This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

FROM PENTAQUARKS TO THE GLUONIC STRUCTURE OF THE PROTON

Argonne NATIONAL LABORATORY 75 1946–2021

UPDATE FROM THE HALL C J/Ψ-007 EXPERIMENT

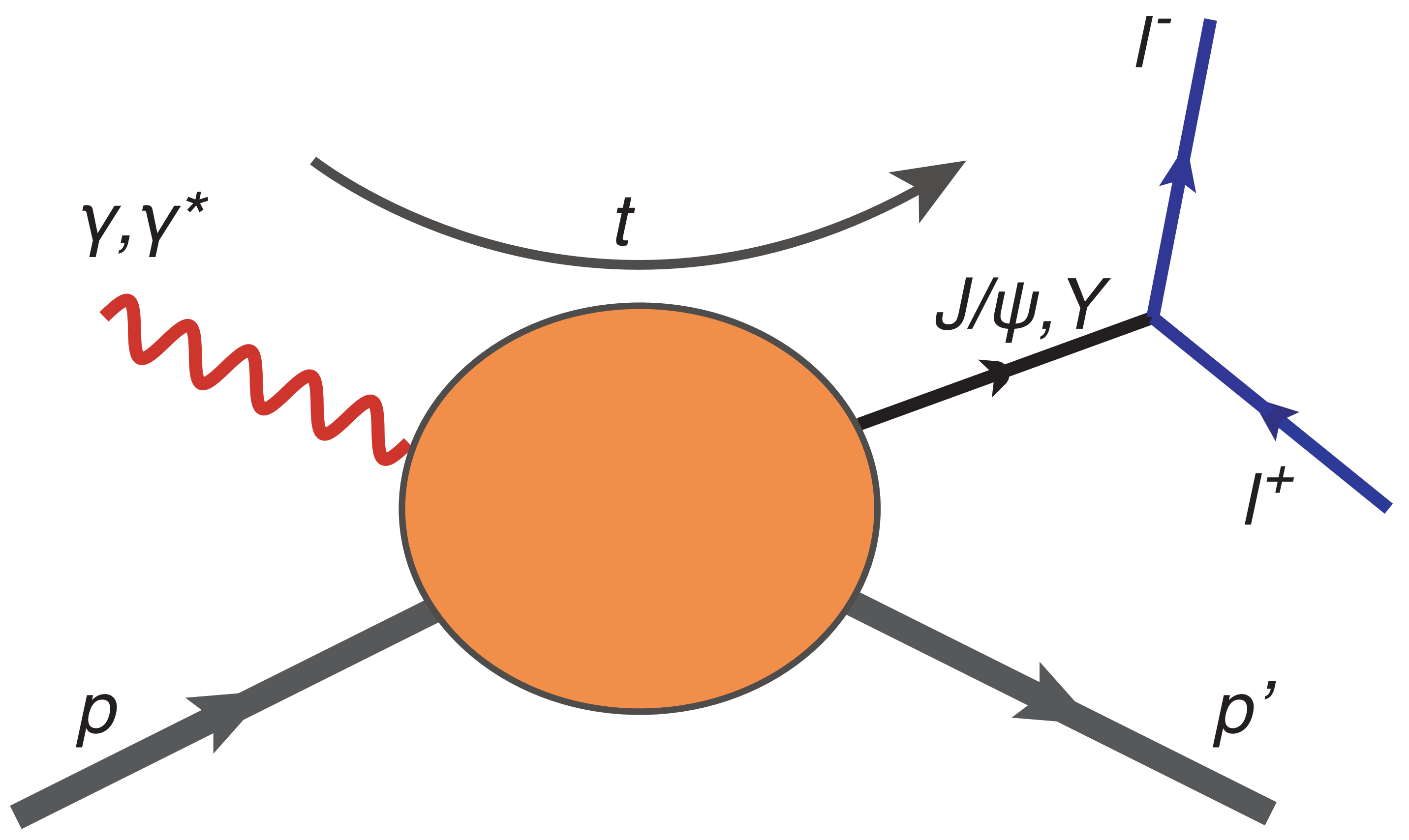
007$^{J/\Psi}$

SYLVESTER JOOSTEN
sjoosten@anl.gov
On behalf of the J/ψ-007 experiment

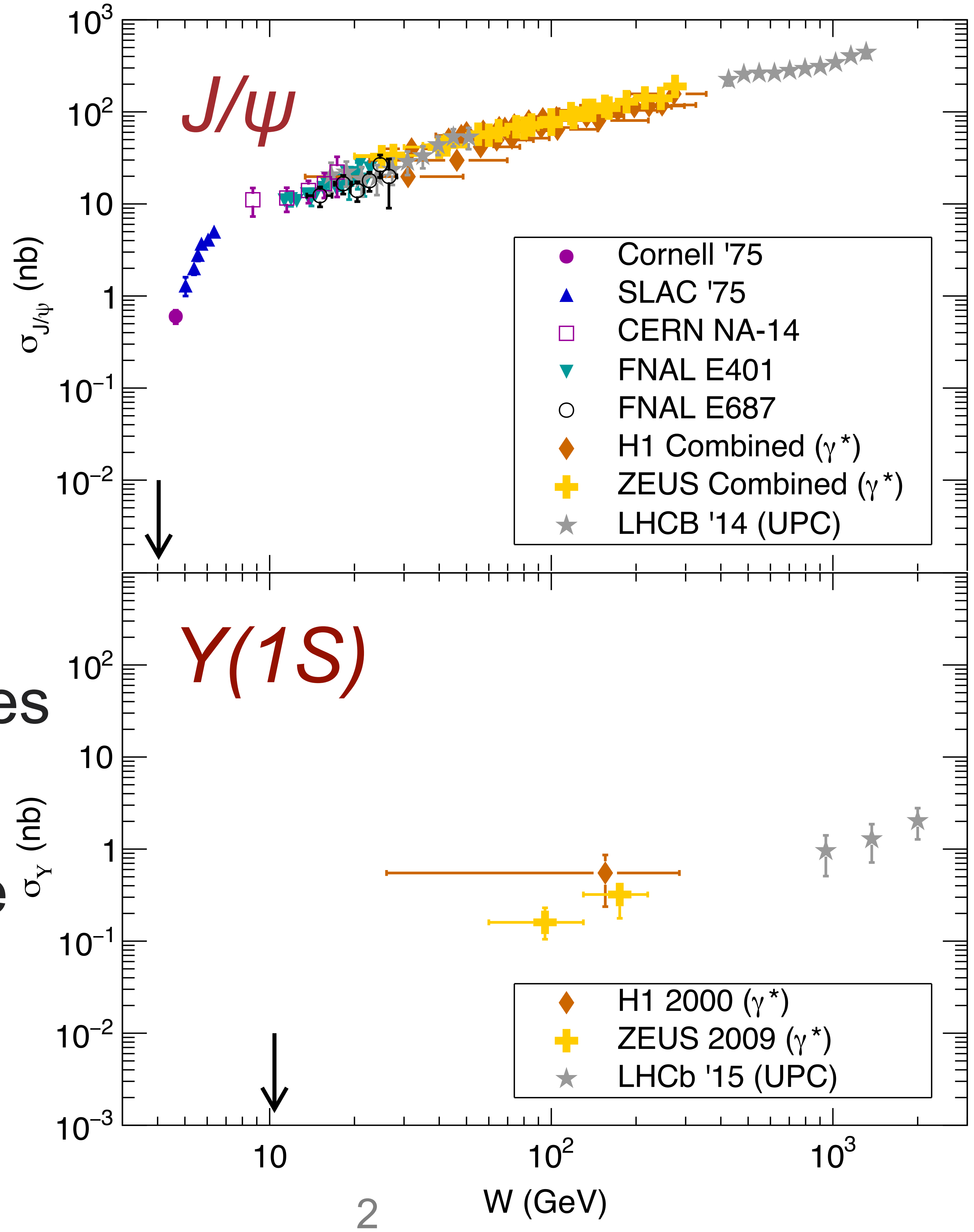
February 17, 2022
Hall C Collaboration Meeting

QUARKONIUM PRODUCTION NEAR THRESHOLD

Probing the energy distribution of gluonic fields inside the proton and nuclei



- *J/ψ* well constrained for high energies
- *Υ(1S)*: not much available
- No electro-production data available
- **Almost no data near threshold before the 12 GeV era of JLab**



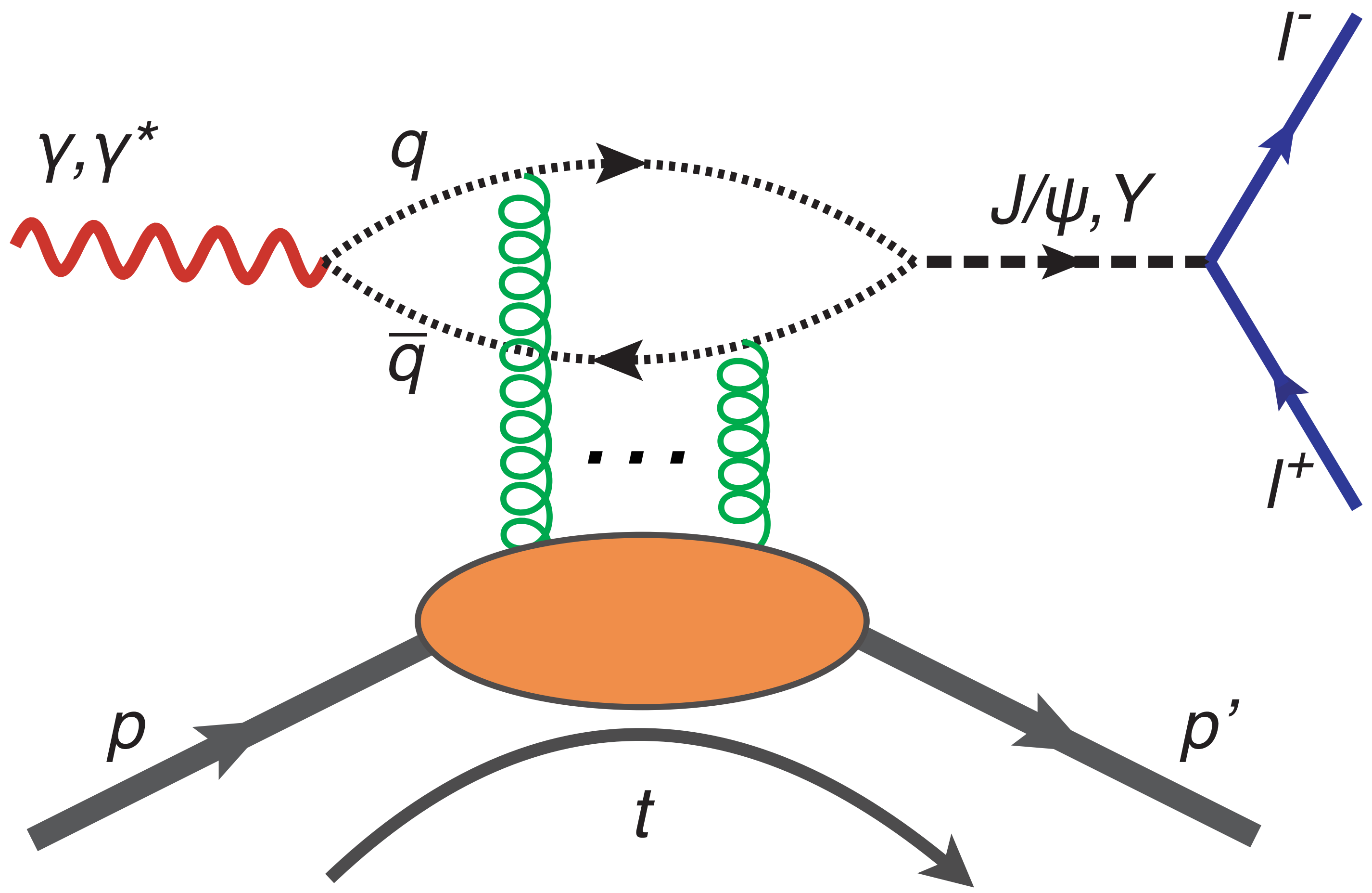
Near-threshold electro- and photoproduction of quarkonium

- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force,** possible quarkonium-nucleon/nucleus bound states
- Do quarkonia enable **pentaquarks** to exist?
- **Mechanism** for quarkonium production itself

J/ψ at JLab
Υ(1s) at EIC

QUARKONIUM PHOTO-PRODUCTION

The kinematics

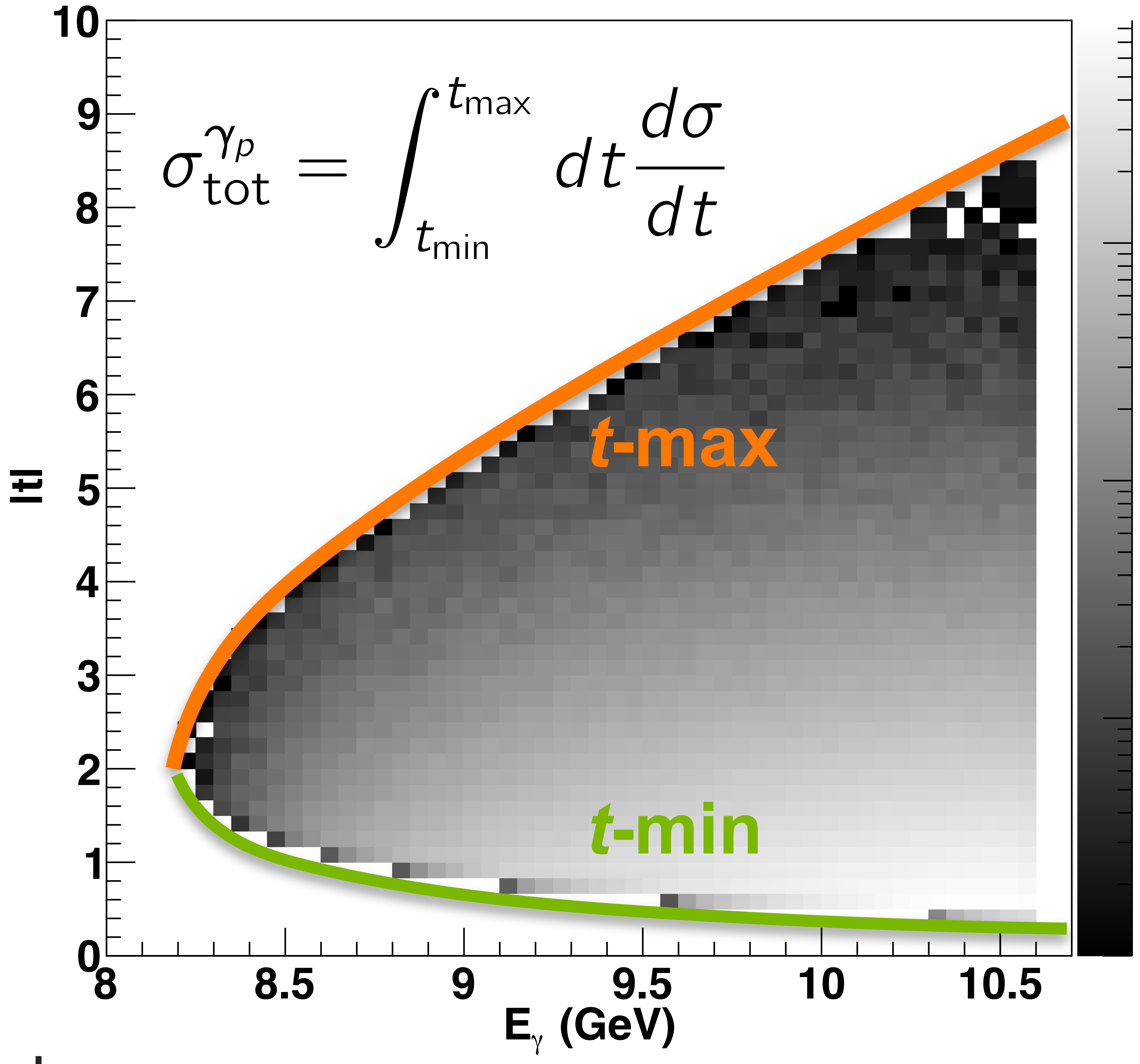


J/ψ threshold:

$W \approx 4.04\text{GeV}$

$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

$t \approx -1.5\text{GeV}^2$

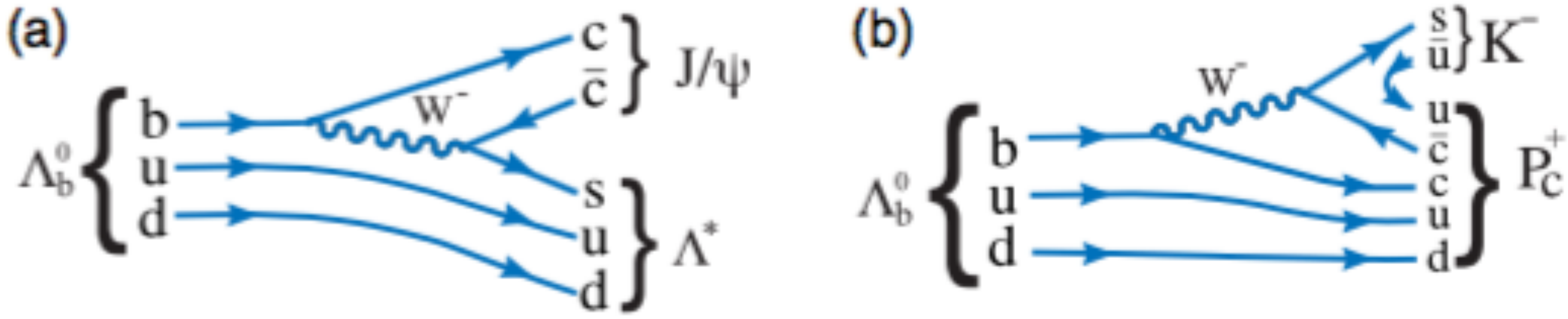


- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\min}$
  - Backward (with proton): $t = t_{\max}$
- Forward direction preferred: t-dependence ~exponential

DISCOVERY OF THE LHCB CHARMED PENTAQUARK

$$\Lambda_b \to \Lambda^* J/\Psi \to (K^- p) J/\Psi$$

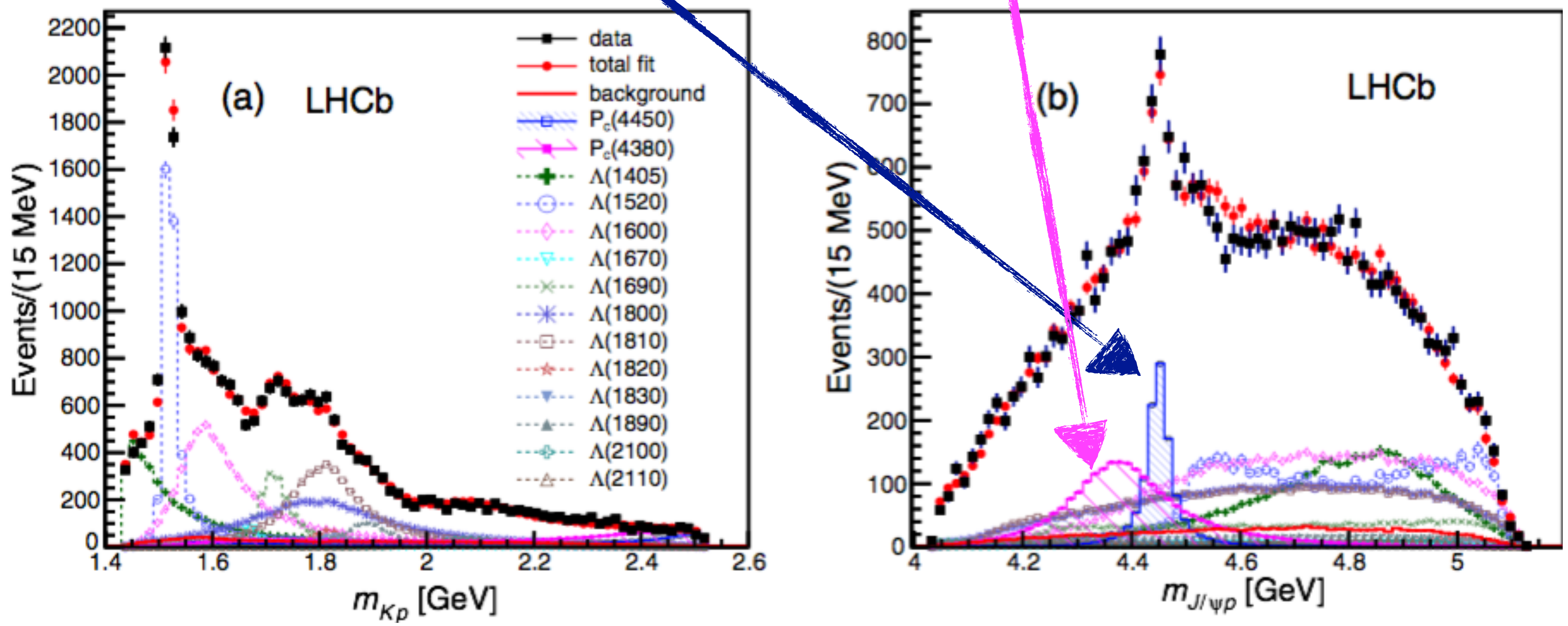
$$\Lambda_b \to K^- P_c \to K^- (p J/\Psi)$$



narrow: P_c(4450) (12 σ)

wide: P_c(4390) (9σ)

- LHCb collaboration findings: **two P_c states needed**:
- Spin/parity not fully constrained:
  - 5/2+ and 3/2- (most likely)
  - 5/2- and 3/2+
  - 3/2- and 5/2+

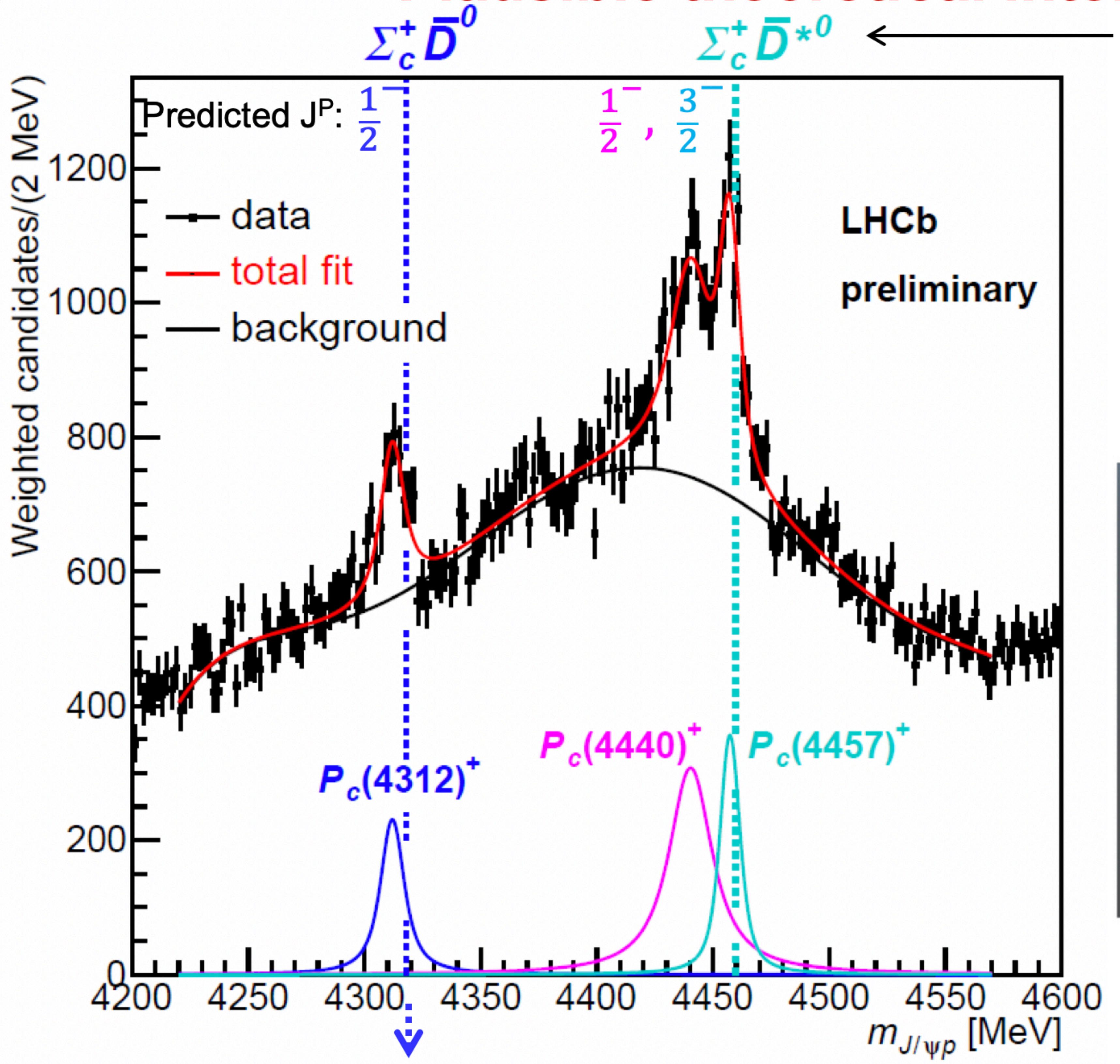


The plot thickens…

NEW LHC-B RESULTS WITH 10X STATISTICS

Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019 14

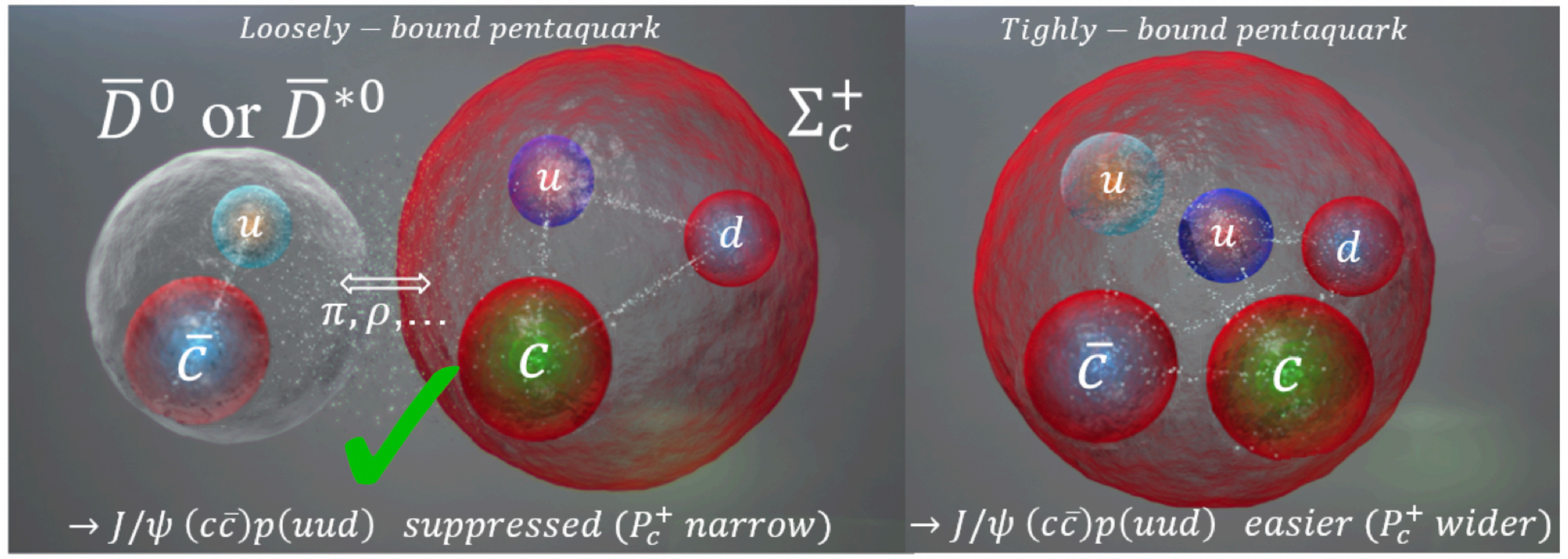
Plausible theoretical interpretation



The **only** thresholds below which molecular bound states are expected in this mass range

LHCb-PAPER-2019-014
in preparation

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!



Existence of $\Sigma_c^+\bar{D}^0$ molecule would imply importance of ρ-exchange

However, we need to measure J^{P}s to confirm molecular hypothesis, find isospin partners, …

Can diquark substructure separated by a potential barrier [Maiani, Polosa, Riquer, PL,B778, 247 (2018)] produce width suppression?
Are masses near thresholds just by coincidence?
This hypothesis is not ruled out

$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is (see backup slides).

X-H Lui *et al.*, PLB 757, 231 (2016) and references therein
Q. Wang *et al.*, PRD 92-3 034022-7 (2015) and references therein

IS THIS A REAL EXOTIC BARYON?

We can confirm this at JLab!

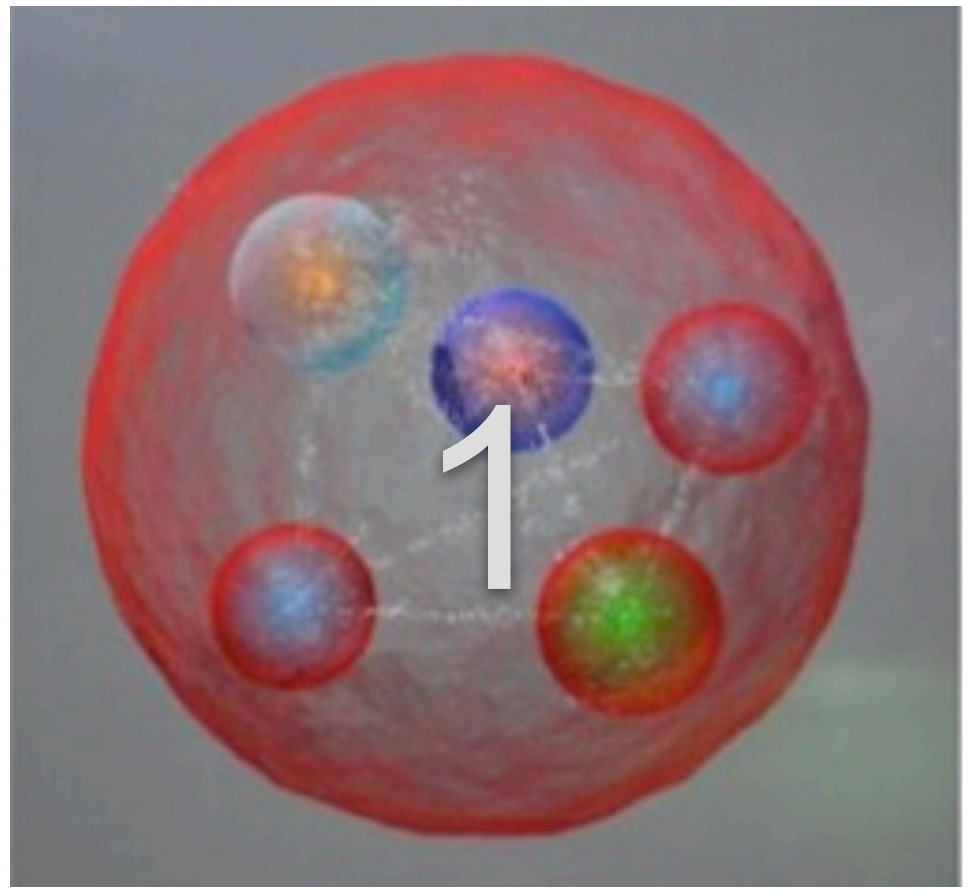
- LHCb definitely saw something, but was it a pentaquark?

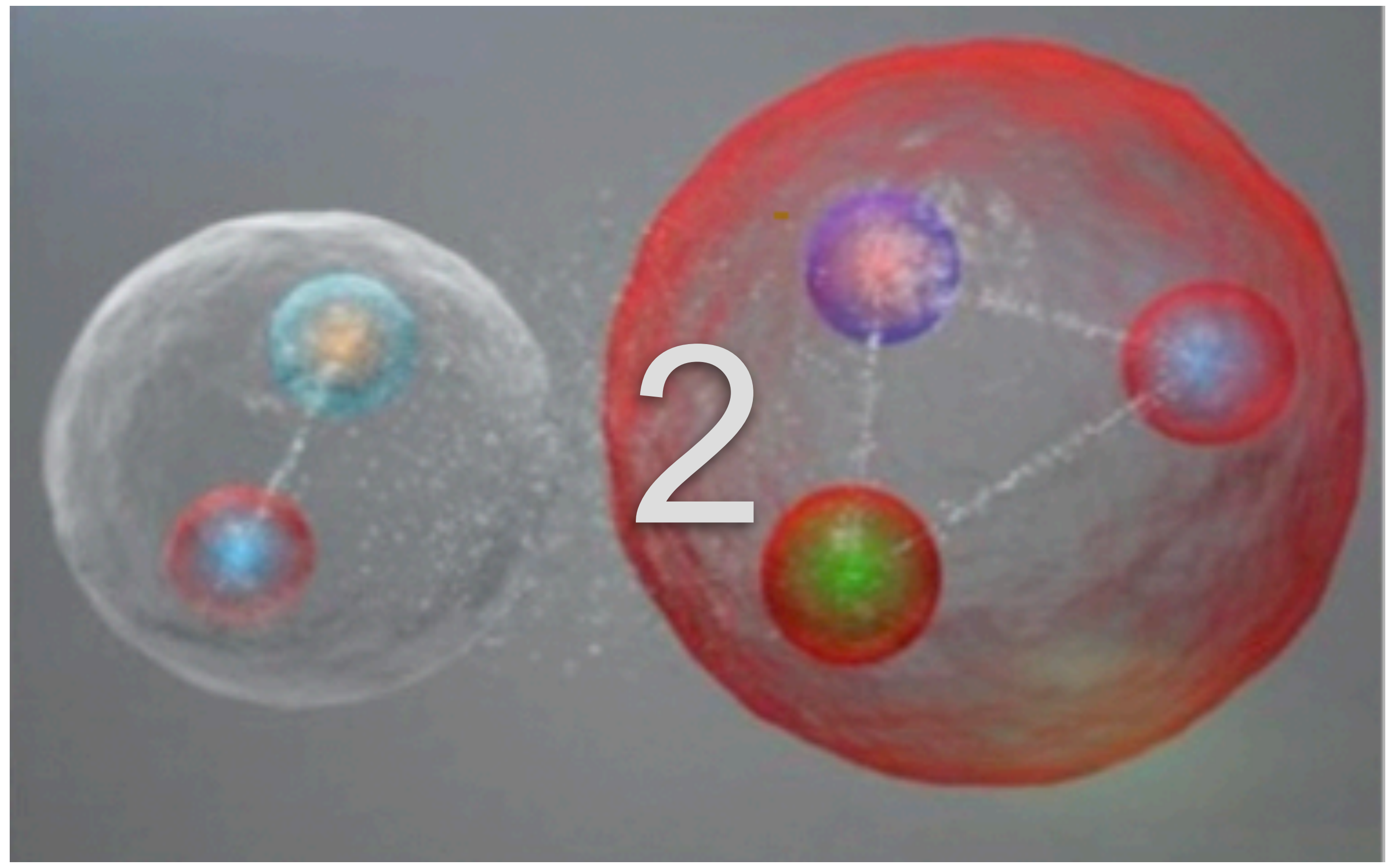
1. **"True" pentaquark state:** tightly bound 5-quark state
2. **"Molecular"** meson-baryon bound state
3. **Kinematic enhancement** through anomalous triangle singularity (ATS)

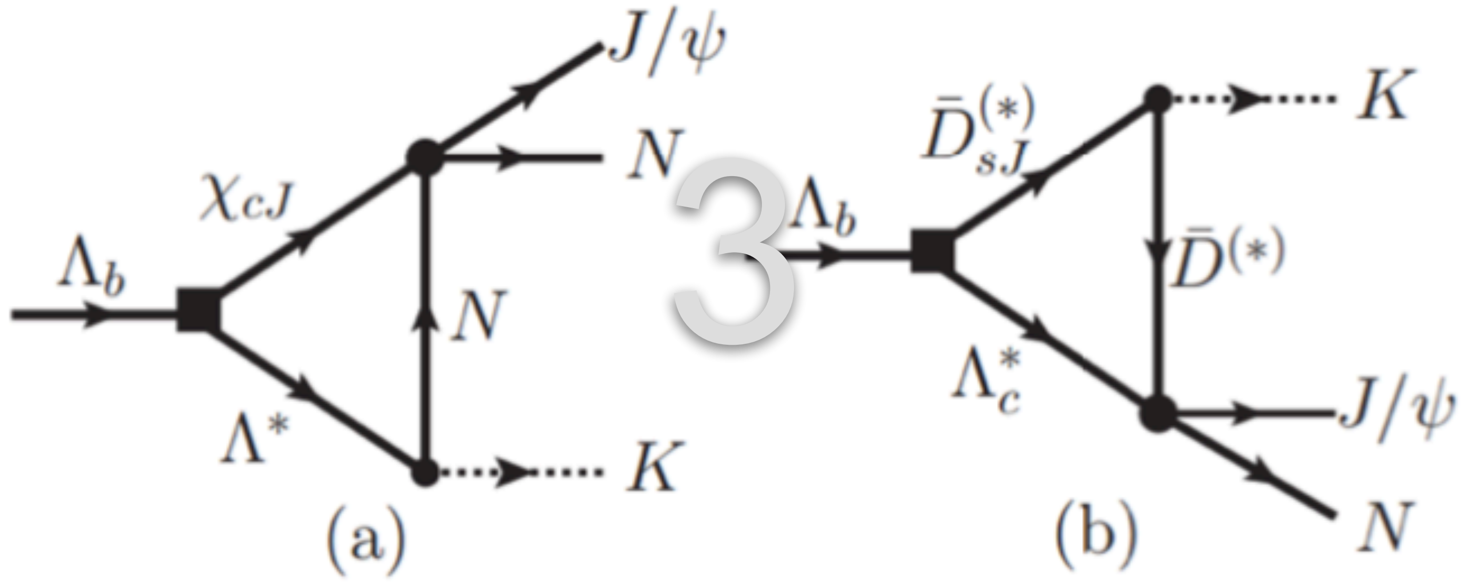
- Photoproduction ideal channel to distinguish:

1. **"True" pentaquark:** strong s-channel resonance
2. **"Molecular"**: small s-channel resonance (less overlap with γp and J/ψp states)
3. **ATS** not a factor in photoproduction

Jefferson Lab the perfect place to search for P_c in photoproduction



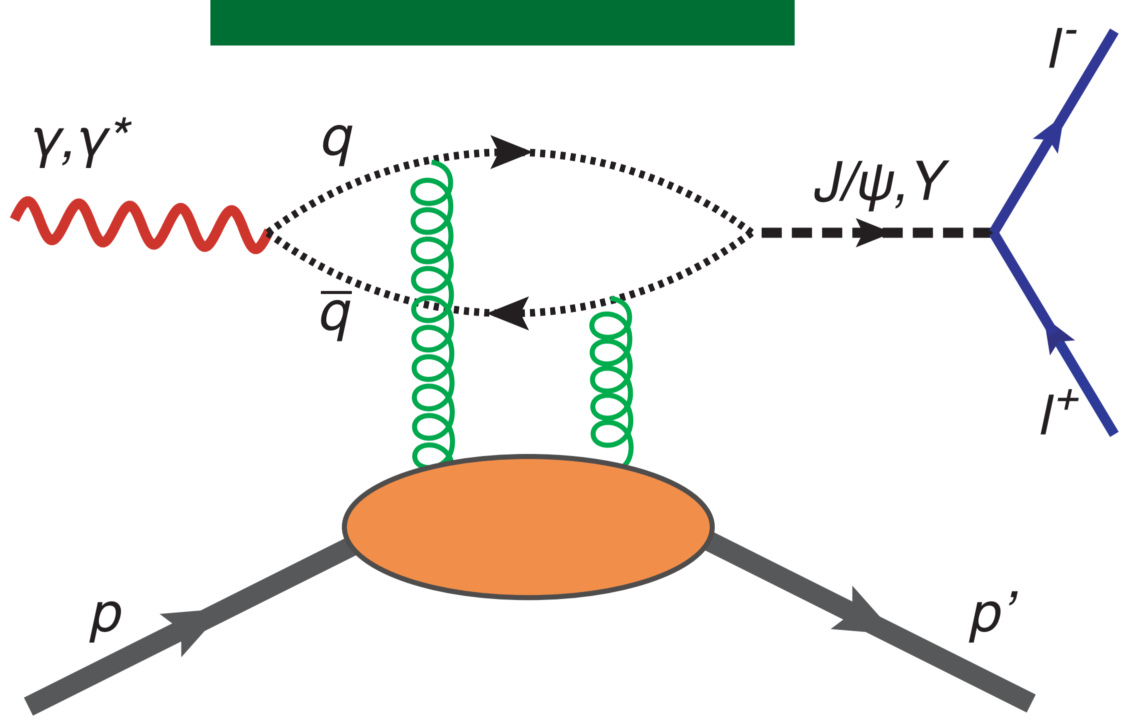




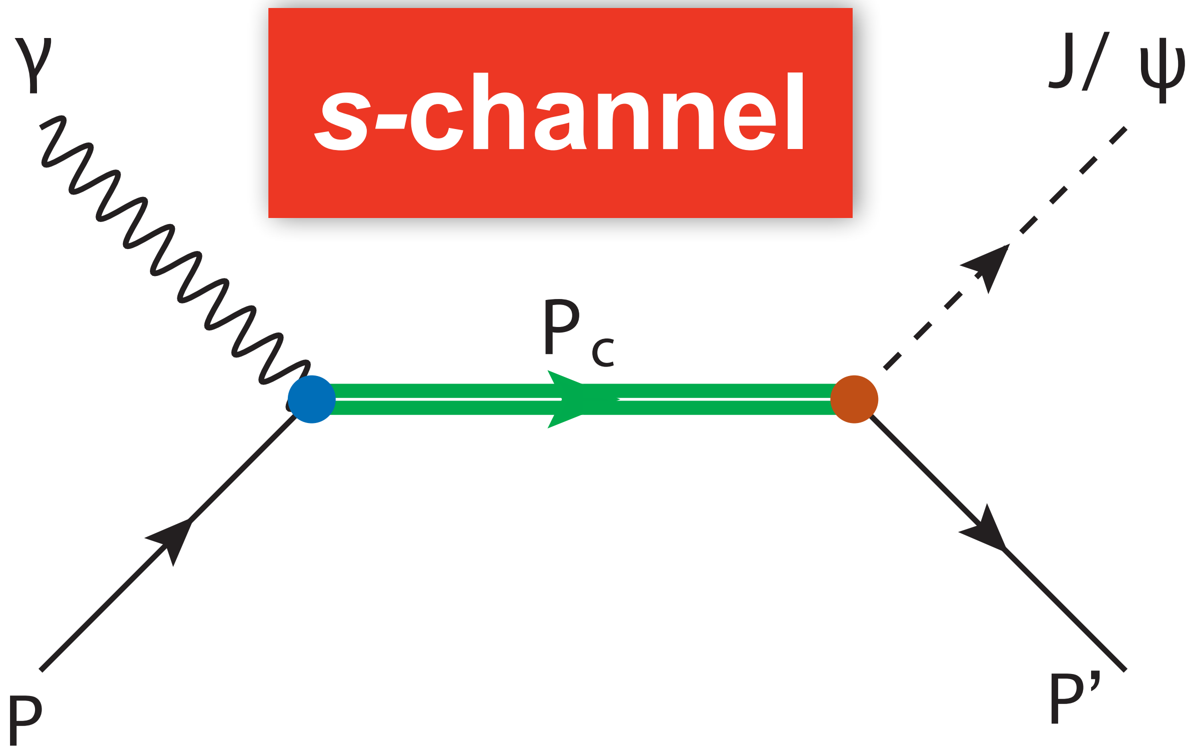
MAXIMIZING THE SENSITIVITY

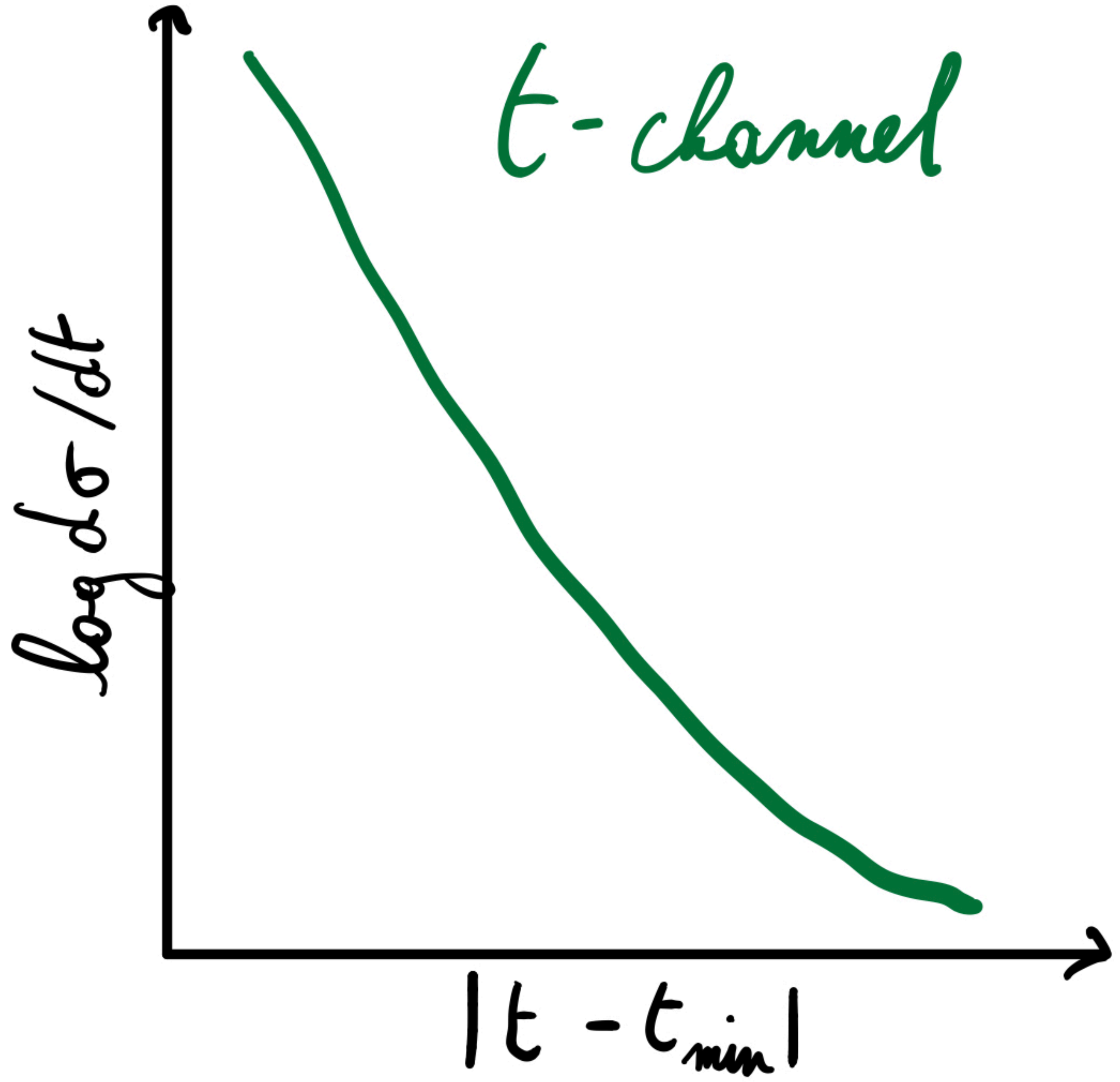
Maximum sensitivity for s-channel resonance at high *t*

t-channel

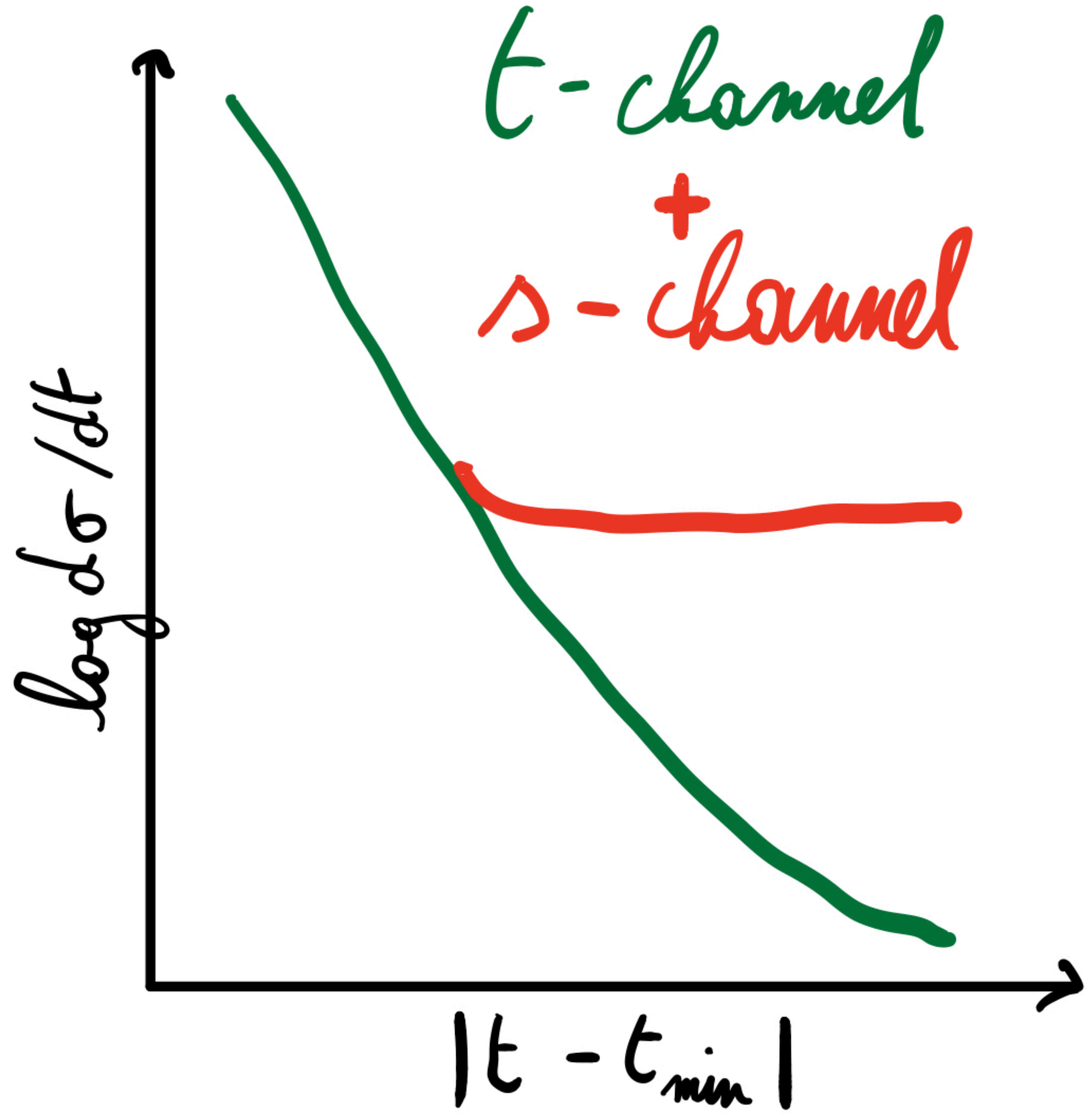


s-channel





t-channel production mostly forward (exponential-like *t*-dependence)



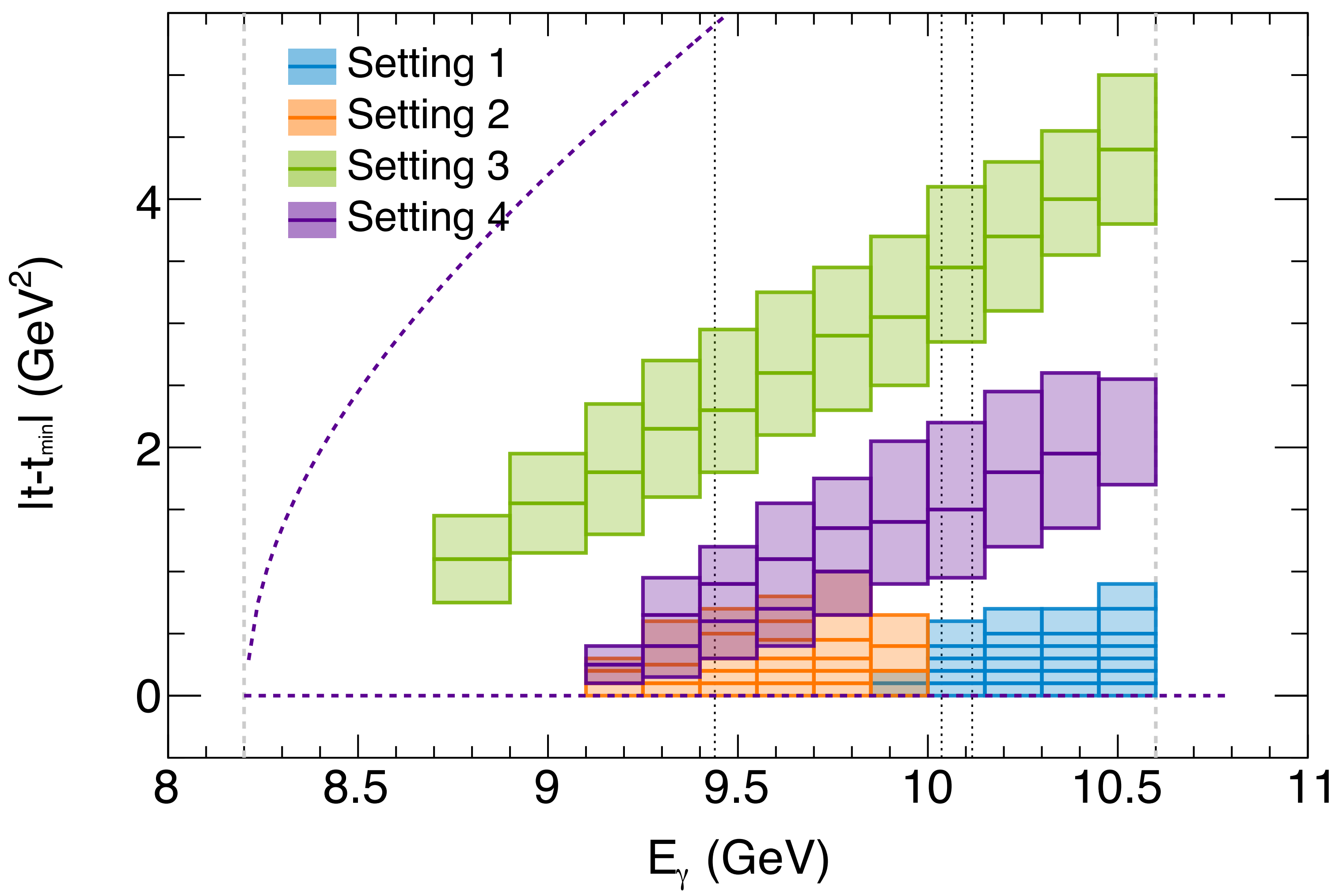
s-channel production more isotropic (flatter *t*-dependence)

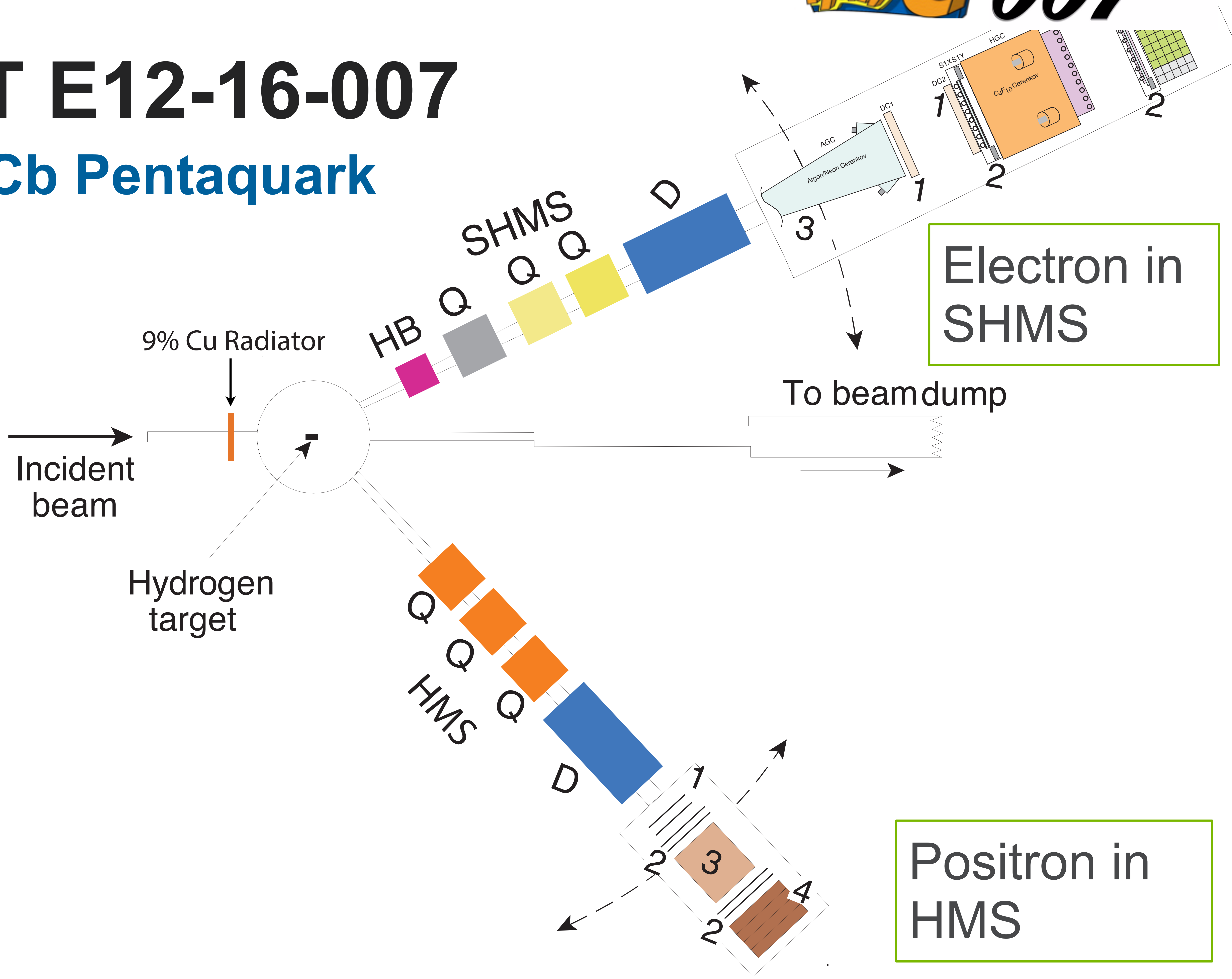
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained



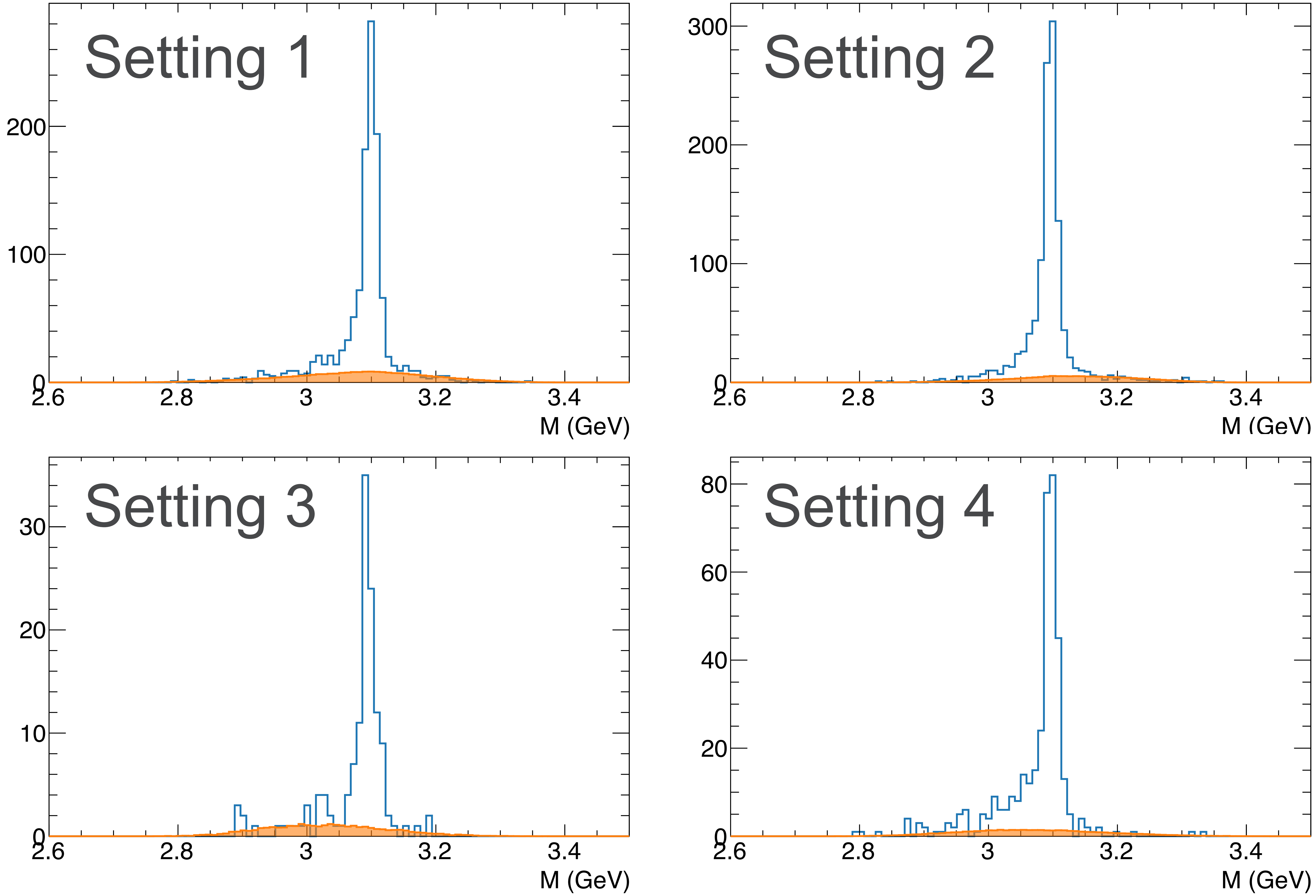


Electron in SHMS

Positron in HMS

CLEAR J/Ψ SIGNAL WITH MINIMAL BACKGROUND

settings	HMS	SHMS	target	charge [C]	goal
setting 1	19.1^o at +4.95GeV	17.0^o at -4.835GeV	LH2 with radiator	5.2	low-t and high energy
			dummy with radiator	0.6	target wall
			LH2, no radiator	0.1	electroproduction
setting 2	19.9^o at +4.6GeV	20.1^o at -4.3GeV	LH2 with radiator	8.2	low-t and low energy
			dummy with radiator	0.3	target wall
setting 3	16.4^o at +4.08GeV	30.0^o at -3.5GeV	LH2 with radiator	13.8	high-t
setting 4	16.5^o at +4.4GeV	24.5^o at -4.4GeV	LH2 with radiator	6.9	medium-t
			dummy with radiator	0.2	target wall

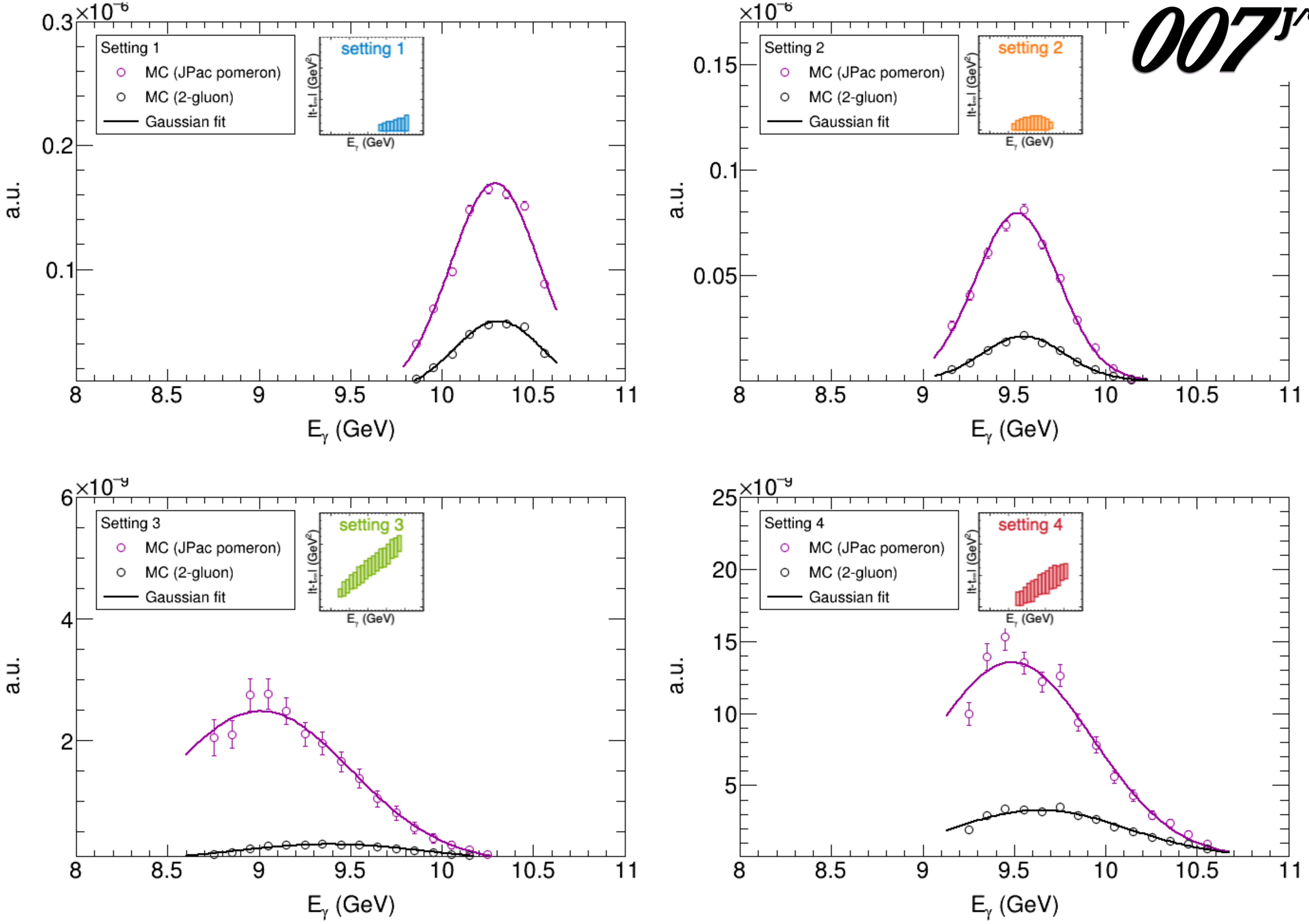


WHAT DOES A PURE T-CHANNEL BACKGROUND LOOK LIKE?

Need model-independent fit shape to fit the t-channel background **inside the spectrometer acceptance**

A **gaussian shape**, mostly driven by the spectrometer acceptance, does a good job describing both (very different!) Monte-Carlo models

For now used as independent shapes between the settings, could in principle gain even more sensitivity by leveraging the 2D t-profiles of the cross section



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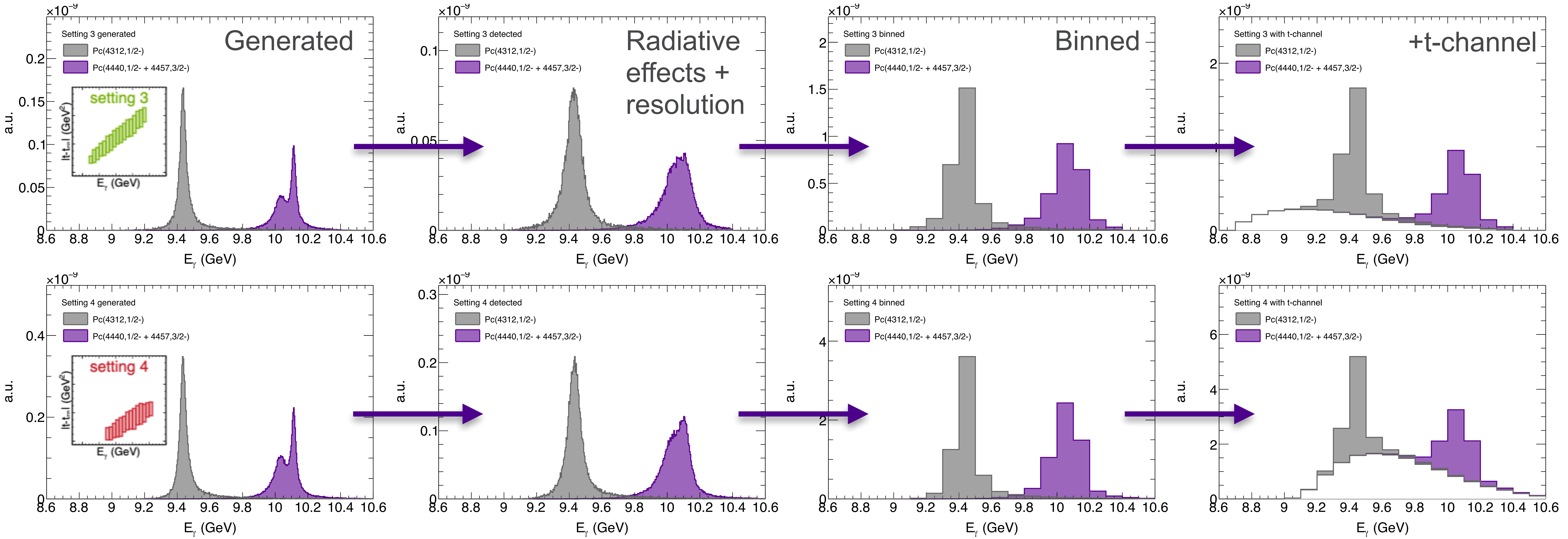
PENTAQUARK MODEL

Need to know pentaquark signatures in our experimental sample

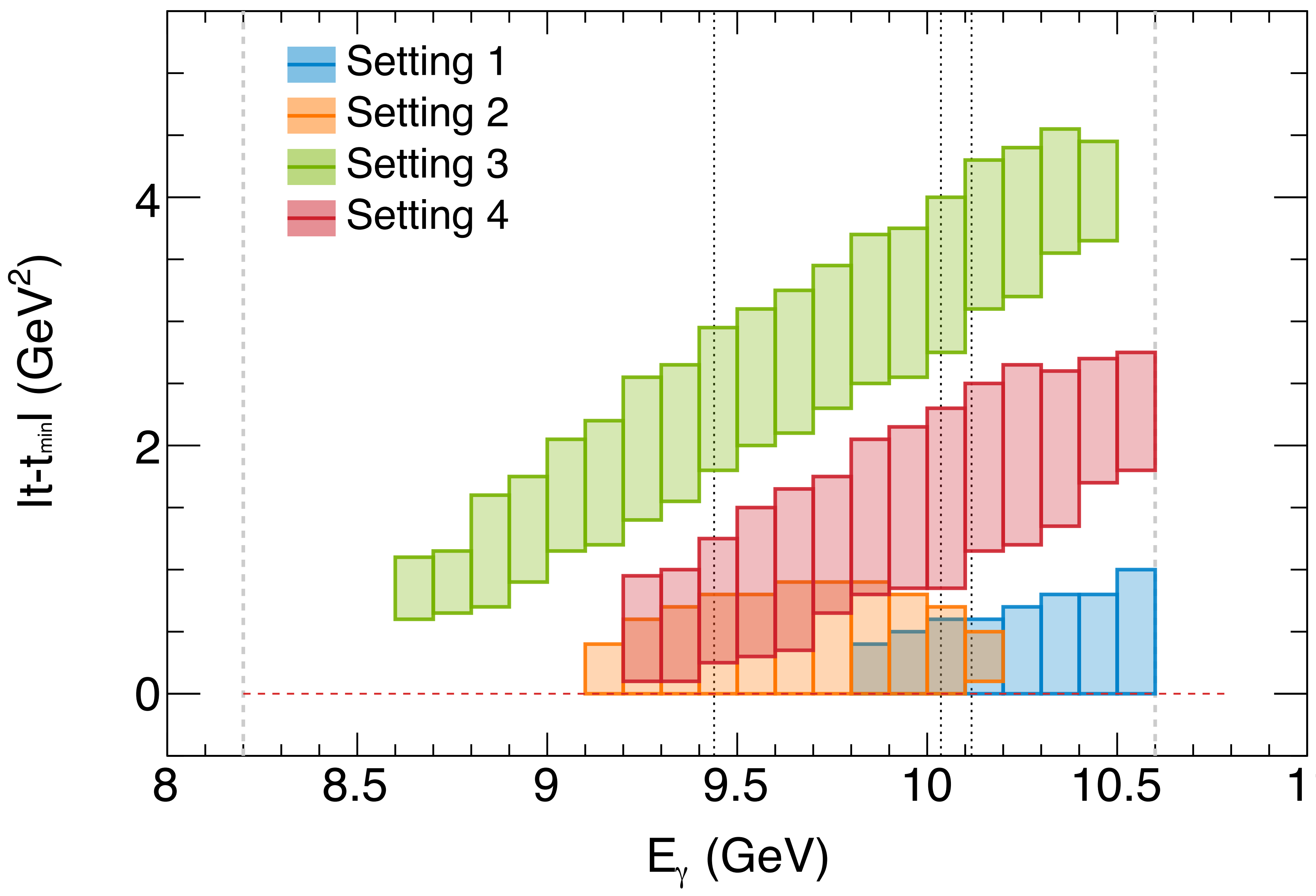


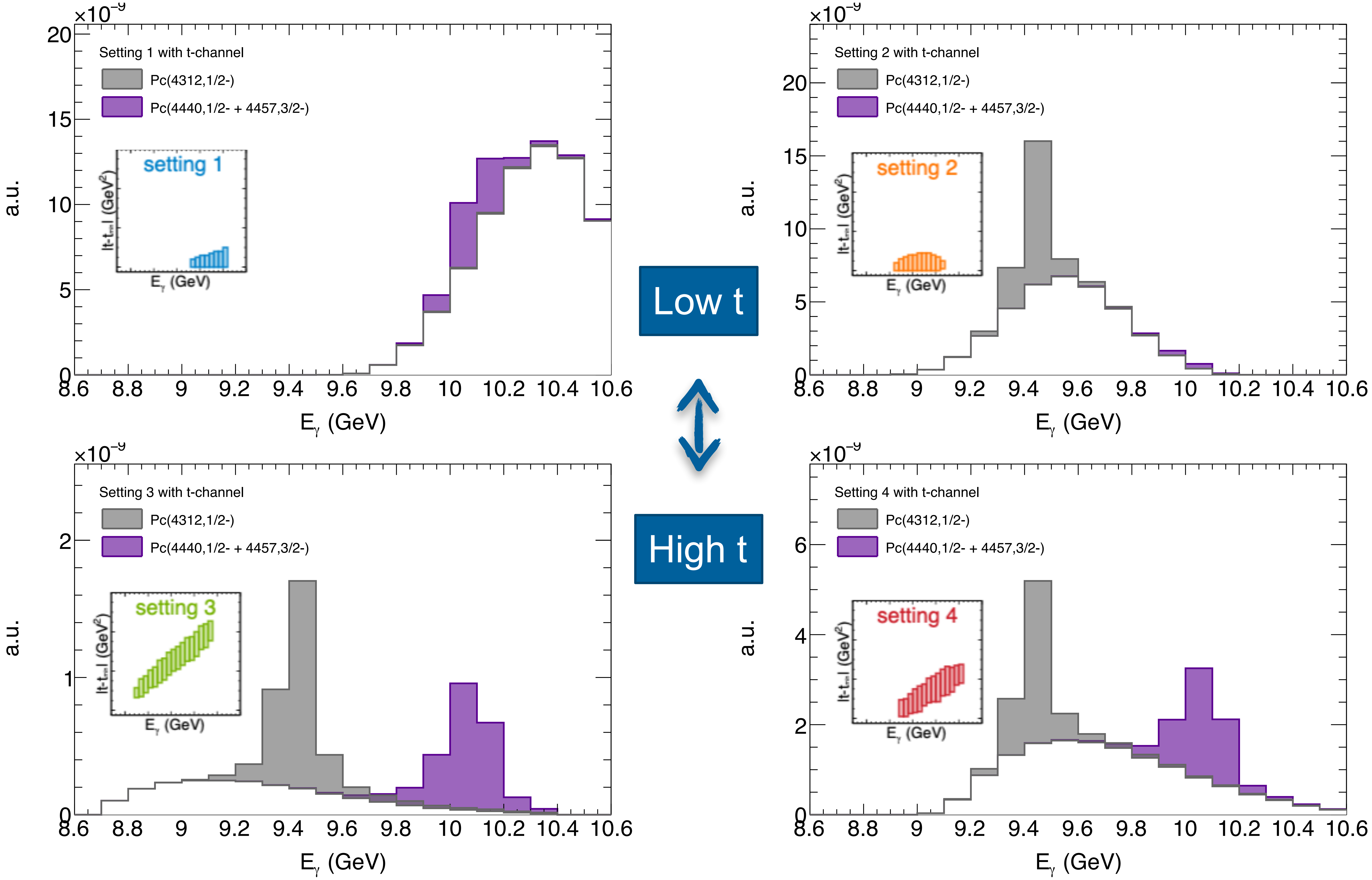
P_c resonances calculated at GlueX 90% upper limit from MC (JPacPhoto + Detector Simulation)

Difficult to separate higher-mass states due to radiative and detector smearing, and limited statistics (coarse binning)

HIGH-T SETTINGS CRUCIAL FOR SENSITIVITY

Improved sensitivity at high t for a given coupling





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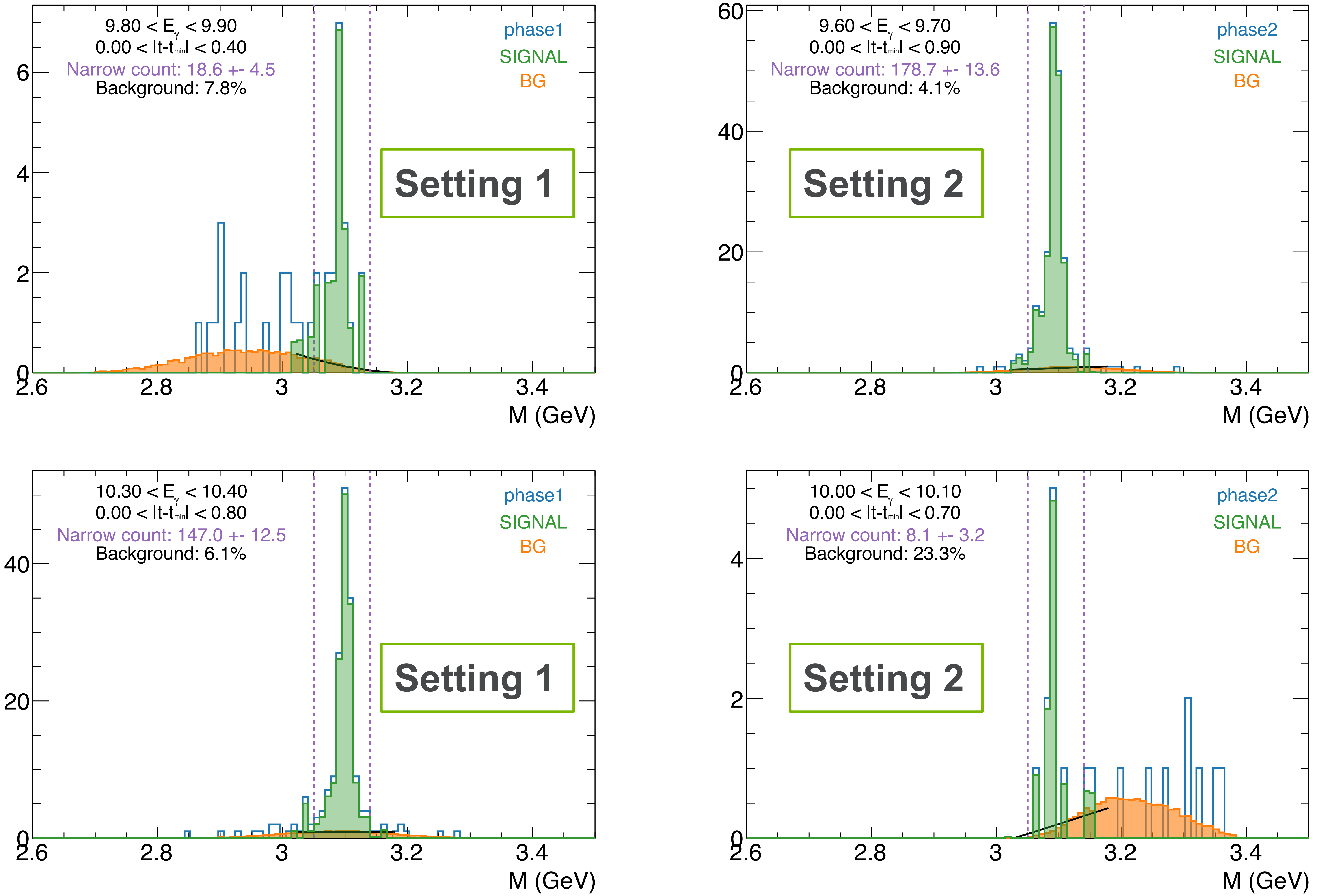
BACKGROUND SUBTRACTION

Counting J/ψ

- Scale down measured background within each experimental bin
- Fit background with POL2 curve around J/ψ invariant mass window to remove statistical fluctuations
- Subtract fit curve within J/ψ integration window from measure spectrum
- Use both narrow and wide window to constrain systematic uncertainties due to background subtraction and model description of the J/ψ radiative tail



4% scale uncertainty on cross section

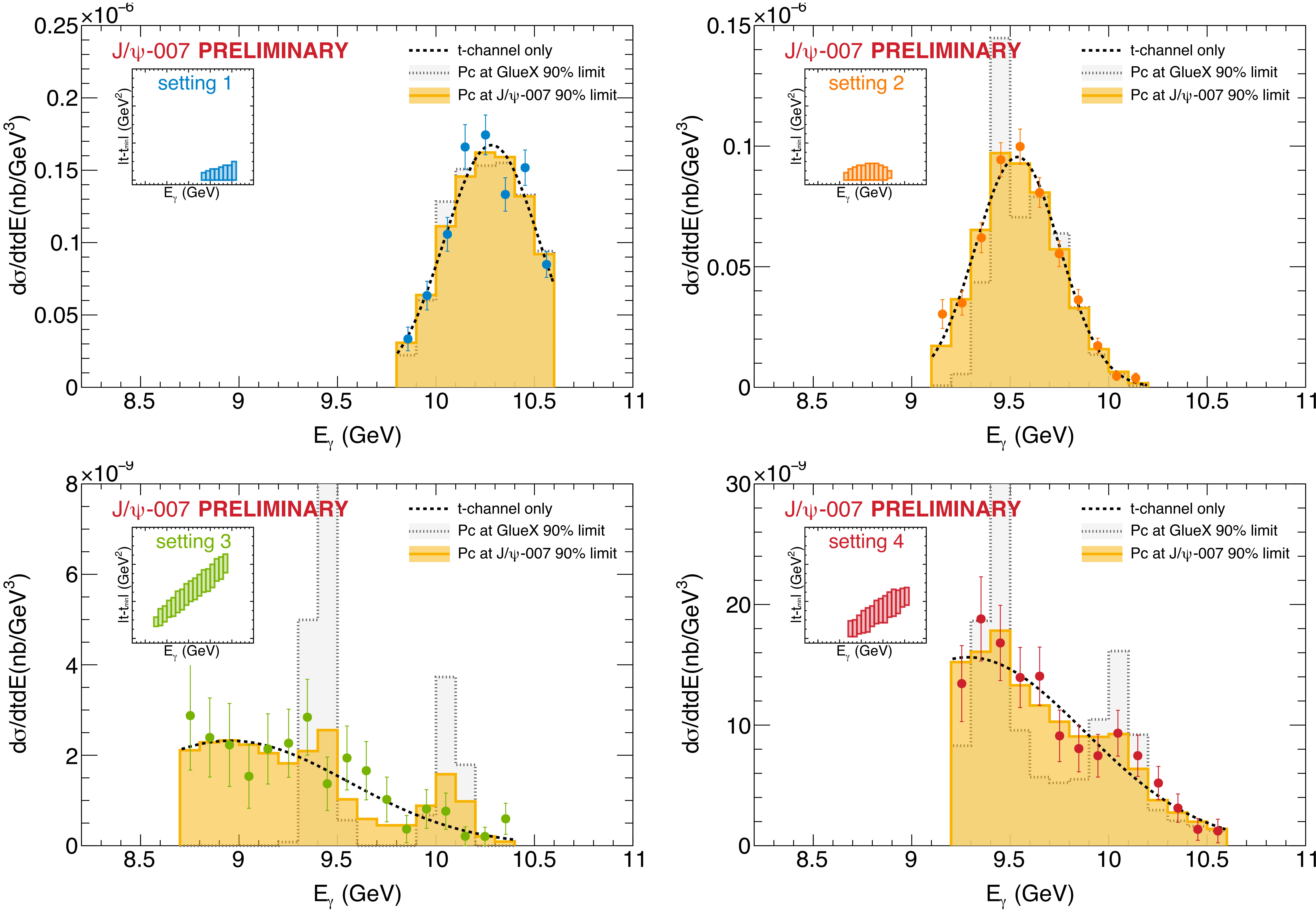
SIGNIFICANCE FIT

Fit 1: bare Gaussian shape describes the cross section well

Fit 2: Signal + background at GlueX upper limit (90% confidence interval). The resonances lead to major tension with the data at high-t.

Fit 3: Same as 2, but with Pc at upper limit (90% confidence interval) from the preliminary J/ψ-007 results themselves

The data suggest a stringent upper limit on the resonant cross section (see next slide).



4% scale uncertainty on cross section limit

RESULTS AND IMPLICATIONS

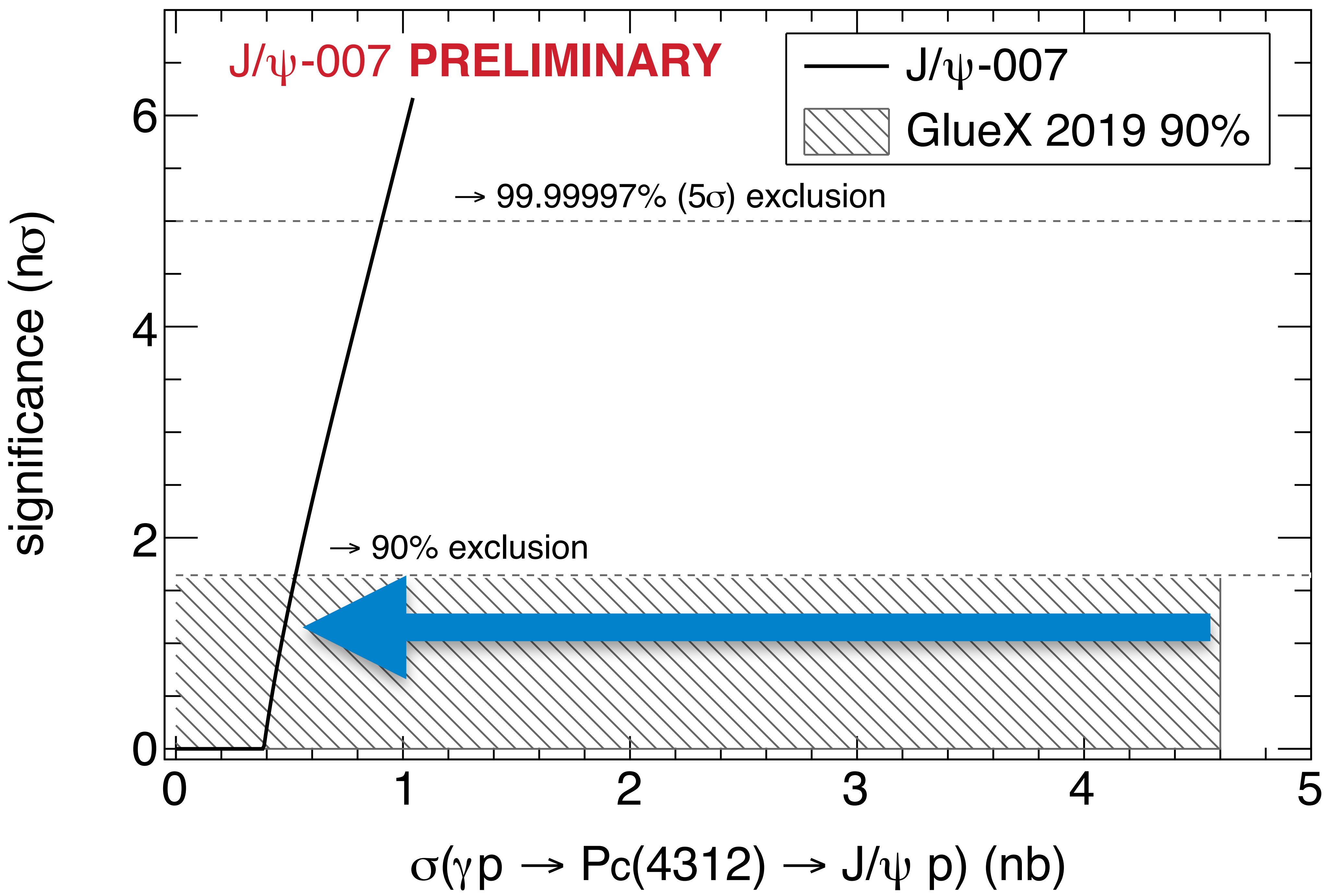
Cross-section at the resonance peak for model-independent upper limits

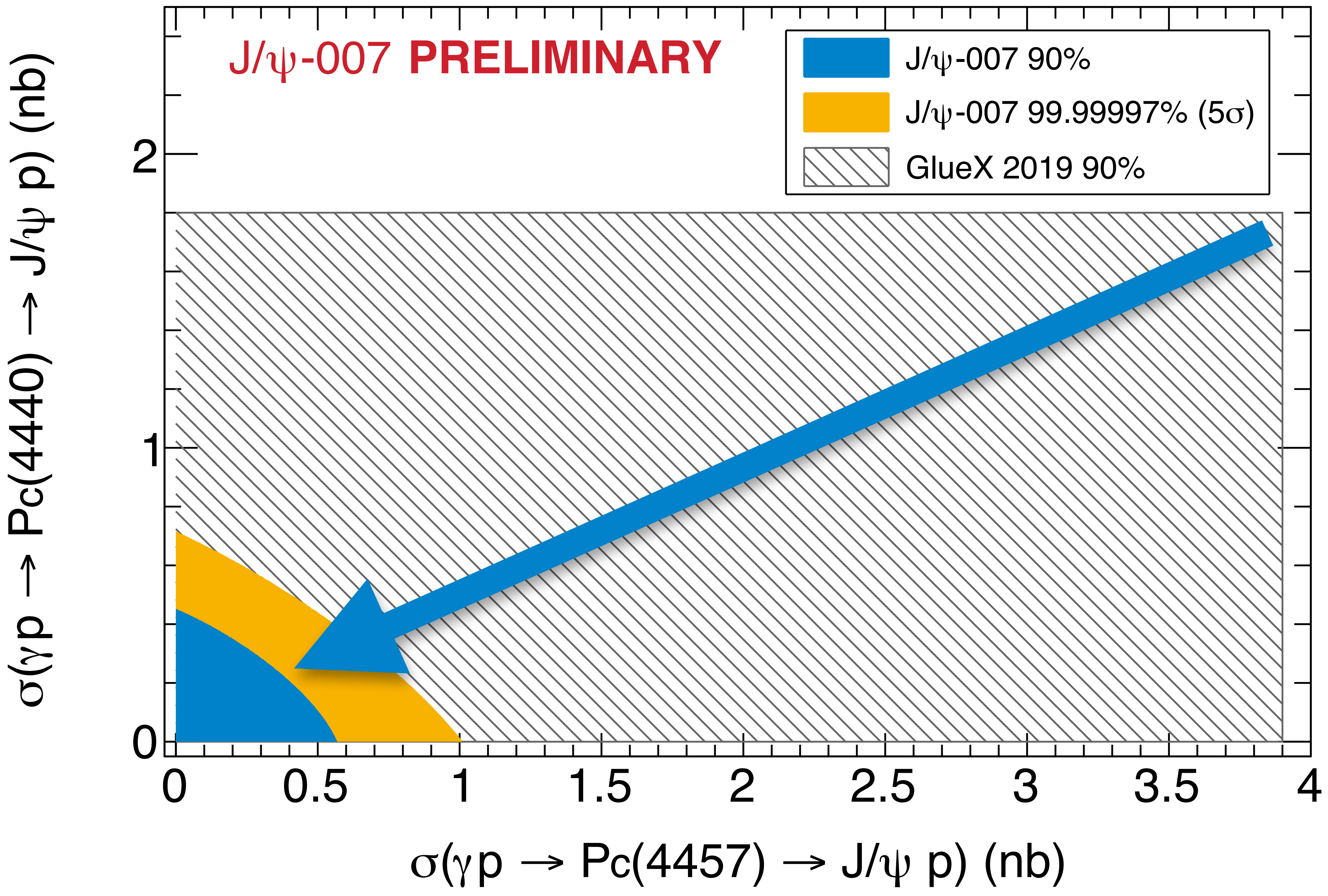
Upper limit for P_c cross section almost order of magnitude below GlueX limit.

Results are inconsistent with reasonable assumptions for true 5-quark states.

Door is still open for molecular states, but will be very hard to measure in photoproduction due to small overlap with both γp initial state and J/ψp final state.

To learn more we need a large-acceptance high-intensity photoproduction experiment, and potentially access to polarization observables. **This can be achieved with the SoLID-J/ψ experiment**





2D J/Ψ MEASUREMENT IN HALL C

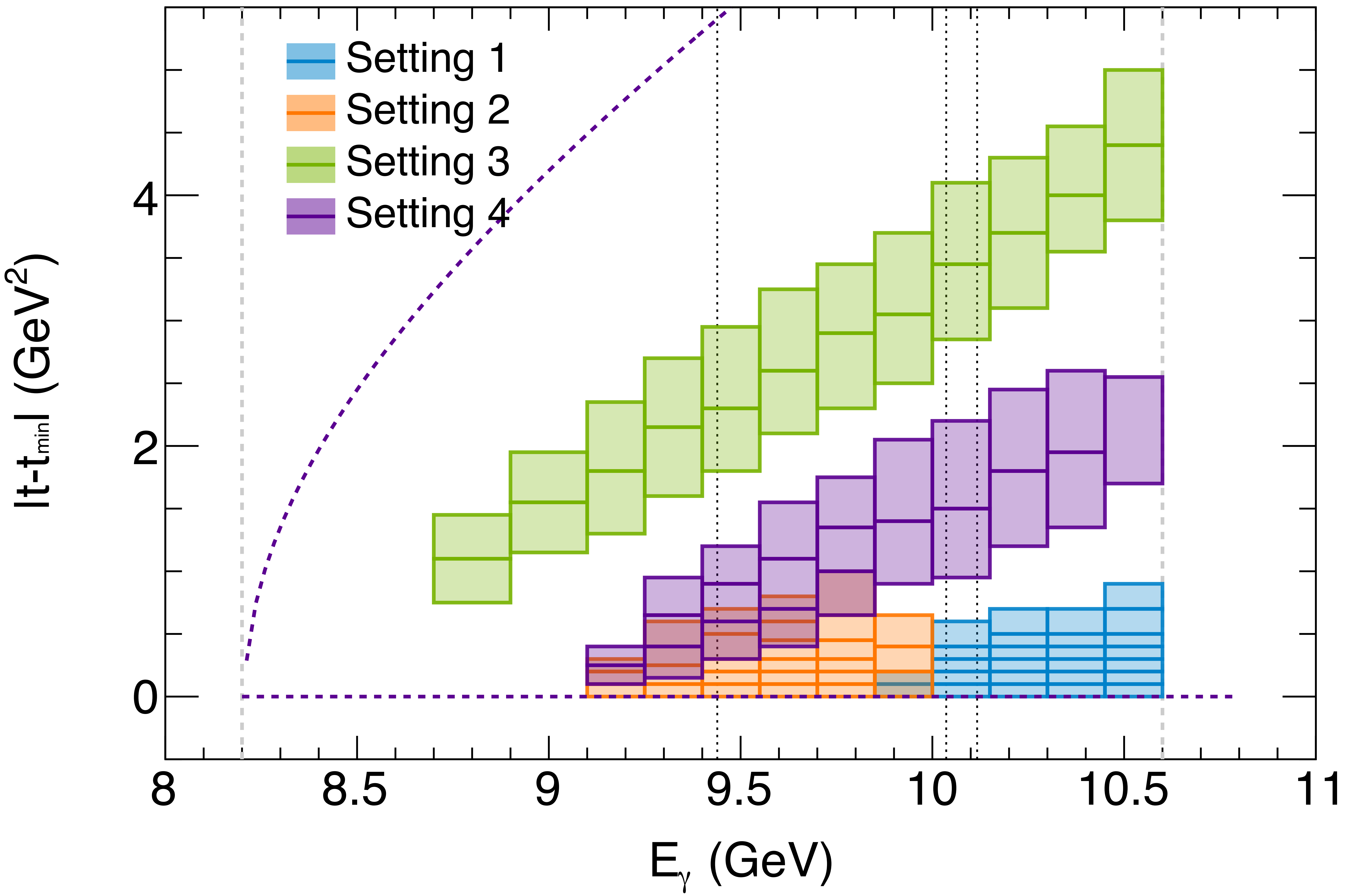
2D cross sections will provide access to the matter radius of the proton

Independent muon and electron channels (only electron results shown)

Largest dataset (>4000 counts) of J/ψ produced with a real photon beam

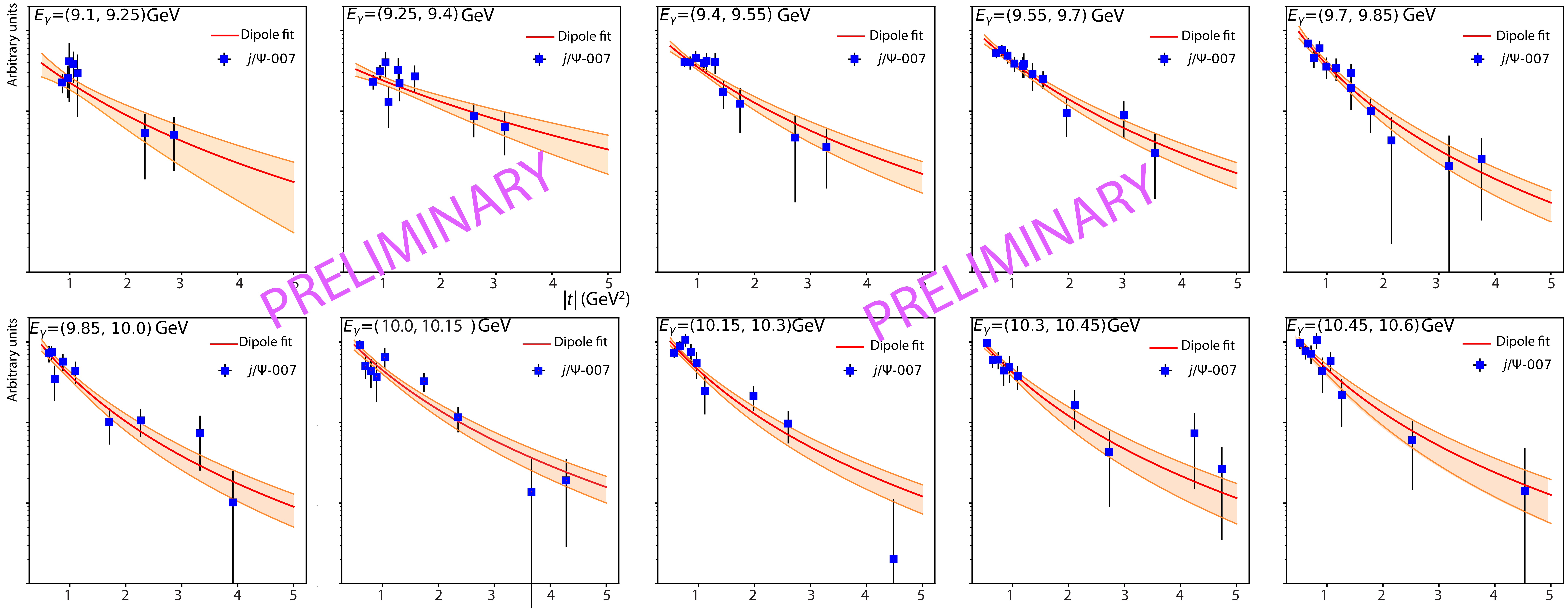
First 2D J/ψ cross section results near threshold

t-dependence between 9.1-10.6GeV in bins of 150 MeV



2D J/Ψ CROSS SECTION RESULTS IN A.U.

t-dependence consistent with a dipole slope



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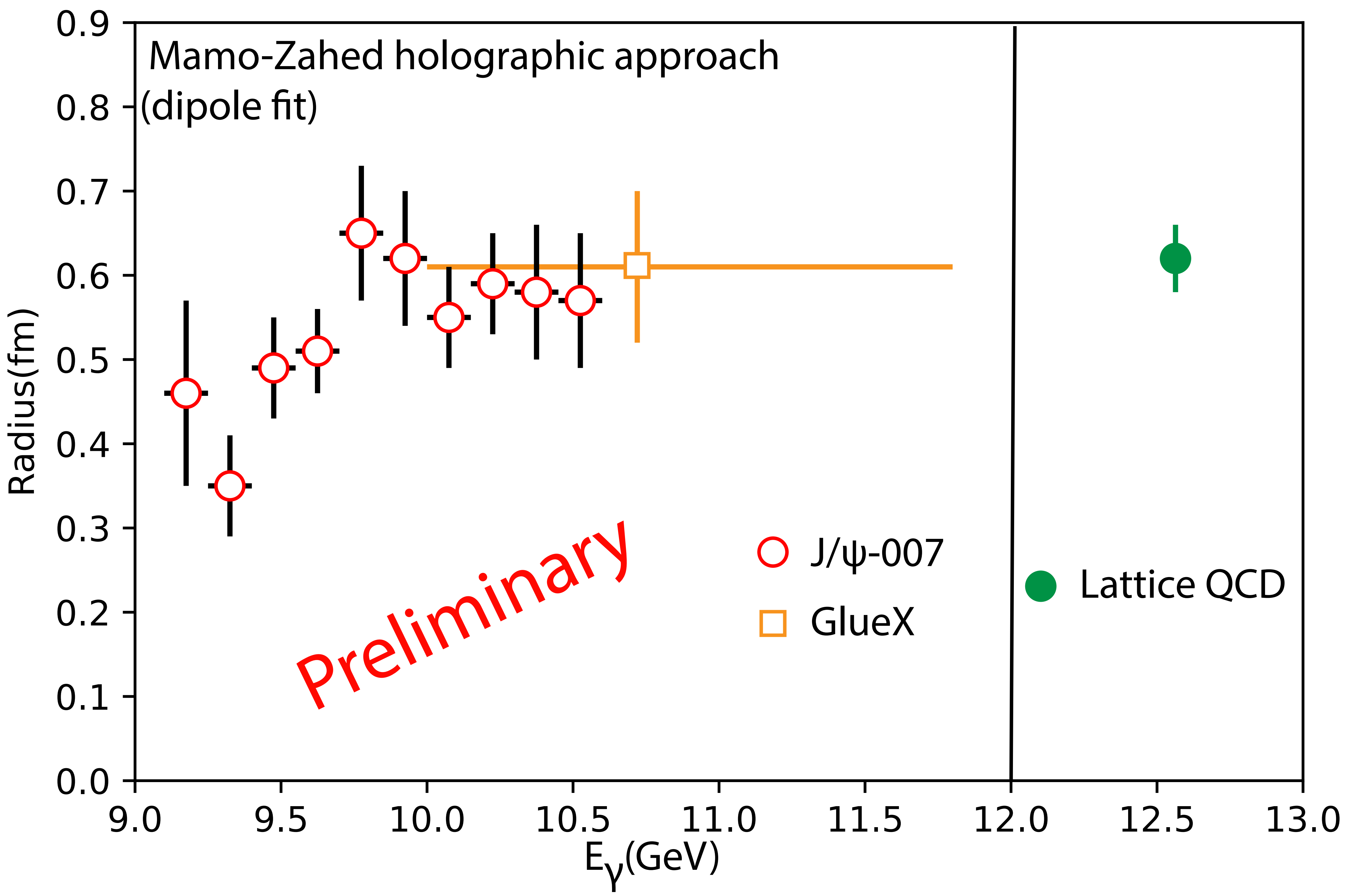
AN ENERGY SCAN OF THE GLUON RADIUS

NEW

First ever access of the energy dependence of the gluon radius in two models



- Mass radii can be extracted for each of the 10 energy bins by means of a dipole fit
- Figure shows results following the approach from Mamo-Zahed (Phys. Rev. D 101, 086003, 2020).
- Similar results can be obtained following D. Kharzeev's approach (Phys. Rev. D 104, 054015, 2021)
- Data can also be used to constrain the gravitational form factors falling the approach from Guo-Ji-Liu (Phys. Rev. D 103, 096010, 2021)
- The results can also be used to study the energy-momentum tensor of QCD following the approach from Hatta-Rajan-Yang (Phys. Rev. D 100, 014032, 2019)

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

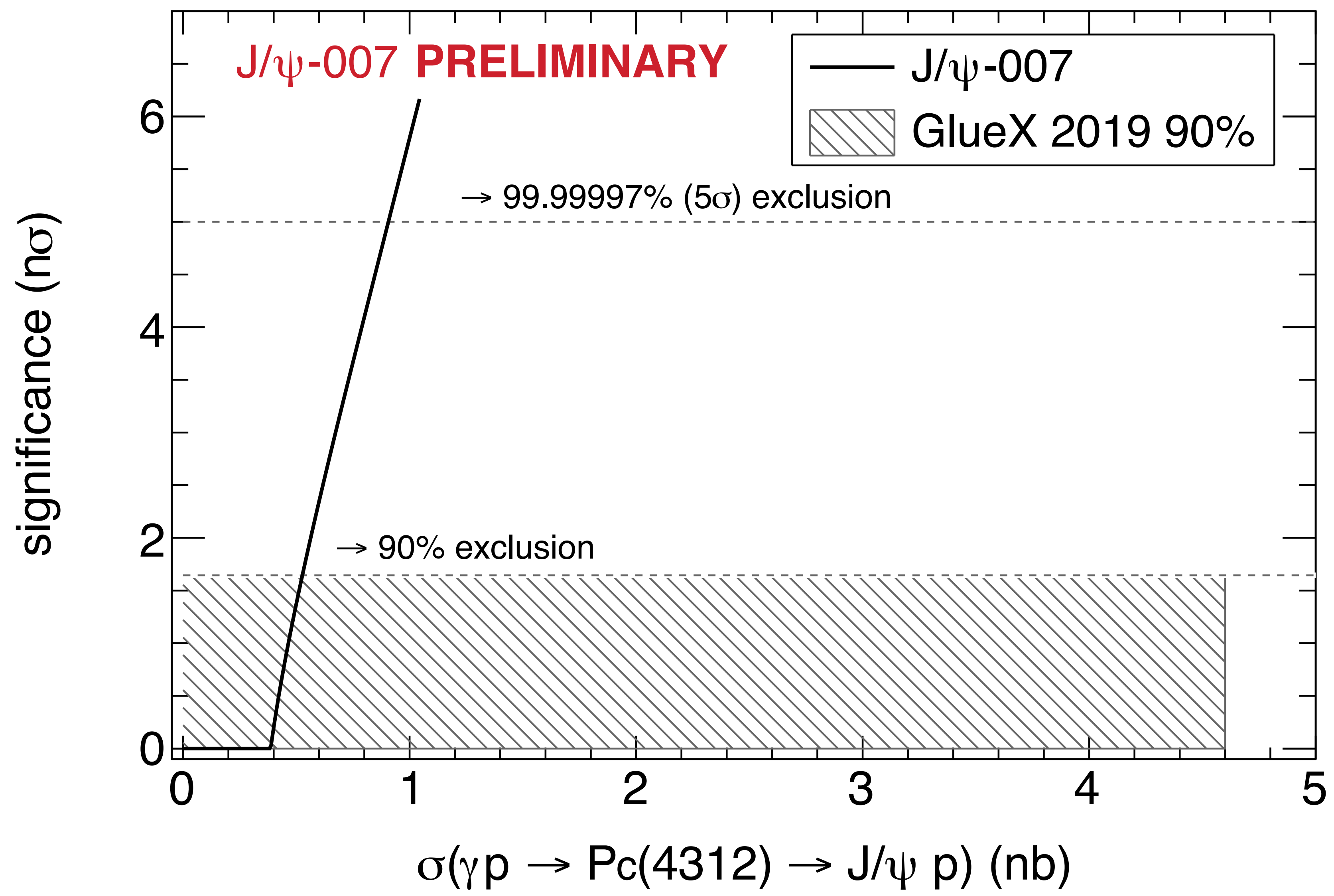
SUMMARY

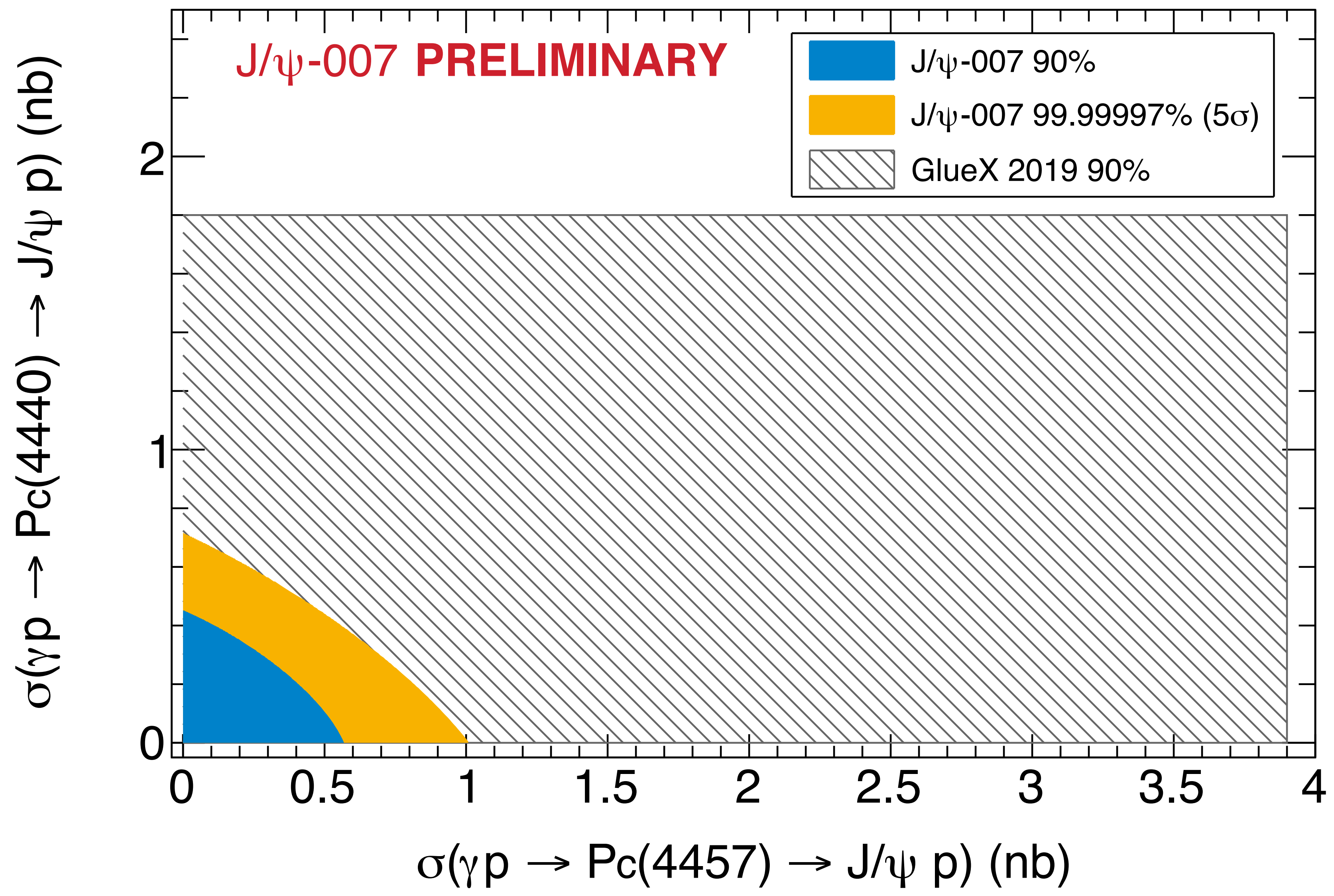
Near-threshold electro- and photoproduction of quarkonium

- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus bound states
- Do quarkonia enable **pentaquarks** to exist?
- **Mechanism** for quarkonium production itself

Hall C J/ψ-007 experiment sees no evidence for hidden-charm pentaquarks in photoproduction

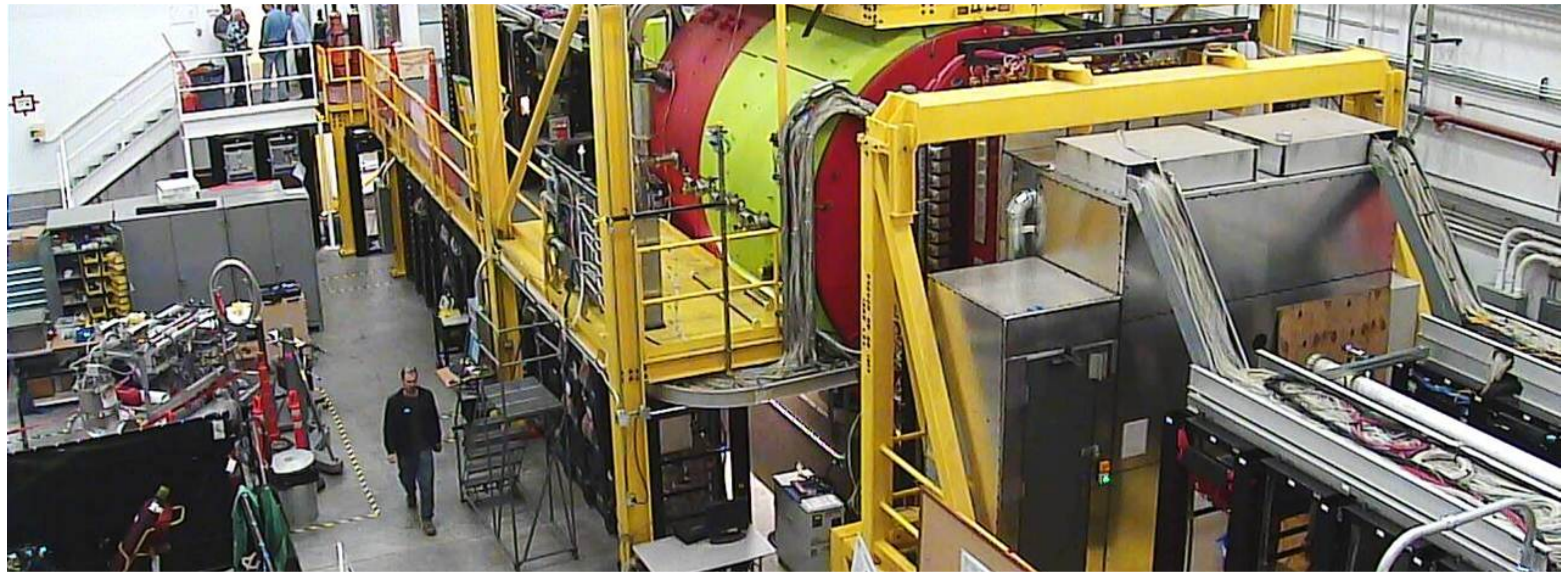
First paper on the pentaquark, and second paper on 2D J/ψ cross-sections) almost ready for collaboration review!



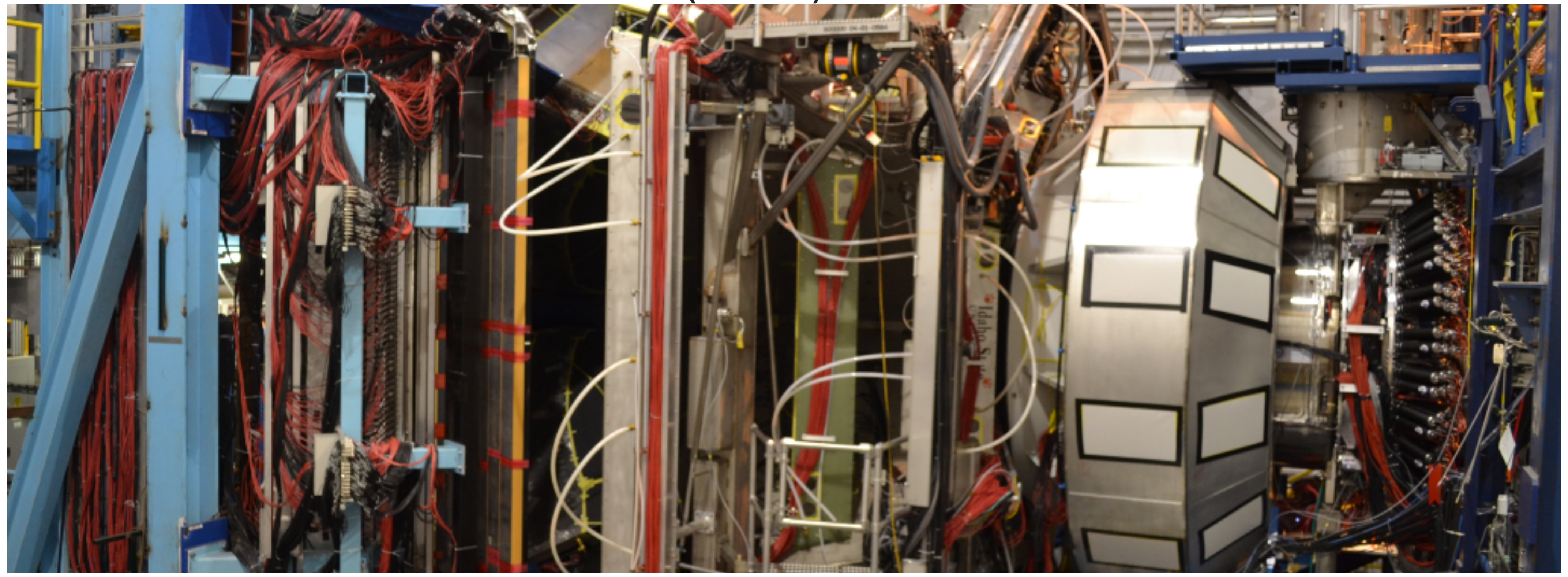


THE END

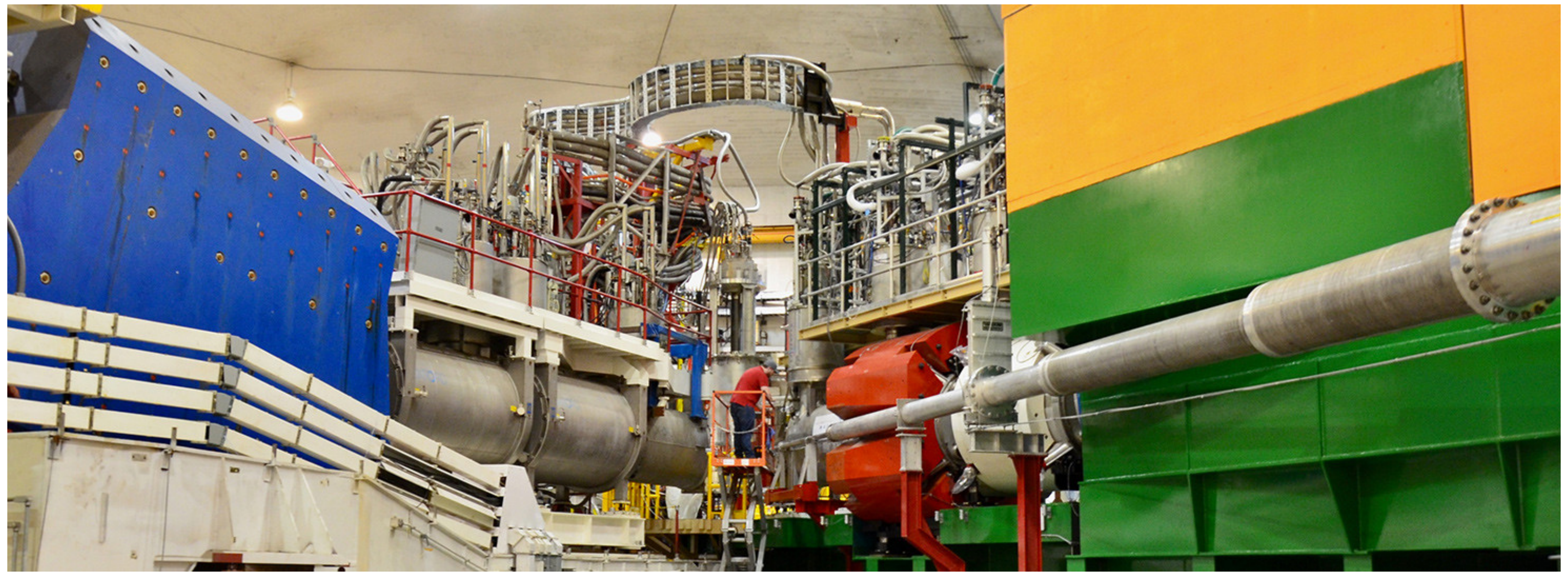
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



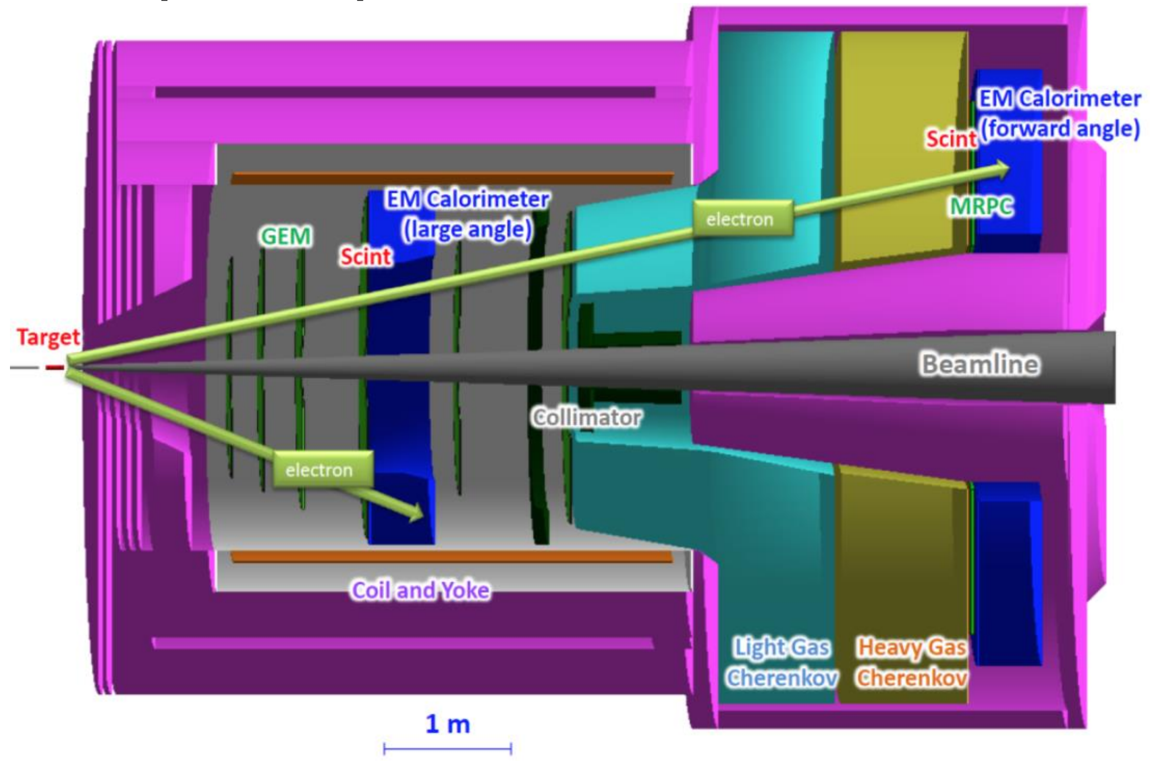
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



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/Ψ EXPERIMENTS AT JLAB COMPARED

	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	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/Ongoing	Finished	Ongoing/Proposed	~8 years?

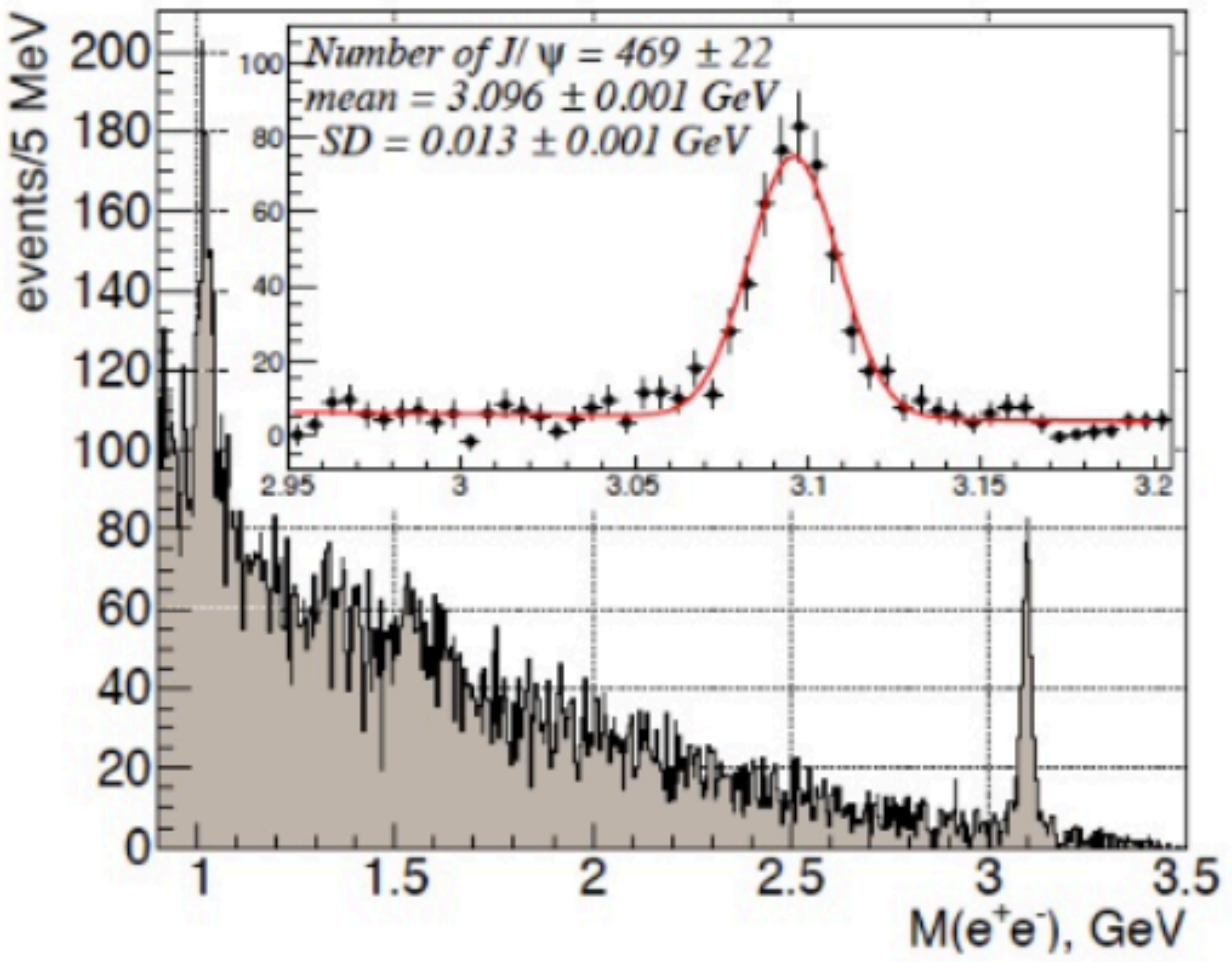
[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2\times10^{35}/cm^2/s$

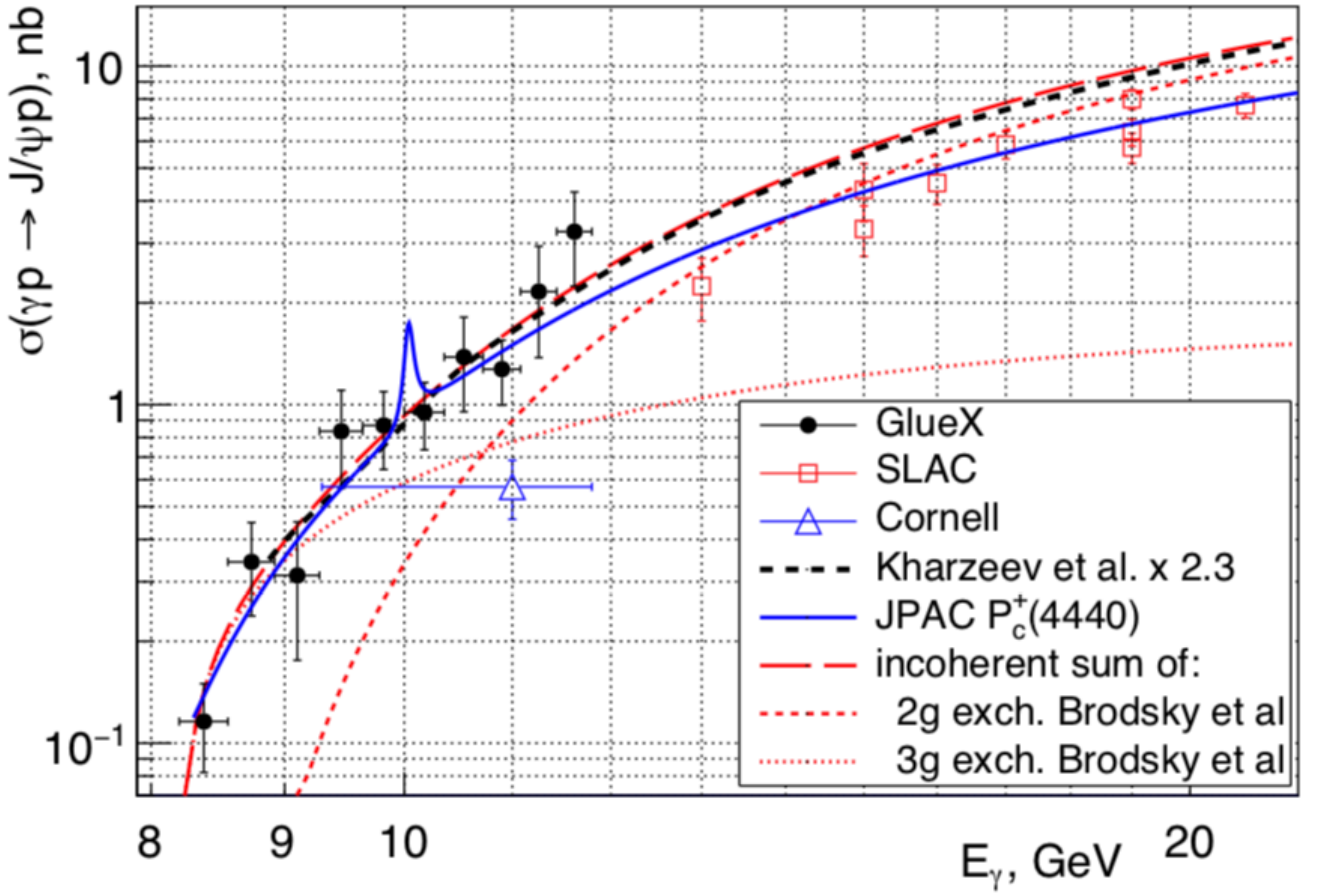
J/Ψ NEAR THRESHOLD IN HALL D

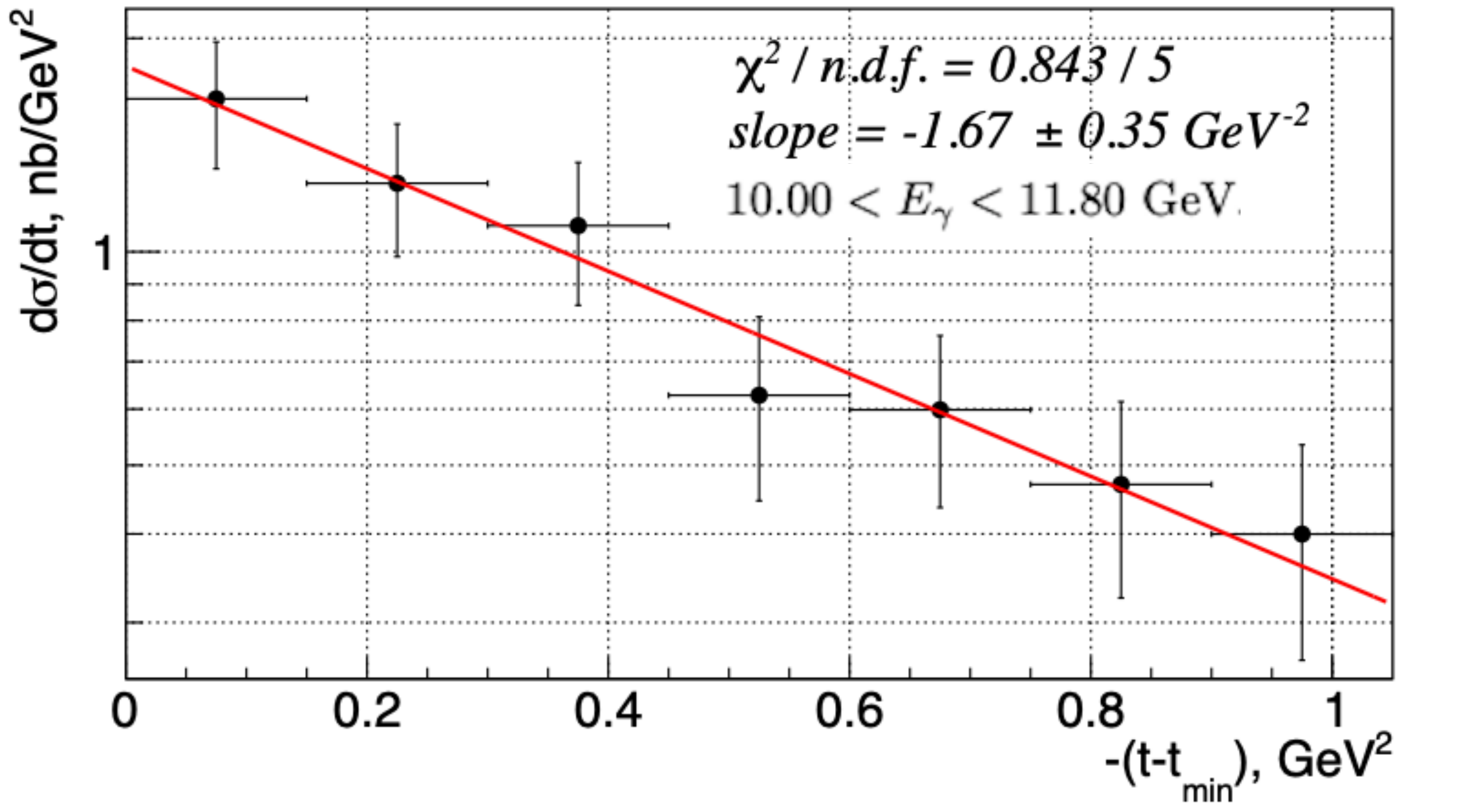
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Also released a single 1D t-profile
- Published upper limits for s-channel pentaquark resonances at 90% confidence level
  - 1D limits on $\sigma(\gamma p \to Pc) \times \Gamma(Pc \to J/\psi\ p)$: resp. <4.6nb, <1.8nb, and <3.9nb at 90%
- Still consistent with pentaquark and molecular models
- 4x more statistics being analyzed

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







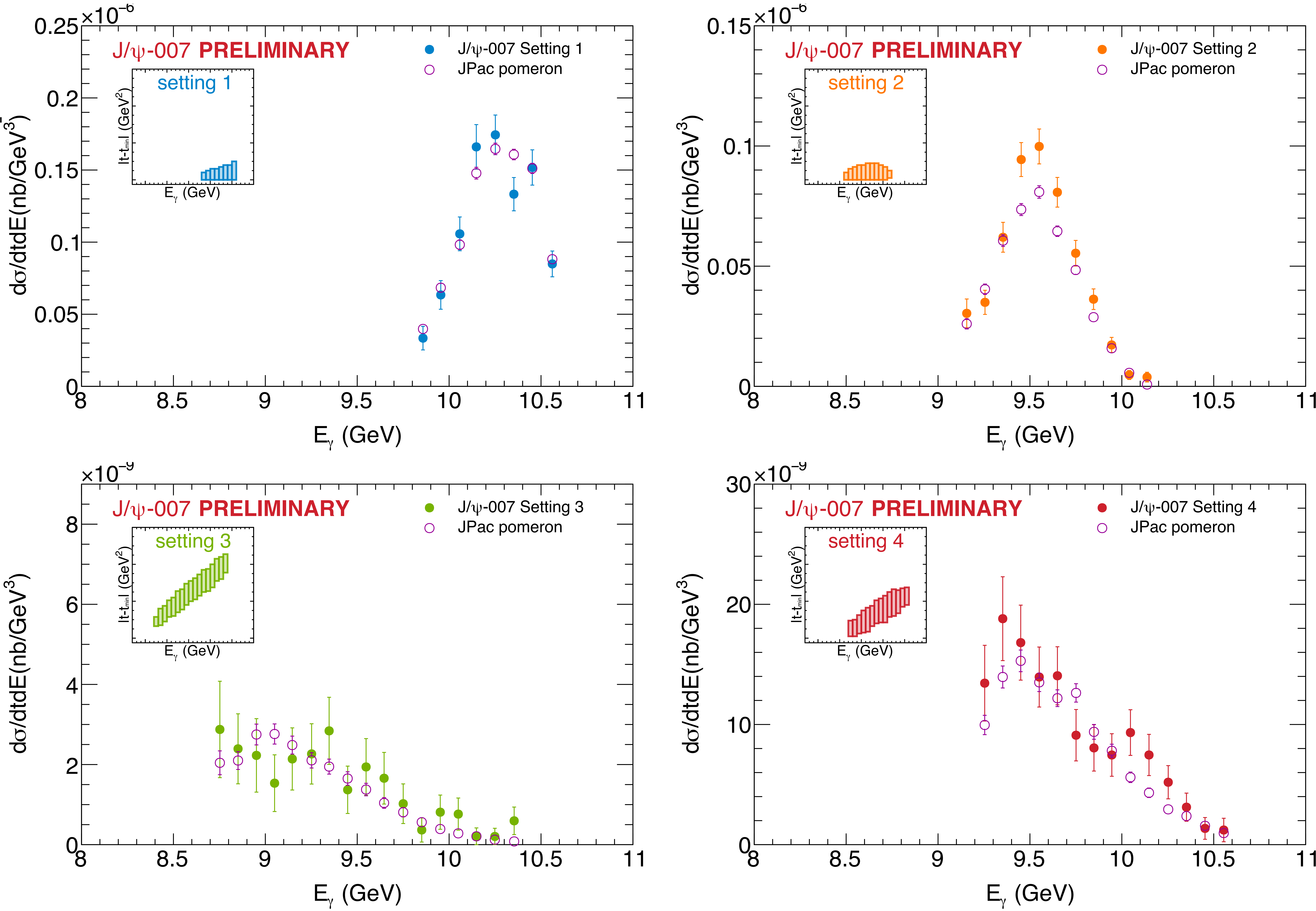
4% scale uncertainty on cross section

COMPARISON WITH T-CHANNEL MODEL CALCULATION

Measured 1D results show decent agreement with predictions from the JPac Pomeron model (constrained by old world data + GlueX 2019 results)

Largest deviations at lower energies

To get more sensitivity to details in the near-threshold cross section, we need the 2D cross section results (see next slides)



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