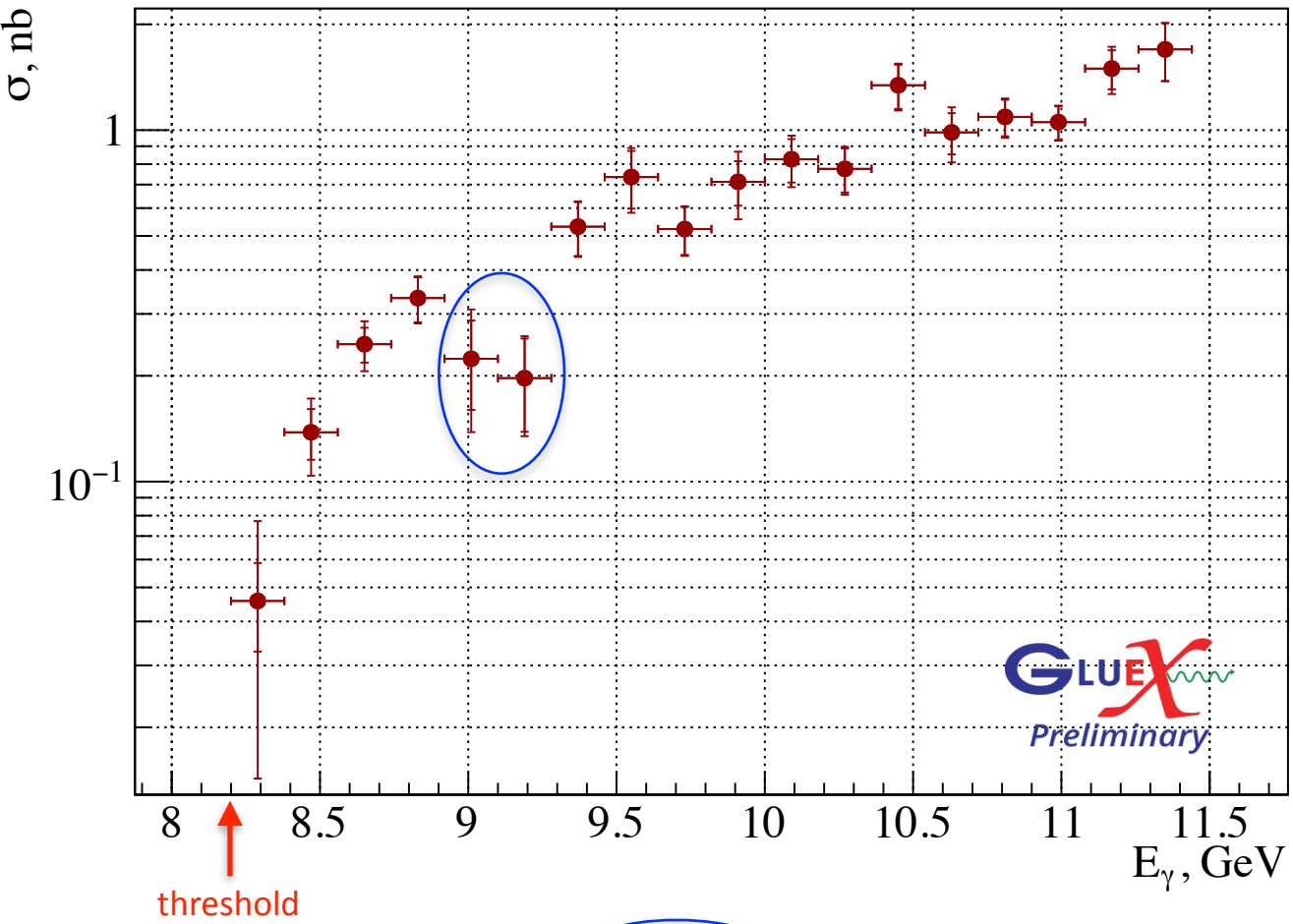


$$r_m = \frac{6}{m_p} \frac{dG}{dt}\Big|_{t=0} = \frac{12}{m_s^2}$$

D.Kharzeev PRD104(2021)

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

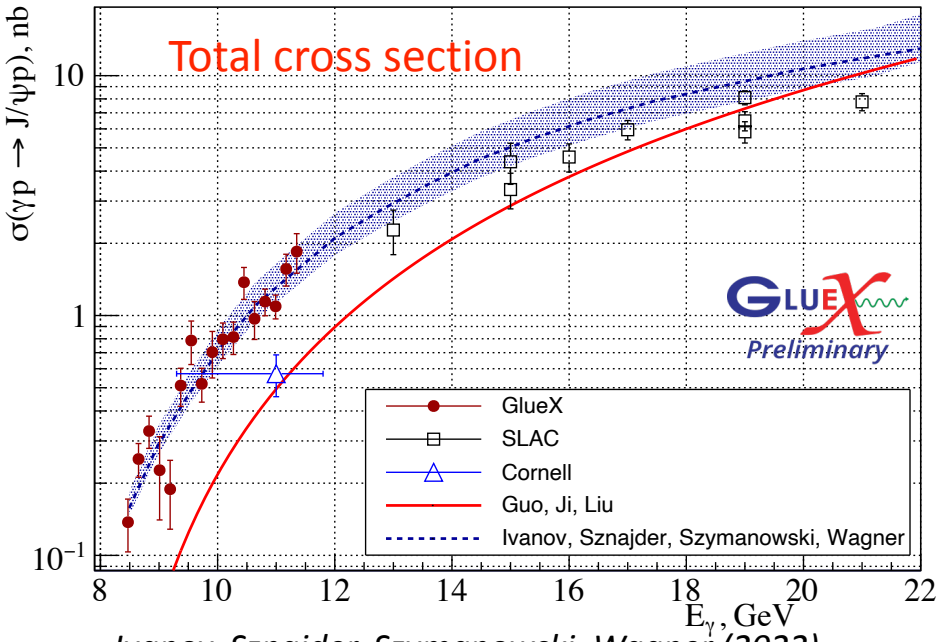
Preliminary results: total cross-section

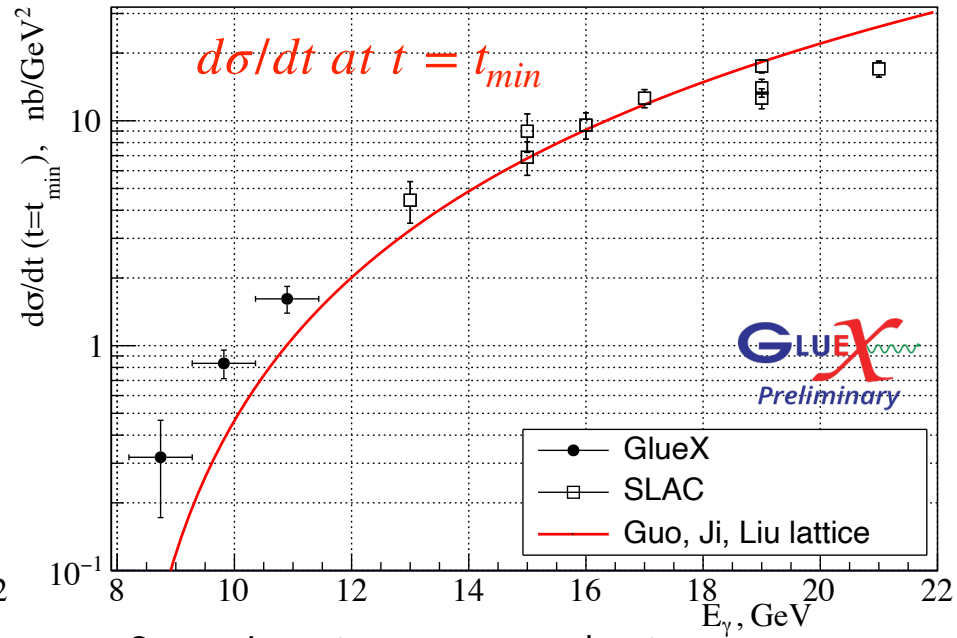


- 20% scale uncertainty
- Statistical significance of the two "dip" points 2.6σ; if include look-elsewhere effect - 1.3σ

$$\sigma_{J/\psi}(E_\gamma) = \frac{N_{J/\psi}(E_\gamma)}{N_{BH}(E_\gamma)} \frac{\sigma_{BH}(E_\gamma)}{\mathcal{B}_{J/\psi}} \frac{\varepsilon_{BH}(E_\gamma)}{\varepsilon_{J/\psi}(E_\gamma)}$$

QCD factorization models





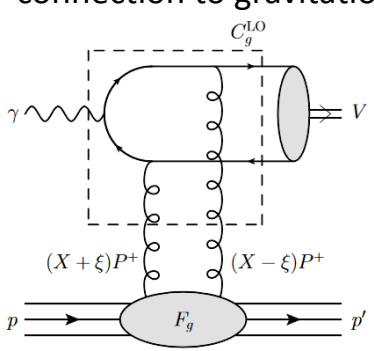
Ivanov, Sznajder, Szymanowski, Wagner (2022)

- GPD LO calculations

Guo, Ji, Liu PRD103 (2021),

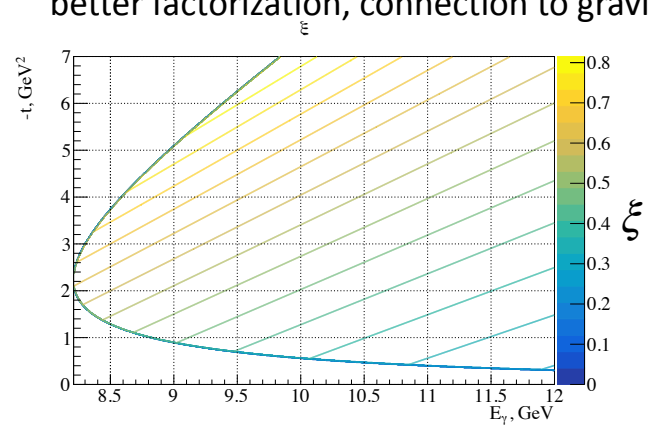
in $m_c \to \infty$ limit, $\xi \to 1$ extension:

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

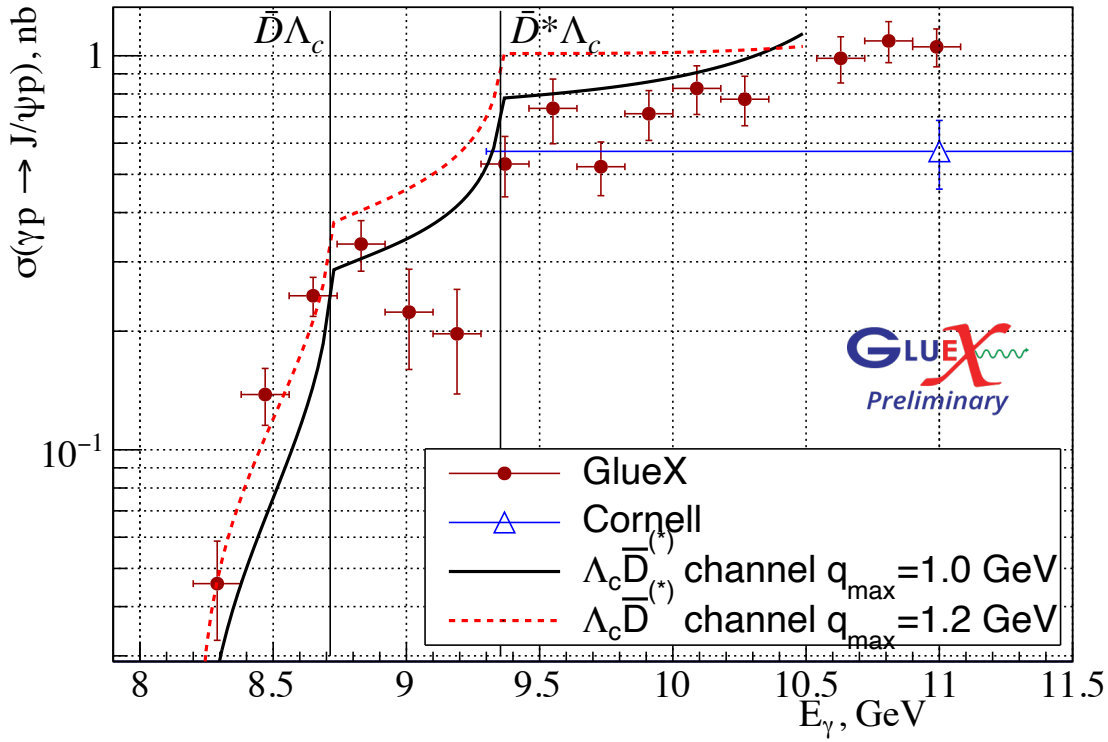


Comparison at $t = t_{min}$ → advantages:

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



Open-charm exchange



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

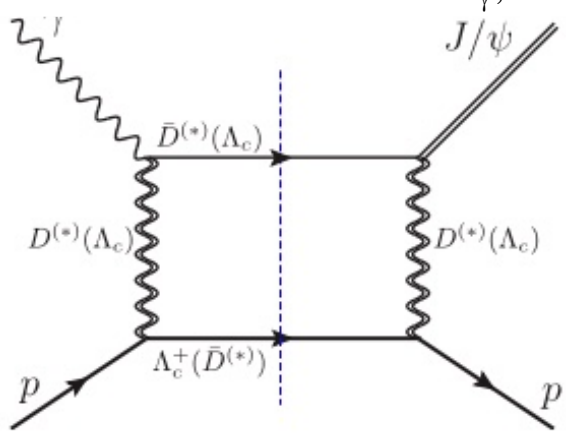
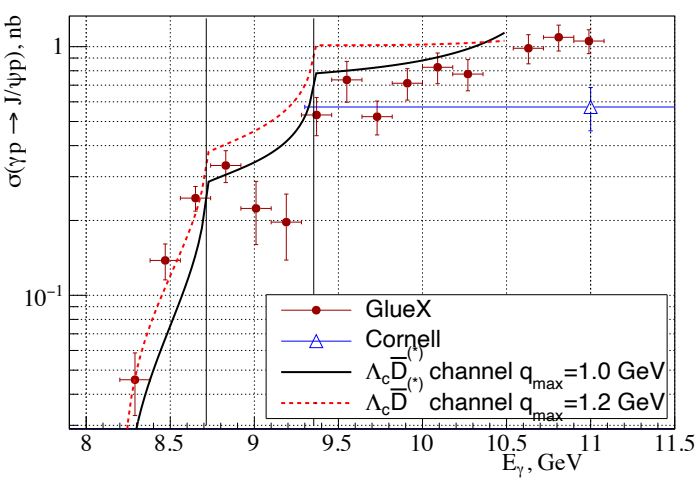


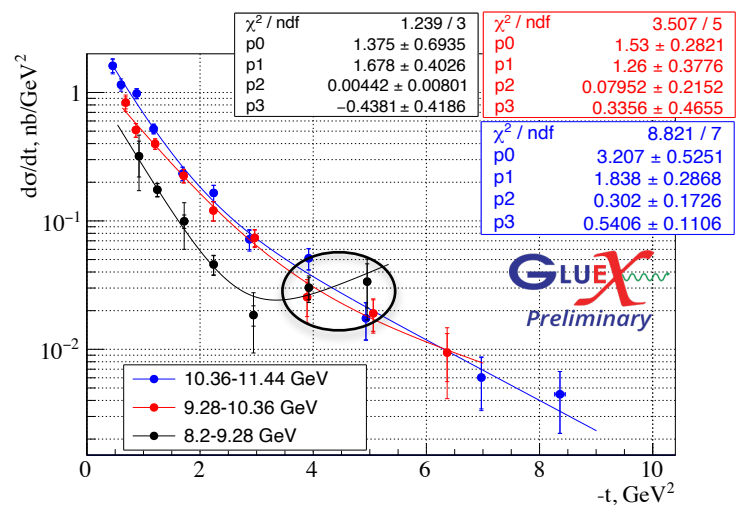
FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

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?
Naturality ?	unnatural $\bar{D}$ exchange ?	2g - natural parity exchange 3g - unnatural (C-parity violation)



?



Double-exponent fits: $p_0 e^{tp_1} + p_2 e^{tp_3}$

Conclusions

- Threshold J/ψ production and mass properties of the proton? - new GlueX data poses more questions than answers:
- Proximity of the reported total/differential cross sections to threshold in the full kinematic space allows (more reliable) extrapolation to $t = 0 \; and \; E_{thr.}$ and gives access to very important physics - mass properties of the proton - however

  … assuming VMD, QCD factorization

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

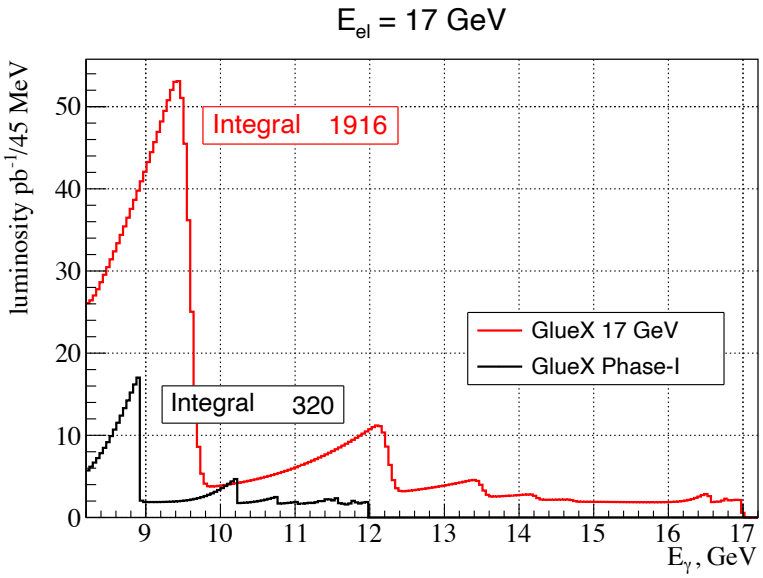
  … assuming gluon exchange over open-charm exchange mechanism:
- Total cross section - in agreement with open-charm exchange, while QCD predictions underestimate the data
- Differential cross section - generally consistent with gluon exchange and predicted by lattice QCD
- More precise measurements near threshold (including polarization quantities) are needed to better understand the reaction mechanism - expect x4 more data from Phase-II
- Important input from theorists is expected

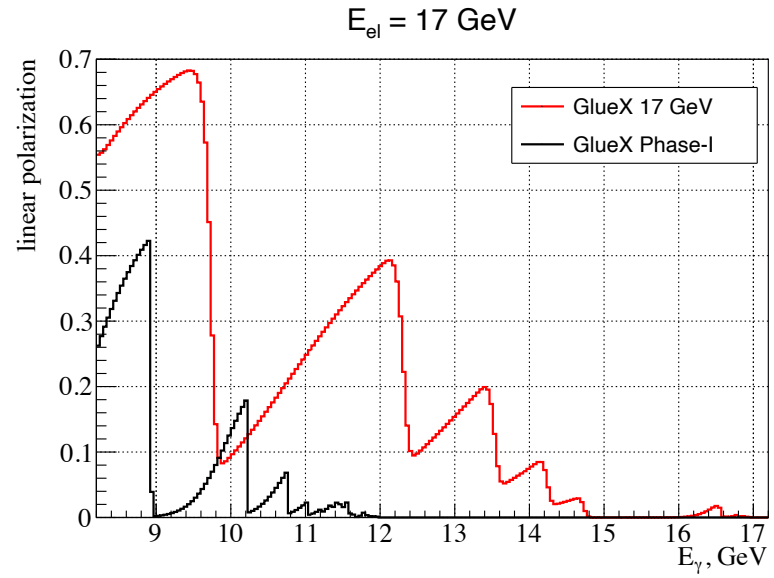
Back-ups

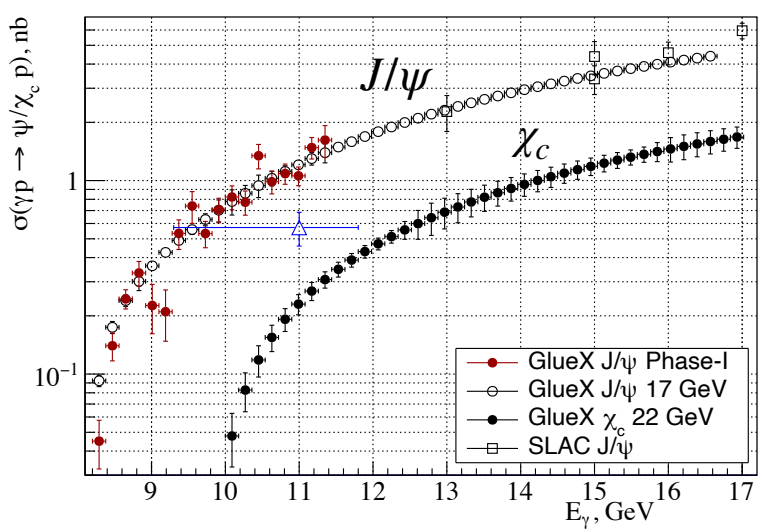
Charmonium studies in Hall D with the CEBAF energy upgrade

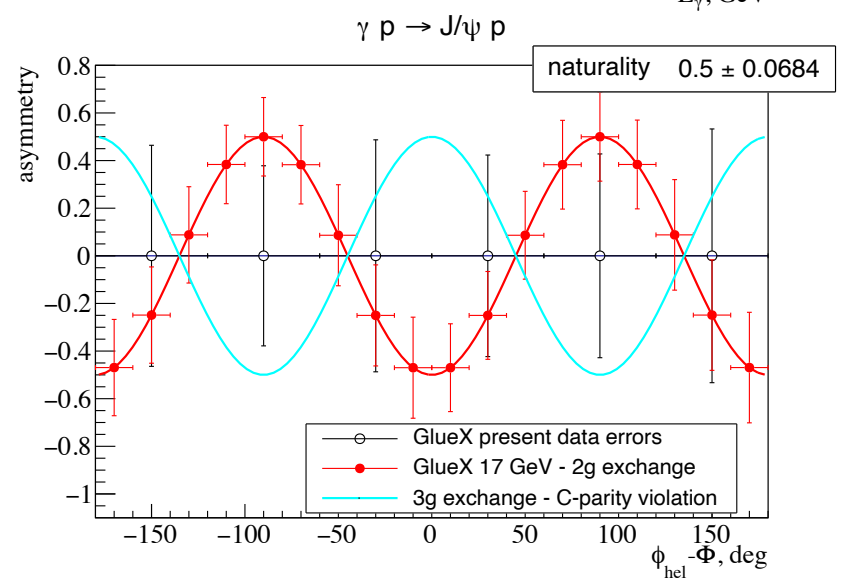
Substantial increase of the flux in the coherent peak allows precise cross section measurements covering the whole region down to threshold

Significant increase of the linear polarization allows to do important polarization measurements in the threshold region

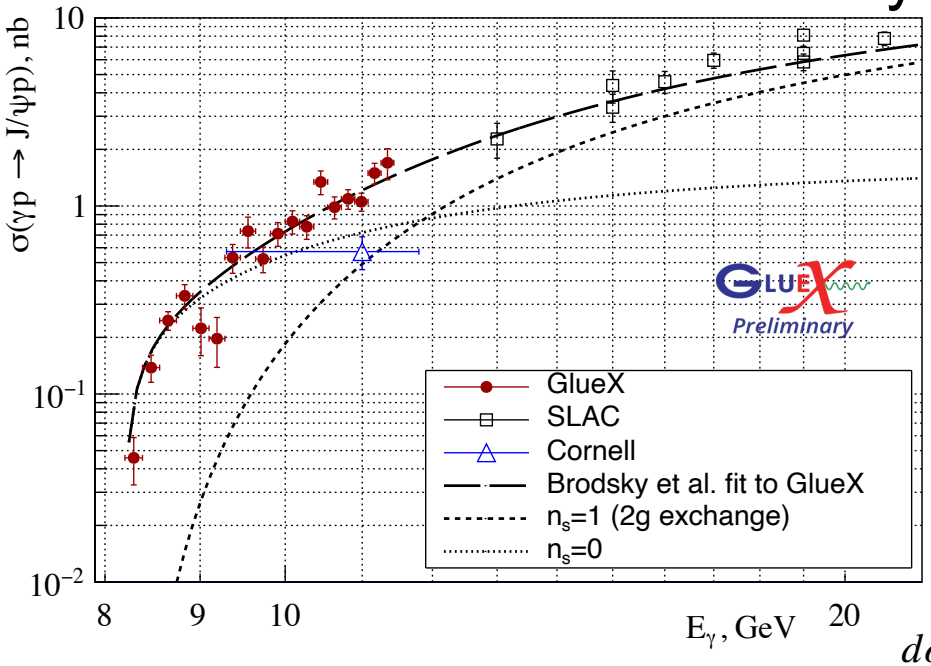


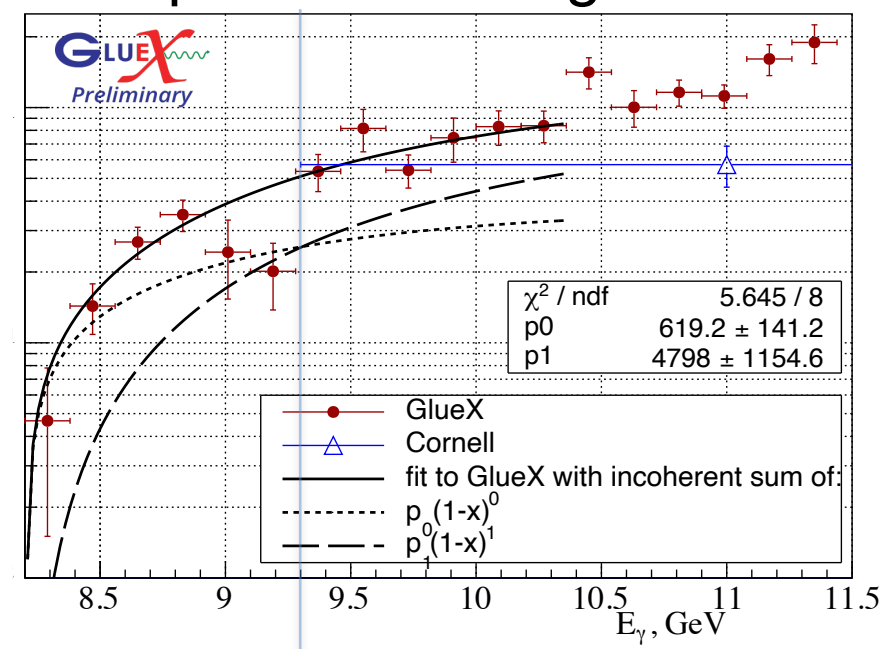






Total cross section asymptotic - power counting





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

Sun, Tong, Yuan PRD 105.054032 (2021):

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

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

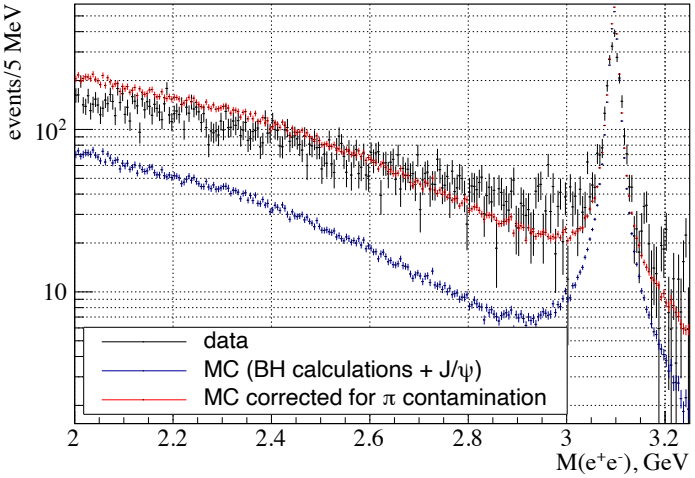
number of spectators in proton;

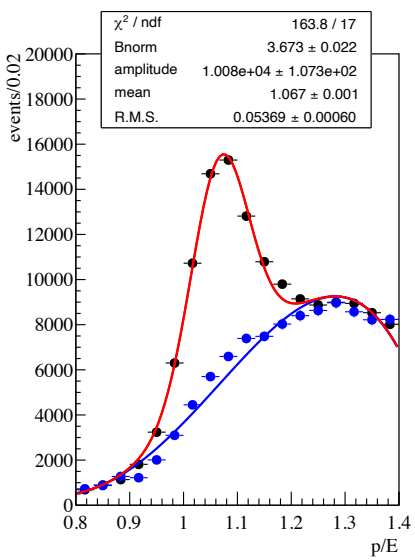
$n_s = 0$ *associated with 3g exchange*

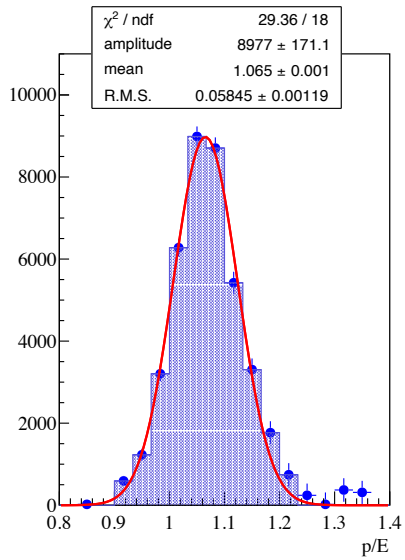
Brodsky et al. PLB498 (2001)

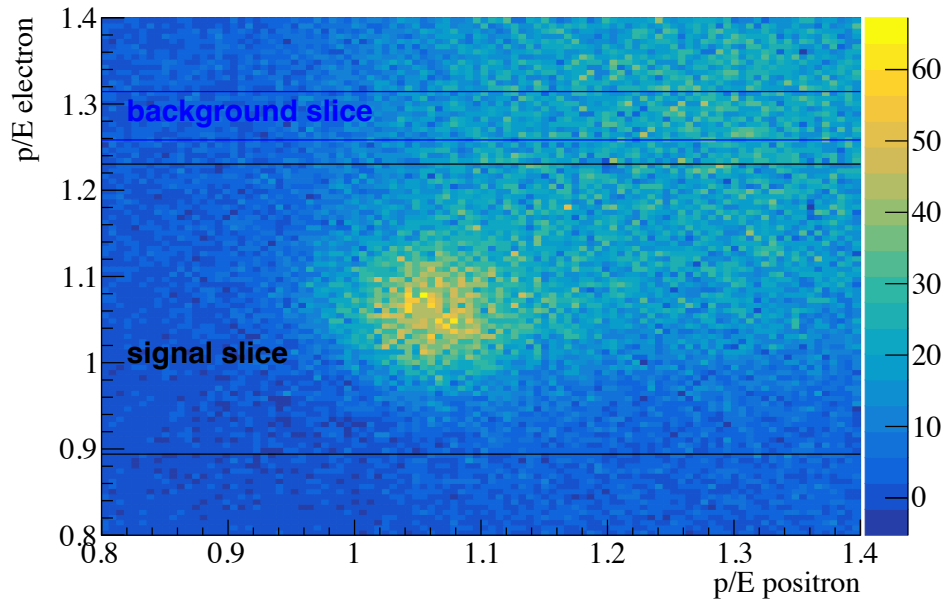
Twist-4	Twist-3
no energy dependance	vanishes at threshold
$1/t^5$	$1/t^4$
proton spin flip	no spin flip
$\sim E_g(t,x,\xi)$	$\sim H_g(t,x,\xi)$

e/π separation



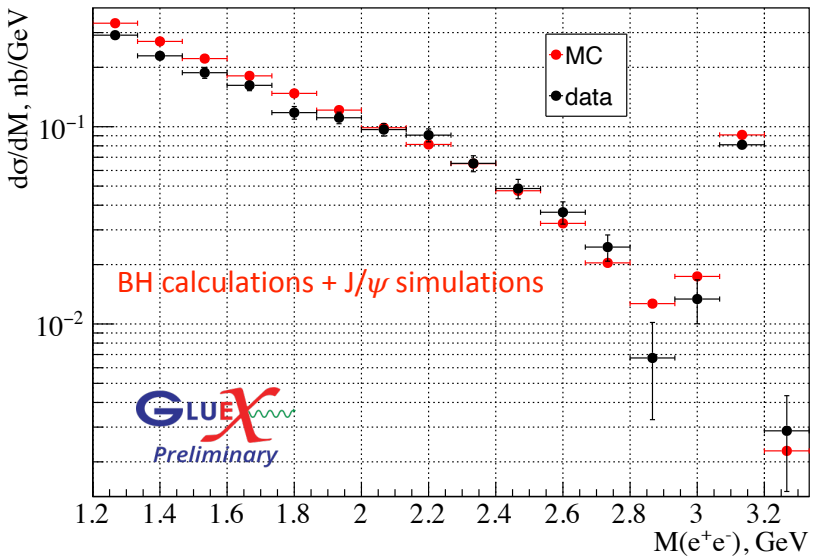


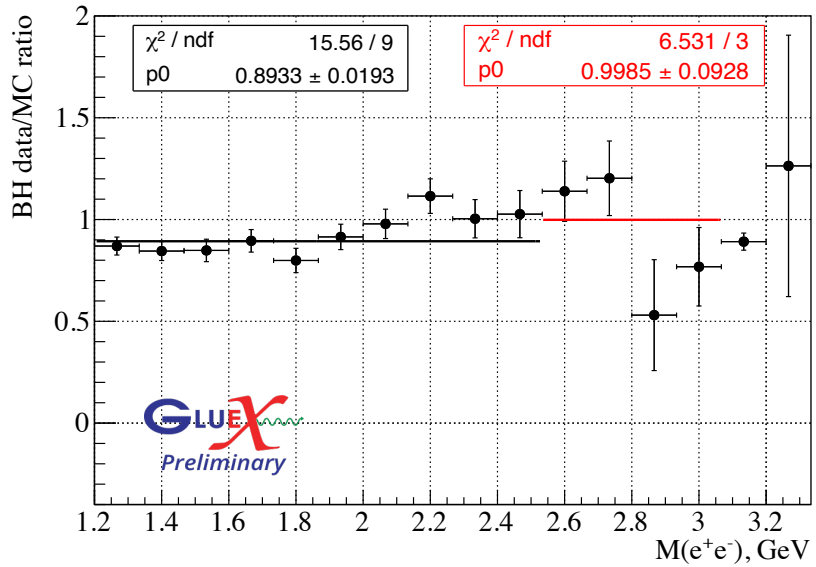


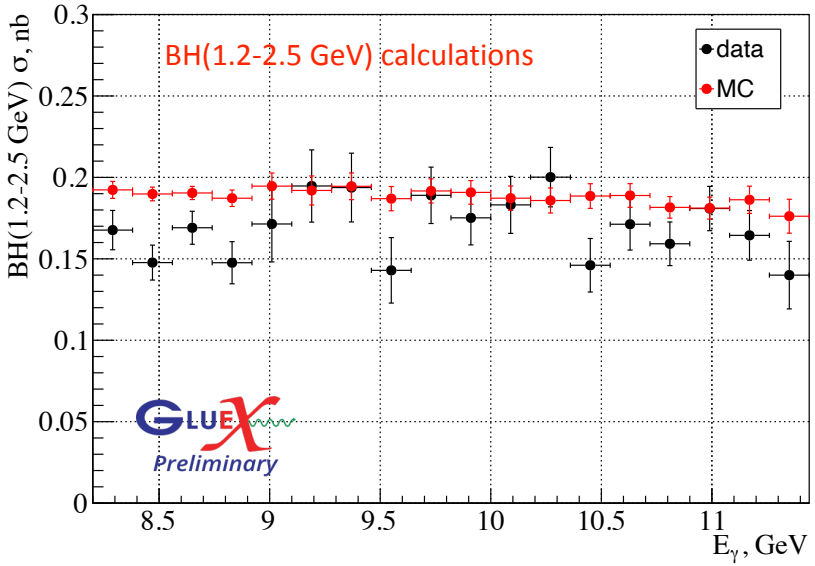


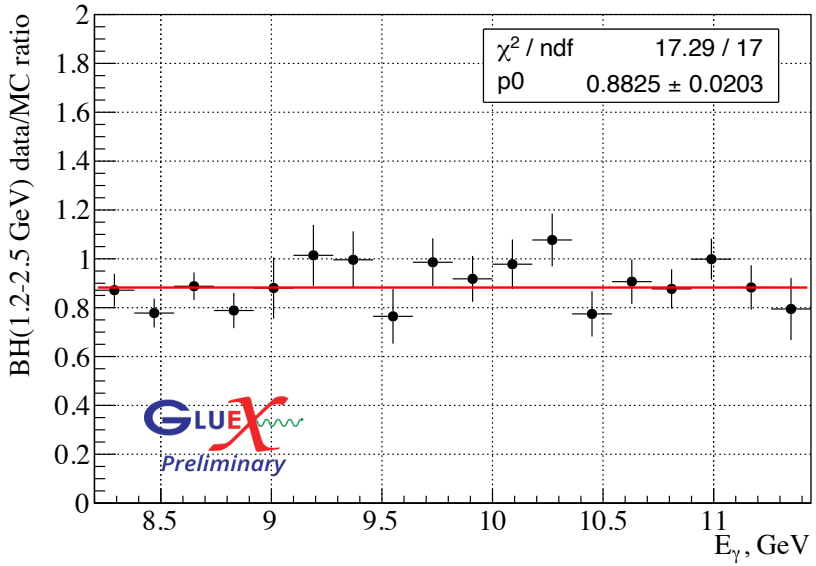
- Pion contamination ~50% in the continuum (using p/E fits to estimate it)

BH e.m. calculations vs data



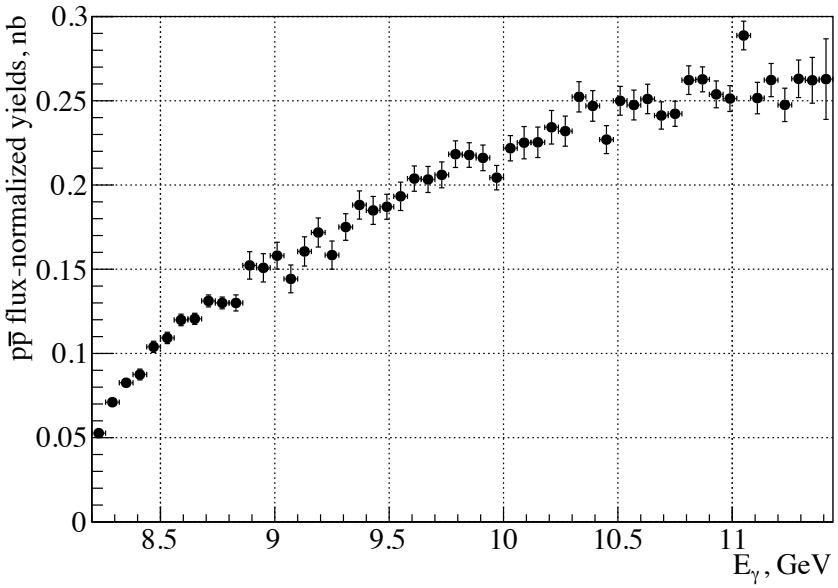


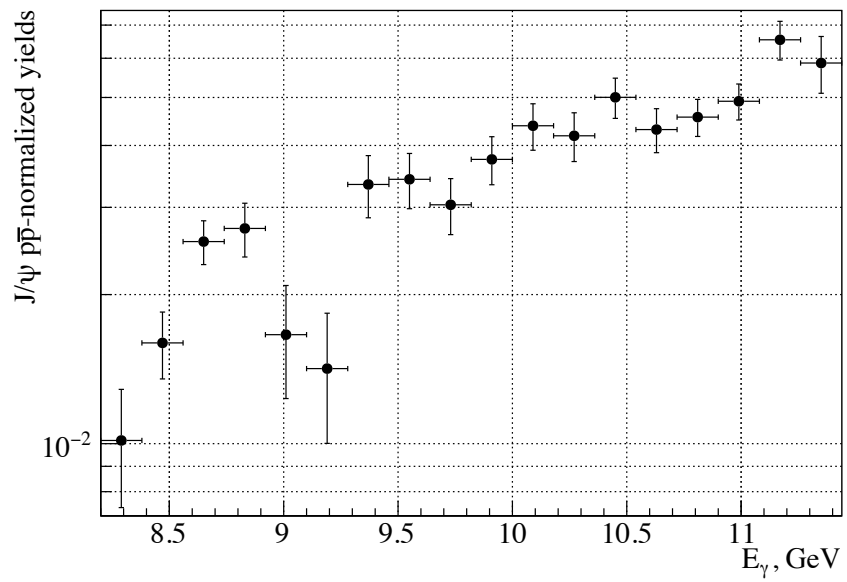


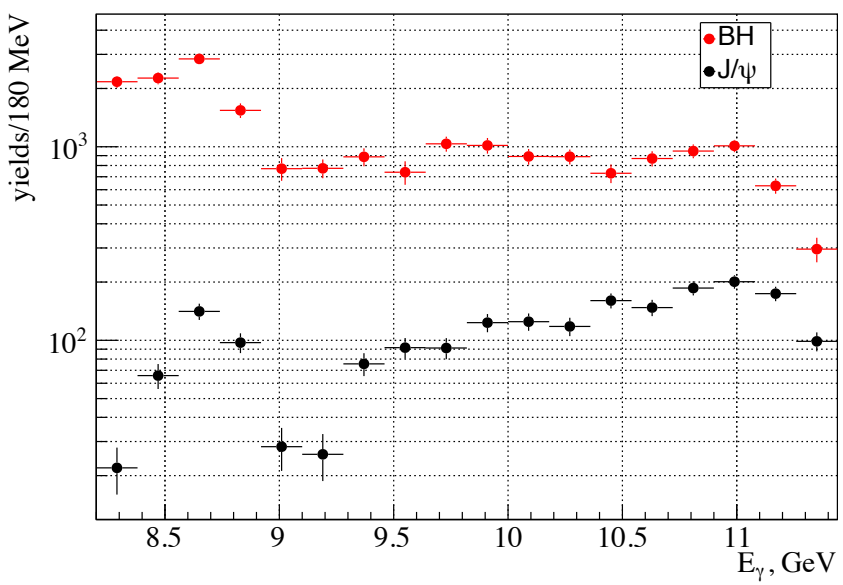


BH yields extracted from fits of E/p distributions

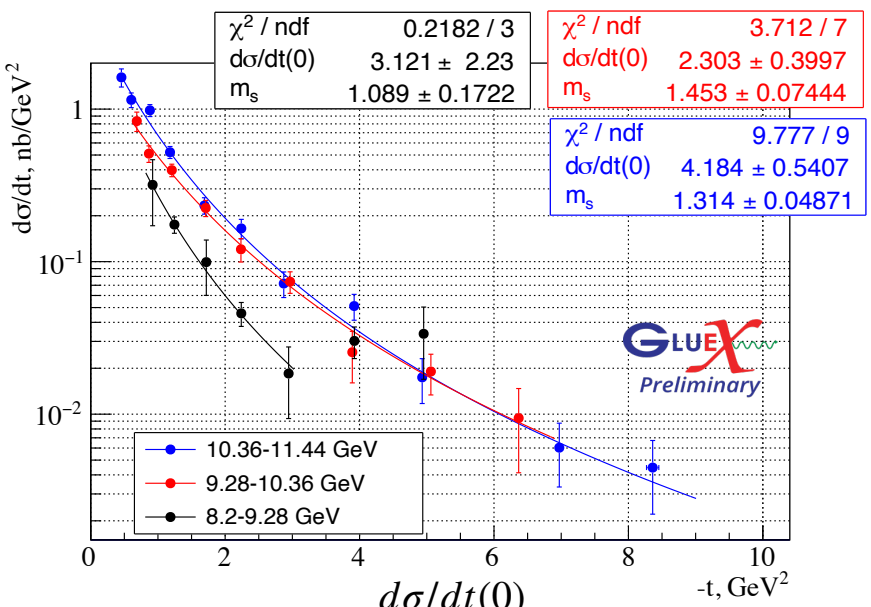
$\gamma p \to (p\bar{p})p$ with $M(p\bar{p}) \sim M_{J/\psi}$



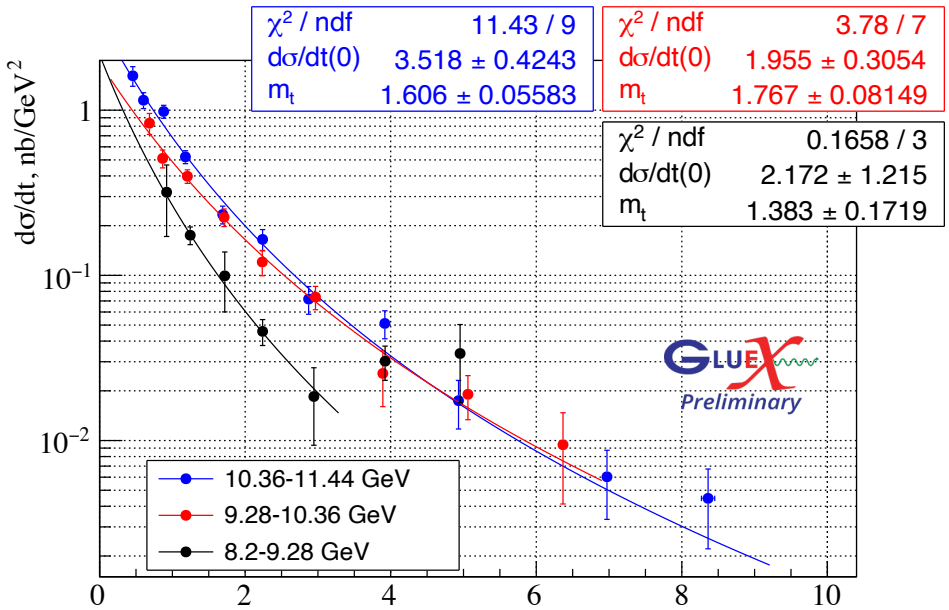




QCD: high-*t* asymptotic



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



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

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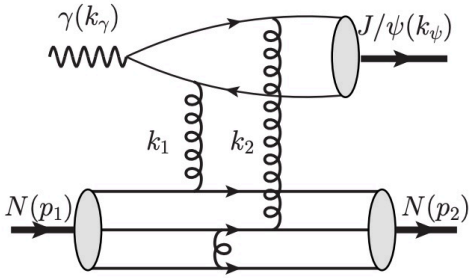
Asymptotic *t*-dependance $1/t^5$ $(vs\ 1/t^4)$ due to helicity flip



Not enough statistics to test the *t*-asymptotic

However we can check J/psi helicity conservation/flip, naturality?