Pentaquark Search through J/ψ Measurements at Jefferson Lab

Burcu Duran

The 11th workshop of the APS Topical Group on Hadronic Physics (GHP2025)

Anaheim, CA

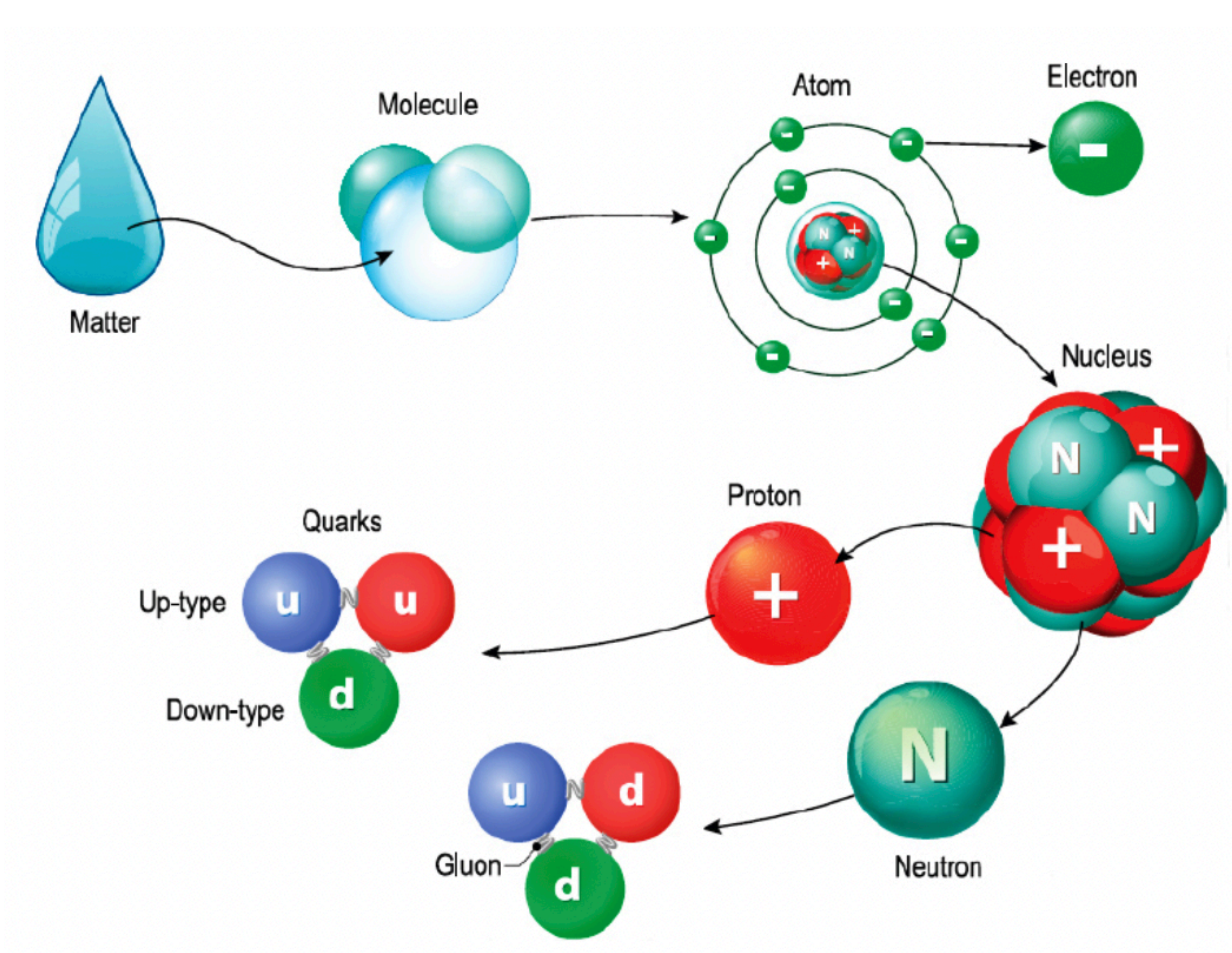
March 14, 2025

$007^{J/\psi}$

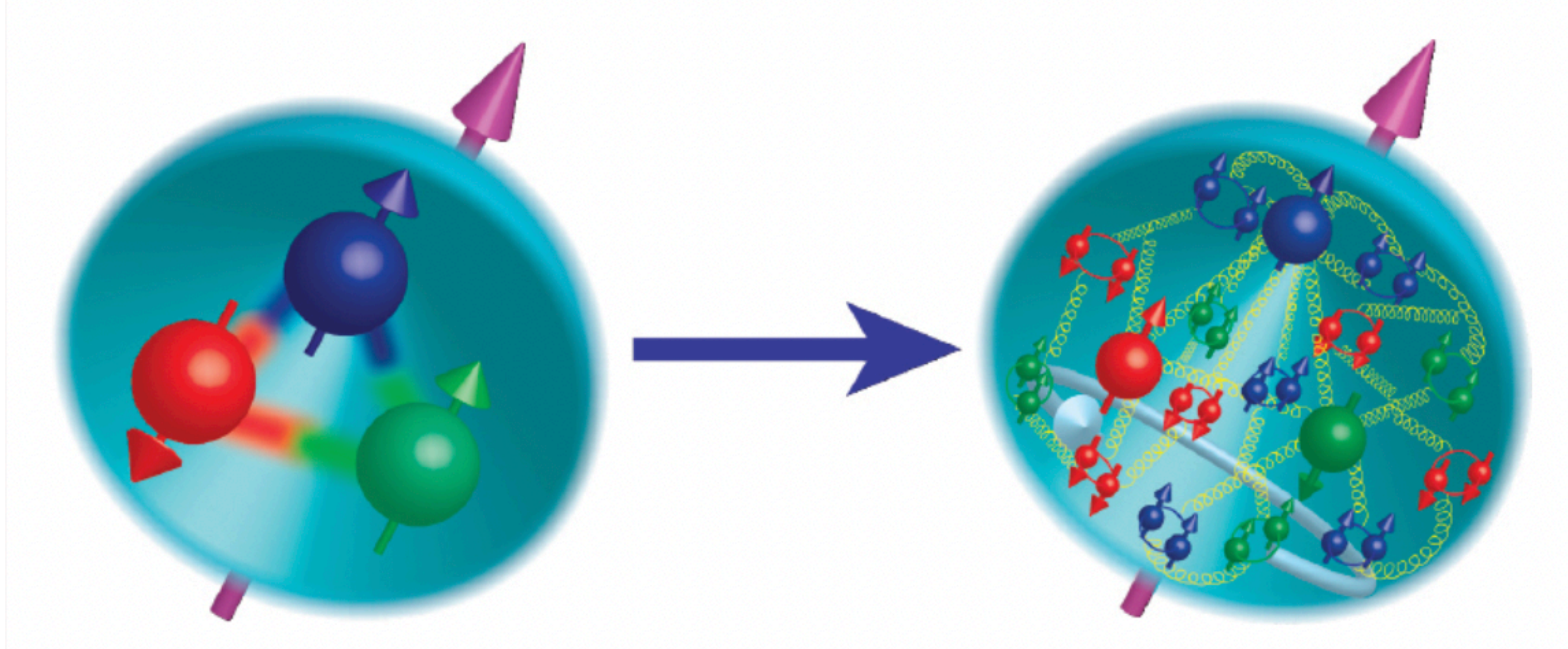
Pentaquark analysis (this talk)

Proton mass radius from Gravitational Form Factors (Sylvester Joosten's plenary talk at 8:30 am tomorrow at room 255)

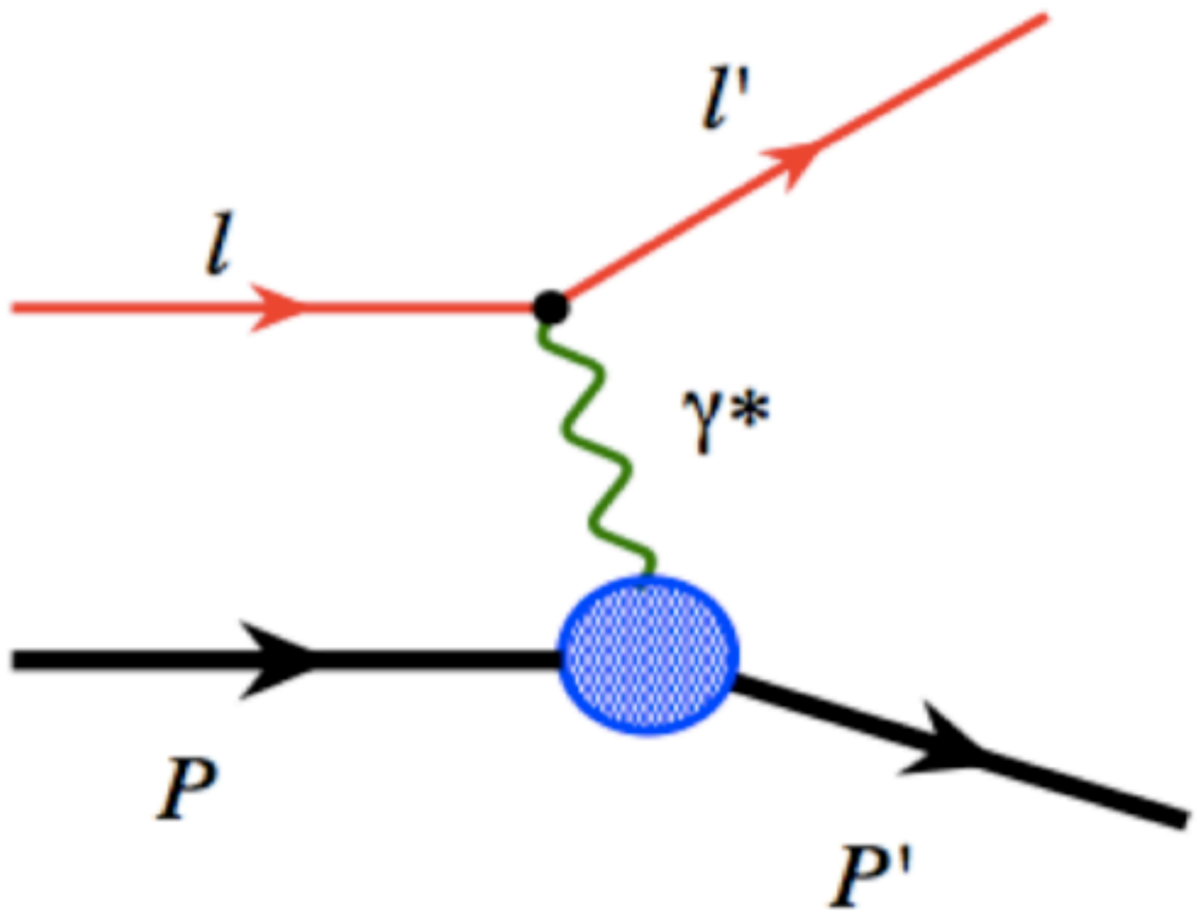
Understanding the Fundamental Building Blocks of Visible Matter



- **protons and neutrons (nucleons)** are the main building blocks of visible matter in the universe
- nucleon isn't static but has a complex and dynamic structure
- **nucleon:** strongly interacting relativistic bound state of quarks and gluons (partons)
- how do quarks and gluons give rise the fundamental properties of nucleons: mass, spin, charge etc.?



Electron Scattering as Our Microscope



energy of the photon determines its resolving power

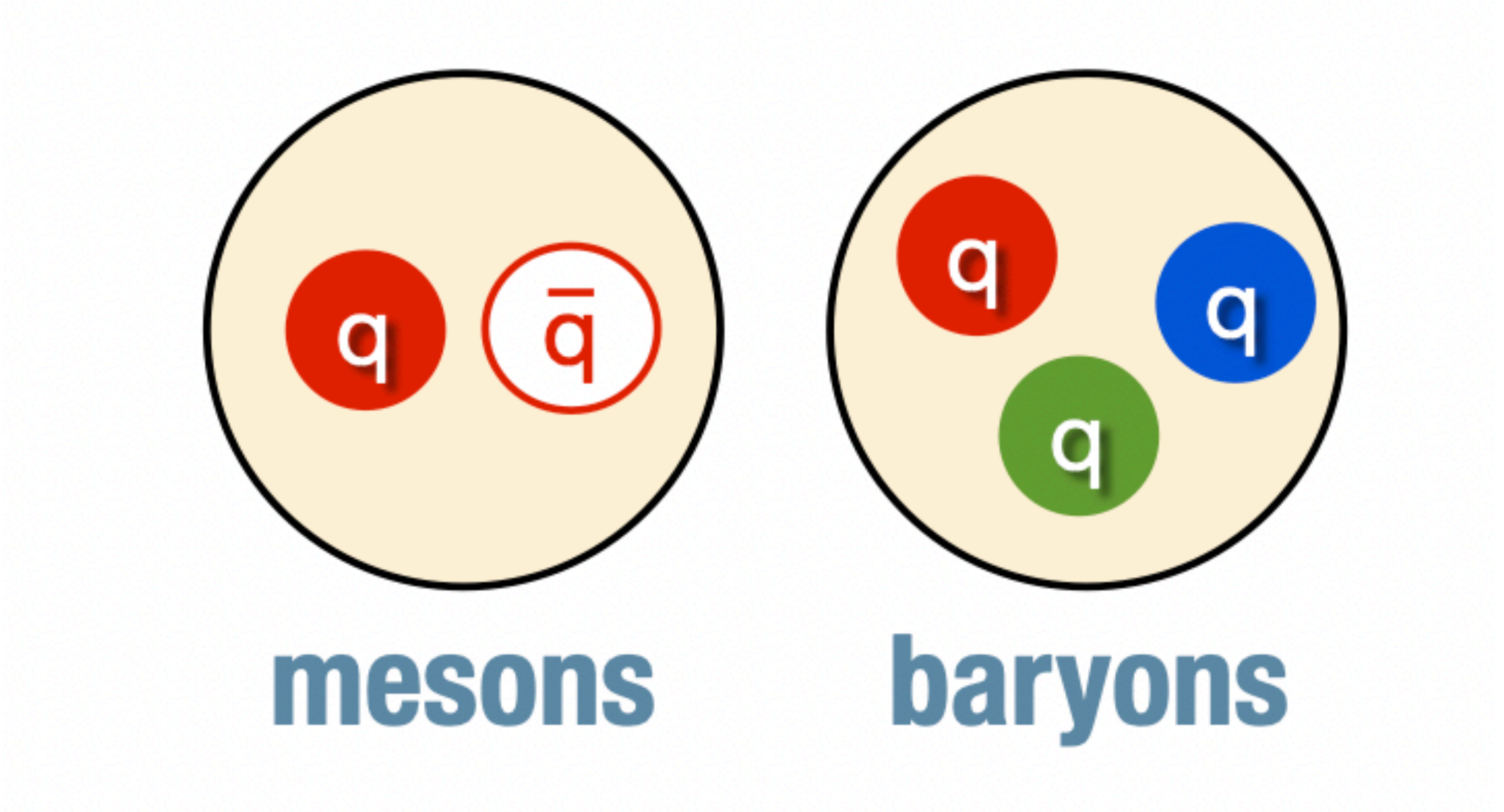
$$\lambda \approx \frac{1}{\vec{q}}$$

Electron-proton scattering - 1954 Robert Hofstadter: **proton is a composite particle!**

Nobel Prize - 1961

Late 1960s deep inelastic scattering experiments at SLAC: nucleon in fact is composed of point-like particles, "partons"

Confined States of Quarks and Gluons



Well described by the 1st principles of QCD!

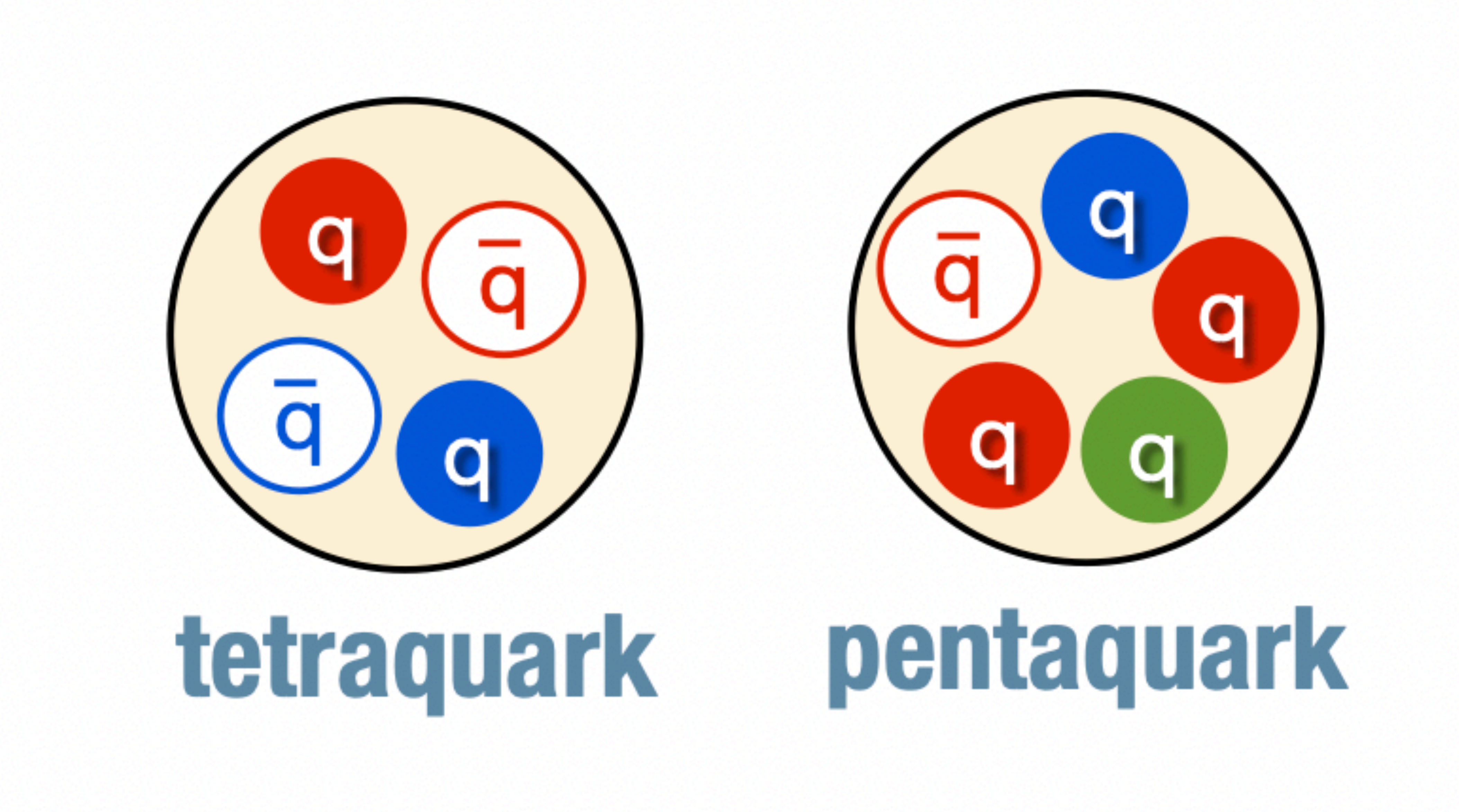
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

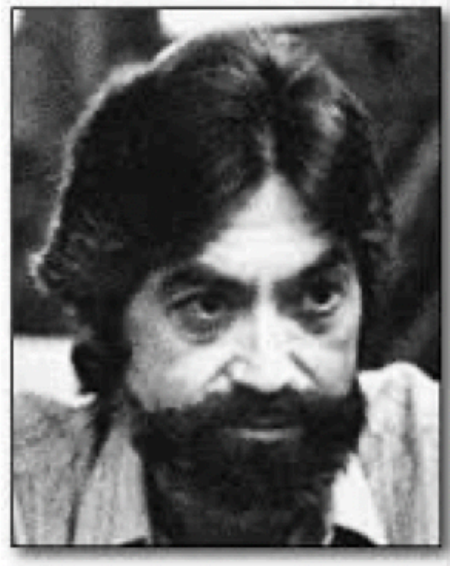
Phys. Lett. 8 (1964) 214

But they are not the only states permitted by the QCD



AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva



Discovery of LHCb Charm Pentaquarks

$$\Lambda_b^0 \to J/\psi\ p\ K^-$$

R. Aaij et al. (LHCb) (2015)
PRL 115-7

2
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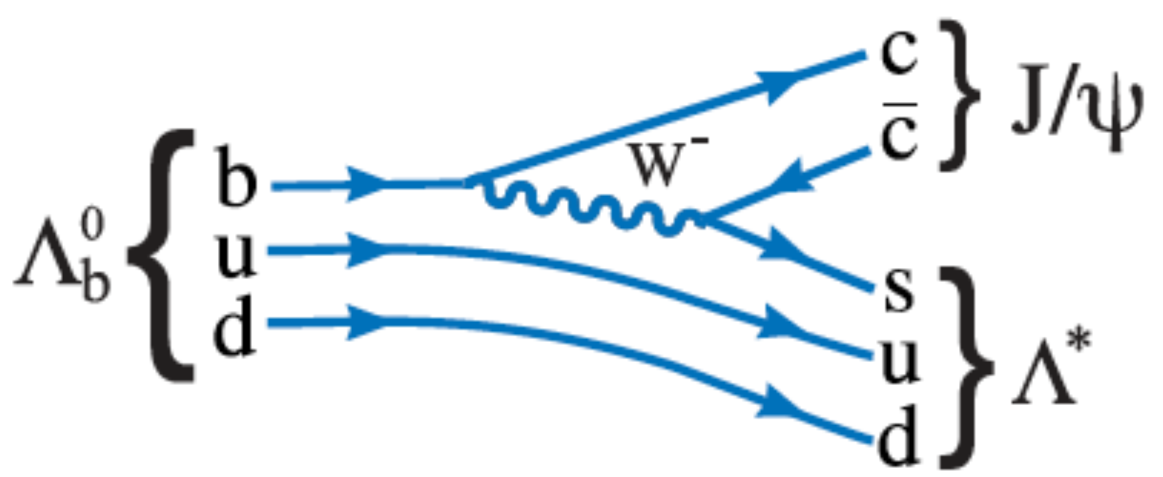

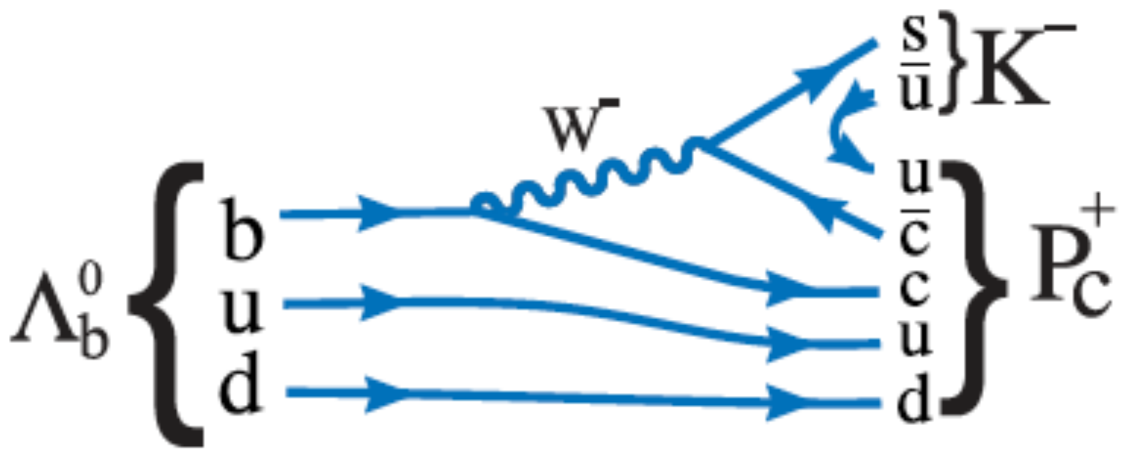

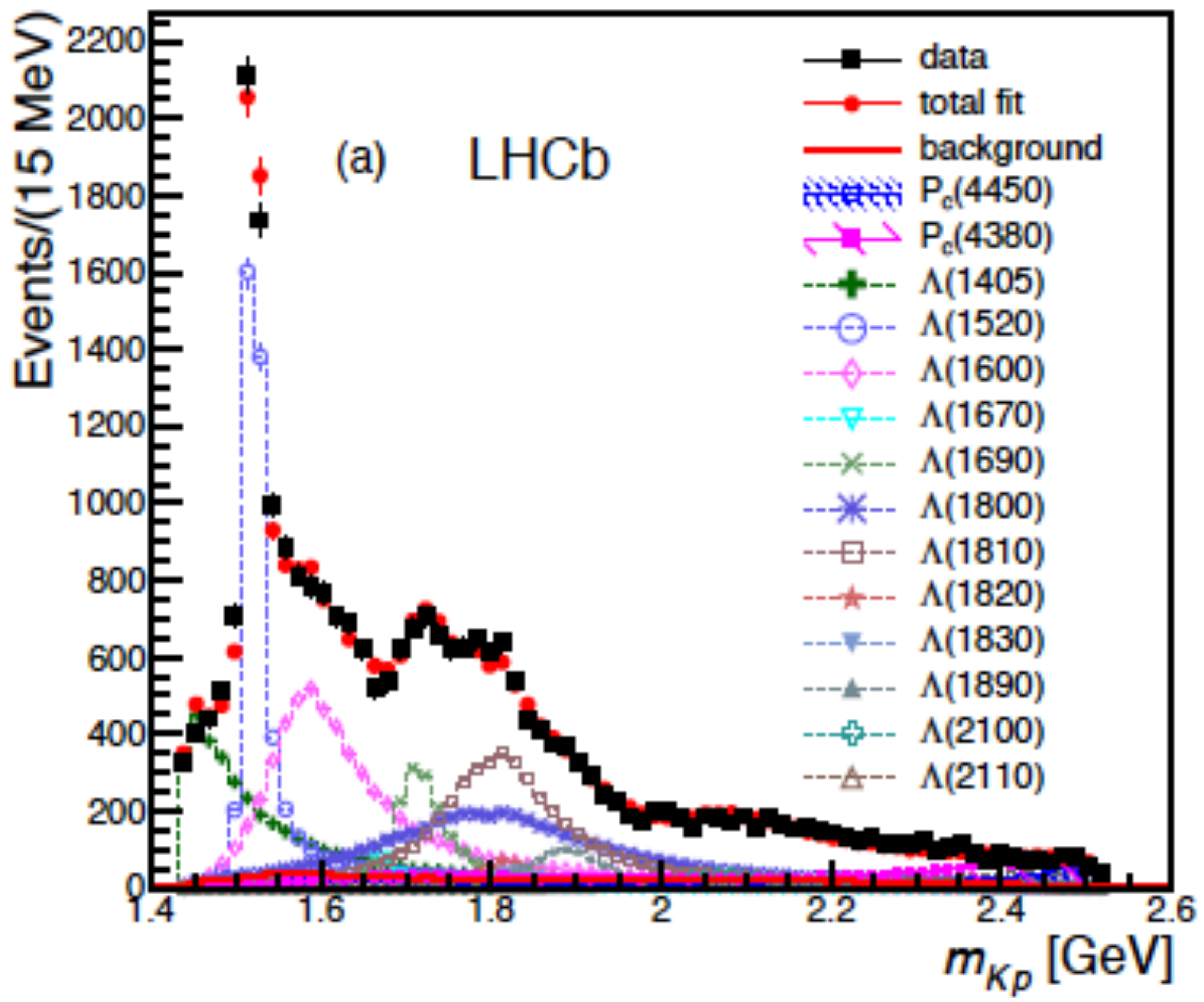

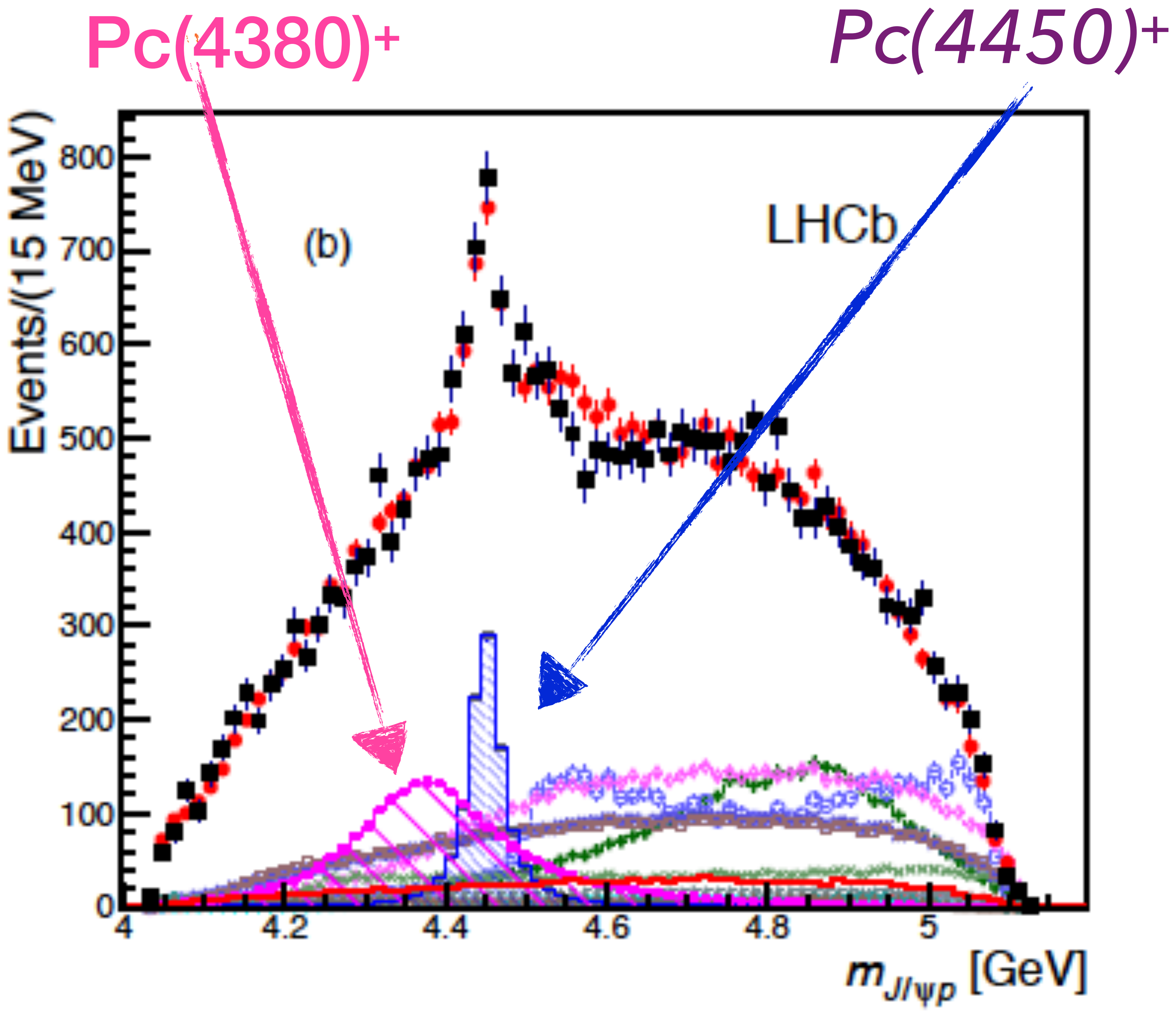

Update on LHCb Charm Pentaquarks

$\Lambda_b^0 \to J/\psi \; p \; K^-$

R. Aaij et al. (LHCb) (2019)
PRL 22, 222001

2
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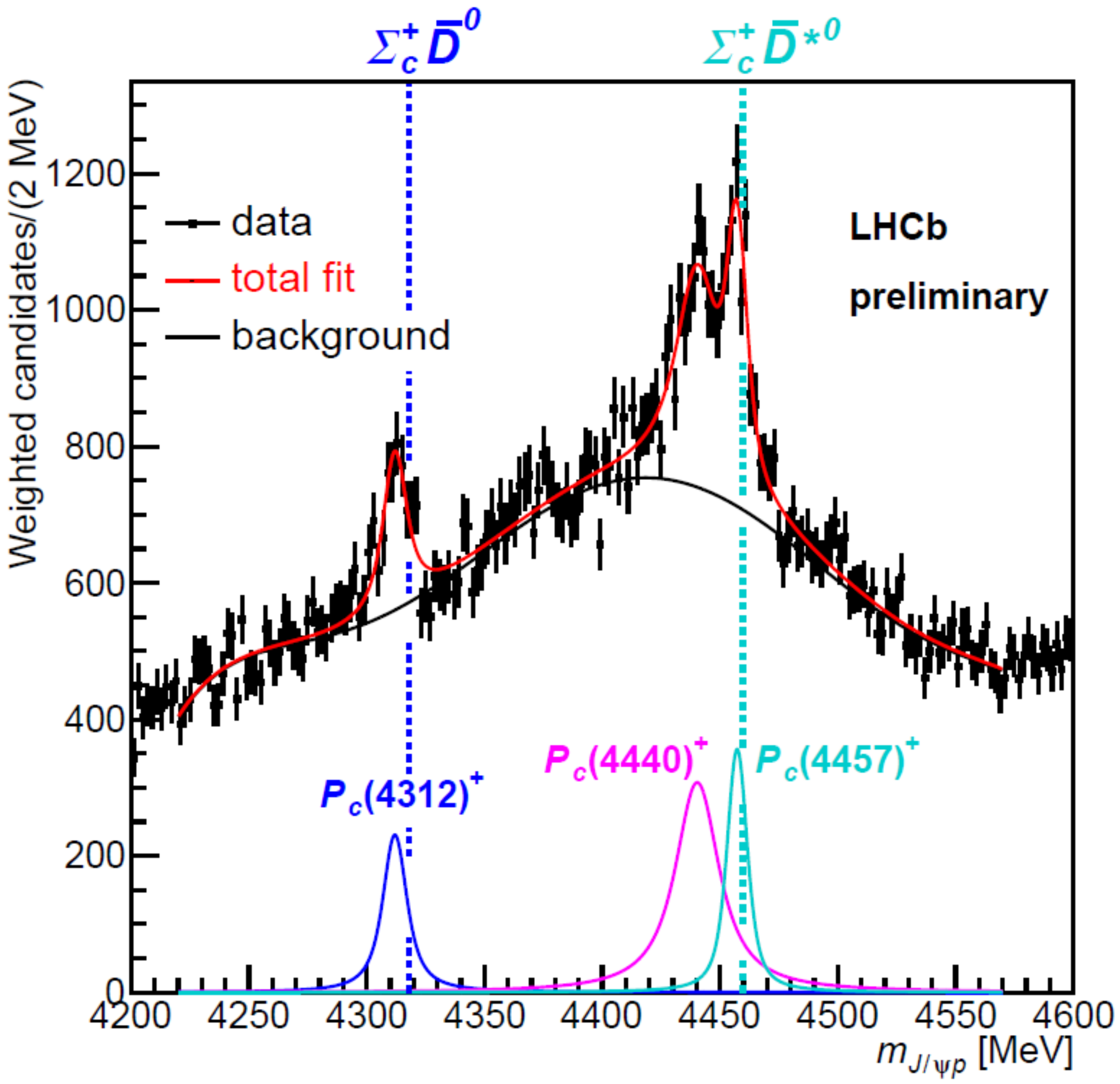
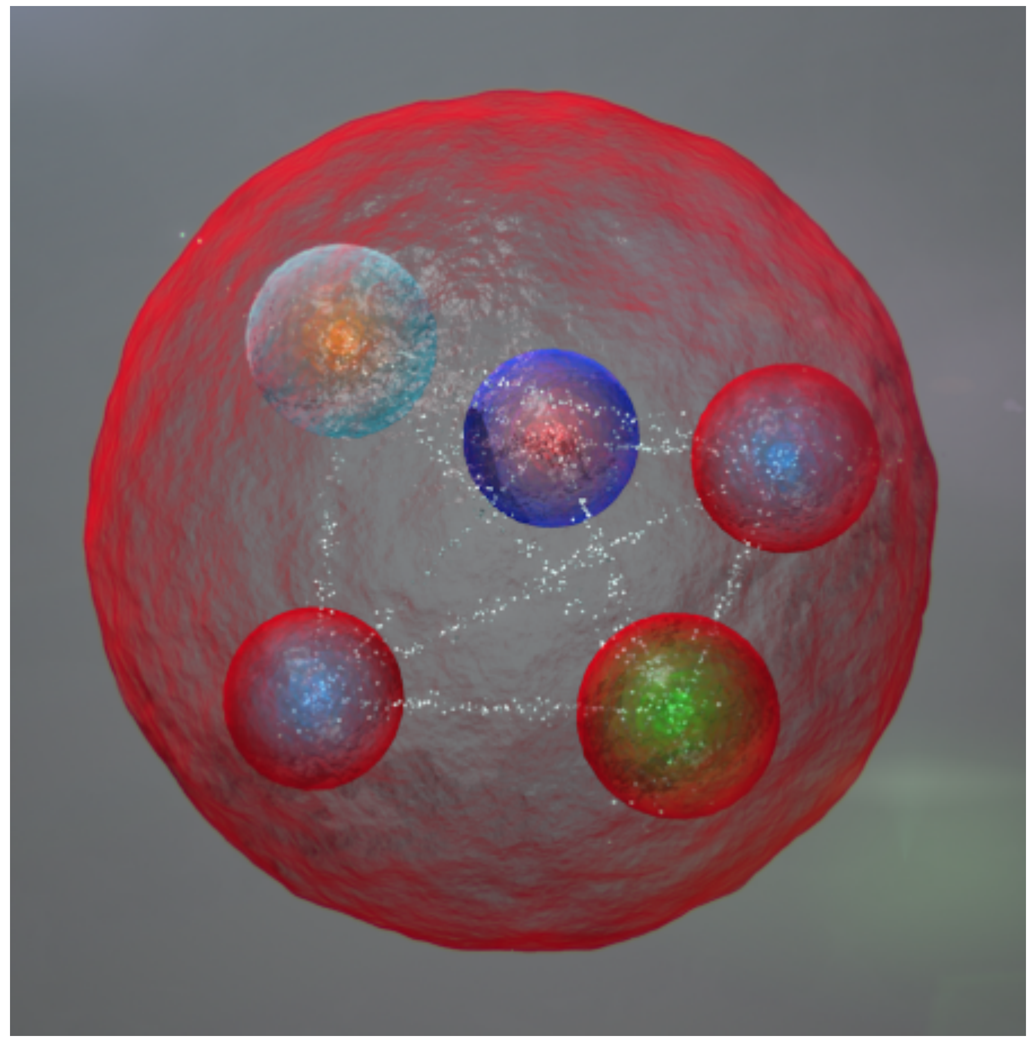
1
9



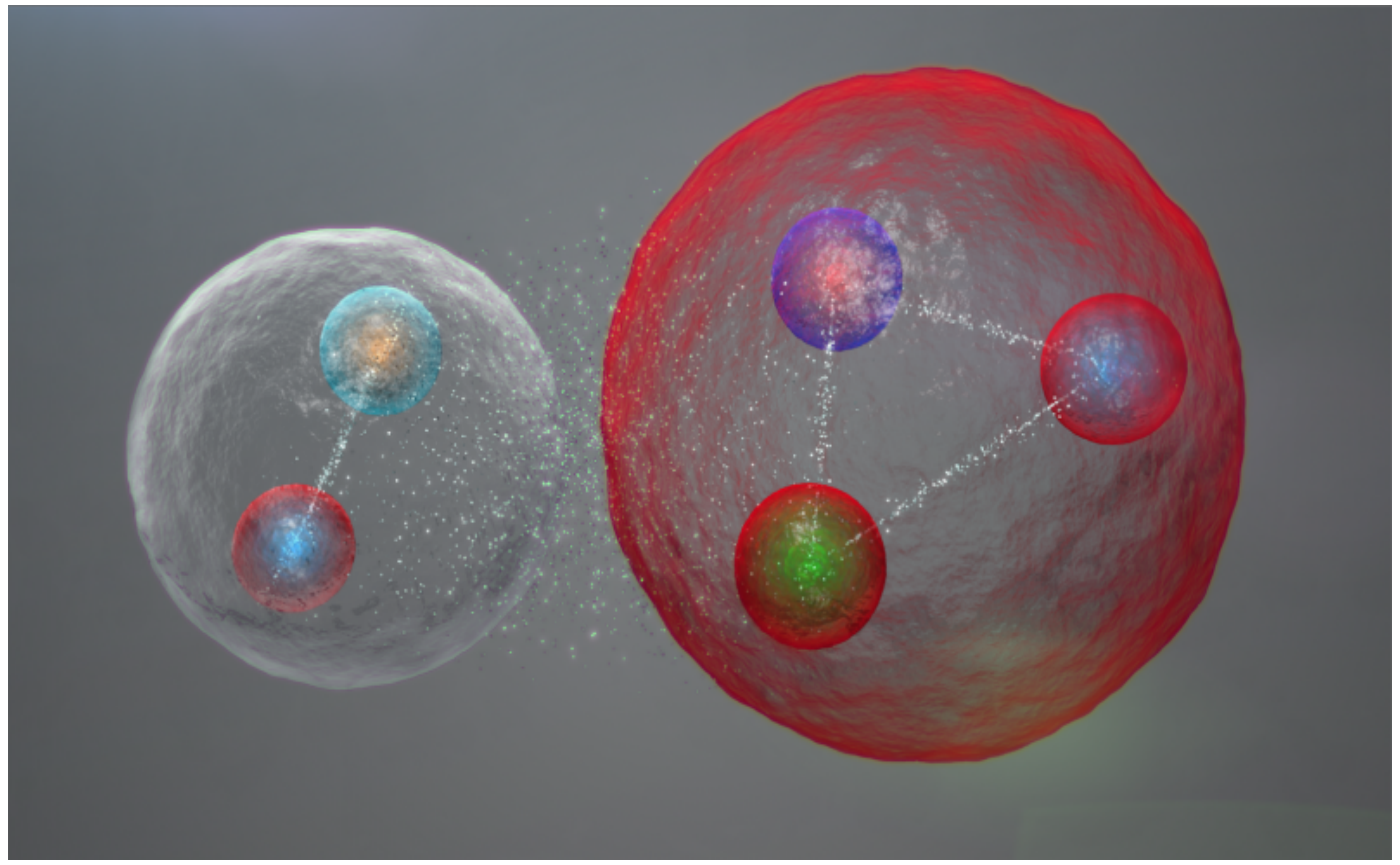
- 10x more data than 2015
- New P_c state: *Pc(4312)*$^+$
- Narrow *Pc(4450)*$^+$ *from 2015 data* resolved into 2 narrower peaks: *Pc(4440)*$^+$ and Pc(4457)$^+$.
- All three Pc candidates are still in the energy range of the $J/\psi - 007$ experiment.

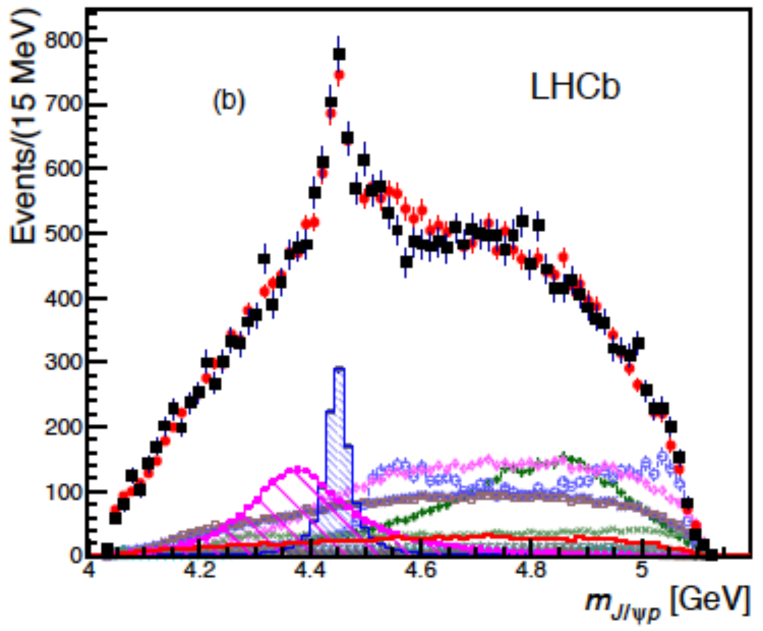
LHCb Charm Pentaquarks: A Resonance or Else?

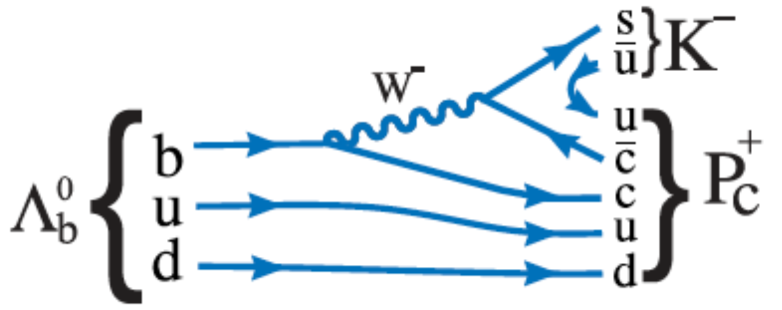
1a) pentaquarks: tightly bound 5-quark



1b) pentaquarks: hadronic molecule



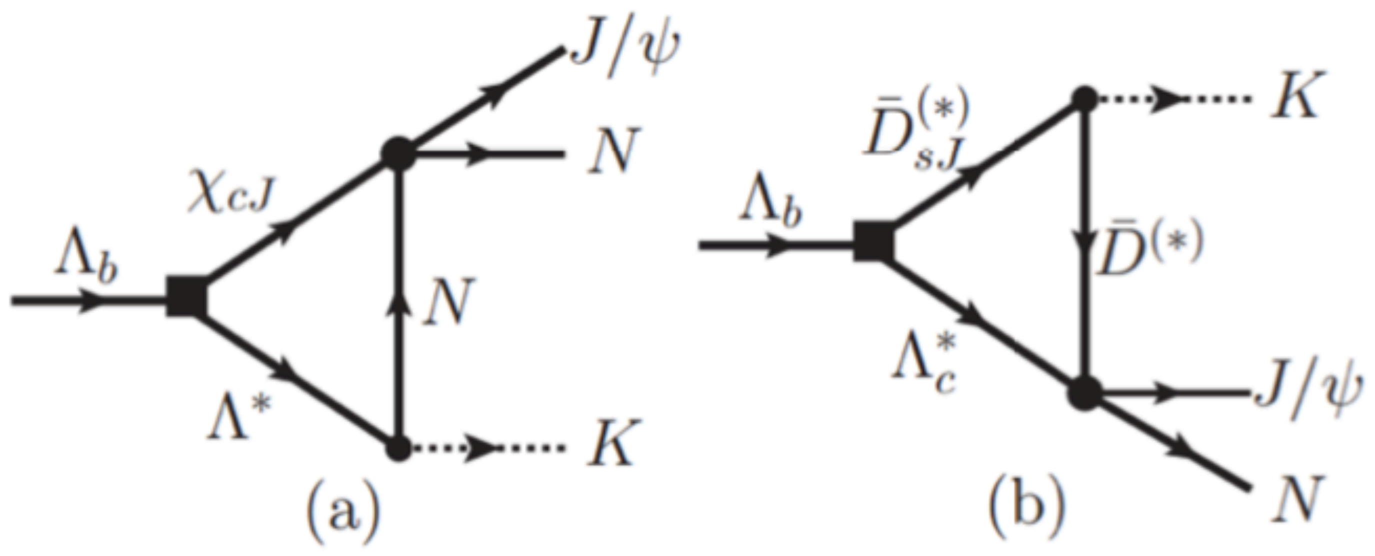




$$P_c^+ \to J/\psi p$$

2. Non-resonant Rescattering Effects

$$\Lambda_b^0 \to J/\psi\ p\ K^-$$



ENTER J/ψ!

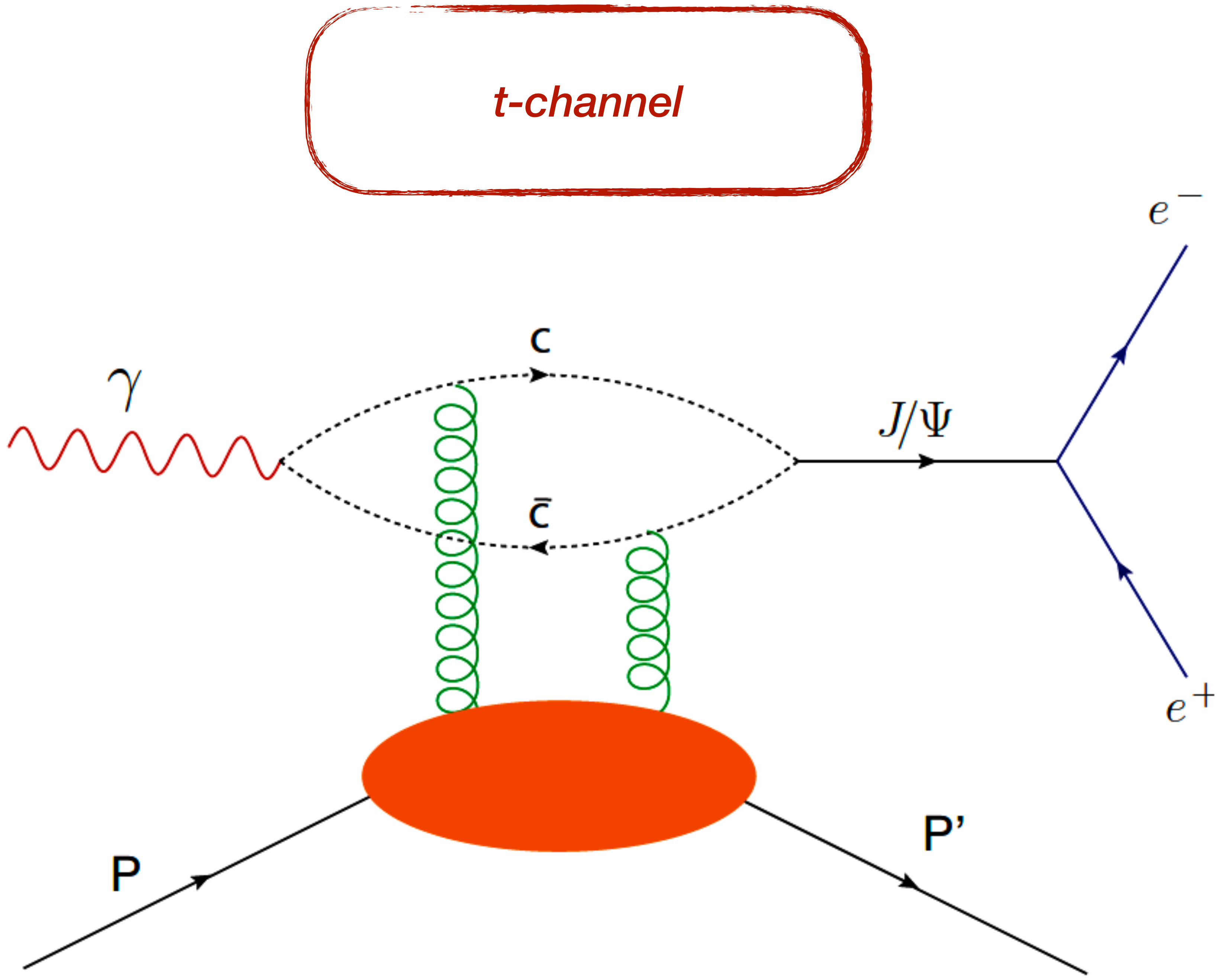
Case 1a: Clear visible signal expected in ***photo-production***.

Case 1b: Small overlap of their wave functions with $J/\psi\ p$ in ***photo-production***. Coupling is slightly suppressed.

Case 2: Not possible in ***photo-production***.

An Experimental Perspective: J/ψ Production near Threshold

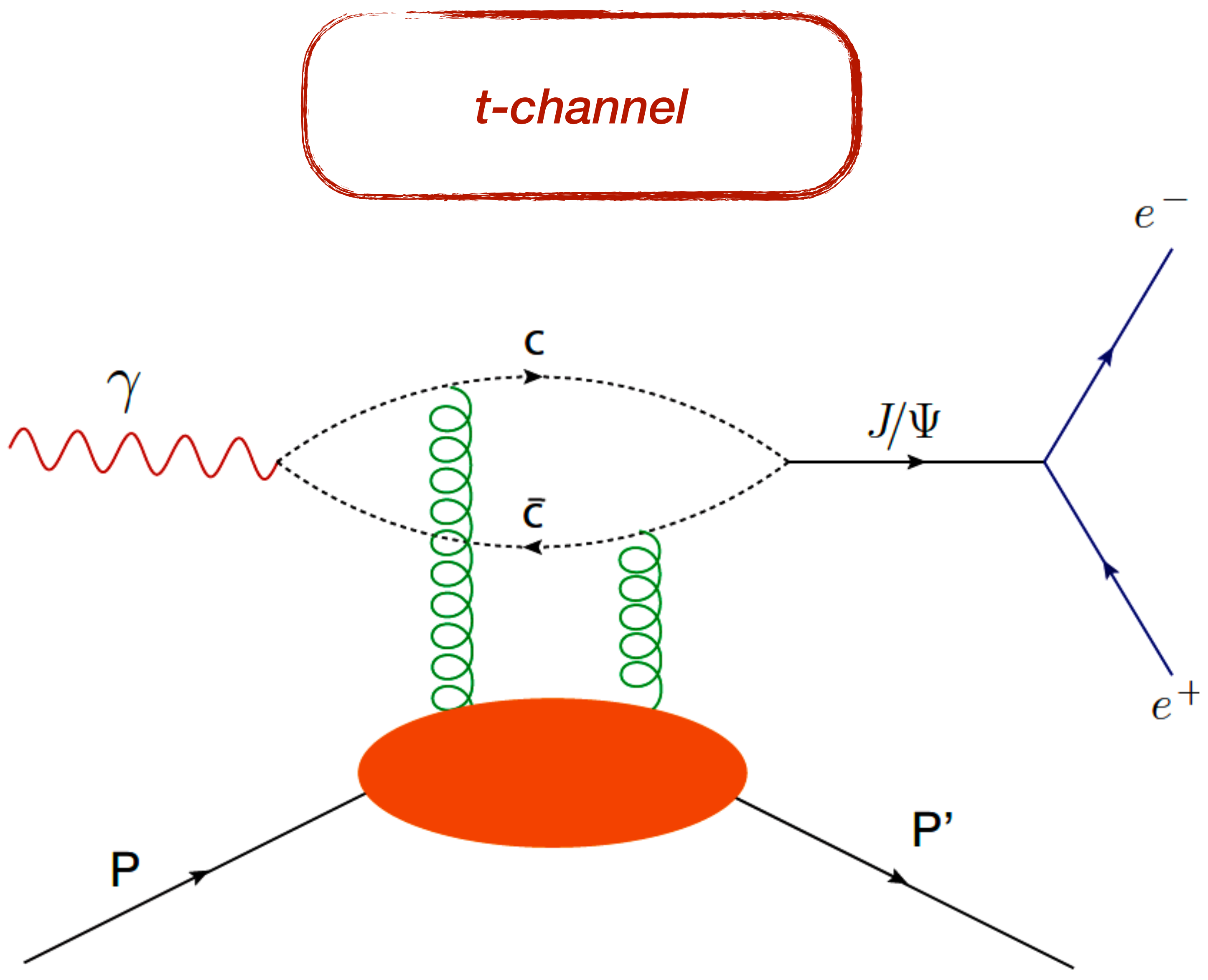
- Proton charge radius mainly carried out by charged moving quarks
    - electromagnetic probe to study proton charge radius
- Proton mass distribution mainly carried out by gluons and gluons have NO charge!

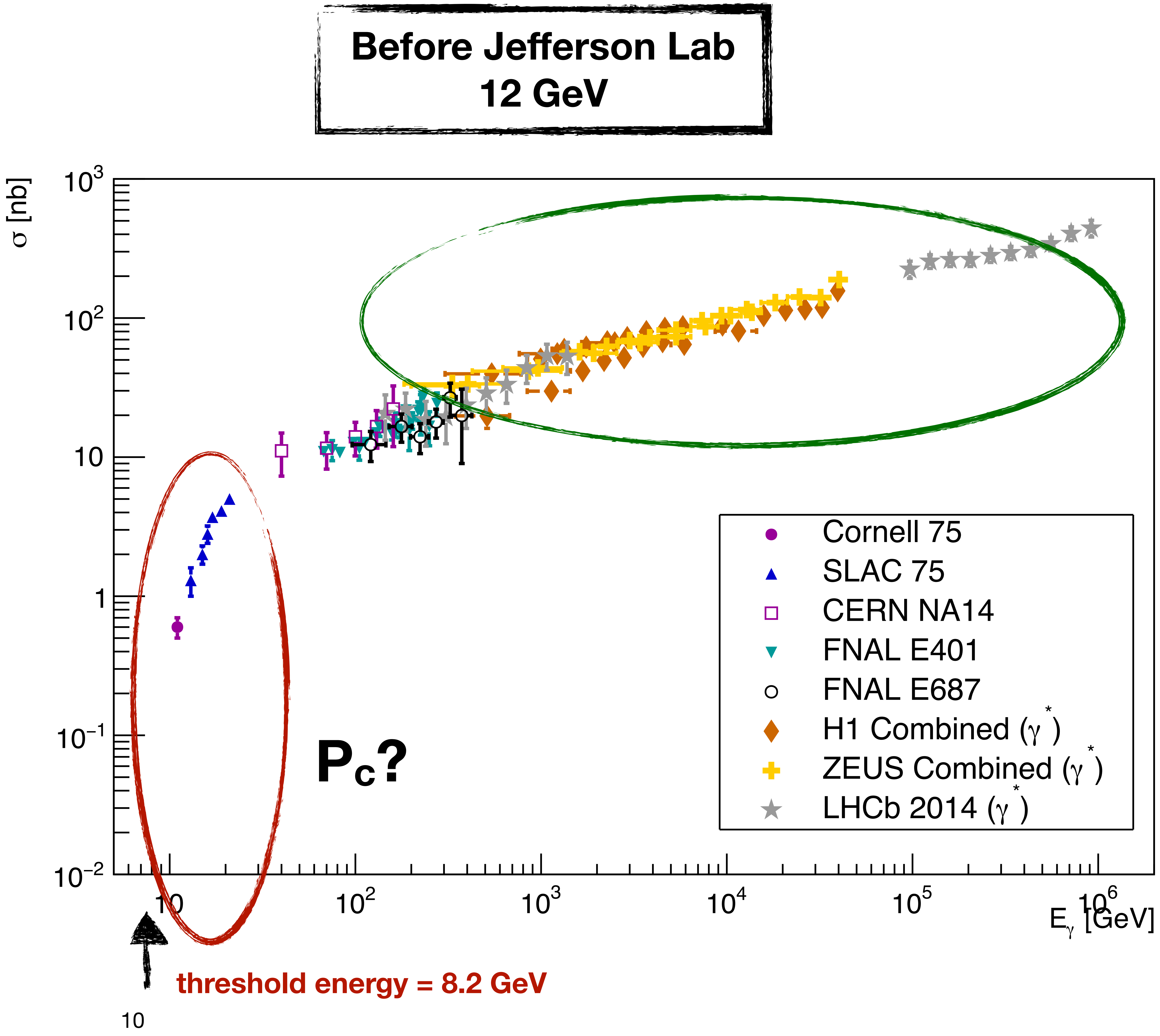


- J/ψ production near threshold to probe gluons
    - Sensitive to the gluonic structure of the proton:

  only couples to the gluons, not light quarks!
- Mandelstam variable t for the momentum transfer from photon to J/ψ

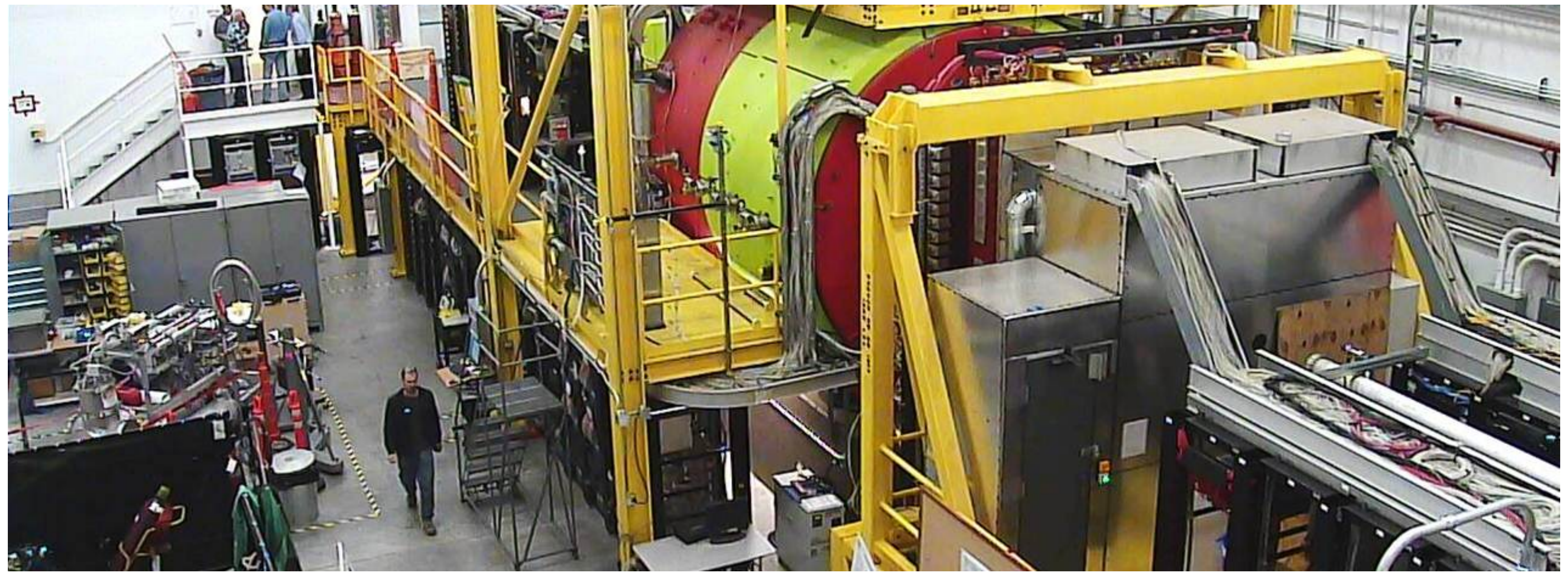
J/ψ Production: Current Data Status



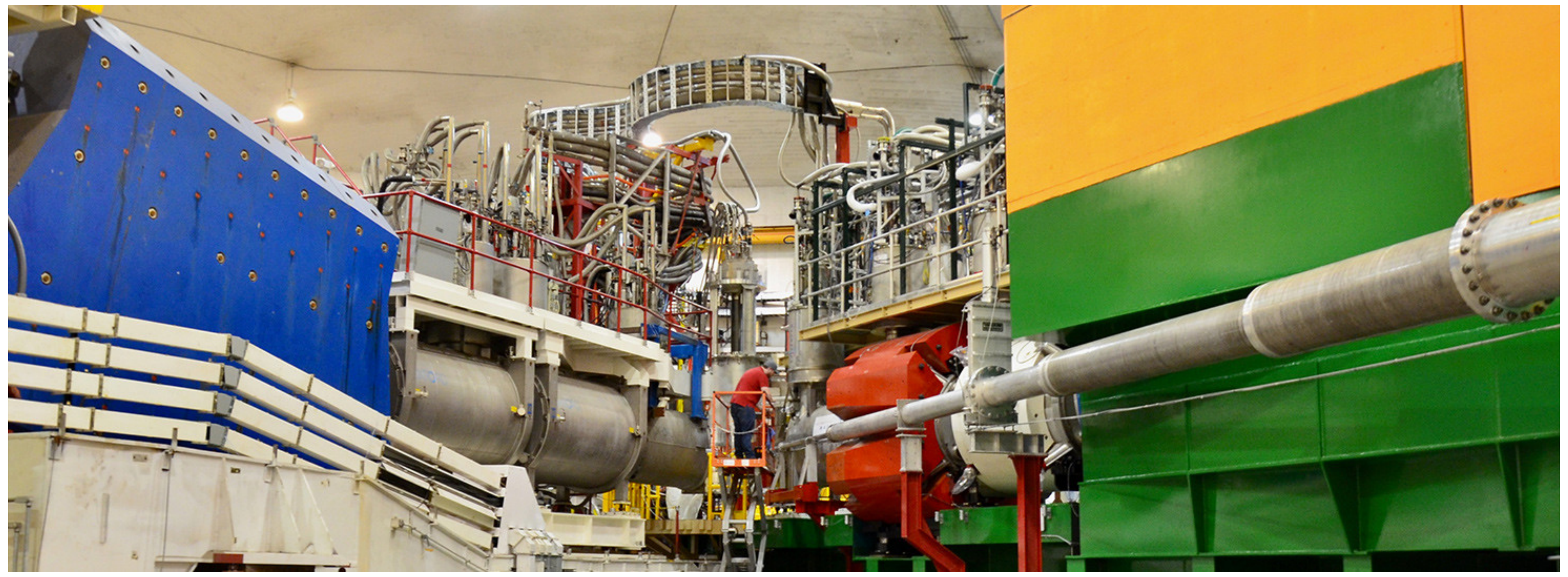


- Well constrained high energy region
- Scarce in the energy range of interest i.e. near threshold region

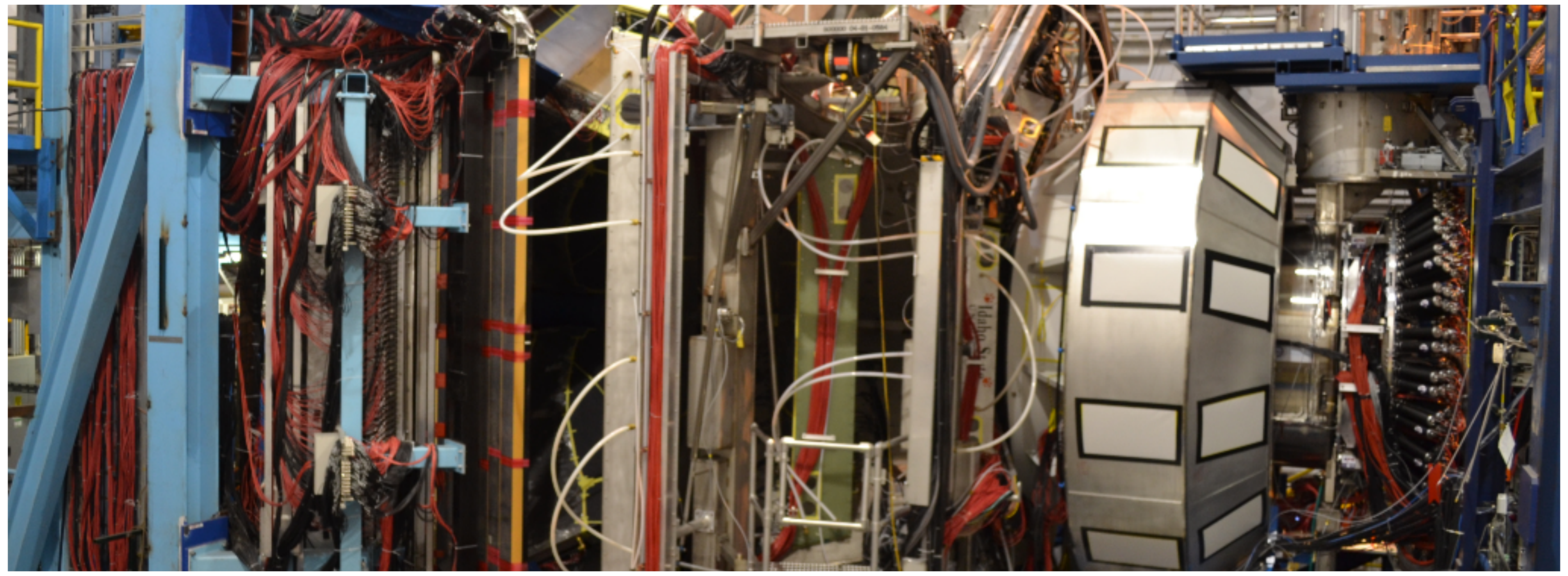
J/ψ Experiments at Jefferson Lab 12 GeV Era



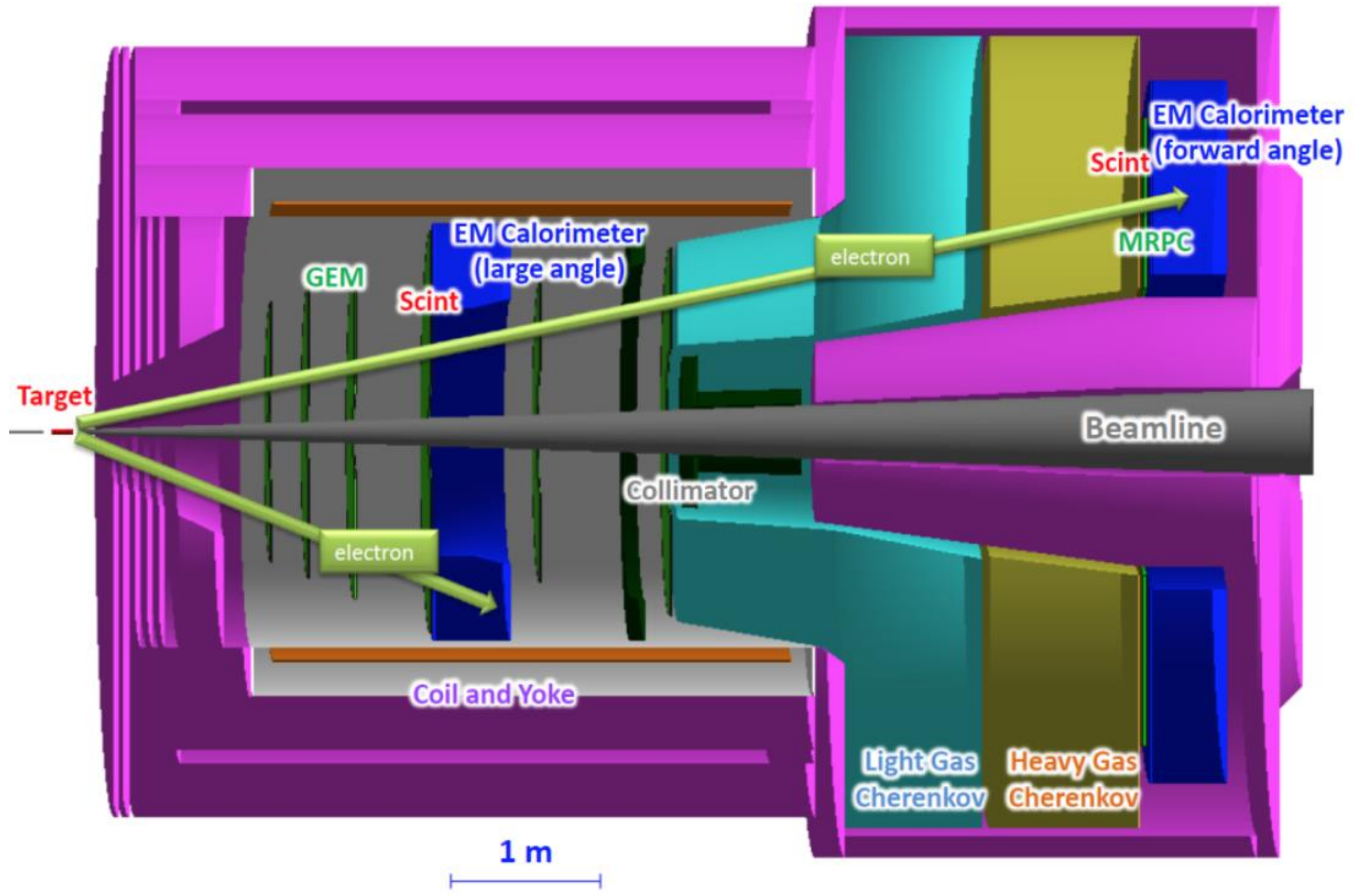
Hall D - GlueX the first J/ψ measurement at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



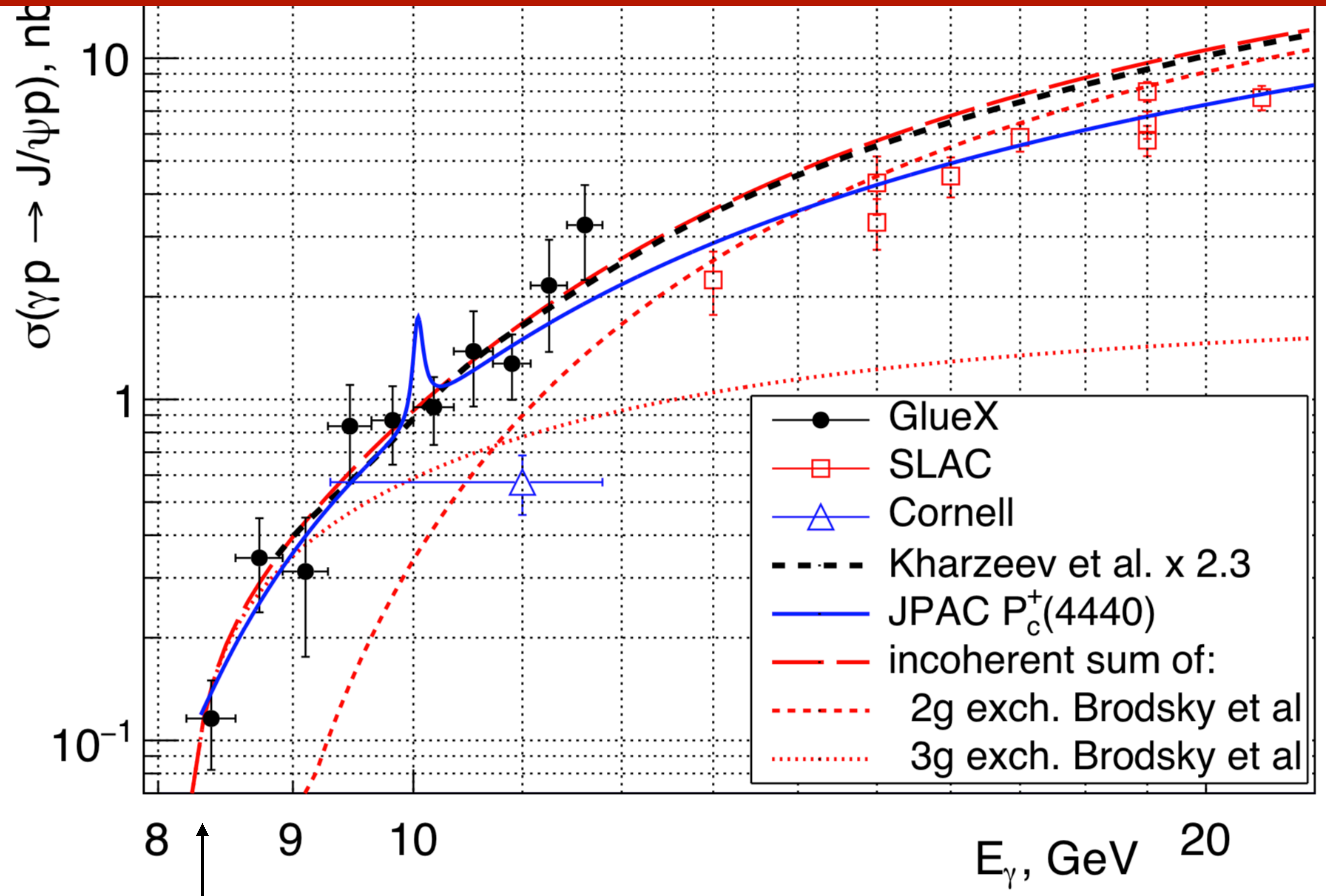
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B



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**

GLUEX 2019 Results

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

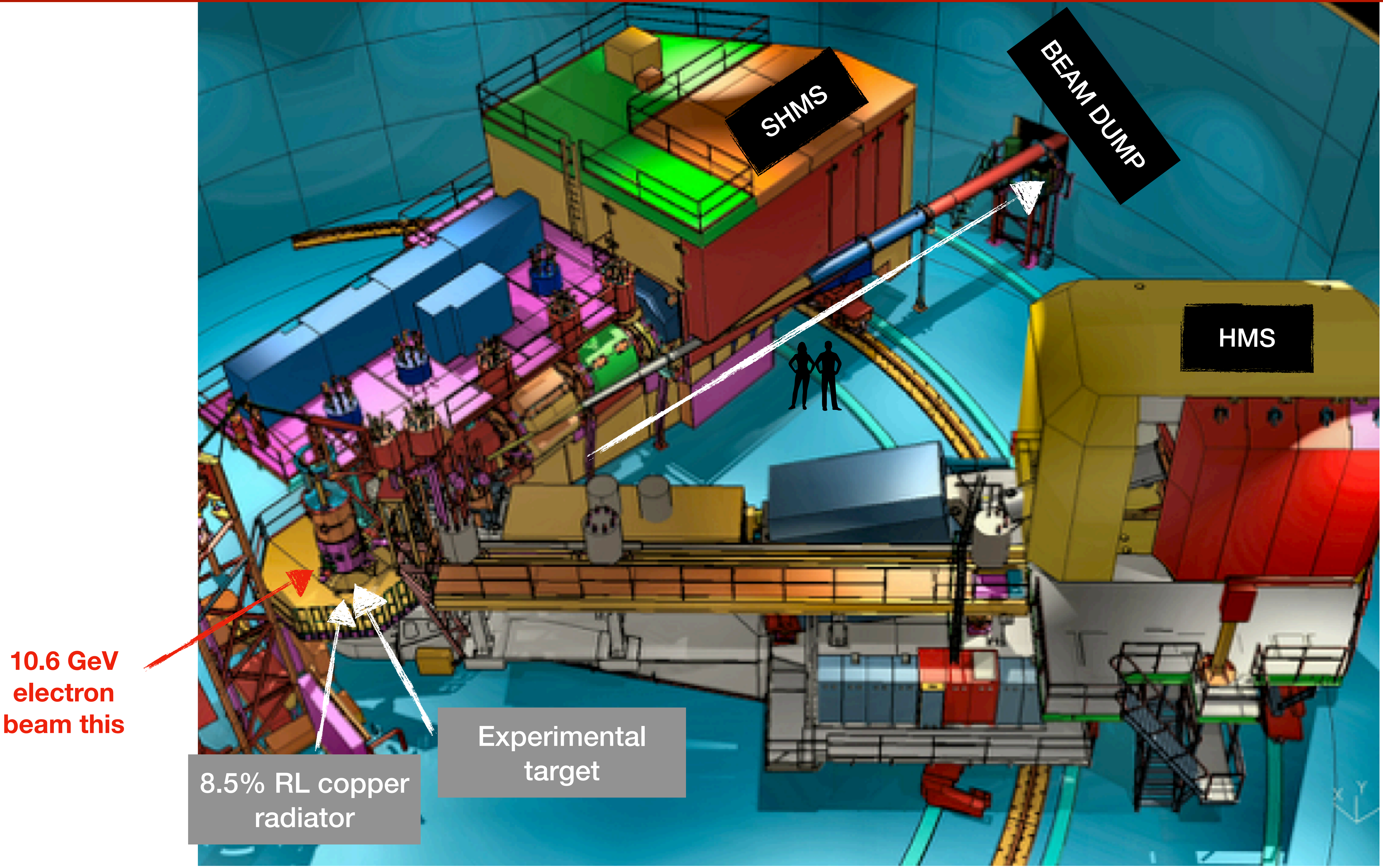


E_{th} = 8.2 GeV

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

- 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%.

Hall C during $J/\psi - 007$ Experiment

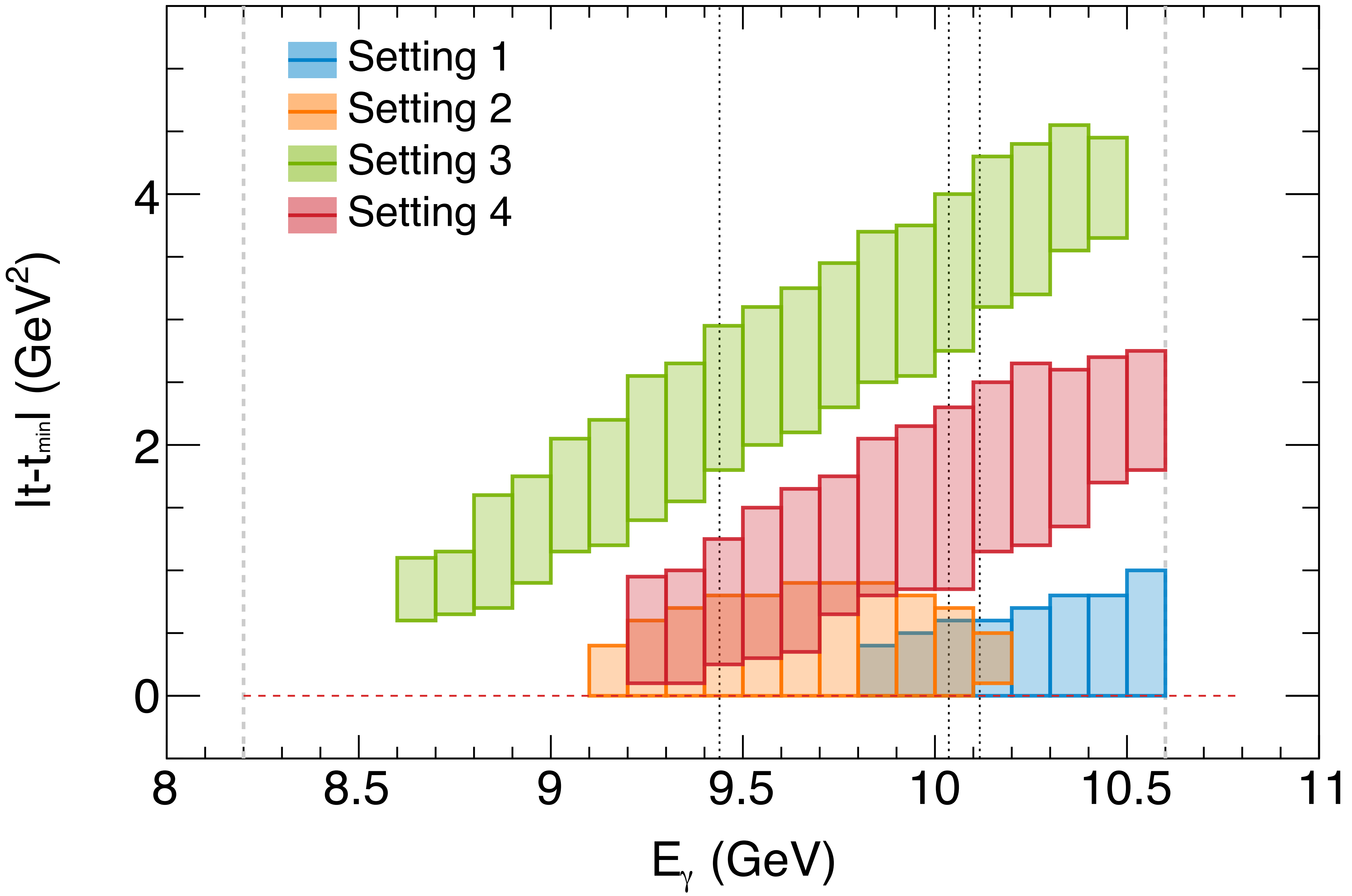


J/ψ-007 Experiment in Hall C at JLab

- 4 kinematic settings to measure both t- and s-channel processes.
- Settings were optimized for enhanced sensitivity at higher t region to the s-channel resonant production measurement.
- SHMS (-) POLARITY and HMS (+) POLARITY

	SHMS P(GeV)	SHMS θ (deg)	HMS P (GeV)	HMS θ (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

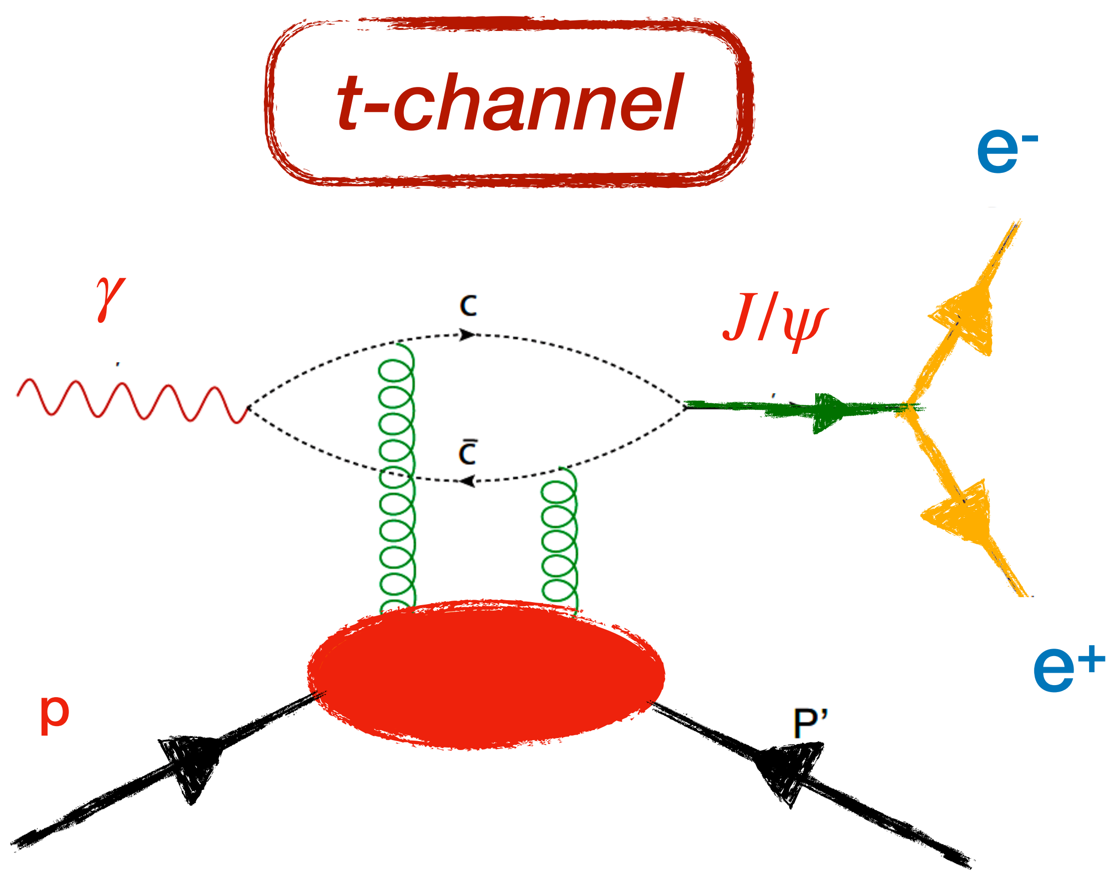
Higher-*t* region where the sensitivity is maximum for the pentaquarks (Hall C, high luminosity!)

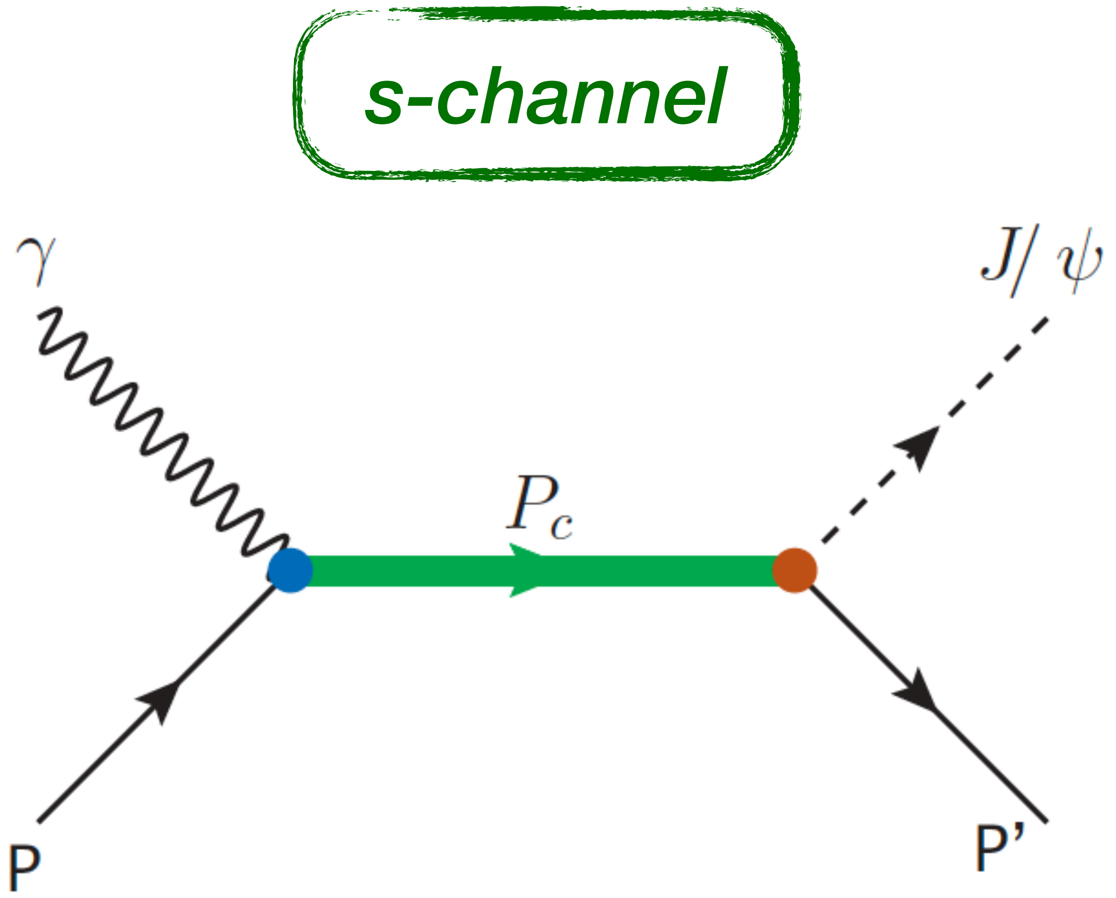


KIN 1 and KIN 2
t-channel cross section measurement

KIN 3 and KIN 4
s-channel cross section measurement

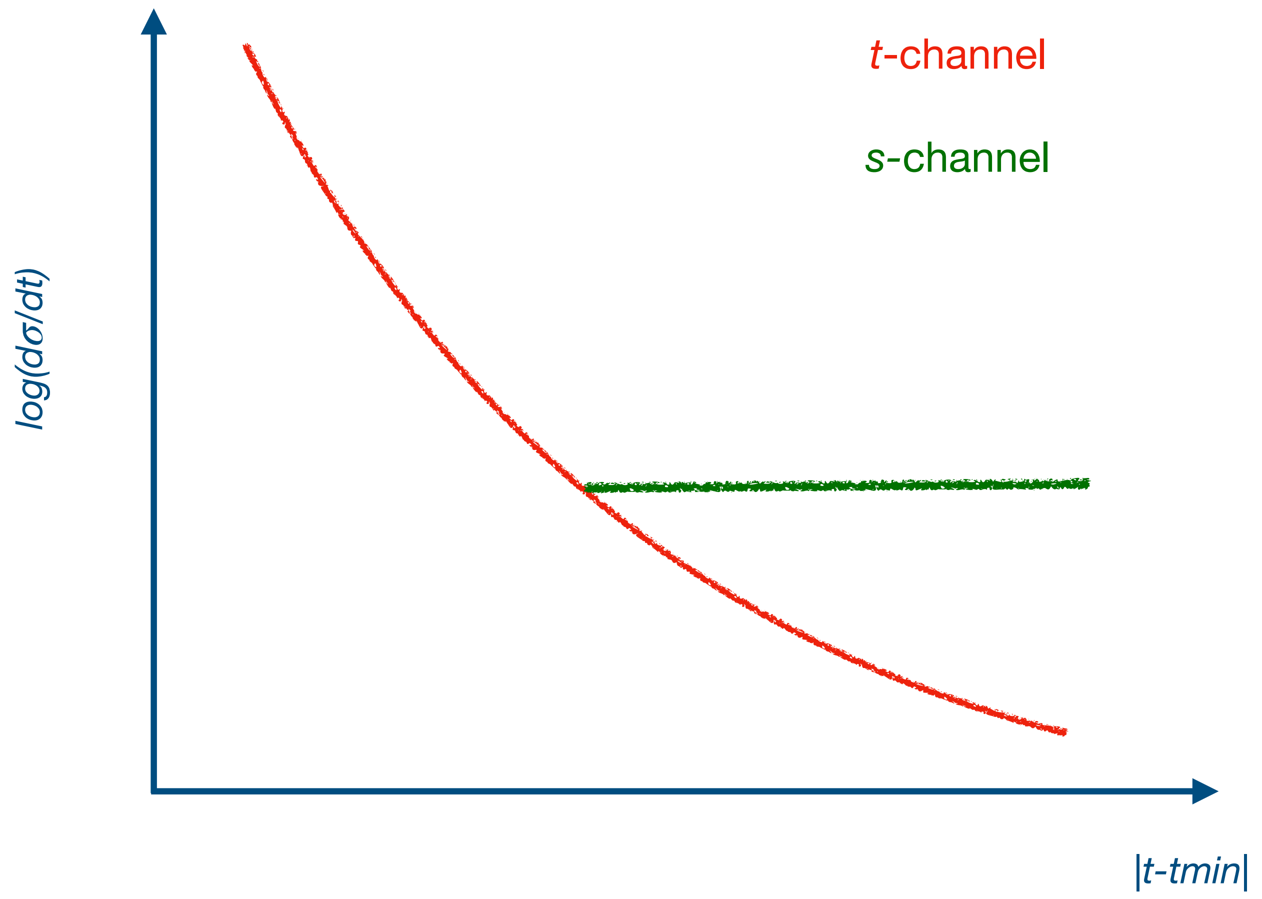
High Luminosity and Enhanced Sensitivity to Resonant process in Hall C





Background t-channel production: forward peaked

Signal s-channel production: decays isotropically



- 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!!!

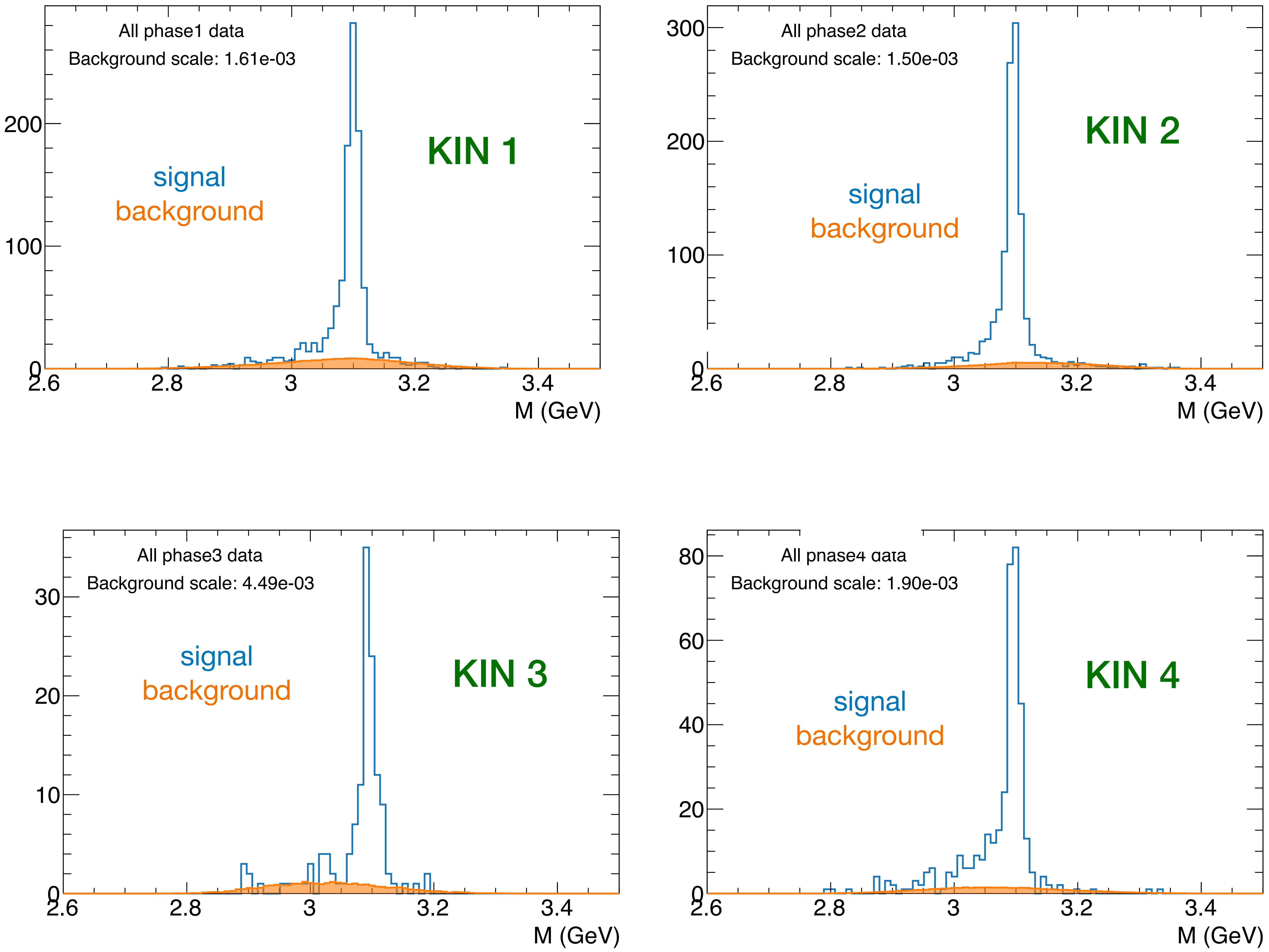
J/ψ Invariant Mass & Background Subtraction

Possible BG considerations:

- $e^-\pi^+$, $\pi^-\pi^+$ and e^-e^+.
- $e^-\pi^+$ is dominant and $\pi^-\pi^+$ or e^-e^+ negligible.
- Measured the background!
  - Potential BG reactions 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:** SHMS Calorimeter
  - **pions:** HMS Calorimeter + HMS Cherenkov



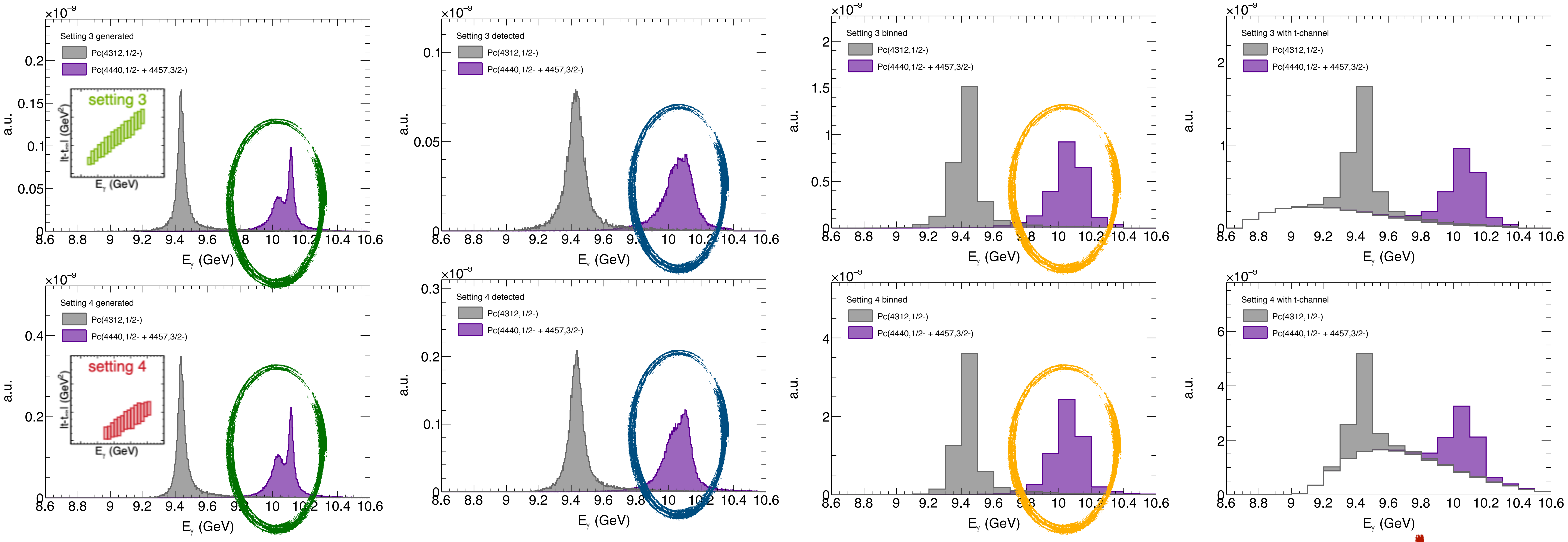
- Fit BG shape to the sidebands of the signal to obtain the BG scale.

Pentaquark Signatures at $J/\psi - 007$

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.

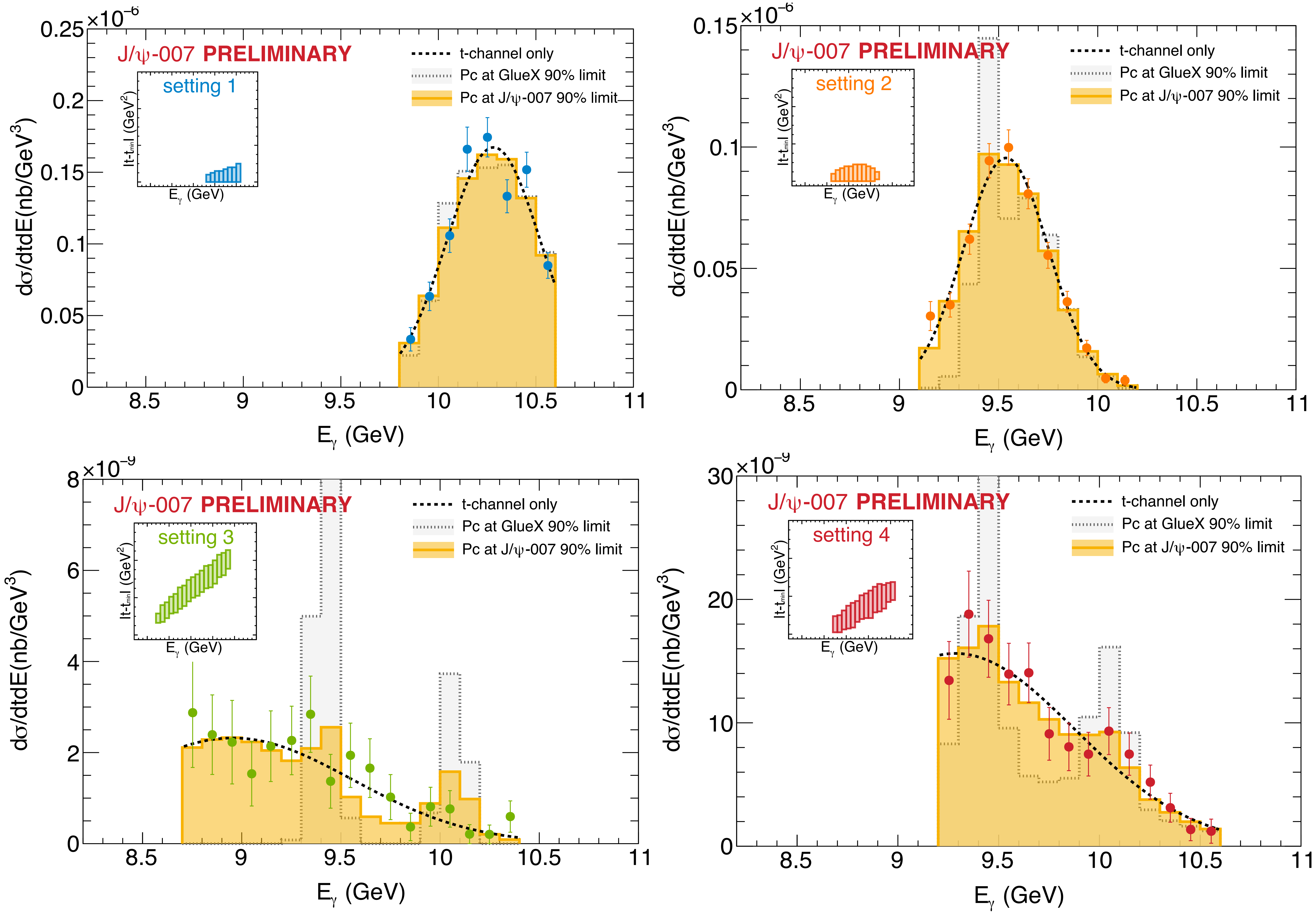
Pentaquark Results from J/ψ-007 Experiment

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)

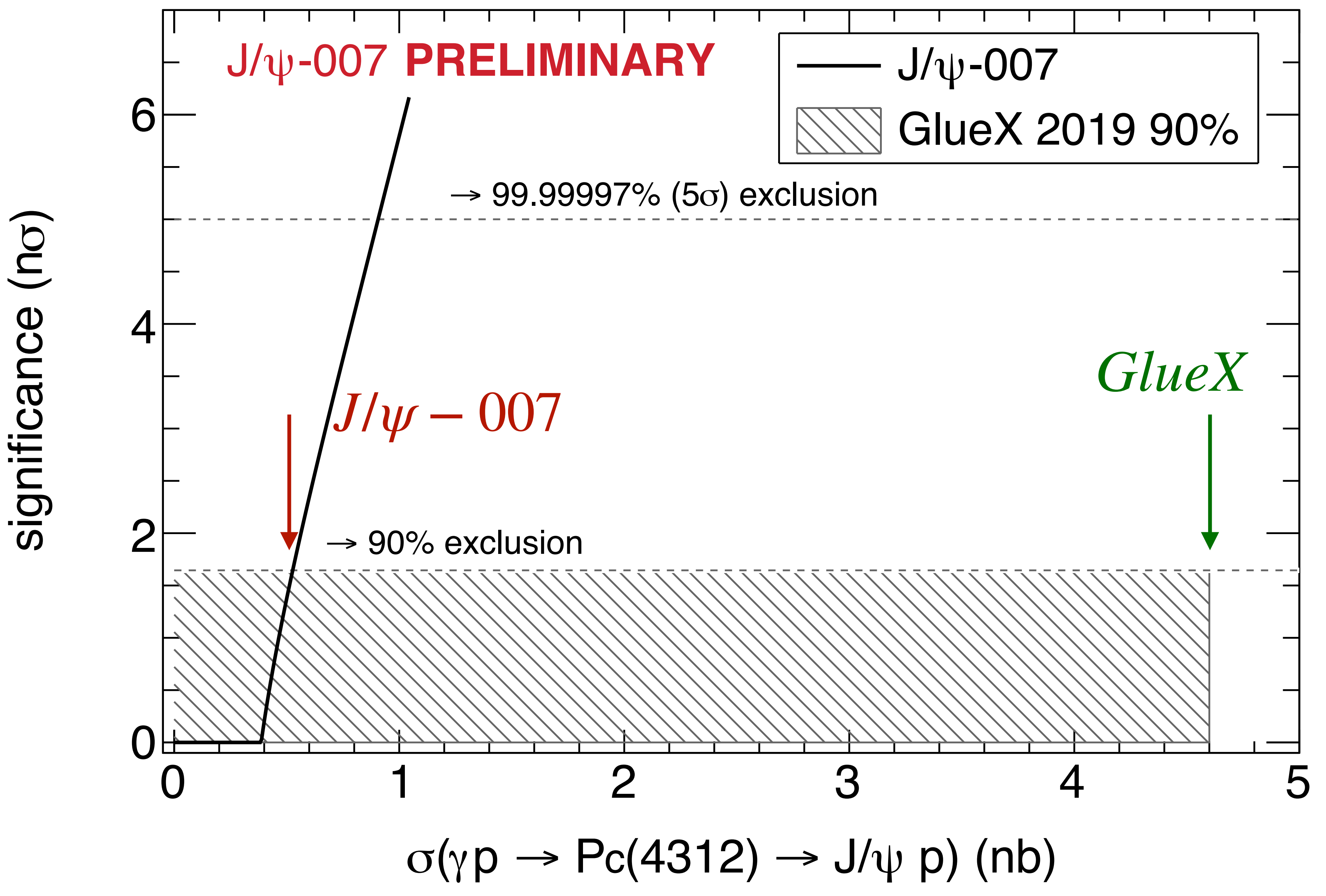
Fit 3: Gaussian shape + "predicted" Pc states at determined $J/\psi - 007$ upper limits at 90% confidence interval.

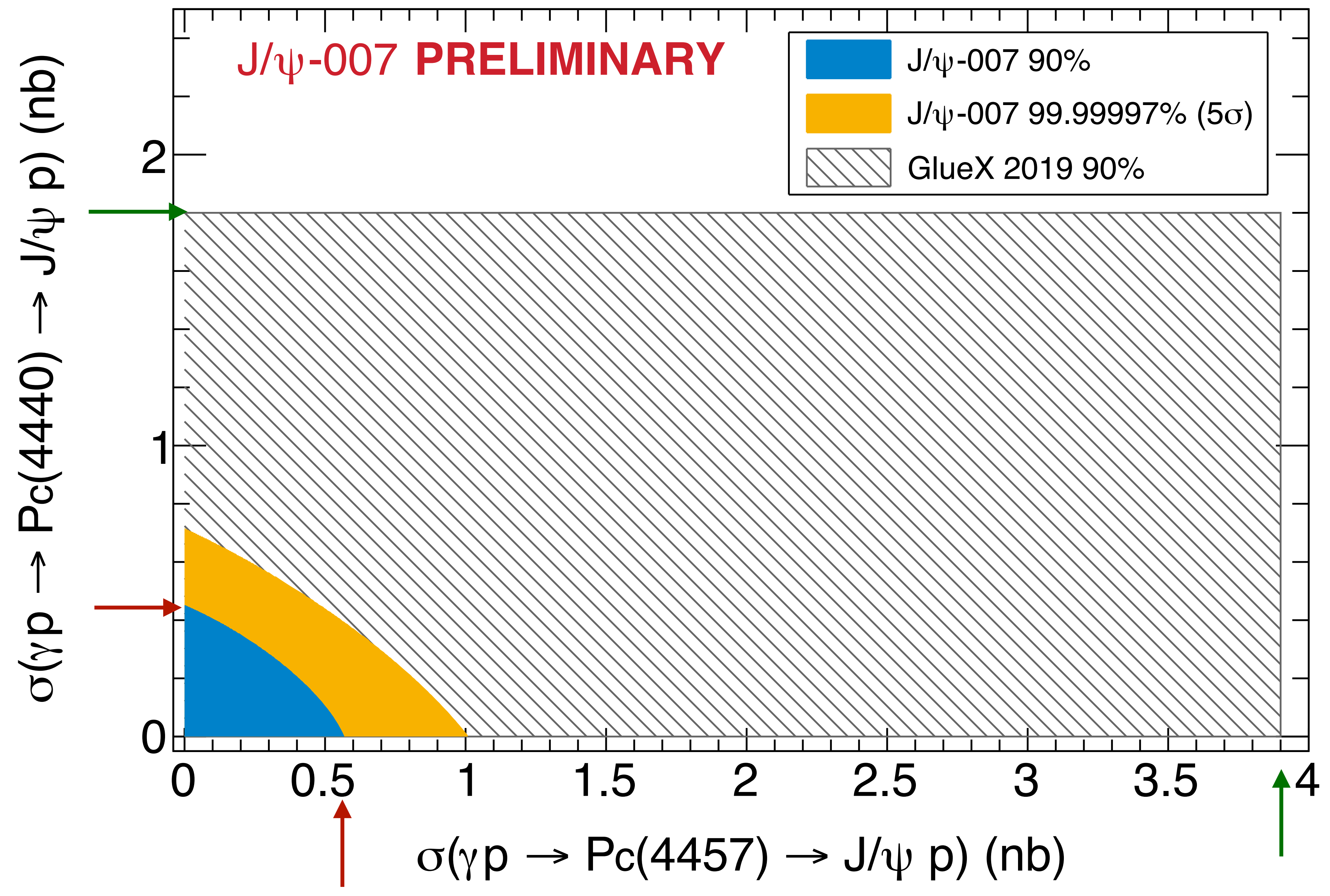


Gaussian curve for t-channel only constrains data very well
Data isn't consistent with the LHCb's pentaquark observation

Pentaquark Results from J/ψ-007 Experiment

- 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.

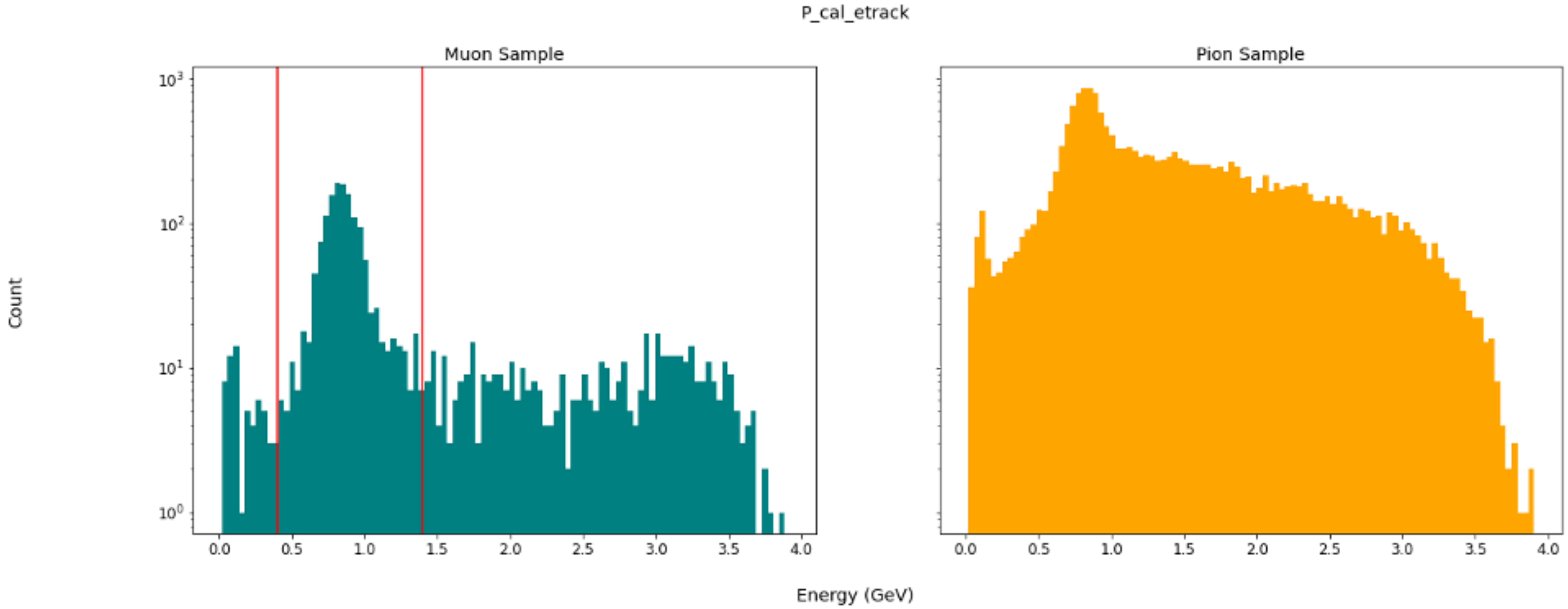




- No evidence for LHCb's pentaquarks!
- Molecular state interpretation: the cross section in photo production not quite settled yet.

Analysis of Muon Channel J/ψ Decay

- Dipion events are the main background
- In setting 1 data, use Cherenkov detector to distinguish $\mu^+\mu^-$ and $\pi^+\pi^-$ events. Then, plot histogram of calorimeter data
- Take cut around MIP peak. In later settings, use MIP peak cut to remove $\pi^+\pi^-$ events from $\mu^+\mu^-$ sample

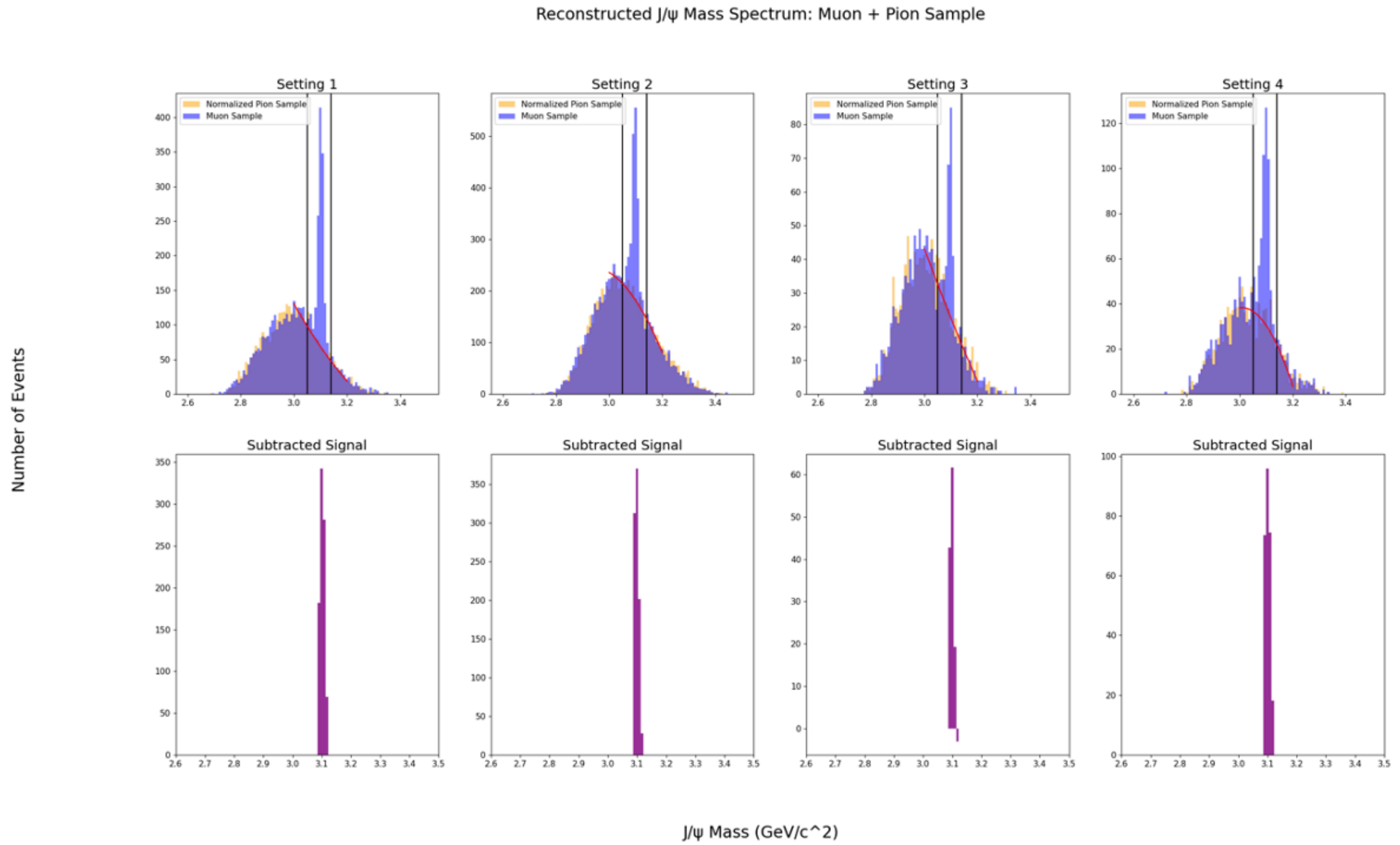


Analysis by Jackson Swartz (U. Of Chicago)

Analysis of Muon Channel J/ψ Decay

BACKGROUND SUBTRACTION

- Calorimeter cuts remove some, but not all π+π- events
- Plot reconstructed J/Ψ invariant mass histograms for muon and pion samples:

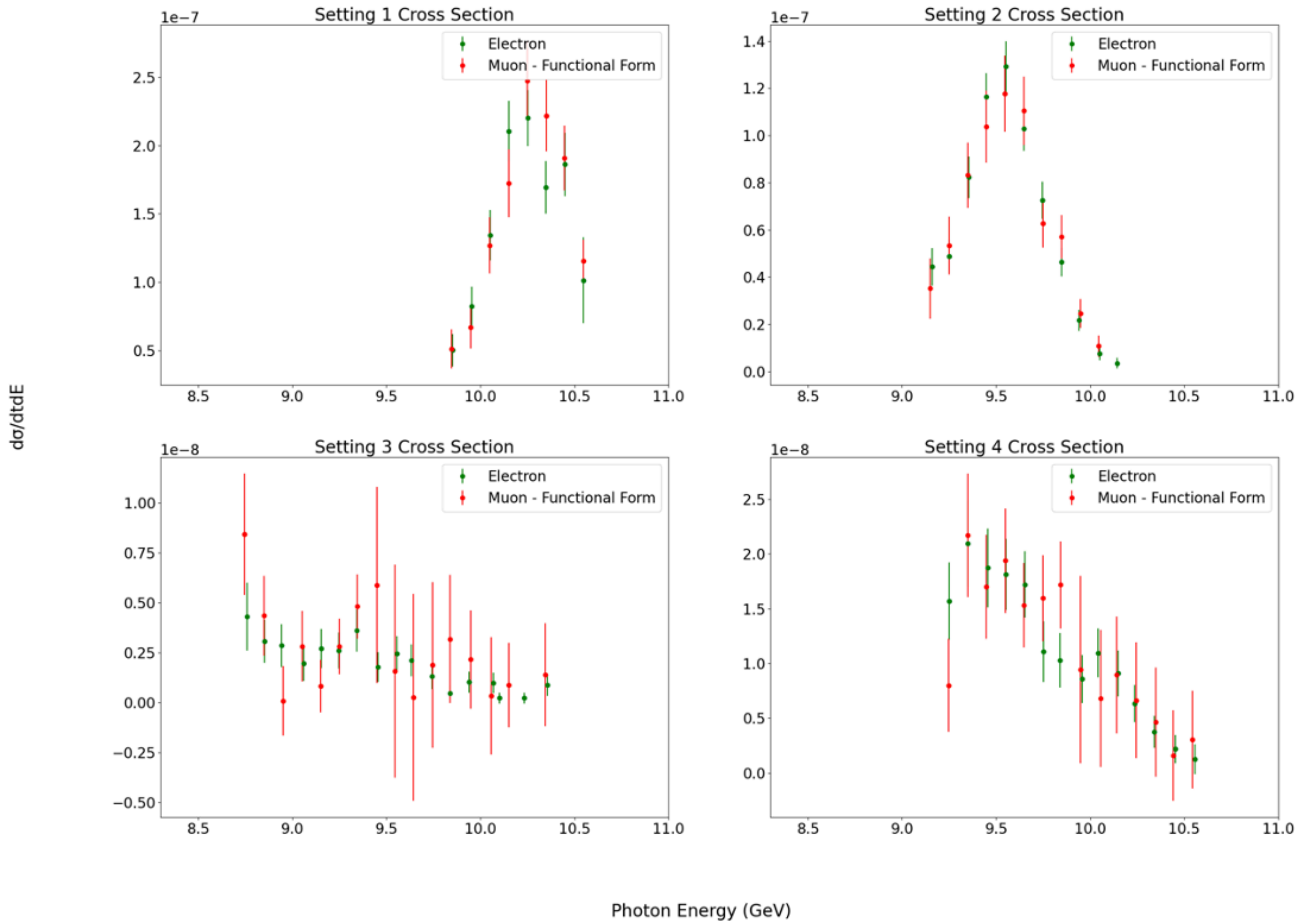


Background subtraction method. Fit pion histogram to muon histogram and subtract out. Finally, take cut around J/Ψ mass peak to obtain the Subtracted Signal.

Analysis and slide by Jackson Swartz (U. Of Chicago)

Analysis of Muon Channel J/ψ Decay

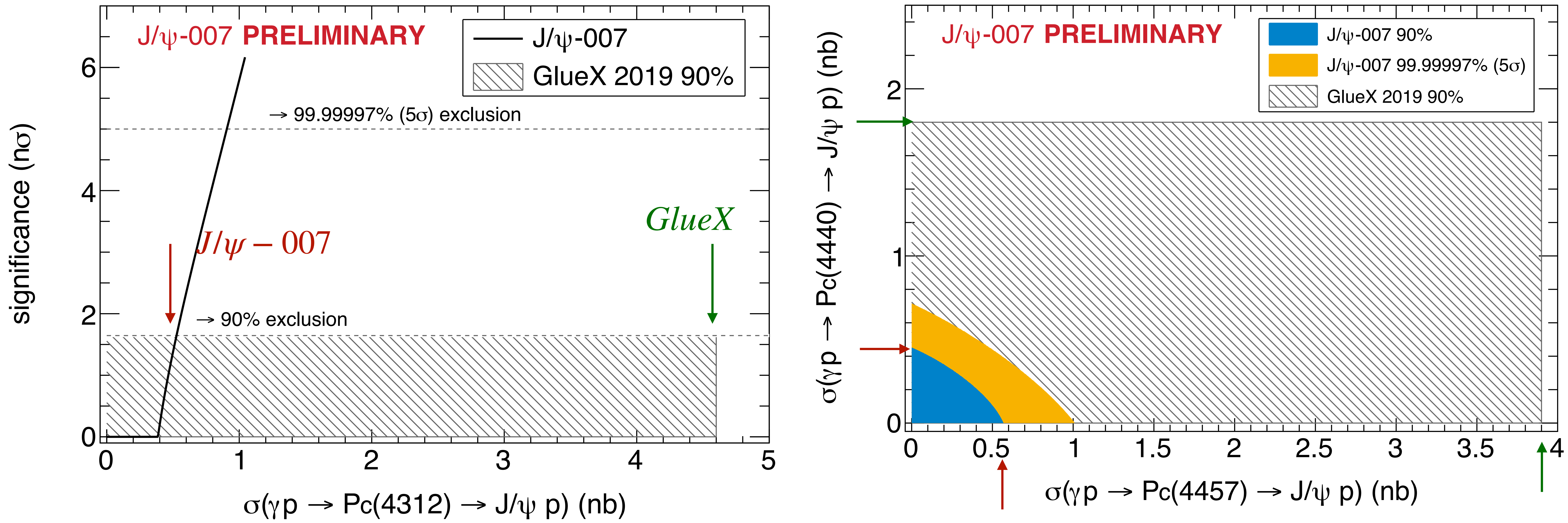
- Differential cross sections obtained from muon and electron analyses agree:



 Analysis and slide by Jackson Swartz (U. Of Chicago)

Summary

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



BACK UP SLIDES

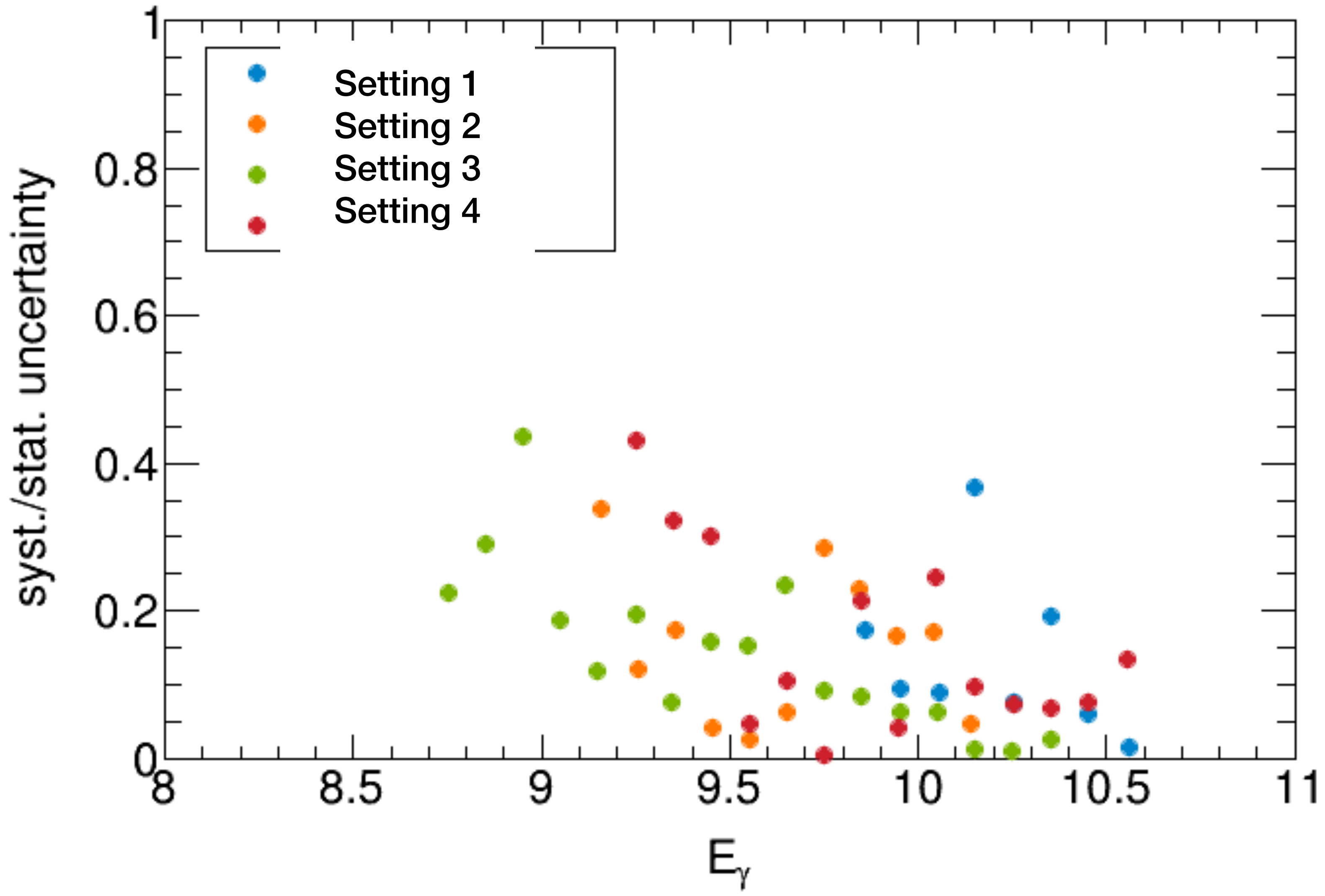
States (P_c)	**mass (MeV)**	**width(MeV)**	**significance** (σ)
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	9σ
$P_c^+(4450)$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	12σ

P_c **States**	**mass (MeV)**	**width(MeV)**	**significance** (σ)
$P_c^+(4312)$	$4311.9 \pm 0.7 \pm^{6.8}_{0.6}$	$9.8 \pm 2.7 \pm^{3.7}_{4.5}$	7.3σ
$P_c^+(4440)$	$4440.3 \pm 1.3 \pm^{4.1}_{4.7}$	$20.6 \pm 4.9 \pm^{8.7}_{10.1}$	5.4σ
$P_c^+(4457)$	$4457.3 \pm 0.6 \pm^{4.1}_{4.7}$	$6.4 \pm 2 \pm^{5.7}_{1.9}$	5.4σ

SCALE AND SYSTEMATIC UNCERTAINTIES

SOURCE	UNCERTAINTY
total charge for normalization	1%
rate dependent efficiency	1%
other efficiency corrections	< 1%
spectrometer acceptance	3%
target wall subtraction	1%
electroproduction subtraction	1%
residual delta- y target dependence correction	1%
radiator thickness - Bremsstrahlung spectrum	1%
TOTAL SCALE UNCERTAINTY	4%

Point to Point Systematic Uncertainty
Mostly from background subtraction, radiative effects in generator and material effects in simulation



DOMINATED BY STATISTICAL UNCERTAINTIES!

inelastic *t*-channel (γp -> $J/\psi p \pi$)

- Threshold at 9 GeV
- Reconstructed photon energy $\underline{E}_{rc}$ is ~1 GeV too low
- **less than 30% of the elastic *t*-channel** background
- Contaminates the **8 GeV $< \underline{E}_{rc} <$ 9.7 GeV** range for a photon end-point energy of 10.7
  - **not an issue for the P_c(4450) ($\underline{E}_{rc} >$ 9.7GeV)!**

Photon Energy Reconstruction

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

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