Argonne NATIONAL LABORATORY

THE J/Ψ-007 EXPERIMENT IN HALL C

NEW RESULTS ON NEAR-THRESHOLD PHOTOPRODUCTION OF J/ψ

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

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

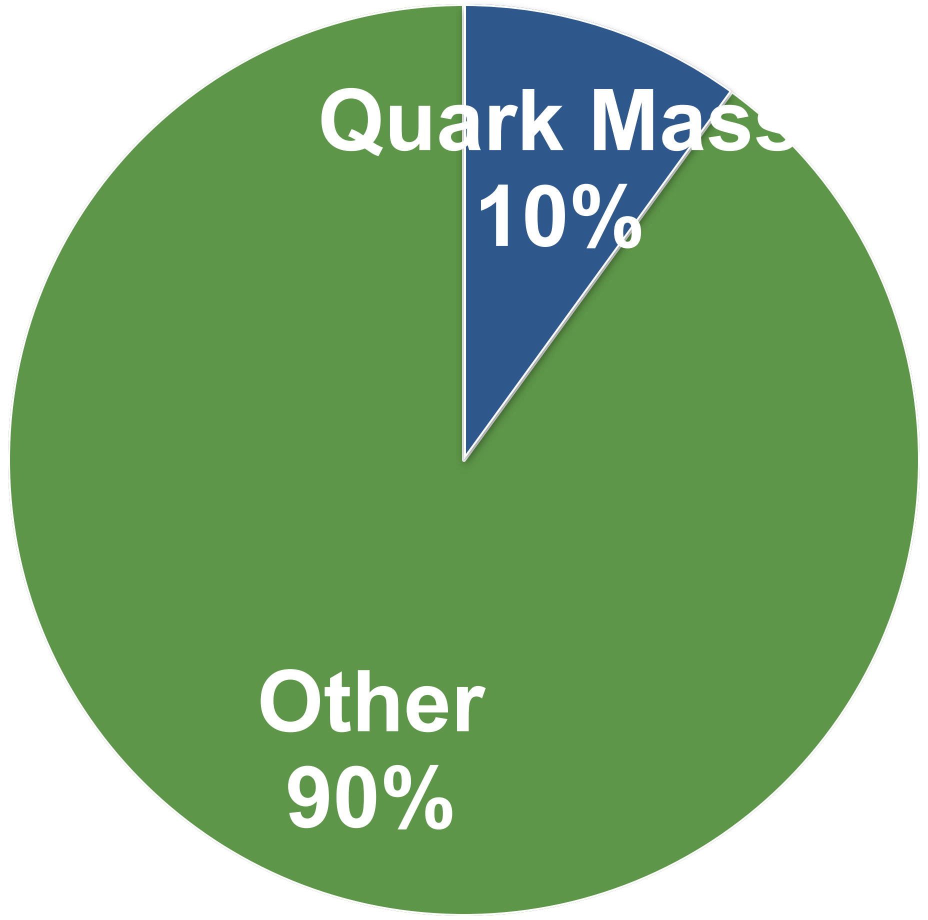
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

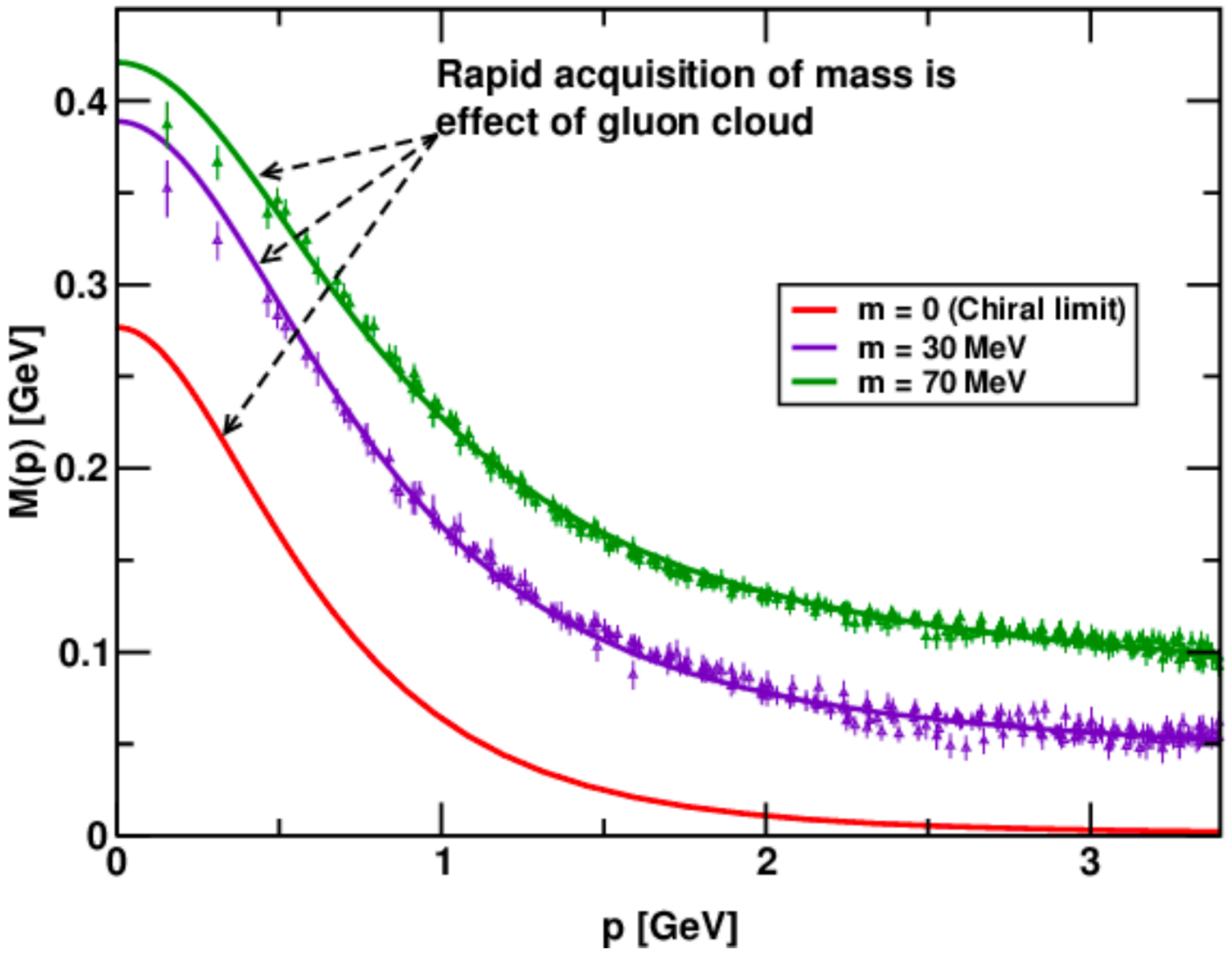
JLUO Meeting
June 14, 2022

WHY IS THE PROTON SO HEAVY?

Nucleon mass is an emergent phenomenon

- The proton mass is much larger than the mass sum of its constituents
- Calculations have shown that even in the massless limit, the proton mass would be almost unchanged
- This implies interactions with the Standard Model Higgs field are largely irrelevant for "normal" matter





M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
I. C. Cloet et al., Prog. Part. Nucl. Phys. 77, 1-69 (2014)

How do massless gluons provide for the large proton mass?

How is the proton mass distributed inside its confinement size?

PROTON MASS: REST-FRAME DECOMPOSITION

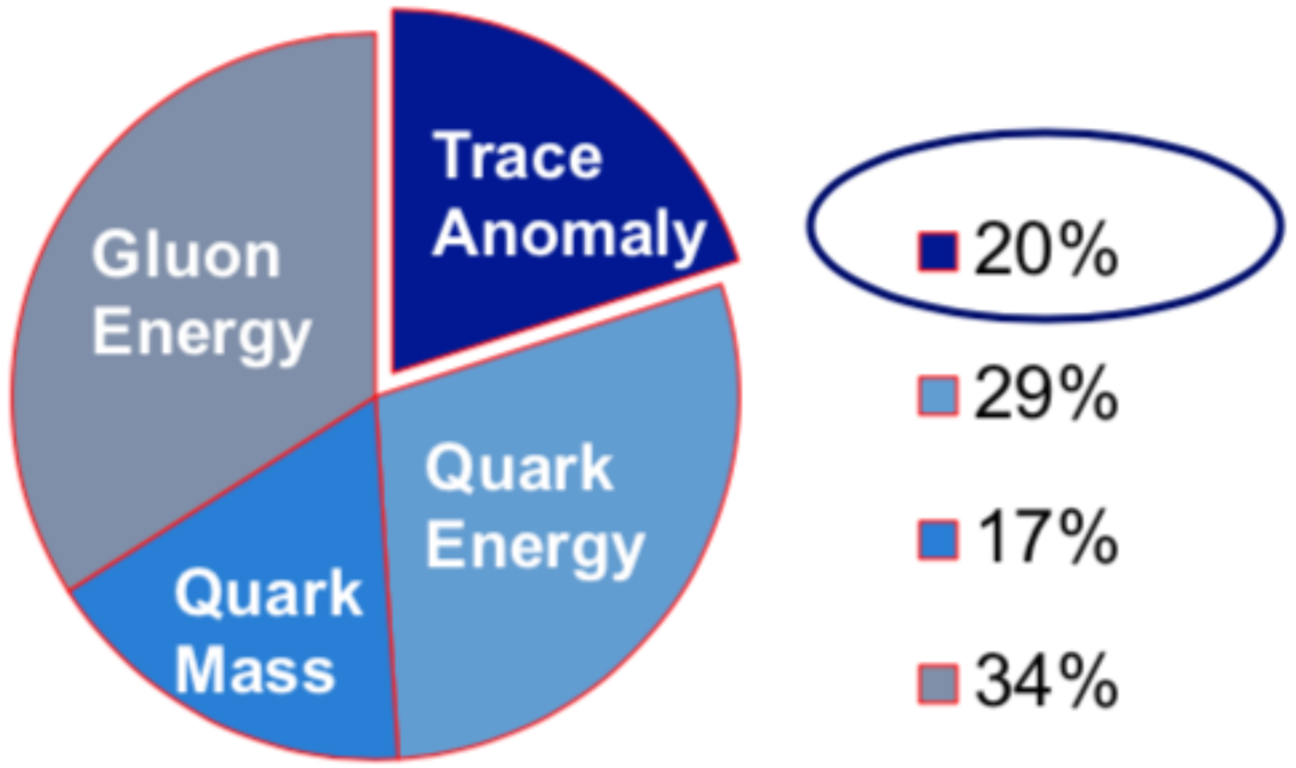
Disentangling the proton mass in its rest frame

- 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:

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



a(μ) related to PDFs, well constrained

b(μ) related trace anomaly, unconstrained

GRAVITATIONAL FORM FACTORS (GFFS)

The matter structure of the proton

GFFs are the form factors of the EMT for quarks and gluons

$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

Physics encoded in these GFFs:

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

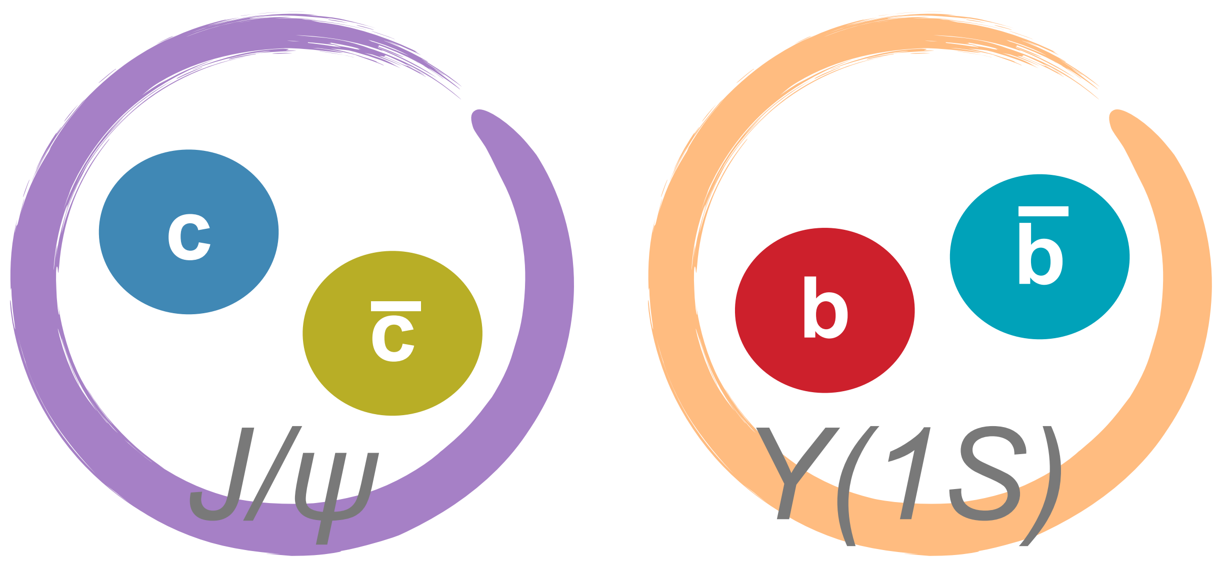
Gluonic GFFs provide access to the mass radius of the proton

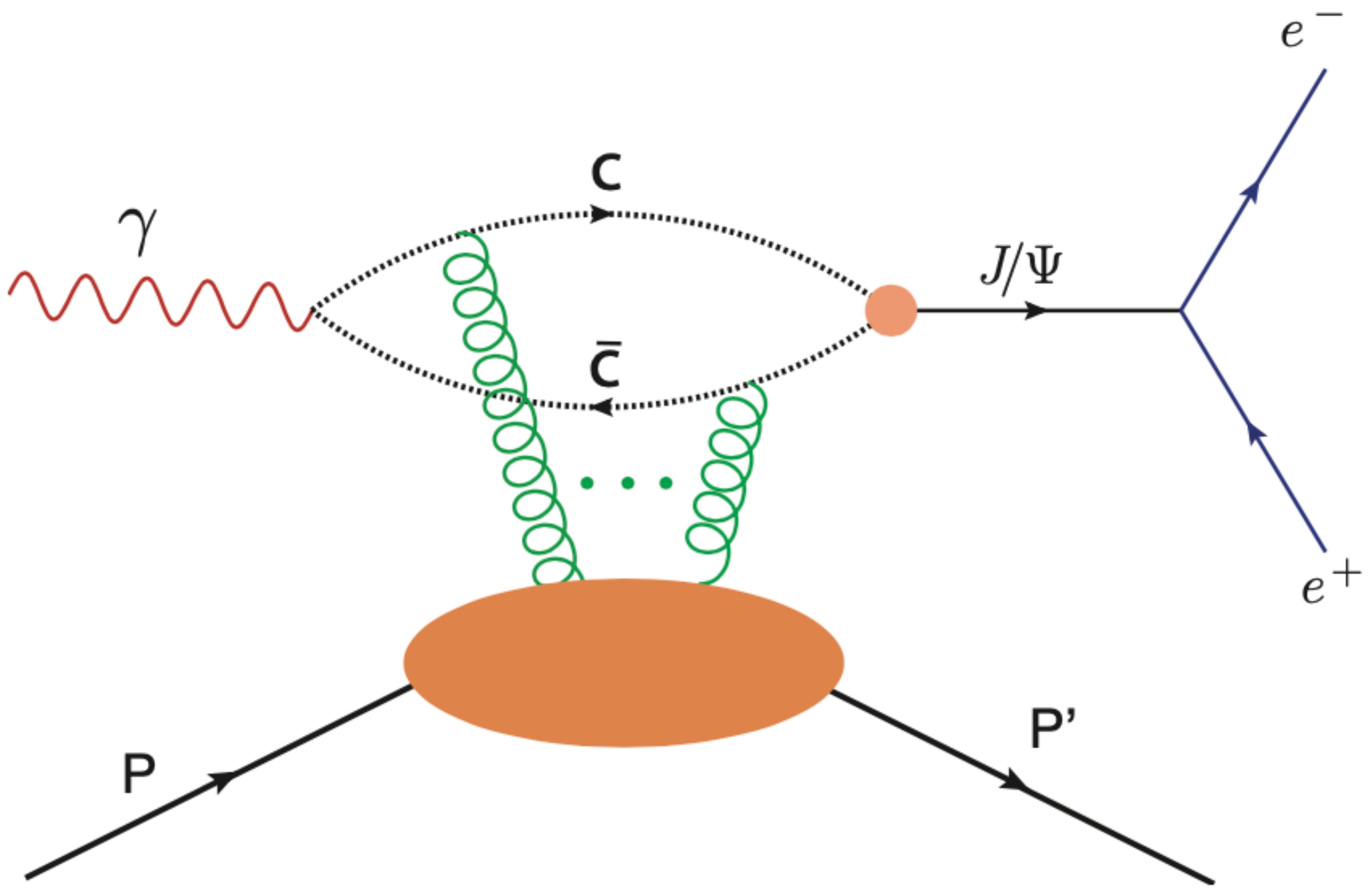
$$\left\langle r_m^2 \right\rangle = \frac{6}{A_g(0)}\frac{dA_g(t)}{dt}\bigg|_{t=0} - \frac{6}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

WHY QUARKONIUM PRODUCTION NEAR THRESHOLD

Gluons are hard to probe

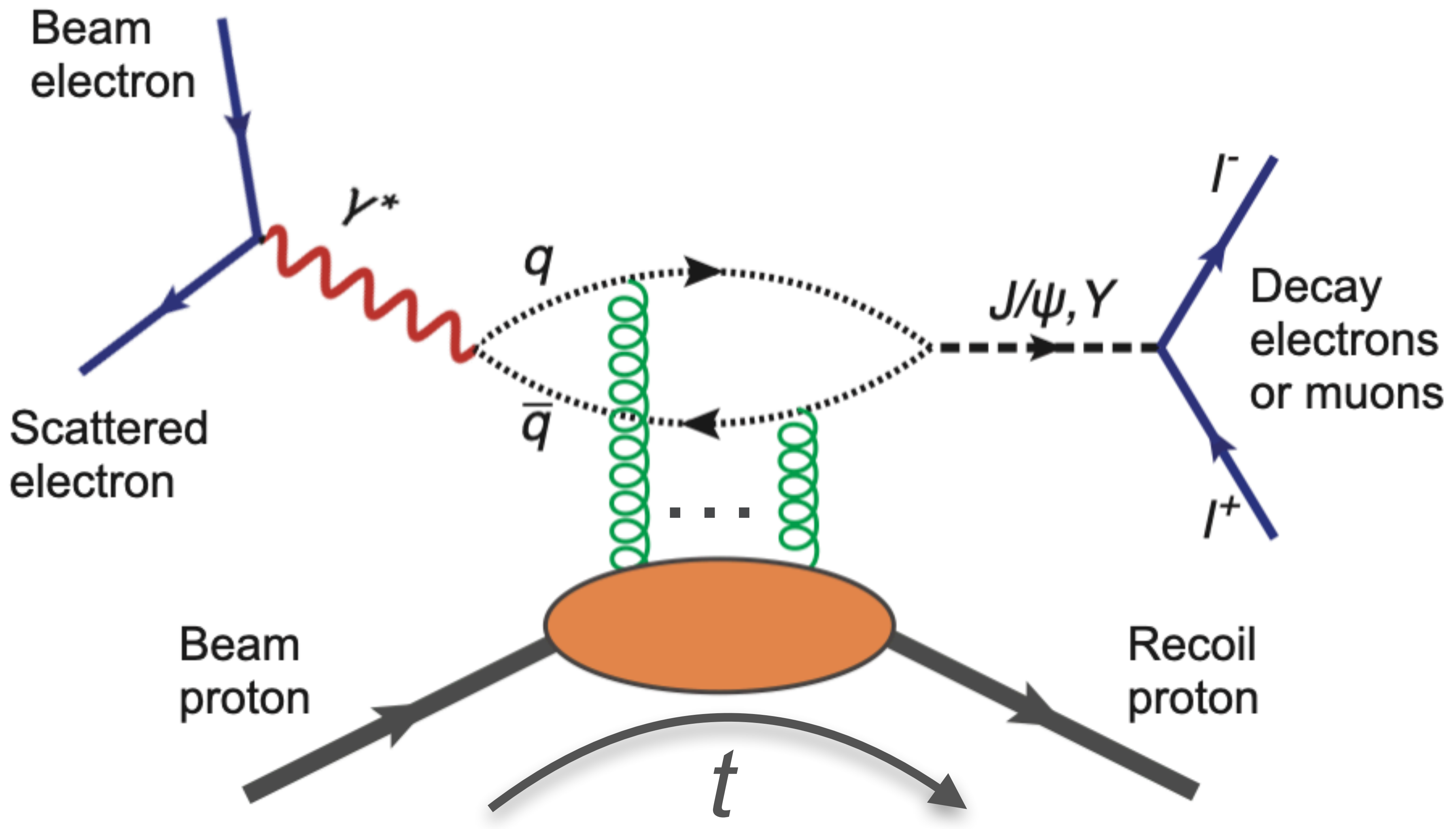
- Electromagnetic charge and spin of the proton well-studied through electron scattering
- Gluons are harder to directly access, as they do not carry electromagnetic charge
  - Description of mass still in infancy, as most energy (and hence mass) carried by the gluons
  - J/ψ and Υ(1S) only couple to gluons, not light quarks
  - Differential cross section of quarkonium near threshold promising channel to directly probe gluons
  - Sufficient data at different photon energies can constrain the GFF slopes and magnitudes in the forward limit (t=0)
  - **Access the matter distribution, mass radius, and potentially the trace anomaly of the EMT.**





EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

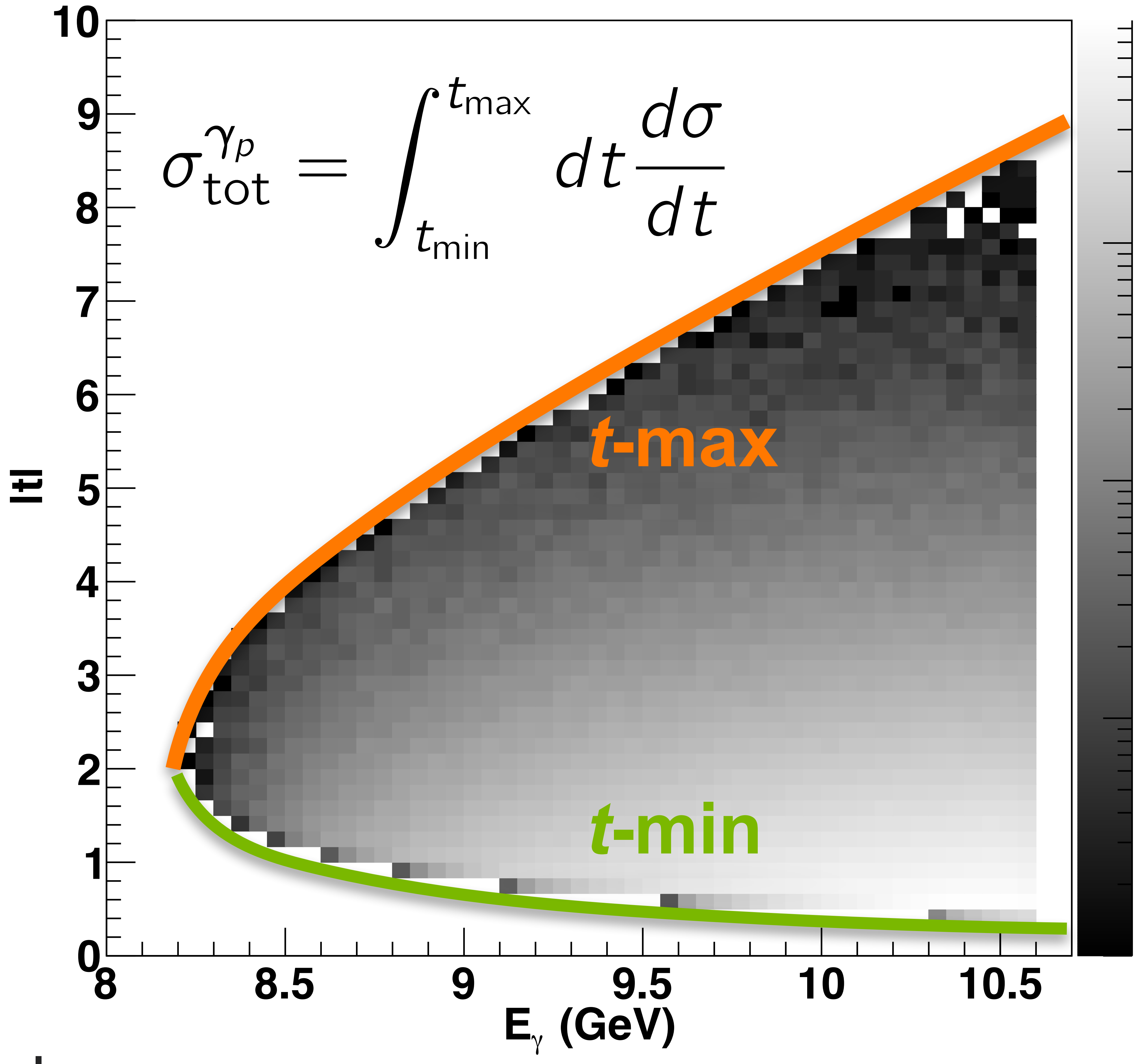
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

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

Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

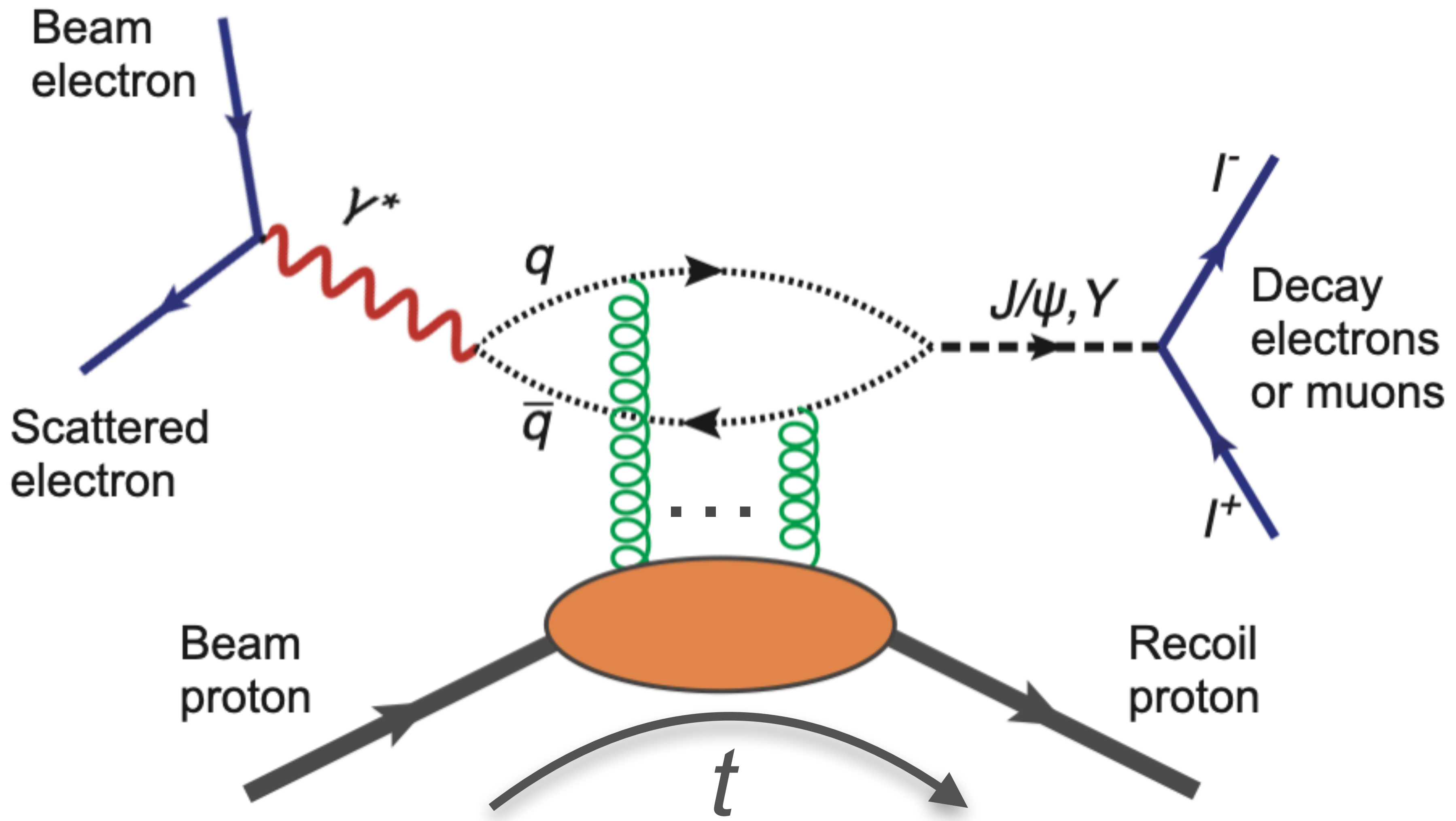
$t \approx -8.1\text{GeV}^2$

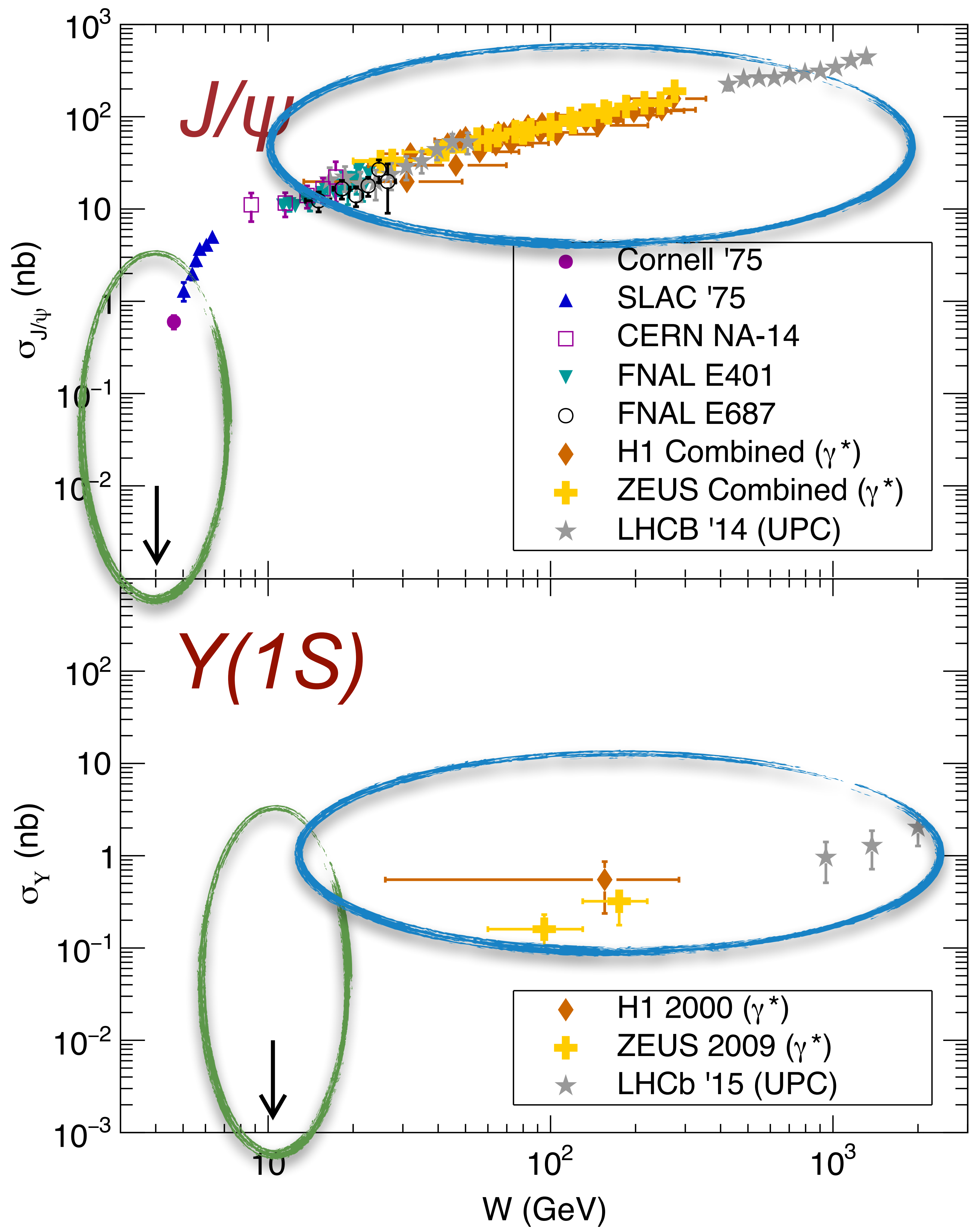


- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred: *t*-dependence ~exponential

EXCLUSIVE QUARKONIUM PRODUCTION

What do we know?





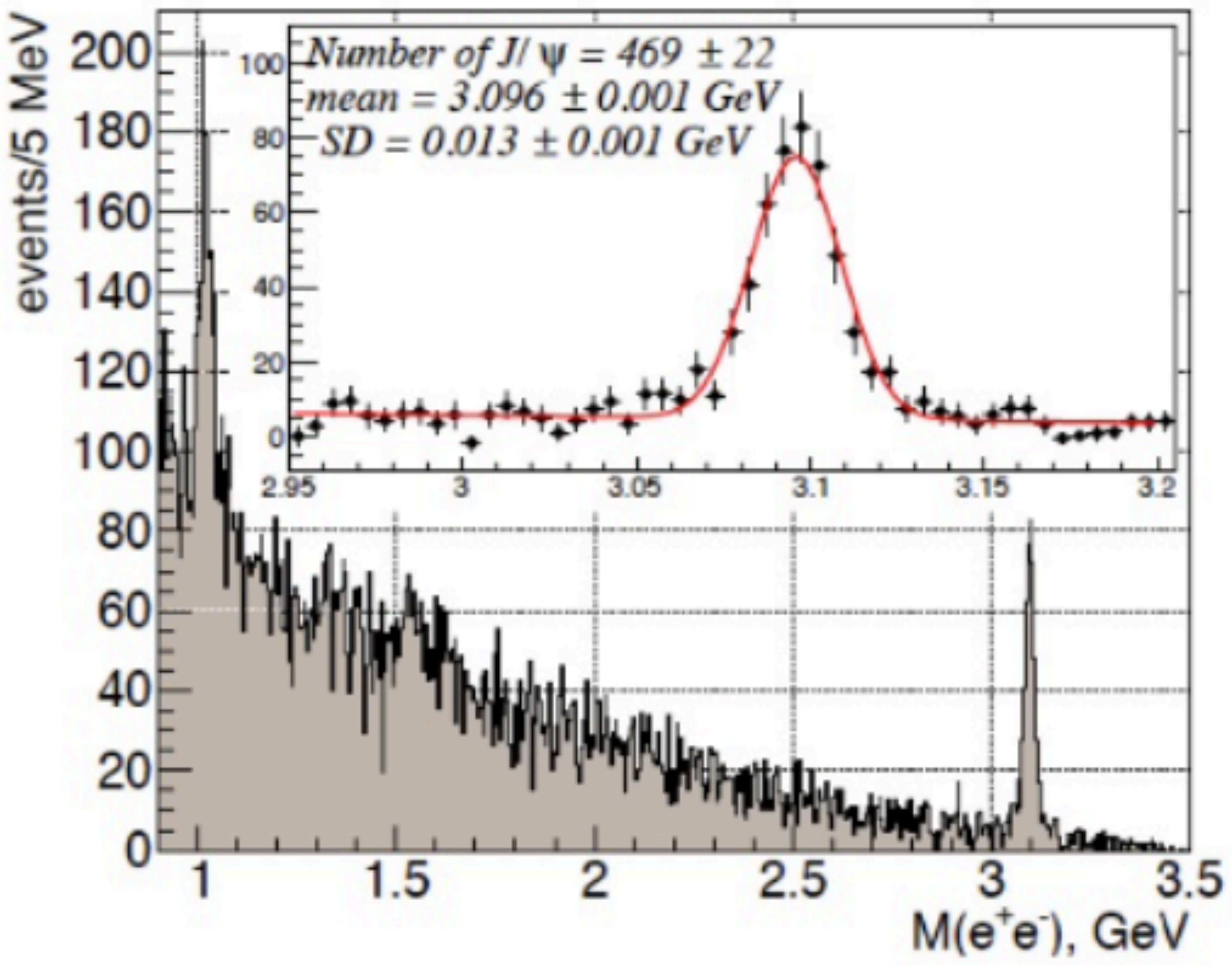
- J/ψ well constrained for high energies in photoproduction
- Υ(1S): not much available
- No significant electroproduction data available
- **Almost no data near threshold before JLab 12 GeV**

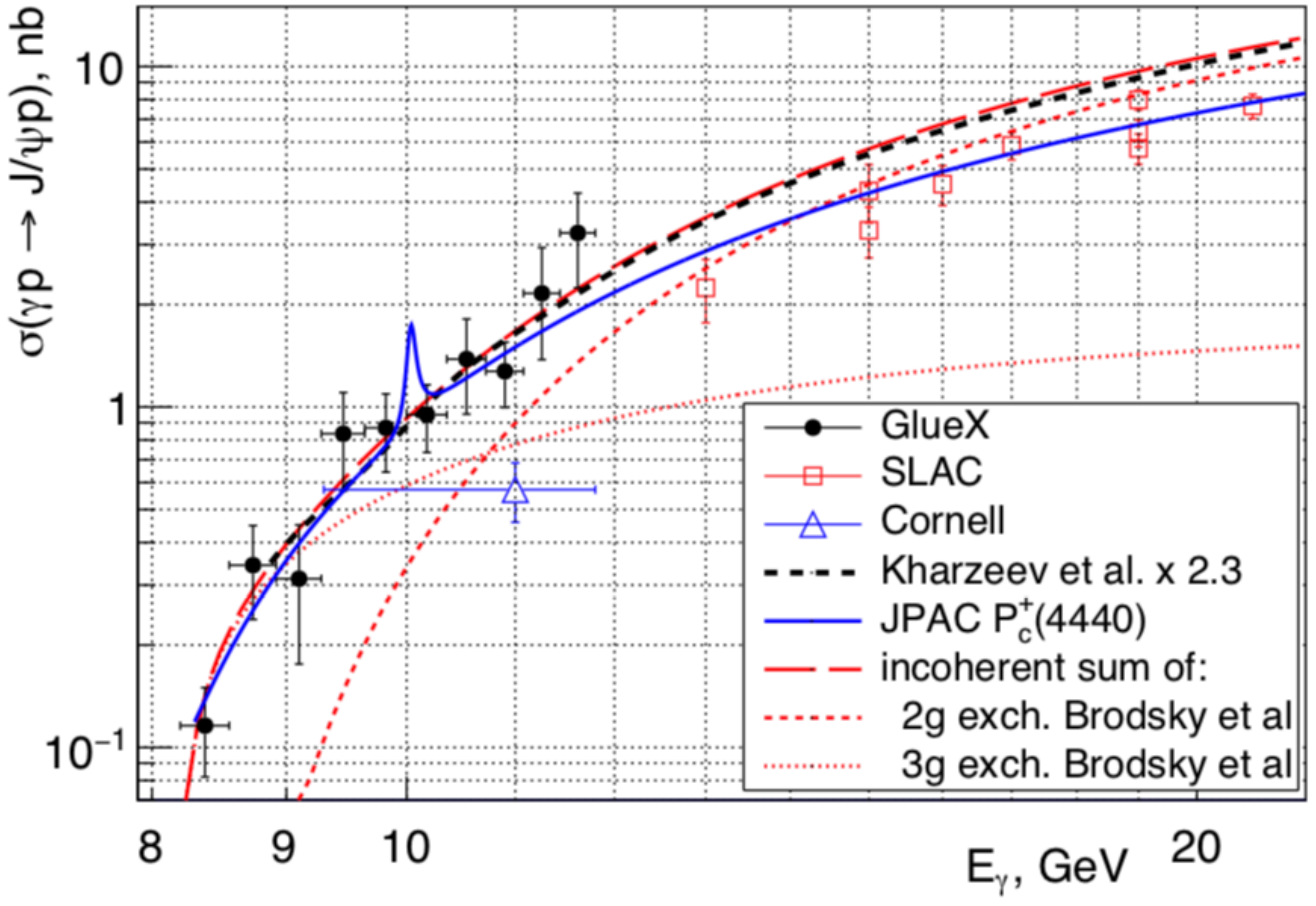
J/Ψ NEAR THRESHOLD IN HALL D

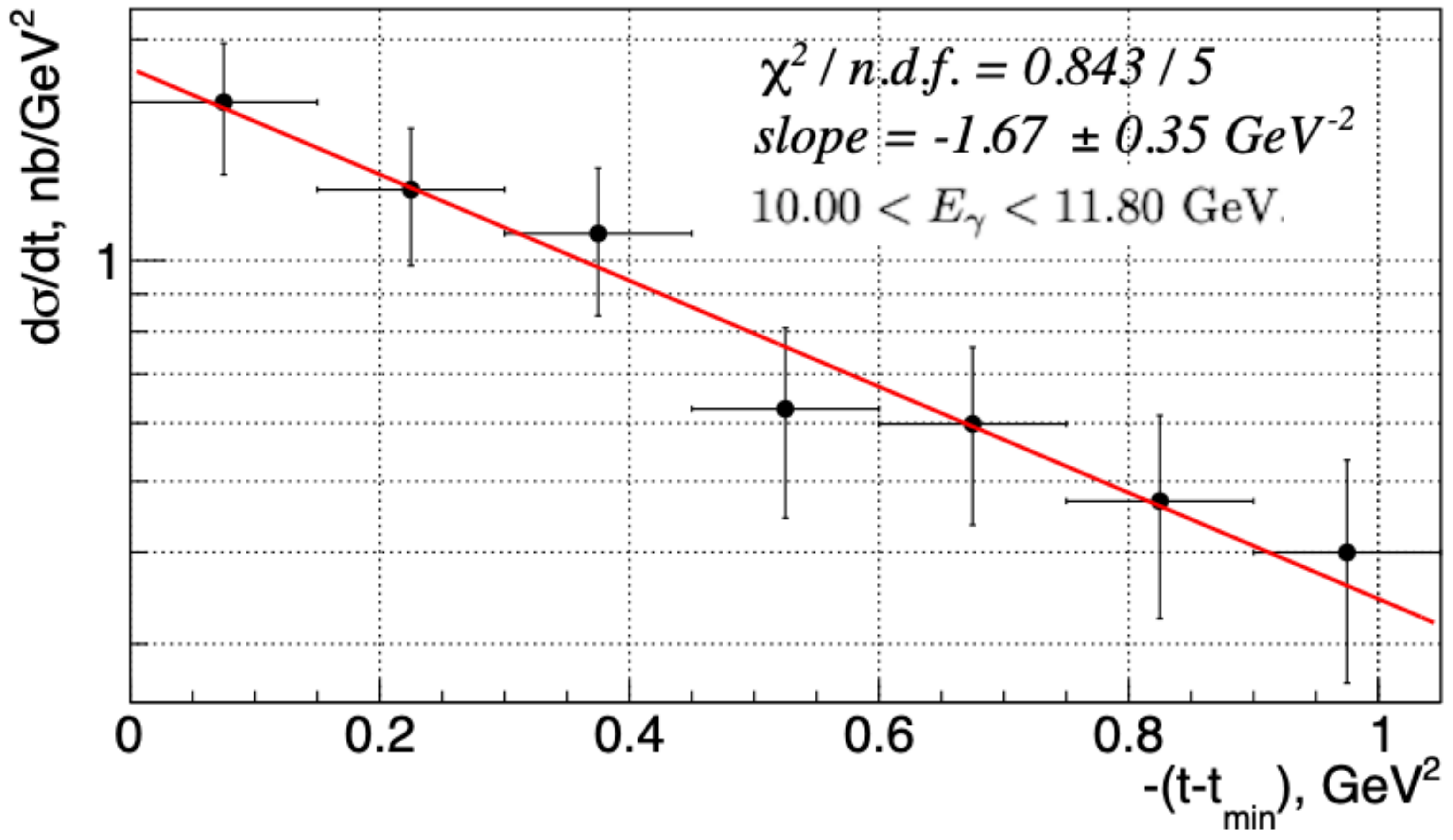
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Also released a single 1D t-profile
- Did not see evidence for hidden-charm pentaquarks
- 4x more statistics being analyzed

$\gamma p \rightarrow p\, J/\psi \rightarrow p e^+ e^-$



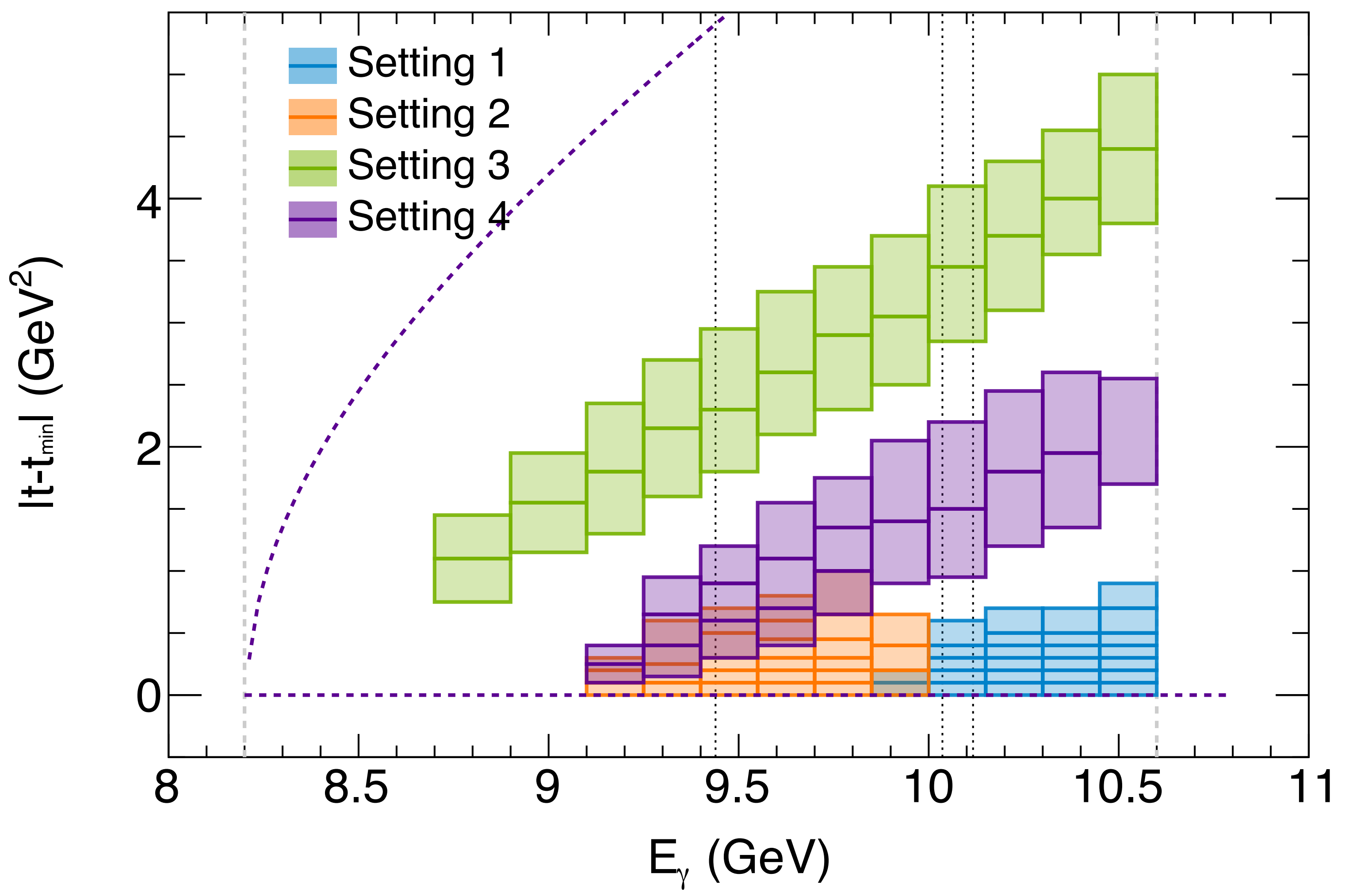


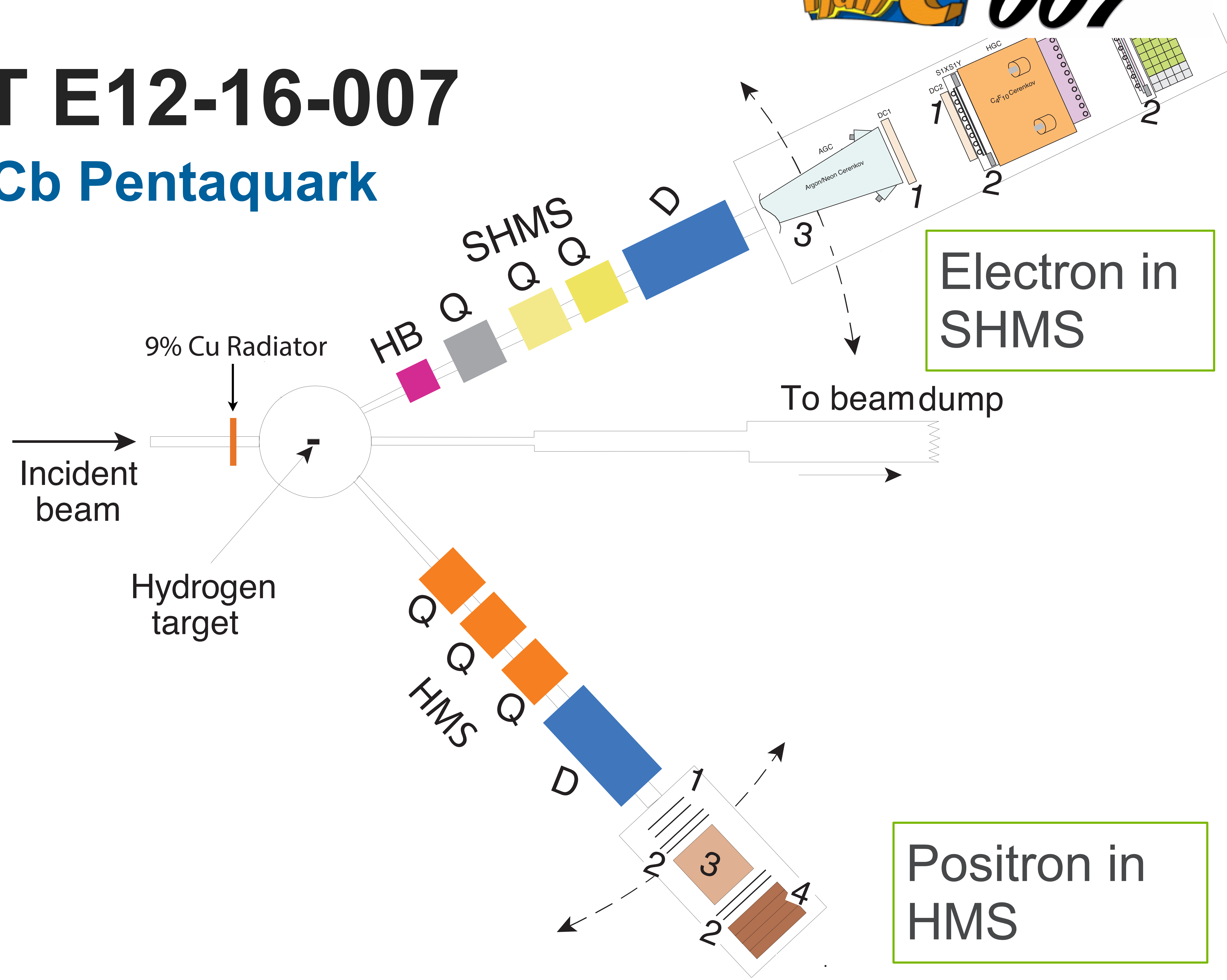


JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

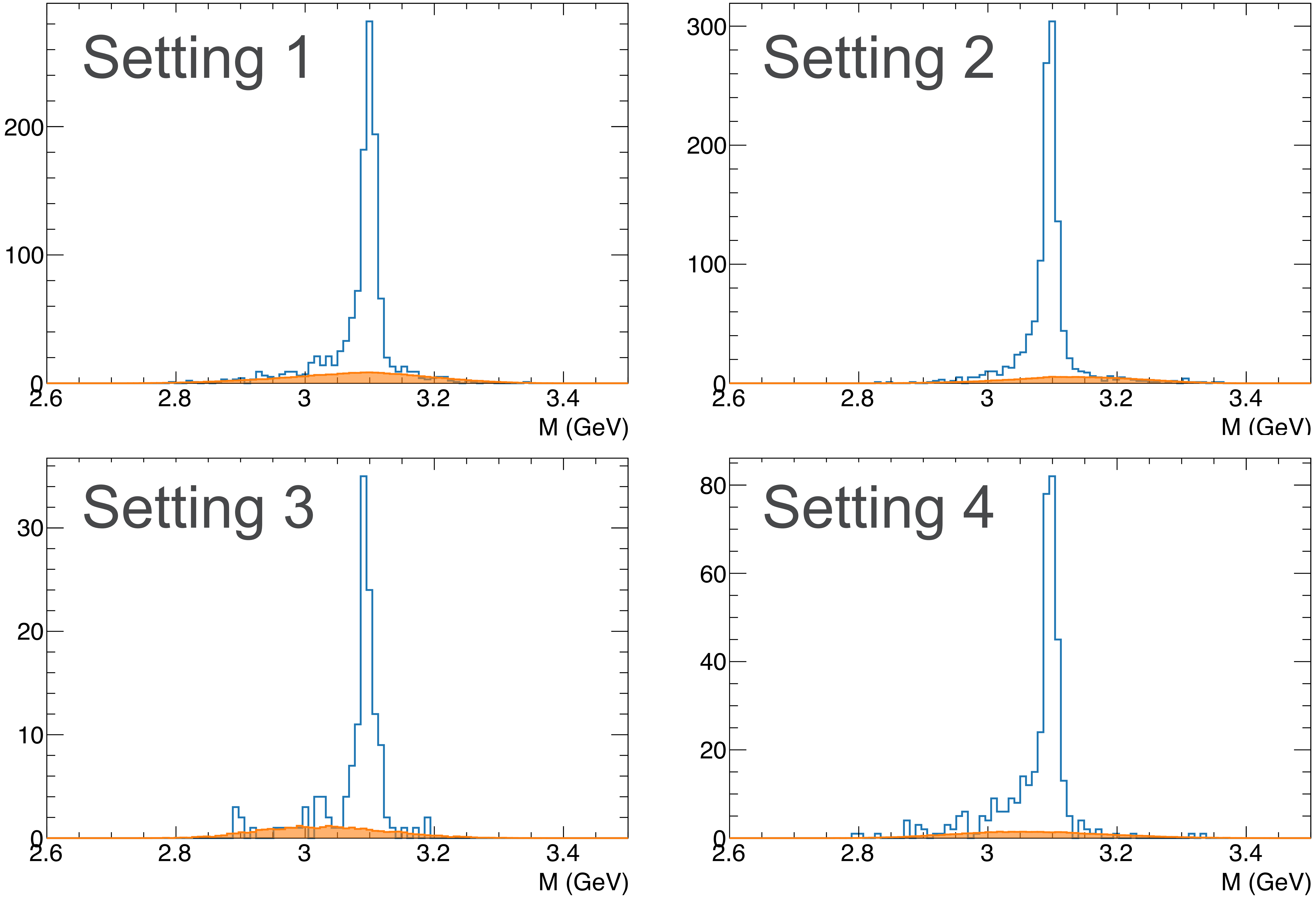
- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained





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

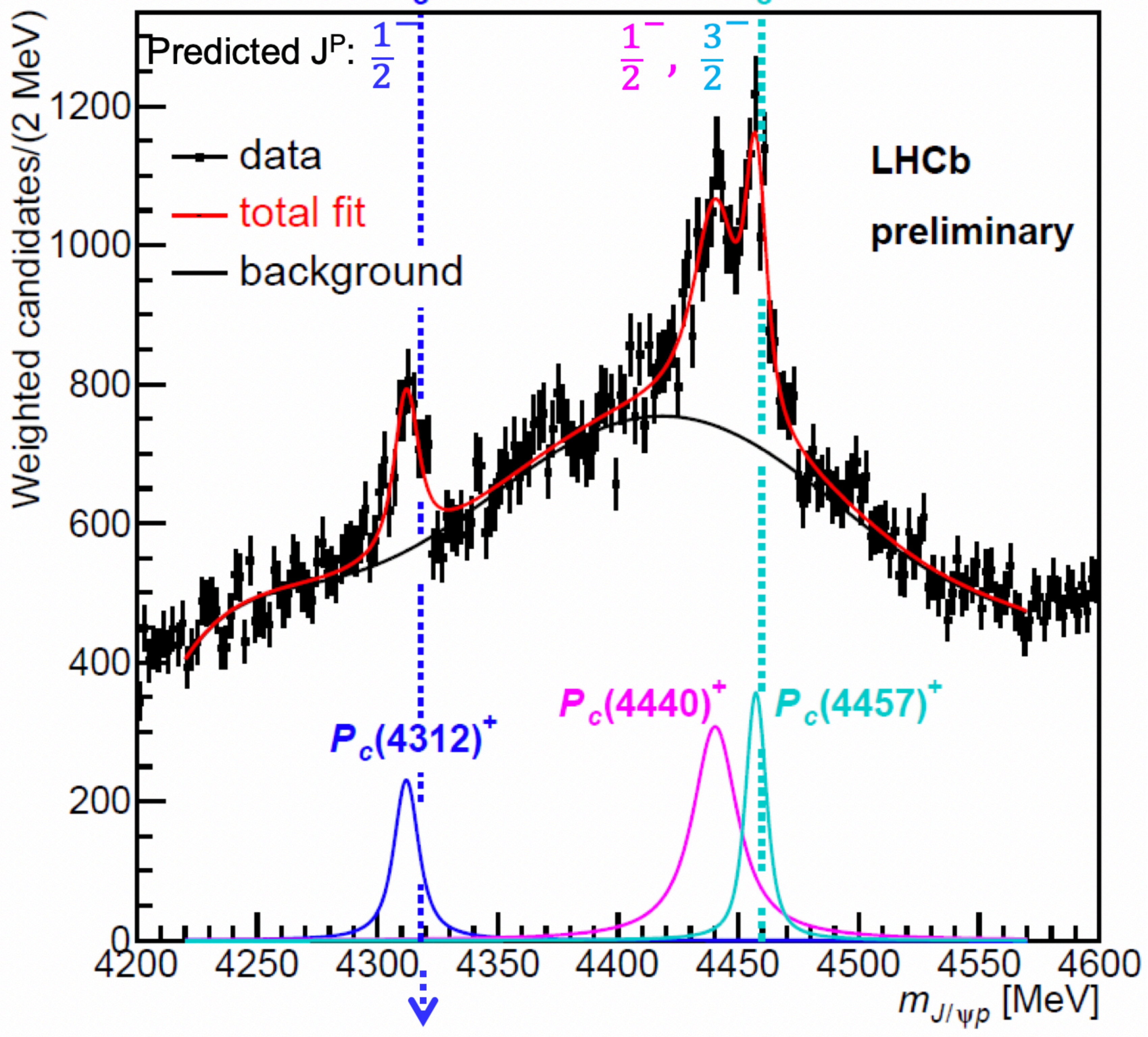


LHCb sees strong evidence for 3 resonant states

THE LHC-B CHARMED PENTAQUARKS

Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019 — 14

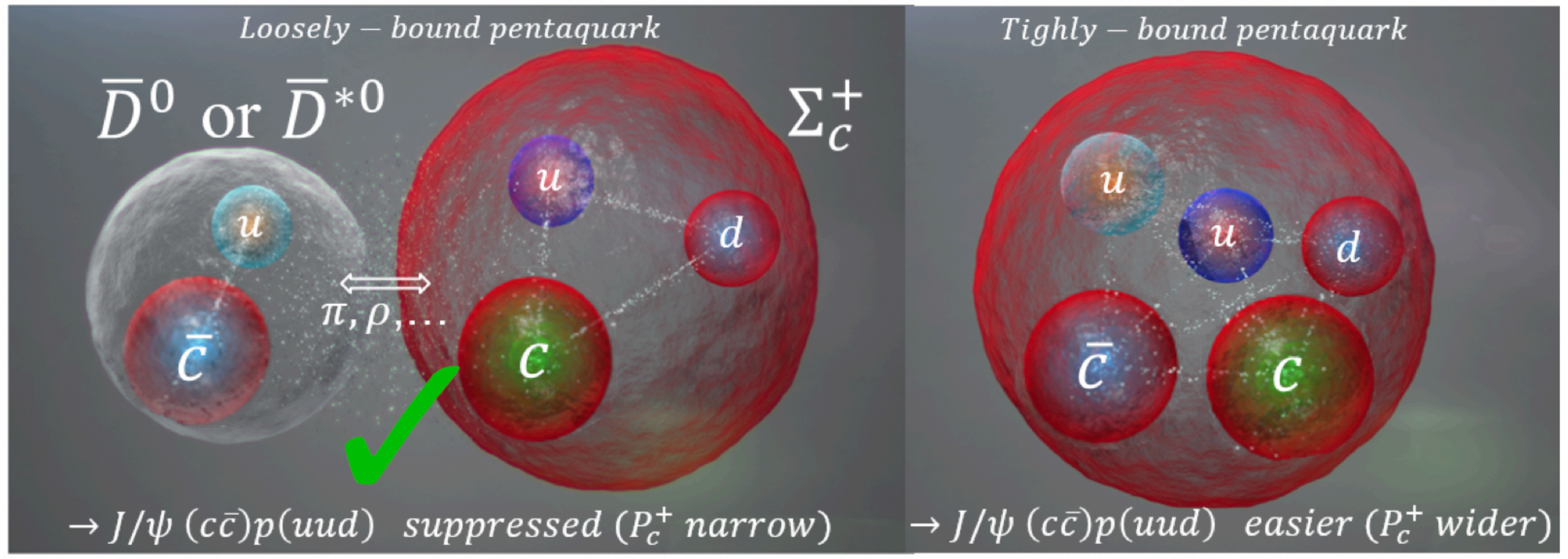
Plausible theoretical interpretation



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^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).

4% scale uncertainty on cross section

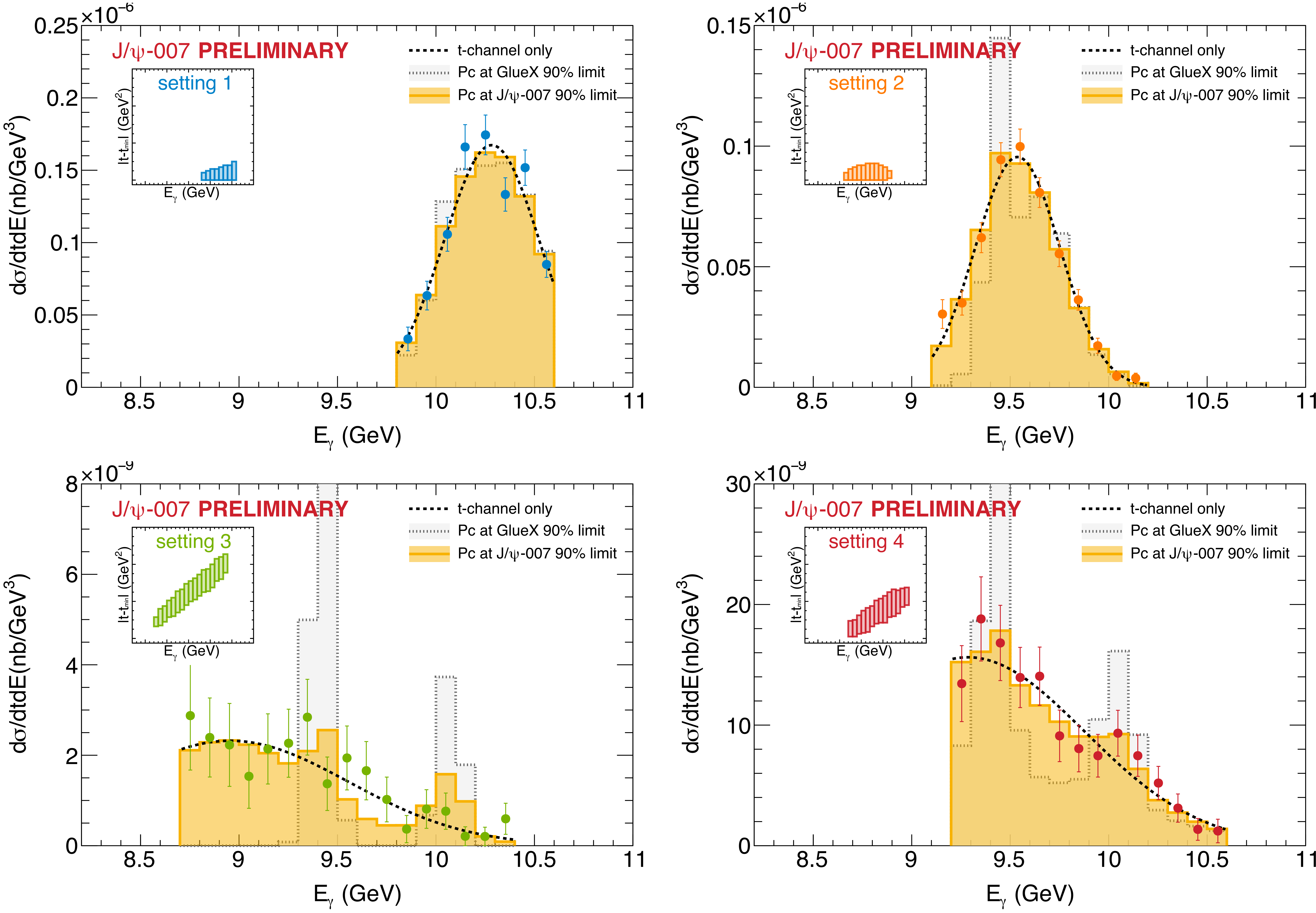
SCANNING THE SPECTRUM

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).



B. Duran, S. Joosten, Z.-E. Meziani, final results

4% scale uncertainty on cross section limit

RESULTS ON THE PENTAQUARK RESONANCES

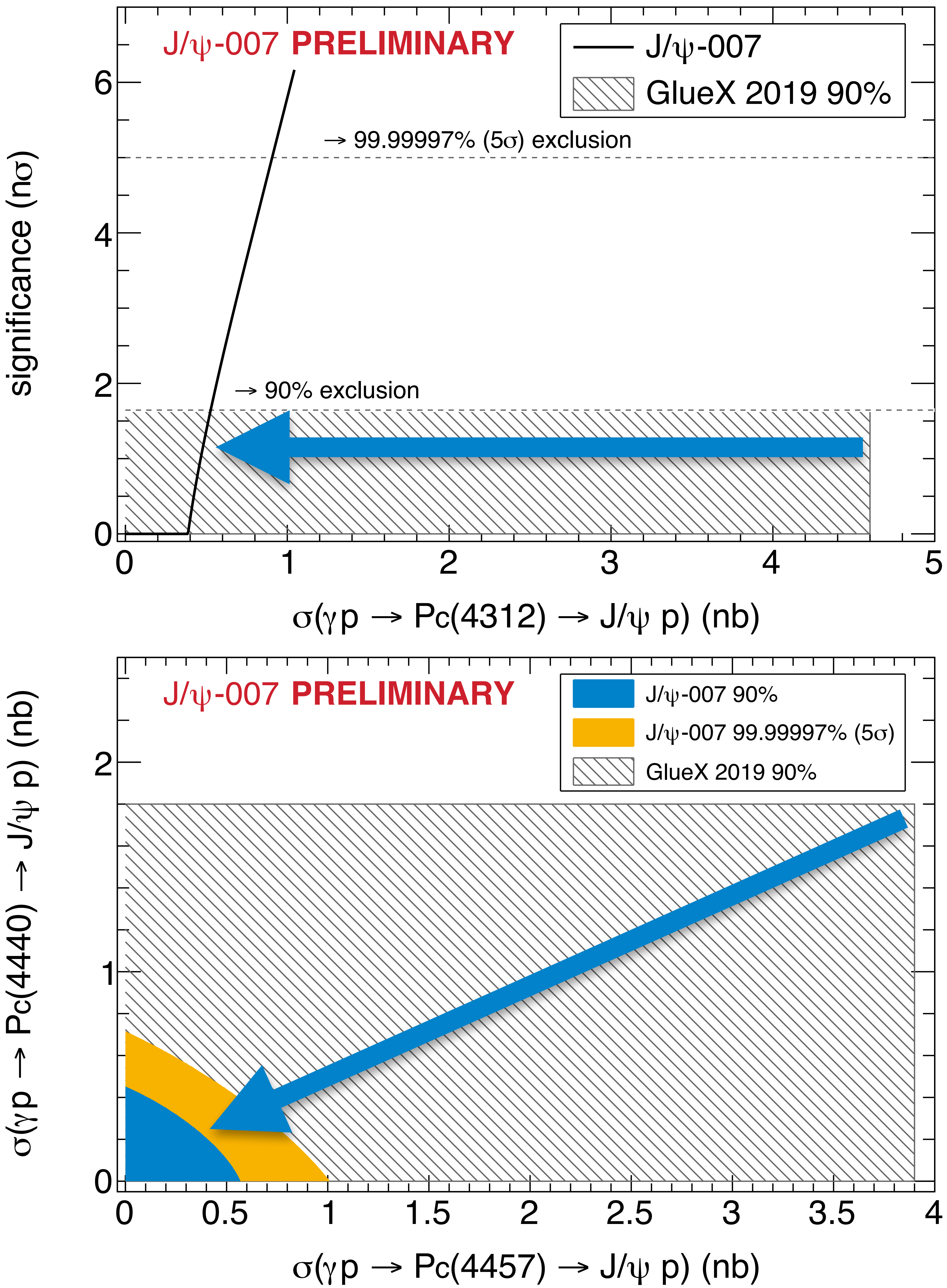
Cross-section at the resonance peak for model-independent upper limits

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.

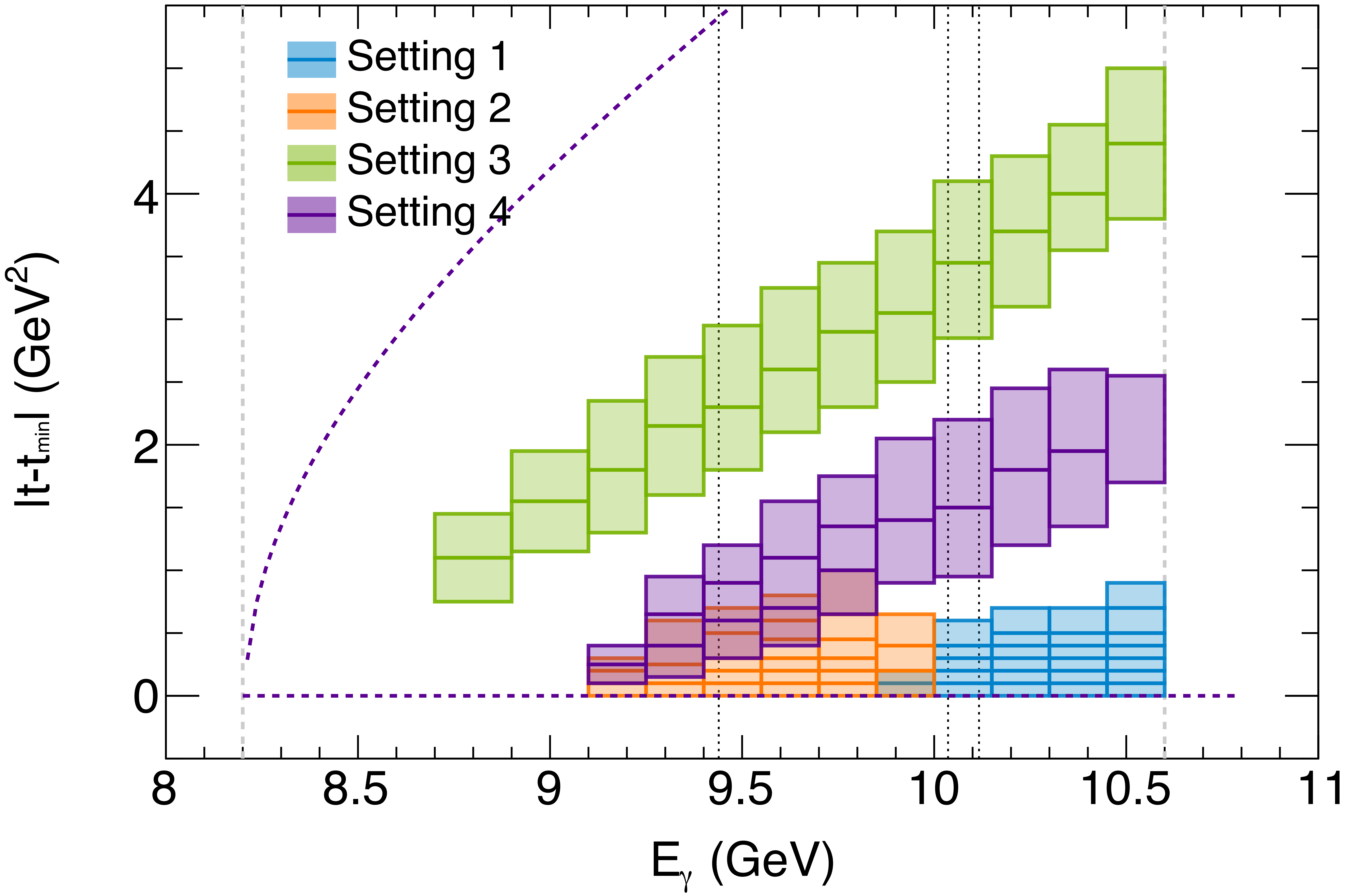
To learn more we need a large-acceptance high-intensity photoproduction experiment, and potentially access to polarization observables. **This can be achieved with the future SoLID-J/ψ experiment at Jefferson Lab**



PHASE SPACE COVERAGE

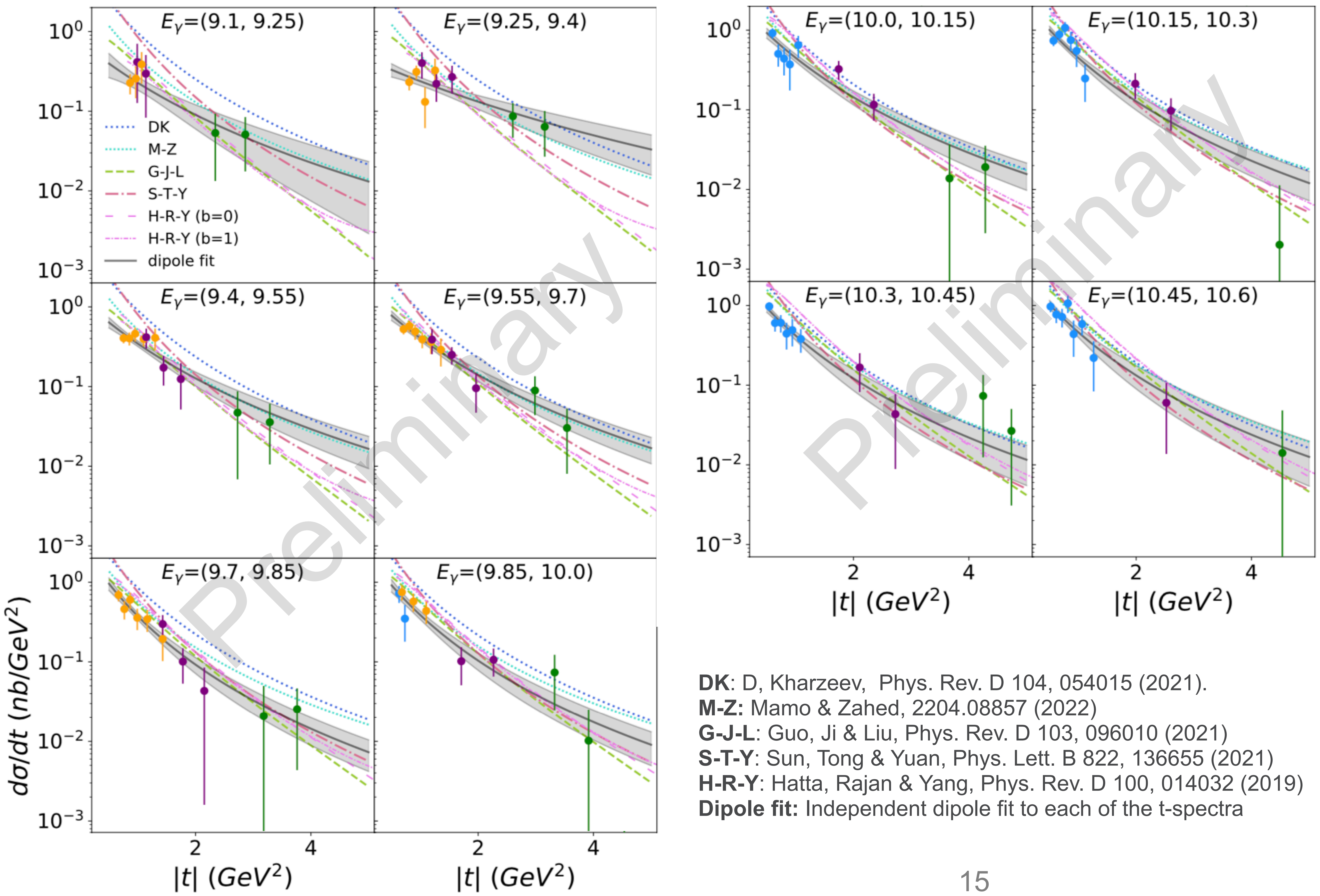
Unprecendented access to large-t region

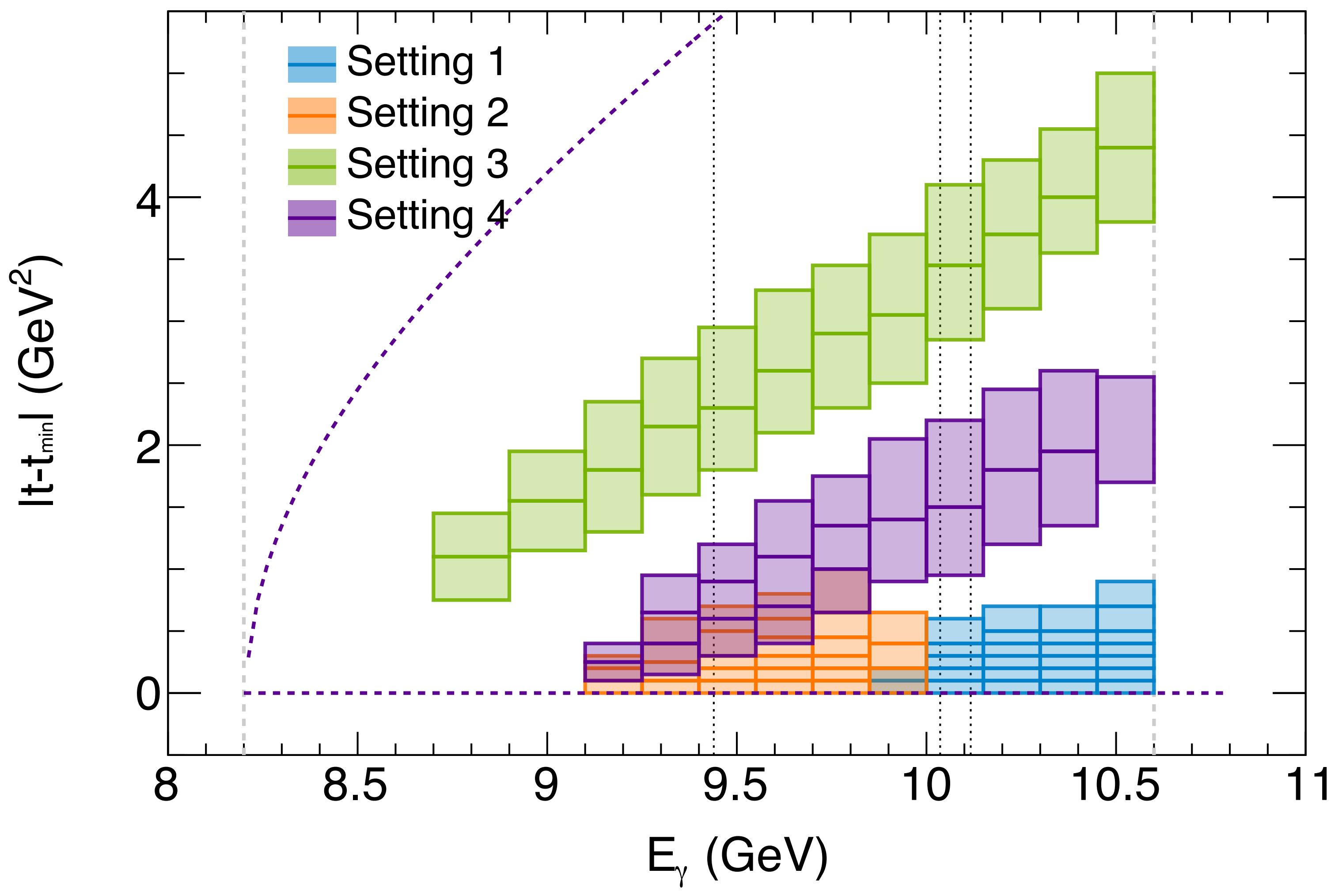
- Truly 2D measurement
- ~2000 counts in electron channel
- Additional 2000 counts in muon channel still under analysis



Results currently under peer-review

PRELIMINARY 2D J/Ψ CROSS SECTION RESULTS



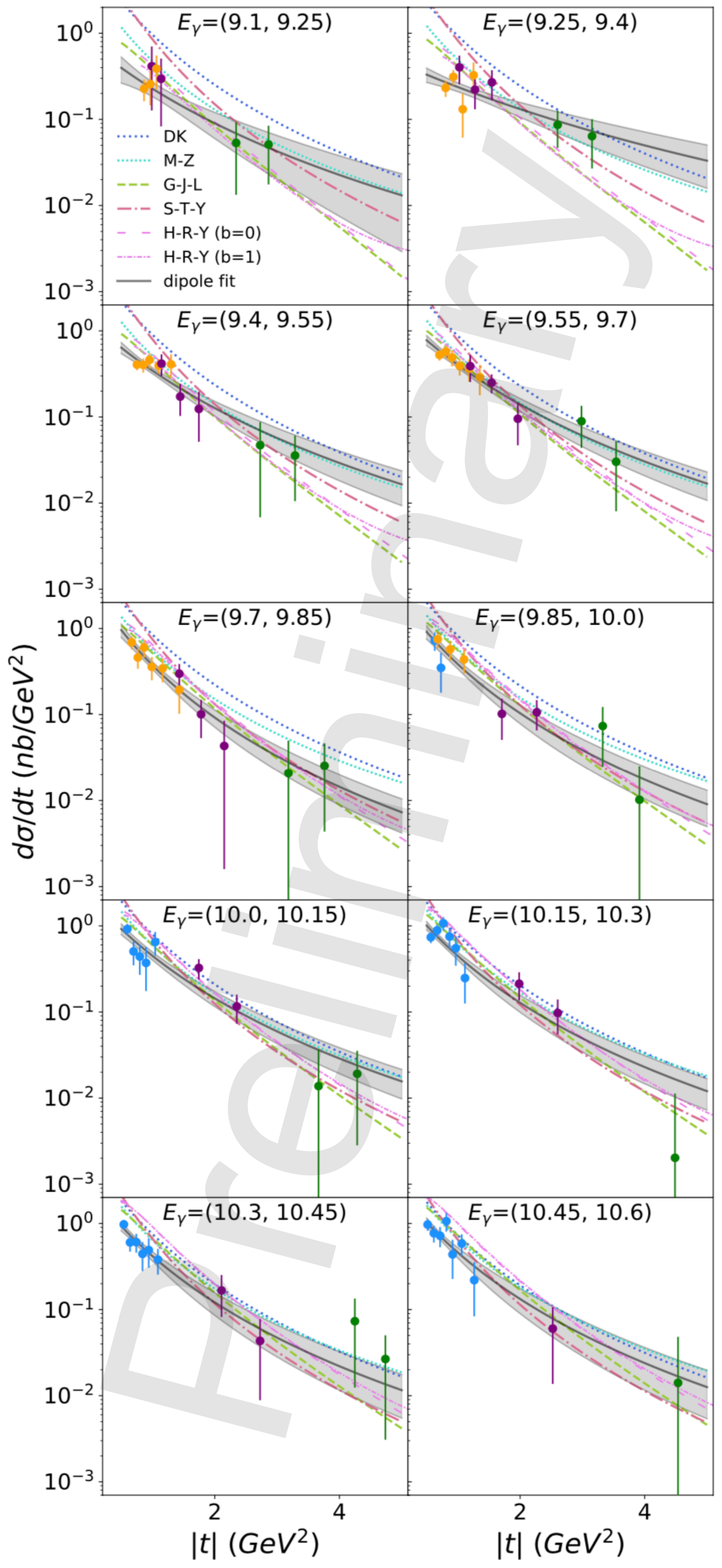


DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)
Dipole fit: Independent dipole fit to each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

- Unfolded 2D cross section results compared to various model predictions informed by the 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

EXTRACTING GFFS FROM THE 2D PROFILES

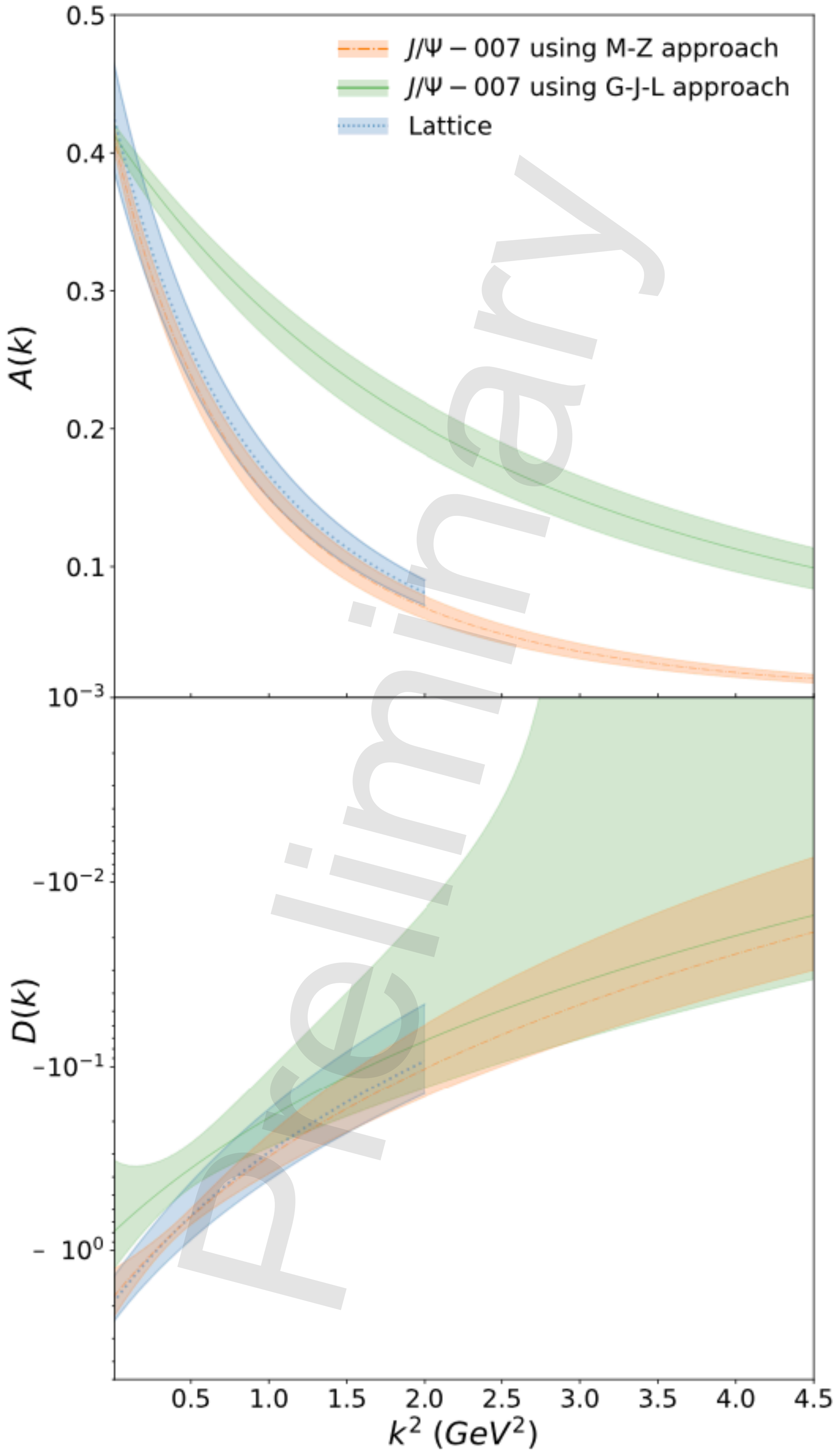
First ever extraction of gluonic GFFs from purely experimental data!



- Model dependent extractions using the available approaches in the literature
  - Holographic QCD approach: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
  - GPD+VMD approach: Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
  - In both cases assume $B_g(t)$ contributes little (supported by lattice)
- Use tripole form for $A_g(t)$ and $C_g(t)$ (differences with dipole negligible)
- Use $A_g(0) = \langle x_g \rangle$ from the CT18 global fit, fit remaining 3 parameters $(m_A, C_g(0), m_C)$ to 2D cross section results.

GLUONIC GFF RESULTS

Good agreement between Holographic QCD and Lattice results!



- Results from the 2D gluonic GFF fits
- Gluonic $A_g(t)$ and $D_g(t) = 4C_g(t)$ form factors
- χ^2/n.d.f. in both cases very close to 1
- M-Z (holographic QCD) approach fit to only experimental data gives results very close to the latest lattice results!
- In both cases the extracted mass radius is substantially smaller than the proton charge radius, hinting at a picture where the proton has a dense, energetic core surrounded by a larger quark region.

$$\langle r_m^2 \rangle = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\bigg|_{t=0} - \frac{6}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
G-J-L: Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
Lattice: D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

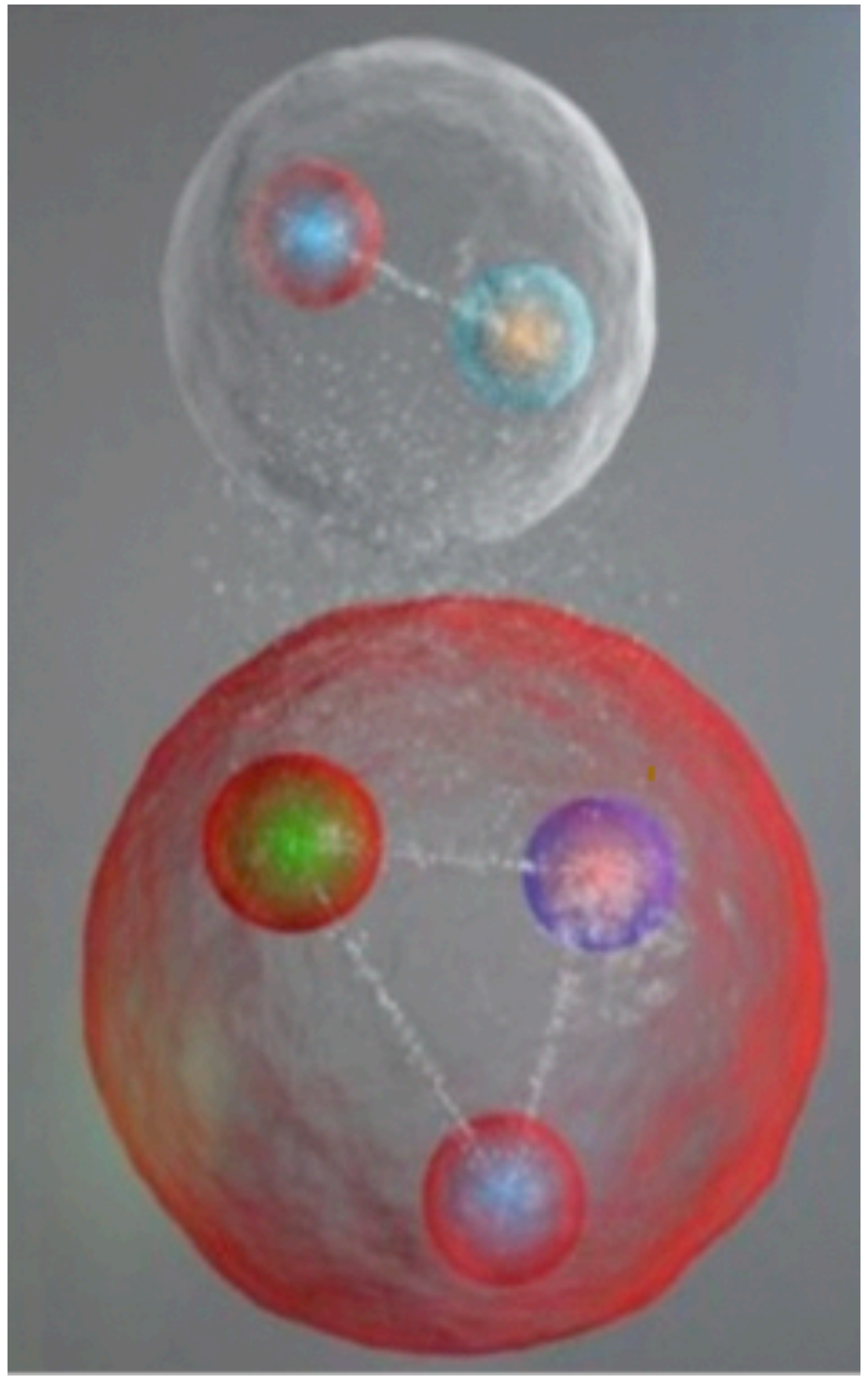
J/Ψ EXPERIMENTS AT JLAB COMPARED

	GlueX HALL D	HMS+SHMS HALL C[2]	CLAS 12 with upgrade[1] HALL B	SoLID HALL A[2]
J/ψ counts (photo-prod.)	**469 published ~10k phase I + II**	**2k electron channel 2k muon channel**	**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 $2\times10^{35}/cm^2/s$
[2]Led by Argonne MEP

CONCLUSION

- Threshold production of quarkonium can shed light on the trace anomaly, quarkonium-nucleon/nucleus binding, the LHCb pentaquark and the matter structure of the proton.
- The Hall C J/ψ-007 experiment has the first near-threshold 2D J/ψ cross section results in this area, currently under peer review.
  - Stringent exclusion limit for the LHCb charmed pentaquarks in photoproduction
  - New window on the gluonic GFFs in the proton
  - Does the proton have a dense energetic core?
- The matter structure of the proton and threshold quarkonium production are rapidly evolving topics that reach from Jefferson Lab to the EIC. Dedicated proton mass workshop happening right now at the INT!



QUESTIONS?