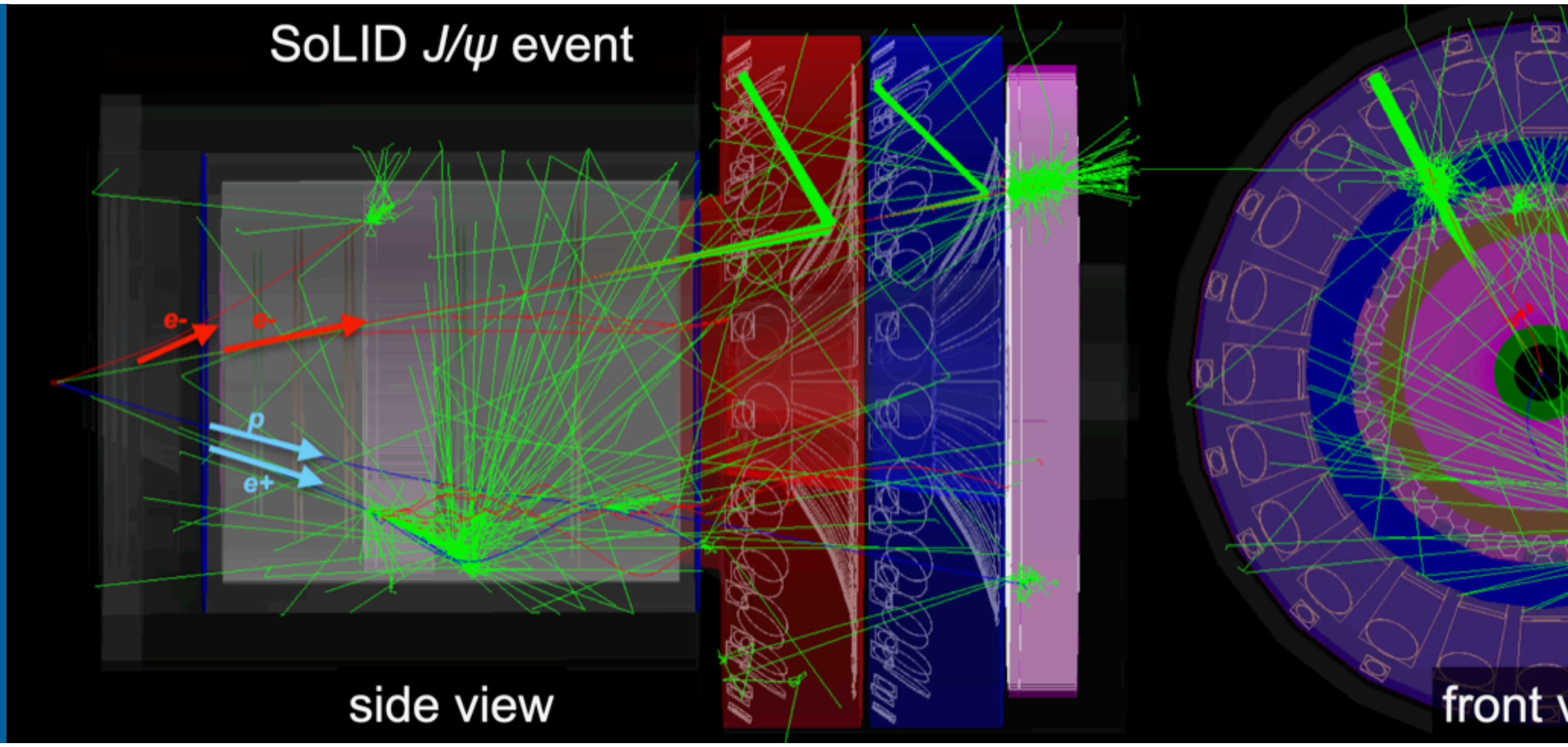
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY

WHAT COULD BE DONE WITH SOLID NEAR-THRESHOLD J/Ψ & Ψ' PRODUCTION AT ~20 GEV



SYLVESTER JOOSTEN
sjoosten@anl.gov

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

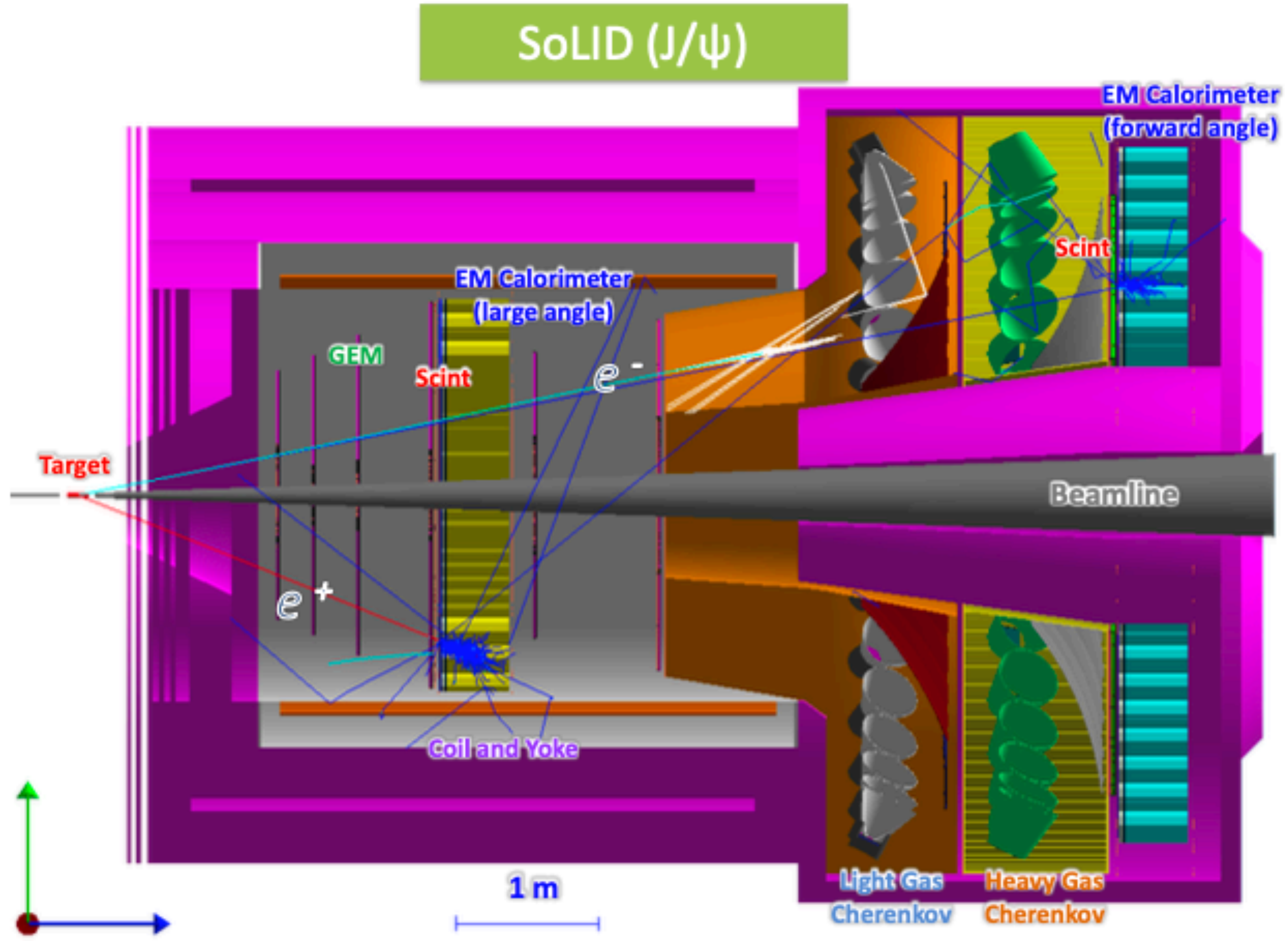
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

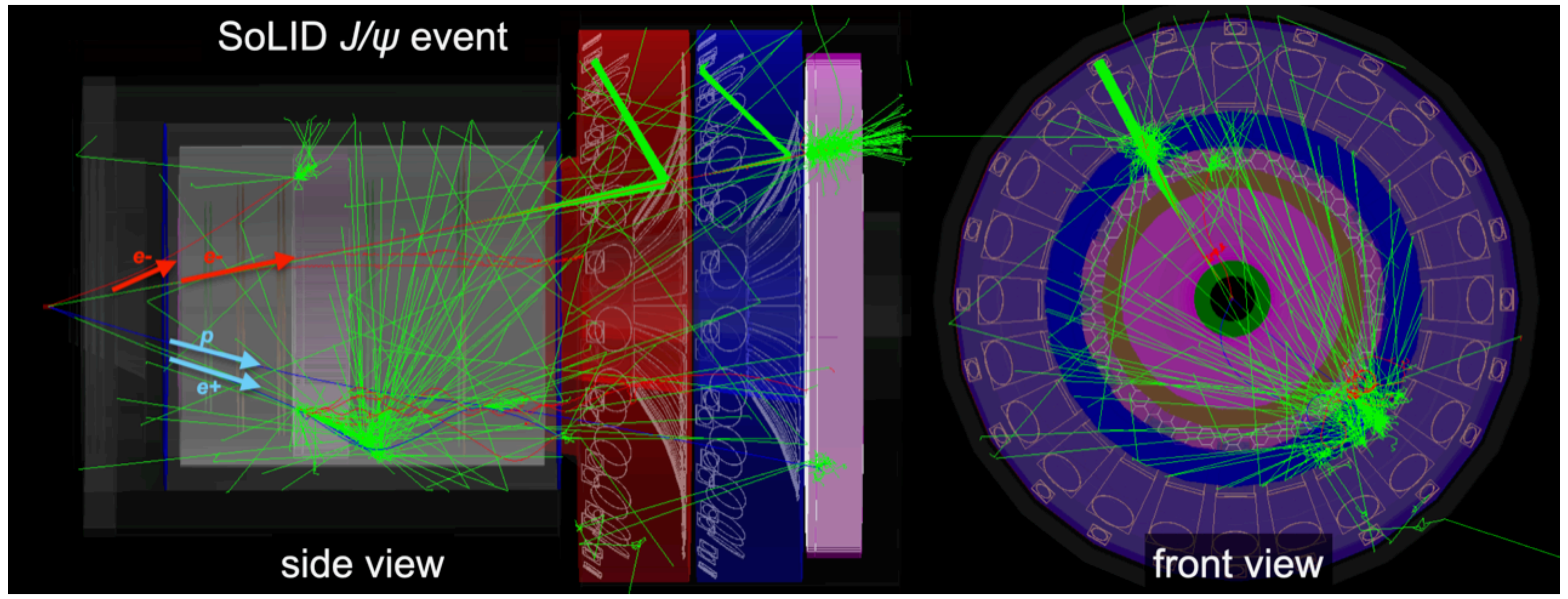
J/psi and Beyond Workshop
August 16, 2022

THE SOLID-J/Ψ EXPERIMENT

Ultimate factory for near-threshold J/ψ

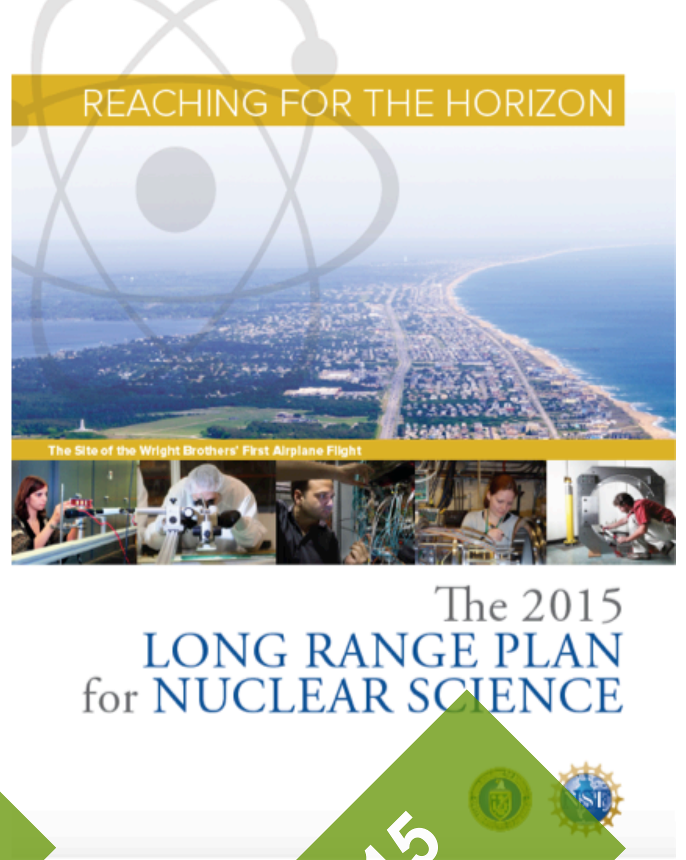
- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target ($10^{37}/cm^2/s$)
- **Ultra-high luminosity**: $43.2ab^{-1}$
- **Open 2-particle trigger,** covering J/ψ production in four channels: Electroproduction (e,e^-e^+), photoproduction (p,e^-e^+),
inclusive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

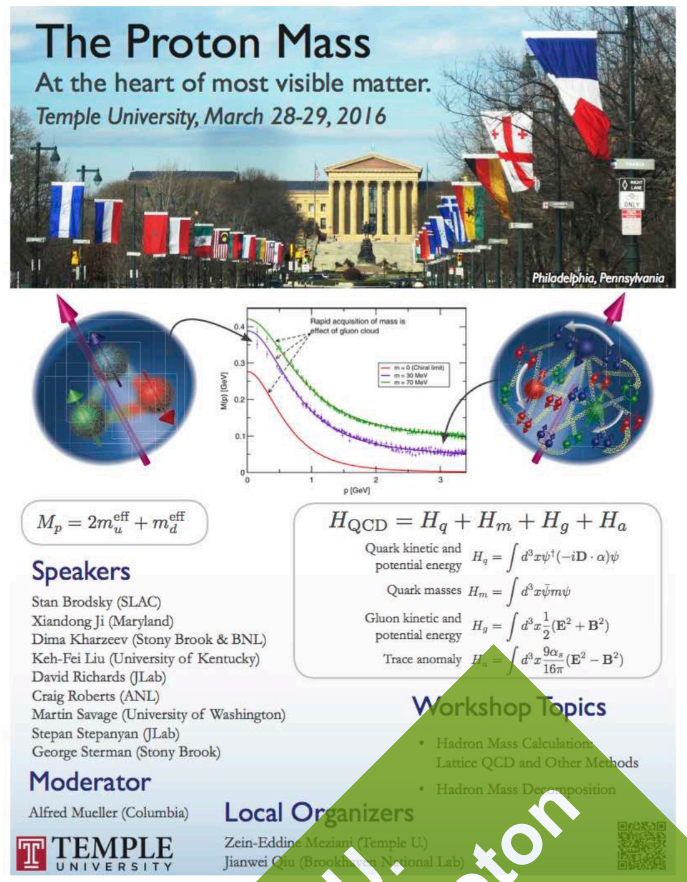


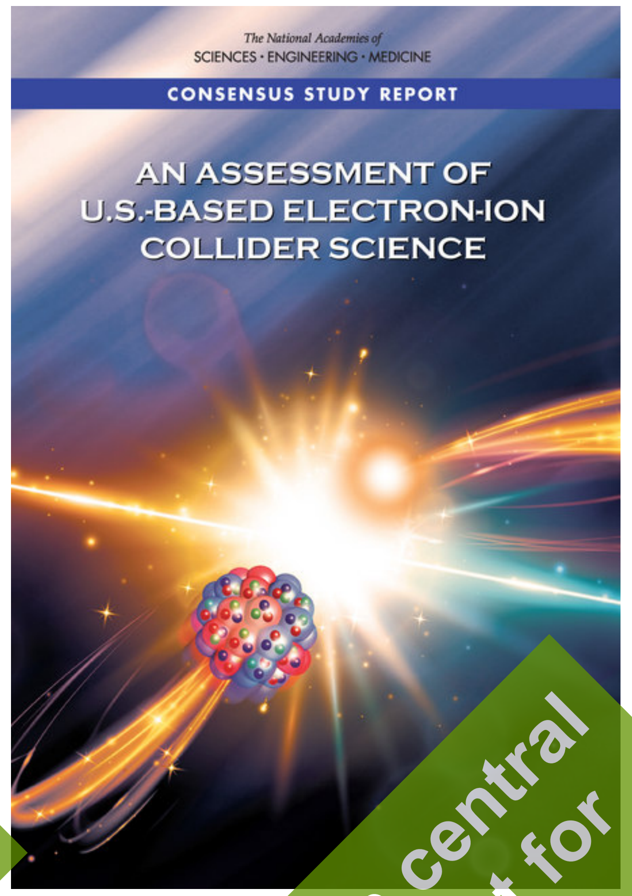


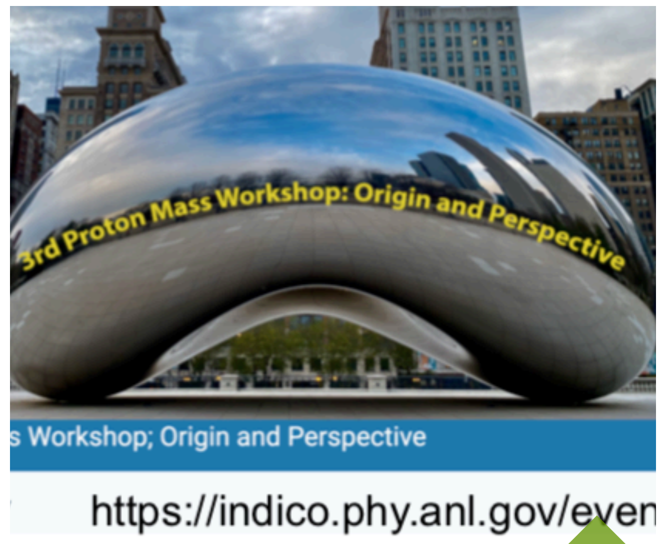
The proton mass: An important topic in contemporary hadronic physics!

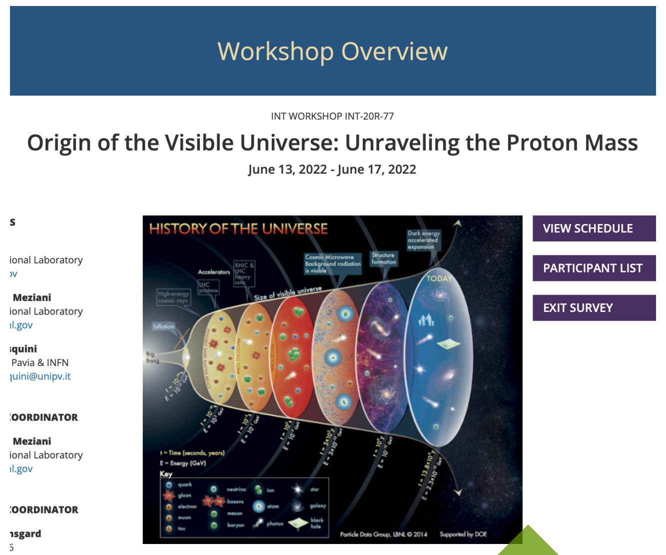
RAPIDLY EVOLVING











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

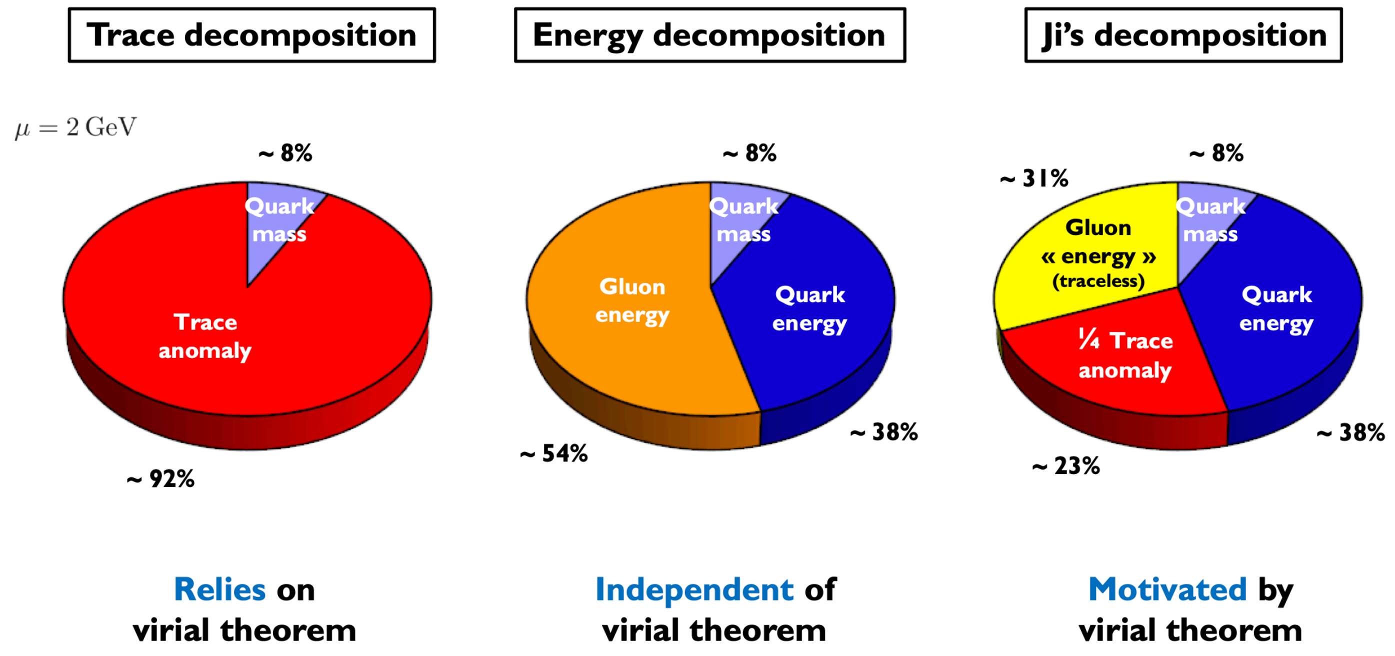
2021 First Hall C results on the pentaquark search

2022 INT Workshop on the proton mass

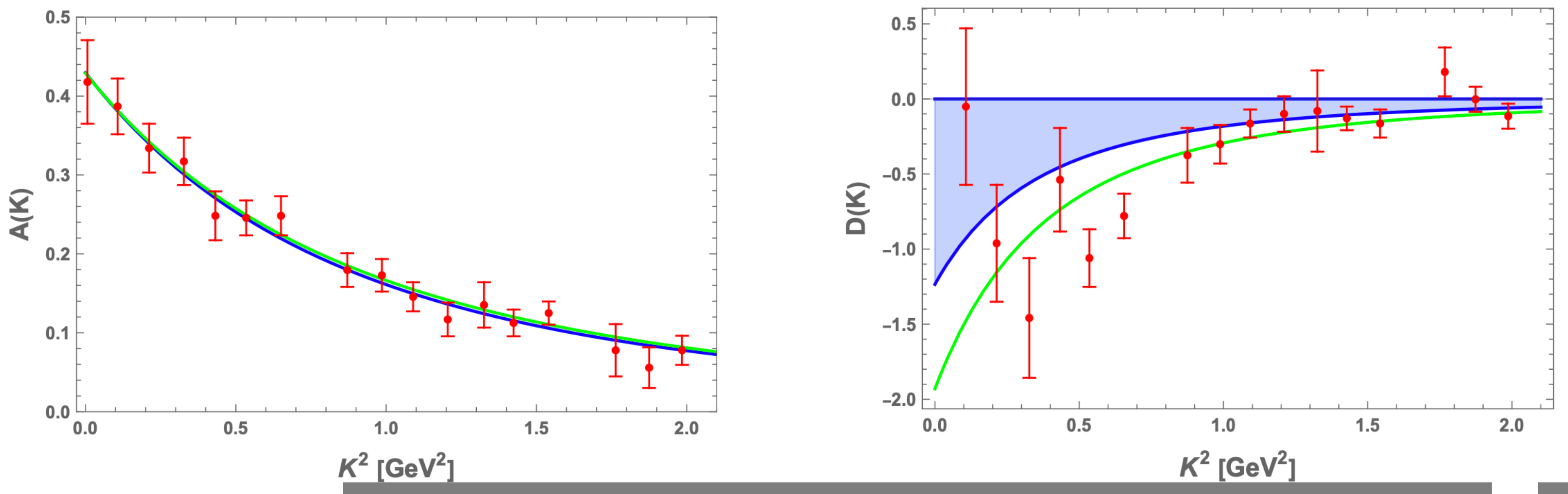
2022 First 2D near-threshold J/ψ results from Hall C

Science case rapidly evolving

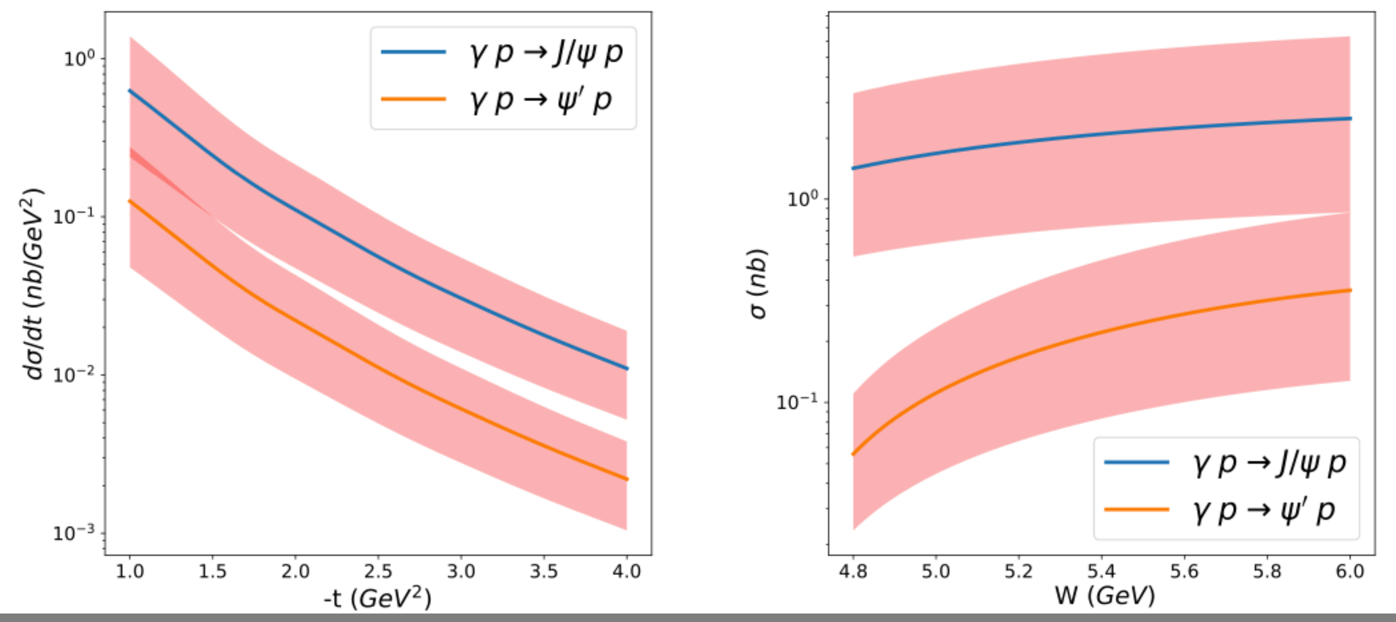
PROMINENT NEW DEVELOPMENTS



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

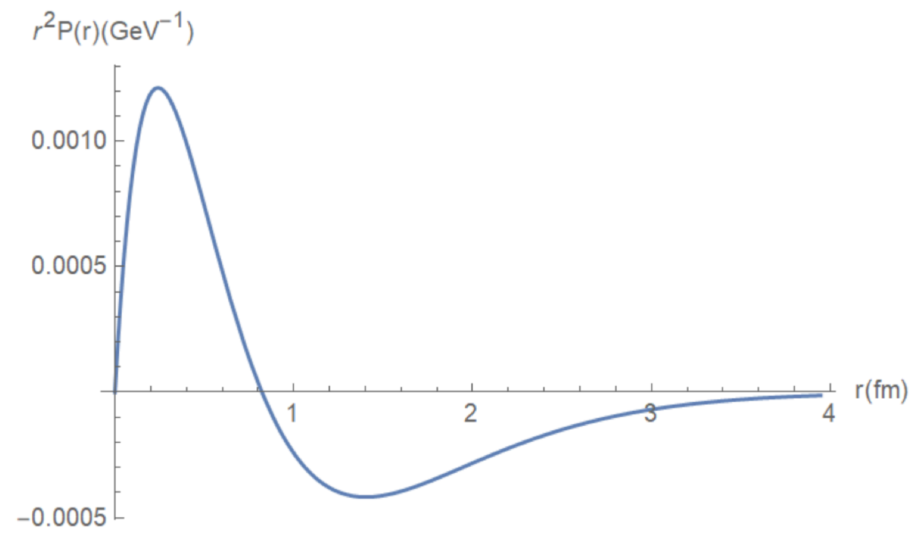


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

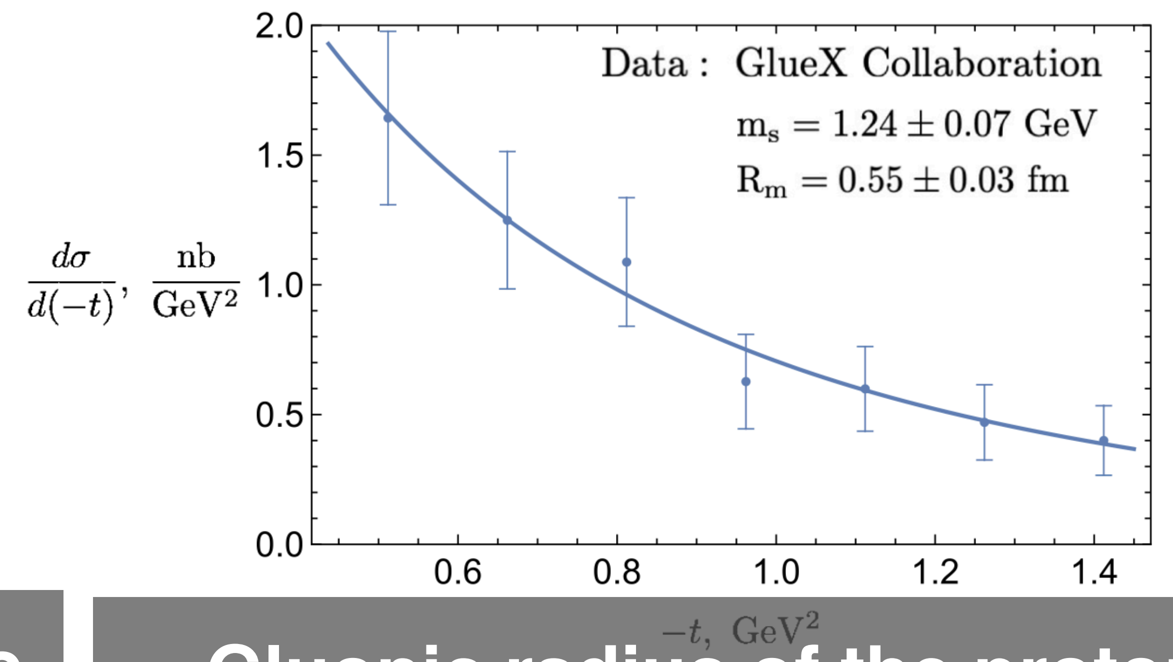


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- 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. Best way to mitigate is high-precision data at high-t.



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

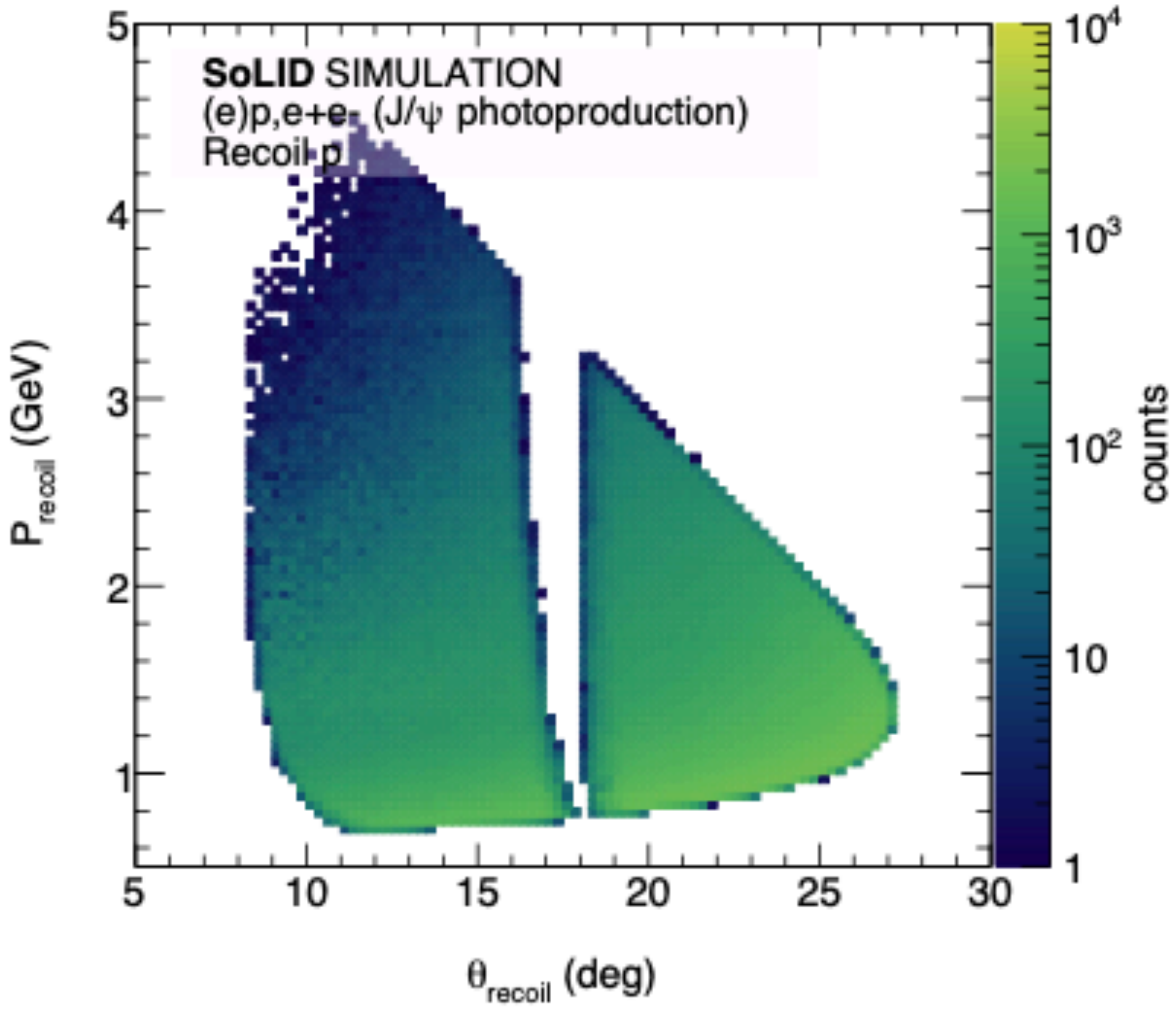


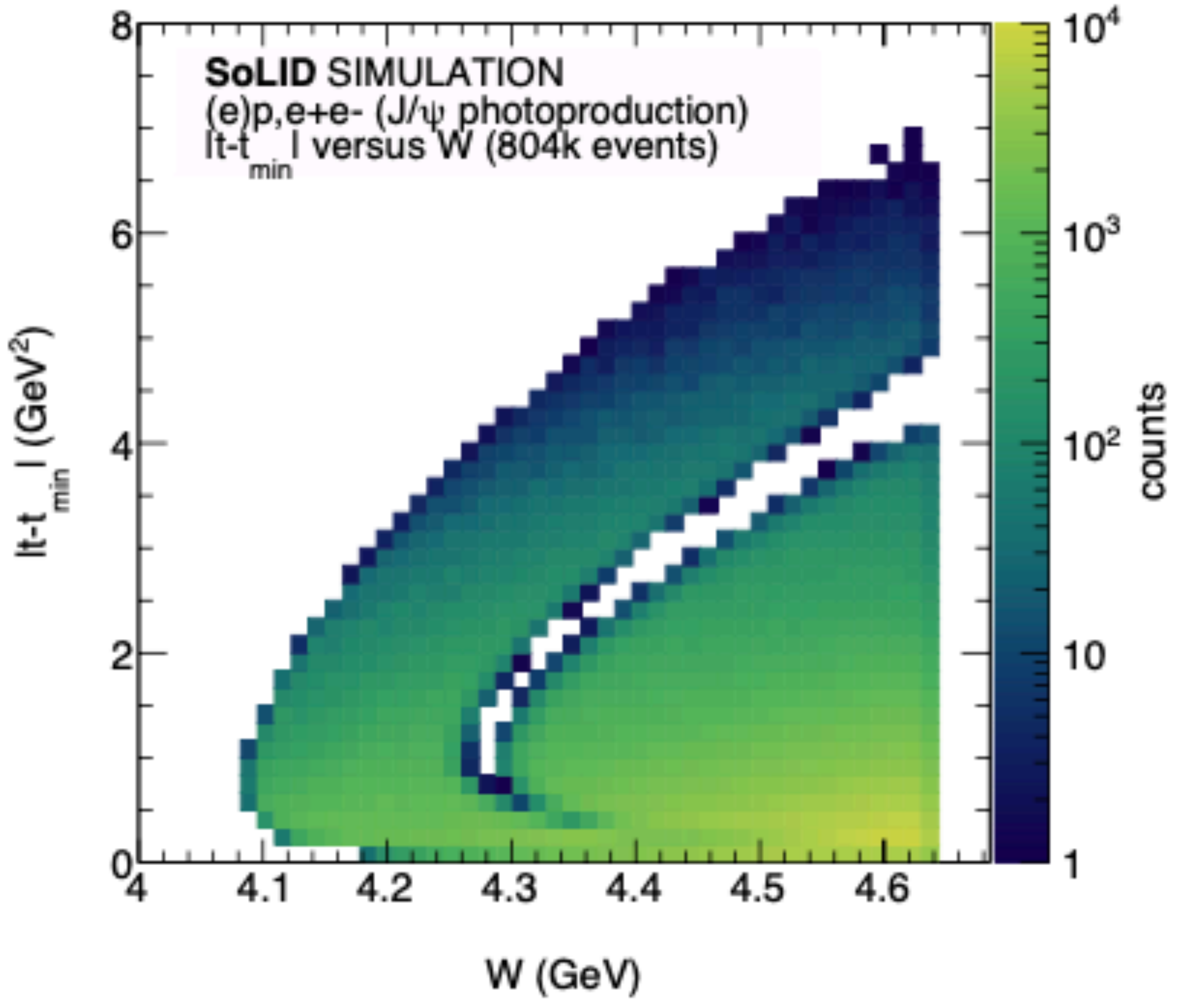
Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

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*.

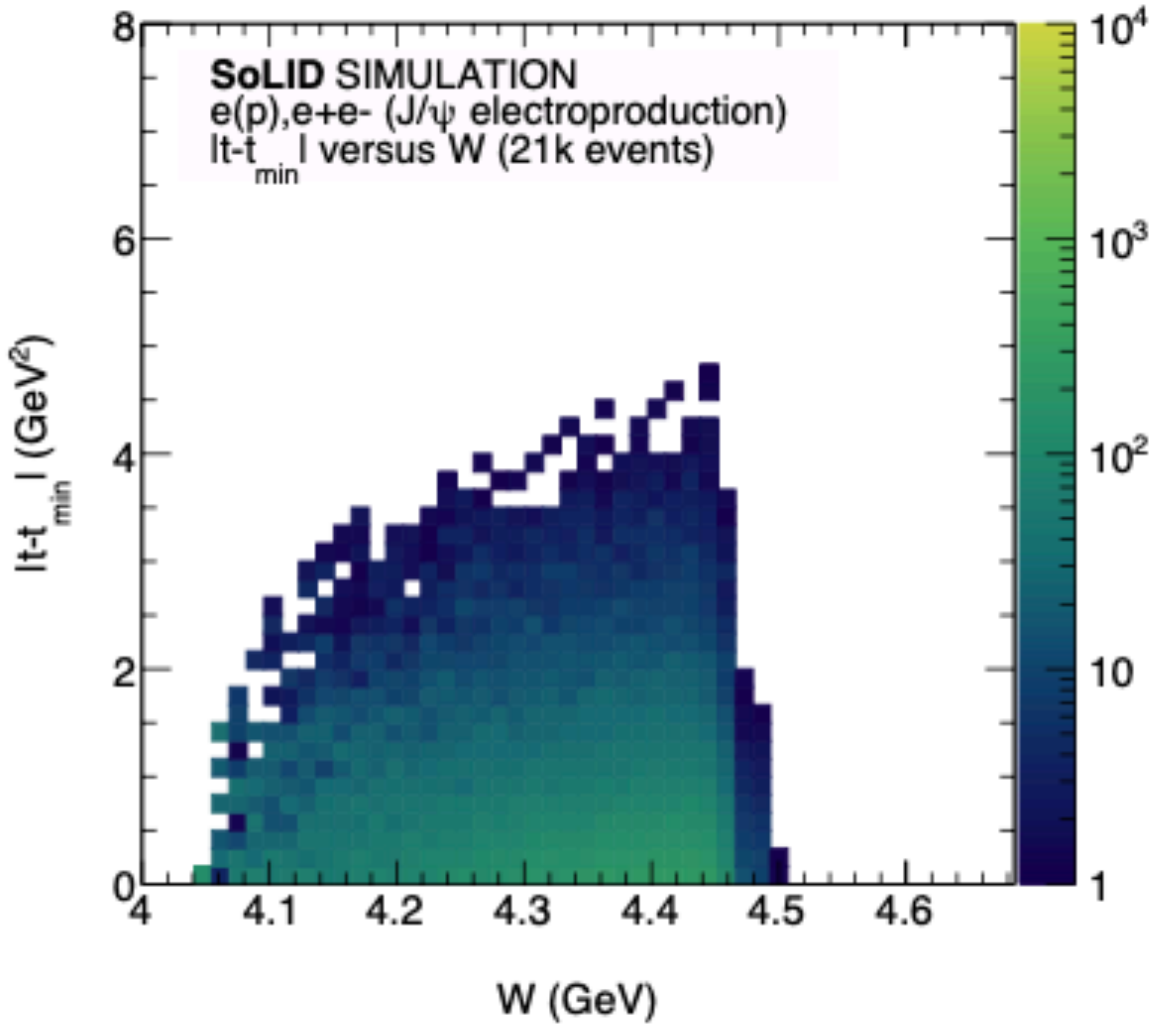


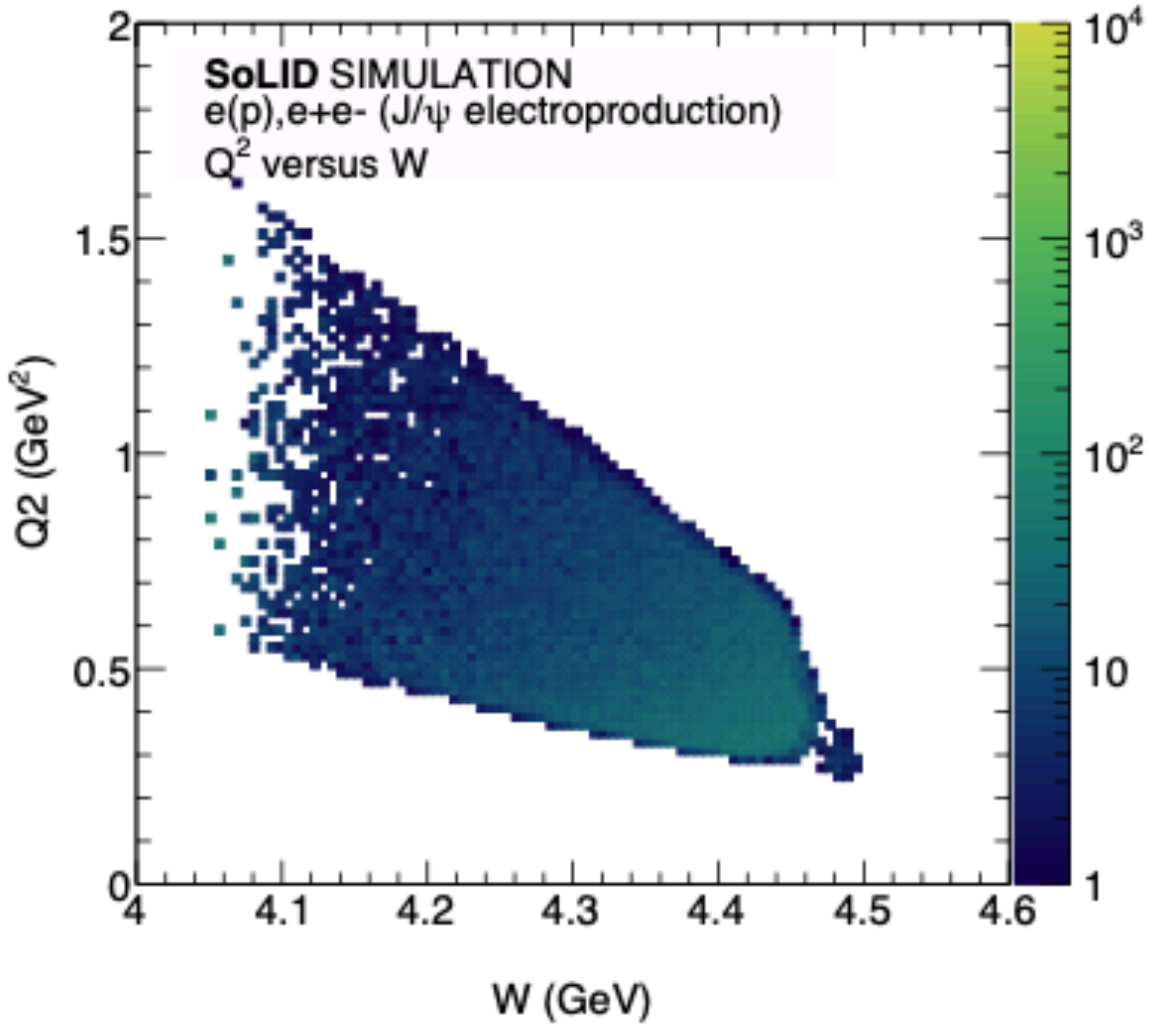


ELECTROPRODUCTION

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

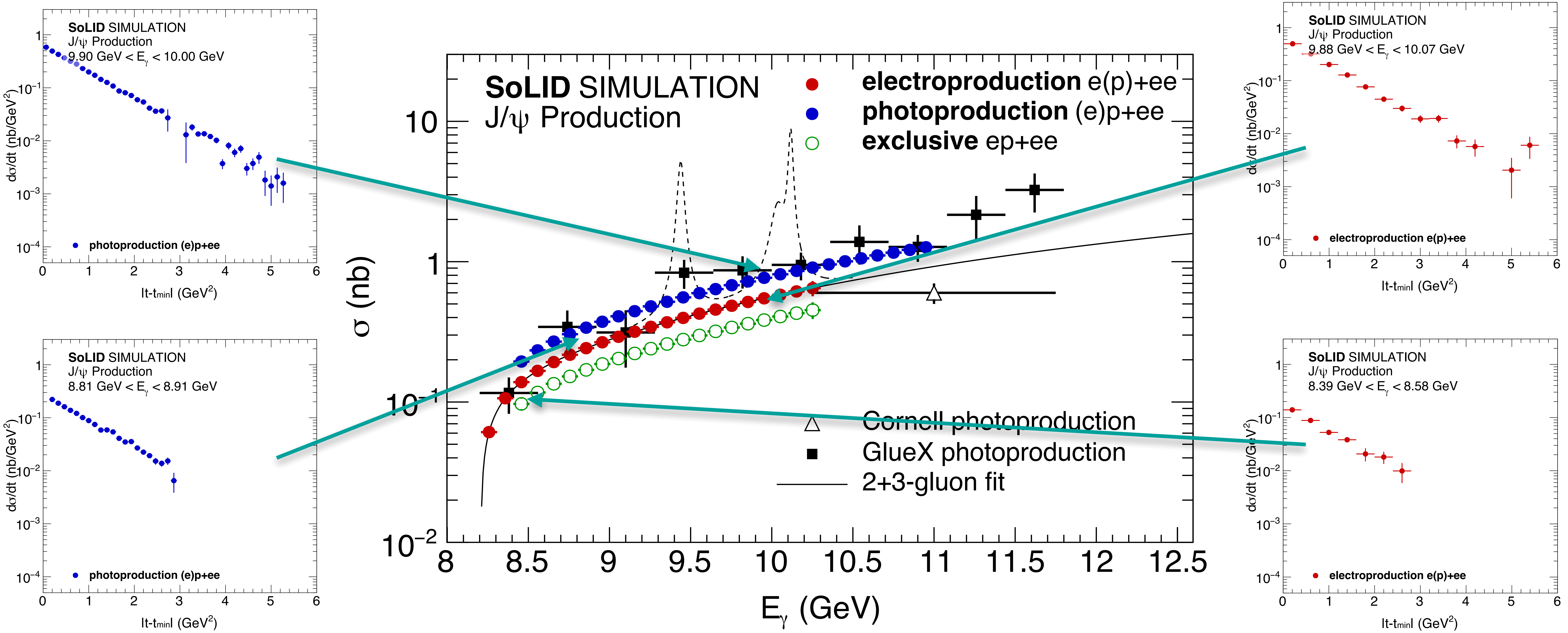
- Production through virtual photons
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify scattered electron in the forward spectrometer.
- Coverage up to larger values of t very close to threshold.



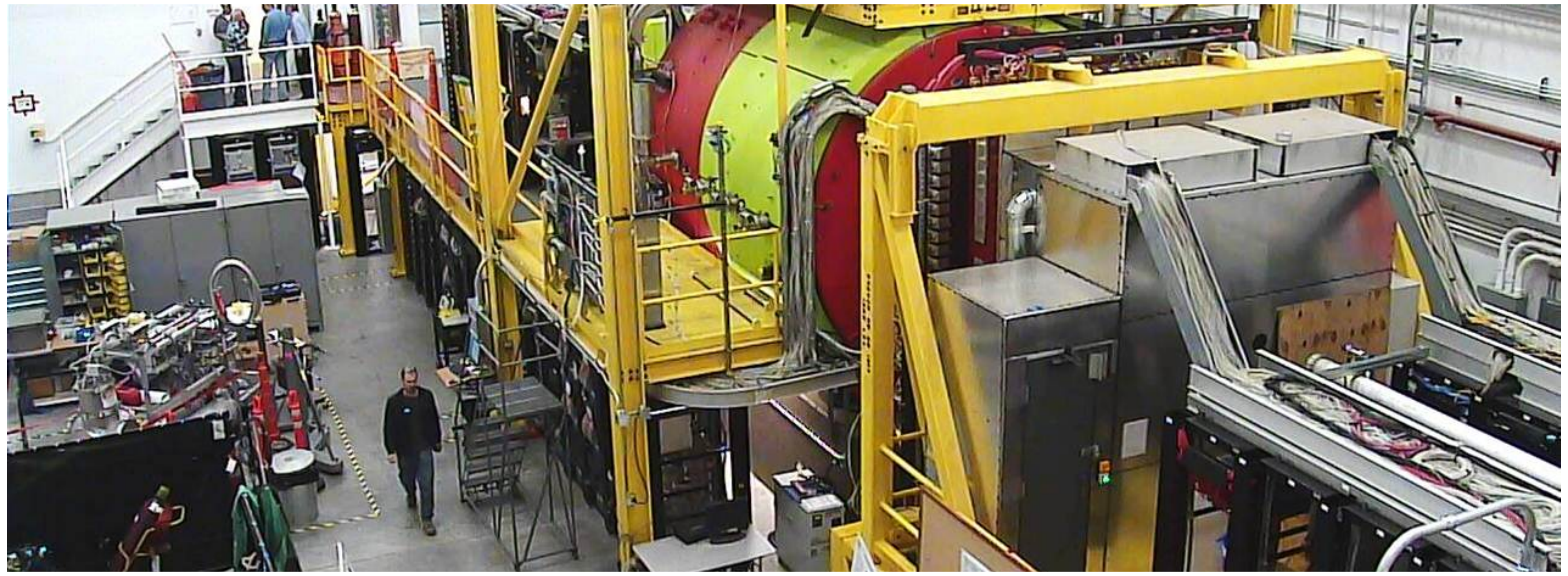


SOLID-J/Ψ PROJECTIONS

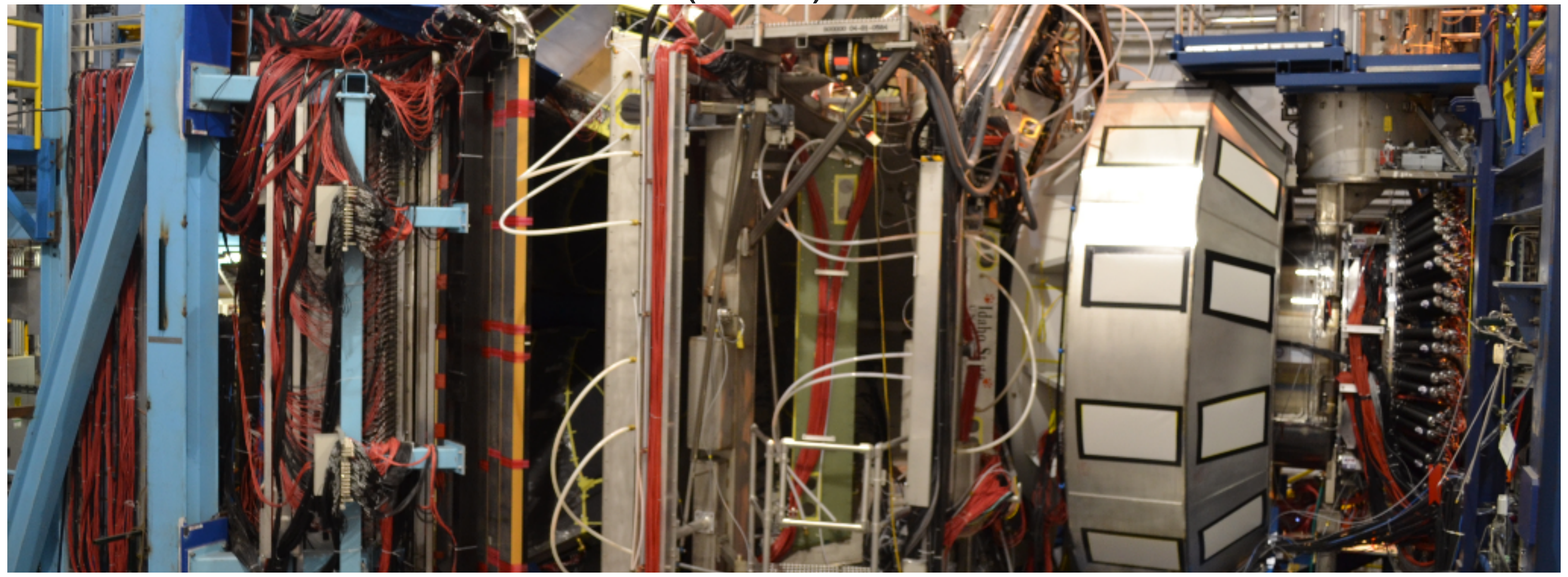
Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



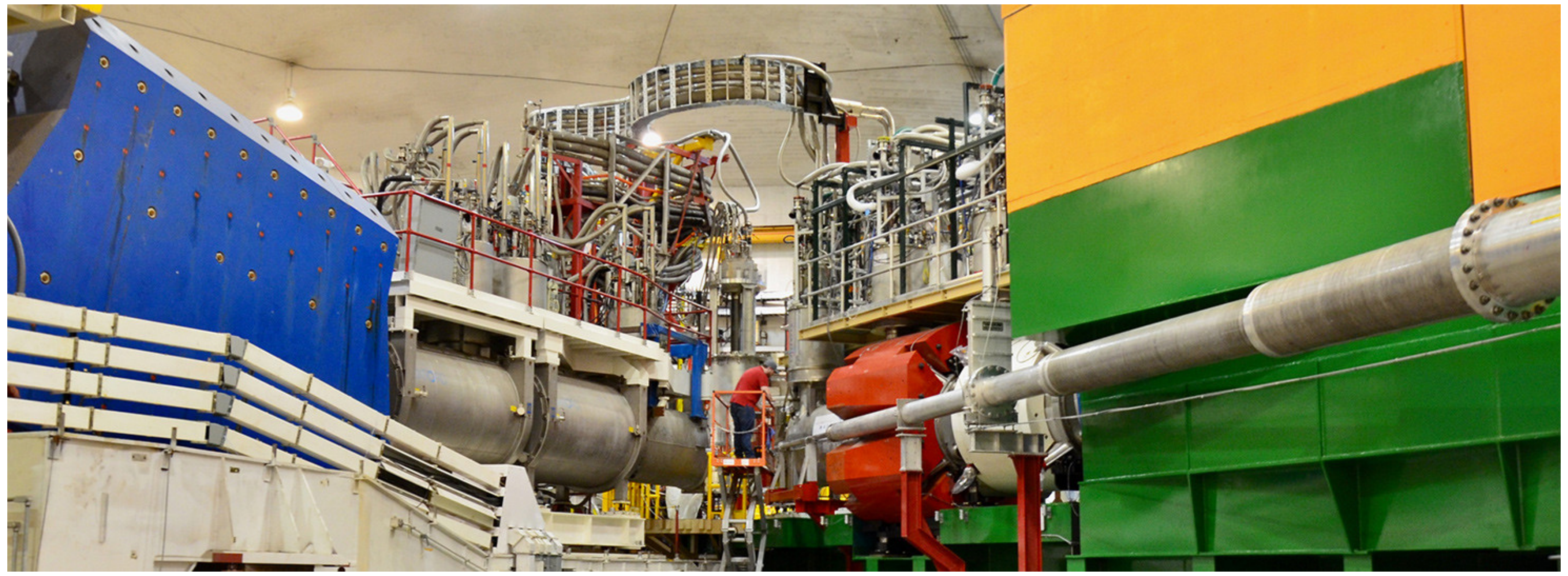
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



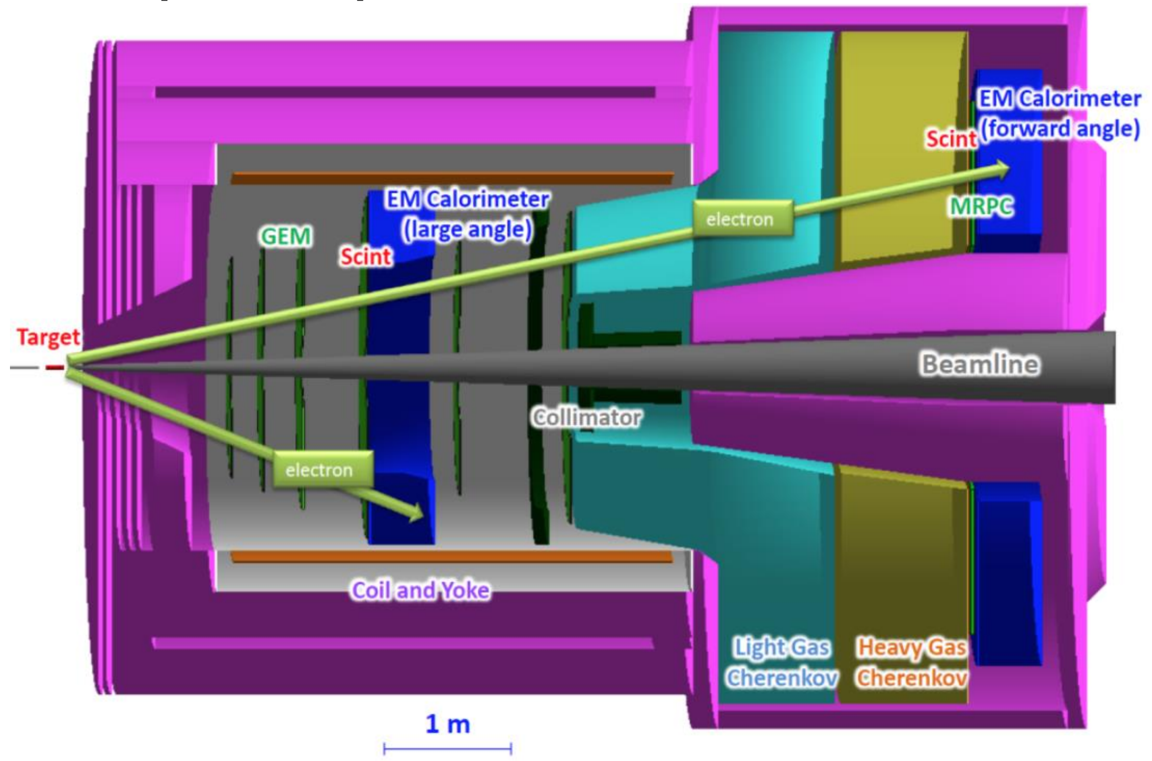
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B



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



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

J/Ψ EXPERIMENTS AT JLAB COMPARED

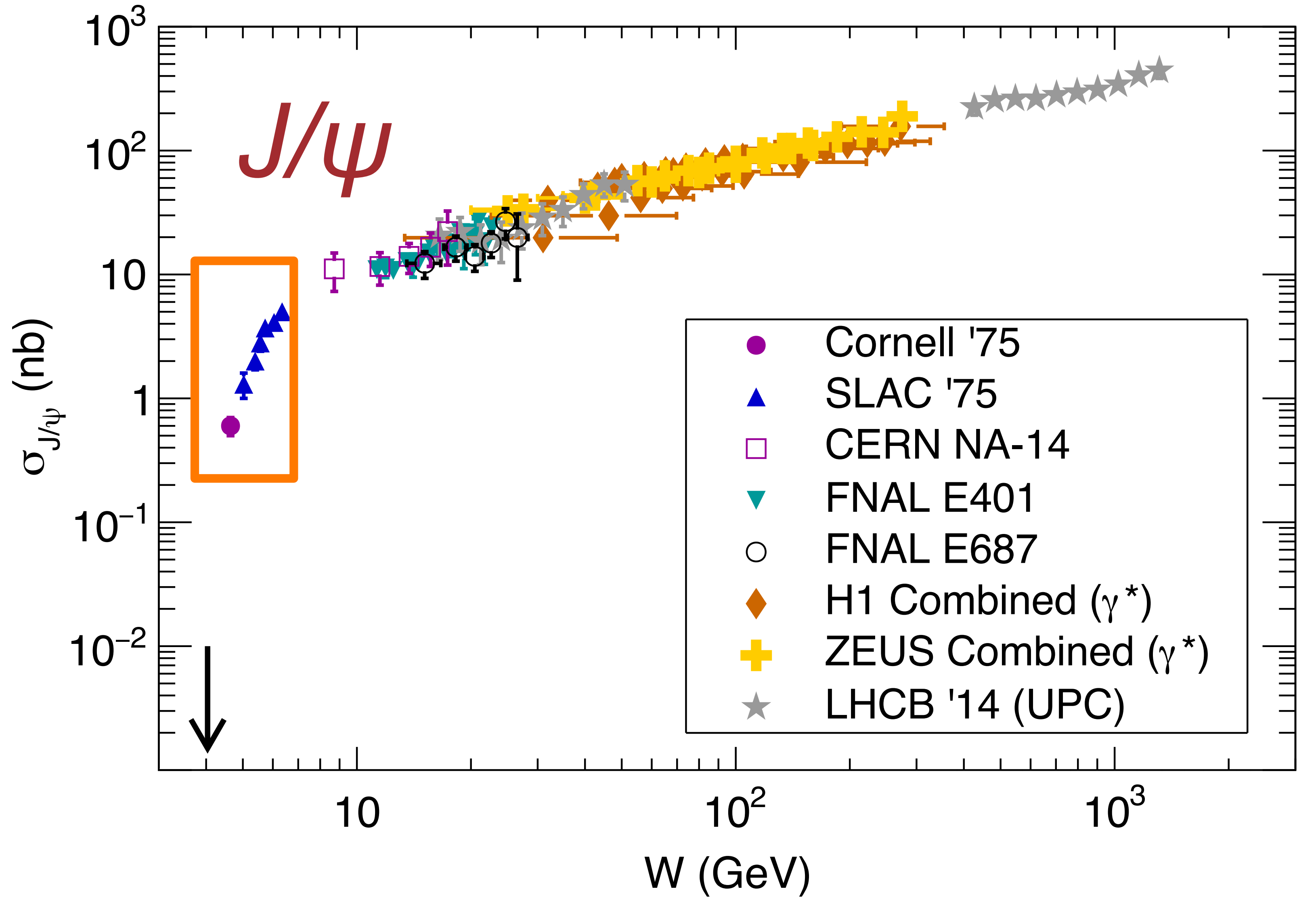
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	**469 published** **~10k phase I + II**	**2k electron channel** **2k muon channel**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
Features	Good reach to threshold. No high-t reach.	Can reach high-t only at higher energies. Low statistics.	No high-t reach. Electroproduction low statistics.	Enough luminosity to reach high t. High precision.
When?	Finished/Ongoing	Finished	Ongoing/Proposed	Future

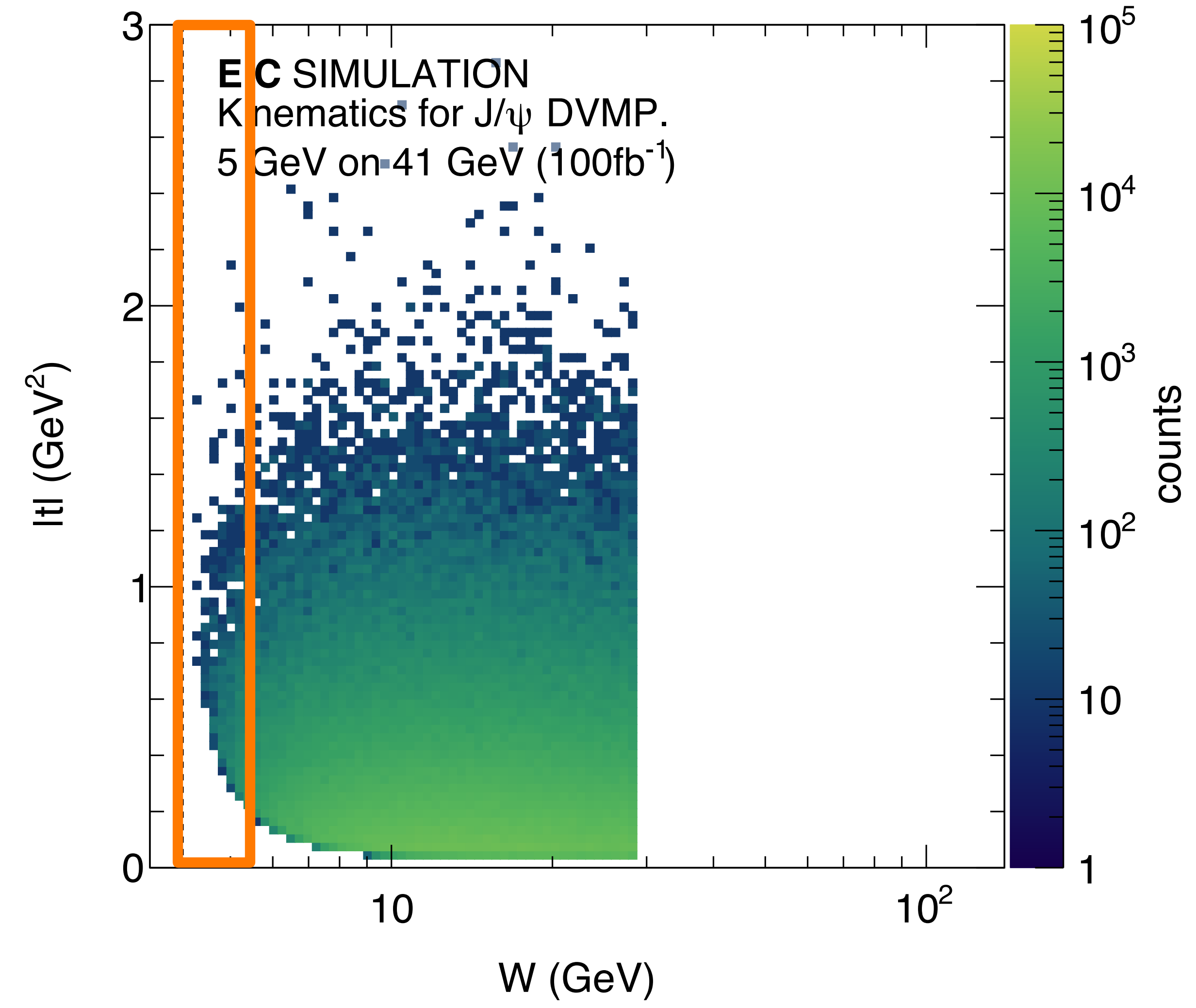
[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2x10^{35}/cm^2/s$

WHY GO TO HIGHER ENERGIES?

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

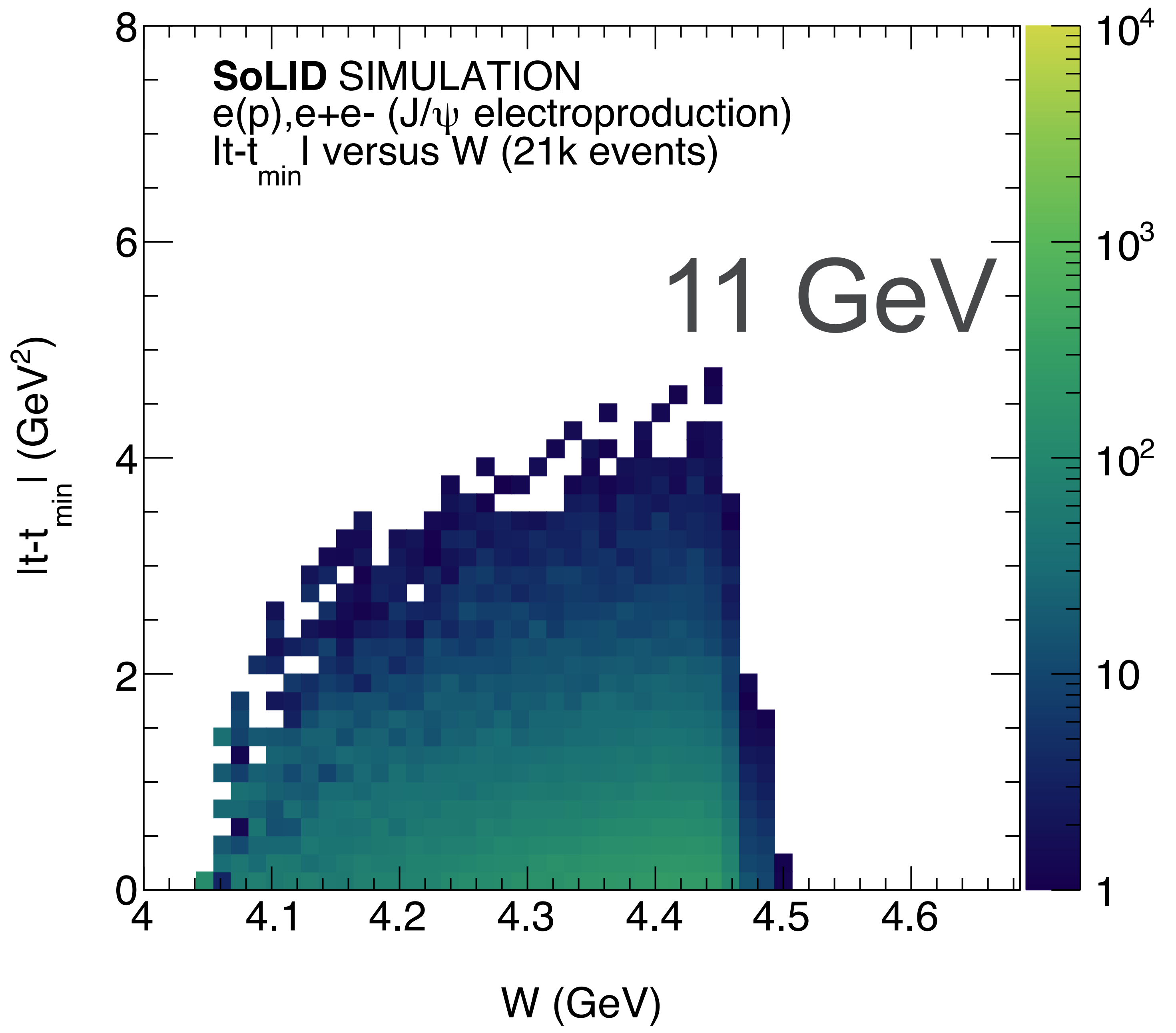
- Potential benefits:
  - Larger reach in Q^2 near threshold with high precision
  - Precision measurement to supersede old SLAC and Cornell measurement
  - High-precision for EIC at lower energies (but with much higher W resolution)
  - Extend high-t reach unique to Jlab to higher energies - cannot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

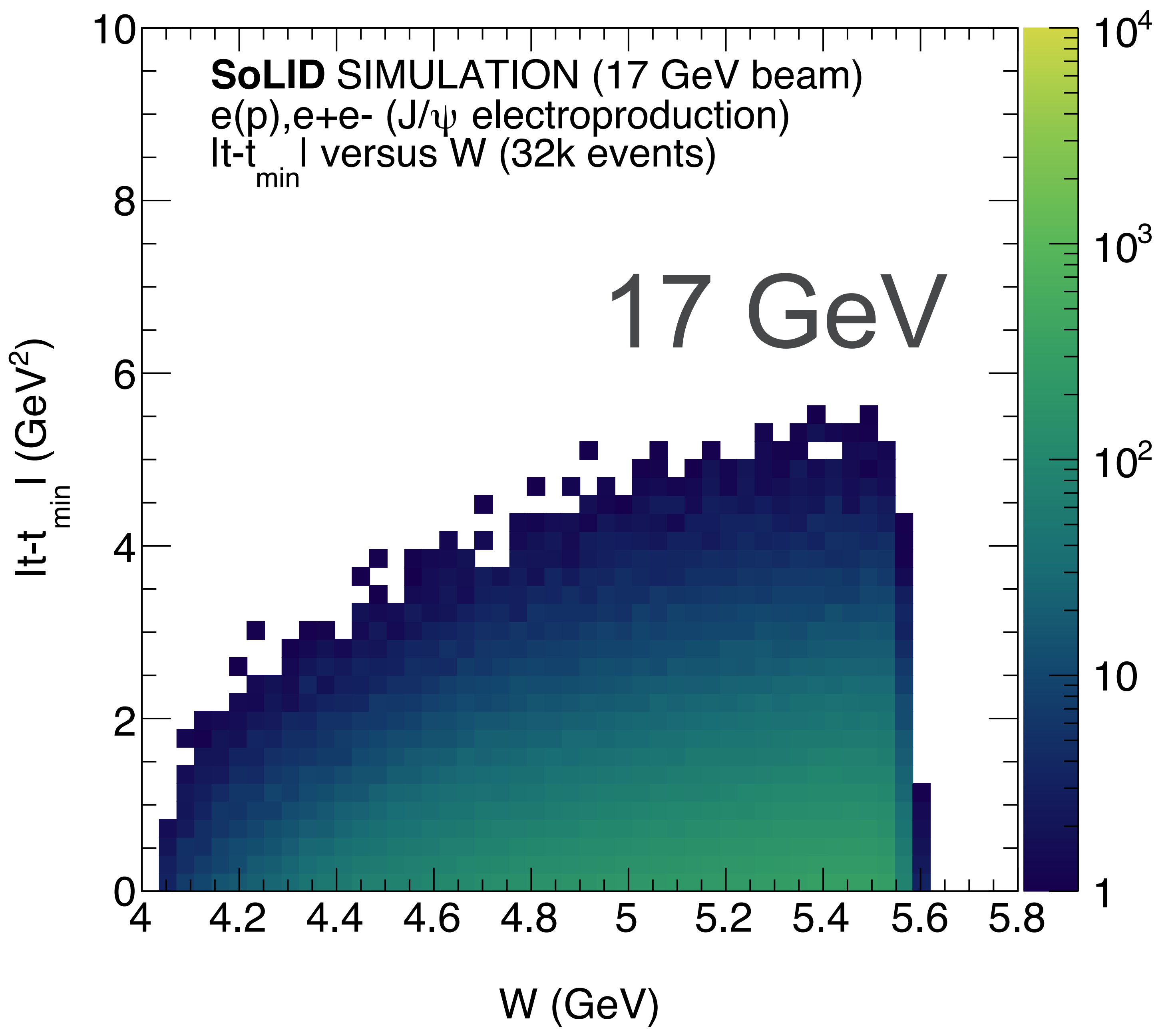


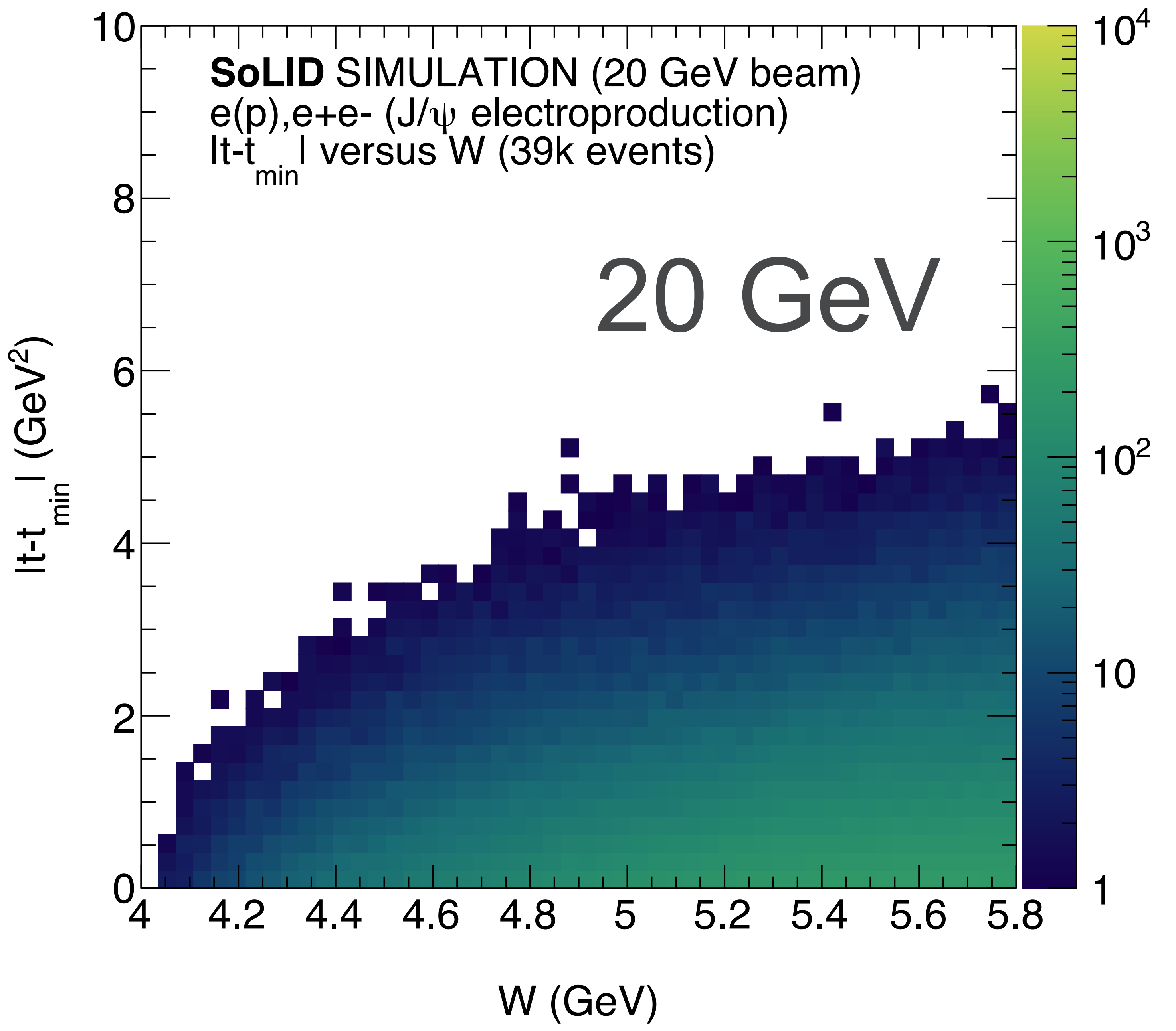


ELECTROPRODUCTION LOOKS PROMISING

Good kinematic coverage with standard setup

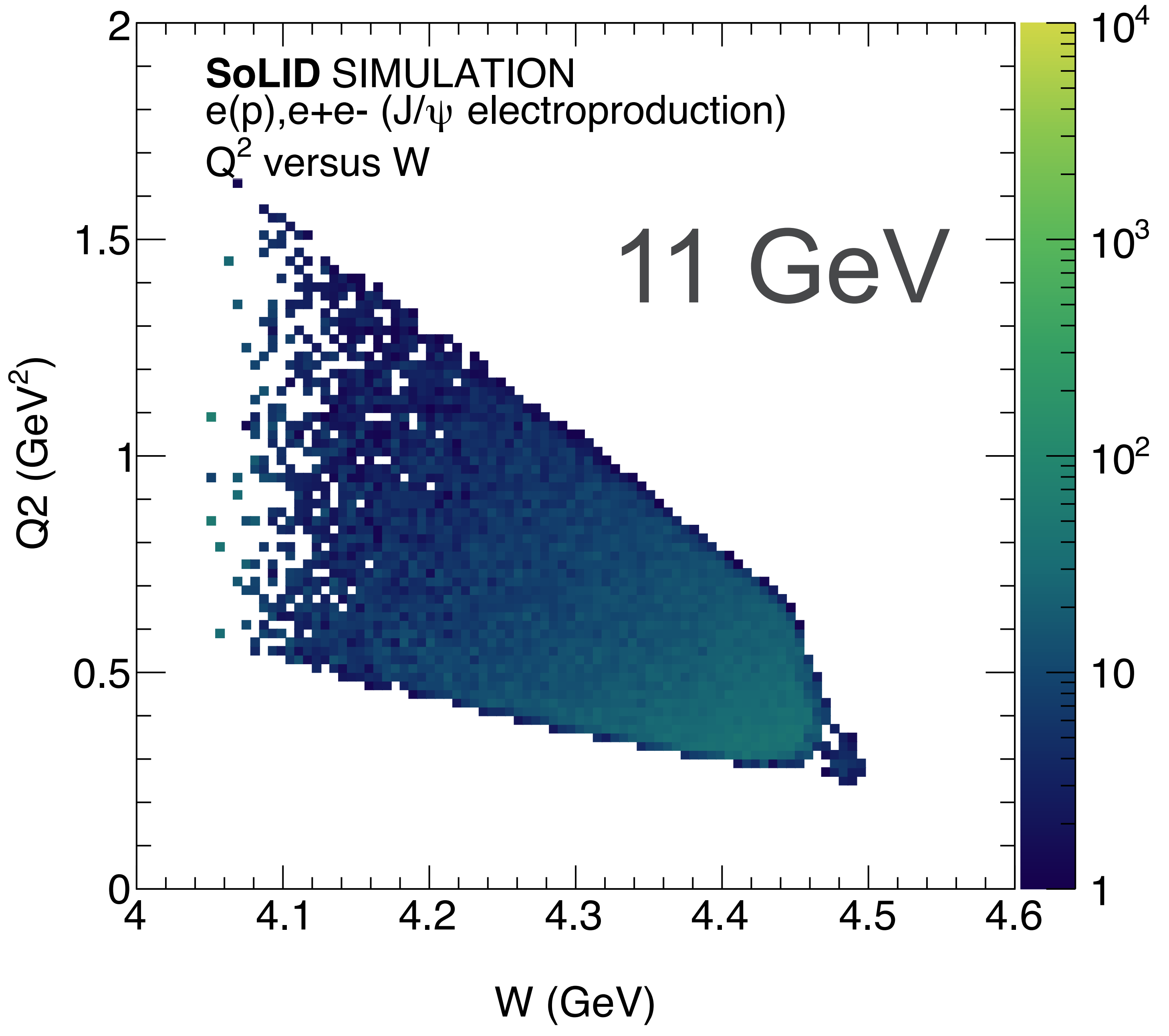


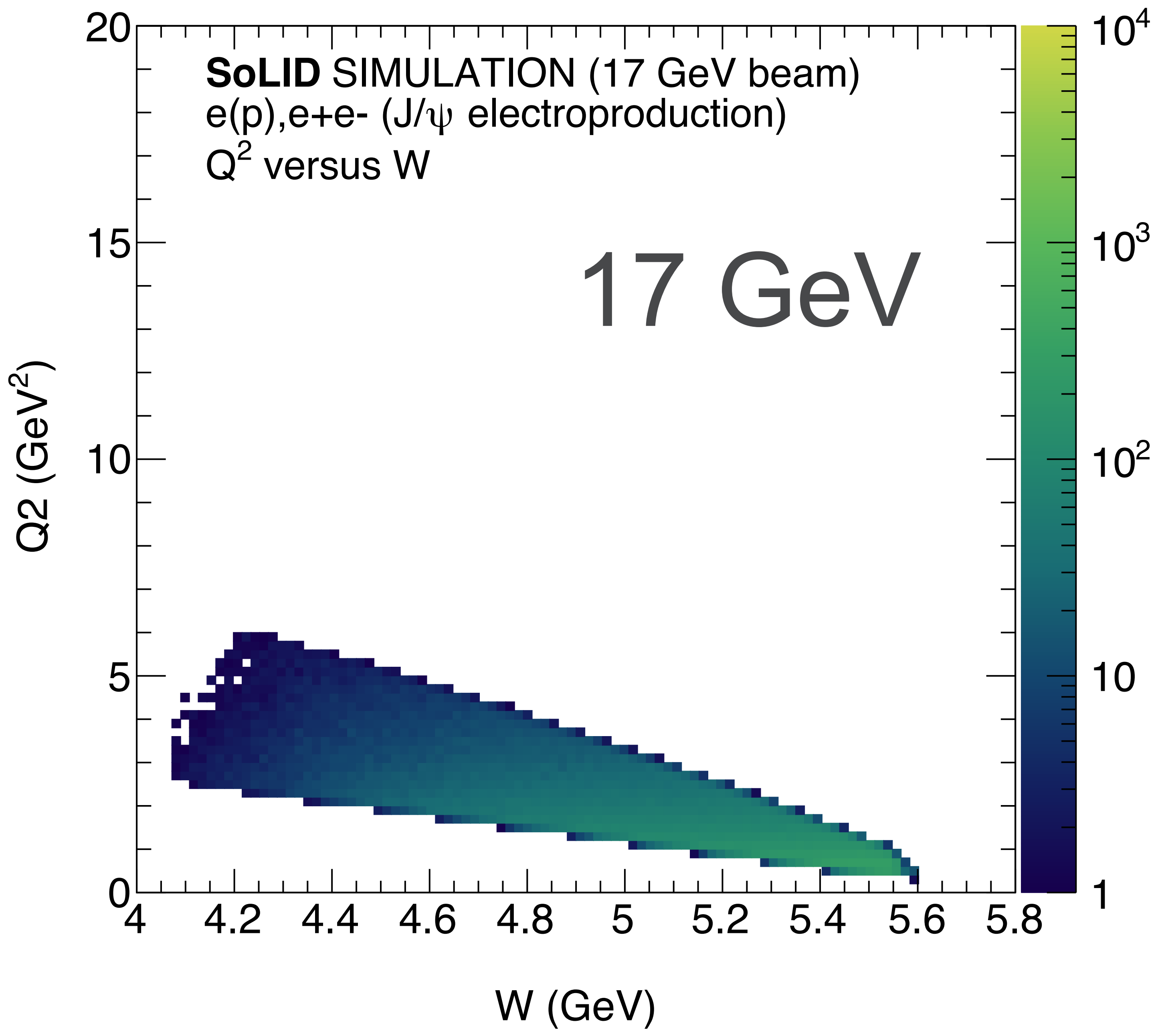


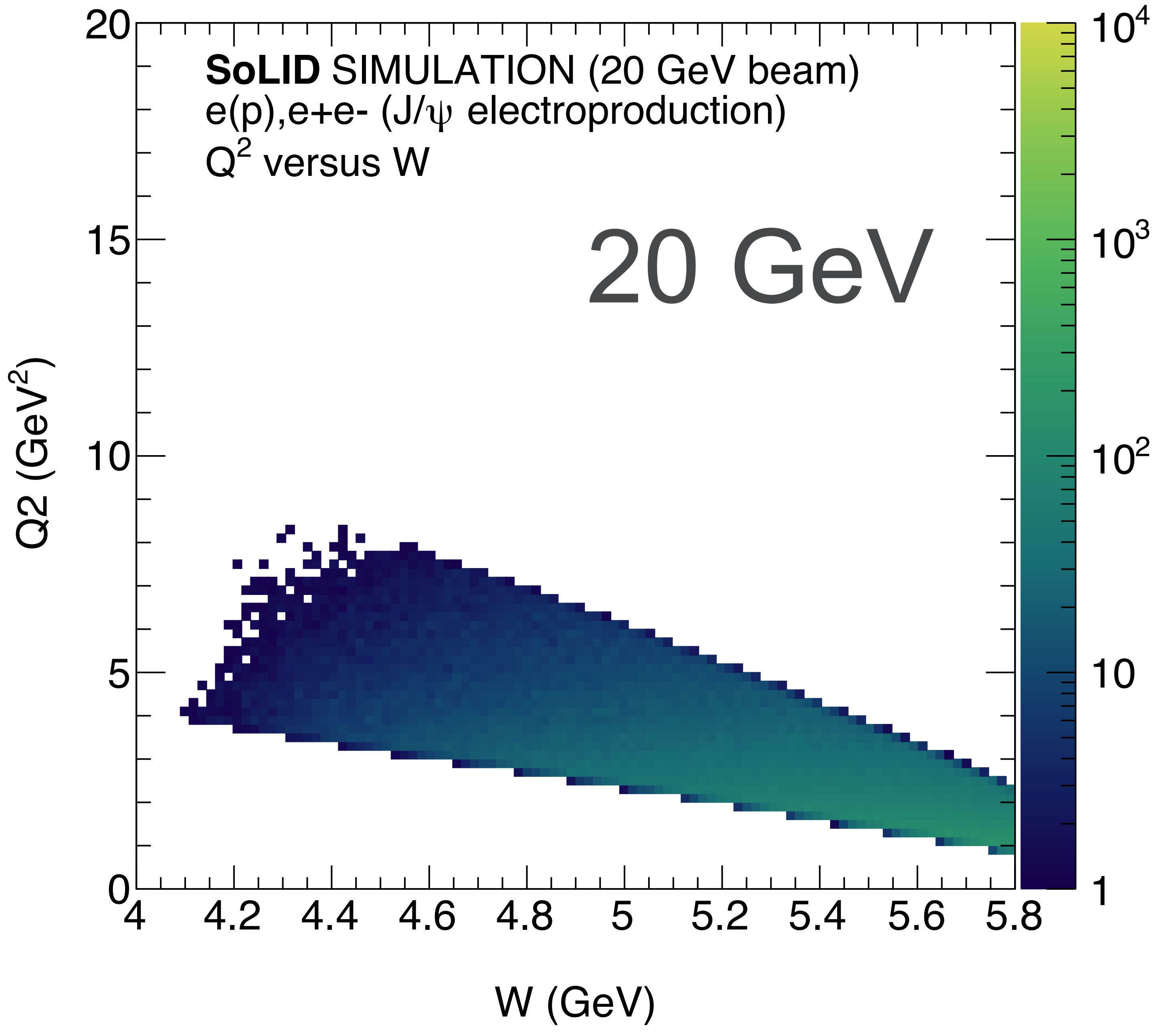


ELECTROPRODUCTION LOOKS PROMISING

Get near-threshold lever-arm in Q2

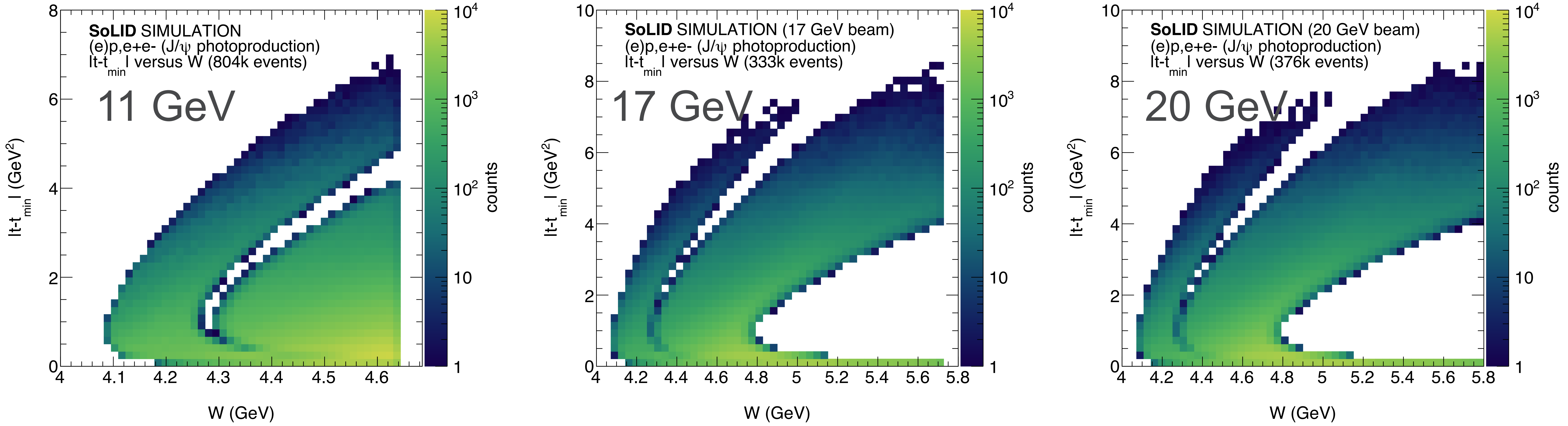






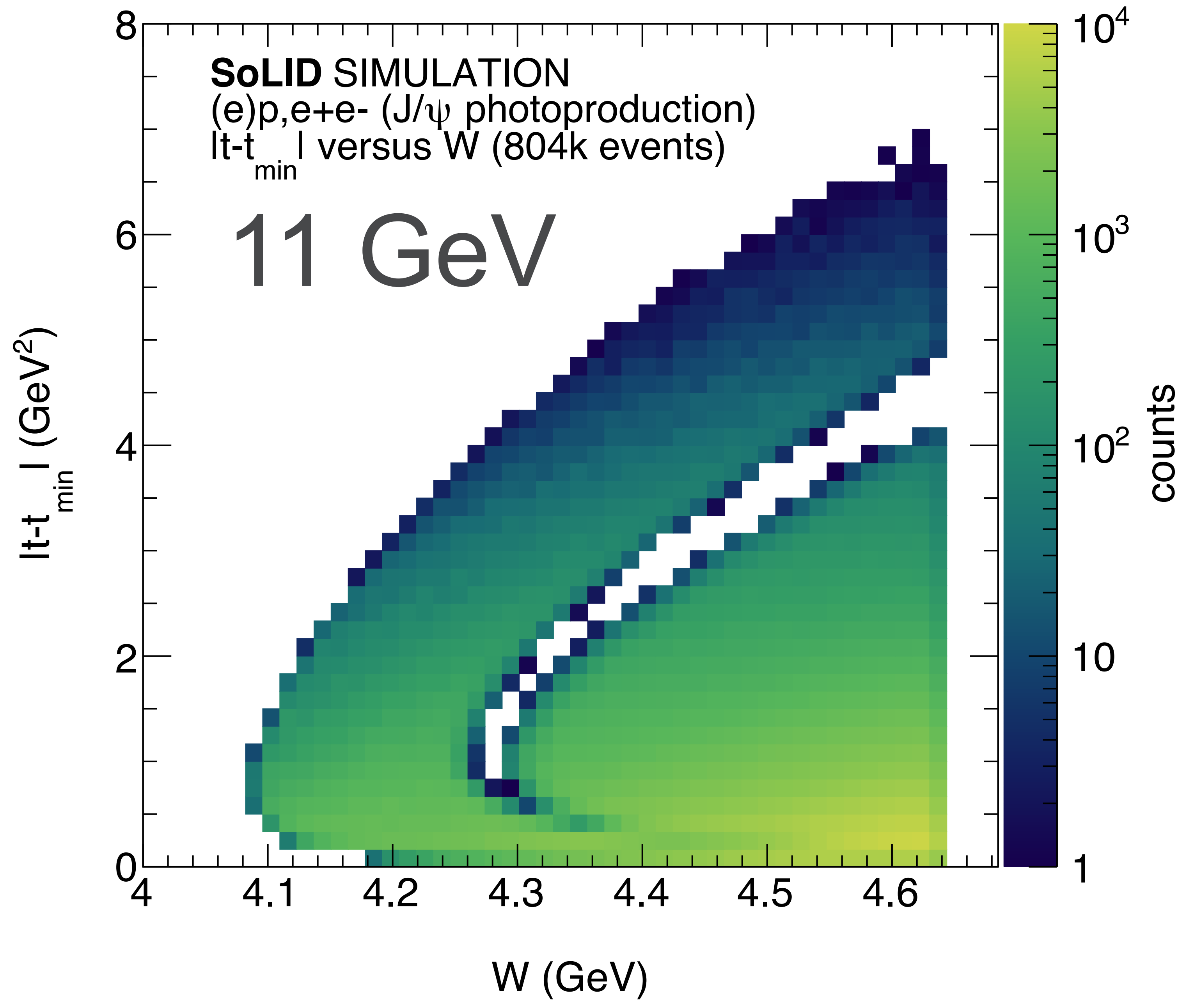
PHOTOPRODUCTION A BIT MORE DIFFICULT

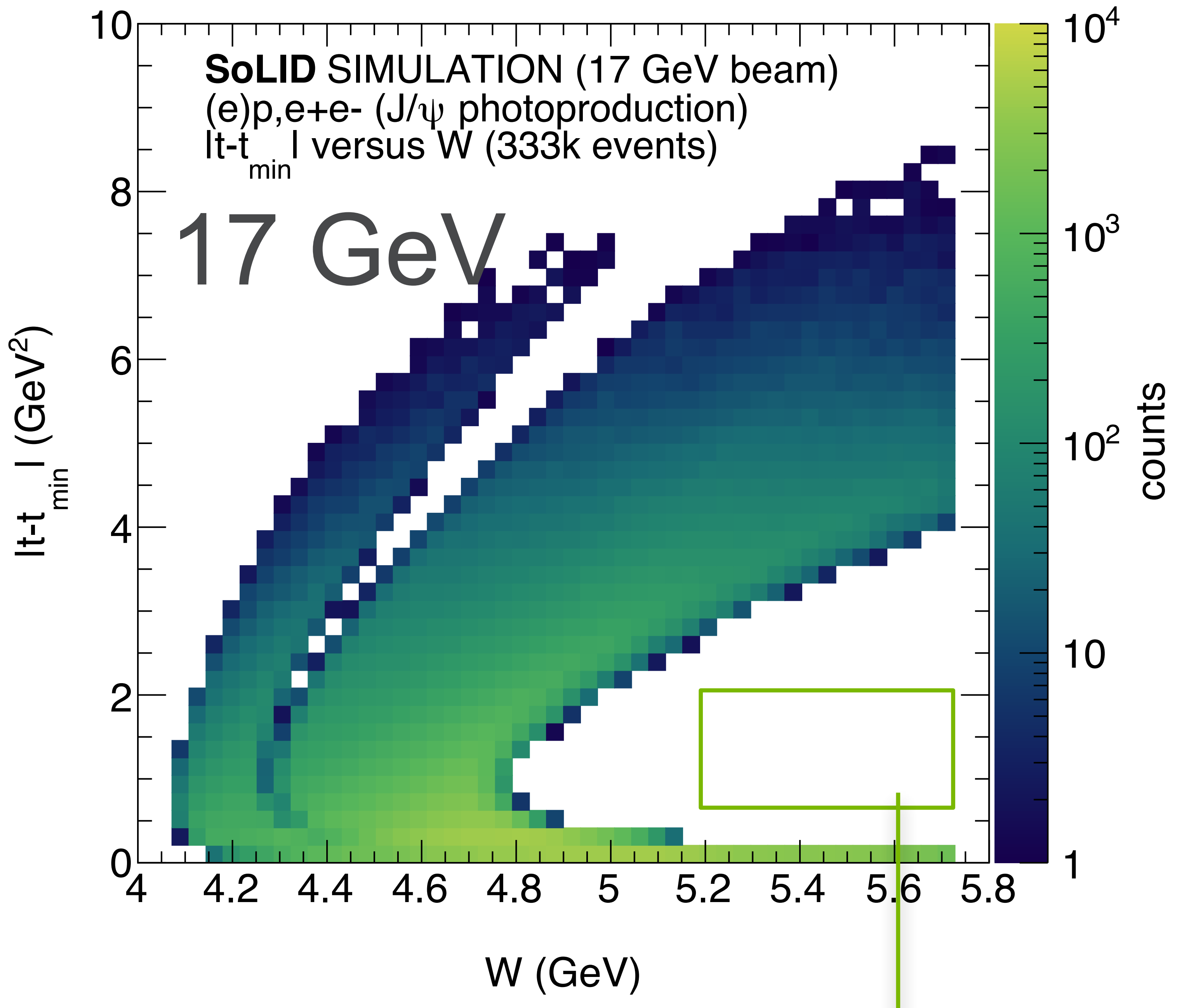
Missing events at high W - medium t

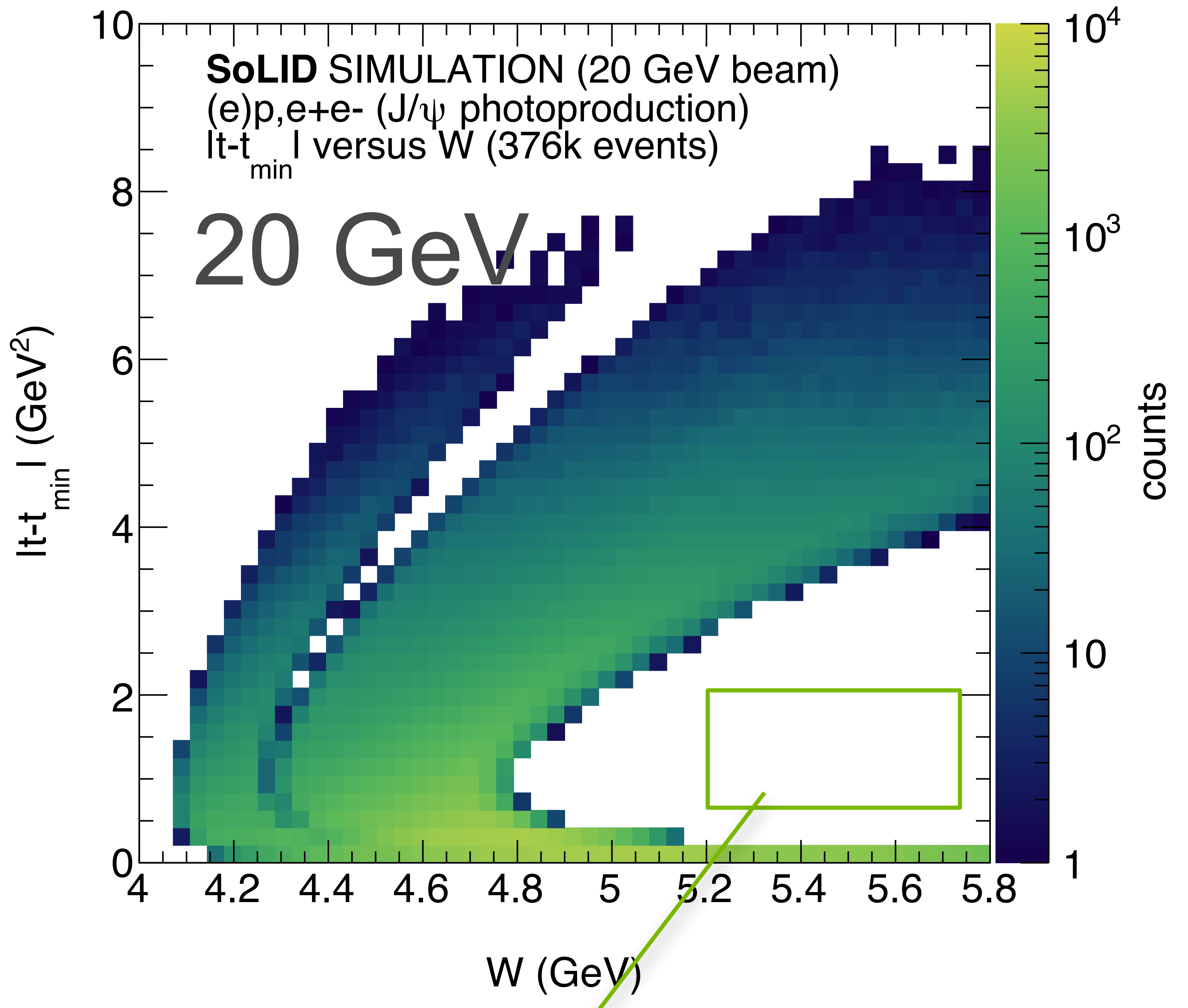


PHOTOPRODUCTION A BIT MORE DIFFICULT

What is the root cause for this?



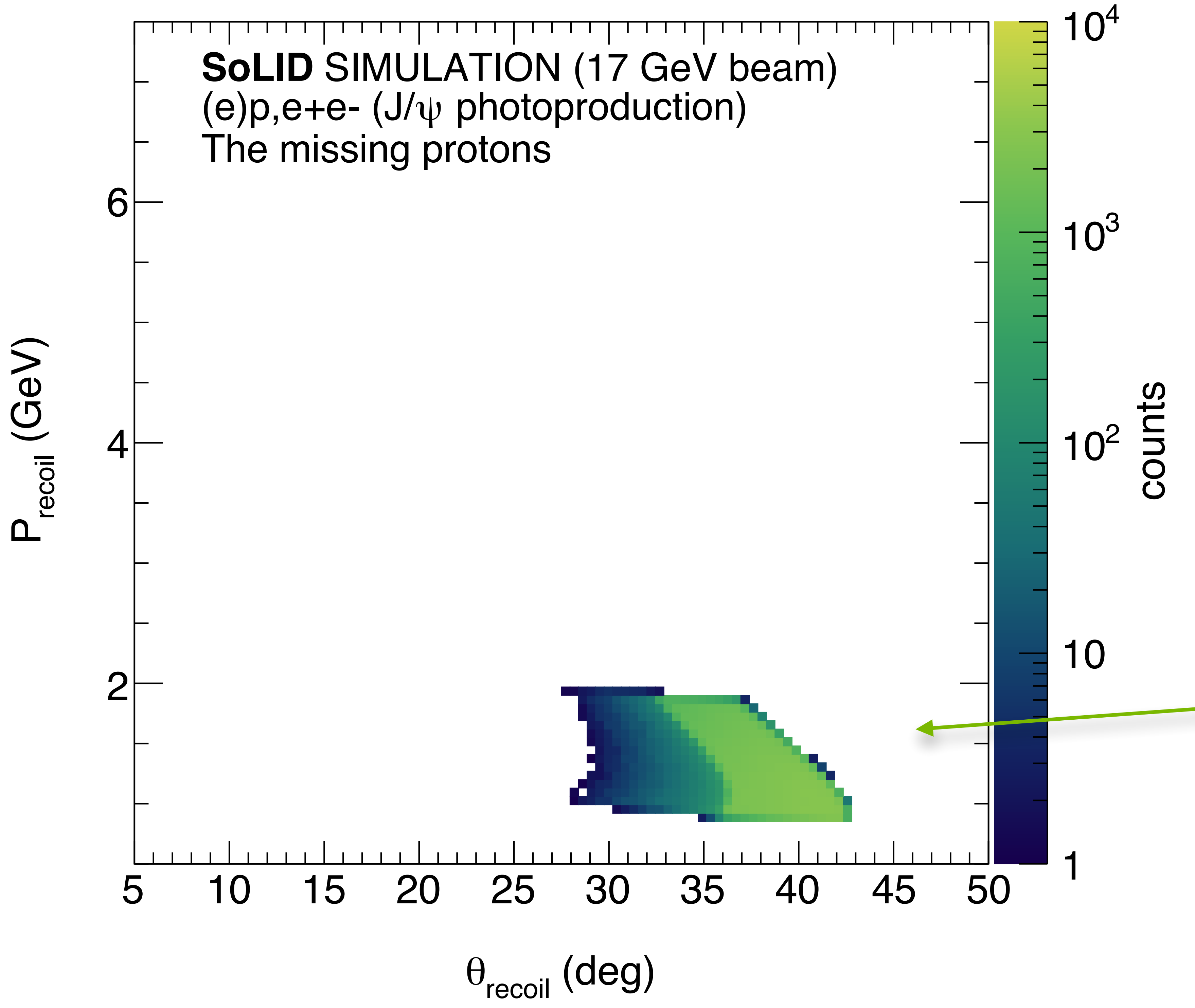


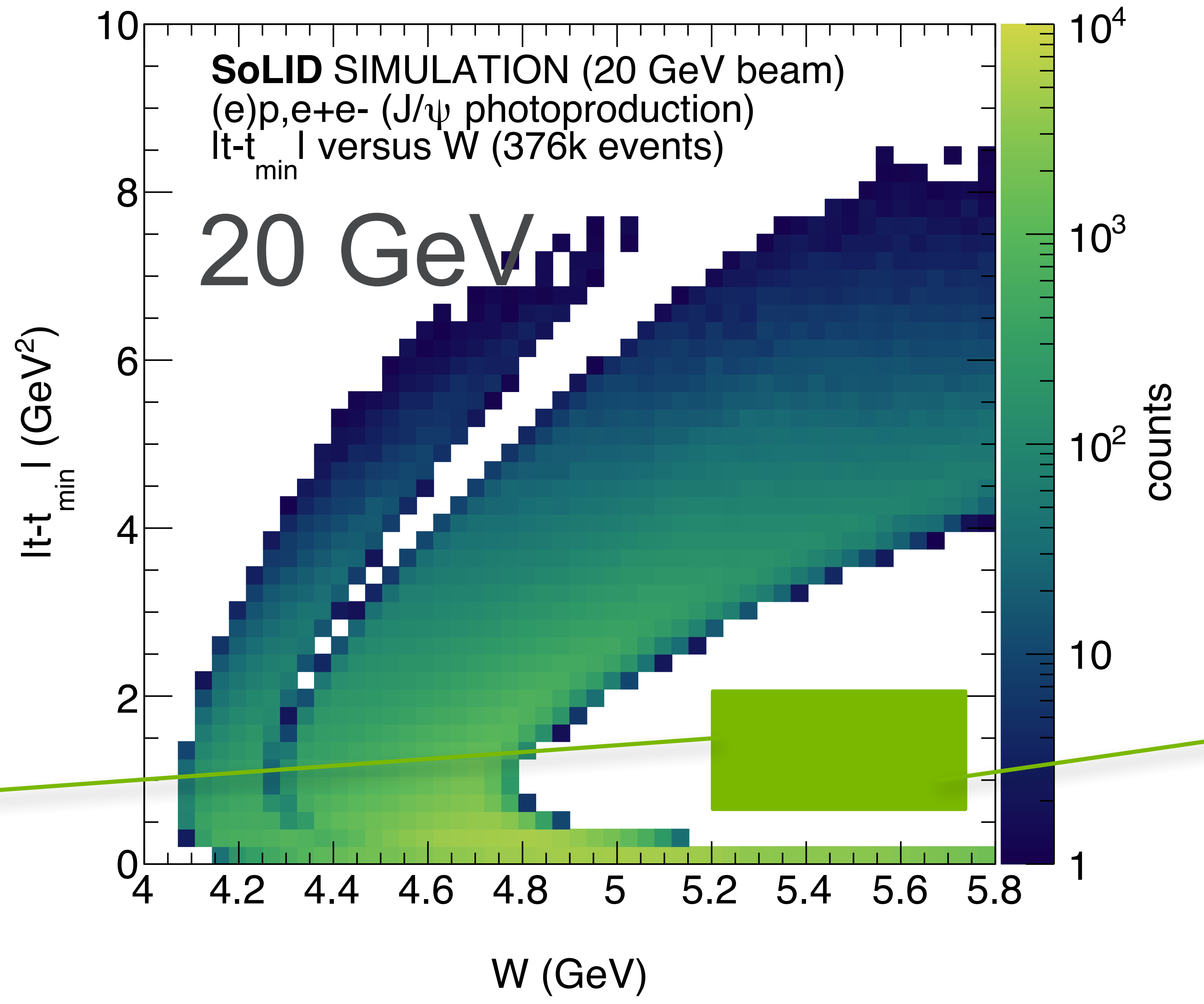


Let's look at the missing events

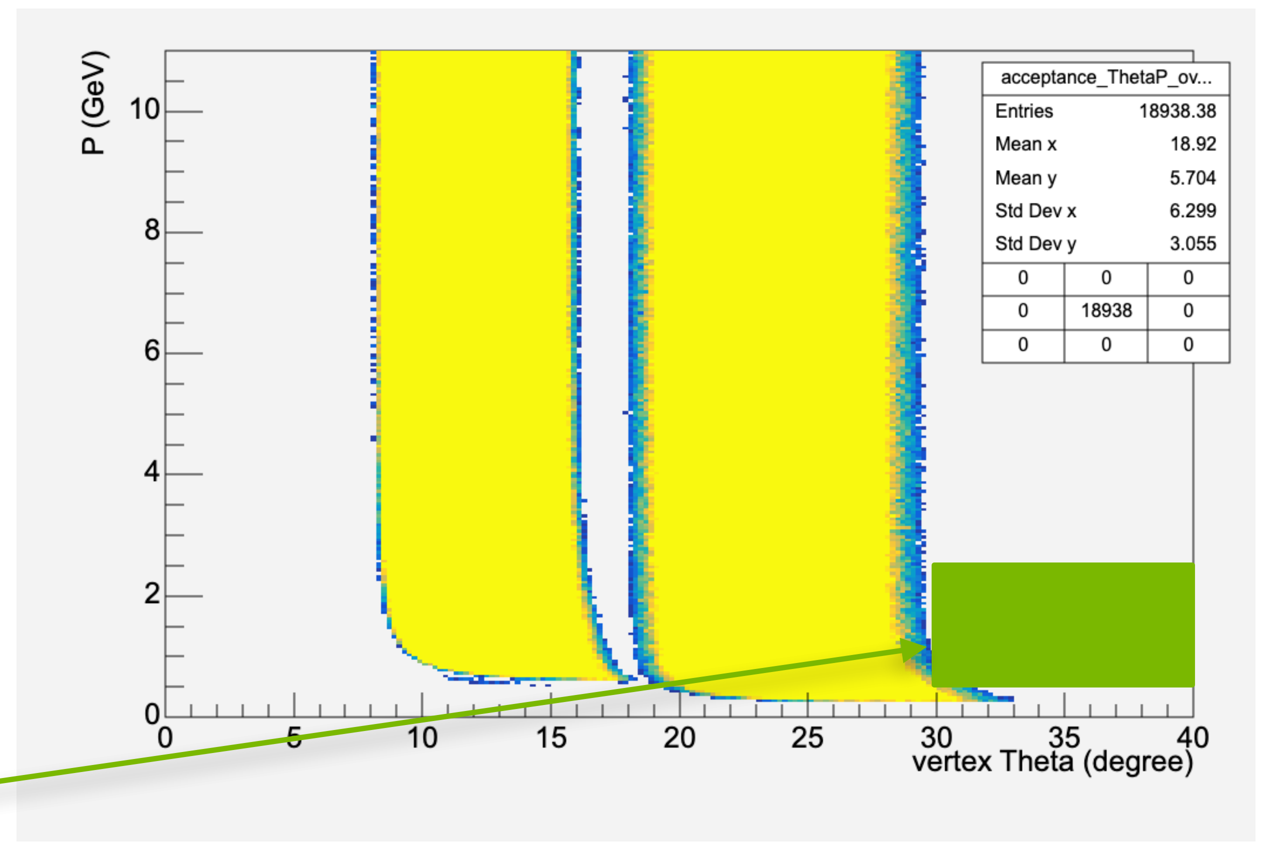
THE MISSING EVENTS… AT LARGE ANGLE???

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





SoLID-Jpsi acceptance

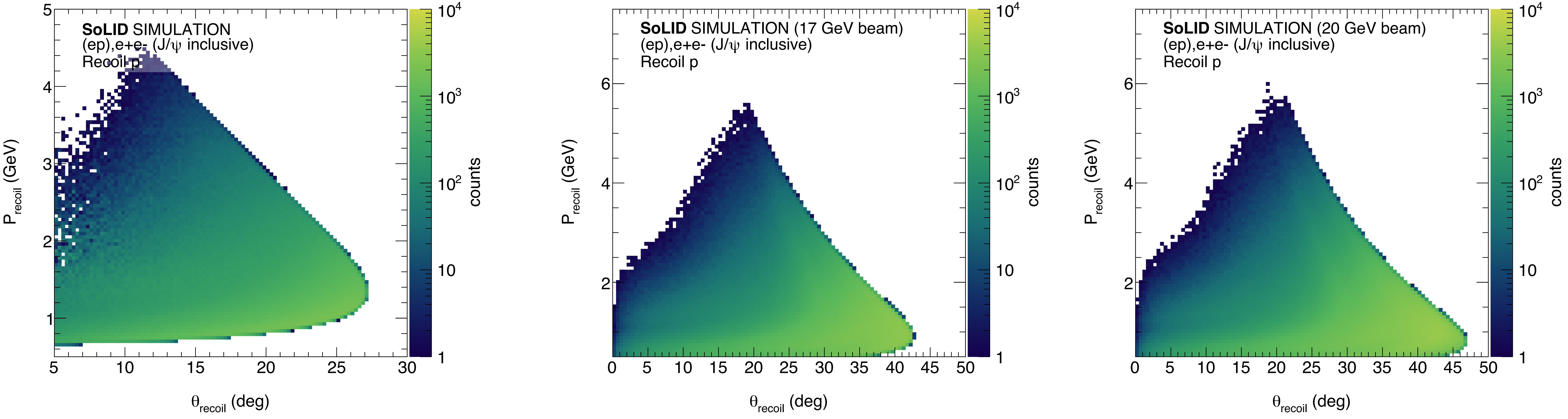


Counterintuitive…, why recoil proton at *larger* angle?

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

Recoil moving to larger and larger angles for increasing energy

Notice change in scale!



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: Either larger-angle recoil detector, or instrument SoLID to smaller angles should recover these events!

WHY Ψ’ PRODUCTION?

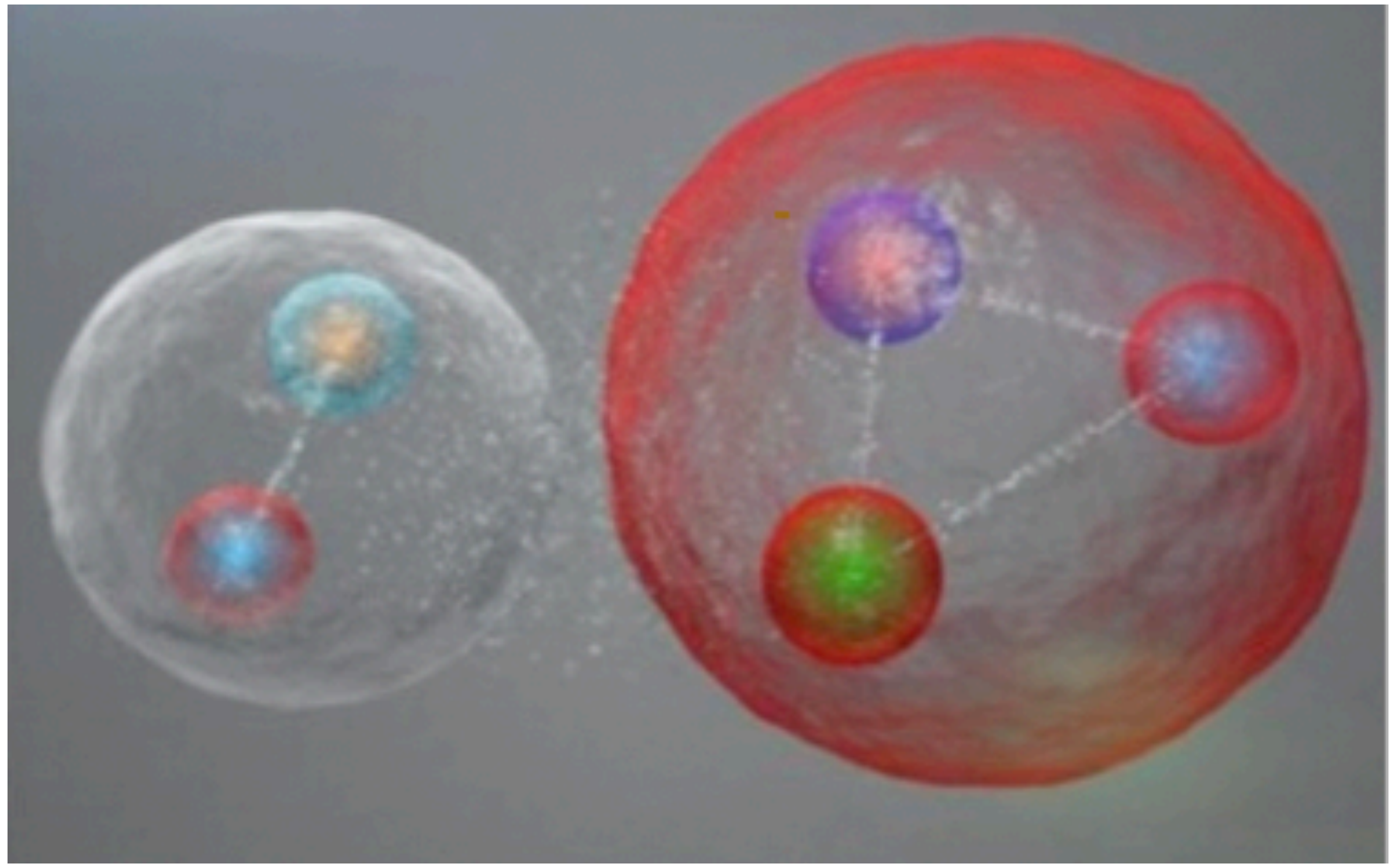
Independent, more sensitive probe (larger color dipole!)

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

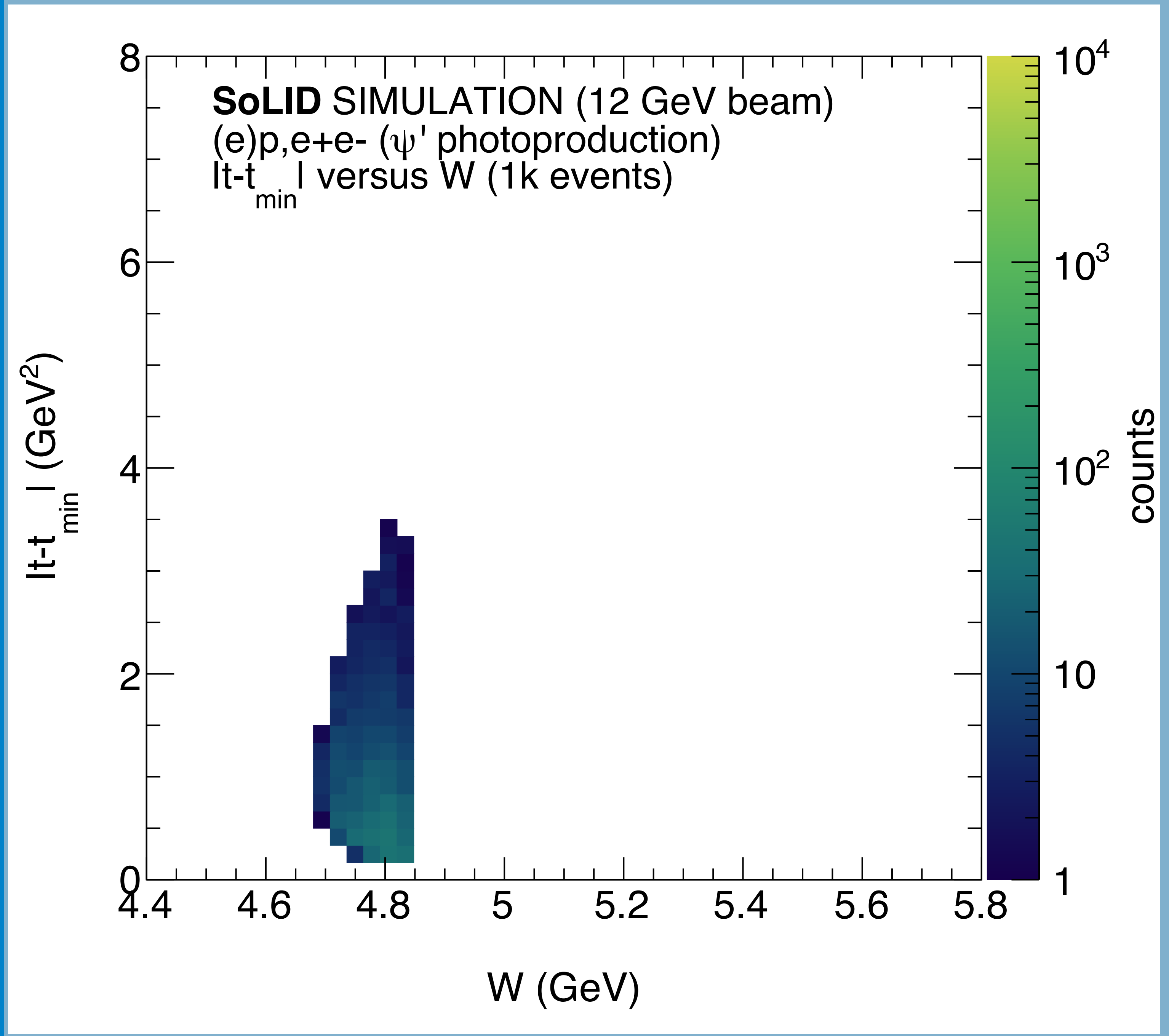
End result: factor of about 47 reduction in rate for $(\gamma p \rightarrow \psi(2s)p \rightarrow pe^{+}e^{-})$.

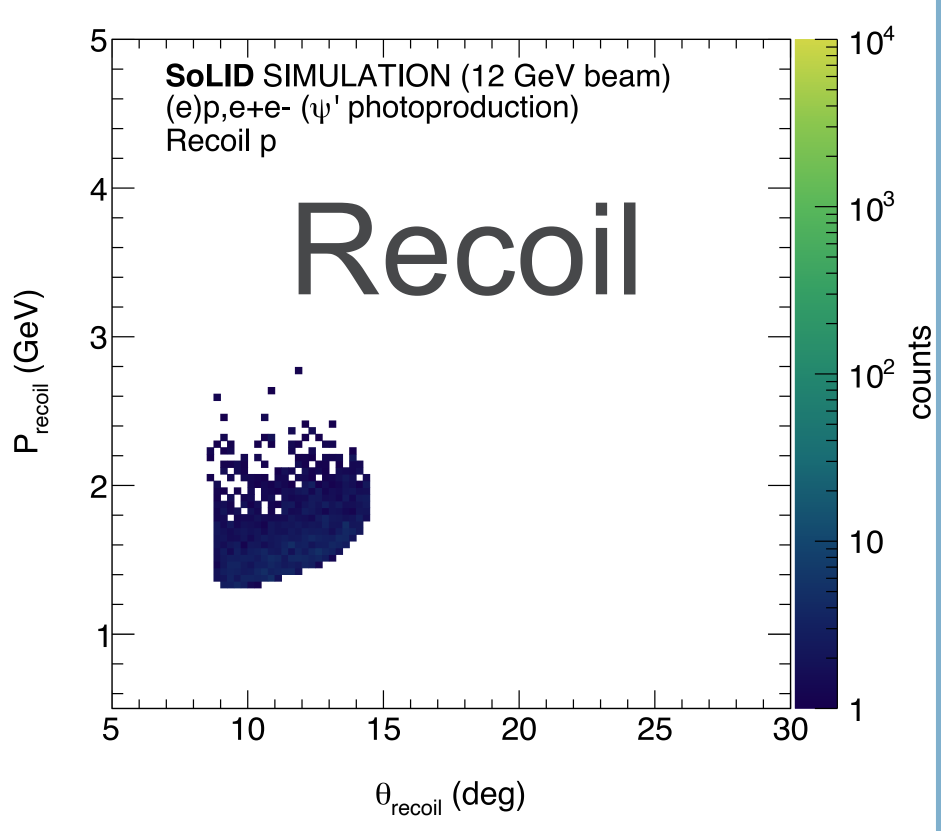
Hence, measurement requires very high luminosity. Could also be approached by exploring other decay channels

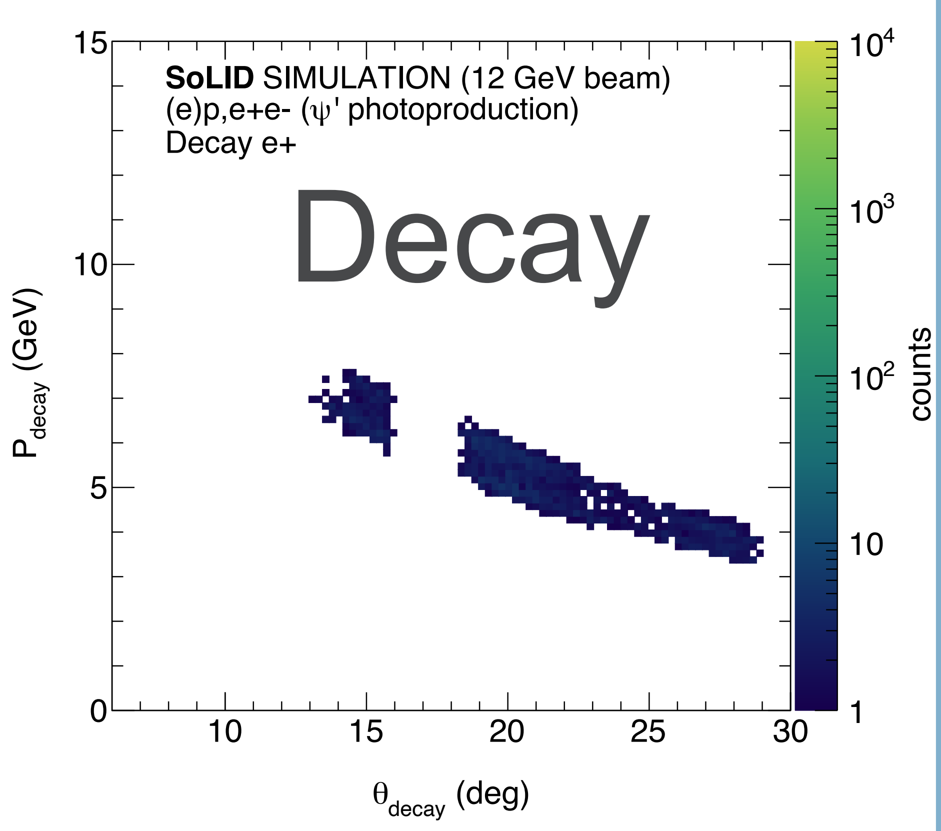
EXPERIMENTAL CONSIDERATIONS WITH SOLID

12 GeV is only enough to see ψ’

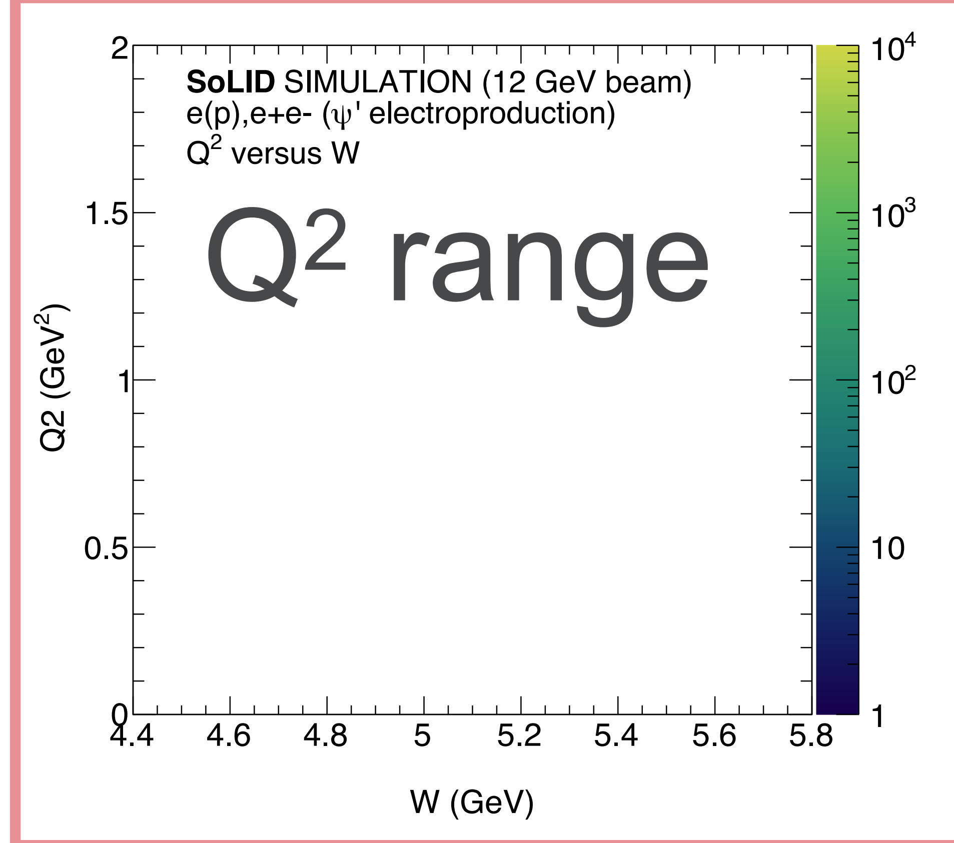
Triple-coincidence phase space for ψ’ production at SoLID assuming 50 days at $10^{37}/cm^2s$

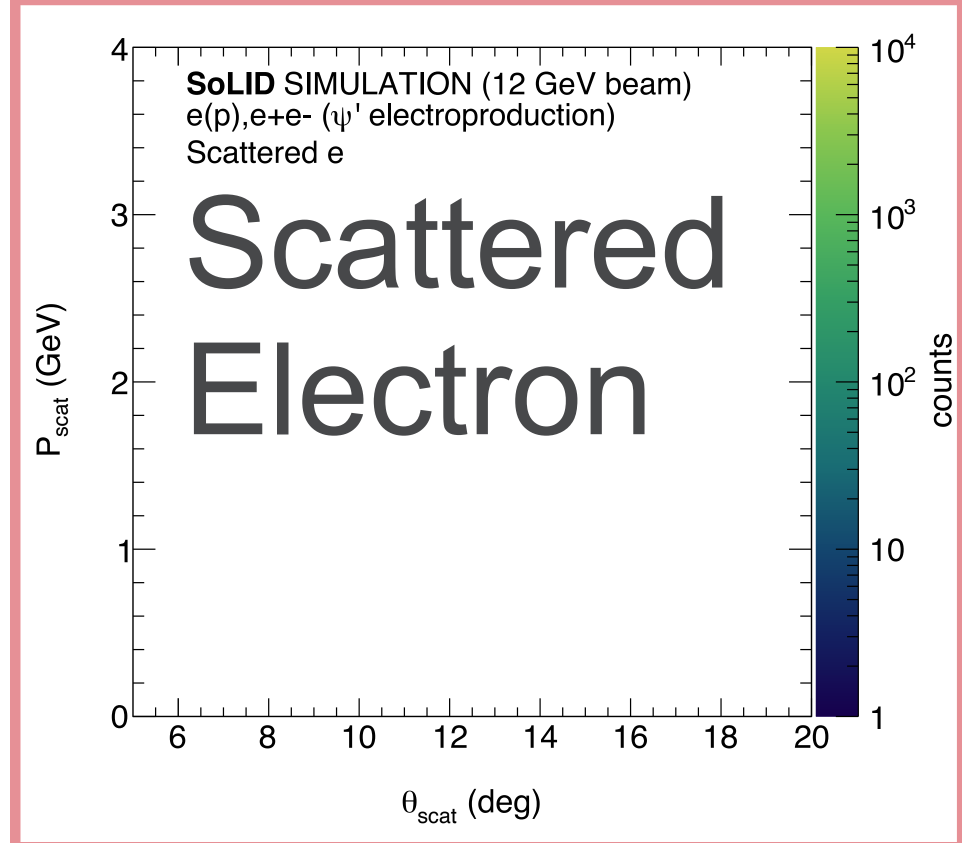


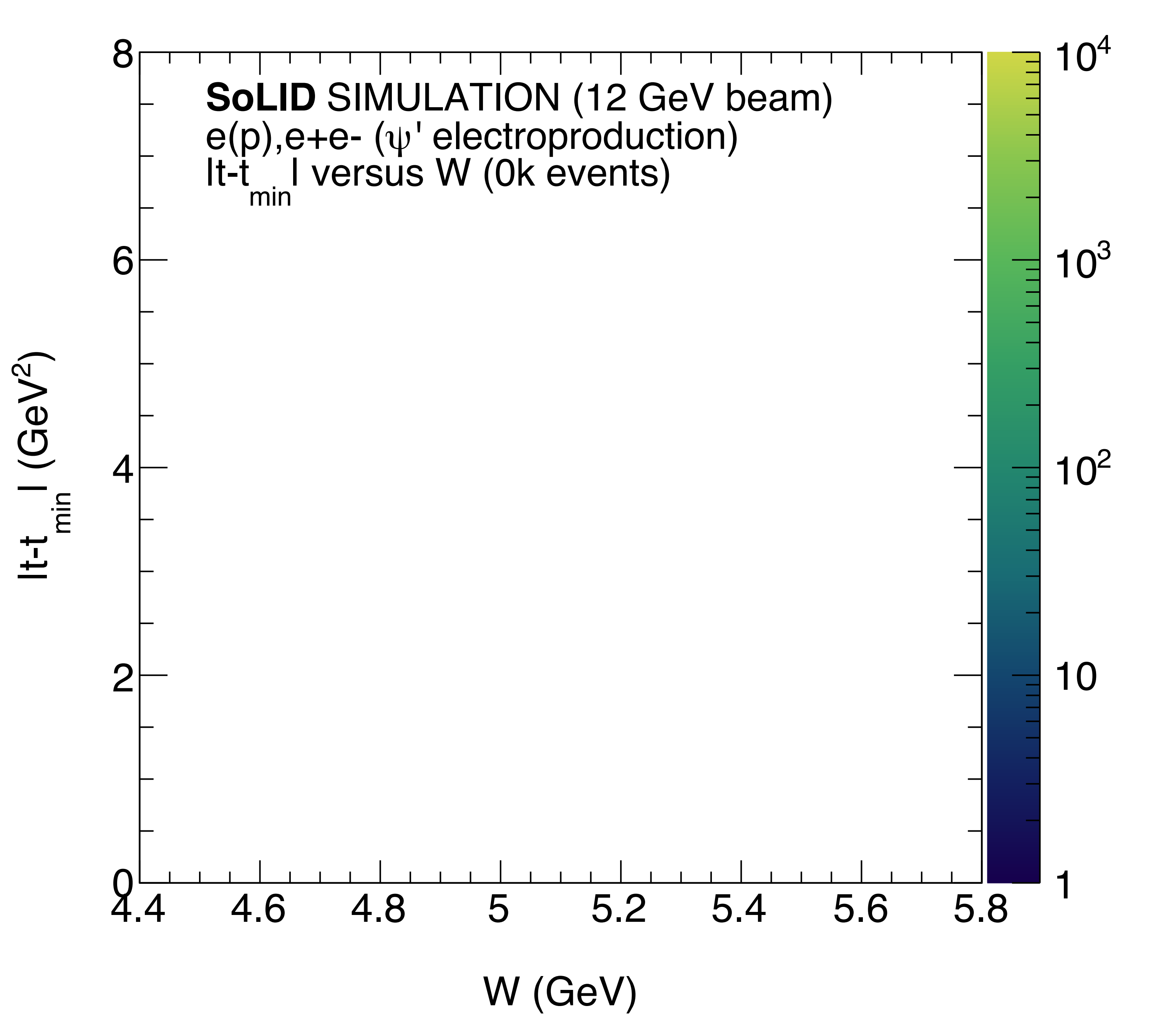




Photoproduction





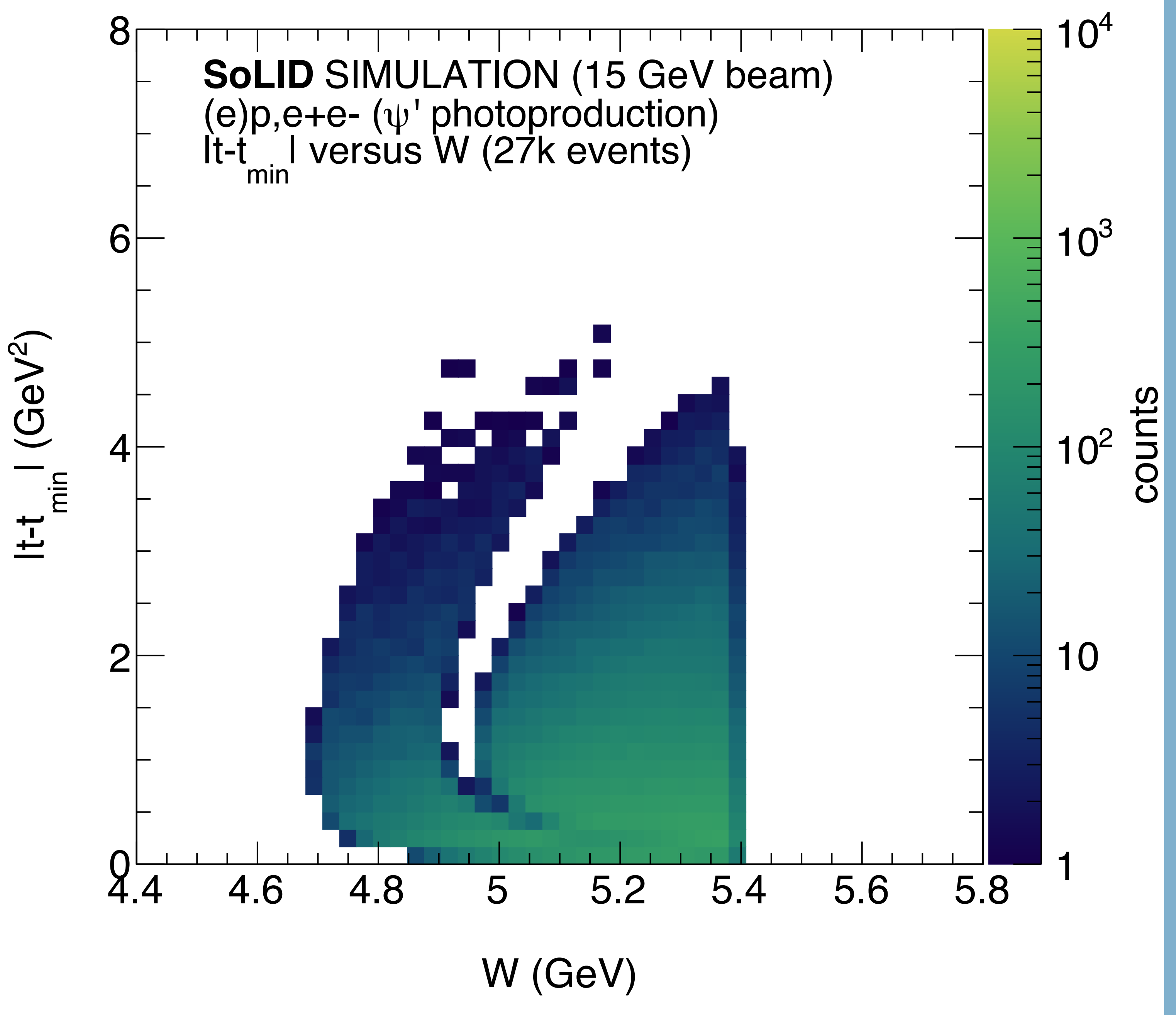


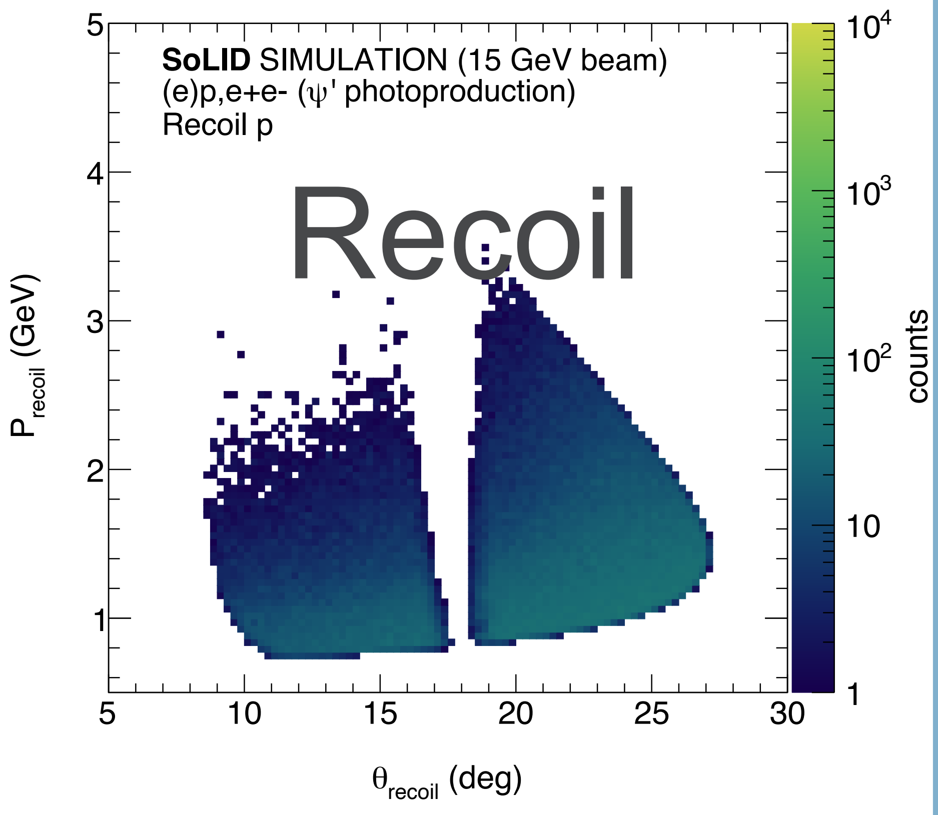
Electroproduction

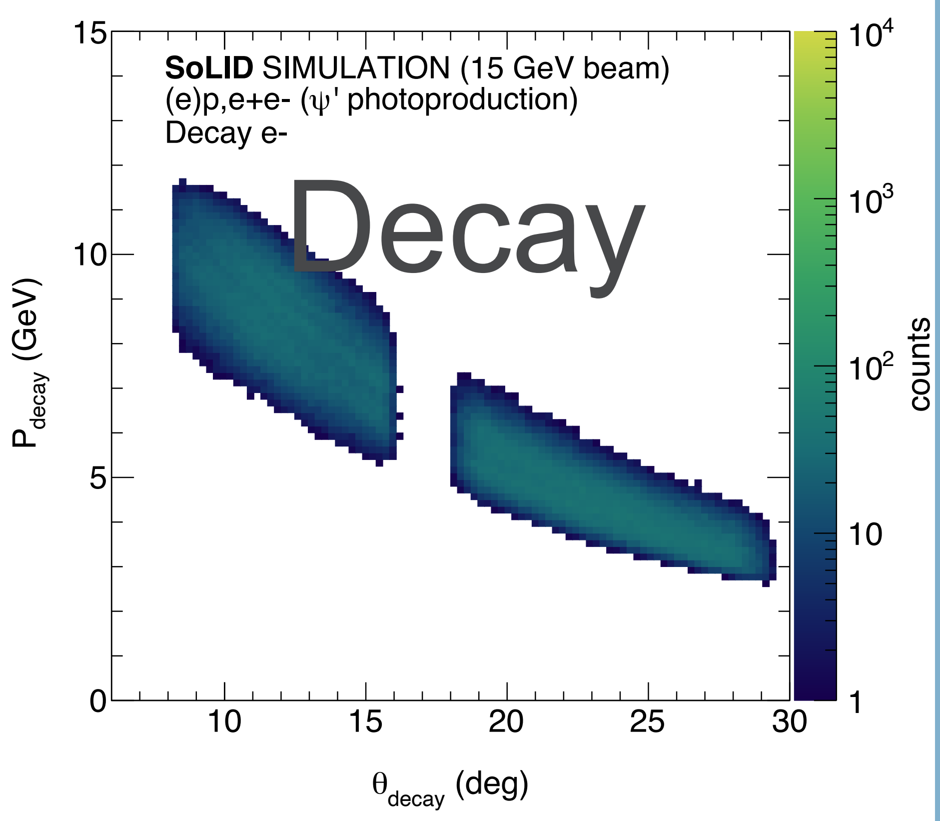
EXPERIMENTAL CONSIDERATIONS WITH SOLID

15 GeV starts giving access to a 2D cross section

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







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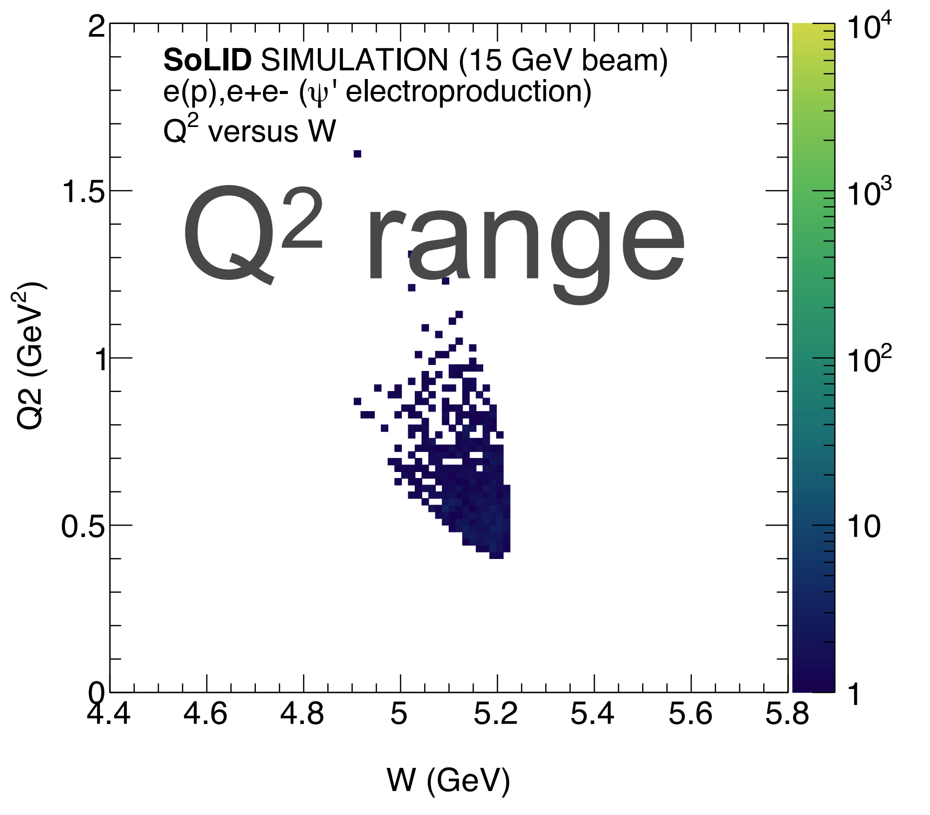
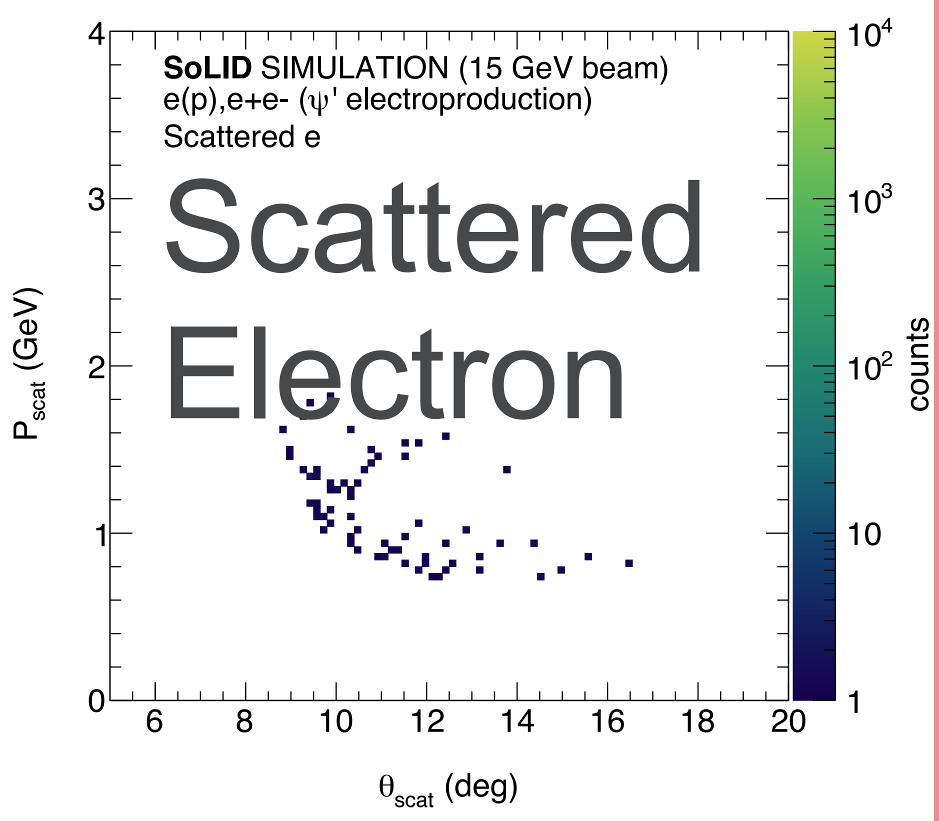
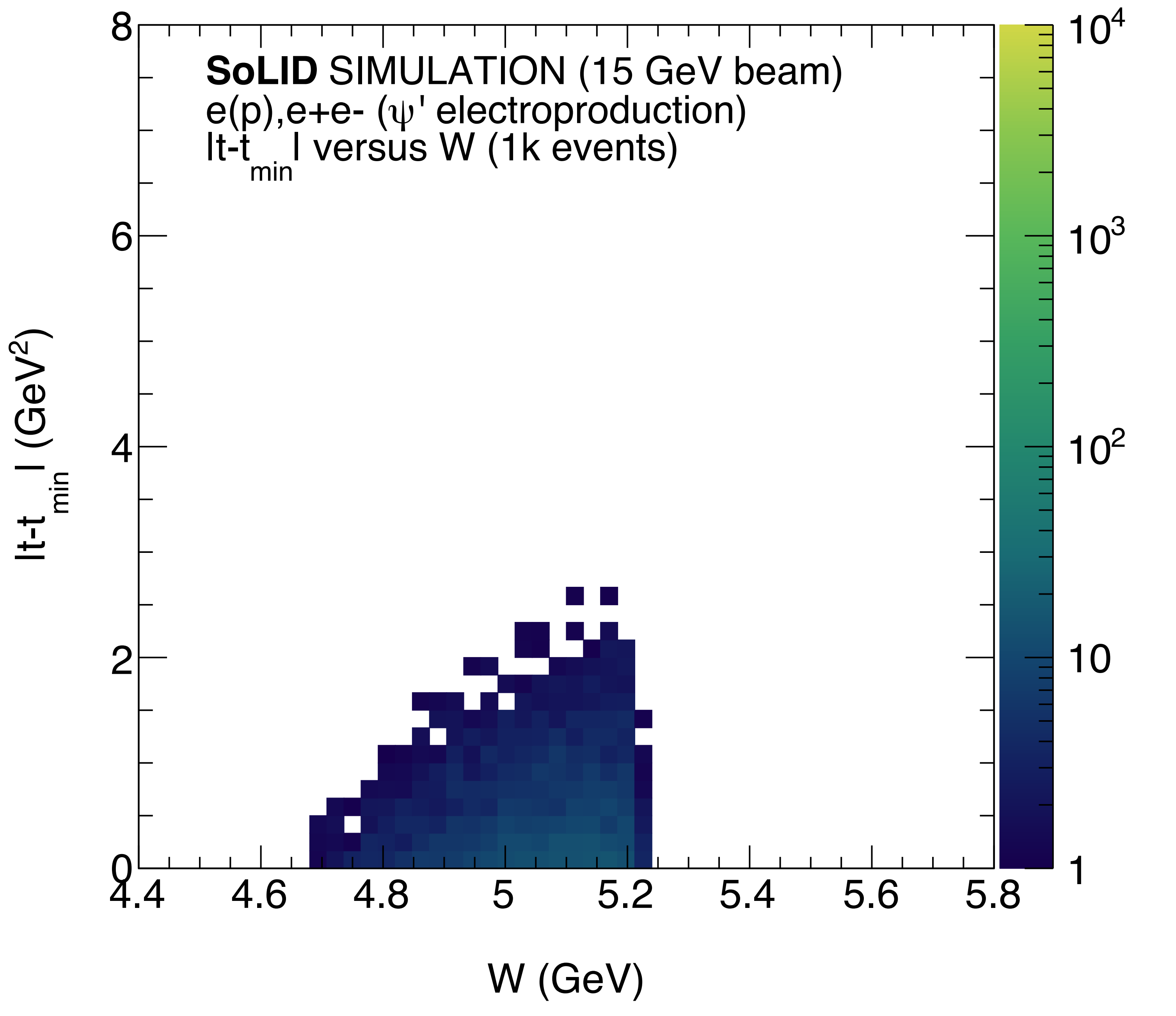




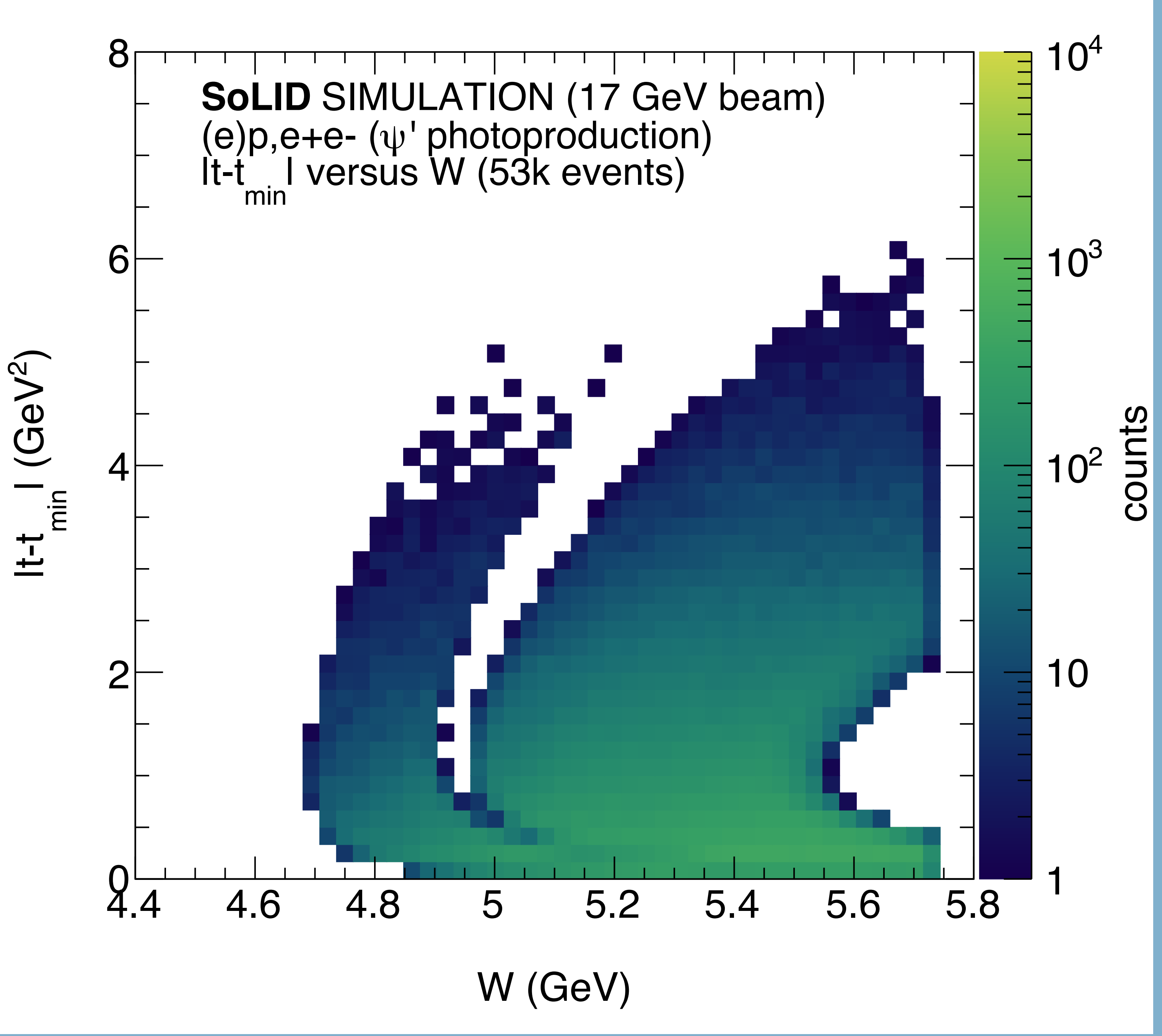


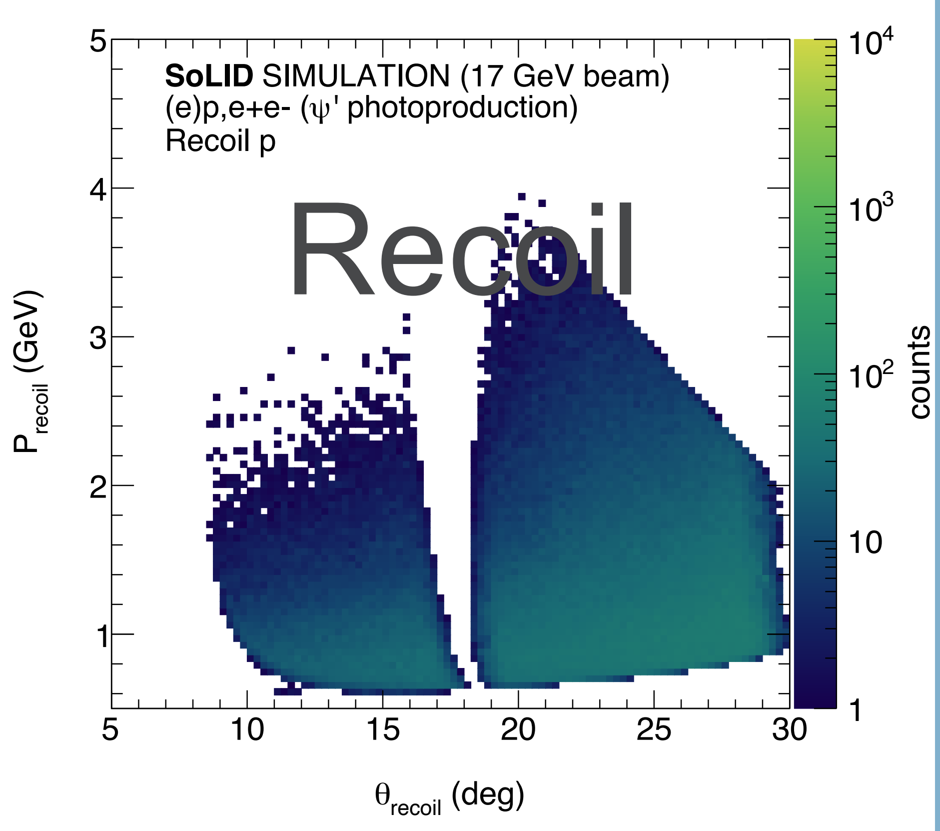
Electroproduction

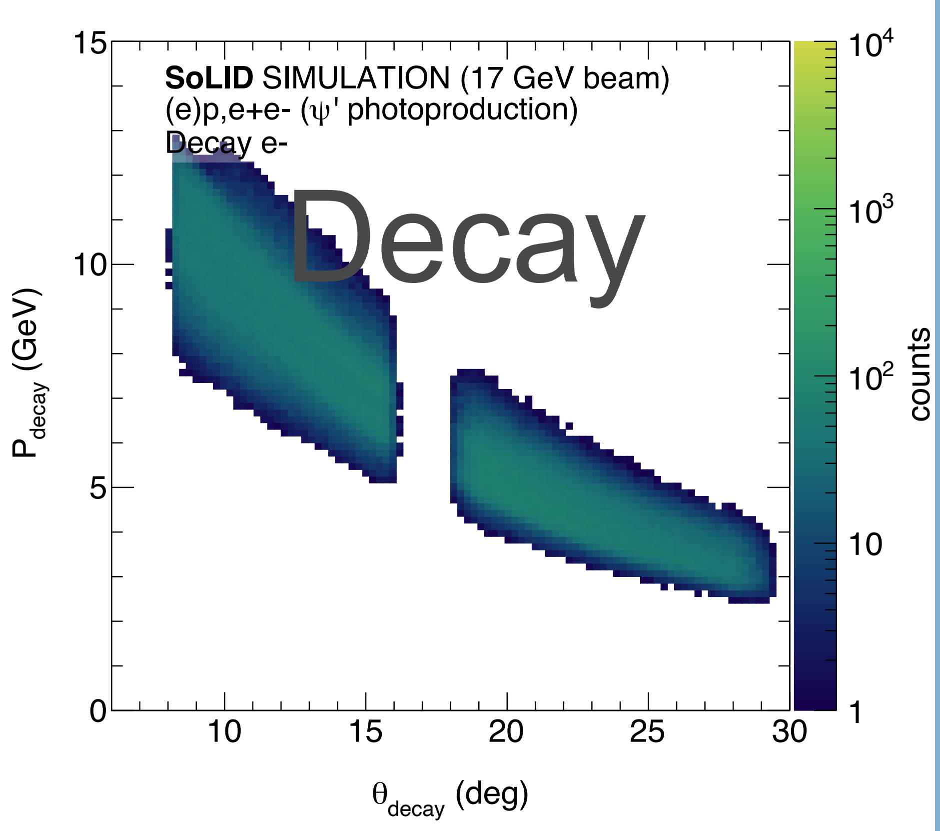
EXPERIMENTAL CONSIDERATIONS WITH SOLID

17 GeV optimum with current SoLID-J/ψ setup

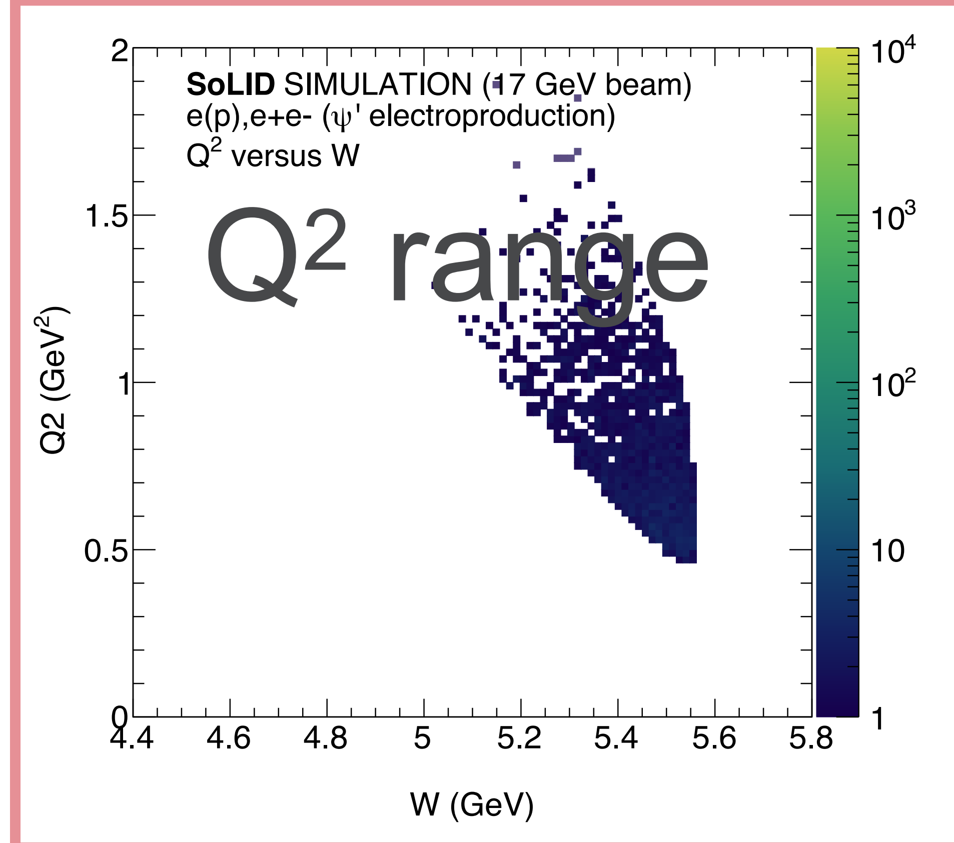
Triple-coincidence phase space for ψ’ production at SoLID assuming 50 days at $10^{37}/cm^2s$

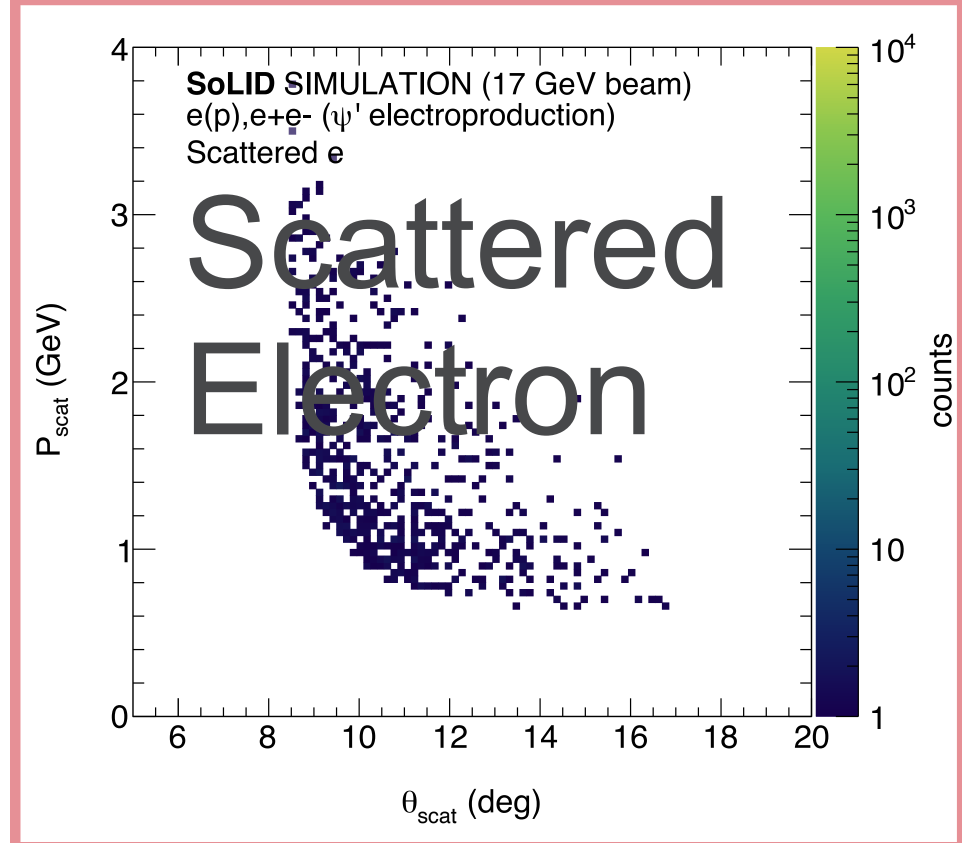


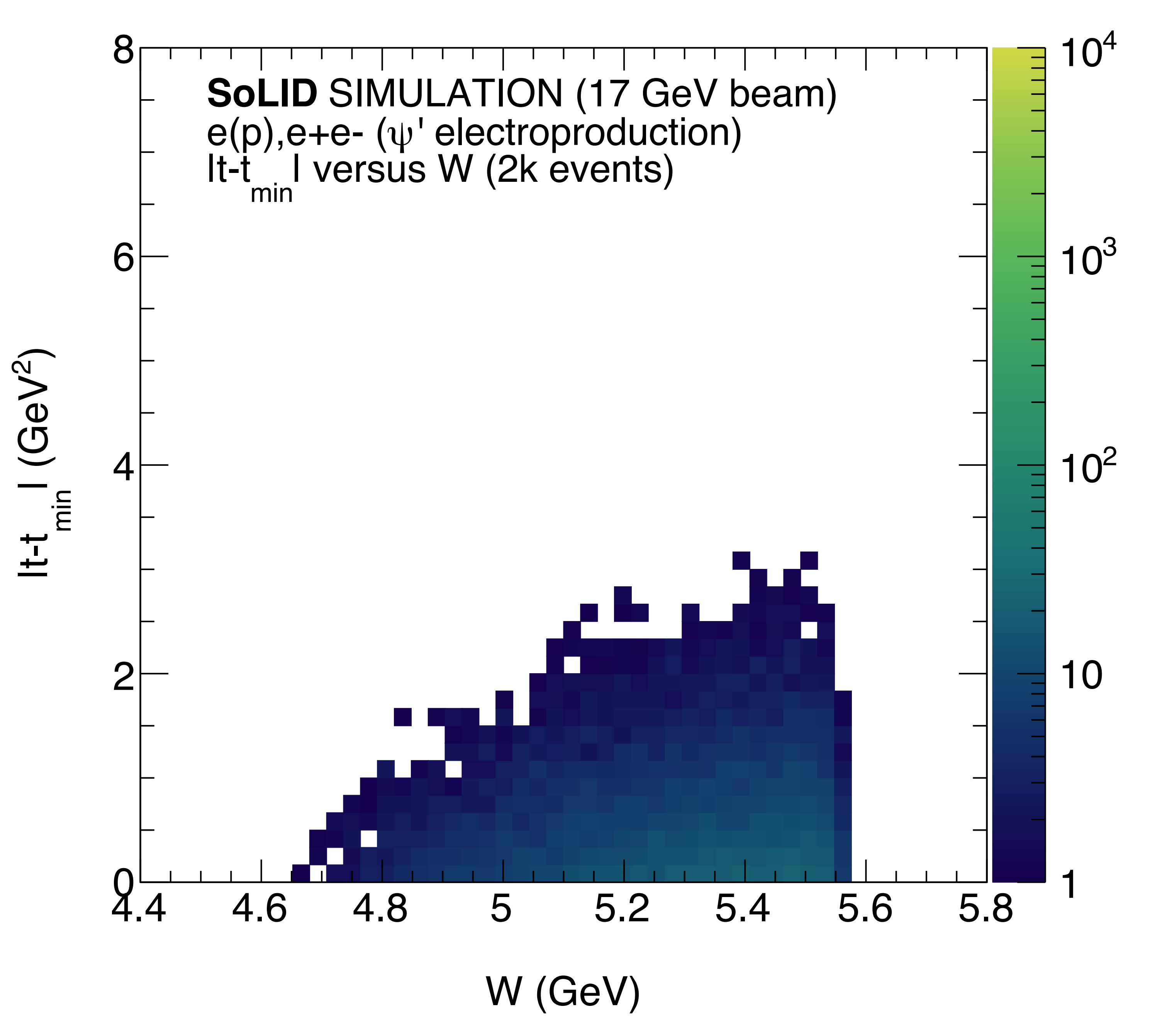




Photoproduction





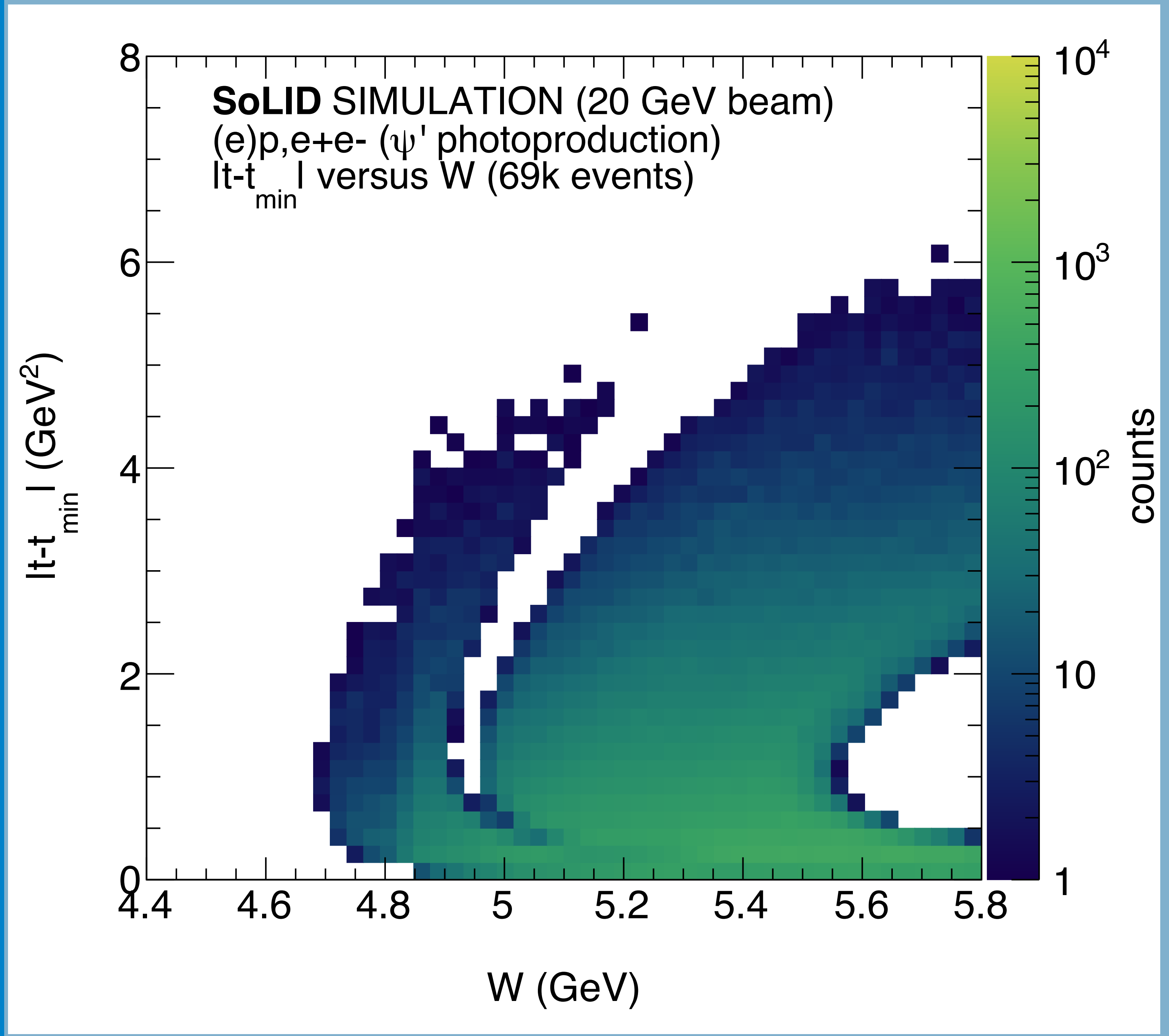


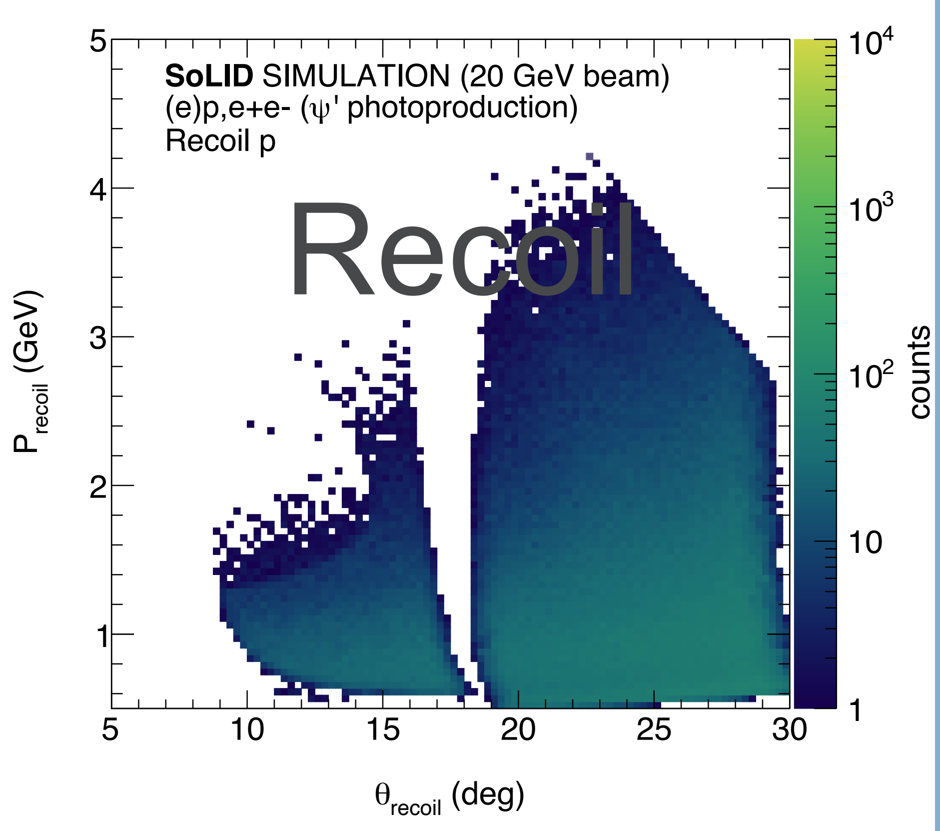
Electroproduction

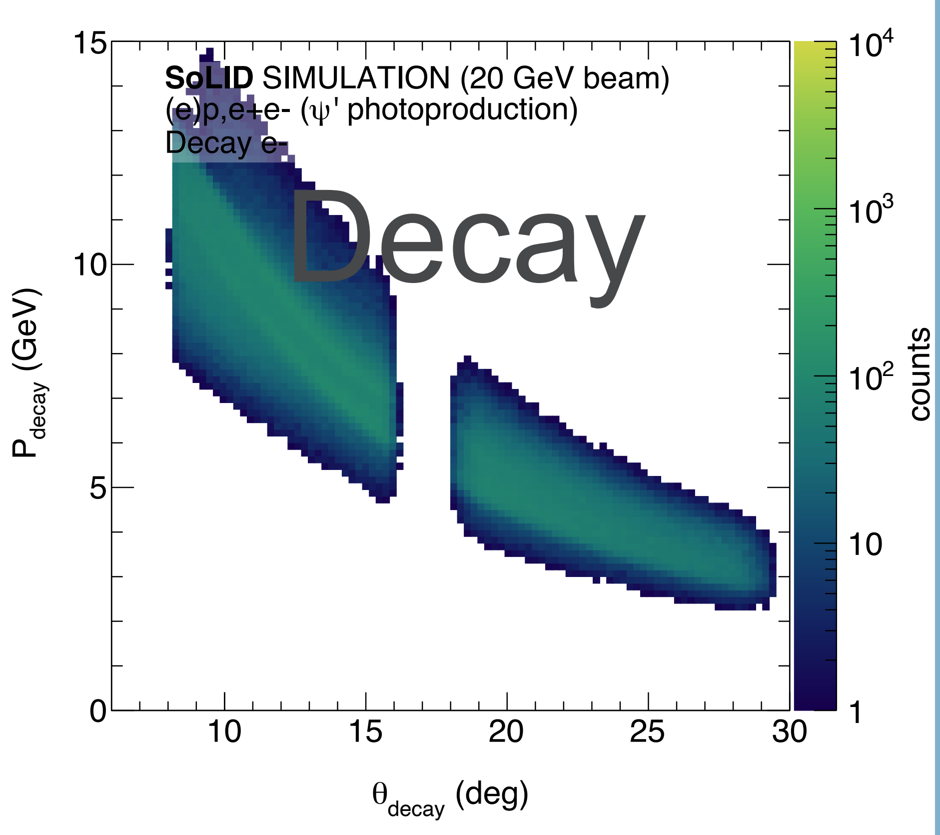
EXPERIMENTAL CONSIDERATIONS WITH SOLID

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

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







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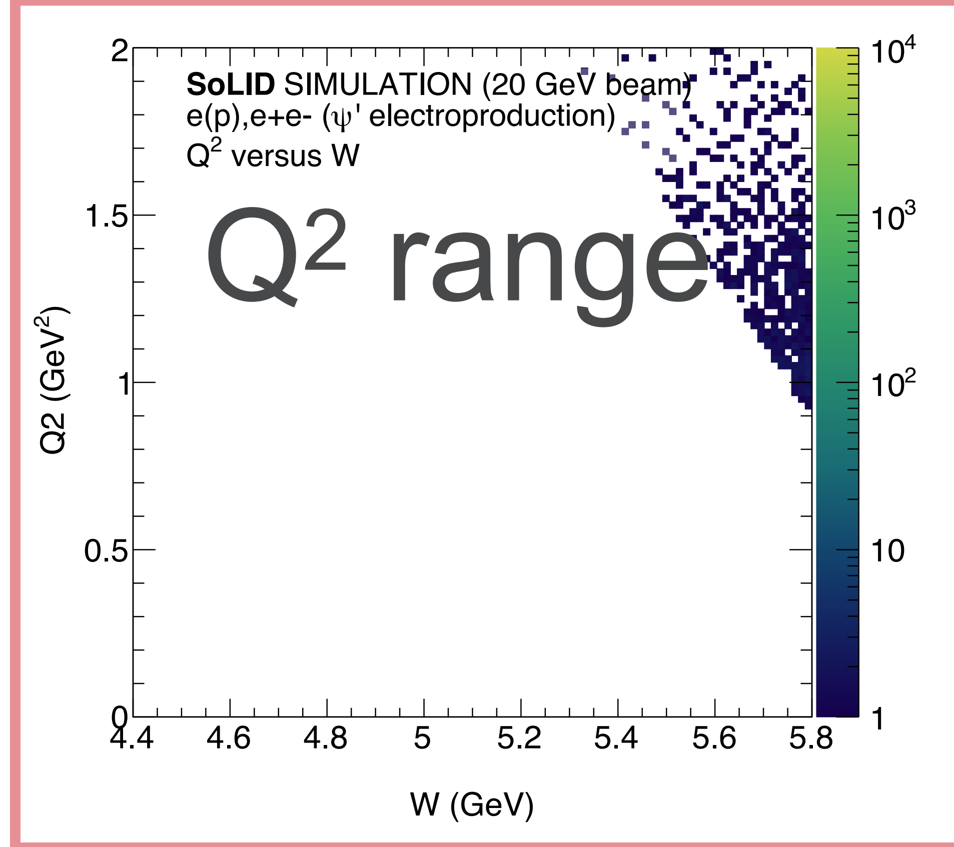
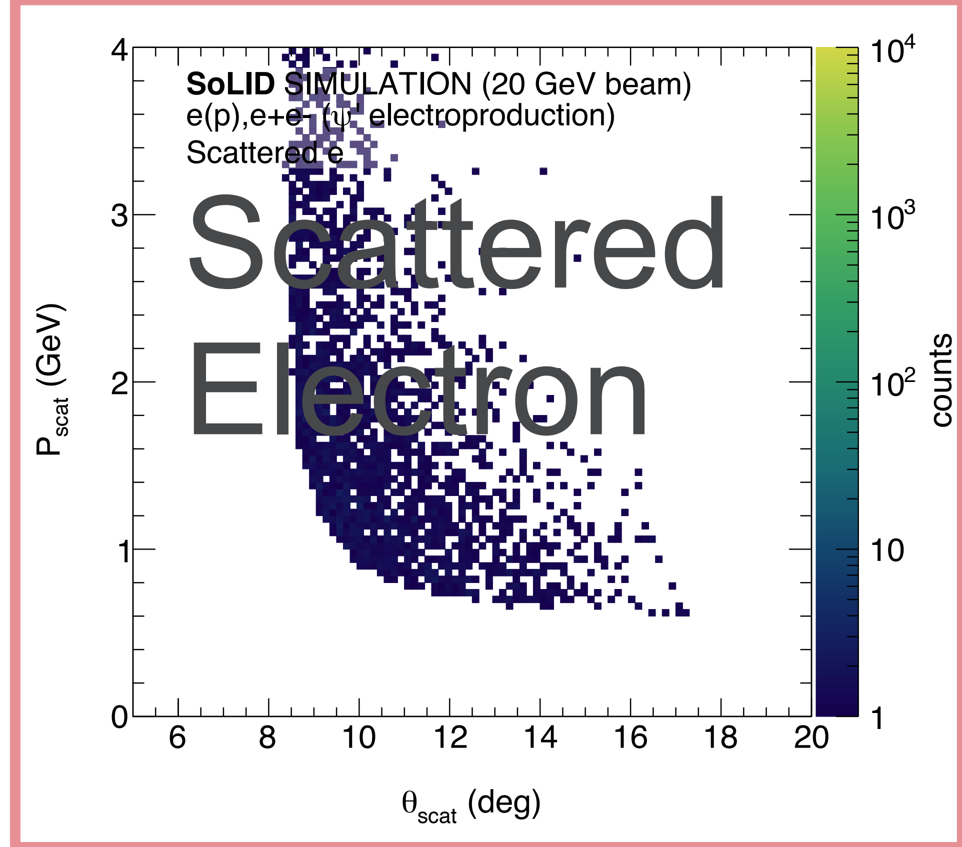
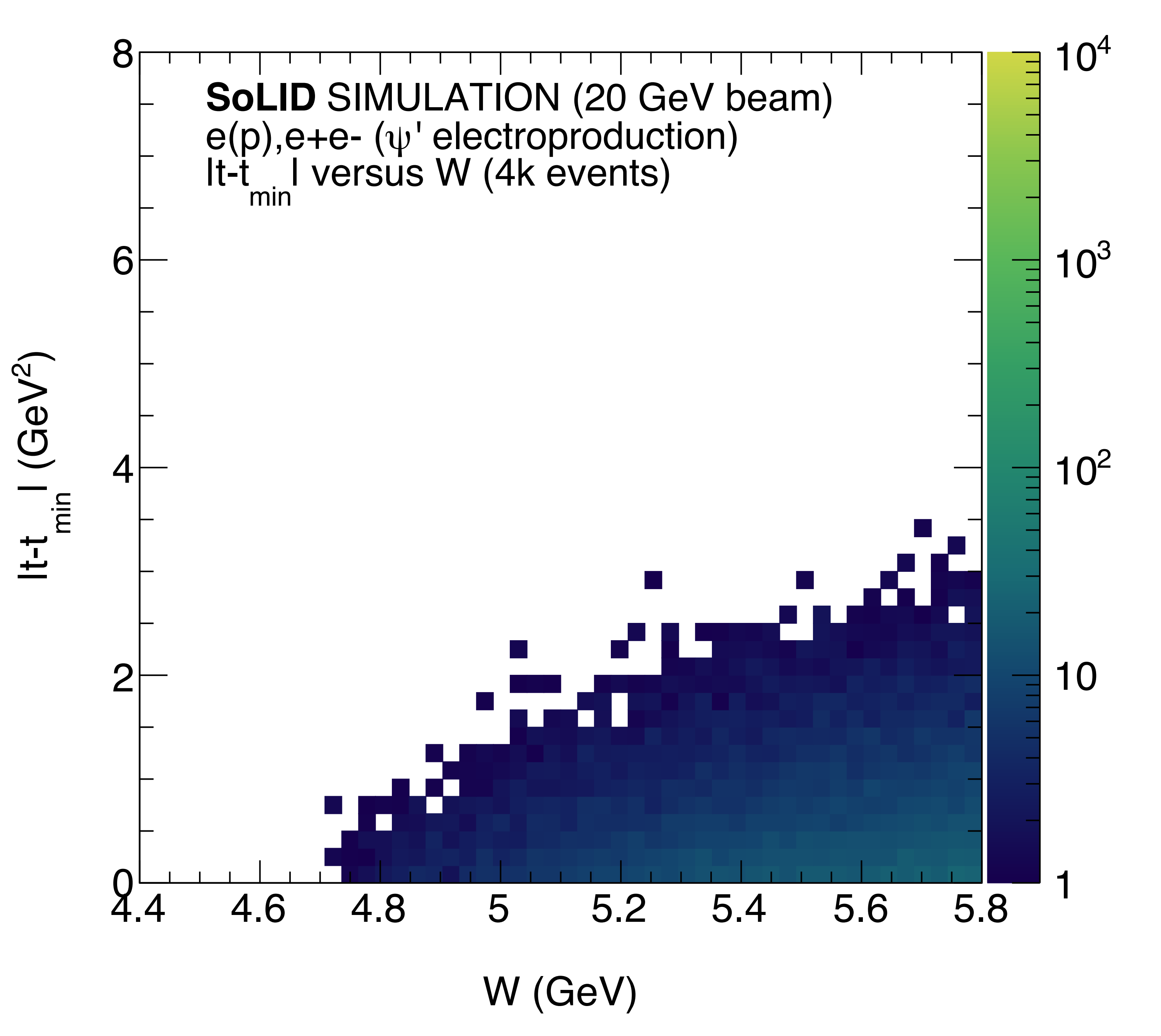
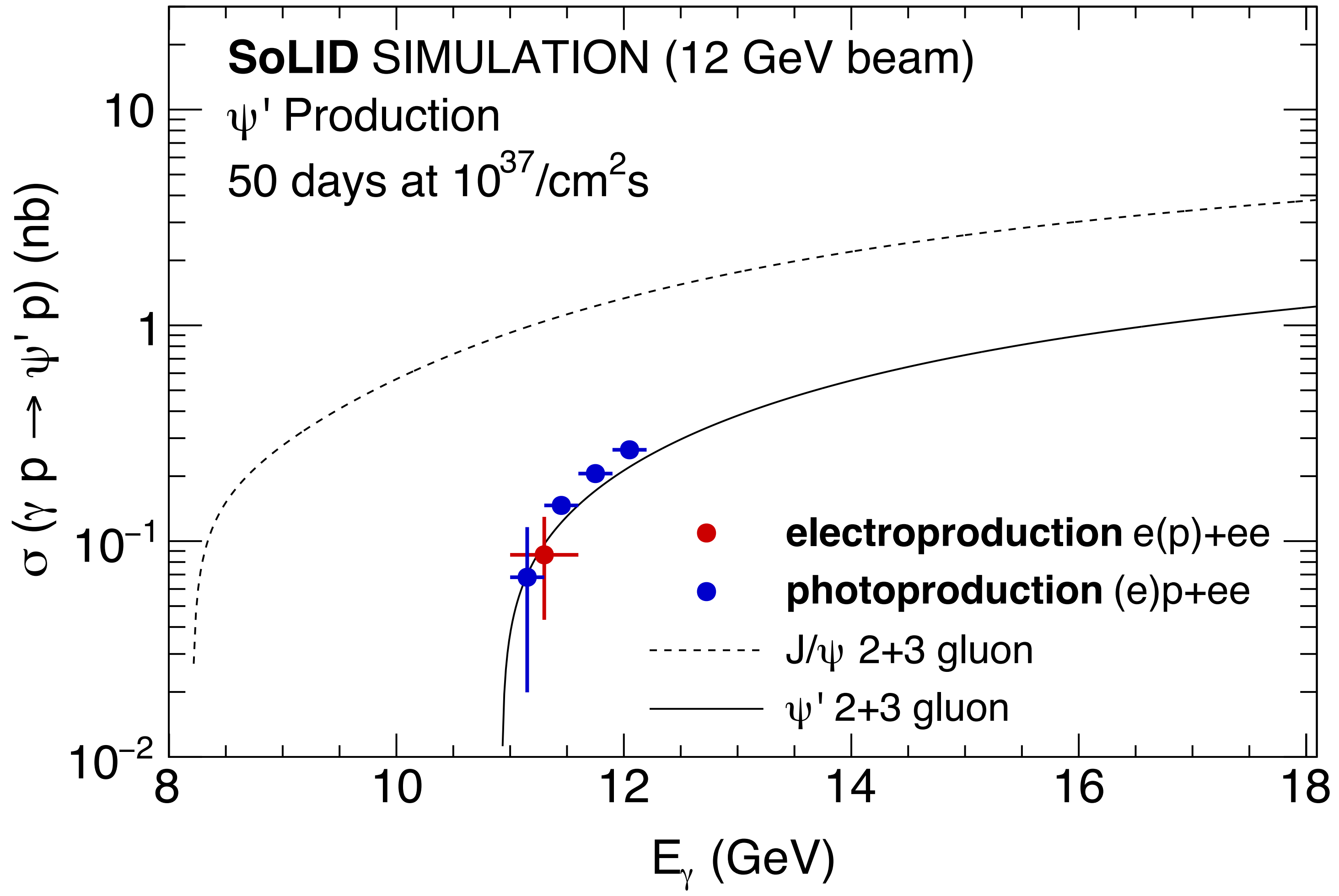


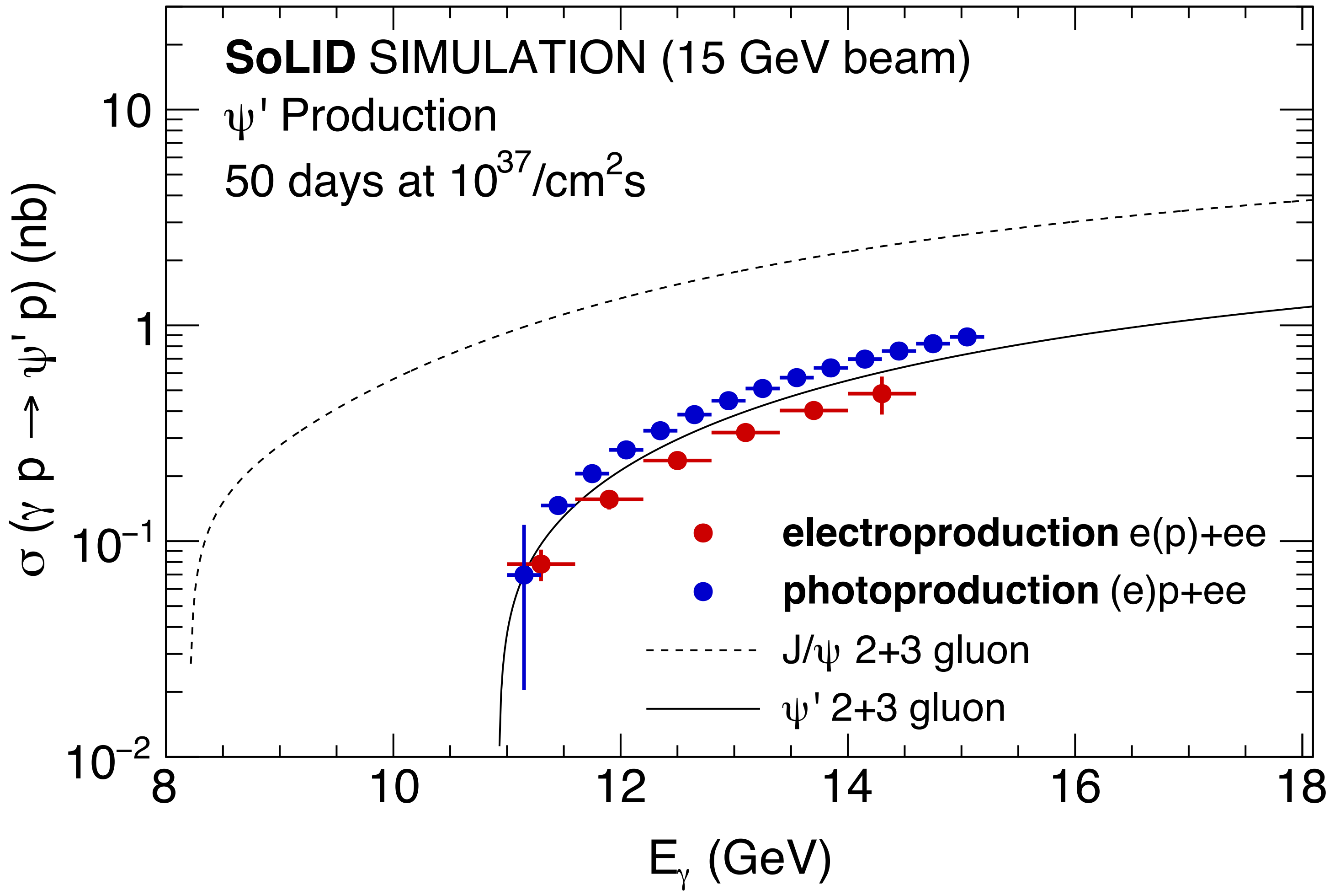


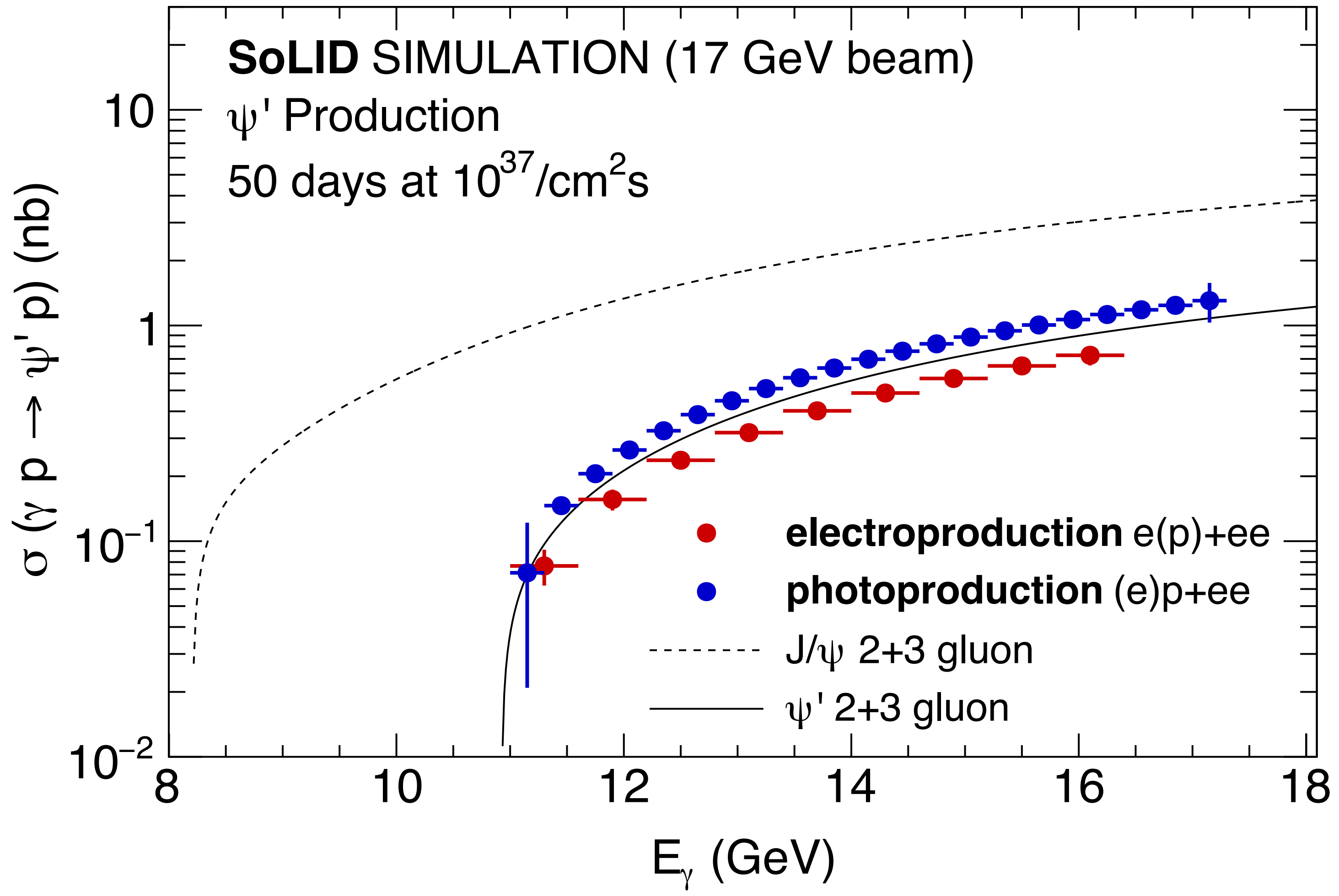


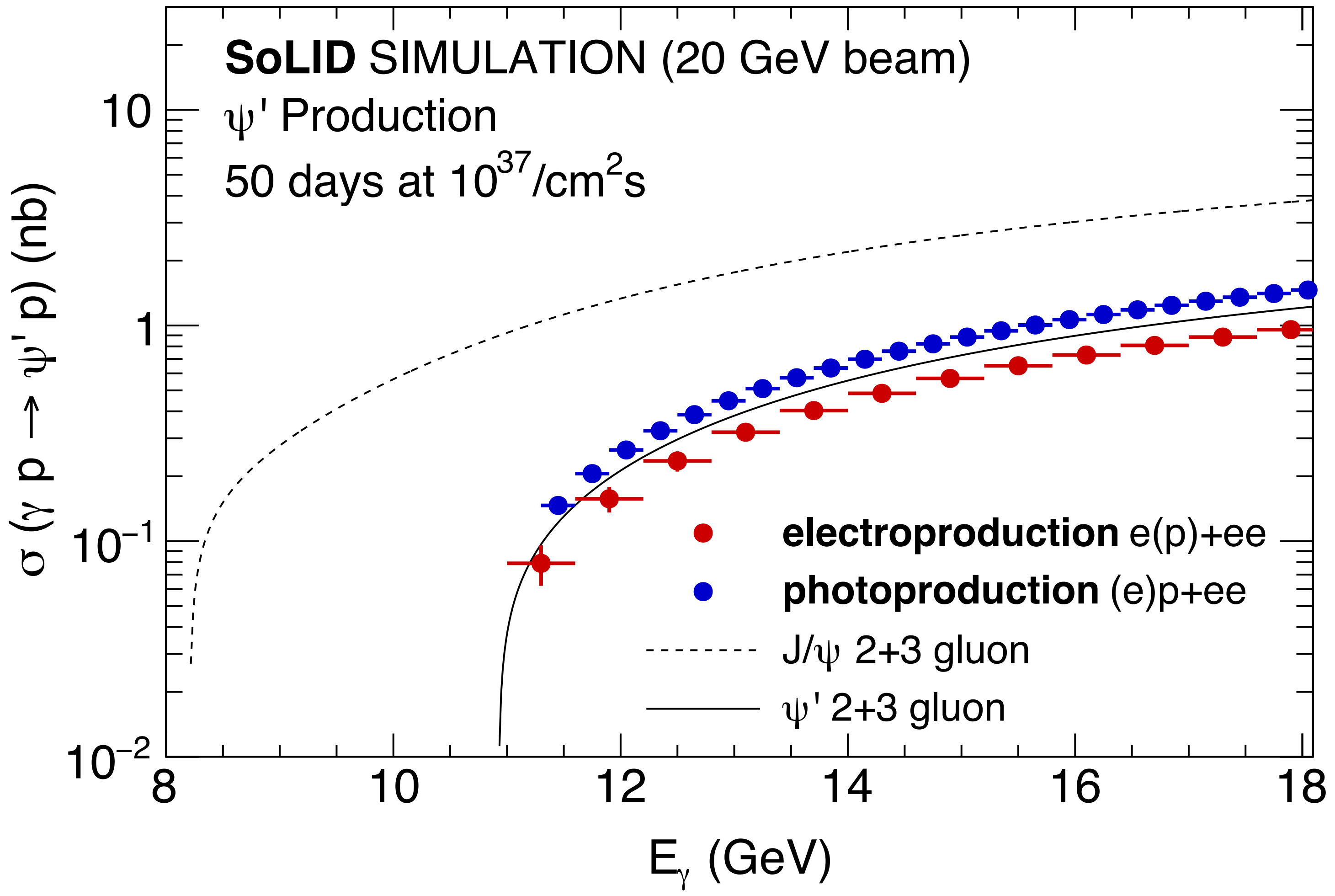
Electroproduction

PHYSICS REACH WITH DIFFERENT BEAM ENERGIES



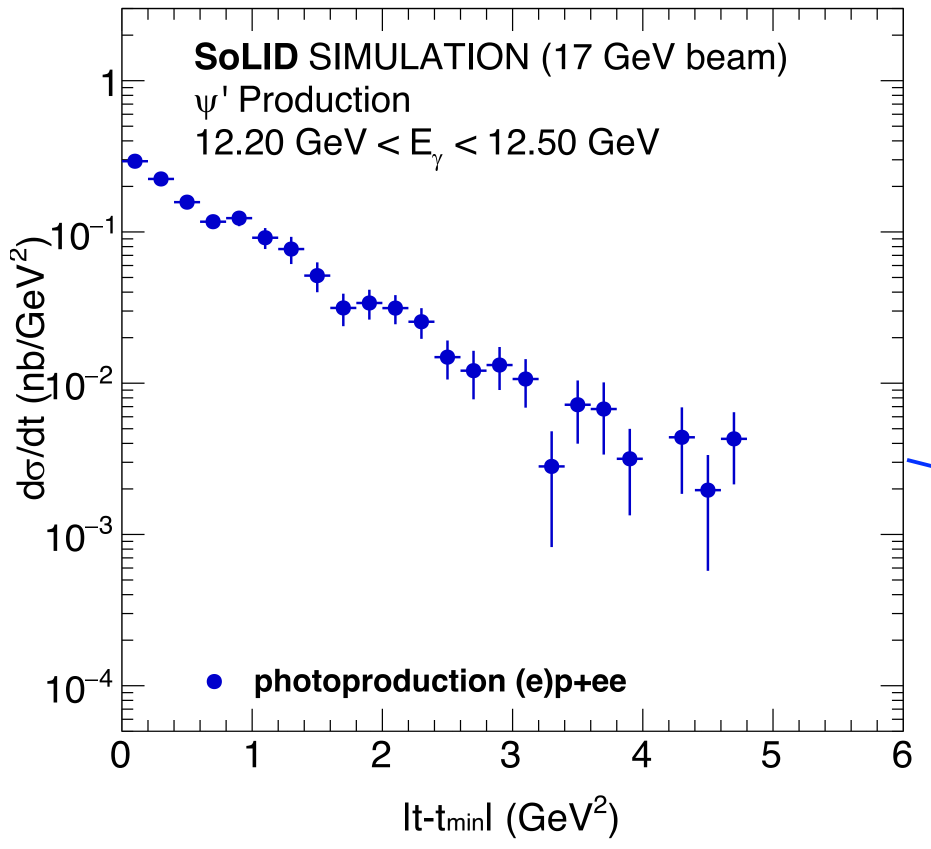


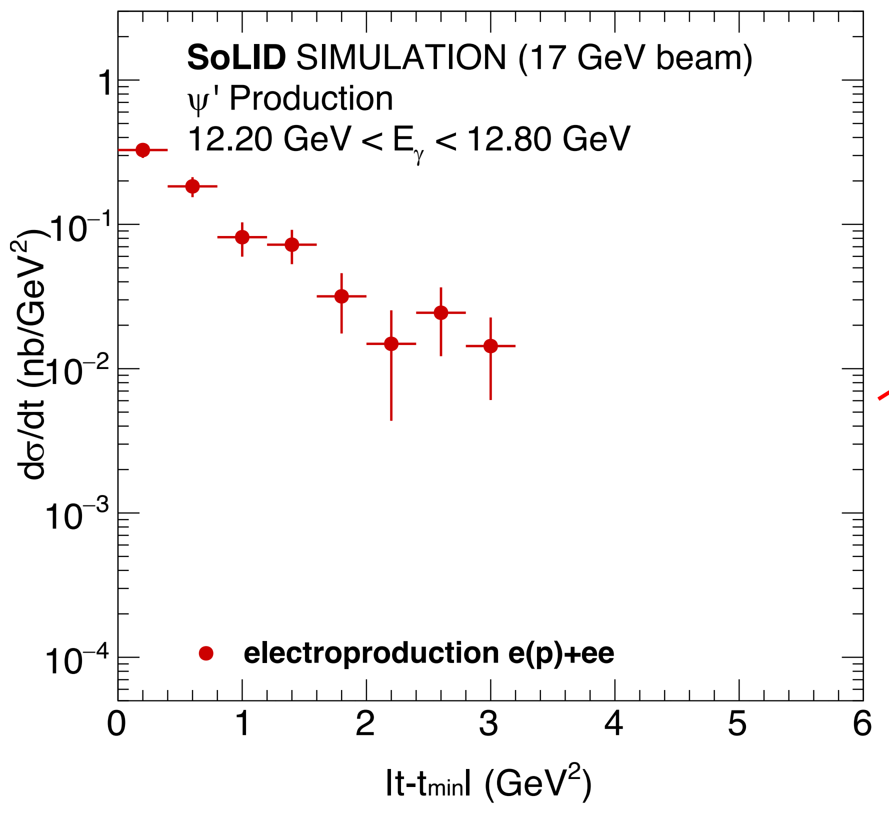


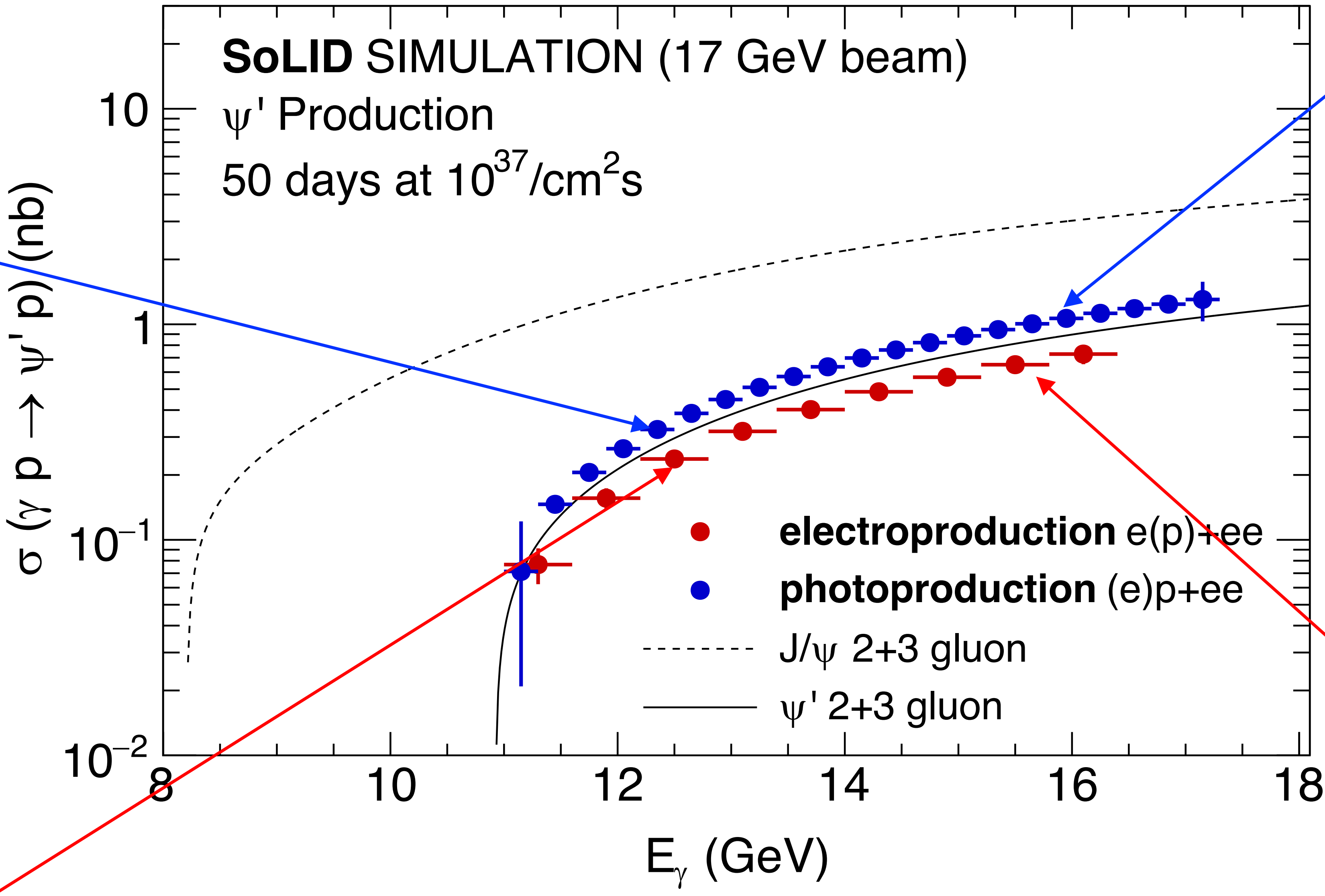


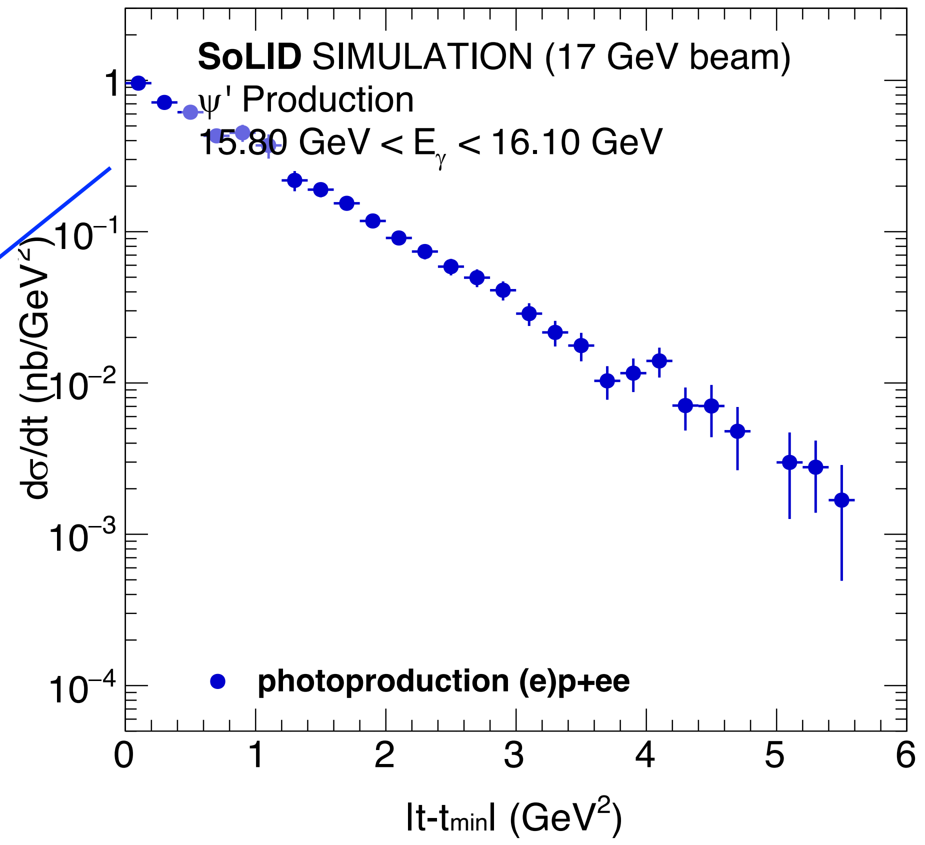
2D CROSS SECTION POTENTIAL

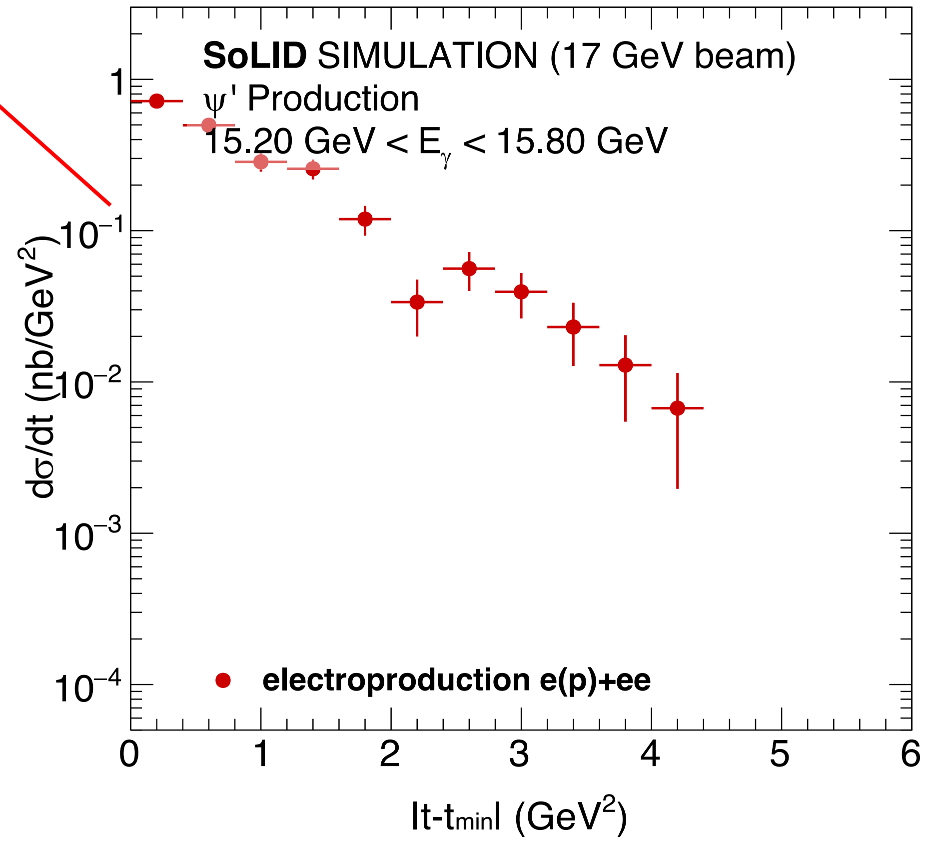
$\psi(2S)$ production with a 17 GeV incident Electron beam











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

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

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

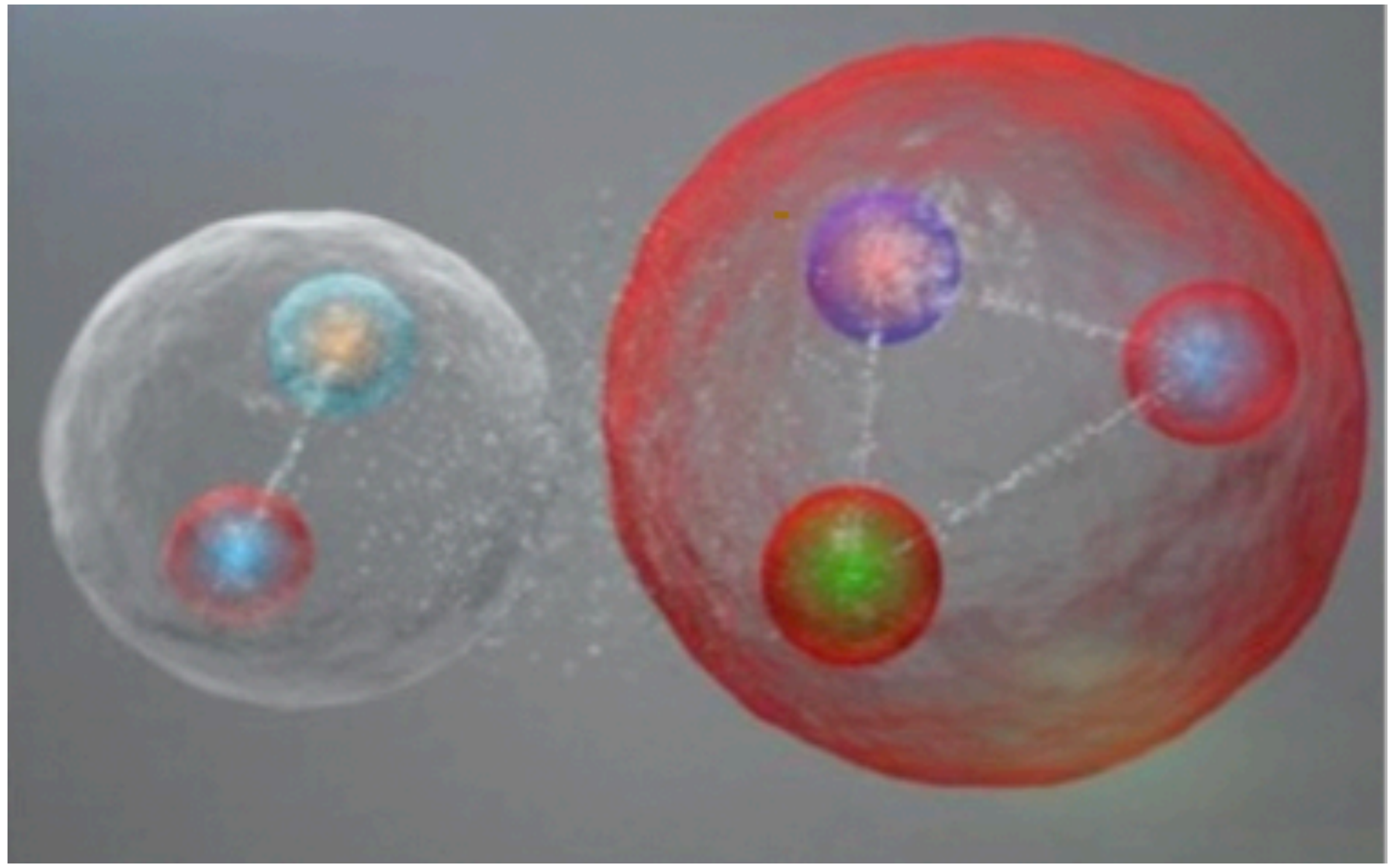
Expect enhanced color Van der Waals force in nuclei due to the larger color field: measure e.g. coherent J/ψ production off ^{4}He

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!)



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SUMMARY

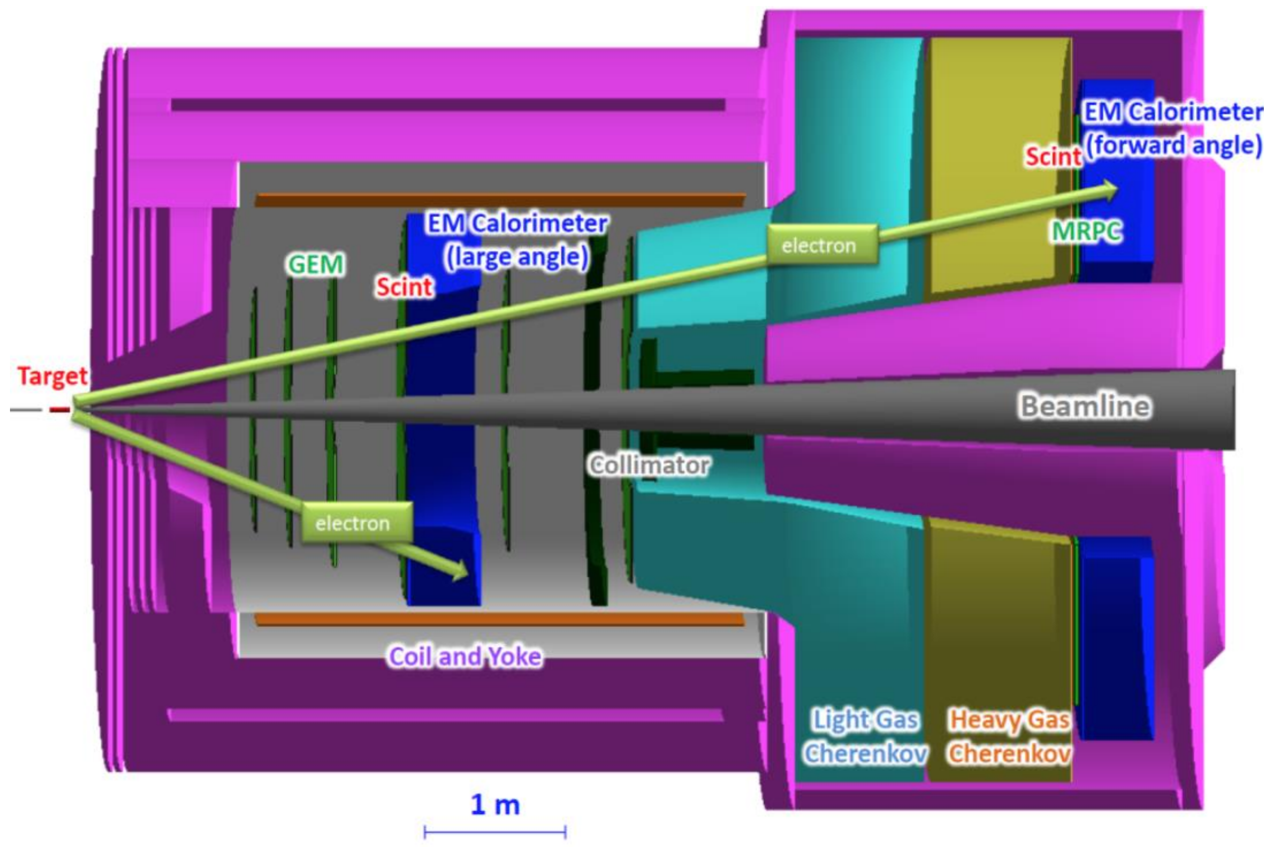
SoLID is the ultimate place for near-threshold quarkonia measurements due to luminosity and kinematic reach

SOLENOIDAL LARGE INTENSITY DEVICE

With a higher beam energy, SoLID can accomplish a complementary J/ψ and ψ' with the same detector

Higher beam energies also provide Q2 as an additional knob (comparing photoproduction with electroproduction)!

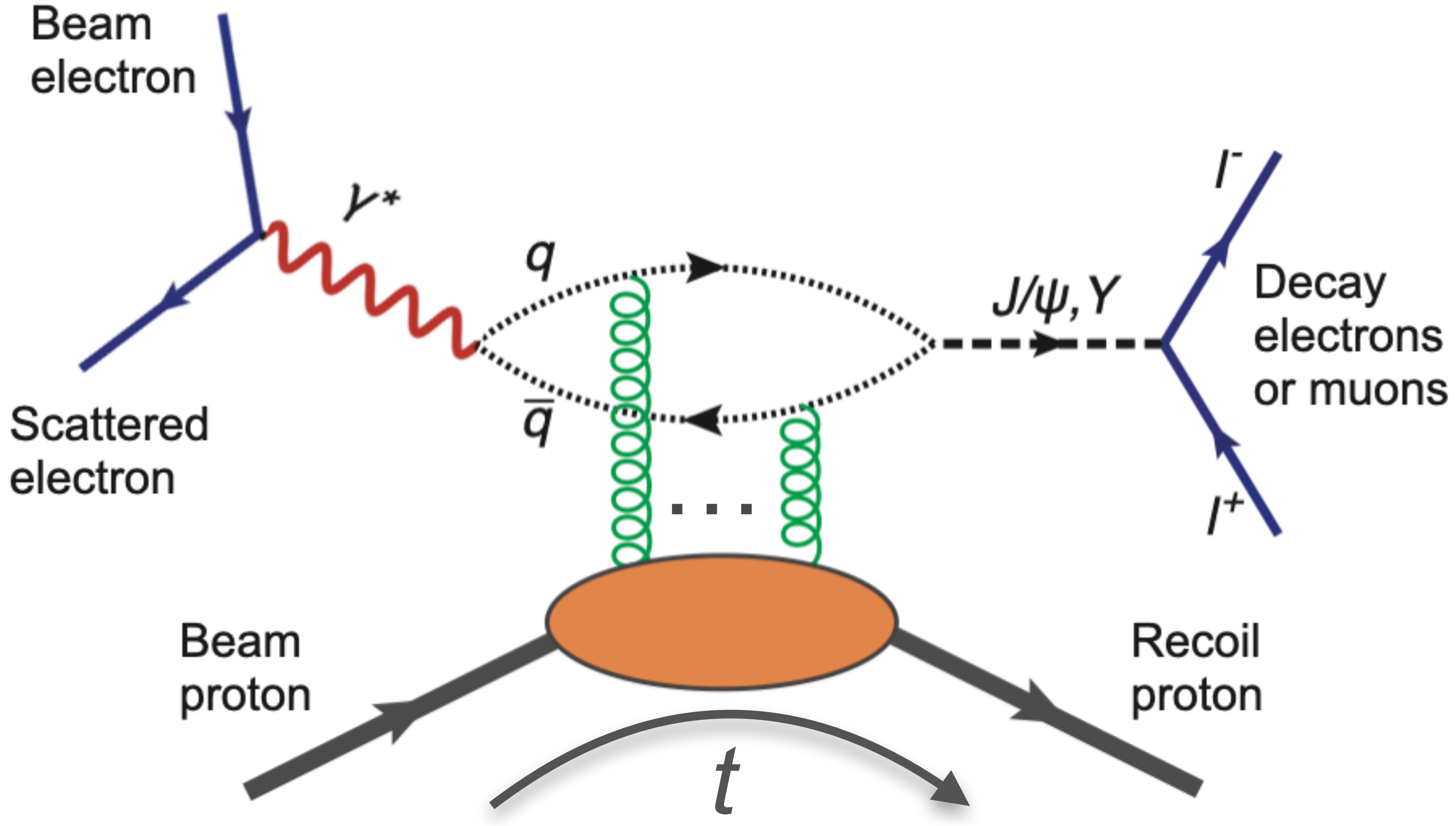
Electroproduction at higher energies does not require any changes to the apparatus, while Photoproduction would benefit from either a small-angle calorimeter or large-angle recoil detector



THE END

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

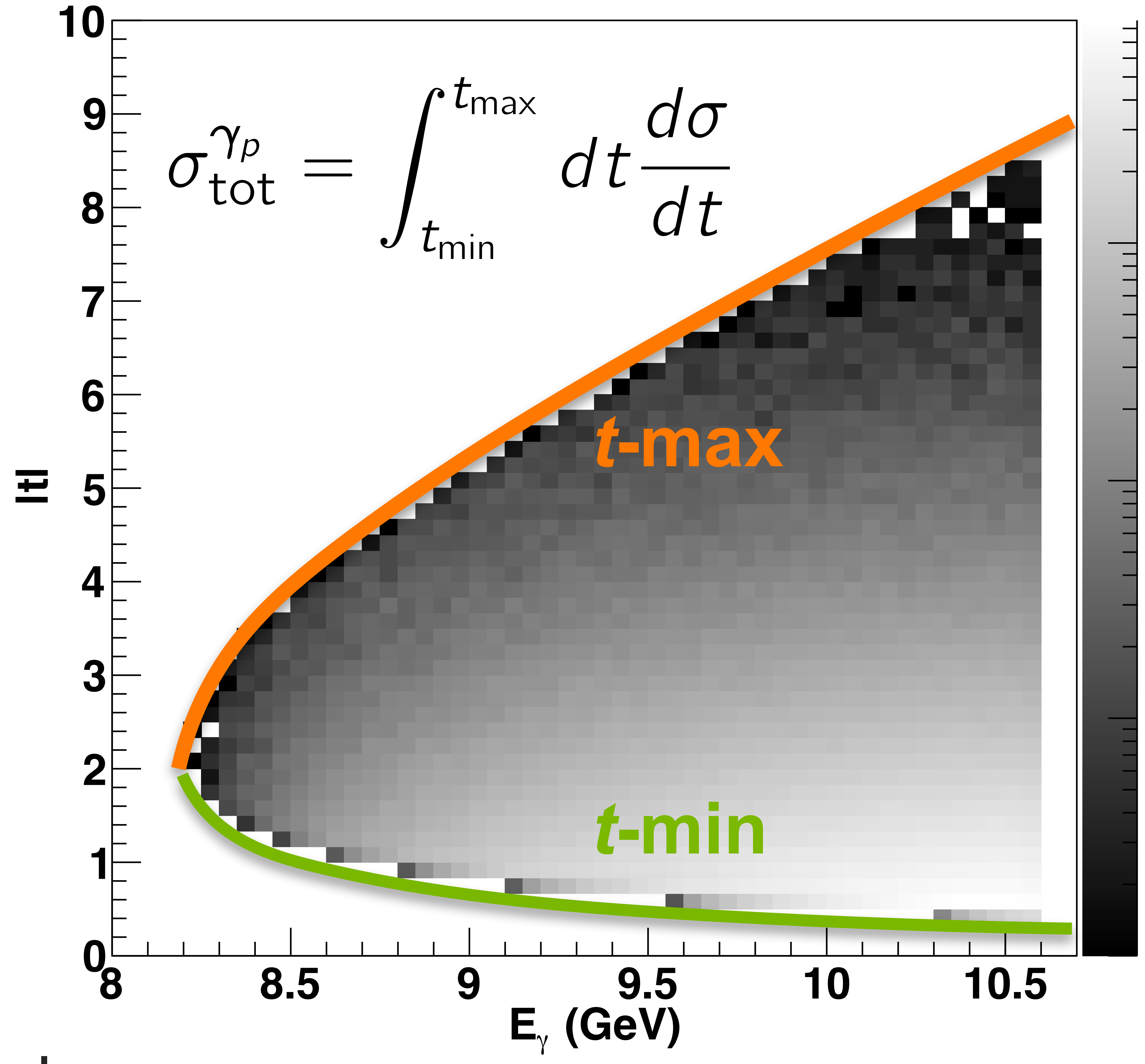
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

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

Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

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

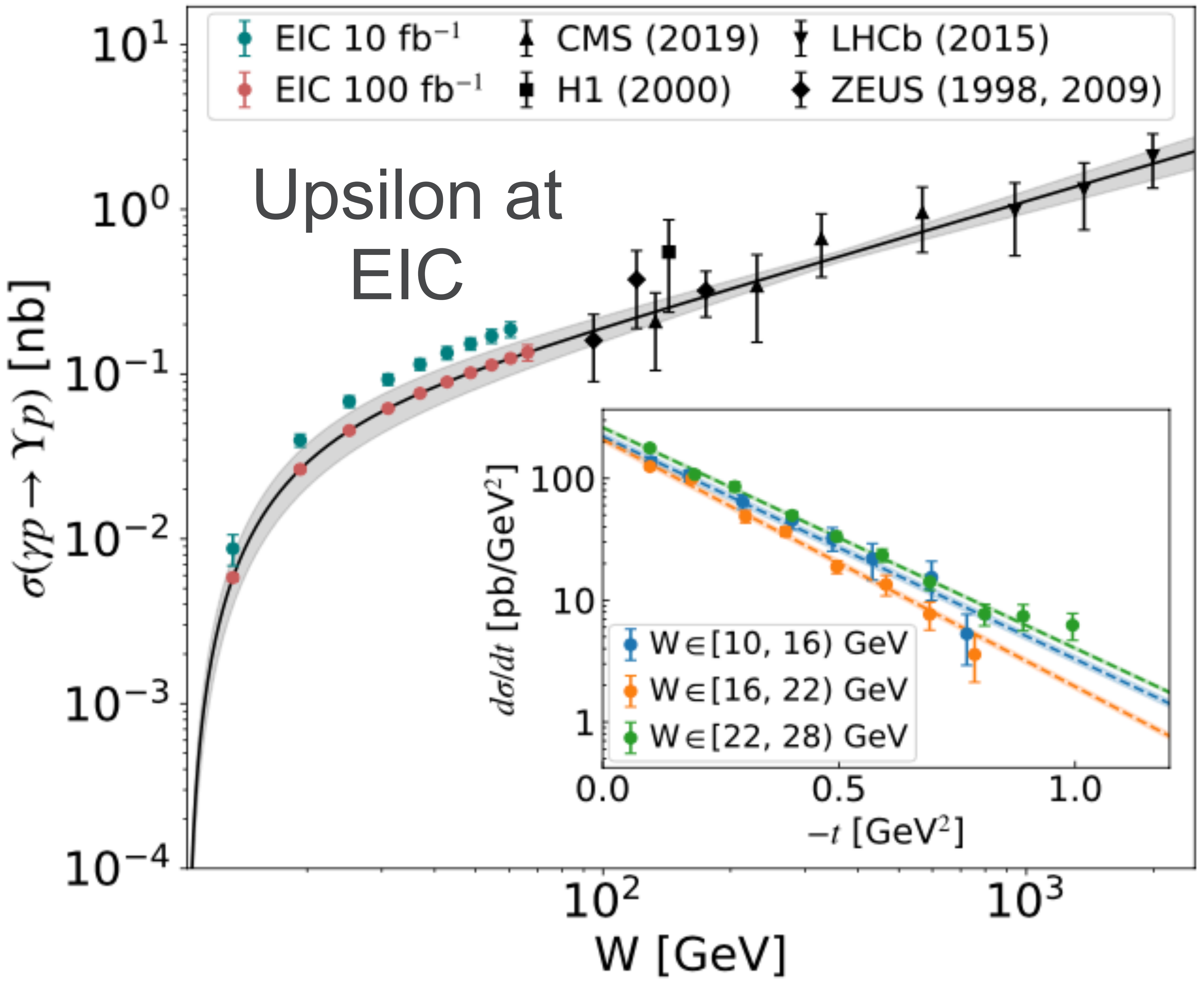


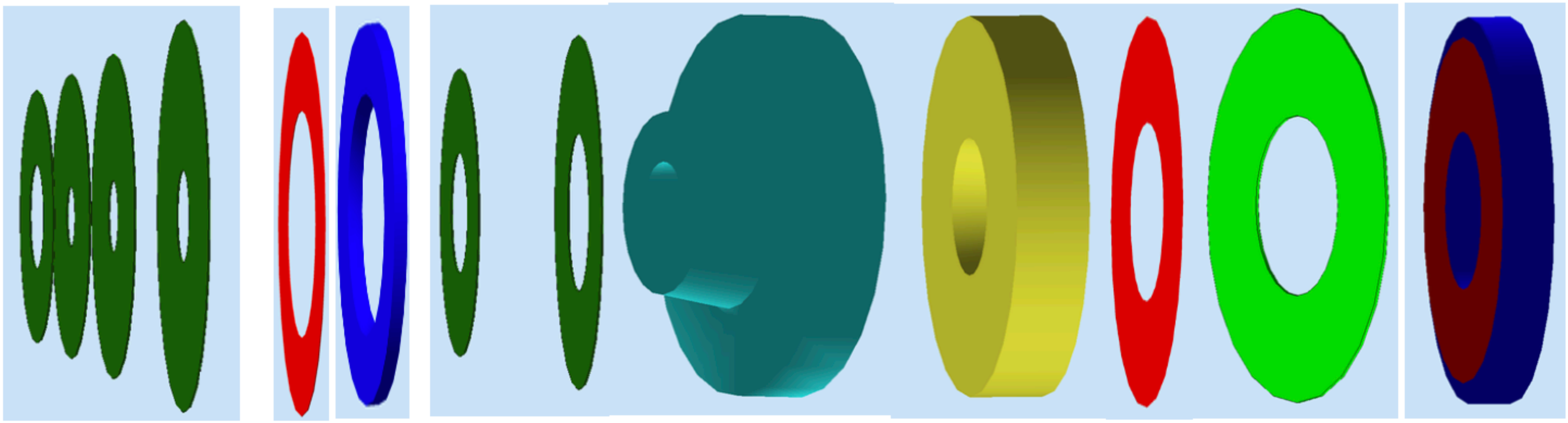
- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred: *t*-dependence ~exponential

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 (mostly at higher energies).





J/ψ : 4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC

Requirements for the J/ψ Measurements (C3)

$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

$$\begin{aligned} W^2 &= 2\nu \cdot M_p + M_p^2 - Q^2 \\ &= 2E_\gamma^{eff} \cdot M_p + M_p^2 \end{aligned}$$

- Large solid angle coverage 2π azimuth symmetric in e^+ and e^-
- Full coverage of t-t_{min} with the highest statistical precision to discriminate among functional forms
- Electron, positron and proton identification with good momentum resolution and high efficiency
- Pion rejection at the level 1000:1 for the scattered electron
- Good J/psi invariant mass resolution: 50 MeV or less
- Virtual photon beam energy resolution: 30 MeV or less
- Good t resolution near threshold: 0.15 GeV^2 or less for electroproduction 0.04 GeV^2 or less for photoproduction