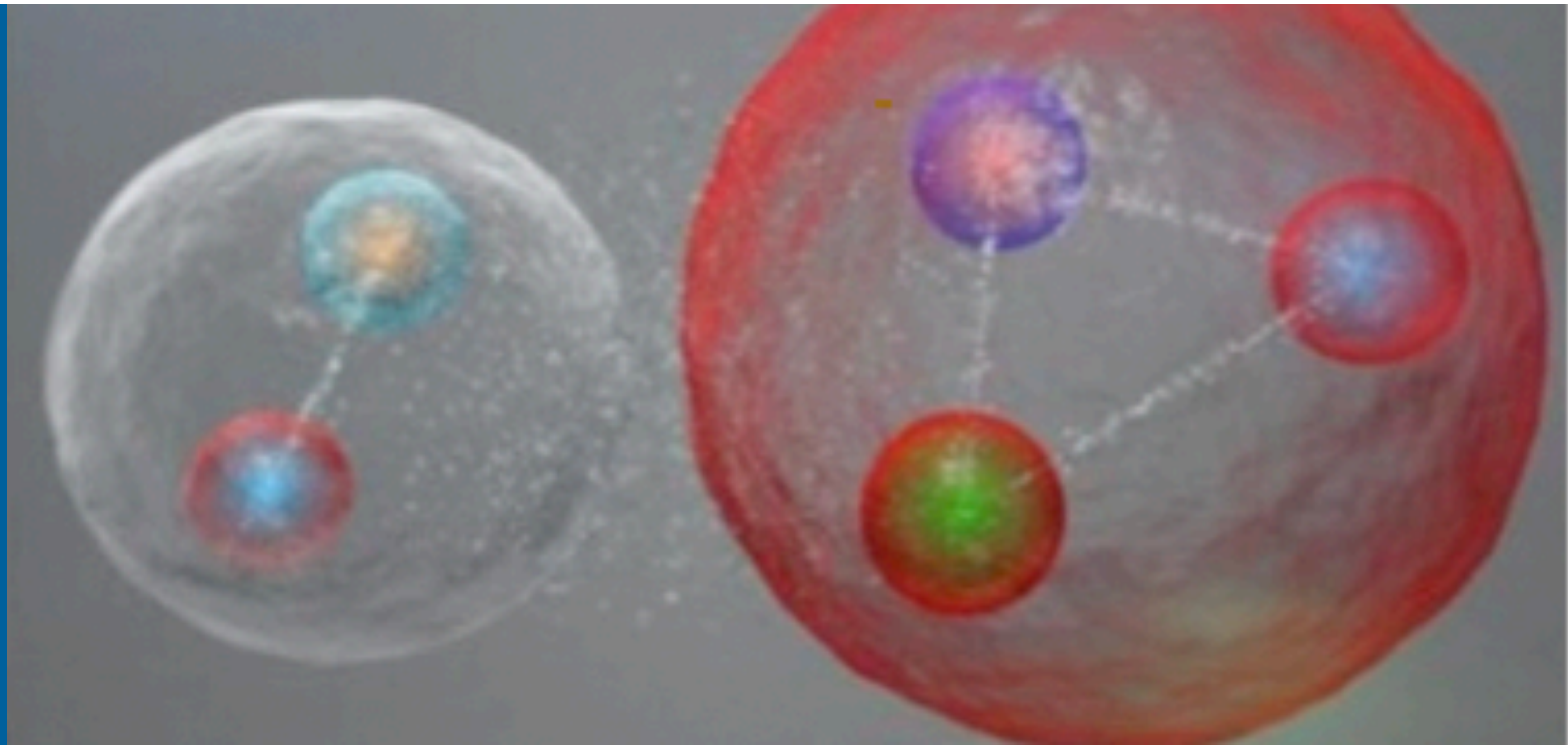
NEAR-THRESHOLD QUARKONIUM PROGRAM AT JEFFERSON LAB AND THE EIC

QUARKONIUM PRODUCTION NEAR THRESHOLD



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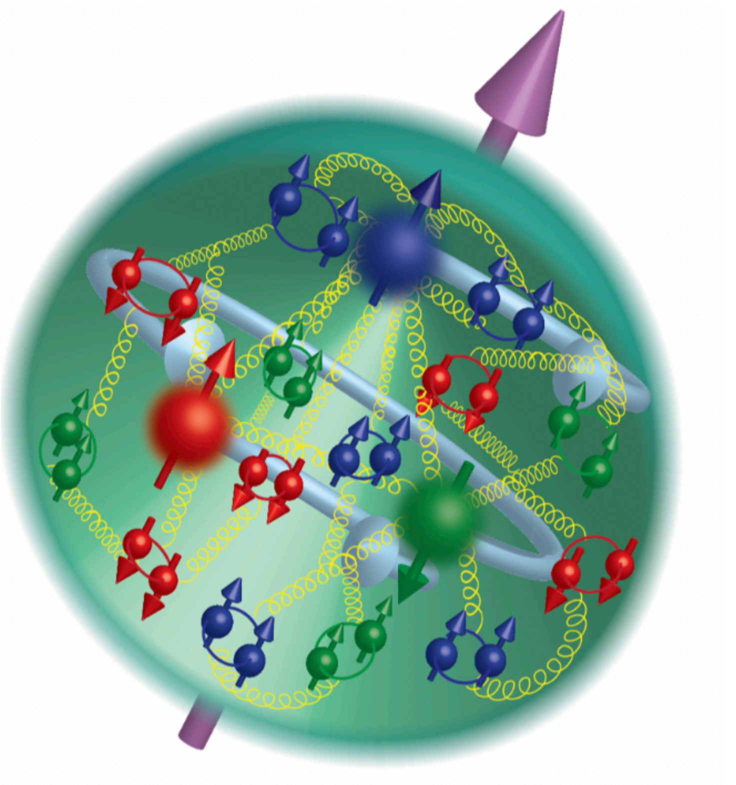
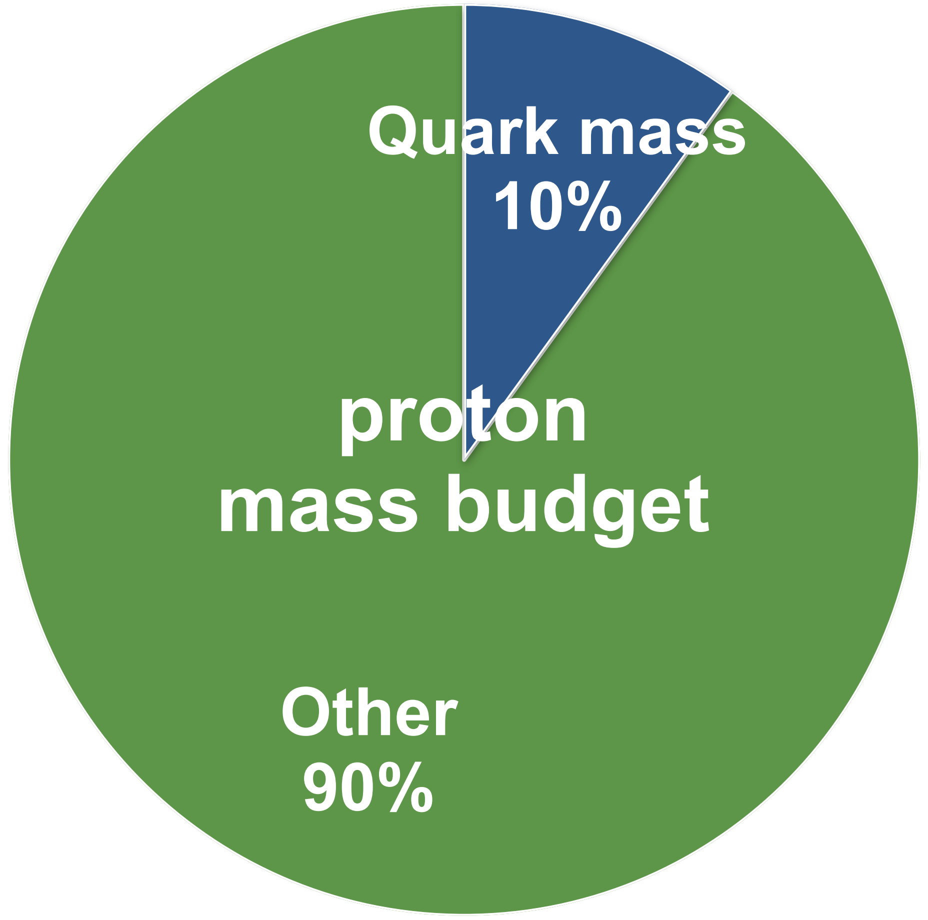
INT 22-3
October 12, 2022

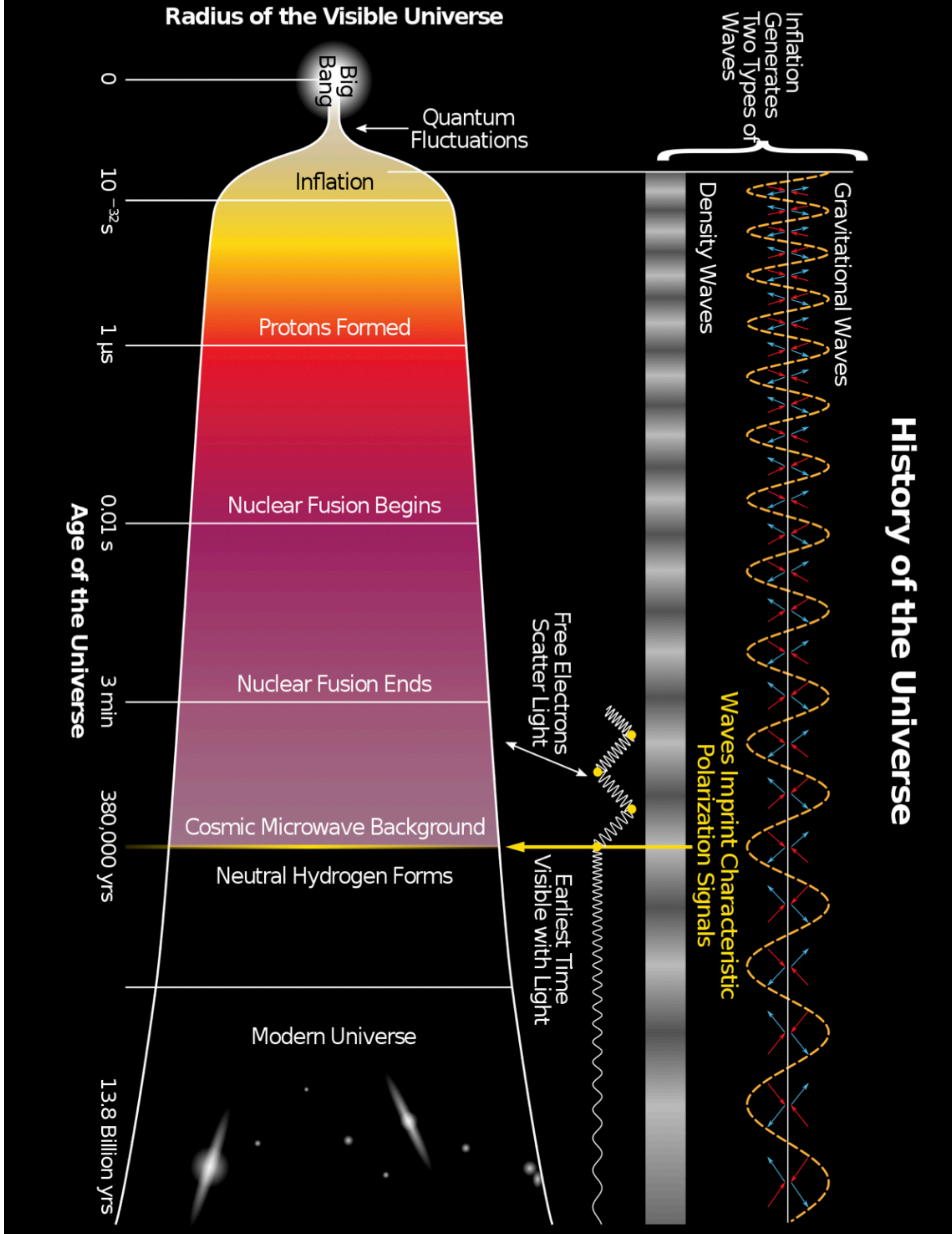
The emergence of nucleon mass

QCD IN THE STANDARD MODEL



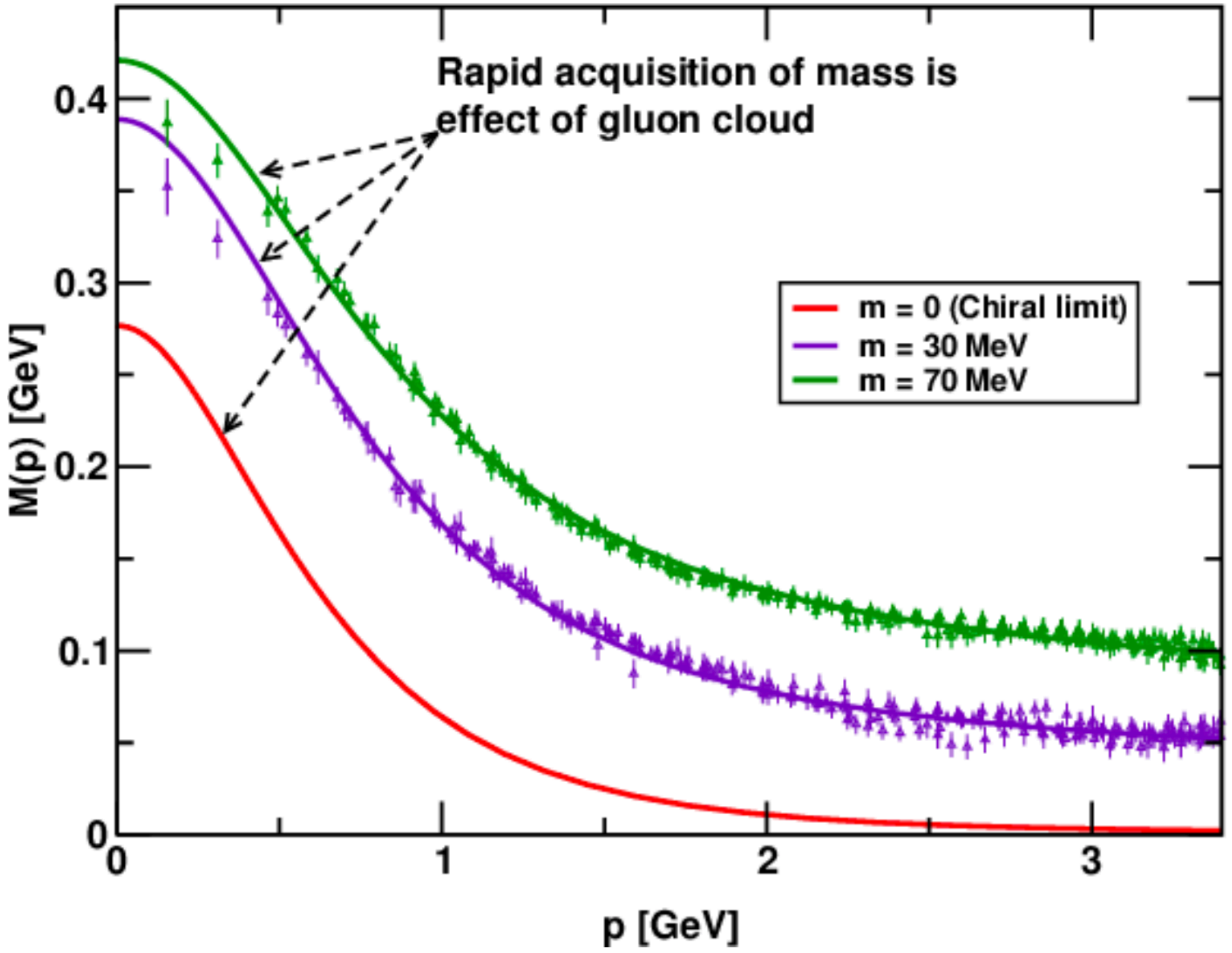


- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement size?*



NUCLEON MASS IS AN EMERGENT PHENOMENON

QCD responsible for the proton mass



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

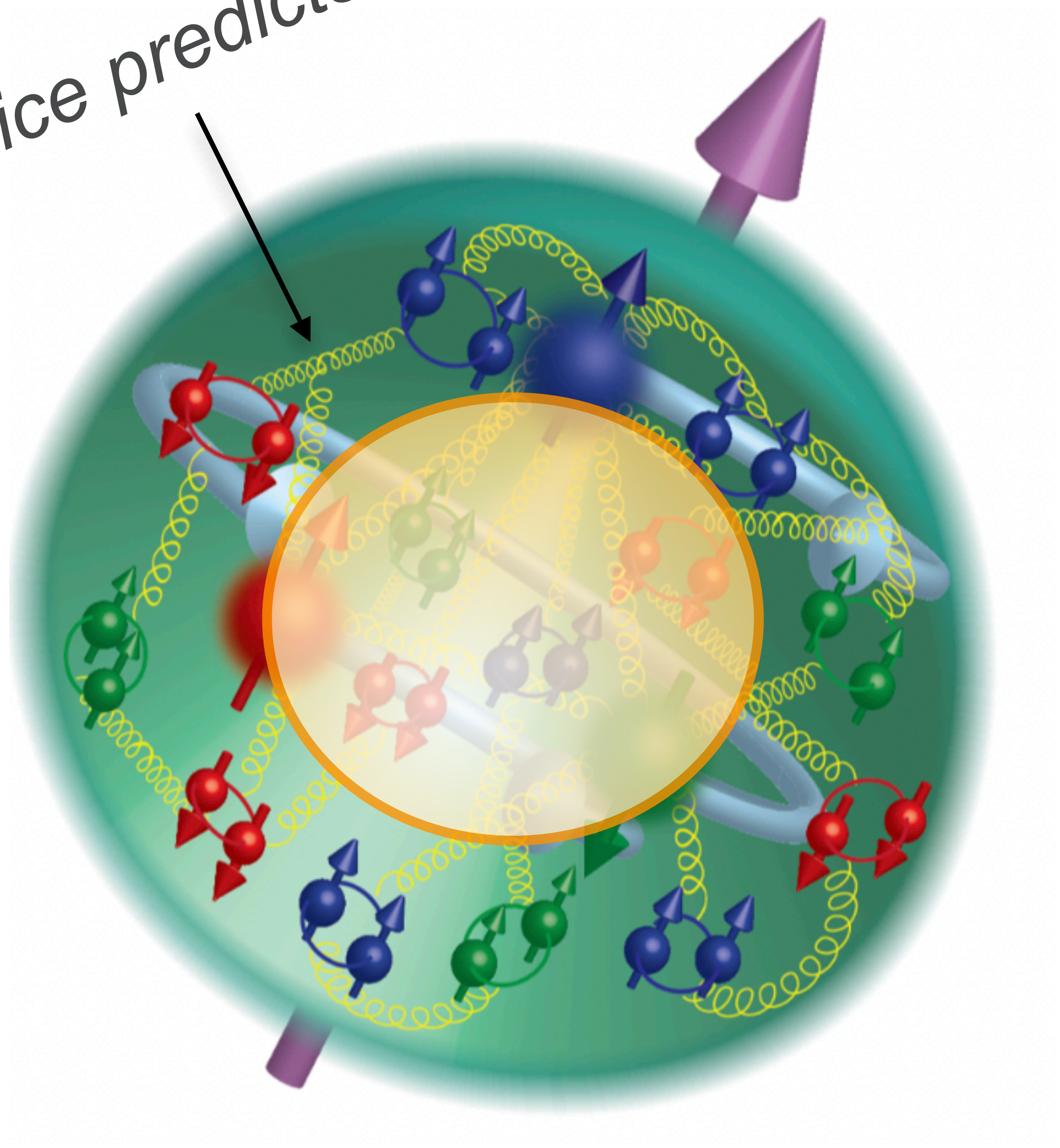
- In the proton rest frame, low momentum gluons attach to the current quarks (DCSB, demonstrated by many calculations and on the lattice)
- Each constituent quark accumulates ~300 MeV by “eating” these low momentum gluons.
- Even in when we assume quarks to be massless!
- **Mass from nothing? - No, mass from energy!**

Bottom line: The Higgs mechanism is largely irrelevant for most of “normal” visible matter!

WHERE IS THE ENERGY INSIDE THE PROTON?

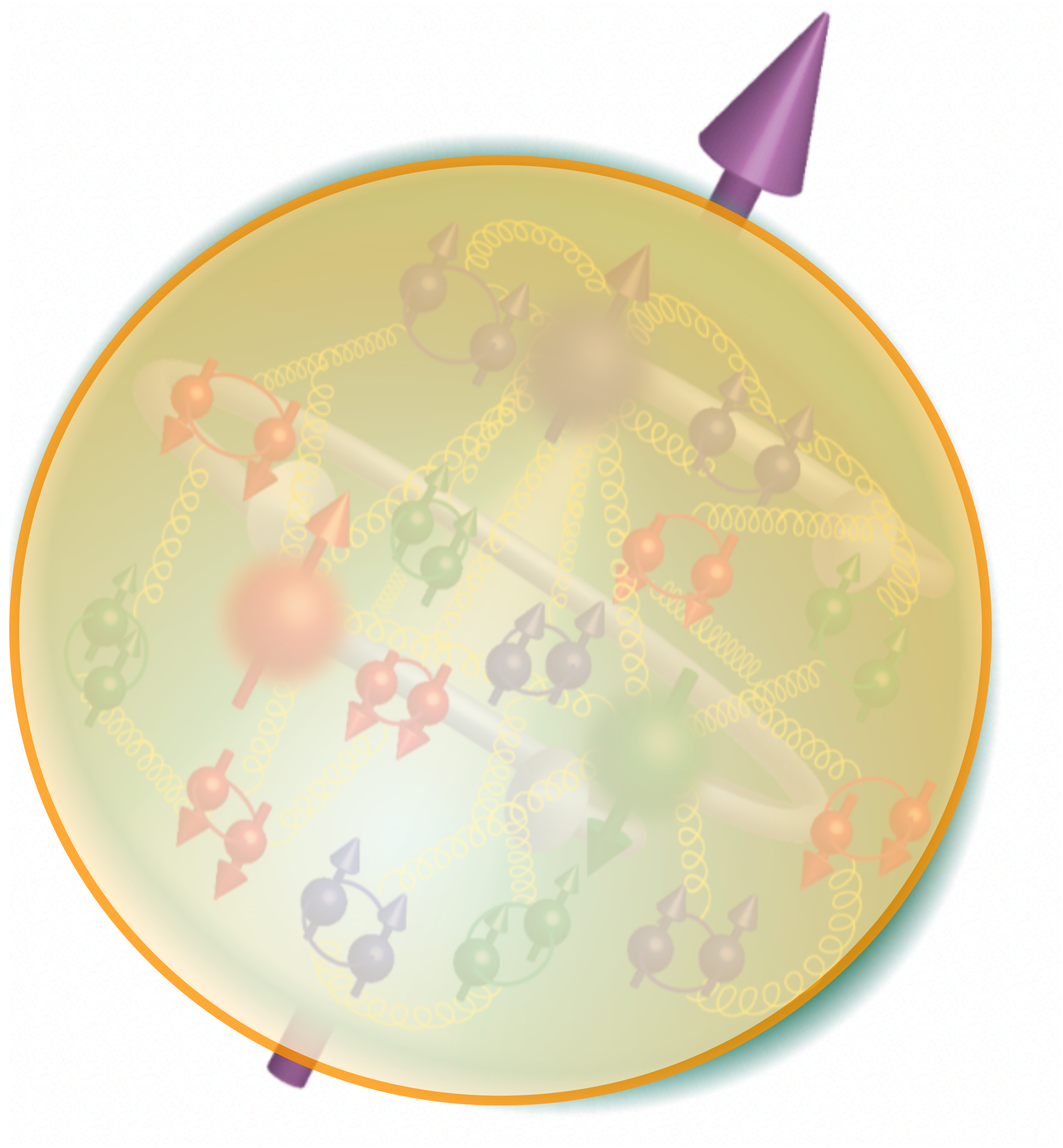
How does the mass radius compare to the charge radius?

Lattice predicts this one



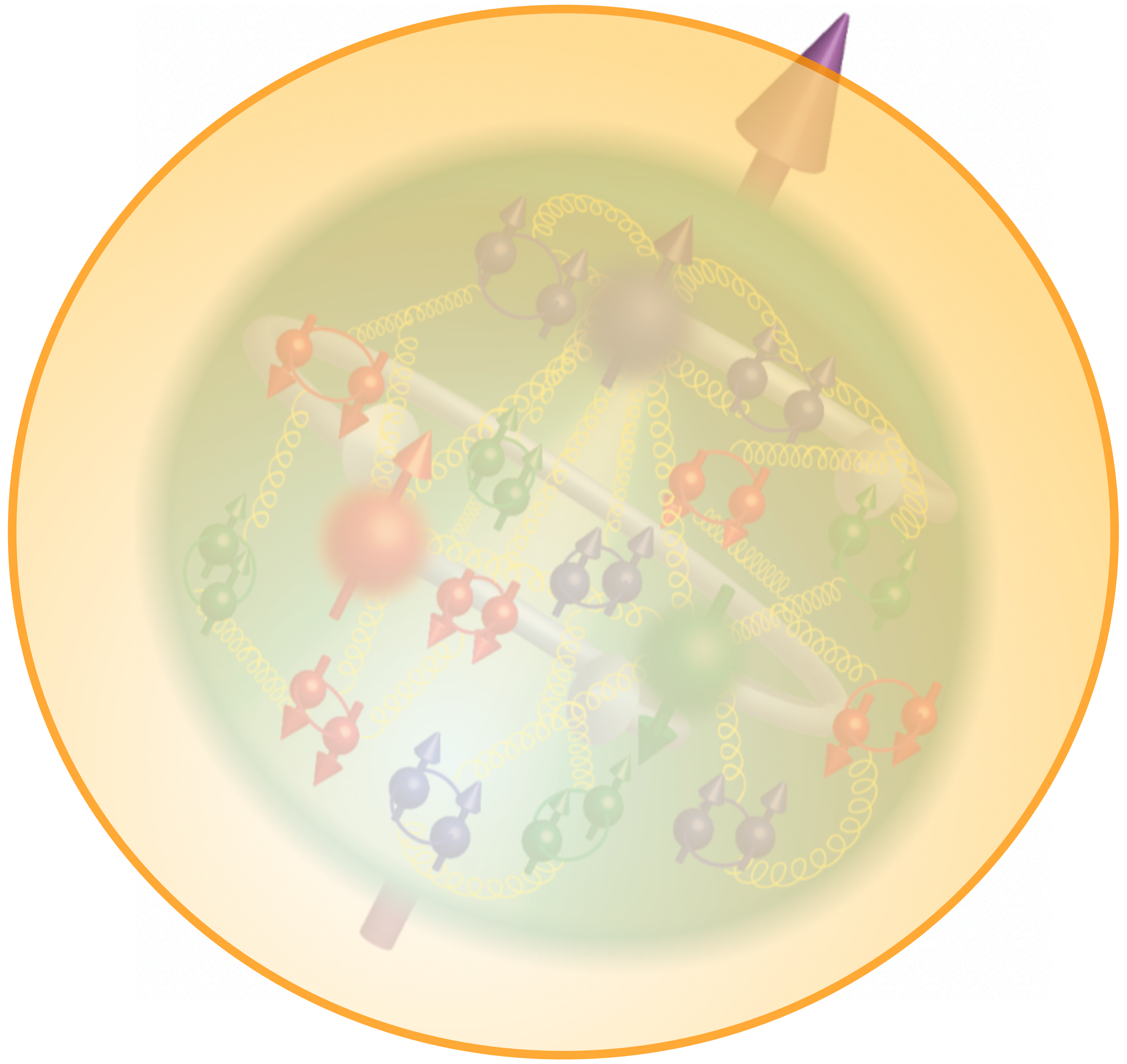
Dense energetic core?

Vs



Same as charge radius?

Vs



Energy halo beyond
charge radius?

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables of the matter structure of the proton

GFFs are the form factors of the QCD energy-momentum tensor (EMT) for quarks and gluons

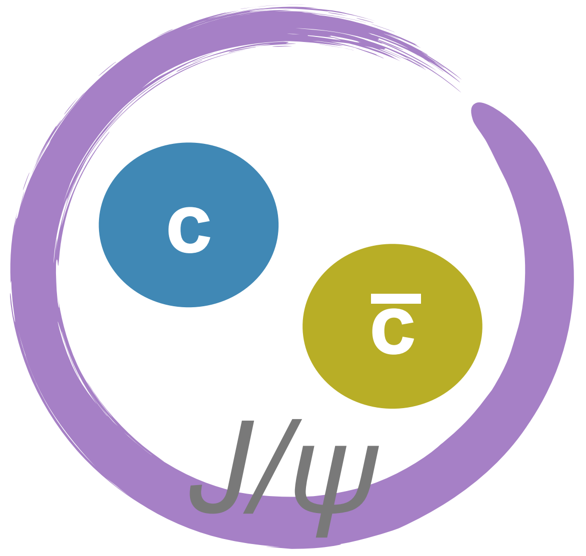
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_{\rho}}{2M} + C_{g,q}(t)\frac{\Delta^{\mu}\Delta^{\nu} - g^{\mu\nu}\Delta^{2}}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

EMT physics encoded in these GFFs:

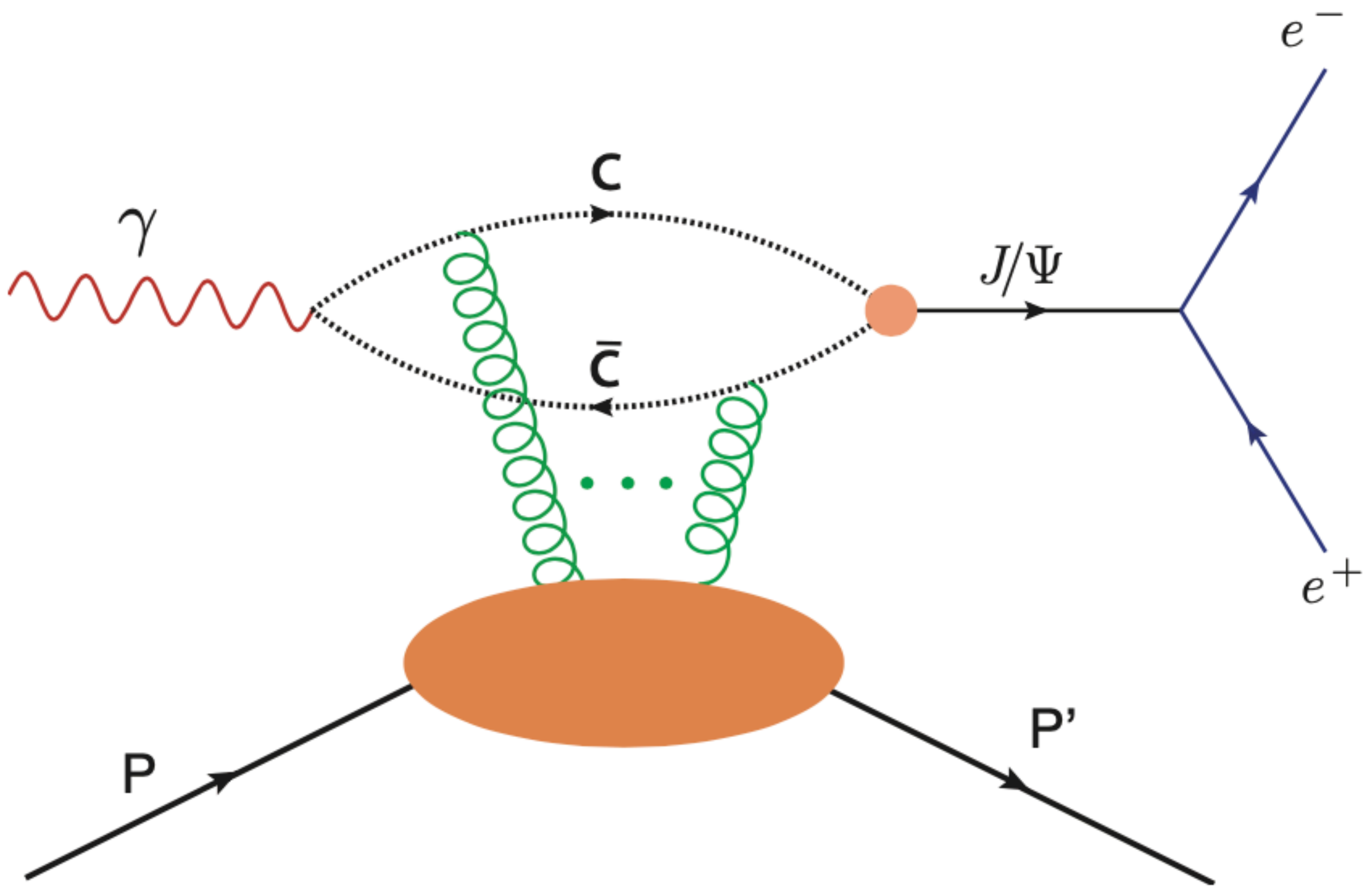
- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

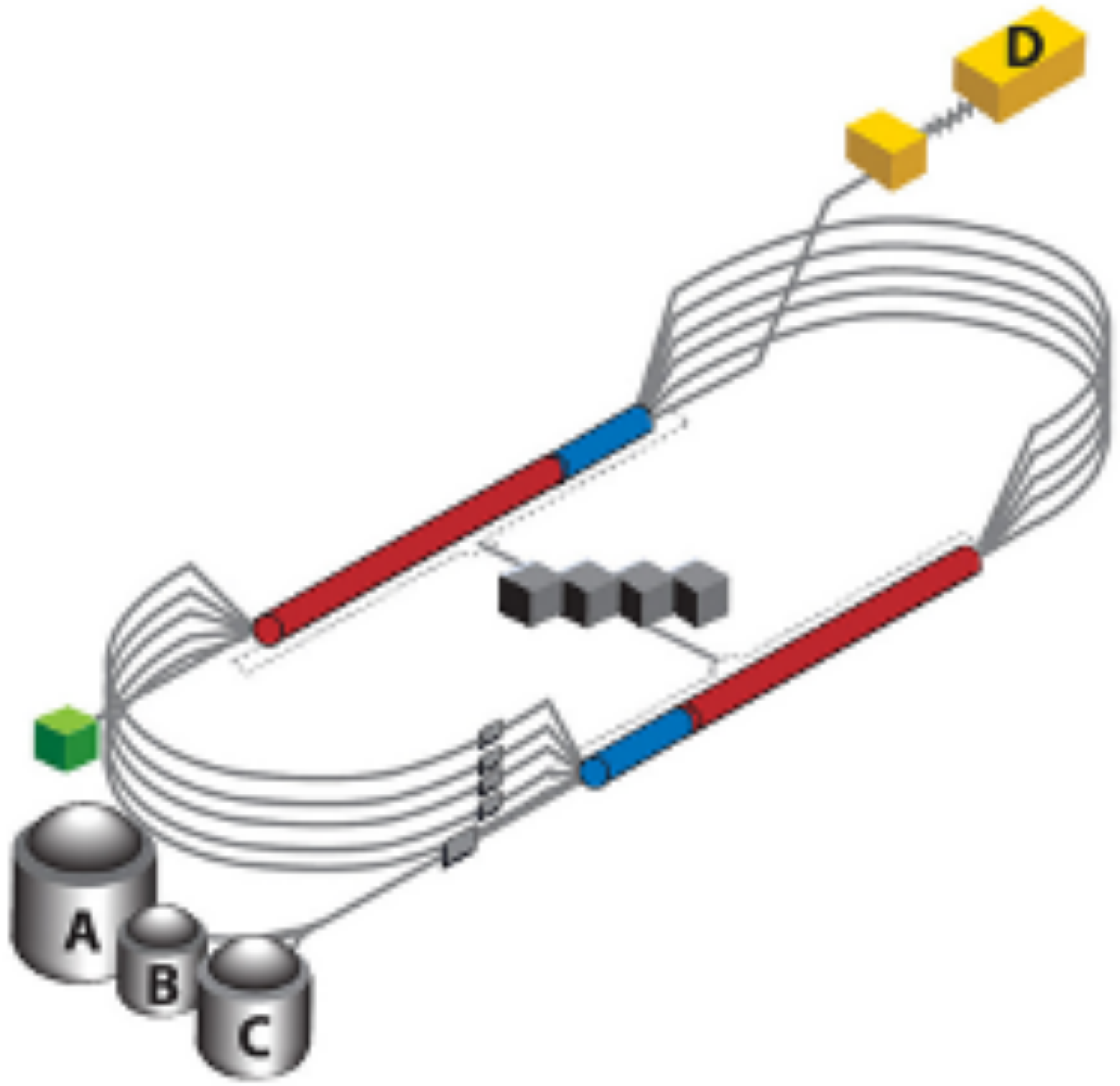
PROBING THE GLUONS

Exclusive quarkonium production near the threshold



- Electromagnetic charge and spin of the proton well-studied through electron scattering
- Electromagnetic neutral gluons harder to access directly
  - Quarkonium uniquely sensitive to gluons: they do not couple to 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.**





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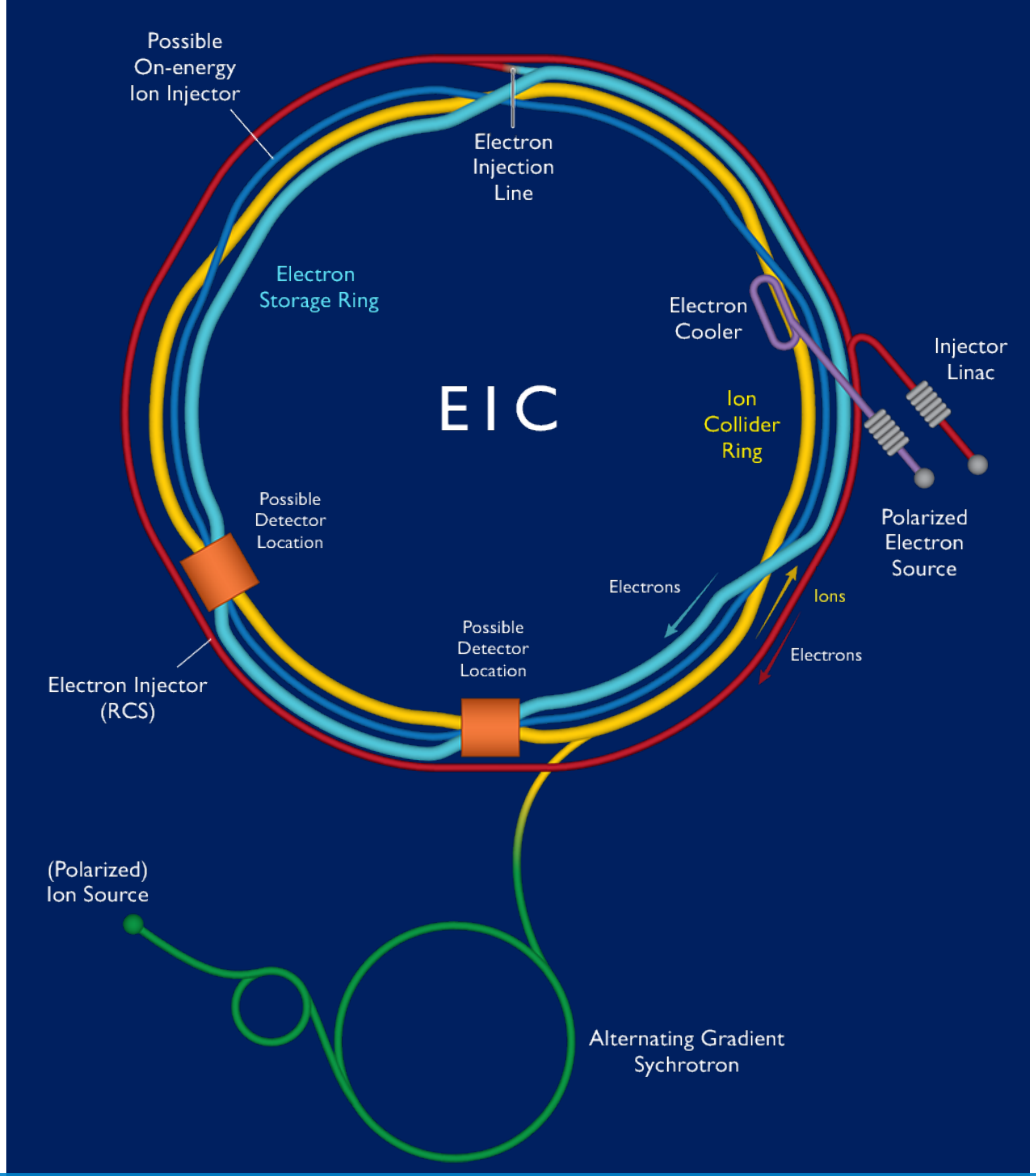
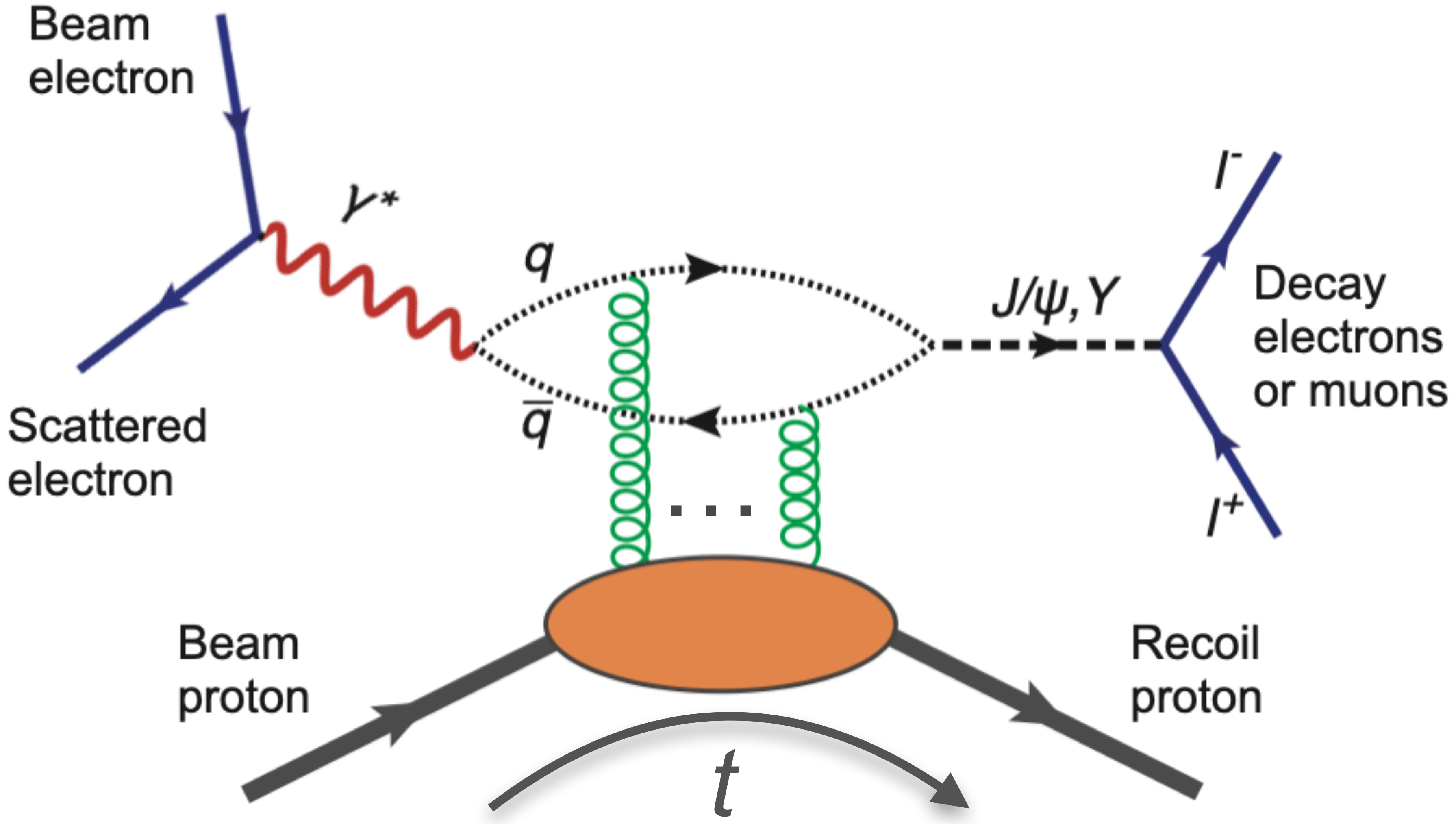
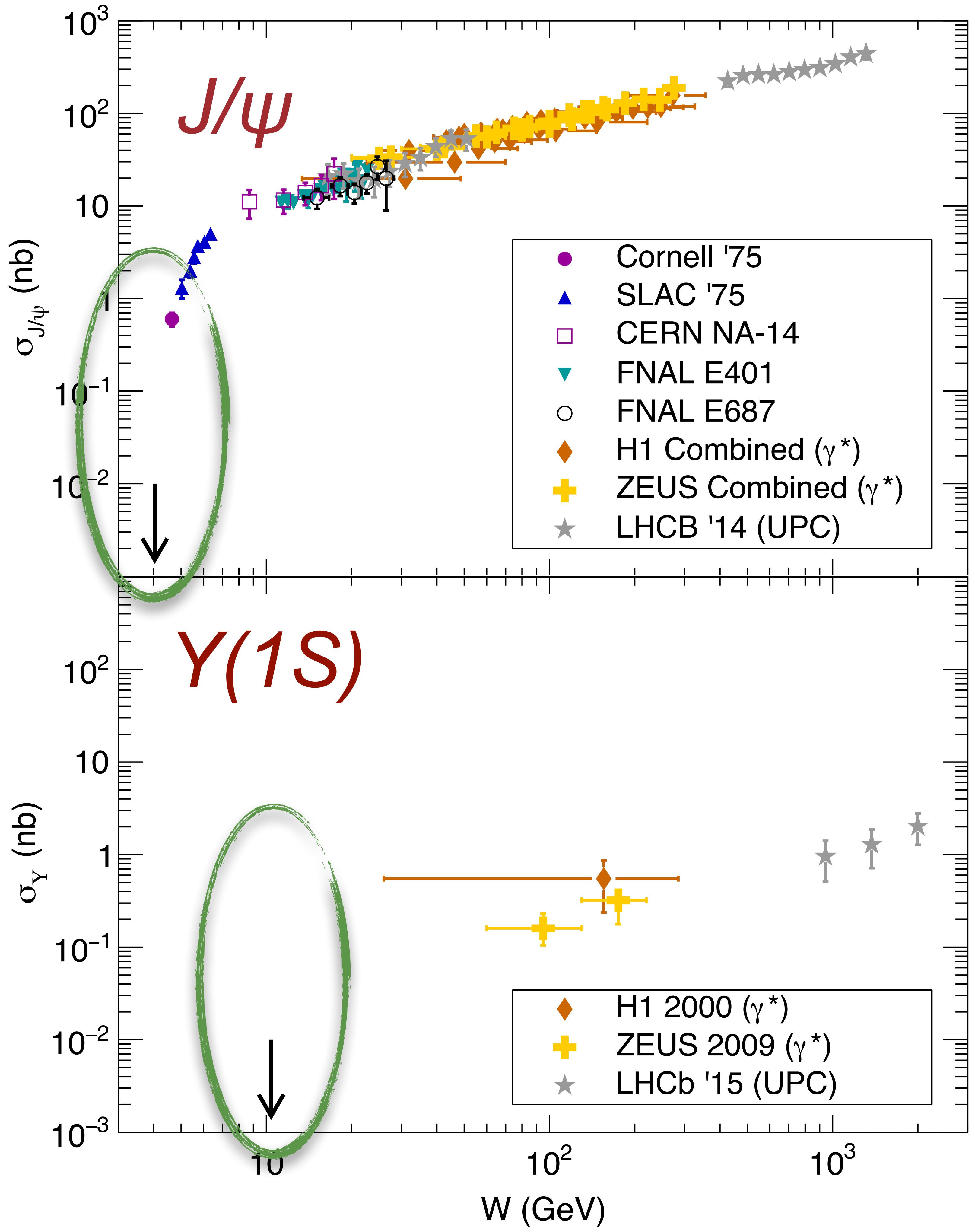


CURRENT AND UPCOMING NEAR-THRESHOLD QUARKONIUM EXPERIMENTAL PROGRAM

EXCLUSIVE QUARKONIUM PRODUCTION

Before Jefferson Lab 12 GeV





- No near-threshold data available
- In case of Y(1S): not much available overall
- **Almost no data near threshold before JLab 12 GeV**

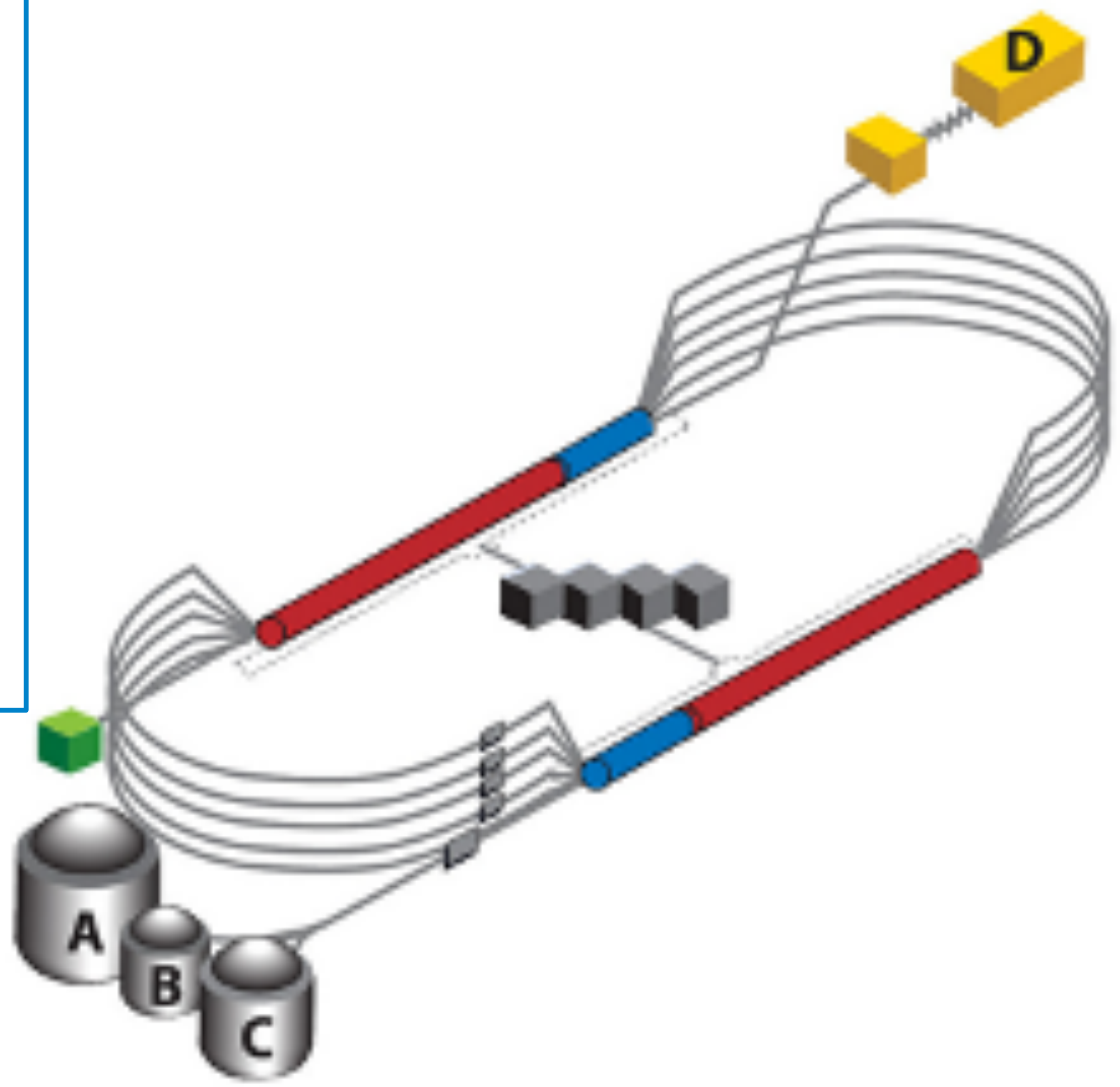
QUARKONIUM AT JEFFERSON LAB AND EIC

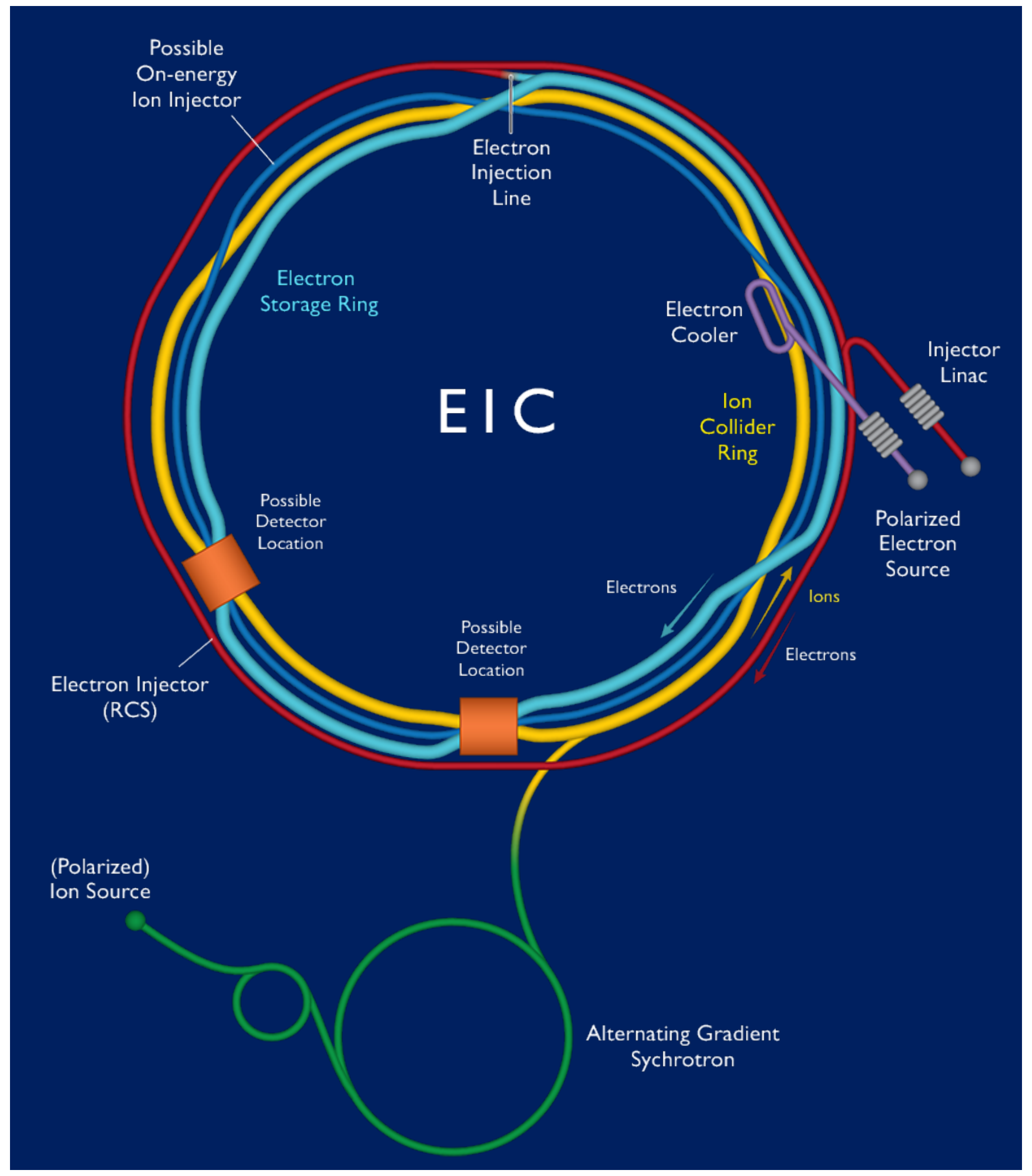
Jefferson Lab

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

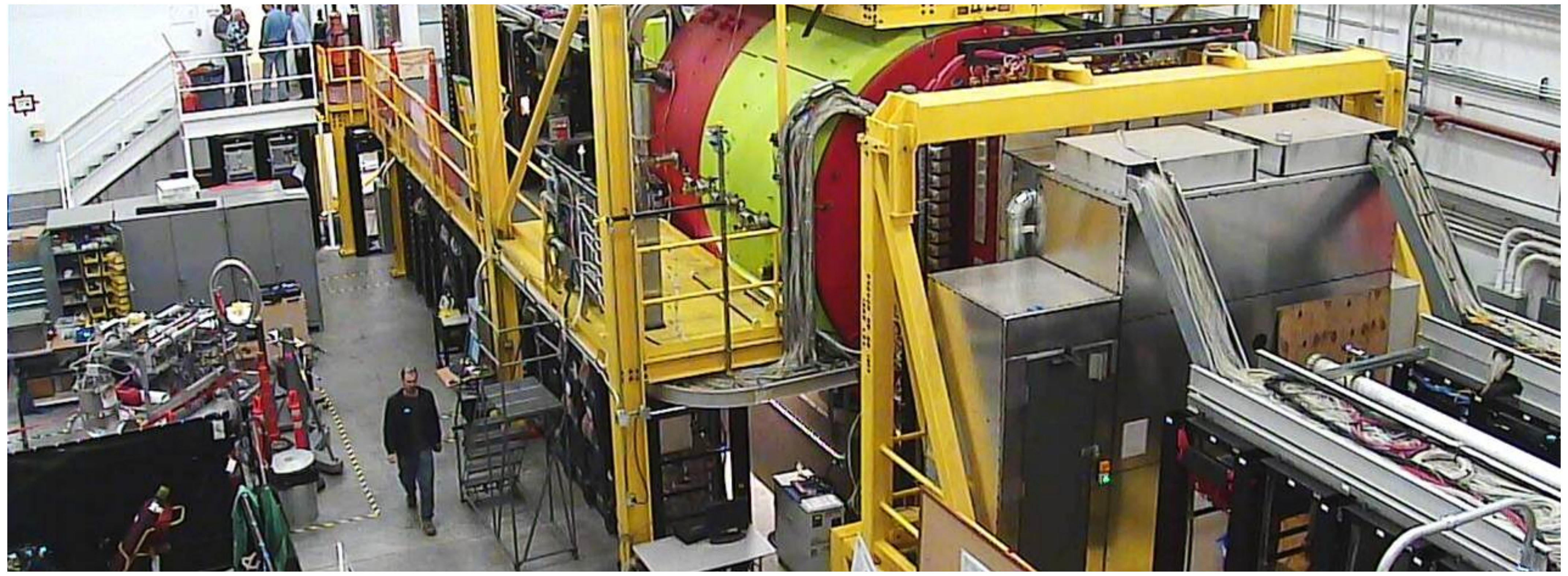
EIC: high luminosity (10^{33}-10^{34} cm^{-2}s^{-1}) polarized electron polarized ion collider

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

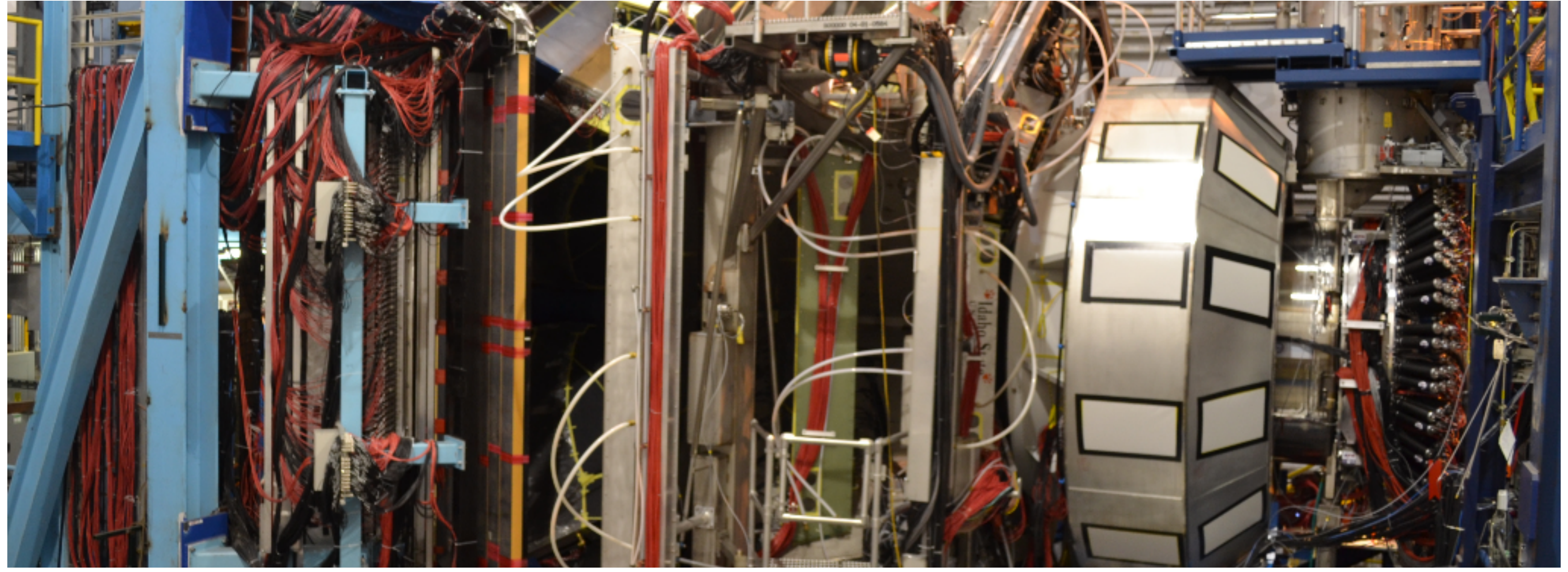
Reach to J/ψ threshold more difficult, sufficient energy and luminosity to study Υ near threshold.

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

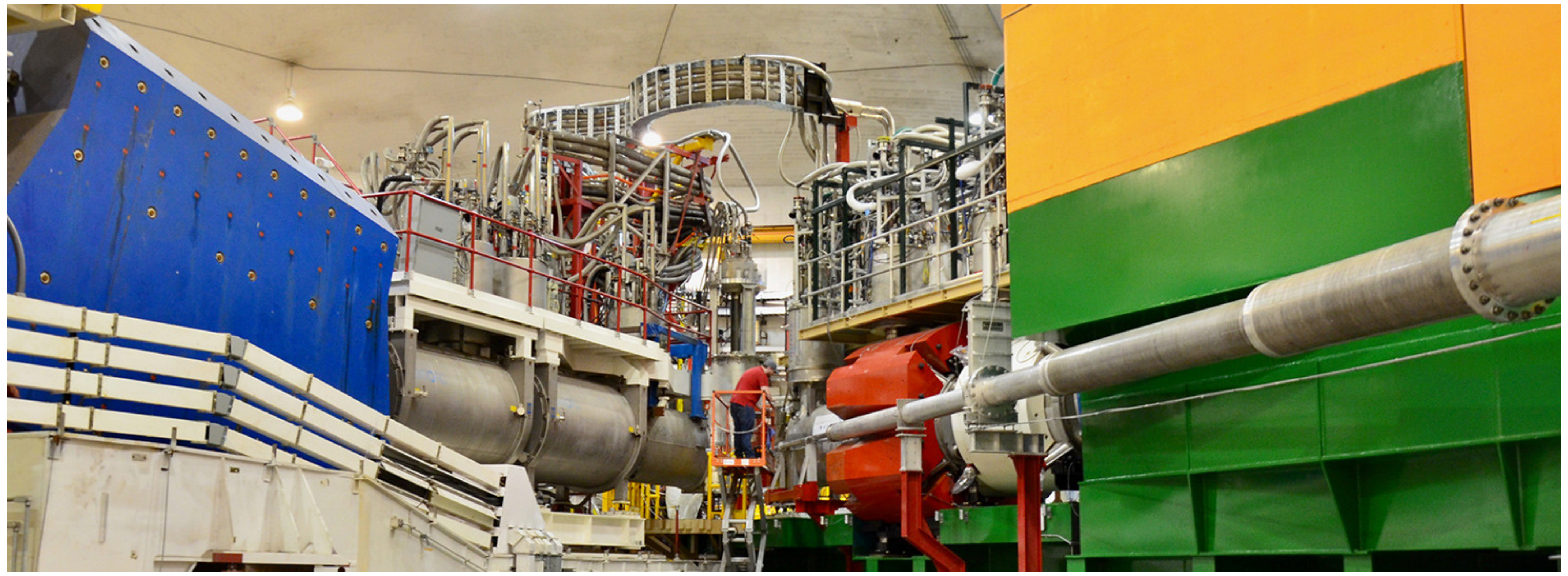
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



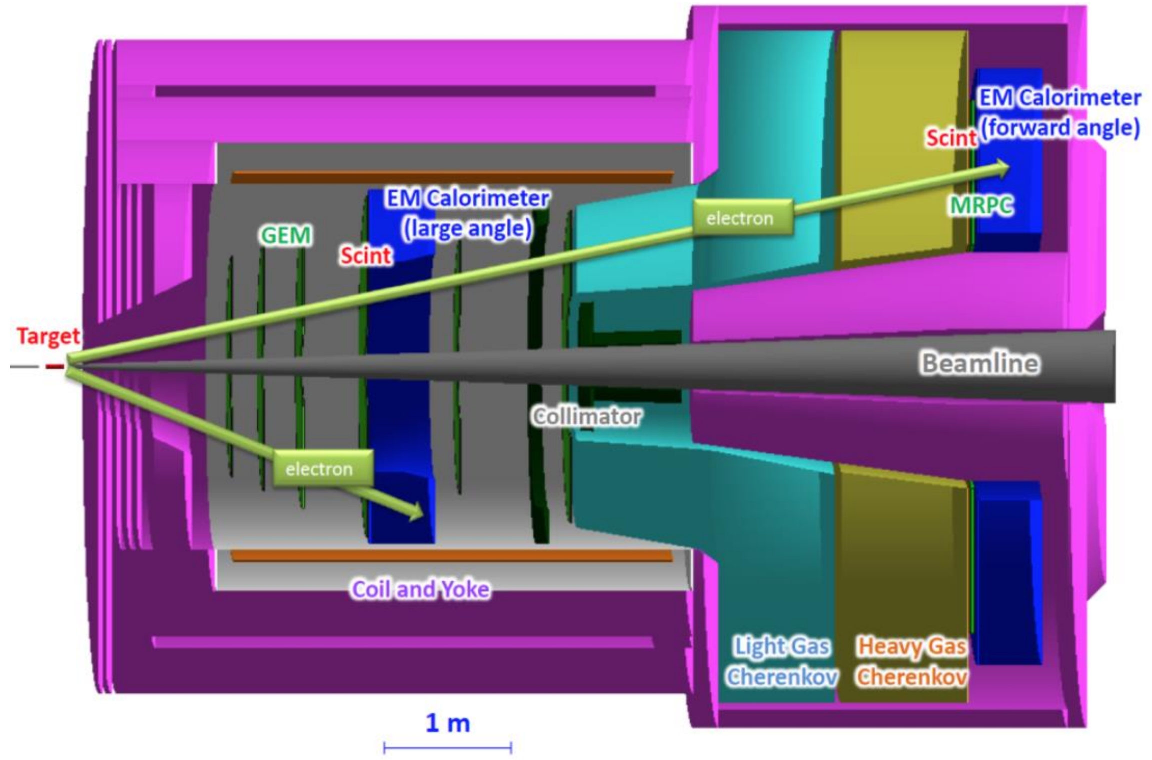
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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

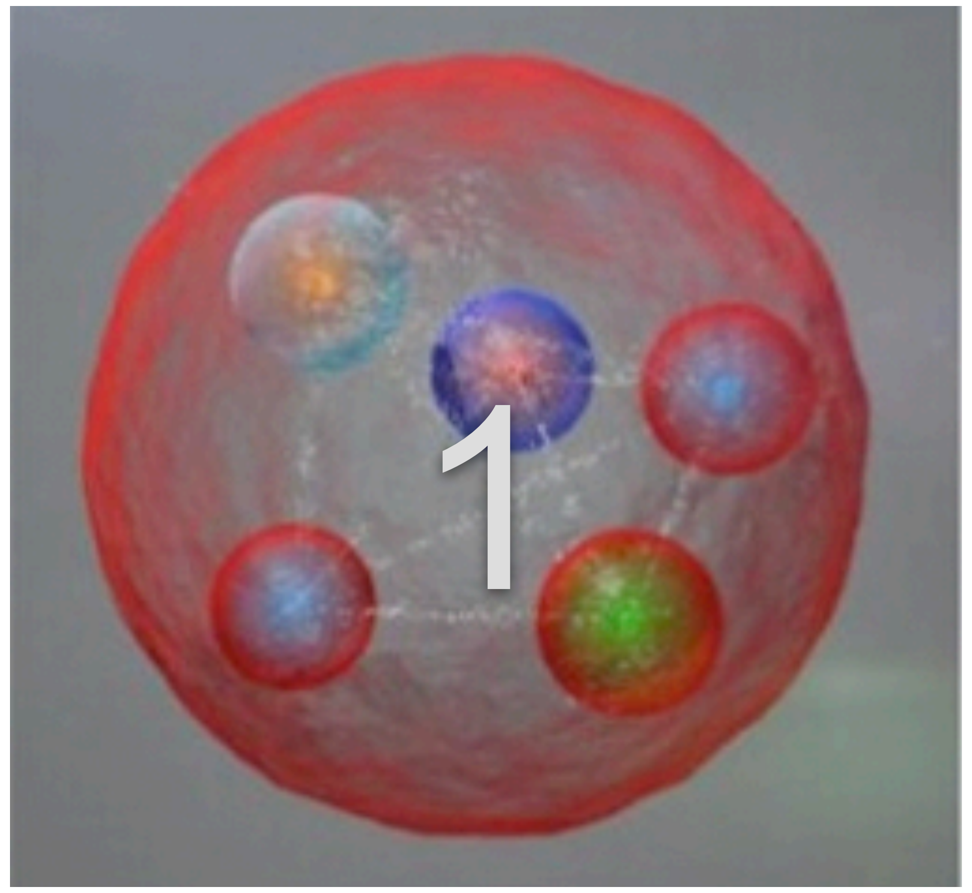


Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

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

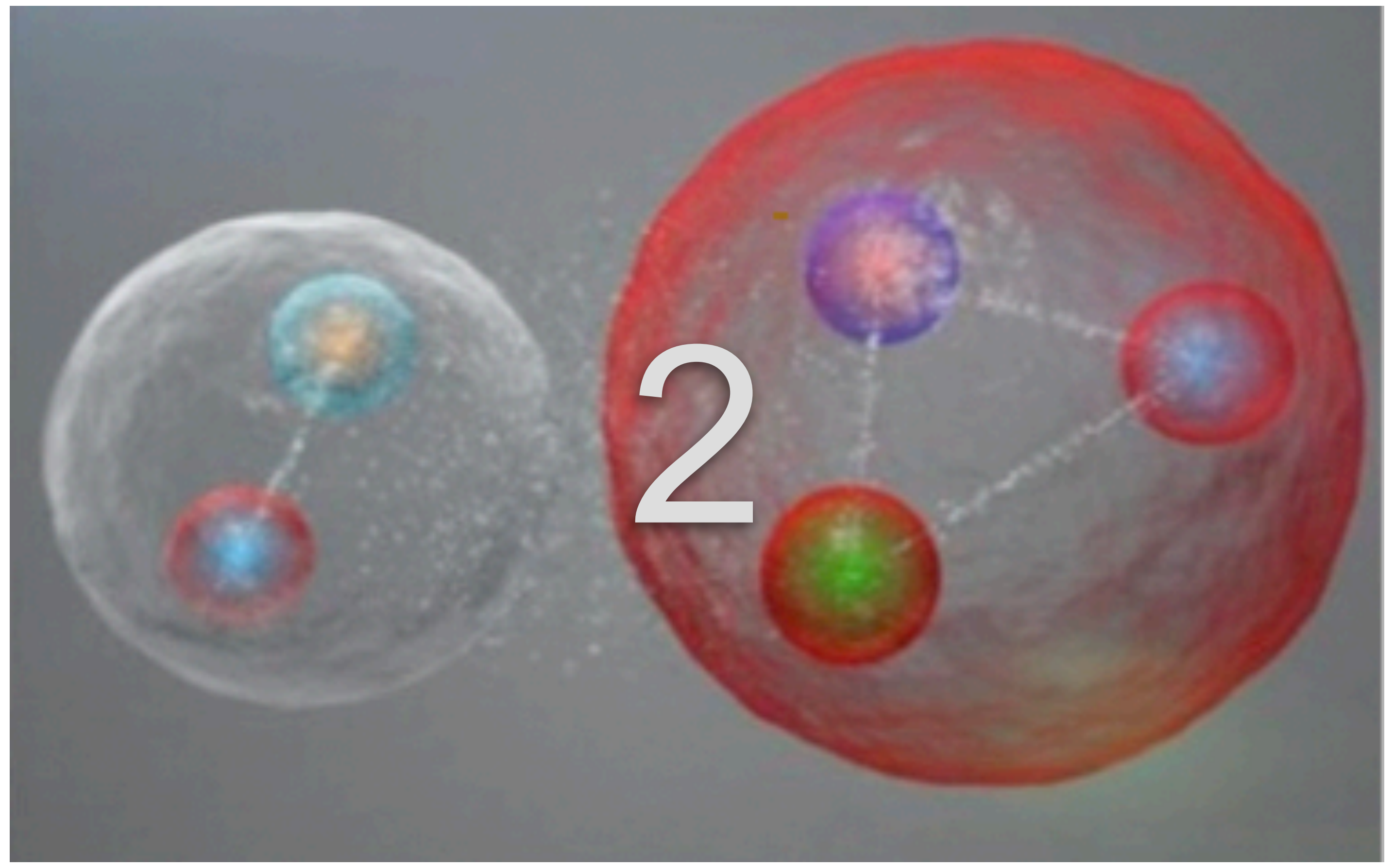
PENTAQUARKS IN PHOTOPRODUCTION?

Looking for pentaquarks at Jefferson Lab



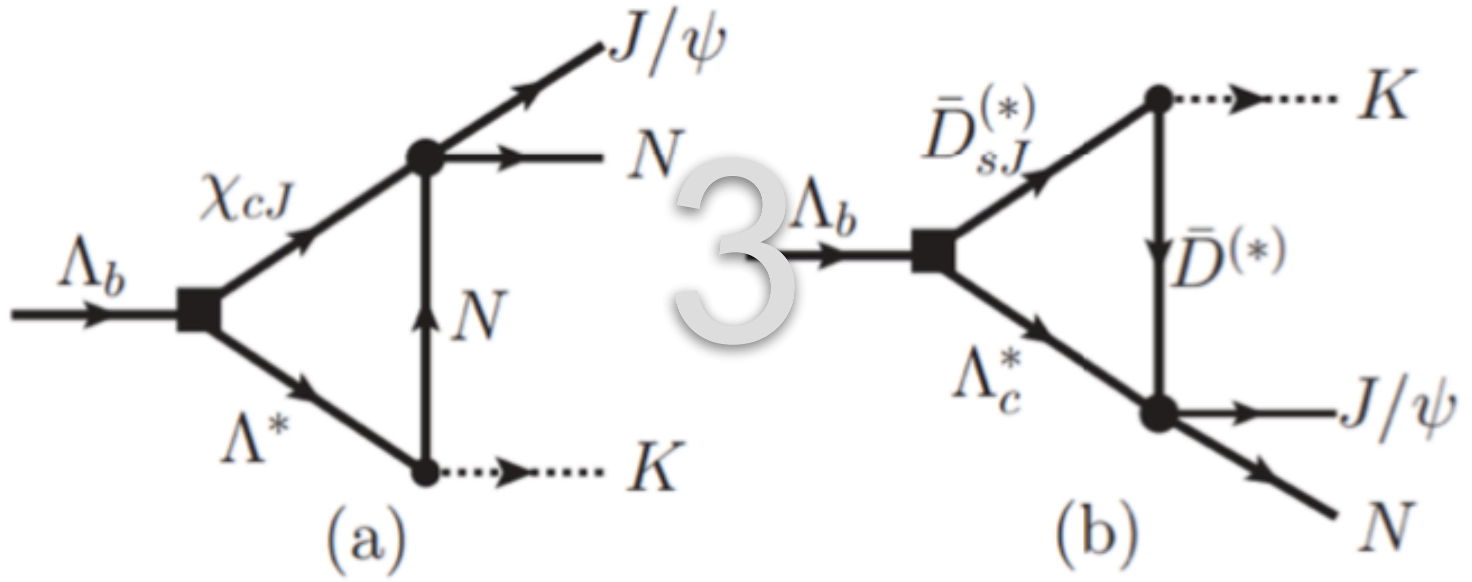
What is the nature of the LHCb pentaquarks?

1. **“True” pentaquark state:** tightly bound 5-quark state
2. **“Molecular”** meson-baryon bound state
3. **Kinematic enhancement** through, eg., anomalous triangle singularities (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



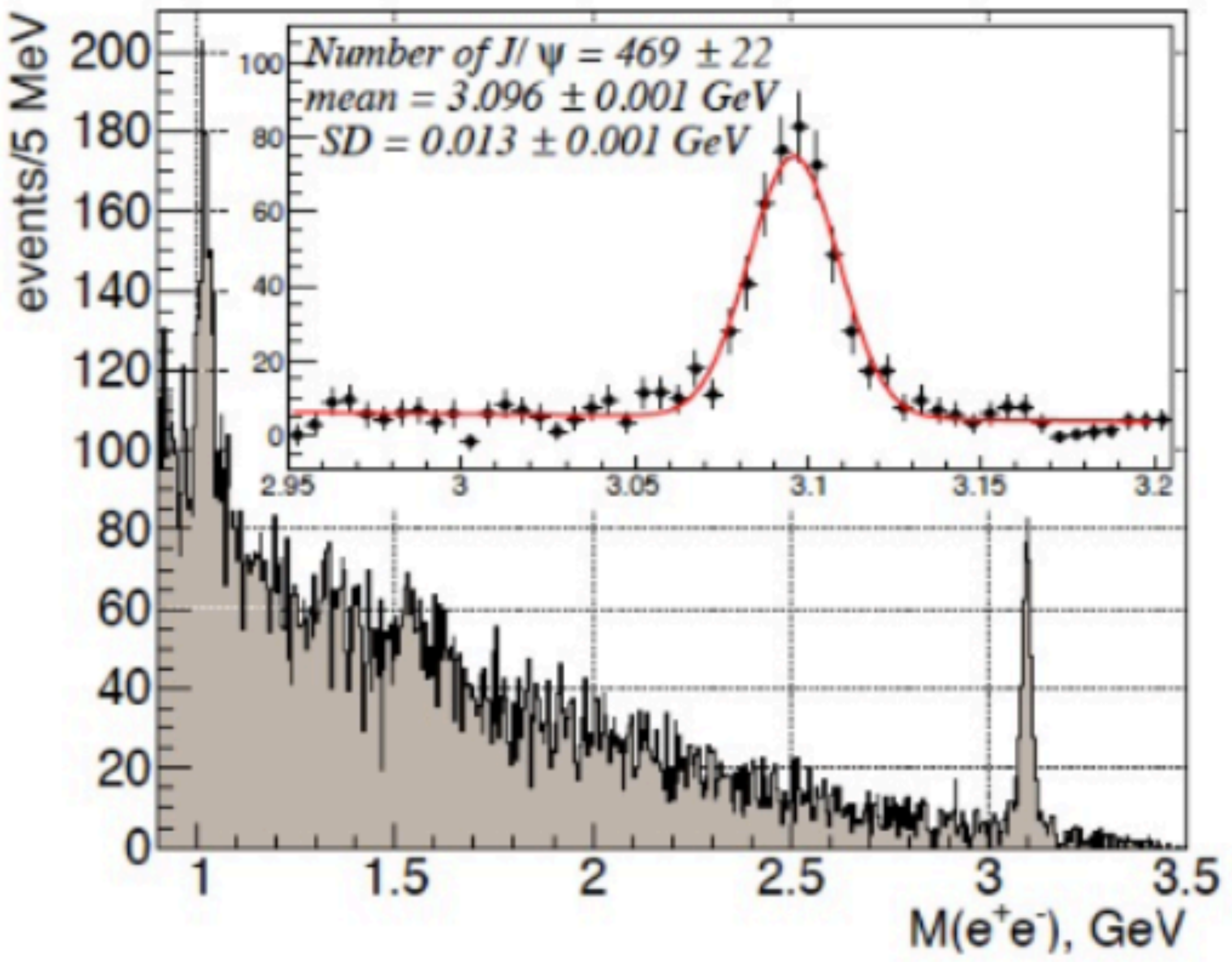
Jefferson Lab the perfect place to search for P_c in photoproduction

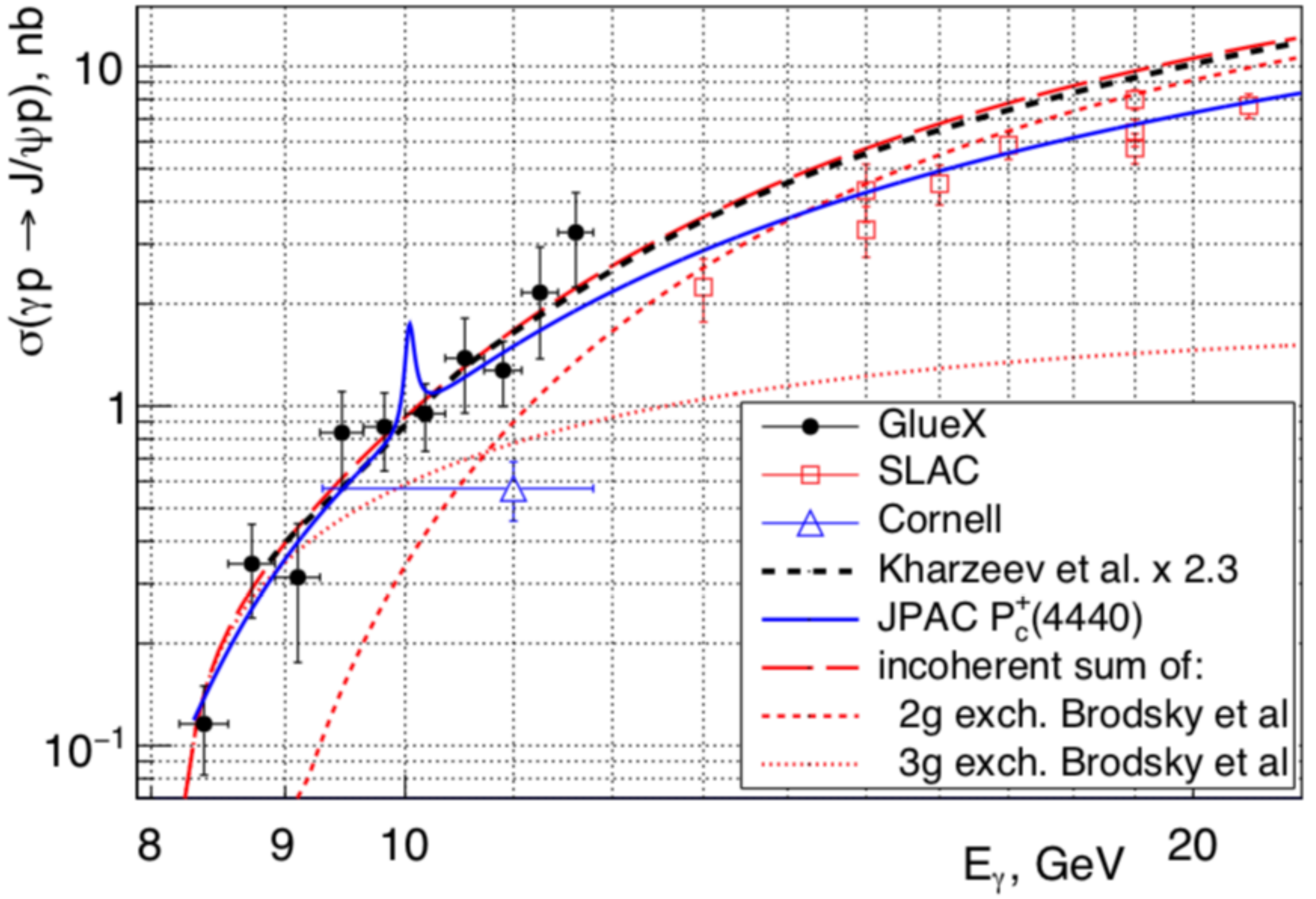
J/Ψ NEAR THRESHOLD IN HALL D

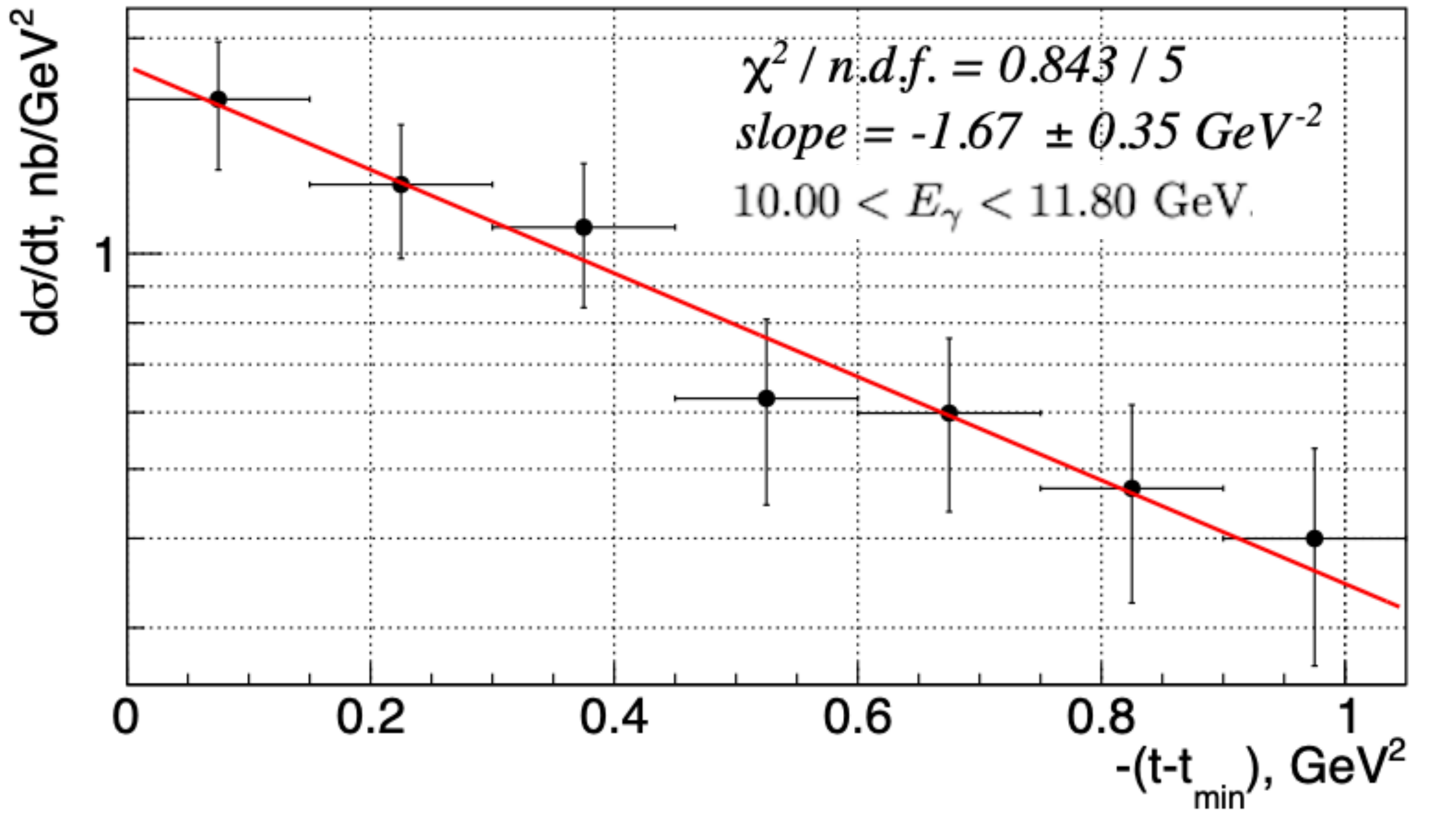
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Single 1D t-profile spurred on many new theoretical calculations
- Did not see evidence for hidden-charm pentaquarks

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



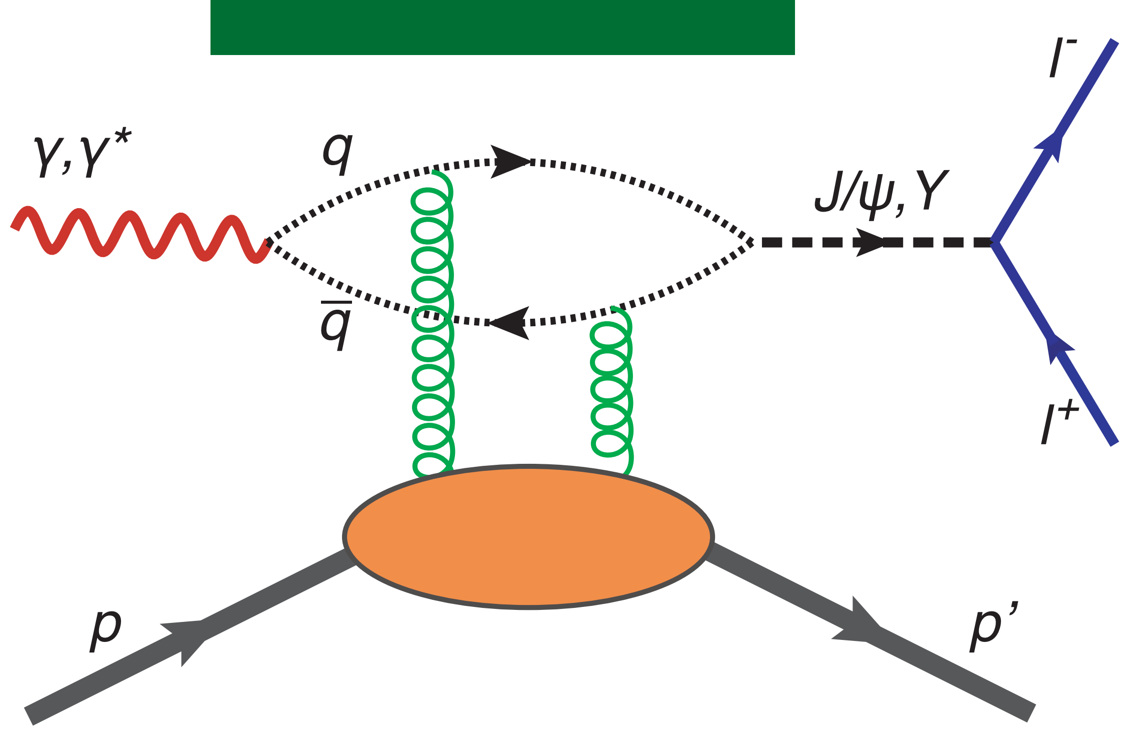




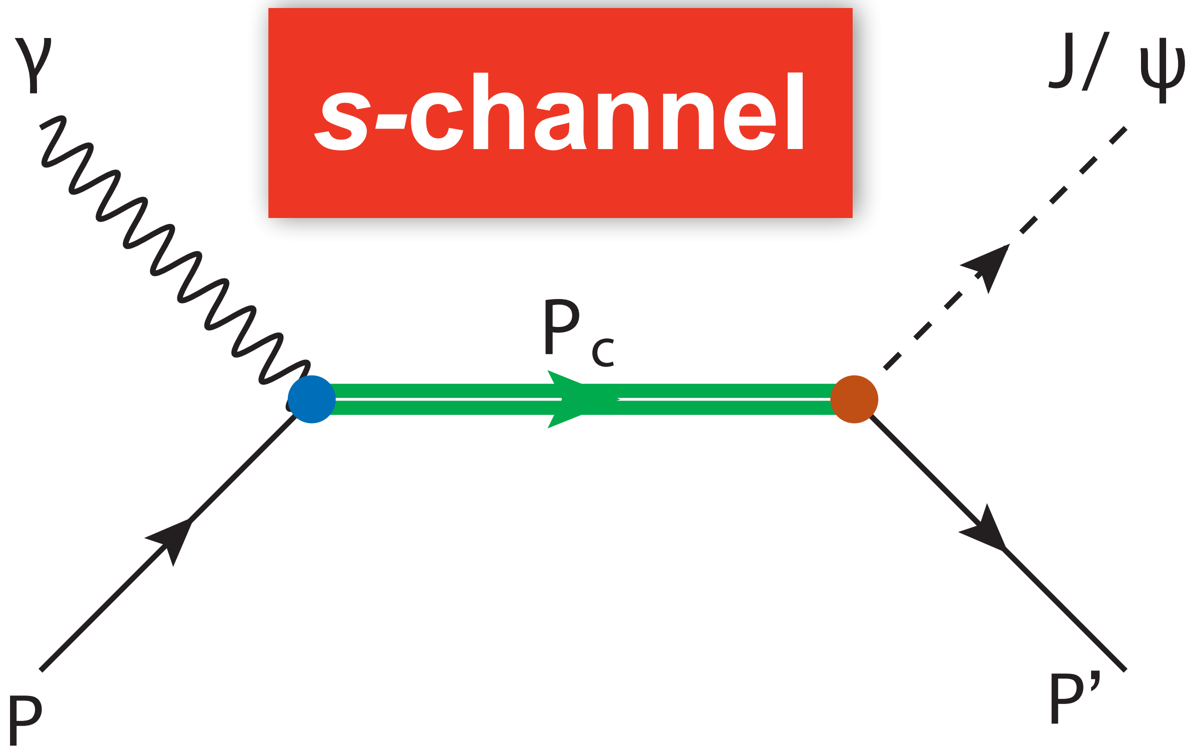
MAXIMIZING THE SENSITIVITY

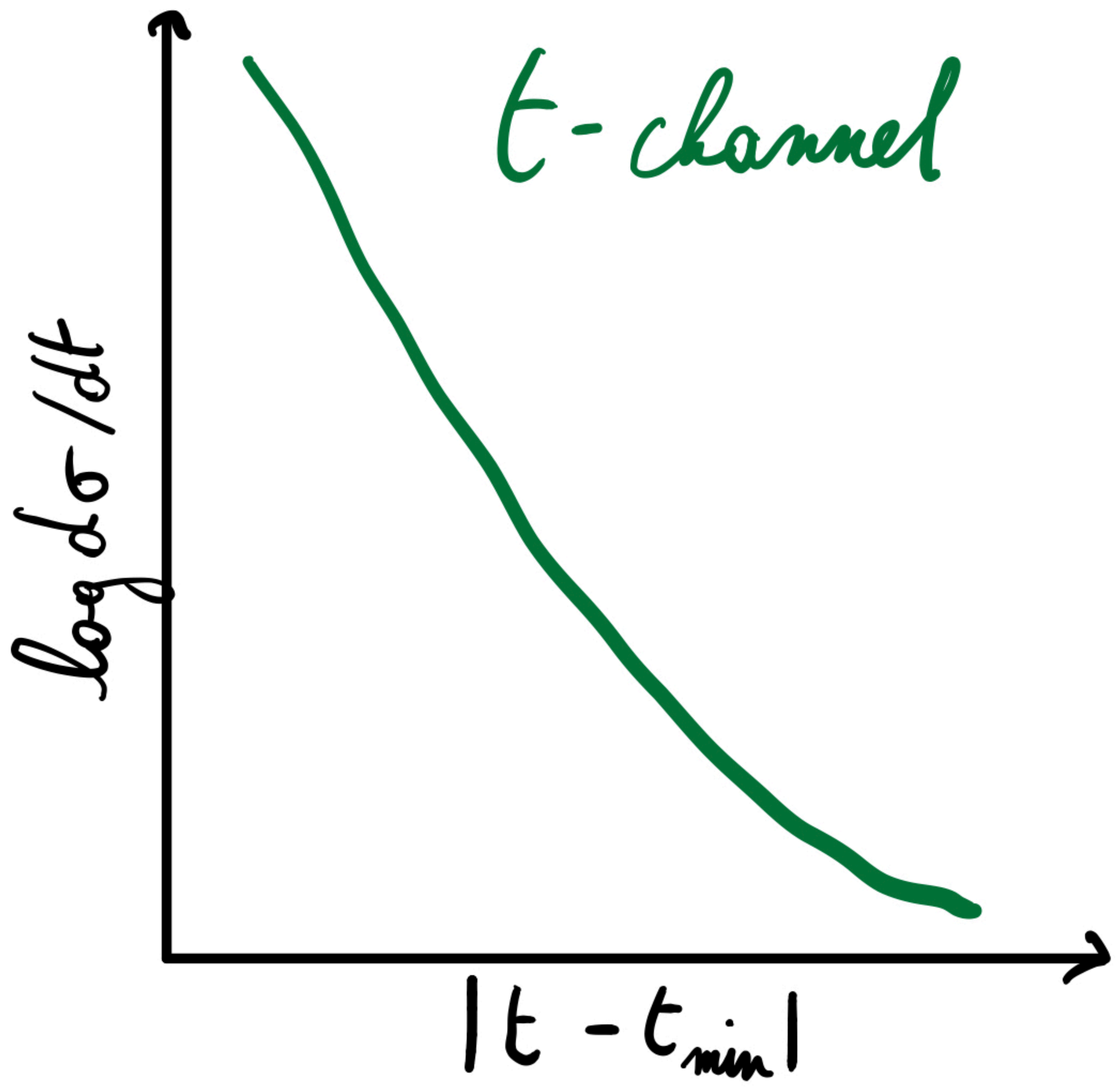
Maximum sensitivity for s-channel resonance at high *t*

t-channel

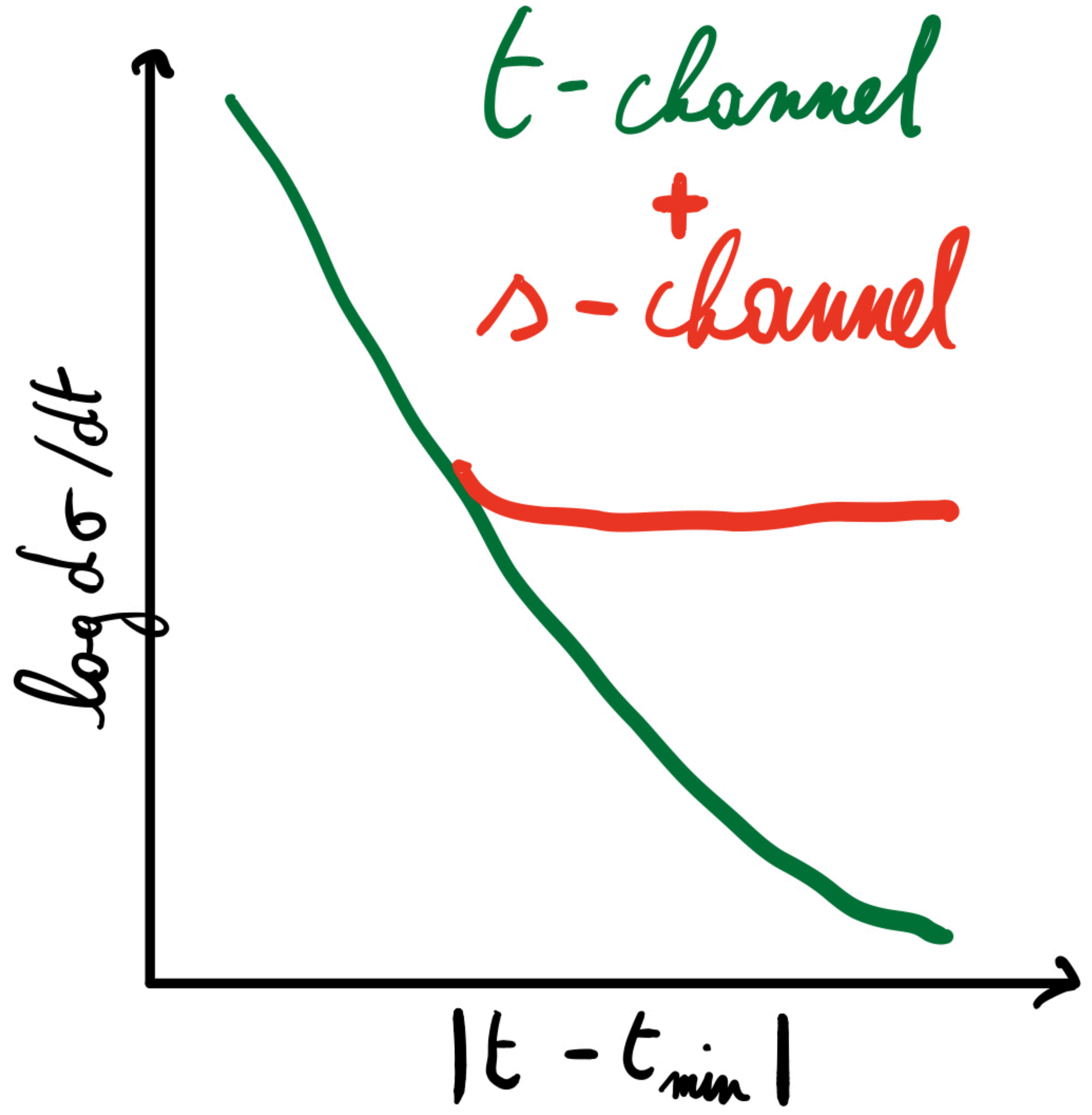


s-channel





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



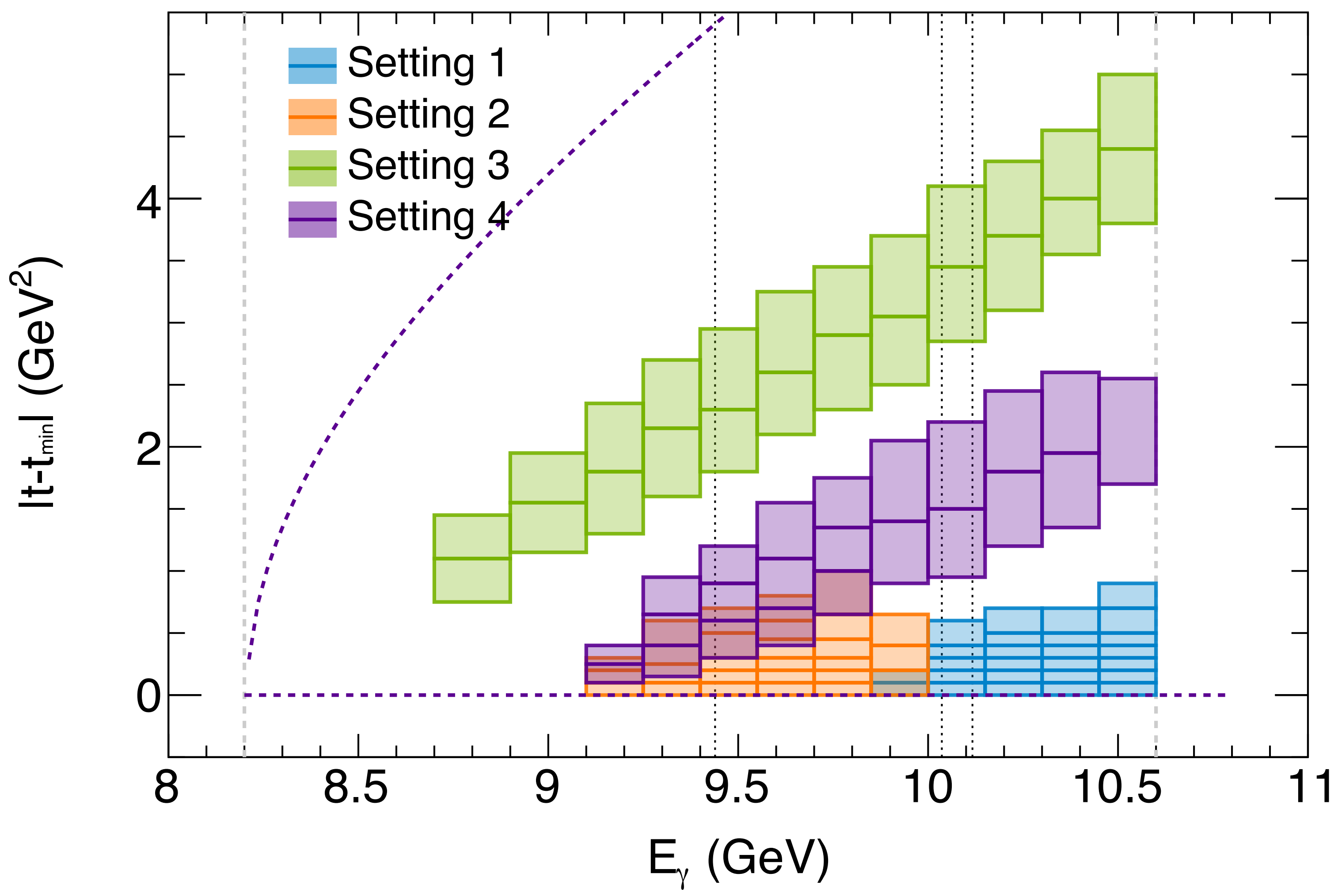
s-channel production more isotropic (flatter *t*-dependence)

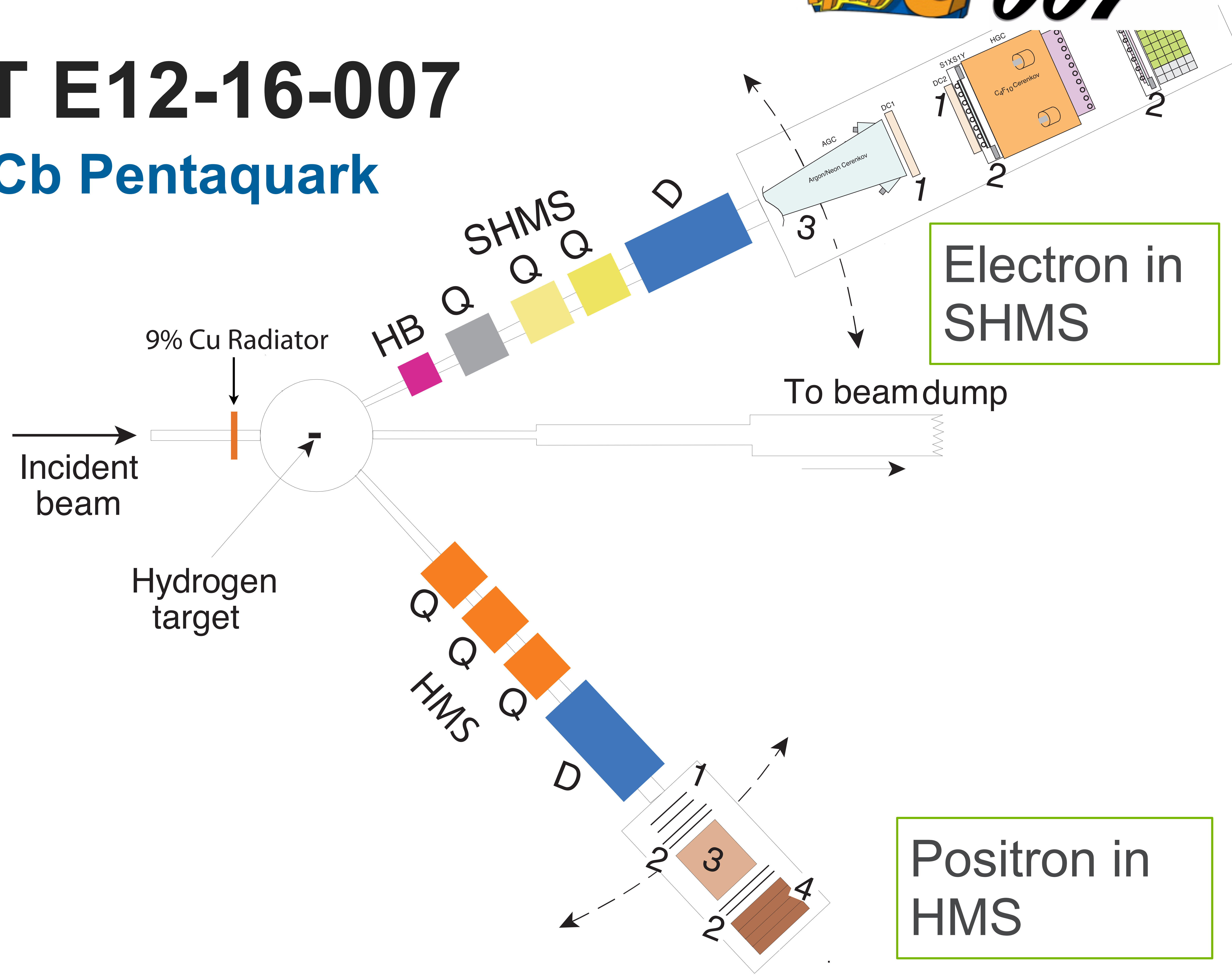
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

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

THE J/Ψ-007 COLLABORATION


B. Duran


Z.-E. Meziani


S. Joosten


M. Jones


S. Prasad


C. Peng


W. Armstrong


M. Paolone

…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]**

4% scale uncertainty on cross section

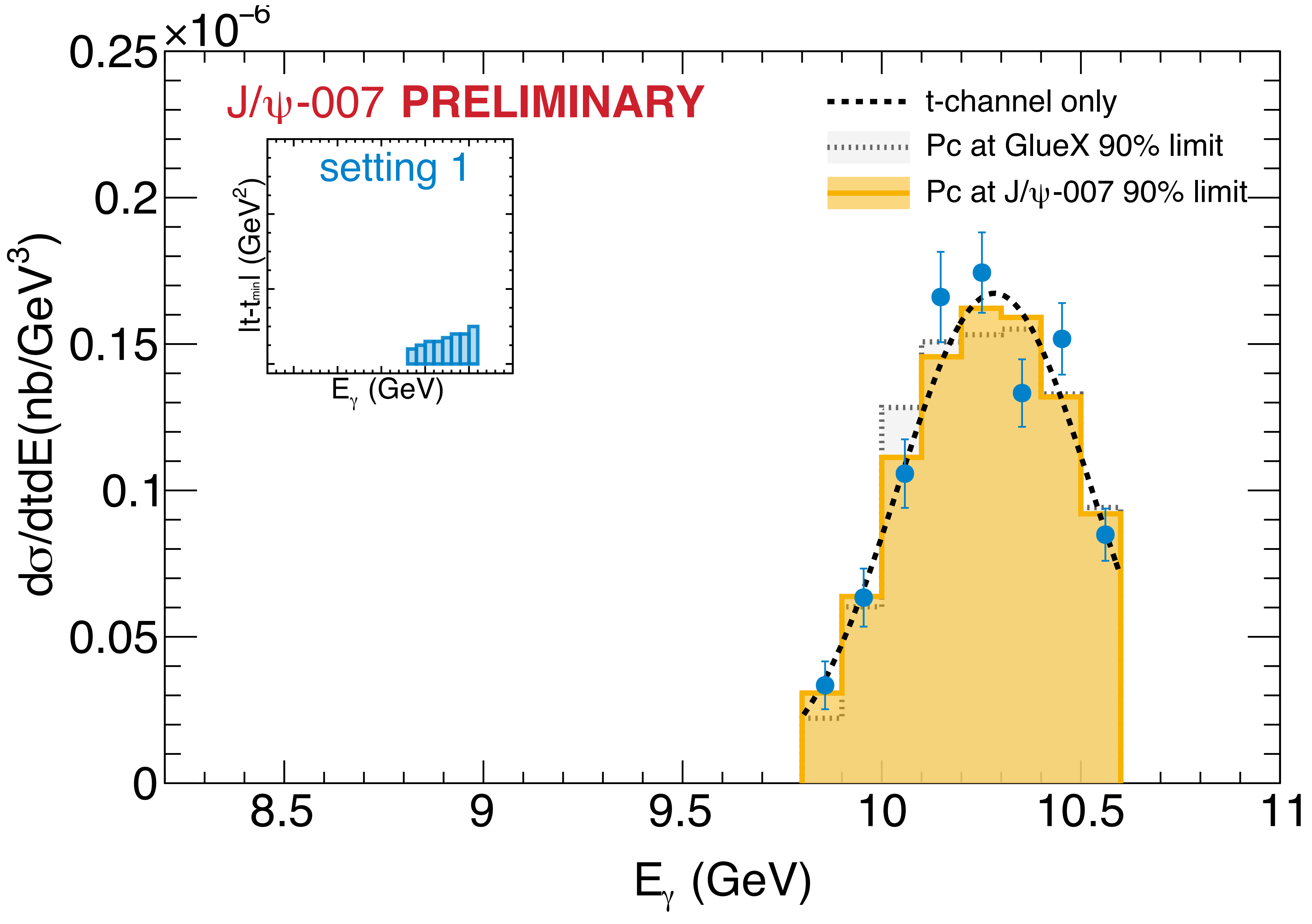
SCANNING THE SPECTRUM

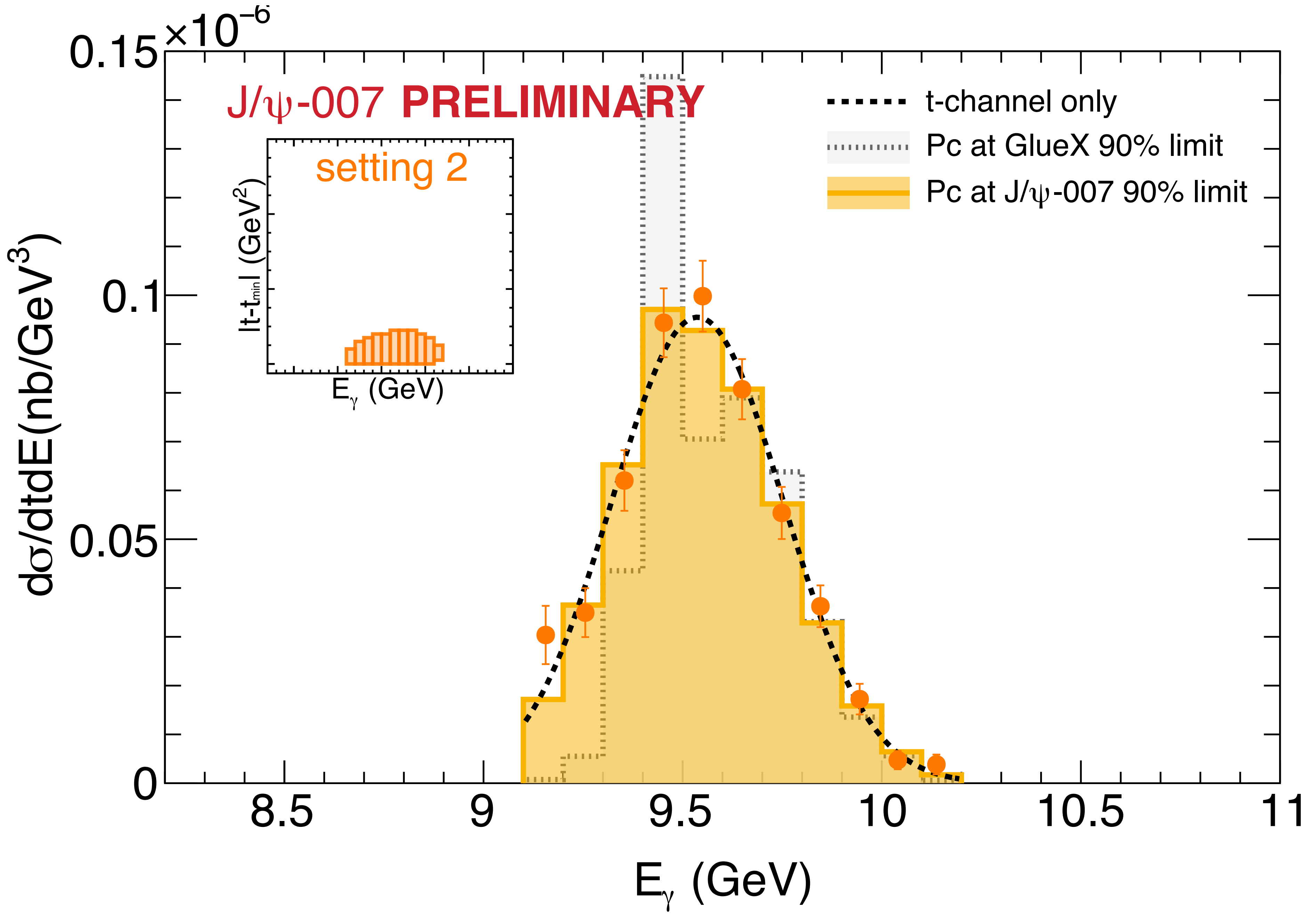
Fit 1: bare Gaussian shape describes the cross section well

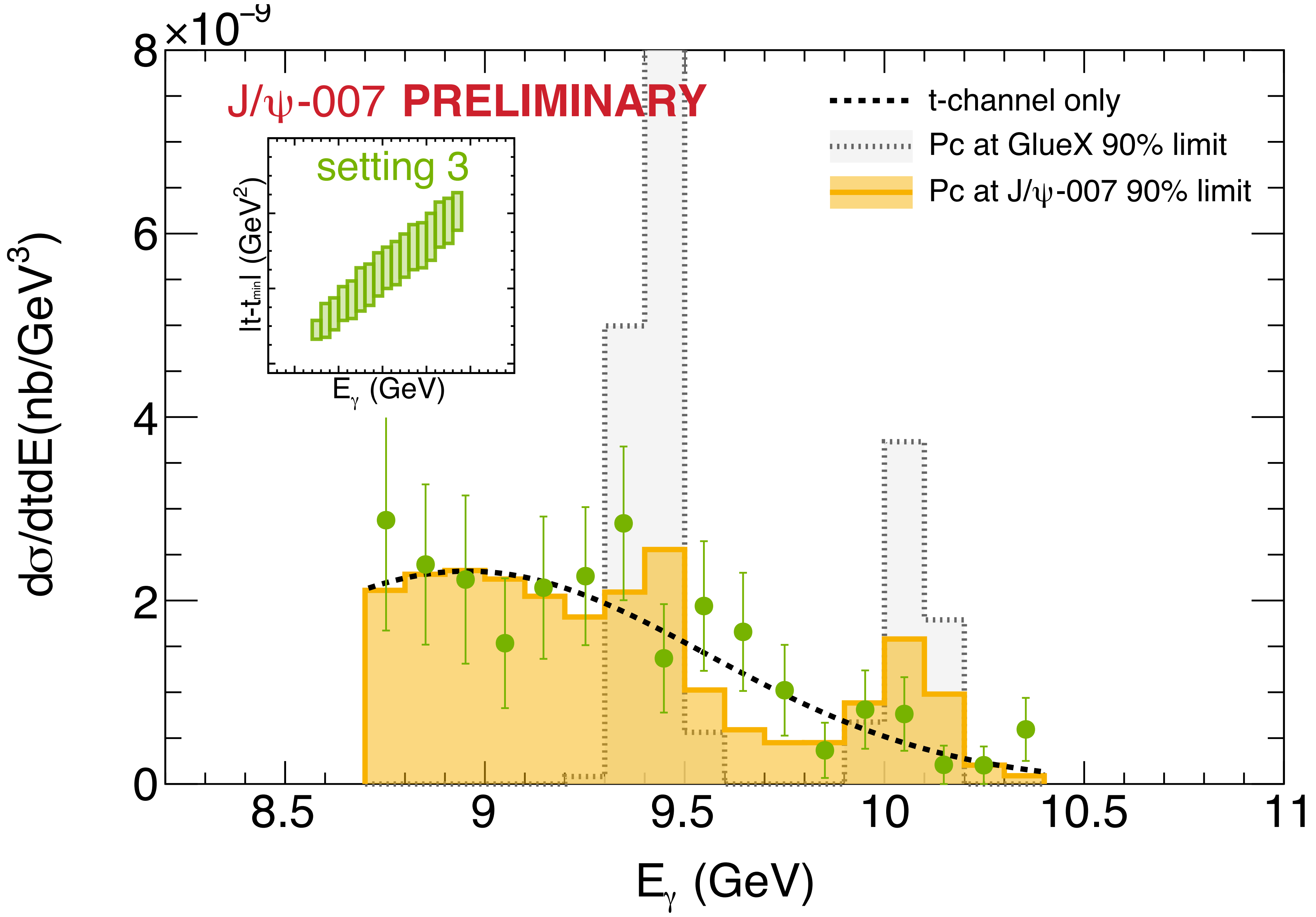
Fit 2: Signal + background at 2019 GlueX upper limit (90% confidence interval). The resonances lead to major tension with the data at high-t.

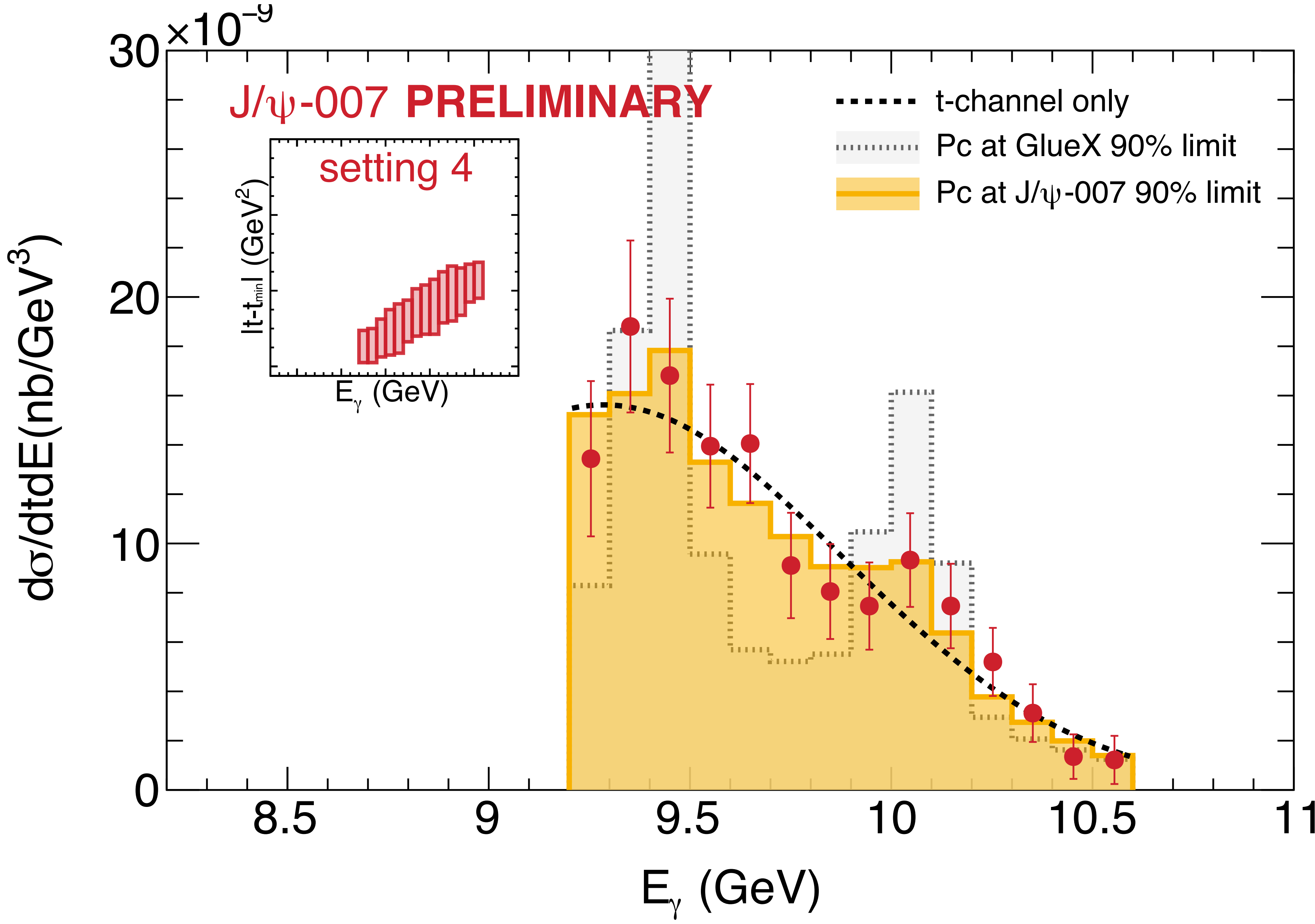
Fit 3: Same as 2, but with Pc at upper limit (90% confidence interval) from the preliminary J/ψ-007 results themselves

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

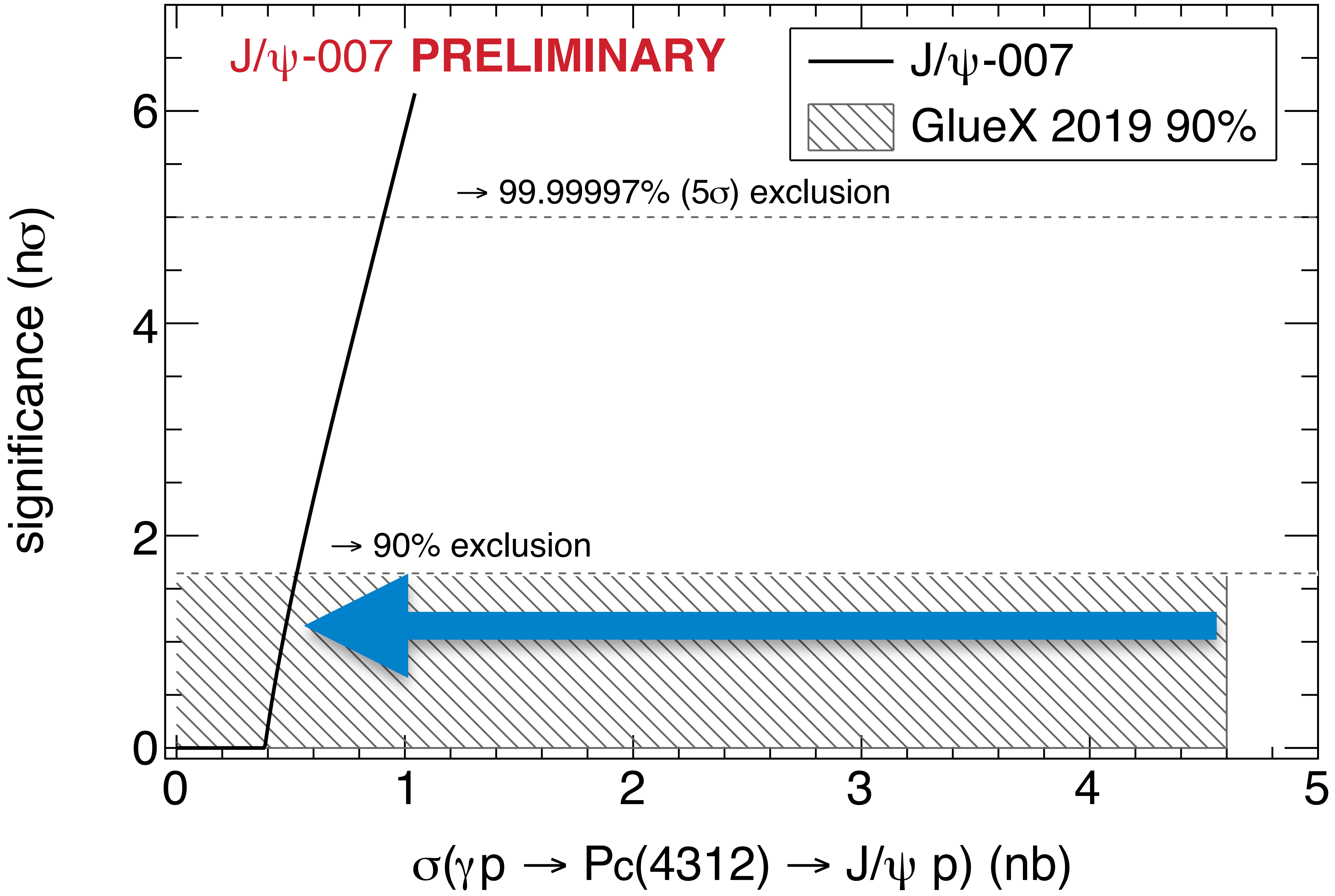
Cross-section at the resonance peak for model-independent upper limits

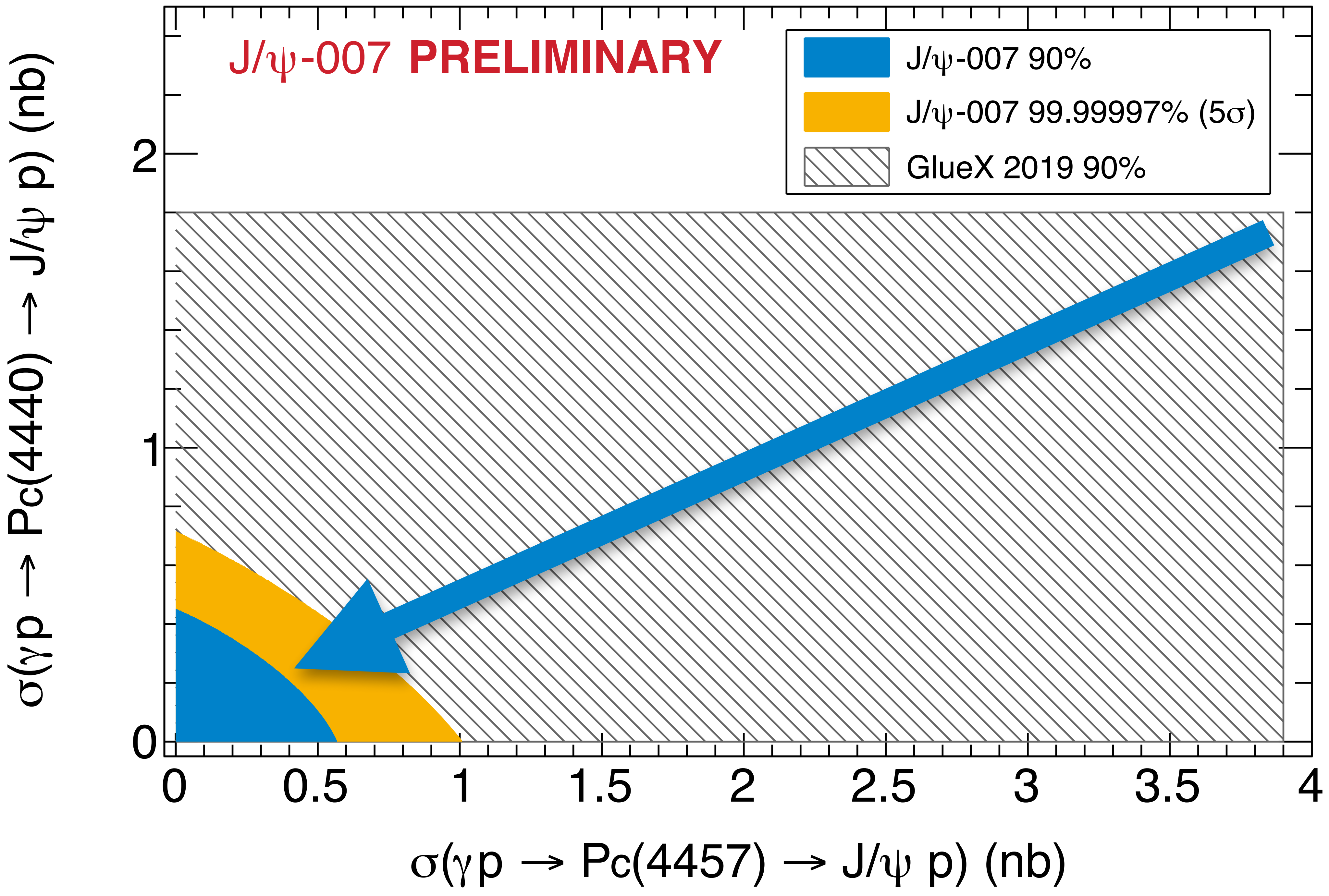
Upper limit for P_c cross section almost order of magnitude below GlueX limit.

Results seem 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**

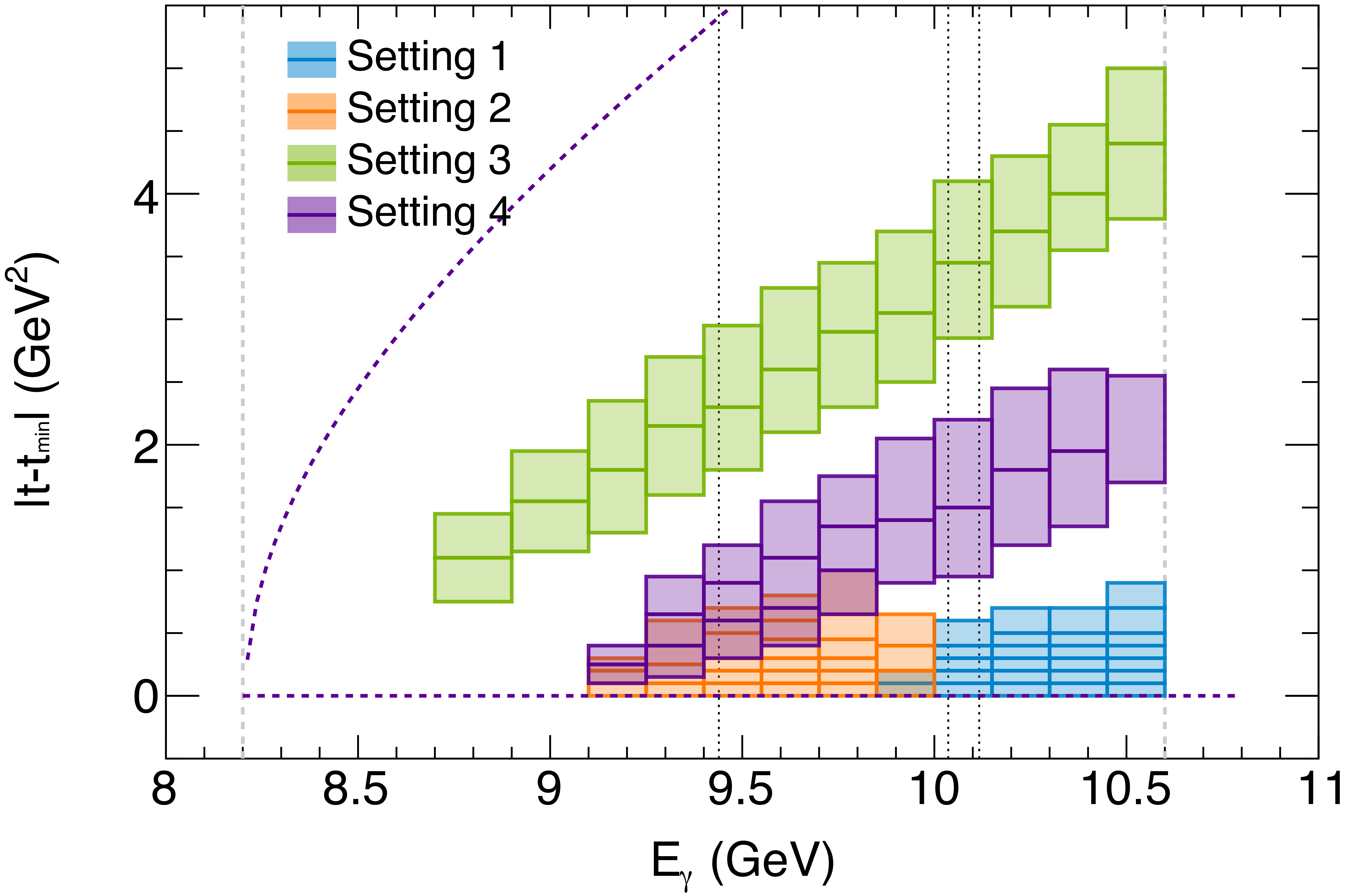




DIFFERENTIAL CROSS SECTION NEAR THRESHOLD

Unprecendented access to large-t region

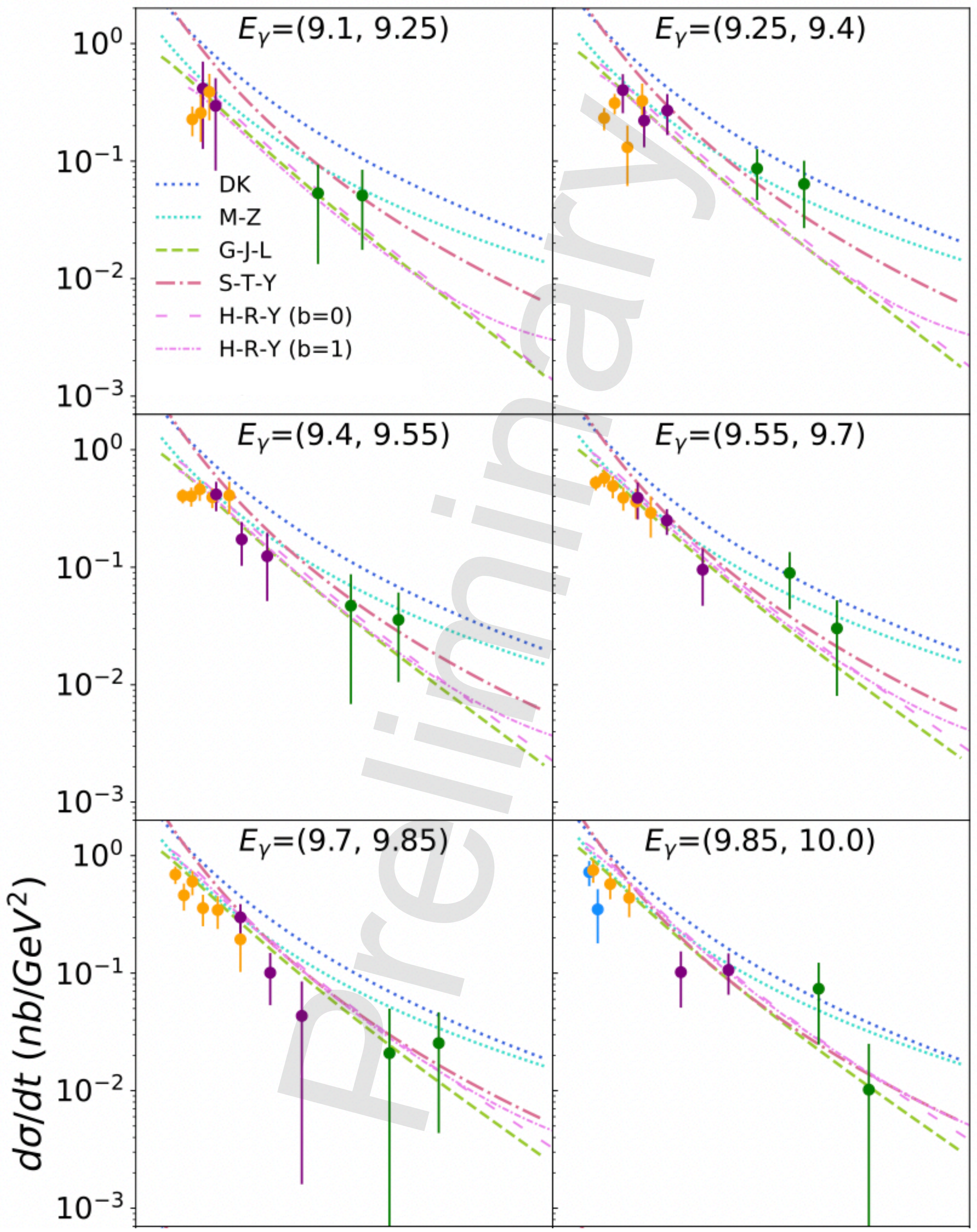
- Truly 2D measurement
- ~2000 counts in electron channel
- Additional 2000 counts in muon channel still under analysis

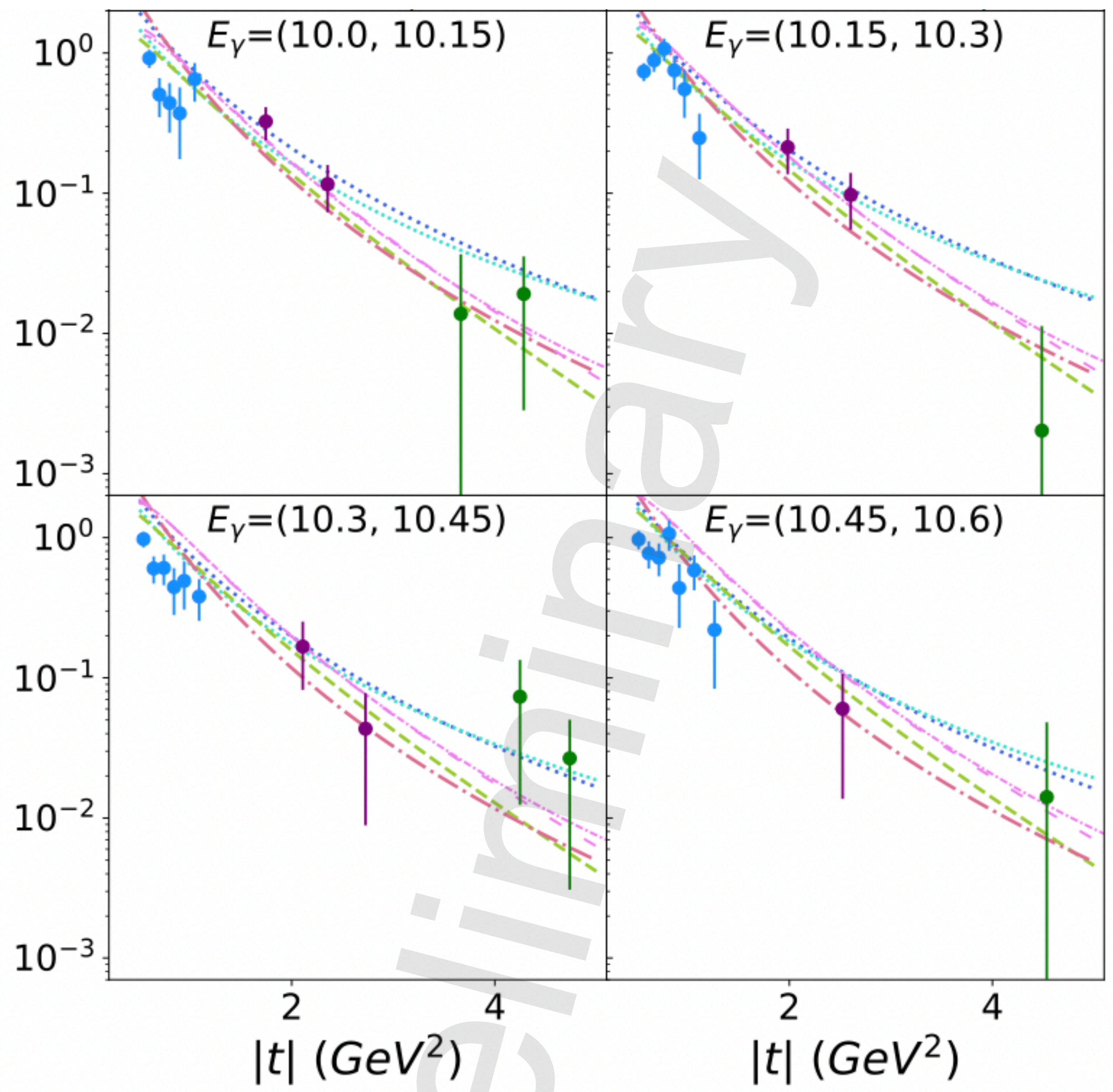


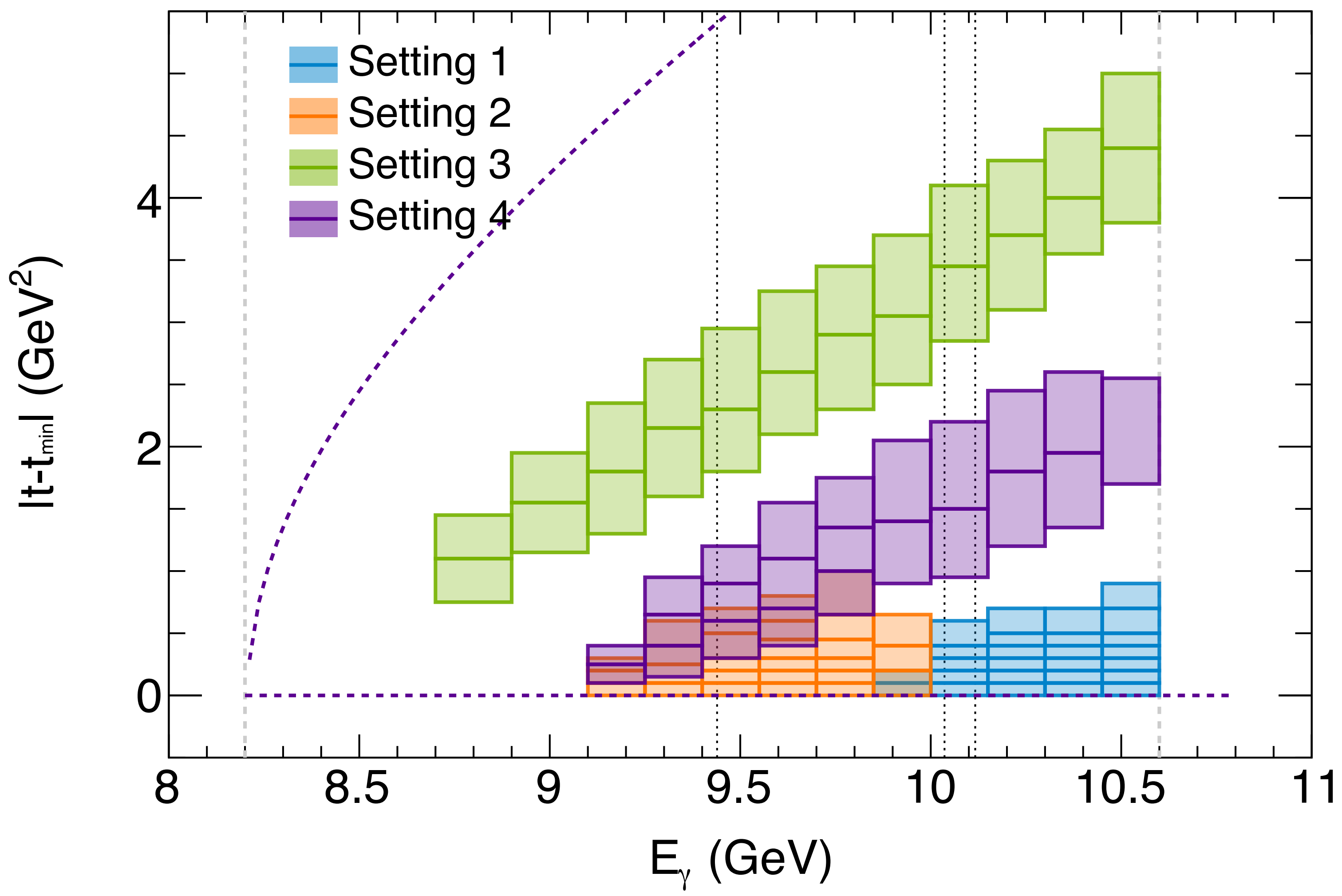
Preprint: https://arxiv.org/abs/2207.05212

Results currently under peer-review

PRELIMINARY 2D J/Ψ CROSS SECTION RESULTS







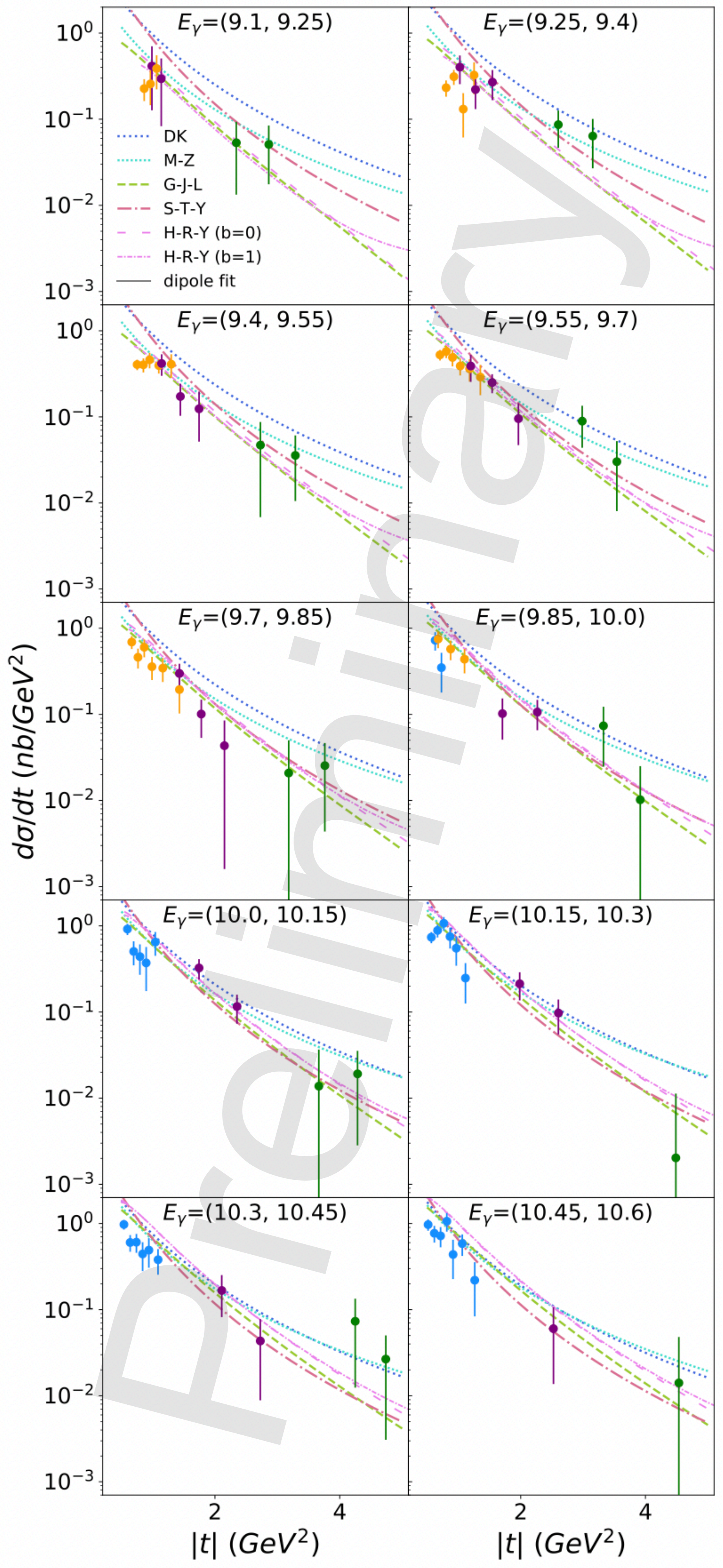
DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

Preprint: https://arxiv.org/abs/2207.05212

EXTRACTING GFFS FROM THE 2D PROFILES

First ever extraction of gluonic GFFs from purely experimental data!

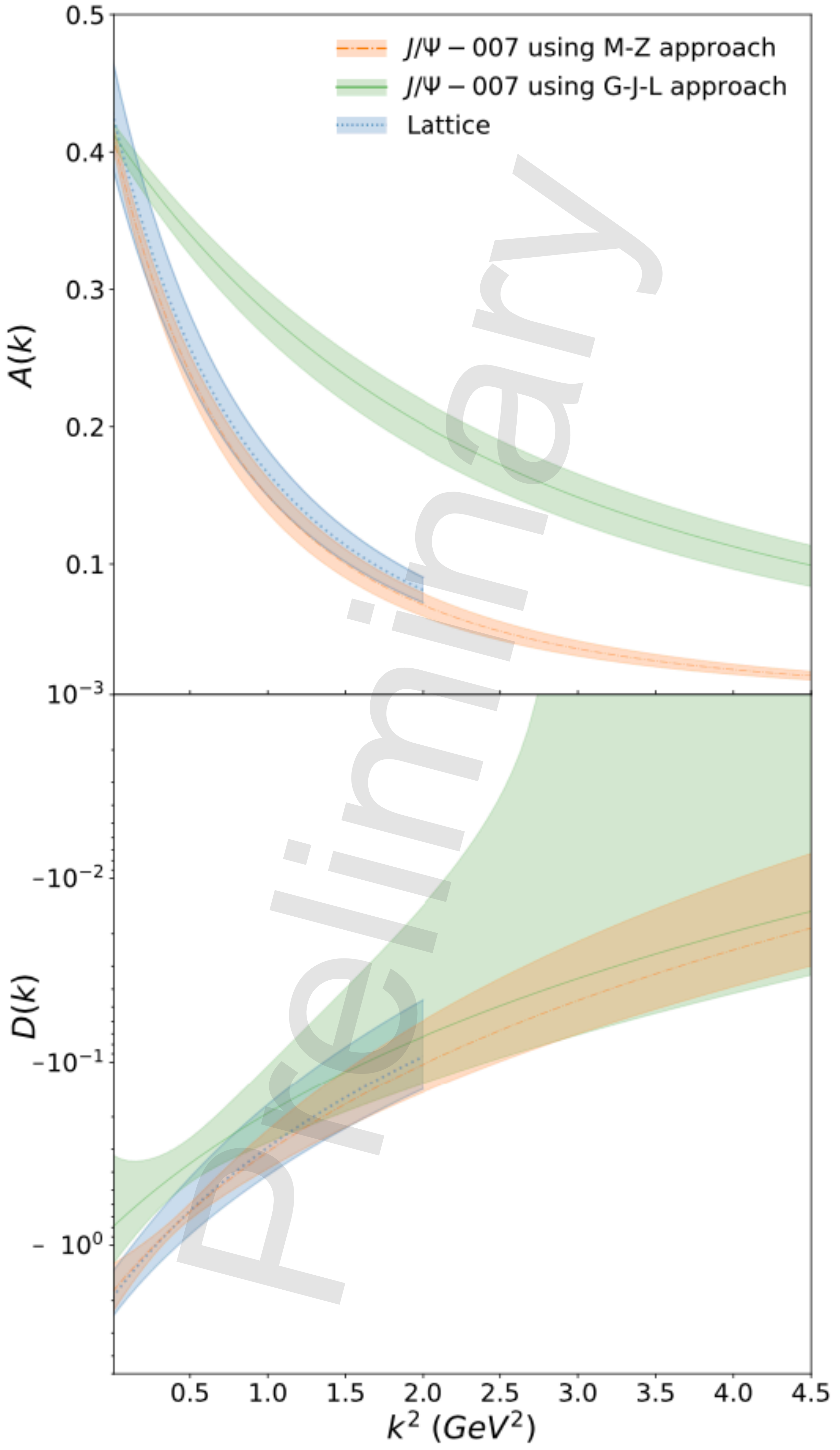


- **Model dependent extractions** using the available approaches in the literature
  - Holographic QCD approach: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
  - GPD approach: Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
  - In both cases assume $B_g(t)$ contributes little (supported 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.

Preprint: https://arxiv.org/abs/2207.05212

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!
- GPD approach gives very different values, may indicate (expected) issues with the factorization assumption

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).

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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).

WHAT ABOUT THE MASS AND SCALAR RADII?

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

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

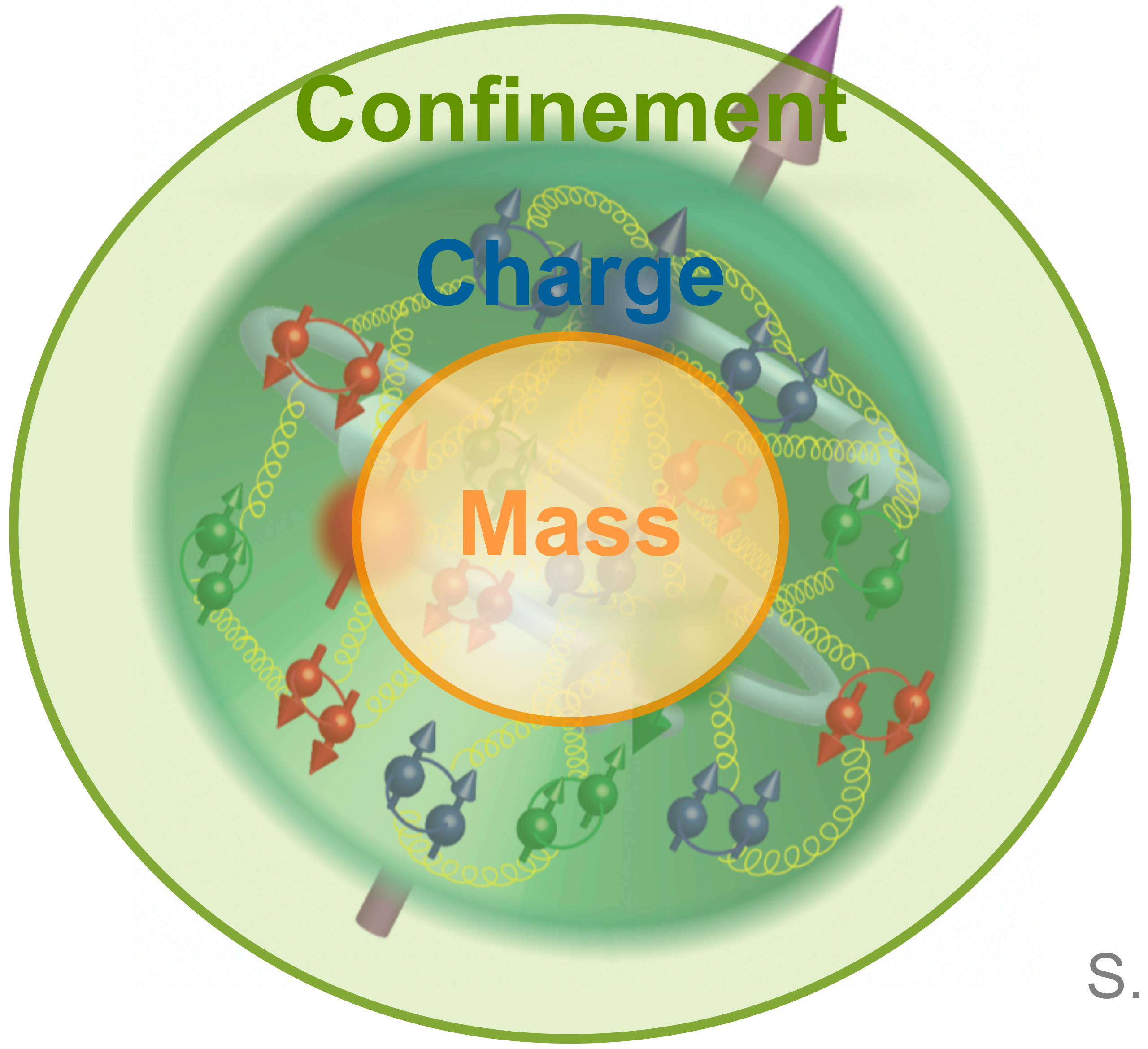
$$\left\langle r_m^2 \right\rangle_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\bigg|_{t=0} - \frac{6}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

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

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

Both the holographic QCD fit to our data, and the latest Lattice calculations find a gluonic confining scalar potential radius of about 1 fermi

A picture of three zones



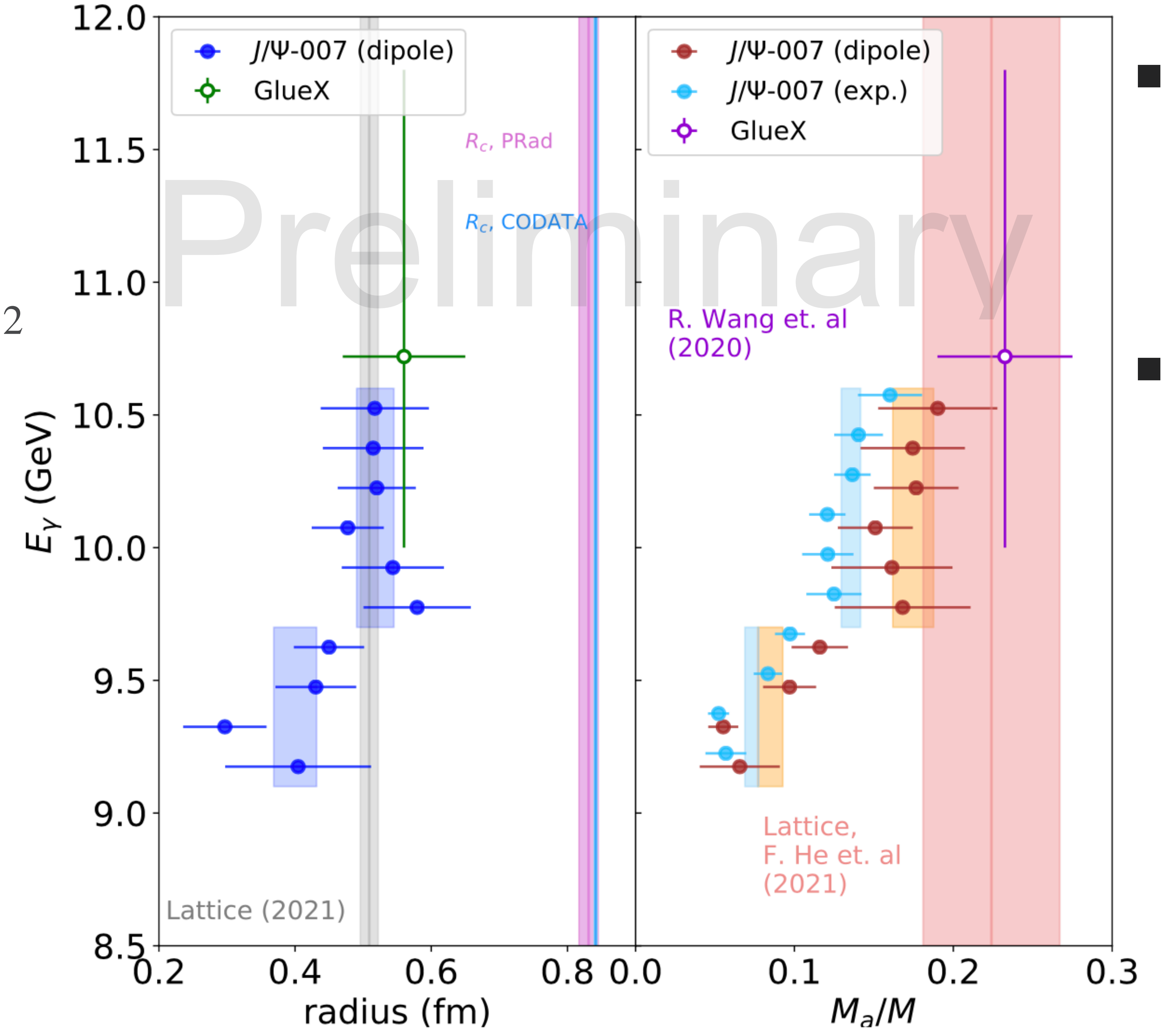
VARIOUS MODEL-DEPENDENT EXTRACTIONS

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

D-K formalism for radius

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

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



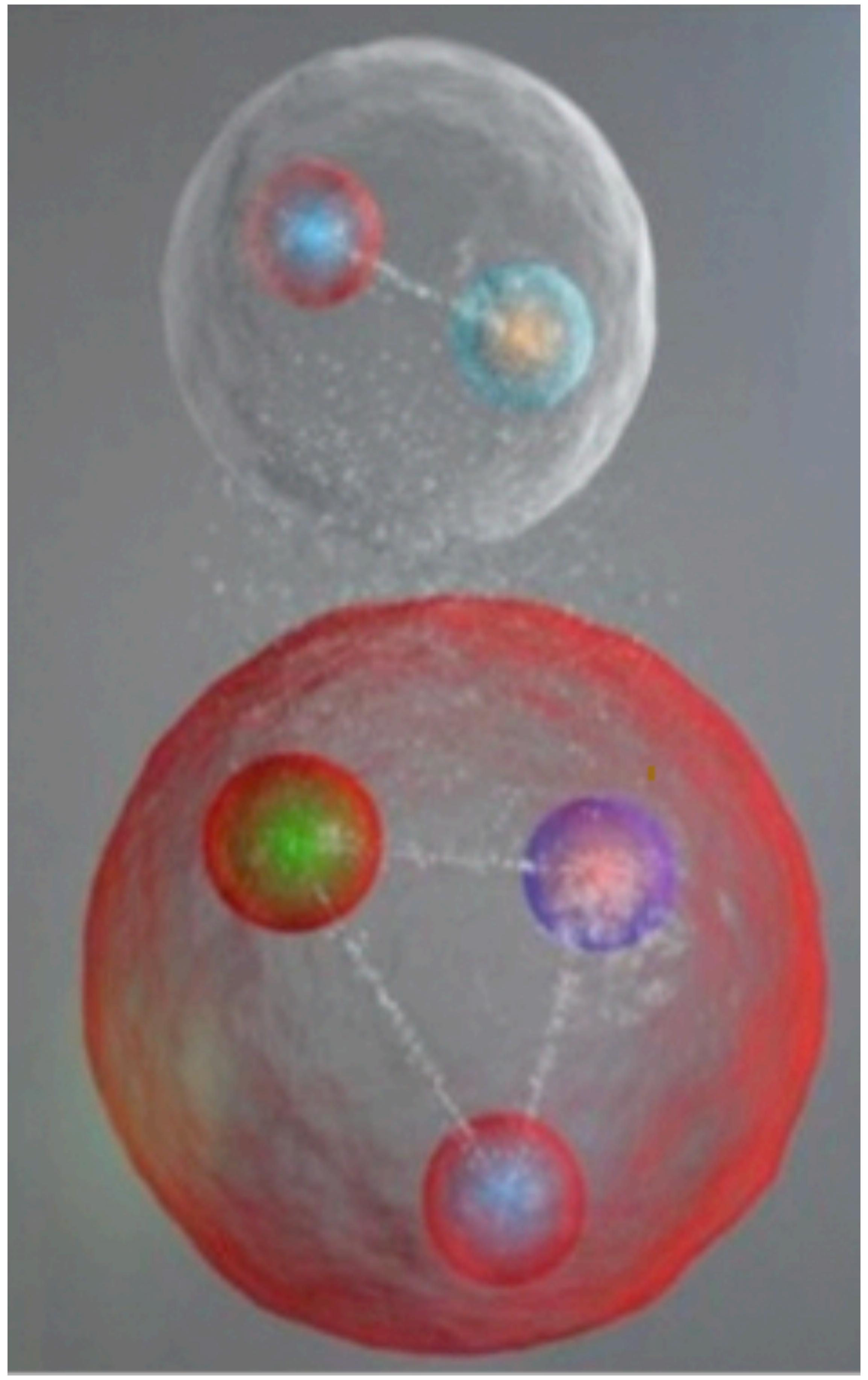
- Find flat region at higher energies, which seems to break below 9.7 GeV
- Good agreement with lattice in flat region ($9.7\,\mathrm{GeV} < E_\gamma < 10.6\,\mathrm{GeV}$)
  - $\sqrt{\langle r_m^2\rangle} = 0.52 \pm 0.03\ \mathrm{fm}$
  - $M_a/M = 0.175 \pm 0.013$

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)

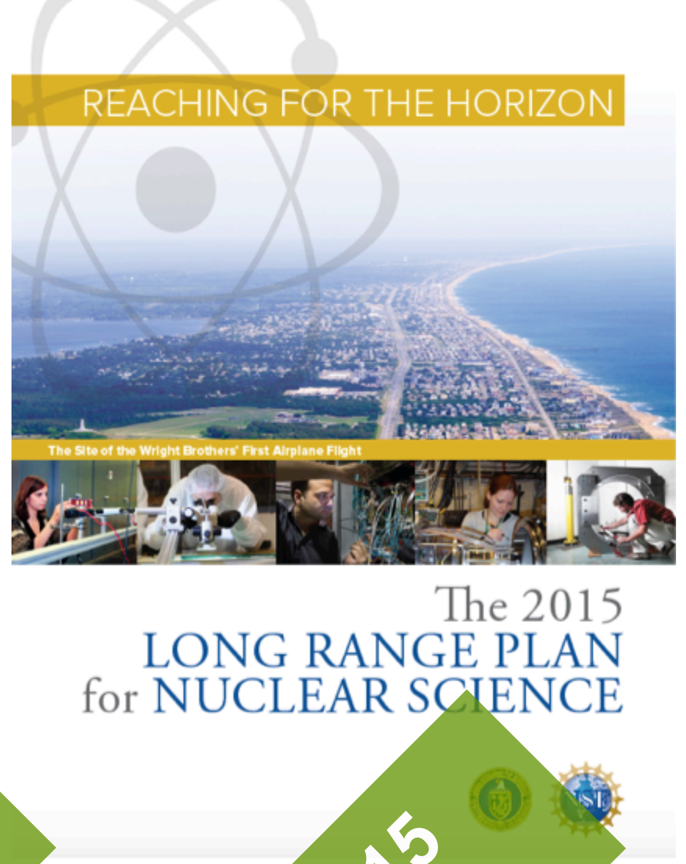
HALL C J/Ψ-007 RESULTS IN A NUTSHELL

- 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?



The proton mass: An important topic in contemporary hadronic physics!

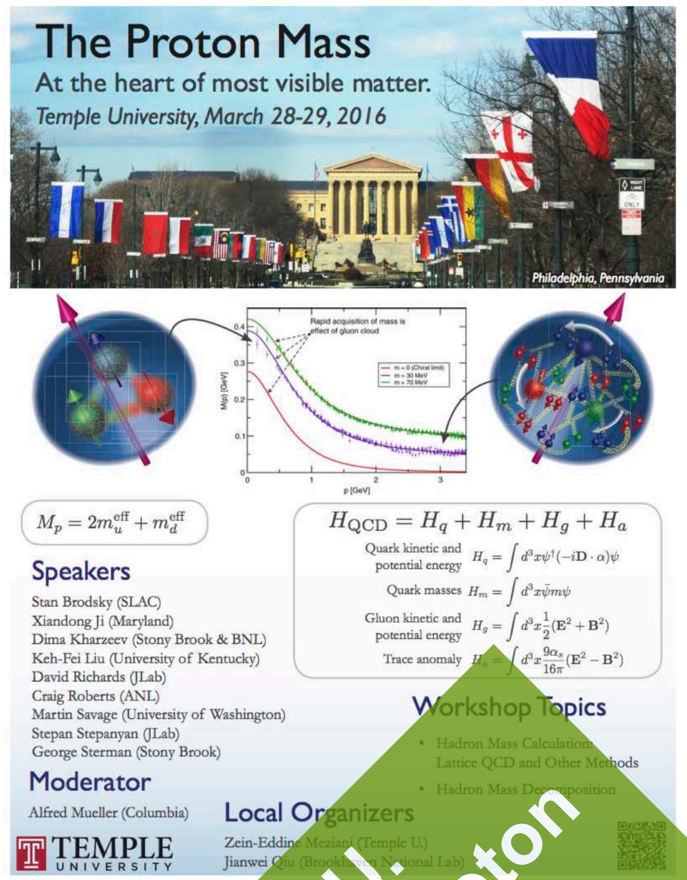
RAPIDLY EVOLVING



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



The Proton Mass

At the heart of most visible matter.

Temple University, March 28-29, 2016

Philadelphia, Pennsylvania

$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$

$H_{\text{QCD}} = H_q + H_m + H_g + H_a$

Quark kinetic and potential energy $H_q = \int d^3x \psi^\dagger(-i\mathbf{D}\cdot\alpha)\psi$

Quark masses $H_m = \int d^3x \bar{\psi} m \psi$

Gluon kinetic and potential energy $H_g = \int d^3x \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2)$

Trace anomaly $H_a = \int d^3x \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$

Speakers

Stan Brodsky (SLAC)
Xiandong Ji (Maryland)
Dima Kharzeev (Stony Brook & BNL)
Keh-Fei Liu (University of Kentucky)
David Richards (JLab)
Craig Roberts (ANL)
Martin Savage (University of Washington)
Stepan Stepanyan (JLab)
George Sterman (Stony Brook)

Workshop Topics

- Hadron Mass Calculation: Lattice QCD and Other Methods
- Hadron Mass Decomposition

Moderator

Alfred Mueller (Columbia)

Local Organizers

Zein-Eddine Meziani (Temple U.)
Jianwei Qiu (Brookhaven National Lab)

TEMPLE UNIVERSITY

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC

TEMPLE UNIVERSITY

INFN Istituto Nazionale di Fisica Nucleare

Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

The Proton Mass: At the Heart of Most Visible Matter

Trento, April 3 - 7, 2017

Main Topics

Hadron mass decomposition in terms of constituents:
Uniqueness of the decomposition, Quark mass, and quark and gluon energy contribution, Anomaly contribution, ...
Hadron mass calculations:
Lattice QCD (total & individual mass components), Approximated analytical methods, Phenomenological model approaches, ...
Experimental access to hadron mass components:
Exclusive heavy quarkonium production at threshold, nuclear gluonometry through polarized nuclear structure function, ...

Confirmed speakers and participants

Alexandrou Constantia (*Cyprus University*), Brodsky Stan (*SLAC*), Burkardt Matthias (*New Mexico State University*), Chen Jian-Ping (*Jefferson Lab*), Chudakov Eugene (*Jefferson Lab*), Cloët Ian (*Argonne National Lab*), de Teramond Guy (*University Costa Rica*), Deshpande Abhay (*Stony Brook University*), Eichmann Gernot (*Giessen University*), Hafidi Kawtar (*Argonne National Lab*), Hoelbling Christian (*University of Wuppertal*), Lin Huey-Wen (*Michigan State University*), Liu Keh-Fei (*University of Kentucky*), Lorcé Cédric (*École Polytechnique, Palaiseau*), Mulders Piet (*Vrije University of Amsterdam*), Papavassiliou Joannis (*Valencia University*), Pascalutsa Vladimir (*Johannes Gutenberg University of Mainz*), Richards David (*Jefferson Lab*), Roberts Craig (*Argonne National Lab*), Slifer Karl (*University of New Hampshire*), Mauro Anselmino (*University of Torino & INFN*), Bob Jaffe (*Massachusetts Institute of Technology*), Dima Kharzeev (*Stony Brook University*), Xiangdong Ji (*University of Maryland*).

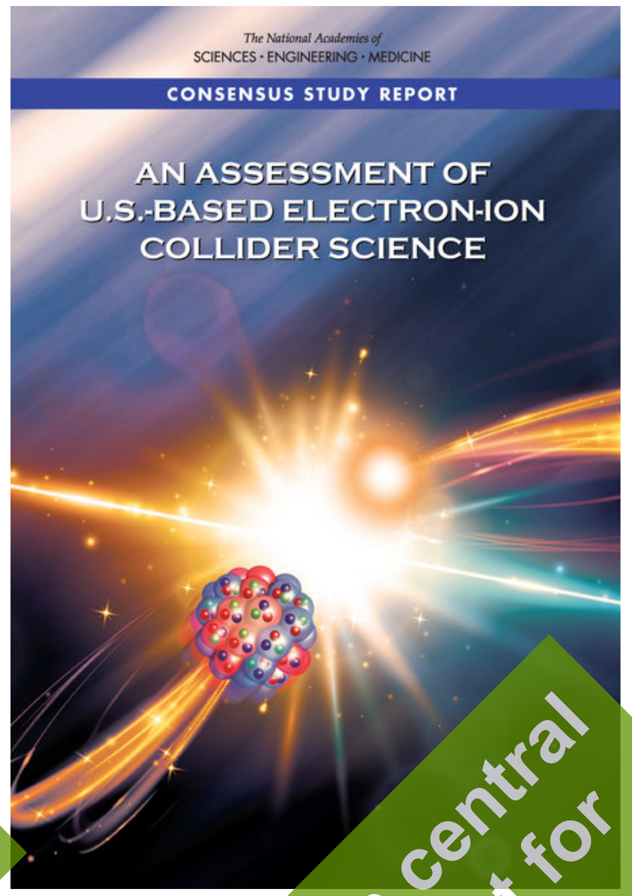
Organizers

Zein-Eddine Meziani (*Temple University*)
Barbara Pasquini (*University of Pavia*)
Jianwei Qiu (*Jefferson Lab*)
Marc Vanderhaeghen (*Universität Mainz*)

Director of the ECT*: Professor Jochen Wambach (ECT*)

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.

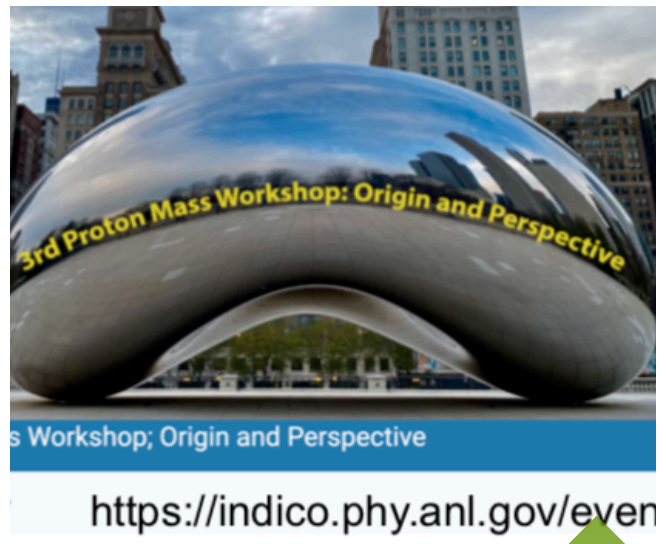
For local organization please contact: Gianmaria Ziglio - ECT* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 - 38123 Villazzano (Trento) - Italy
Tel.:(+39-0461) 314721 Fax:(+39-0461) 314750, E-mail: **ect@ectstar.eu** or visit **http://www.ectstar.eu**



The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

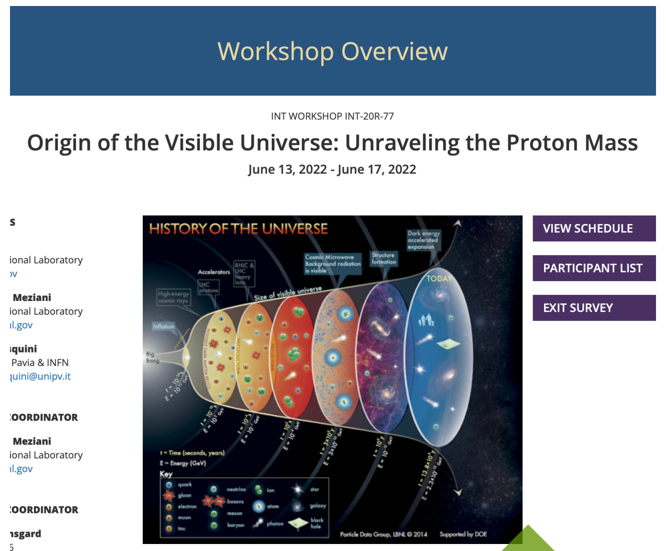
AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE



3rd Proton Mass Workshop: Origin and Perspective

s Workshop; Origin and Perspective

https://indico.phy.anl.gov/even



Workshop Overview

INT WORKSHOP INT-20R-77

Origin of the Visible Universe: Unraveling the Proton Mass

June 13, 2022 - June 17, 2022

2012 Temple U. Workshop on heavy quarkonia

2015 LHCb finds resonance in J/ψ-p channel consistent with pentaquarks

Featured in the 2015 Long Range plan

2016 Temple U. Workshop on the proton mass

2016 Proposal for Hall C Pentaquark search

2017 ECT* Workshop on the proton mass

2018 Proton mass central in NAS assessment for EIC

2019 First GlueX near-threshold J/ψ results

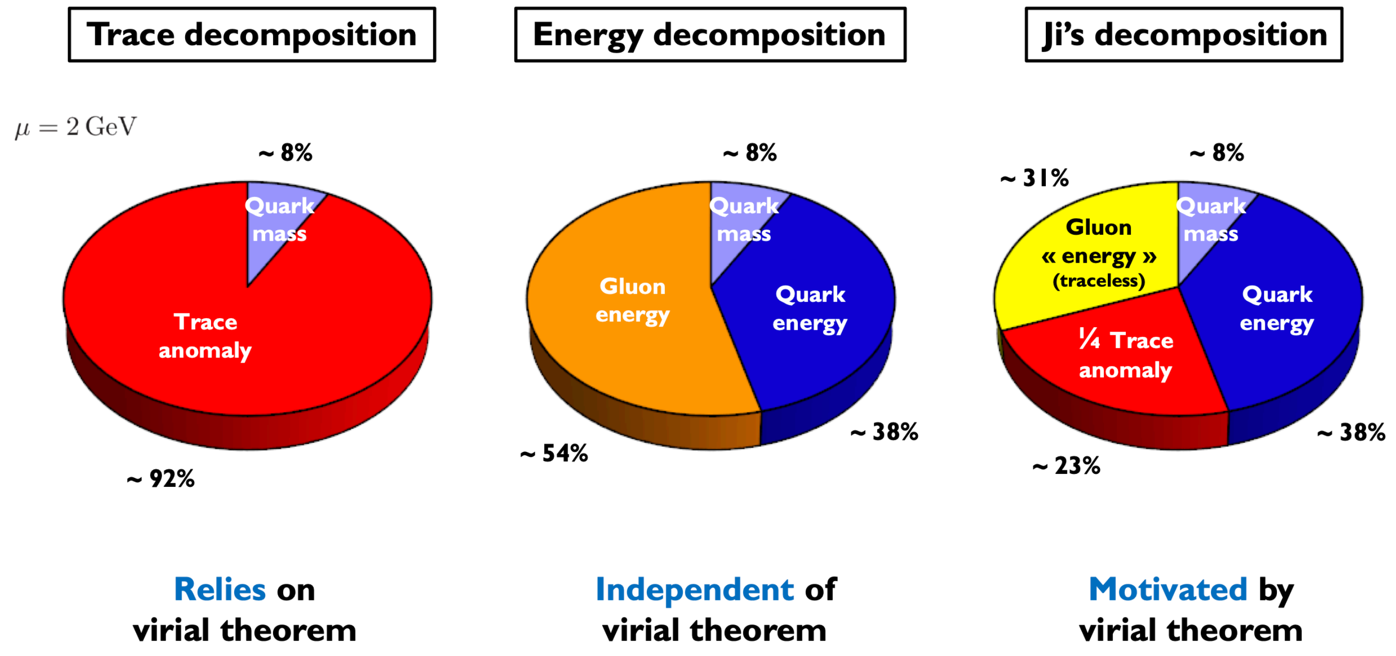
2021 Remote Workshop on the proton mass

2021 First Hall C results on the pentaquark search

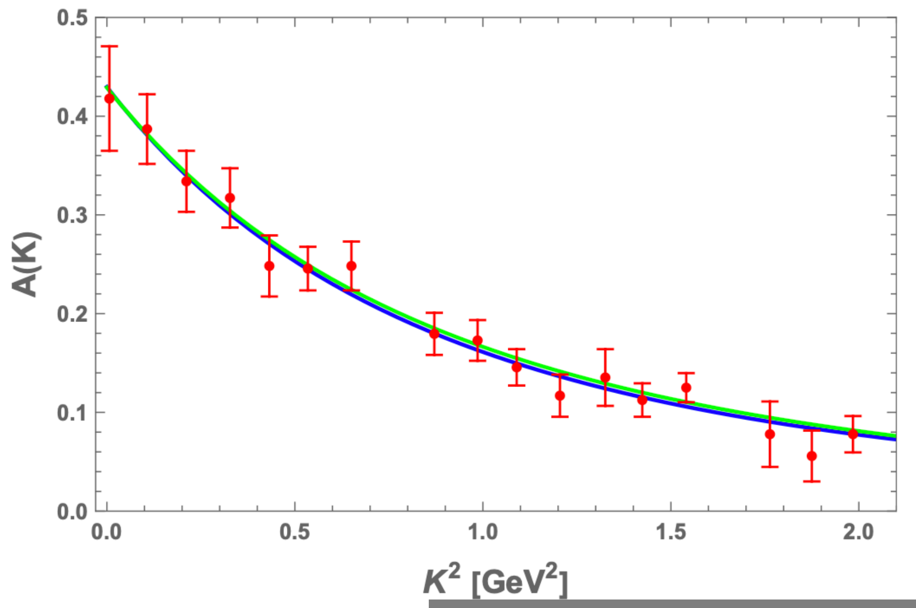
2022 INT Workshop on the proton mass

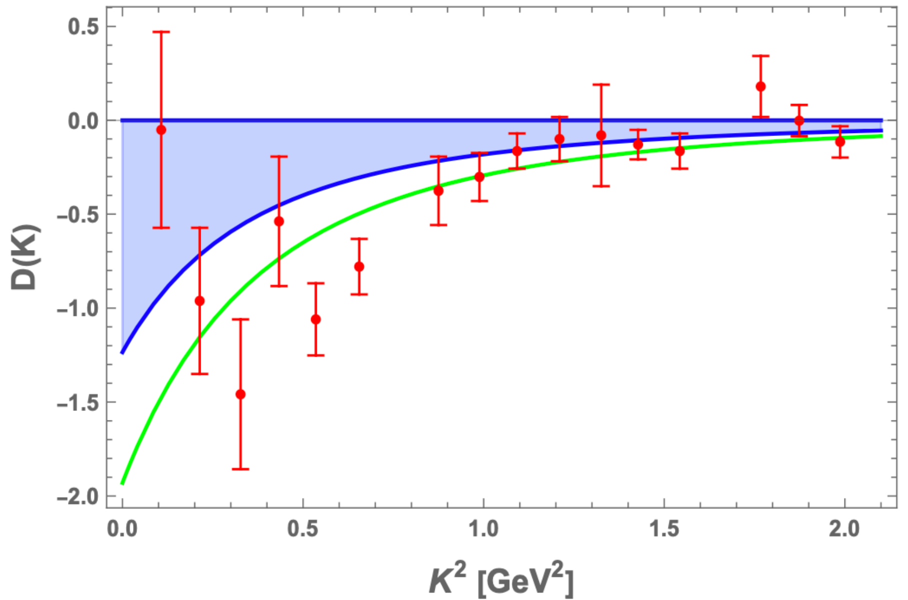
2022 First 2D near-threshold J/ψ results from Hall C

PROMINENT RECENT DEVELOPMENTS

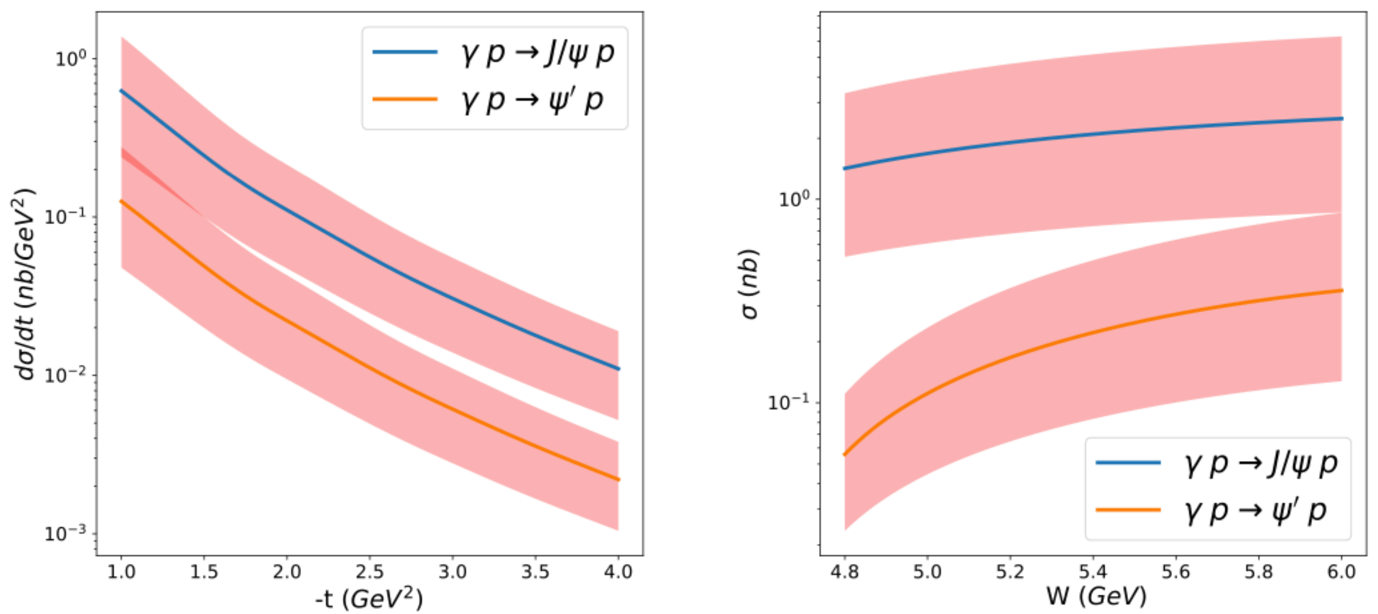


Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)



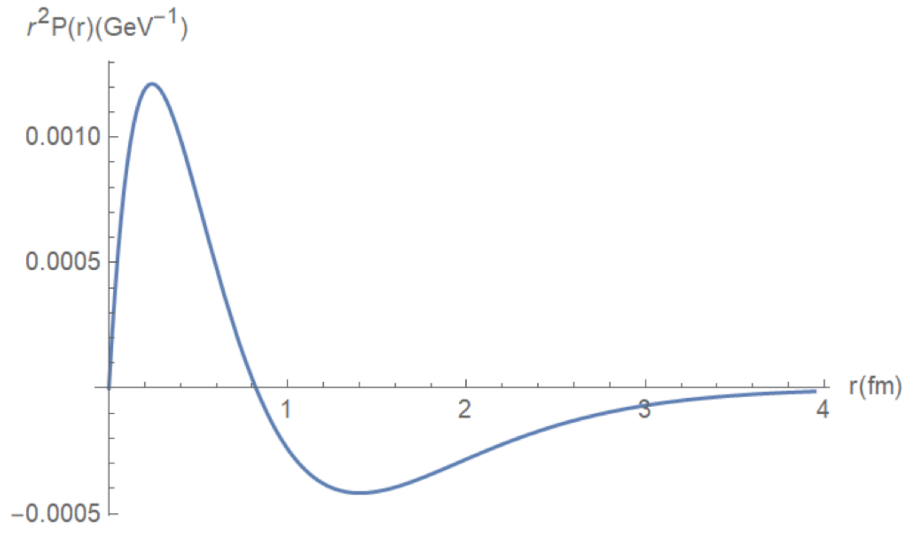


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

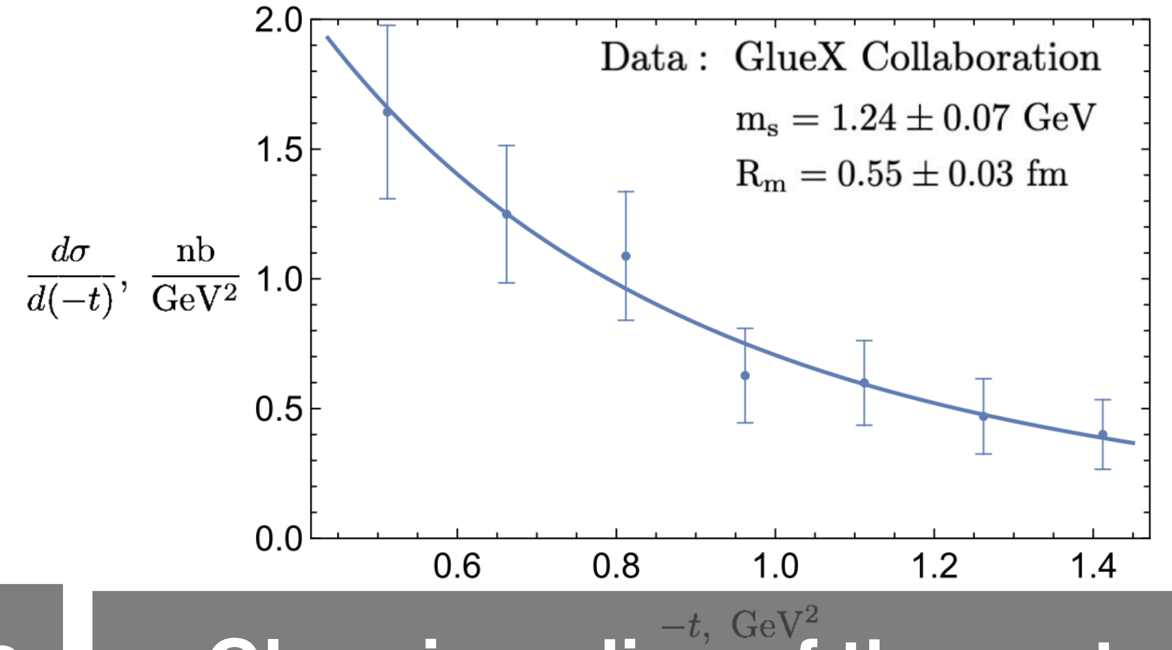


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- A hot topic: many theoretical developments, and pace of publications only speeding up!
- Many extractions depend on extrapolating to the forward limit (t=0), which introduces theoretical systematic uncertainties. Precise high-t as a function photon energy crucial.



Gluon contribution to pressure in GPD formalism, Y. Guo, X. Ji, Y. Liu, (PRD 2021)

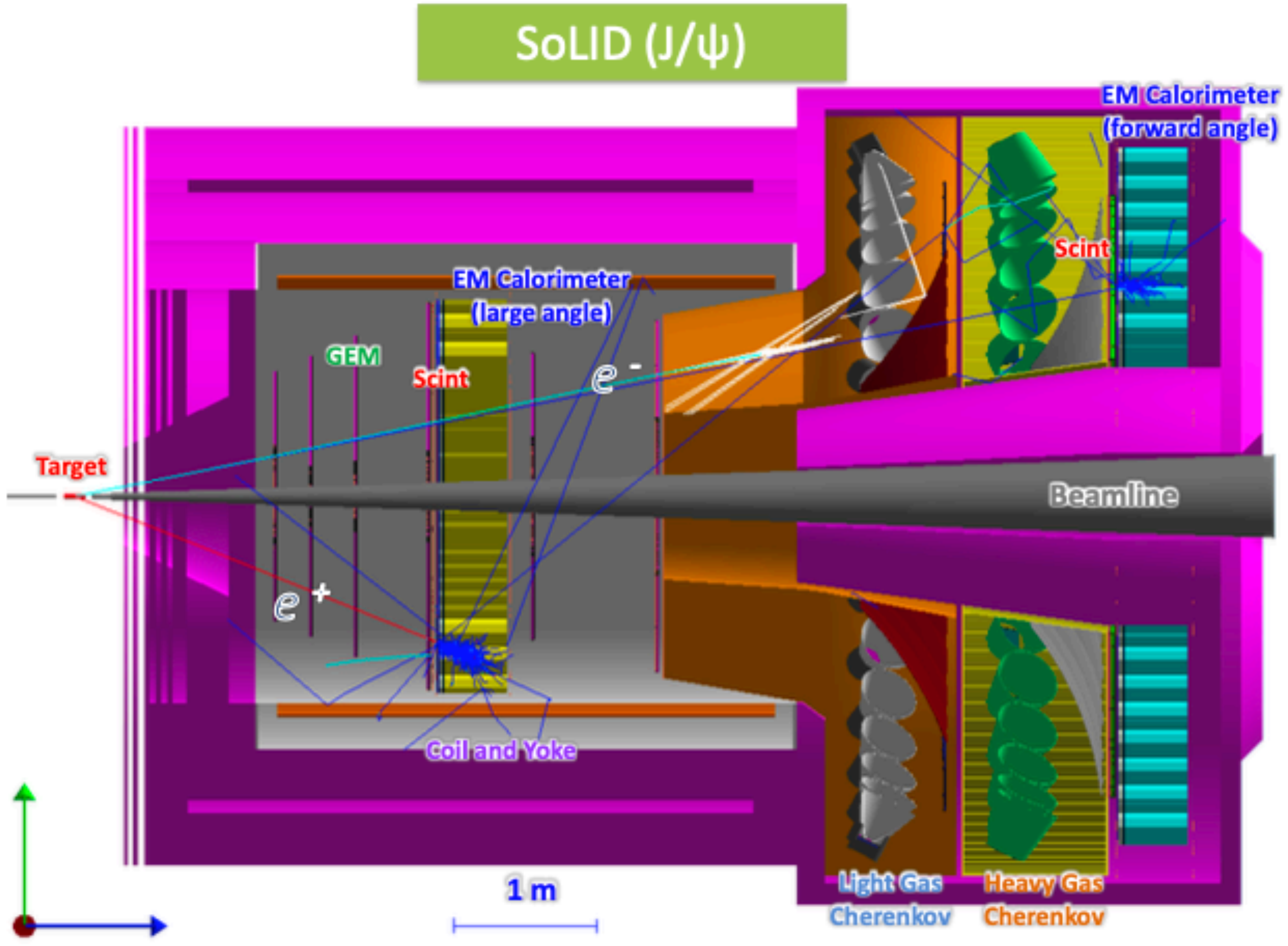


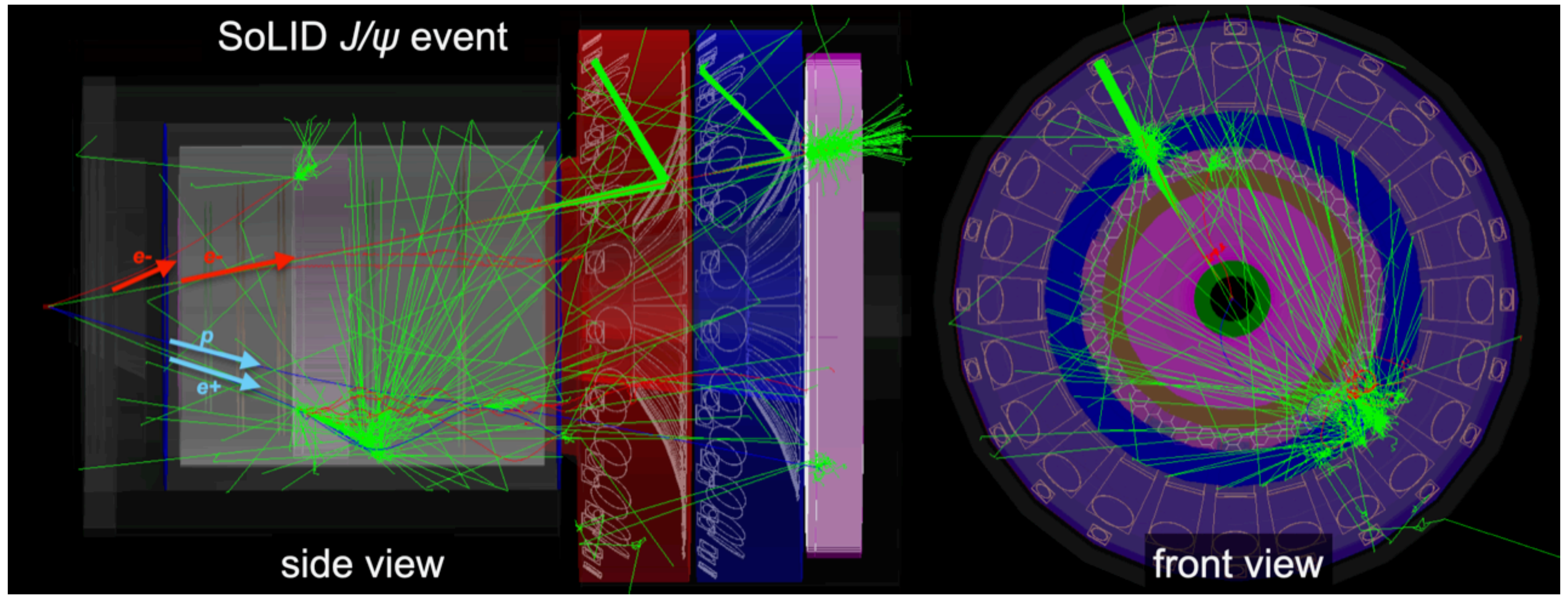
Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

THE SOLID-J/Ψ EXPERIMENT

Ultimate factory for near-threshold J/ψ

- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target ($10^{37}/cm^2/s$)
- **Ultra-high luminosity**: $43.2 ab^{-1}$
- **Open 2-particle trigger,** covering J/ψ production in four channels: Electroproduction (e,e^-e^+), photoproduction (p,e^-e^+), inclusive (e^-e^+), exclusive (ep,e^-e^+)
- The electoproduction channel provides for a modest lever-arm in Q^2 near threshold

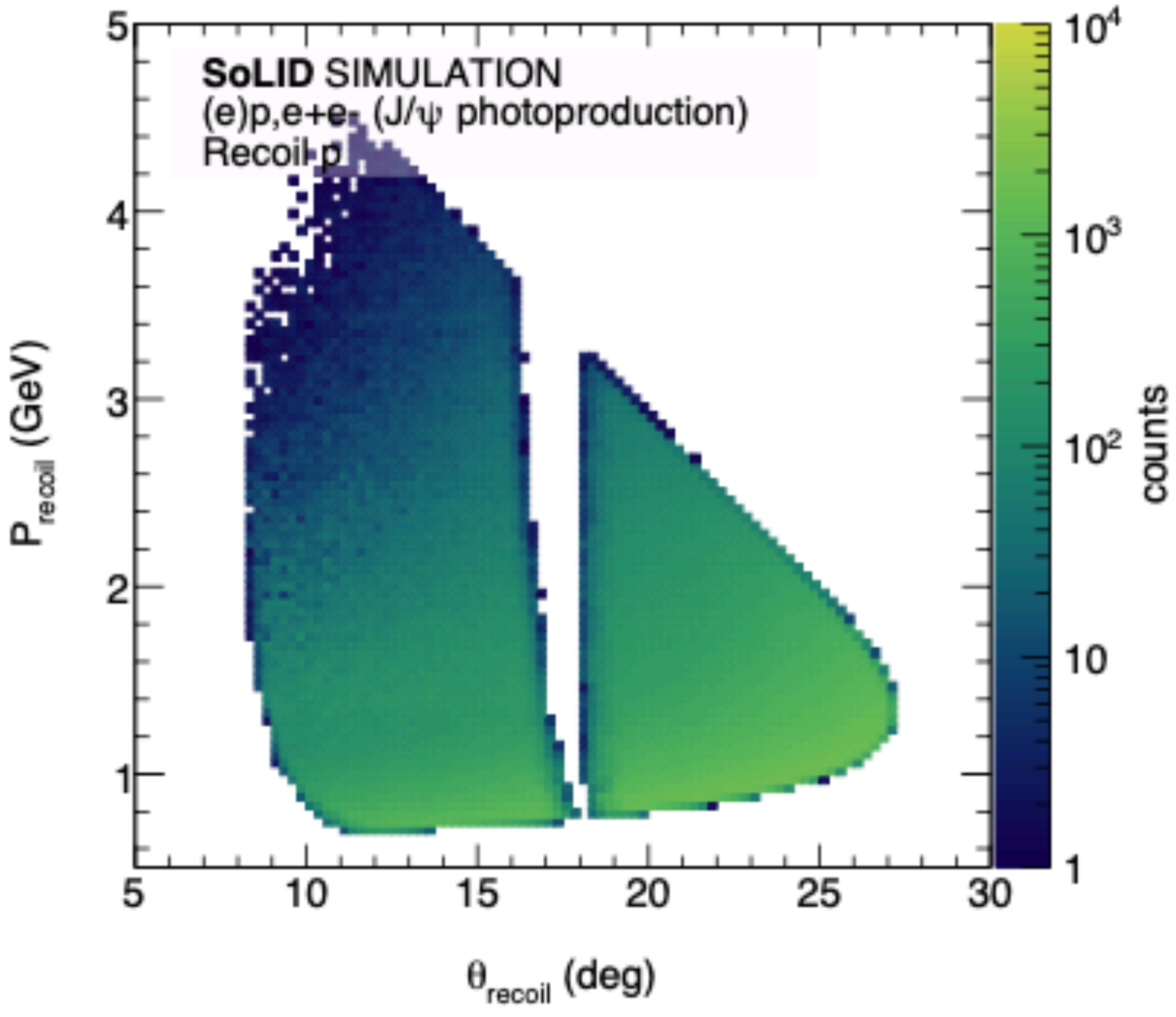


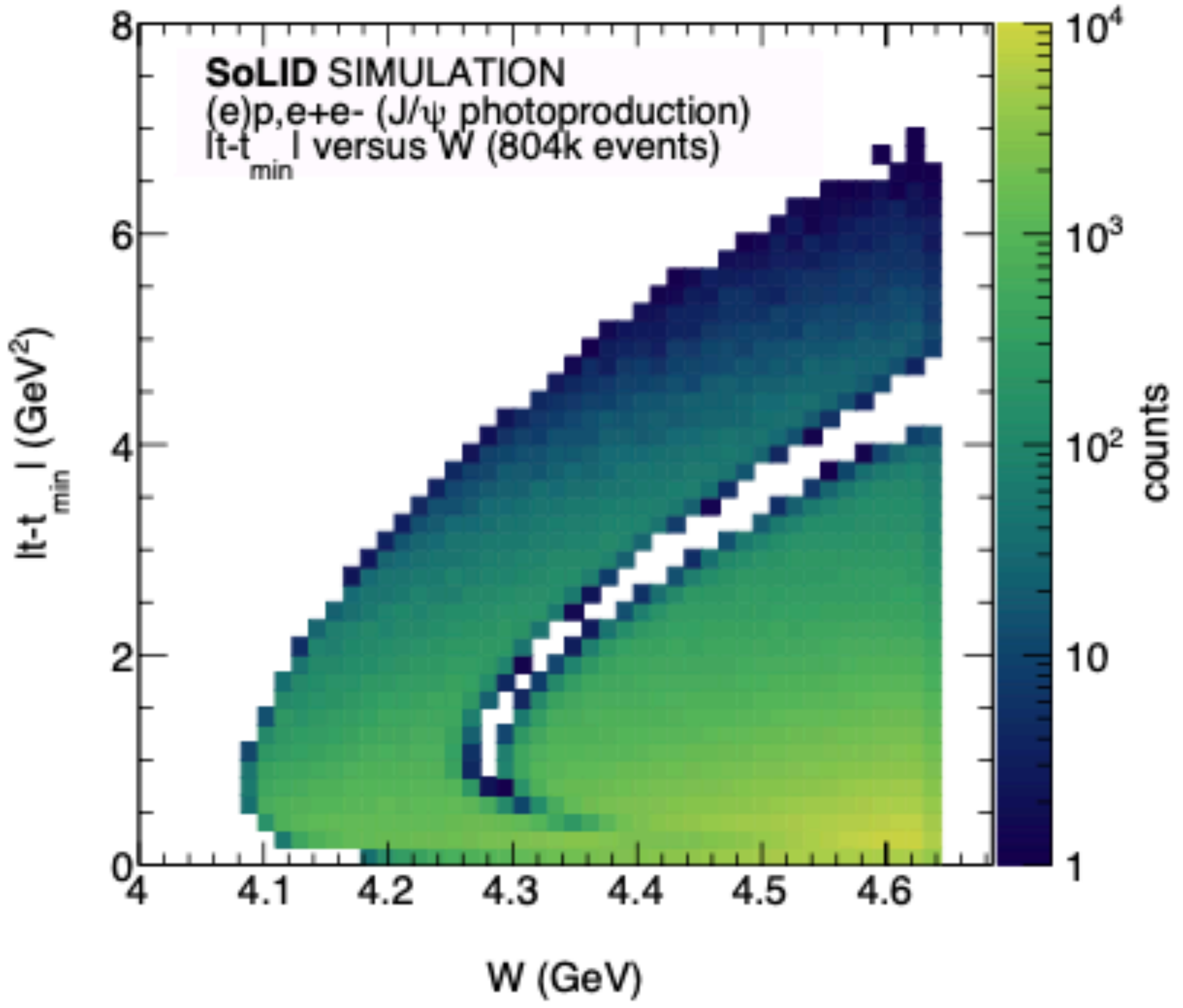


PHOTOPRODUCTION

Ultra-high statistics and best reach to high energies

- Production through quasi-real photons, and bremsstrahlung in the extended target.
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify recoil proton (which is slow) through time-of-flight with the SPDs and MRPCs.
- Can make measurement up to very large values of *t*.

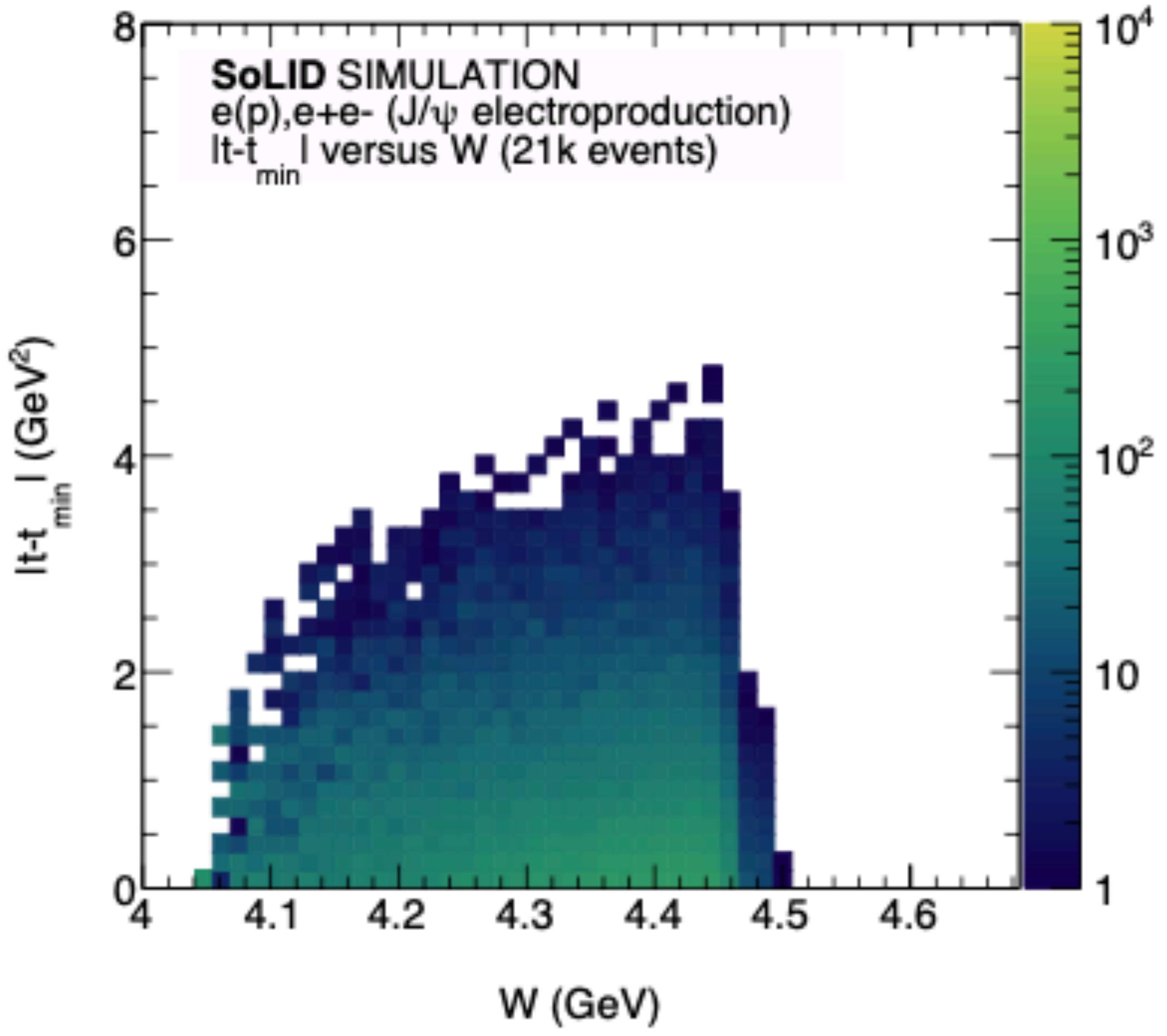


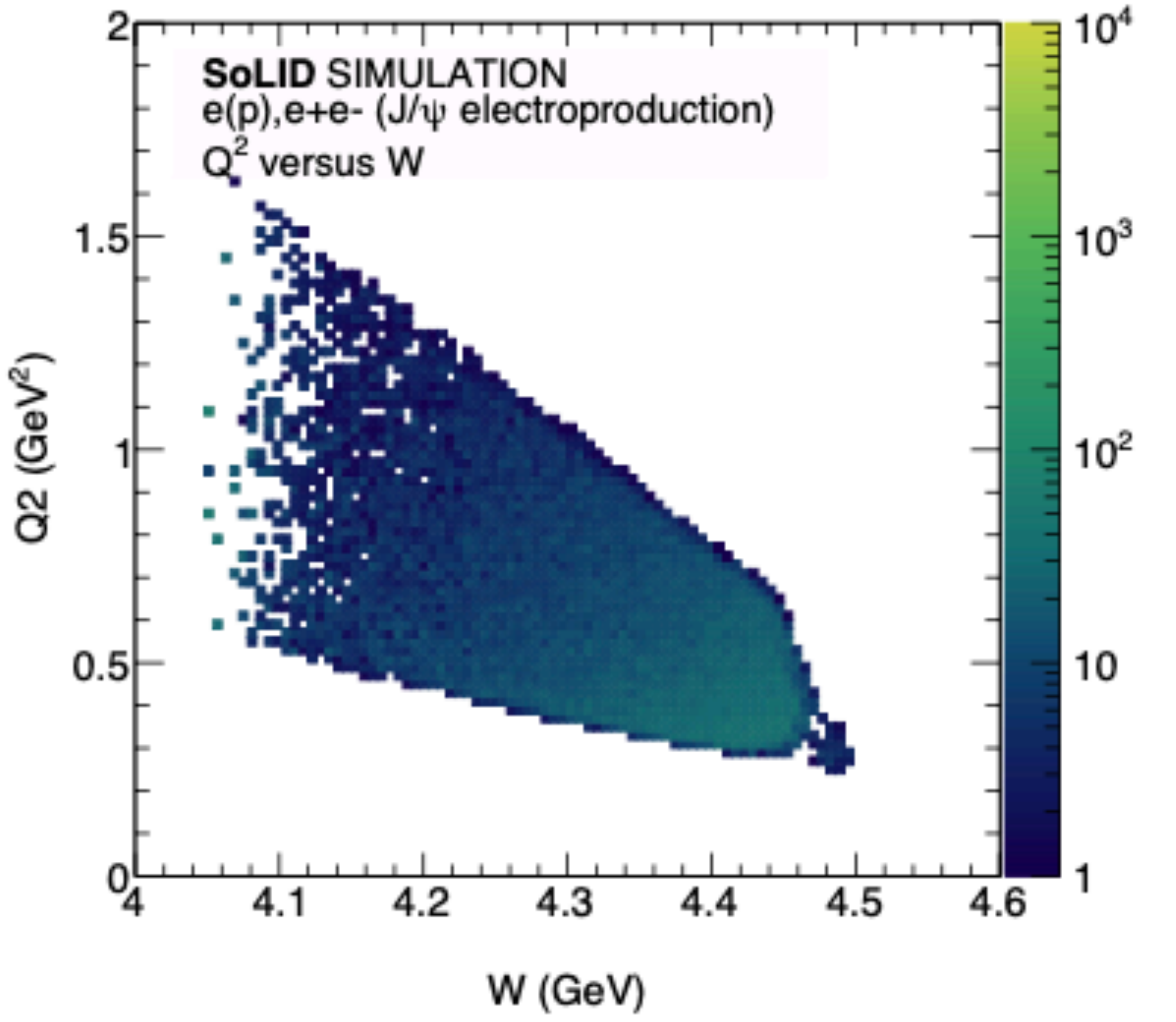


ELECTROPRODUCTION

Unrivaled reach towards the threshold and modest lever-arm in Q^2

- Production through virtual photons
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify scattered electron in the forward spectrometer.
- Coverage up to larger values of t very close to threshold.

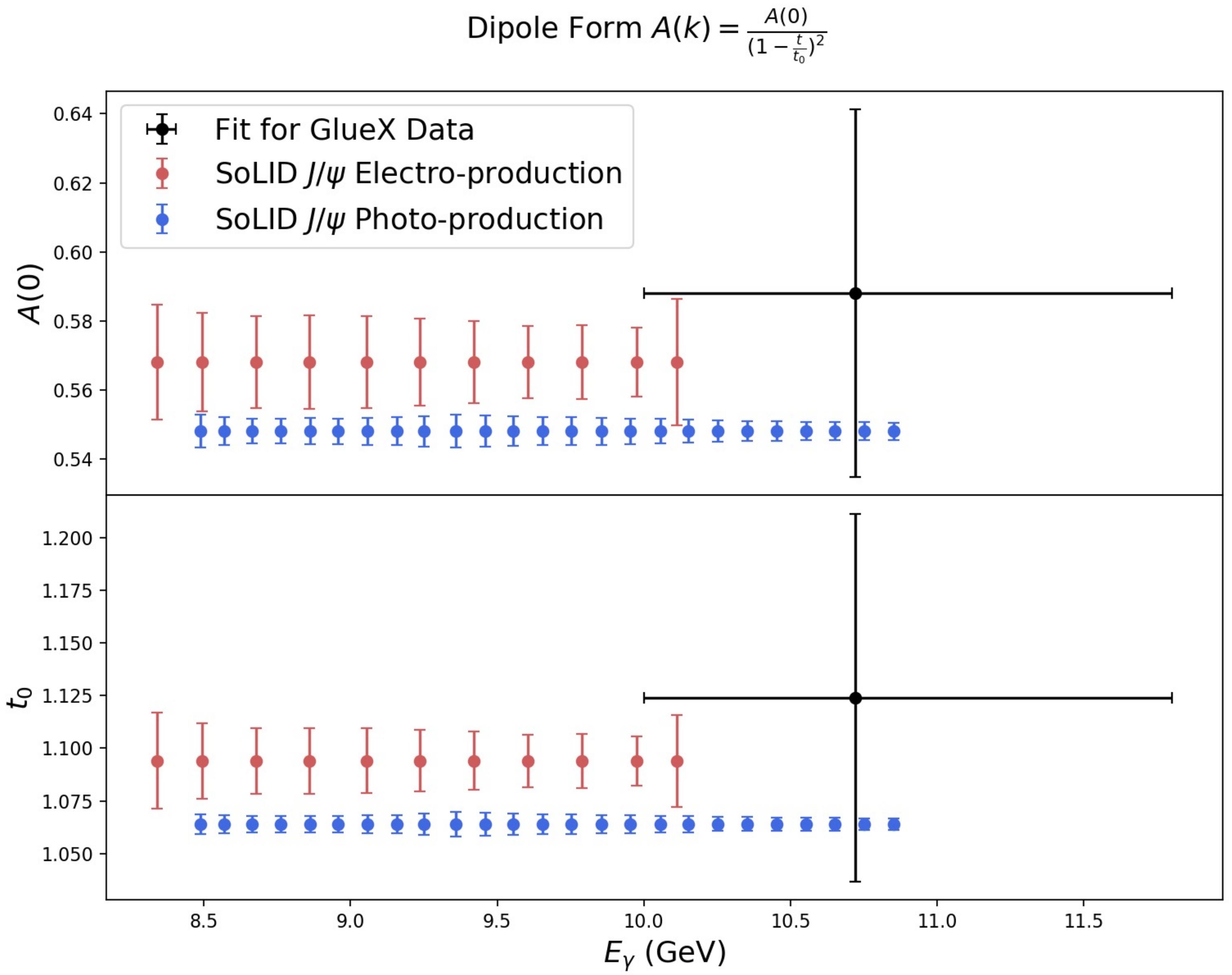


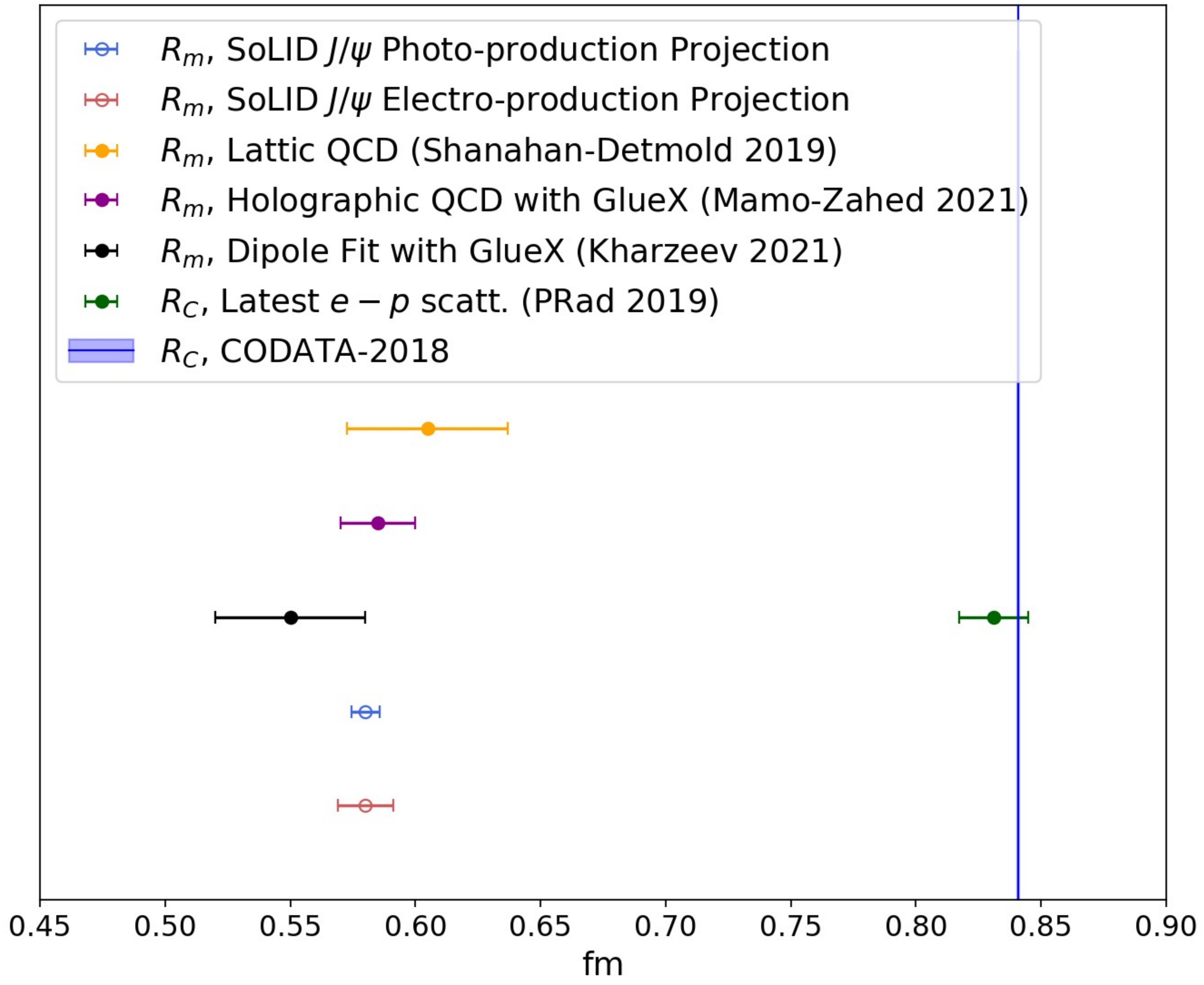


PROJECTED IMPACT FOR SOLID-J/Ψ

Radius following the DK approach

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



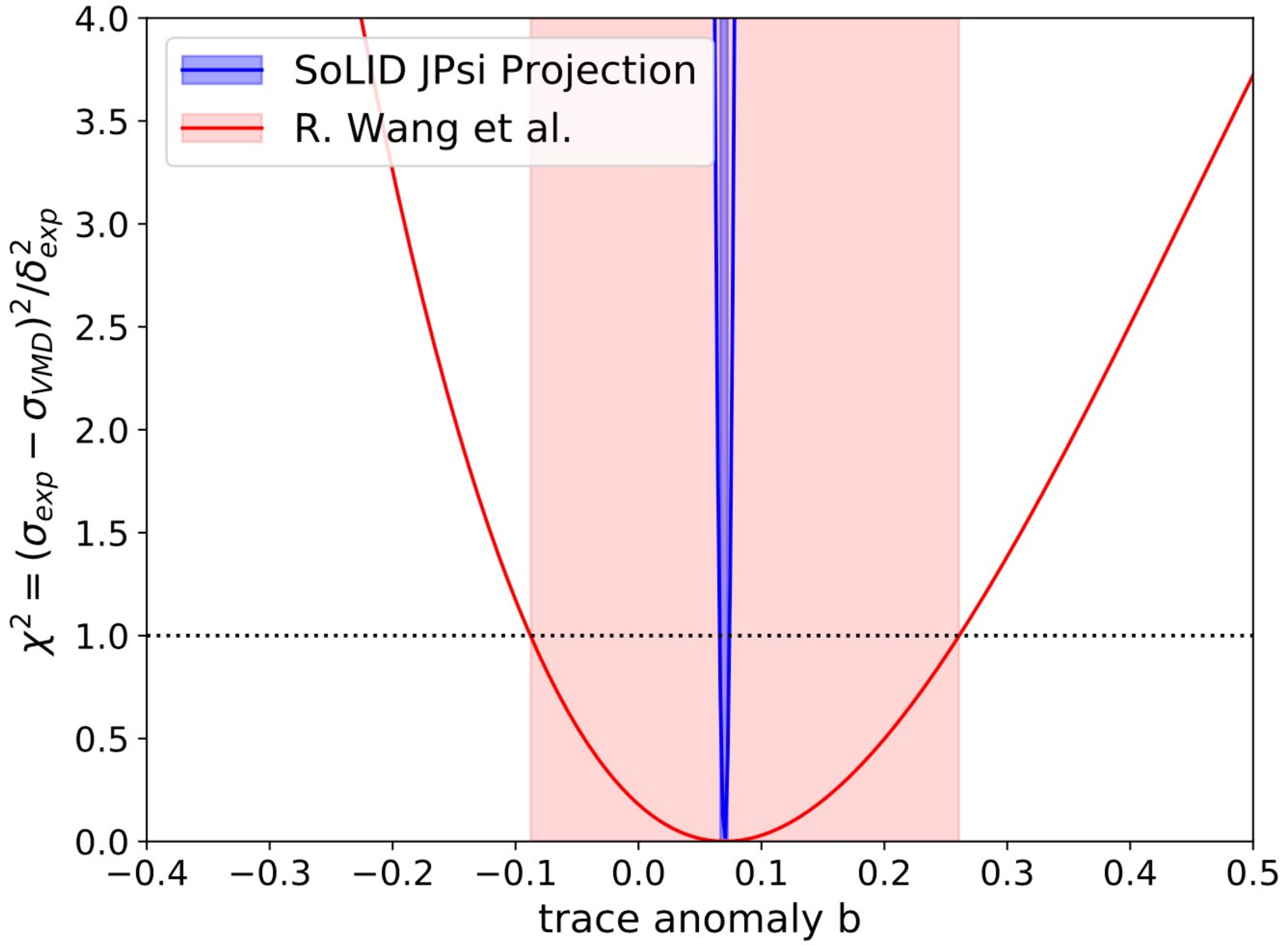


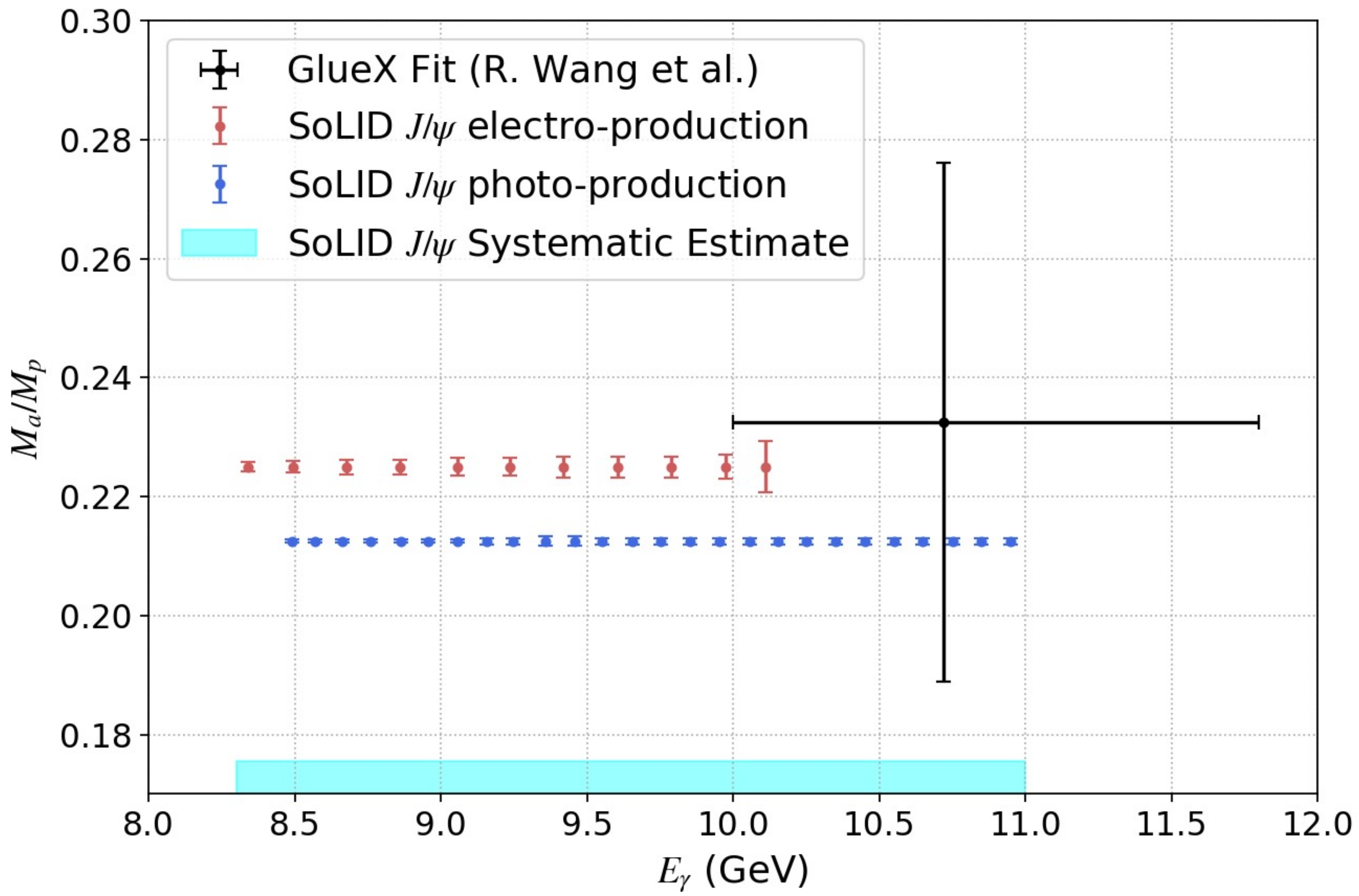
High sensitivity over the full photon energy range

PROJECTED IMPACT FOR SOLID-J/Ψ

Ma/M following Ji's approach

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



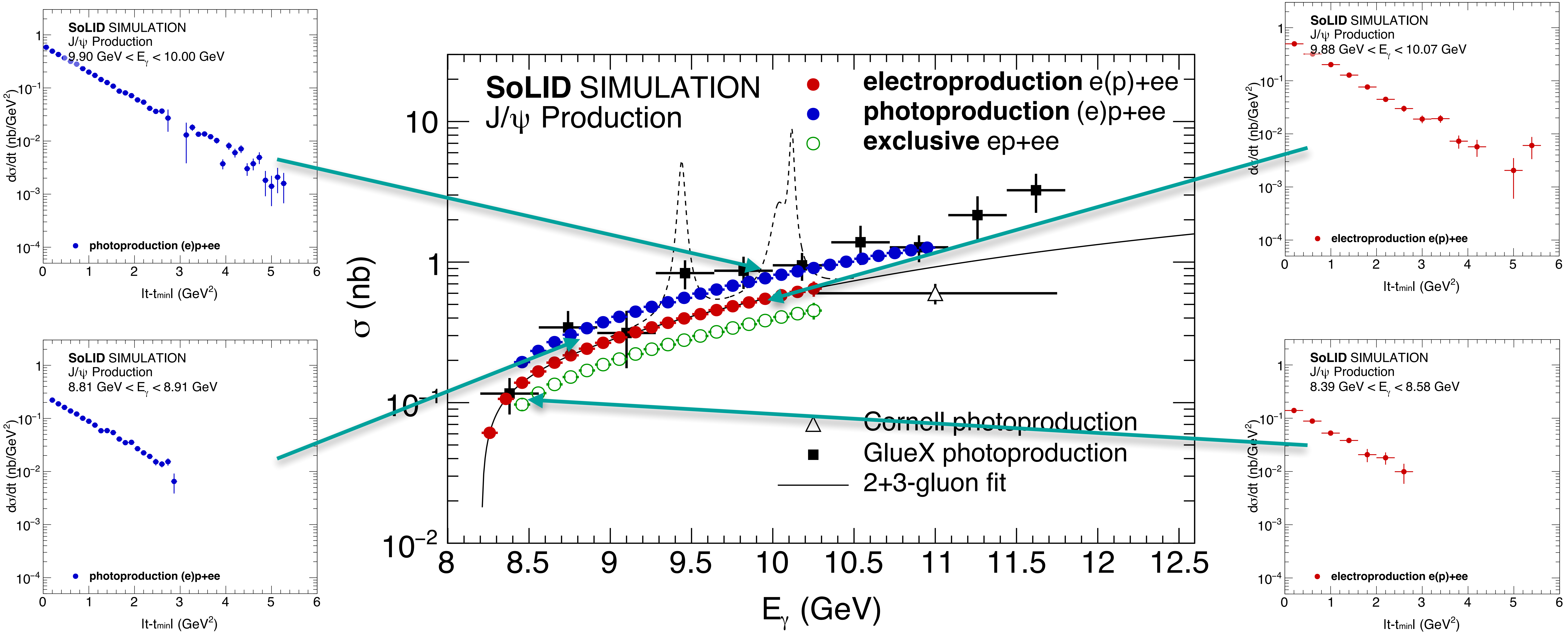


GlueX extraction from R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

High sensitivity over the full photon energy range

SOLID-J/Ψ PROJECTIONS

Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



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**	**2k electron channel 2k muon channel**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
When?	Finished/Ongoing	Finished	Ongoing/Proposed	Future

[1] The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2\text{x}10^{35}/\text{cm}^2/\text{s}$

THE COLOR VAN DER WAALS FORCE BEYOND SOLID-J/Ψ

Increasing sensitivity with J/ψ and ψ' production off nuclei

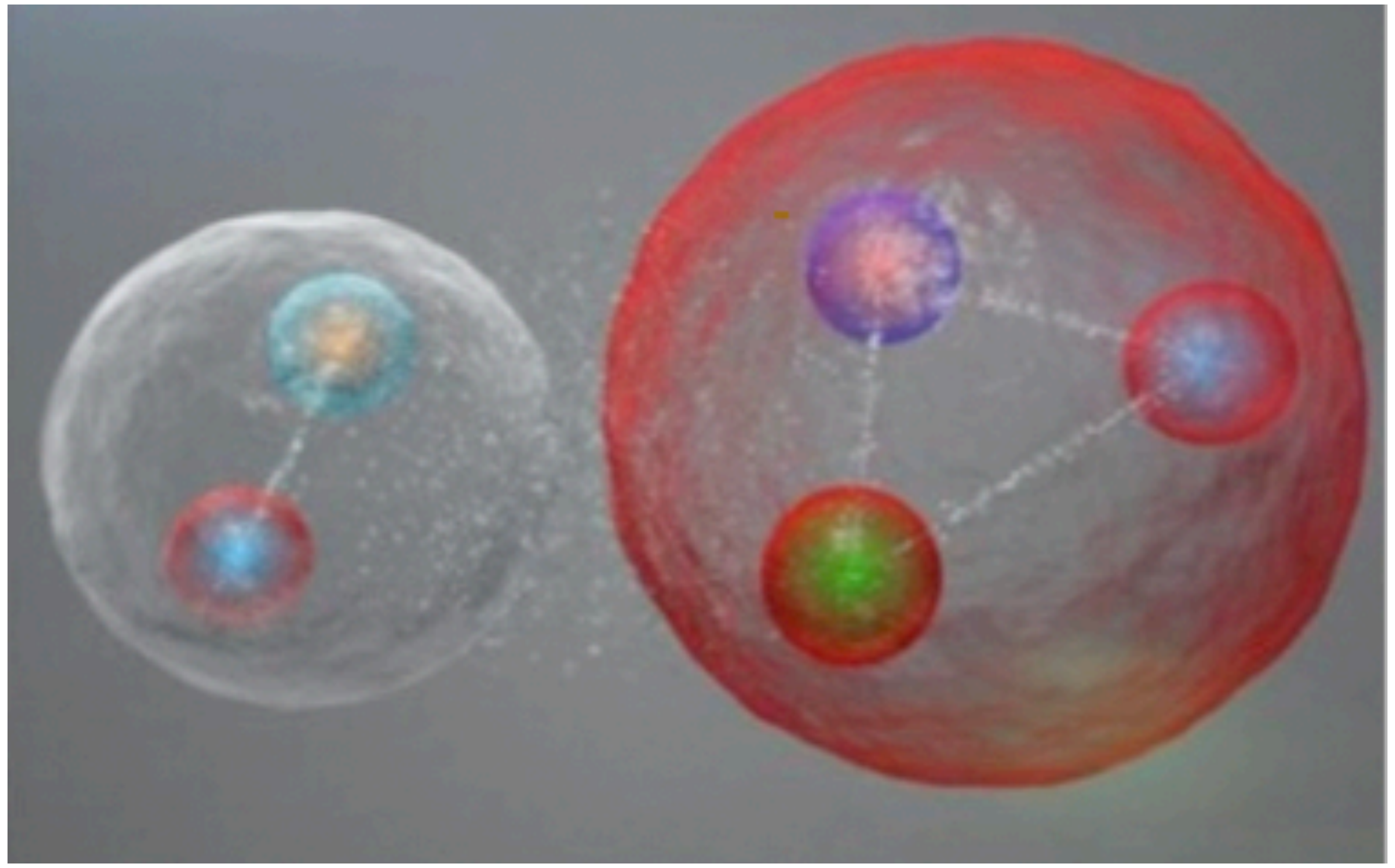
Expect enhanced color Van der Waals force in nuclei due to the larger color field: measure e.g. coherent J/ψ production off ^{4}He

Nuclei also enable ψ' production at lower energies: threshold for coherent ψ' production off ^{4}He at 7.4GeV

ψ' a larger color dipole, expect stronger binding (larger enhancements in the near-threshold cross section)

A coherent J/ψ and ψ' program off ^{4}He at SoLID would open many avenues to study the nature of the color Van der Waals force.

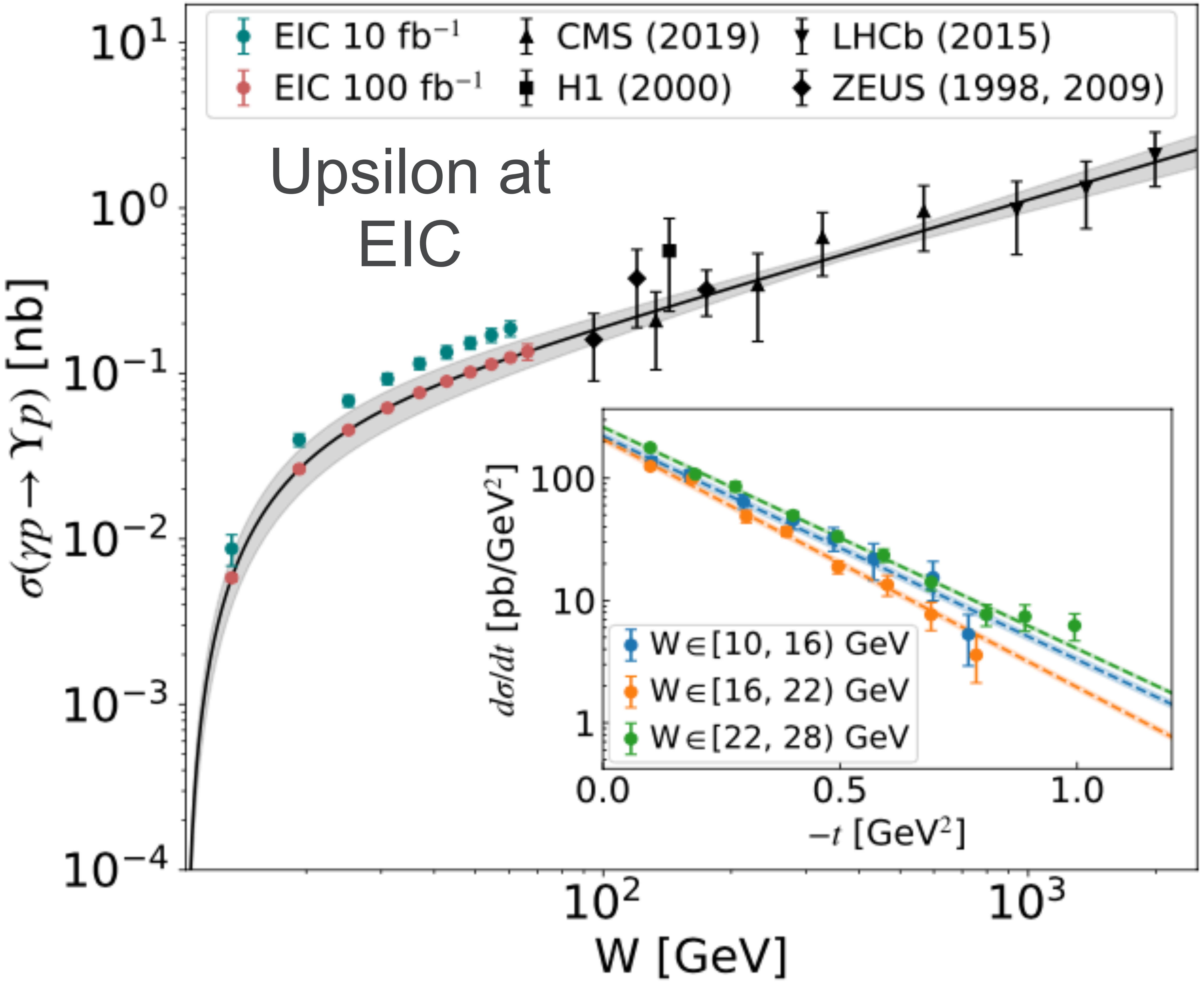
With higher beam energies: coherent production off ^{4}He to higher energies (imaging!)

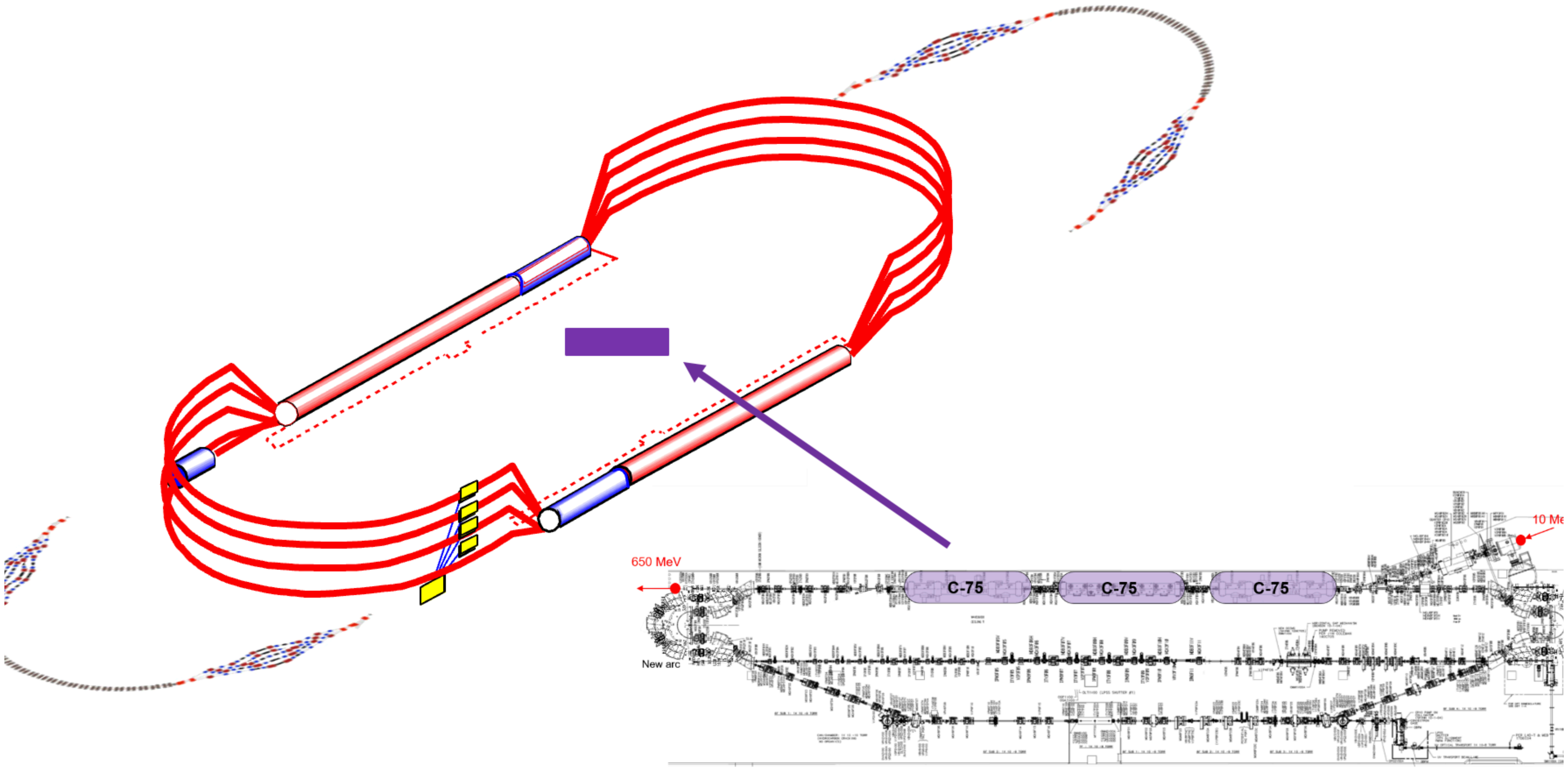


COMPLEMENTARITY WITH EIC

J/ψ at SoLID and Υ at EPIC

- Υ(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties, and extra channel to study universality.
- Large Q^2 reach at EIC an additional knob to study production, near-threshold J/ψ production at large Q^2 may be experimentally feasible!





SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

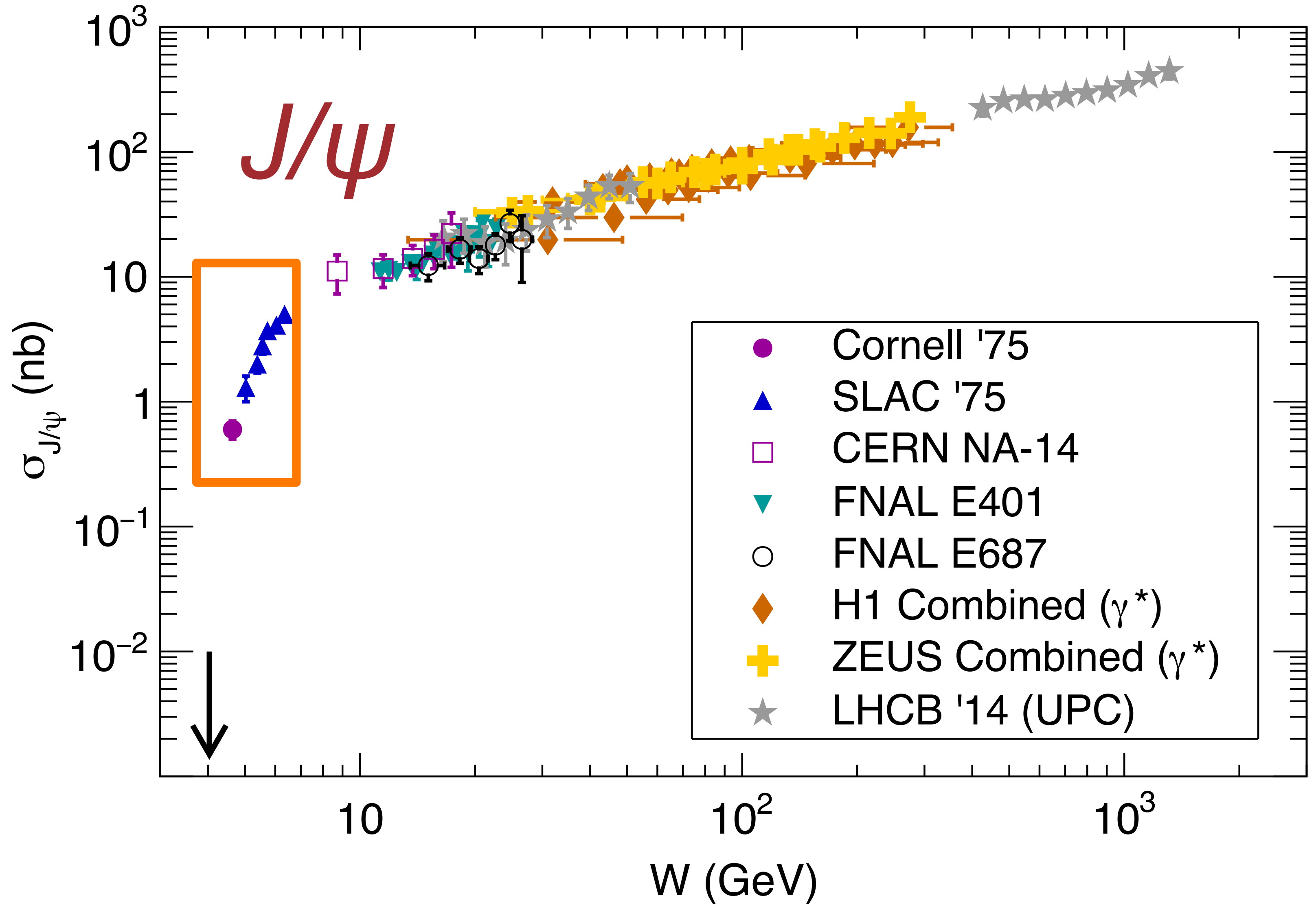
GlueX

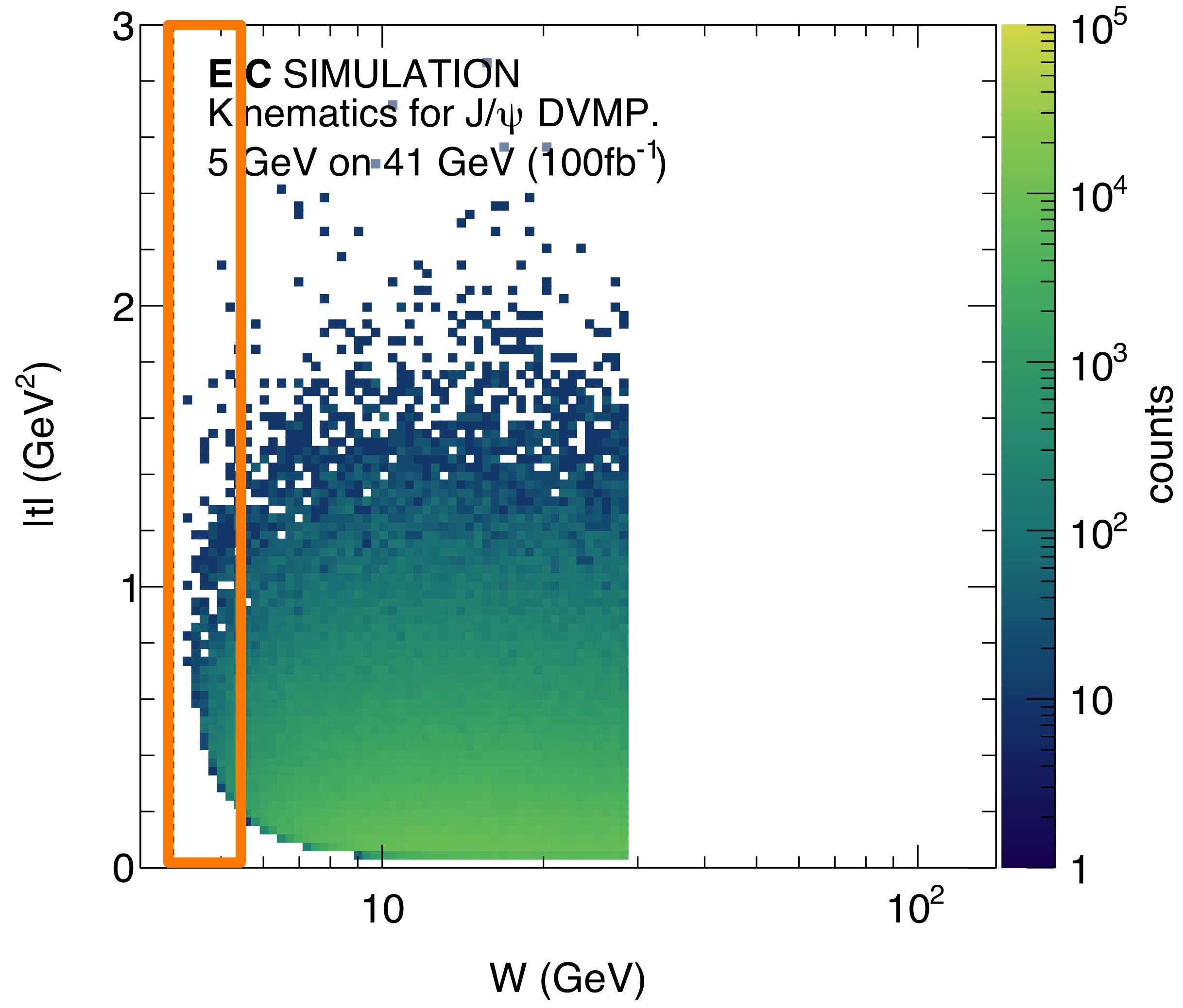
JLAB BEYOND: OPPORTUNITIES WITH A LARGER CEBAF BEAM ENERGY (~22 GeV)

JLAB BEYOND: WHY HIGHER ENERGIES AT JLAB?

What can we learn?
How do we compare to EIC?

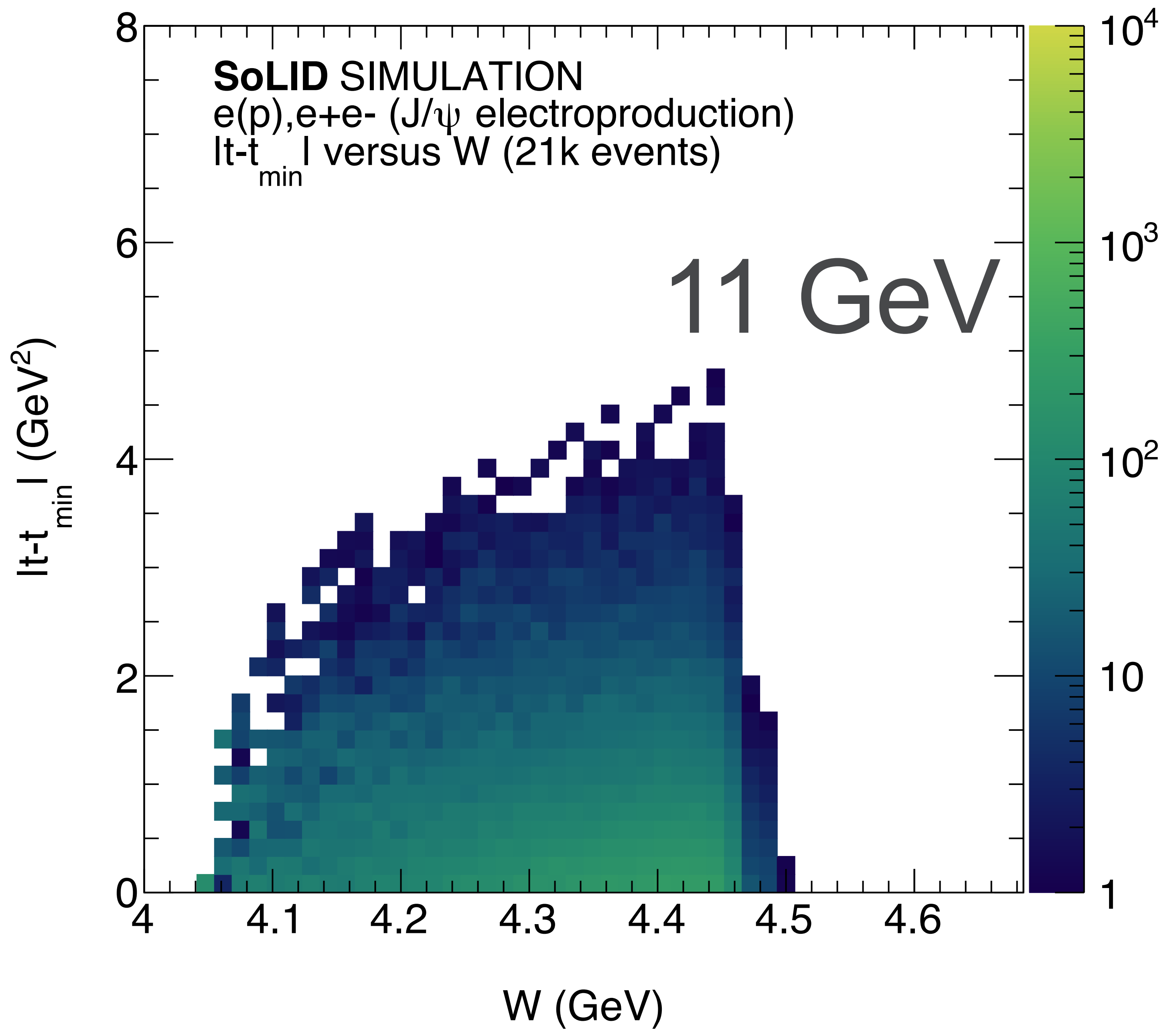
- Potential benefits:
  - Larger reach in Q^2 near threshold with high precision
  - Precision measurement to supersede old SLAC and Cornell measurement
  - High-precision for EIC at lower energies (but with much higher W resolution)
  - Extend high-t reach unique to Jlab to higher energies - cannot be done with EIC.
  - Can extend program from J/ψ to ψ’ (larger color dipole, independent knob to constrain physics)

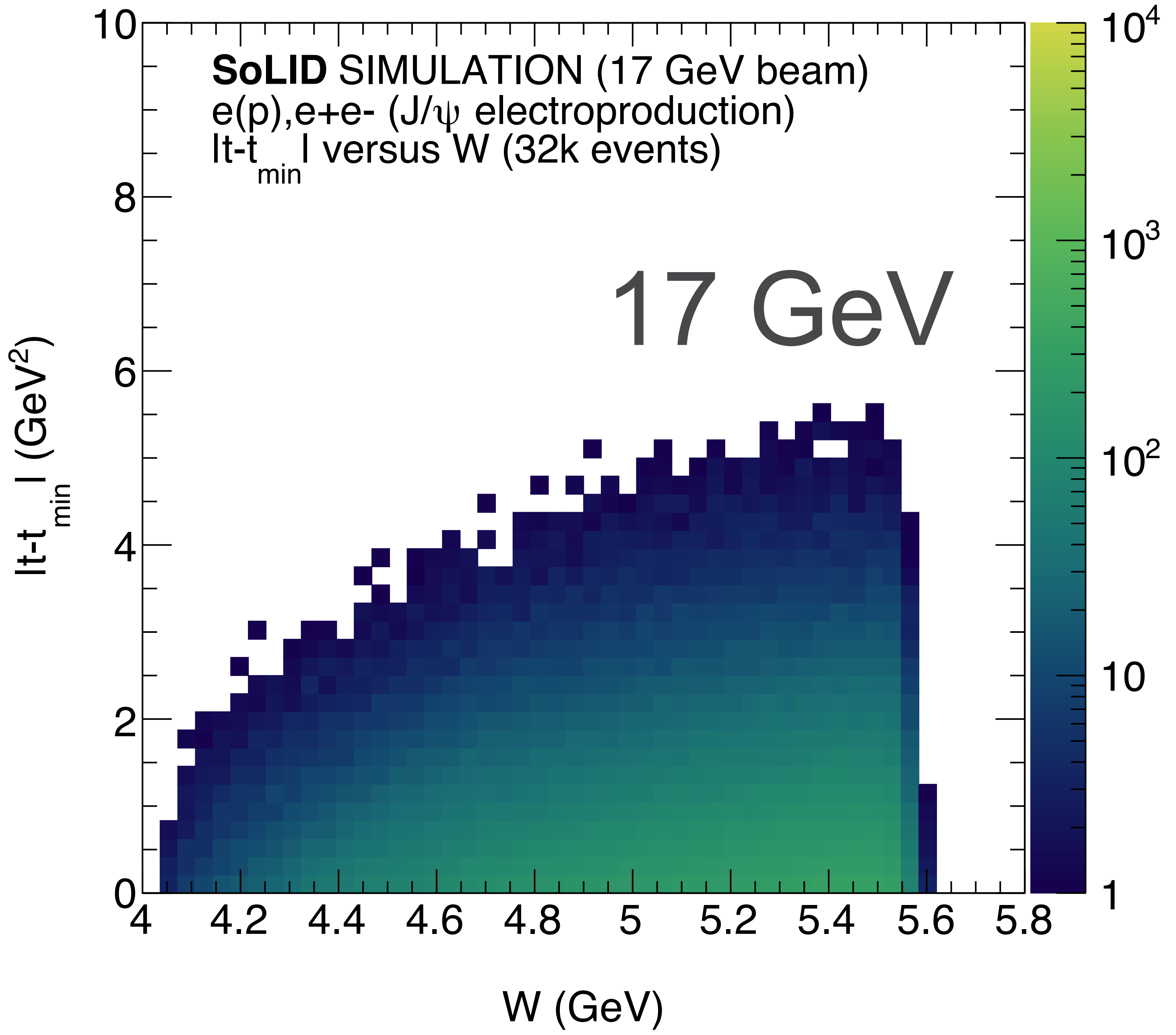


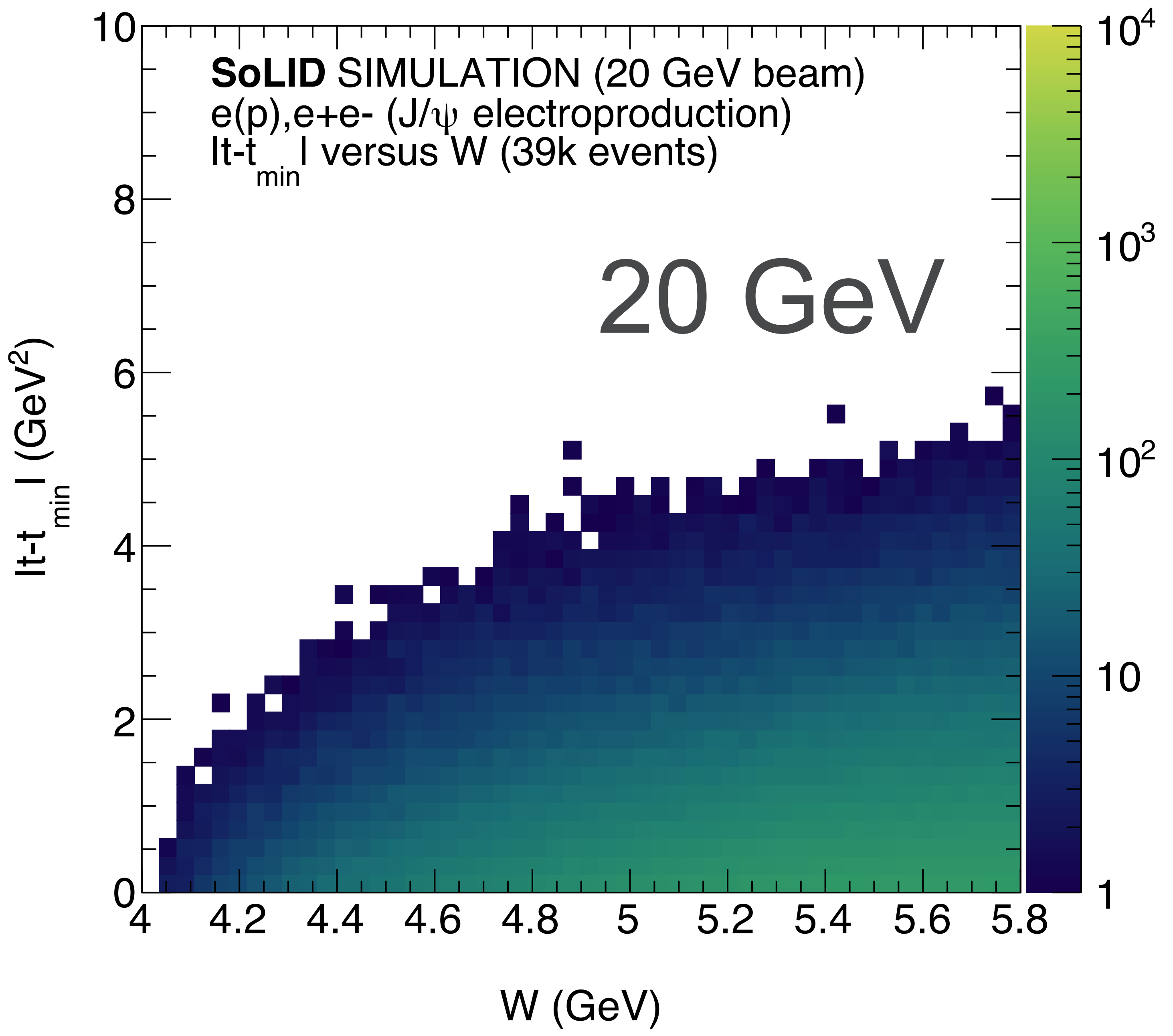


ELECTROPRODUCTION@SOLID LOOKS PROMISING

Good kinematic coverage with standard setup without changes

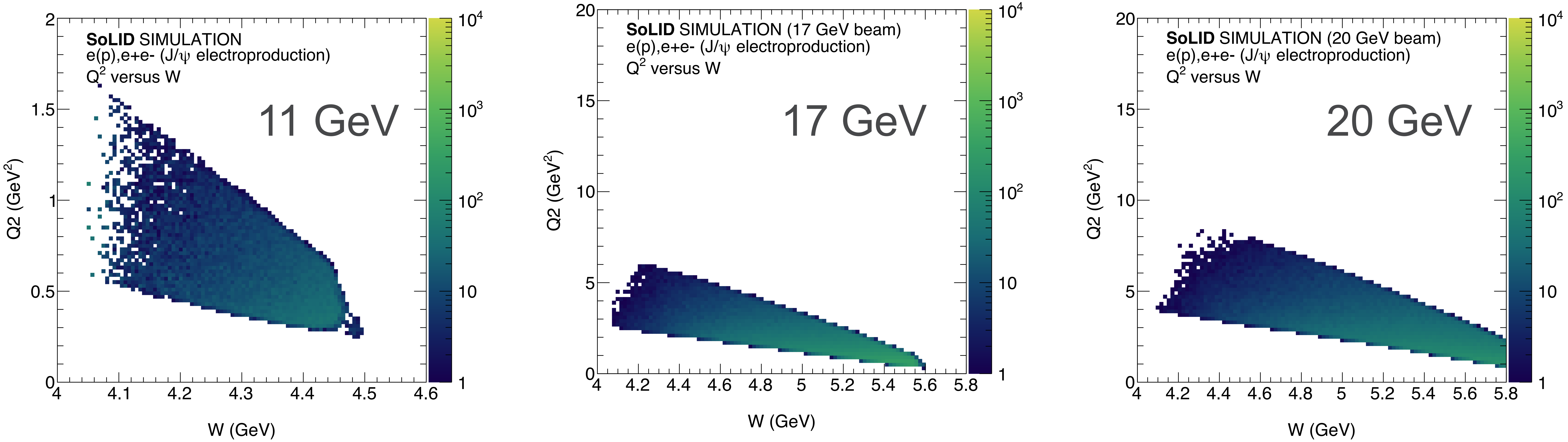






ELECTROPRODUCTION@SOLID LOOKS PROMISING

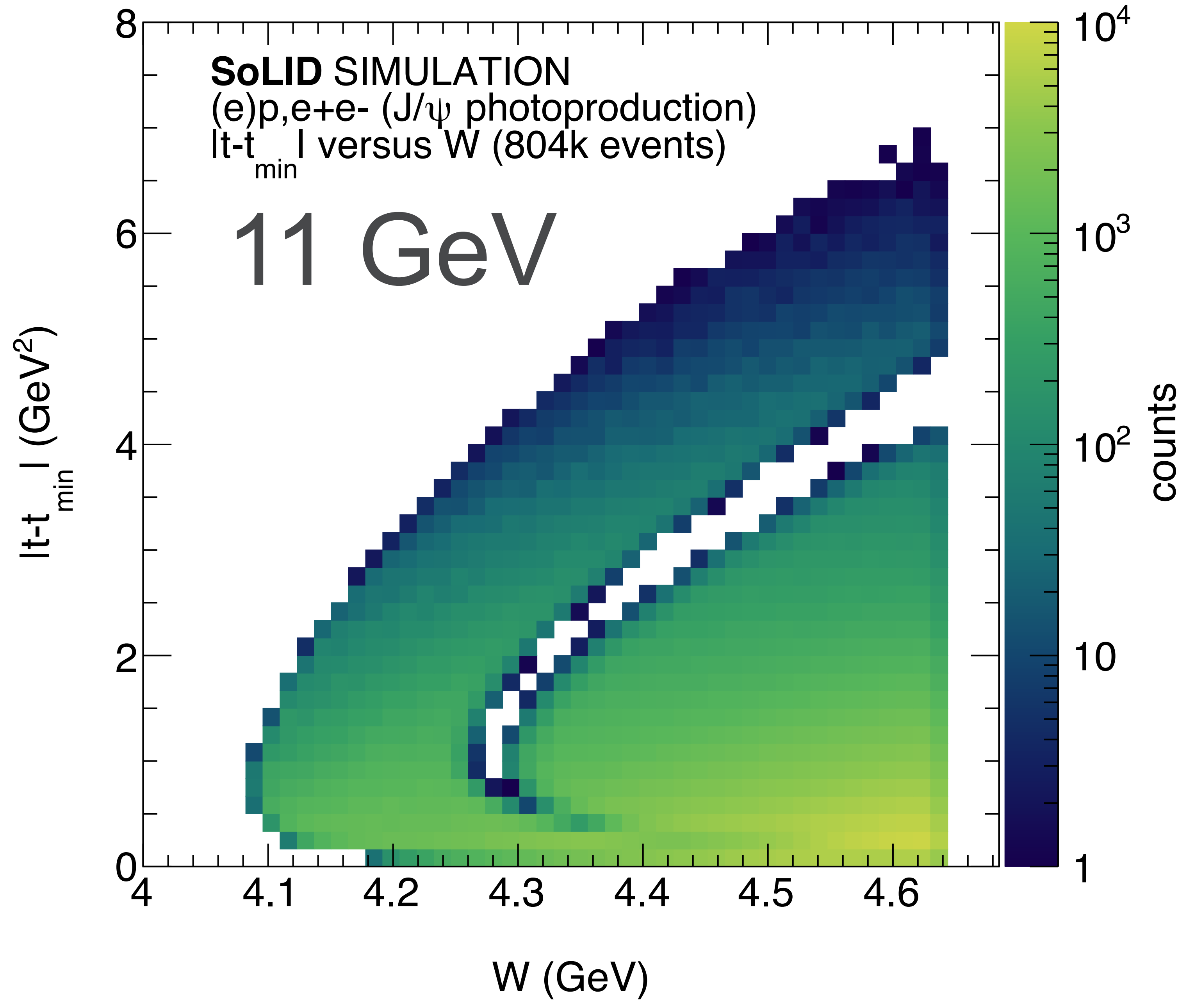
Larger near-threshold lever-arm in Q2

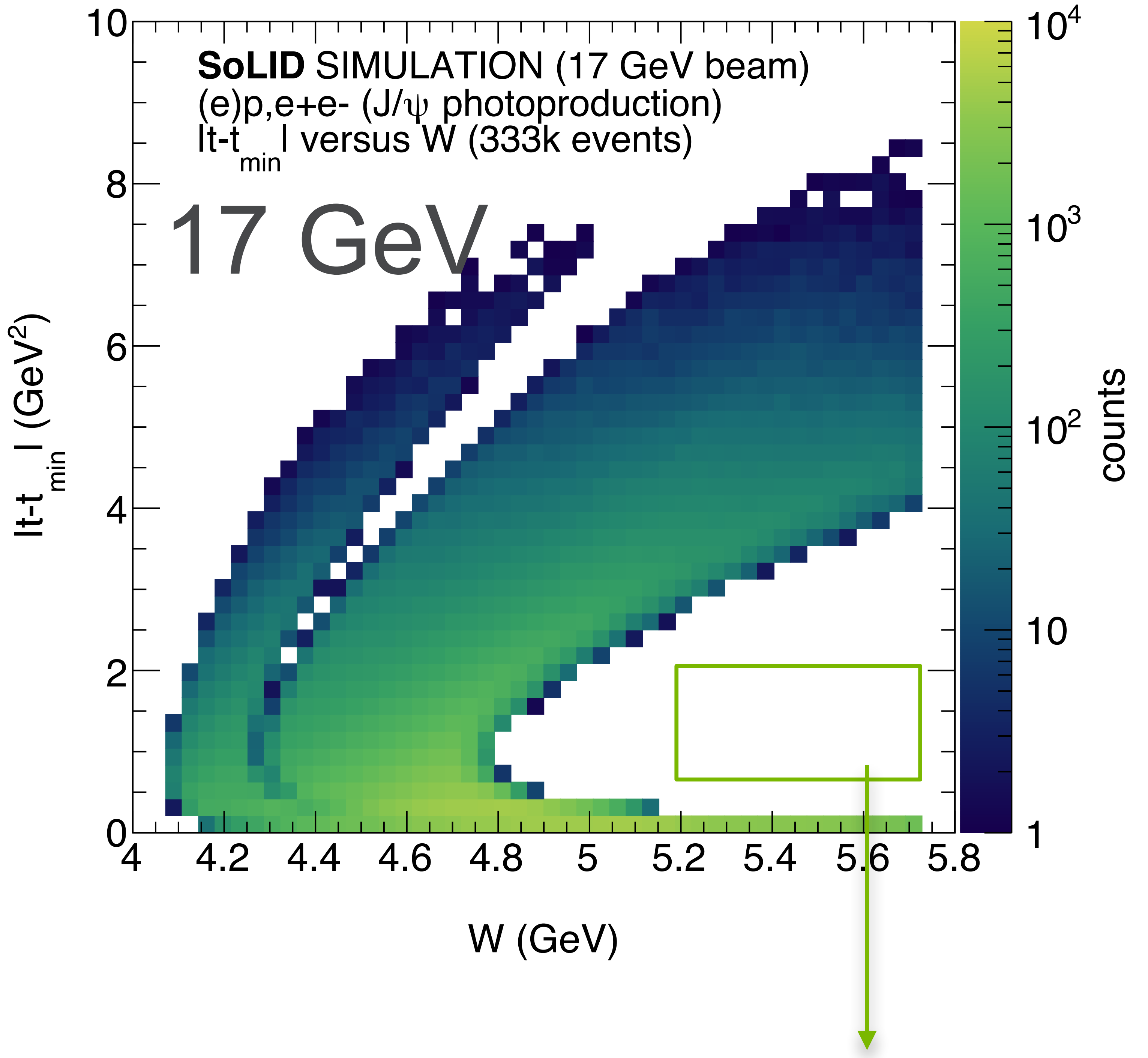


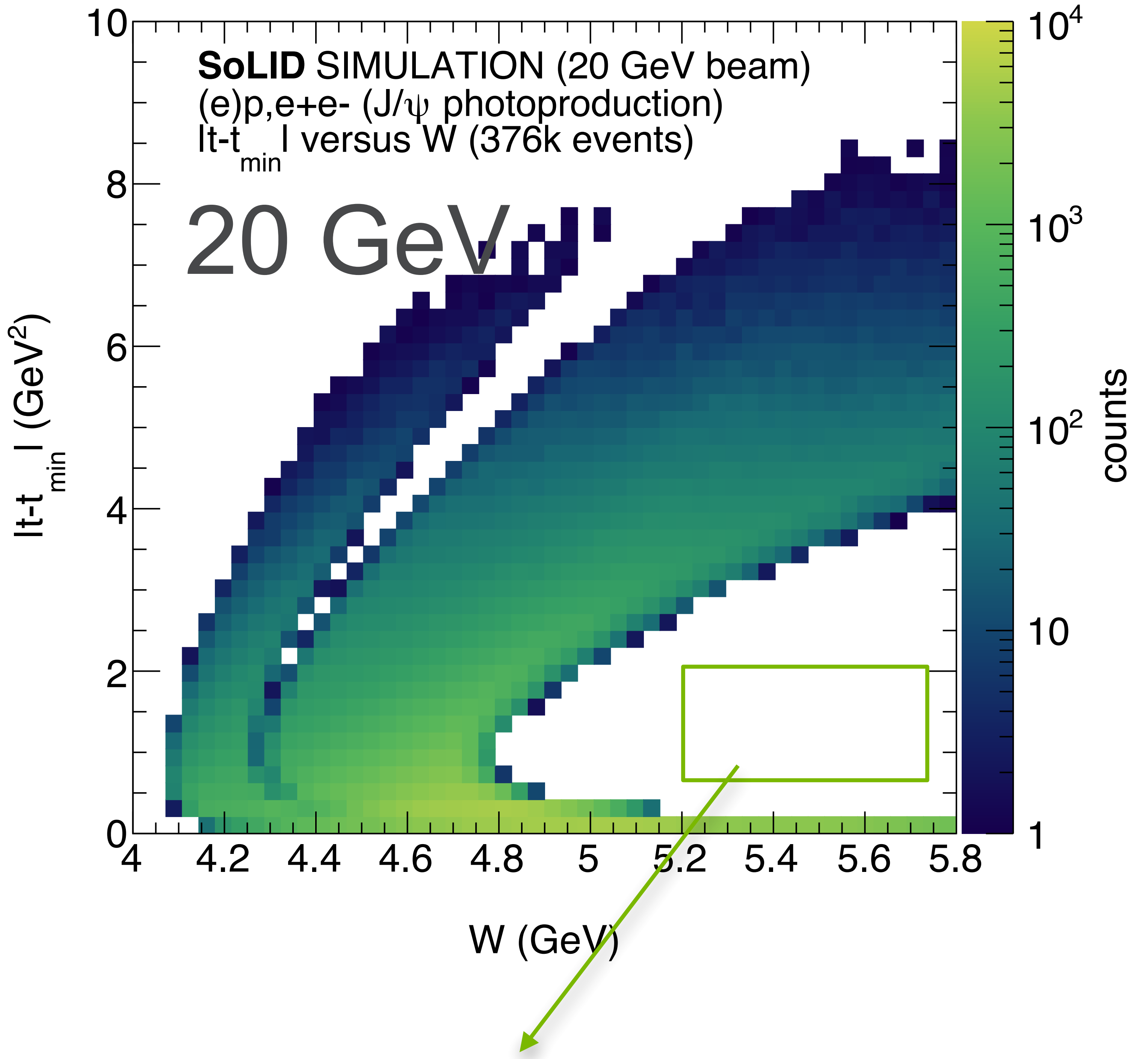
Some room for re-optimization towards larger Q2 by moving the target position

PHOTOPRODUCTION A BIT MORE DIFFICULT

Standard setup misses a large fraction of events at higher energies



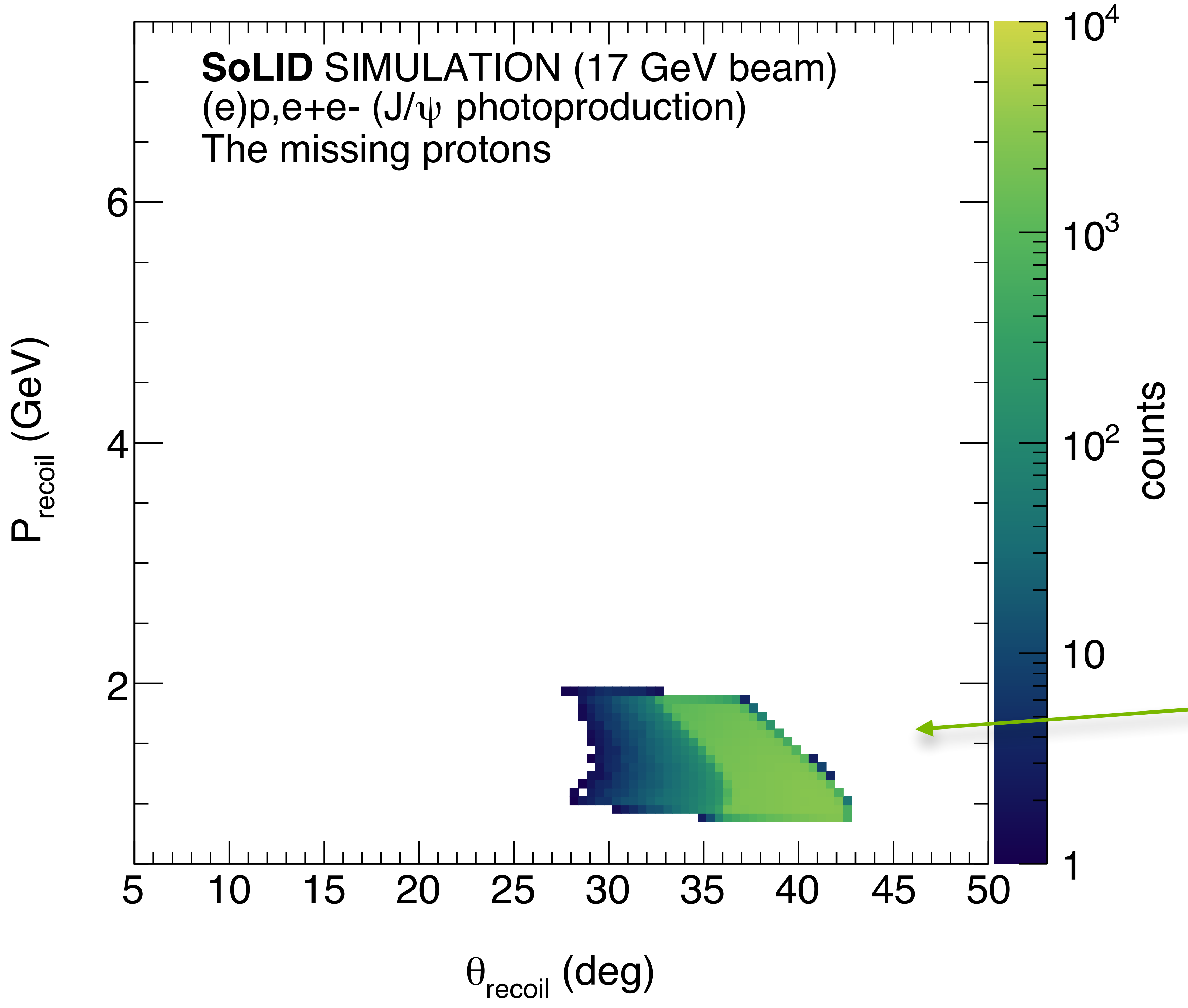


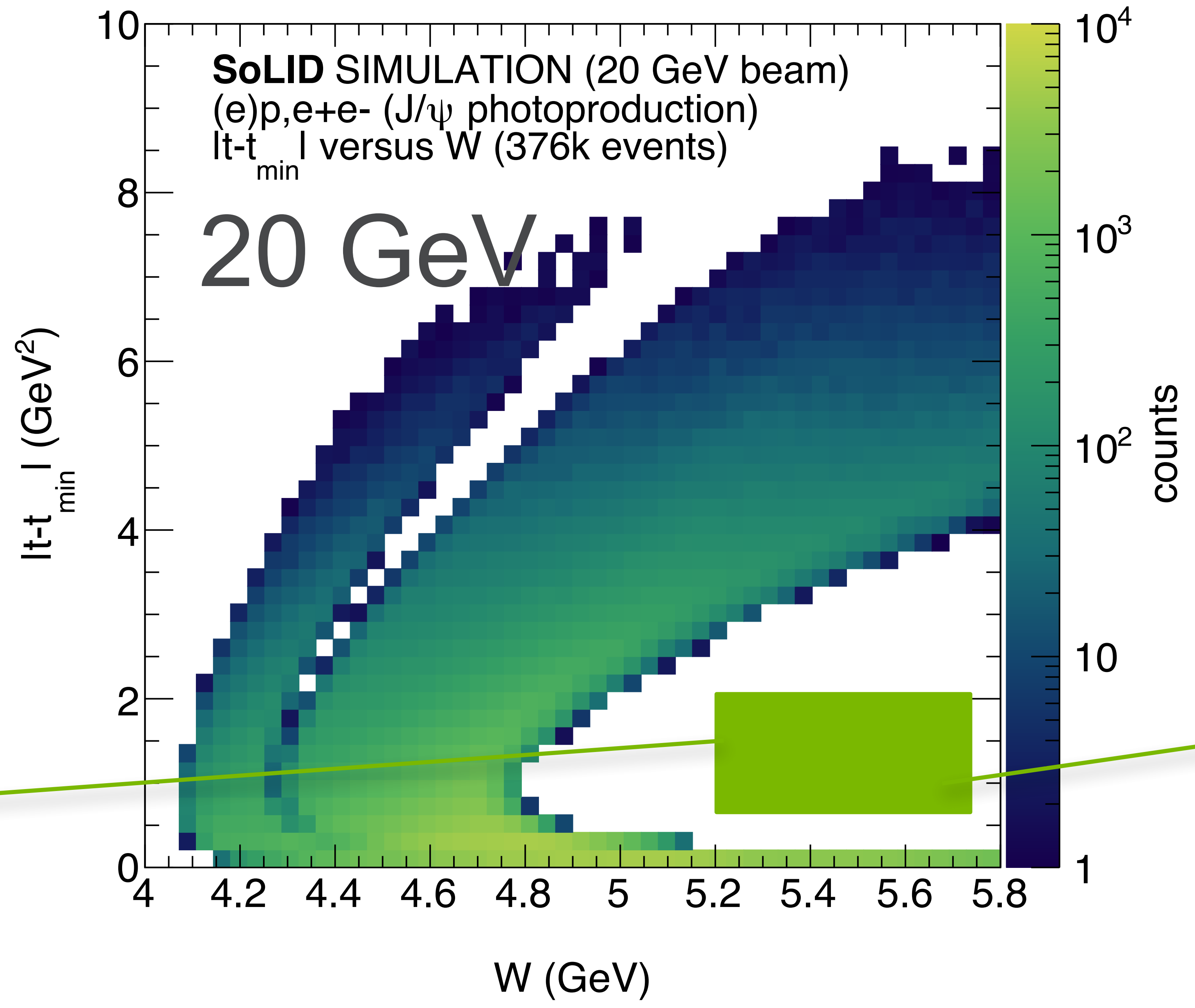


Let's look at the missing events

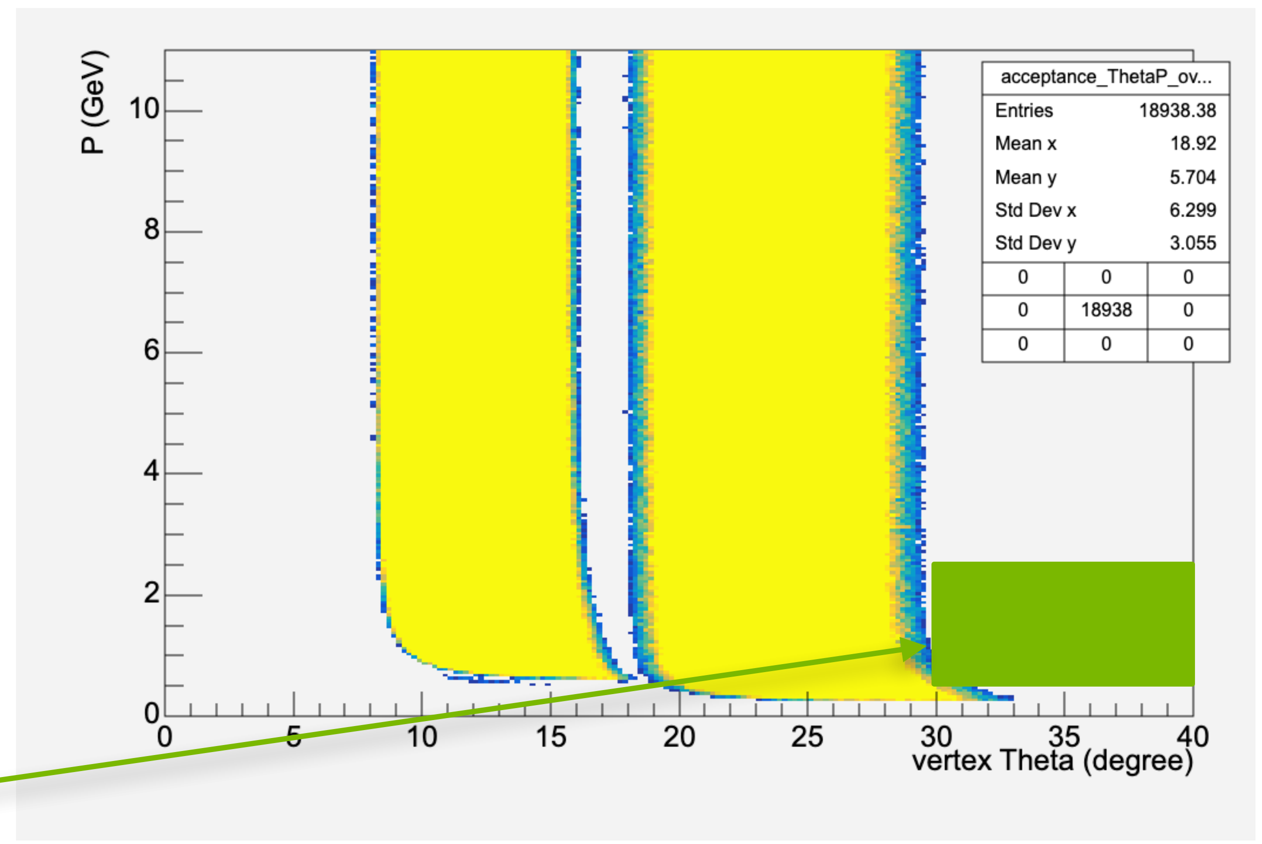
THE MISSING EVENTS… AT LARGE ANGLE???

W > 5.2 GeV, $|t-t_{min}|$ between 0.5 and 2 GeV²





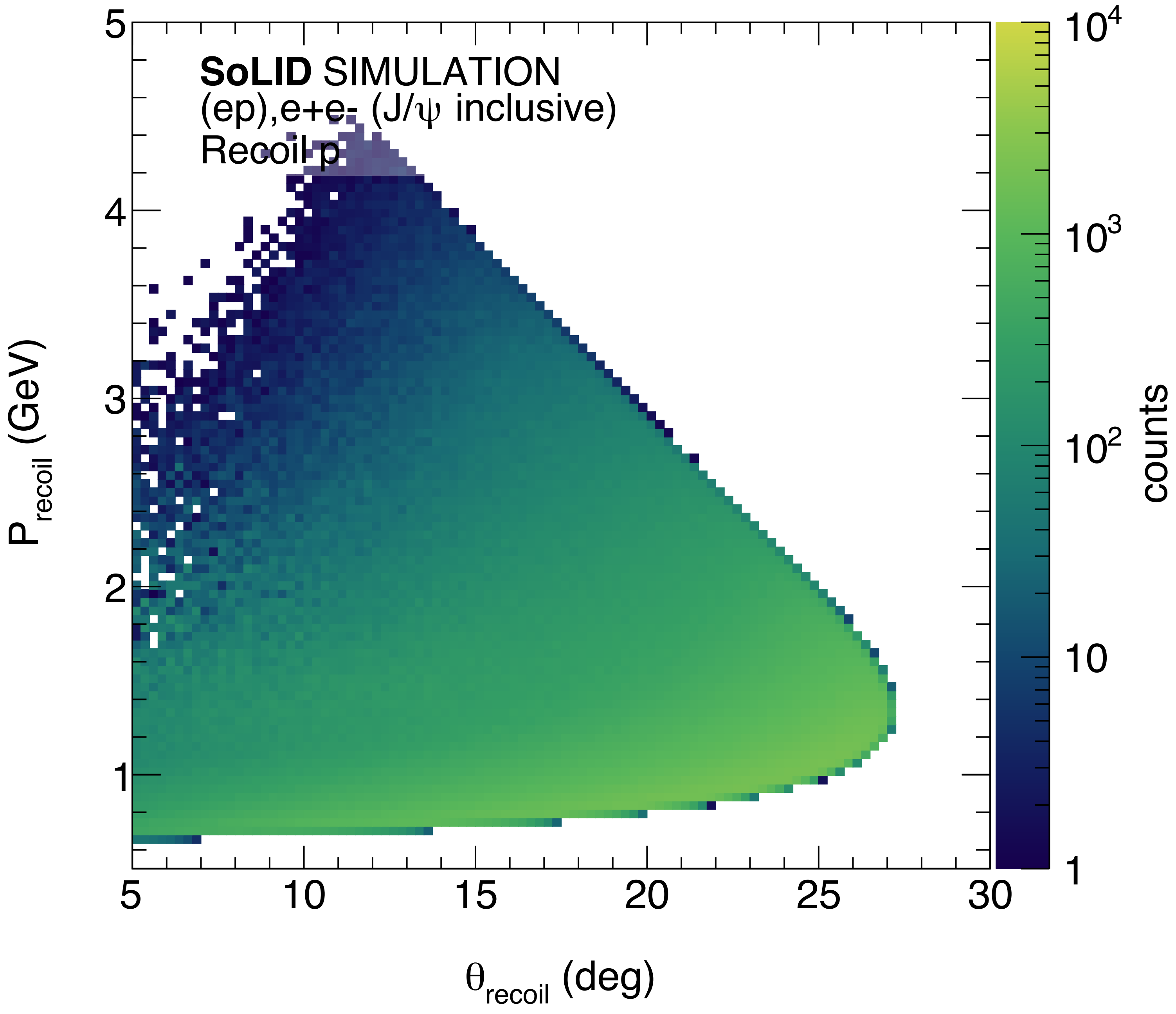
SoLID-Jpsi acceptance

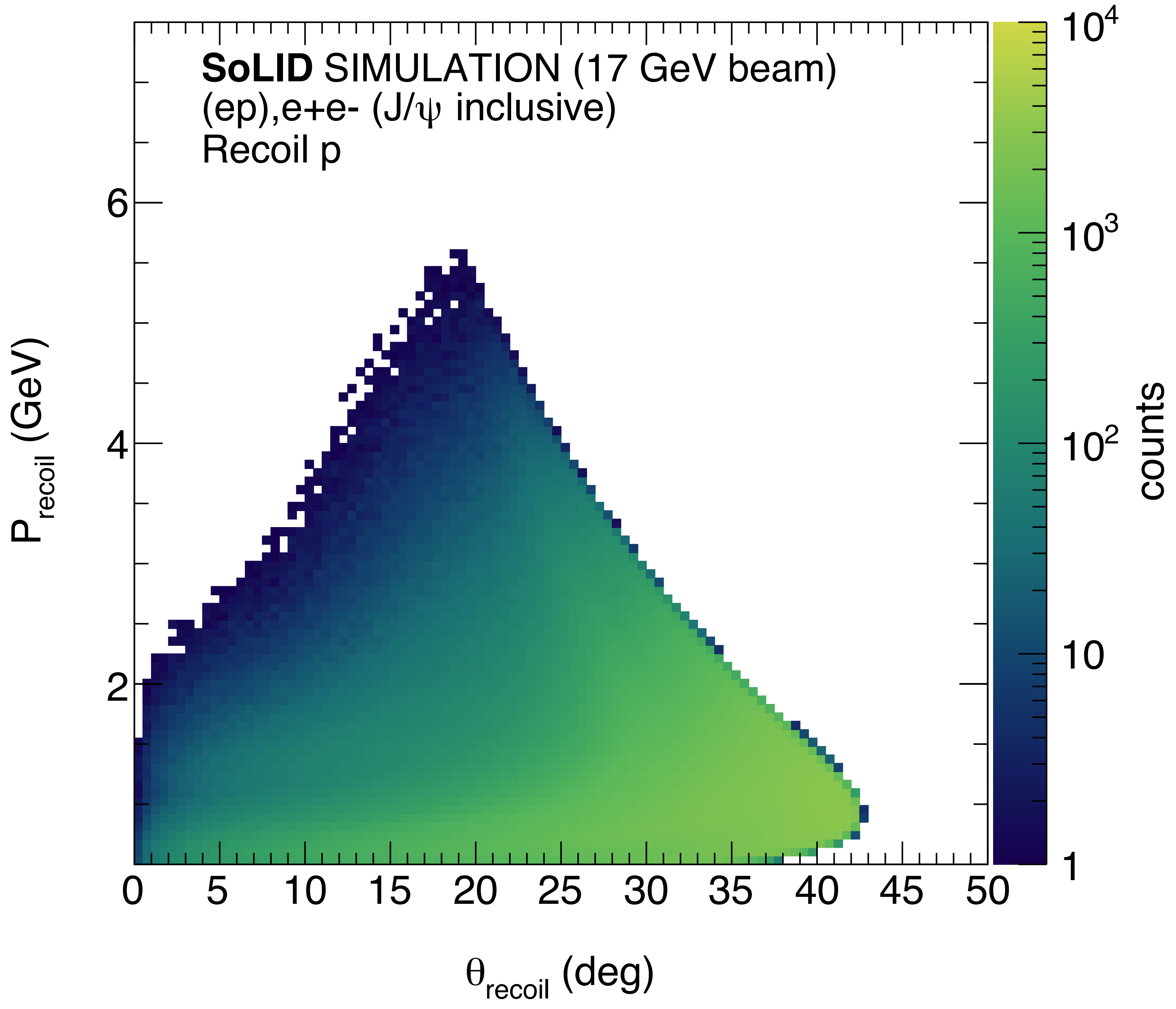


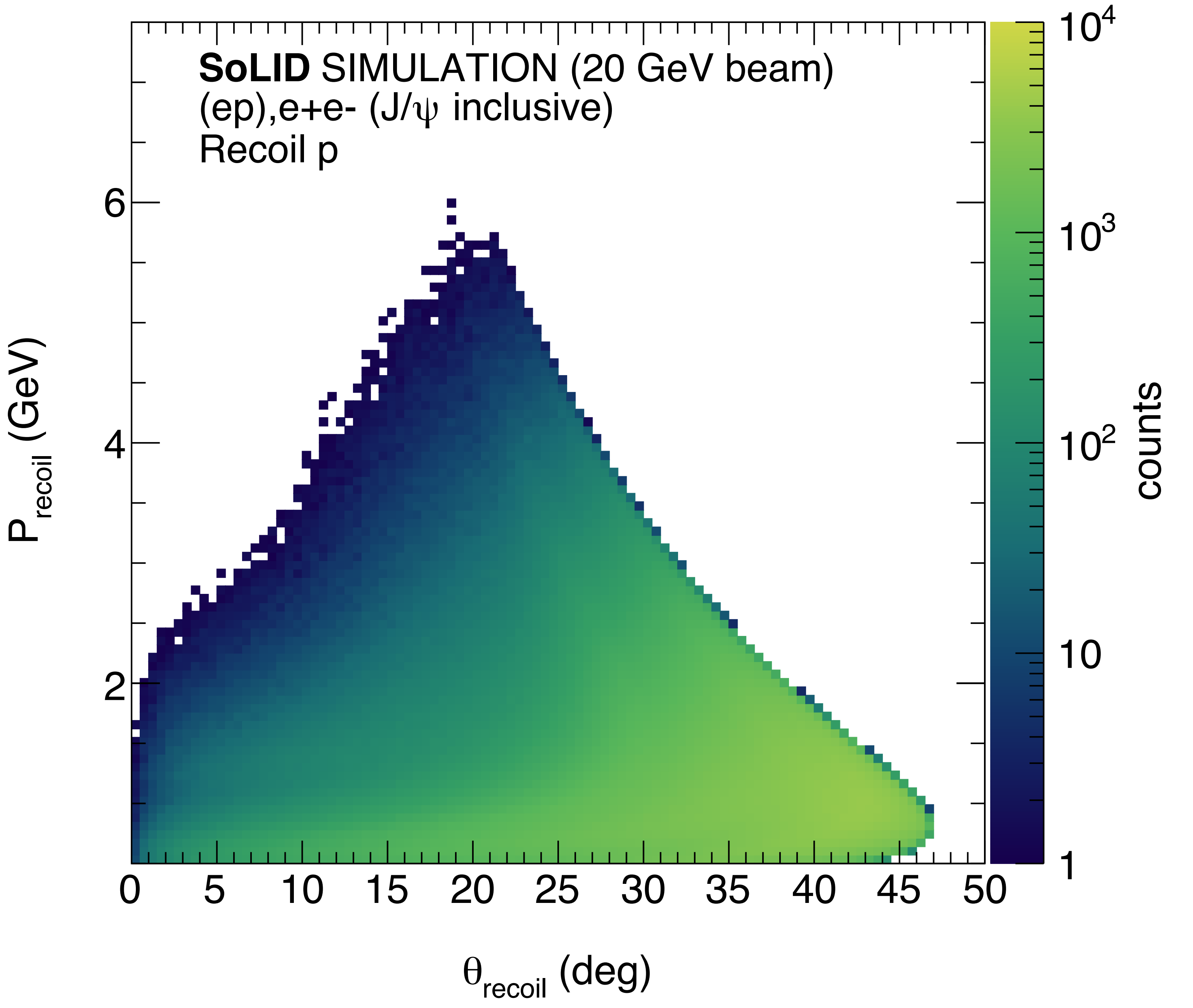
Counterintuitive…, why recoil proton at *larger* angle?

LET’S LOOK AT ALL RECOILS FOR A DETECTED J/PSI

Recoil moving to larger and larger angles for increasing energy







Reason: J/psi are boosted forward at higher energies, so we are selecting at relatively speaking events at increasingly large angles. Momentum conservation then also starts selecting events with a larger recoil angle, leading to an overall drop in acceptance.

Solution: combination of a re-optimized target position, larger-angle recoil detector, instrumenting SoLID to smaller angles should recover these events!

Question: is there a tradeoff with an optimization for high-Q^2 or can we do both?

WHY Ψ’ PRODUCTION?

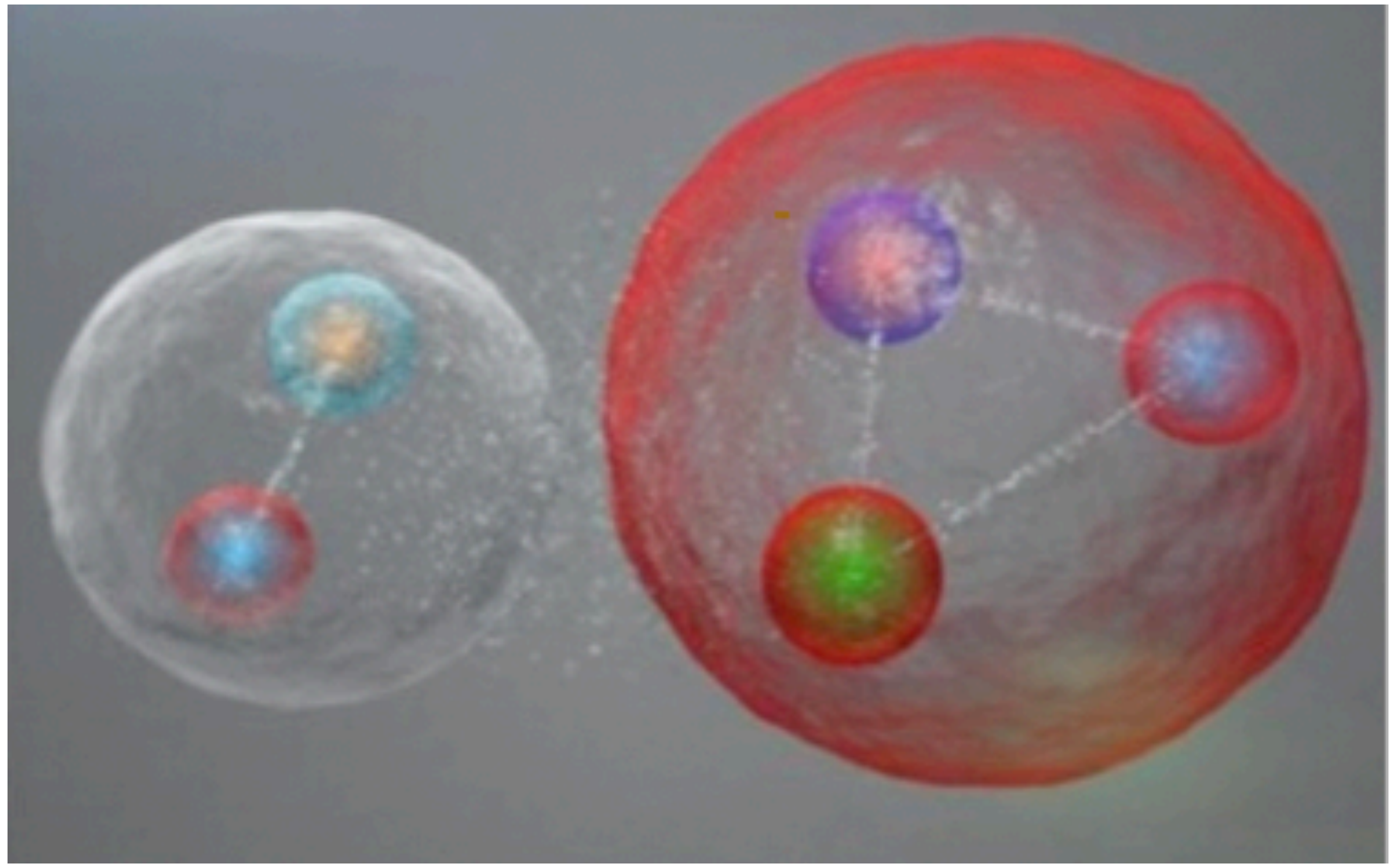
Independent, more sensitive probe (larger color dipole!)

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.



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

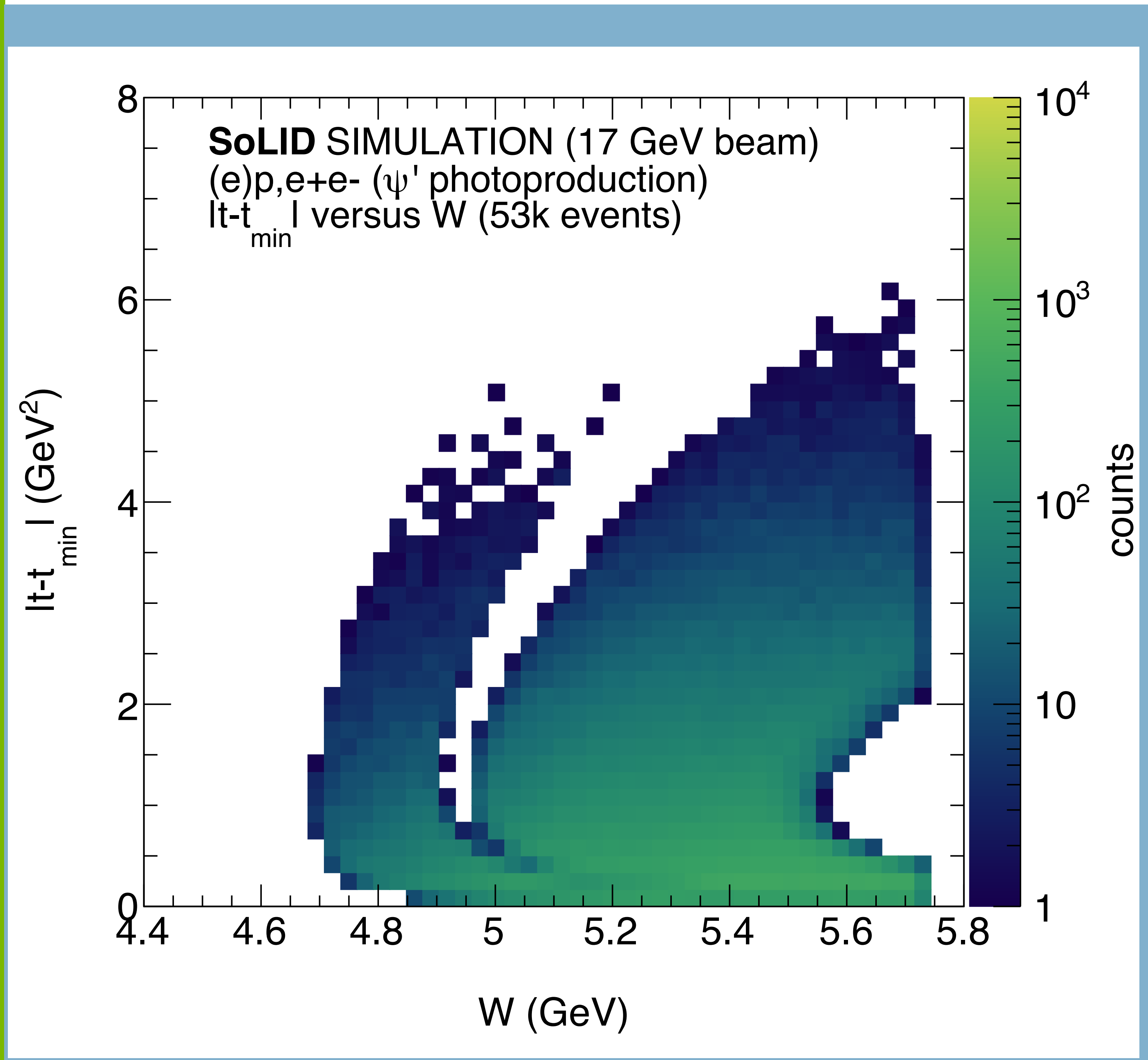
End result: factor of about 47 reduction in rate for $(\gamma p \rightarrow \psi(2s)p \rightarrow pe^+e^-)$.

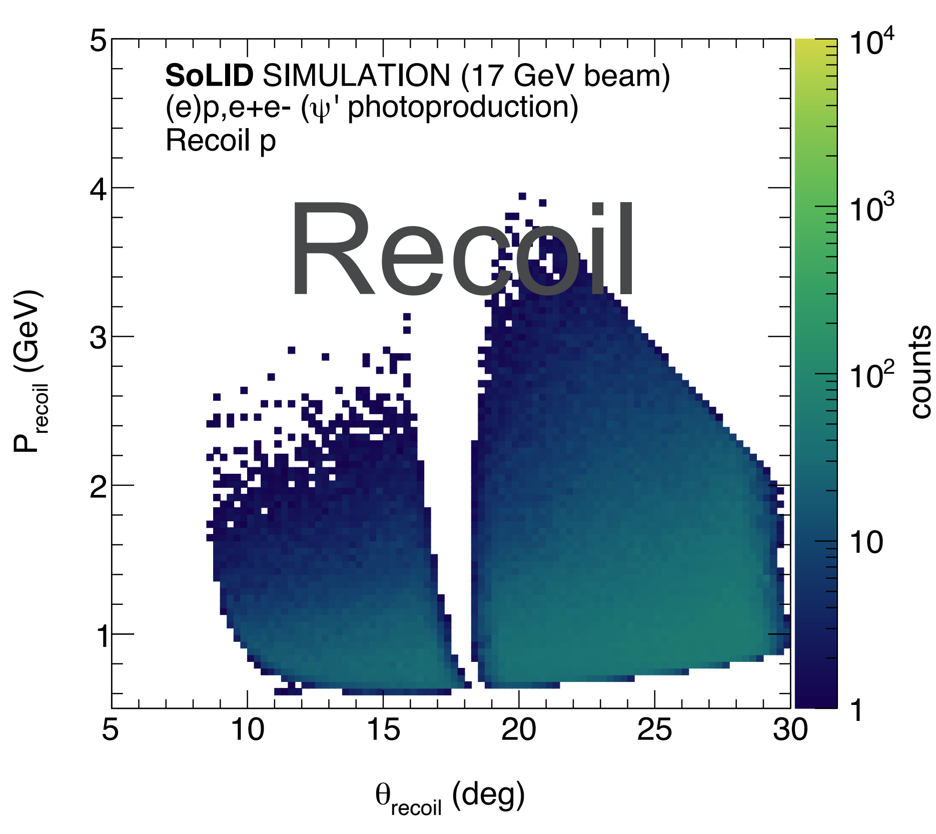
Hence, measurement requires very high luminosity. Could also be approached by exploring other decay channels

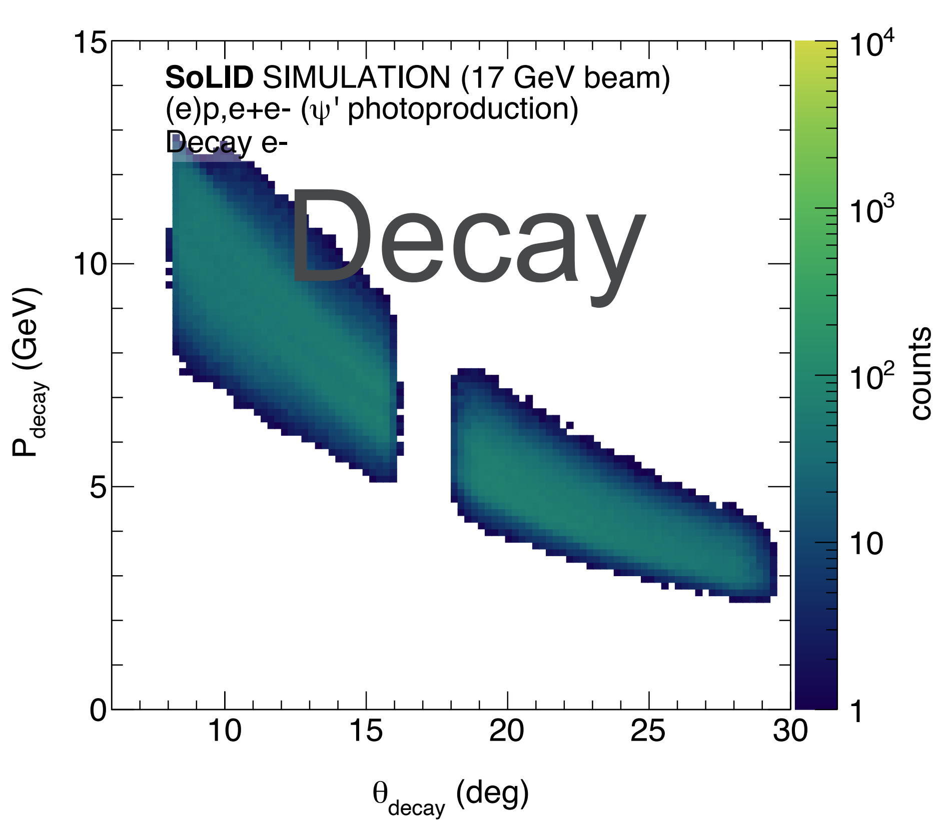
EXPERIMENTAL CONSIDERATIONS WITH SOLID

17 GeV optimum with current SoLID-J/ψ setup

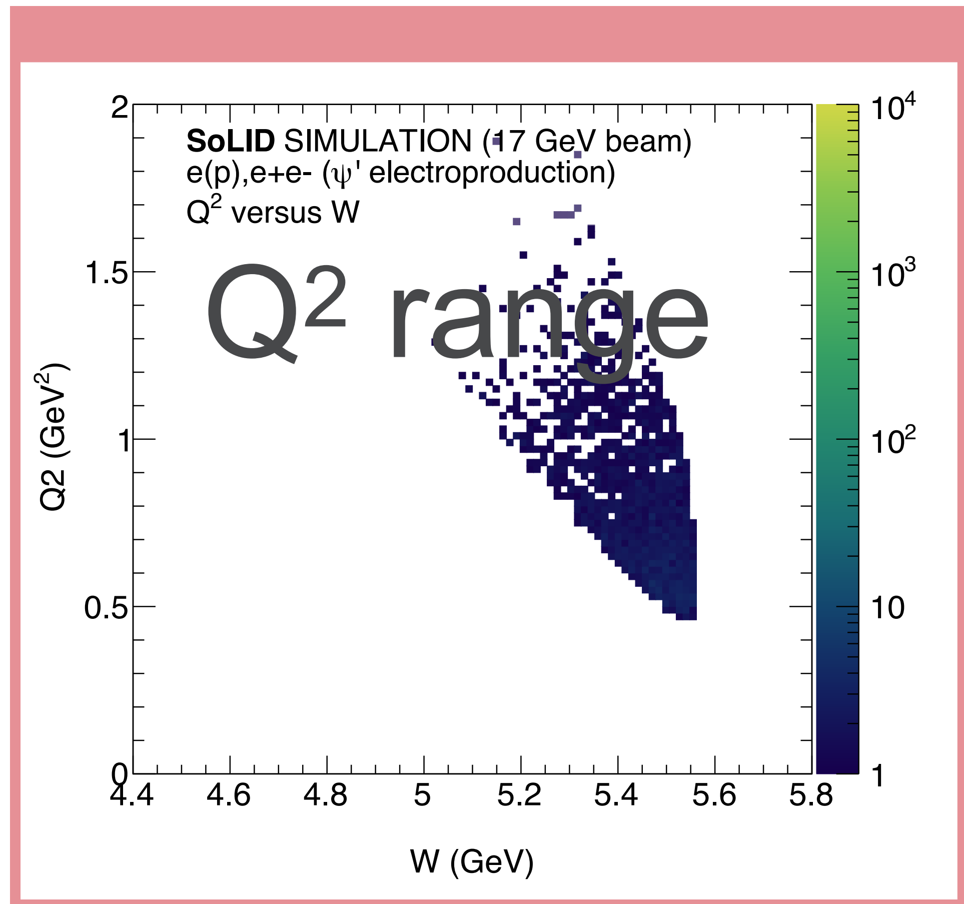
Triple-coincidence phase space for ψ' production at SoLID assuming 50 days at 10^{37}/cm^{2}s

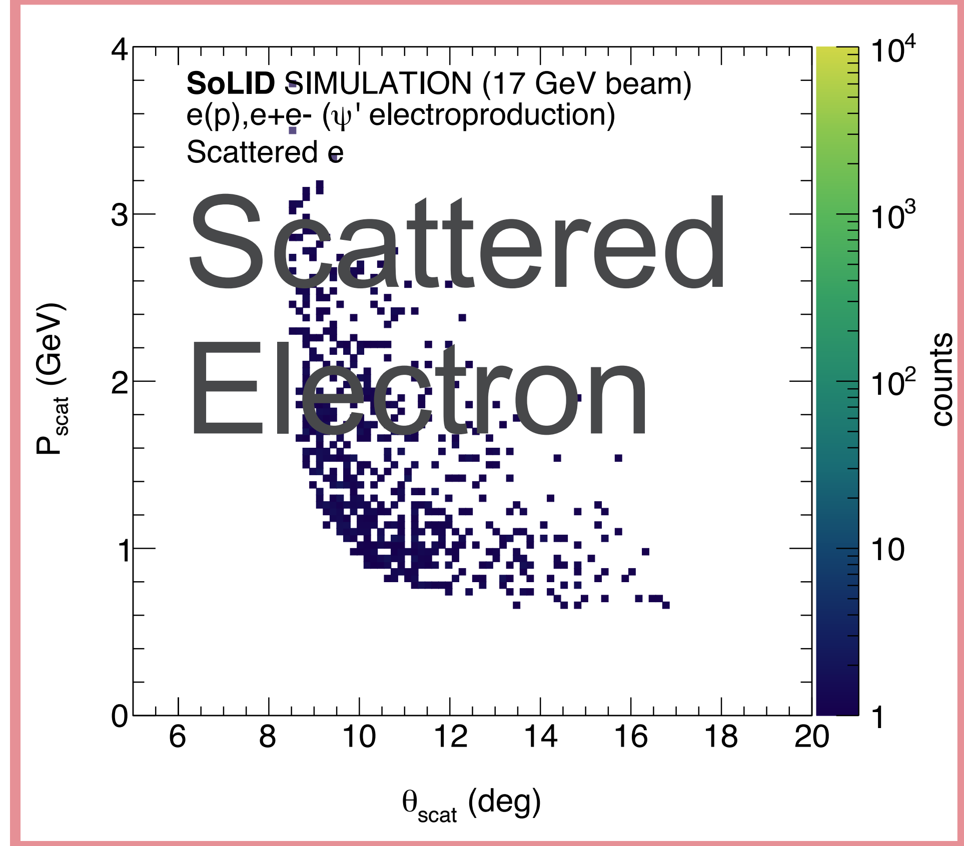


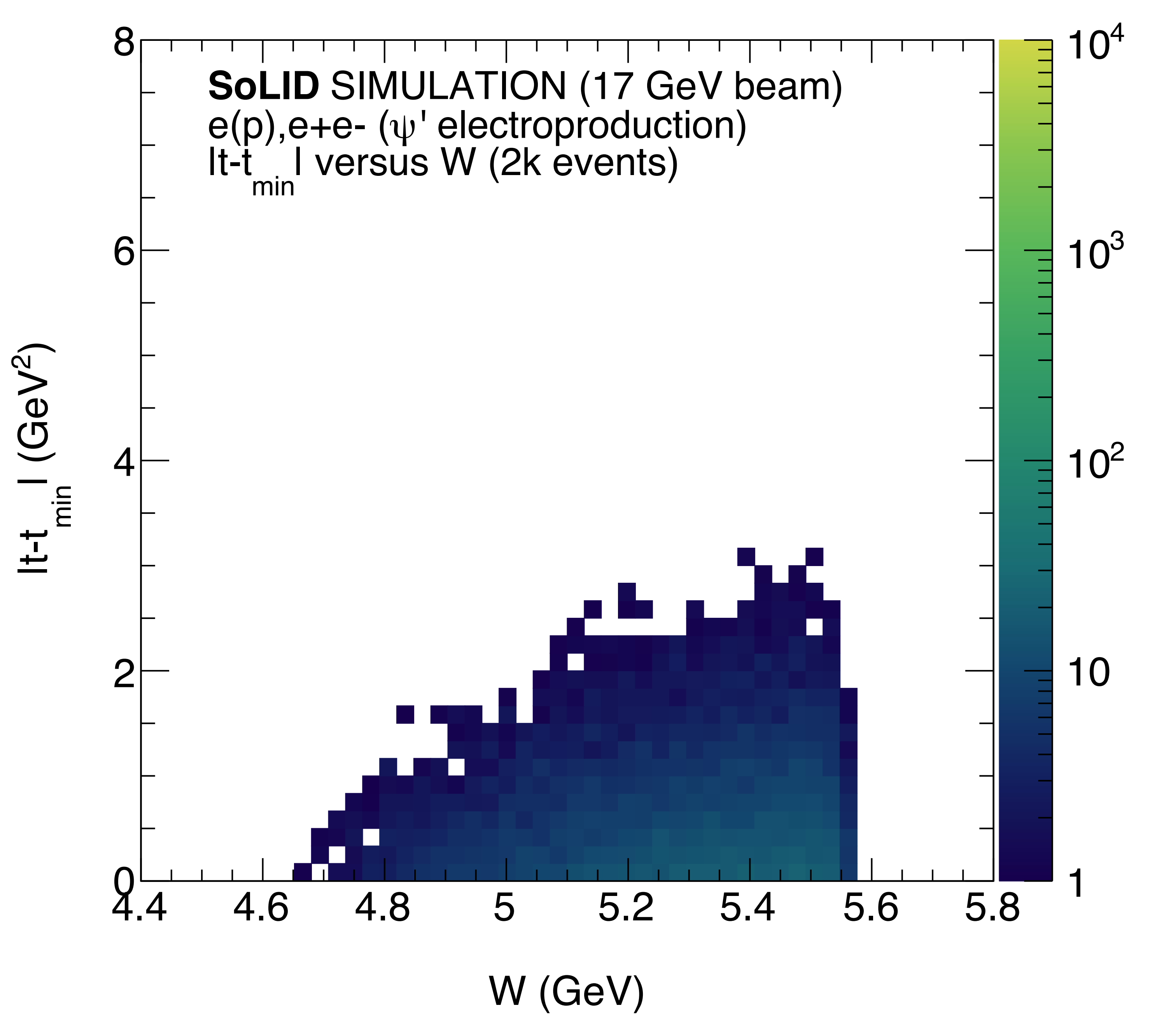




Photoproduction





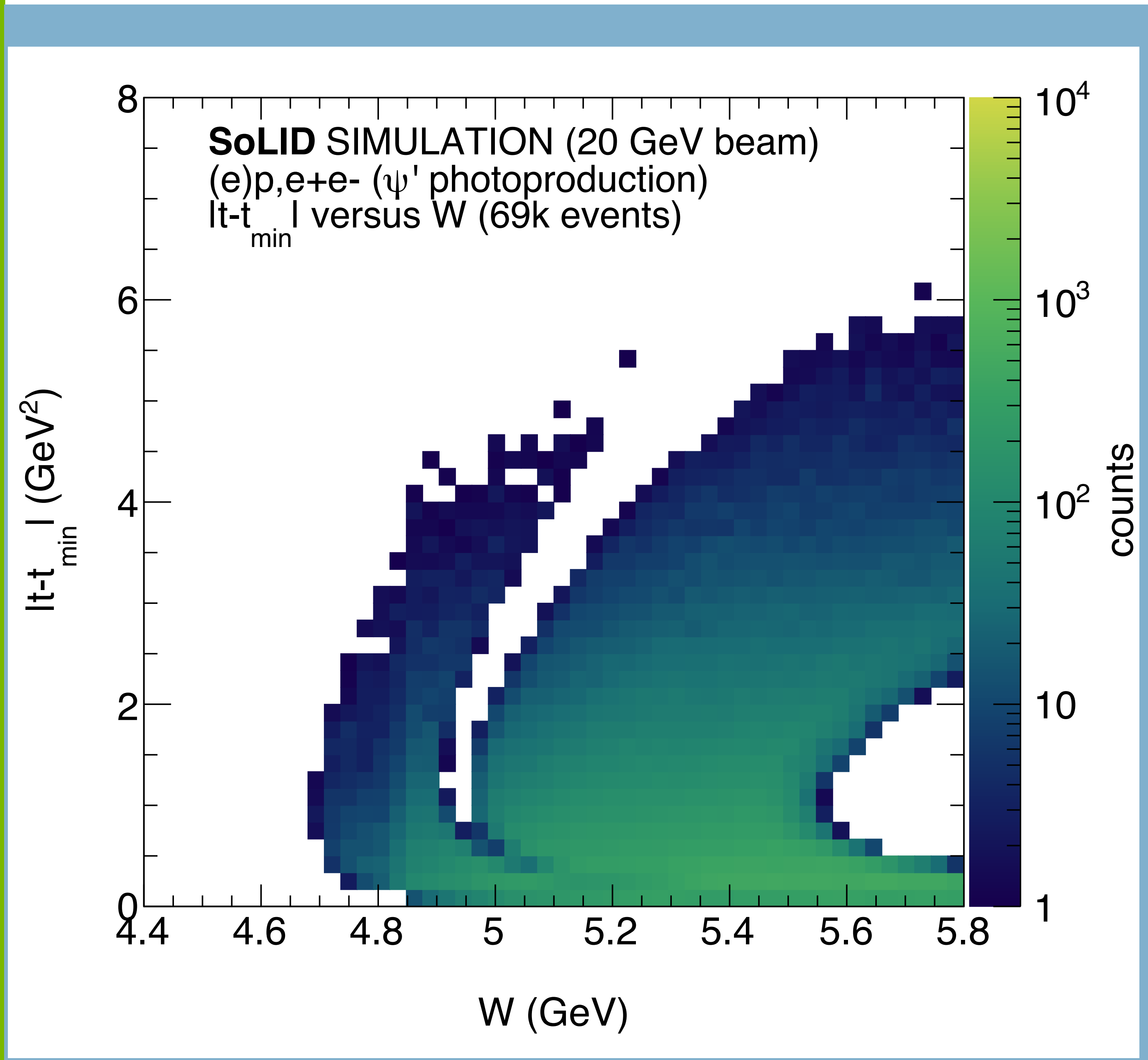


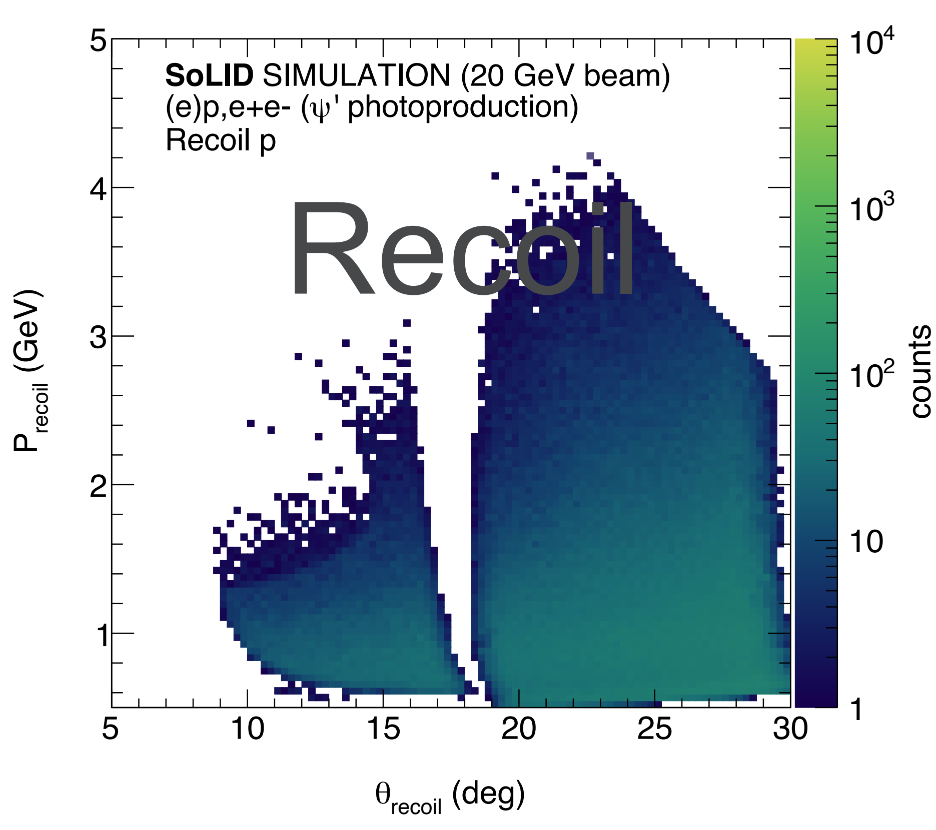
Electroproduction

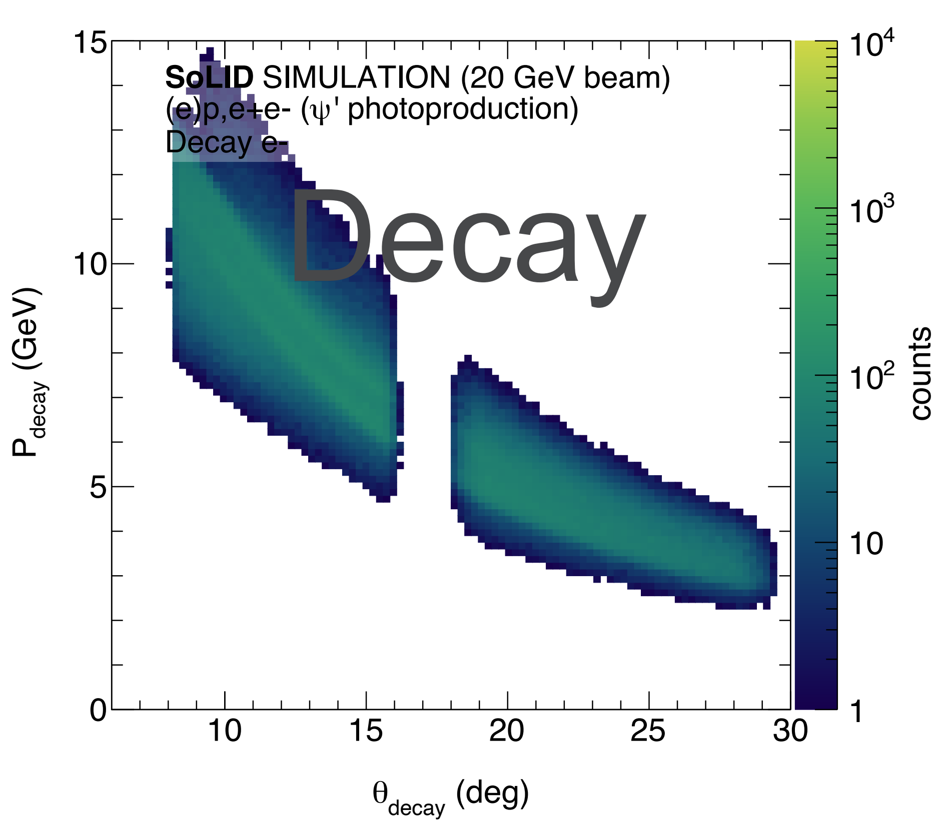
EXPERIMENTAL CONSIDERATIONS WITH SOLID

20 GeV (and higher) would require modifications to target location

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







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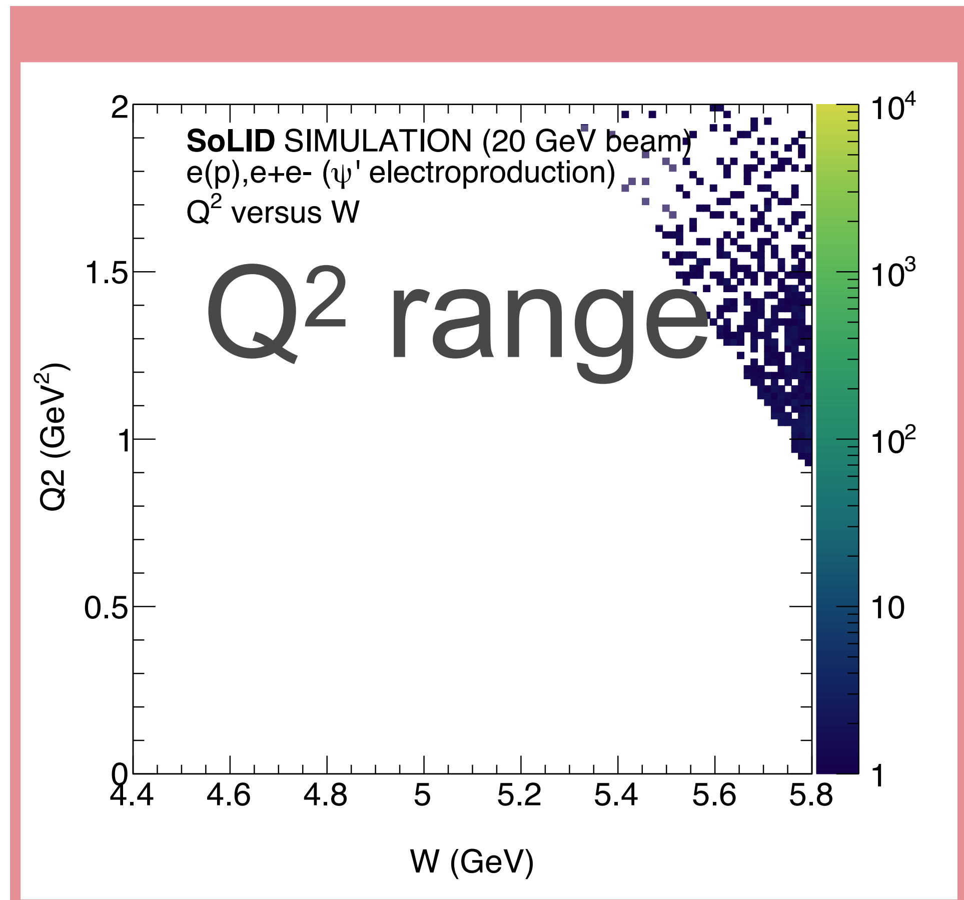
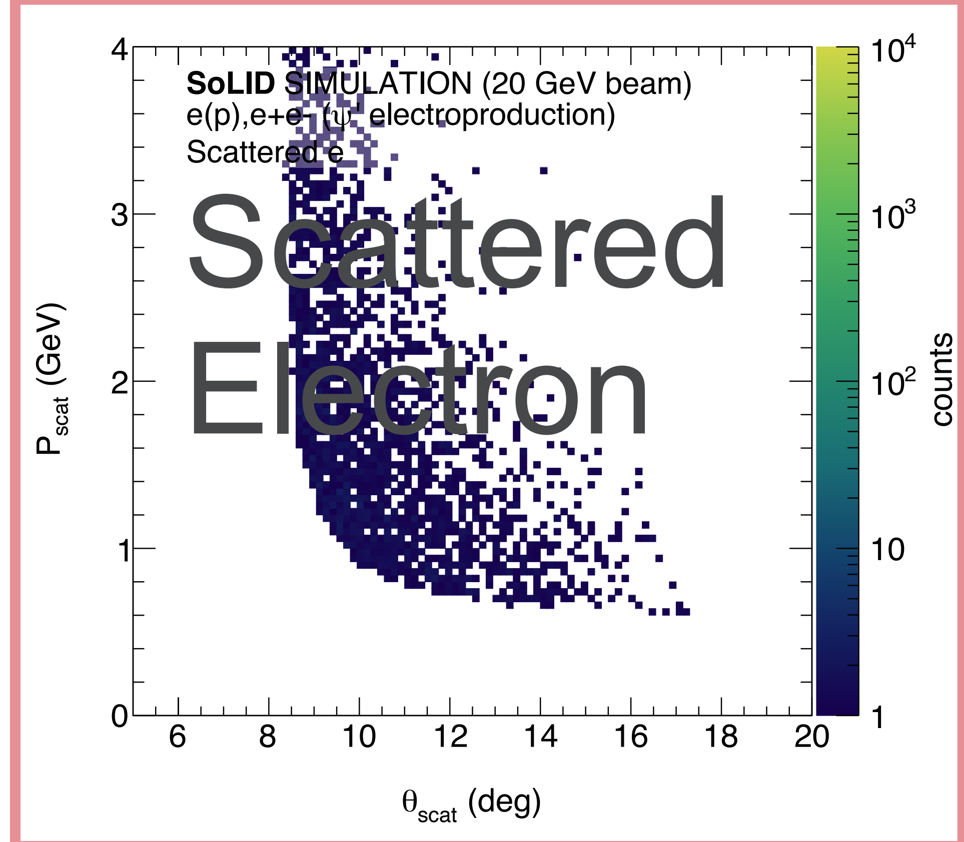
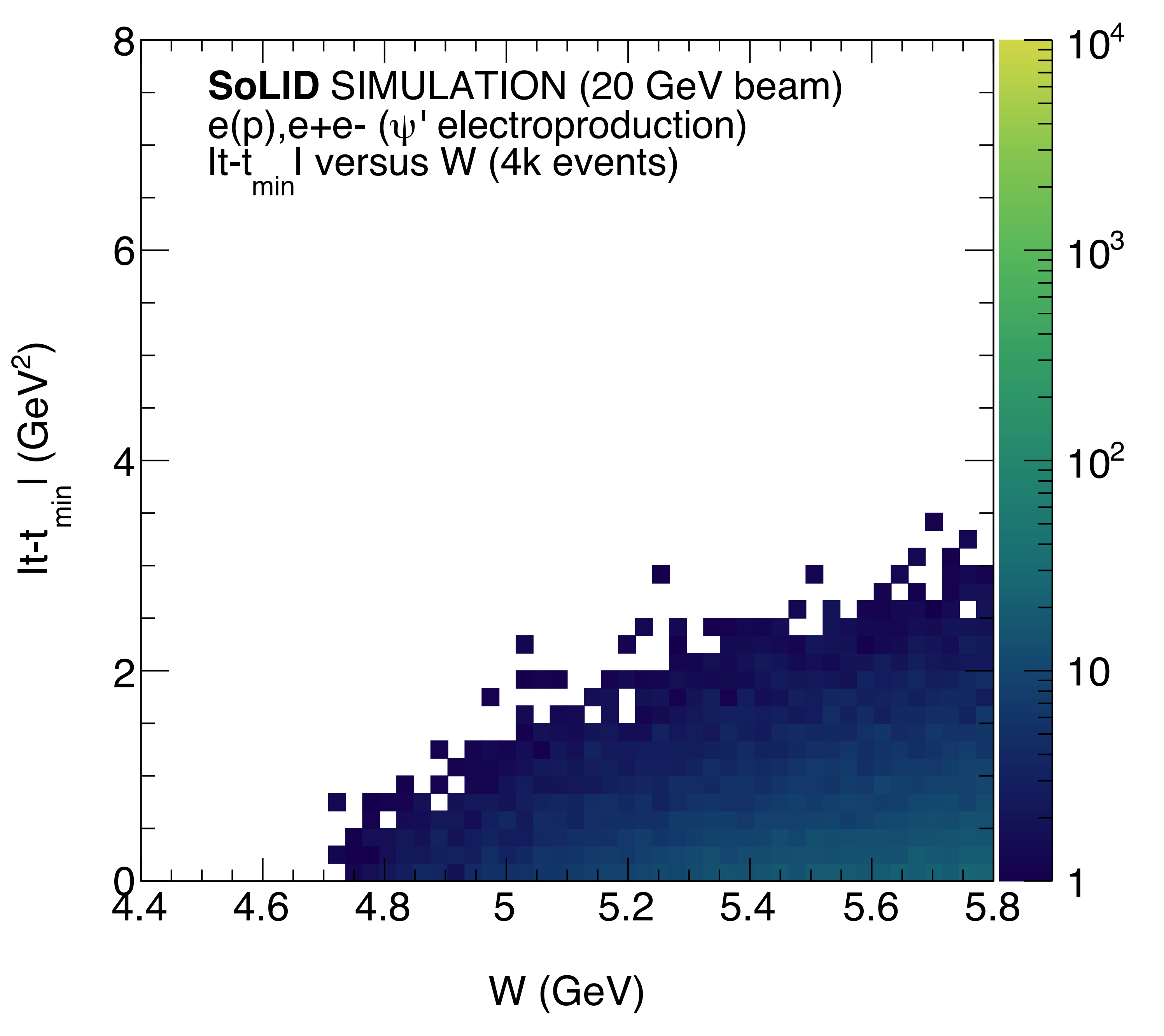
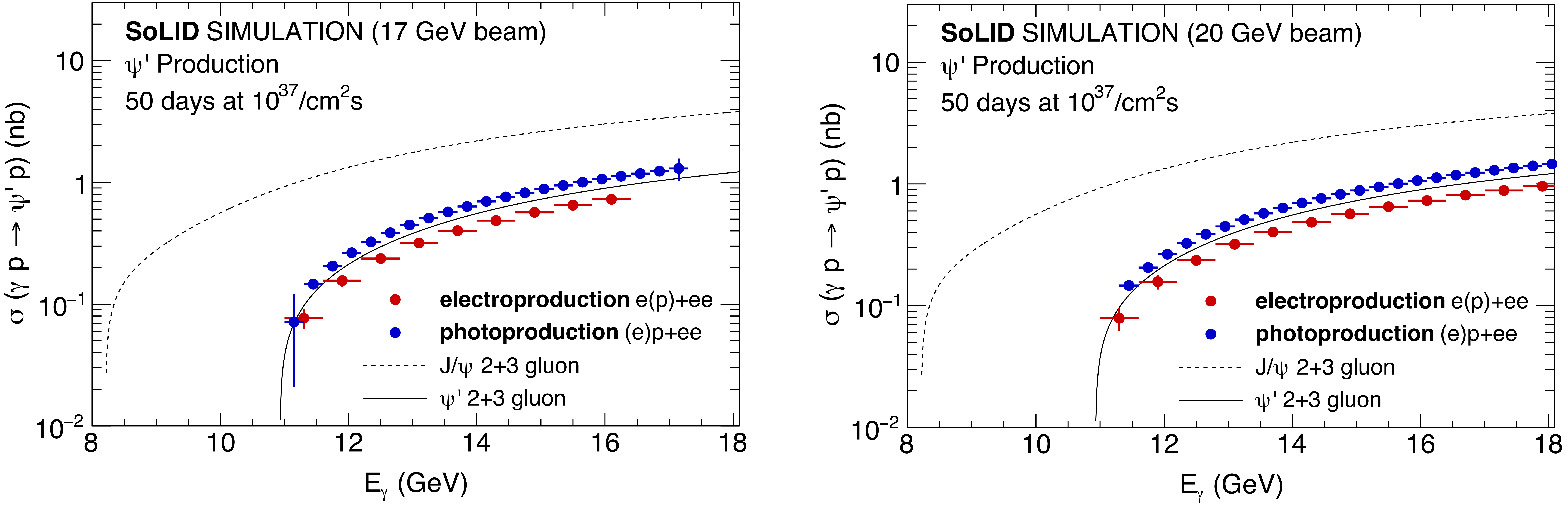




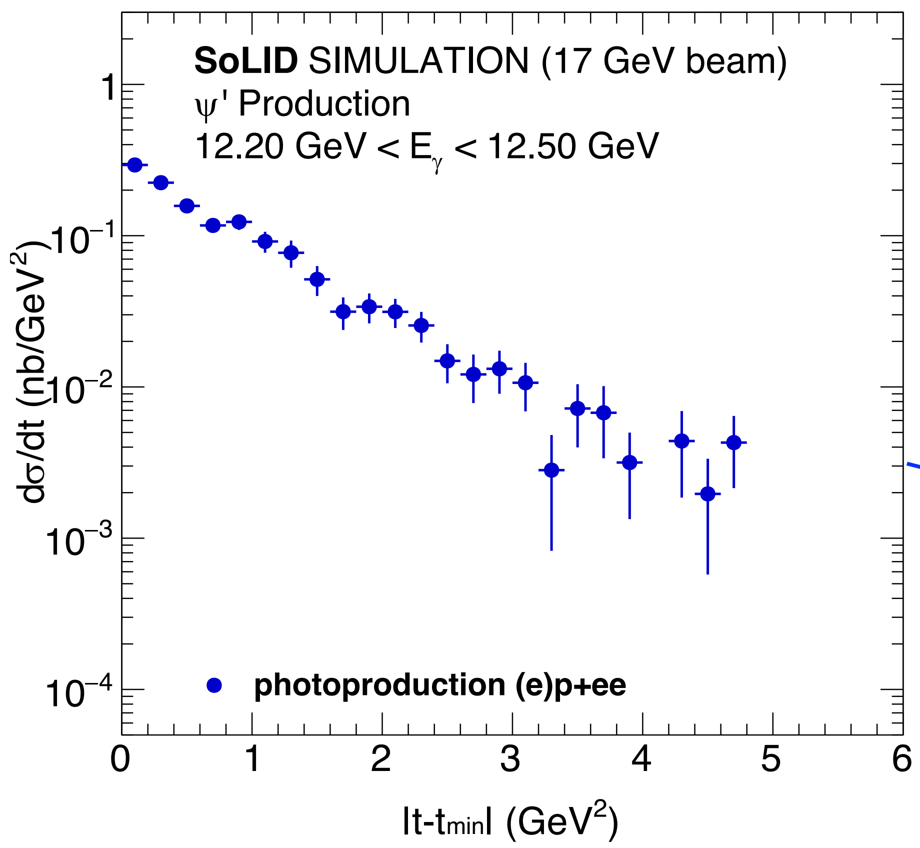


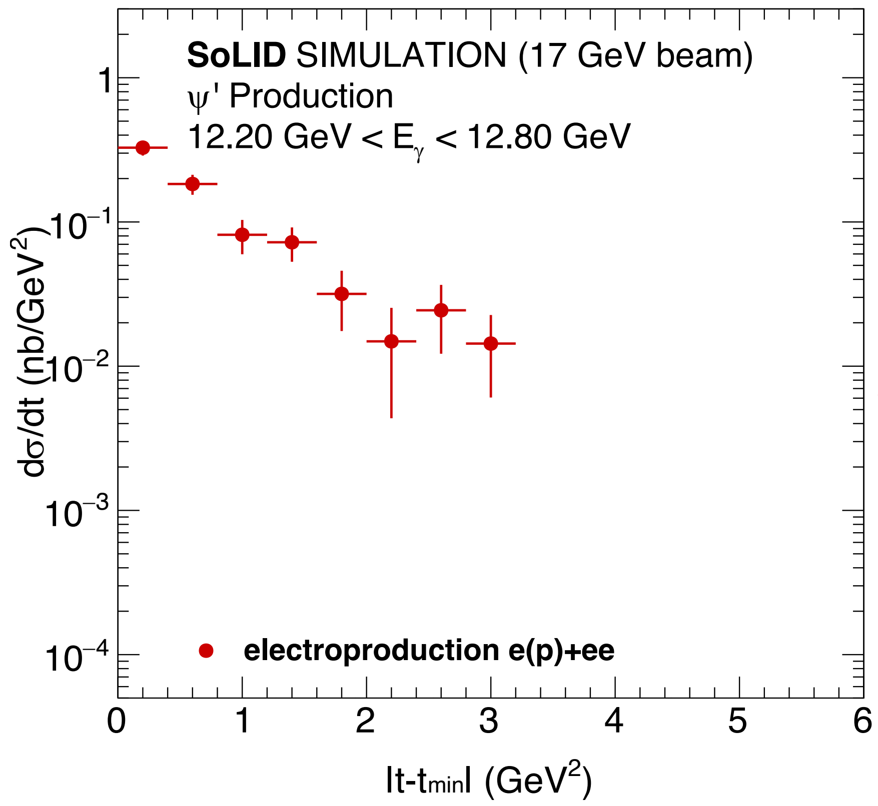
Electroproduction

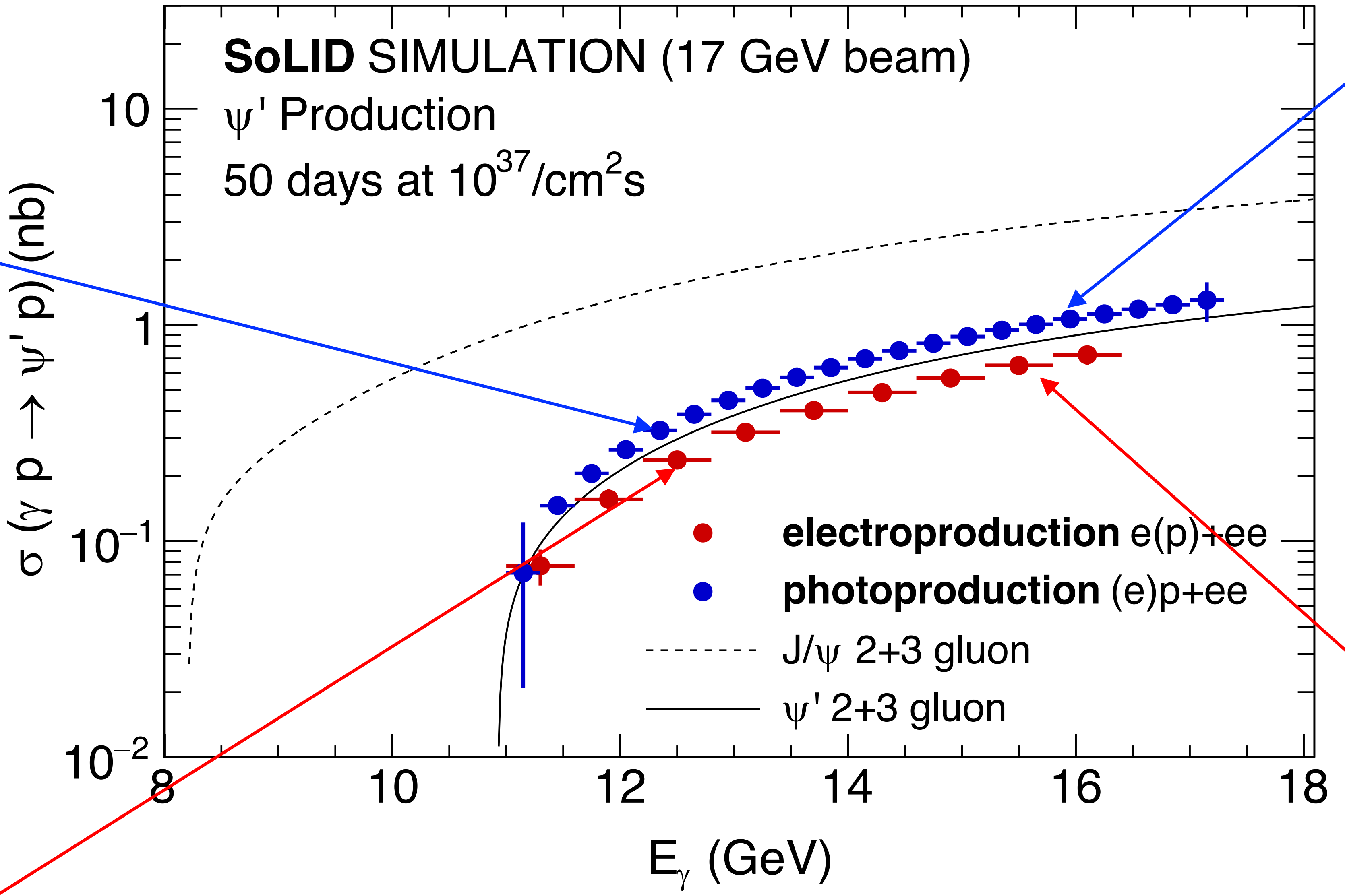
PHYSICS REACH WITH DIFFERENT BEAM ENERGIES

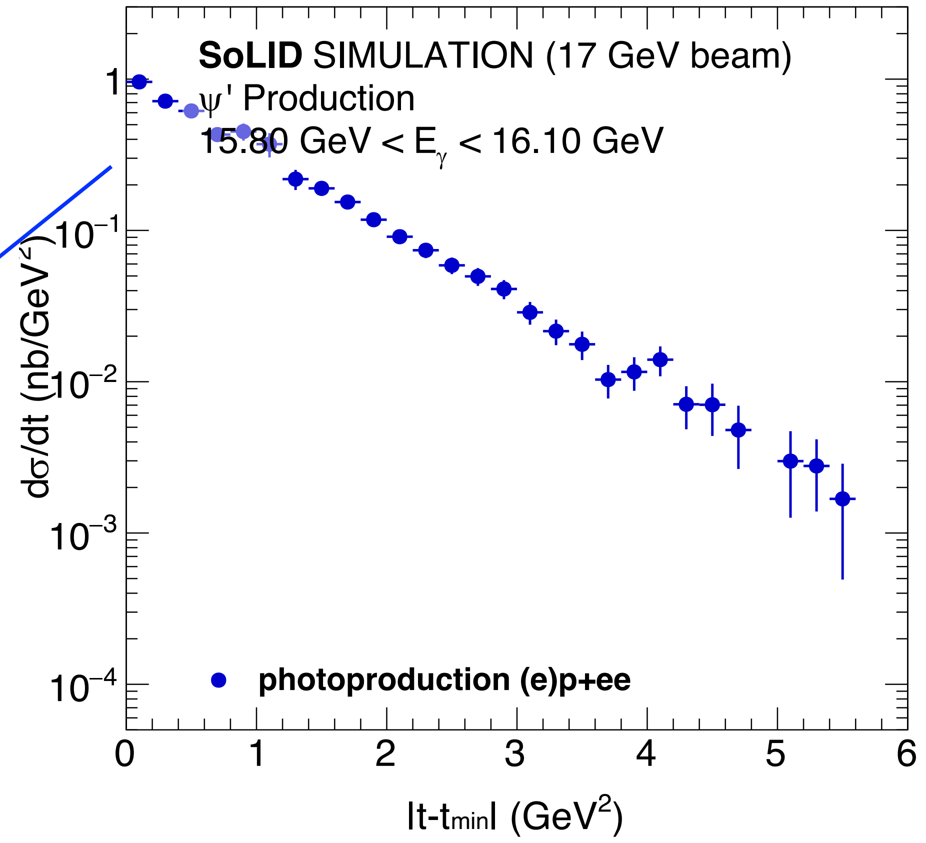


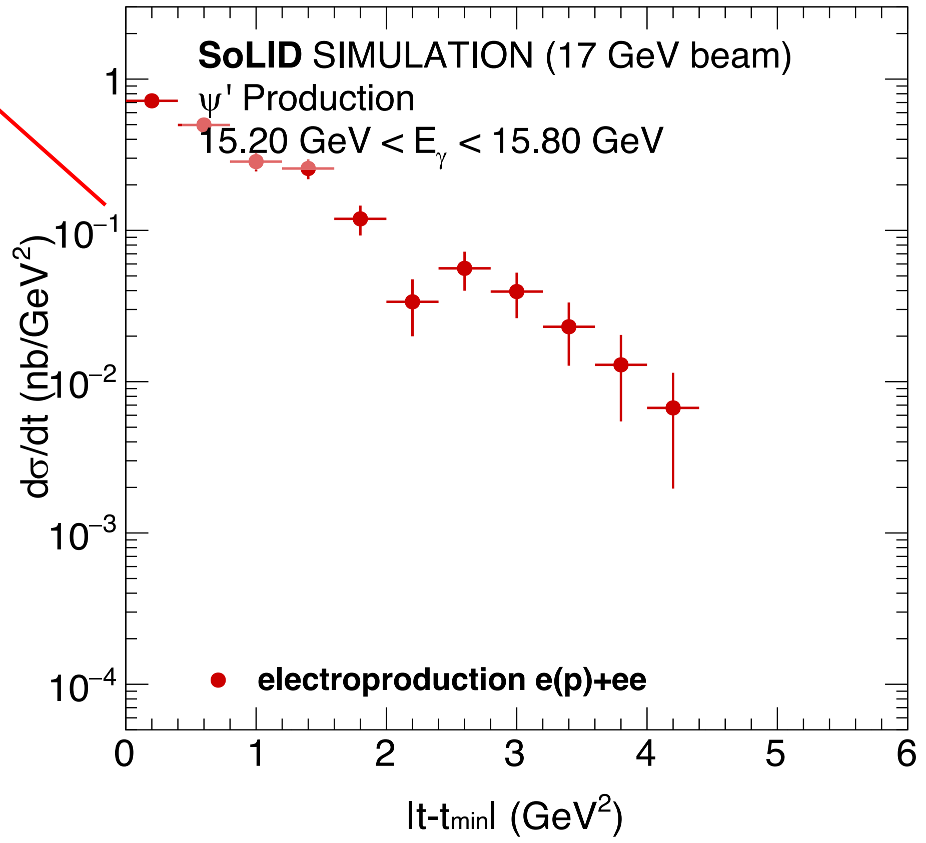
2D CROSS SECTION POTENTIAL









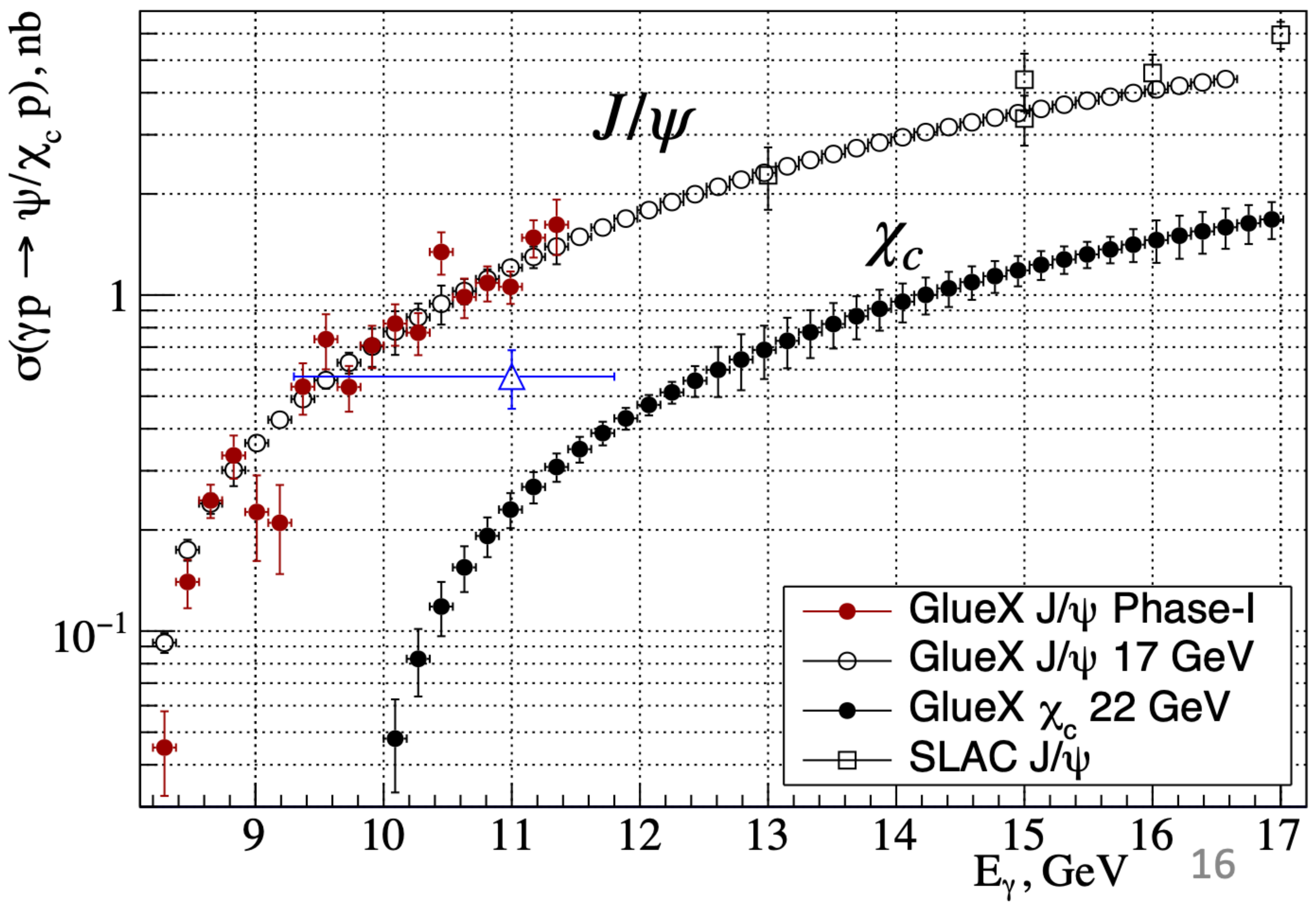


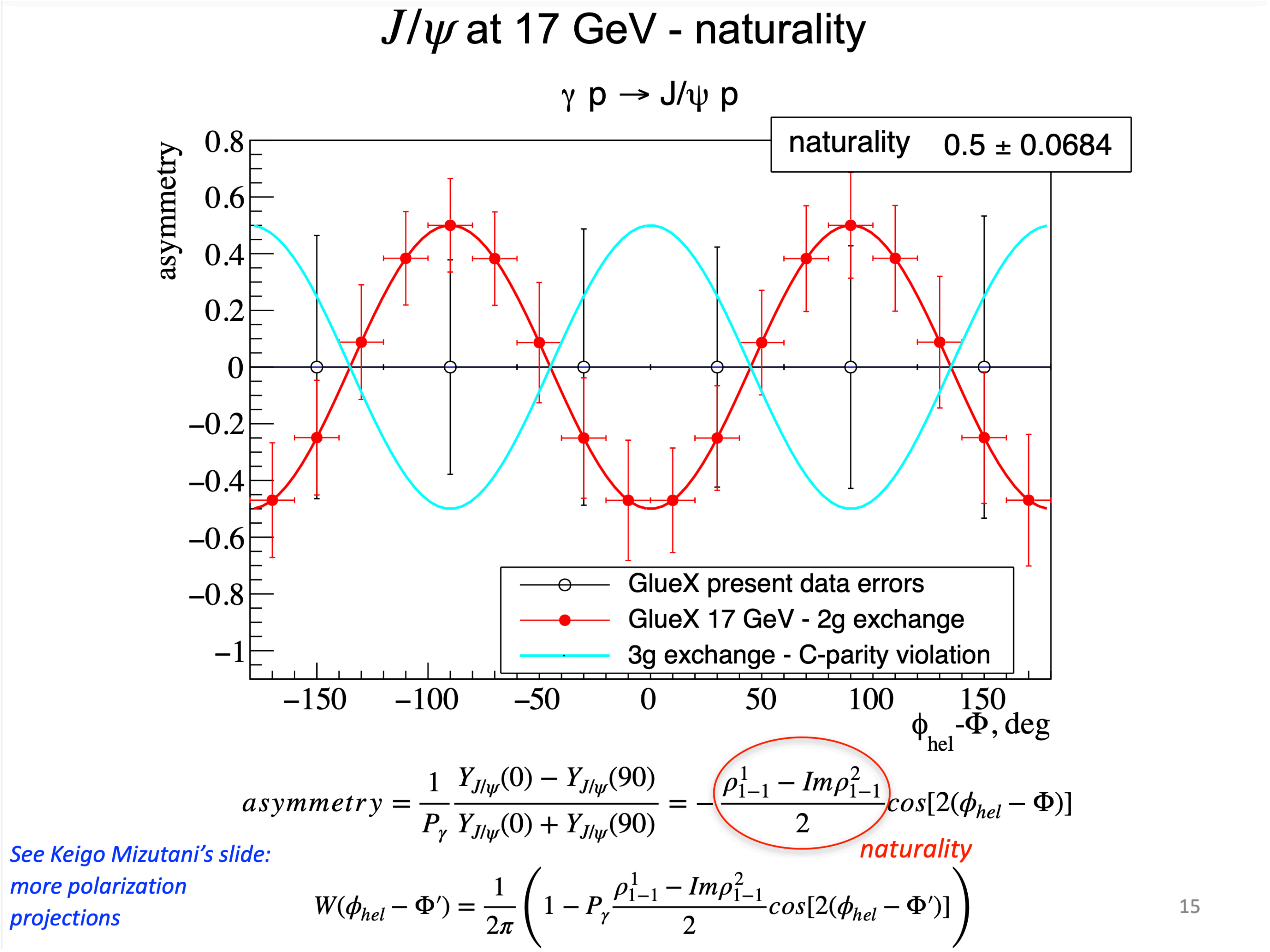
2D measurement of ψ(2s) cross section feasible for both photoproduction and electroproduction with the nominal SoLID-J/ψ setup.

THOUGHTS ON “JLAB BEYOND”

What can be done with a JLab energy upgrade at GlueX?

- 17+GeV at GlueX will allow for **measurements of polarization observables** that can help separate different contributions to J/ψ production
- Energy upgrade would enable looking at C-even charmonium states





J/ψ at 17 GeV - naturality

$$asymmetry = \frac{1}{P_\gamma}\frac{Y_{J/\psi}(0) - Y_{J/\psi}(90)}{Y_{J/\psi}(0) + Y_{J/\psi}(90)} = -\frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi)]$$

naturality

See Keigo Mizutani’s slide: more polarization projections

$$W(\phi_{hel} - \Phi') = \frac{1}{2\pi}\left(1 - P_\gamma \frac{\rho^1_{1-1} - Im\rho^2_{1-1}}{2} cos[2(\phi_{hel} - \Phi')]\right)$$

15

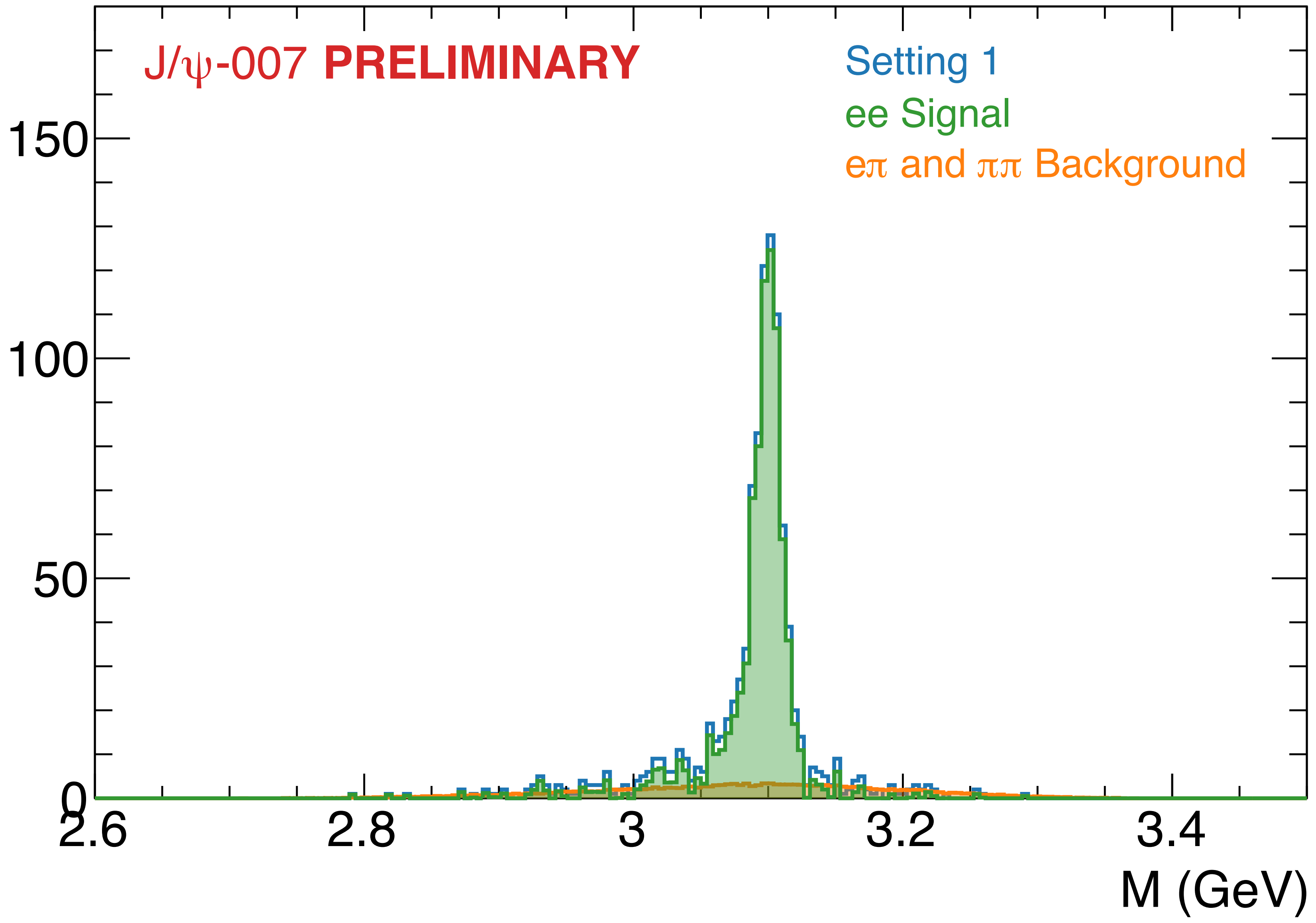
Figures by Lubomir Pentchev
(J/ψ Beyond workshop)

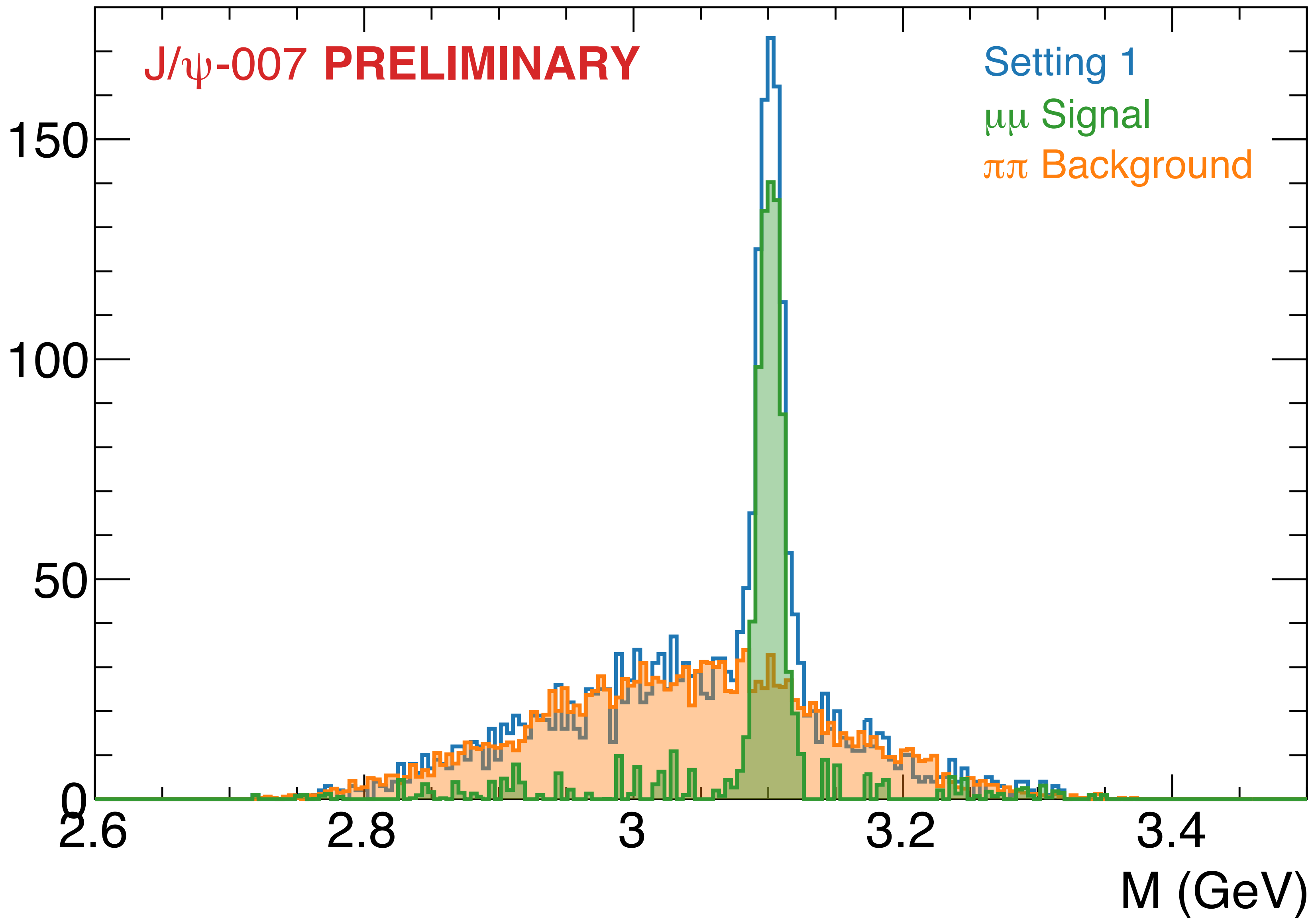
CONCLUSION

- The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ-007)
  - New window on the gluonic GFFs in the proton
  - Does the proton have a dense energetic core?
- The planned near-threshold J/ψ production program at Jefferson Lab crucial to further our understanding of the origin of mass.
  - This includes the approved program at GlueX, CLAS12 with luminosity upgrade, and importantly SoLID-J/ψ in Hall A.
  - SoLID can reach J/ψ observables that cannot be achieved anywhere else, including precision measurements at high t, and precision electroproduction near threshold.
- The matter structure of the proton and threshold quarkonium production are rapidly evolving topics that reach from Jefferson Lab to the EIC
  - EIC is complimentary: enables measurement of high-mass vector mesons and production at high Q2, important to understand factorization. High-luminosity crucial for these measurements.
  - A possible JLab energy upgrade could expand its scientific reach for near-threshold quarkonium production without too much overlap with the EIC.

QUESTIONS?

ELECTRON AND MUON CHANNELS





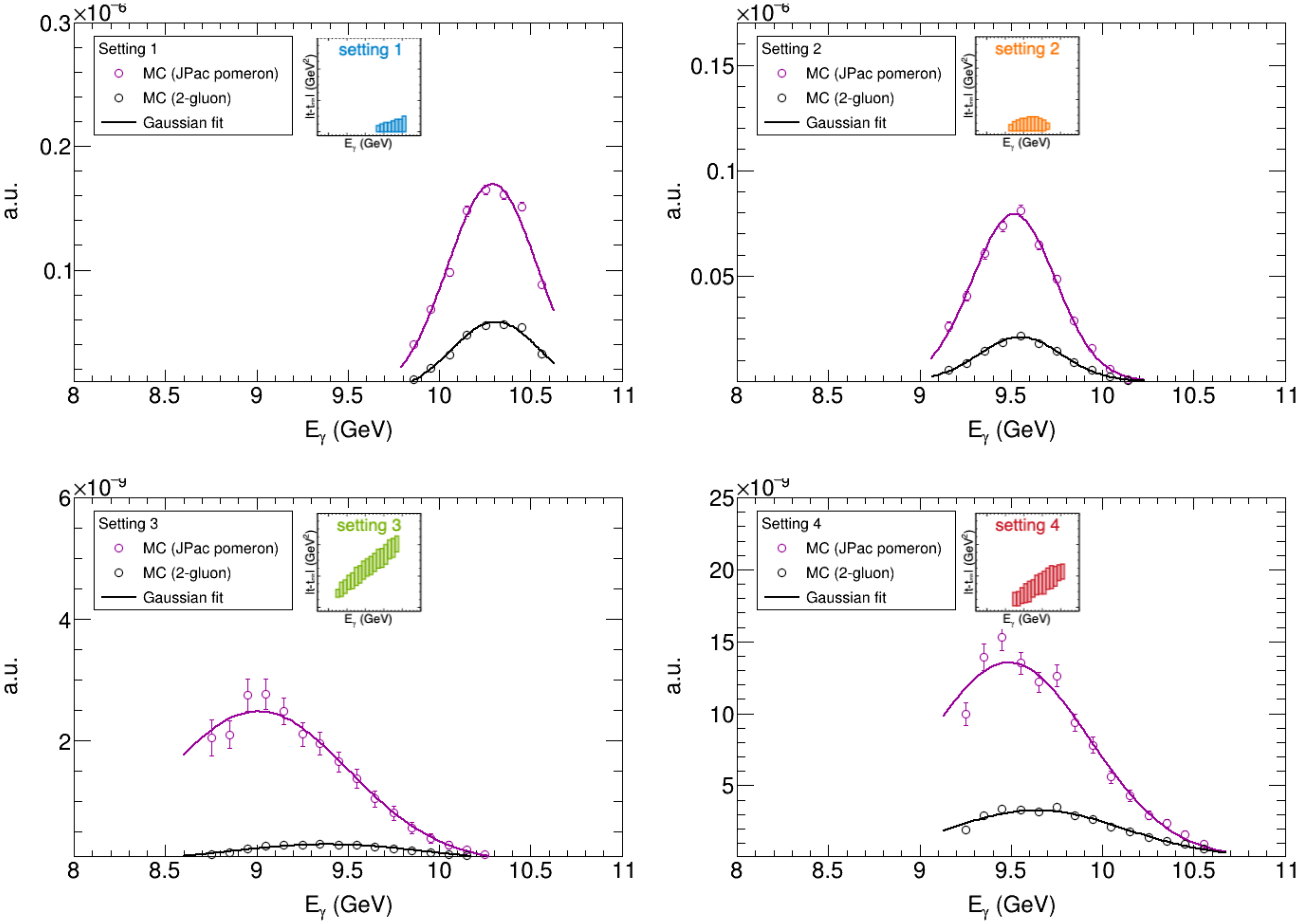
- **Electron and muon channels independent measurements, same statistics but different systematics**
- **Electrons:**
  - Low background with Cherenkov and ECAL for PID
  - Undergo multiple scattering and more sensitive to radiative losses
  - Slightly worse resolution (10MeV)
- **Muons**
  - More background using only ECAL (require coincidence MIP in 4 layers in HMS and 2 layers in SHMS), but still reasonable
  - Background dominated by 2-pion events, can get shape from dataset
  - Less sensitive to multiple scattering and radiative losses
  - Better resolution (8MeV)
- **Invariant mass positition *stable* between phases, well described by Monte Carlo!**

WHAT DOES A PURE T-CHANNEL BACKGROUND LOOK LIKE?

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

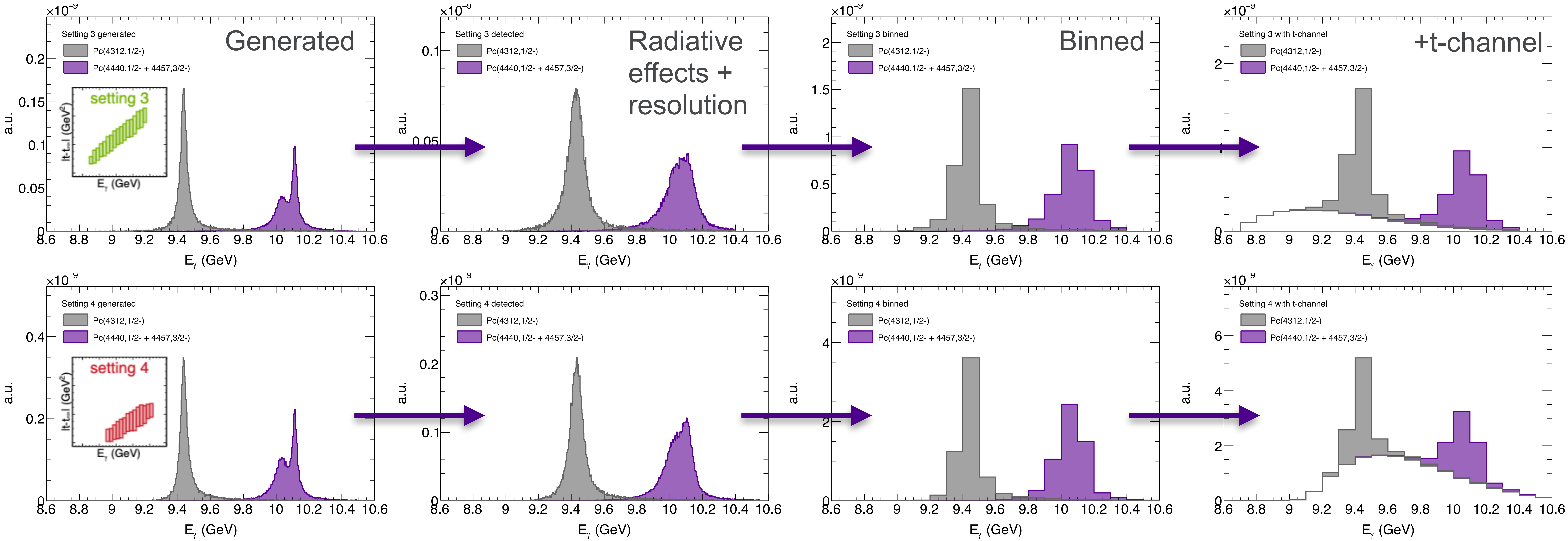
A **gaussian shape**, mostly driven by the spectrometer acceptance, does a good job describing both (very different!) Monte-Carlo models

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

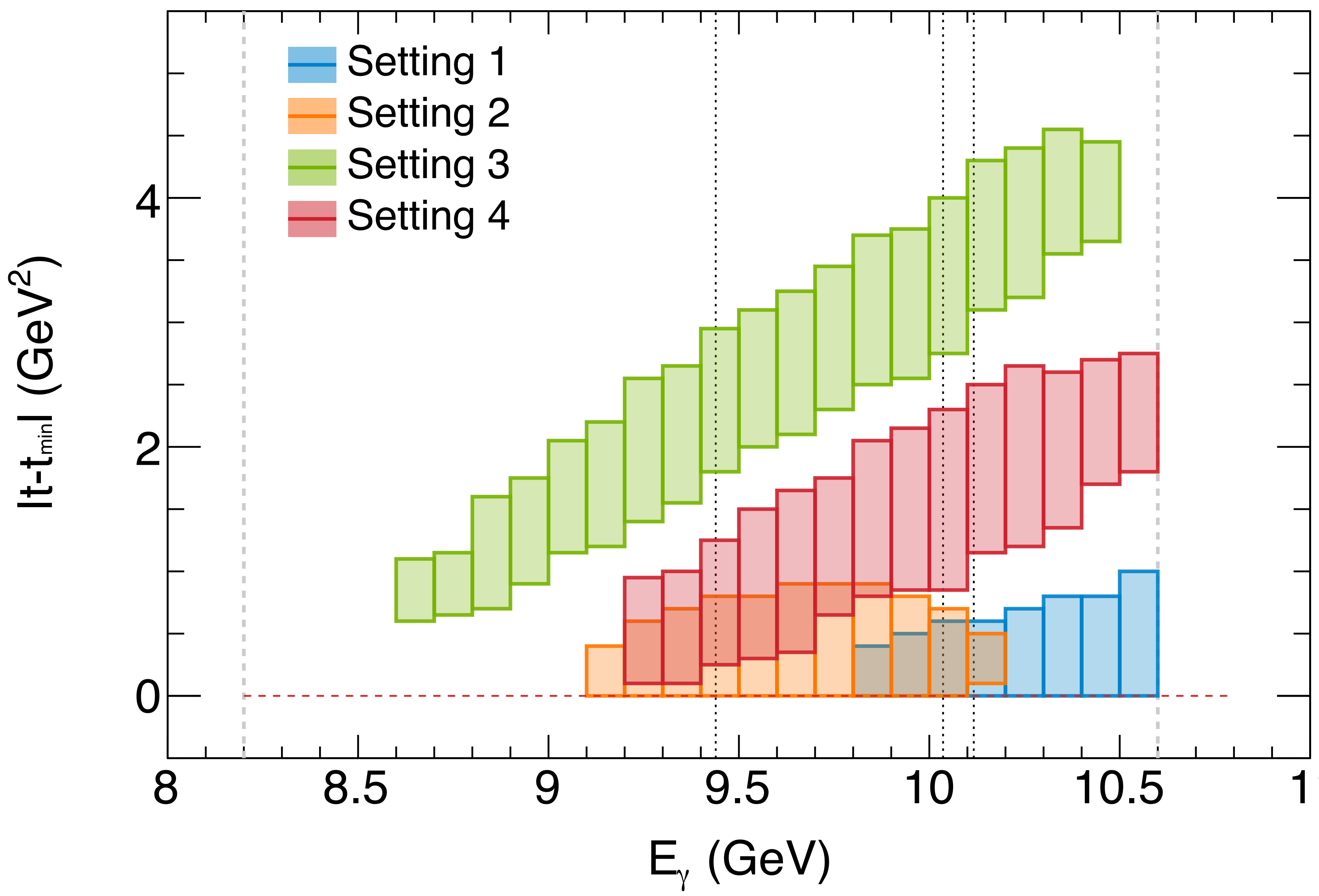


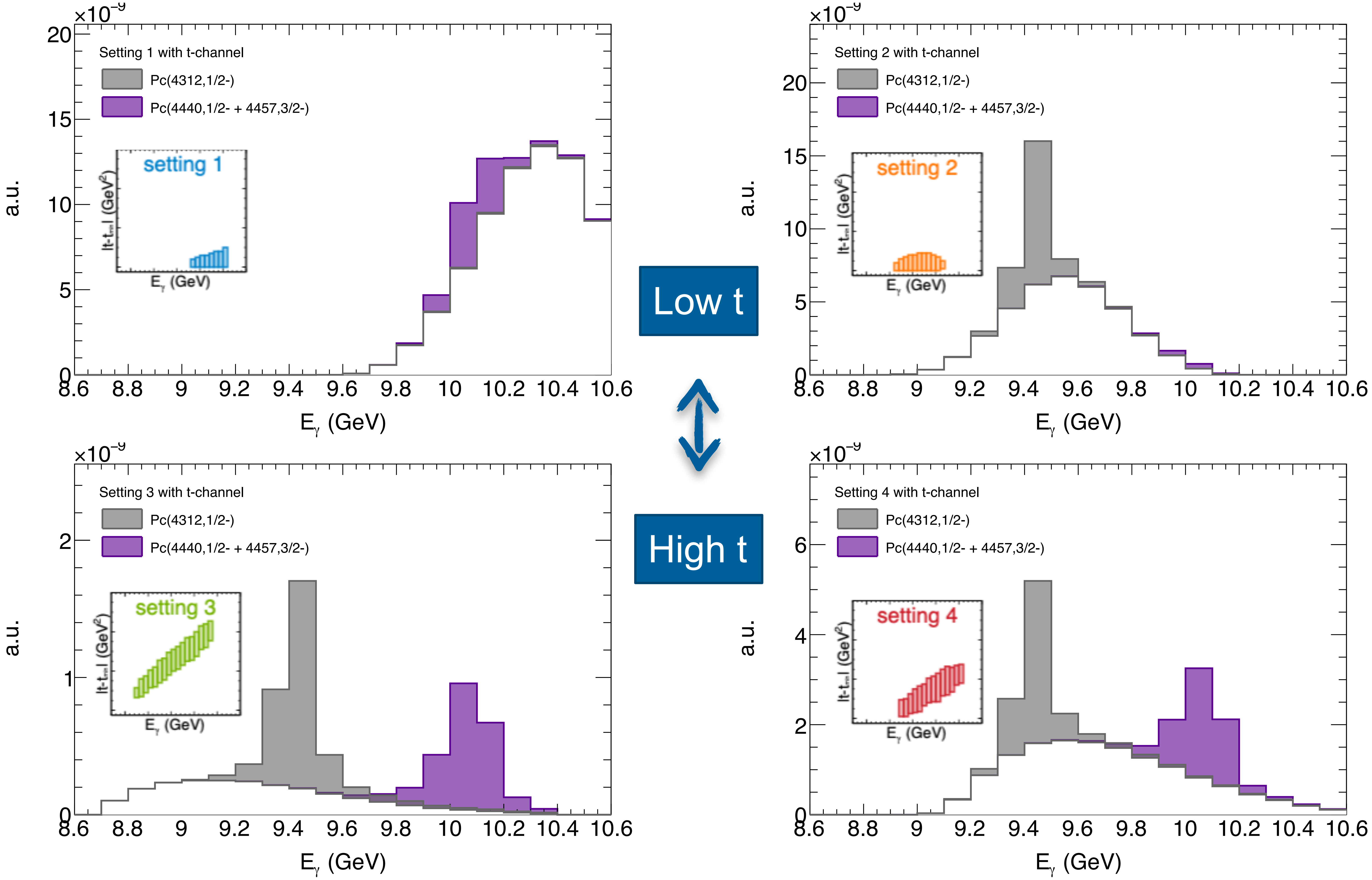
P_c resonances calculated at GlueX 90% upper limit from MC (JPacPhoto + Detector Simulation)

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





4% scale uncertainty on cross section

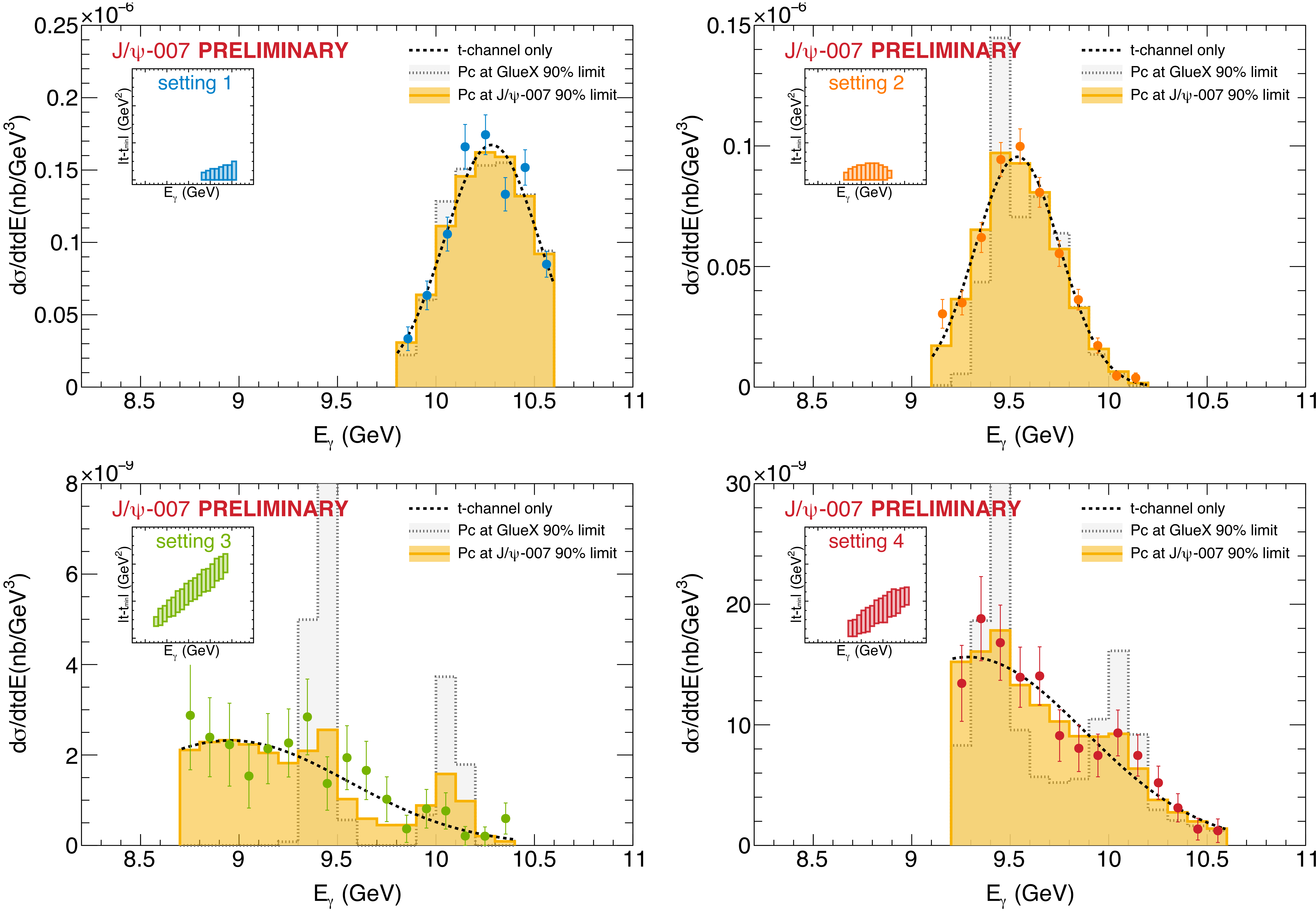
SIGNIFICANCE FIT

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).



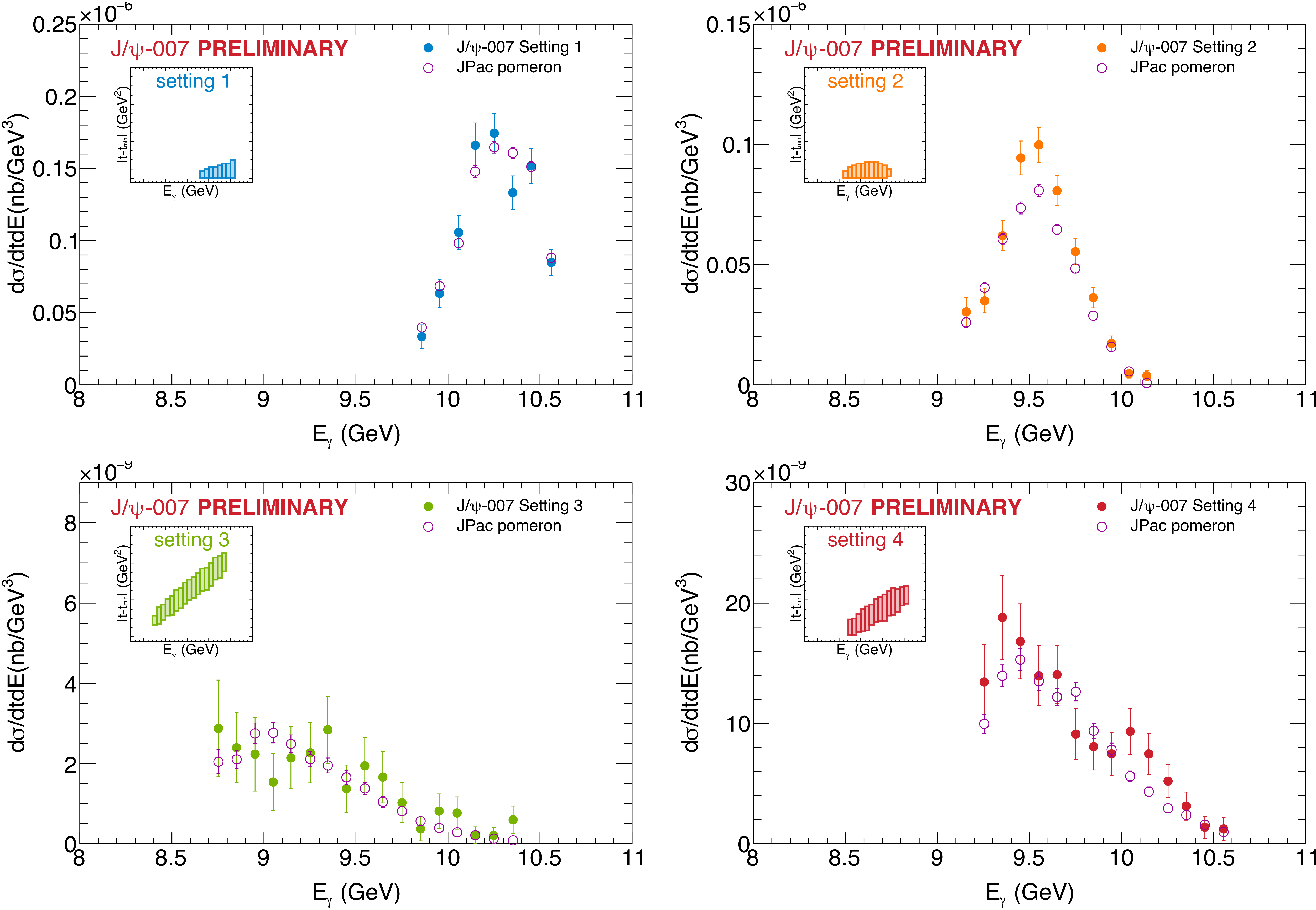
4% scale uncertainty on cross section

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

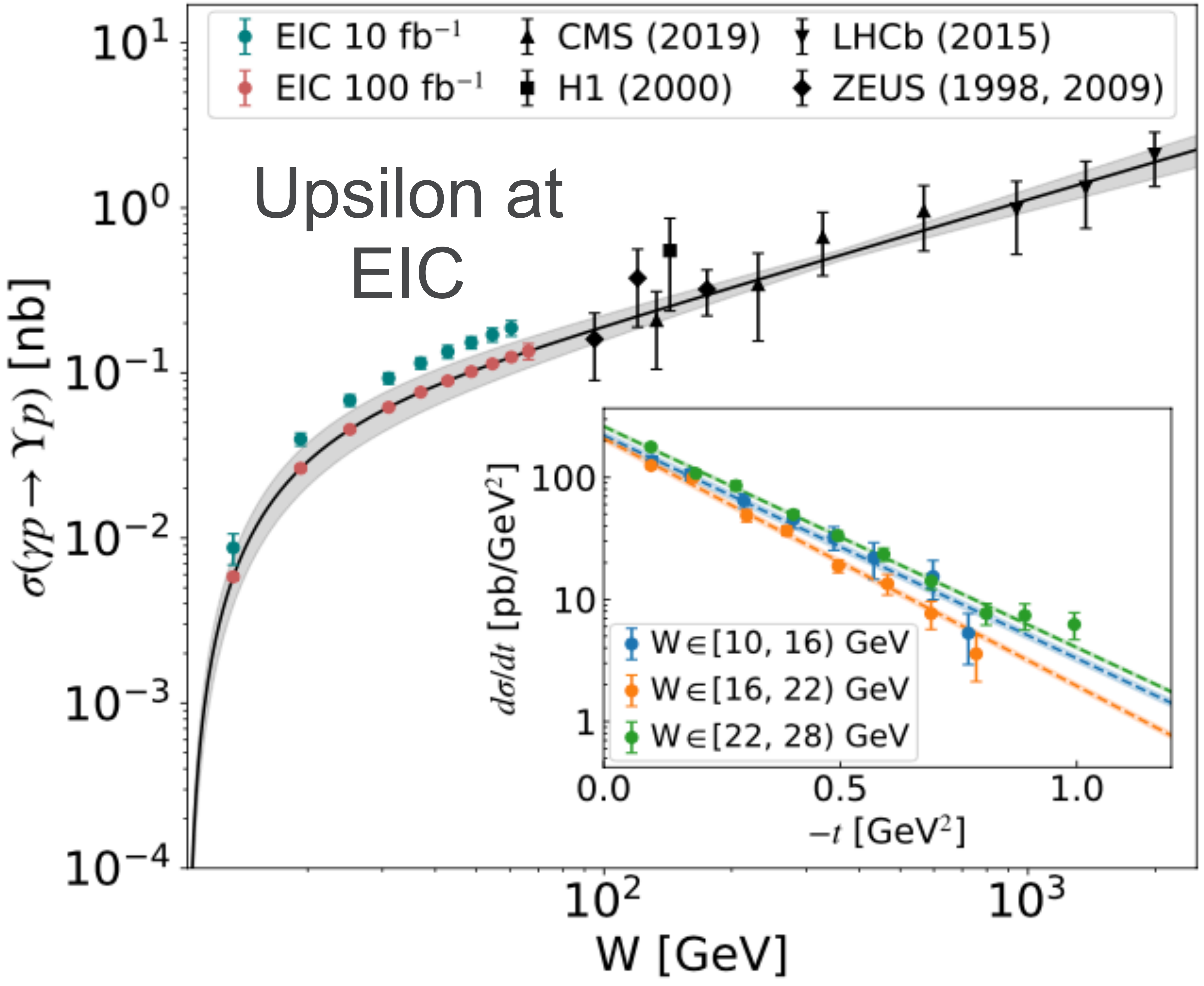
To get more sensitivity to details in the near-threshold cross section, we need the 2D cross section results (see next slide)



COMPLEMENTARITY WITH EIC (LONG)

J/ψ at SoLID and Υ at EIC

- In principle, EIC creates J/ψ at threshold, but events hard to reconstruct due to limited experimental resolution.
- Threshold production of higher-mass quarkonia (e.g. Υ(1S)) can be measured much more precisely.
- Υ(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties, and extra channel to study universality.
- Large Q^2 reach at EIC an additional knob to study production

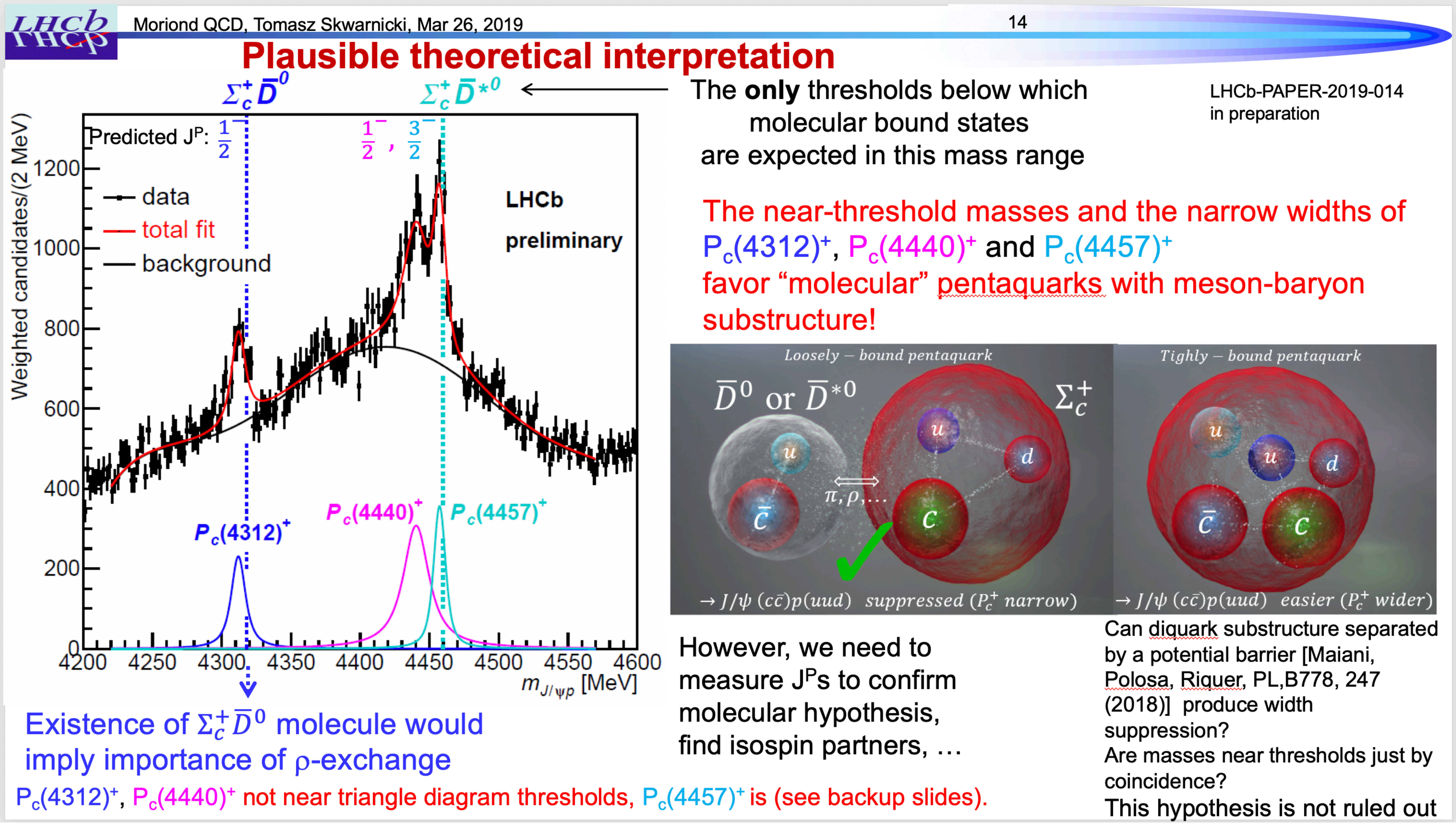


Upsilon at EIC

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

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).