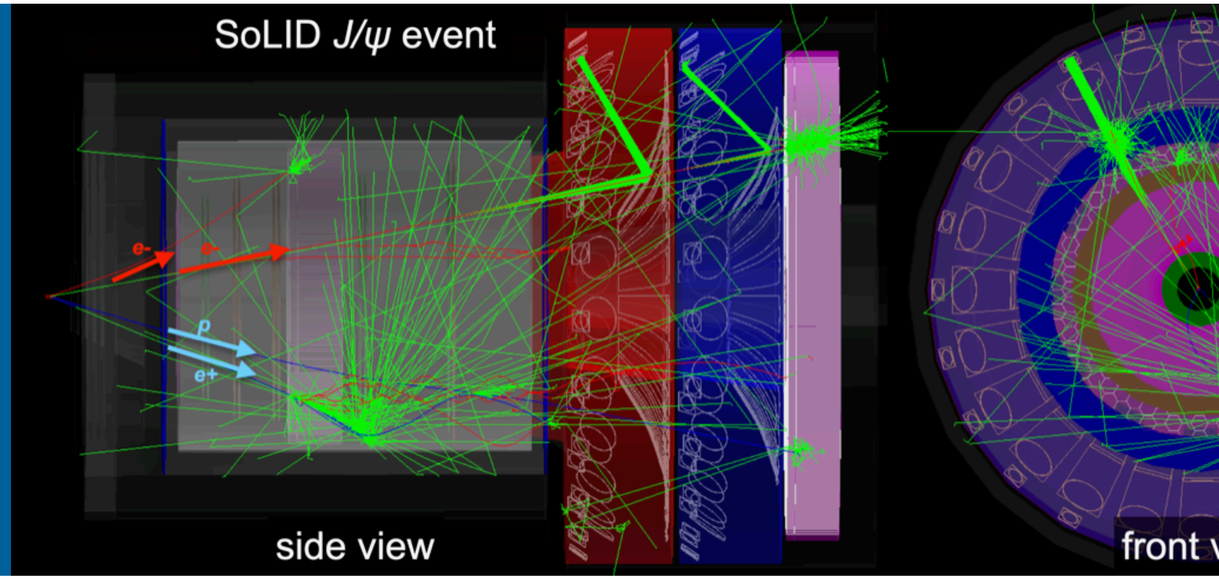
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY 75 1946–2021

FROM SOLID J/Ψ TO Ψ' PRODUCTION AT 24 GEV



SYLVESTER JOOSTEN
sjoosten@anl.gov

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

U.S. DEPARTMENT OF ENERGY
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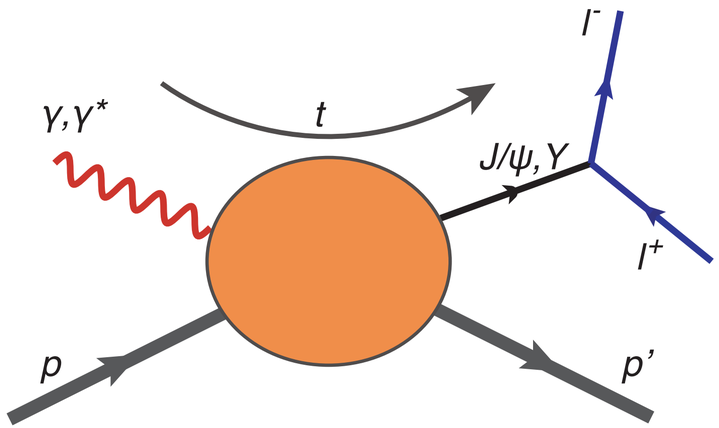
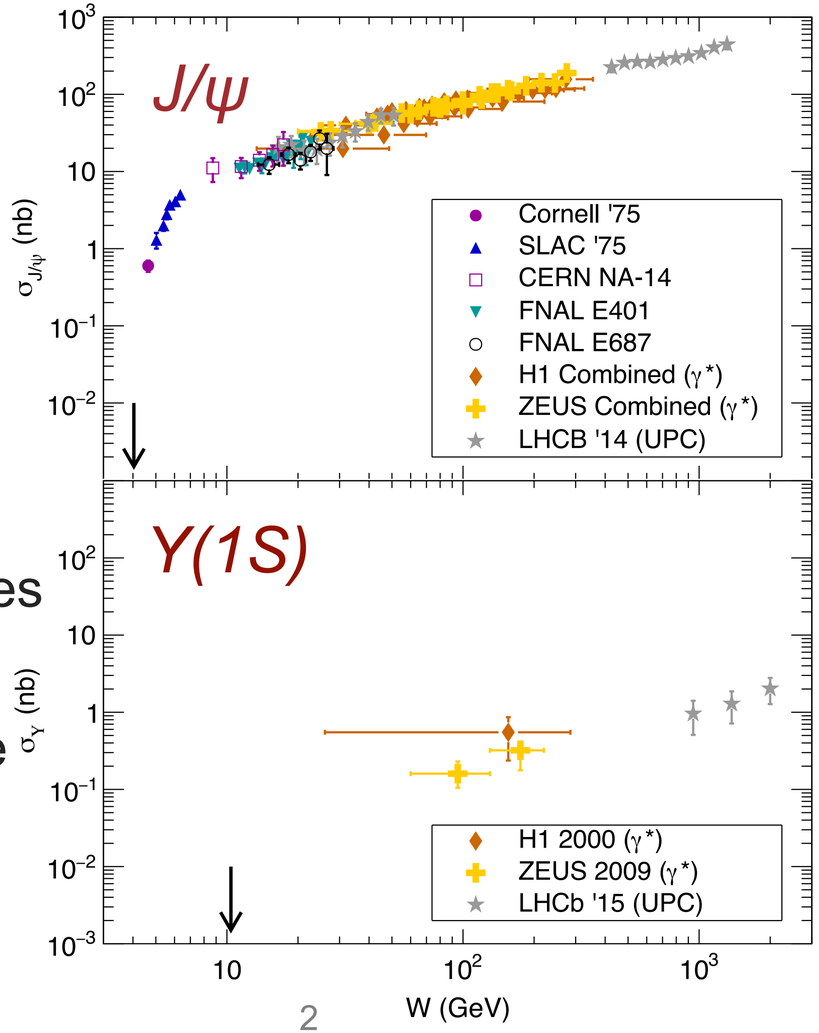
J-Future Workshop
March 30, 2022

QUARKONIUM PRODUCTION NEAR THRESHOLD

Probing the energy distribution of gluonic fields inside the proton and nuclei



- *J/ψ* well constrained for high energies
- *Υ(1S)*: not much available
- No electro-production data available
- **Almost no data near threshold before the 12 GeV era of JLab**



Near-threshold electro- and photoproduction of quarkonium

- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus bound states
- Do quarkonia enable **pentaquarks** to exist?
- Study the **gluonic gravitational form-factors (gGFFs),** access to the matter radius

J/ψ at JLab
Υ(1s) at EIC

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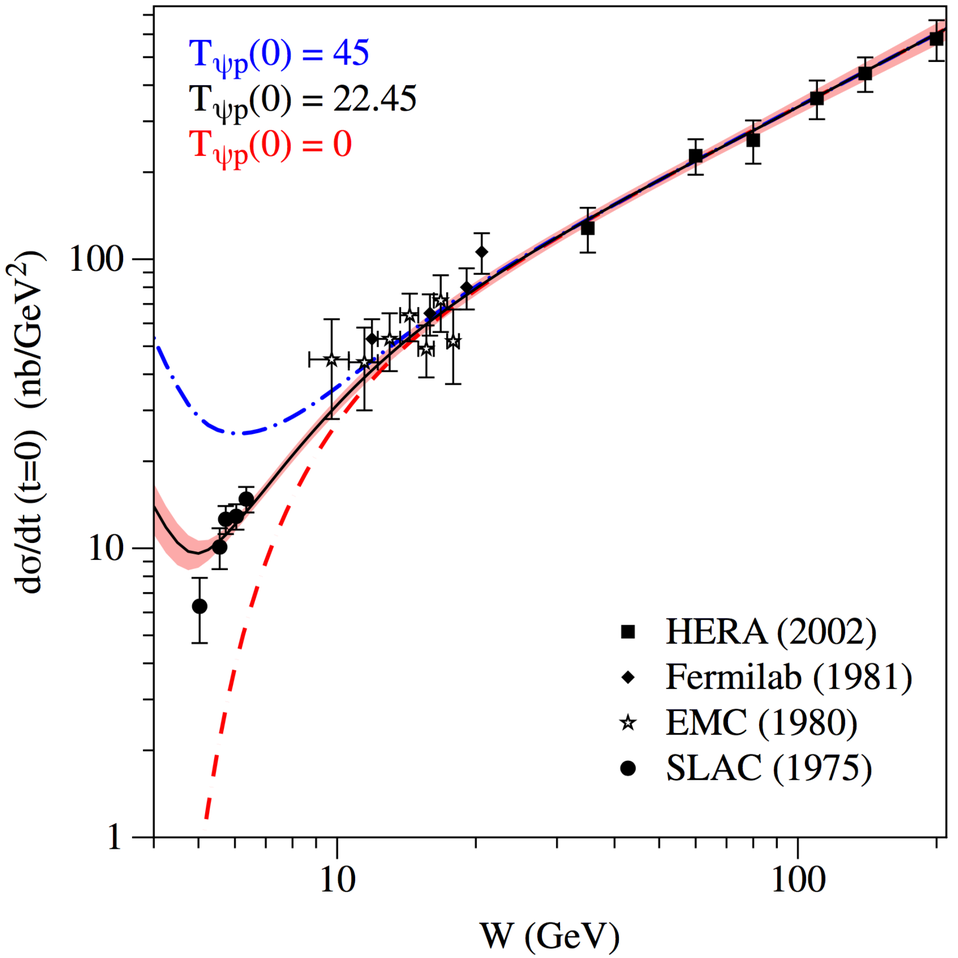
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
S. R. Beane *et al.*, PRD 91, 114503 (2015)

BINDING ENERGY OF THE *J/Ψ* - NUCLEUS POTENTIAL

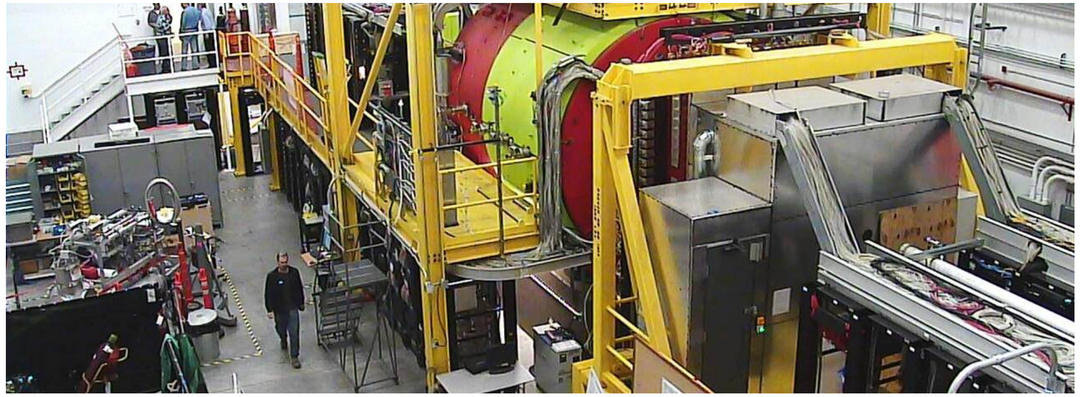
The nature of the gluonic Van der Waals force

- Force between color neutral quarkonium (color dipole) and nucleon/nucleus purely gluonic
- Binding energy $B_{\psi p}$ can be derived from s-wave scattering length $a_{\psi p}$ at threshold
  - $T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$
  - Experimental access through quarkonium photo-production at threshold
  - Note: *link with trace anomaly, gluonic gravitational form-factors*
- Current estimates between 0.05-0.30fm (3-20MeV)
- Lattice QCD (at large pion mass): $B_{\psi p} < 40$ MeV

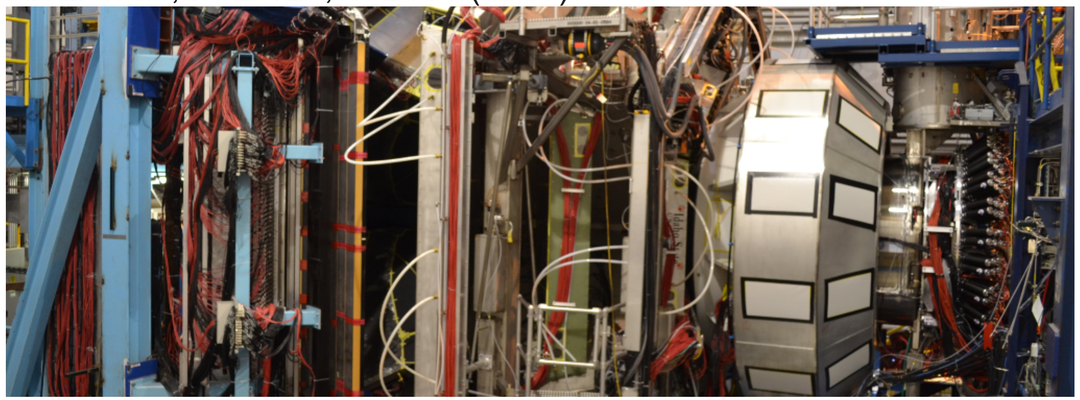
Need high-precision photo-production data near threshold



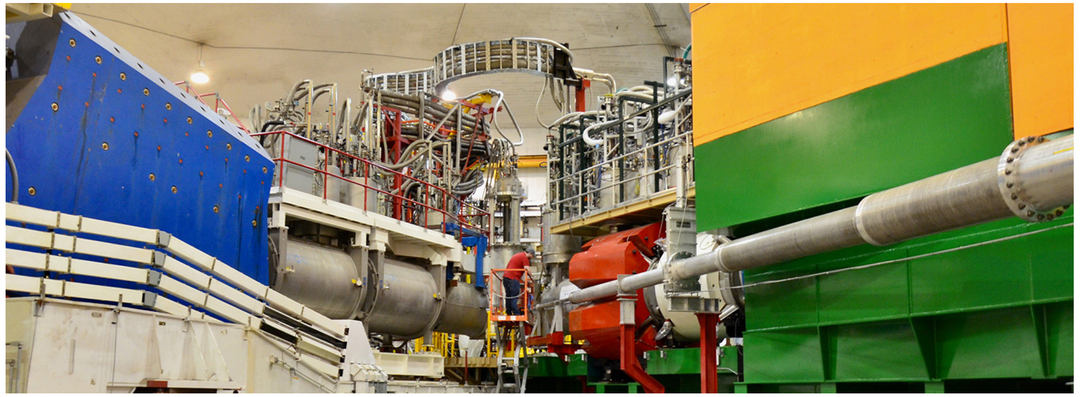
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



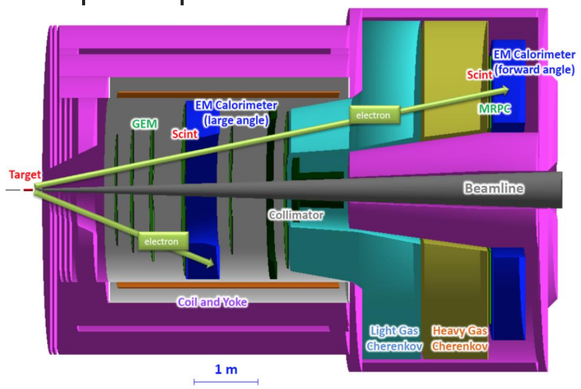
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



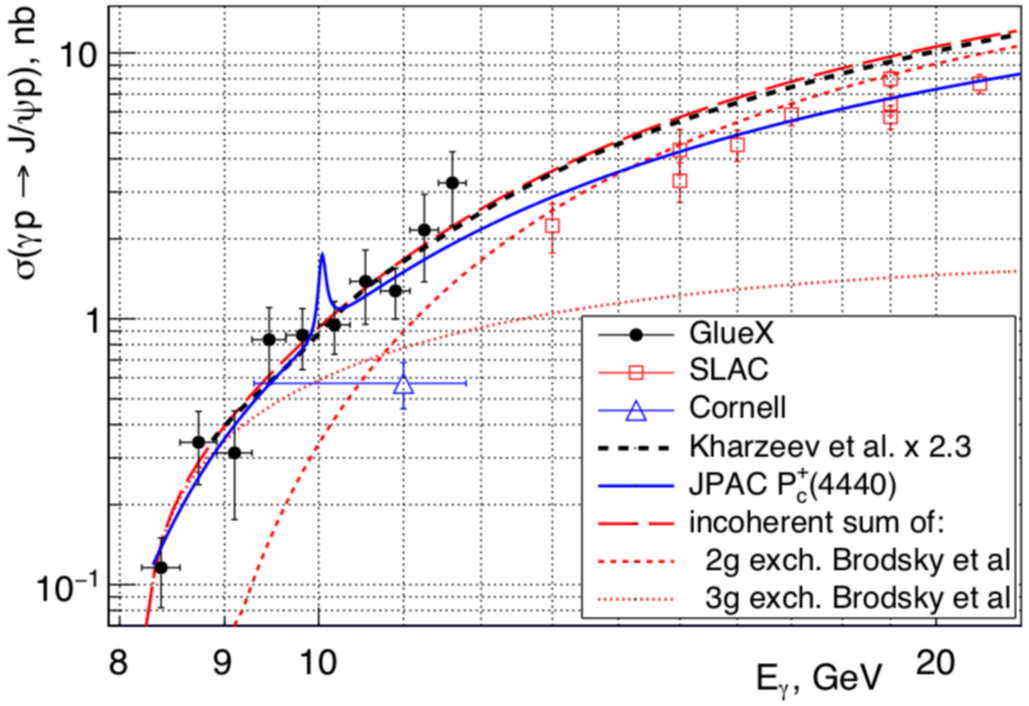
Hall C has the **J/ψ-007** experiment (E12-16-007) to search for the LHCb hidden-charm pentaquark

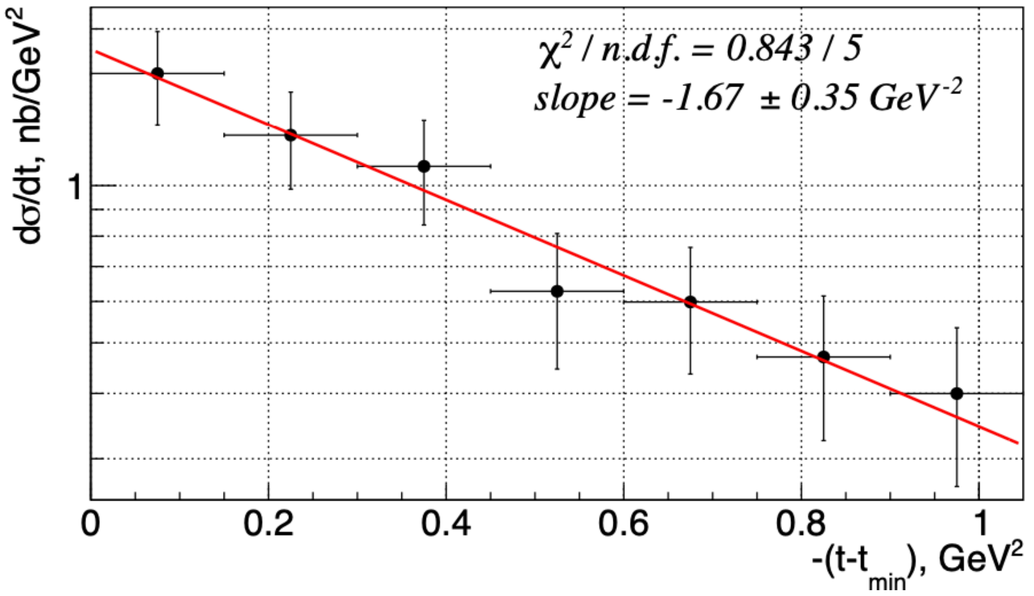


Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

First J/ψ at Jefferson lab: 1D cross sections from GlueX

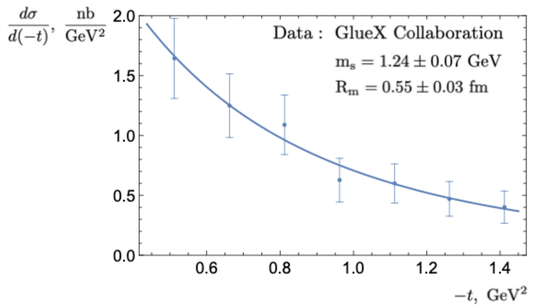
A. Ali *et al.*, PRL 123, 072001 (2019)



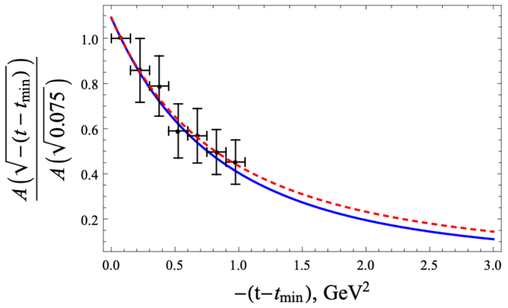


REACH OF NEAR-THRESHOLD QUARKONIUM PRODUCTION

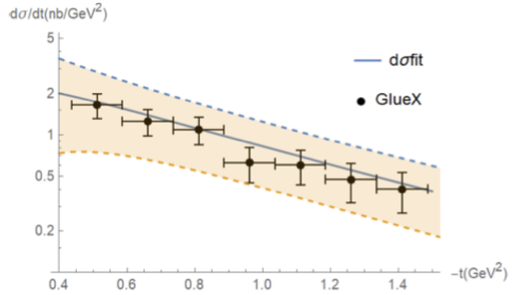
Very active field, lots of theoretical developments in the last year



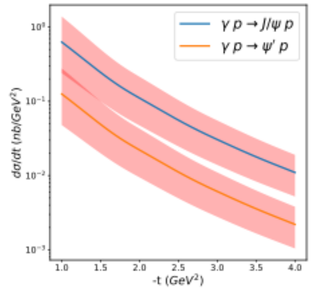
VMD-style description:
Sensitive to mass radius
D. Kharzeev, PRD 104 (2021) 5, 054015
Sensitive to anomalous mass of proton
R. Wang, X. Chen, J. Evslin, EPJC (2020) 6, 504

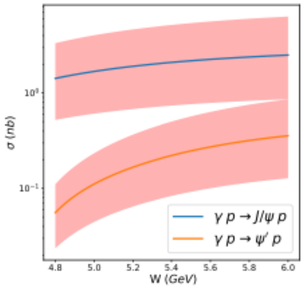


AdS/QCD description:
Sensitive to gGFFs
K. Mamo, I. Zahed, PRD 101 (2020) 9, 086003
K. Mamo, I. Zahed, PRD 103 (2021) 9, 094010
K. Mamo, I. Zahed, PRD 104 (2021) 6, 066023

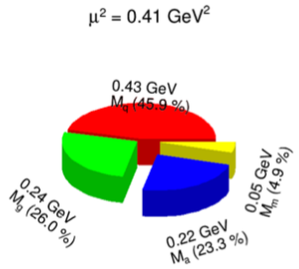


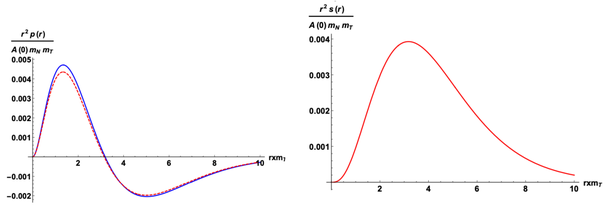
GPD Description
Sensitive to gGFFs
Y. Guo, X. Ji, Y. Liu, PRD 103 (2021) 9, 096010

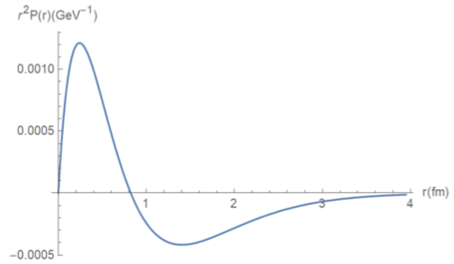




pQCD at large t
Connection with gGFF through GPD formalism
P. Sun, X. Tong, F. Yuan 2203.13493



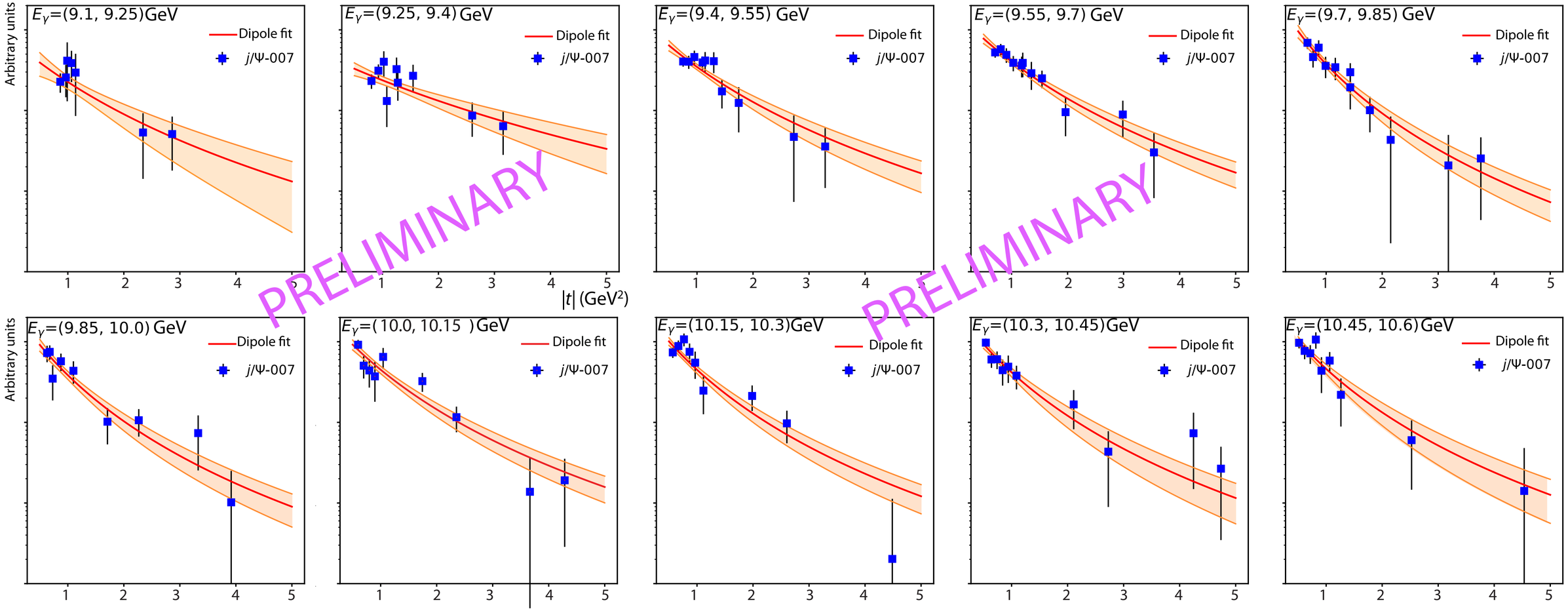




To properly understand near-theshold region: need high-precision 2D quarkonium cross section, **with reach good experimental reach to high-t region**

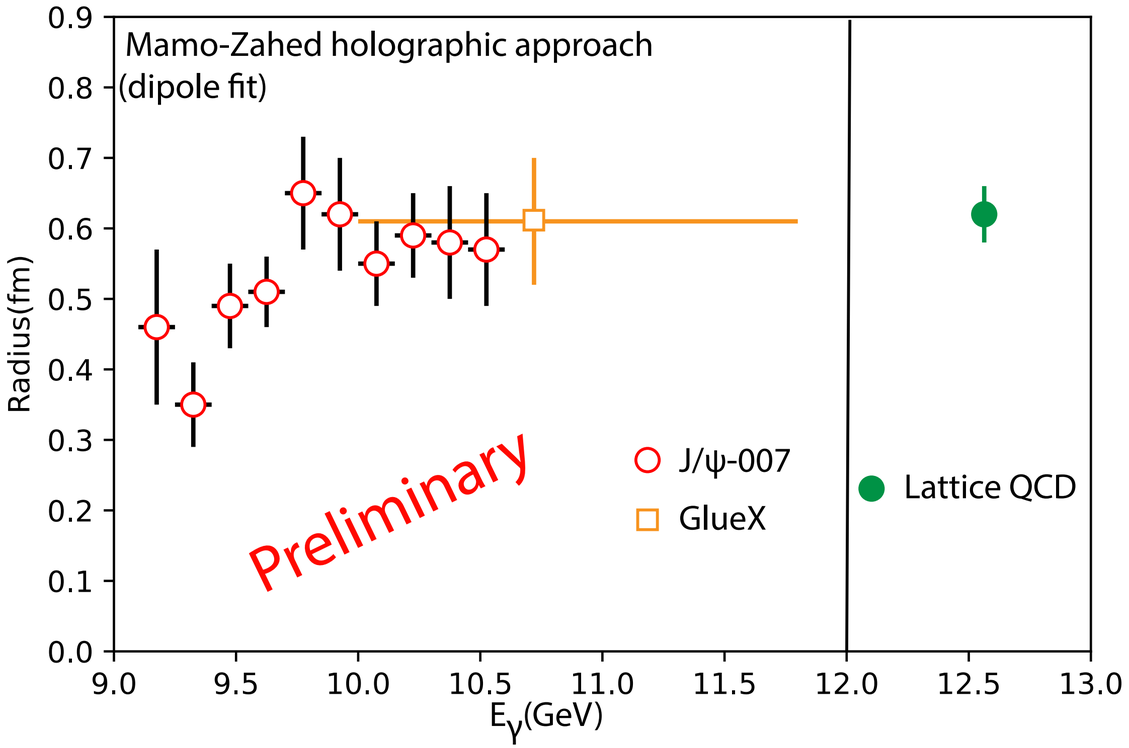
FIRST LOOK AT NEAR-THRESHOLD J/Ψ IN 2D

Upcoming results from Hall C



FIRST LOOK AT NEAR-THRESHOLD J/Ψ IN 2D

Upcoming results from Hall C



- Mass radii can be extracted for each of the 10 energy bins by means of a dipole fit
- Figure shows results following the approach from Mamo-Zahed (Phys. Rev. D 101, 086003, 2020).
- Energy-scan of near-threshold region important to study validity of different approaches
- For more precise results: need much more statistics at large t (and those are hard to get!)

12 GEV J/Ψ EXPERIMENTS AT JLAB COMPARED

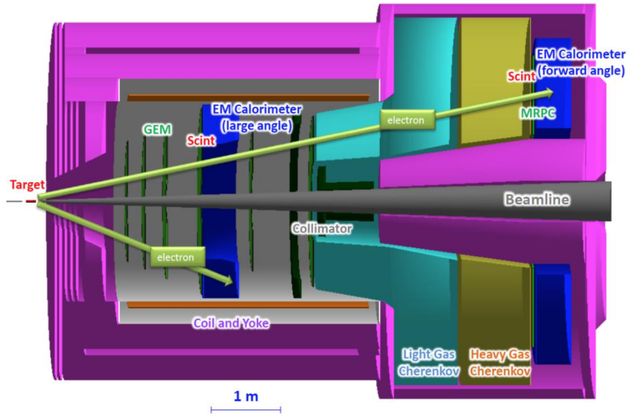
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	**469 published ~10k phase I + II**	**4k**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
Acceptance	4π	$<4x10^{-4}$	<2π	2π
When?	Finished	Finished	Ongoing/Proposed	~8 years?

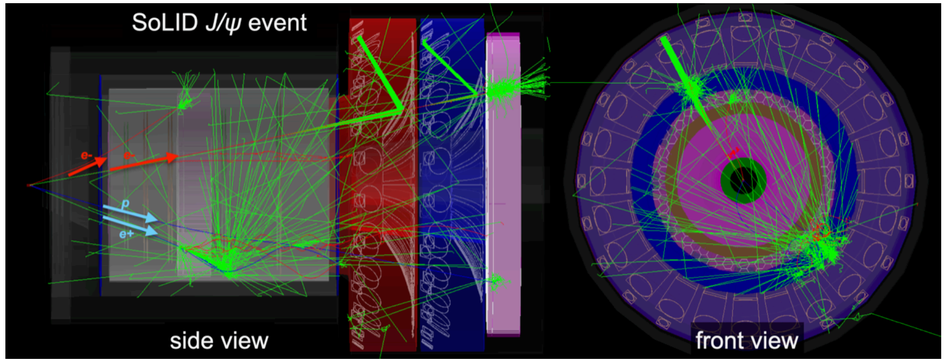
[1]The CLAS12 projected count rates assume the proposed CLAS12 luminosity upgrade to $2x10^{35}/cm^2/s$

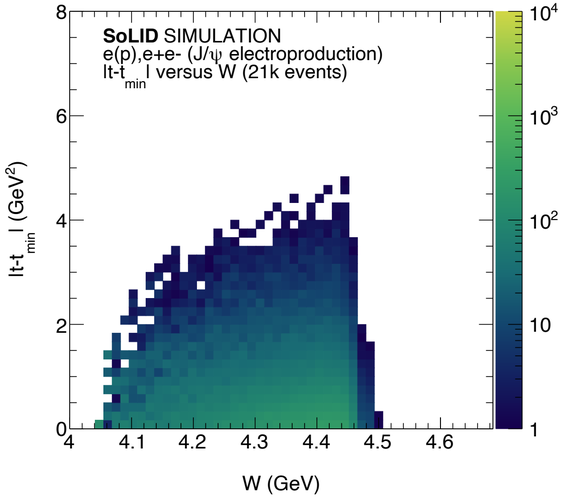
FUTURE SOLID-J/Ψ EXPERIMENT AT JLAB

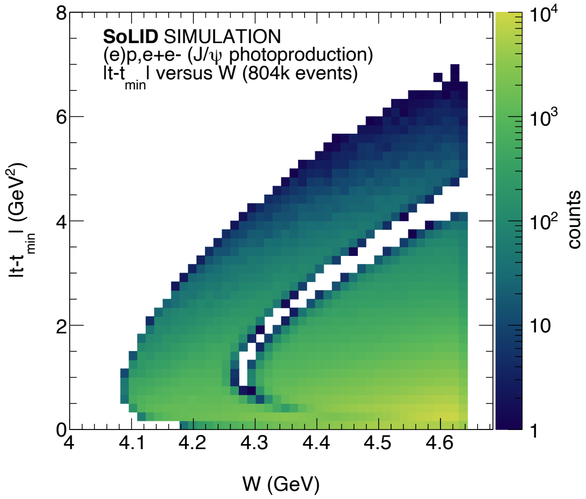
Ultimate experiment for near-threshold J/ψ production

- 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+)









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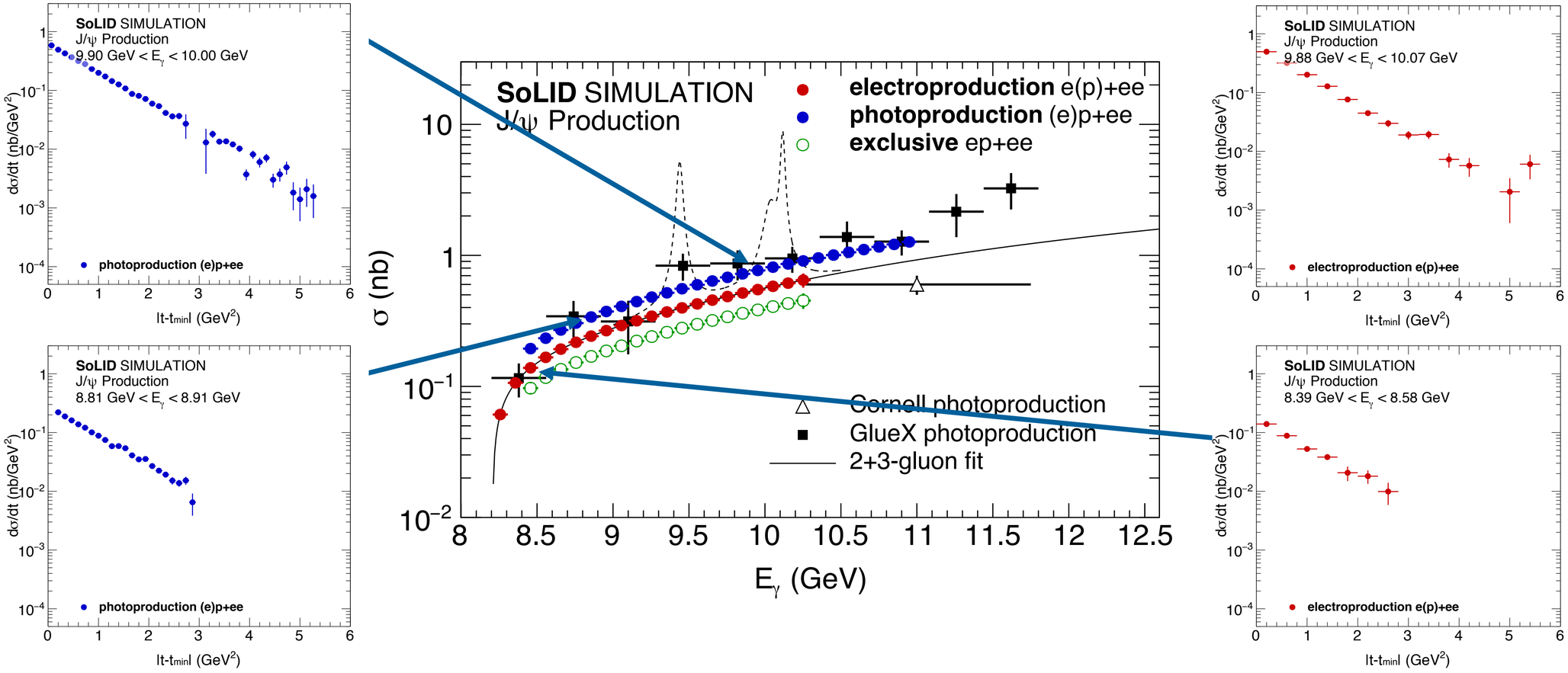
FUTURE SOLID EXPERIMENT AT JLAB

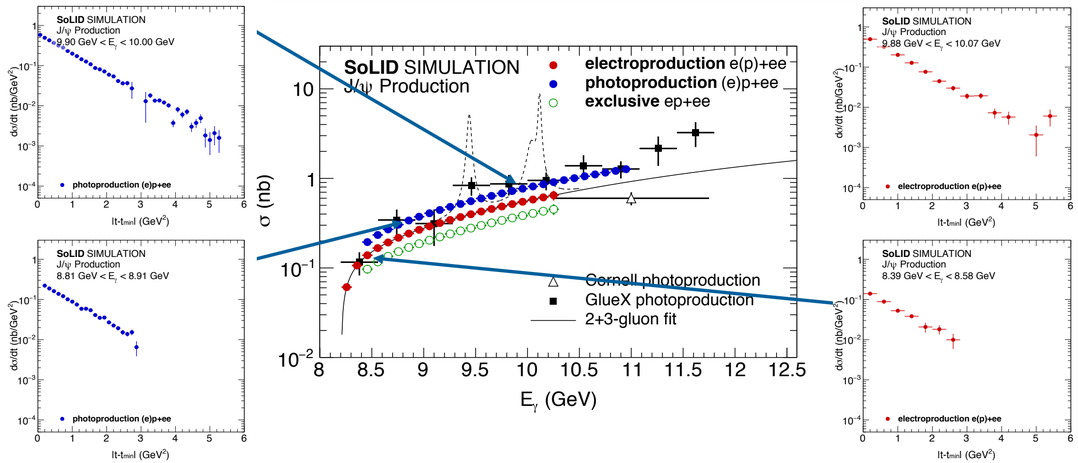
Precision measurement of quarkonium near threshold



EXAMPLE: SCATTERING AMPLITUDE IN VMD

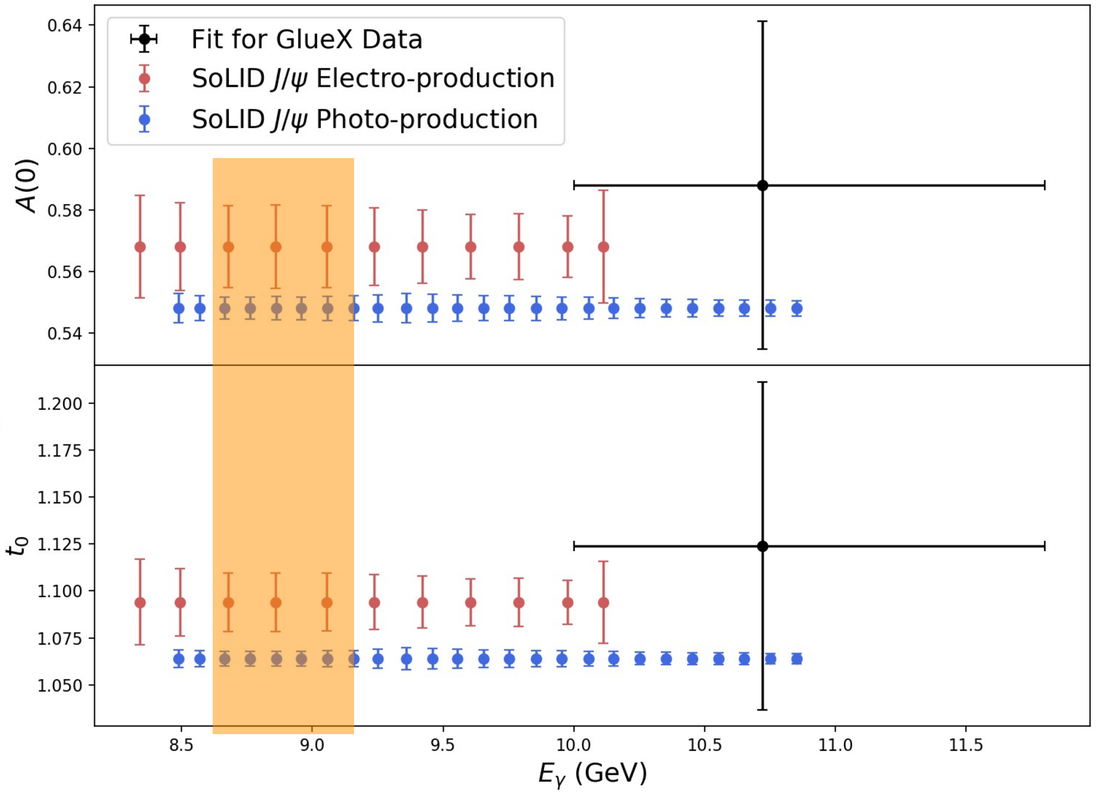
High-precision results from both electro- and photoproduction!

1. From 2D cross section

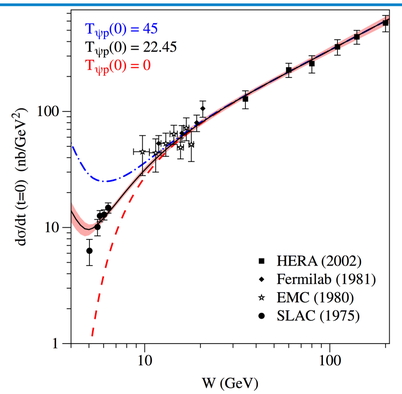


2. To description at the forward limit (t=0)_

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



3. To the scattering length



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WHY Ψ' PRODUCTION?

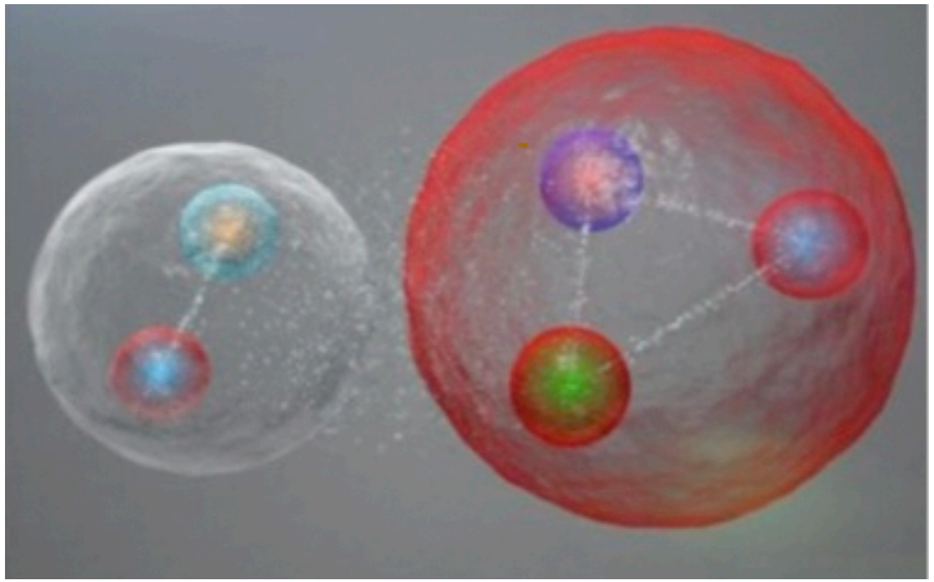
Independent, more sensitive probe (larger color dipole!)

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

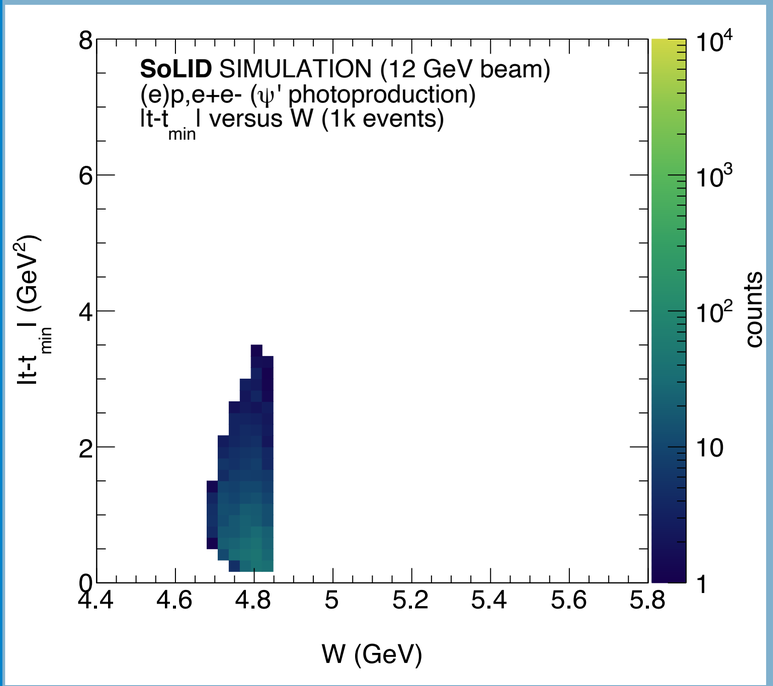
End result: factor of about 47 reduction in rate for ($\gamma p \rightarrow \psi(2s)p \rightarrow pe^+e^-$).

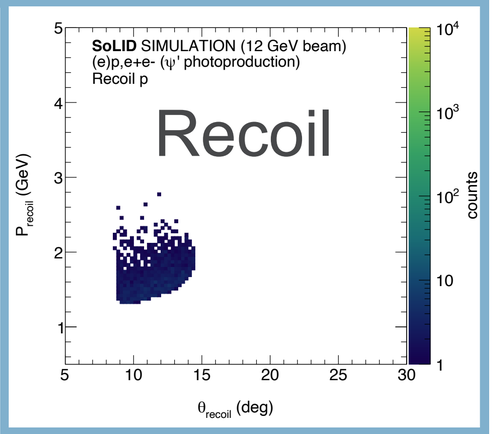
Hence, measurement requires very high luminosity. Could also be approached by exploring other decay channels

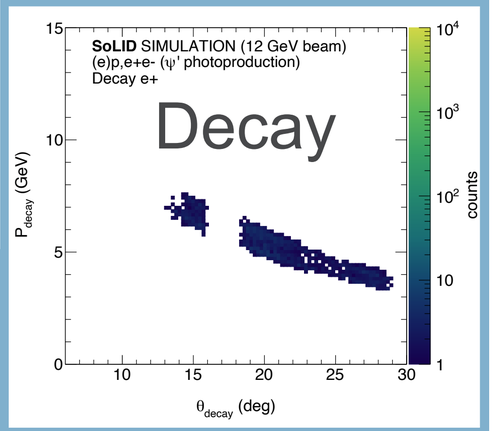
EXPERIMENTAL CONSIDERATIONS WITH SOLID

12 GeV is only enough to see ψ’

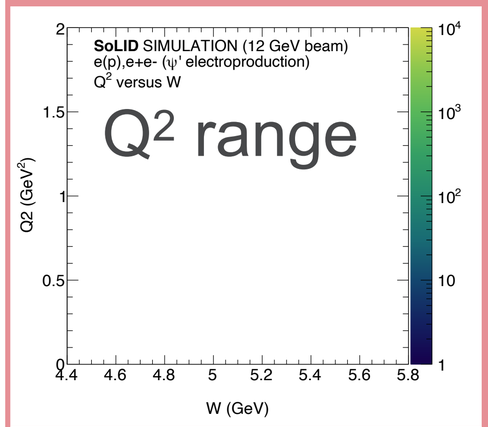
Triple-coincidence phase space for ψ’ production at SoLID assuming 50 days at $10^{37}/cm^2s$

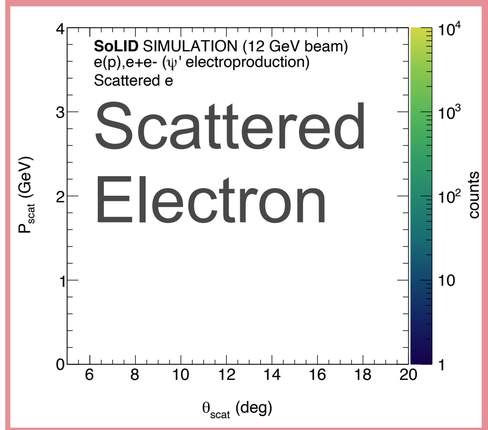


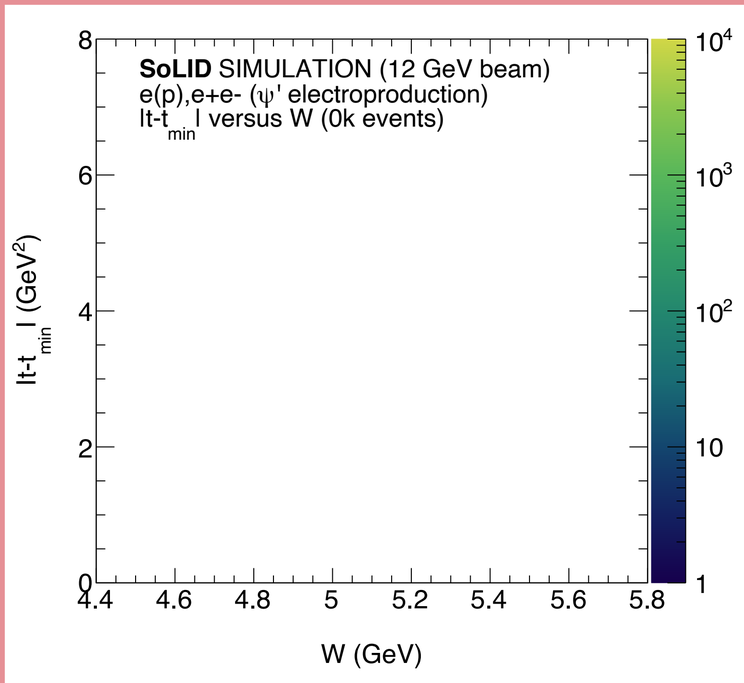




Photoproduction





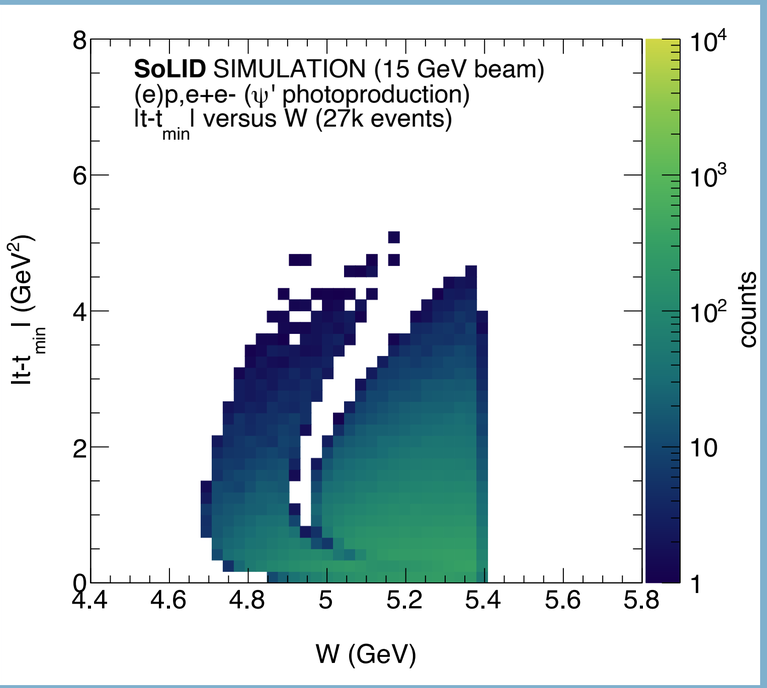


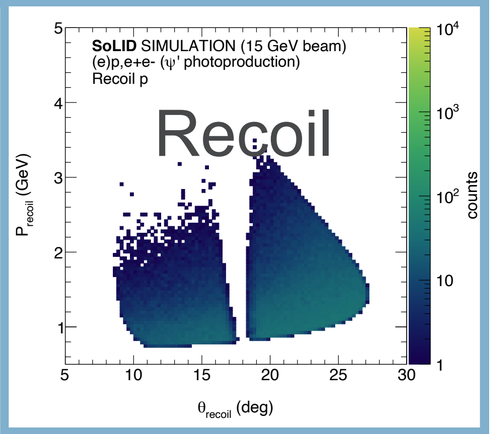
Electroproduction

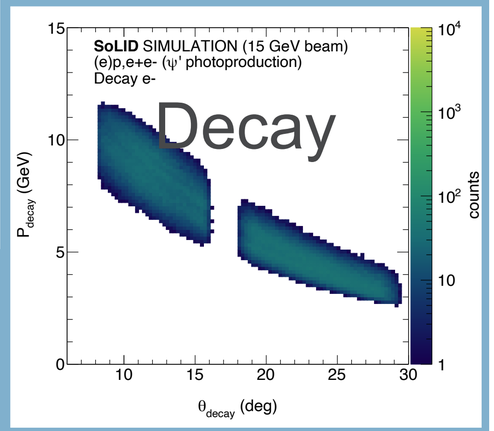
EXPERIMENTAL CONSIDERATIONS WITH SOLID

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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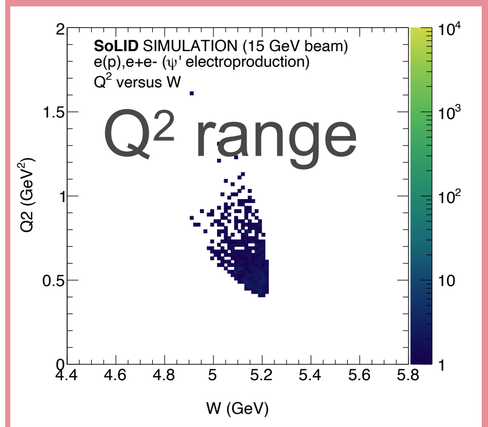
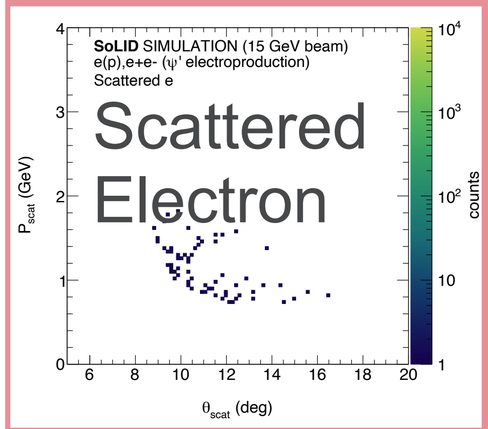
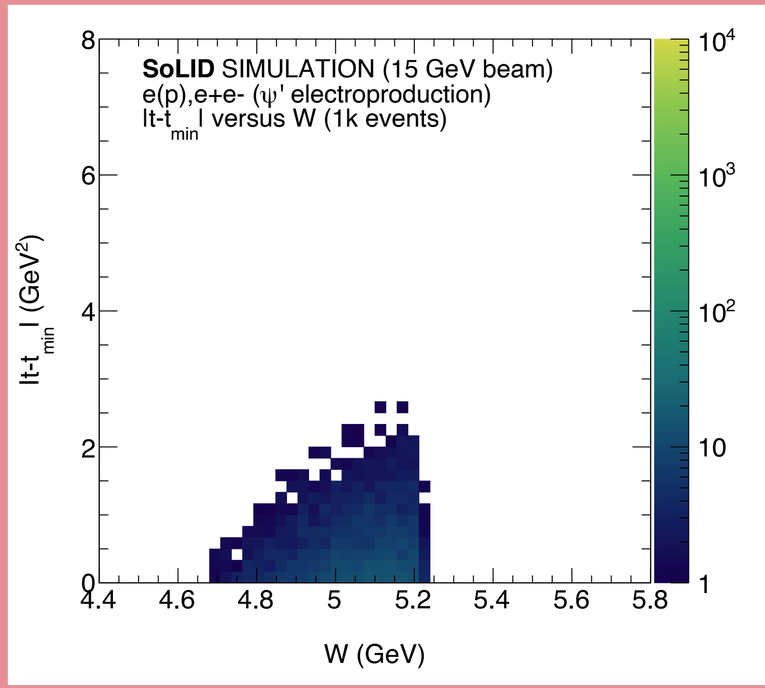




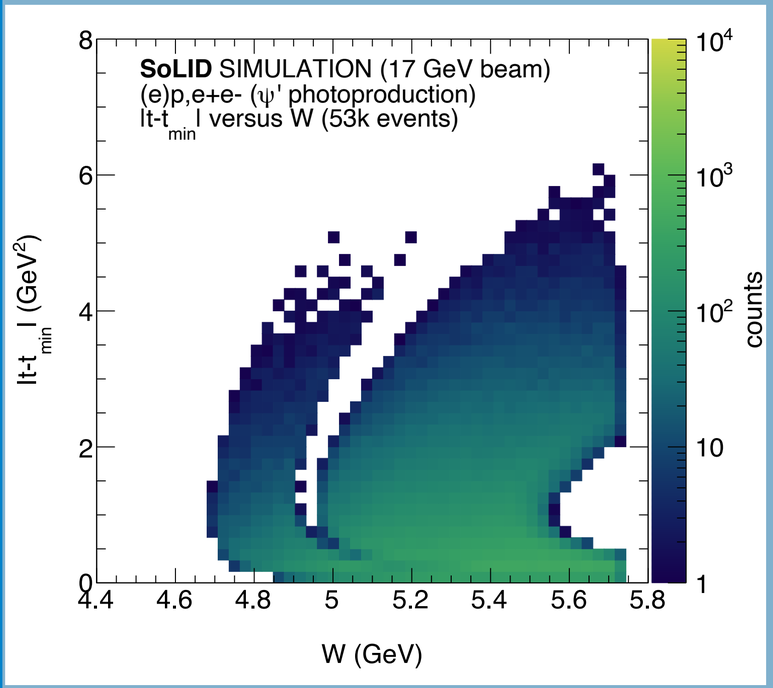


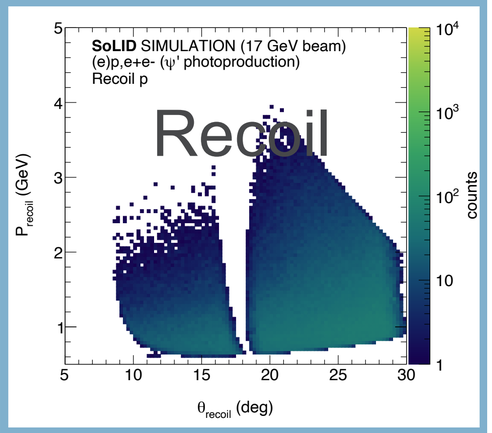
Electroproduction

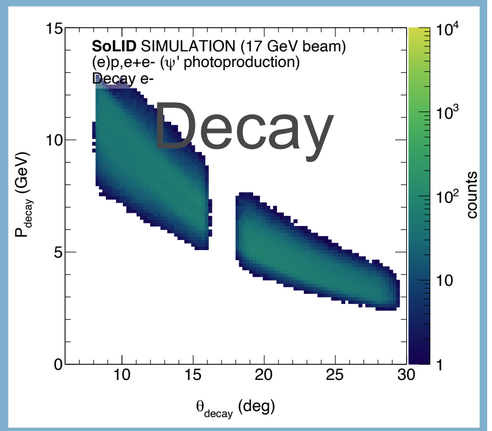
EXPERIMENTAL CONSIDERATIONS WITH SOLID

17 GeV optimum with current SoLID-J/ψ setup

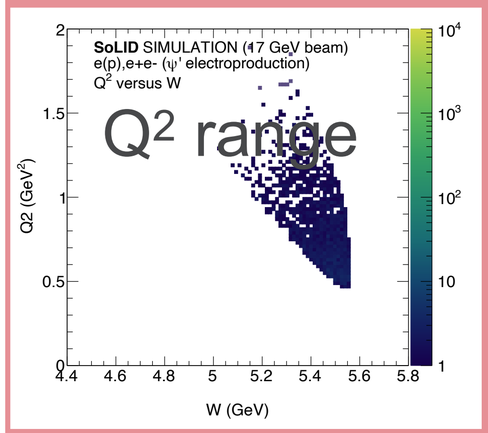
Triple-coincidence phase space for ψ' production at SoLID assuming 50 days at $10^{37}/cm^2s$

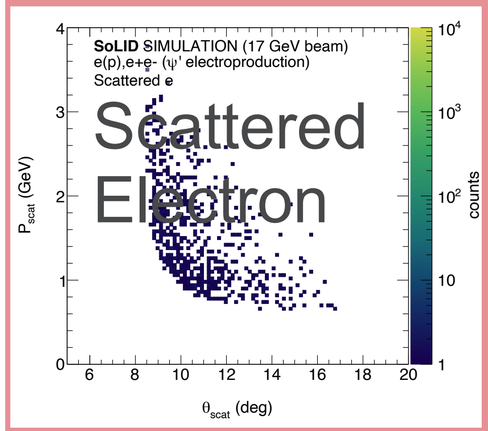


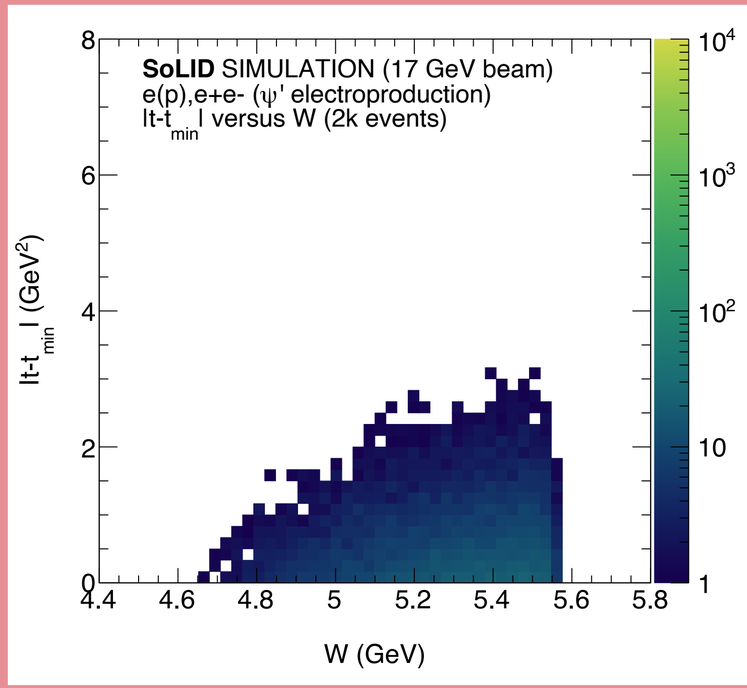




Photoproduction





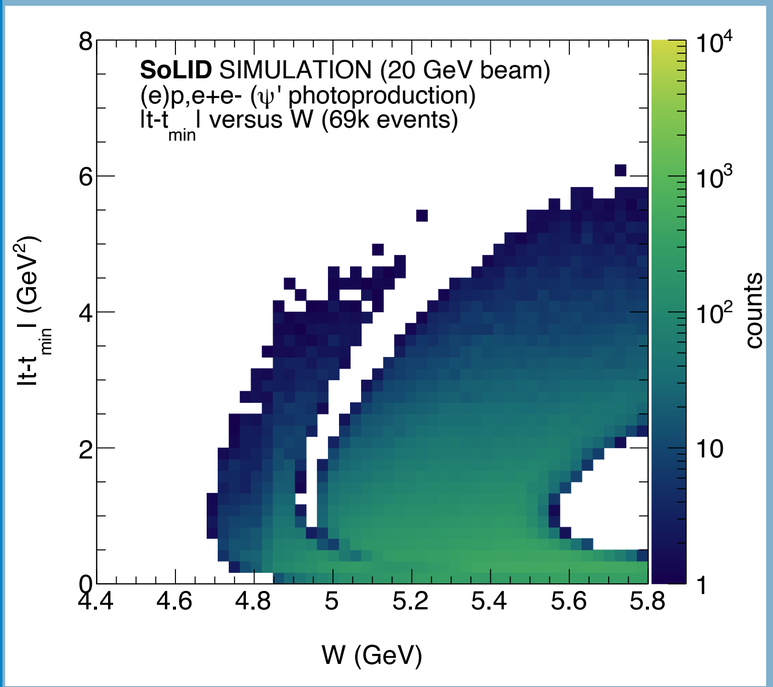


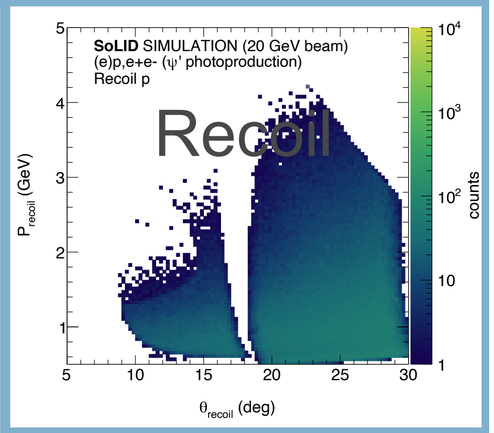
Electroproduction

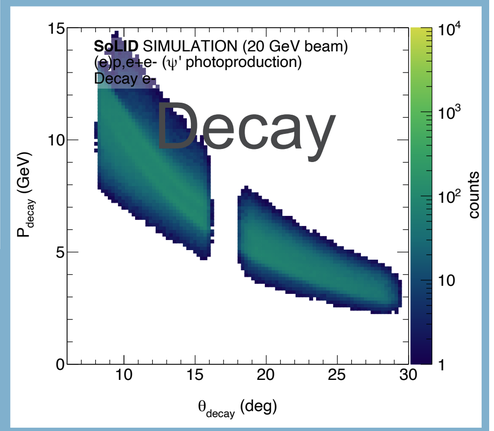
EXPERIMENTAL CONSIDERATIONS WITH SOLID

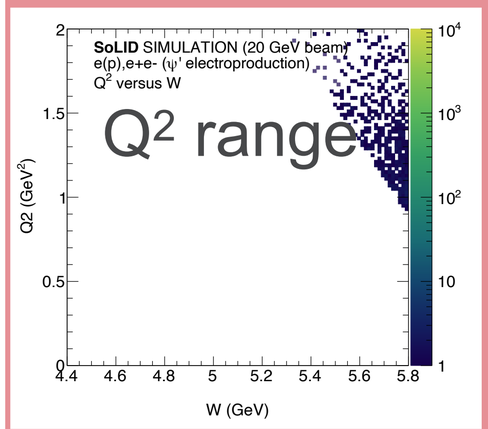
20 GeV (and higher) would require modifications to target location

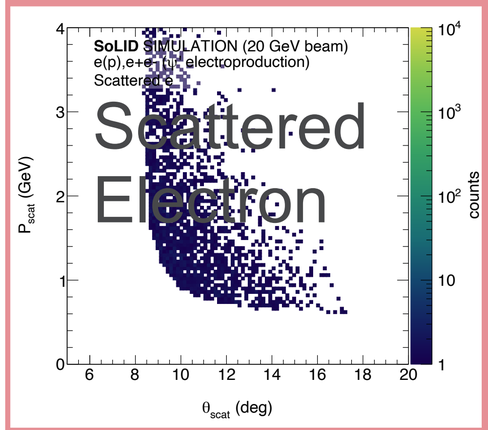
Triple-coincidence phase space for ψ' production at SoLID assuming 50 days at 10^{37}/cm^{2}s

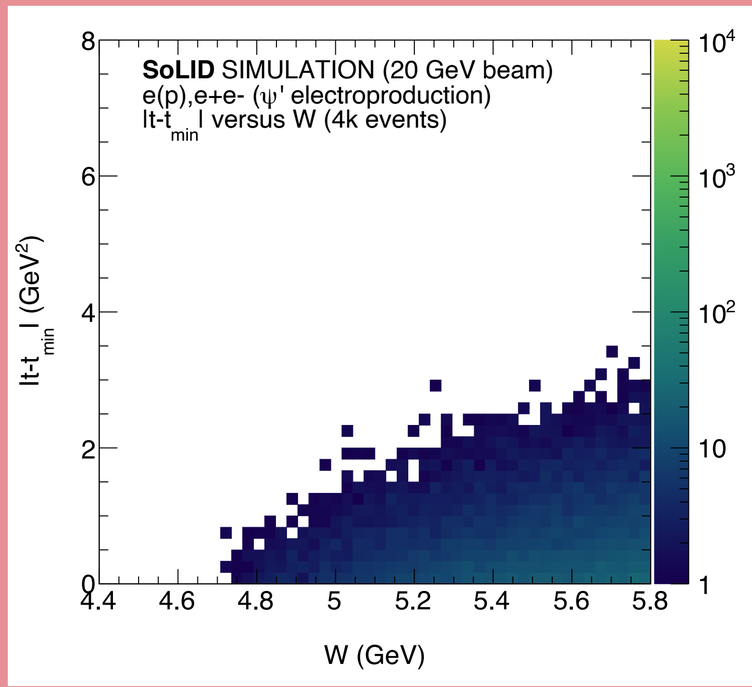








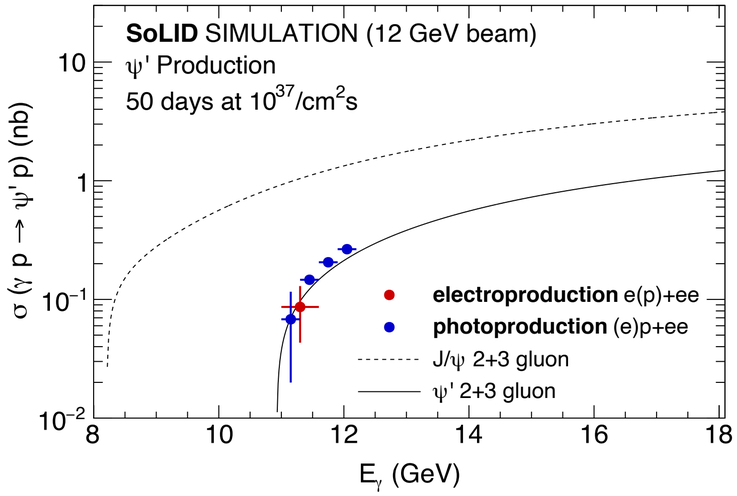


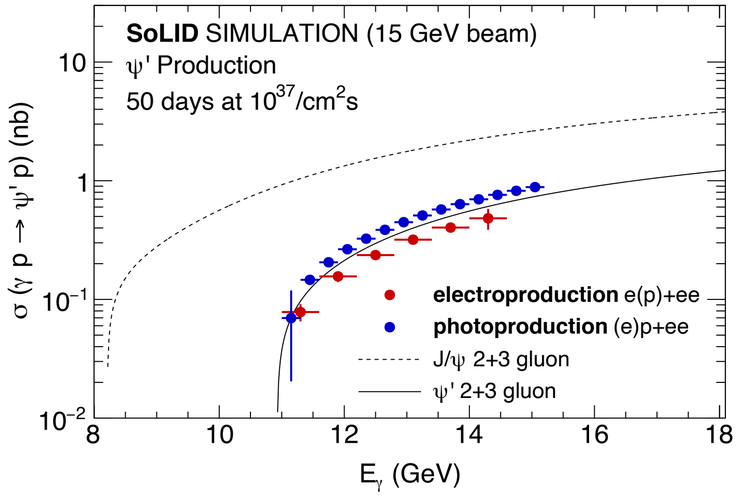


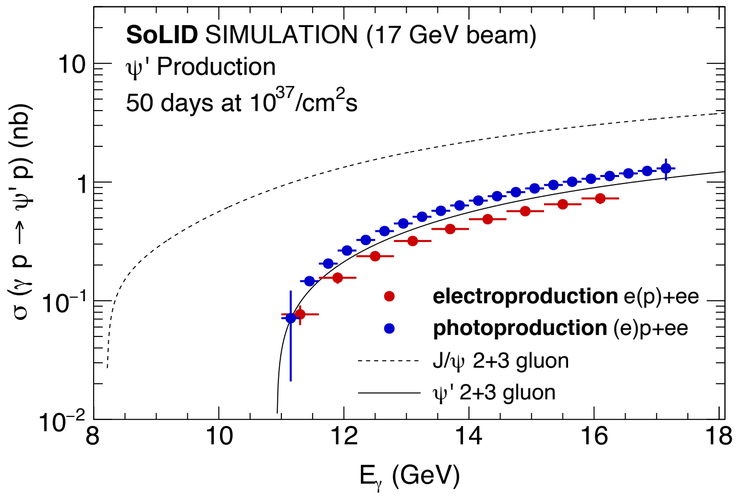
Photoproduction

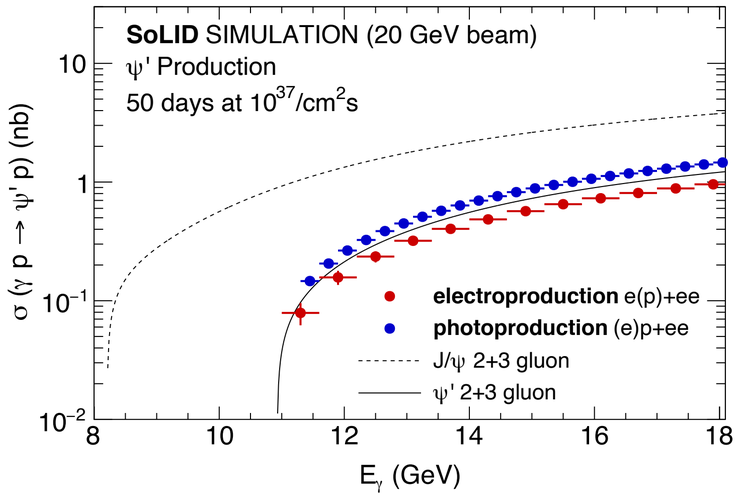
Electroproduction

PHYSICS REACH WITH DIFFERENT BEAM ENERGIES



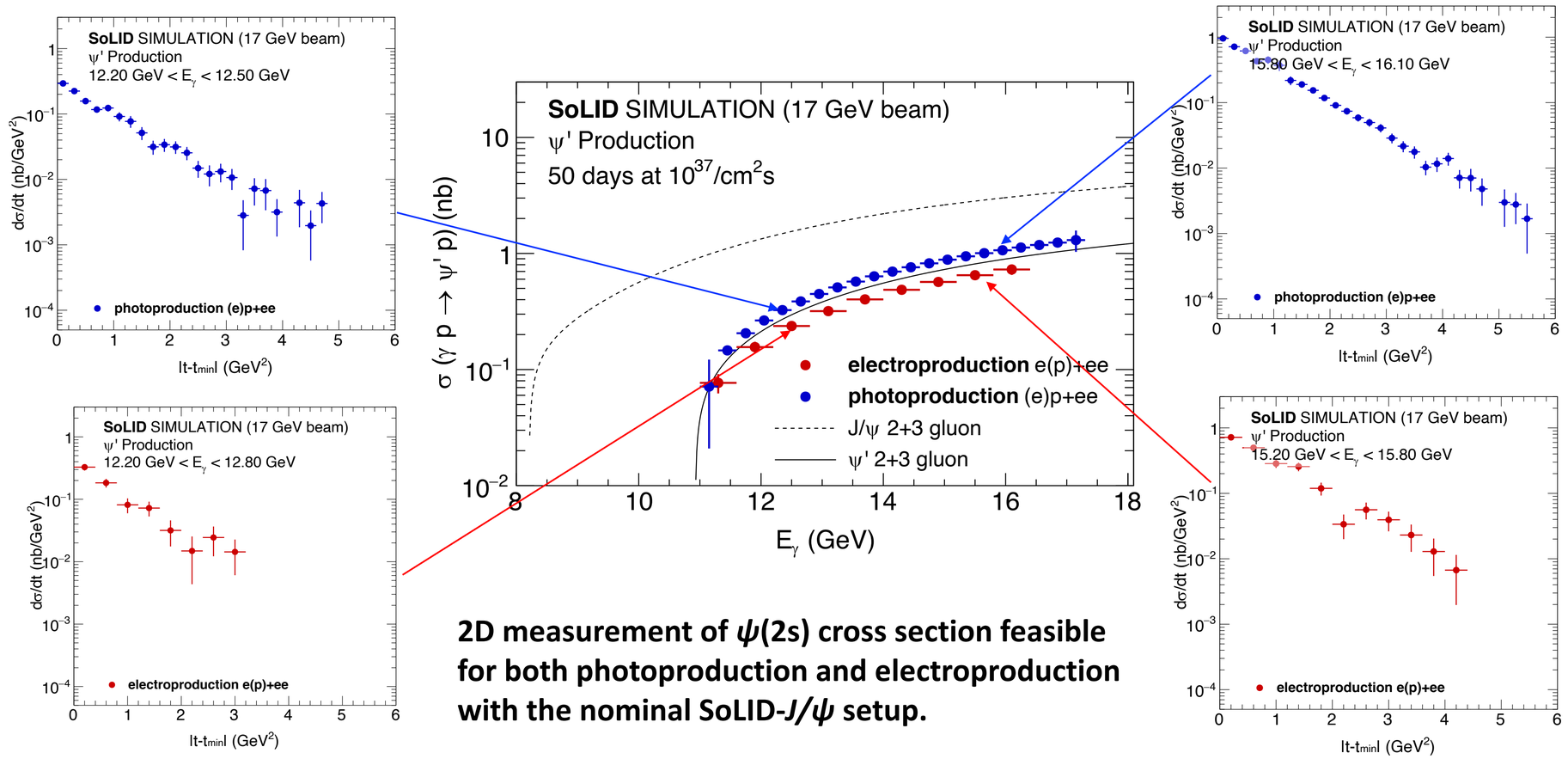






2D CROSS SECTION POTENTIAL

ψ(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

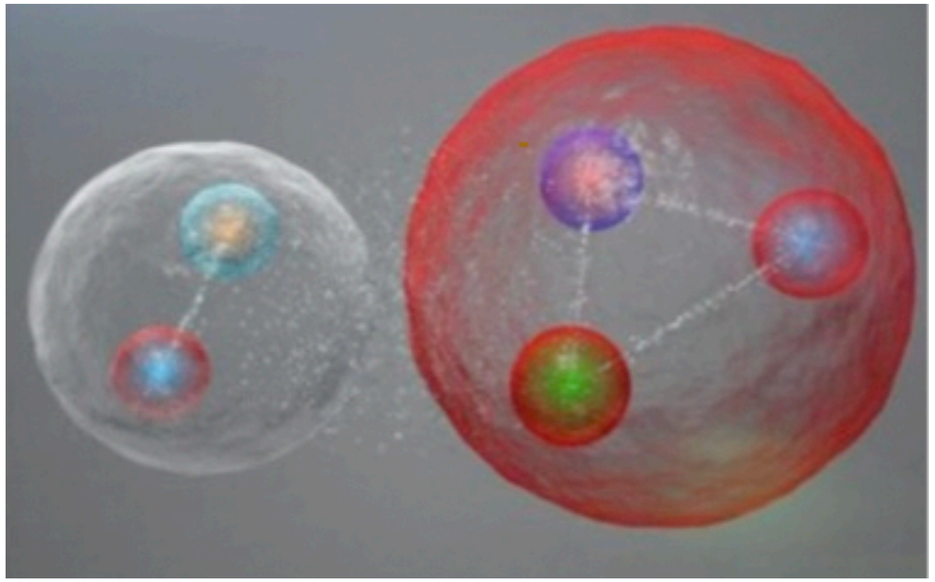
Expect enhanced color Van der Waals force in nuclei due to the larger color field: measure e.g. coherent J/ψ production off ^{4}He

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

Near-threshold electro- and photoproduction of quarkonium

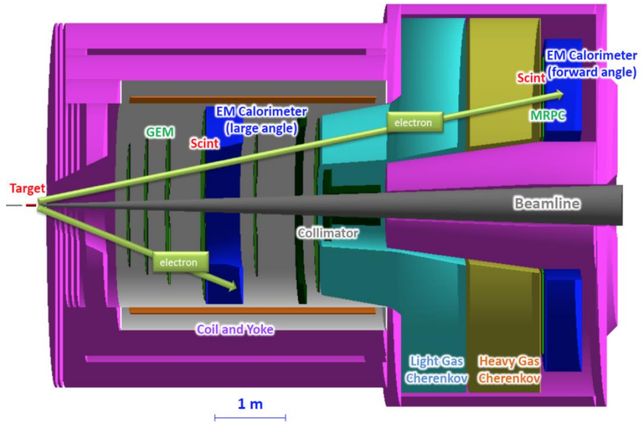
- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus bound states
- Do quarkonia enable **pentaquarks** to exist?
- **Mechanism** for quarkonium production itself

SOLENOIDAL LARGE INTENSITY DEVICE

SoLID is the ultimate place to research these topics due to luminosity and kinematic reach

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)!



THE END