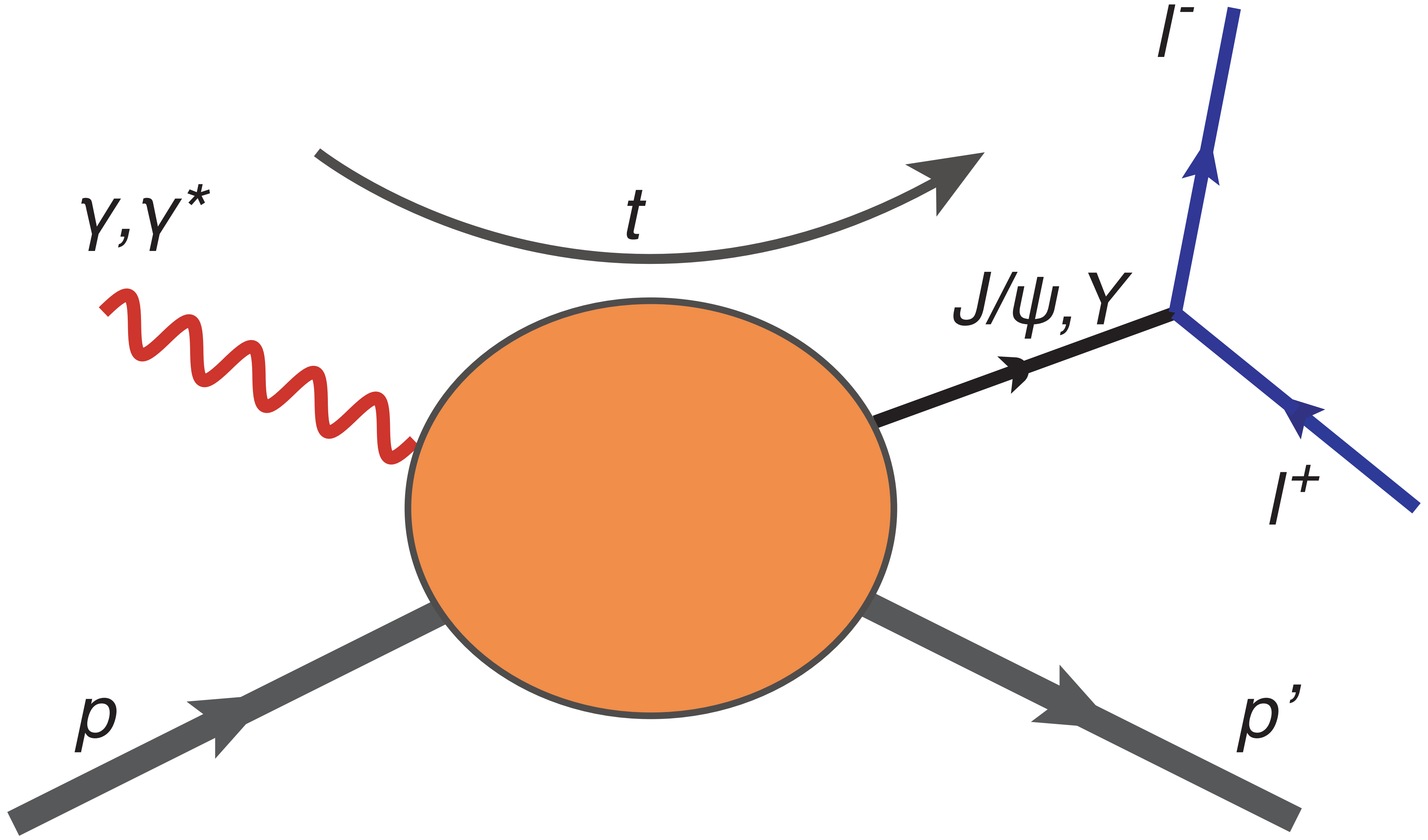
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

FROM HIDDEN-CHARM PENTAQUARKS
TO THE QUANTUM ANOMALOUS ENERGY OF THE PROTON

Argonne NATIONAL LABORATORY 75 1946–2021

QUARKONIUM PRODUCTION NEAR THRESHOLD AT JLAB AND EIC



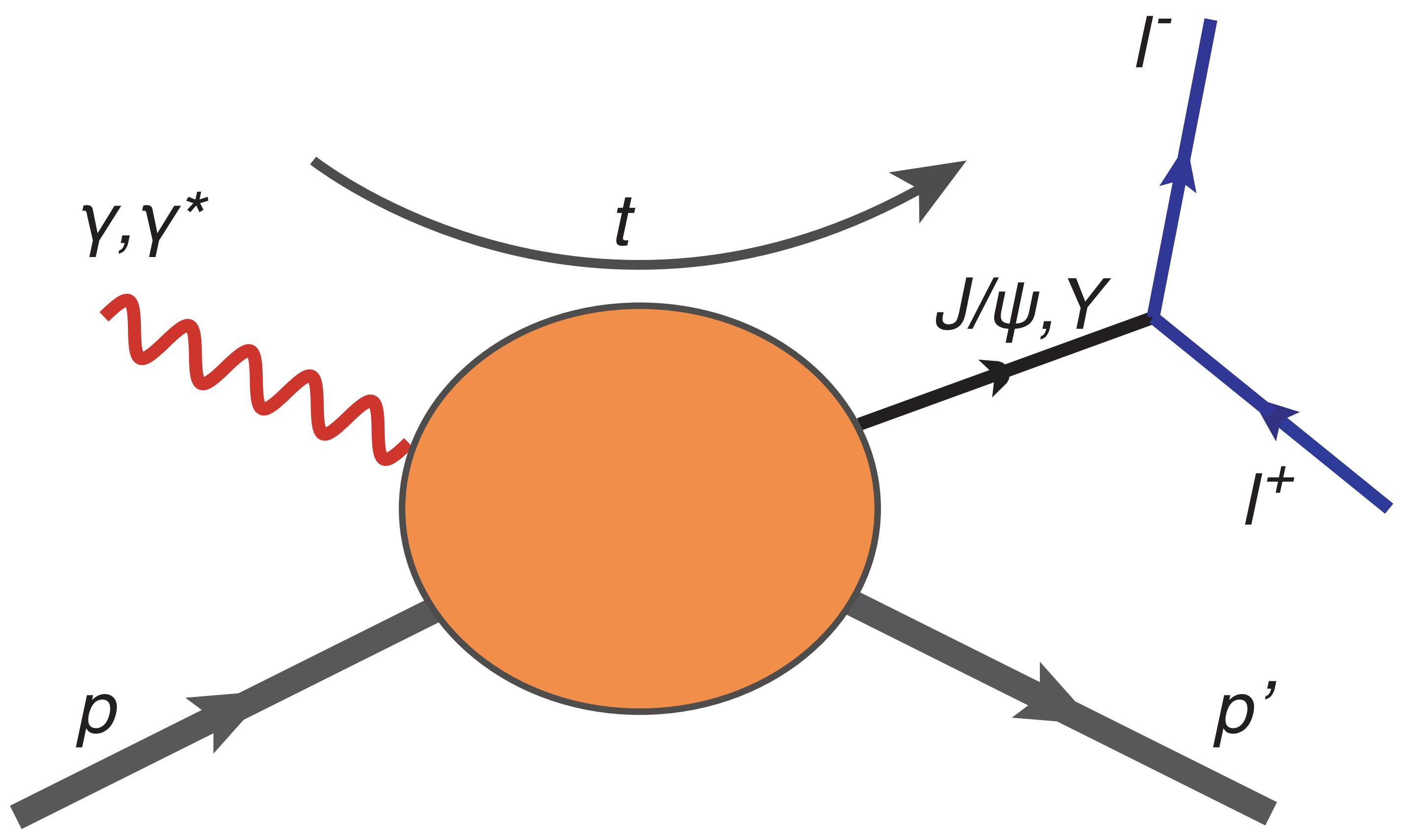
007 J/ψ SoLID SOLENOIDAL LARGE INTENSITY DEVICE EIC

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

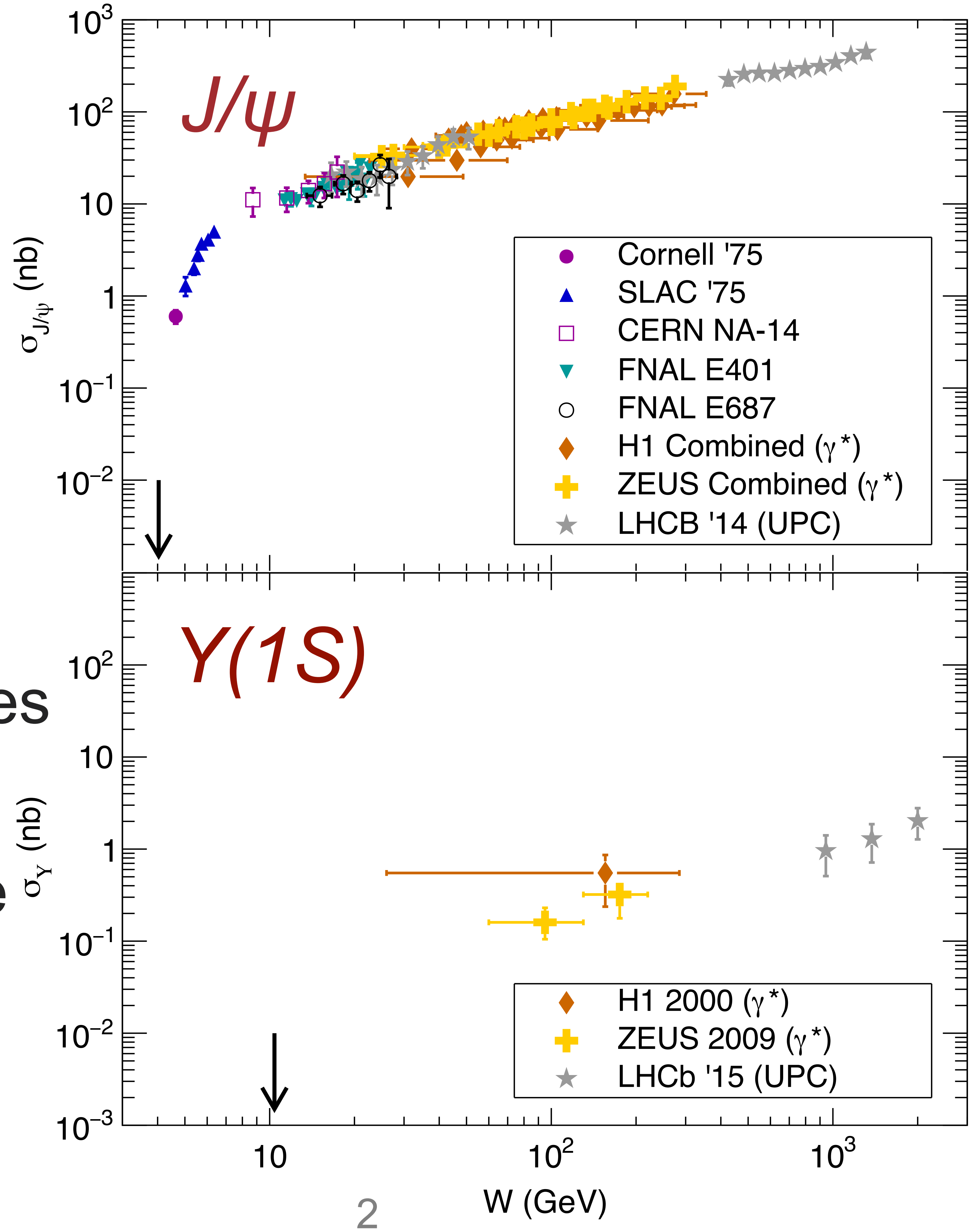
April 16, 2021
Remote GHP Meeting

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

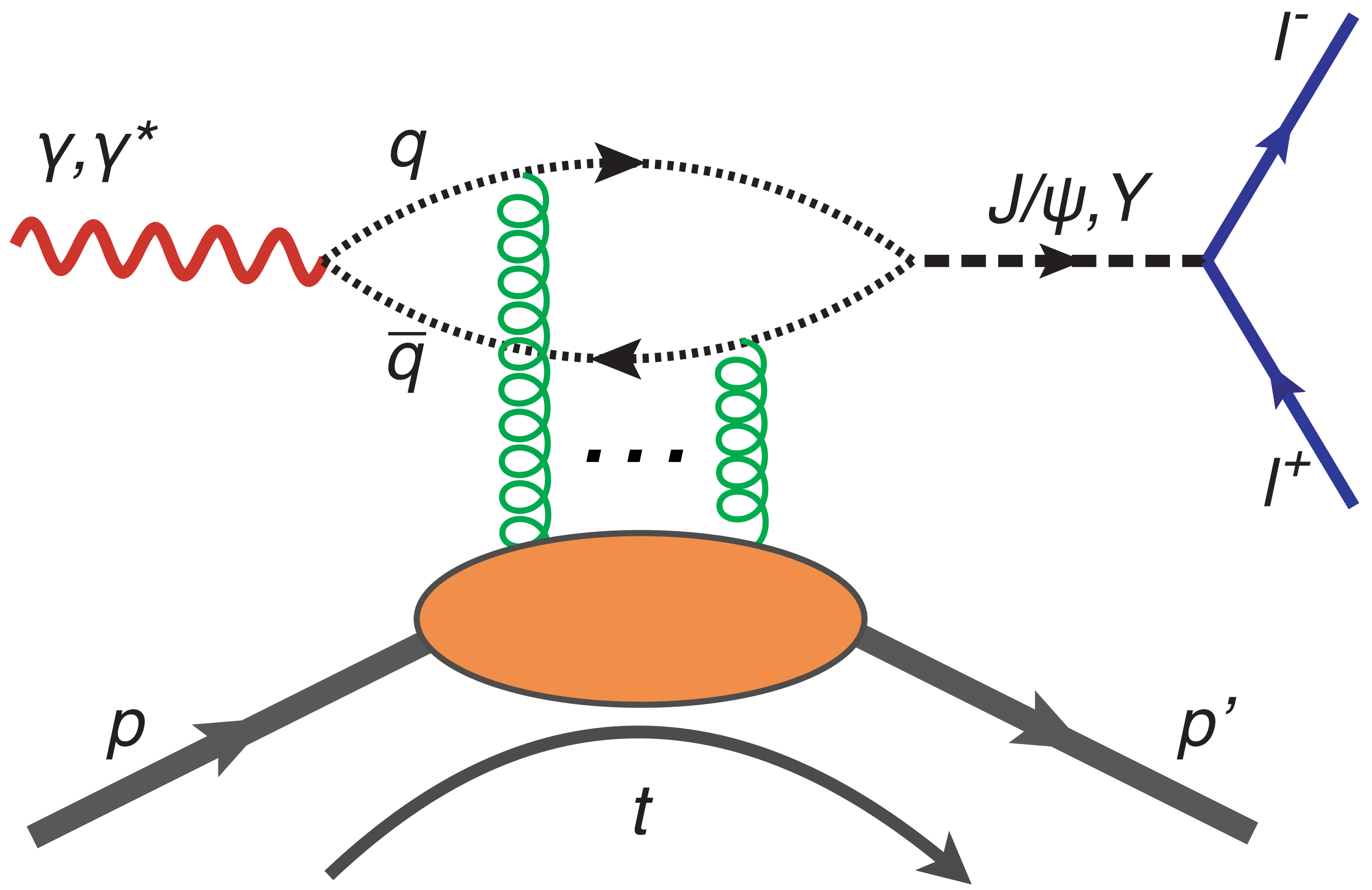
↕

J/ψ at JLab
Υ(1s) at EIC

S. Joosten

QUARKONIUM PHOTO-PRODUCTION

The kinematics

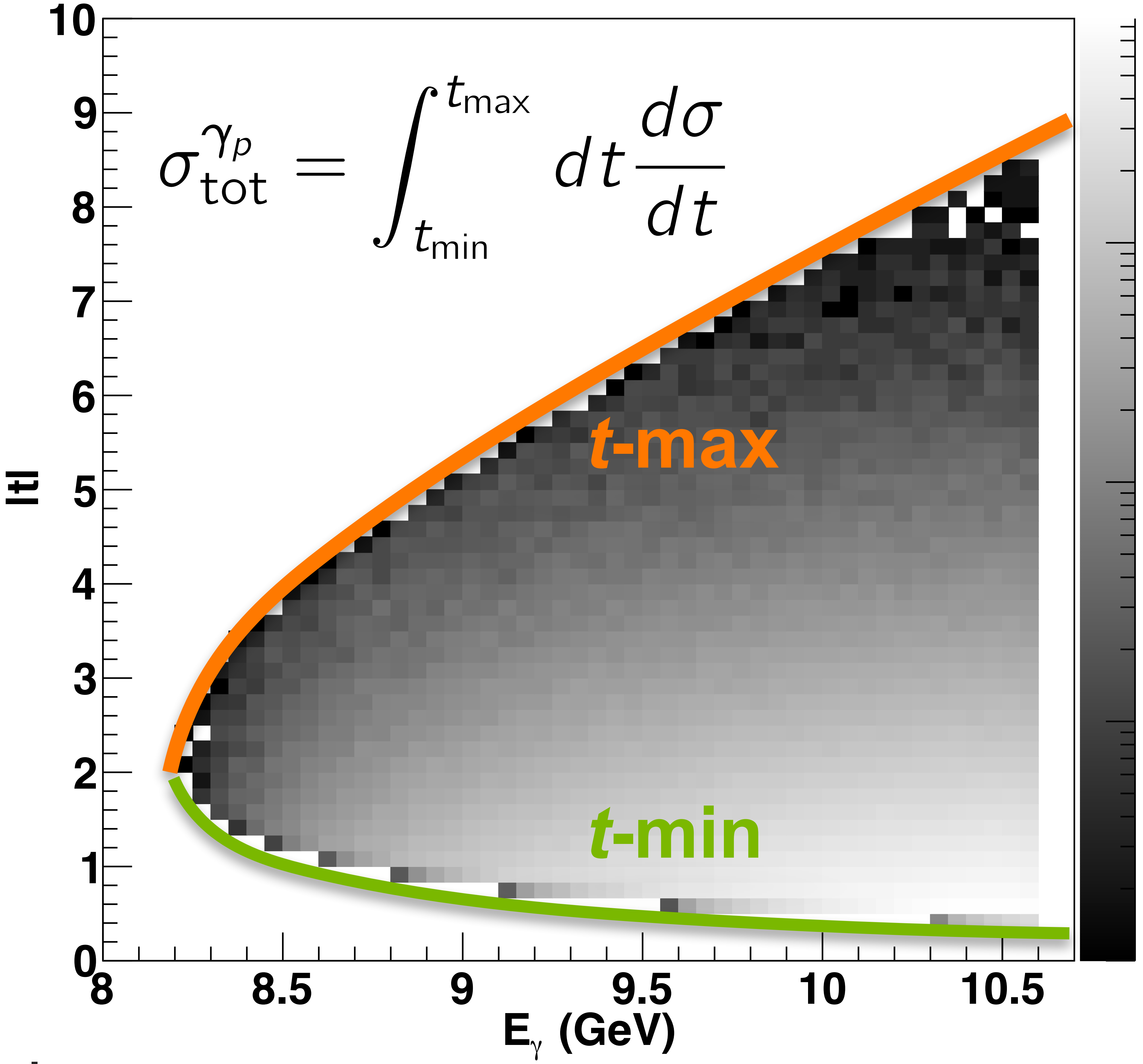


J/ψ threshold:

$W \approx 4.04\text{GeV}$

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

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



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

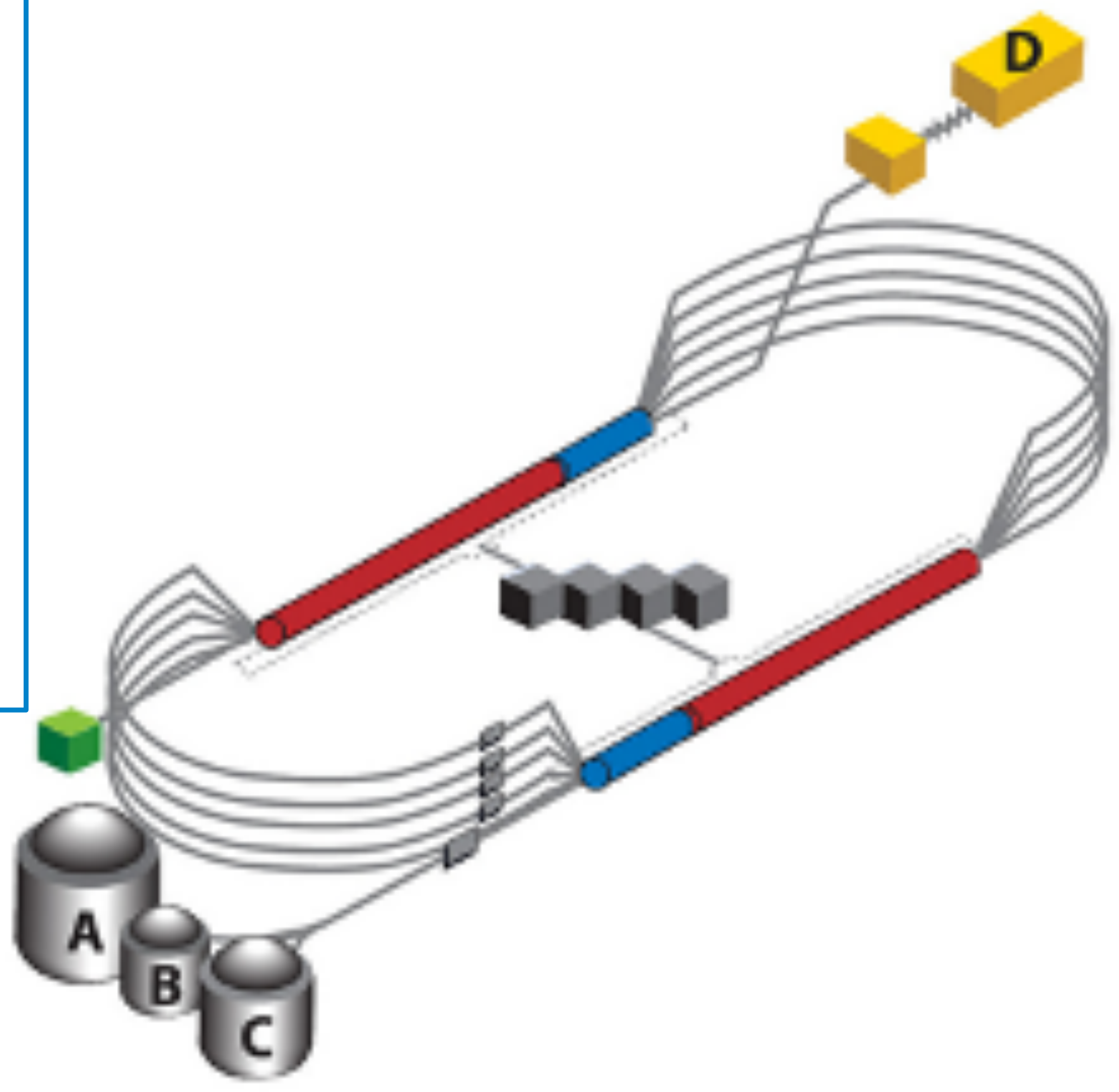
QUARKONIUM AT JEFFERSON LAB AND EIC

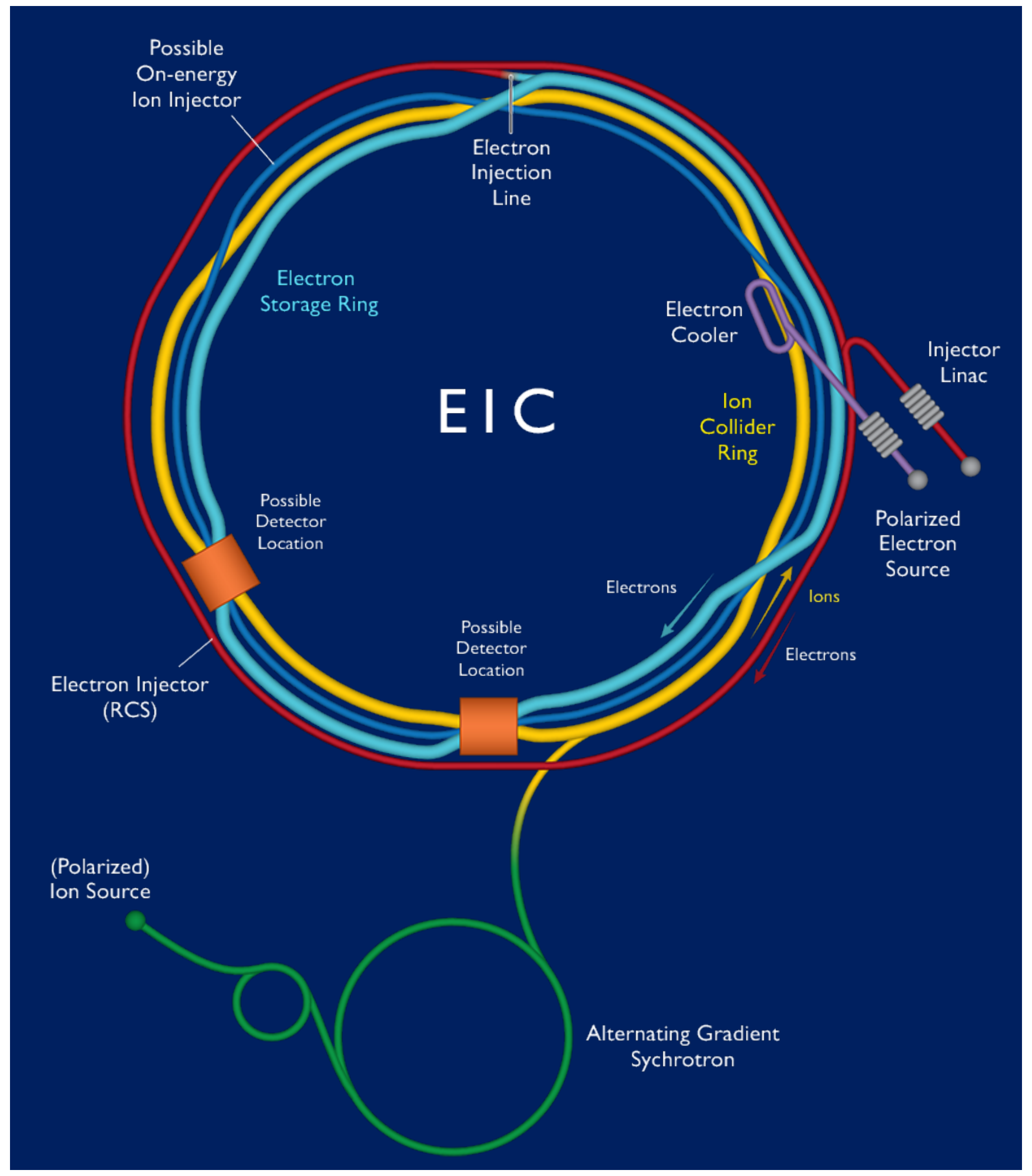
Jefferson Lab

CEBAF: very high luminosity (10^{35}-10^{39} $cm^{-2}s^{-1}$) continuous electron beam on fixed target

4 experimental halls:
- 11GeV in Hall A, B &C
- 12GeV in Hall D

Jefferson Lab is the ideal laboratory to measure J/ψ near threshold,
due to luminosity, resolution and energy reach





Electron-ion Collider

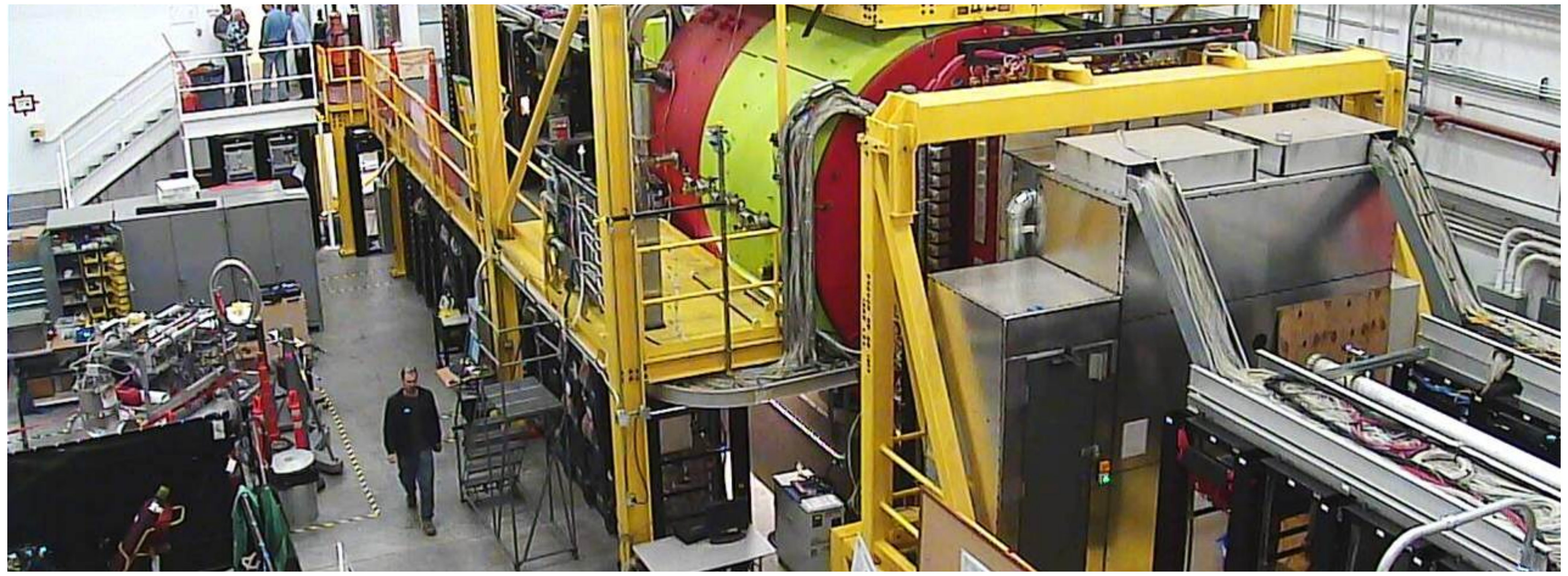
EIC: high luminosity (10^{33}-10^{34} $cm^{-2}s^{-1}$) polarized electron polarized ion collider

Variable CM energies: 29-140 GeV with 2 possible interactions regions

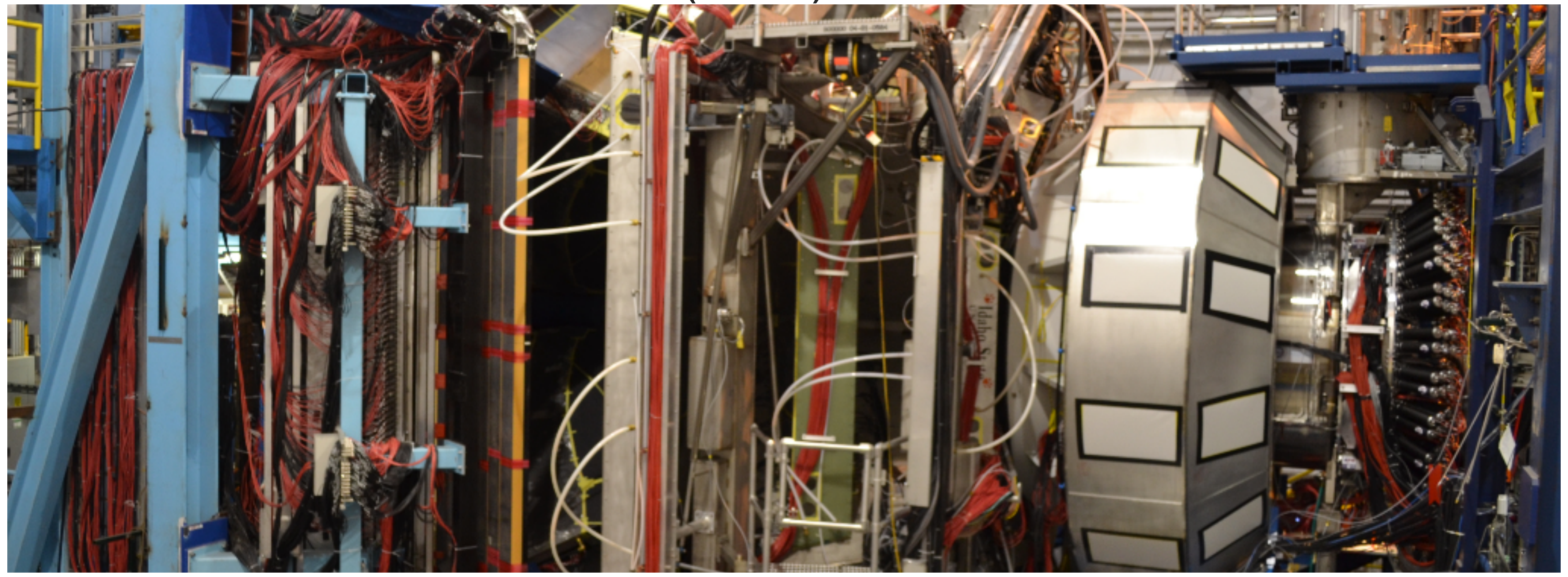
Reach to J/ψ threshold more difficult, sufficient energy and luminosity to study Υ near threshold.

Complementary programs: Jefferson Lab is the ideal laboratory to measure J/ψ near threshold, and EIC has sufficient luminosity to measure Υ near threshold

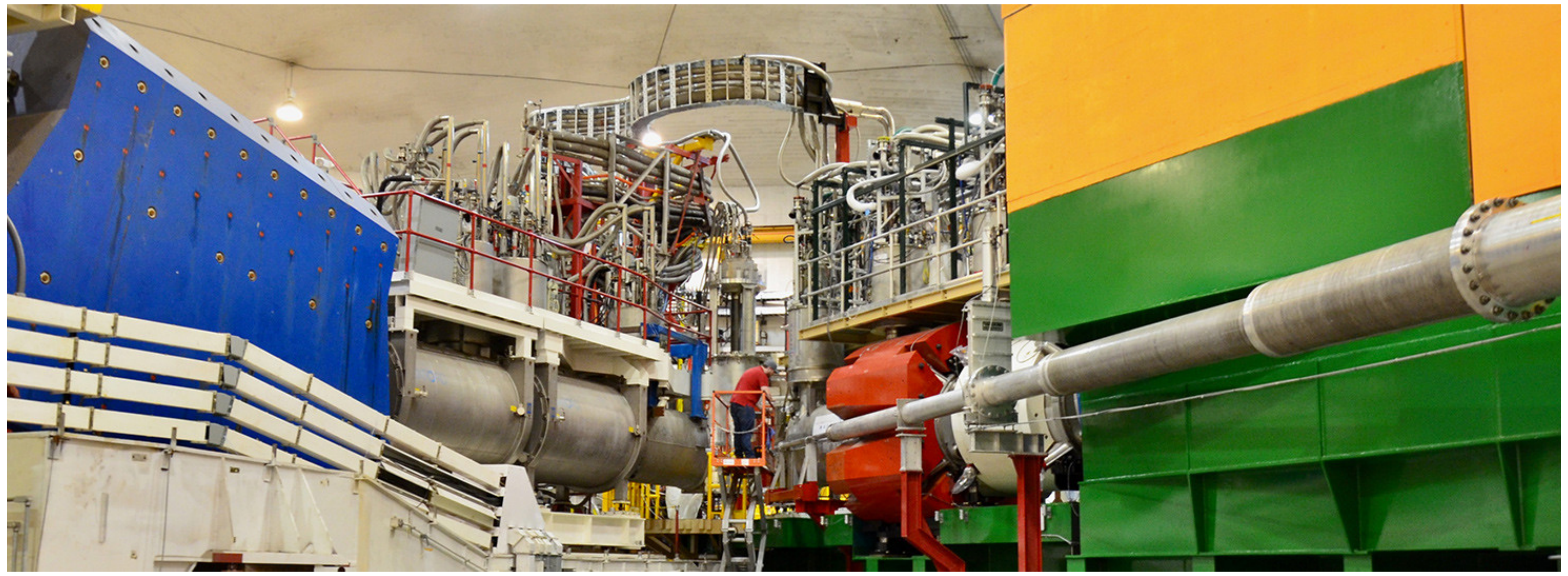
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



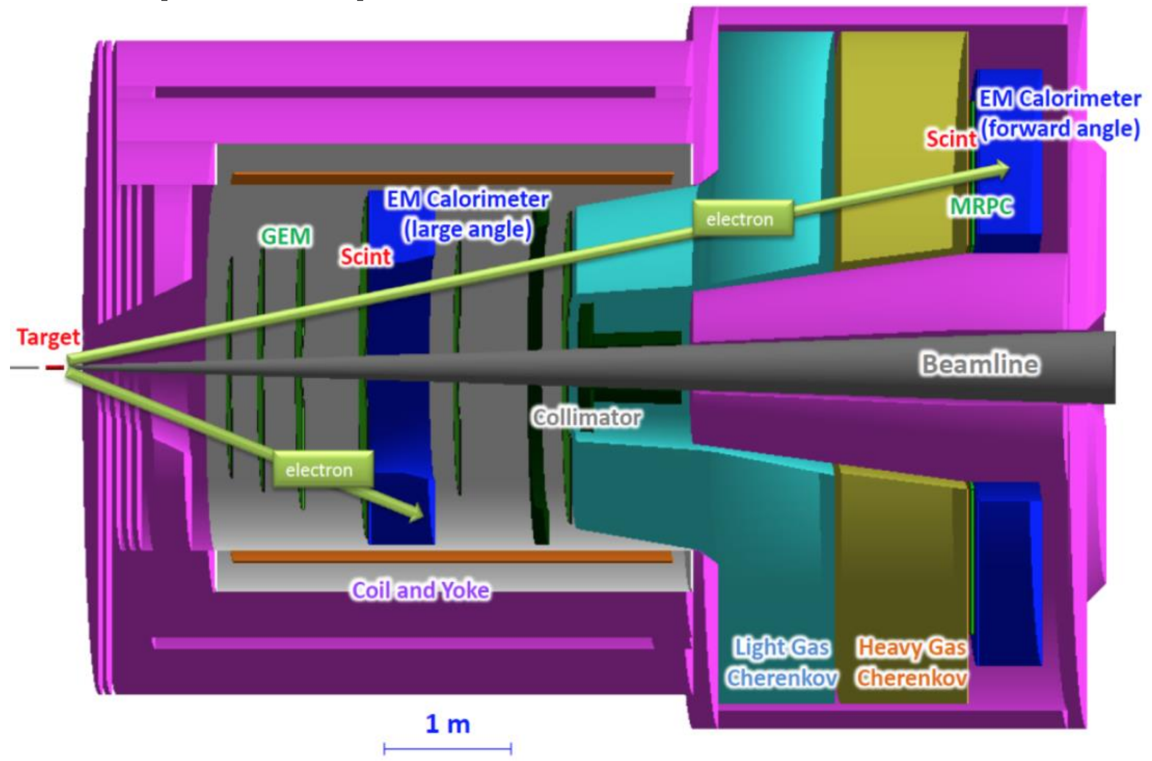
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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	Finished	Ongoing/Proposed	~8 years?

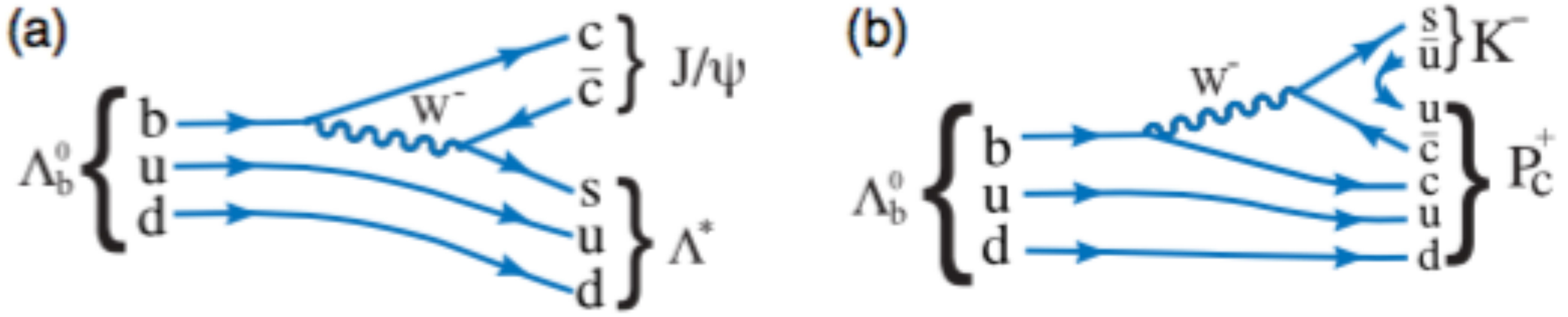
[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2\times10^{35}/cm^2/s$

THE LHC-B HIDDEN CHARM PENTAQUARK

DISCOVERY OF THE LHCB CHARMED PENTAQUARK

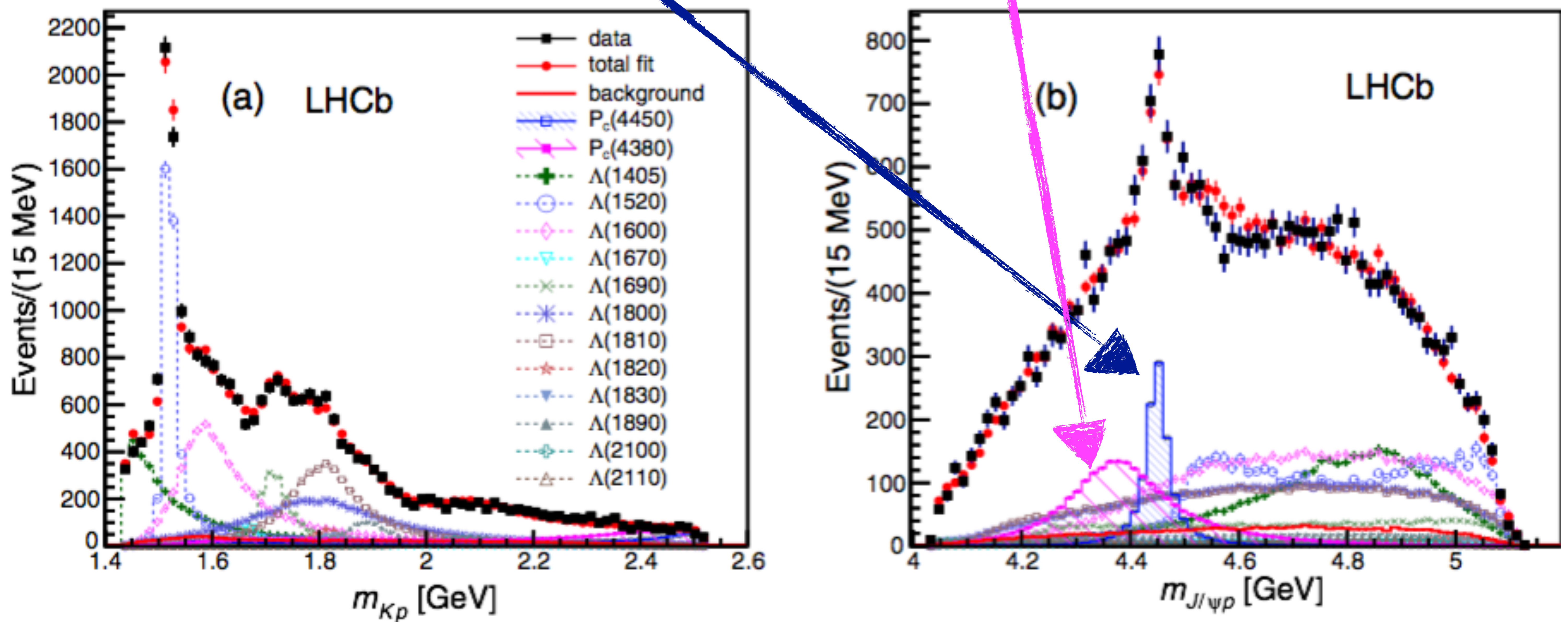
$$\Lambda_b \to \Lambda^* J/\Psi \to (K^- p) J/\Psi$$

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



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+

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?

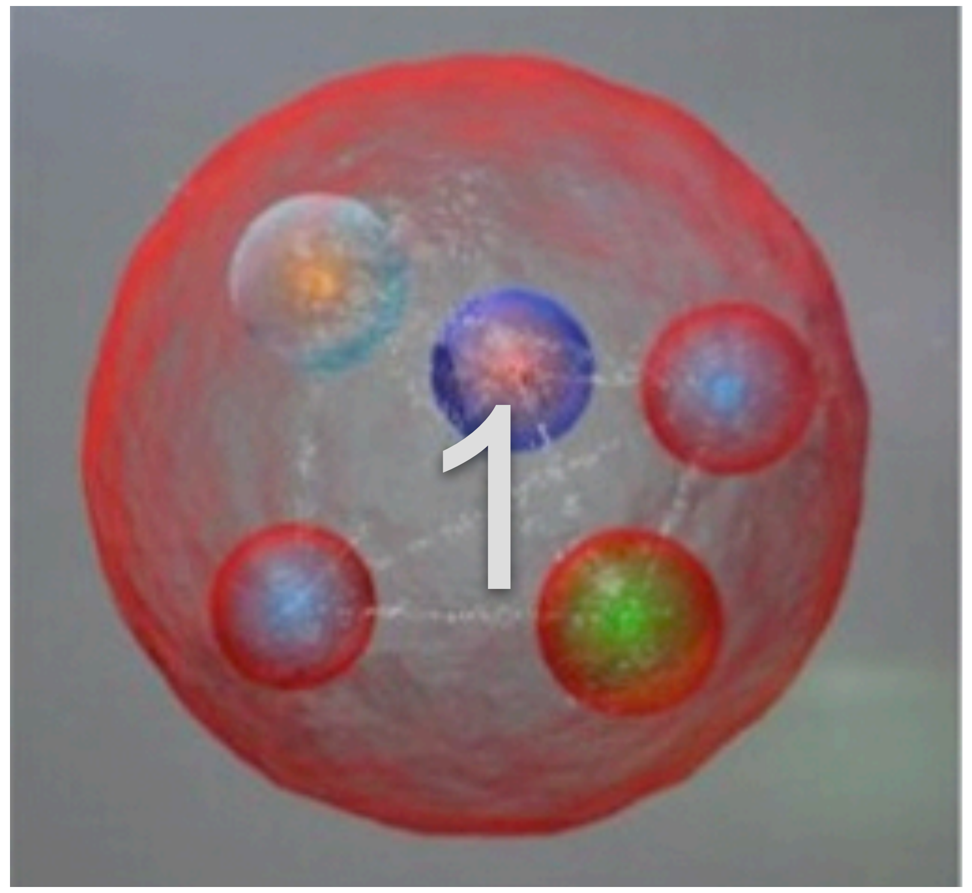
We can confirm this at JLab!

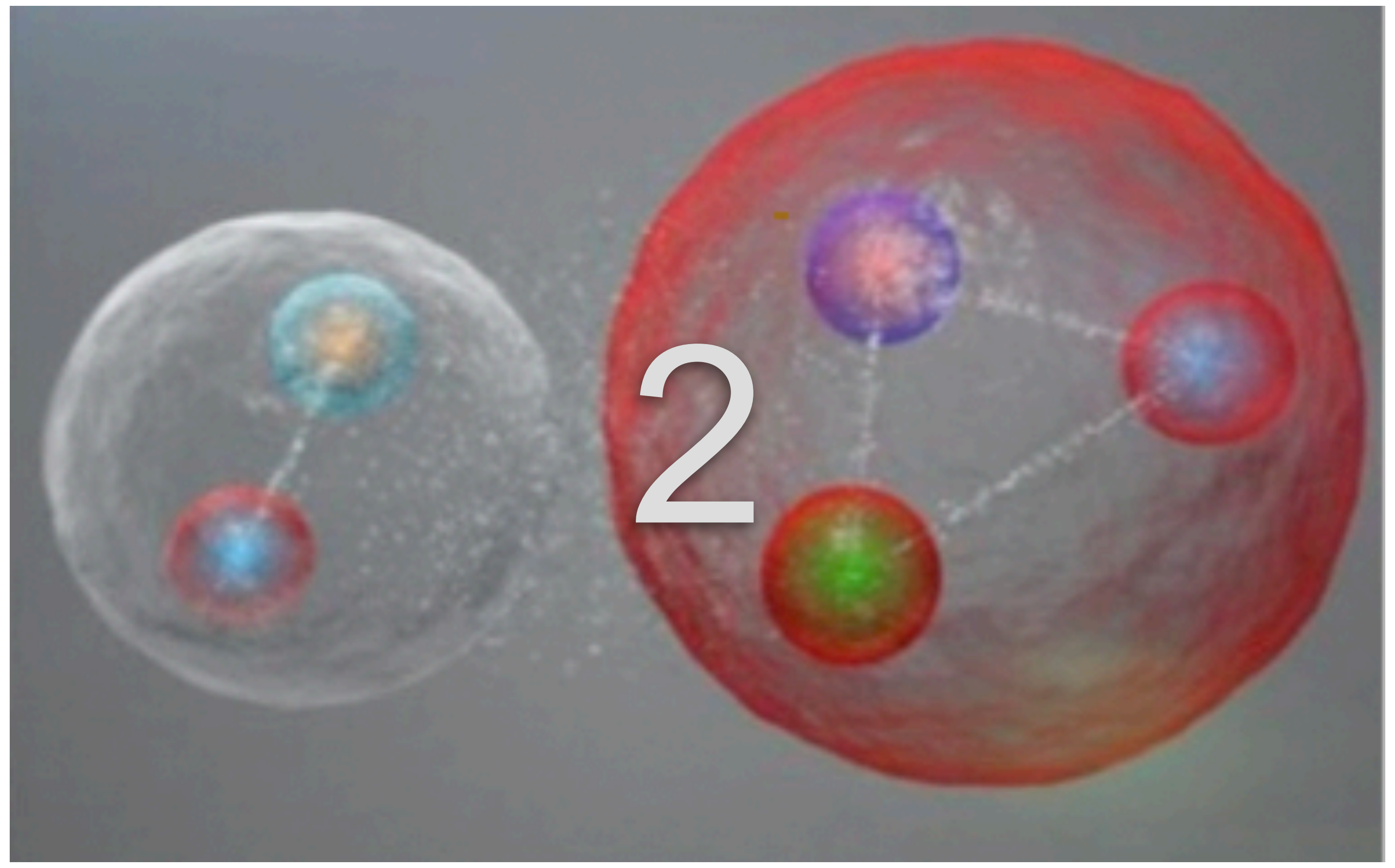
- LHCb definitely saw something, but was it a pentaquark?

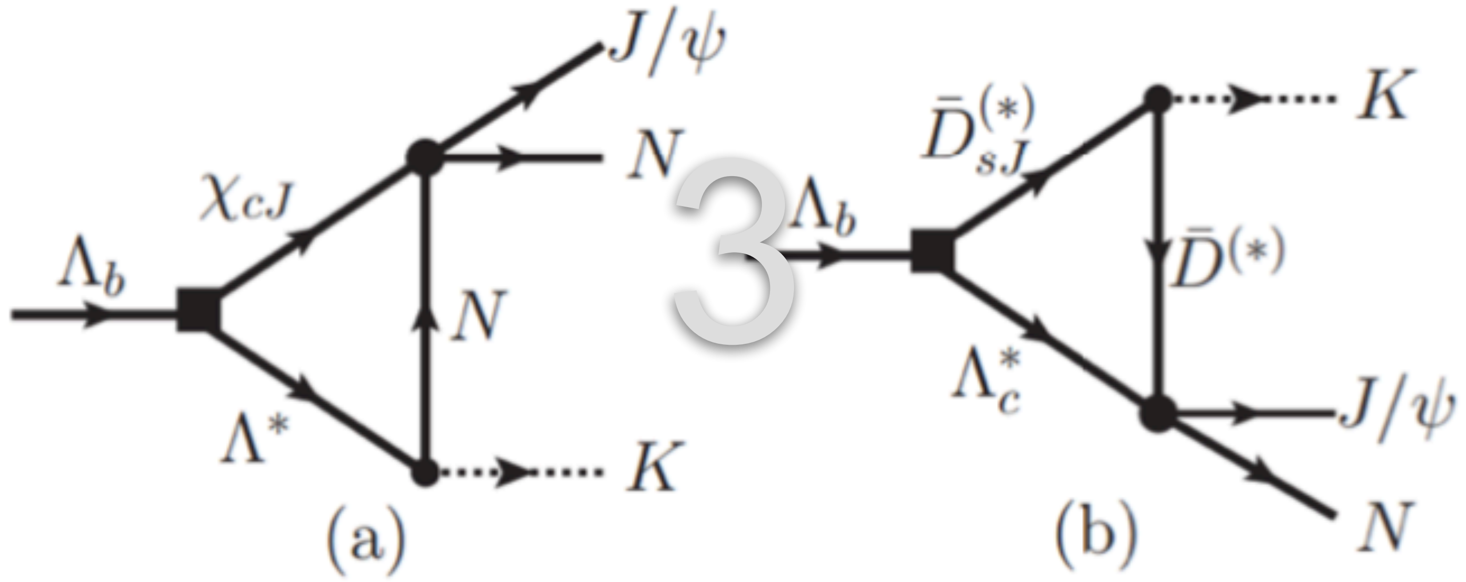
1. **"True" pentaquark state:** tightly bound 5-quark state
2. **"Molecular"** meson-baryon bound state
3. **Kinematic enhancement** through anomalous triangle singularity (ATS)

- 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





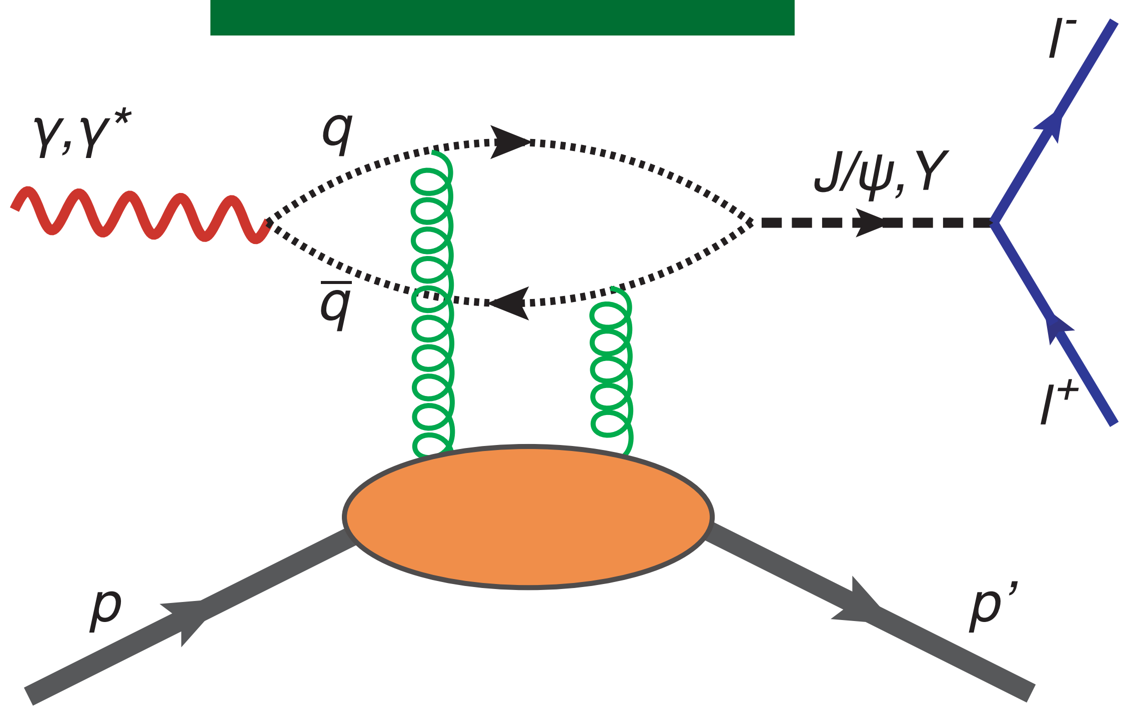


Jefferson Lab the perfect place to search for P_c in photoproduction

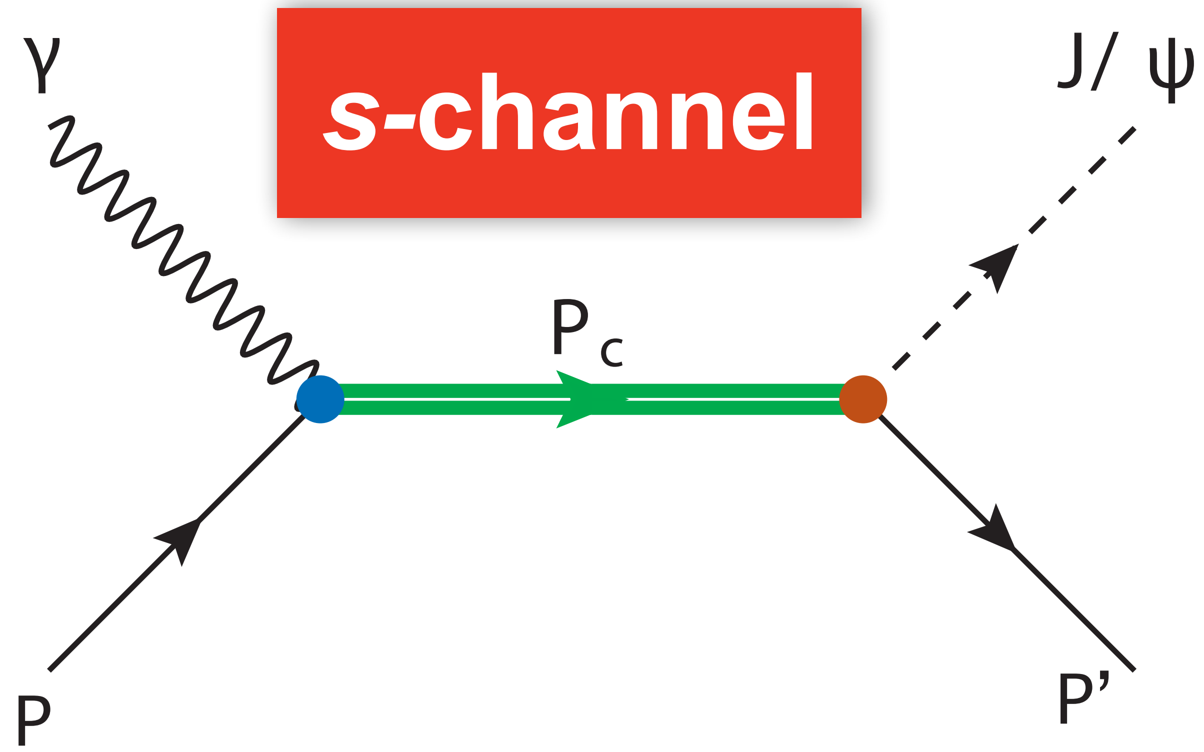
MAXIMIZING THE SENSITIVITY

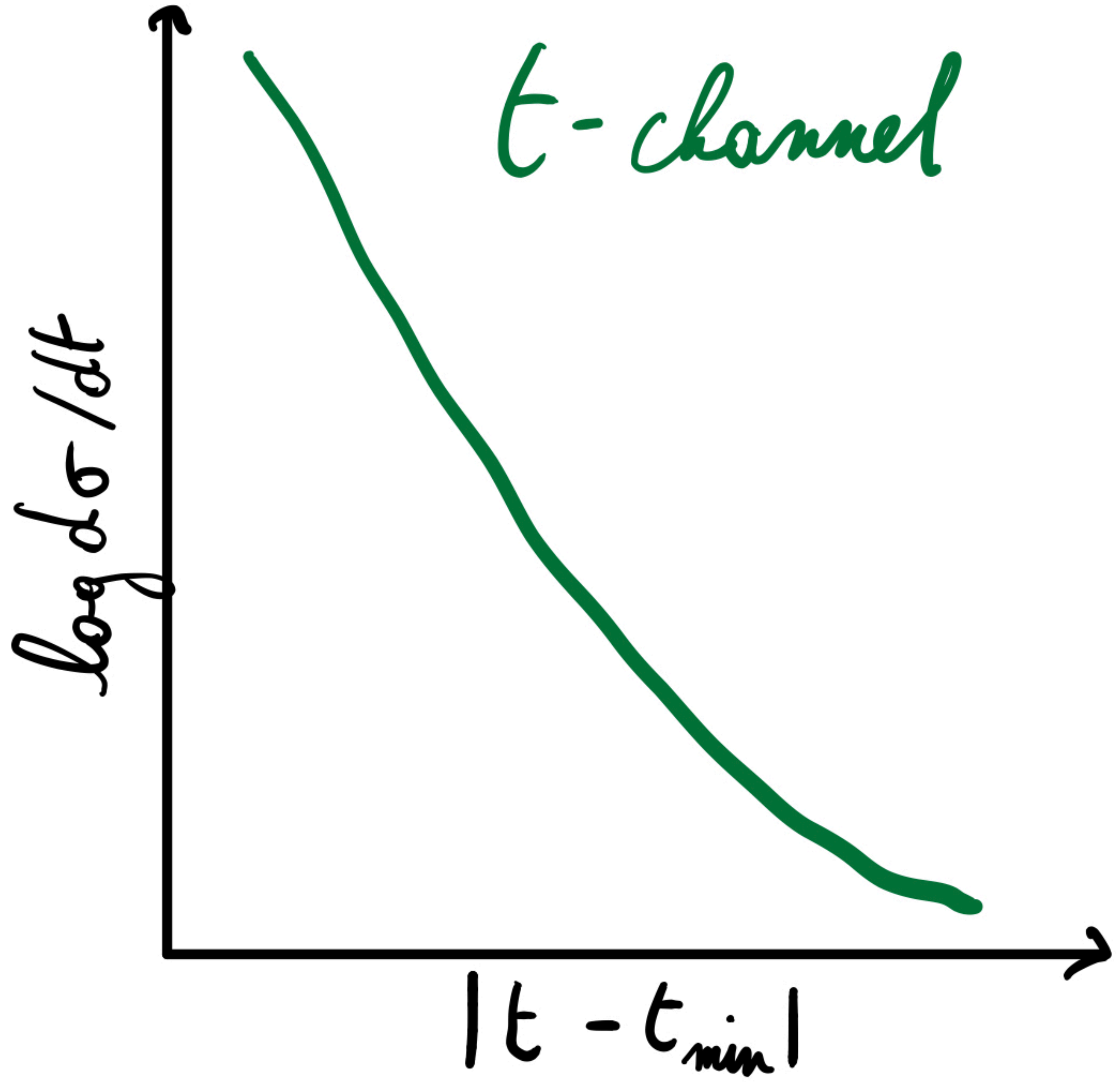
Maximum sensitivity for s-channel resonance at high *t*

***t*-channel**

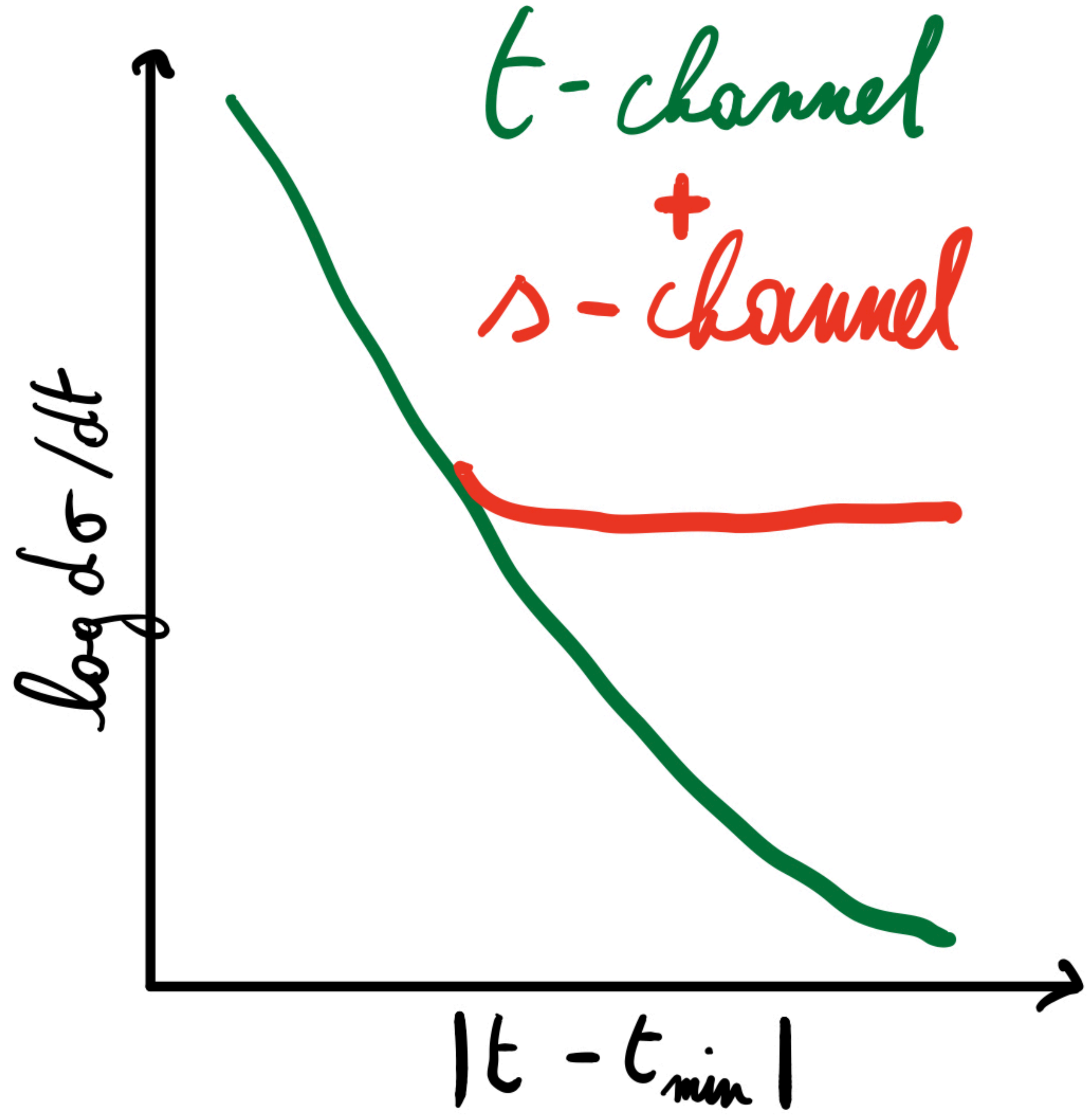


***s*-channel**





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



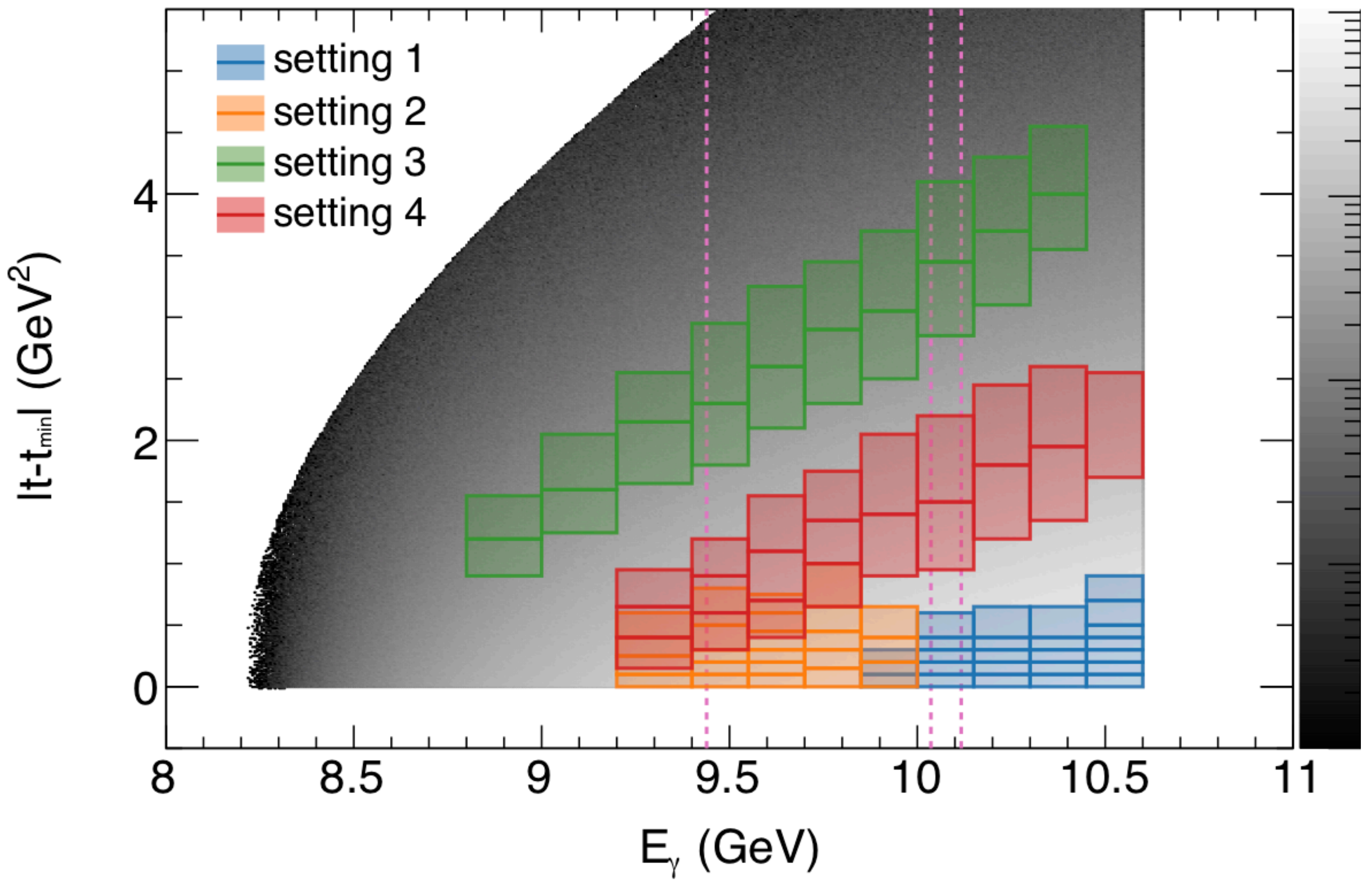
s-channel production more isotropic (flatter *t*-dependence)

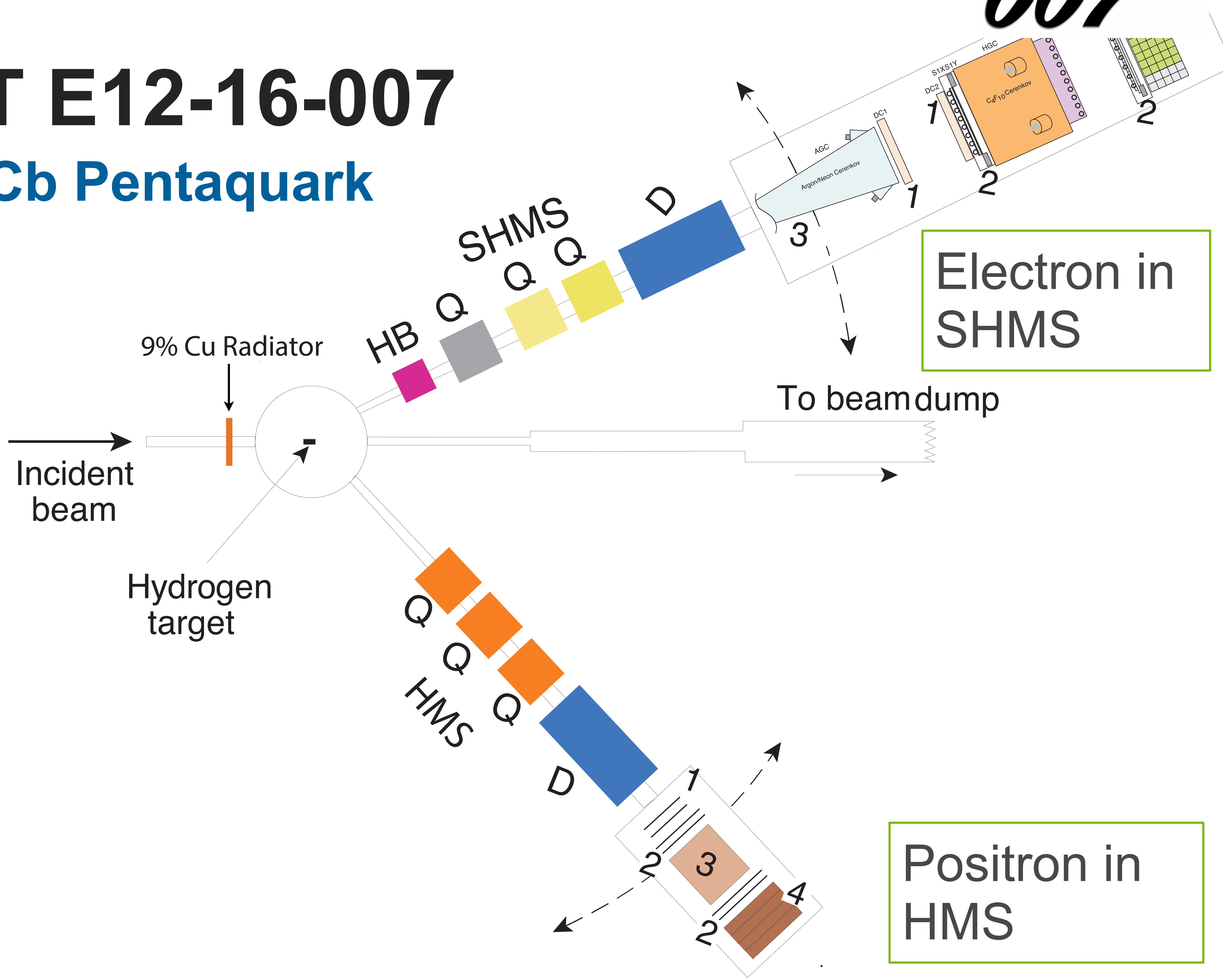
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

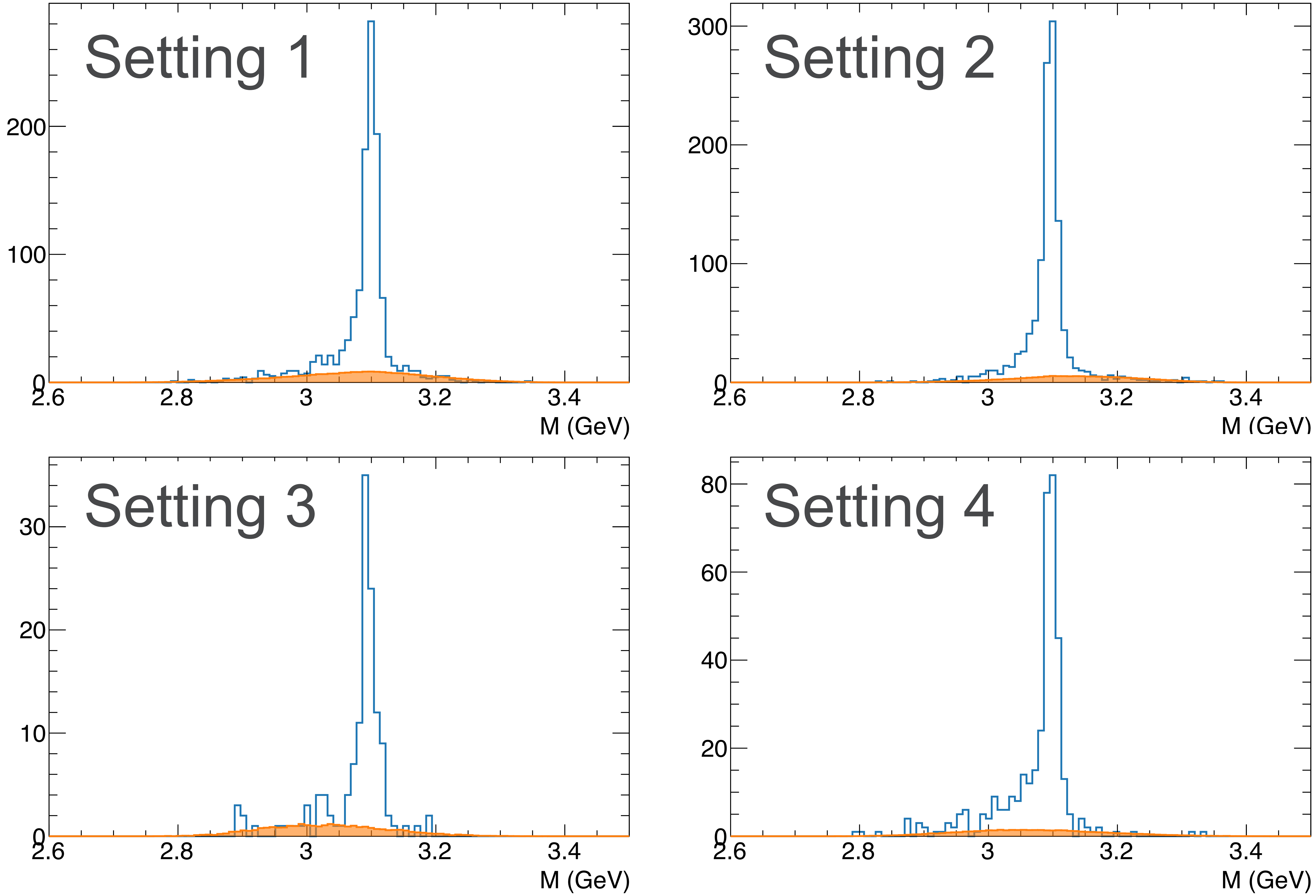
- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained





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

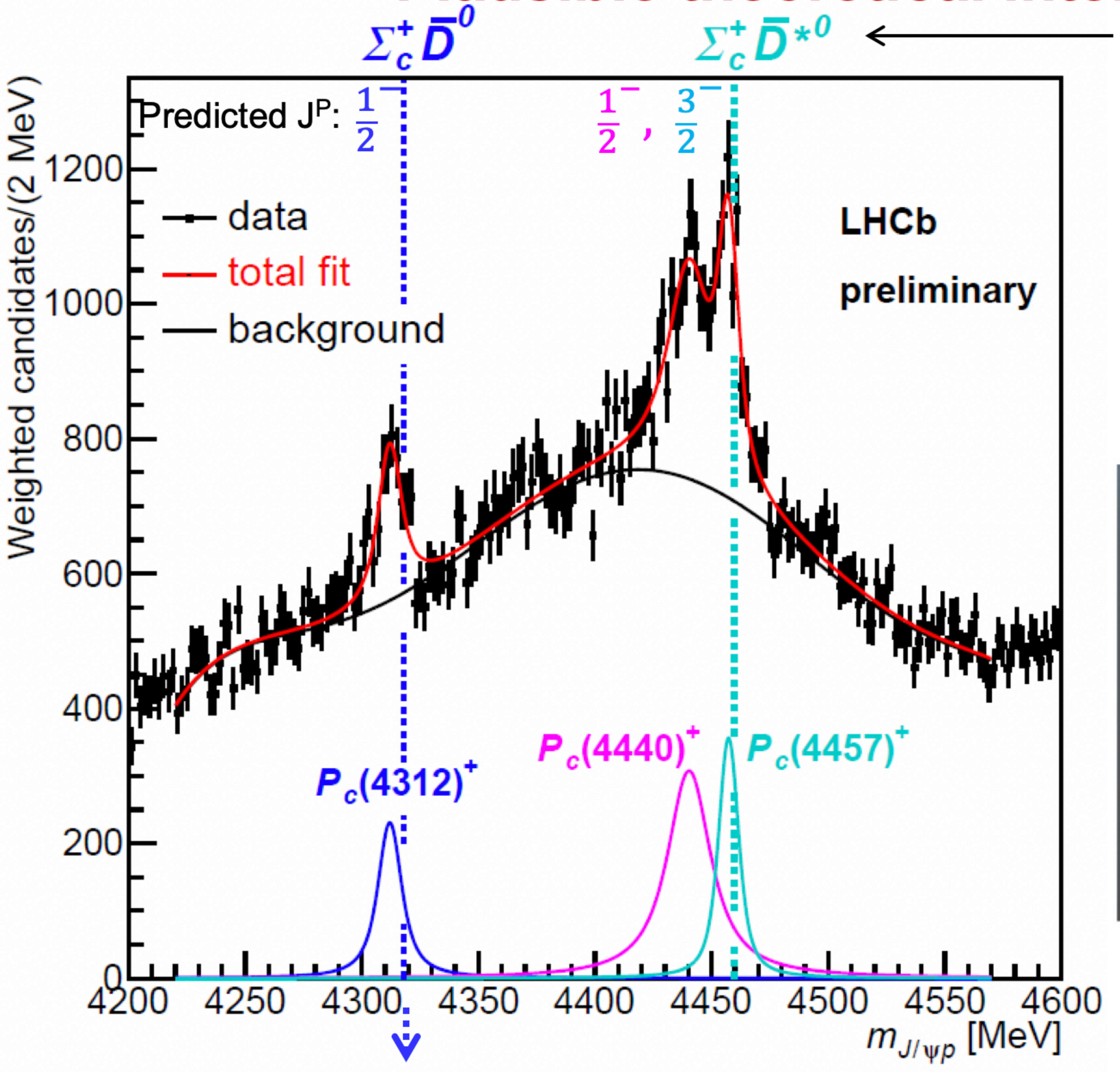


R. Aaij *et al.* (LHCb), Phys.Rev.Lett. 122 (2019) no.22, 222001

The plot thickens…

NEW LHC-B RESULTS WITH 10X STATISTICS

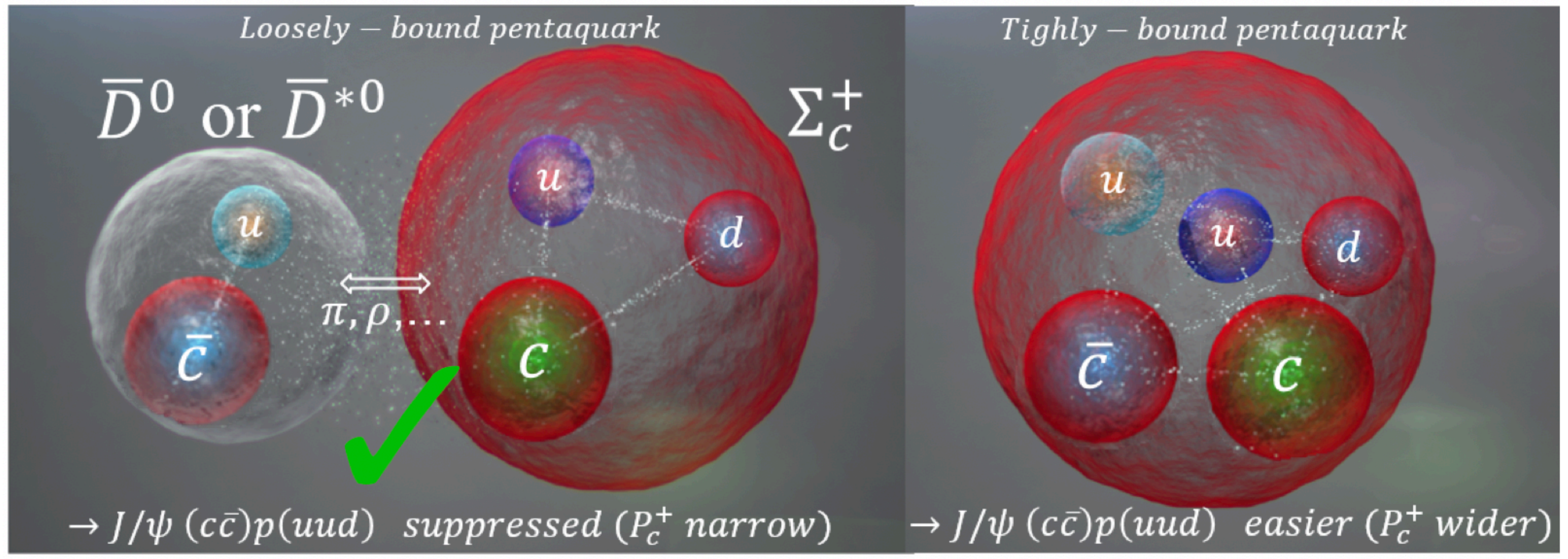
Plausible theoretical interpretation



← 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!

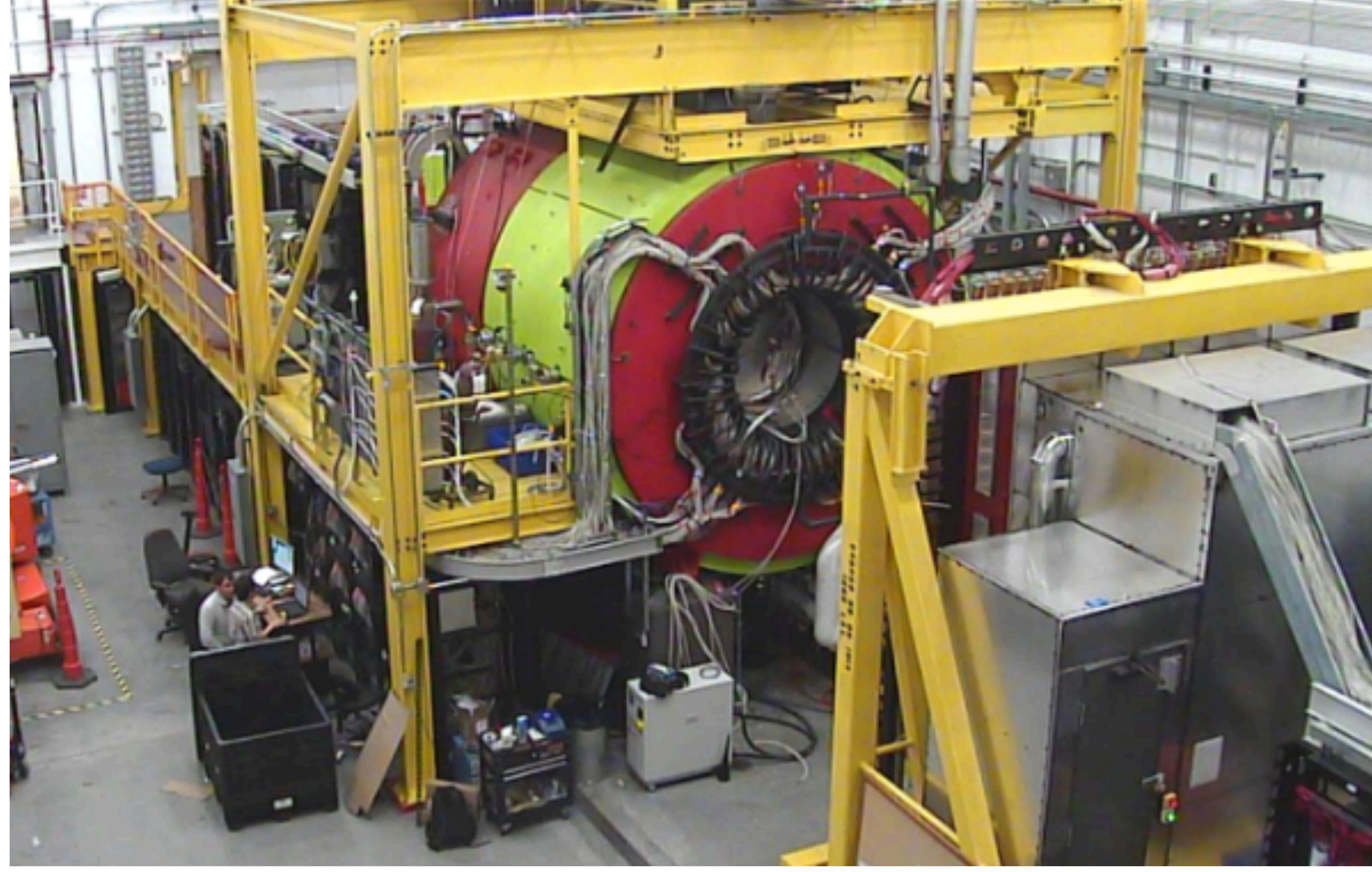


Existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of ρ-exchange

However, we need to measure J^Ps 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

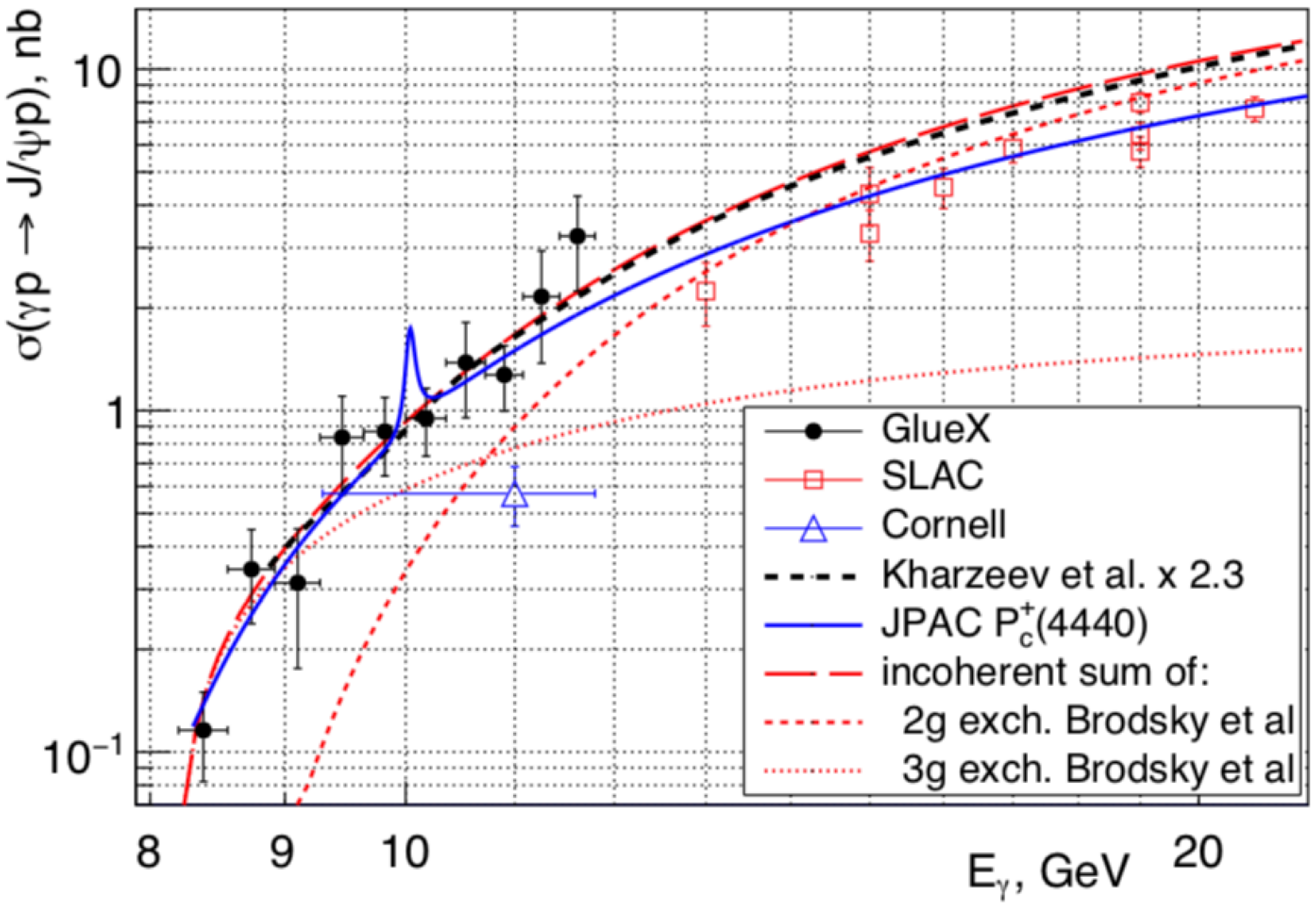
$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is (see backup slides).



…MEANWHILE IN HALL D

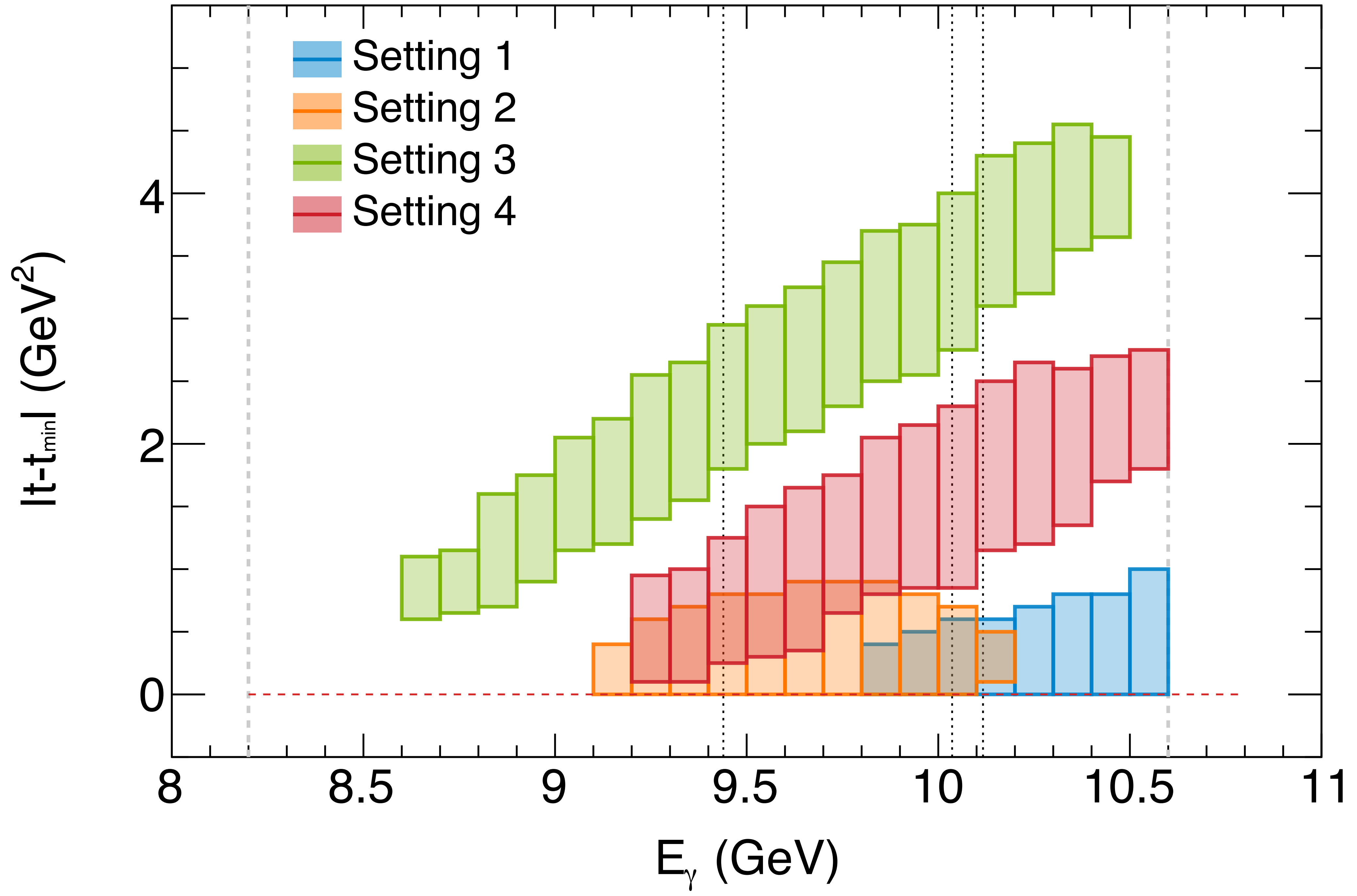
First J/ψ results from JLab, published in PRL (2019)

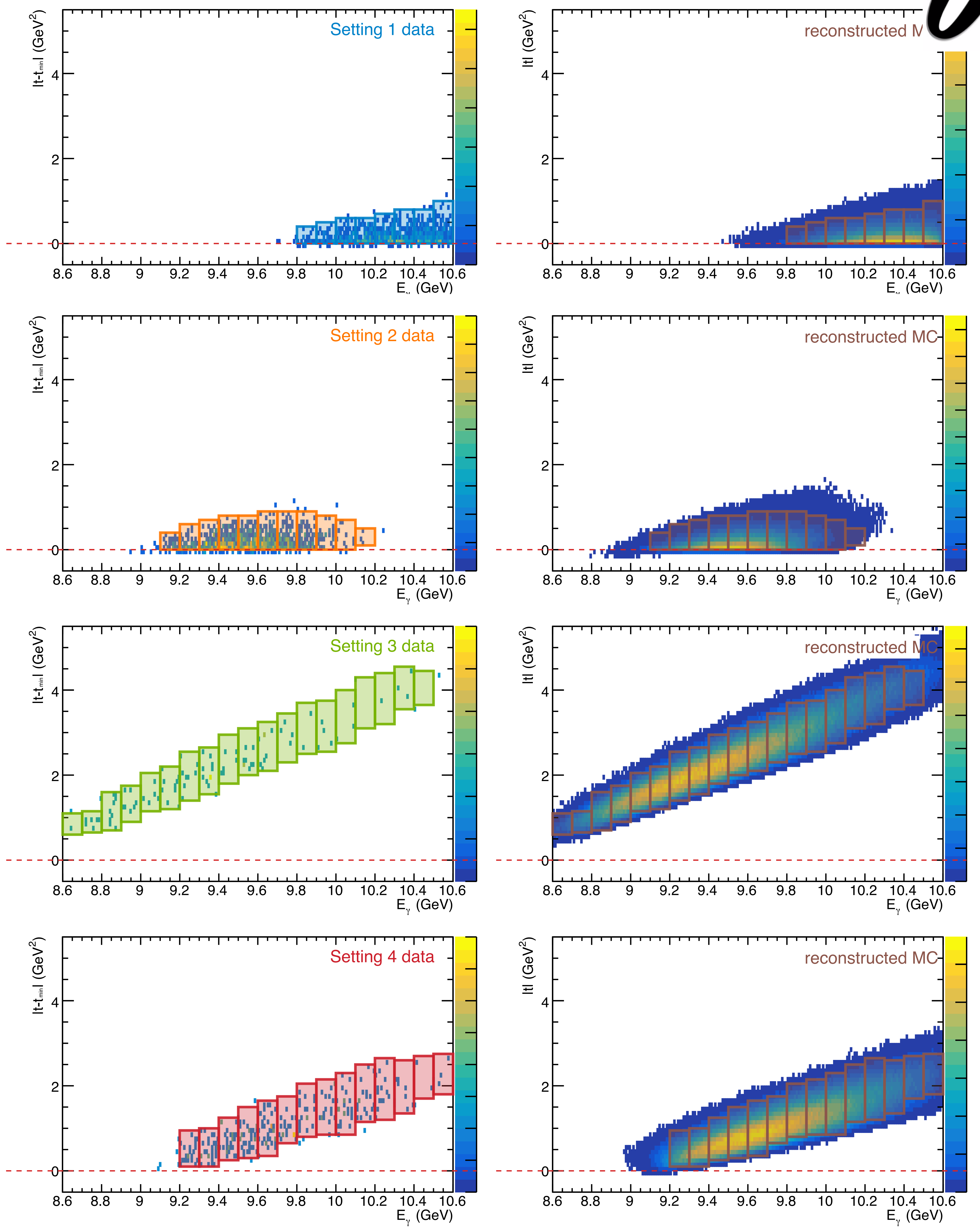
- 1D cross section (~469 counts)
- Also released 1D integrated *t*-dependence for photon energy between 10-11.8GeV
- Trends significantly higher than old measurements, but large 27% scale uncertainty
- Published upper limits for s-channel resonances at 90% confidence level
  - 1D limits on σ(γp ➟ Pc) x Γ(Pc➟J/ψ p): resp. <4.6nb, <1.8nb, and <3.9nb at 90%
  - Assuming spin-parity 3/2- for all 3 states, Γ(Pc(3/2-) ➟ J/ψ p): resp: <4.6%, <2.3%, and <3.8%
    note: these coupling numbers are model dependent and vary by factors based on the spin-parity assumption - they increase for 1/2- and decrease for 5/2-
- Still consistent with some pentaquark models



BINNING

Binning chosen to maximize the available precision in E_γ to search for Pc signal



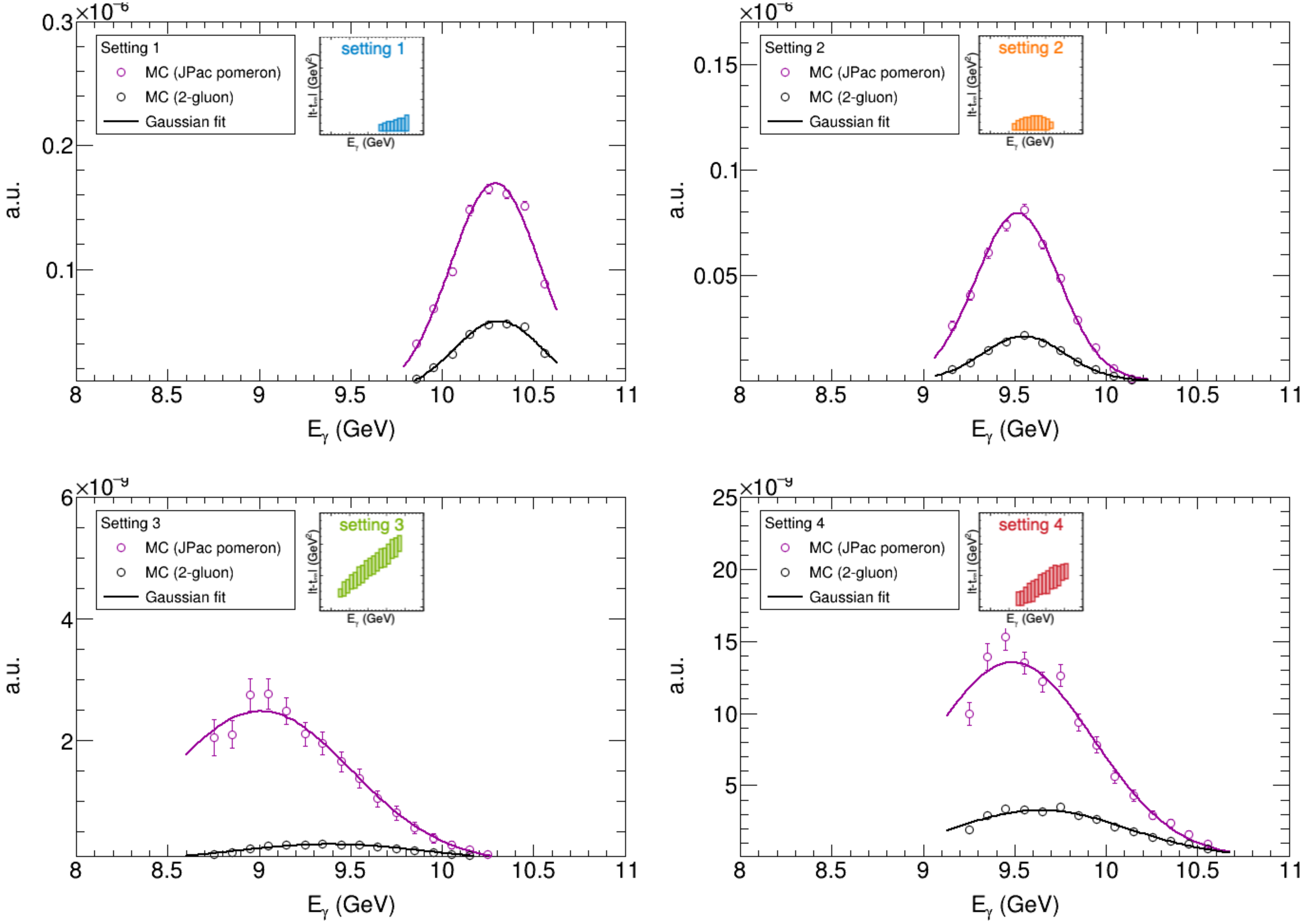


WHAT DOES A PURE T-CHANNEL BACKGROUND LOOK LIKE?

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

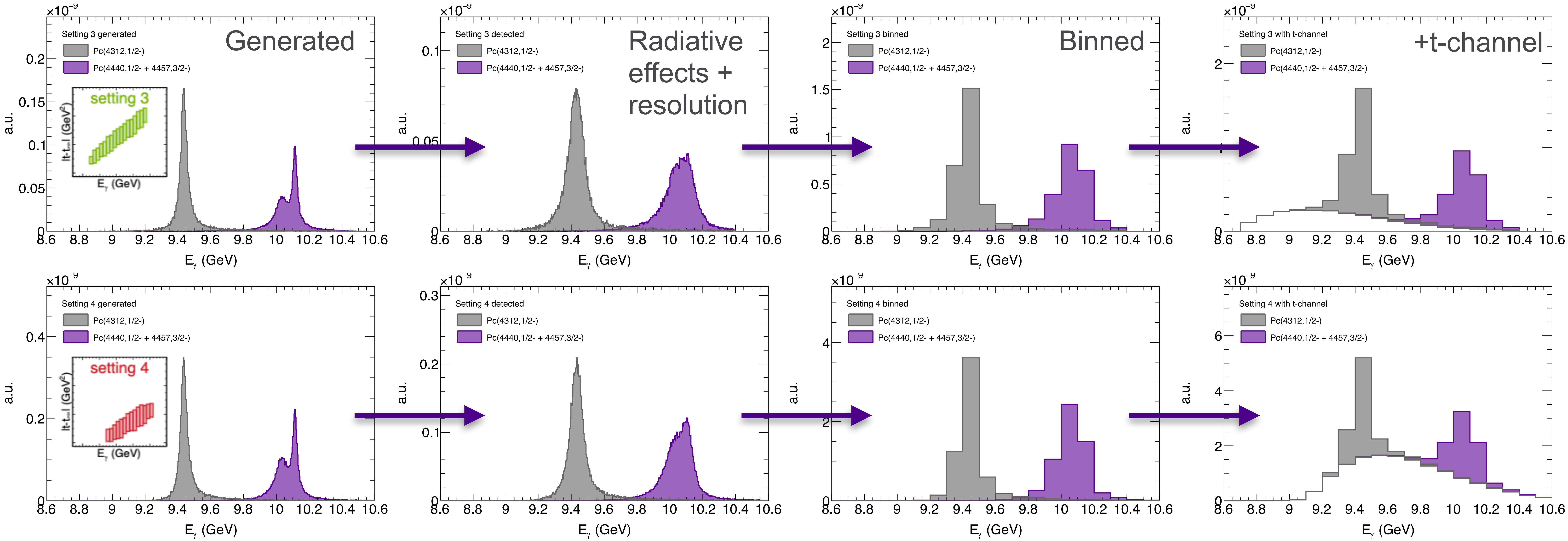
A **gaussian shape**, mostly driven by the spectrometer acceptance, does a good job describing both (very different!) Monte-Carlo models

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



PENTAQUARK MODEL

Need to know pentaquark signatures in our experimental sample

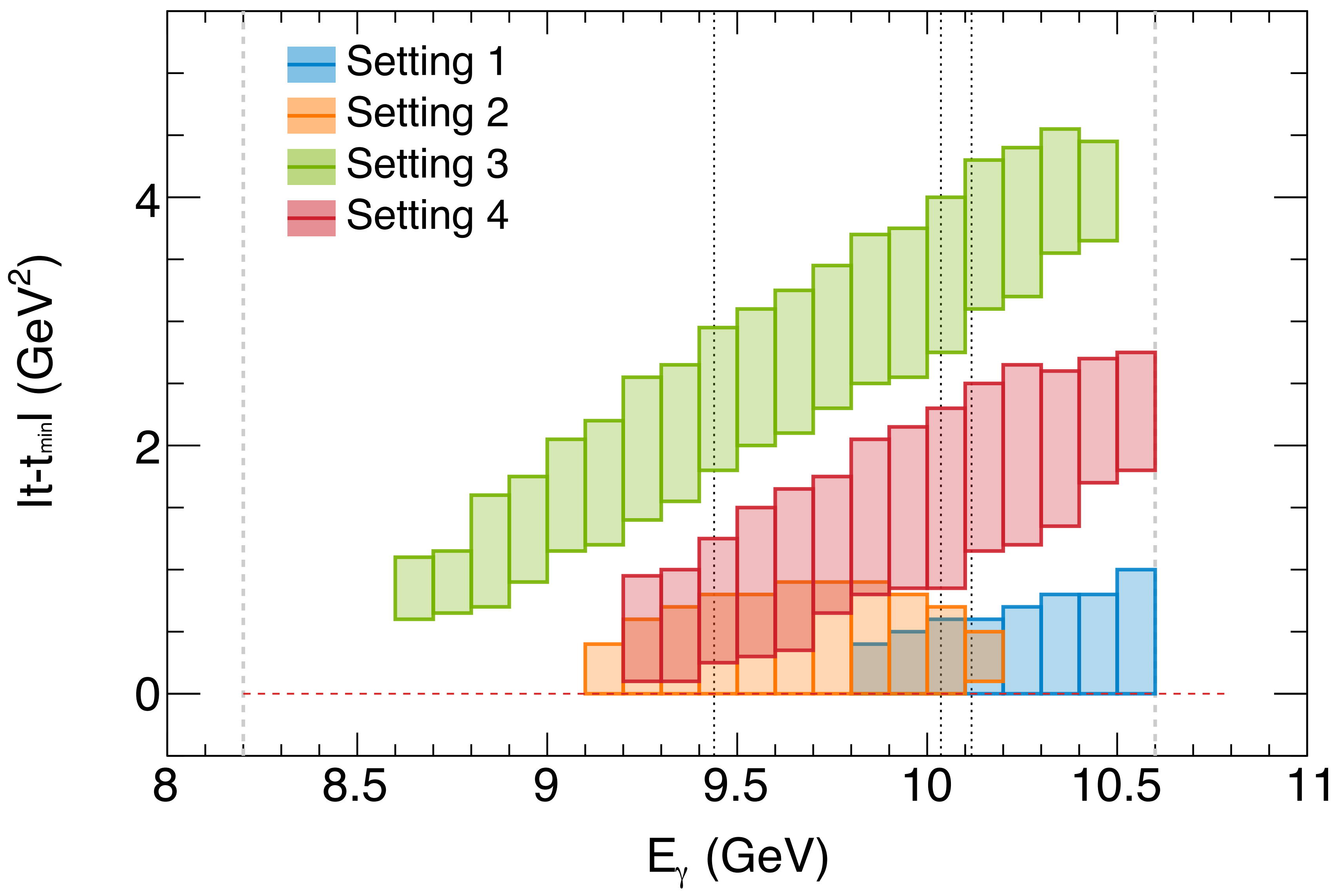


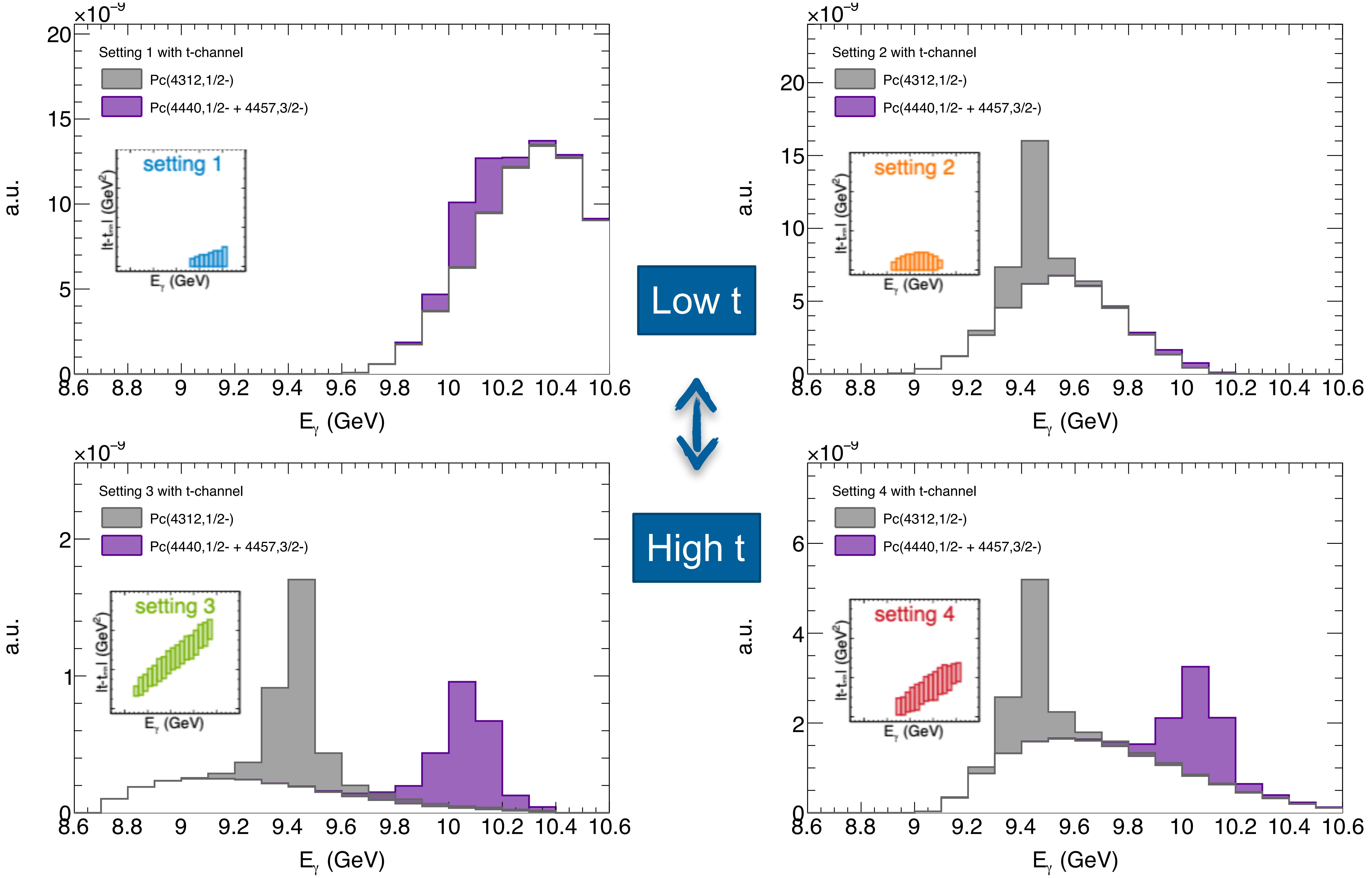
P_C resonances calculated at GlueX 90% upper limit using MC (with JPacPhoto + Detector Simulation)

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





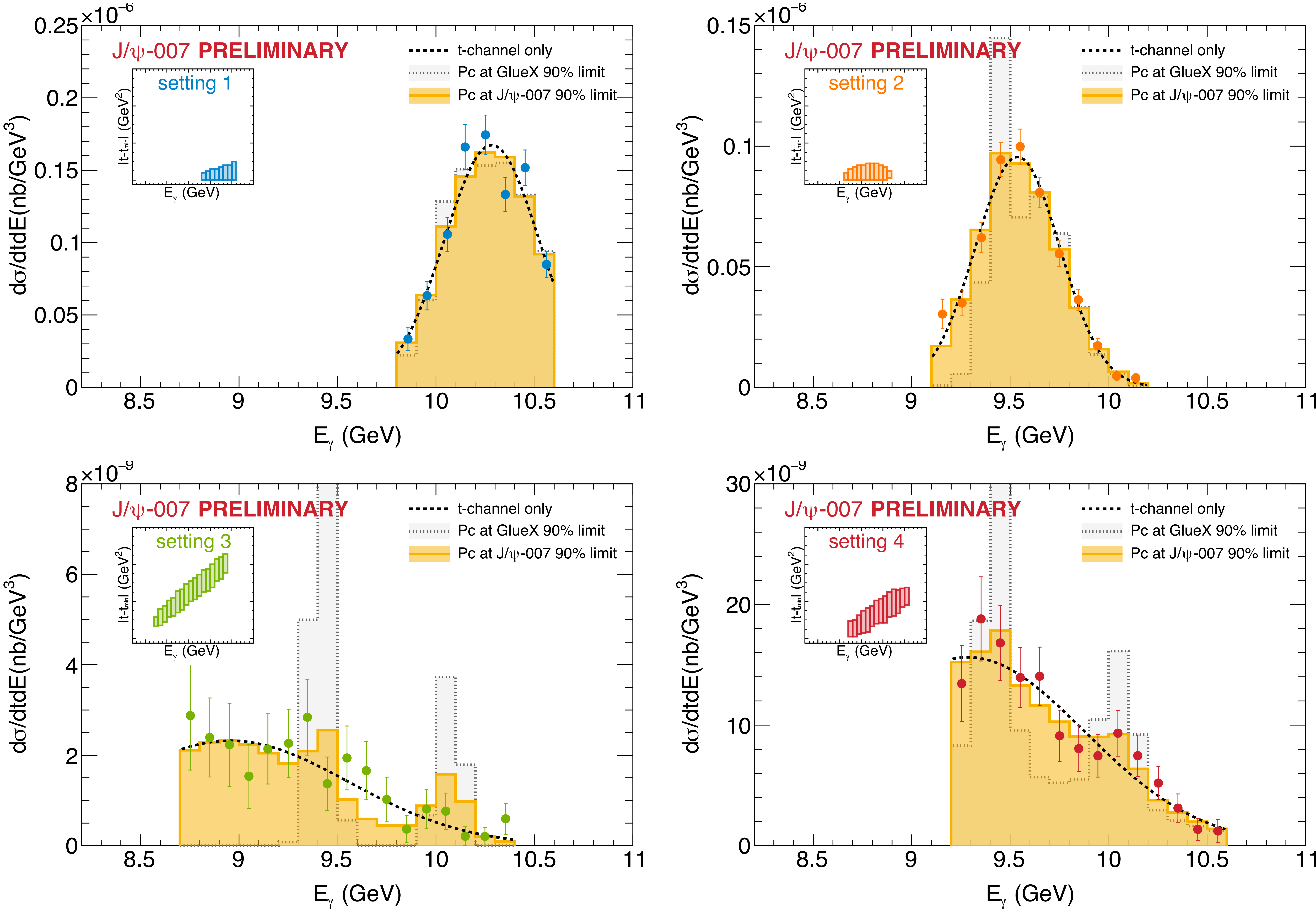
4% scale uncertainty on cross section

SIGNIFICANCE FIT

Fit 1: bare Gaussian shape describes the cross section well

Fit 2: Gaussian shape with Pc (from MC) at GlueX upper limit (90% confidence interval). Presence of the large resonances creates a lot of 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 (see next slide).



4% scale uncertainty on cross section limit

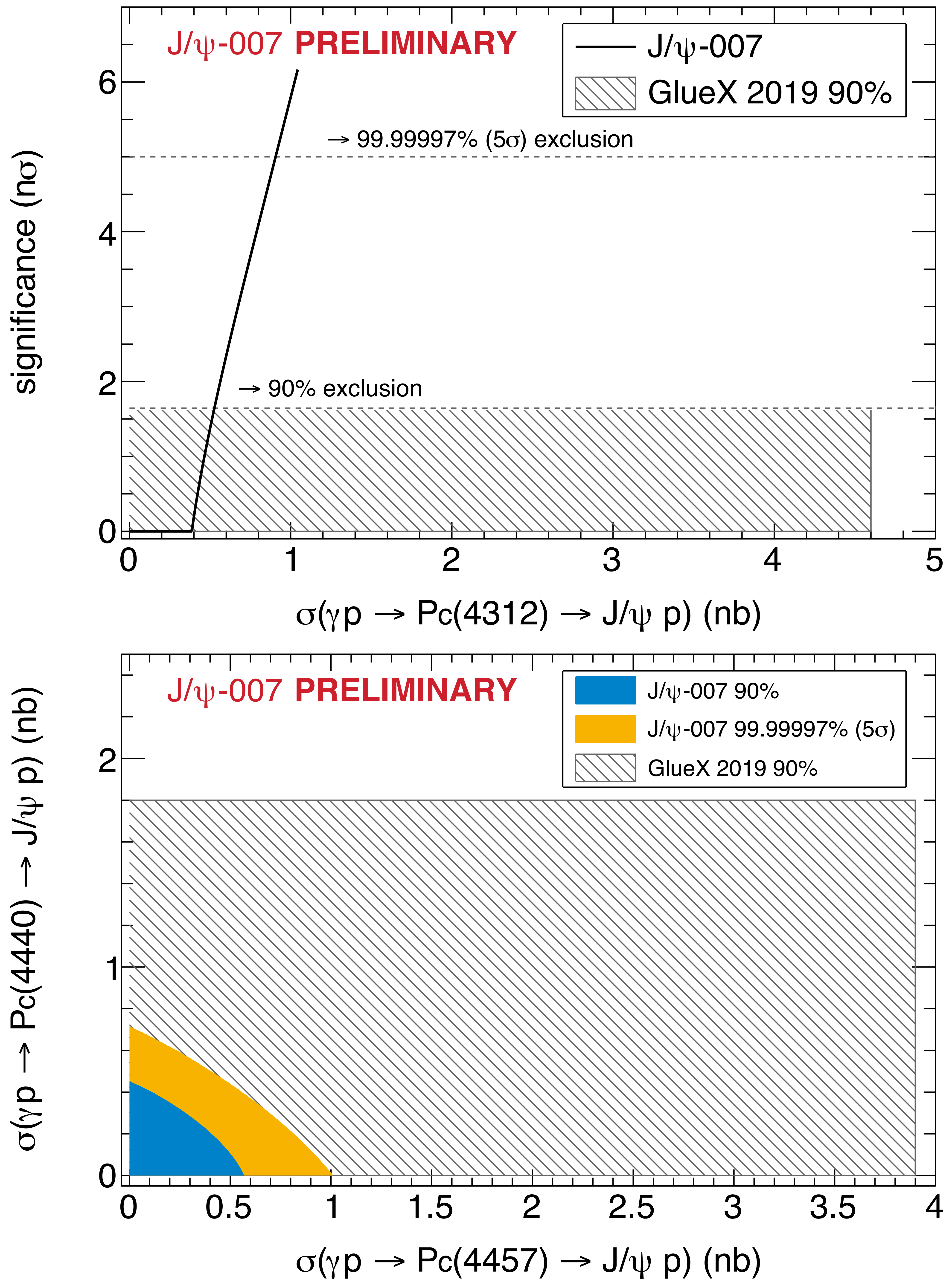
RESULTS AND IMPLICATIONS

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



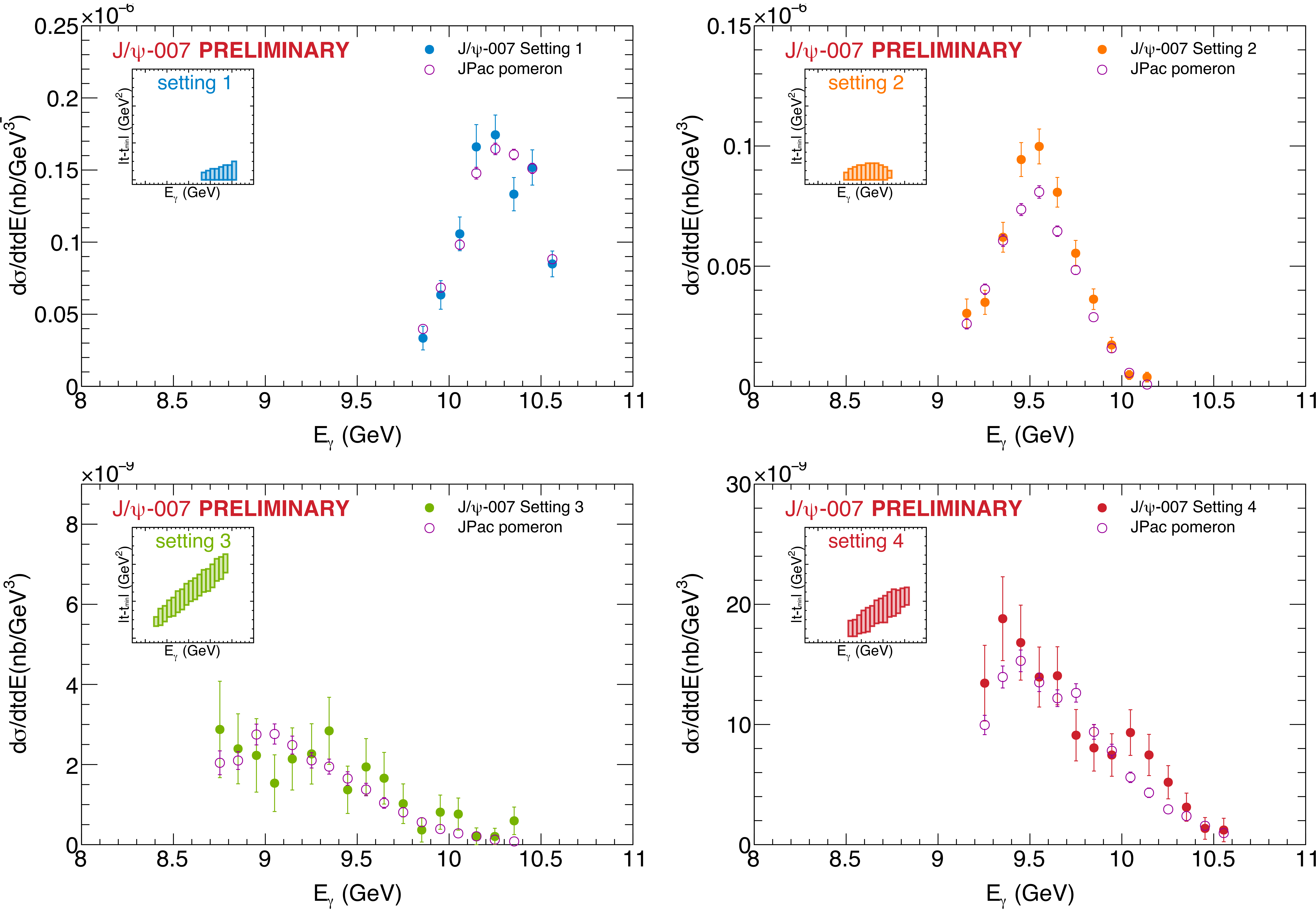
4% scale uncertainty on cross section

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 slide)



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MORE J/Ψ RESULTS TO COME…

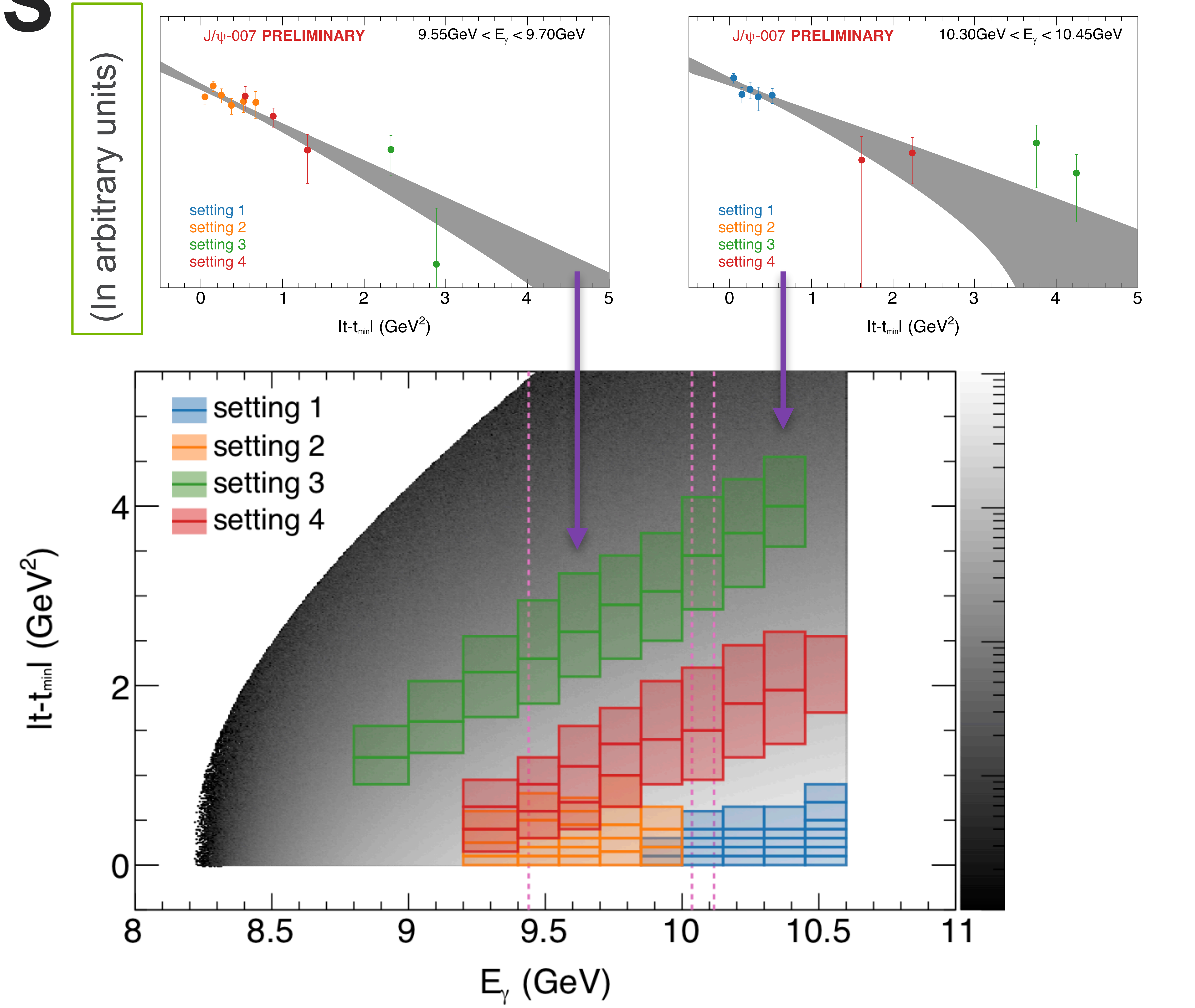
2D cross sections will provide access to the matter radius of the proton

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

2D analysis in advanced state, results expected soon.



S. Joosten

ORIGIN OF PROTON MASS AND THE MATTER STRUCTURE OF HADRONS

X. Ji, PRL 74, 1071 (1995) & PRD 52, 271 (1995)

PROTON MASS: REST-FRAME DECOMPOSITION

Disentangling the proton mass in its rest frame

- Proton mass is the matrix element of the QCD Hamiltonian in the proton rest frame

$$H_{\rm QCD} = \int d^3x T^{00}(0, \vec{x})$$
$$= H_q + H_m + H_g + H_a$$

At leading order:

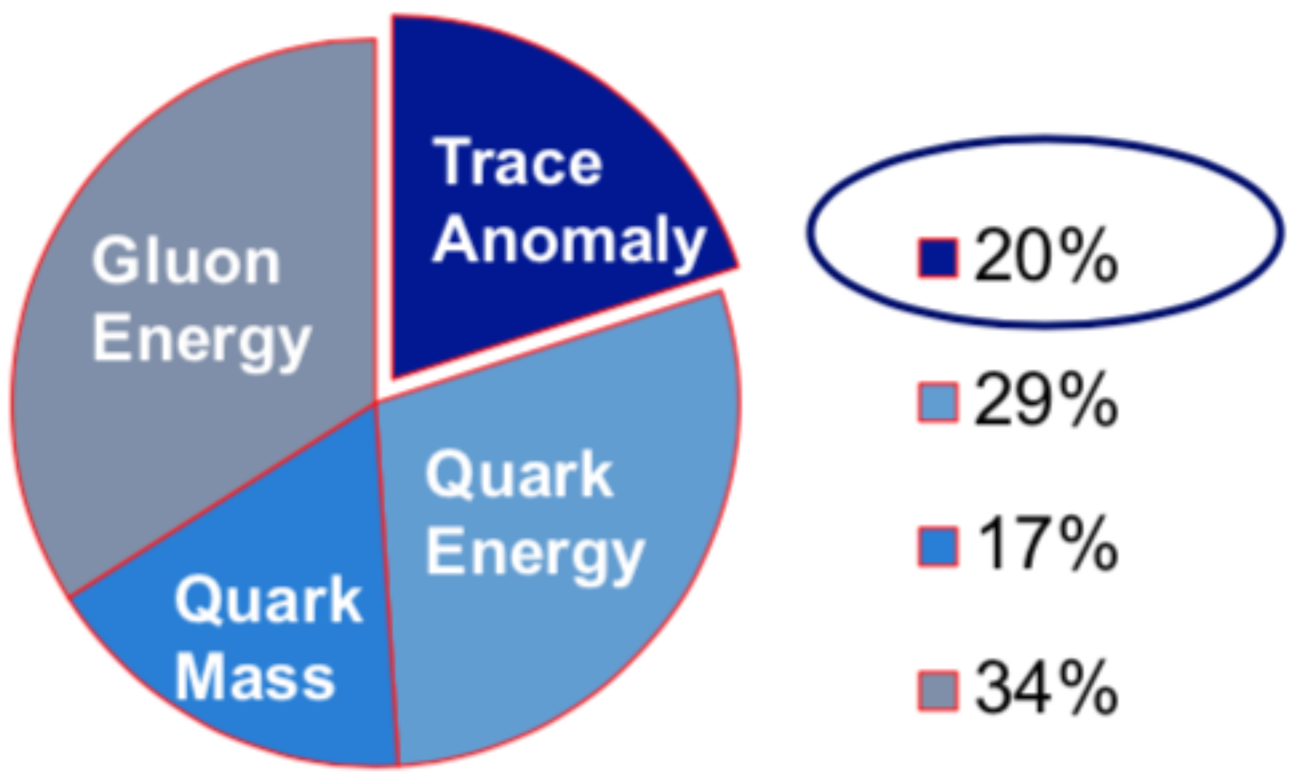
$$M_N = M_q + M_m + M_g + M_a$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M$$

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} bM$$

$$M_g = \frac{3}{4}(1-a)M$$

$$M_a = \frac{1}{4}(1-b)M$$



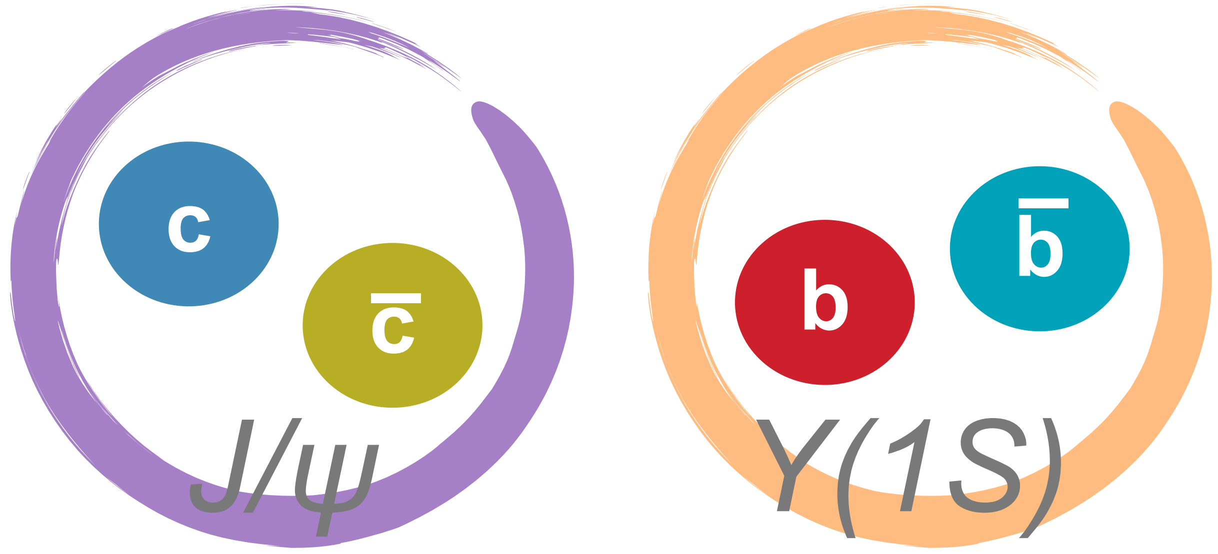
For μ = 1GeV

a(μ) related to PDFs, well constrained

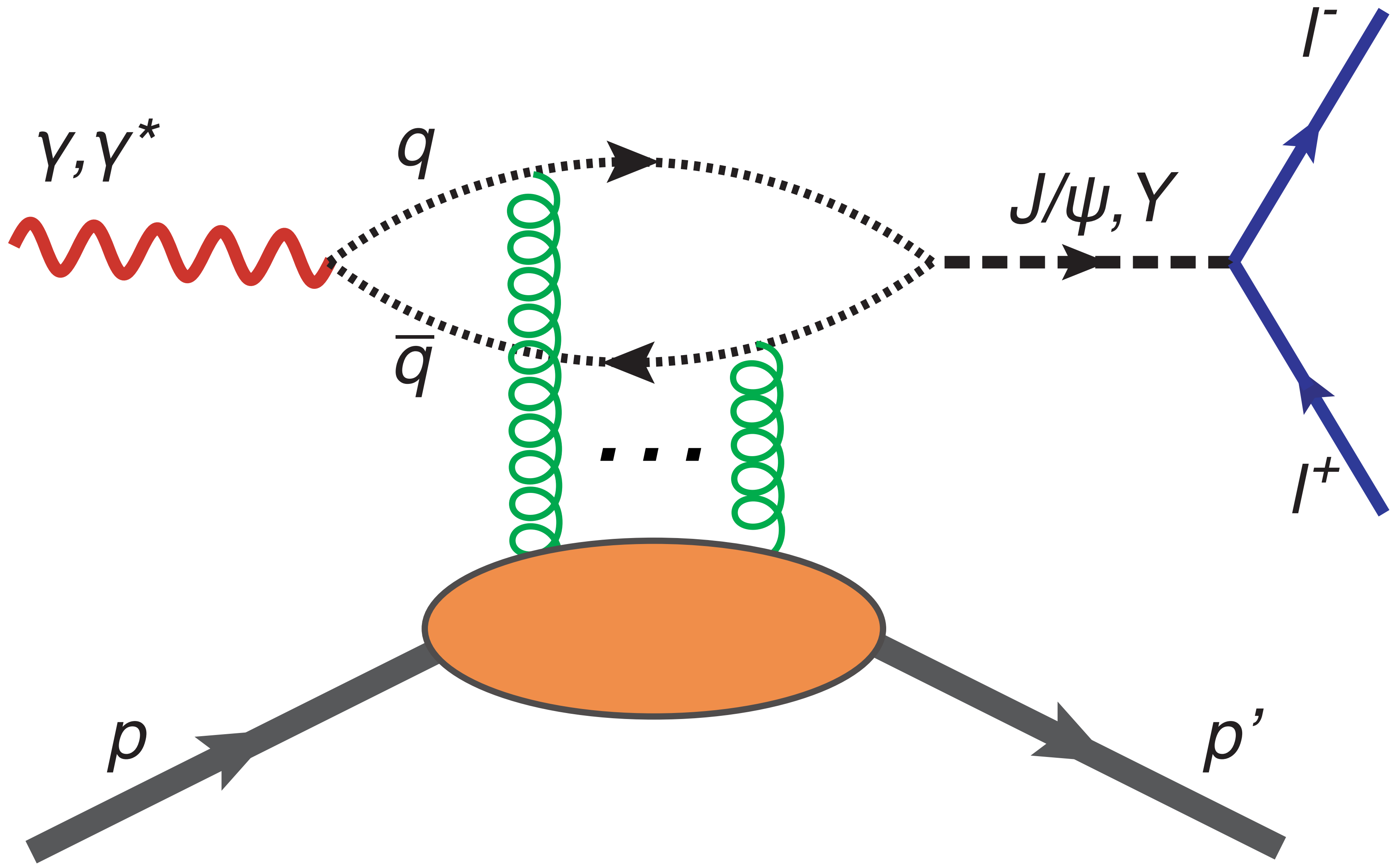
b(μ) related trace anomaly, unconstrained

CAN WE PROBE THE QUANTUM ANOMALOUS ENERGY?

…Quarkonium production near threshold!



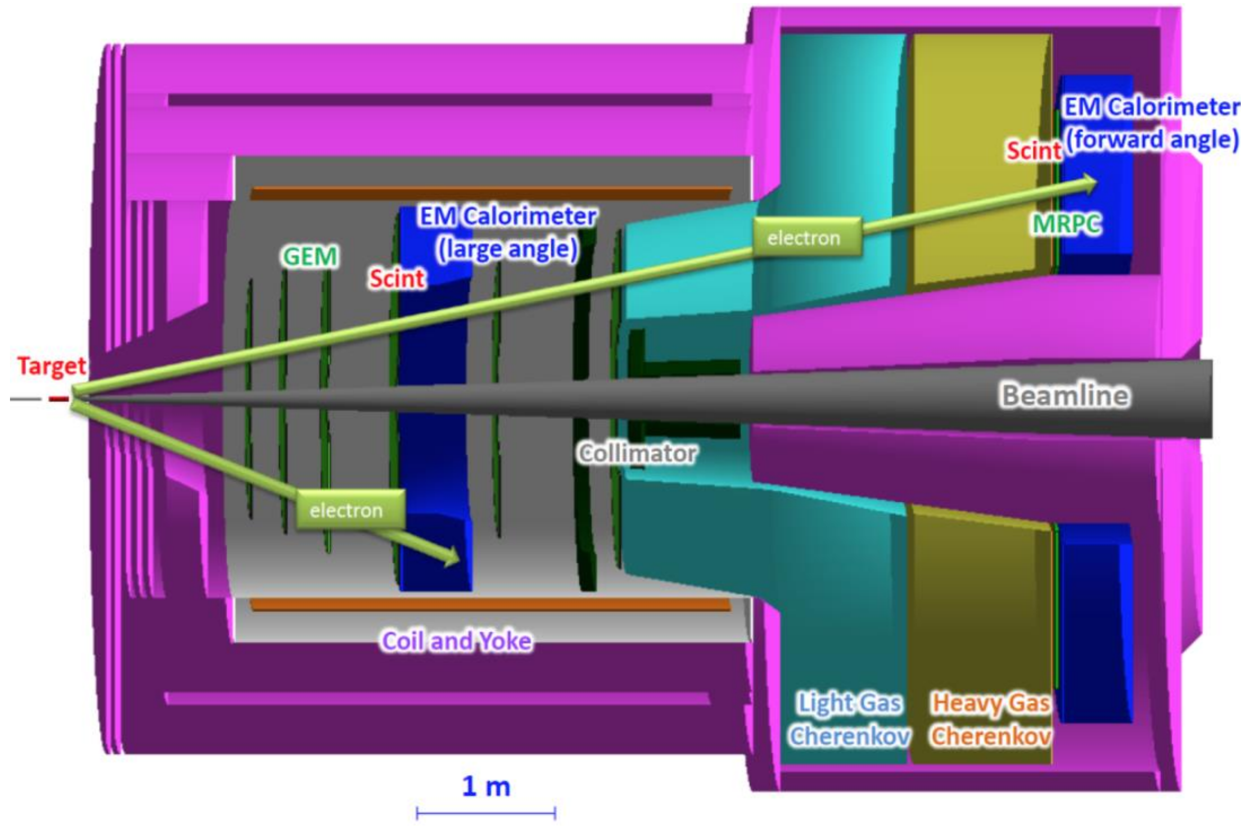
- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established
- Solution found in **low energy scattering** (production near threshold)
  - In VMD: anomaly might be related to quarkonium-proton cross-section near threshold in the forward limit.
  - In large-mass QCD factorization, related to the gluonic form-factor near threshold.

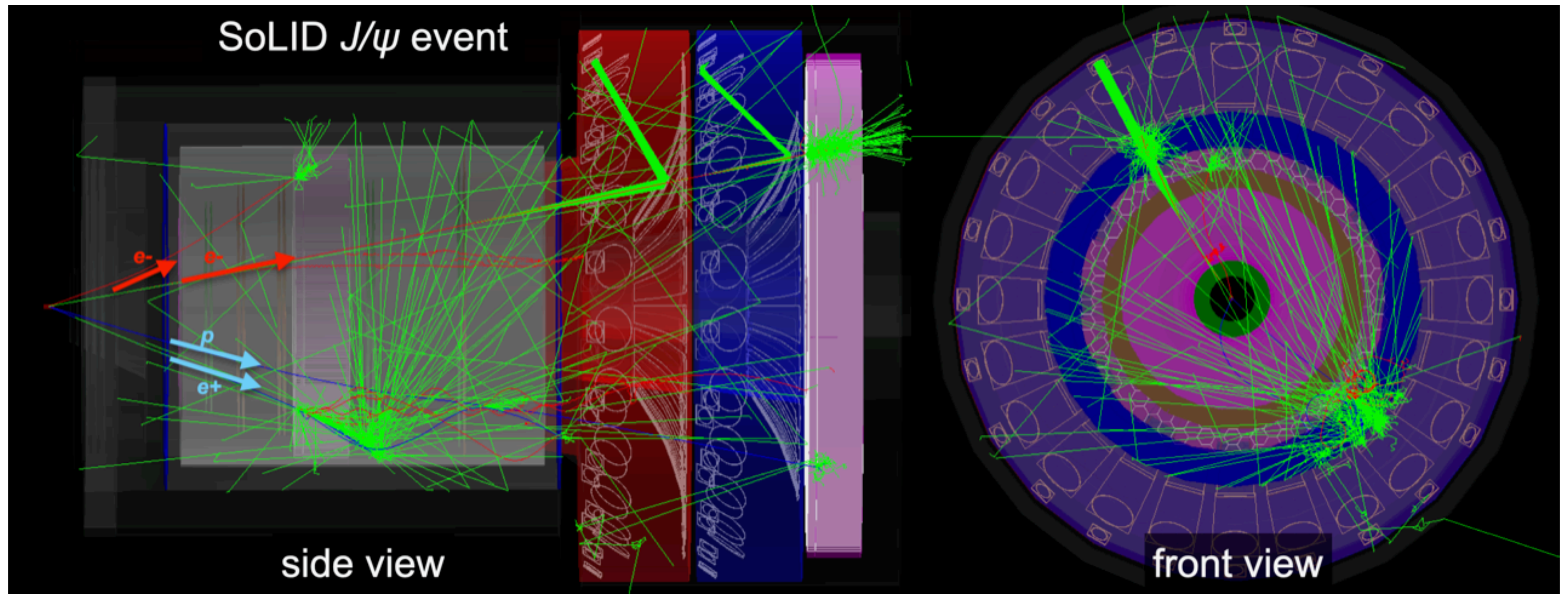


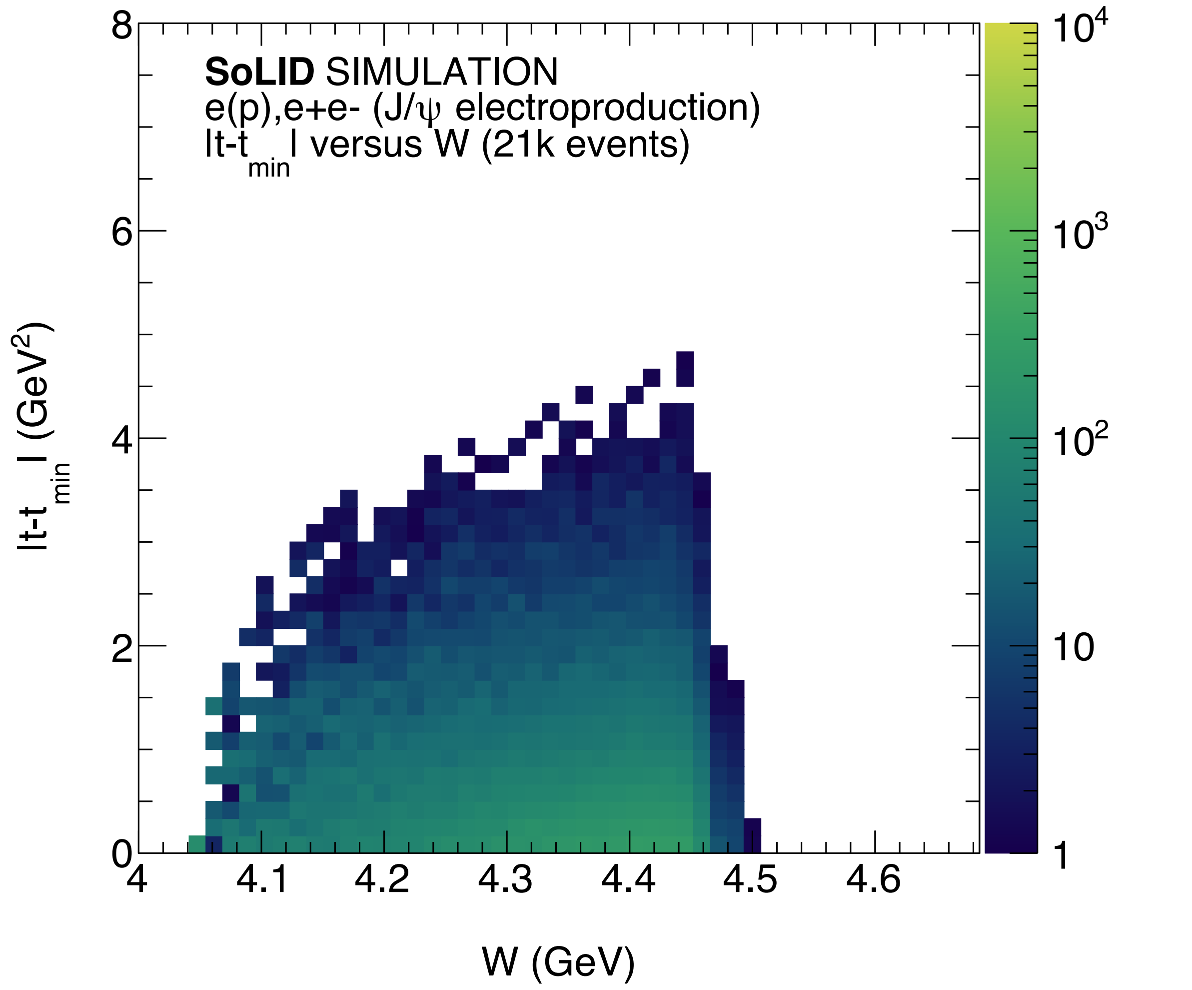
FUTURE SOLID EXPERIMENT AT JLAB

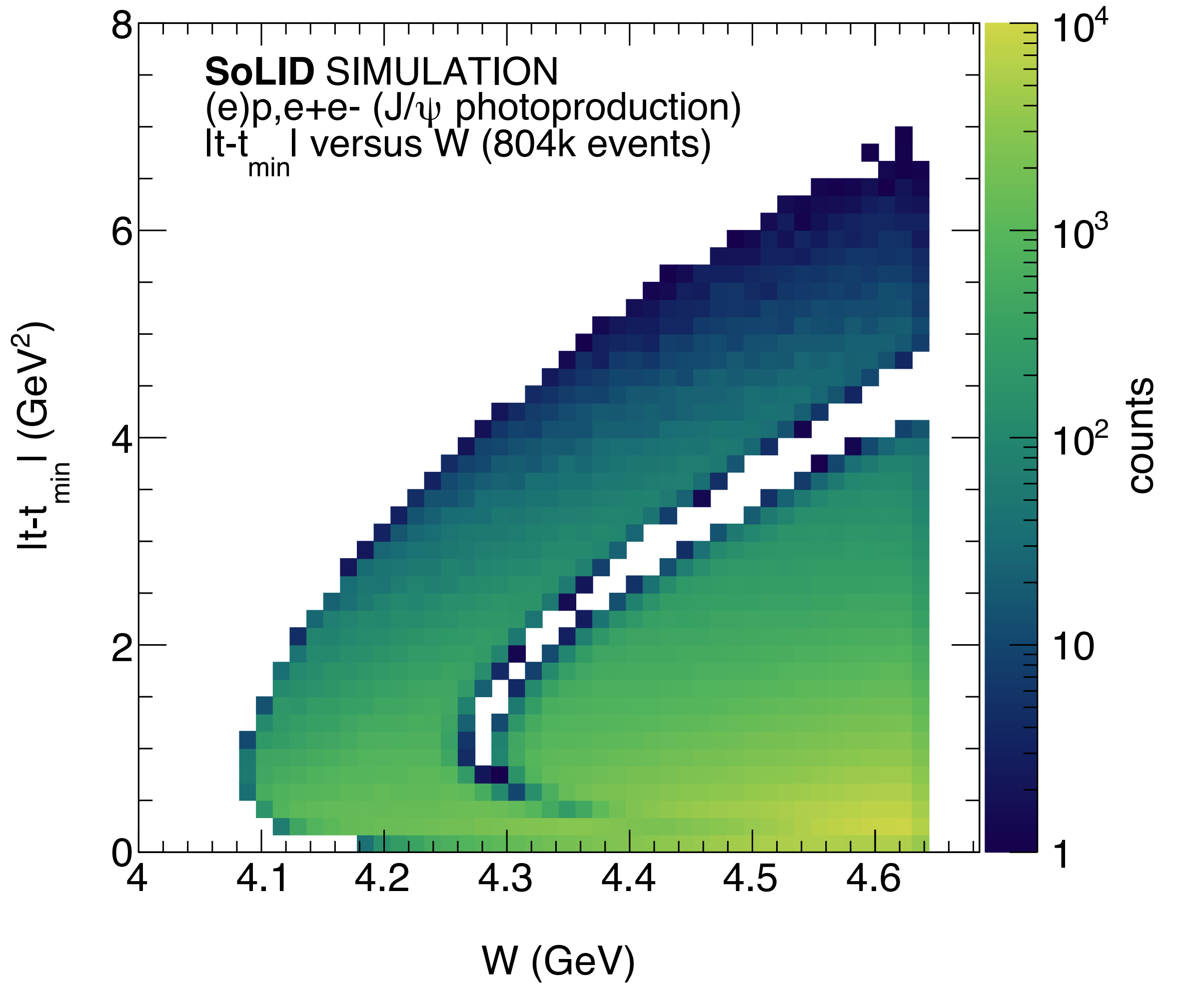
Ultimate experiment for near-threshold J/ψ production

- General purpose large-acceptance spectrometer
- 50 days of **3μA** beam on a **15cm** long LH2 target ($10^{37}/cm^2/s$)
- Ultra-high luminosity: 43.2ab^{-1}
- 4 channels:
  - **Electroproduction** (e,e-e+)
  - **Photoproduction** (p,e-e+)
  - **Inclusive** (e-e+)
  - **Exclusive** (ep,e-e+)



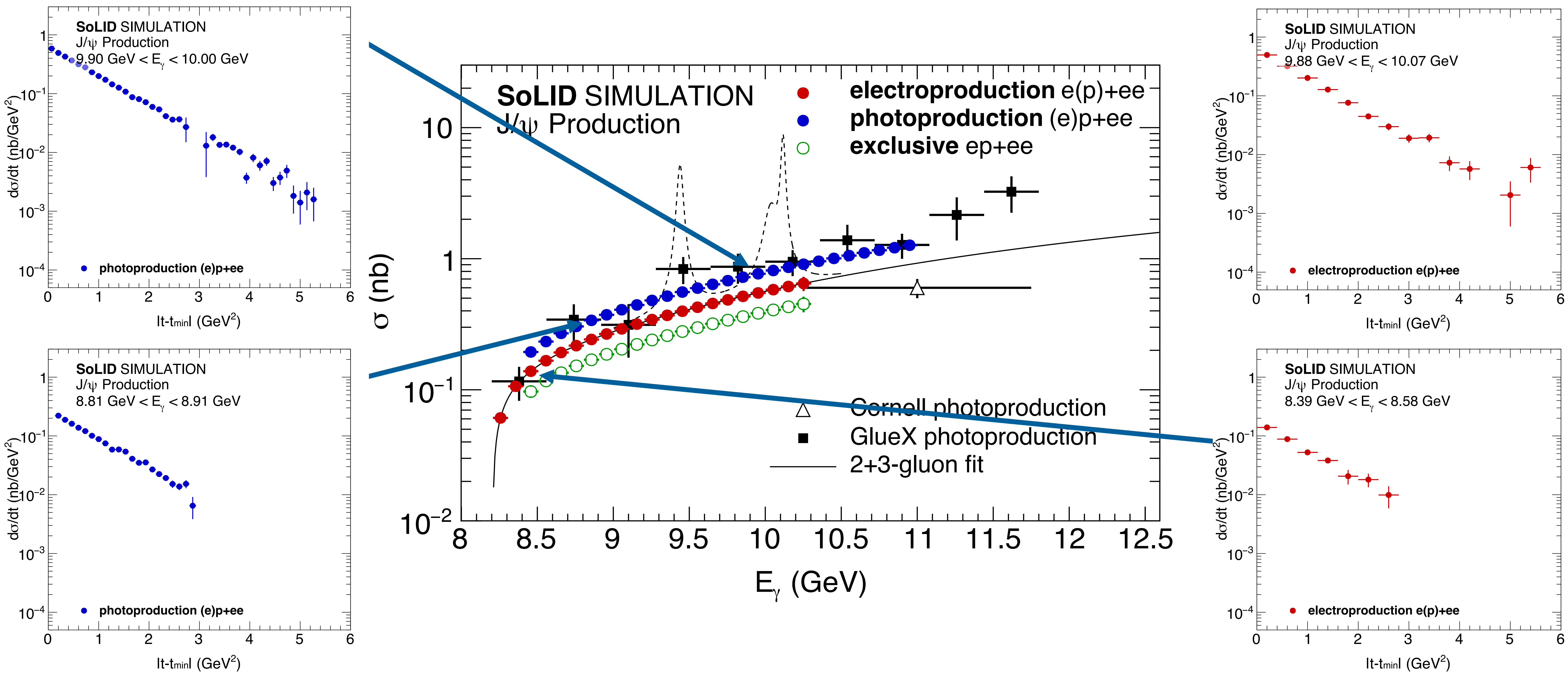






FUTURE SOLID EXPERIMENT AT JLAB

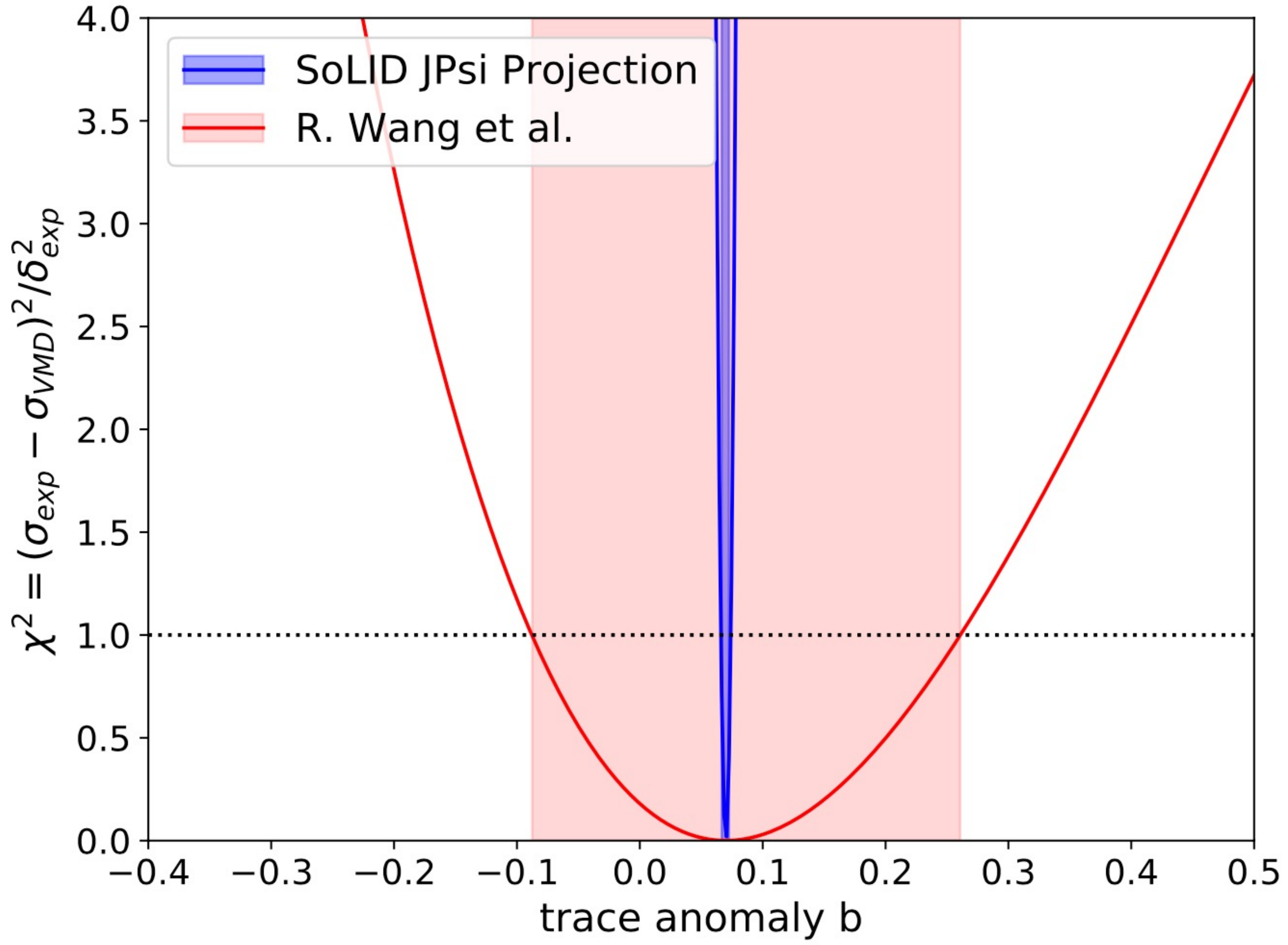
Precision measurement of quarkonium near threshold

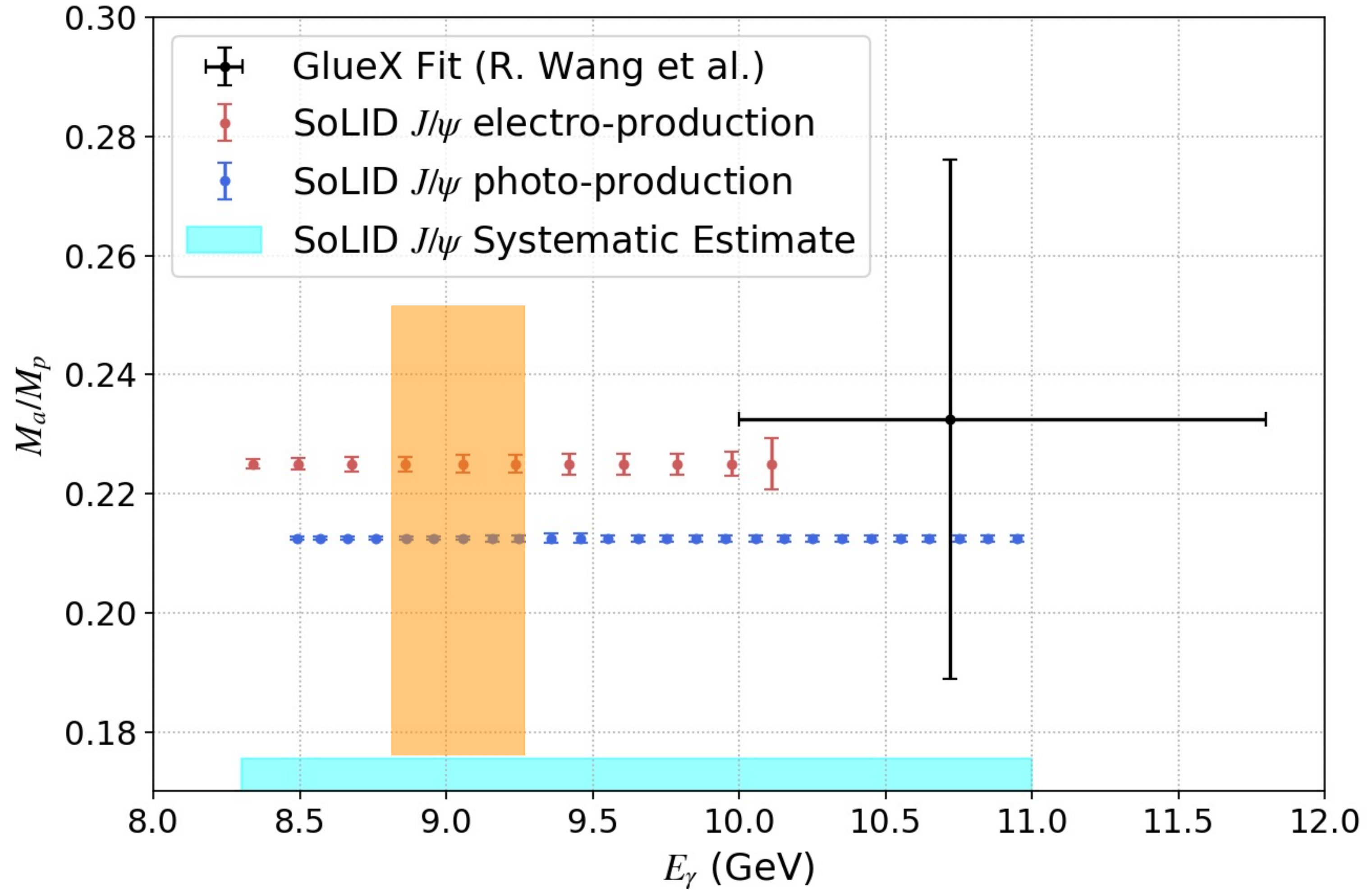


QUANTUM ANOMALOUS ENERGY MEASUREMENT

Projected impact of SoLID

- "Sweet spot" to extract quantum anomalous energy (to minimize theory uncertainties):
  - Stay away from threshold as t_{min} is too large
  - Stay below open charm thresholds
  - Scan the sweet spot where the J/ψ amplitude factorizes into a short-distance part describing the E polarizability of the ccbar and the matrix element of the EMT operator
  - D. Kharzeev, "the mass radius of the proton", arXiv:2101.00110 [hep-ph]



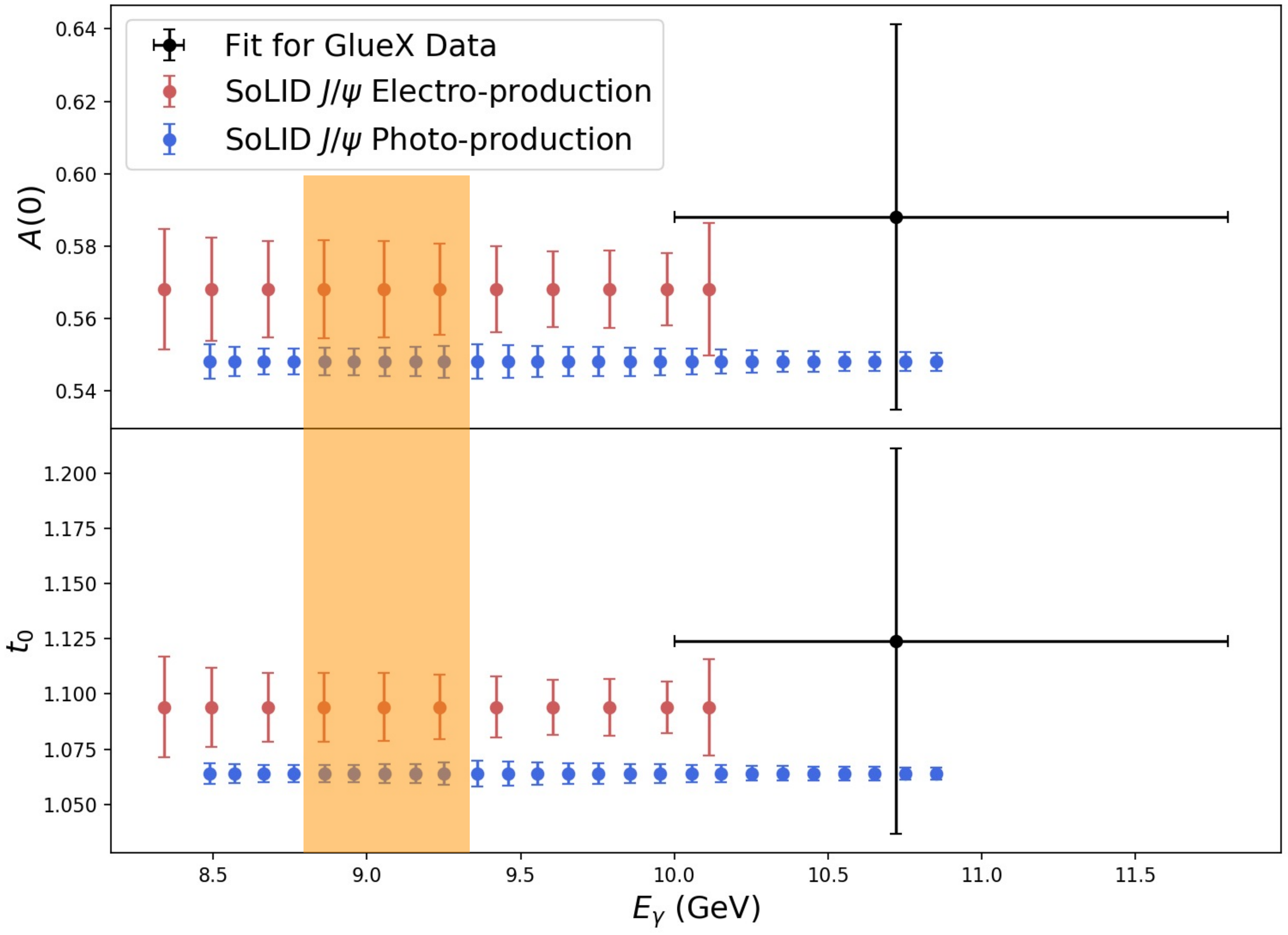


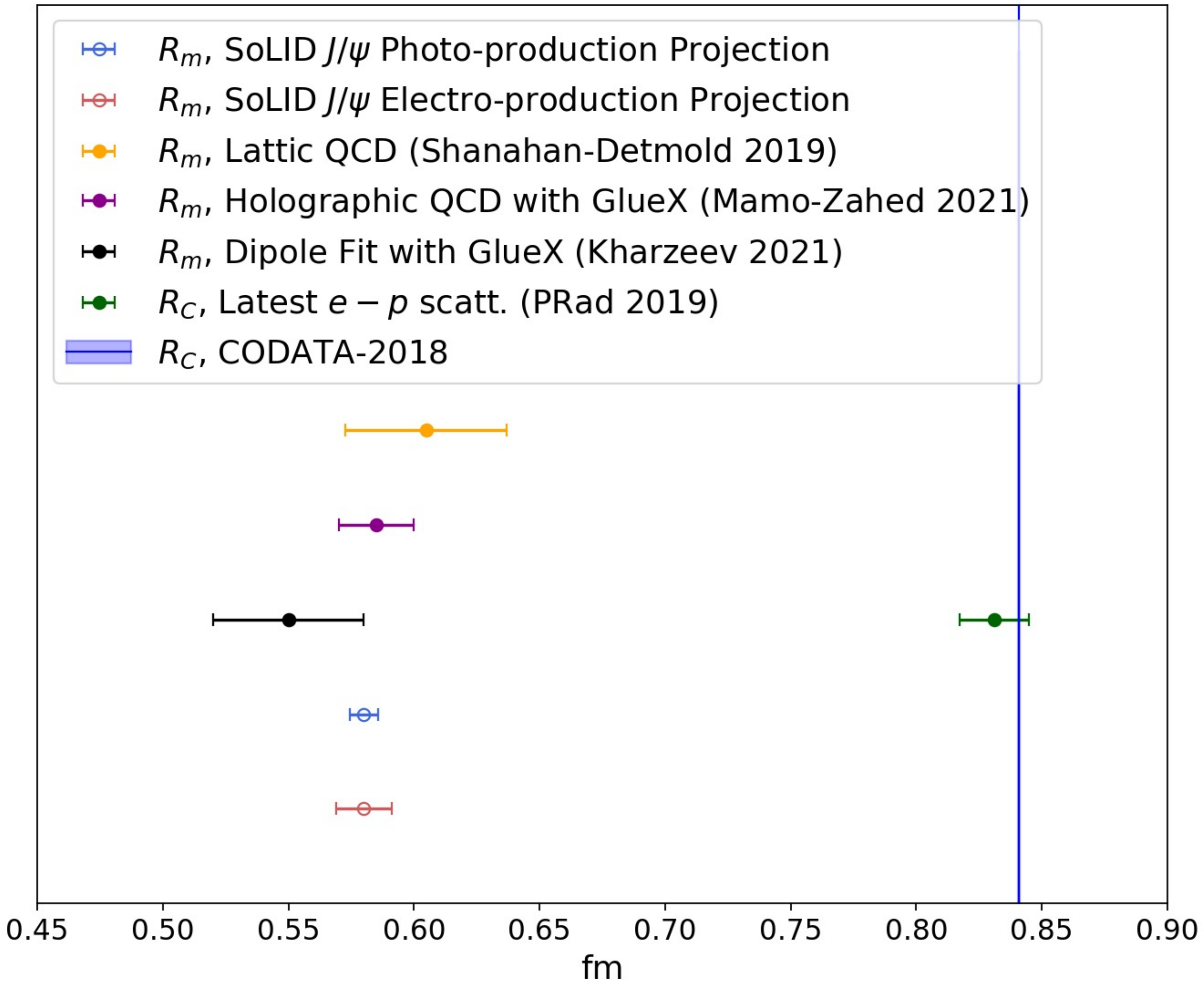
GlueX extraction from R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

MASS RADIUS

Projected impact of SoLID

Dipole Form $A(k) = \frac{A(0)}{(1-\frac{t}{t_0})^2}$



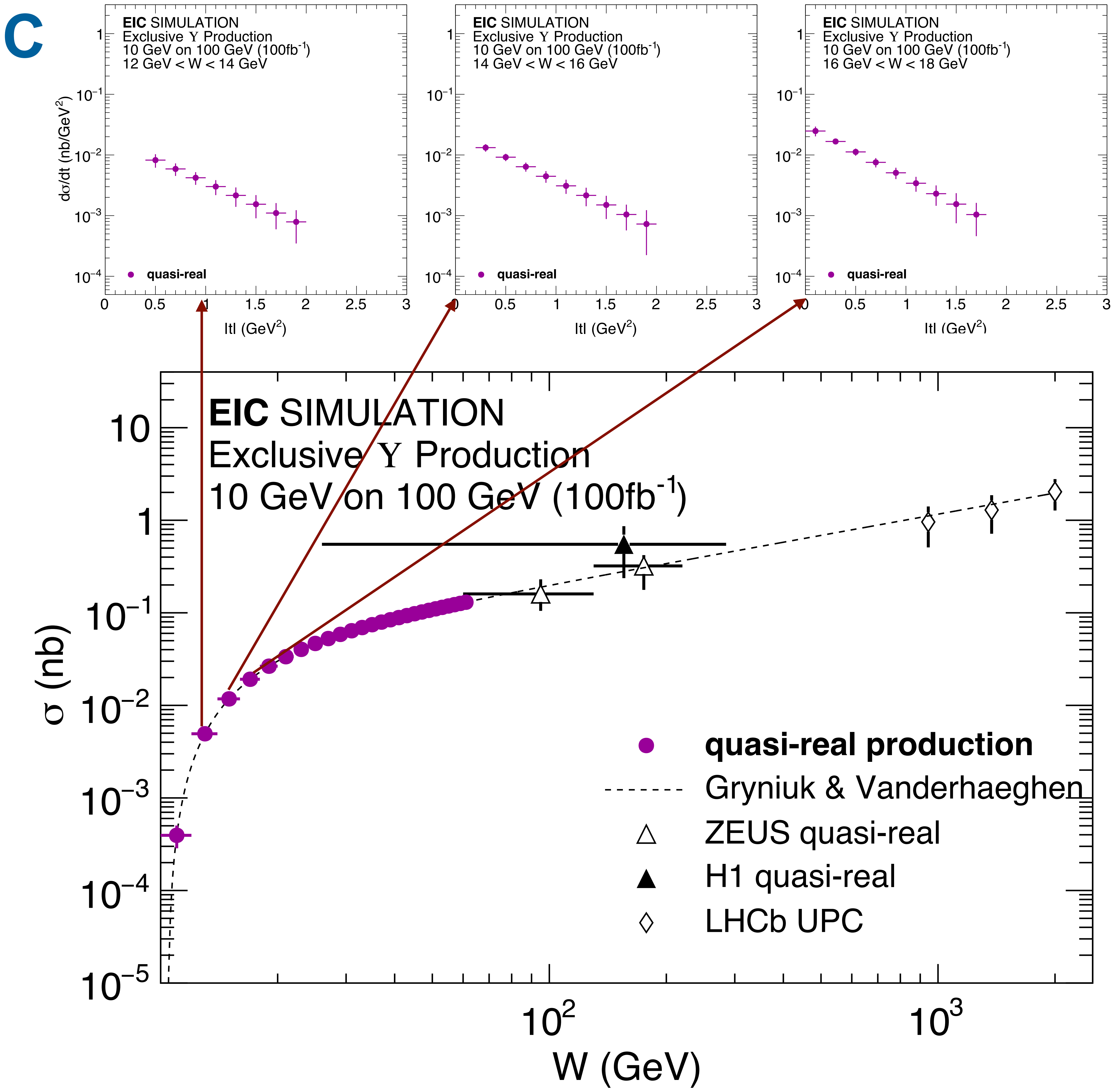


S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
O. Grynyuk, S. Joosten, Z.-E. Meziani, M. Vanderhaeghen PRD 102, 014016 (2020)

Υ(1S): AN IDEAL GLUONIC PROBE?

Threshold measurement possible at EIC

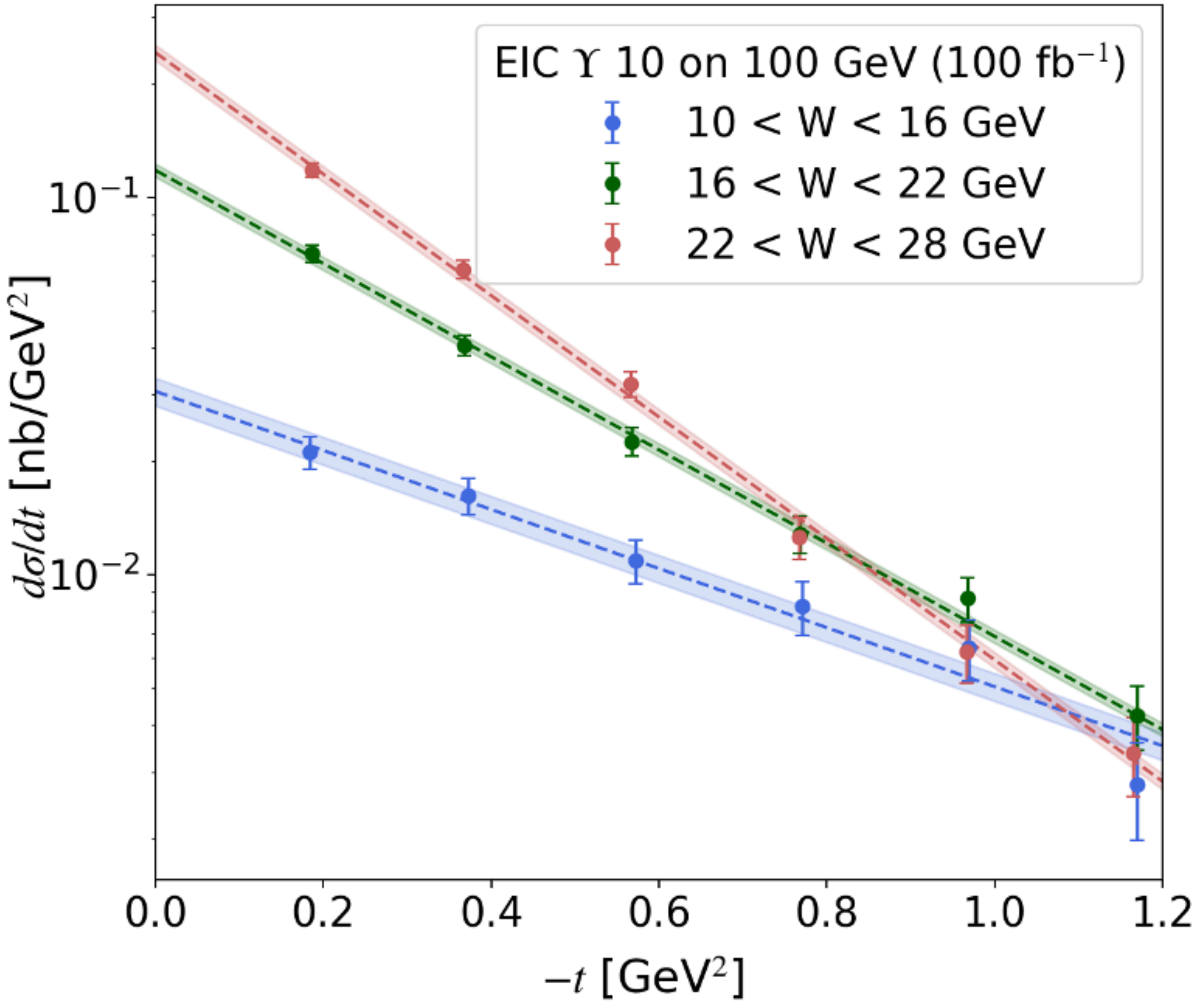
- *Υ*(1S) only couples to glue in proton, threshold production ideal probe to probe quantum anomalous energy in proton.
- Can use both **quasi-real production** and **electroproduction** at larger Q^2
- Can go to near-threshold region

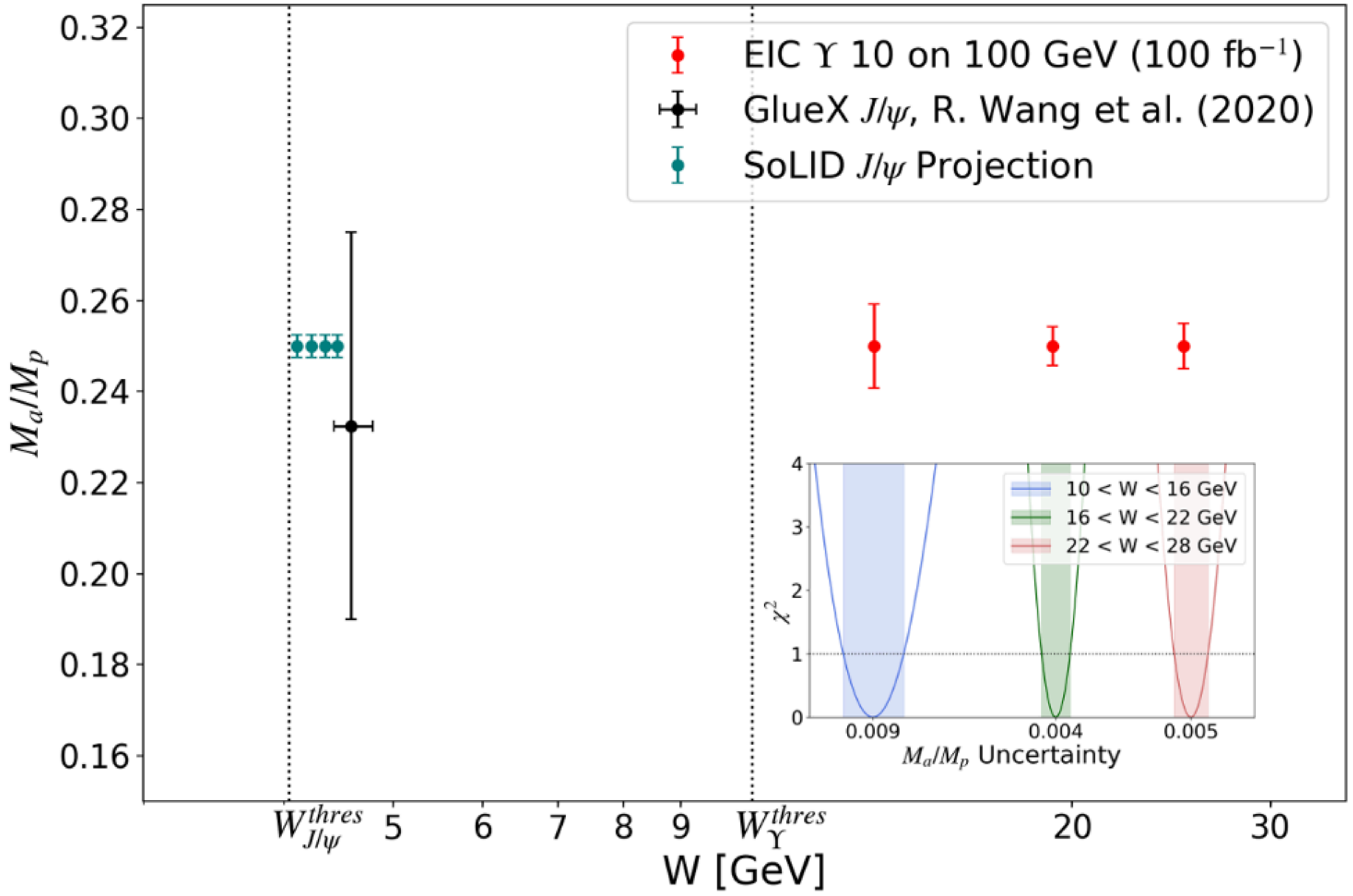


- ***Υ(1s)*** production possible at threshold!
  - Are there a "beautiful" pentaquarks?
- Sensitivity down to ~10^{-3} nb!

PROJECTED IMPACT OF UPSILON AT EIC

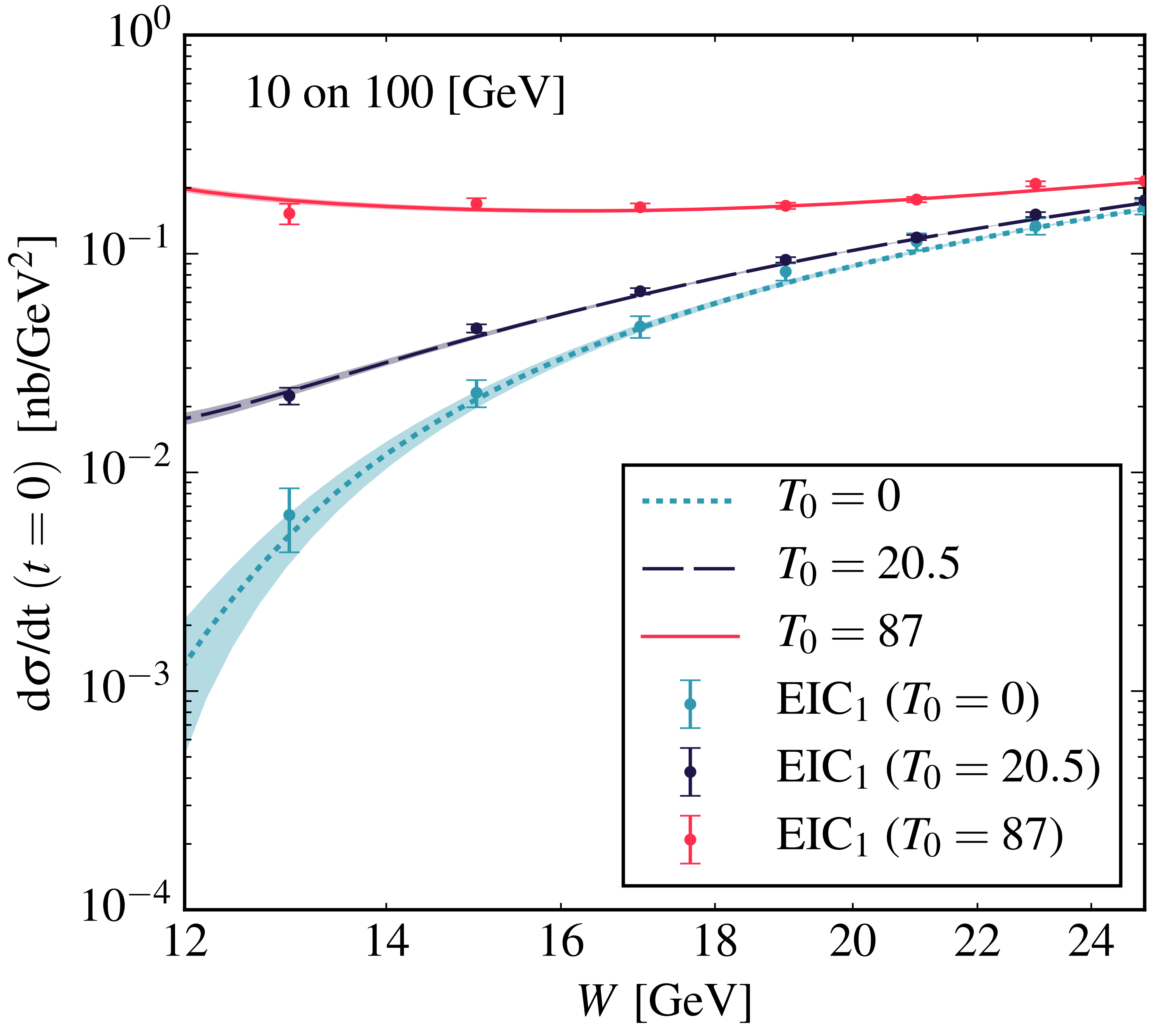
From t-distributions to the quantum anomalous energy



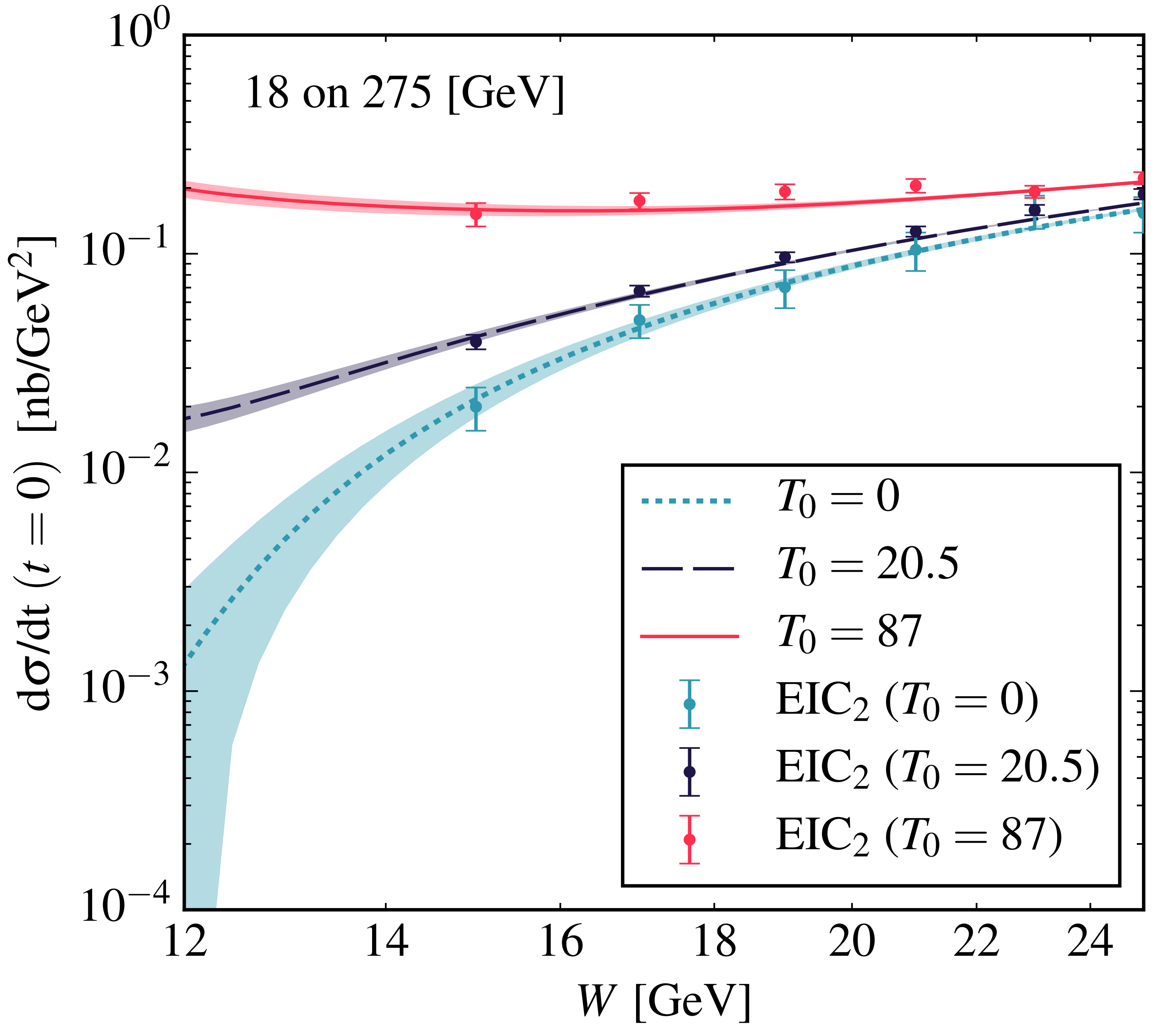


PROJECTED IMPACT OF UPSILON AT EIC

Constraining the Υ scattering length



Setting 1: 10 on 100 GeV
Medium-energy configuration



Setting 2: 18 on 275 GeV
High-energy configuration

Good sensitivity to scattering length and binding energy for multiple nominal EIC configurations.

Setting	$T_{\Upsilon p}(0)$	$a_{\Upsilon p}$ (in fm)	B_Υ (in MeV)
1	0	$\simeq 0$	$\simeq 0$
	20.5 ± 0.9	0.016 ± 0.001	0.78 ± 0.03
	87 ± 2	0.066 ± 0.001	3.23 ± 0.06
2	0	$\simeq 0$	$\simeq 0$
	20.5 ± 1.9	0.016 ± 0.001	0.78 ± 0.07
	87 ± 4	0.066 ± 0.003	3.23 ± 0.16

It is essential to use the mass of heavy quarks and the Q^2 range as knobs for our theoretical understanding of the reaction mechanism at threshold and the extraction of the anomaly, or the mass radius of the proton.

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

SUMMARY

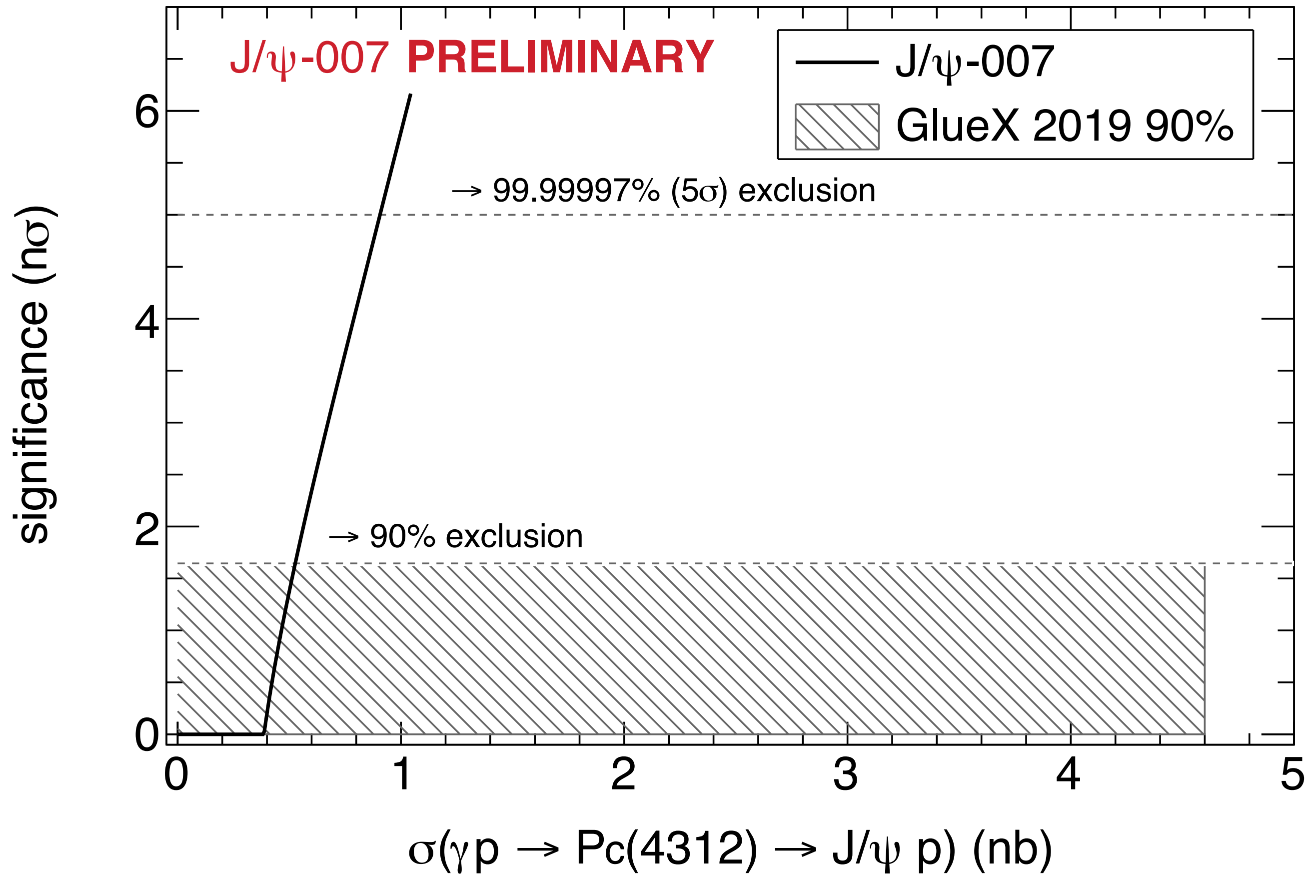
Near-threshold electro- and photoproduction of quarkonium

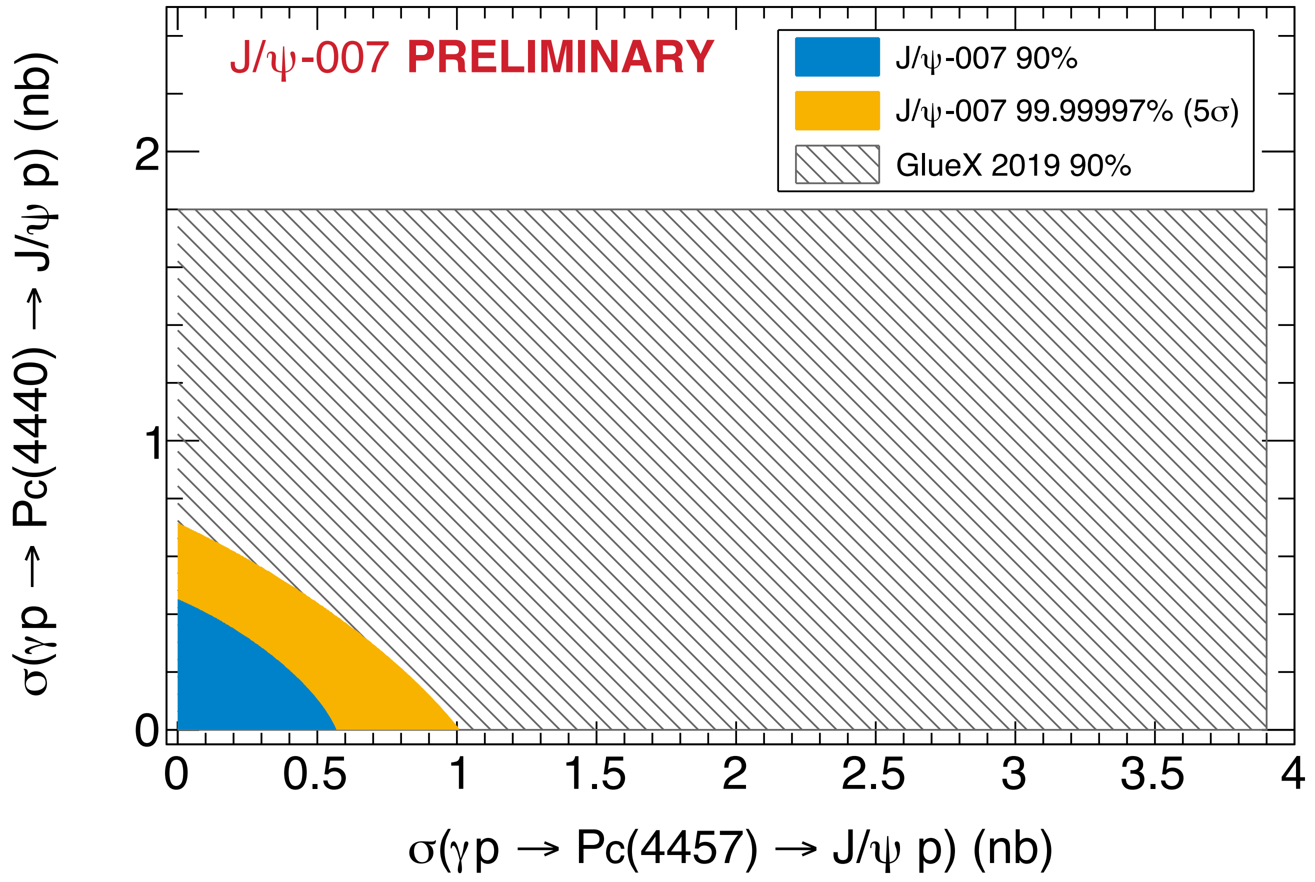
- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus bound states
- Do quarkonia enable **pentaquarks** to exist?
- **Mechanism** for quarkonium production itself

Direct calculations of trace anomaly and gravitational form factors important towards understanding proton mass. Precision data on quarkonium production near threshold will be necessary to benchmark these calculations.

Statistical precision (reach to high t) will help avoid systematic uncertainties of the extraction of the anomaly, mass radius and scattering length

Jefferson Lab and EIC are truly complimentary to address these topics!





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

QUARKONIA NEAR THRESHOLD: A RAPIDLY DEVELOPING FIELD!