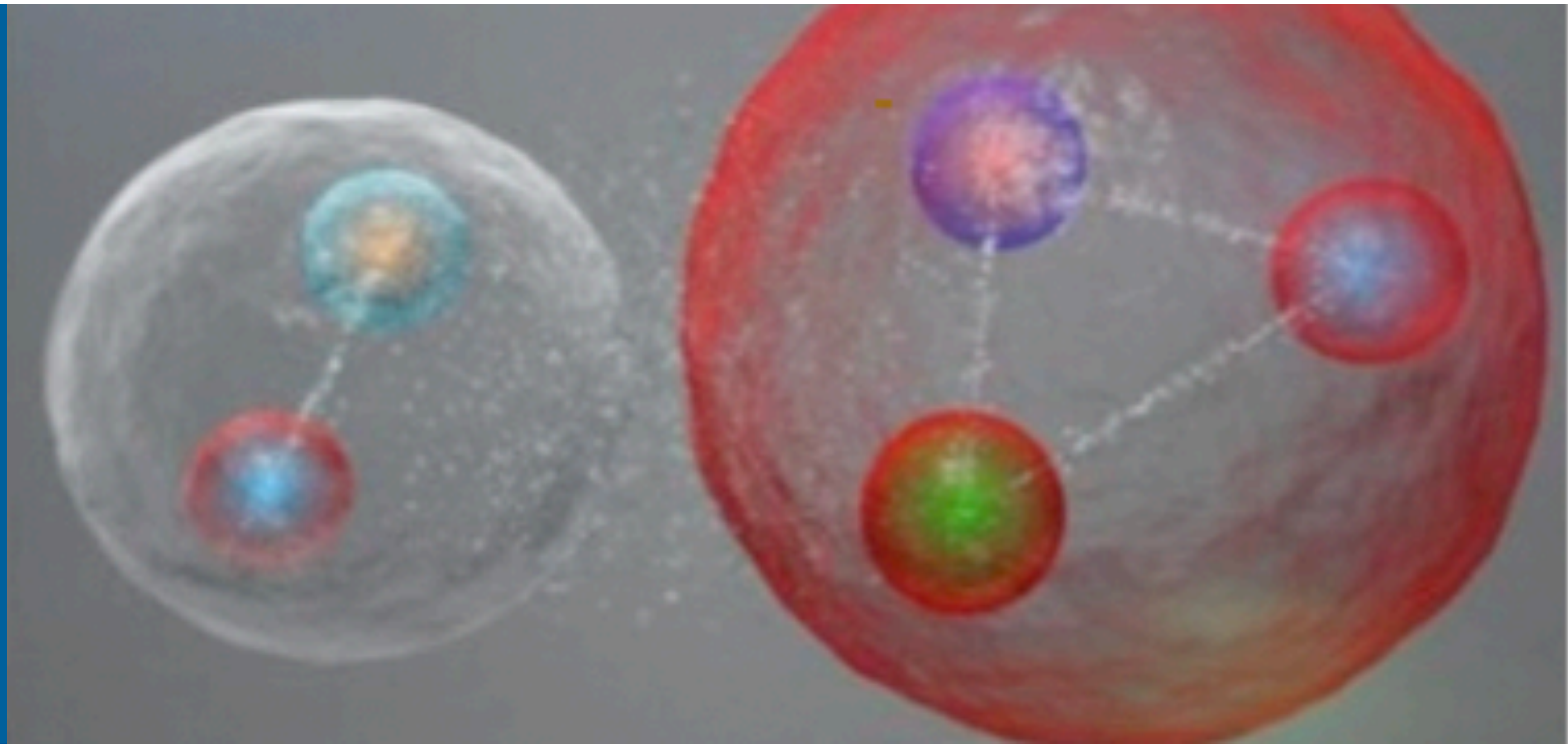
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY

FROM J/Ψ AT JEFFERSON LAB TO Υ AT EIC

New results on threshold J/ψ production from Hall C and future potential at JLab and the EIC



SYLVESTER JOOSTEN
sjoosten@anl.gov

NEW RESULTS ON BEHALF OF
THE HALL C J/Ψ-007 COLLABORATION

007J/ψ Hall-C

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

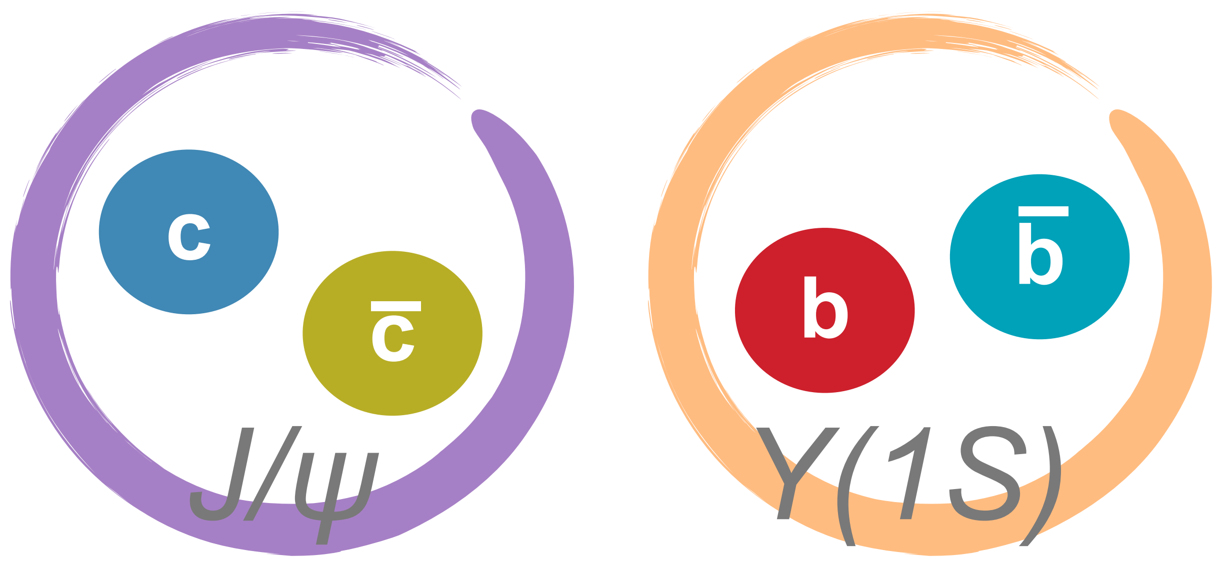
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

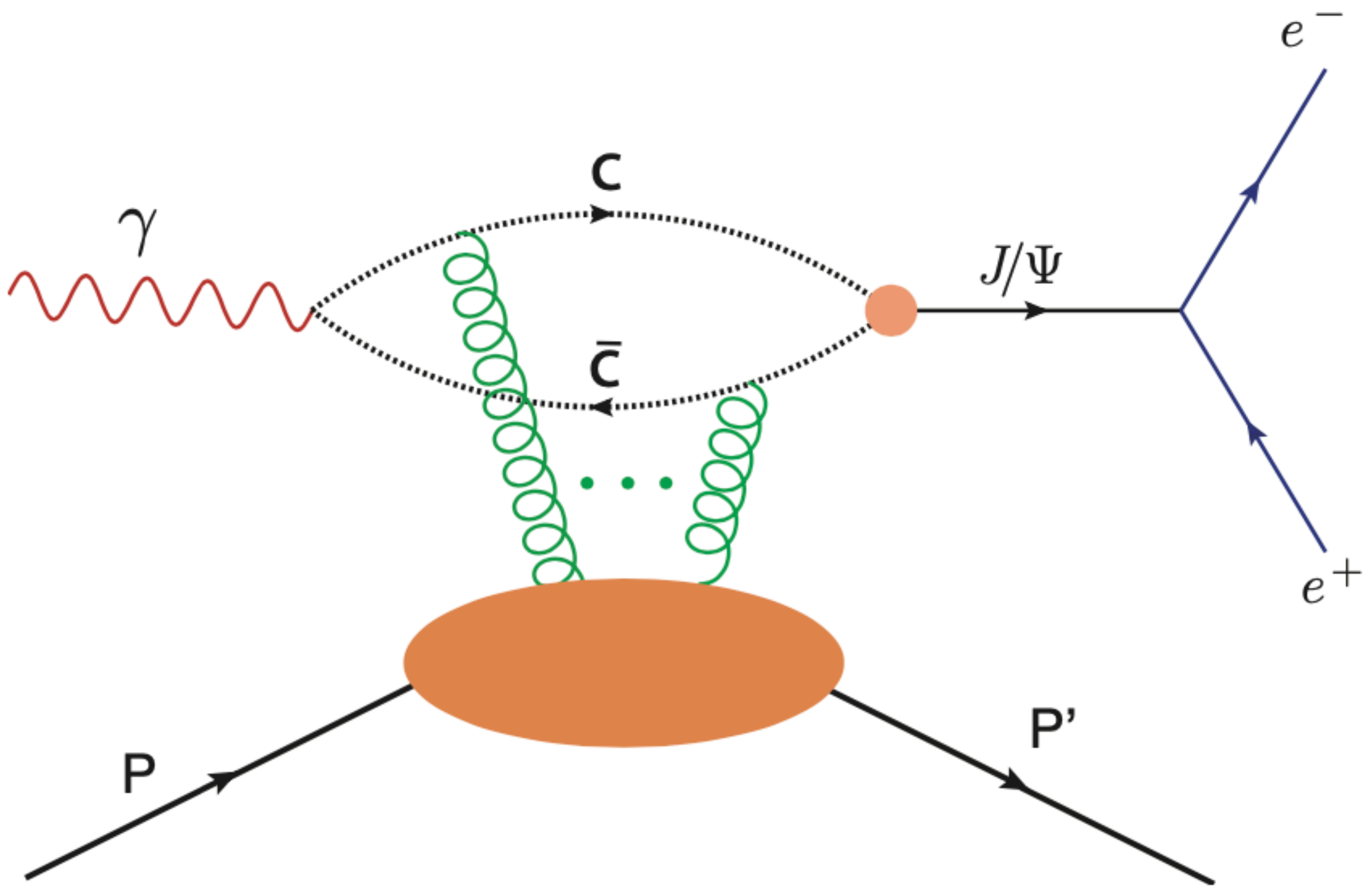
Proton Mass Workshop
INT, June 14, 2022

WHY QUARKONIUM PRODUCTION NEAR THRESHOLD

Gluons are hard to probe

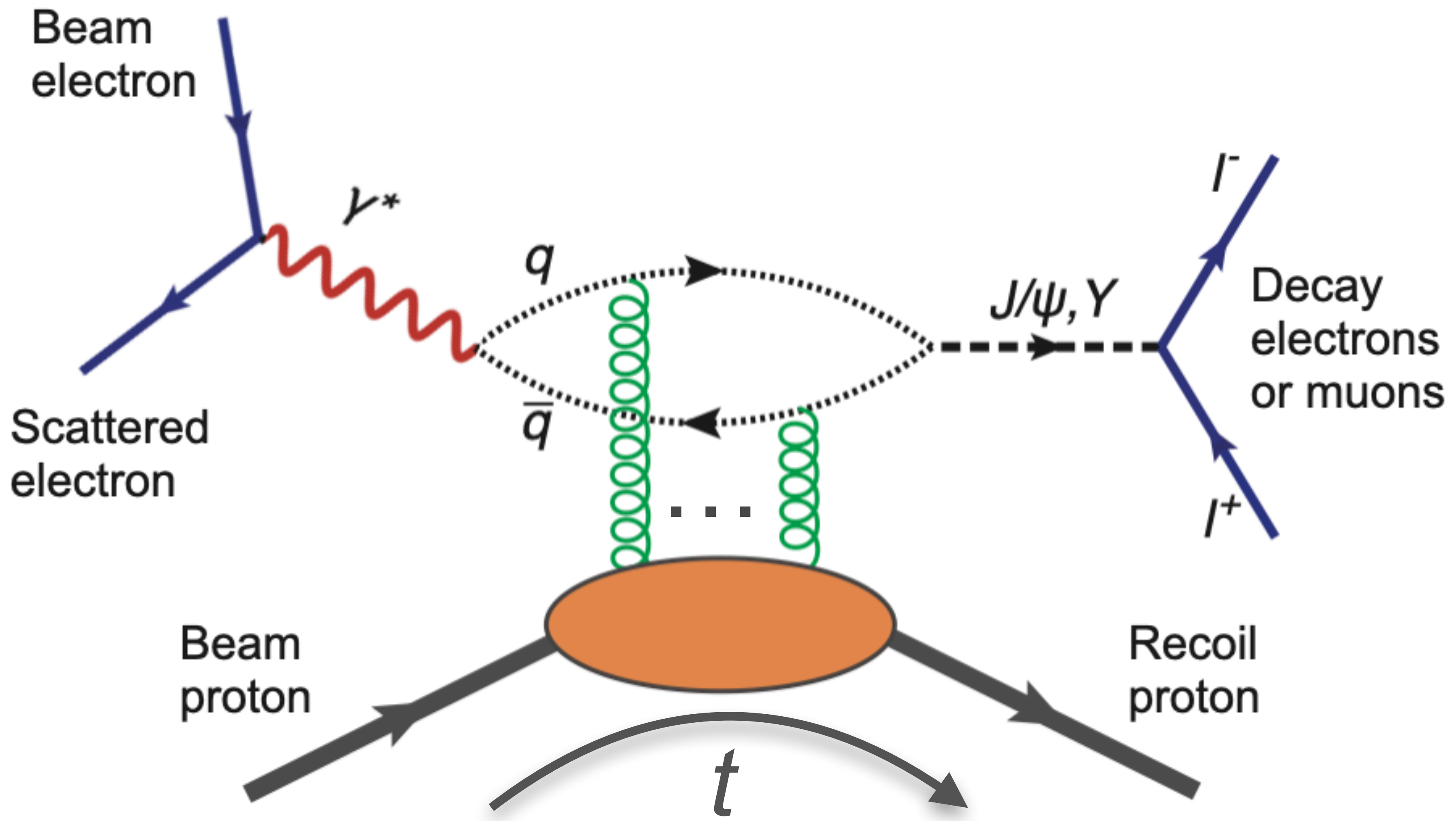
- Electromagnetic charge and spin of the proton well-studied through electron scattering
- Gluons are harder to directly access, as they do not carry electromagnetic charge
  - Description of mass still in infancy, as most energy (and hence mass) carried by the gluons
  - J/ψ and Y(1S) only couple to 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.**

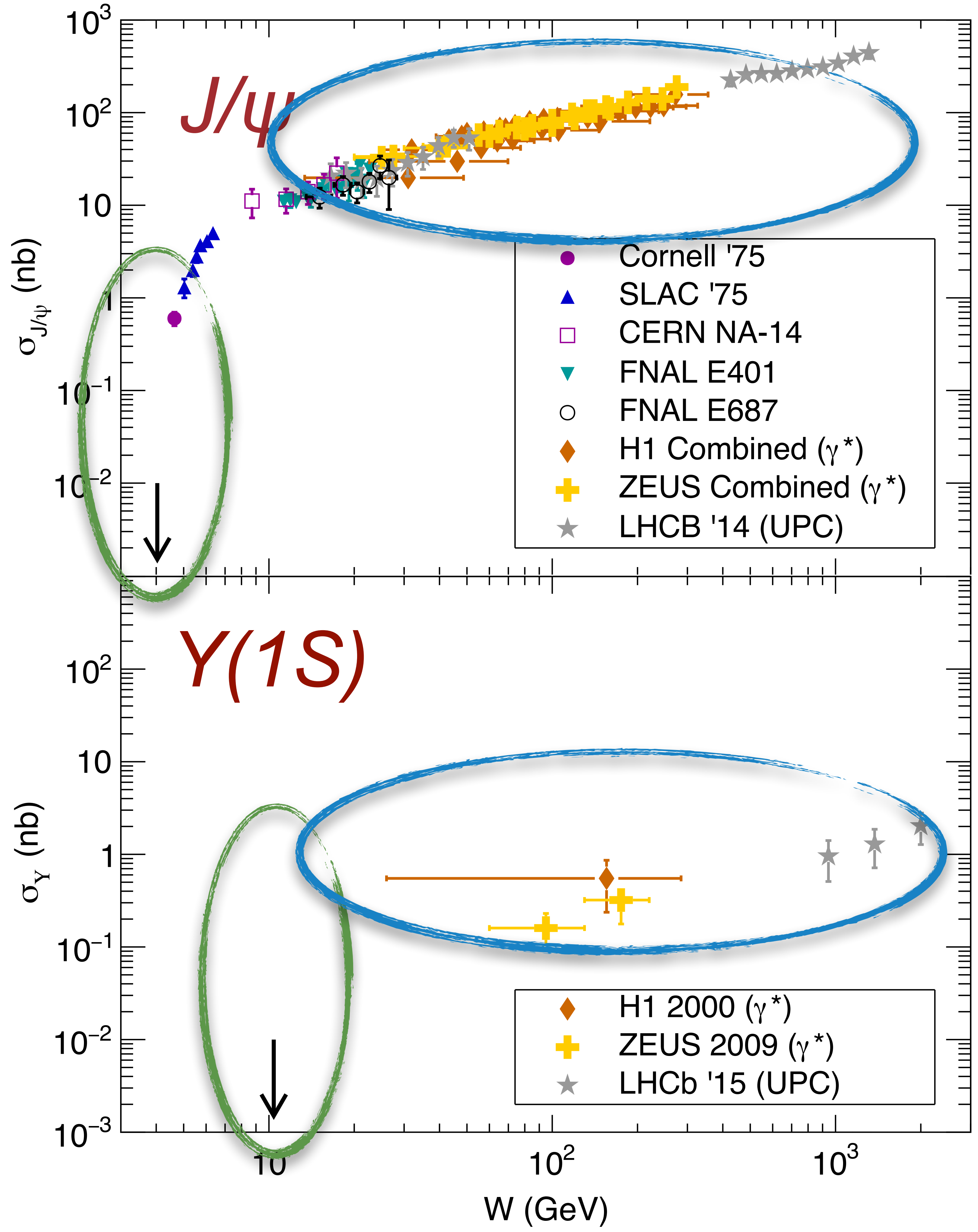




EXCLUSIVE QUARKONIUM PRODUCTION

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**

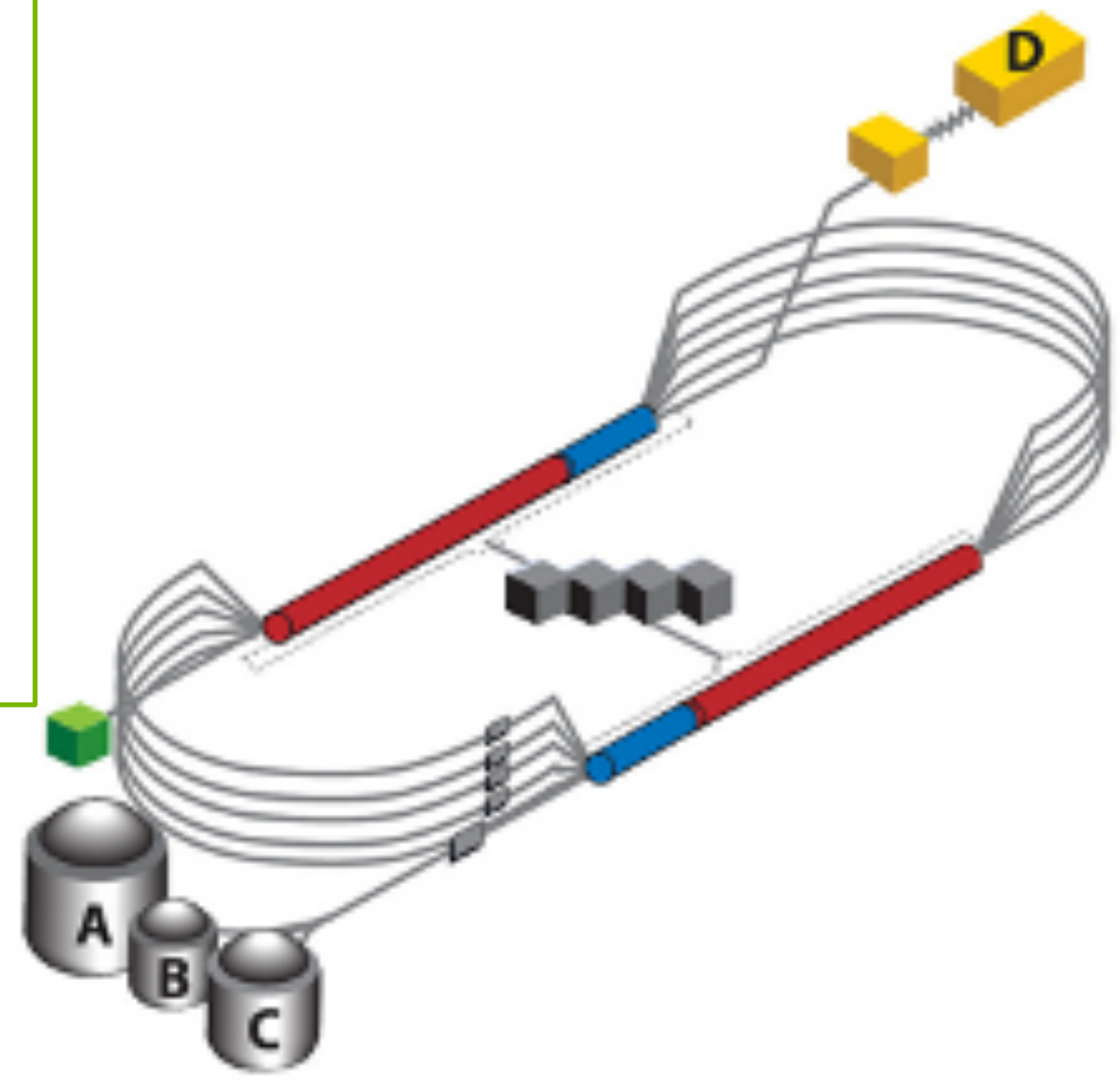
QUARKONIUM AT JEFFERSON LAB AND EIC

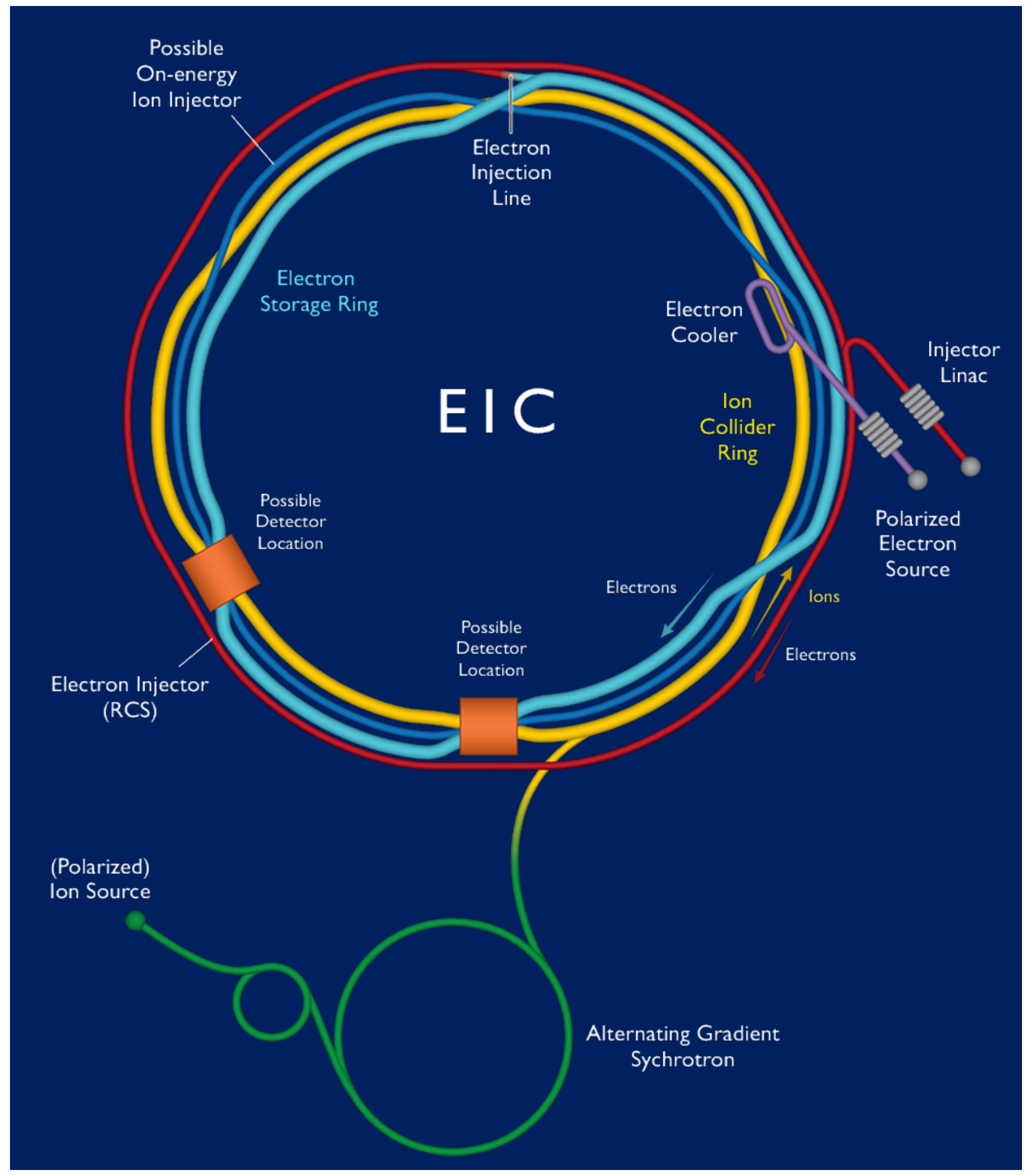
Jefferson Lab

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

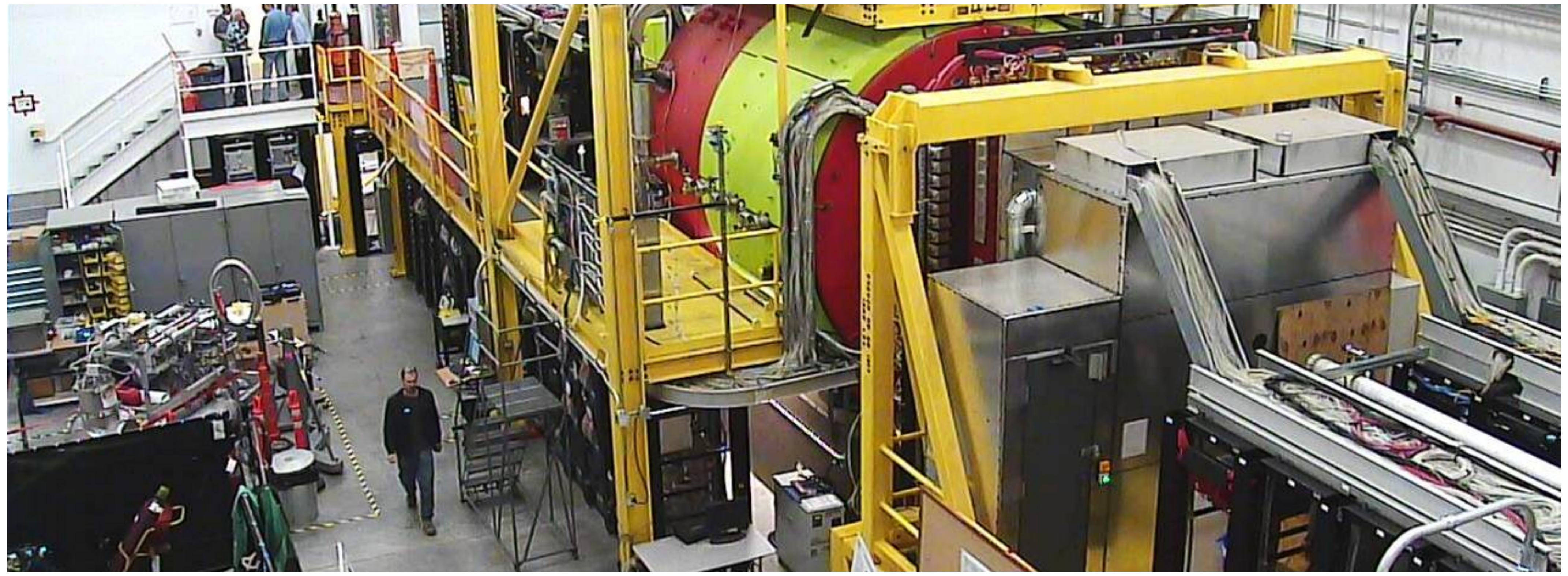
EIC: high luminosity (10^{33}-10^{34} $cm^{-2}s^{-1}$) polarized electron polarized ion collider

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

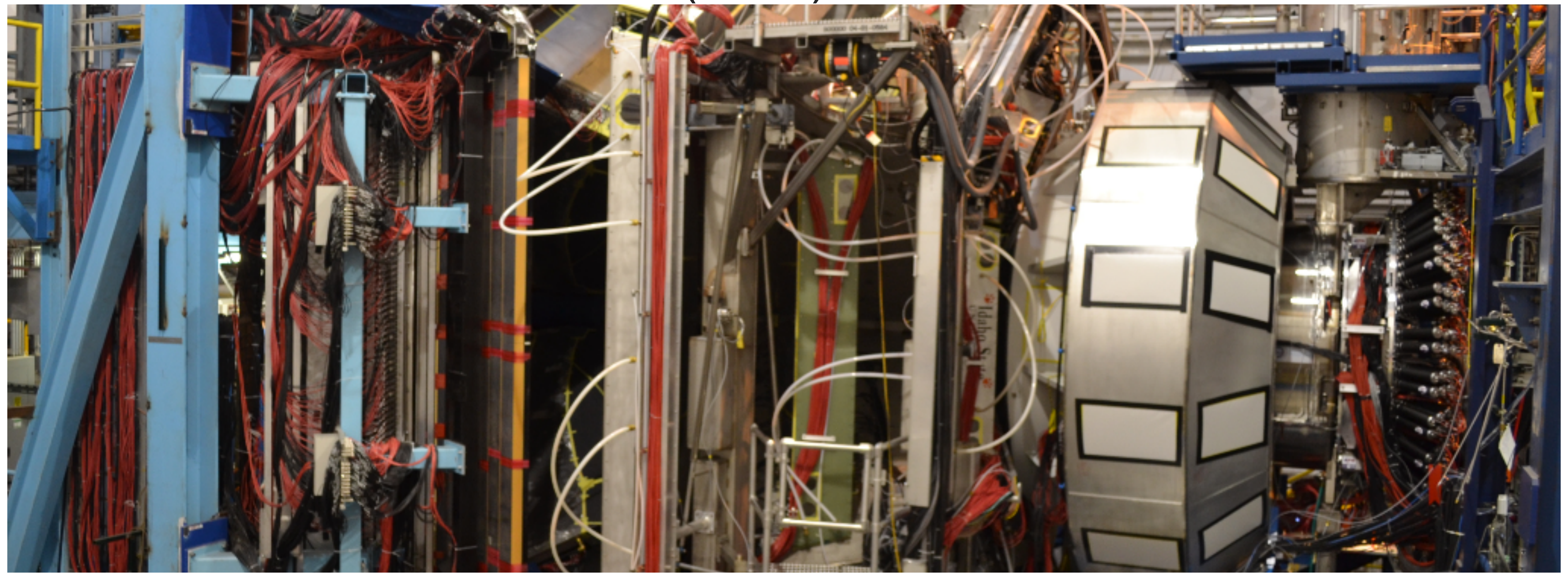
Reach to J/ψ threshold more difficult, sufficient energy and luminosity to study Υ near threshold.

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

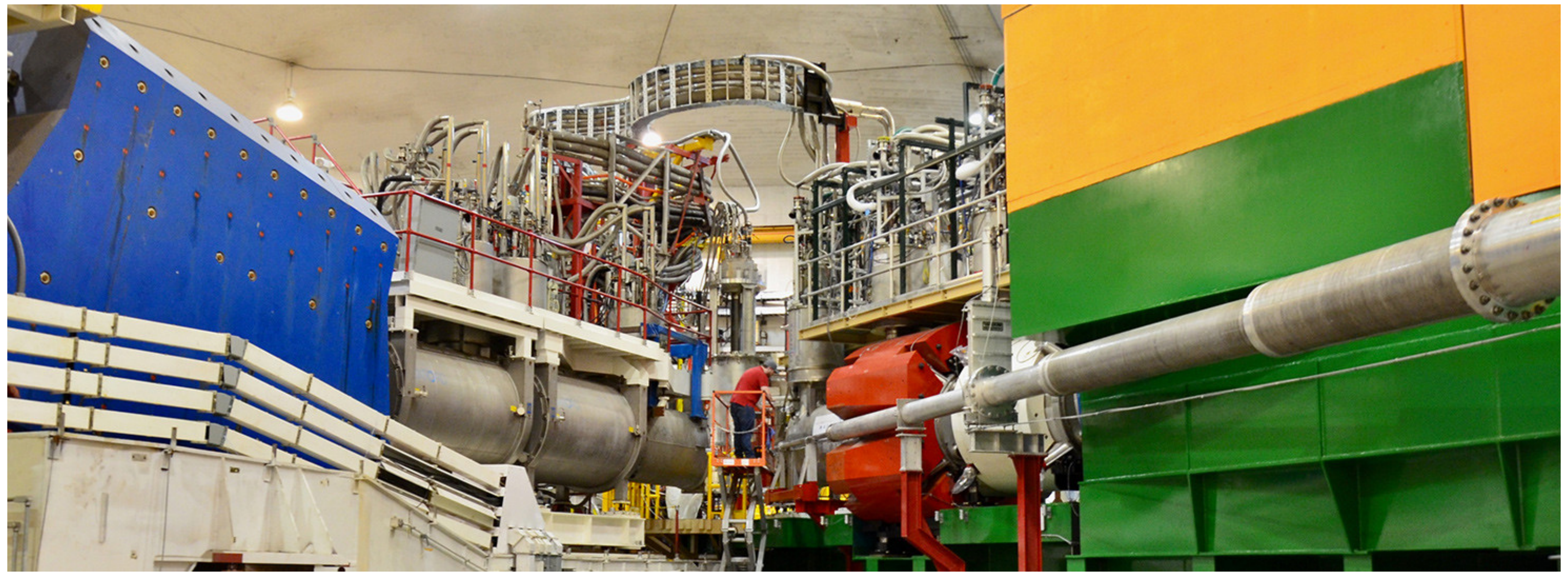
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



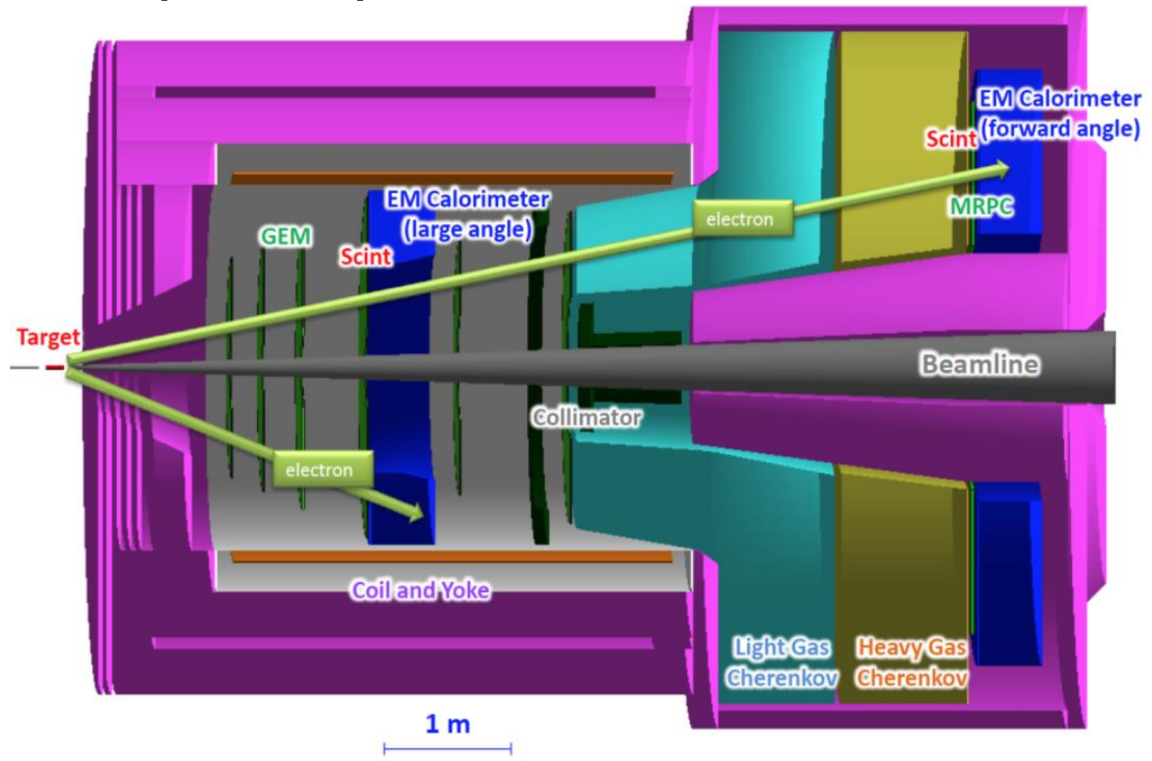
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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[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?

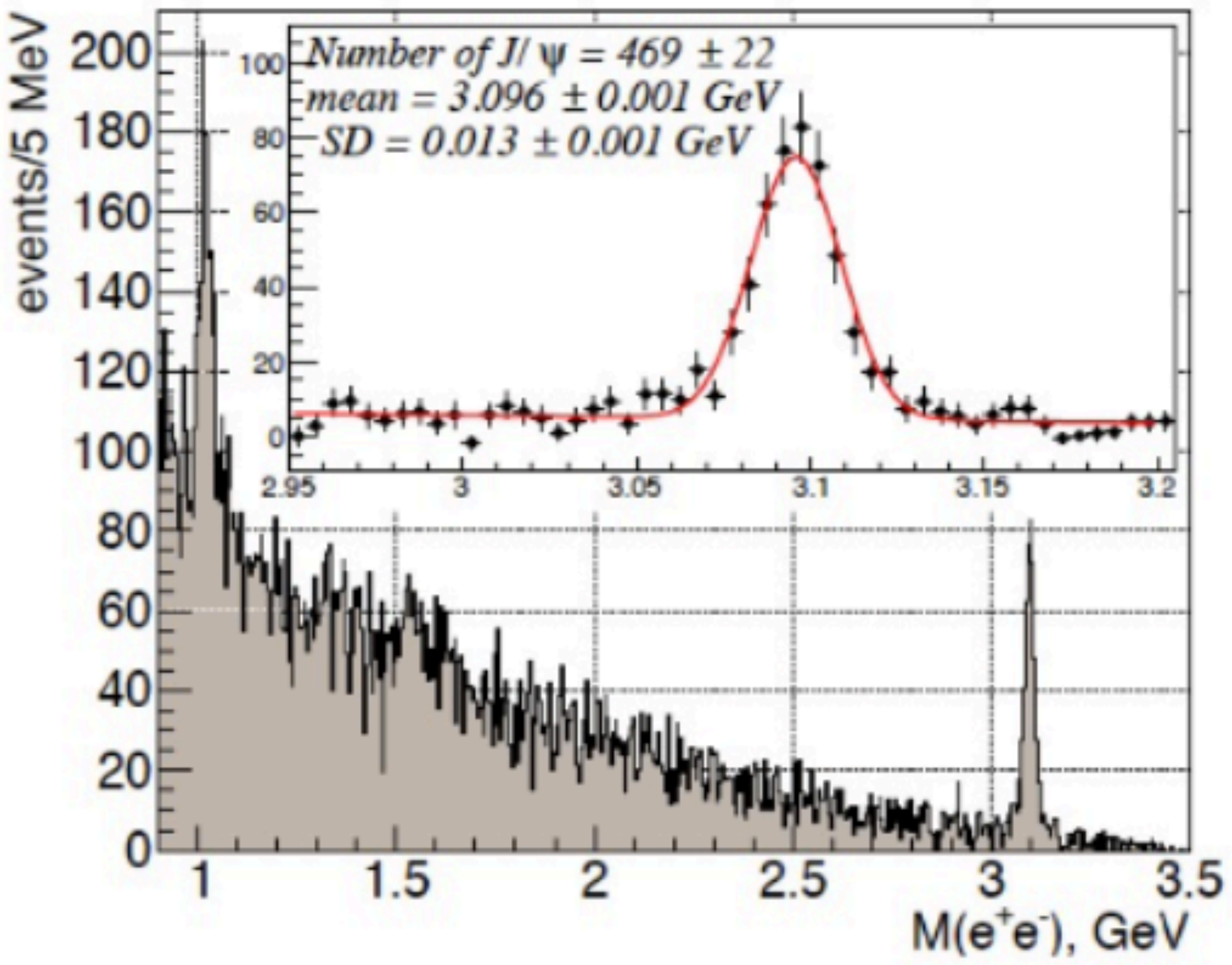
[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2\times10^{35}/cm^2/s$
[2]Led by Argonne MEP

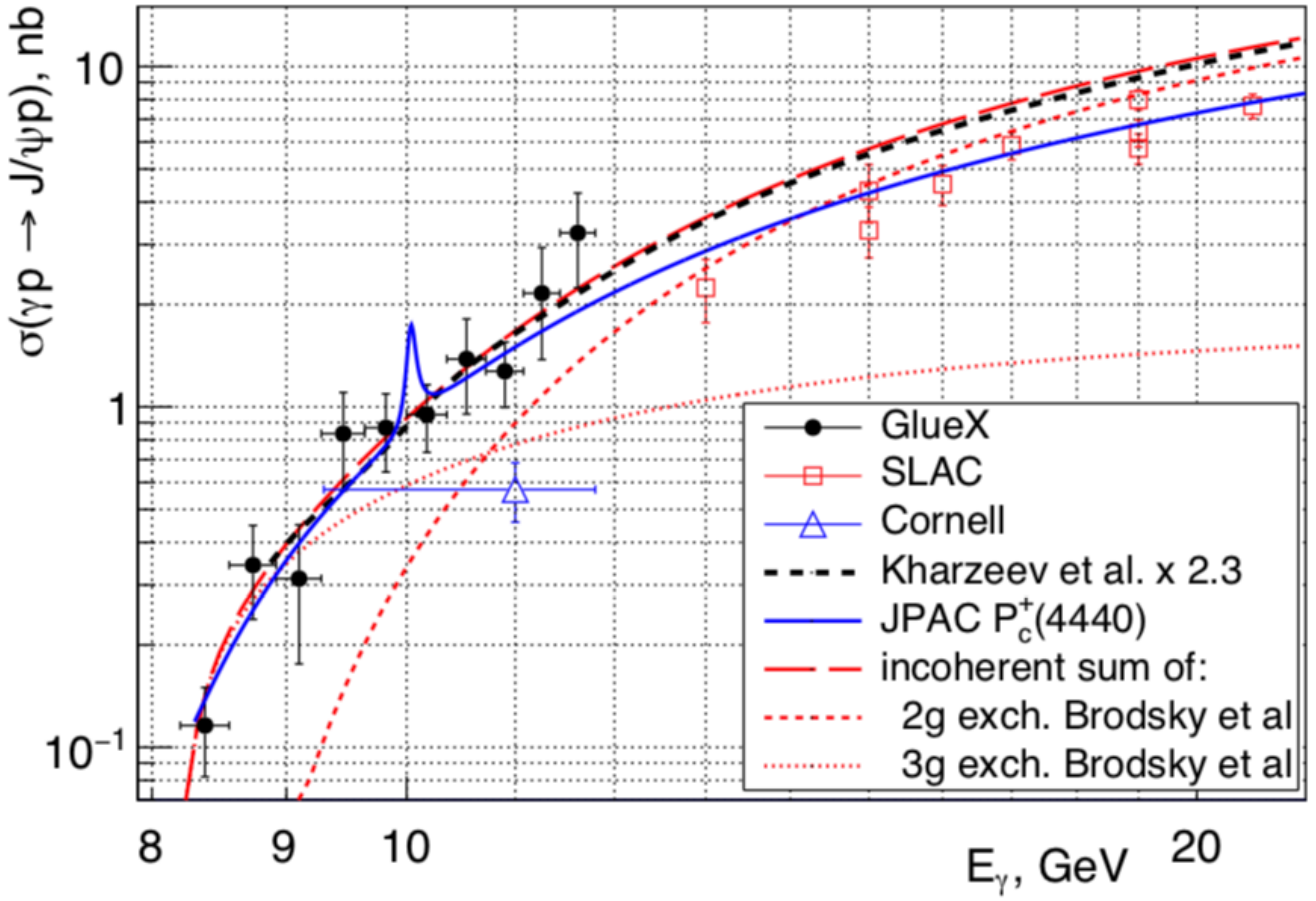
J/Ψ NEAR THRESHOLD IN HALL D

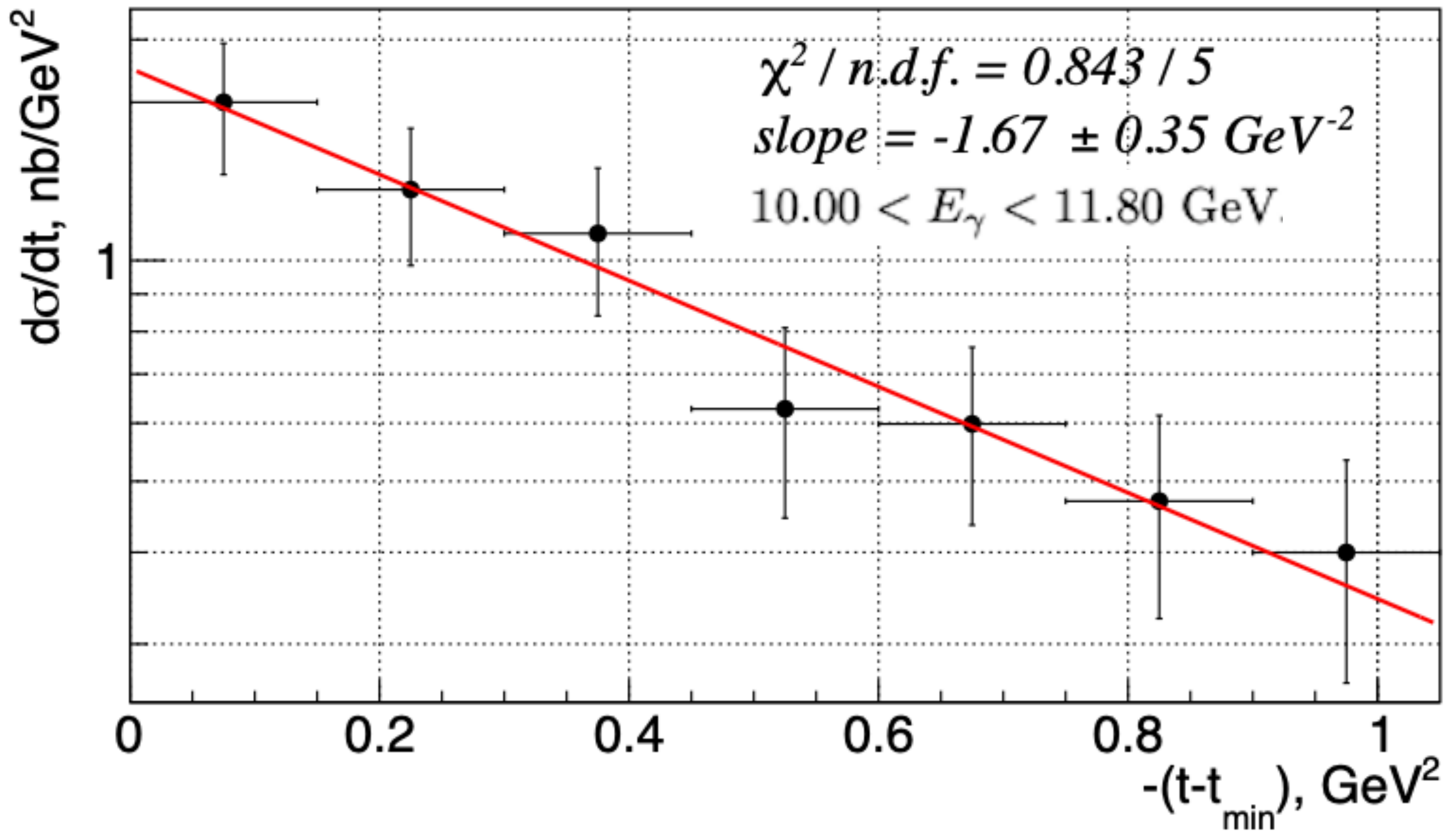
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 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

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





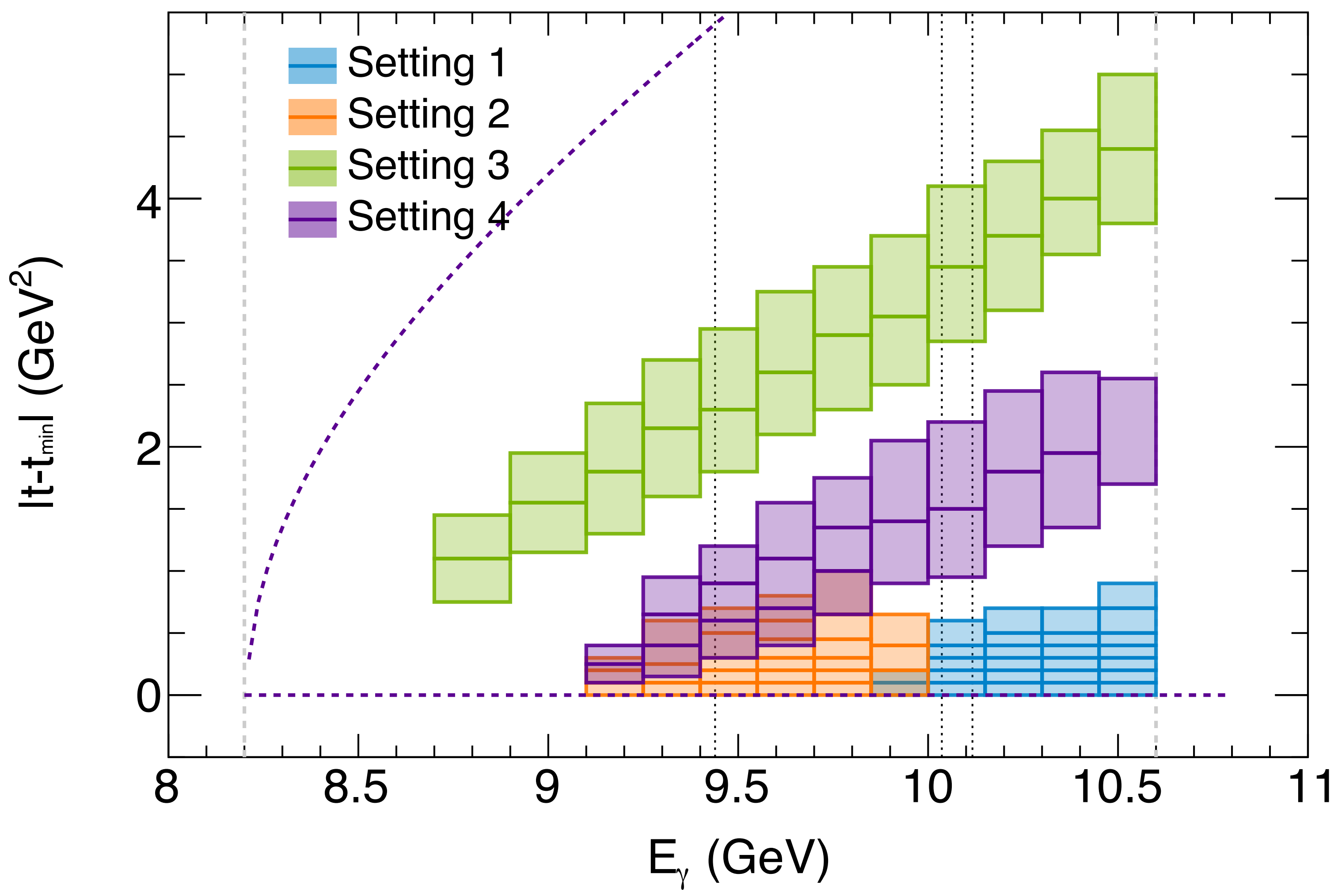


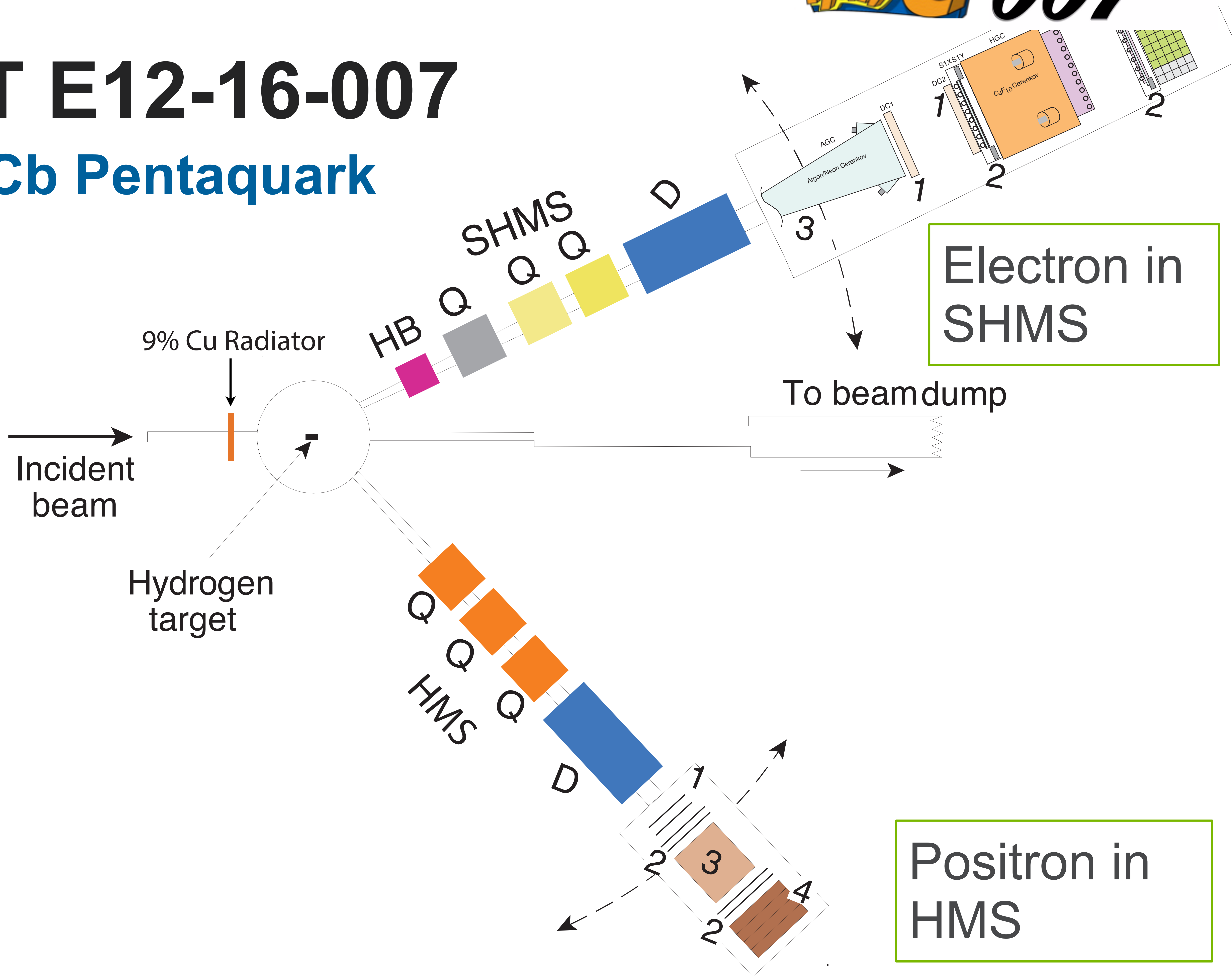
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

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

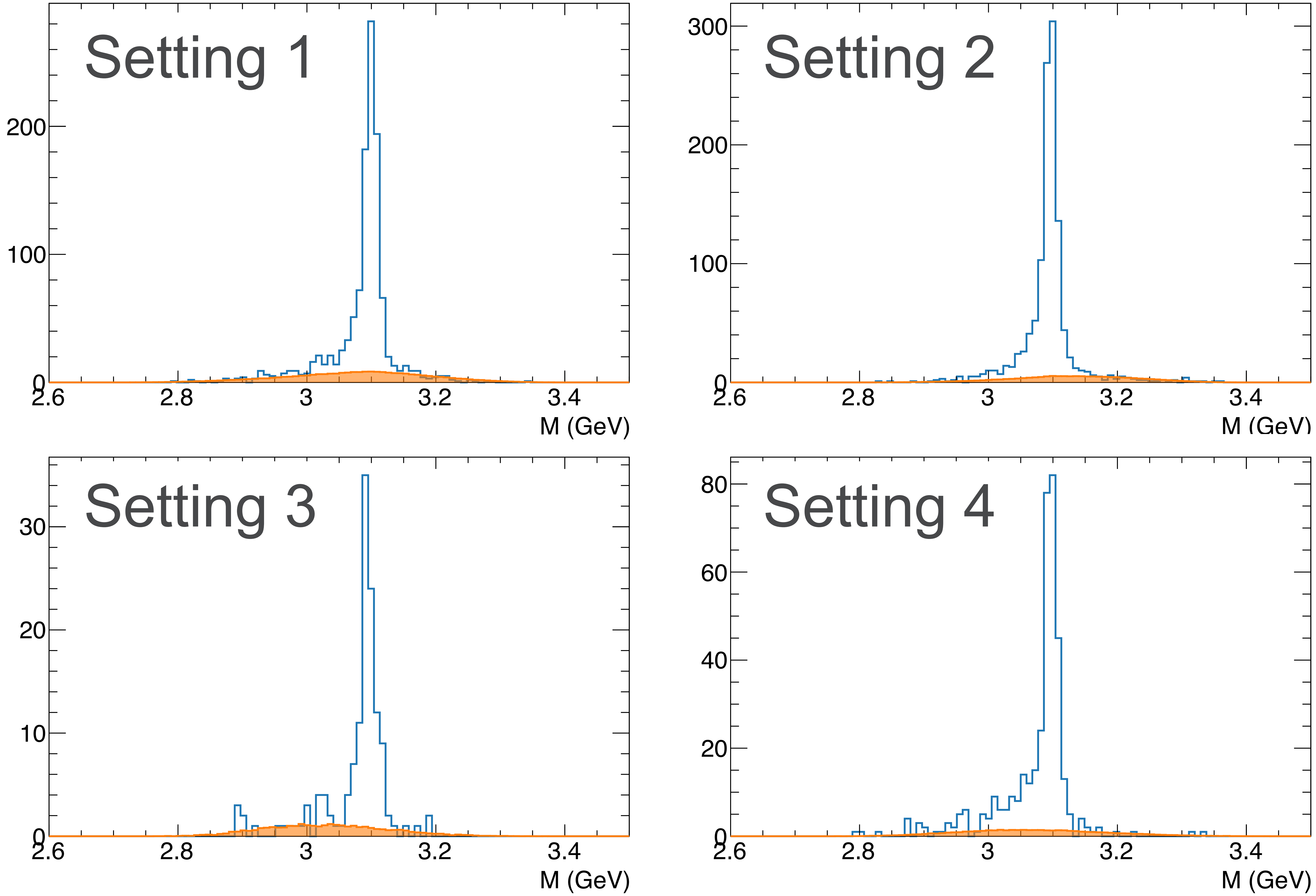




S. Joosten

CLEAR J/Ψ SIGNAL WITH MINIMAL BACKGROUND

settings	HMS	SHMS	target	charge [C]	goal
setting 1	19.1° at +4.95GeV	17.0° 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° at +4.6GeV	20.1° at -4.3GeV	LH2 with radiator	8.2	low-t and low energy
			dummy with radiator	0.3	target wall
setting 3	16.4° at +4.08GeV	30.0° at -3.5GeV	LH2 with radiator	13.8	high-t
setting 4	16.5° at +4.4GeV	24.5° at -4.4GeV	LH2 with radiator	6.9	medium-t
			dummy with radiator	0.2	target wall



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

4% scale uncertainty on cross section limit

RESULTS ON THE PENTAQUARK RESONANCES

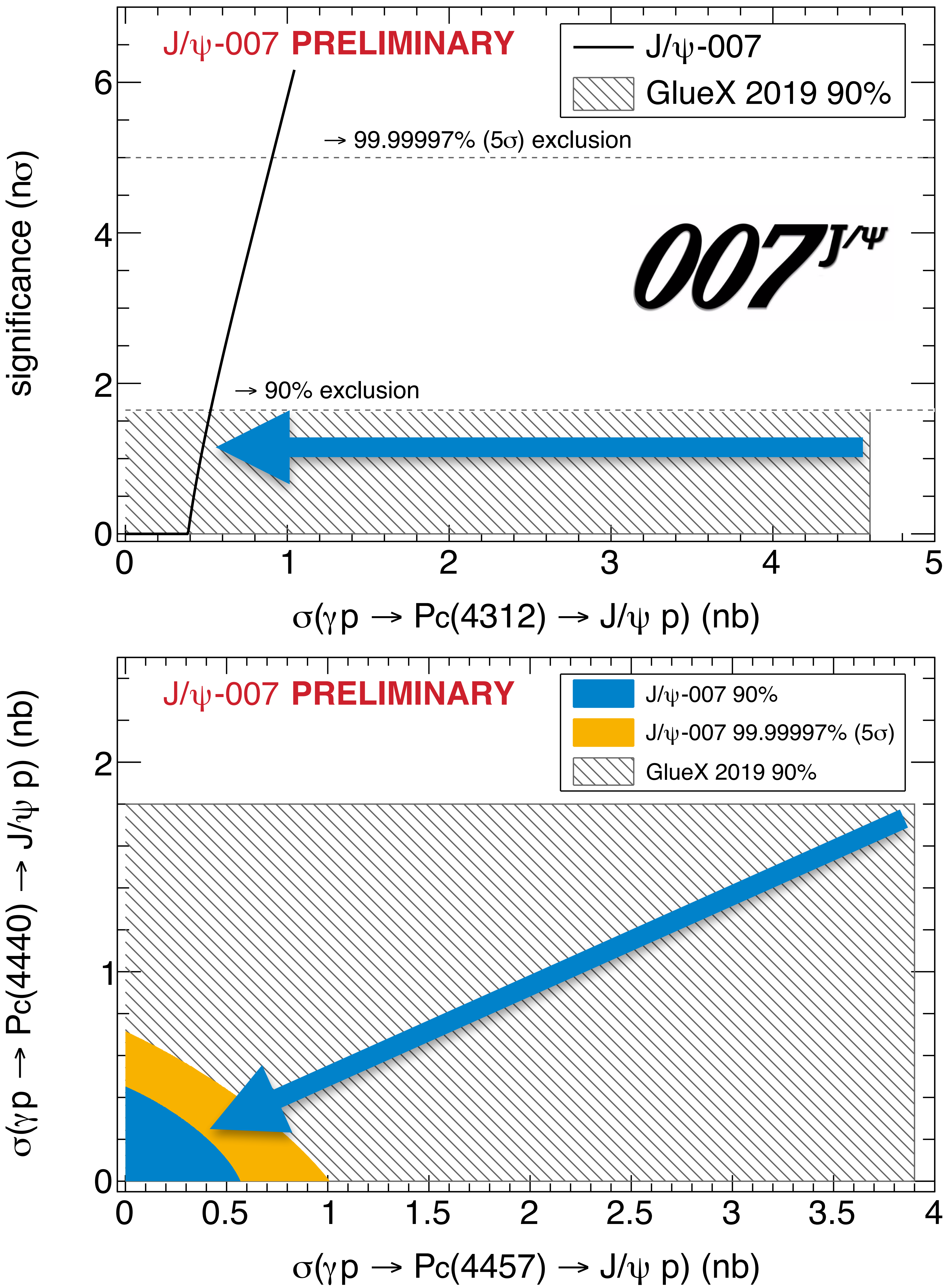
Cross-section at the resonance peak for model-independent upper limits

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.

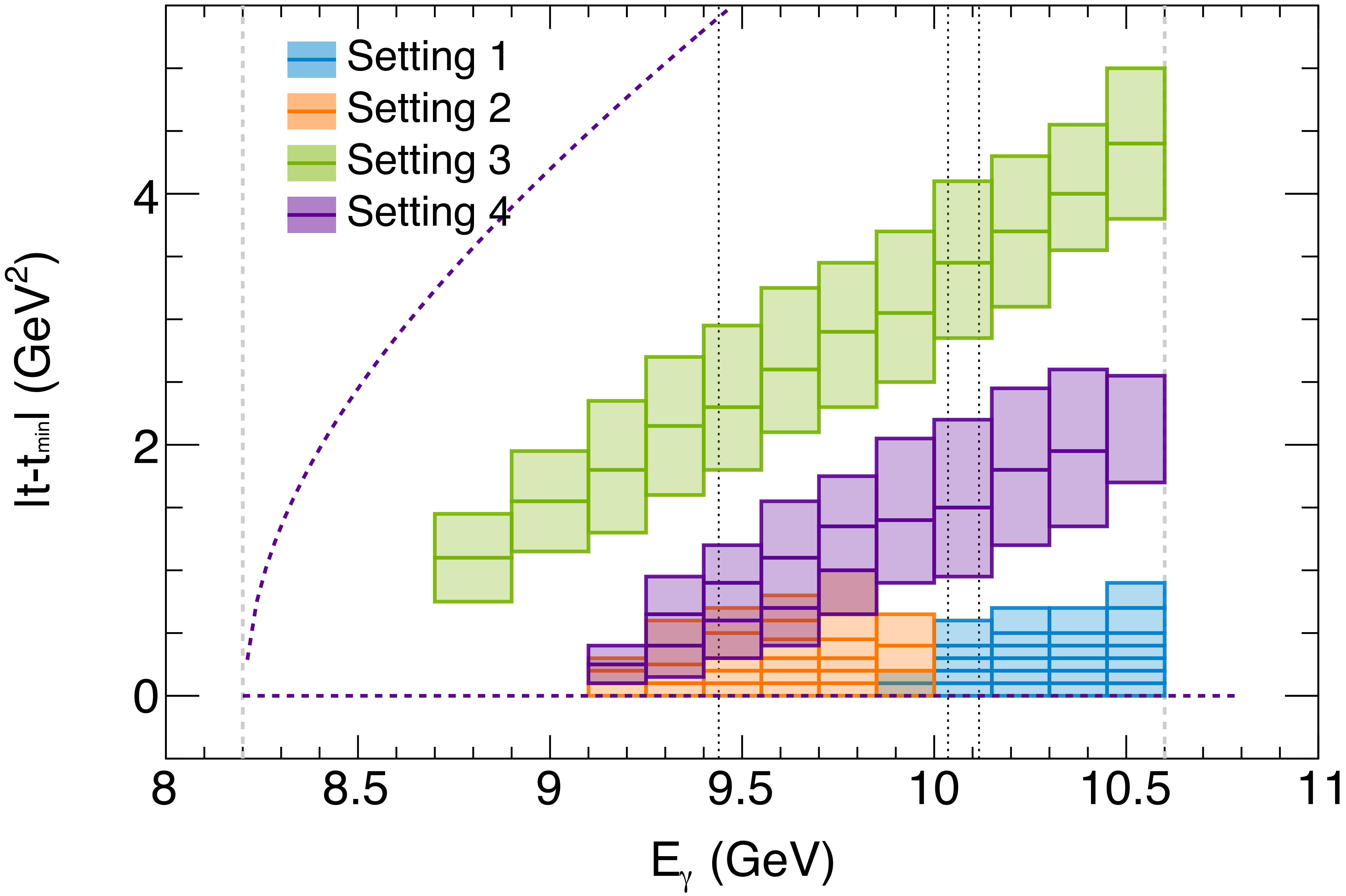
To learn more we need a large-acceptance high-intensity photoproduction experiment, and potentially access to polarization observables. **This can be achieved with the future SoLID-J/ψ experiment at Jefferson Lab**



PHASE SPACE COVERAGE

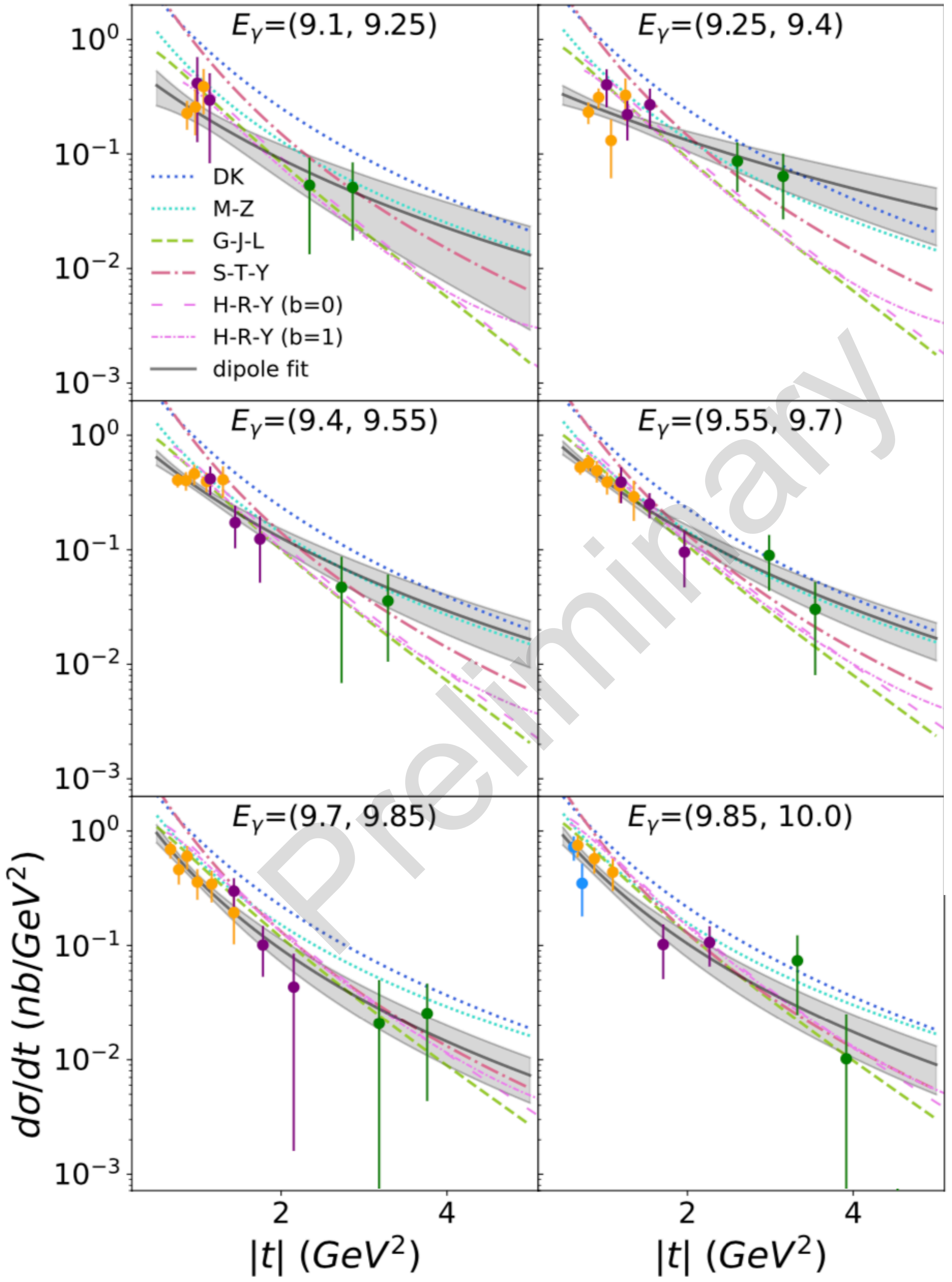
Unprecedented access to large-t region

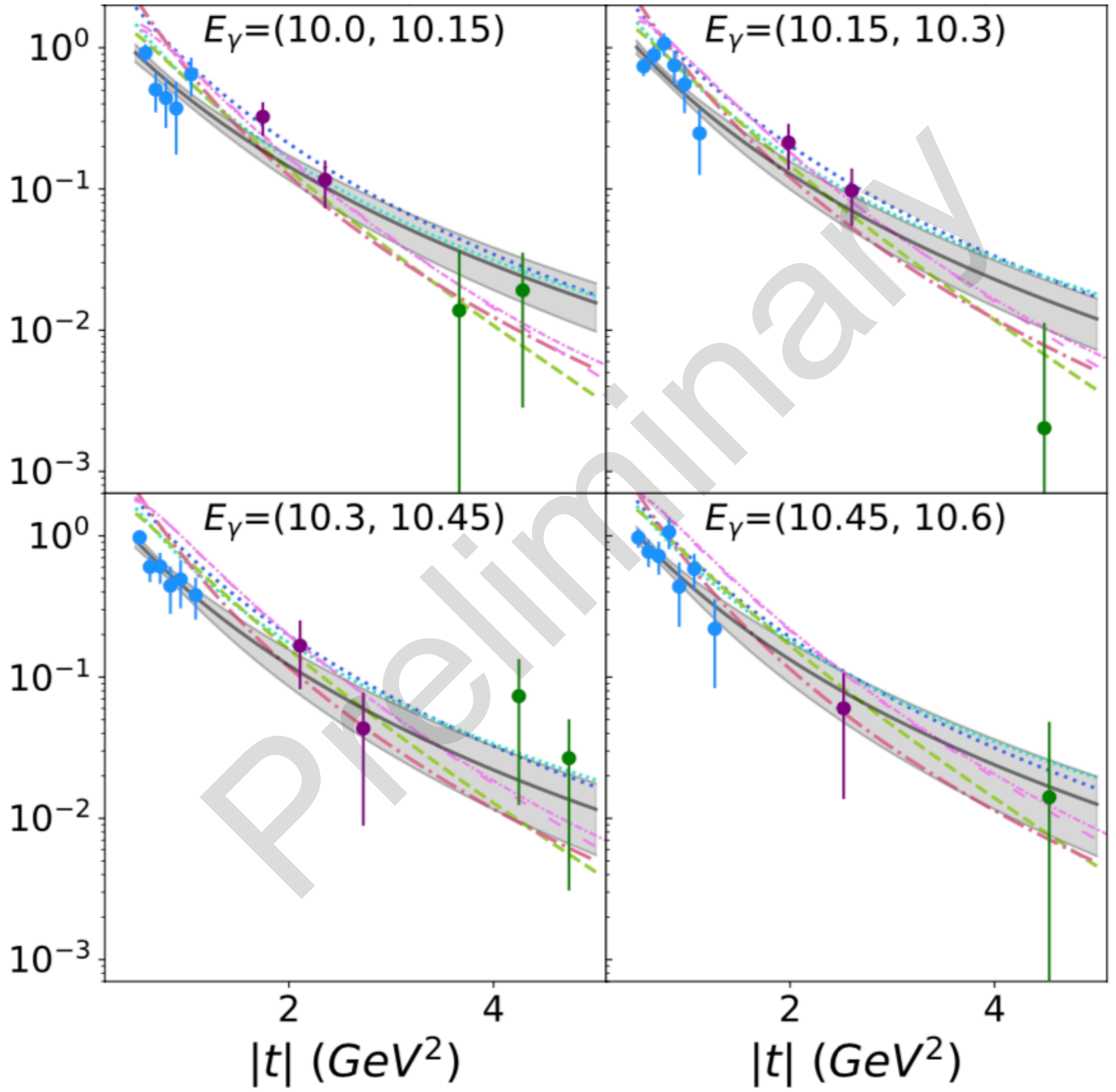
- Truly 2D measurement
- ~2000 counts in electron channel
- Additional 2000 counts in muon channel still under analysis



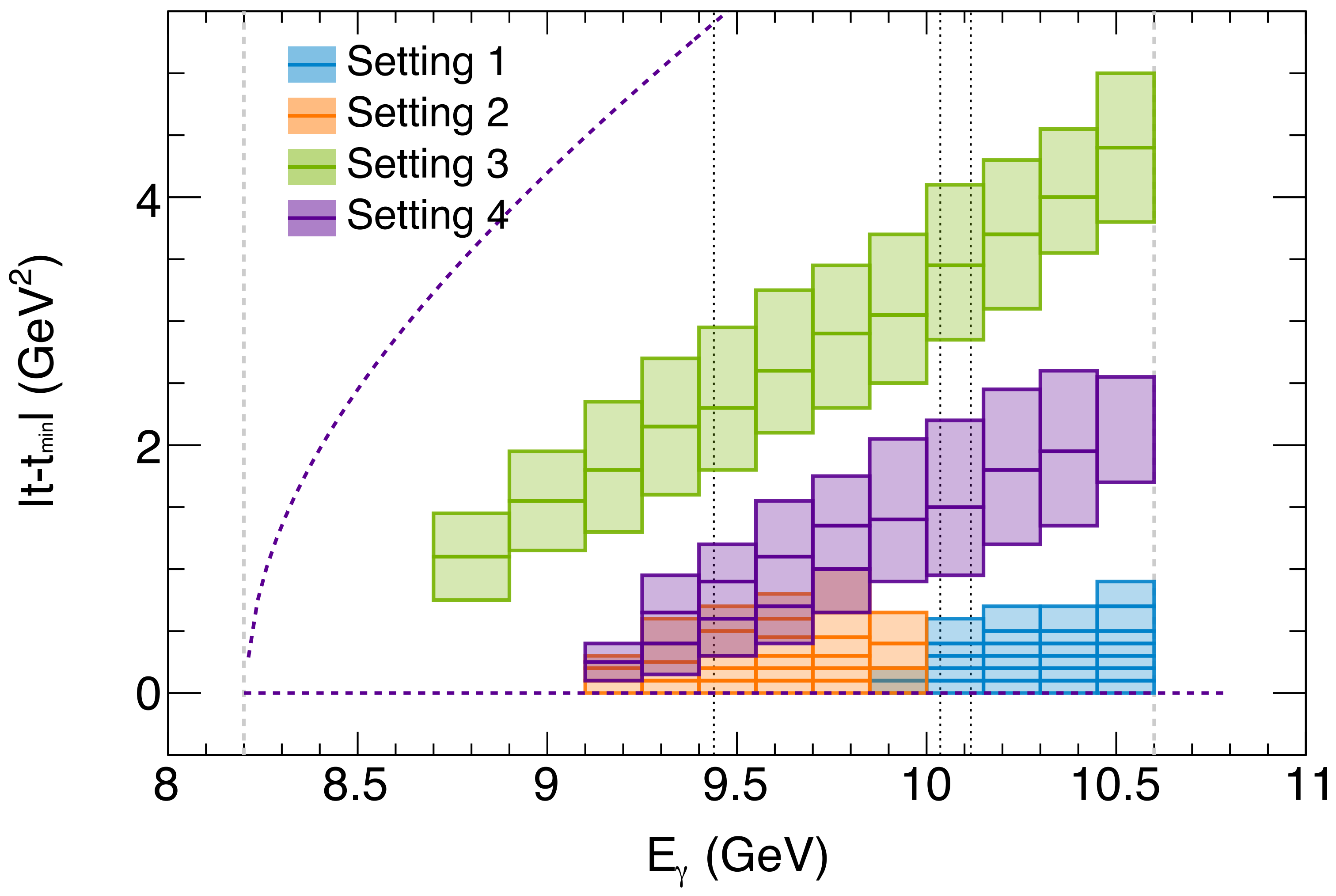
Results currently under peer-review

PRELIMINARY 2D J/Ψ CROSS SECTION RESULTS





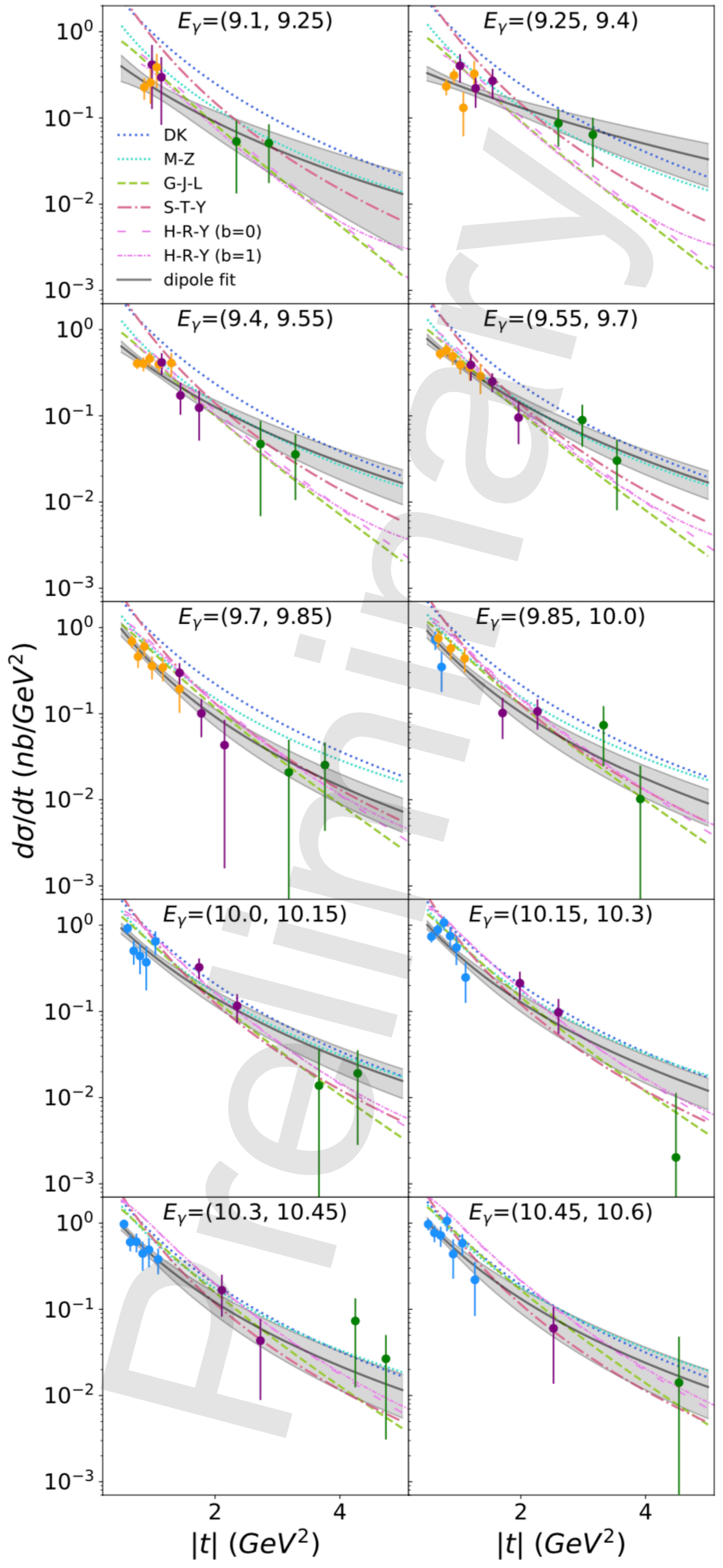
DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)
Dipole fit: Independent dipole fit to each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

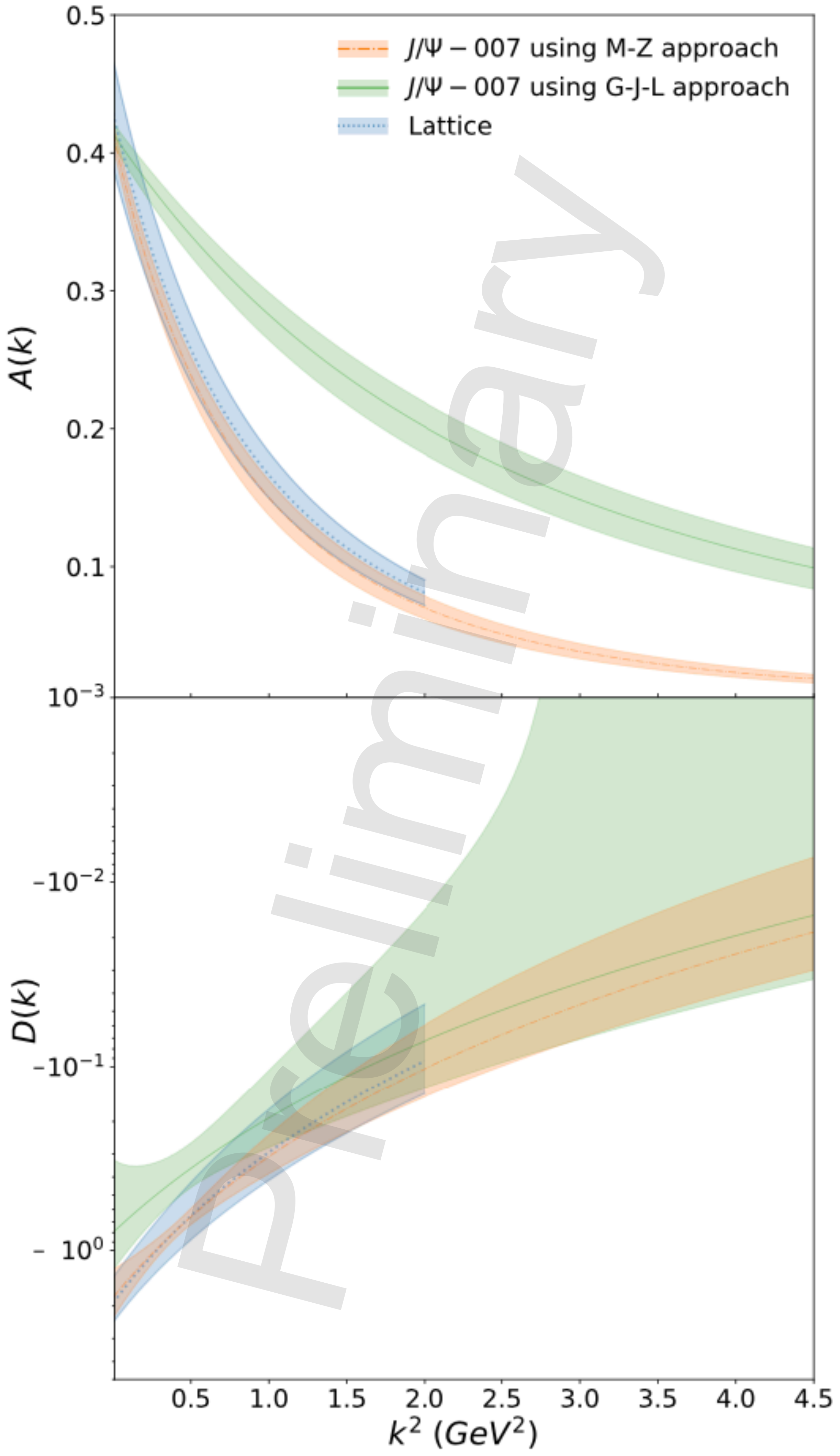
First ever extraction of gluonic GFFs from purely experimental data!



- **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 of the same quantities!

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).

$007^{J/\psi}$

MASS AND SCALAR RADII

Extracted from gluonic GFF results following M-Z and G-J-L

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

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

Theoretical approach GFF functional form	χ^2/n.d.f	m_A (GeV^2)	m_C (GeV^2)	$C_g(0)$	$\sqrt{\langle r_m^2 \rangle}$ (fm)	$\sqrt{\langle r_s^2 \rangle}$ (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 + VMD 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

In all cases the extracted r_m is substantially smaller than the proton charge radius

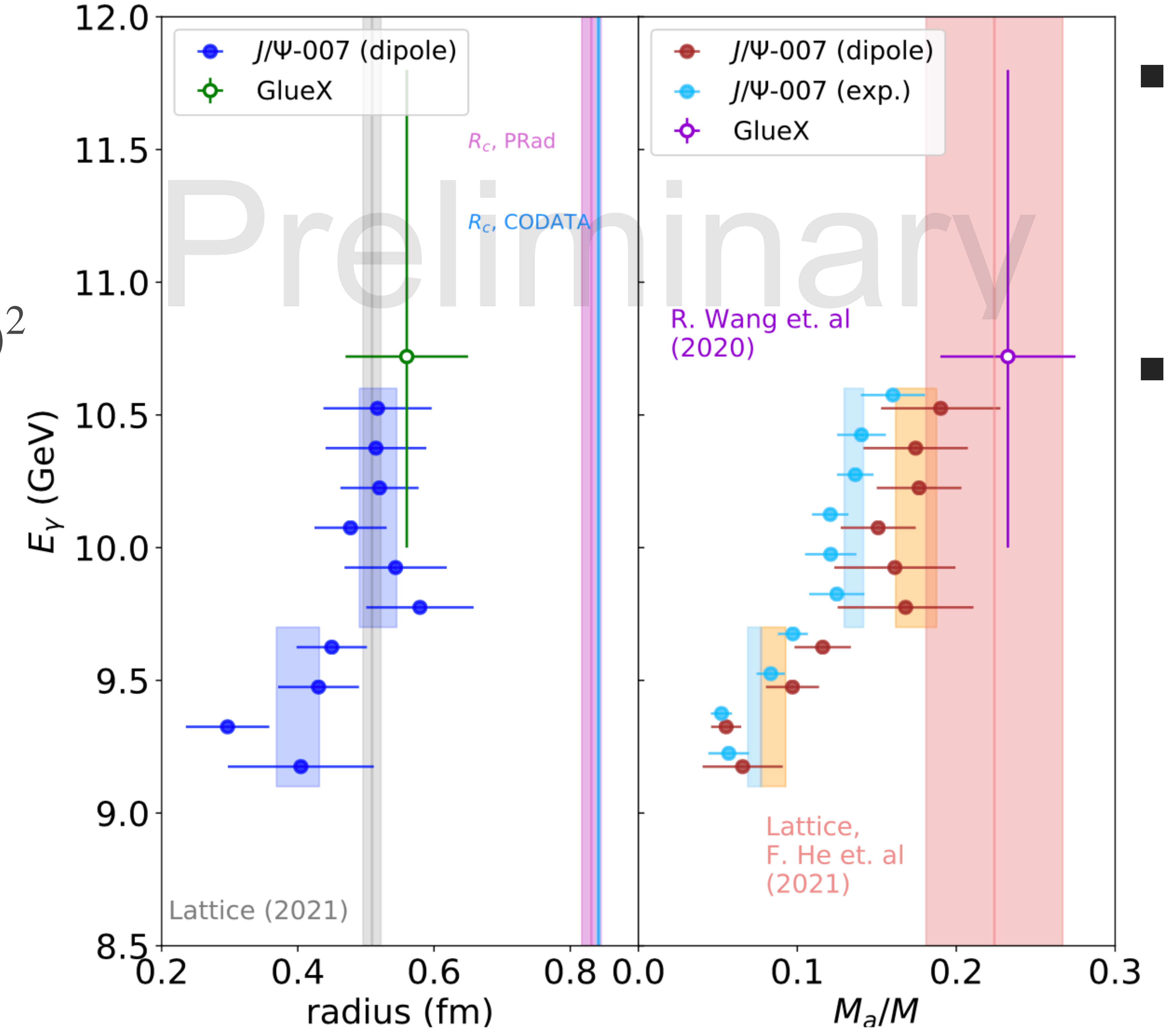
VARIOUS MODEL-DEPENDENT EXTRACTIONS

Radius (following DK), and Ma/M (following Ji), for each energy slice

D-K formalism for radius

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

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



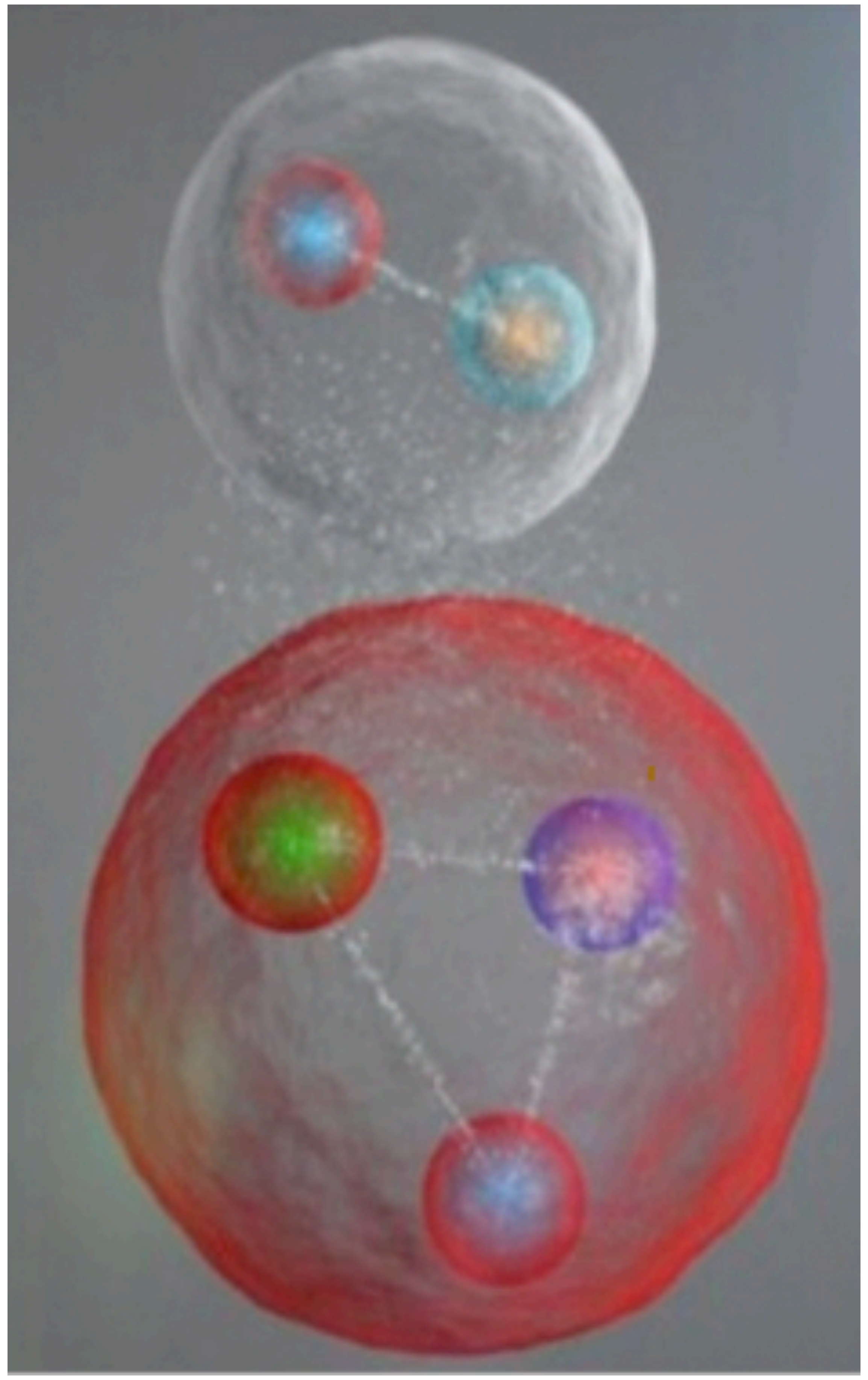
- Find flat region at higher energies, which seems to break below 9.7 GeV
- Good agreement with lattice in flat region ($9.7\,\mathrm{GeV} < E_\gamma < 10.6\,\mathrm{GeV}$)
  - $\sqrt{\langle r_m^2 \rangle} = 0.52 \pm 0.03\ \mathrm{fm}$
  - $M_a/M = 0.175 \pm 0.013$

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)

HALL C J/Ψ-007 RESULTS IN A NUTSHELL

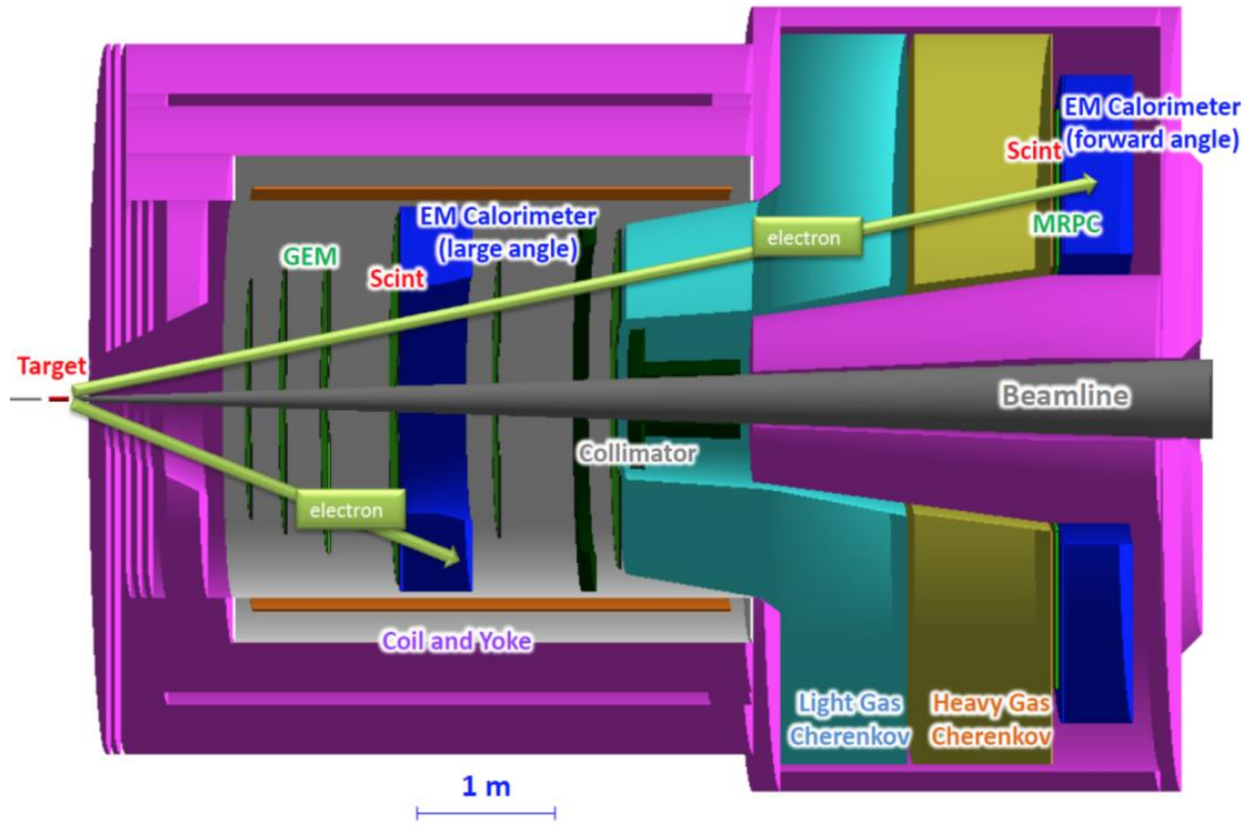
- The Hall C J/ψ-007 experiment has the first near-threshold 2D J/ψ cross section results in this area, currently under peer review.
  - Stringent exclusion limit for the LHCb charmed pentaquarks in photoproduction
  - New window on the gluonic GFFs in the proton
  - Does the proton have a dense energetic core?

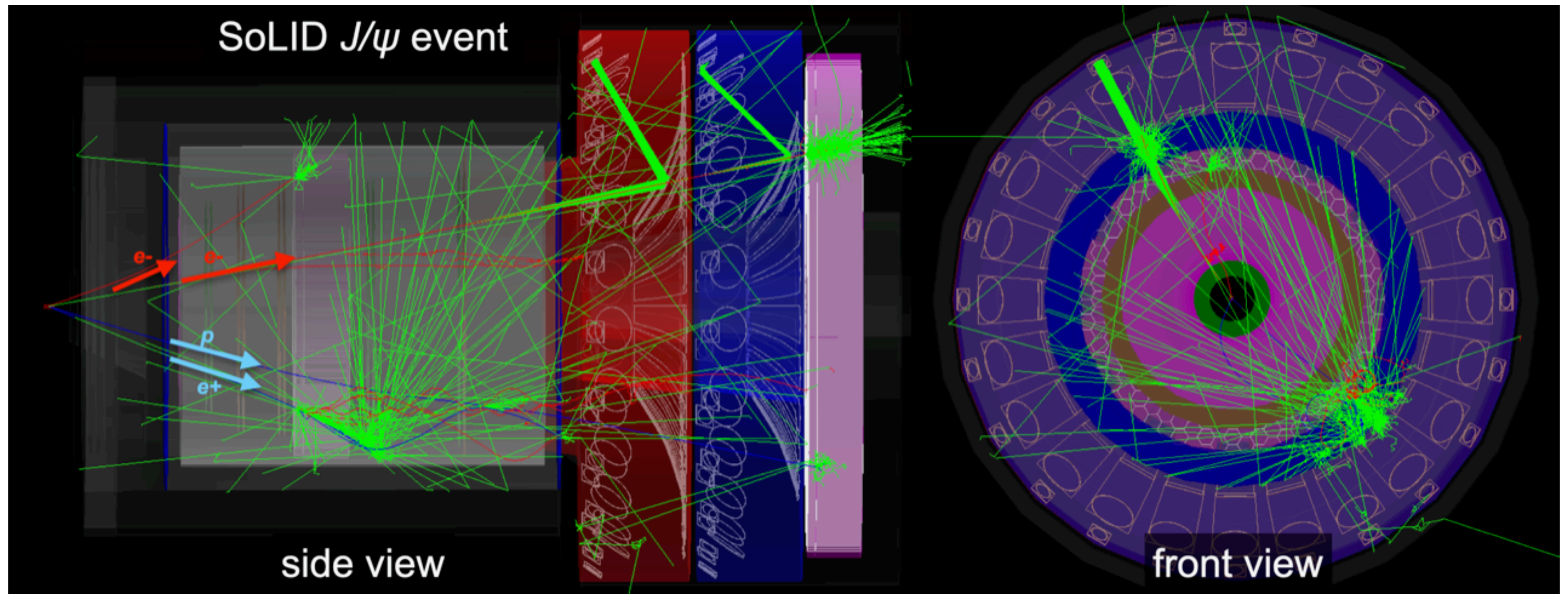


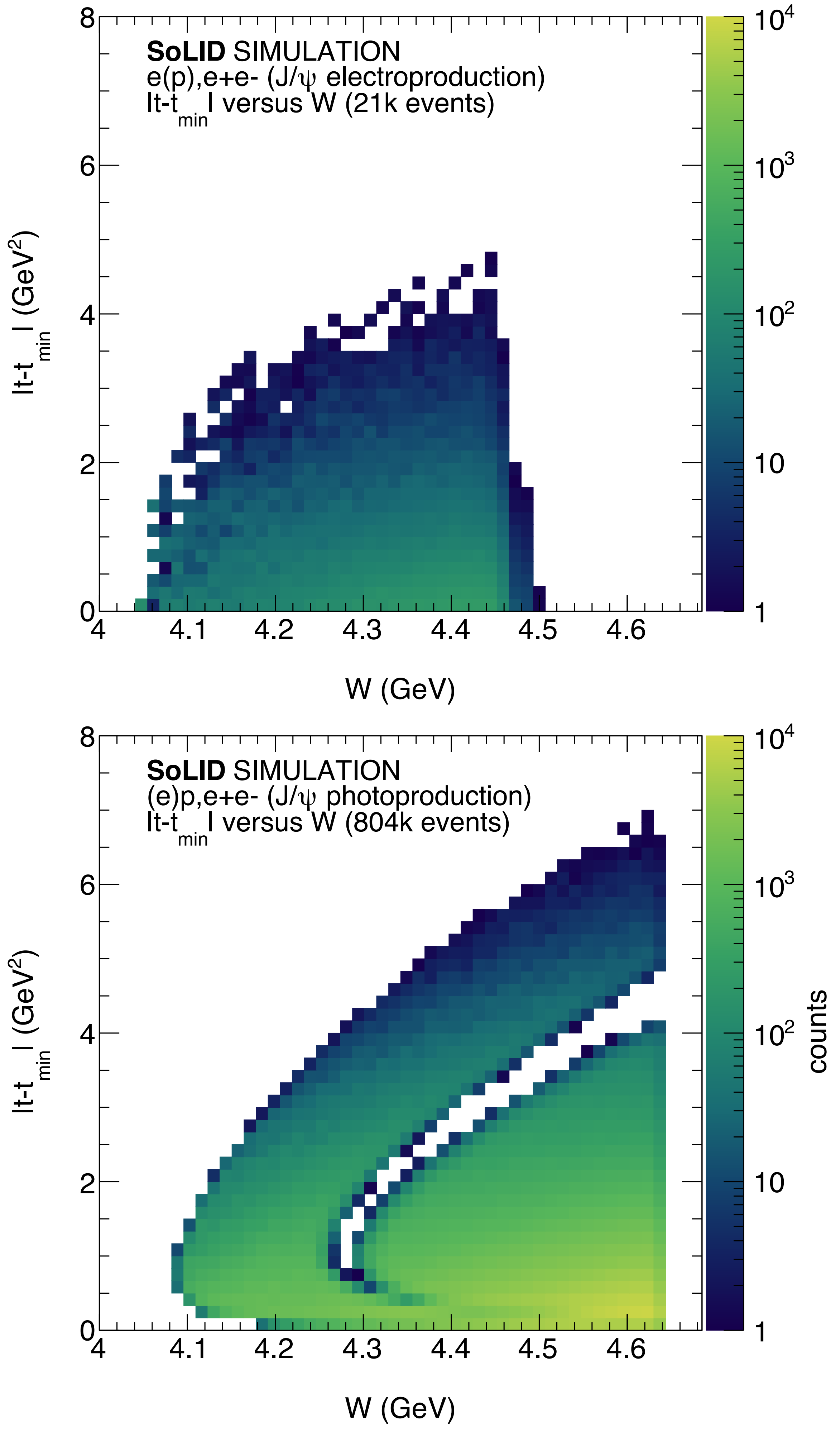
FUTURE SOLID EXPERIMENT AT JLAB

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+)

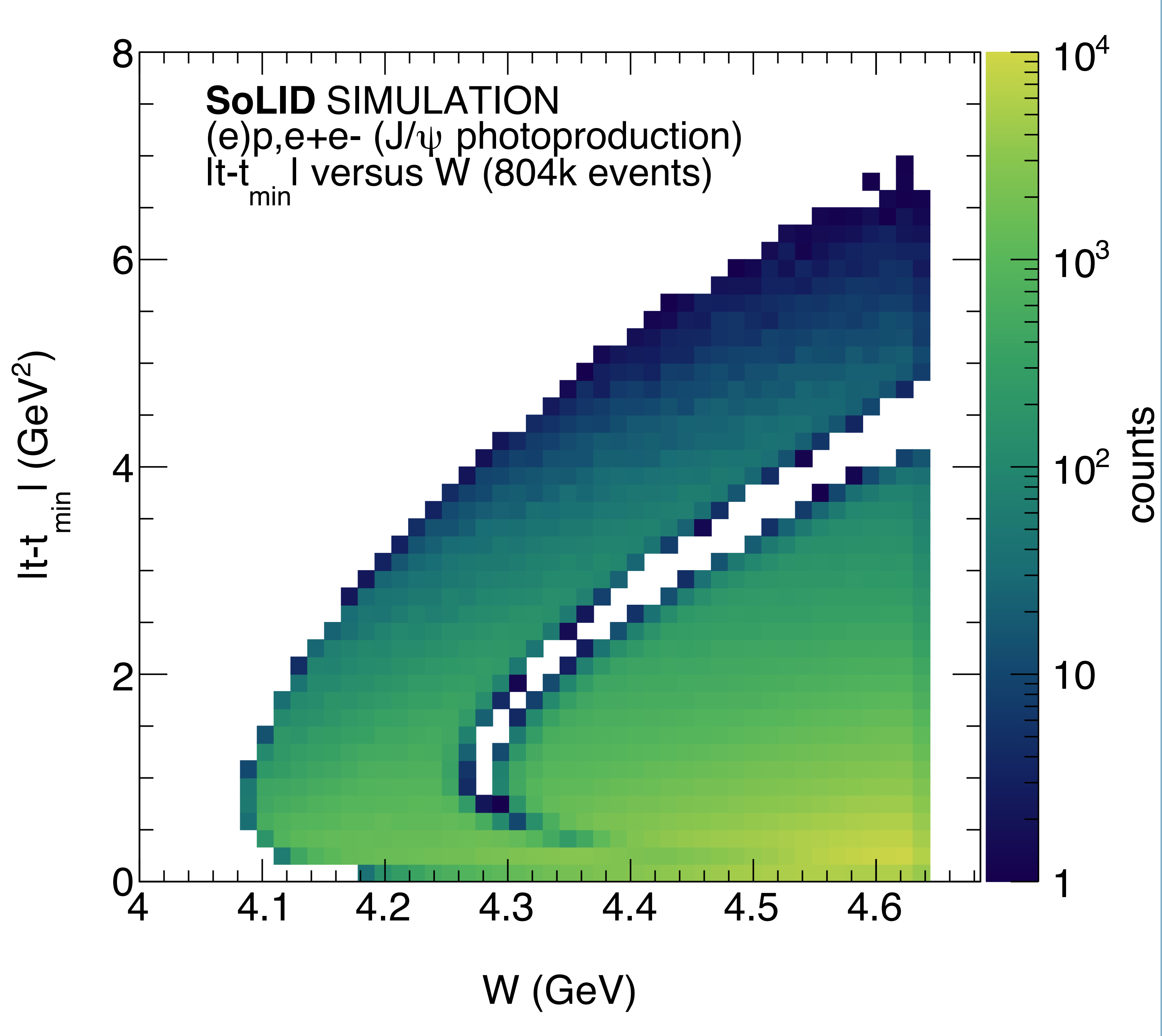


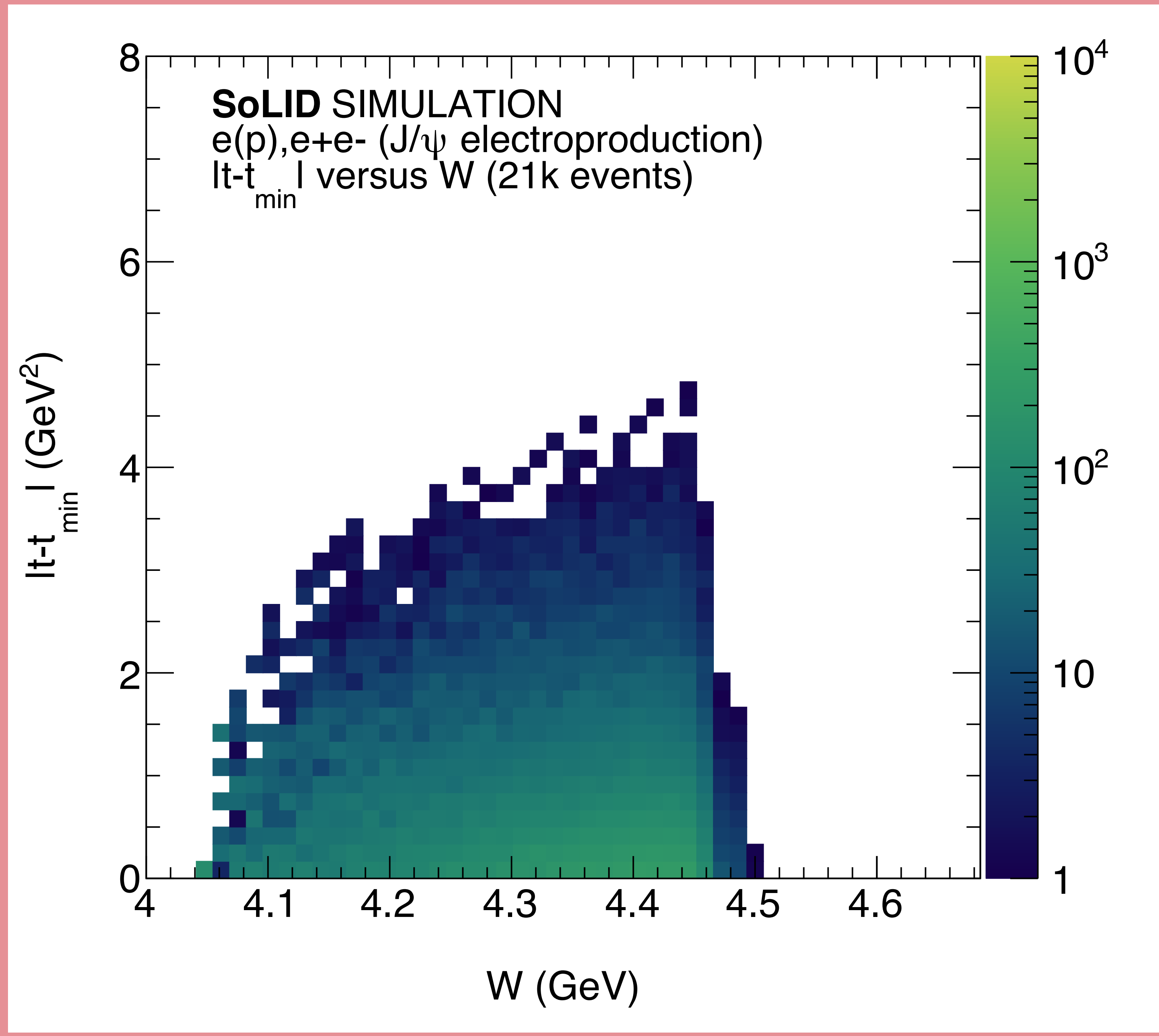


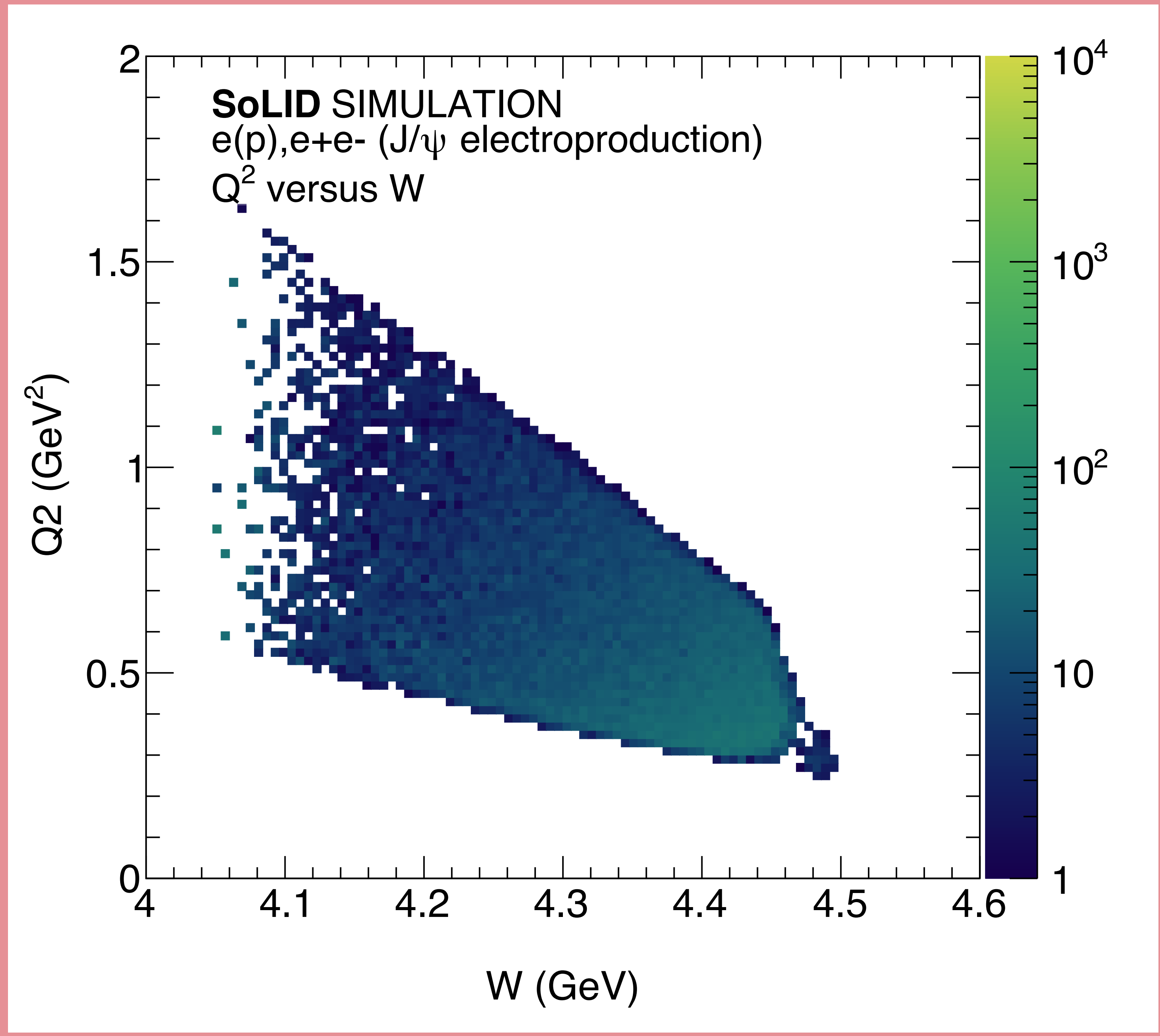


EXPERIMENTAL CONSIDERATIONS WITH SOLID

Kinematic coverage for SoLID-J/ψ





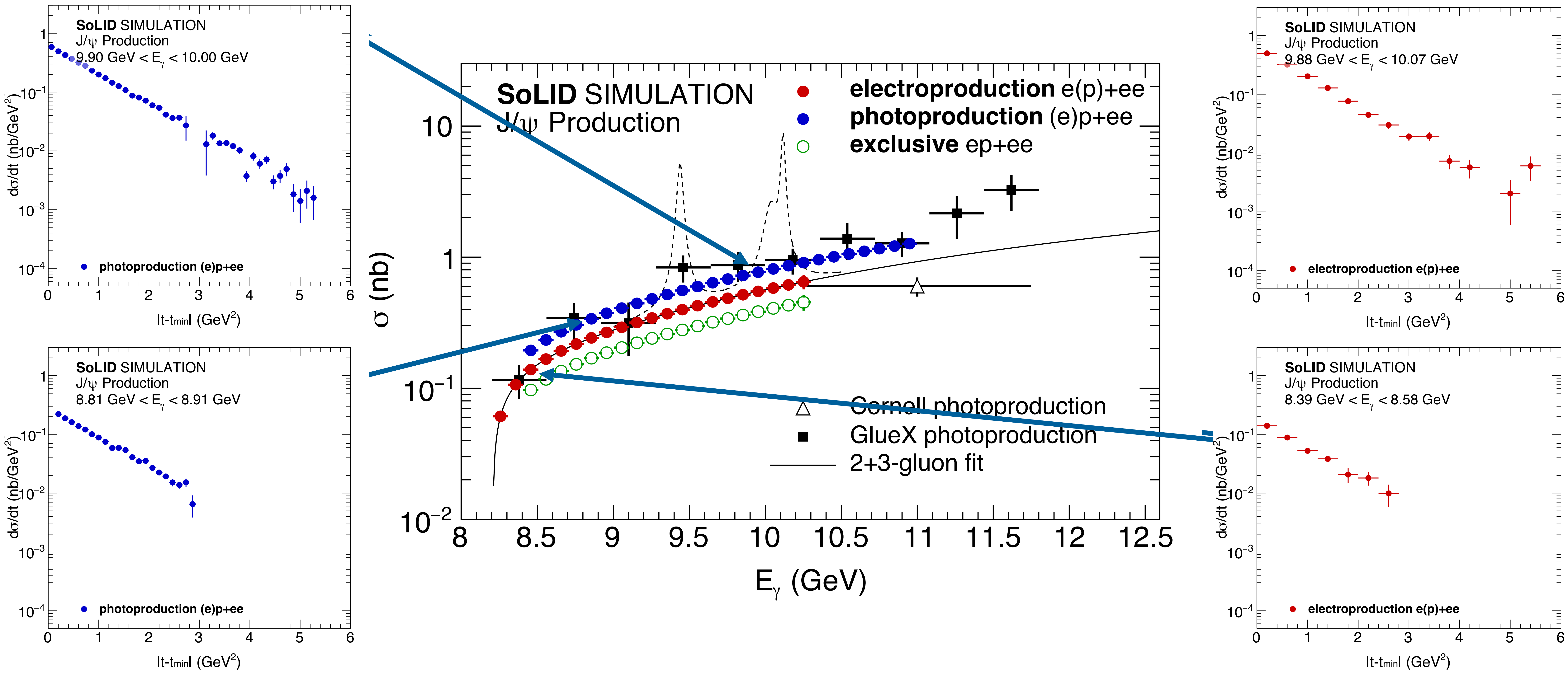


Photoproduction

Electroproduction

FUTURE SOLID EXPERIMENT AT JLAB

Precision measurement of quarkonium near threshold

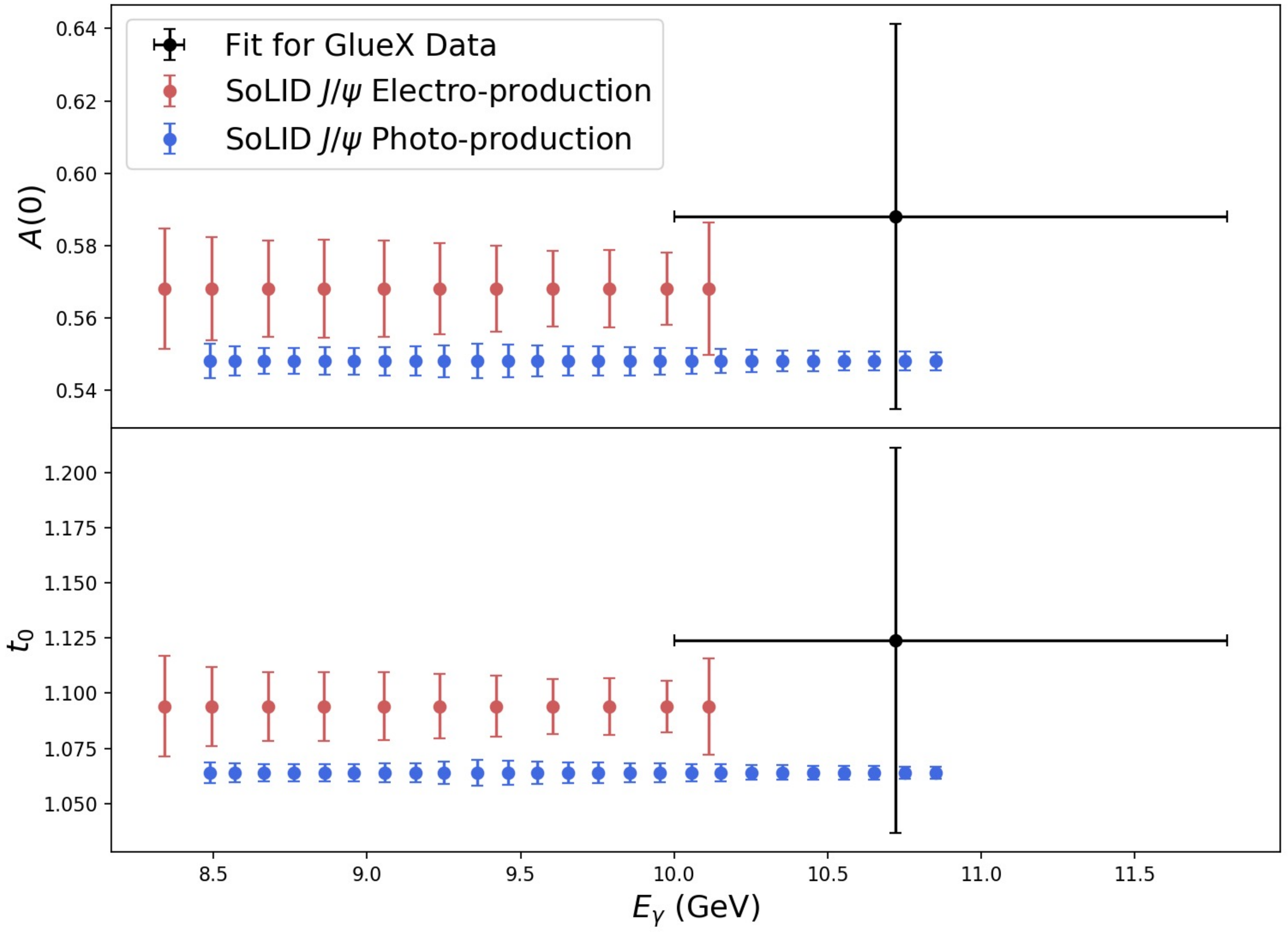


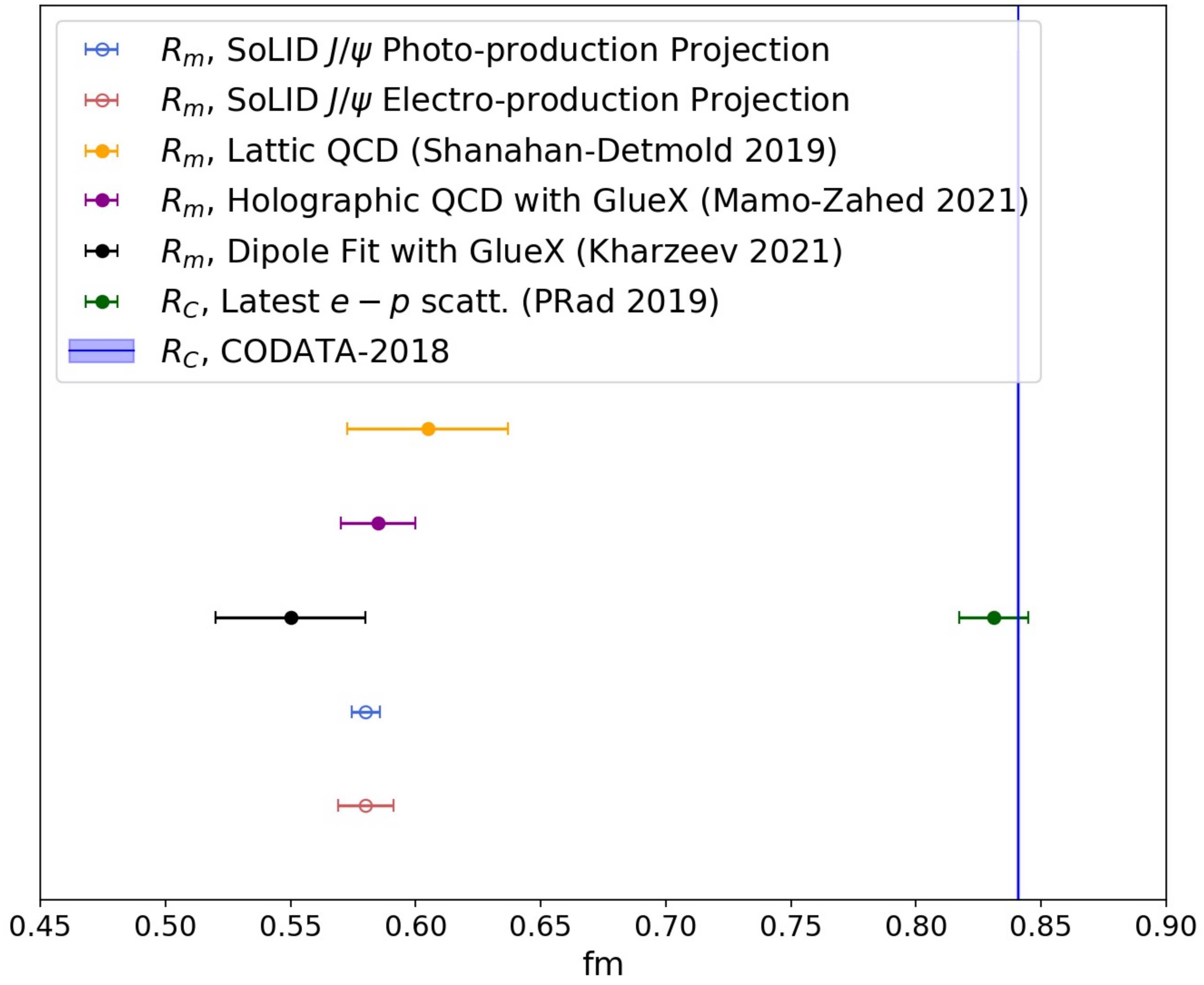
PROJECTED IMPACT FOR SOLID-J/Ψ

Radius following the DK approach

D, Kharzeev, Phys. Rev. D 104, 054015 (2021)

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



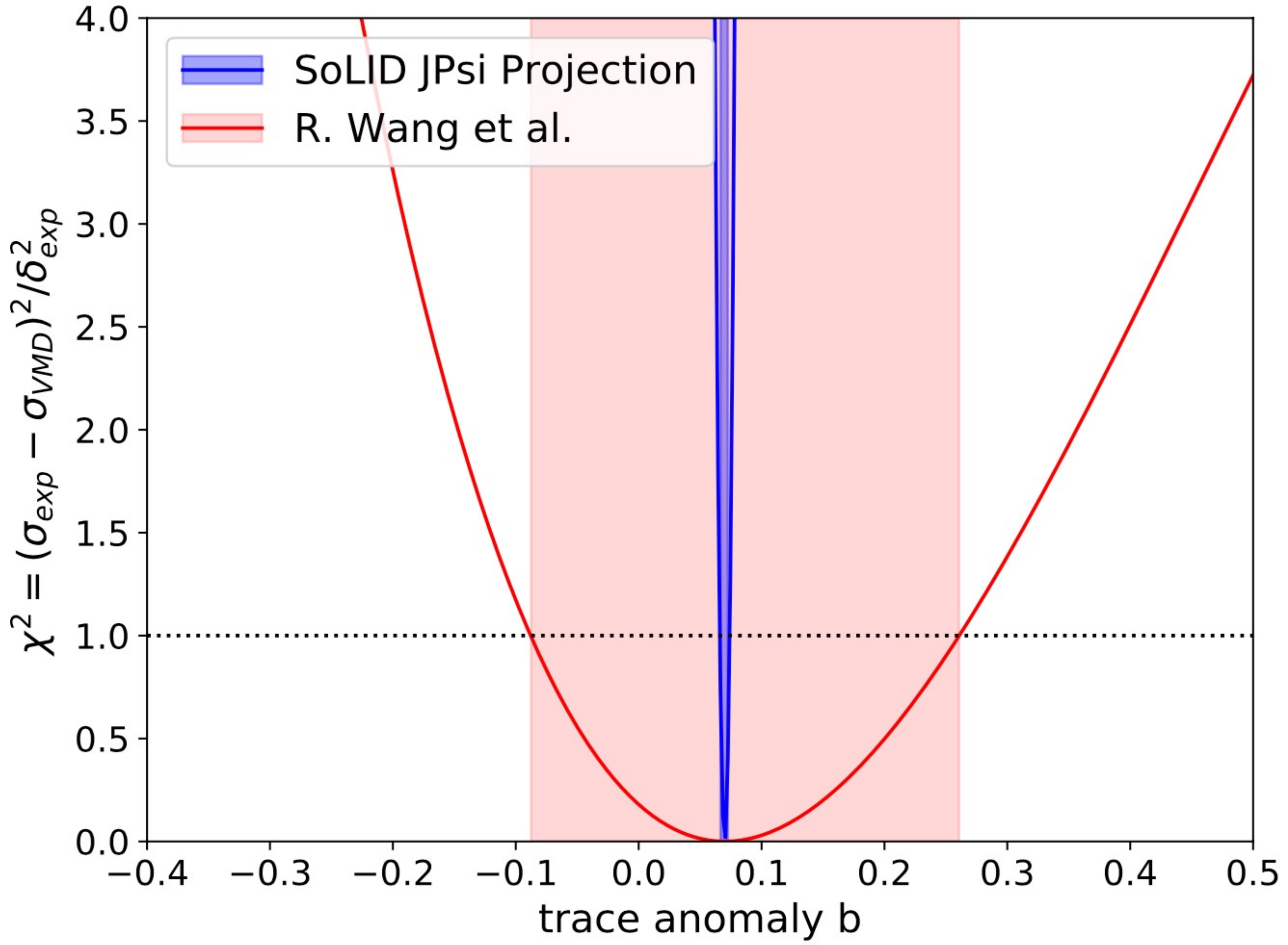


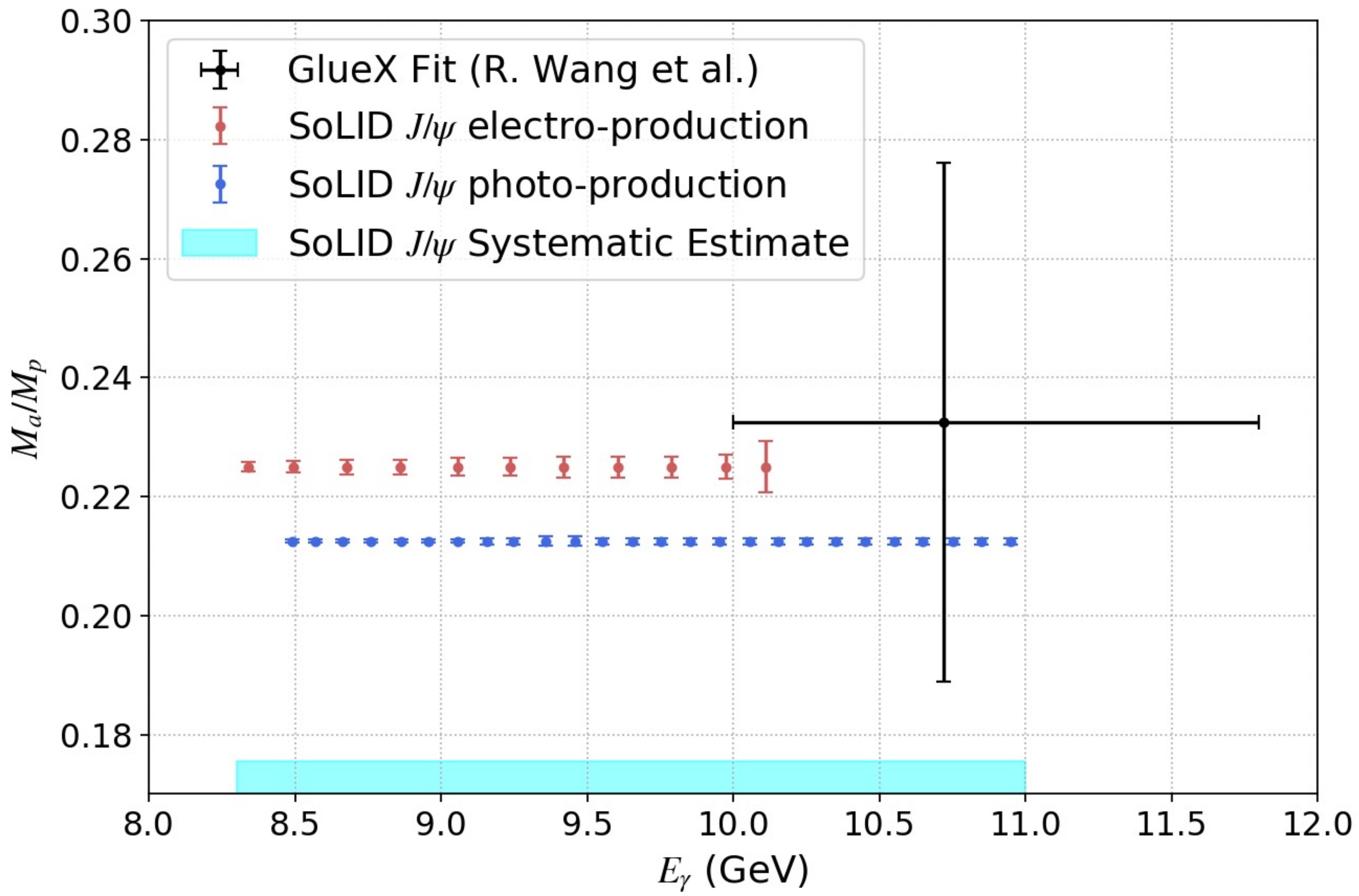
High sensitivity over the full photon energy range

PROJECTED IMPACT FOR SOLID-J/Ψ

Ma/M following Ji's approach

X. Ji, Phys. Rev. Lett. 74, 1071–1074 (1995)





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

High sensitivity over the full photon energy range

HOW ABOUT Ψ' PRODUCTION AT JLAB?

What can we do with a larger color dipole?

ψ' a larger color dipole: expect stronger gluonic interactions

Complementary probe: provides an extra handle (color dipole size) to probe the gluonic field in the proton

Better constrain on model dependencies and factorization assumptions from Jefferson Lab alone (do not need to wait for Y at EIC)

Only really possible at Solid as ultra-high luminosity is required, also requires higher beam energy.

$\psi(2S)$ $I^G(J^{PC}) = 0^-(1^{--})$

See the Review on "$\psi(2S)$ and χ_c branching ratios" before the $\chi_{c0}(1P)$ Listings.

$\psi(2S)$ MASS

OUR FIT includes measurements of $m_{\psi(2S)}$, $m_{\psi(3770)}$, and $m_{\psi(3770)} - m_{\psi(2S)}$.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
3686.09 ±0.04 OUR FIT Error includes scale factor of 1.6.				
3686.093±0.034 OUR AVERAGE Error includes scale factor of 1.4. See the ideogram below.				
3686.111±0.025±0.009		AULCHENKO 03	KEDR	$e^+e^- \to$ hadrons
3685.95 ±0.10	413	[1] ARTAMONOV 00	OLYA	$e^+e^- \to$ hadrons
3685.98 ±0.09 ±0.04		[2] ARMSTRONG 93B	E760	$\bar{p}p \to e^+e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3686.00 ±0.10	413	[3] ZHOLENTZ 80	OLYA	e^+e^-

Ψ' PHYSICS AT JLAB?

Designing a ψ' experiment

ψ(2s) mass is $3686.097 \pm 0.025\,\mathrm{MeV}$, with photoproduction threshold at about 11 GeV

Experimentally:

- Easiest decay channel is e^+e^- (BR: $0.793 \pm 0.017\,\%$)
- Plenty resolution (<50 MeV) at SoLID to distinguish J/ψ and ψ(2s)
- Contamination of higher ψ states strongly suppressed in this channel
- Other promising channel (J/ψ,ππ, BR: $34.67 \pm 0.30\,\%$) requires more study (4- particle final state after J/ψ decay)

Conclusion: ψ' physics possible at JLab with even modest beam energy increase, assuming sufficient cross section

Ψ' CROSS SECTION?

Extrapolating down to threshold

Experimentally, at higher energies ψ(2s)/ψ(1s) is about 0.16 (from HERA and LHC)

Ansatz (as we really don't know): use n-gluon formalism, assume same ratio between 2- and 3-gluon amplitudes as for J/ψ production

In practice: fix ratio of 2- and 3-gluon amplitudes to n-gluon fit to GlueX data, then fit to higher energy J/ψ data scaled down by 0.16

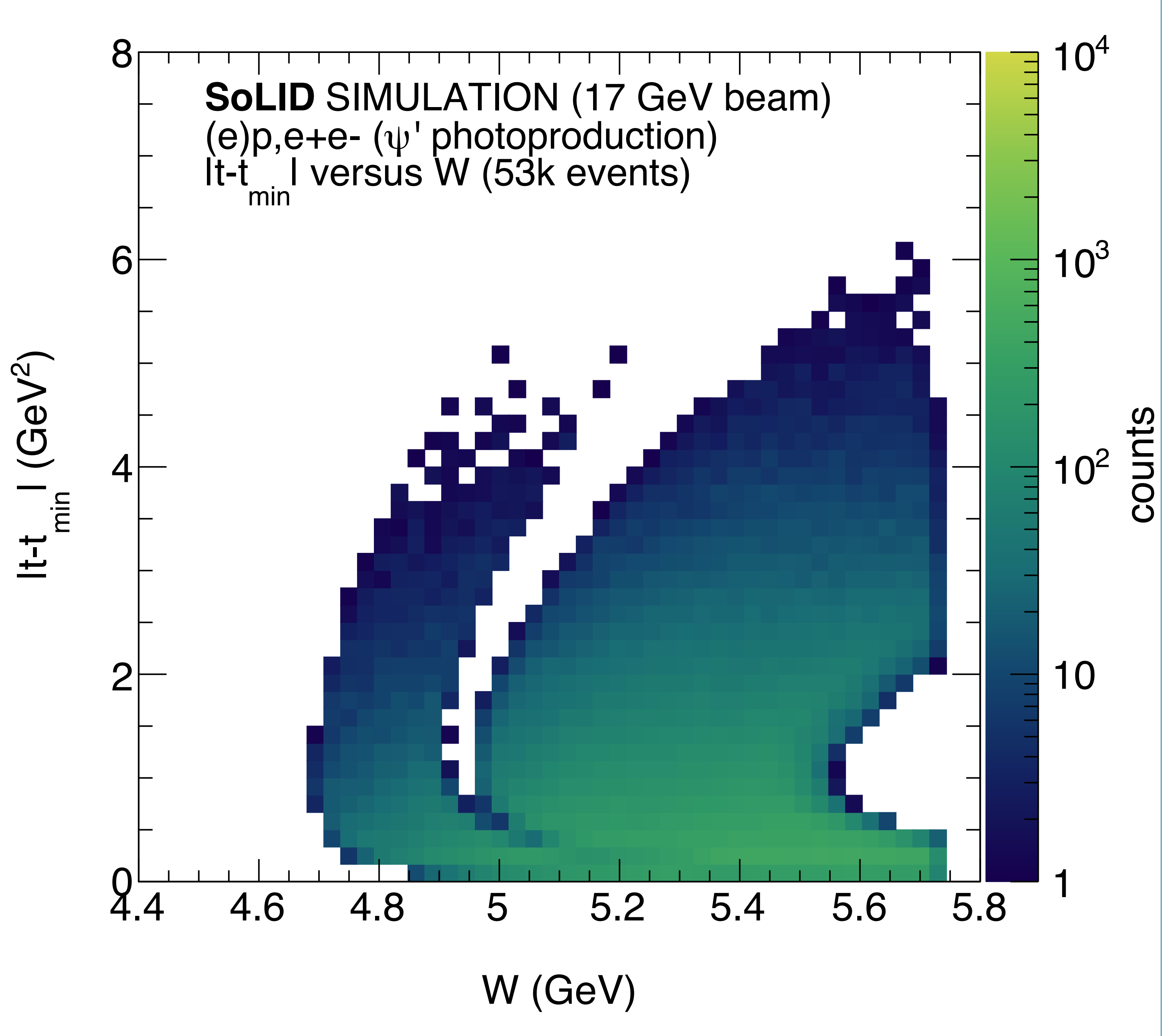
End result: factor of about 47 reduction in rate for $(\gamma p \rightarrow \psi(2s)p \rightarrow pe^+e^-)$.

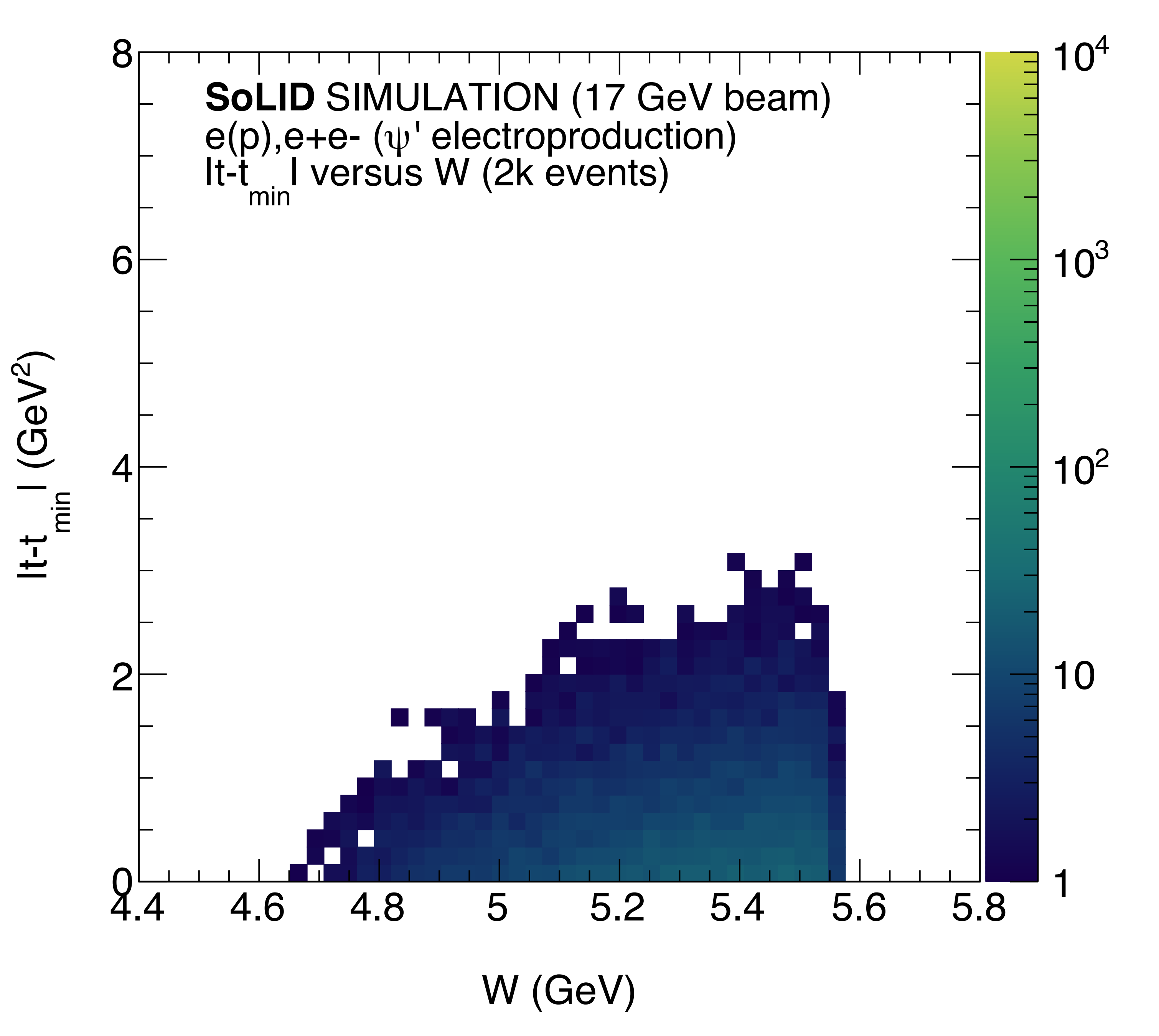
Hence, measurement requires very high luminosity. Could also be approached by exploring other decay channels

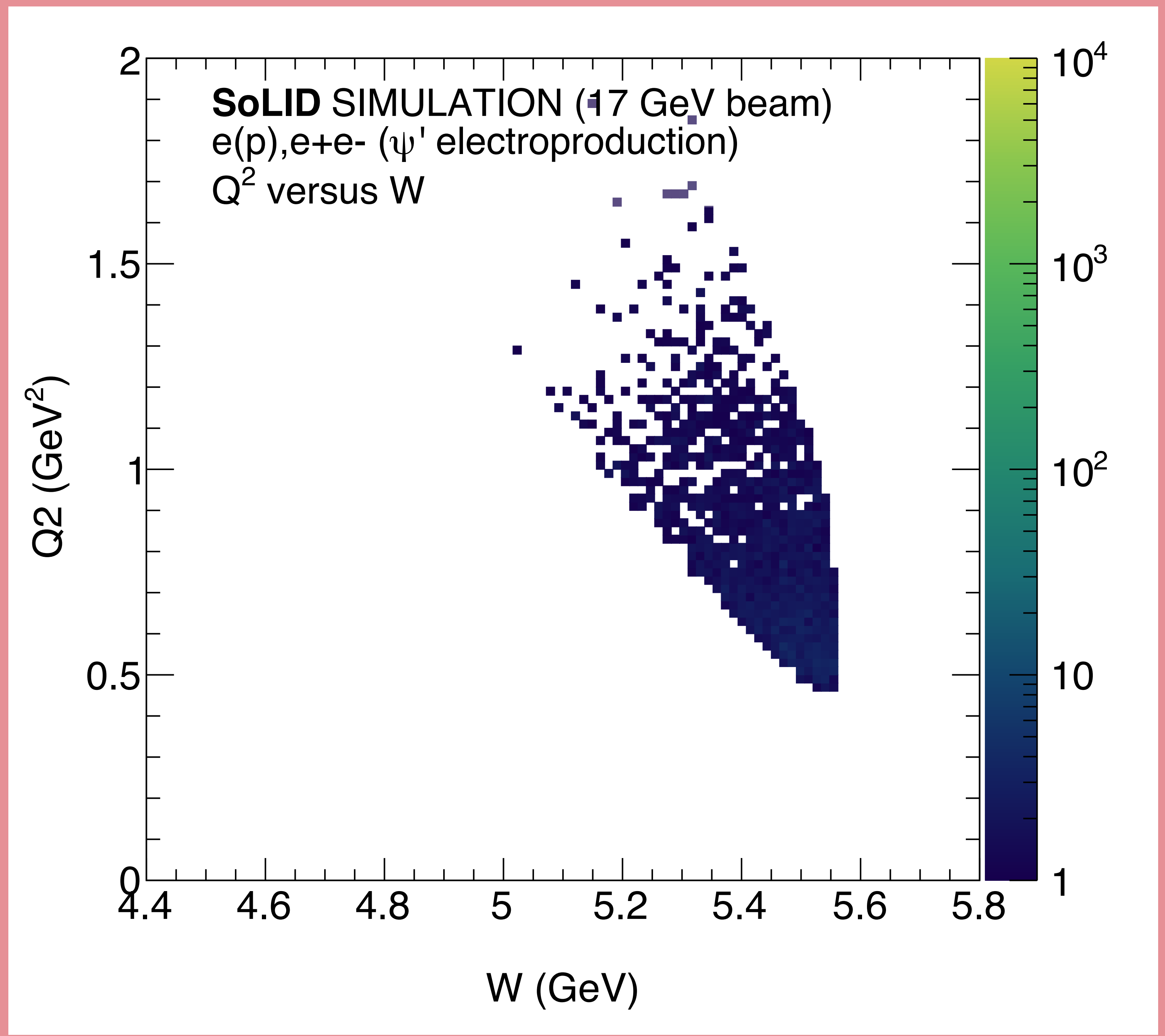
Triple-coincidence phase space for ψ' production at SoLID assuming 50 days at $10^{37}/cm^2s$

Ψ' PRODUCTION WITH SOLID AT HIGHER ENERGIES

17 GeV optimum with current SoLID-J/ψ setup



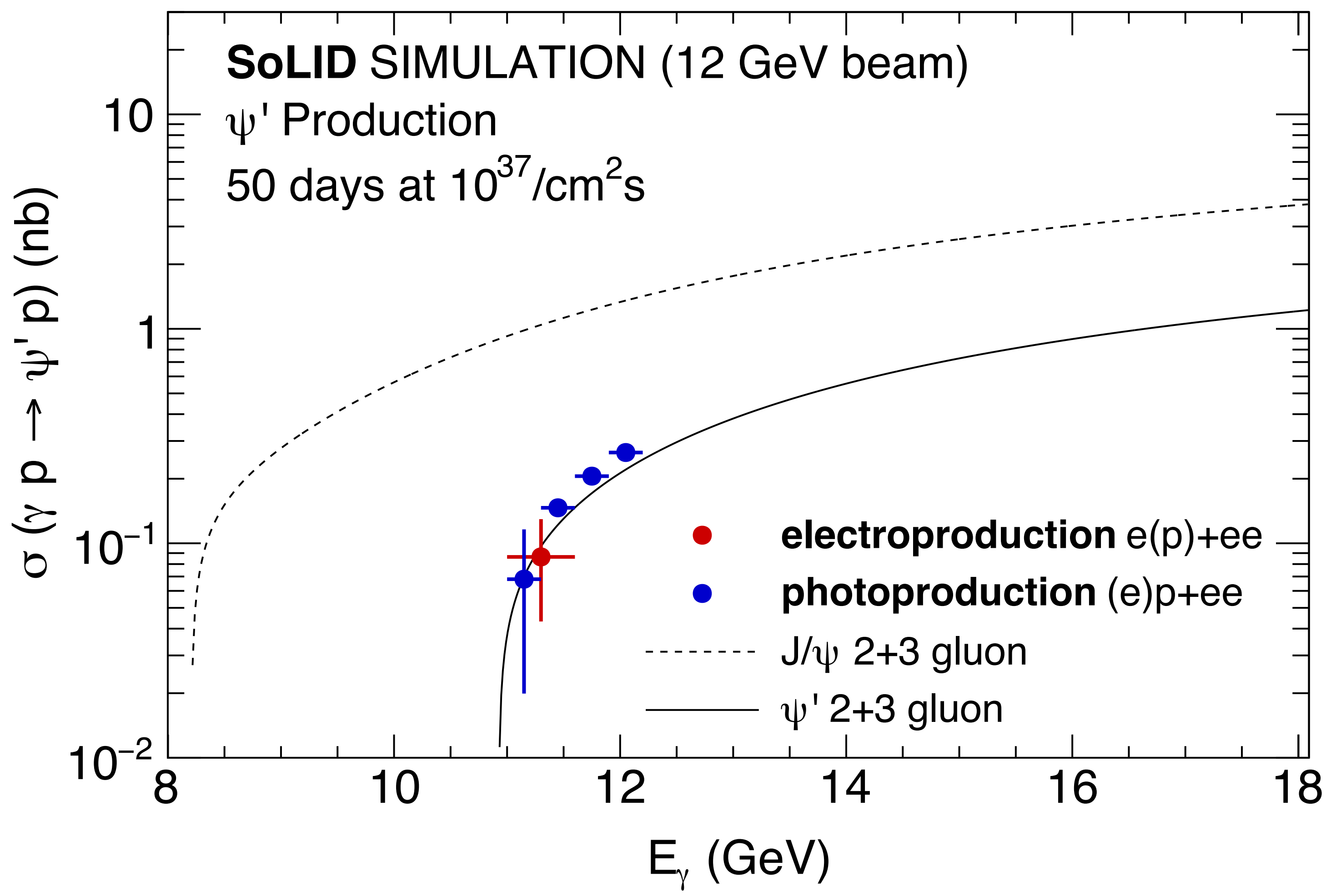


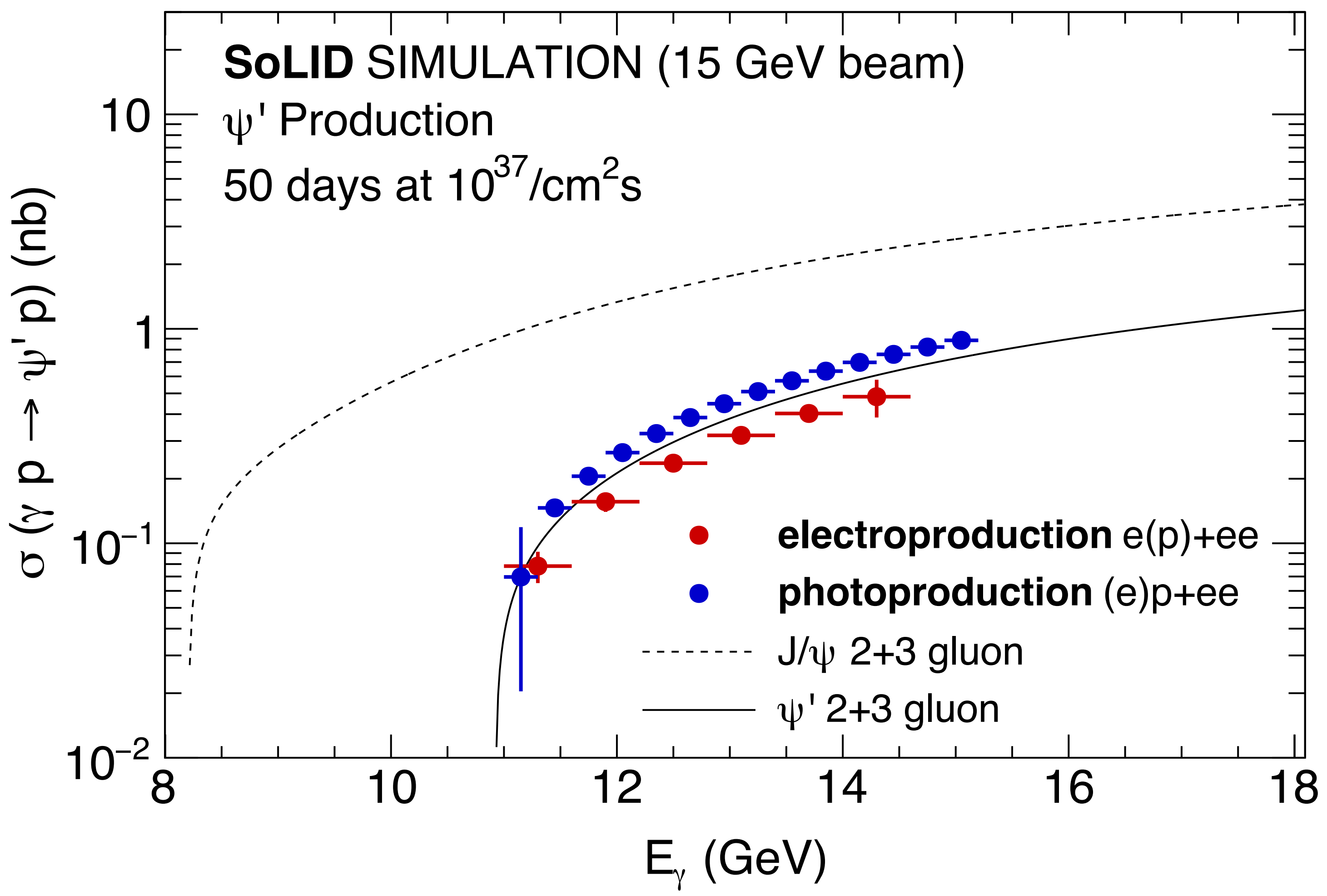


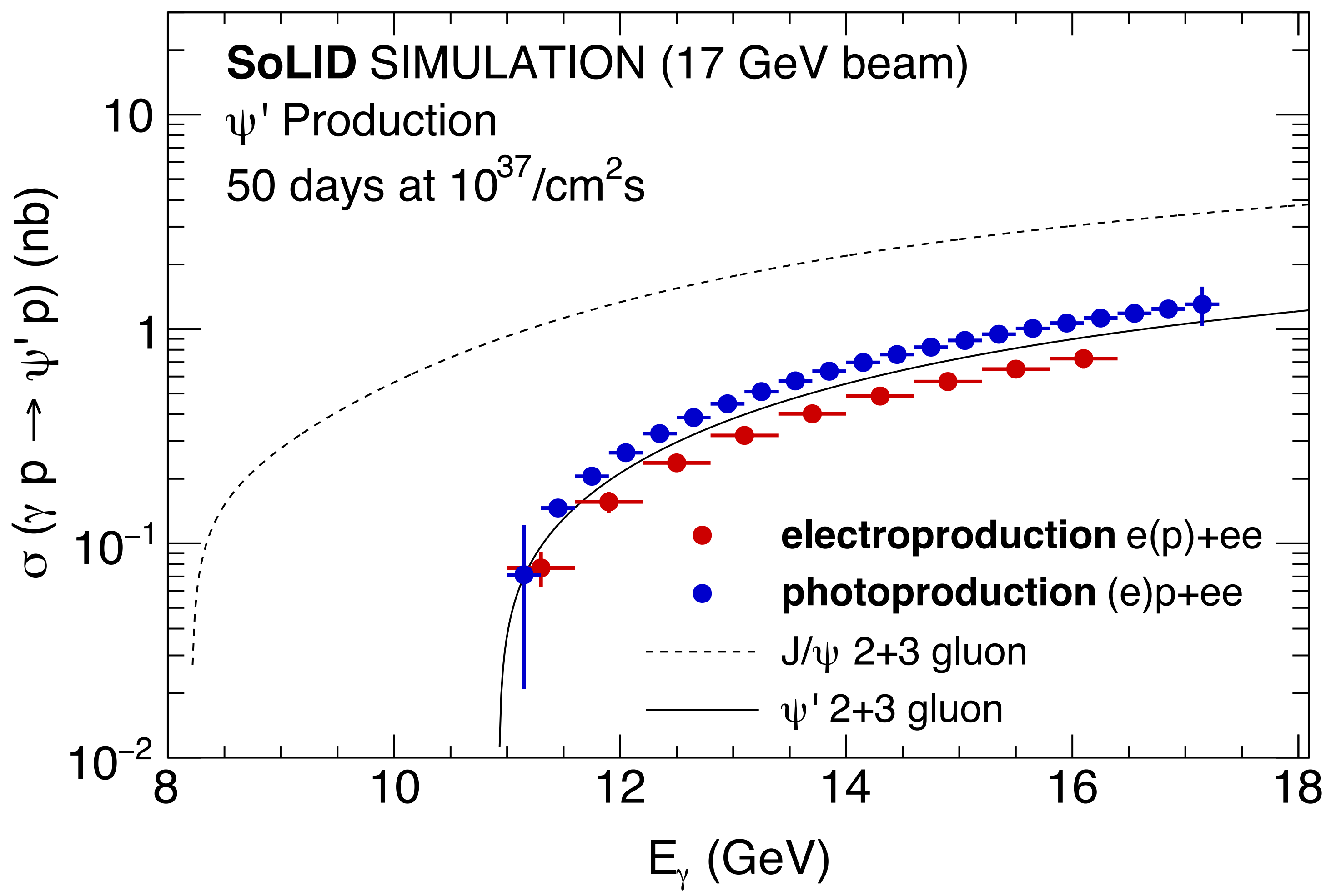
Photoproduction

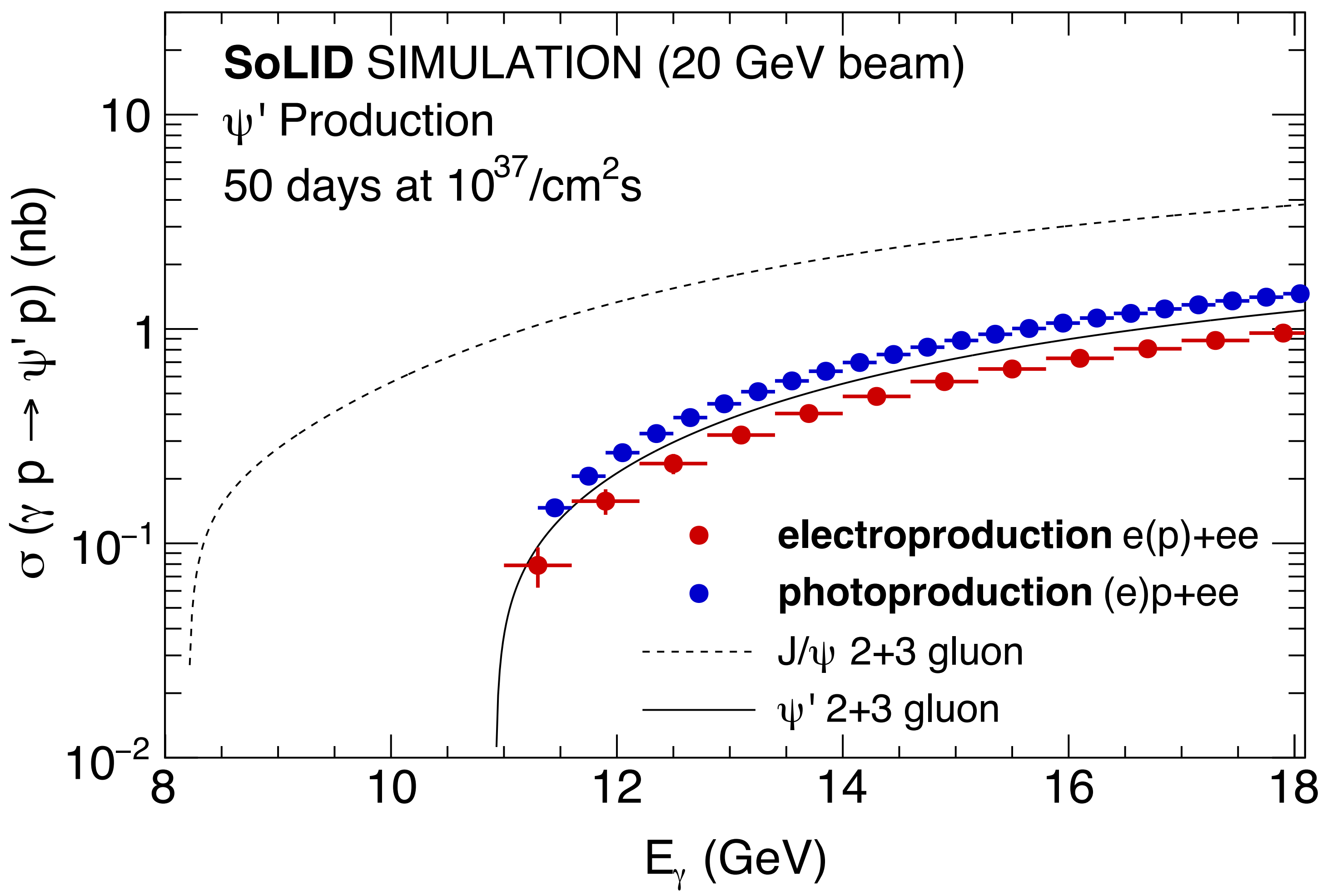
Electroproduction

PHYSICS REACH WITH DIFFERENT BEAM ENERGIES



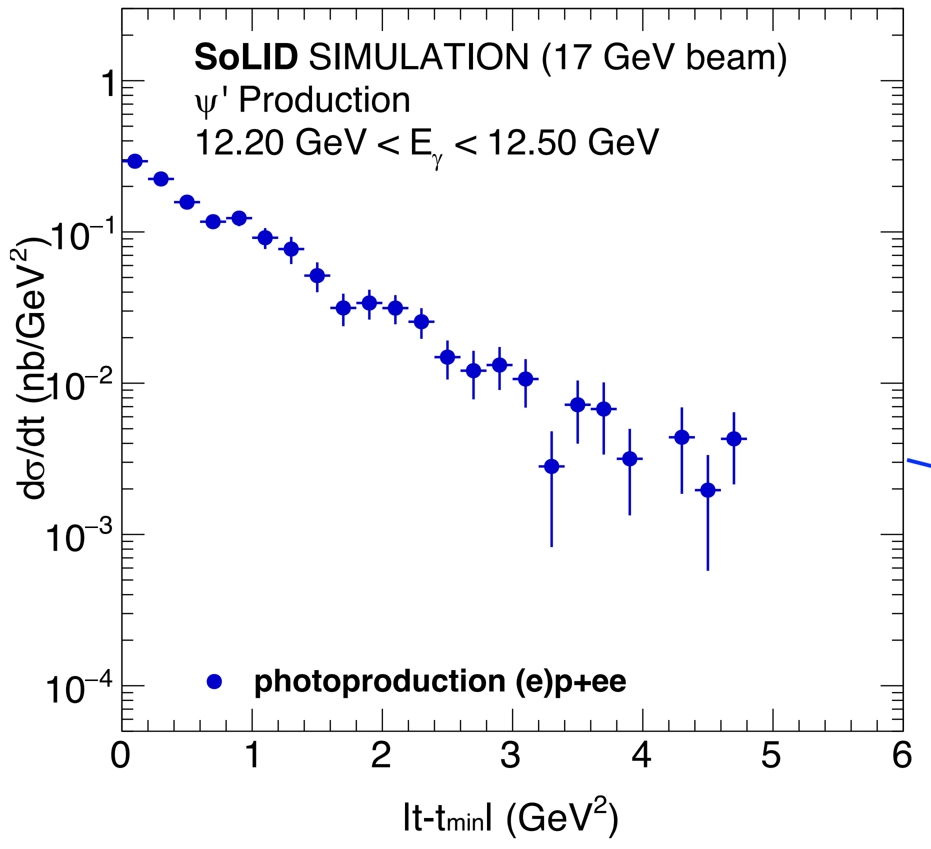


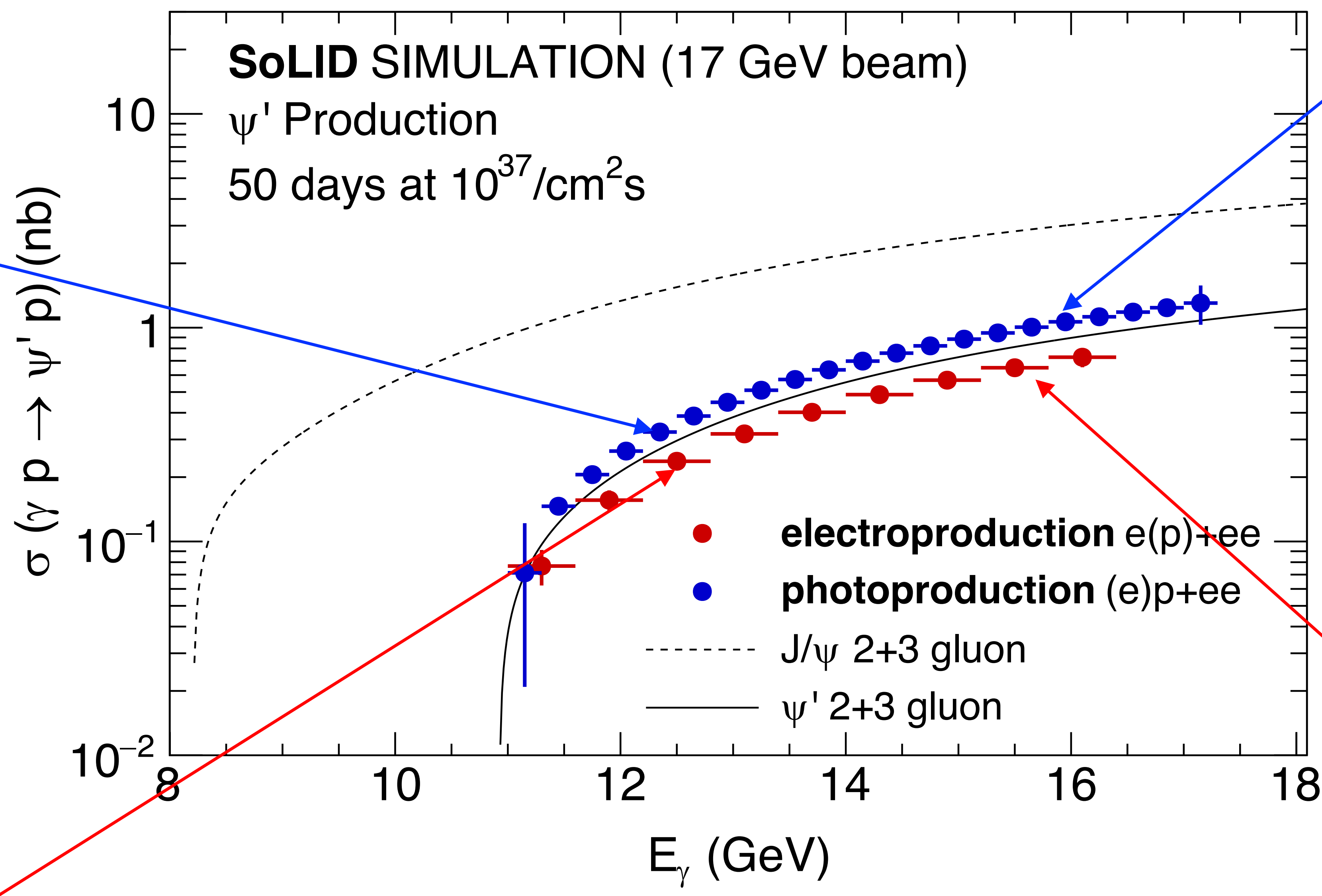


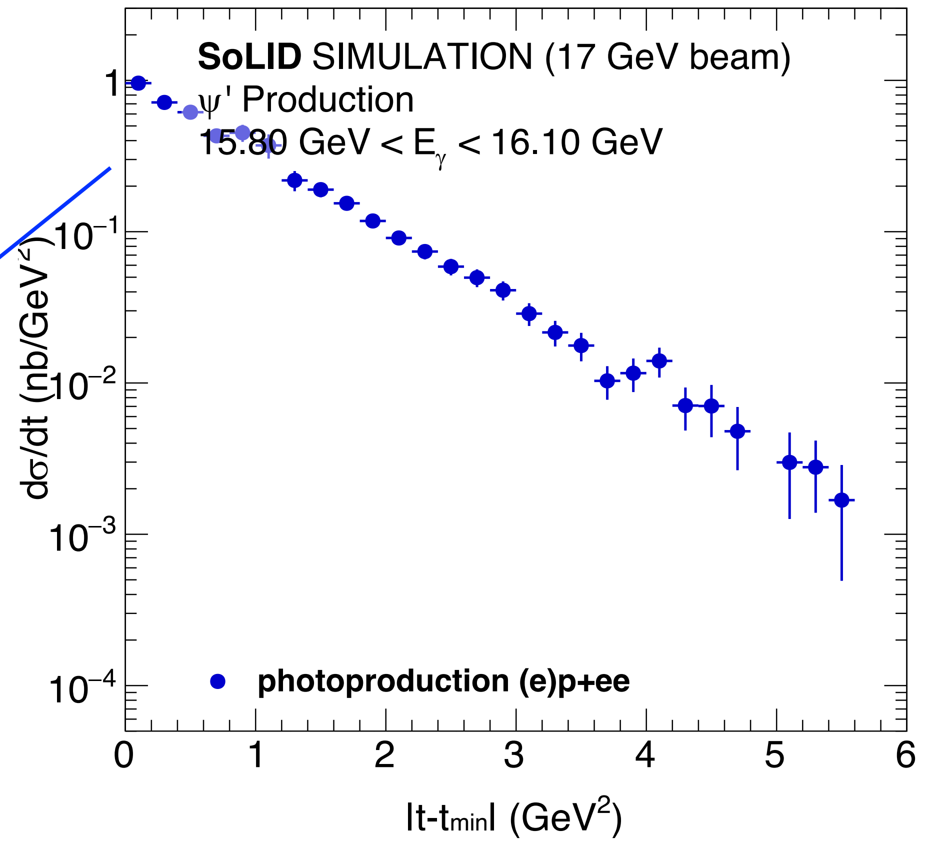


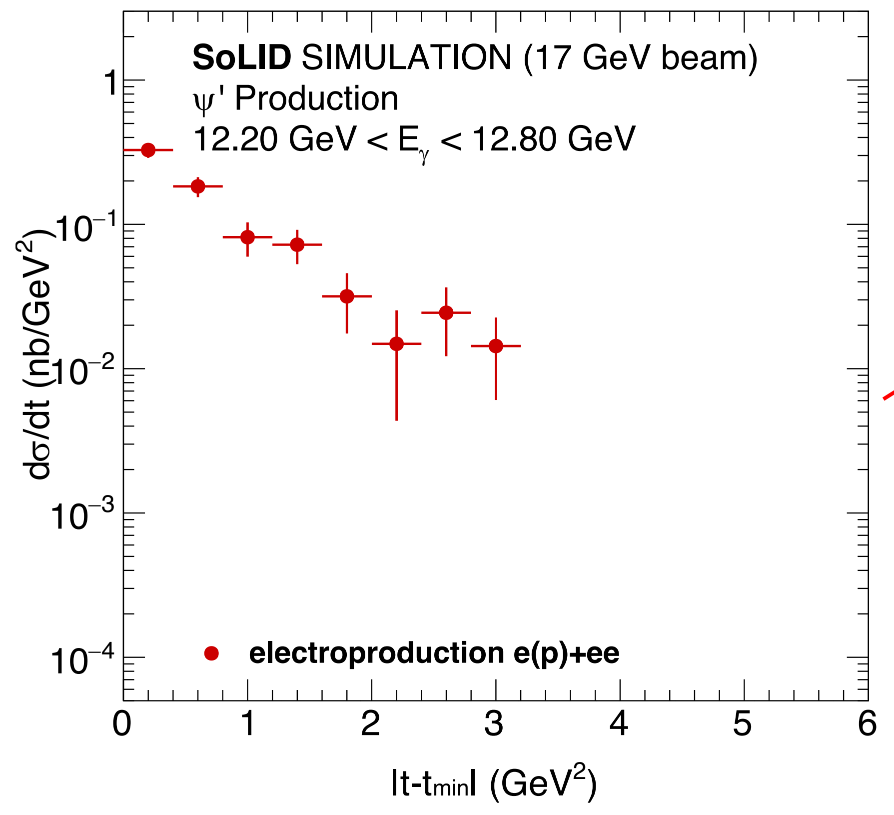
2D CROSS SECTION POTENTIAL

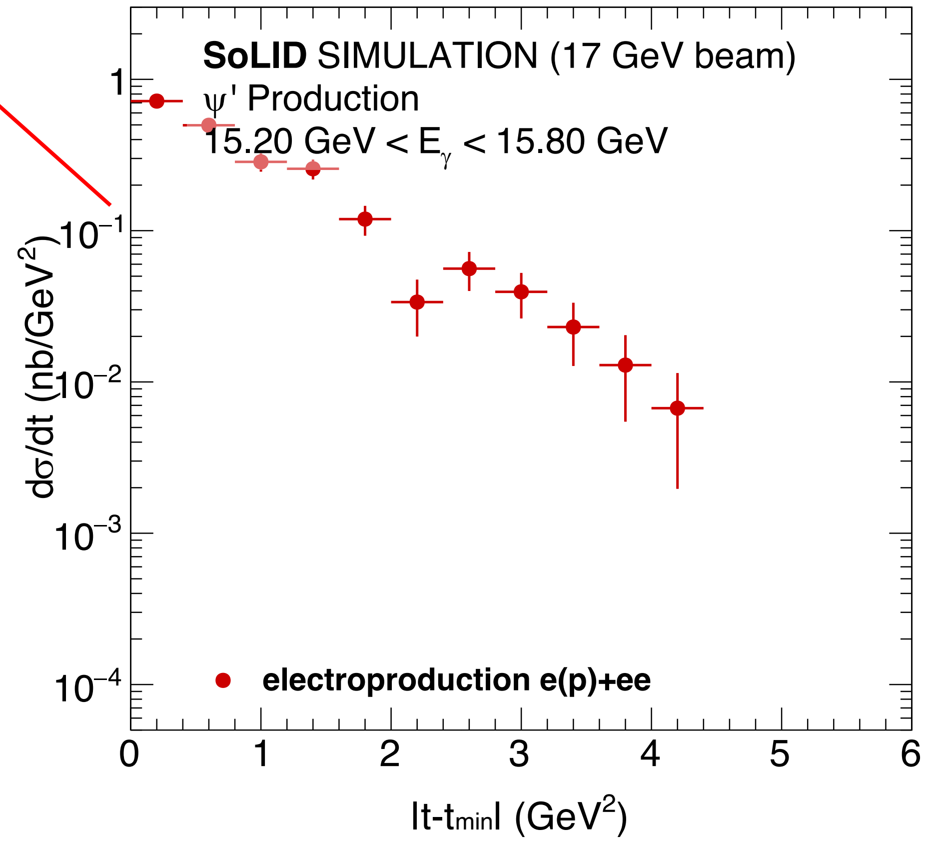
$\psi(2S)$ production with a 17 GeV incident Electron beam











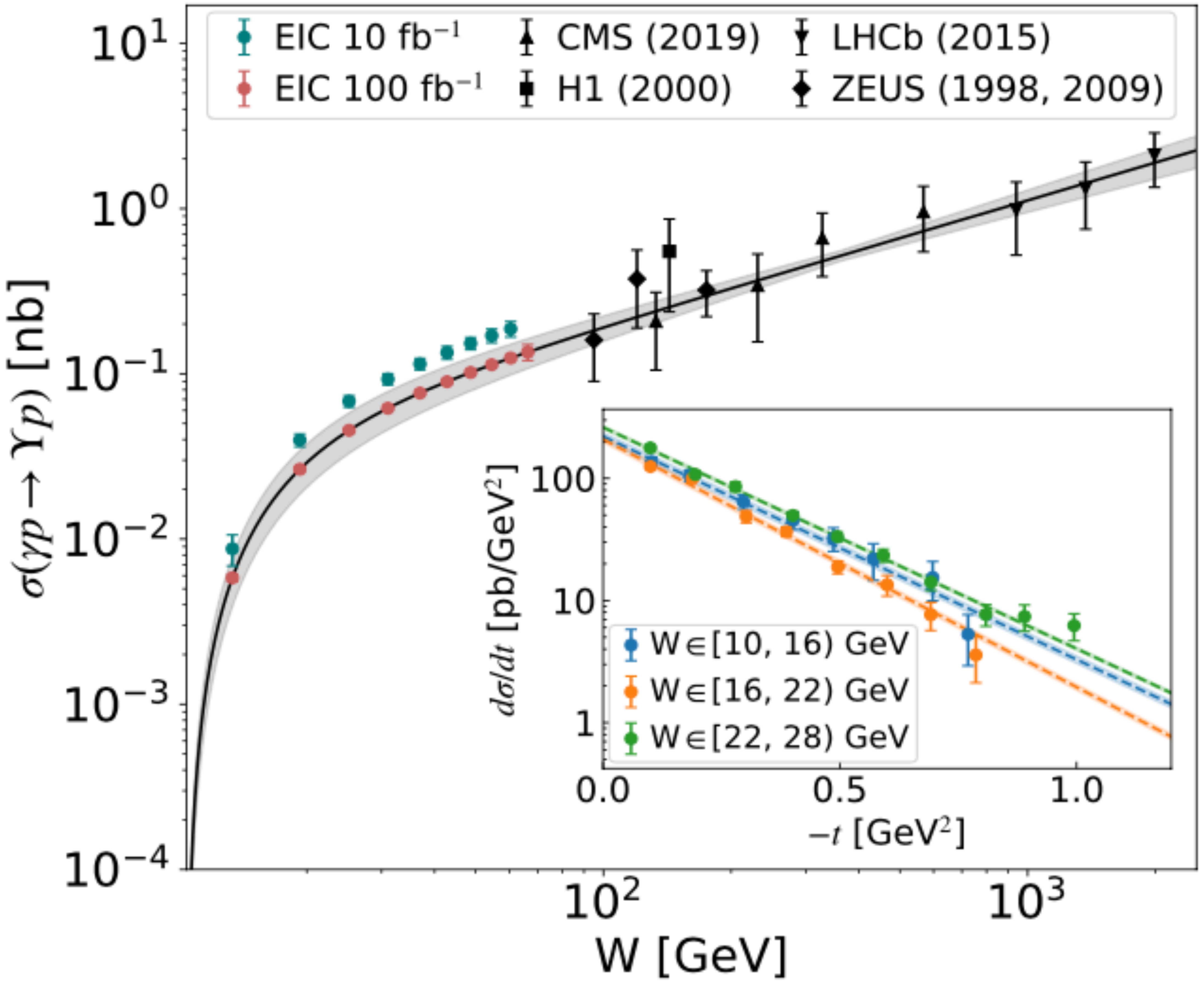
2D measurement of ψ(2s) cross section feasible for both photoproduction and electroproduction with the nominal SoLID-J/ψ setup.

Y(1S): AN IDEAL GLUONIC PROBE?

Threshold measurement possible at EIC

- *Y*(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

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

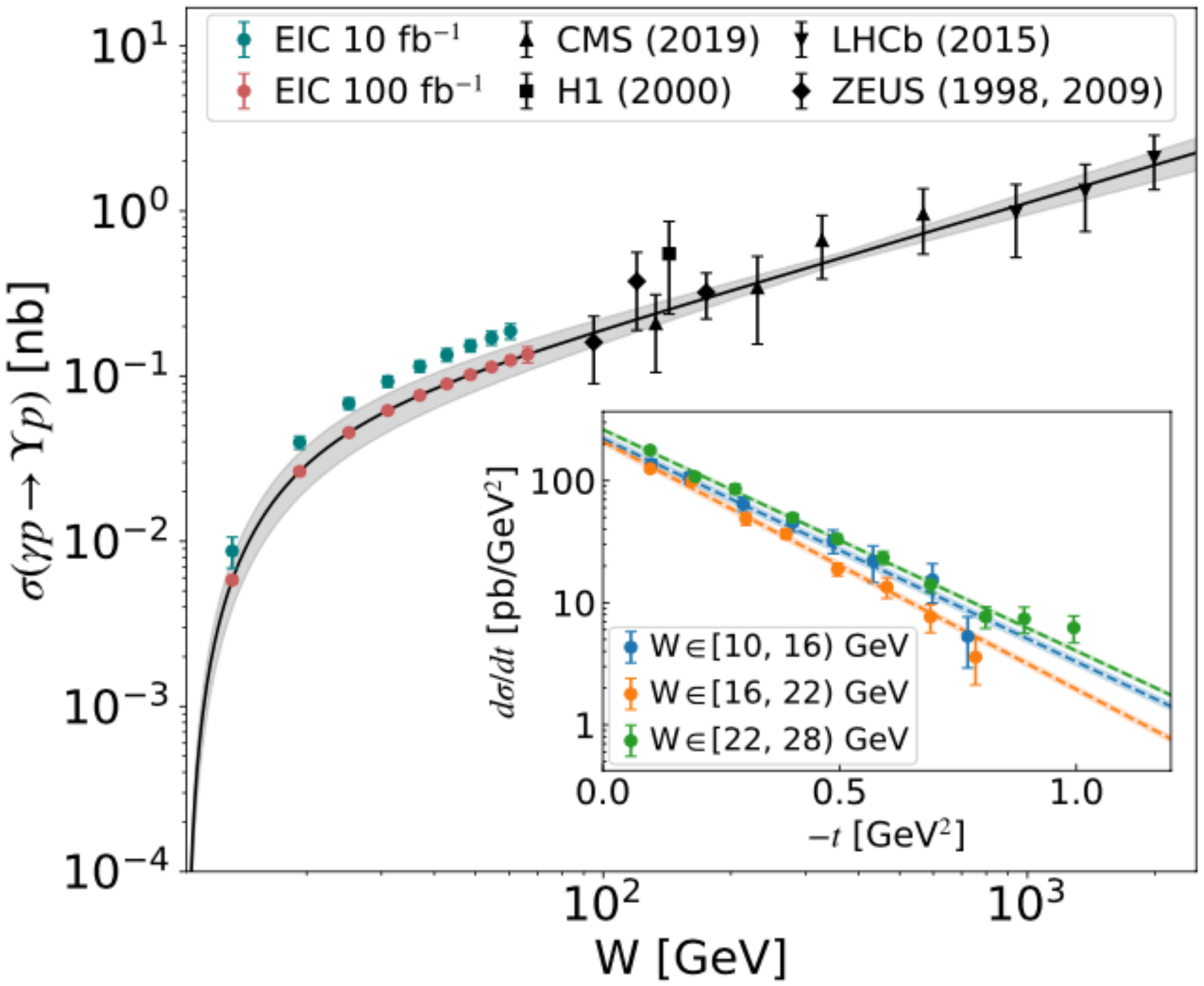


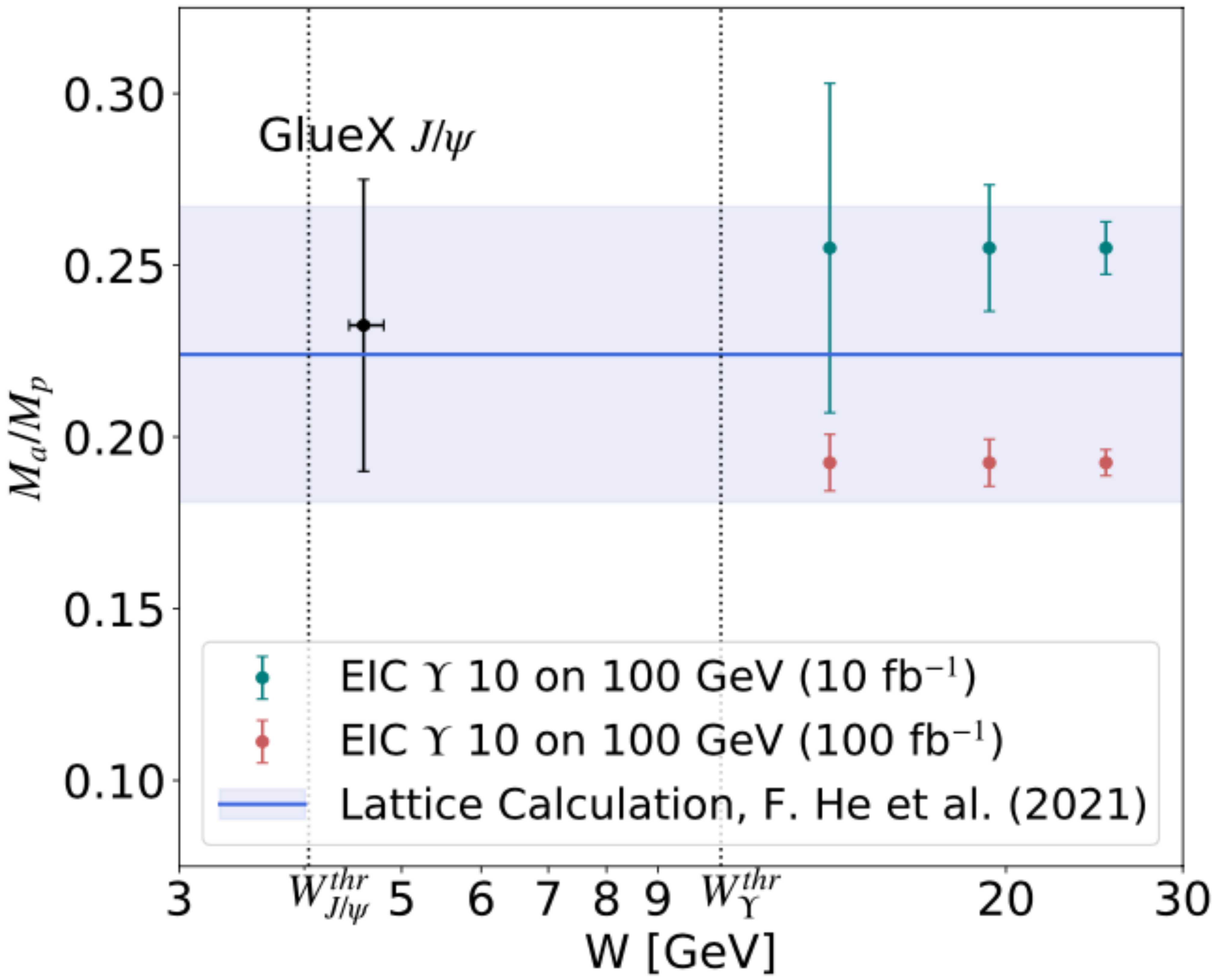
Strong complementarity between threshold J/ψ program at JLab 12 with threshold Y production at EIC

REALISTIC PHYSICS REACH OF AN EIC DETECTOR

Ma/M following Ji's approach

X. Ji, Phys. Rev. Lett. 74, 1071–1074 (1995)



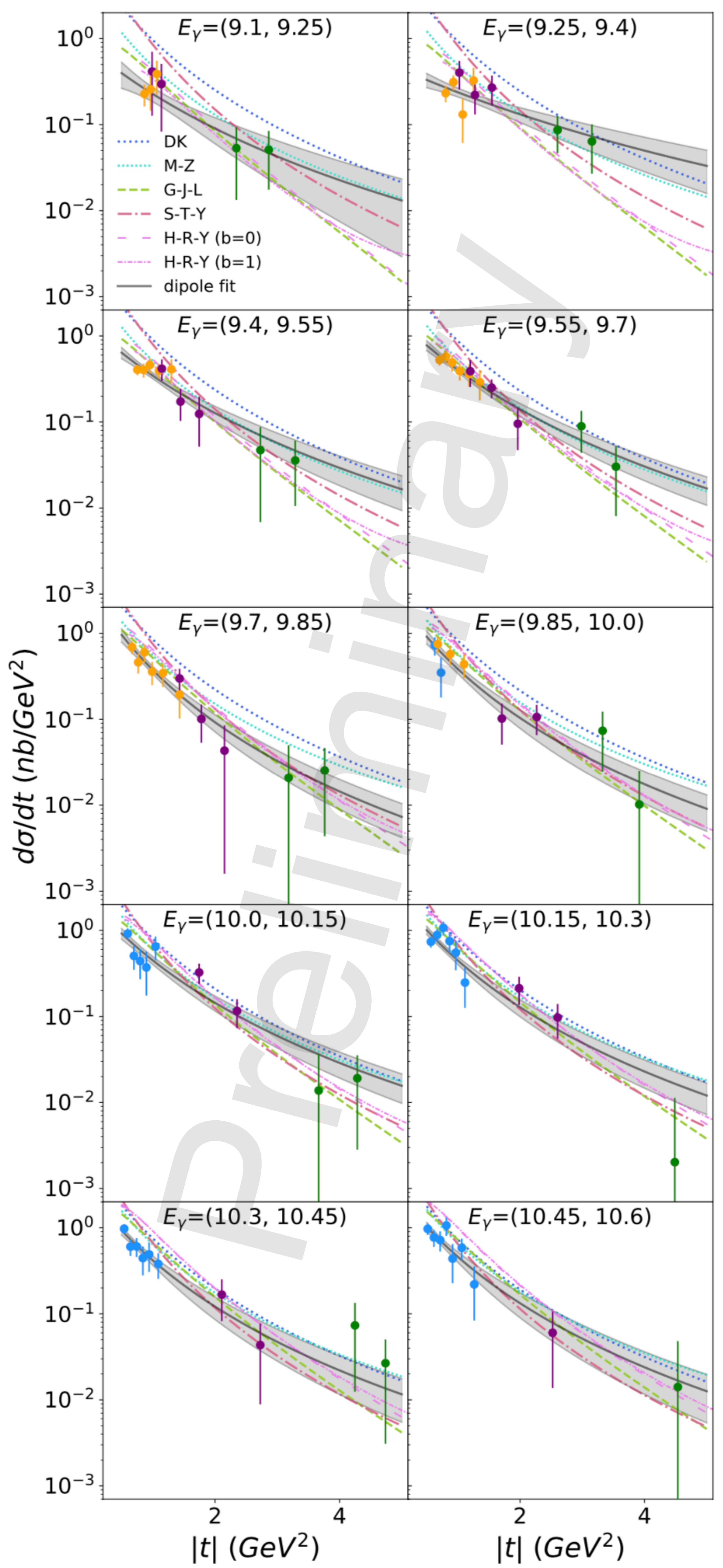


Near-threshold Υ physics is a year-1 measurement:
comparable statistics to early threshold J/ψ results from Jefferson Lab!

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

CONCLUSION

- The matter structure of the proton and threshold quarkonium production are rapidly evolving topics that **reach from Jefferson Lab to the EIC**.
- 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?
- More results expected from GlueX and CLAS12 (short term-medium term), SoLID (longer term). Program could further benefit from a CEBAF beam energy upgrade (higher rates, greater Q2 reach for SoLID, access to ψ').
- **Υ at EIC is perfectly complementary to Jefferson Lab program.** Year-1 measurement comparable to the first GlueX J/ψ results is realistic



With thanks to the J/ψ-007 Collaboration

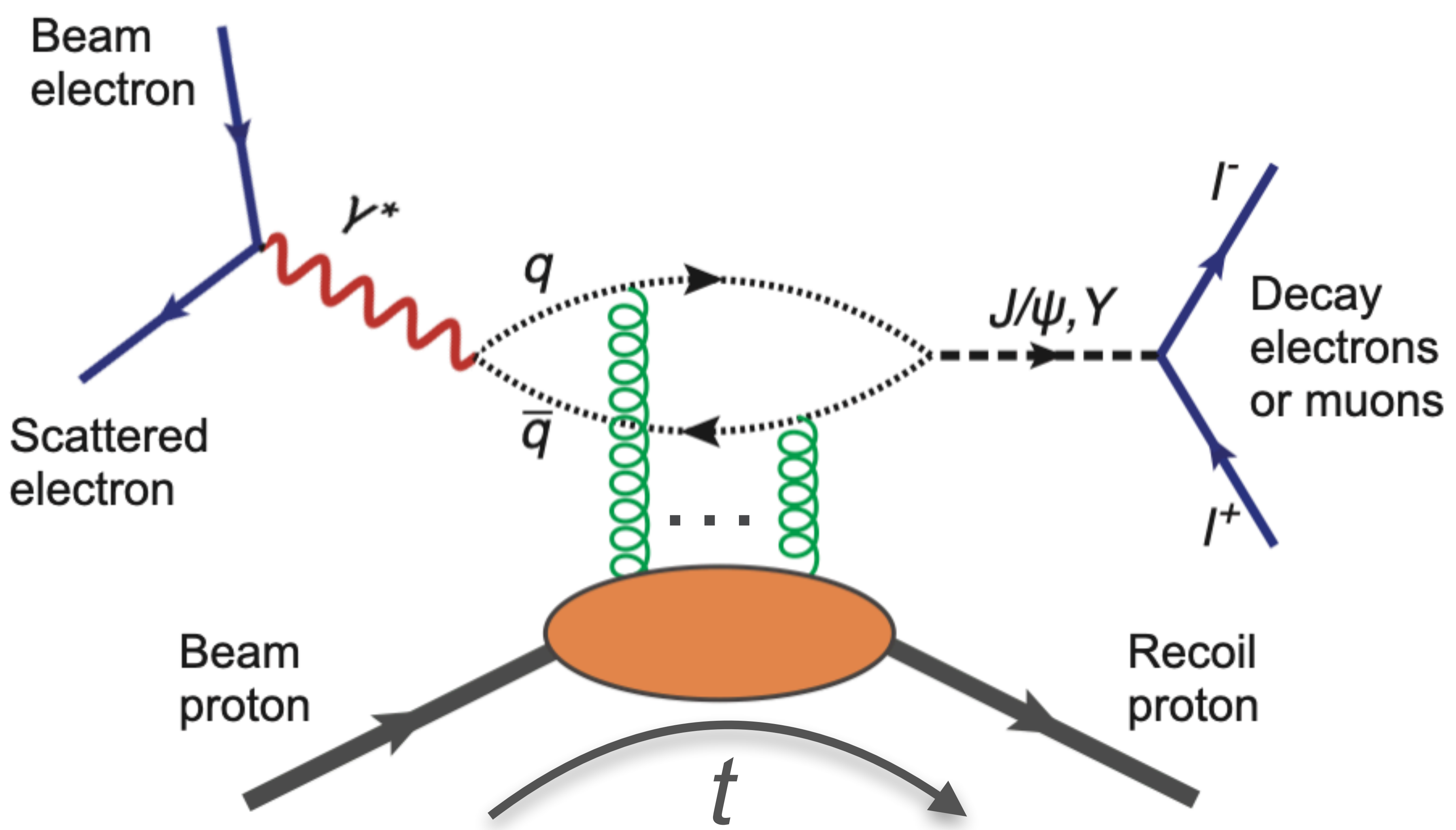
…and many others!

B. Duran[3,1], Z.-E. Meziani[1,3], S. Joosten[1], M. K. Jones[2], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[3], E. Chudakov[2], H. Bhatt[5], D. Bhetuwal[5], M. Boer[11], A. Camsonne[2], J.-P. Chen[2], M. Dalton[2], N. Deokar[3], M. Diefenthaler[2], J. Dunne[5], L. El Fassi[5], E. Fuchey[9], H. Gao[4], D. Gaskell[2], O. Hansen[2], F. Hauenstein[6], D. Higinbotham[2], S. Jia[3], A. Karki[5], C. Keppel[2], P. King[6], H.S. Ko[10], X. Li[4], R. Li[3], D. Mack[2], S. Malace[2], M. McCaughan[2], R. E. McClellan[8], R. Michaels[2], D. Meekins[2], L. Pentchev[2], E. Pooser[2], A. Puckett[9], R. Radloff[5], M. Rehfuss[3], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[2], A. Smith[4], N. Sparveris[3], H. Szumila-Vance[2], S. Wood[2], J. Xie[1], Z. Ye[1], C. Yero[6], and Z. Zhao[4]**

QUESTIONS?

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

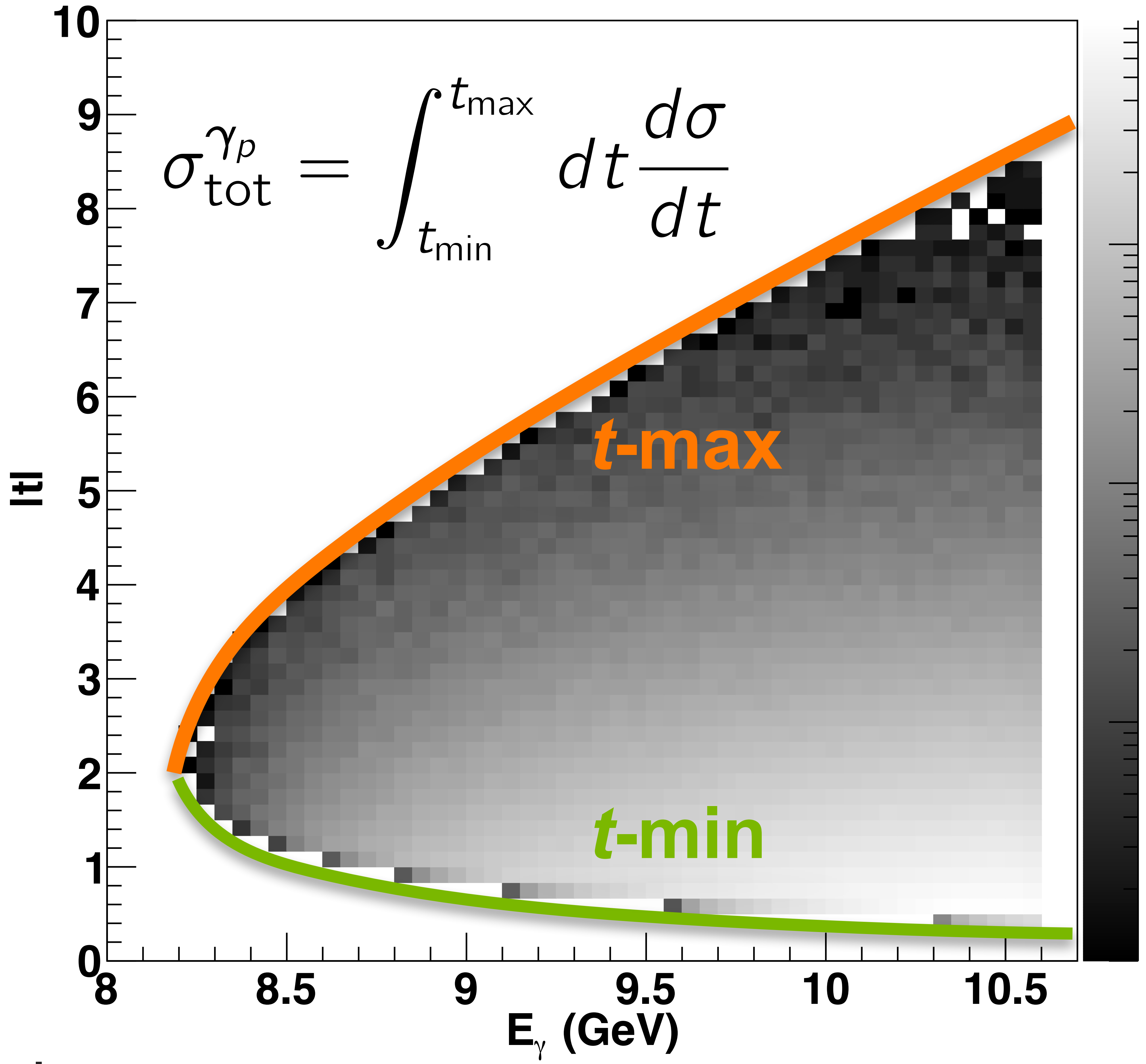
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

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

$\Upsilon(1S)$ 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