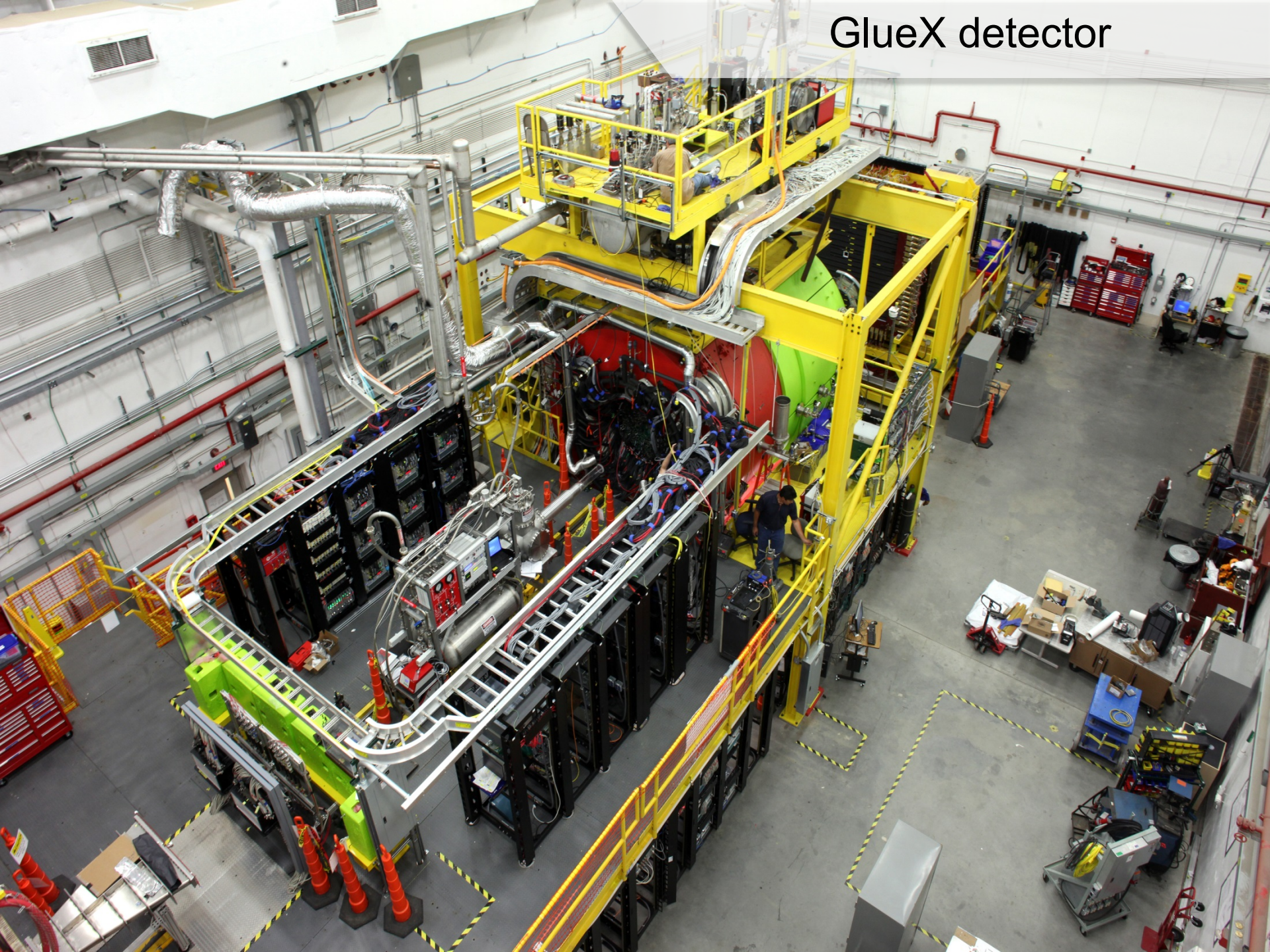
New results on exclusive J/ψ photo-production near threshold with GlueX

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

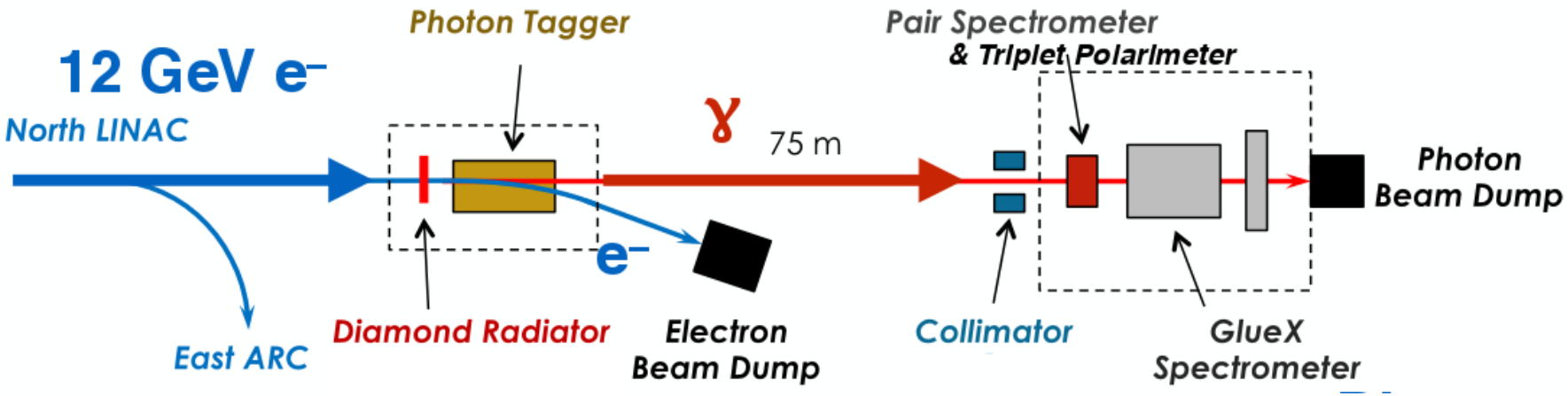
Lubomir Pentchev
(GlueX Collaboration)

- New preliminary results: total and differential cross section in the full near threshold kinematic region - based on full GlueX Phase-I dataset
  - GlueX detector
  - Data analysis: J/ψ identification, normalization
  - 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 ($t \rightarrow 0$, $E_\gamma \rightarrow E_{thr.}$)
  - Gluon exchange: asymptotic, VMD, GPD factorization models
  - Open-charm exchange
  - Discussion: relevance to the gluon properties of the proton
- Outlook

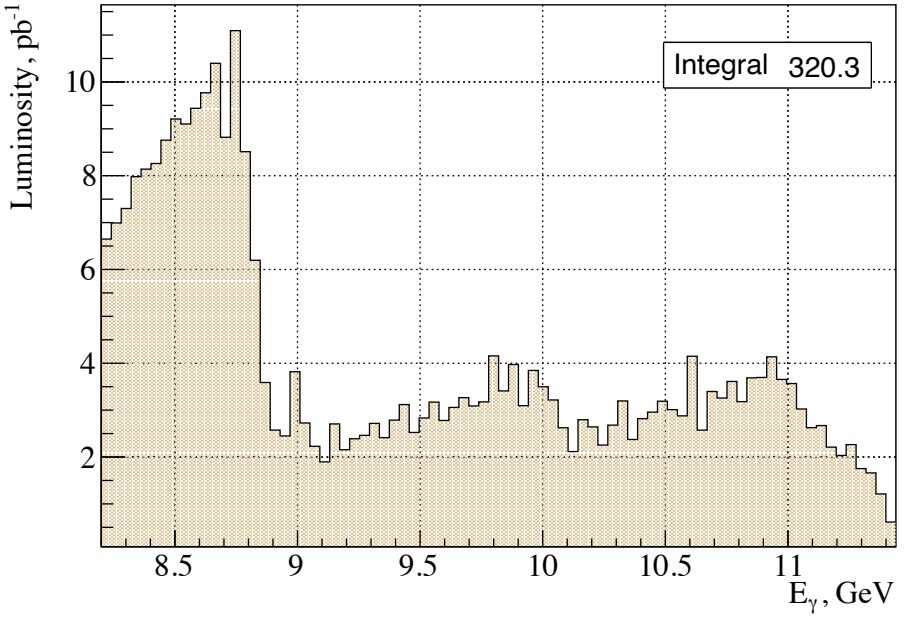
GlueX detector



Hall D Apparatus

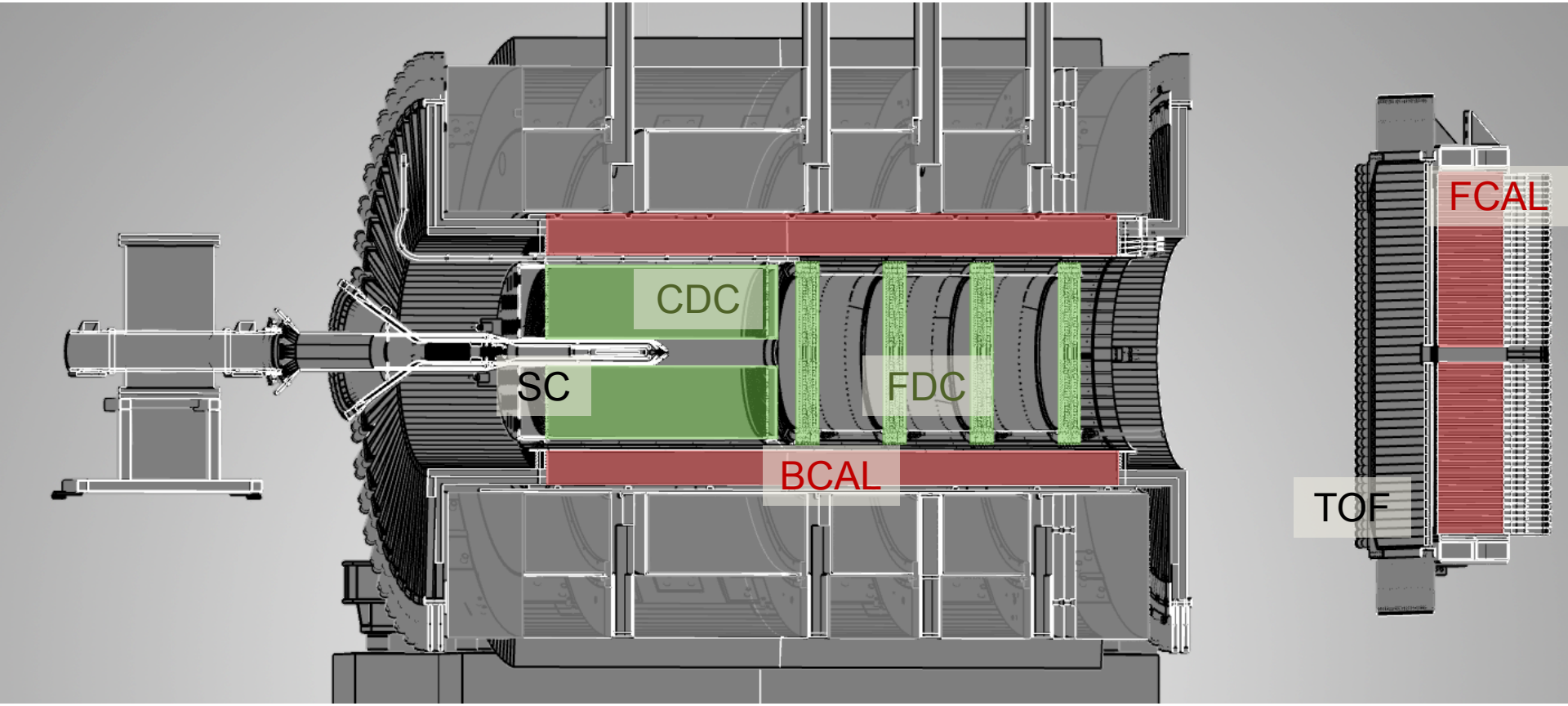


- Photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75m, <35 μrad
- Intensity: ~ 2 10^7 - 5 10^7 γ/sec above J/ψ threshold (8.2 GeV) – total ~320 pb^{-1} in GlueX phase-I runs



GlueX detector

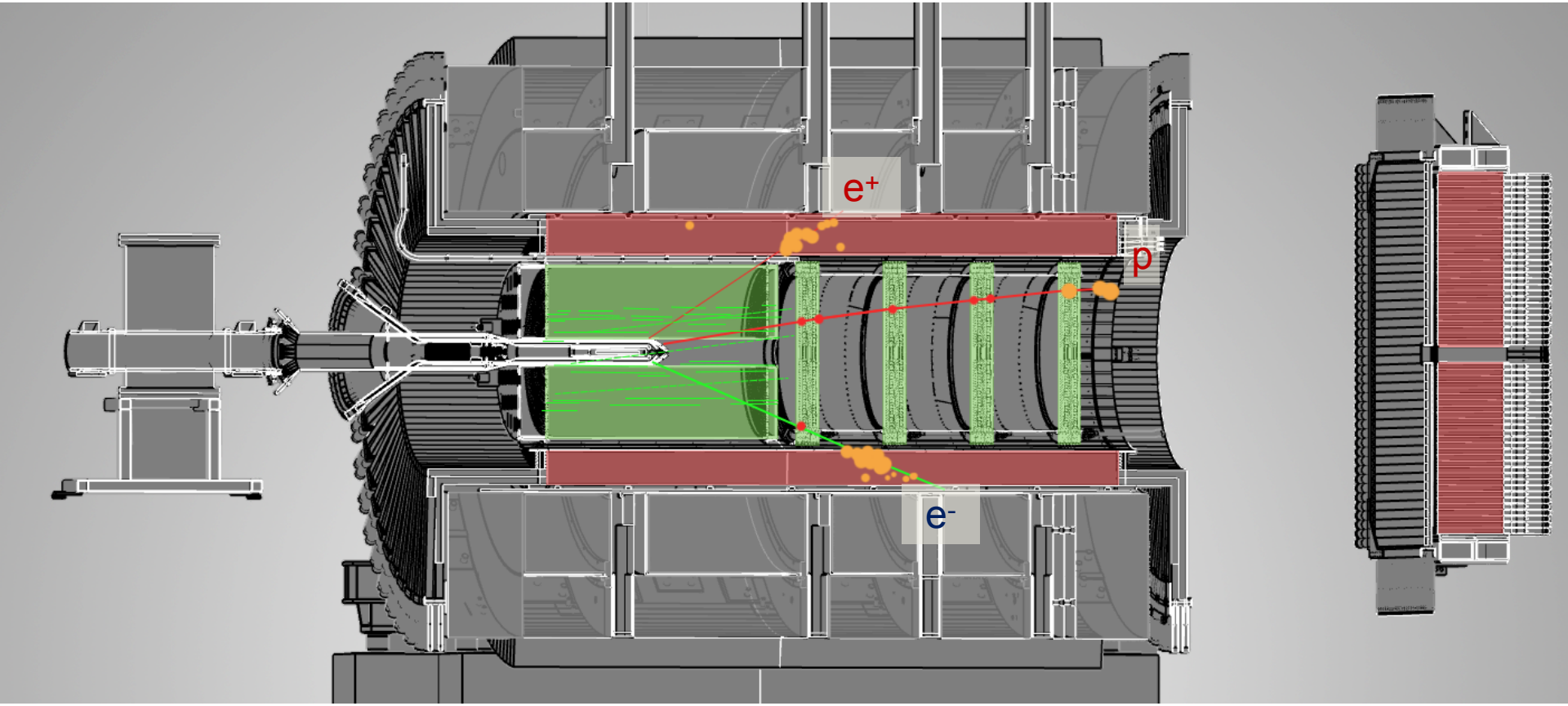
2T-solenoid, LH target
Tracking (FDC,CDC) , Calorimetry (BCAL,FCAL) , Timing (TOF,SC)



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

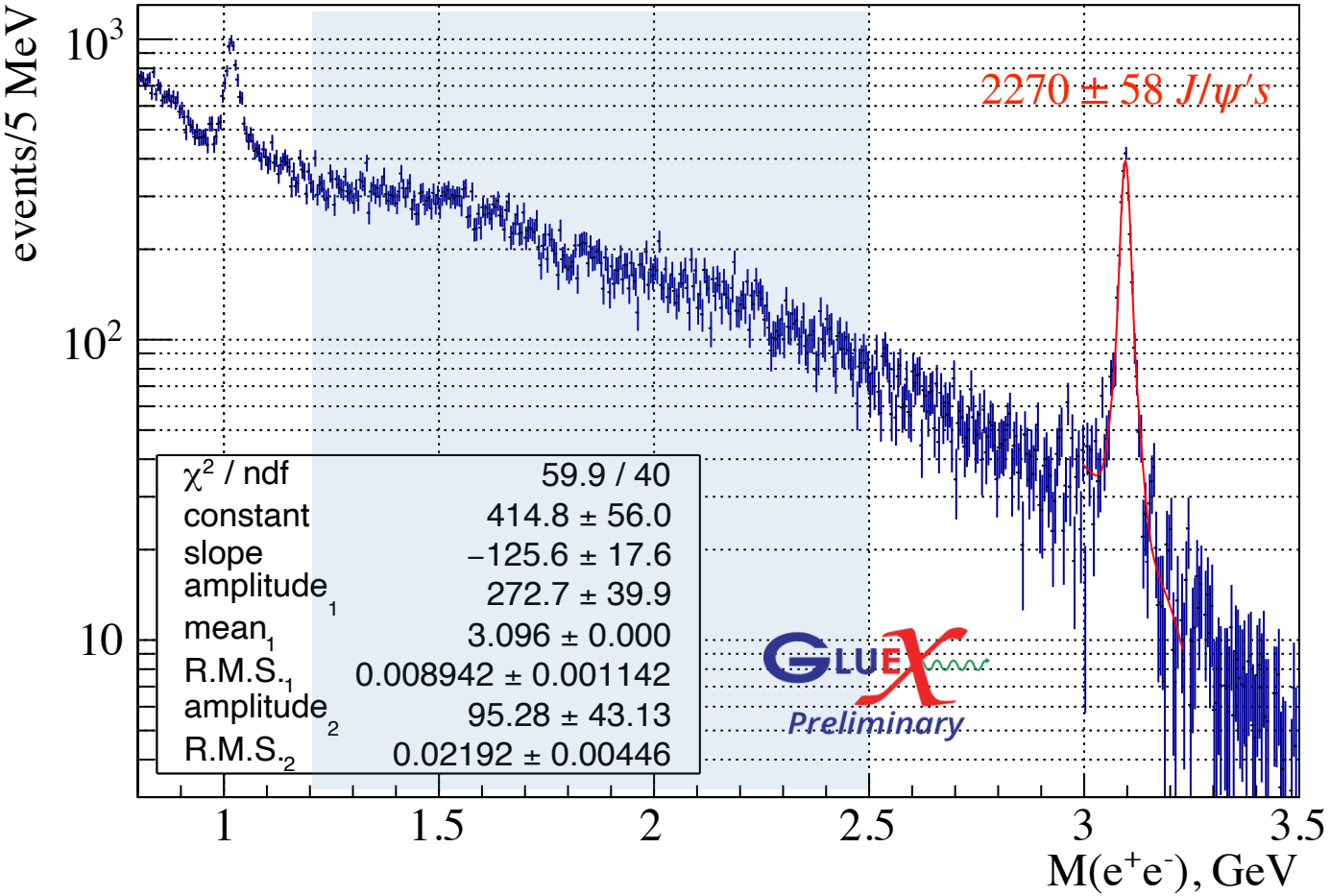
Exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$

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



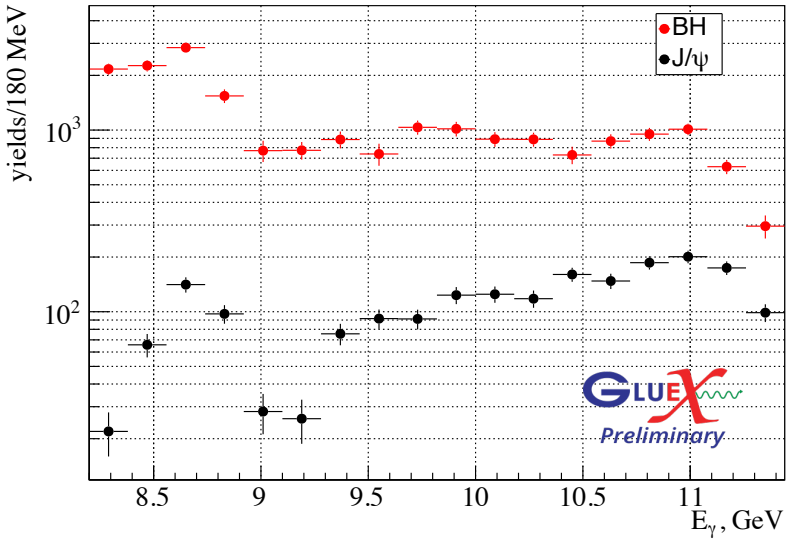
- Electrons separated from pions by E/p – energy deposition in the calorimeters over measured momentum (pions >10^3 times more than electrons)

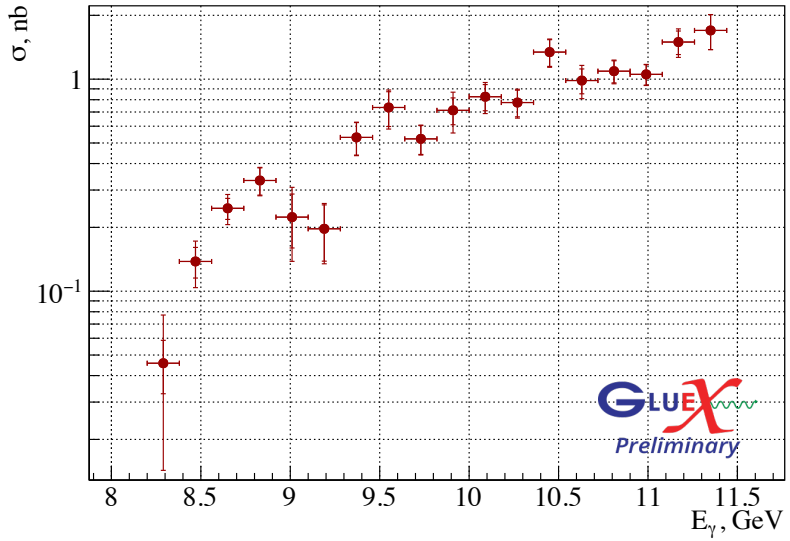
e^+e^- invariant mass spectrum



- 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

Preliminary results: total cross-section

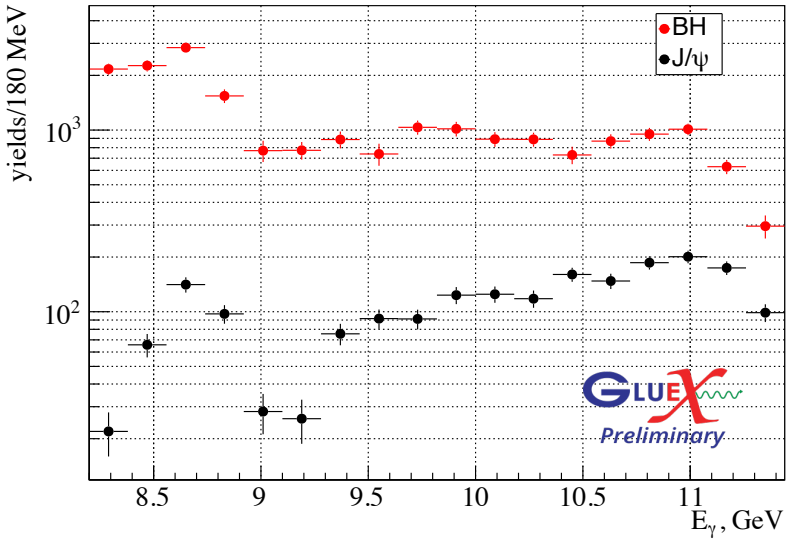


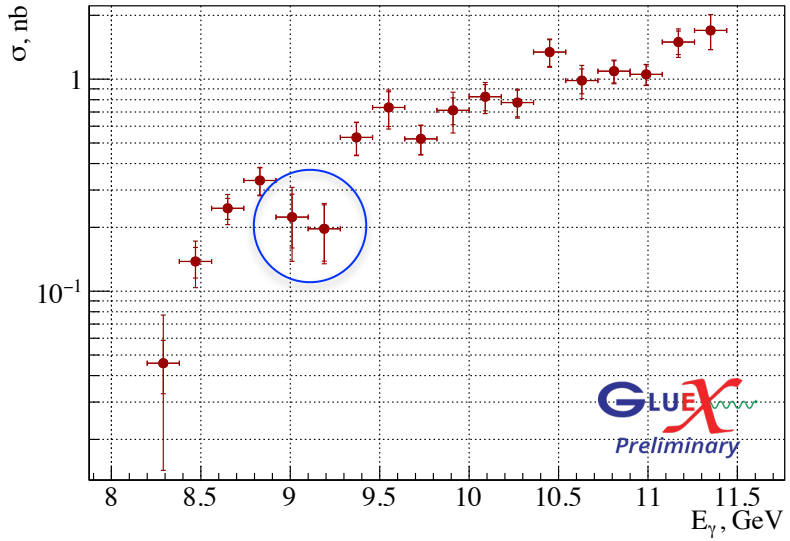


- Yields ($N_{J/\psi}$ and N_{BH}) extracted from fits of $M(e^+e^-)$ and p/E in bins of energy
- σ_{BH} calculated using analytical and numerical calculation of e.m. tree level diagrams
- Systematic errors of individual data points assigned to max deviation when varying fitting methods
- Errors dominated by statistics
- ~20% overall normalization error

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

Preliminary results: total cross-section

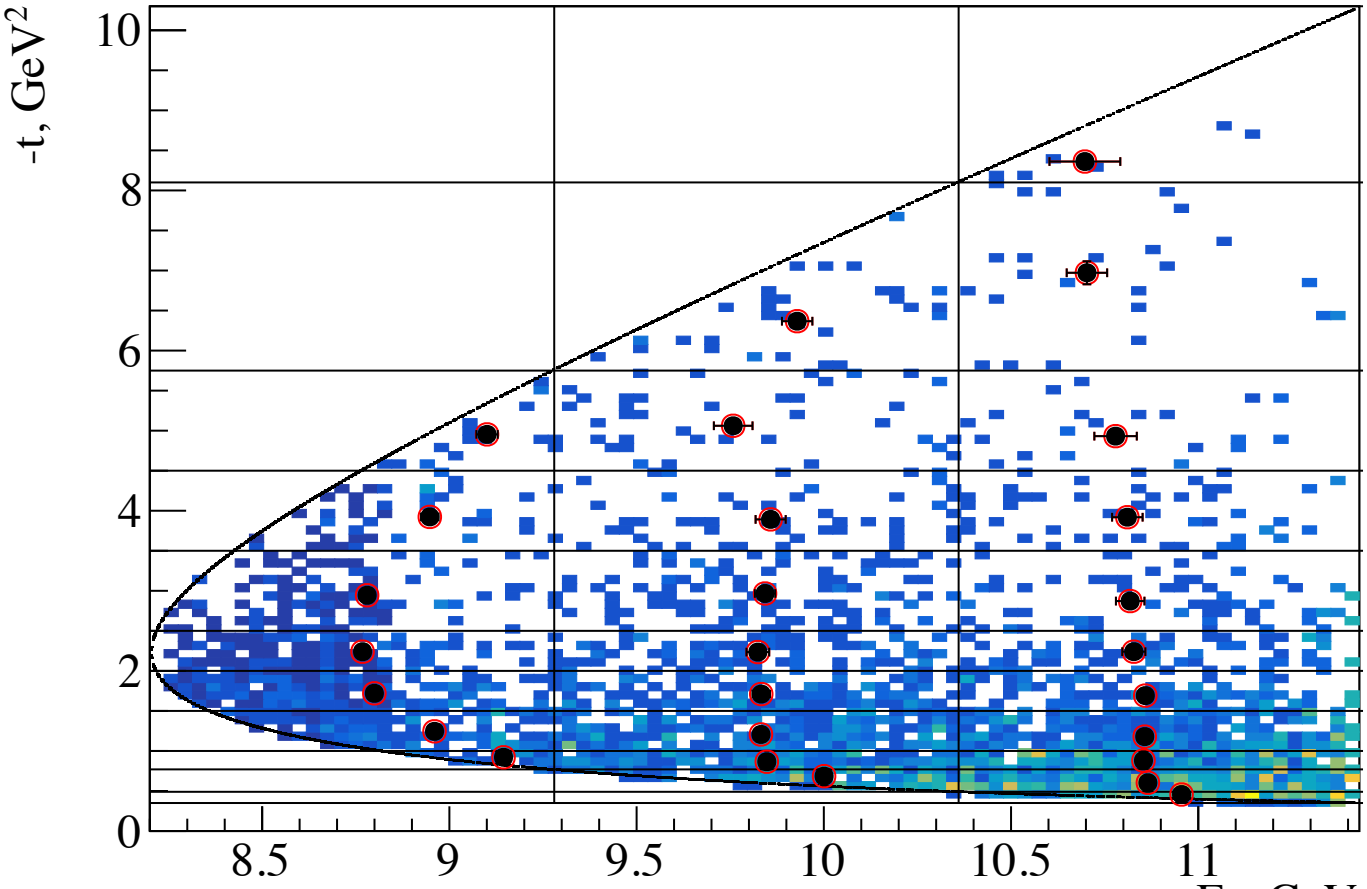




- Yields ($N_{J/\psi}$ and N_{BH}) extracted from fits of $M(e^+e^-)$ and p/E in bins of energy
- σ_{BH} calculated using analytical and numerical calculation of e.m. tree level diagrams
- Systematic errors of individual data points assigned to max deviation when varying fitting methods
- Errors dominated by statistics
- ~20% overall normalization error
- No "dip" seen in BH and also in the $\gamma p \to (p\bar{p})p$ reaction, where $M(p\bar{p})$ fixed at J/ψ mass
- Statistical significance of the two "dip" points 2.6σ; if include look-elsewhere effect - 1.3σ

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

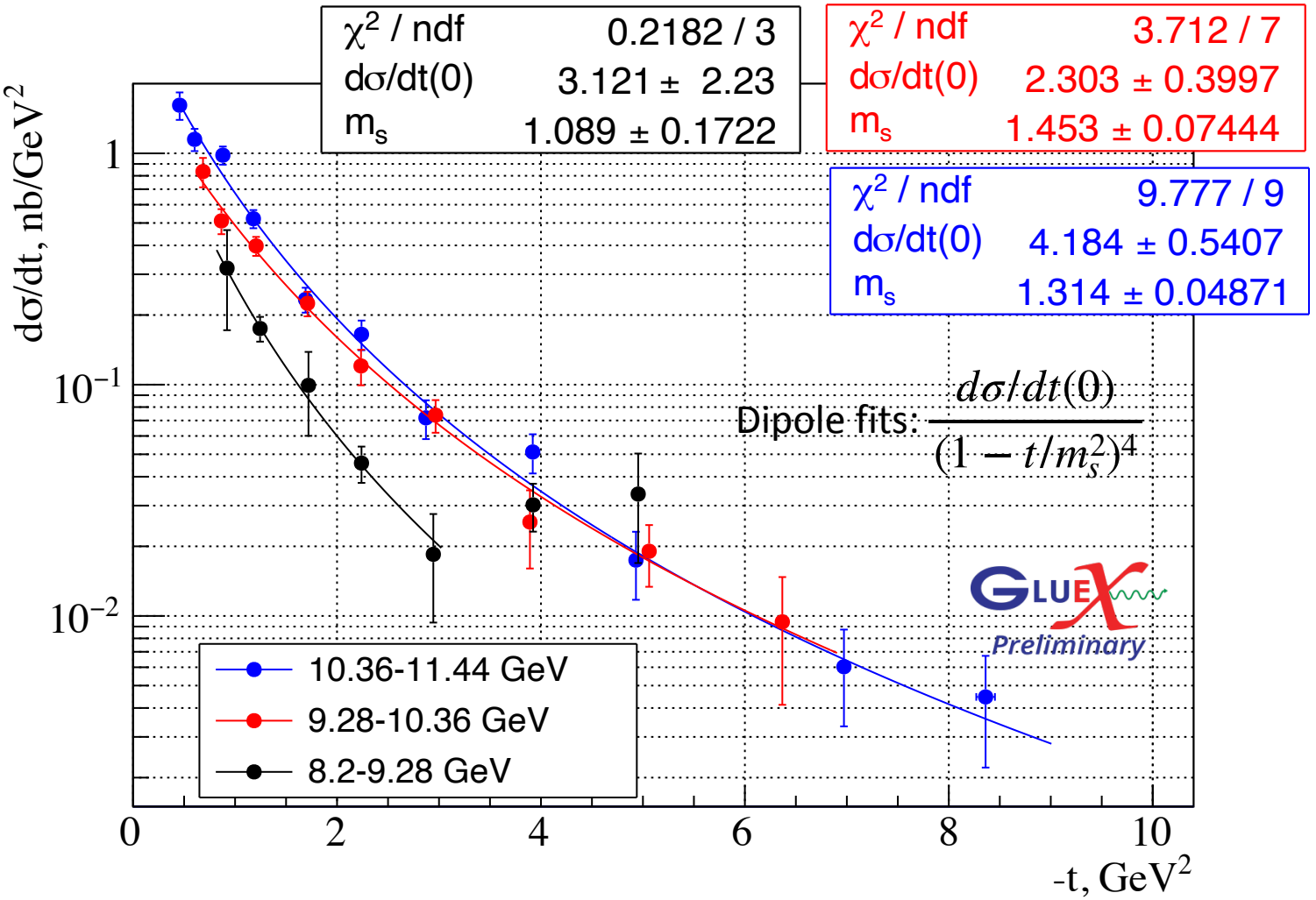
Differential cross-sections



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

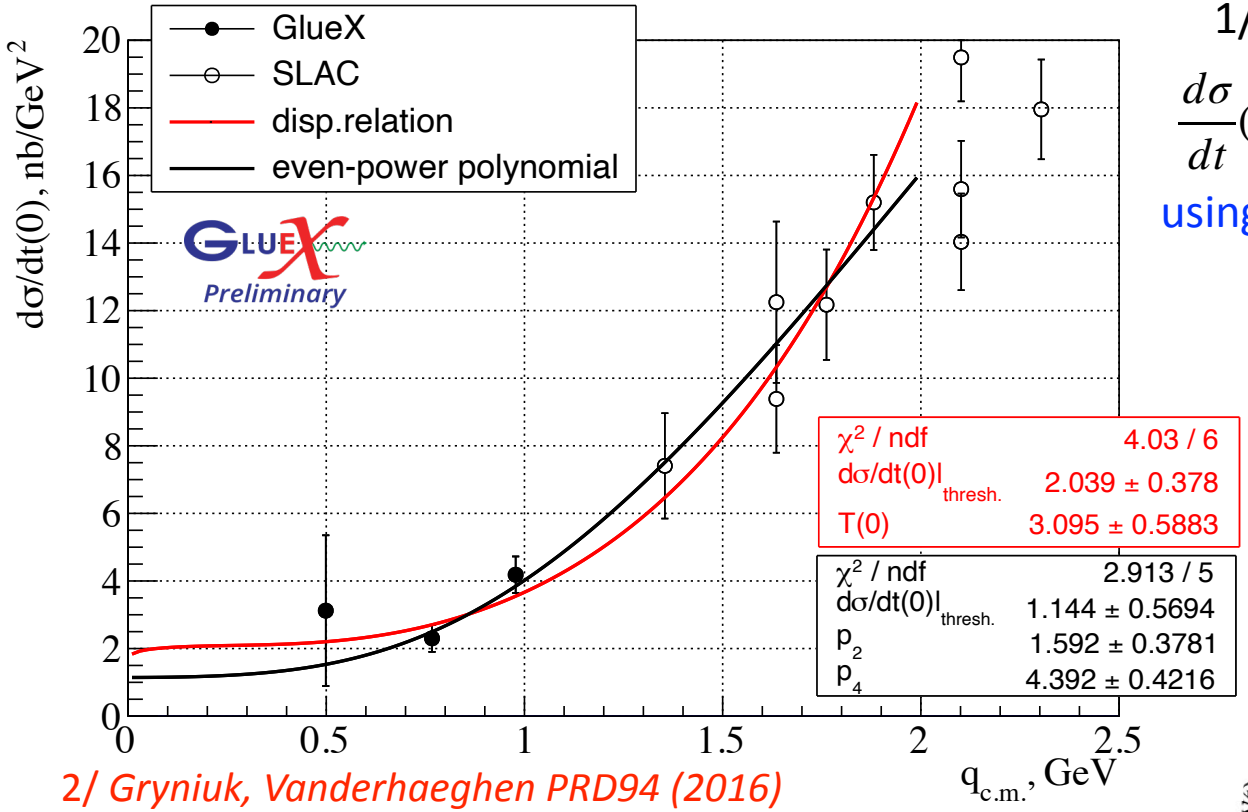
- Event-by-event weighting by luminosity
- Dots - mean energy and t-value for the corresponding bin
- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors

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

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

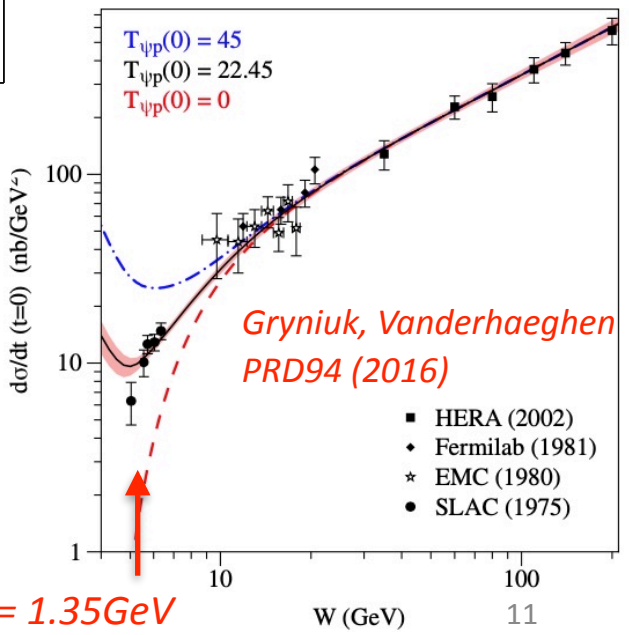
$$\frac{(sk_{\gamma p}^2)_{thr.}}{sk_{\gamma p}^2}[p_0 + p_2 q^2 + p_4 q^4]$$

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 $T(0)$



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

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

Forward differential cross-sections - model dependent applications

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

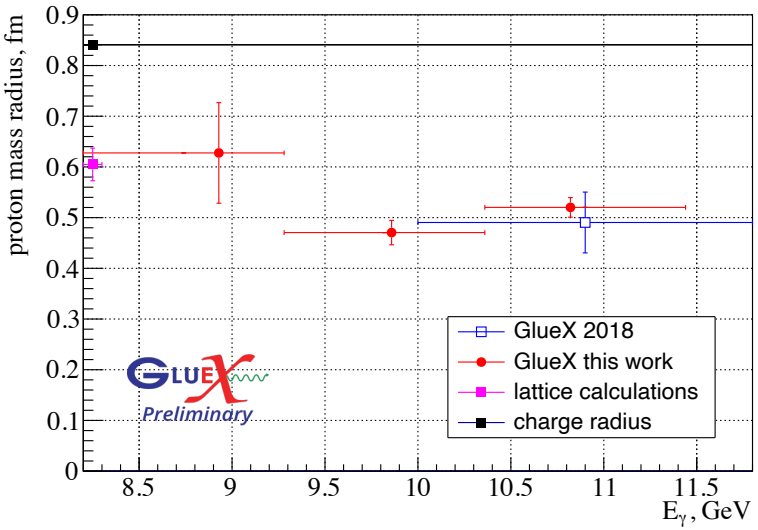
$13.4 \pm 3.8\ mfm,\ 17.9 \pm 1.7\ mfm$

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)

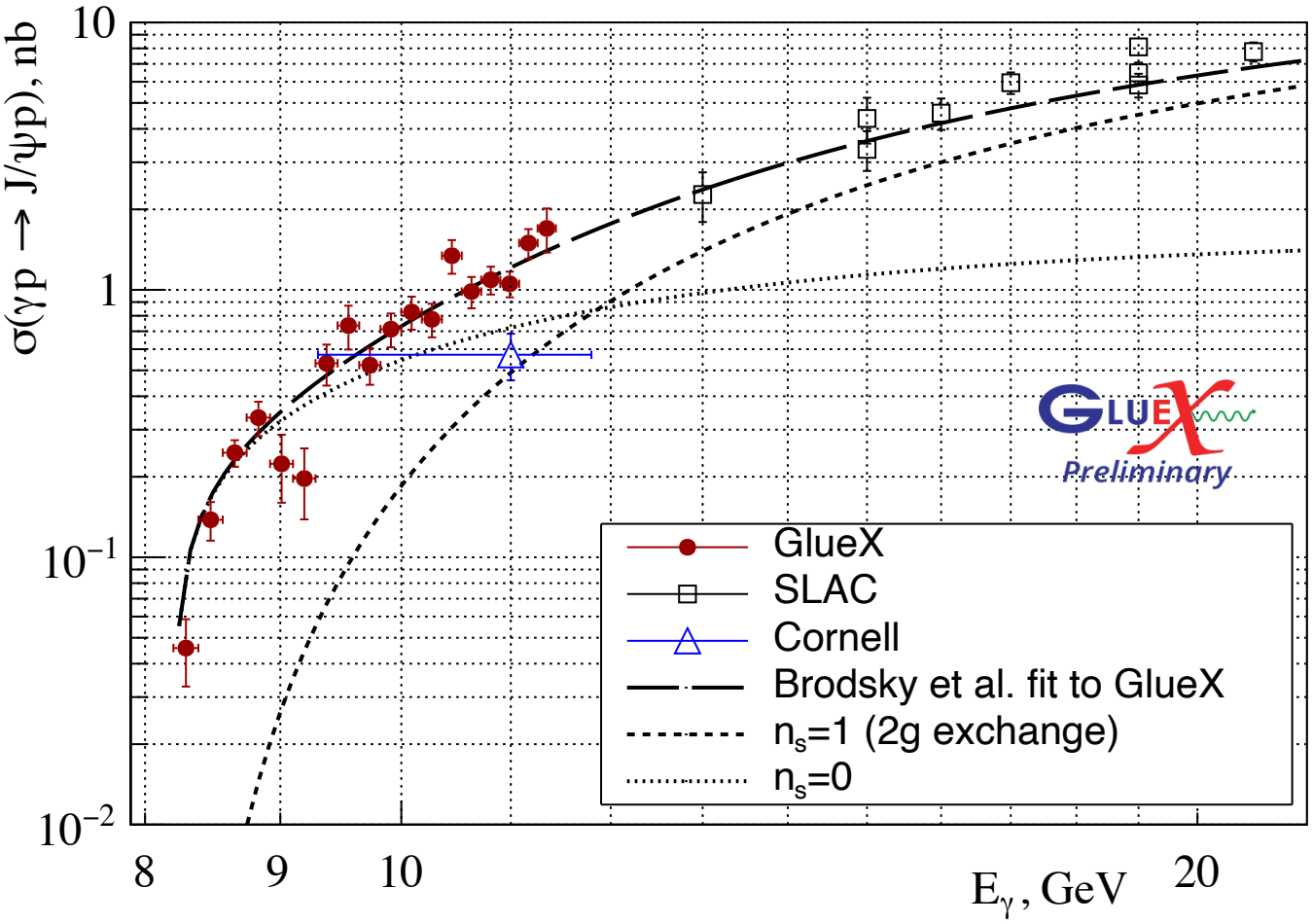
3/ Relation to GFFs - QCD: *Guo, Ji, Liu PRD103 (2021)*; holographic: *Mamo, Zahed PRD104 (2021), Hatta, Rajan, Yang PRD100 (2019)*

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

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)*

Total cross section asymptotic - power counting

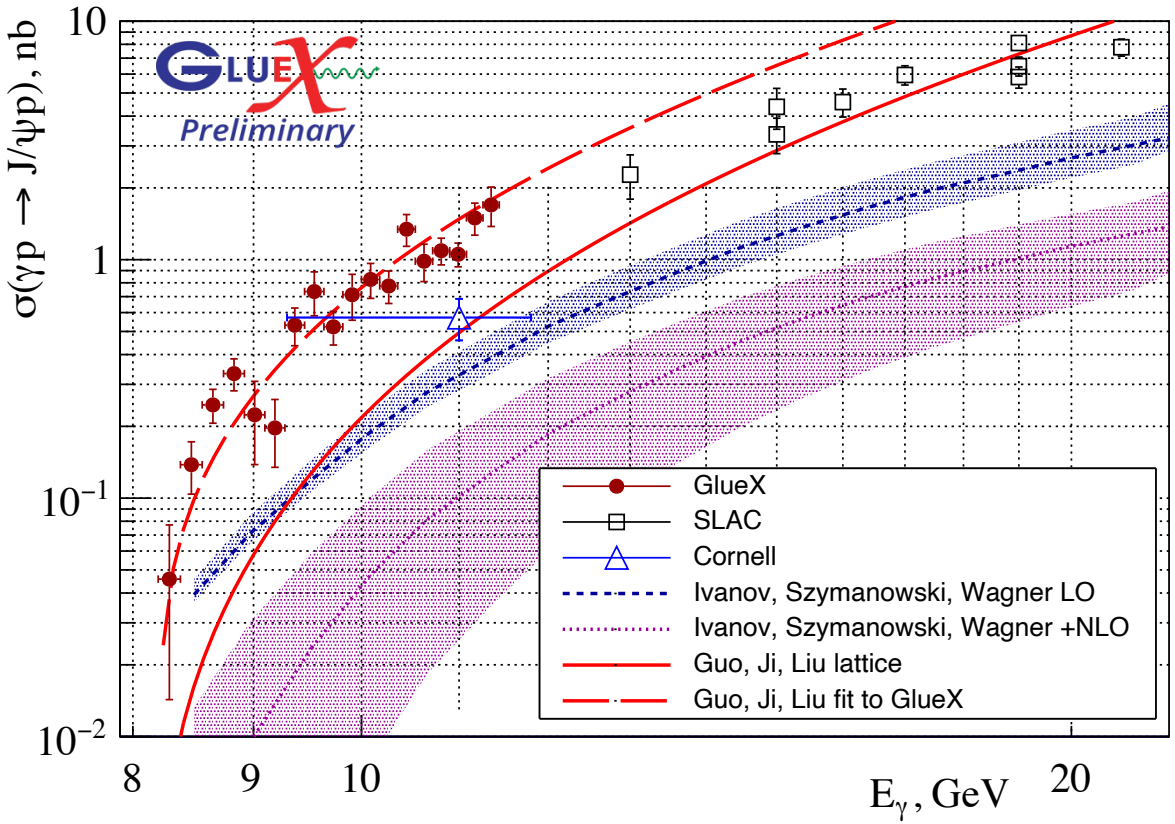


$\frac{d\sigma_{n_s}^{\gamma p}}{dt} = \mathcal{N}_{n_s}(1-x)^{2n_s} \cdot F_{n_s}^2(t)$, n_s is number of spectators in proton

Brodsky et al. PLB498 (2001)

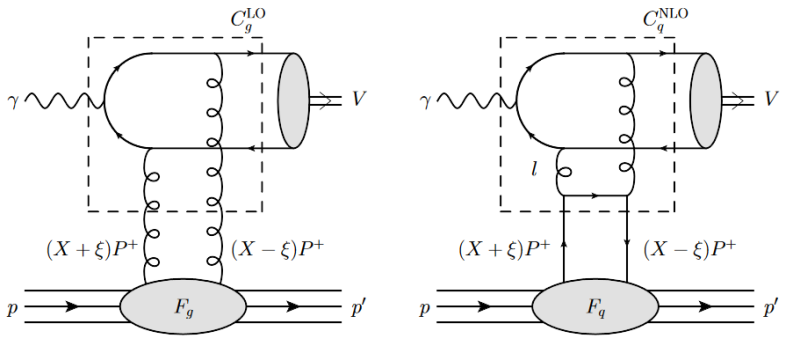
2g exchange alone not enough to describe x-section near threshold

QCD factorization models



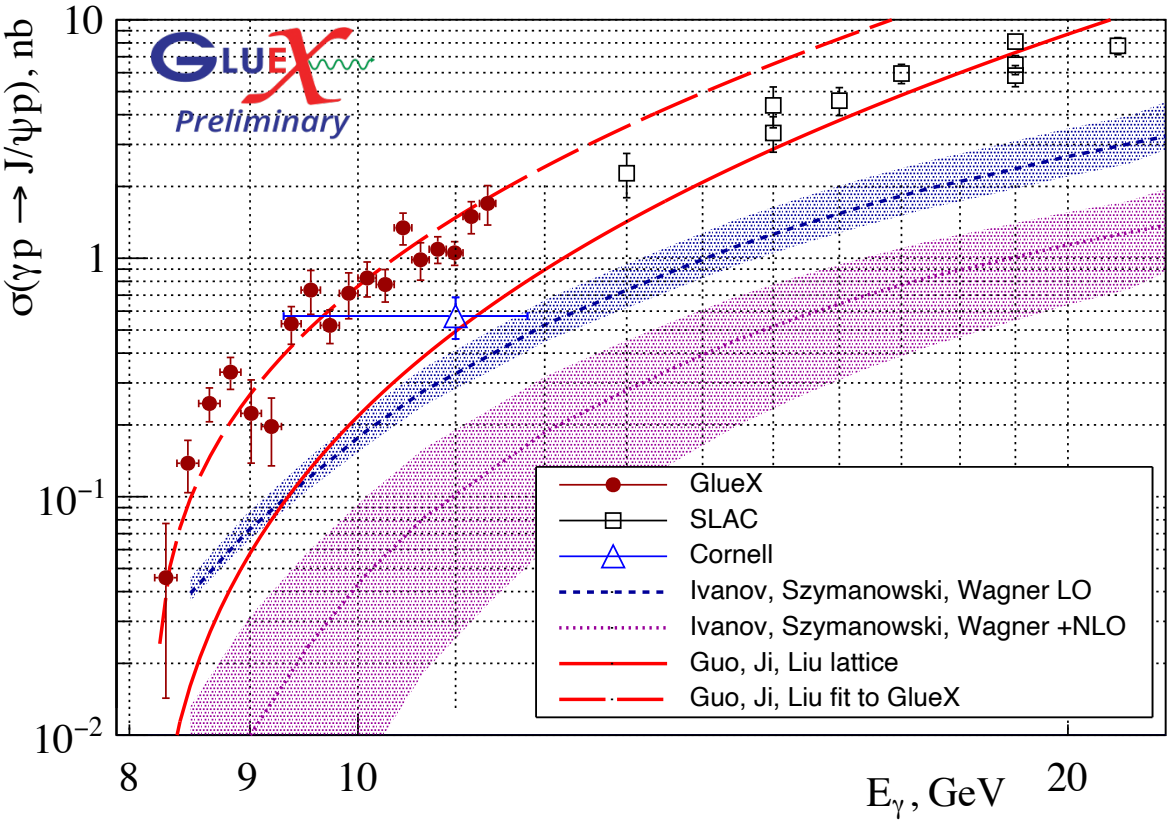
Ivanov, Schafer, Szymanowski, Krasnikov EPJ C34 (2004)
Ivanov, Szymanowski, Wagner - private communication
Factorization LO, NLO at high energies and low *t*

QCD models underestimate x-section significantly



Jones, Martin, Ryskin, Teubner, EPJC 76 (2016)
Flett, Jones, Martin, Ryskin, Teubner, arXiv:1908.08398 (Aug 2019)

QCD factorization models

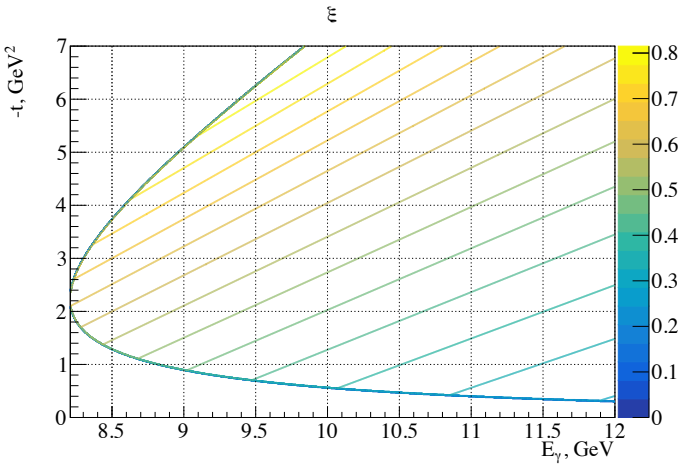


Guo, Ji, Liu PRD103 (2021)

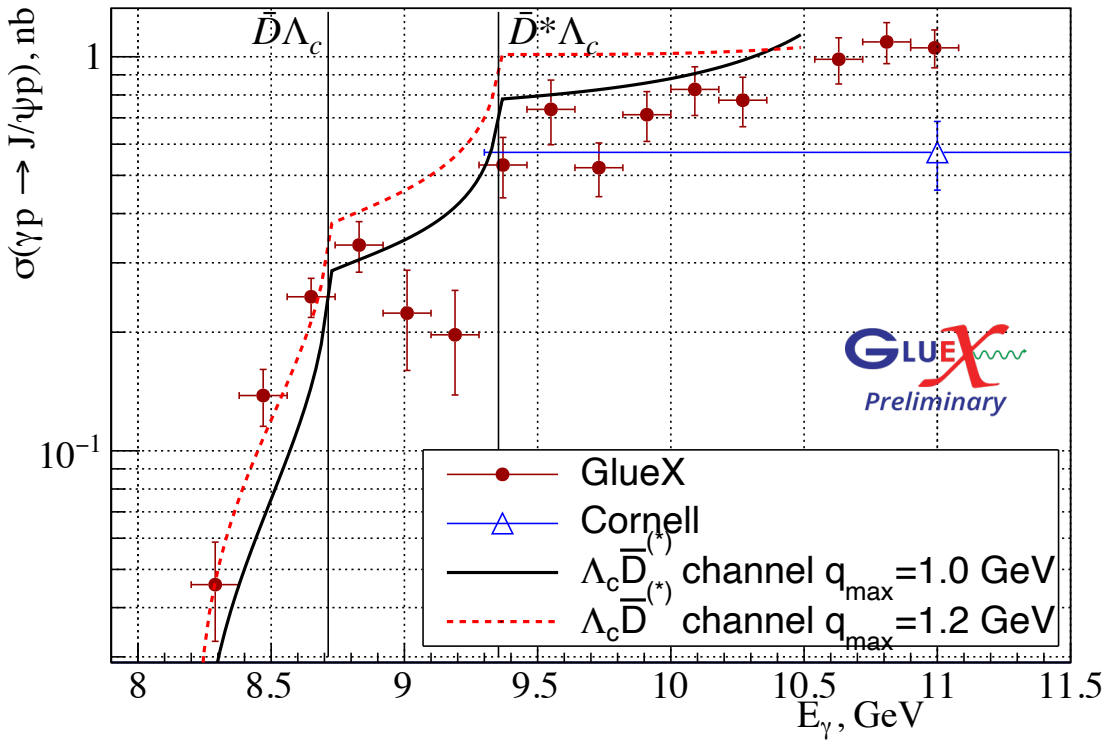
In heavy-quark mass limit - factorization valid near threshold (resp. for high *t*)

- GPD + lattice results for $A_g(t)$ *and* $C_g(t)$
- Fit to published GlueX data (2019)

QCD models underestimate x-section significantly



Open-charm exchange



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

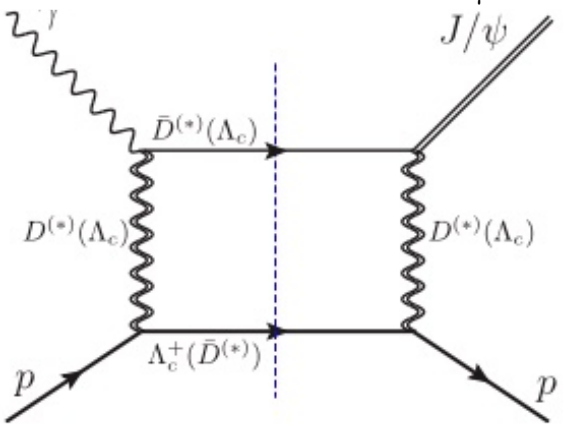
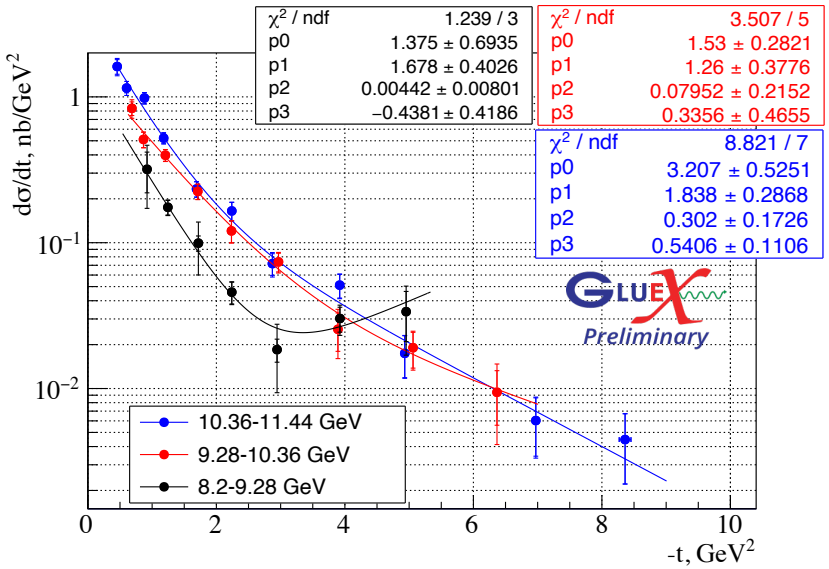


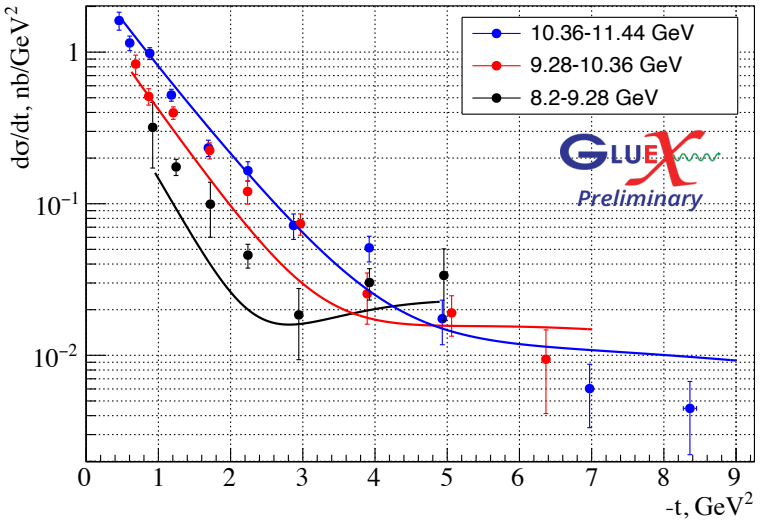
FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

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	u-channel - charm baryon exchange ✓	possible ?
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	?	?
Naturality	?	2g - natural parity exchange



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



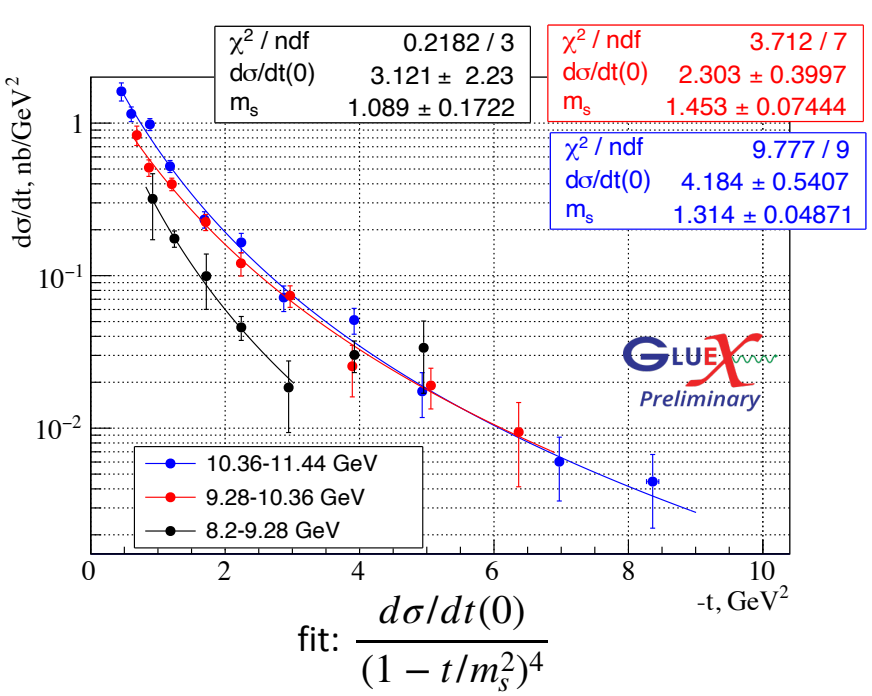
Guo, Ji, Liu PRD103 (2021)
Assuming $C_g(t) = -A_g(t)/2$

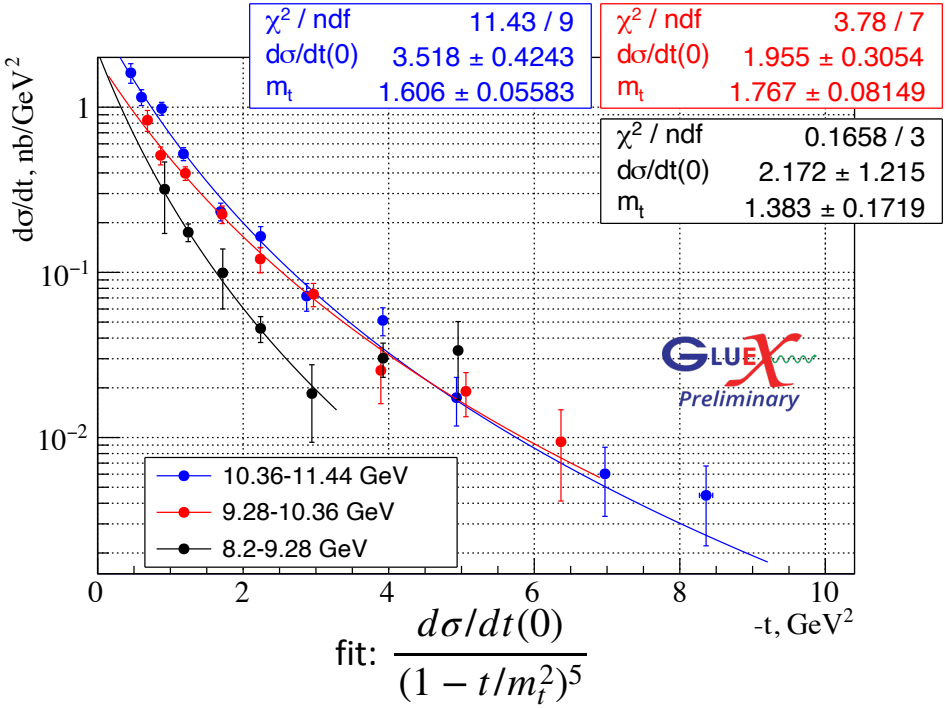
Conclusions

- New GlueX data - 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 - 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:
- 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

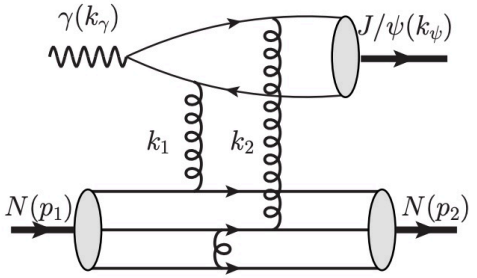
QCD: high-*t* asymptotic





Sun, Tong, Yuan PRD105 (2022)

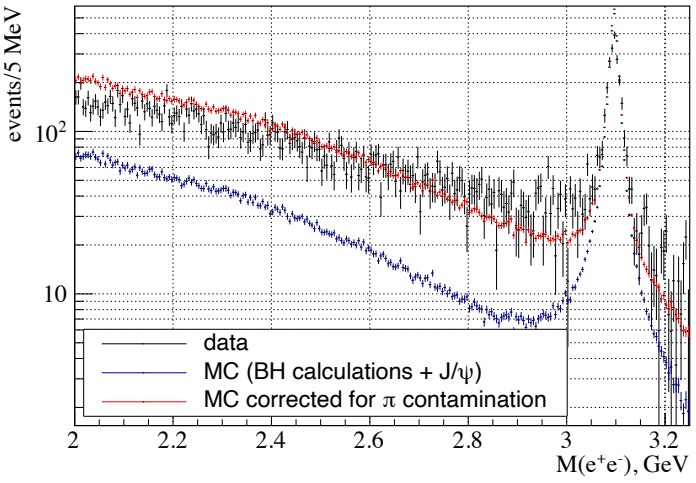
Asymptotic *t*-dependance $1/t^5$ $(vs\ 1/t^4)$ due to helicity flip

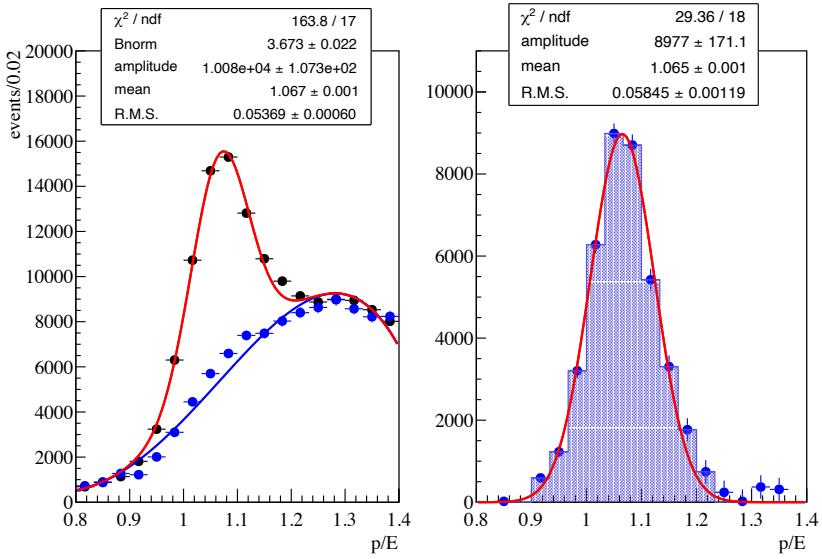


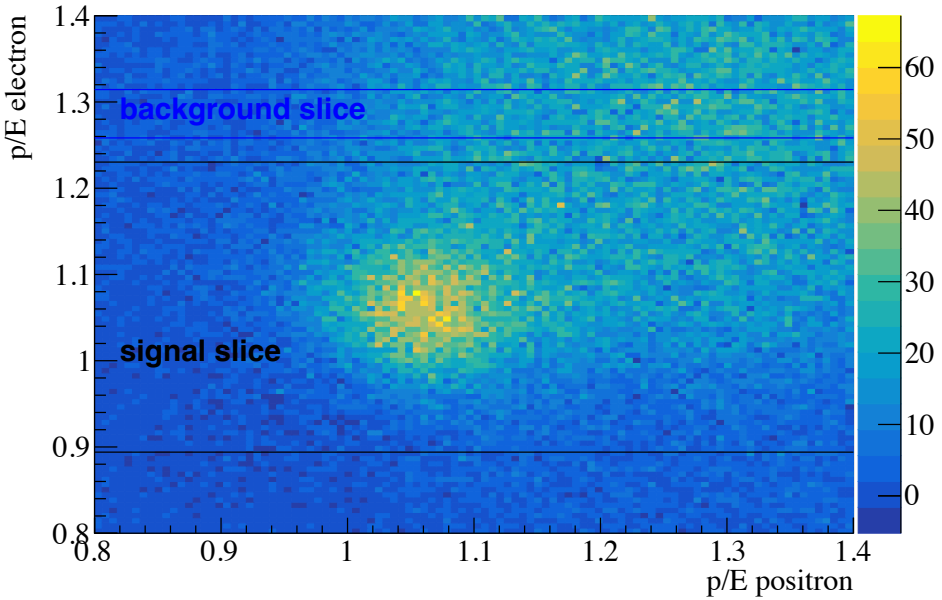
Not enough statistics to test the *t*-asymptotic

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

e/π separation

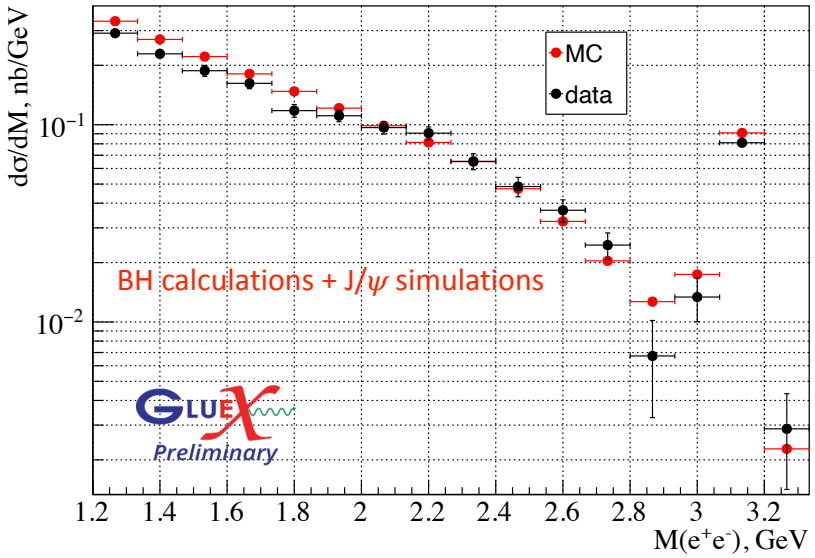


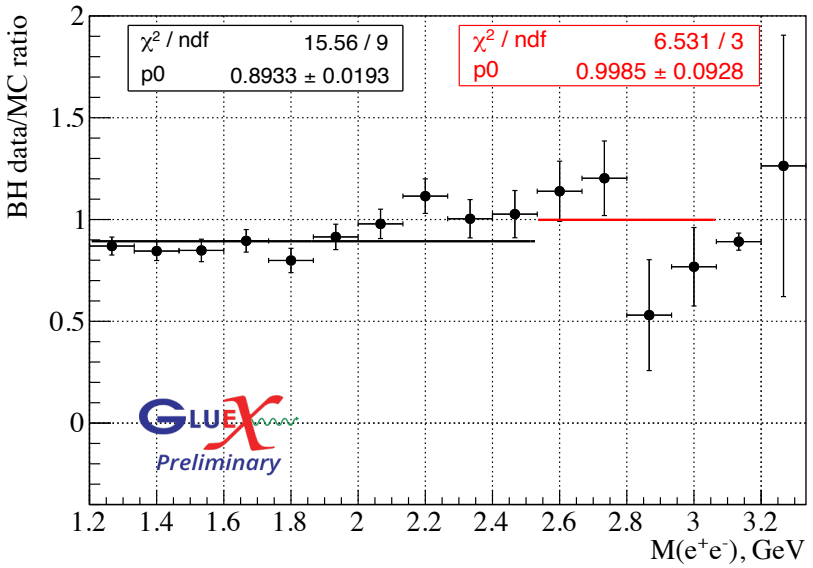


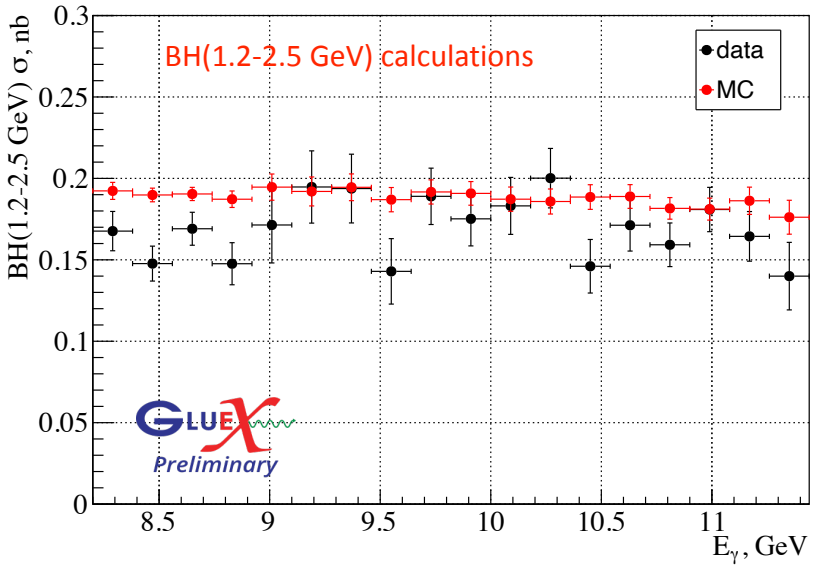


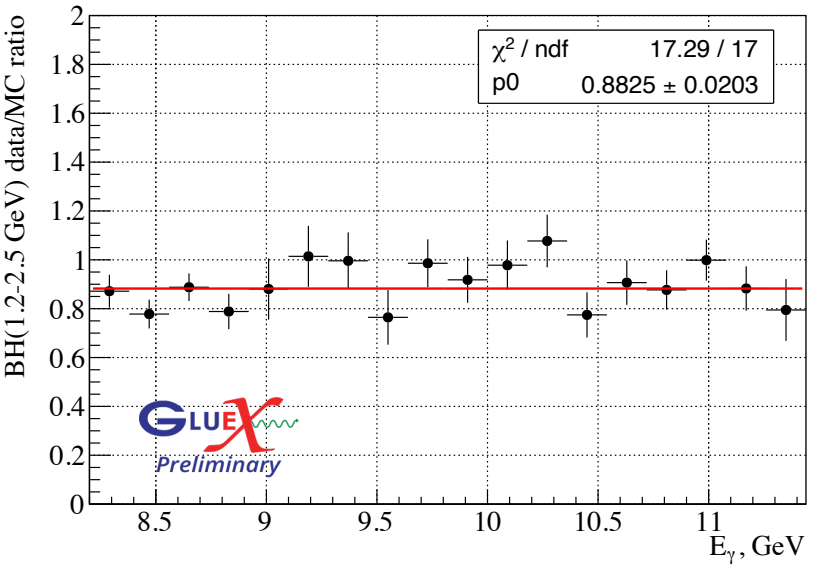
- Pion contamination ~50% in the continuum (using p/E fits to estimate it)

BH e.m. calculations vs data



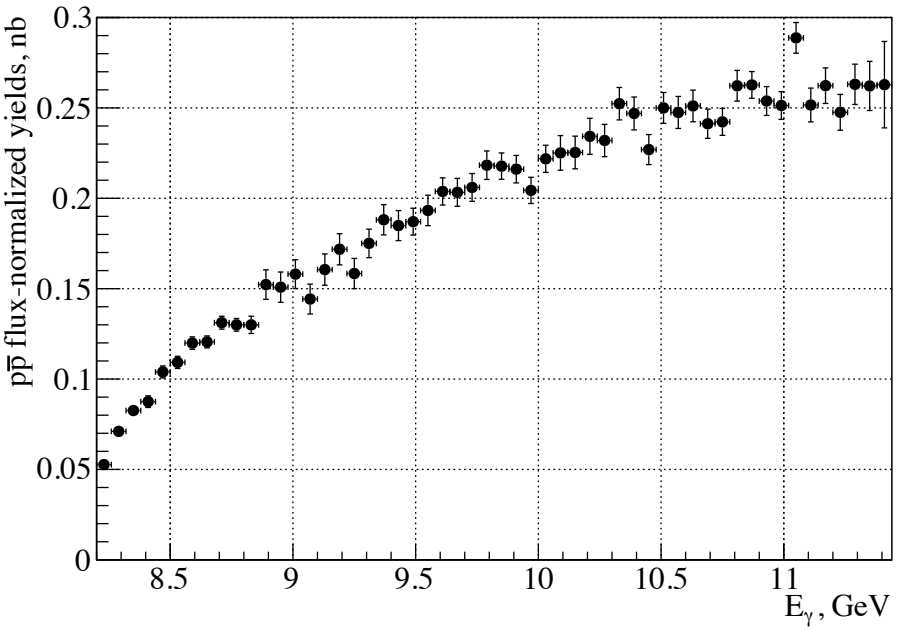


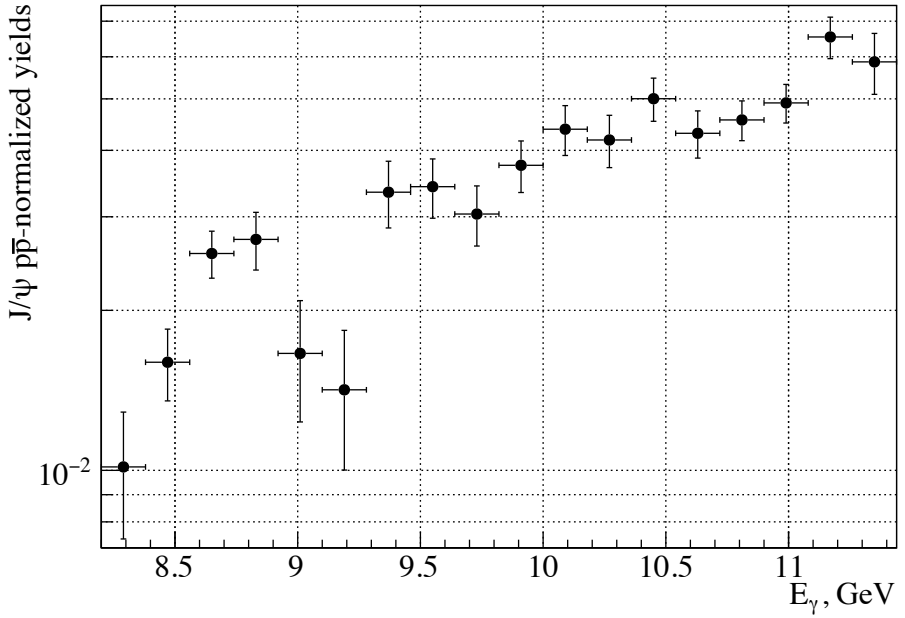




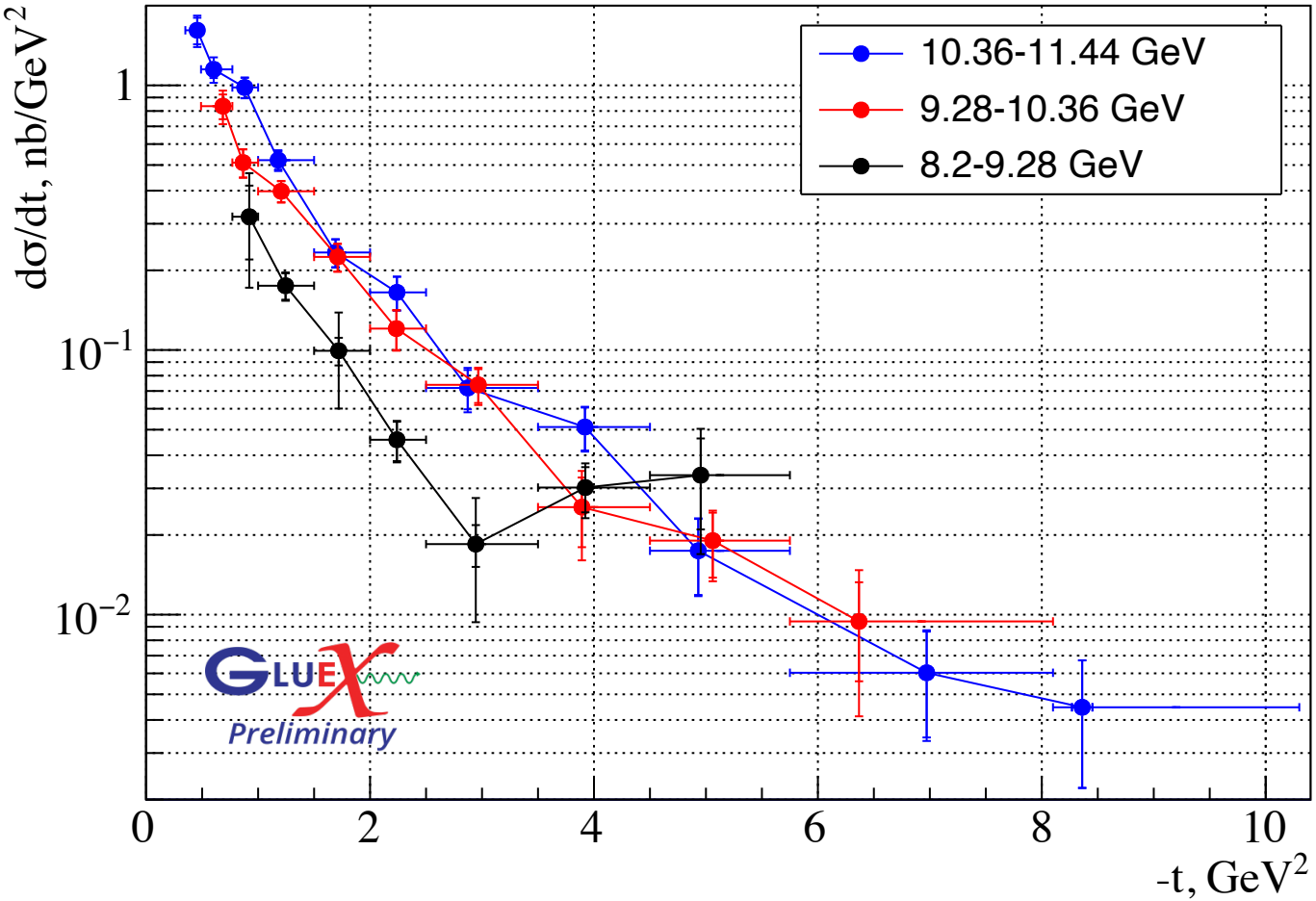
BH yields extracted from fits of E/p distributions

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





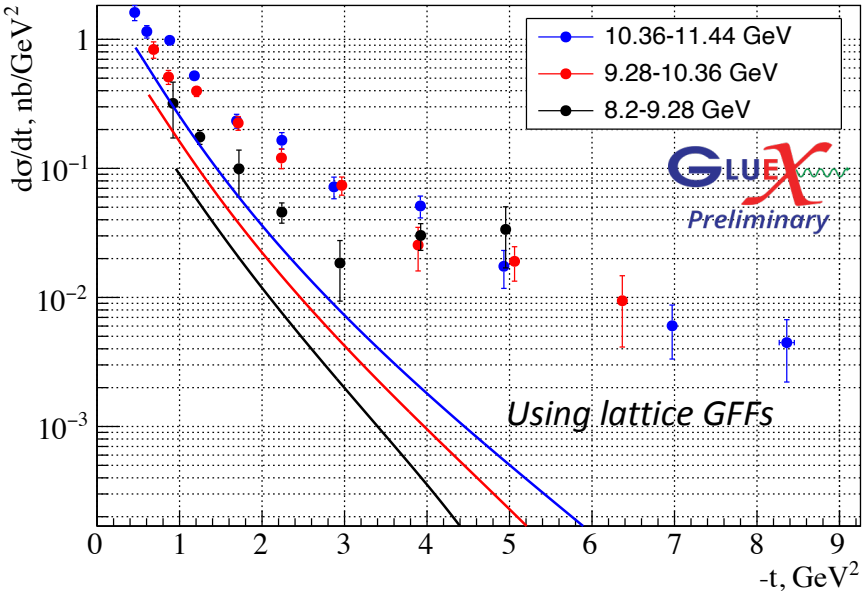
Preliminary results: differential cross-sections

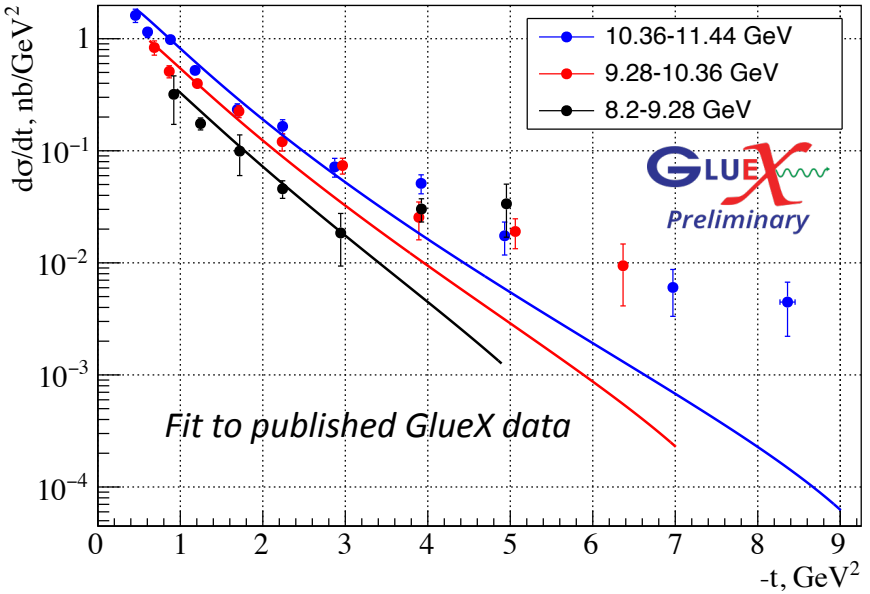


$$\frac{d\sigma}{dt}(E,t) = \frac{N_{J/\psi}}{L(E_\gamma)[nb^{-1}]/0.045GeV} \frac{1}{area(E,t)[GeV \cdot GeV^2]} \frac{1}{\varepsilon(E,t)}$$

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

Differential cross sections - QCD factorization





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