J/ψ photoproduction close to threshold at GlueX

E.Chudakov

JLab, for GlueX collaboration

Presented at

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HADRON2023, Genova, Italy, June 5-9 2023

Motivation

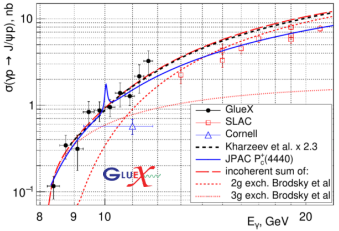
GlueX Collaboration:

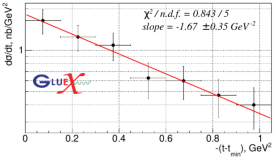
A.Ali et al PRL 123, 072001 (2019)

Considerable interest: about 160 citations.

Measured:

- Reaction: $\gamma p \to J/\psi p$
- Measured: $\sigma(E_\gamma)$, $\frac{d\sigma}{dt}$
- Model-dependent limit $BR(P_C \to J/\psi p) \lessapprox 1\%$





Jefferson Lab GLUEX

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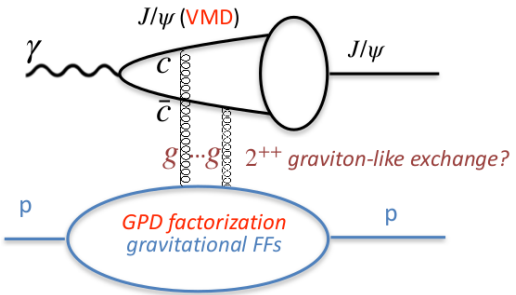
Photoproduction of a heavy vector quarkonium close to threshold



Allows studying gluonic properties of the nucleon
Under certain assumptions

- $J/\psi - p$ scattering length $\approx$ 18 mfm *EPJ A57(2021)2,56*
  $\Rightarrow$ very weak $J/\psi - p$ interaction
- Relation to nucleon gravitational form factors (GFF)
  Guo PRD103(2021); Mamo PRD104; Hatta PRD100
- Relation to EMT *trace anomaly* and nucleon mass
  Kharzeev (1996-1999); Ji (1995)
- Proton mass radius $\approx$ 0.5 fm *Kharzeev PRD104(2021)*

Production models and $\sigma(E)$ dependence

- QCD LO,NLO *Ivanov et al EPJ C34 (2004)*
- GPD+LQCD GFF *Guo et al PRD 103 (2021)*
- Open charm exchange *Du et at EPJ C80 (2020)*

Assumptions

- $m_C \to \infty$ interaction via gluon exchange
- GPD factorization valid at threshold
  Ivanov (2004), Guo (2021)
- VMD relates $\gamma p \to J/\psi p$ to elastic $J/\psi p \to J/\psi p$
- Small contribution from open charm exchange
  $\gamma p \to \Lambda_C \overline{D}^{(*)} \to J/\psi p$

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Detailed studies of the reaction $\gamma p \to J/\psi p$ are needed in order to verify the validity of the assumptions

New results from JLab

- Experiment "J/ψ-007" in Hall C: *Duran et al. Determining the gluonic gravitational form factors of the proton , Nature 615 (2023)*
- Experiment GlueX in Hall D: *Adhikari et al, Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region, arXiv 2304.04924 (2023) subm. to PRC*
  4-times more data in comparison with the first publication

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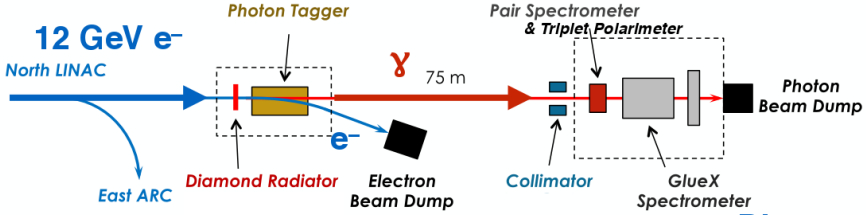

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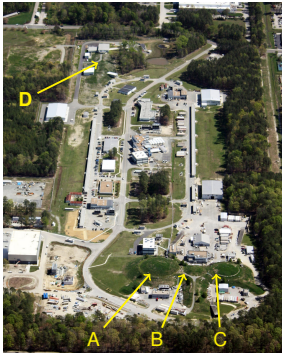

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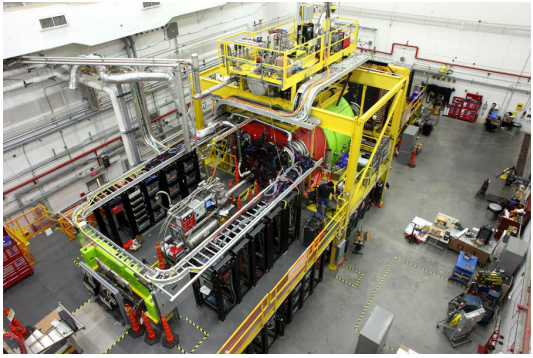

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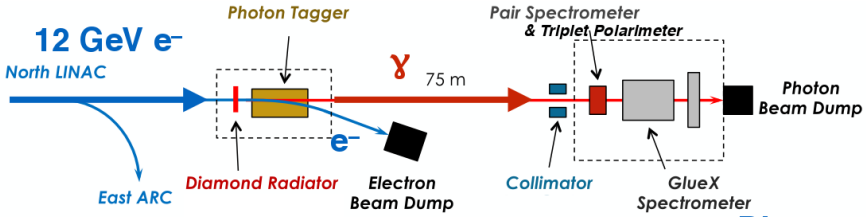
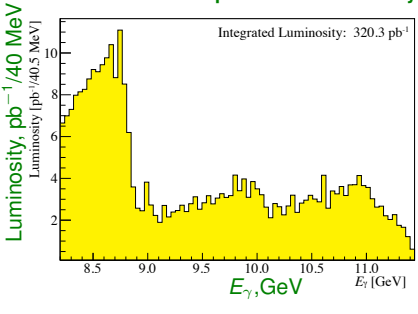


Photon Beam Spectrum & Luminosity



Photon beam: Coherent Bremsstahlung

- Coherent peak at ≈ 9 GeV, linear polarization
- Tagging $\sigma E/E \sim 0.1\%$
- Pair Spectrometer measures beam flux and spectrum

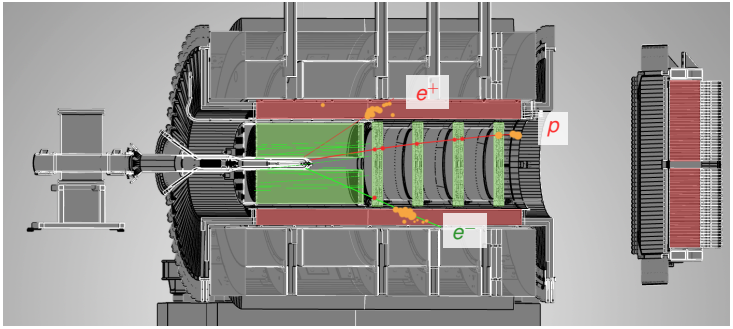
Spectrometer

- Target: 30 cm liquid hydrogen
- Acceptance: $1^\circ < \theta < 120^\circ$
- Resolutions: $h^\pm$: $\sigma_p/p \sim 1-3\%$
  γ: $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$
- Trigger: all photoproduction at $E_{BEAM} > 7$ GeV

Data Analysis for J/ψ

Reaction studied: exclusive $\gamma\, p \to J/\psi\, p, \quad J/\psi \to e^+e^-$

$\sigma(\gamma p \to \psi p) \times BR \sim 30$ pb $\sim 0.3 \cdot 10^{-6} \times \sigma_{tot}(\gamma p \to hadrons)$



Event identification:

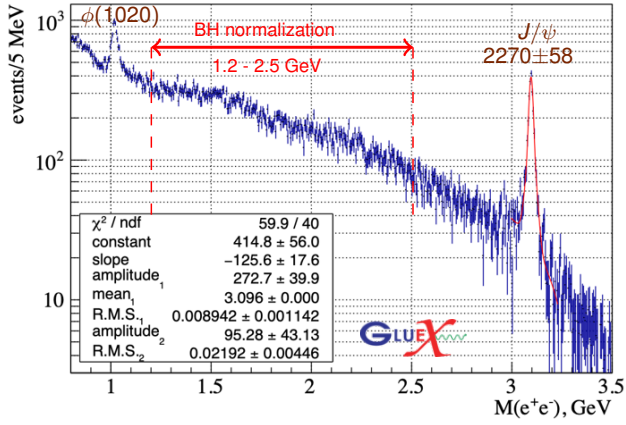
- PID for p: TOF, $\frac{dE}{dx}$ in drift chambers
- PID for $e^{\pm}$: EM calorimeters *(challenge: large BG from $\pi^+\pi^- p$ events)*
- Kinematic fit using the photon energy measured with a 0.1% resolution, 4-momentum conservation improves the resolution and provides exclusivity of the reaction

Detector acceptance: full kinematic coverage

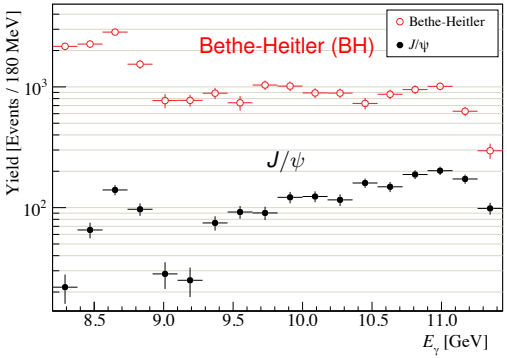
Mass Spectrum of e^+e^-, J/ψ yield and normalization

All beam energies

Effective mass $M(e^+e^-)$



Yield dependence on beam energy E_γ



- $\gamma p \to J/\psi p, J/\psi \to e^+e^-$
- Kin. fit: mass resolution $\approx$ 13 MeV, no radiative tail
- J/ψ yield extracted from fits of $M(e^+e^-)$ distributions
- Bethe-Heitler reaction (BH) $\gamma\, p \to (e^+e^-)p$ at 1.2-2.5 GeV used for normalization

Calculation of the J/ψ production cross section:

$$\sigma_{J/\psi}(E_\gamma) = \frac{N_{J/\psi}(E_\gamma)}{N_{BH}(E_\gamma)} \frac{\sigma_{BH}(E_\gamma)}{BR_{J/\psi}} \frac{\epsilon_{BH}(E_\gamma)}{\epsilon_{J/\psi}(E_\gamma)}$$

BH simulation: R.Paremuzyan, based on E.Berger et al, EPJC 23:675 (2002); σ_{BH} calculated in a given kinematic range

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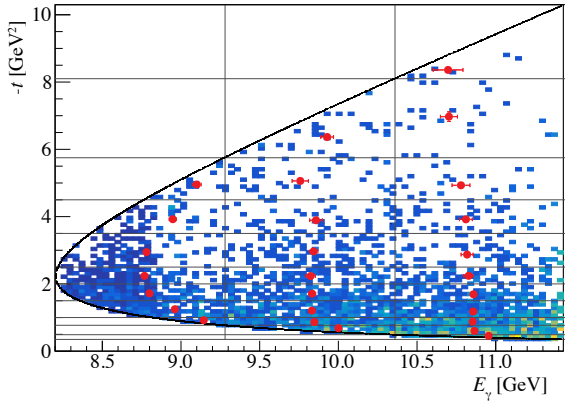
Kinematic coverage

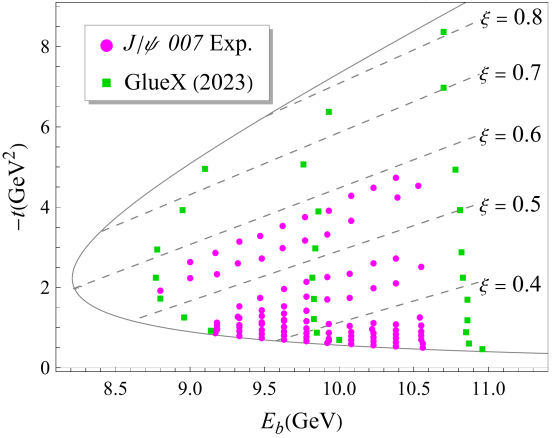
GlueX



- Events ($3.05 < M(e^+e^-) < 3.15$ GeV) beam-flux-weighted at E_γ
- The dots show the mean E_γ and t values per bin

GlueX - Hall C J/ψ-007

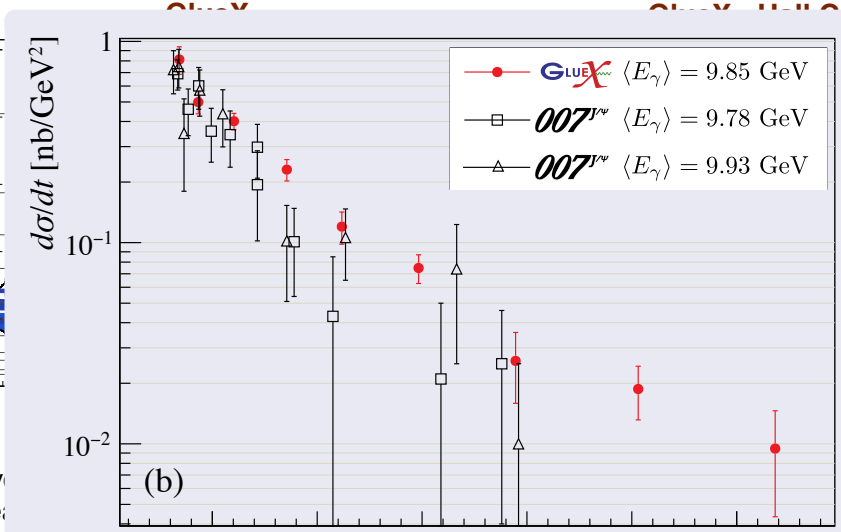
Plot borrowed from Guo et al 2305.06992 (2023)

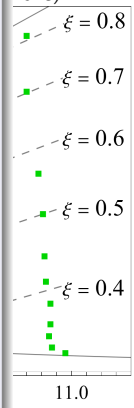


J/ψ-007

- Several kinematic setting of 2 spectrometers

Kinematic coverage





- Ev… be…
- Th… pe…

…ectrometers

GlueX and 007 results on $d\sigma/dt$ are consistent within the uncertainties

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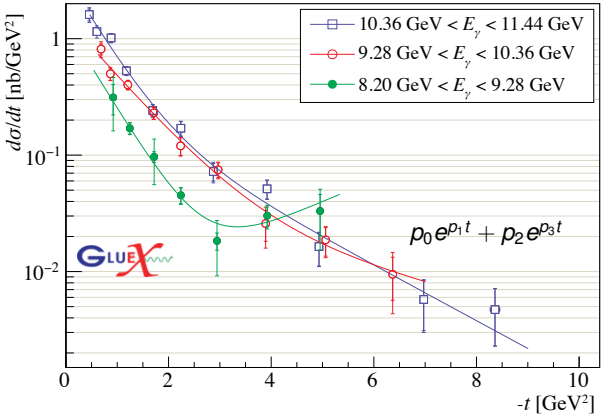
Differential cross section for $\gamma p \to J/\psi p$



- Exponential slopes indicating t-channel
- Enhancement of $d\sigma/dt$ for lowest energy
  s-channel close to threshold?
  u-channel?
  other mechanism?

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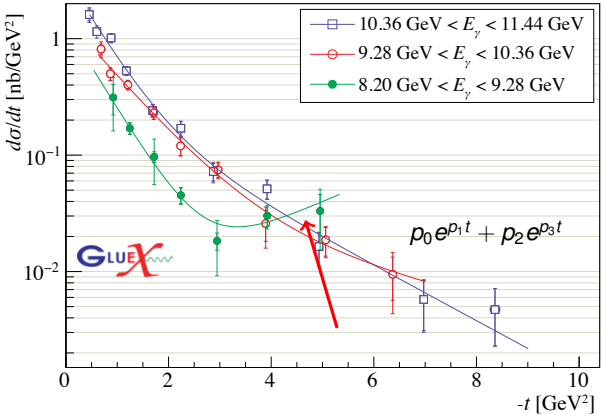

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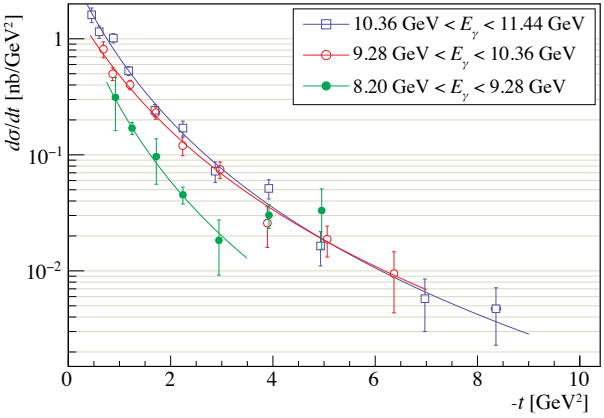
J/ψ differential cross section: dipole parameterization



$\gamma + p \to V + p$

2-gluon form factor *Franfurt, Strikman PRD 66 (2002)*:
for $0.05 < x < 0.3, |t| < 2$ GeV^2
$\Gamma(x_1, x_2, t, \mu^2) \propto 1/(1 - t/m_{2g}^2)^2$, where $m_{2g} \approx 1$ GeV
Dipole parameterization

$\frac{d\sigma}{dt}$ extrapolation to t=0
Dipole fits

$$\frac{d\sigma}{dt} = \frac{d\sigma/dt(0)}{(1 - t/m_S^2)^4}$$

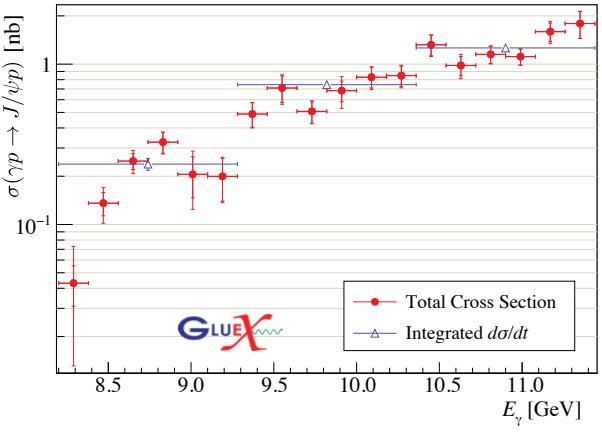
GlueX *Adhikari et al (2023)*:

$\langle E_\gamma \rangle$ [GeV]	8.93	9.86	10.82
q [GeV]	0.499	0.767	0.978
$d\sigma/dt(0)$ [nb/GeV^2]	2.863	2.205	4.268
	± 1.95	± 0.380	± 0.564
m_s [GeV]	1.105	1.472	1.313
	± 0.168	± 0.075	± 0.049

LQCD $A_g(t)$ gluon formfactor:
$m_S = 1.13 \pm 0.06$ GeV *Shanahan, Detmold PRD 99 (2020)*

The results are generally consistent with the gluon-exchange mechanism

Total cross section for $\gamma p \to J/\psi p$



- $\sigma_{tot}(E_\gamma)$ approx. follows phase space
- Structure at 8.6-9.6 GeV
  stat. significance of 2 "dip" points is 2.6σ
  including "look-elsewere" effect 1.3σ

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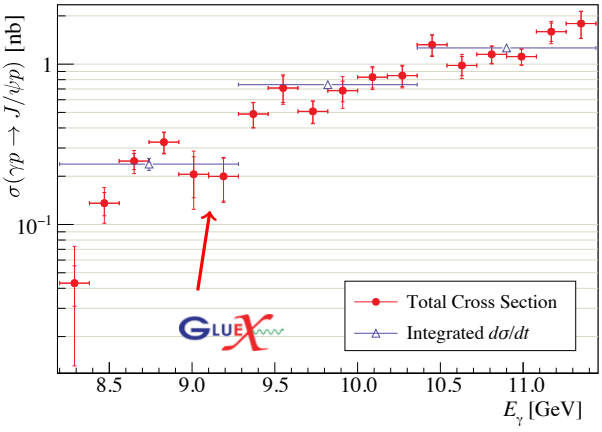

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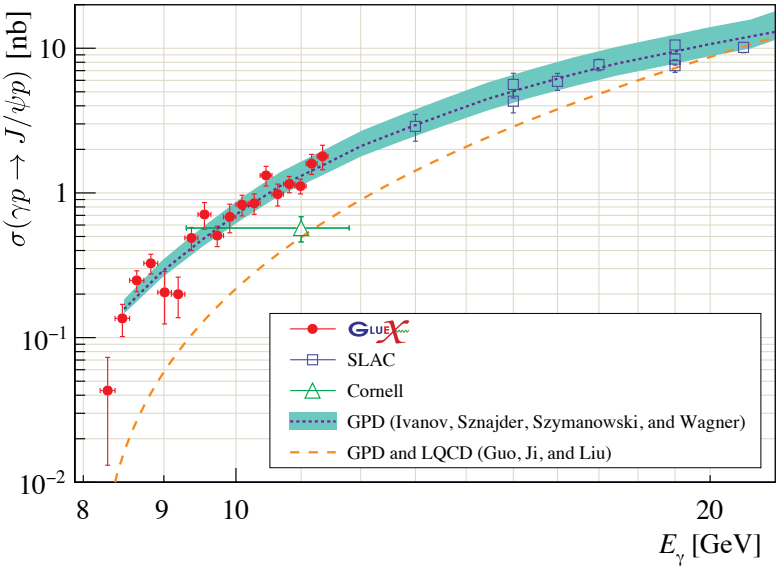
Energy dependence of the $\sigma_{tot}(\gamma p \to J/\psi p)$



Comparison with older data

Data from SLAC and Cornell (1970s)

Theoretical Predictions

QCD LO 2-gluon exchange
Factorization PQCD - GPD

Ivanov et al EPJ C34 (2004)
Ivanov, Sznajder, Szymanowski, Wagner (2022)

Guo,Ji,Liu PRD 103 (2021)
Guo,Ji,Liu,Yang (2023)
GFF from LQCD used
for new results see the next page

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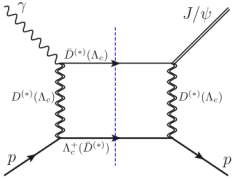
A different mechanism of reaction $\gamma p \to J/\psi p$ close to threshold

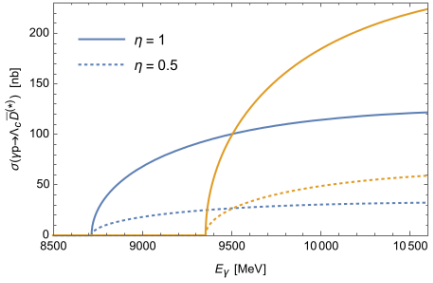
Du et al, EPJ C80 (2020)

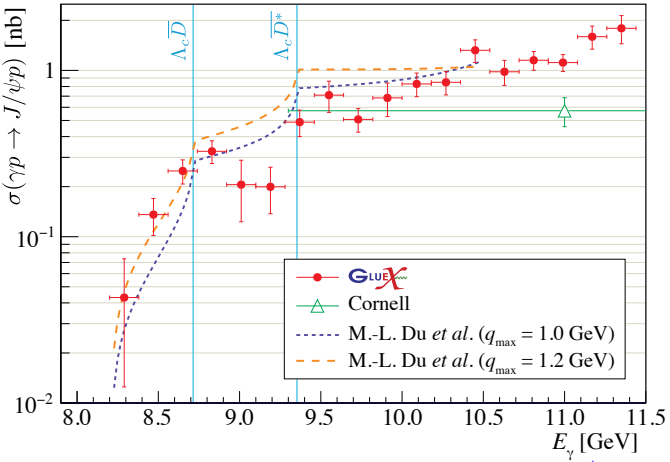
Production via open charm and re-scattering (*CC*: coupled channel)

$\gamma p \to \Lambda_c \overline{D}^{(*)} \to J/\psi p$



Estimate of the open charm x-sec:





Signature: Cusps at the thresholds of $\Lambda_c \overline{D}, \Lambda_c \overline{D}^*$
(an indication is observed in GlueX data)

Needs experimental verification: cusps and $\sigma(\gamma p \to \Lambda_c \overline{D}^{(*)})$

This mechanism is not a 2-gluon exchange and may reduce the relation between $\gamma p \to J/\psi p$ and GFF of the nucleon

Jefferson Lab GlueX

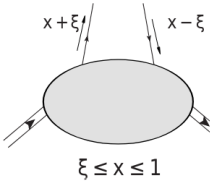
Recent calculations using the new results from GlueX and J/ψ-007

Guo, Ji, Liu, Yang arXiv 2305.06992 (2023)

Extraction of gravitational formfactors from $\frac{d\sigma(\gamma p \to J/\psi)}{dt}(E_\gamma)$

Tripole parameterization:

$$A_g(t) = \frac{A_g(0)}{(1 + \frac{t}{m_A^2})^3}$$



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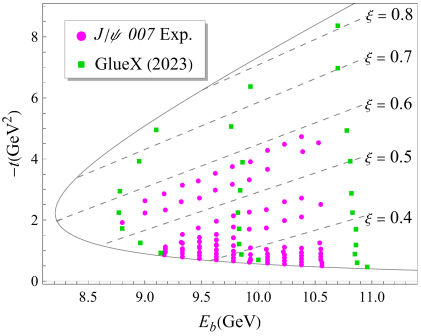
Expansion on the parameter skewness.



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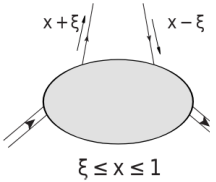

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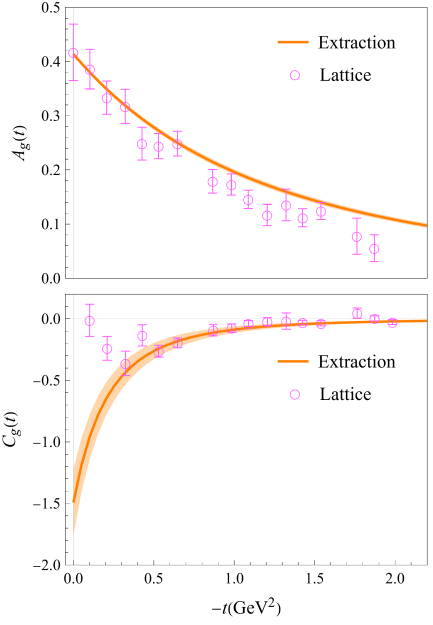

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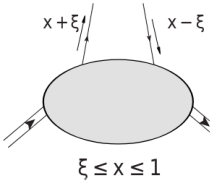

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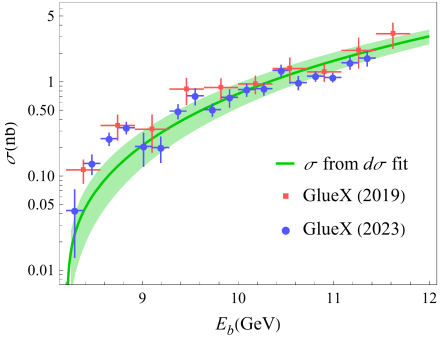

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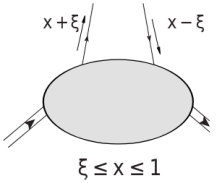

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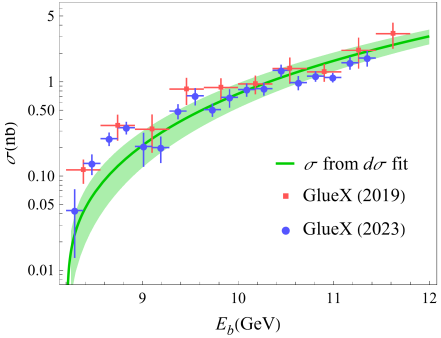
- GlueX $d\sigma/dt$ rise at $|t| > 4$ GeV^2 at the lowest energy does not fit the model - perhaps a different production mechanism
- Fit GFF used to evaluate the total cross section



Conclusion

- General agreement with LQCD
- More quality data at high $|t|$ and high "skewness" are needed

Jefferson Lab GlueX

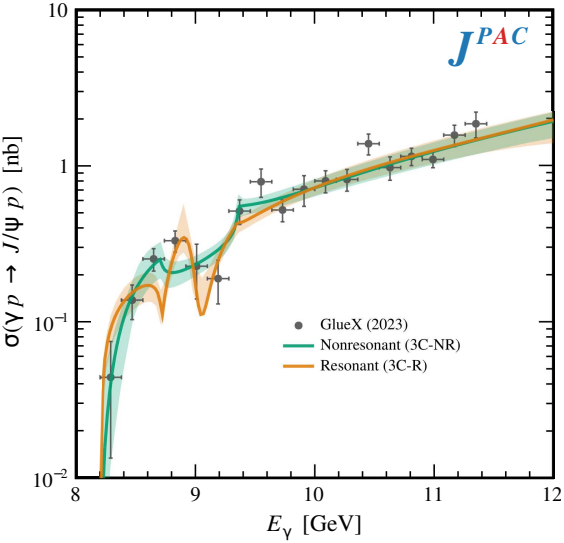
Recent calculations using the new results from GlueX and J/ψ-007

JPAC: *D.Winney et al arXiv 2305.01449 (2023)*
HADRON23: talk by D.Winnie on Tuesday 17:50, DAD Room 4H

- General properties of amplitudes are used
- Near threshold - only lower partial waves matter
- Considered reactions:
  1C $\gamma p \to J/\psi$;
  2C $\gamma p \to \Lambda_c \overline{D}^* \to J/\psi p$ added ;
  3C $\gamma p \to \Lambda_c \overline{D} \to J/\psi p$ added
  R - resonances added
- These models are fit to data from GlueX and "007"
- Several possibilities are compatible with data

Selected conclusions

- The existing data do not exclude severe violation of VMD and factorization
- More data are needed, in particular around the "cusps" at $\sim$9 GeV in order to disentangle different production mechanisms

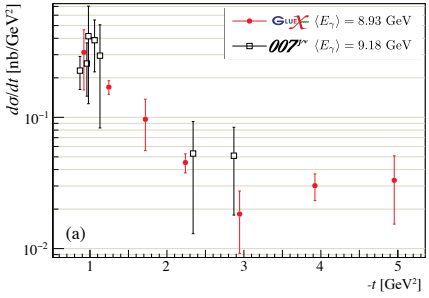


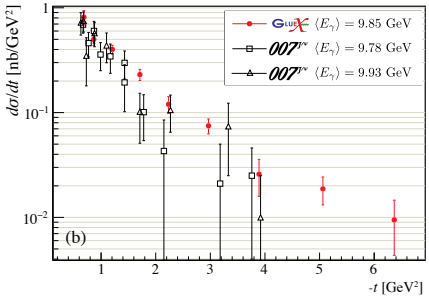
Summary

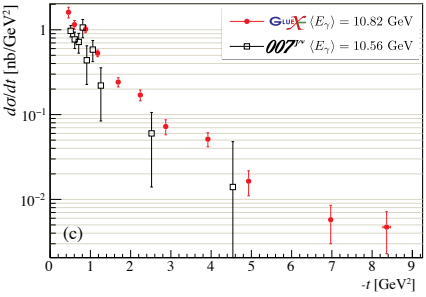
- Considerable interest to the reaction $\gamma p \to J/\psi p$ close to threshold:
  Under certain assumptions provides access to gluonic properties of the nucleon
  (gravitational form factors, mass radius, nucleon mass etc)
- New, higher statistics results from JLab (GlueX and $J/\psi - 007$)
  - In general consistent with the t-channel production via gluon exchange, allowing improving the evaluation of those gluonic properties. Still, the current experimental precision is not sufficient to completely rule out alternative interpretation or the data.
  - Exceptions, pointing at different production mechanism:
    - Possible structure at 9 GeV would be consistent with open charm exchange (or interference with $J/\psi p$ resonances).
    - Flattening of the differential cross section at high $|t|$ close to threshold, may indicate a contribution from processes other than t-channel 2-gluon exchange
- Active field, both theoretically and experimentally. Better experimental precision is critical for the interpretation of the data
  - GlueX: $\times 4$ data expected in 3-4 years

BACKUP PAGES

Comparison with the Hall C measurements







Compared $\frac{d\sigma}{dt}$ with the experiment "007" *Duran et al (2023)*

- "007": 4 out of 10 energy bins are shown
- Normalization uncertainties 20% for GlueX and 4% for "007"
- The results agree at small $|t|$ within the errors
- GlueX provides more data at high $|t|$