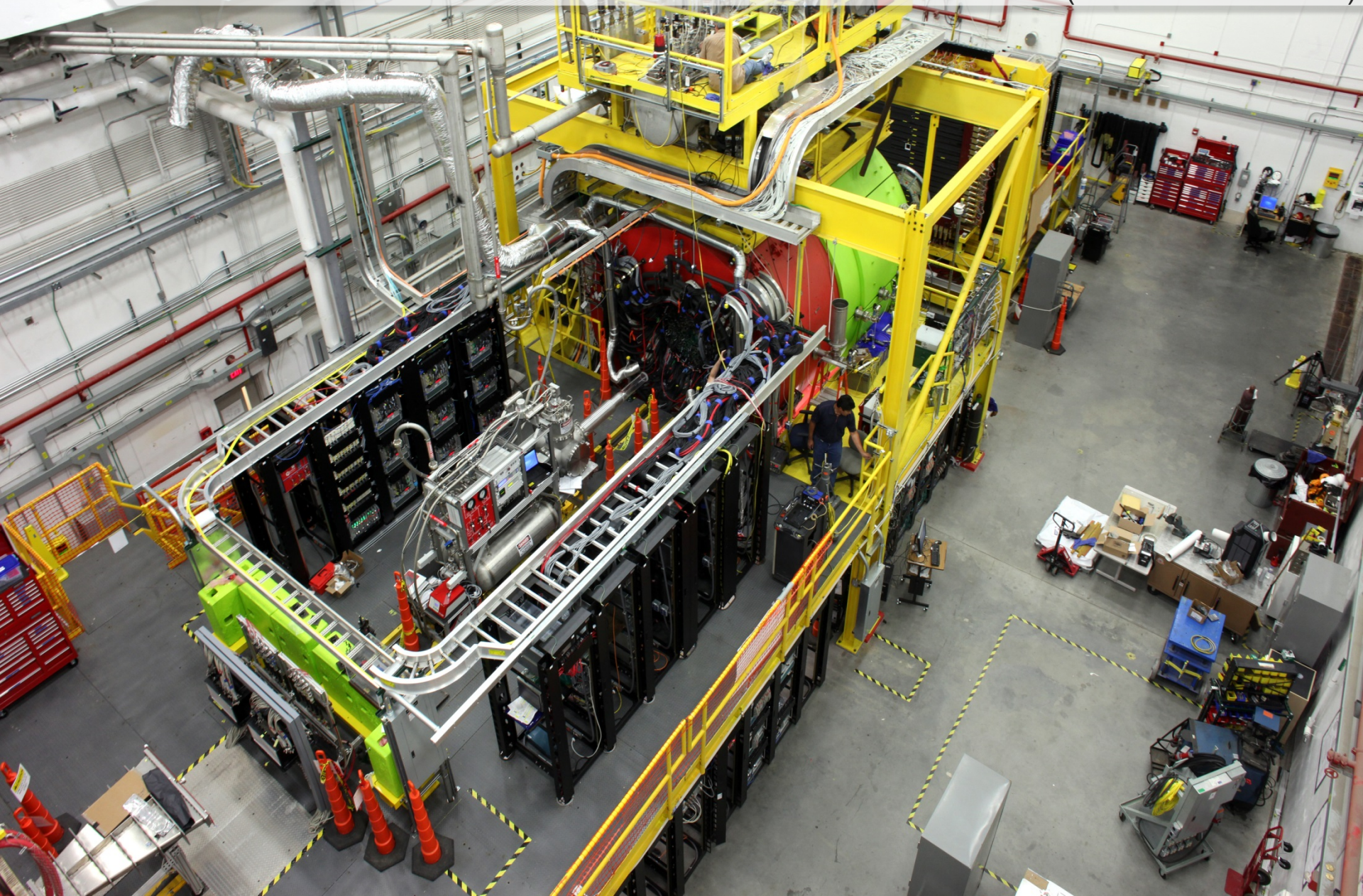
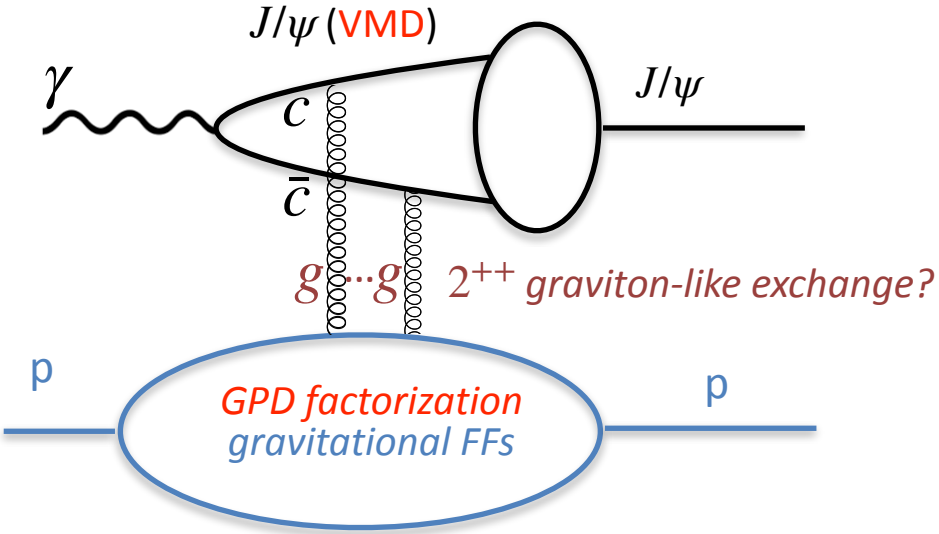
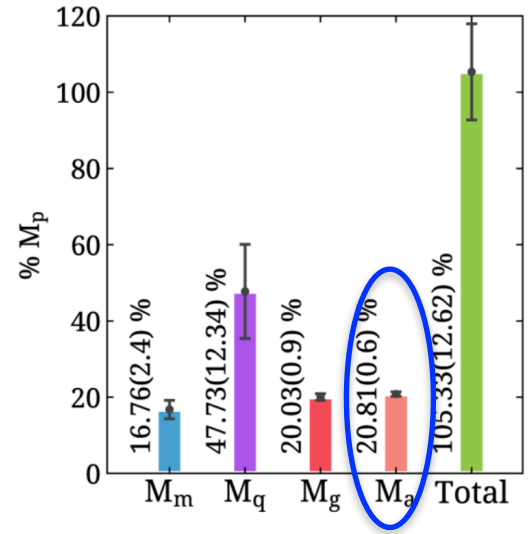
Threshold charmonium photoproduction with GlueX

Lubomir Pentchev
(GlueX Collaboration)



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



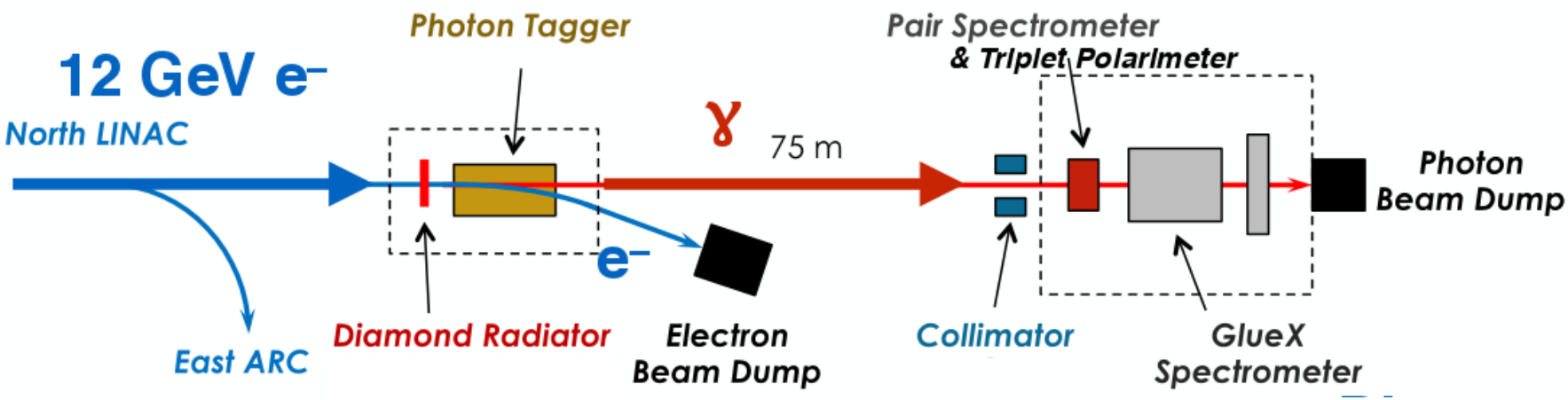


C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

- 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, Hatta, Strikman 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*)

Such ambitious program requires detailed studies of the reaction mechanism to justify these assumptions.

Hall D Apparatus at Jefferson Lab



- Photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron: 0.2% resolution
- Beam collimated at 75m, <35 μrad
- Intensity: ~ $5 \cdot 10^7$ - 10^8 γ/sec above J/ψ threshold (8.2 GeV) – total ~320 pb^{-1} in GlueX phase-I runs
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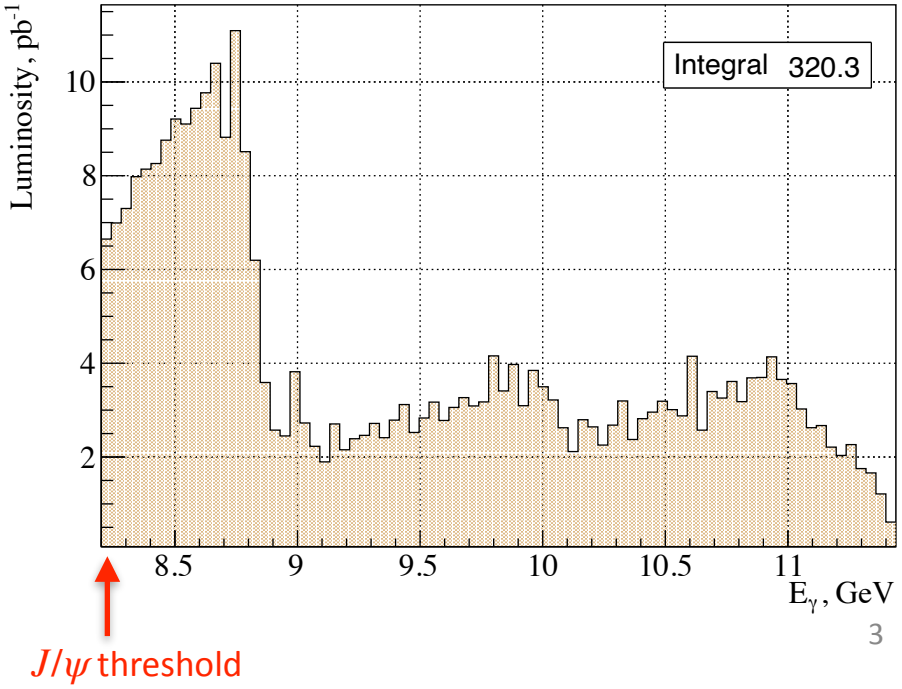
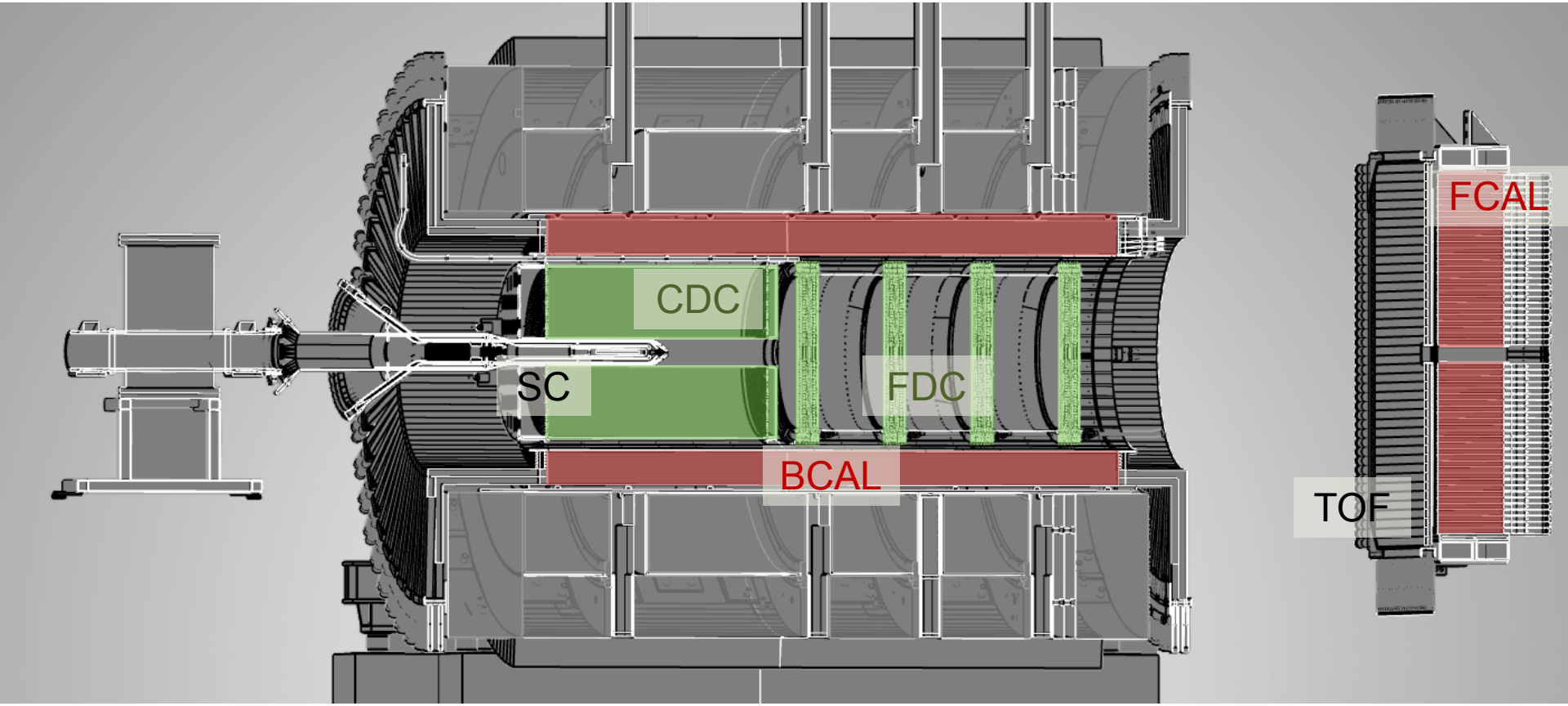


GlueX detector

2T-solenoid, LH2 target

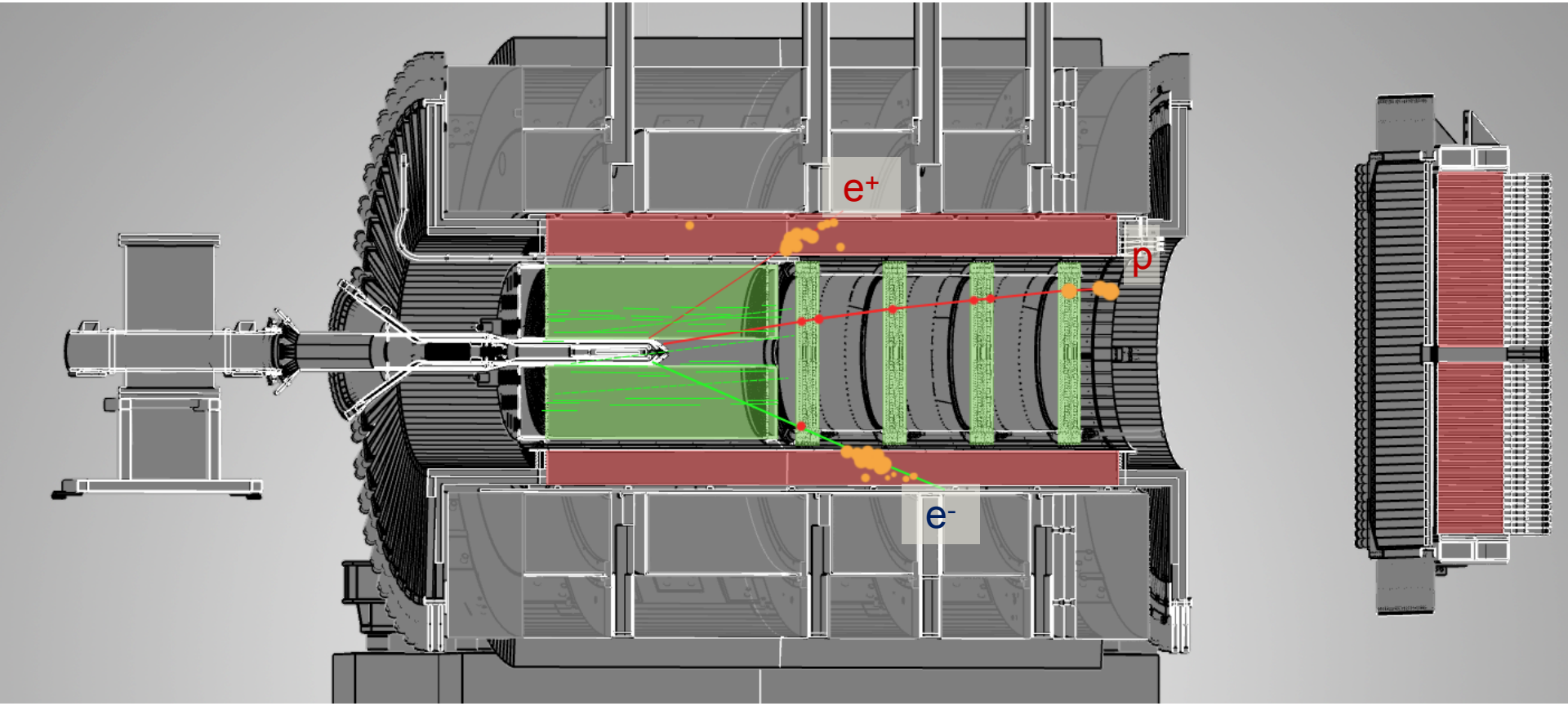
Tracking (FDC,CDC) , Calorimetry (BCAL,FCAL) , Timing (TOF,SC)



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

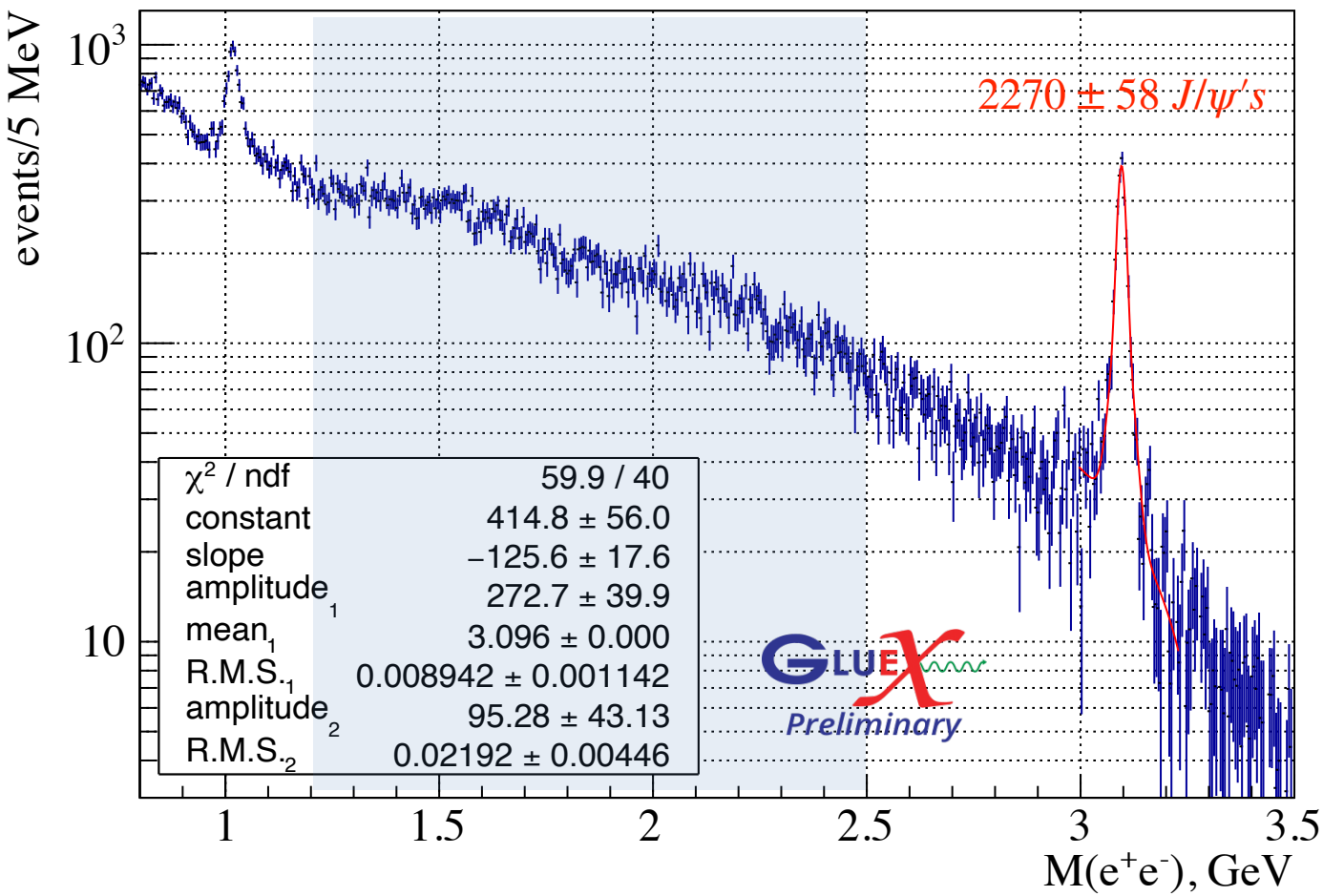
Exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$

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



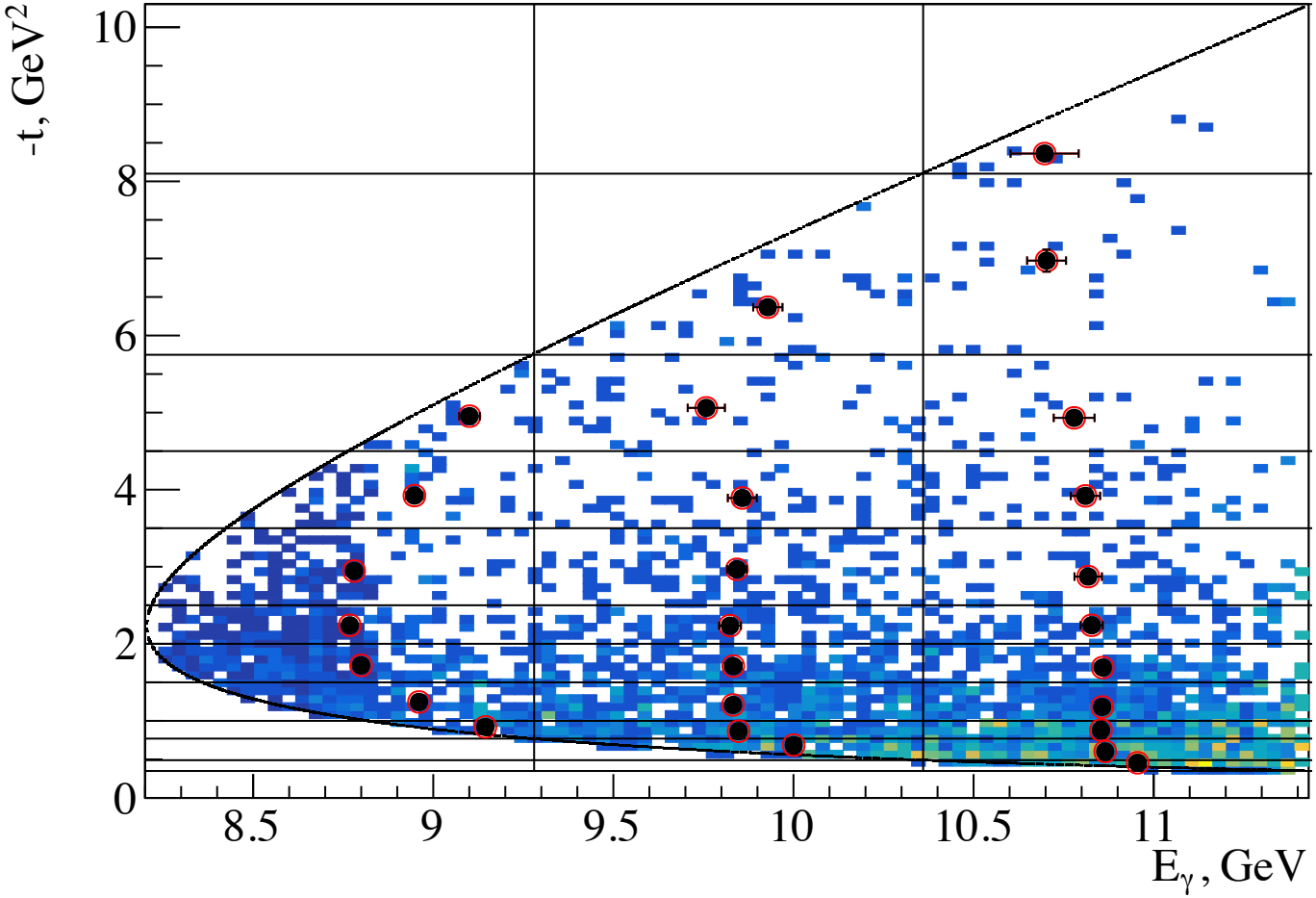
- Electrons separated from pions by E/p – energy deposition in the calorimeters over measured momentum (pions >10^3 times more than electrons)

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

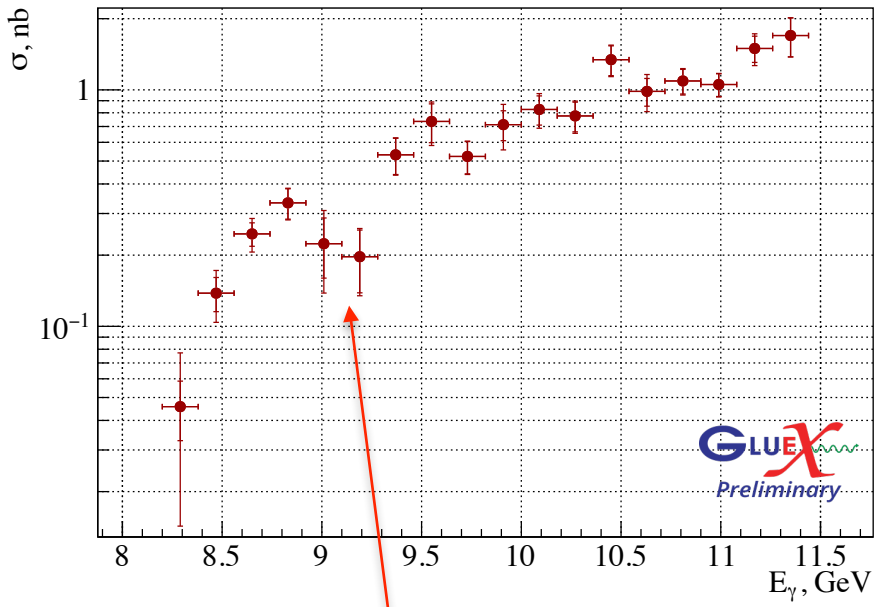
Threshold region coverage

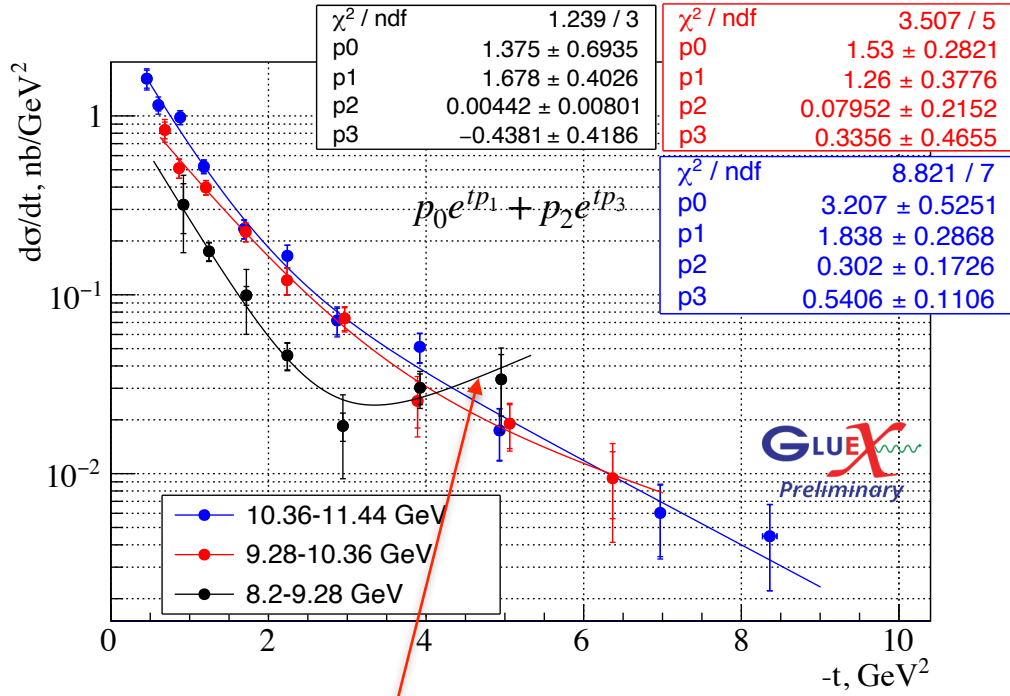


- Event-by-event weighting by luminosity
- Dots - mean energy and t-value for the corresponding bin
- Results reported at mean energy for corresponding slice
- Deviations due to bin averaging included in the systematic errors

Preliminary GlueX results: total and differential cross-sections

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





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

however:

- Possible structure in $\sigma(8.6 - 9.6GeV)$, 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,

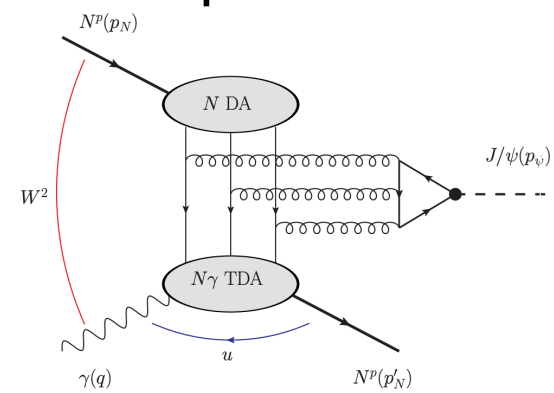
however:

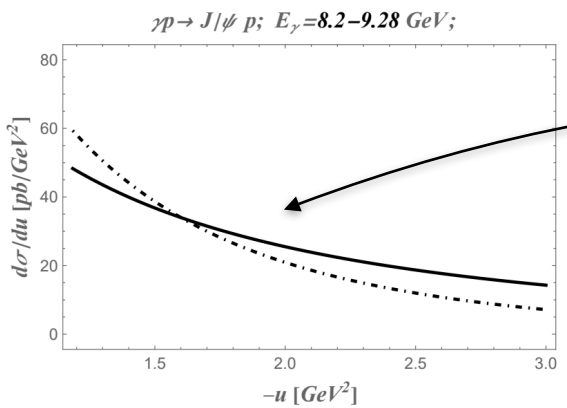
- Enhancement of $d\sigma/dt$ at high t (for the lowest energy slice)

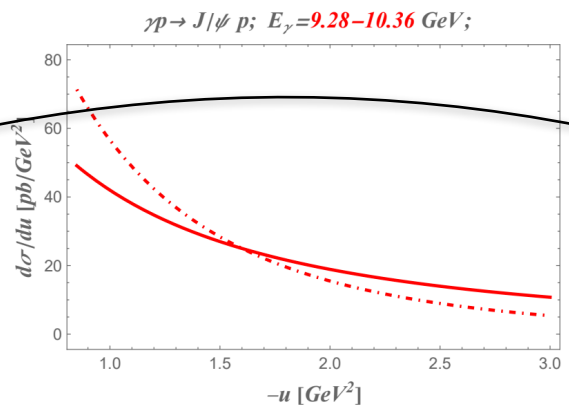
Differential cross-sections - u-channel interpretation

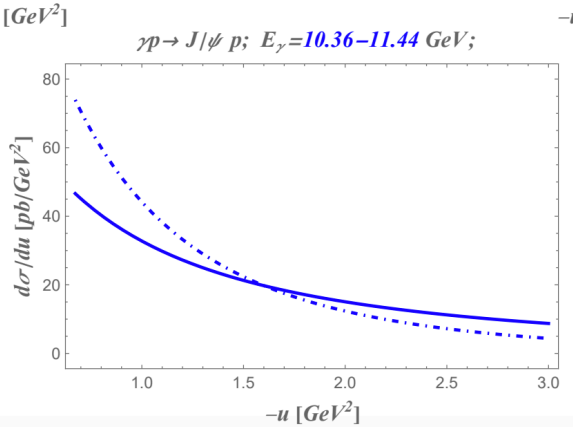
- Assuming factorization in terms of Transition Distribution Amplitudes
- Hard scale provided by M_ψ^2 and W^2
- The high-t enhancement for $E_\gamma = 8.2 - 9.28$ GeV may indicate u-channel contribution, but what about higher energies?

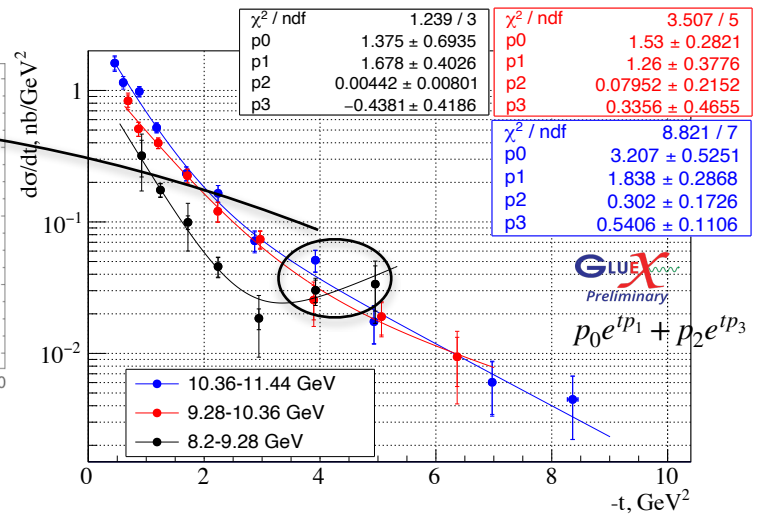
Pire, Semenov-Tian-Shansky, Shaikhutdinova,Szymanowski (2022)





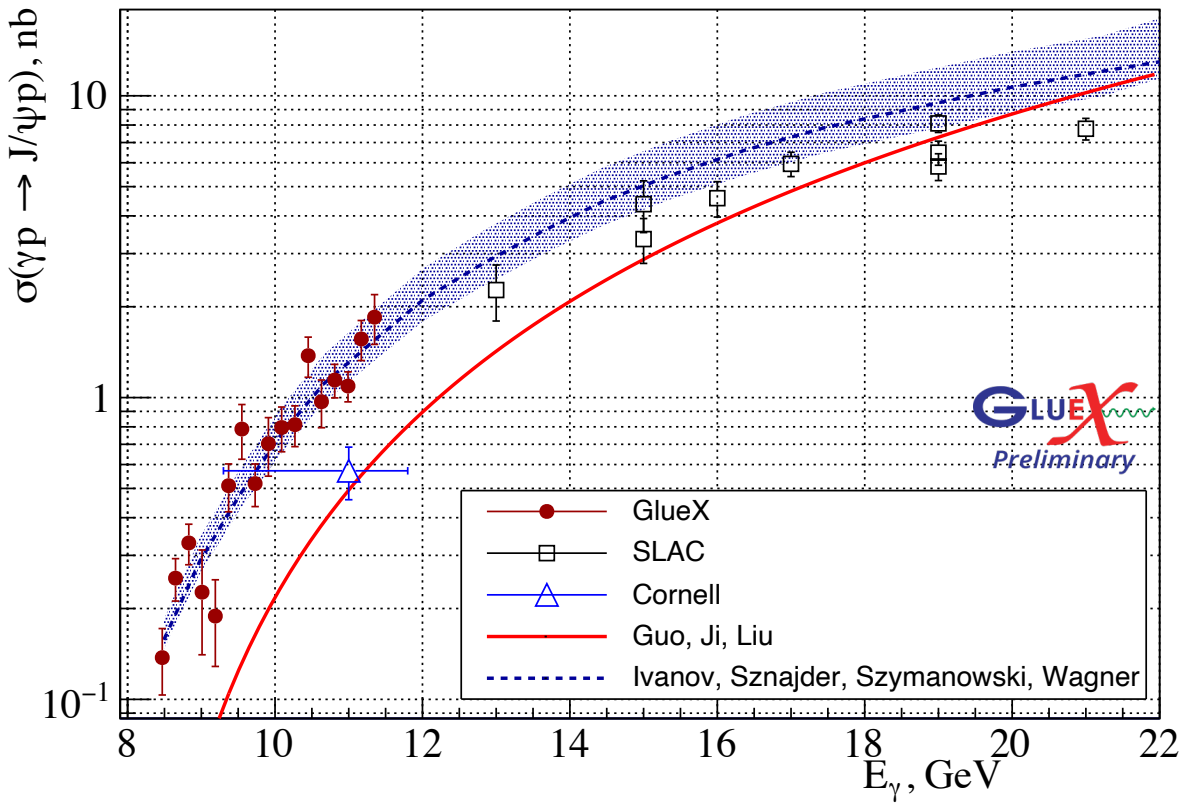






E_γ [GeV]	W [GeV]	$-t_1$ [GeV^2]	$-u_0$ [GeV^2]
$8.2 - 9.28$	$4.04 - 4.28$	$3.99 - 6.58$	$1.54 - 0.98$
$9.28 - 10.36$	$4.28 - 4.51$	$6.58 - 8.84$	$0.98 - 0.75$
$10.36 - 11.44$	$4.51 - 4.73$	$8.84 - 11.01$	$0.75 - 0.61$

GPD factorization models



Ivanov, Sznajder, Szymanowski, Wagner (2022)

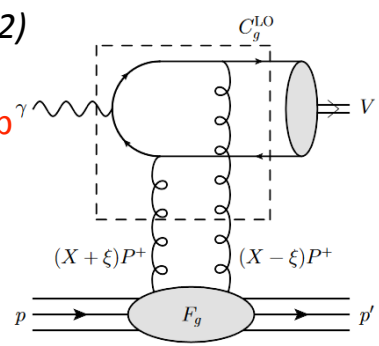
- GPD LO calculations
- Big uncertainties in NLO, data can help to constrain gluon GPDs

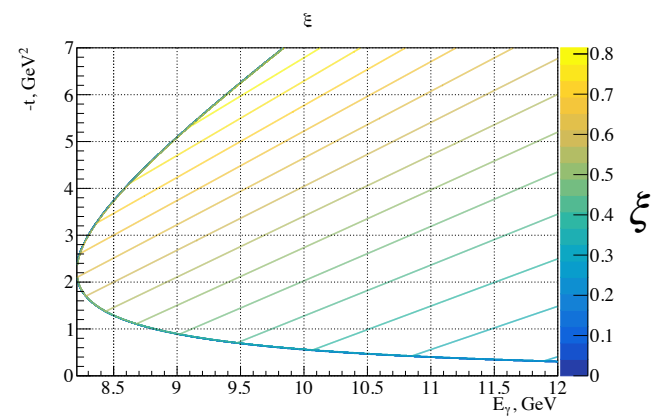
Guo, Ji, Liu PRD103 (2021),

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

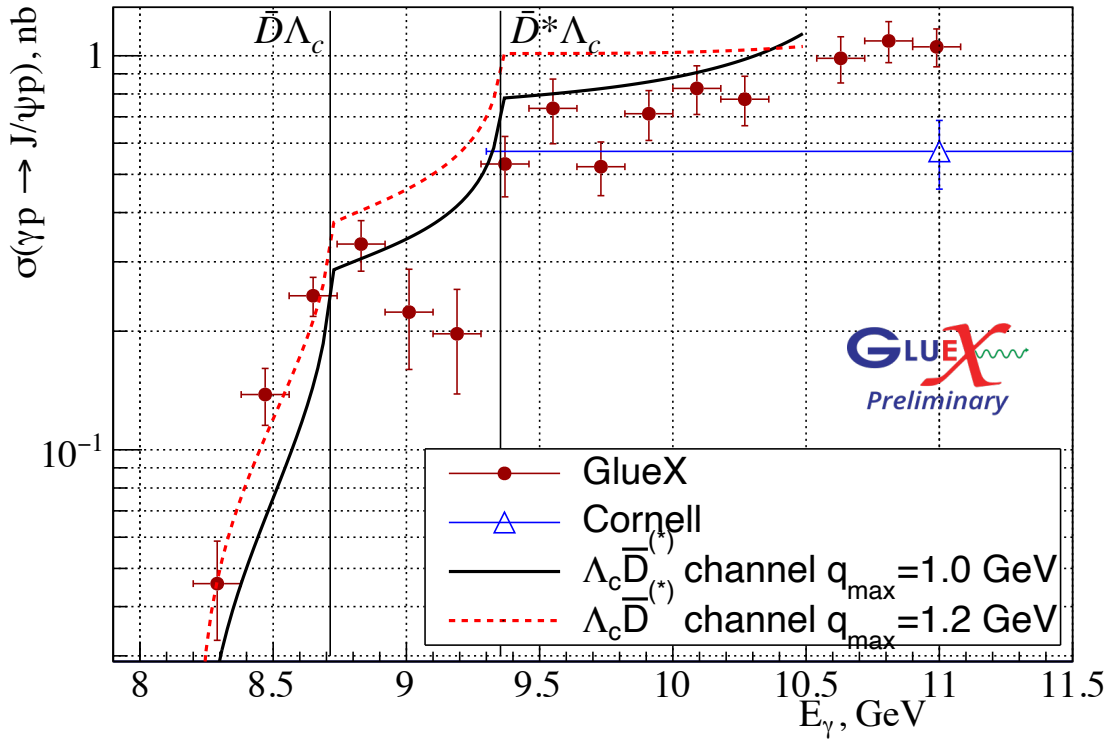
(*Hatta,Strikman 2021):*

- factorization valid near threshold
- connection to gravitational FFs





Open-charm exchange



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

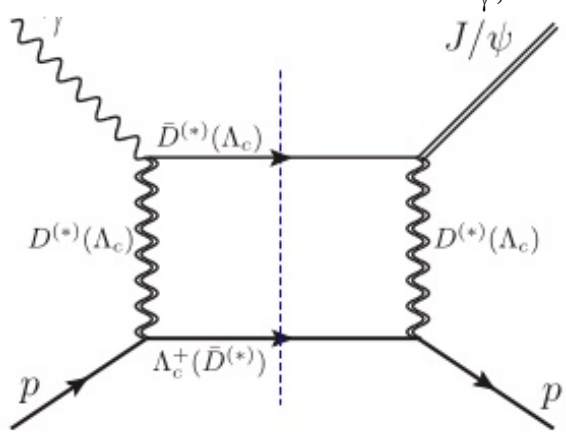
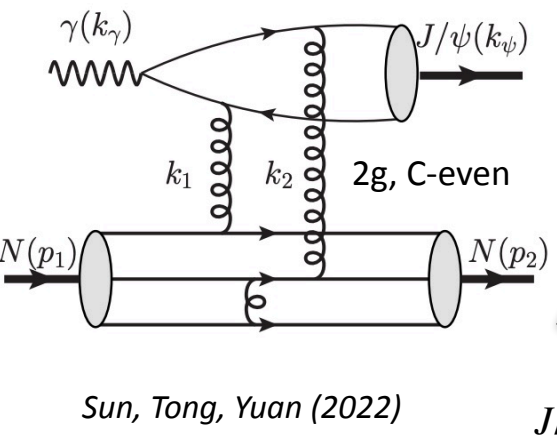


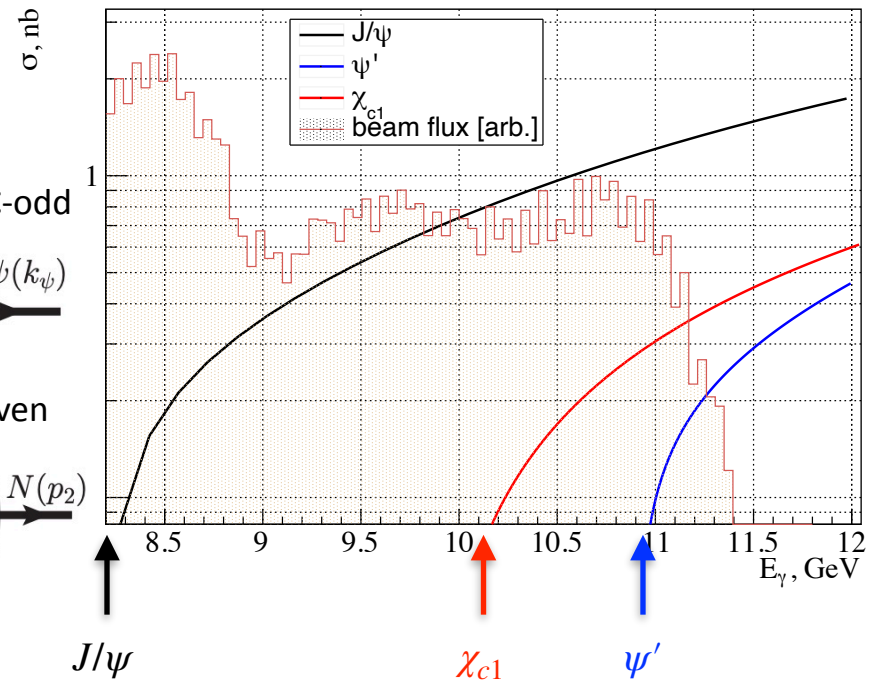
FIG. 3. Feynman diagram for the proposed CC mechanism. The dashed blue line pinpoints the open-charm intermediate state.

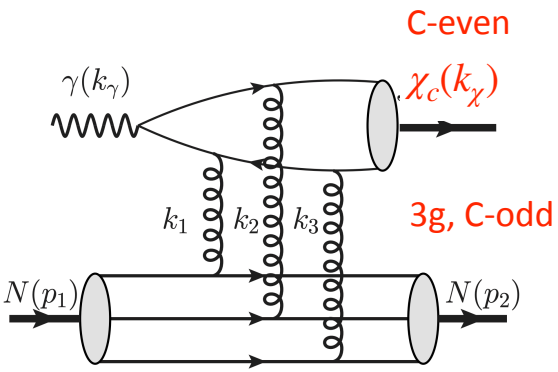
Higher-mass charmonium states at threshold with GlueX

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



Sun, Tong, Yuan (2022)





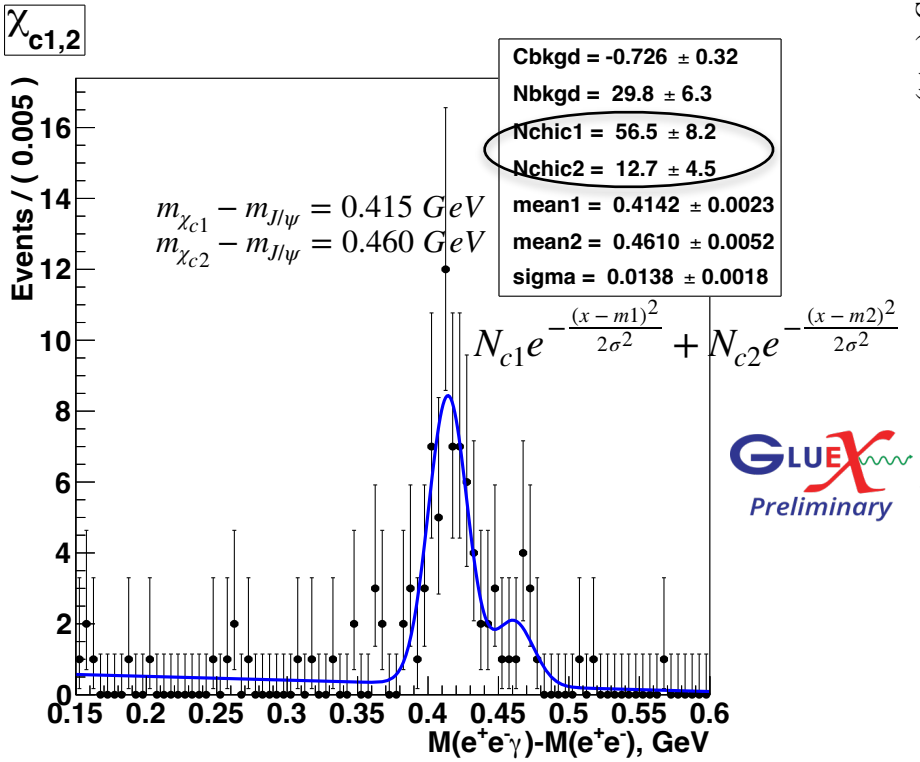
- $\chi_{c1}(3511)$ and $\chi_{c2}(3556)$, 1^{++} and 2^{++} $(1P)$, $E_\gamma^{thr} = 10.1$ GeV
- C-even charmonium states require 3g-exchange

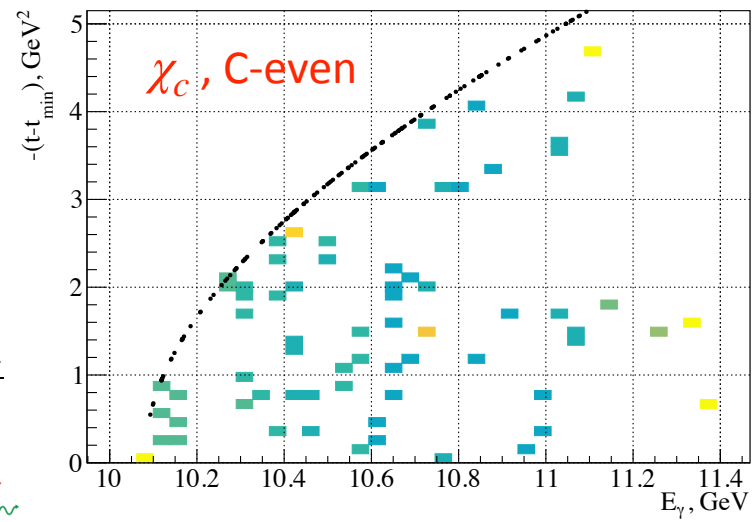
- GlueX has observed also a small number of $\psi'(3686)$ $(2S)$ states in $\gamma p \to \psi' p \to (e^+e^-)\,p$, $E_\gamma^{thr} = 10.9$ GeV

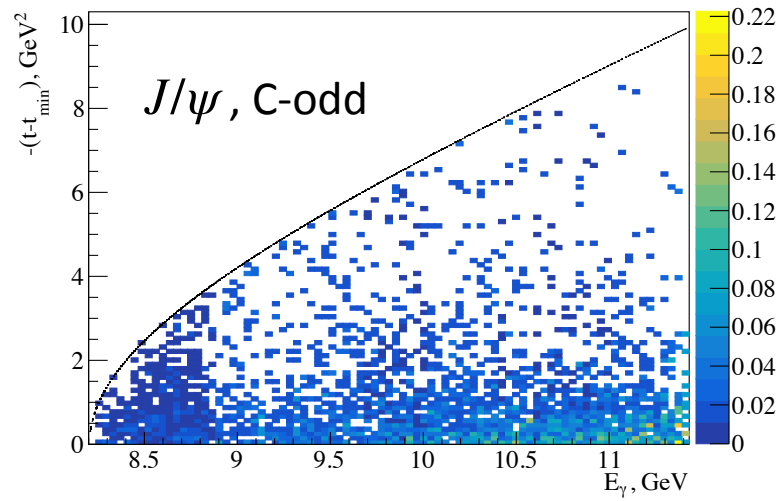
Higher-mass charmonium states with GlueX

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

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







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

- $\chi_{c1}(3511)$ 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

Summary

- The reported total and differential cross sections of J/ψ photoproduction near threshold are generally consistent with gluon exchange (t-slope, GPD factorization), except:
  - possible structure in the total cross section and
  - flattening of the differential cross section near threshold,

  the latter consistent with open charm exchange.

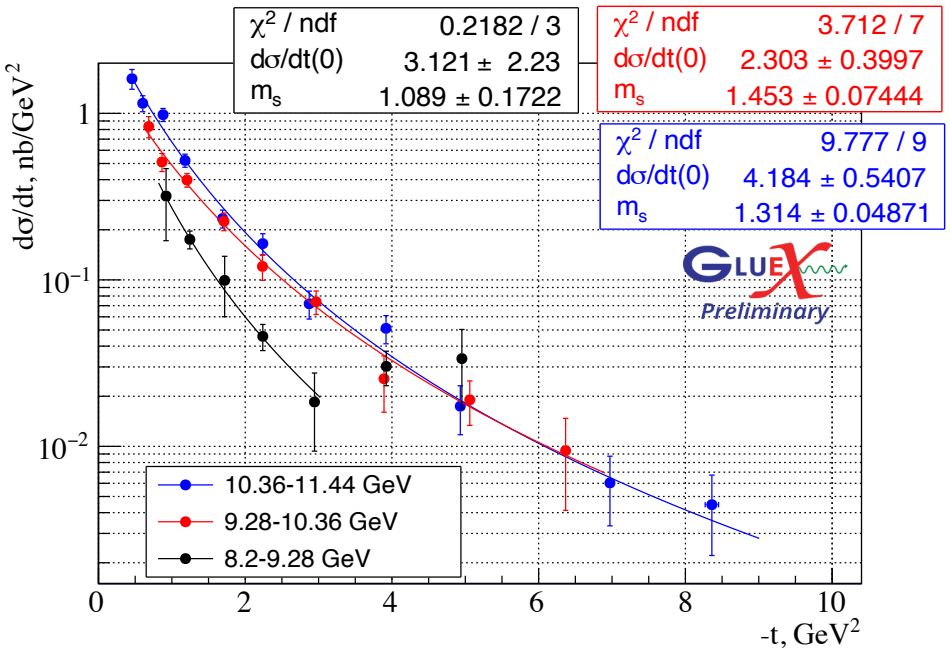
- It is important to separate between the gluon exchange, open-charm exchange, or any other contribution (resonances (P_c's), u-channel) and possibly find a kinematic region that can be used to constrain gGPDs, extract proton gravitational form factors and study mass properties of proton.

- So far, from JPAC simultaneous analysis of gluon and open-charm exchange it is not possible to distinguish b/n two mechanisms, further theoretical work is needed.

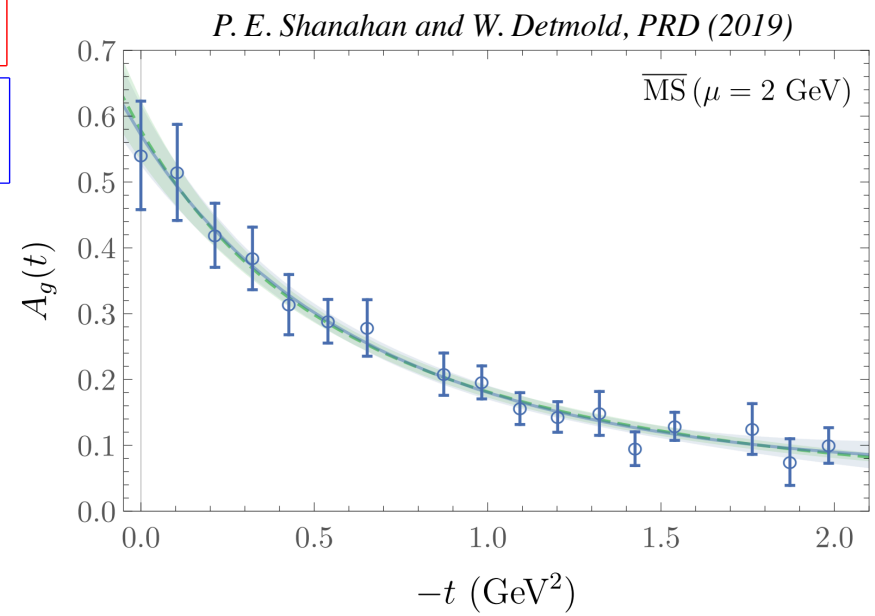
- Experimentally:
  - higher statistics is needed to confirm the above features in the J/ψ cross sections
  - study C-even states at threshold to understand gluon-exchange mechanism
  - GlueX is currently running, expect $\times 4$ higher statistics

Back-ups

Differential cross-sections vs Lattice QCD



Lattice QCD



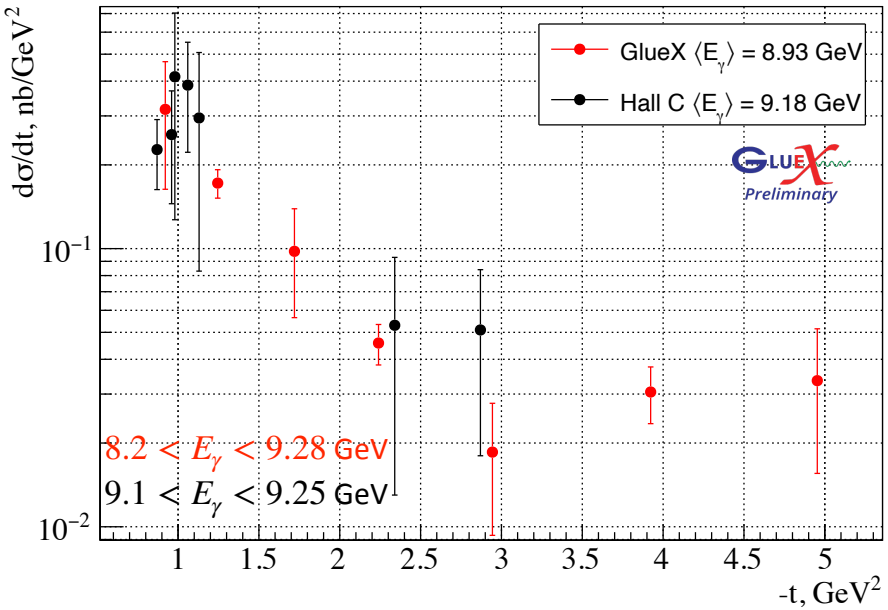
Dipole fits: $\dfrac{d\sigma/dt(0)}{(1 - t/m_s^2)^4}$

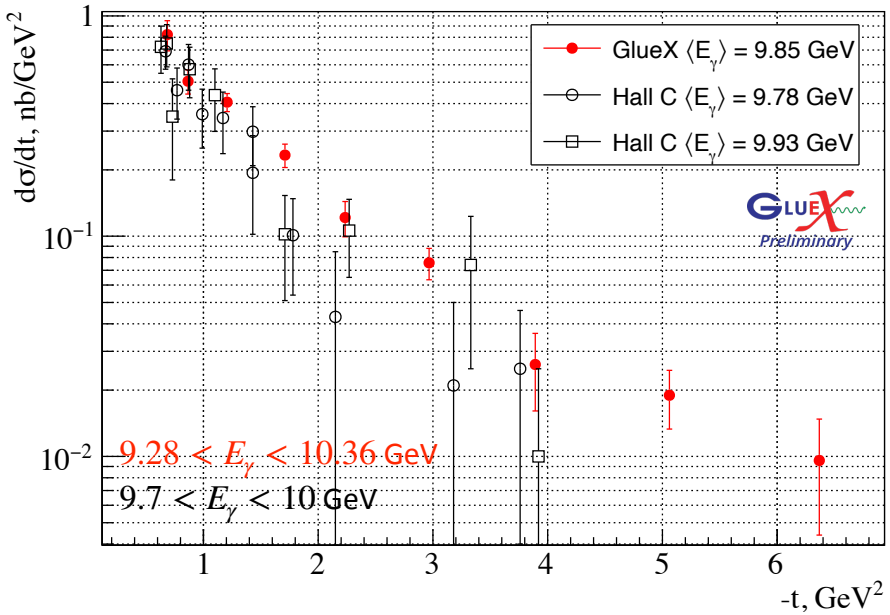
$q_{c.m.}$, GeV (J/ψp c.m.)	0.499	0.767	0.978
$d\sigma/dt(0)$, nb/GeV^2	3.121 ± 2.23	2.303 ± 0.400	4.184 ± 0.541
m_s, GeV	1.089 ± 0.172	1.453 ± 0.074	1.314 ± 0.049

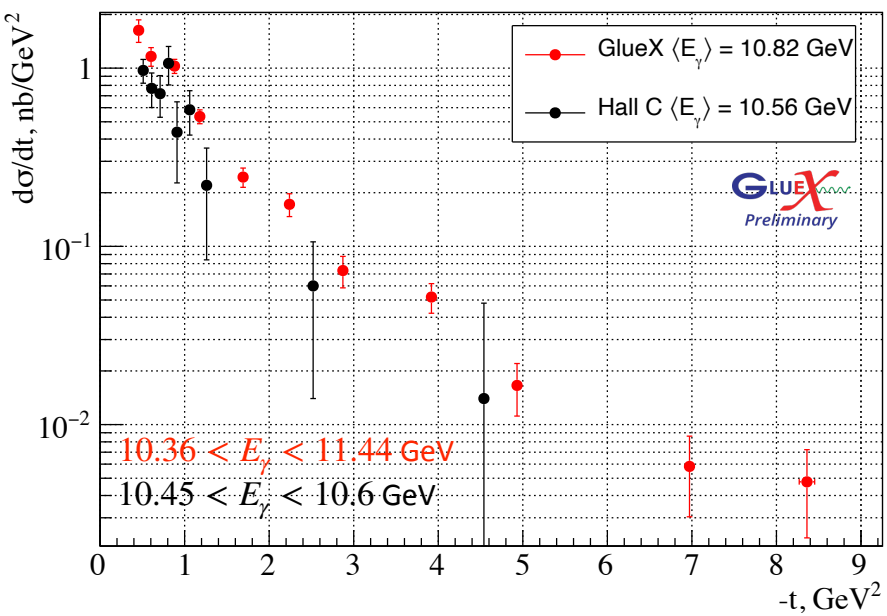
m_s *of* $A_g(t)$, GeV *Lattice QCD* 1.13 ± 0.06

$d\sigma/dt(t)$ generally consistent with gluon exchange mechanism

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







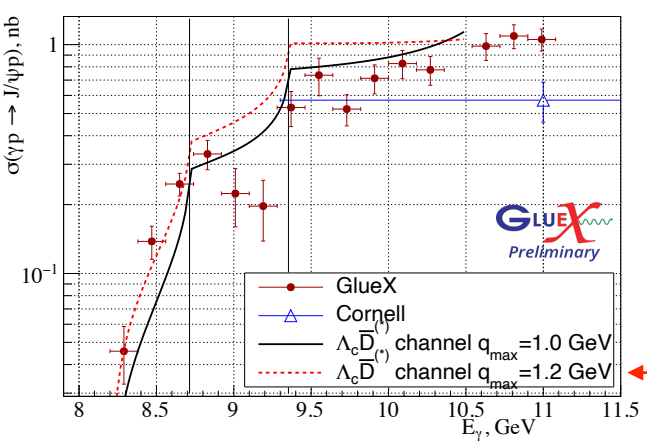
- Three GlueX energies compared to closest Hall C (J/ψ-007) energies
- Shown only 4 out 10 energies for Hall C - common fit of all 10 used to disentangle contributions from $A_g(t)$ and $C_g(t)$ (B.Duran https://arxiv.org/abs/2207.05212)

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

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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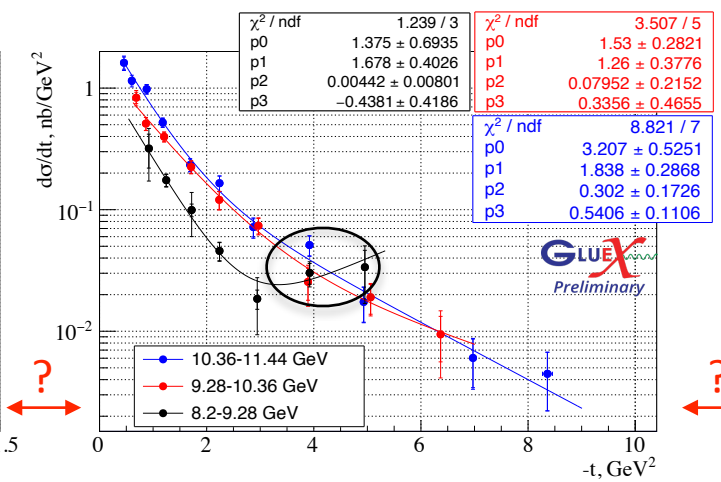

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I.Strakovsky in progress