
# RECENT RESULTS FROM NEAR THRESHOLD J/Ψ PHOTOPRODUCTION MEASUREMENT IN HALL C AT JLAB

**BURCU DURAN**

*On behalf of the E12-16-007 Collaboration*

**QNP2022 - The 9th International Conference on Quarks and Nuclear Physics**
**September 8, 2022**

Jefferson Lab
*Exploring the Nature of Matter*

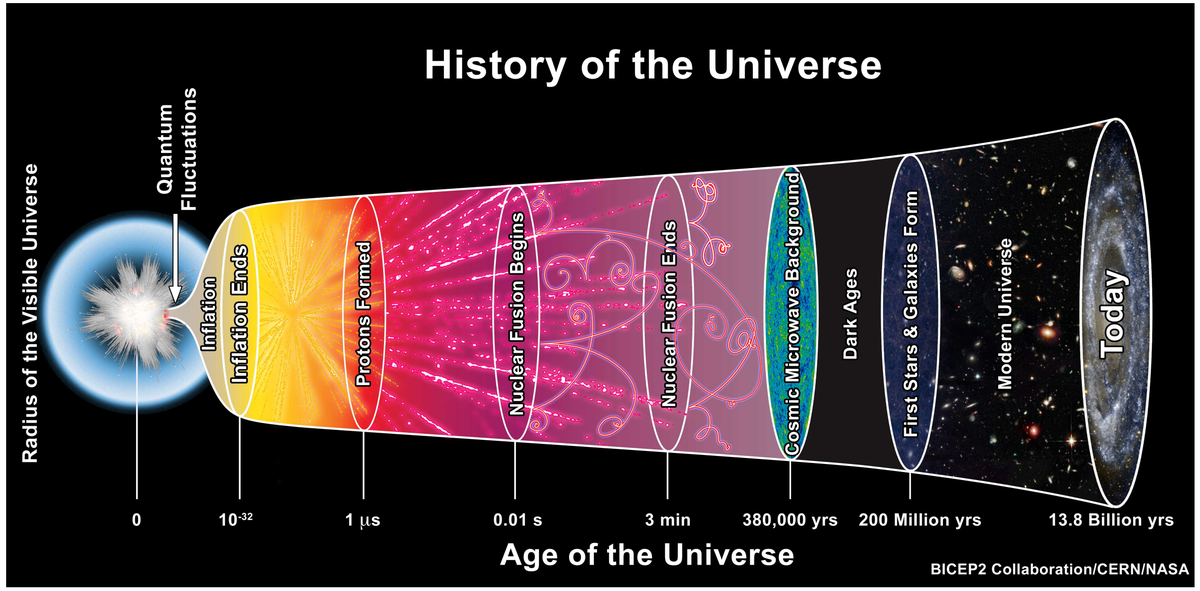
# Understanding Origins of the Proton Mass

- What we have known so far:

***Nearly all the mass of observable universe is within the mass of the protons and neutrons, nucleons.***

- One of the three high-priority science questions identified by the National Academies report **"An Assessment of U.S.-Based Electron-Ion Collider Science (2018)"**:

***"How does the mass of the nucleon arise?"***



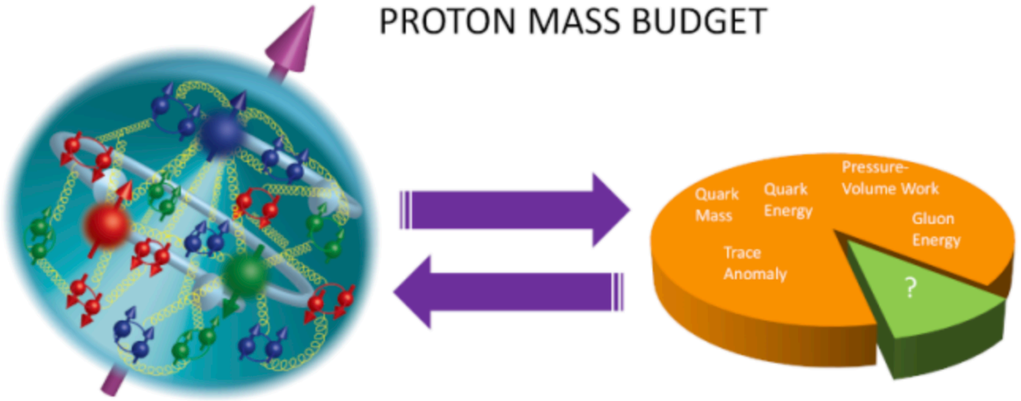




image credit: Z.-E. Meziani

- How do the hadron masses emerge from almost massless quarks and massless gluons?
  - ✦Modest contribution from the Higgs mechanism
  - ✦Mass of the all three valence quarks <<< mass of the nucleon
  - ✦Mass without mass?
  - ✦Better: Nucleon mass from the field energies of the quarks and gluons!

# Insight from Gravitational Form Factors

- Gravitational Form Factors (GFFs) are the matrix elements of the proton's energy-momentum tensor (EMT).

$$\langle N' | T^{\mu,\nu} | N \rangle = \bar{u}(N') \left( A(t) \gamma^{\{\mu} P^{\nu\}} + B \frac{iP^{\{\mu} \sigma^{\nu\}\rho} \Delta_\rho}{2M} + C(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} \right) u(N)$$

Guo, Ji and Liu (2021) Phys. Rev. D 103, 096010

- Proton's mechanical properties are encoded in the GFFs: mass, pressure, and shear distributions of gluons in the proton

$A(t)$: Momentum Fraction

$B(t)$: Angular Momentum $\quad J(t) = \frac{1}{2}(A(t) + B(t))$

$D(t) = 4C(t)$: pressure and shear forces inside proton

- Trace anomaly of the EMT:
deeply connected to the origin of mass according to QCD

- Lattice ab-initio calculations to benchmark our understanding

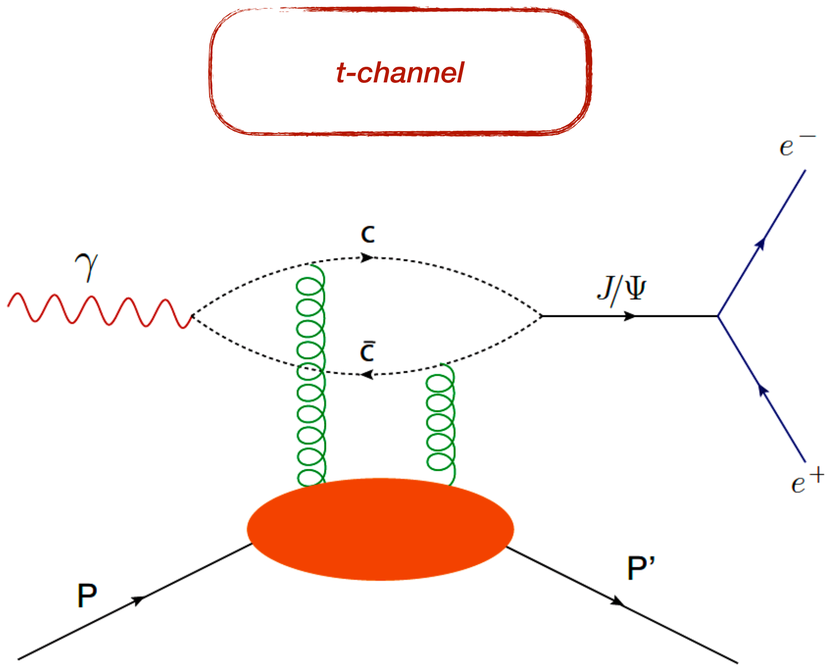
Mass and Scalar Radii of the Proton

$$\langle r_m^2 \rangle = 6 \frac{dA(t)}{dt} \Big|_{t=0} - 6 \frac{C(0)}{M_N^2}$$

$$\langle r_s^2 \rangle = 6 \frac{dA(t)}{dt} \Big|_{t=0} - 18 \frac{C(0)}{M_N^2}$$

# An Experimental Perspective: $J/\psi$ Production near Threshold

- Proton charge radius mainly carried out by charged moving quarks
  - ✦ electromagnetic probe to study proton charge radius
- Proton mass distribution mainly carried out by gluons and gluons have NO charge!

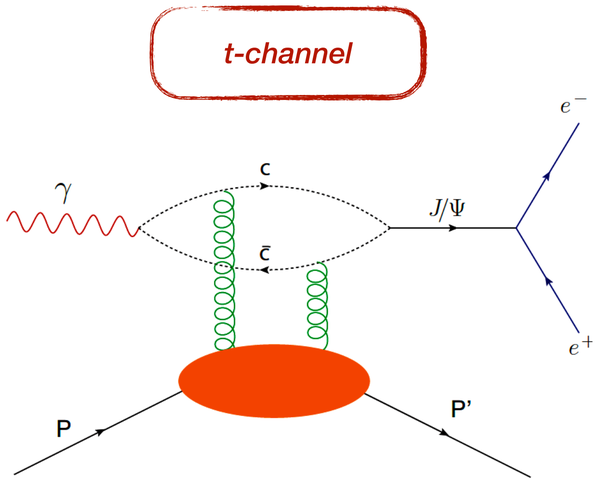



- $J/\psi$ production near threshold to probe gluons
  - ✦ Sensitive to the gluonic structure of the proton:

    only couples to the gluons, not light quarks!
- $t$-distributions at different photon energies to constrain

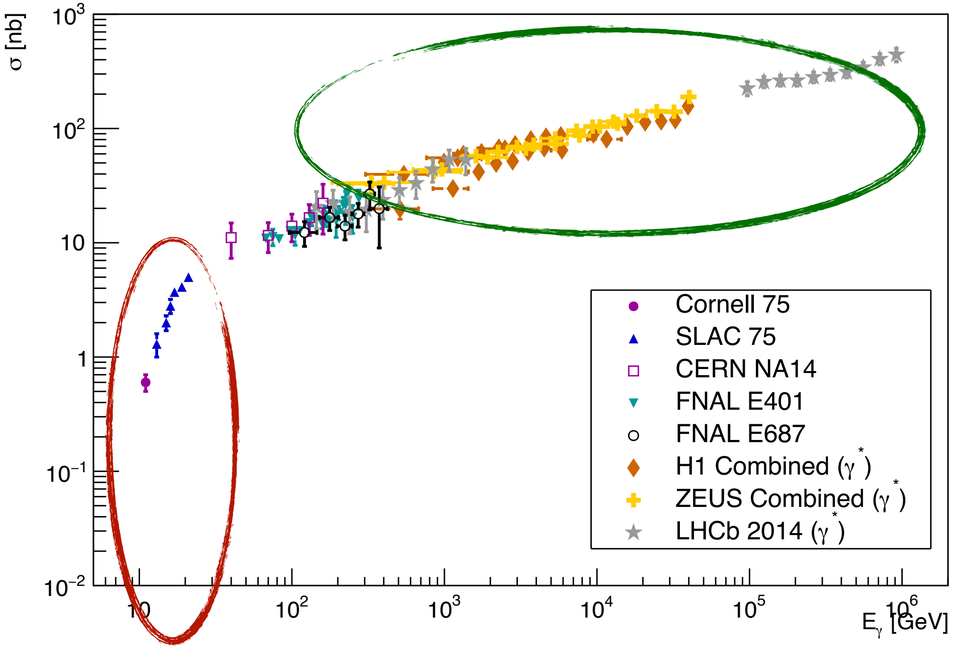
the GFF slopes and magnitudes

# $J/\psi$ Production: Current Data Status

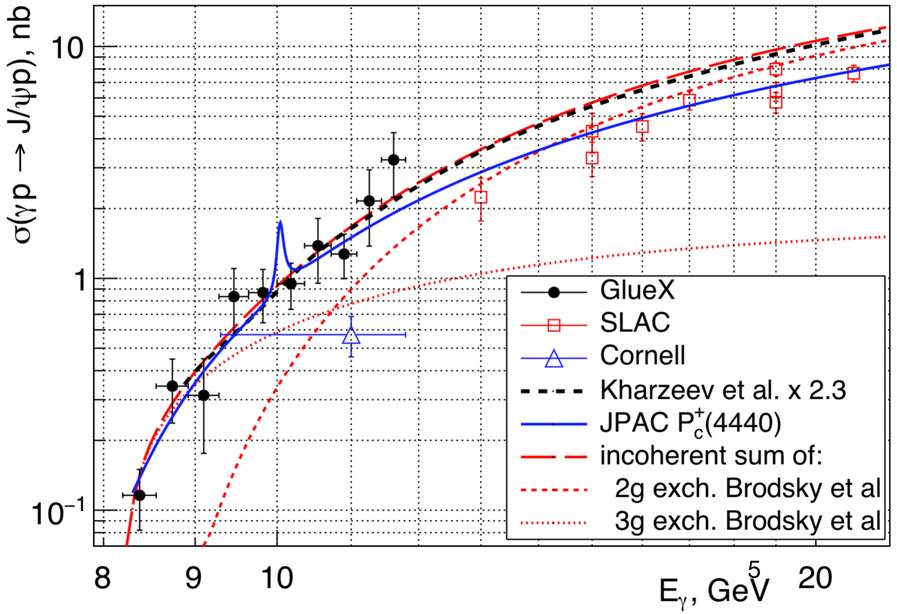


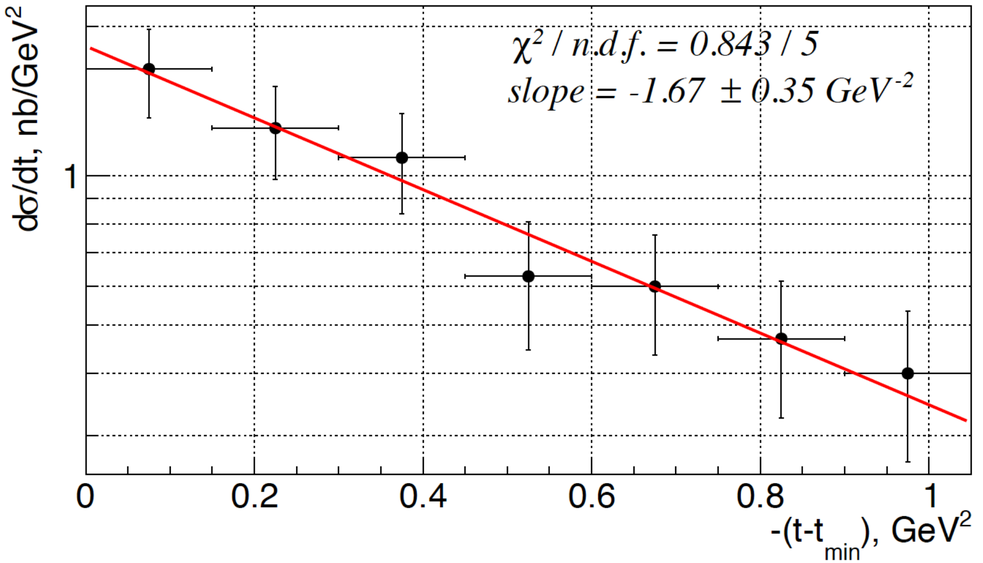

**Before JLab 12 GeV**

- Well constrained high energy region
- Scarce in the energy range of interest i.e. near threshold region




## Current Data Status of $J/\psi$

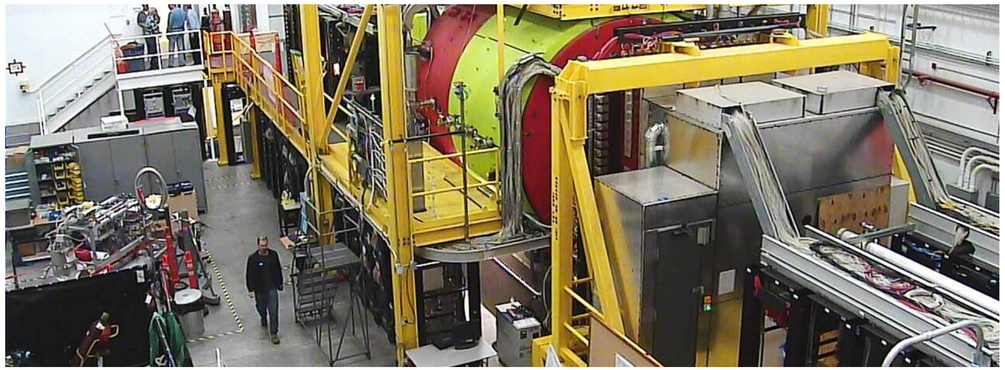


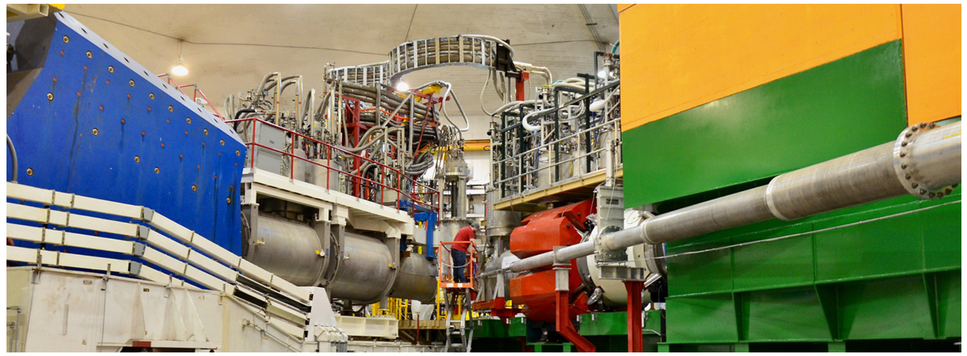

GlueX

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

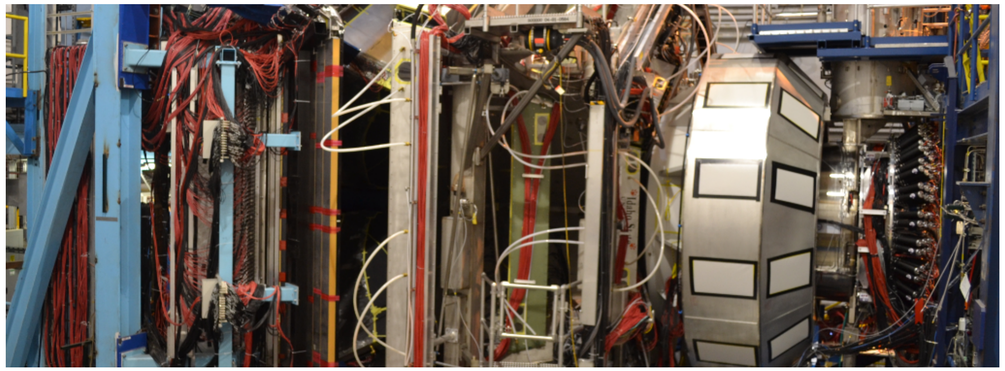
# $J/\psi$ Experiments at Jefferson Lab 12 GeV Era



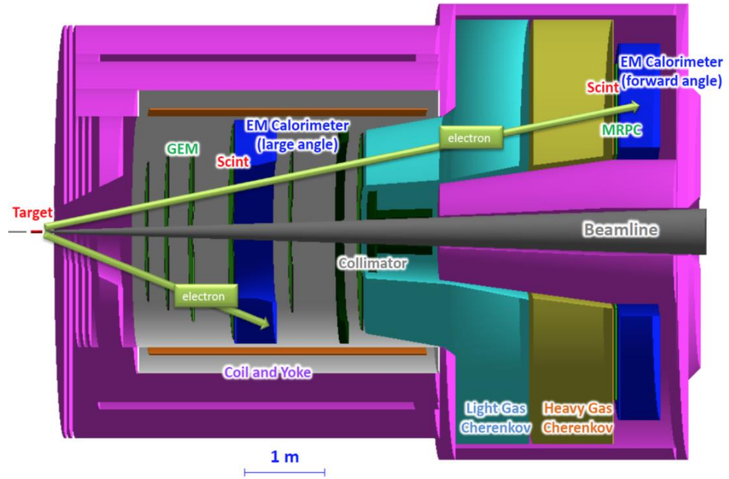
**Hall D - GlueX** the first J/ψ measurement at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



**Hall C** has the **J/ψ-007** experiment (E12-16-007) to search for the LHCb hidden-charm pentaquark

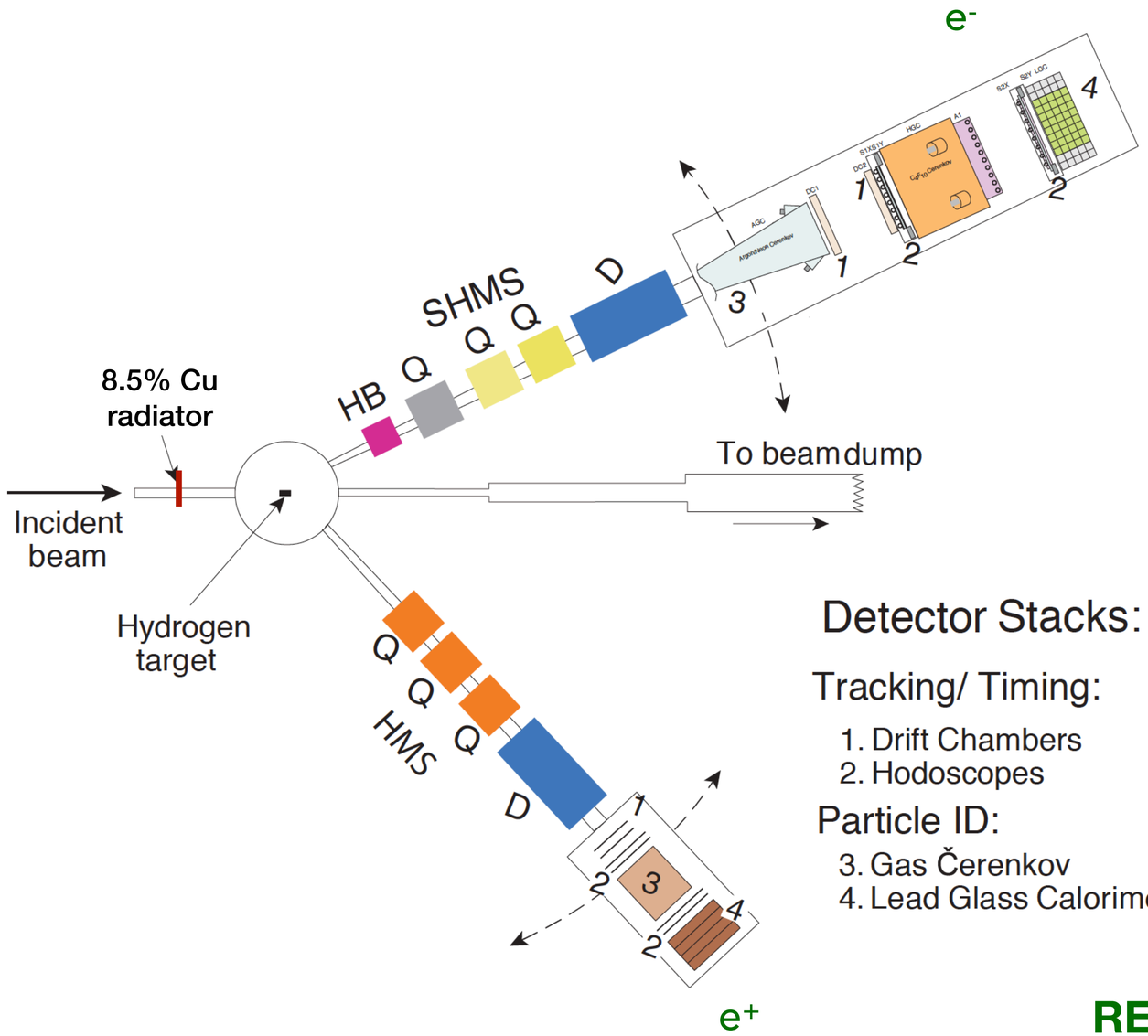


Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B




**Hall A** has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

# $J/\psi$-007 Experiment in Hall C at JLab 007$^{J/\psi}$




Detector Stacks:

Tracking/ Timing:

1. Drift Chambers
2. Hodoscopes

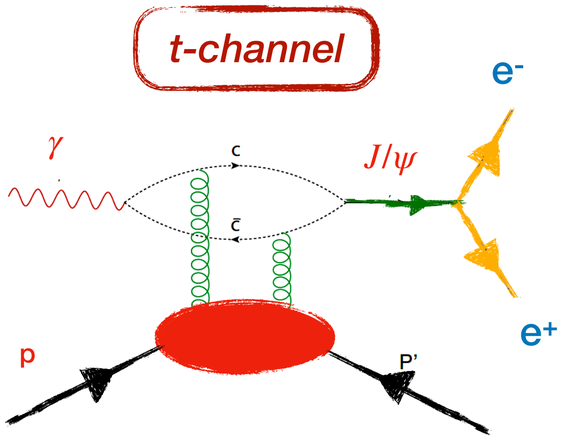
Particle ID:

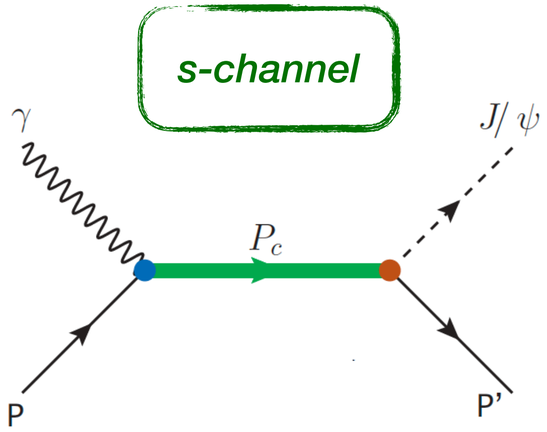
3. Gas Čerenkov
4. Lead Glass Calorimeter

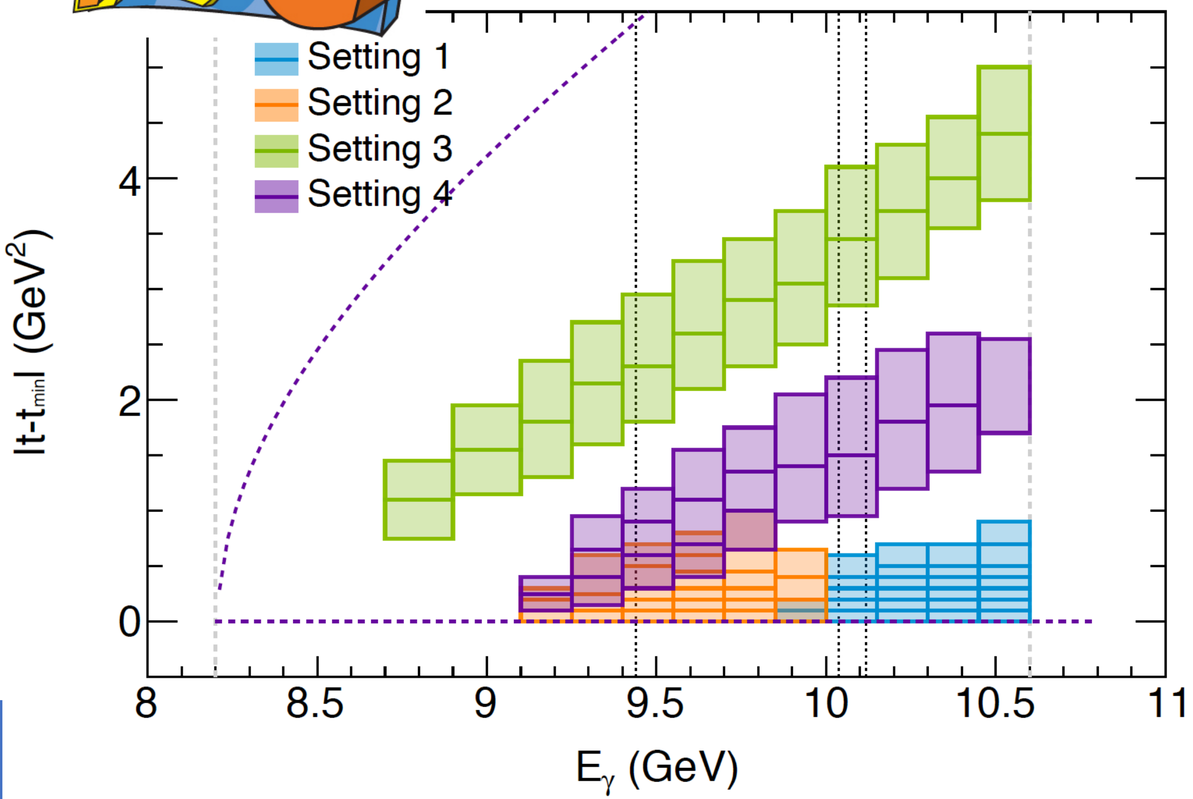
- 10.6 GeV incident electron beam
- 8.5% Cu **radiator** for Bremsstrahlung photon beam
- 10 cm liquid hydrogen target
- Electron positron detection in coincidence in SHMS and HMS, respectively.

**REAL PHOTON BEAM and HIGH LUMINOSITY in Hall C!**

# $J/\psi$-007 Experiment in Hall C at JLab



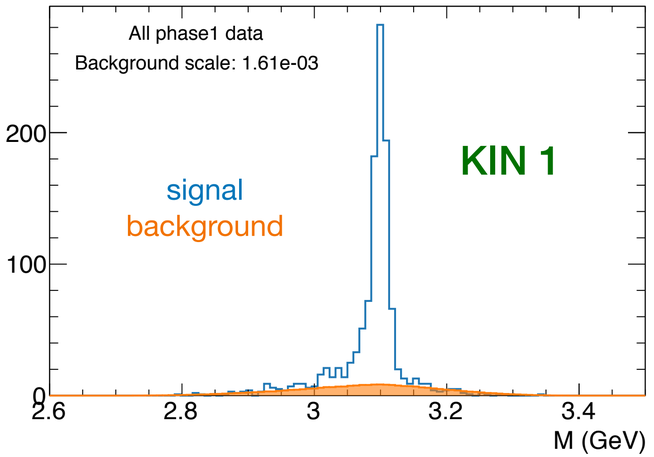

| | SHMS P(GeV) | SHMS $\theta$ (deg) | HMS P (GeV) | HMS $\theta$ (deg) | |
|---|---|---|---|---|---|
| KIN 1 | 4.835 | 17 | 4.95 | 19.1 | high-E/low-t |
| KIN 2 | 4.3 | 20.1 | 4.6 | 19.9 | mid-E/low-t |
| KIN 3 | 3.5 | 30 | 4.08 | 16.4 | high t |
| KIN 4 | 4.4 | 24.5 | 4.4 | 16.5 | medium t |

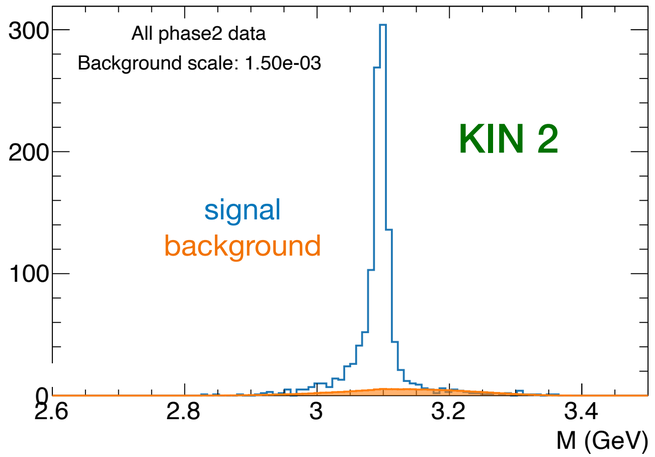
- Settings optimized to measure both *t*- and *s*-channel processes
- 2D cross section measurement of $J/\psi$ (9.1 GeV - 10.6 GeV and *t* up to ~ 4.5 GeV$^2$)
  - Obtained *t* distributions for several photon energy bins

# $J/\psi$-007 Experiment in Hall C at JLab

## Possible BG considerations:

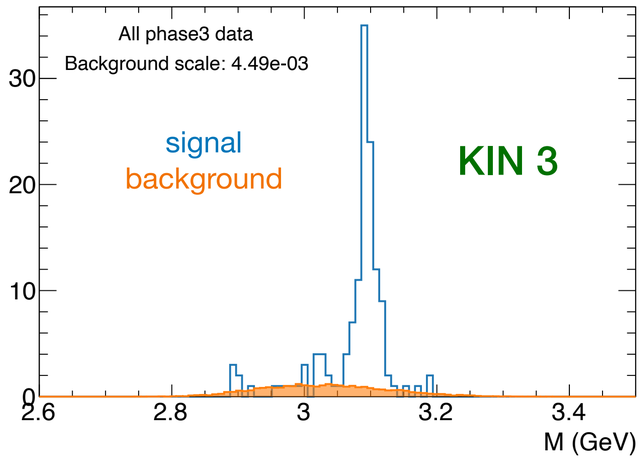
- $e^-\pi^+$, $\pi^-\pi^+$ and $e^-e^+$
- $e^-\pi^+$ is dominant and $\pi^-\pi^+$ or $e^-e^+$ negligible
- Measured the background!
  - Available in the data sample due to the no PID trigger.

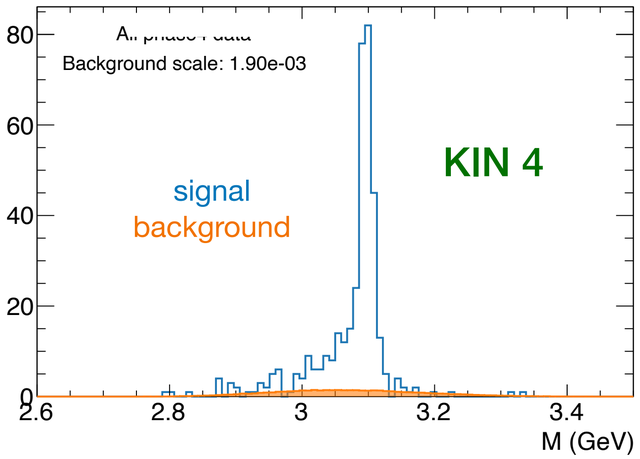



## BG Event Selection:

- Coincidence $e^-\pi^+$ background selected using electron PID in the SHMS and pions in the HMS.
  - **electrons:** Calorimeter
  - **pions:** Calorimeter + Cherenkov



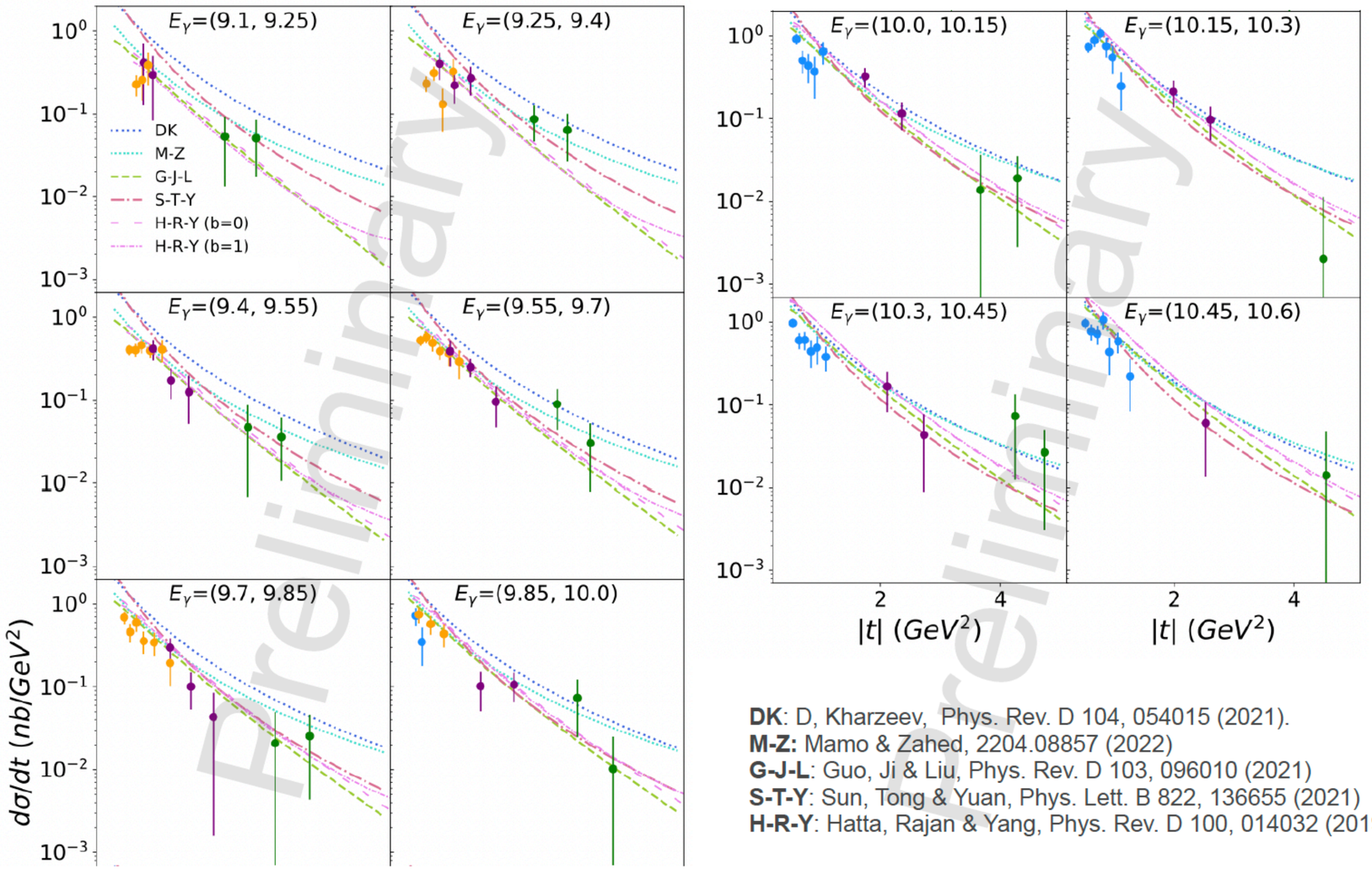

- Fit BG shape to the sidebands of the signal to obtain the BG scale.

# Preliminary Differential Cross Sections Using $J/\psi$-007 Data

- Extracted the differential cross sections for **10 energy bins** using $J/\psi$-007 data
- $J/\psi$-007 data comparison to different model predictions with fixed parameters determined from the GlueX data at an average $E_\gamma$ of 10.72 GeV.
- All models reproduce the data reasonably well close to average GlueX $E_\gamma$.
- Deviations start for $E_\gamma$ < 9.55 GeV.

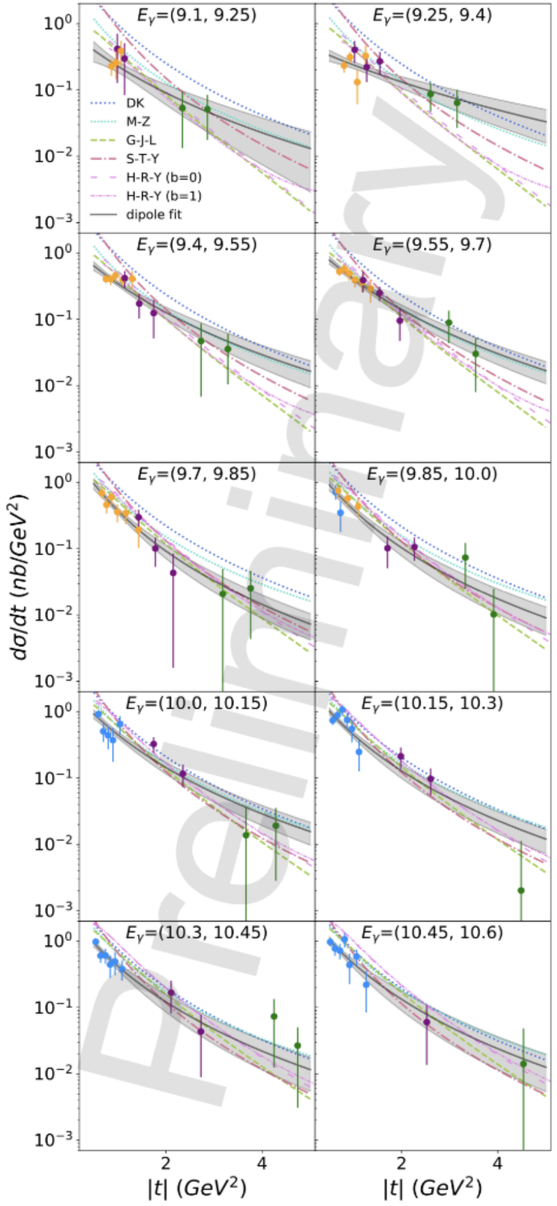
***publication under peer-review***

Preprint: https://arxiv.org/abs/2207.05212




**DK**: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
**M-Z:** Mamo & Zahed, 2204.08857 (2022)
**G-J-L**: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
**S-T-Y**: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
**H-R-Y**: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

# Model Dependent Extraction of the GFFs from $J/\psi$-007 Data




- 2D data fitted using two separate approaches:
  - Holographic approach (Mamo & Zahed Phys. Rev. D 103, 094010 (2021) and 2204.08857 (2022))
  - GPD approach (Guo, Ji & Liu (2021), Phys. Rev. D 103, 096010)
- Both approaches explicitly use two GFFs: $A(t)$ and $C(t)$
- Used the tripole forms for both A(t) and C(t) (parametrized for 3 unknown parameters: $m_t$, $m_s$, and C(t=0). A(t=0) from CT18 global fit 0.414±0.008)
- $B(t)$ contribution assumed to be small (Pefkou, Hackett & Shanahan, Phys. Rev. D 105, 054509 (2022) and Mamo & Zahed Phys. Rev. D 103, 094010 (2021) and 2204.08857 (2022))

***publication under peer-review***

Preprint: https://arxiv.org/abs/2207.05212

# GFFs Results from $J/\psi$-007 Experiment

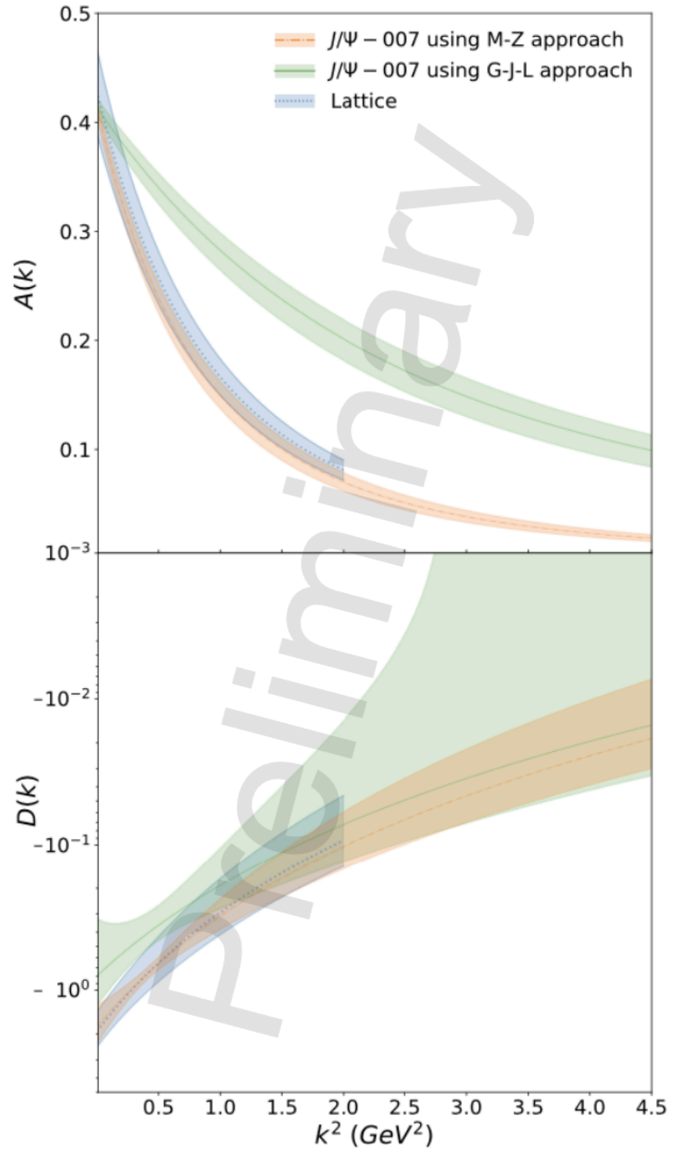
- The gluonic GFFs, $A(t)$ and $D(t) = 4C(t)$ determined using $J/\psi$-007 experiment's data with:

  1. Holographic approach (Mamo & Zahed Phys. Rev. D 103, 094010 (2021) and 2204.08857 (2022))

  2. GPD approach (Guo, Ji & Liu (2021), Phys. Rev. D 103, 096010)

- Results from both approaches compared to the lattice results (Pefkou, Hackett & Shanahan, Phys. Rev. D 105, 054509 (2022))

- Results from holographic approach is in very good agreement with lattice QCD




***publication under peer-review***

Preprint: https://arxiv.org/abs/2207.05212

# Mass and Scalar Radii Results from GFFs using $J/\psi$-007 Data

Mass and Scalar Radii of the

$$\langle r_m^2 \rangle = 6\frac{dA(t)}{dt}|_{t=0} - 6\frac{C(0)}{M_N^2}$$

$$\langle r_s^2 \rangle = 6\frac{dA(t)}{dt}|_{t=0} - 18\frac{C(0)}{M_N^2}$$

| Theoretical approach GFF functional form | $\chi^2$/n.d.f | $m_A$ (GeV) | $m_C$ (GeV) | $C_g(0)$ | $\sqrt{\langle r_m^2 \rangle_g}$ (fm) | $\sqrt{\langle r_s^2 \rangle_g}$ (fm) |
|---|---|---|---|---|---|---|
| Holographic QCD Tripole-tripole | 0.925 | 1.575±0.059 | 1.12±0.21 | -0.45±0.132 | 0.755±0.035 | 1.069±0.056 |
| GPD Tripole-tripole | 0.924 | 2.71±0.19 | 1.28± 0.50 | -0.20 ± 0.11 | 0.472±0.042 | 0.695±0.071 |
| Lattice Tripole-tripole | | 1.641± 0.043 | 1.07± 0.12 | -0.483± 0.133 | 0.7464±0.025 | 1.073±0.066 |



- With each approach, proton mass radius found to be smaller than its charge radius
- Holographic QCD extraction yields a scalar radius of one fermi - substantially larger than the charge radius

***publication under peer-review***

Preprint: https://arxiv.org/abs/2207.05212

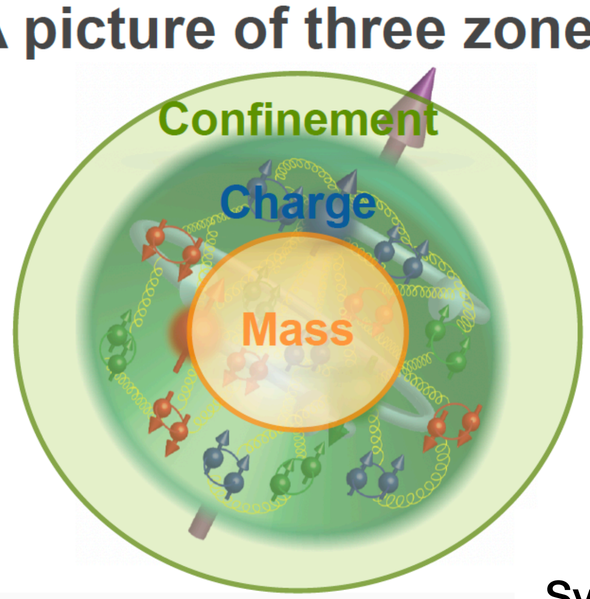



Image Credit:
Sylvester Joosten

# Conclusion and Outlook

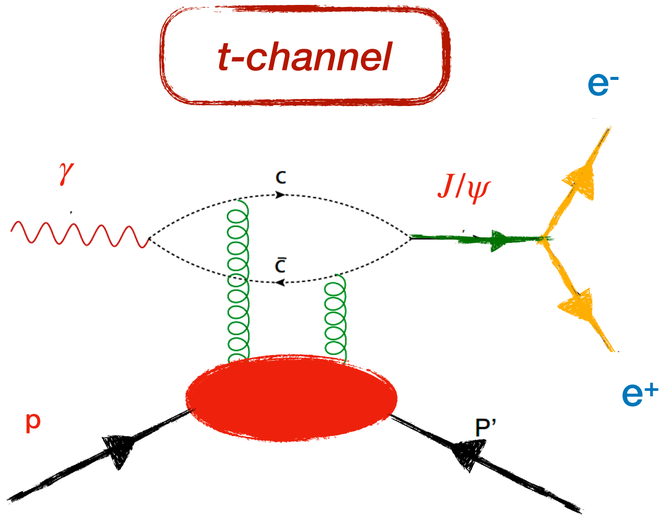
- First ever determination of the **2D cross section** of $J/\psi$ using real photon beam
- Obtained the $\boldsymbol{t}$-distributions for each 150 MeV bin in $E_\gamma$ from 9.1 GeV to 10.6 GeV
- Extracted the GFFs, for the first time, from purely experimental data using holographic and GPD approaches
- Proton's mass radius and scalar radius determined from the GFFs

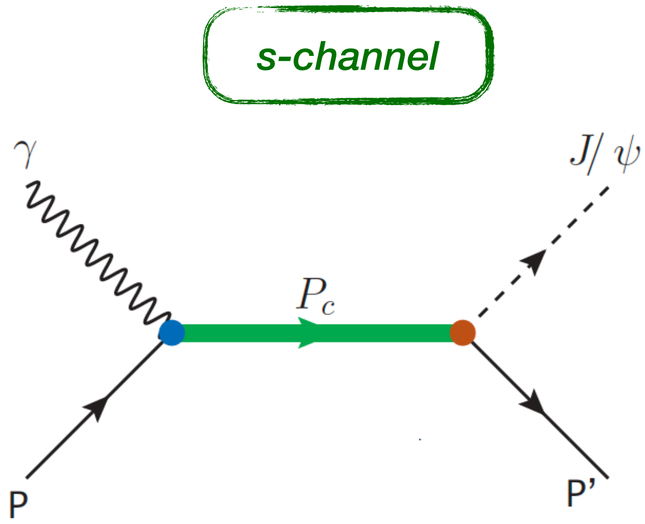
**STAY TUNED!**

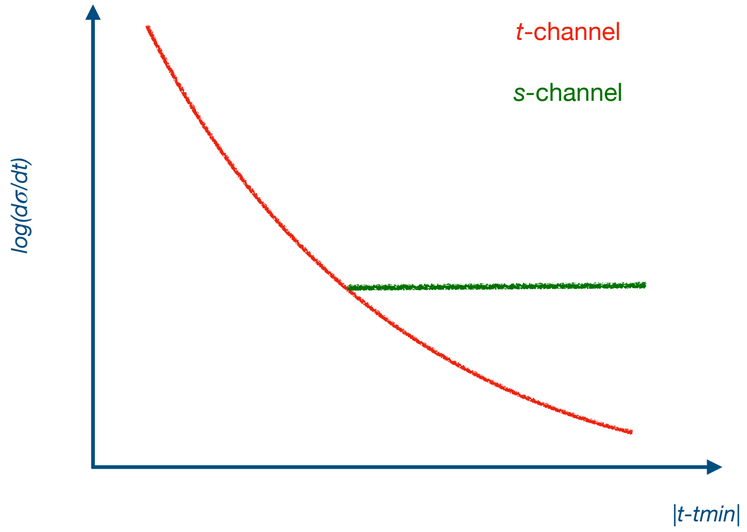
Results under peer-review

Preprint: https://arxiv.org/abs/2207.05212

# BACK UP




- Different angular (*t*) dependences:

1. *t*-channel: exponential like - drops with *t*.
2. *s*-channel: isotropic (flat across same t range)

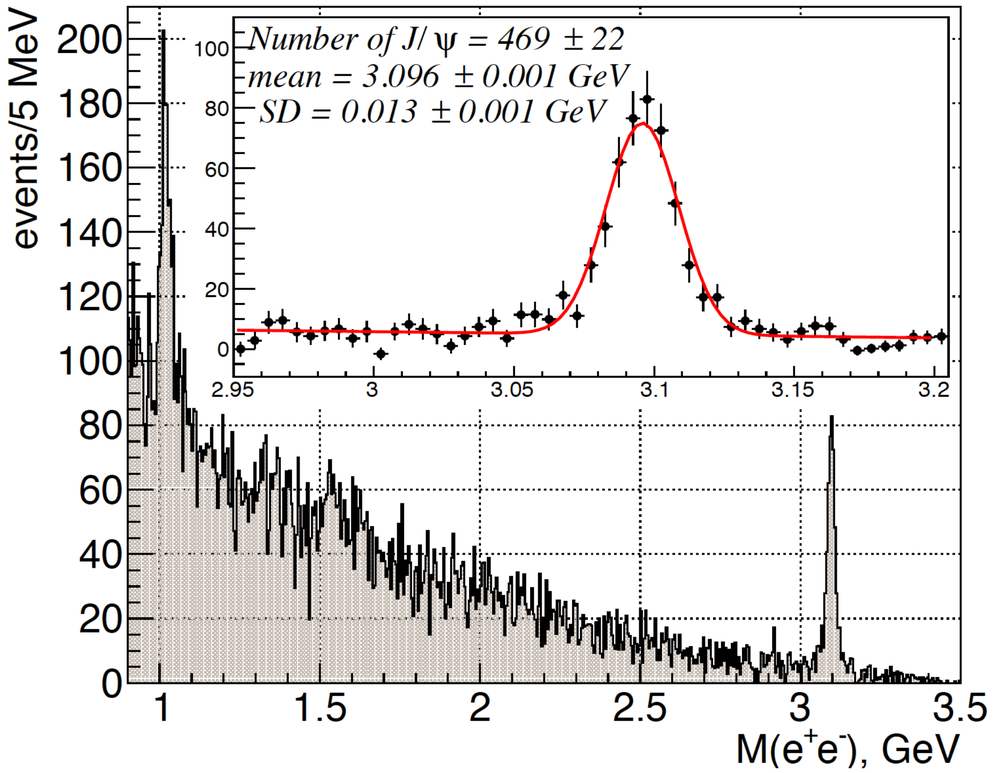
Maximize S/B at higher t region!!!

# LOW BACKGROUND - CLEAR SIGNAL IN HALL C

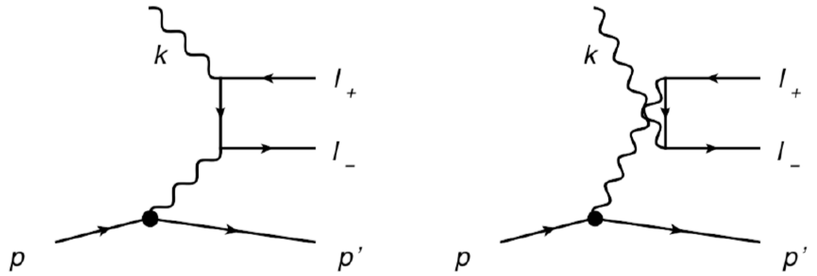
- **Bethe Heitler (BH):** major background for large acceptance $J/\psi$ experiments.
  - BH peaks for leptons emitted in incoming photon direction (small angles).
  - BH shoulder appears to the left of $J/\psi$ signal on the invariant mass spectrum.

GlueX

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

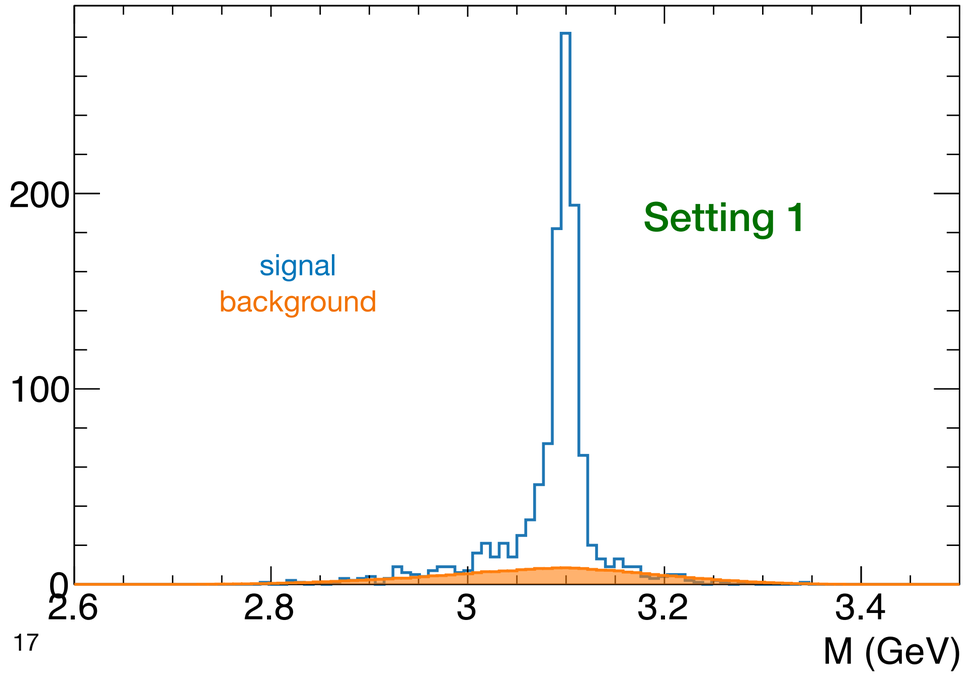



Bethe Heitler Mechanism to $\gamma p \rightarrow l^- l^+ p$



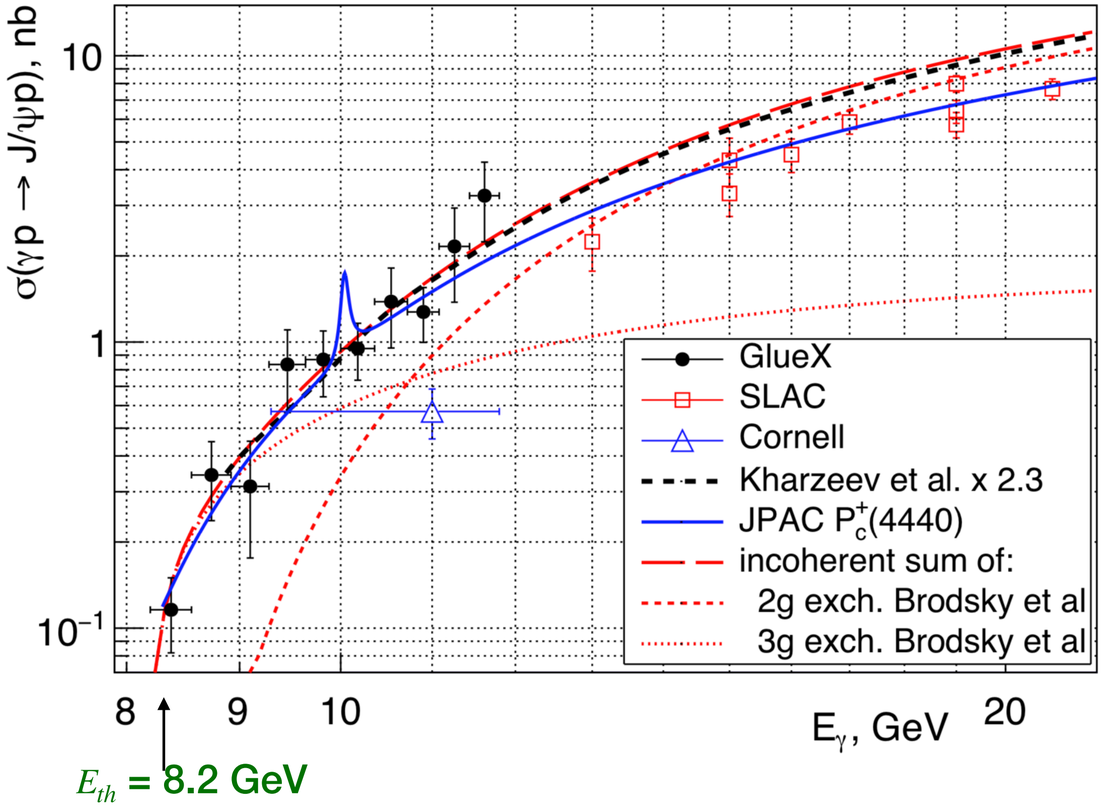

Vladyslav Pauk and Marc Vanderhaeghen
Physical Review Letters, 115(22), 2015.

$J/\psi - 007$



# $J/\psi$ PHOTOPRODUCTION DATA STATUS NEAR-THRESHOLD

## Up-to-date Data Status of near-threshold $J/\psi$ photo production




$E_{th}$ = 8.2 GeV

- 1D limits on σ(γp ➟ Pc) x Γ(Pc➟J/ψ p): 4.6nb, 1.8nb, and 3.9nb at 90% confidence level.
- Assuming spin-parity 3/2- for all 3 states, Γ(Pc(3/2-) ➟ J/ψ p): 4.6%, 2.3%, and 3.8%.

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

- 2019 GlueX 1D exclusive photo-production total cross section (CS).
- Very high CS values compared to the old data + 27% scale uncertainty.
- Shows a trend less steeper than as expected with 2-gluon exchange mechanism.
- Combined 2 gluon + 3 gluon fit.

# PENTAQUARK SIGNATURES AT $J/\psi - 007$ KINEMATICS

- What would the three pentaquark resonances look like at our two higher-t kinematic settings?

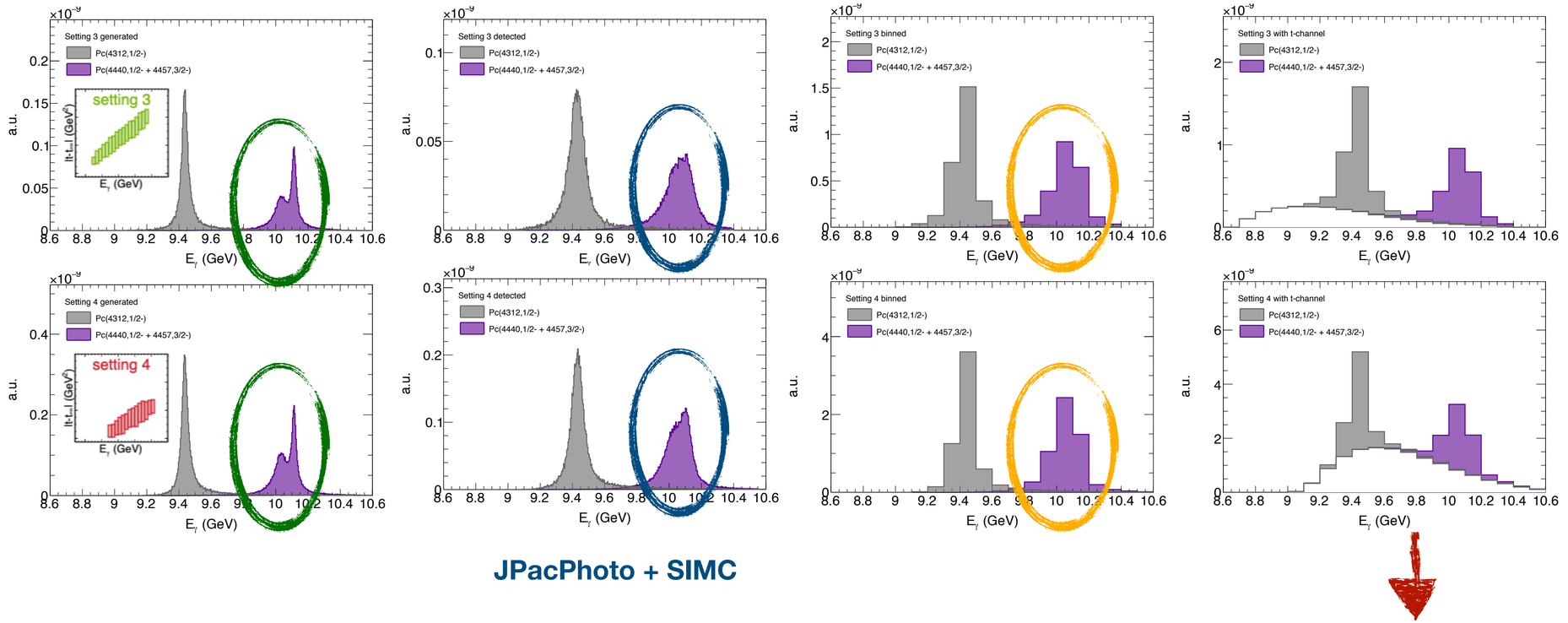
**at GlueX 90% confidence level**

Generated

+ radiative effects and resolution

+binned

+t-channel




**JPacPhoto + SIMC**

- Two higher mass Pc states are predicted to be indistinguishable due to the radiative effects, detector simulation and statistically driven binning at $J/\psi - 007$ kinematics.

*t*-channel is suppressed at higher t region. Potential Pc signals are distinguishable from *t*-channel.

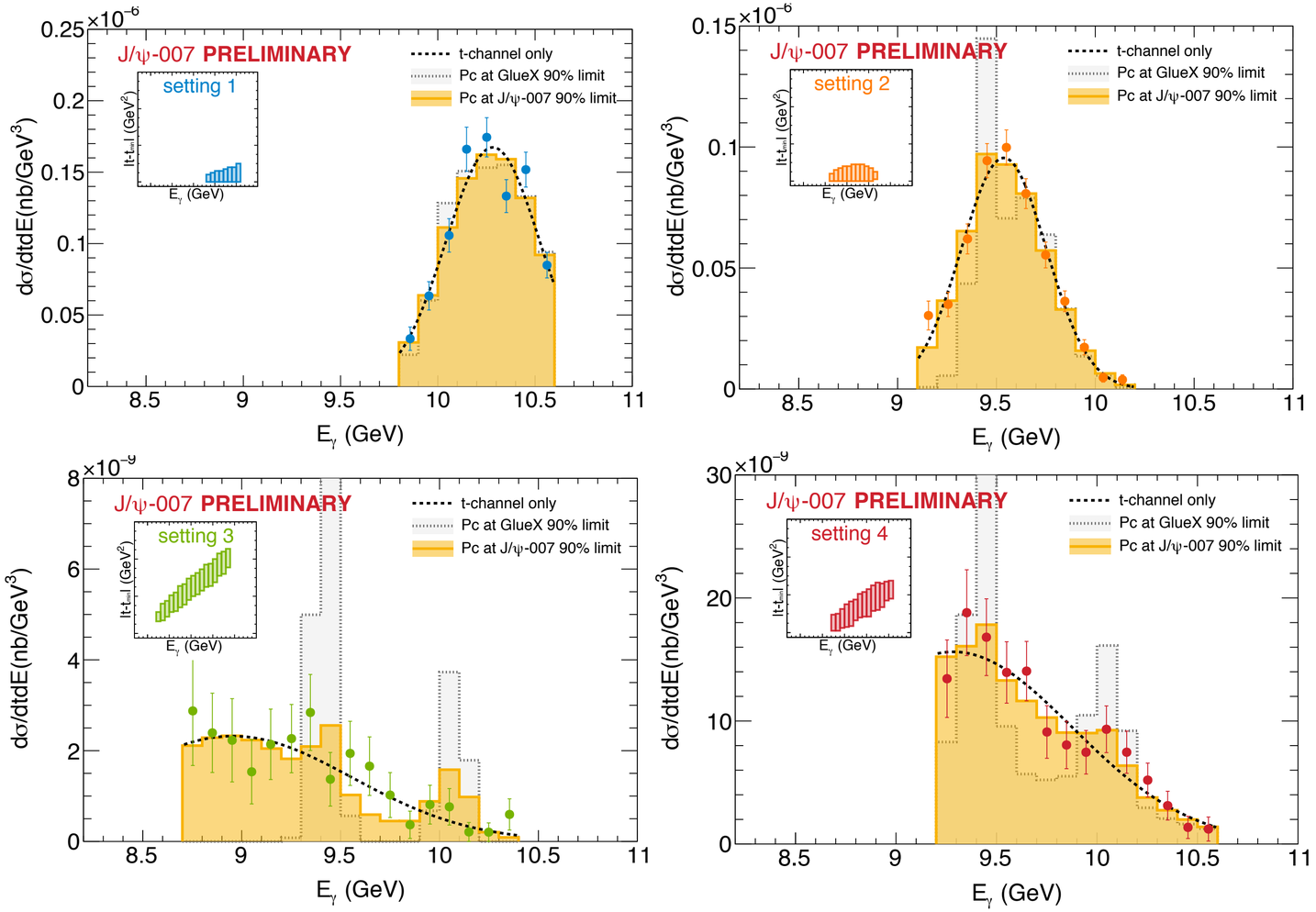
# SIGNIFICANCE FIT RESULTS

3 different fits on data:

**Fit 1**: Gaussian shape used for the t-channel description.

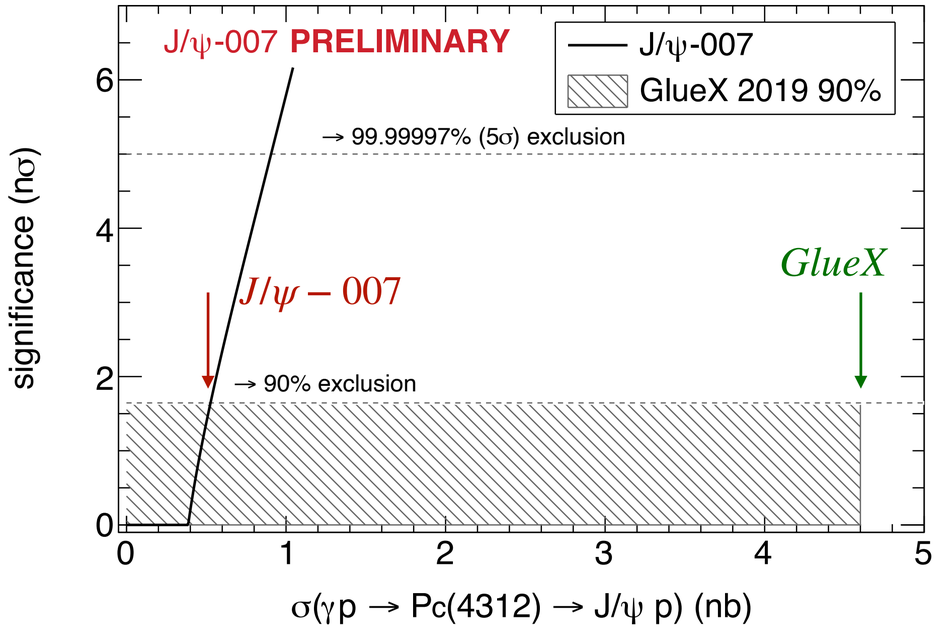
**Fit 2**: Gaussian shape + “predicted” Pc states using GlueX upper limits at 90% confidence interval. Large resonances do not constrain the data at higher t settings (3 and 4)

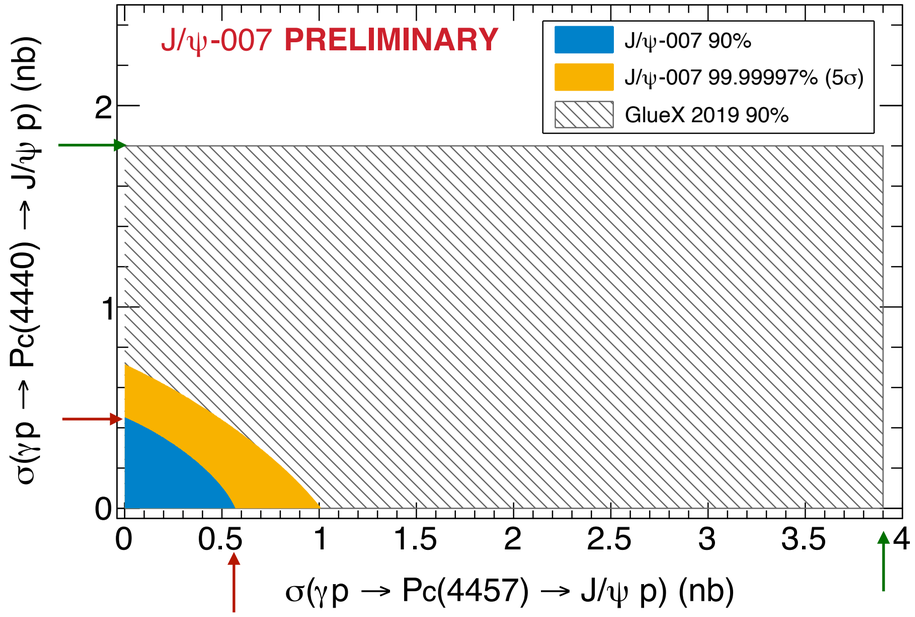
**Fit 3:** Gaussian shape + “predicted” Pc states at determined $J/\psi - 007$ upper limits at 90% confidence interval.




*Data isn’t consistent with the s-channel resonant production description.*

- The upper limit for each case represent the cross sections extracted from the $J/\psi - 007$ experiment's data at the peaks where these candidates are expected to appear.
- The upper limit comparison between $J/\psi - 007$ and GlueX results at 90% confidence level indicates the $J/\psi - 007$ upper limits almost one order of magnitude smaller.




- No evidence for LHCb's pentaquarks!
- Molecular state interpretation: the cross section in photo production not quite settled yet.

# Photon Energy Reconstruction

- Initial photon energy can be unambigously reconstructed from the reconstructed $J/\psi$ momentum and energy
  - **Assumptions**
    - ★ proton target at rest
    - ★ photon beam along the z axis
    - ★ proton and $J/\psi$ are the two final state particles

$$E_\gamma = \frac{M_\psi^2 - 2E_J M_P}{2(E_\psi - M_p - P_\psi \cos\theta_\psi)}$$

# $J/\psi$ Experiments at Jefferson Lab

| | GlueX HALL D | HMS+SHMS HALL C | CLAS 12 with lumi upgrade | SoLID HALL A |
|---|---|---|---|---|
| J/ψ counts (photo-prod.) | **469 published ~10k phase I + II** | **4k** | **14k** | **804k** |
| *J/ψ* Rate (electro-prod.) | **N/A** | **N/A** | **1k** | **21k** |
| Acceptance | 4π | $<4\times10^{-4}$ | <2π | 2π |
| When? | Finished | Finished | Ongoing/ Proposed | ~8 years? |

**DK**: D, Kharzeev, Phys. Rev. D 104, 054015 (2021)
**Charge radius**: CODATA
**Lattice radius:** D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, (2022)

**GlueX point**: R. Wang, J. Evslin, X. Chen, Eur. Phys. J. C, 80, 507 (2020).
**Approach:** X. Ji, Phys. Rev. Lett. 74, 1071–1074 (1995), same procedure as the GlueX point
**Lattice Ma**: F. He, P. Sun,Y.-B. Yang, Phys. Rev. D 104, 074507 (2021)

# Mass Radius with DK Approach

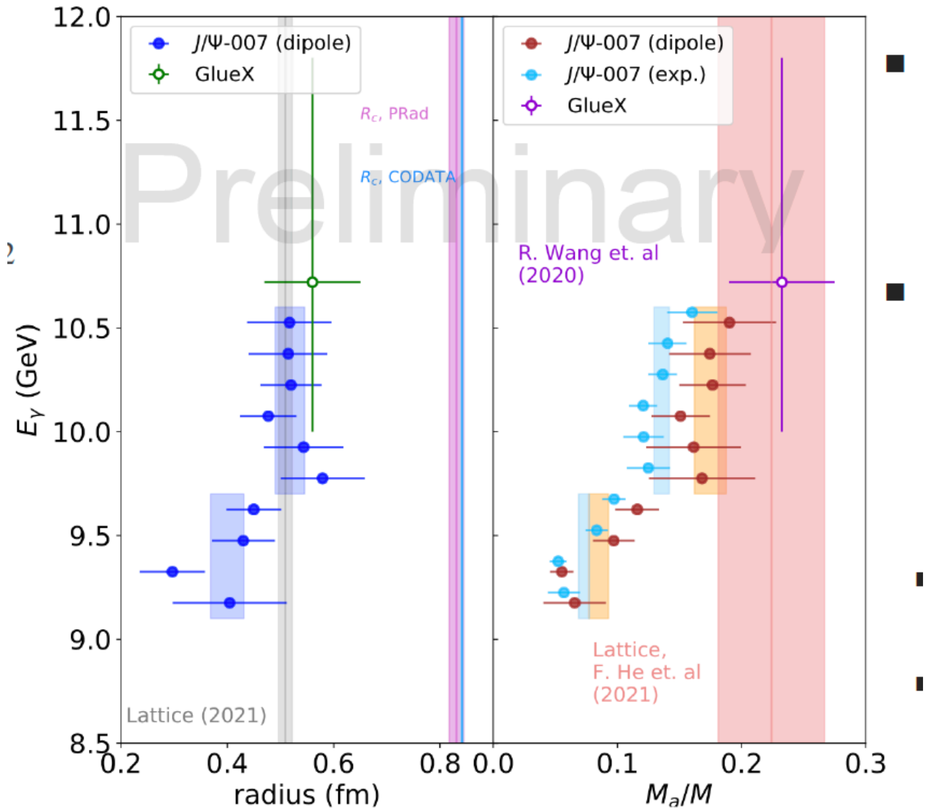
- Extracted the radius at each photon energy according to:

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s}\frac{1}{|p_{\gamma cm}|^2}(Q_e c_2)^2\left(\frac{16\pi^2 M^2}{b}\right)^2 G(t)^2$$

$$\langle r_m^2\rangle = \frac{6}{M}\frac{dG}{dt}|_{t=0} = \frac{12}{m_s^2}$$

- One effective scalar GFF of a dipole form
- Combination of three GFFs: A(t), B(t), and C(t)

$$G(t) = M(1 - t/m_s^2)^{-2}$$




- At higher energies, an energy independent radii consistent with GlueX
- A decrease towards the threshold region
- Good agreement with lattice for > 9.7 GeV

- Quantum anomolous energy assuming a dilaton exchange inferred
- Extracted the $M_a/M$ using both exponential GFF and dipole GFF