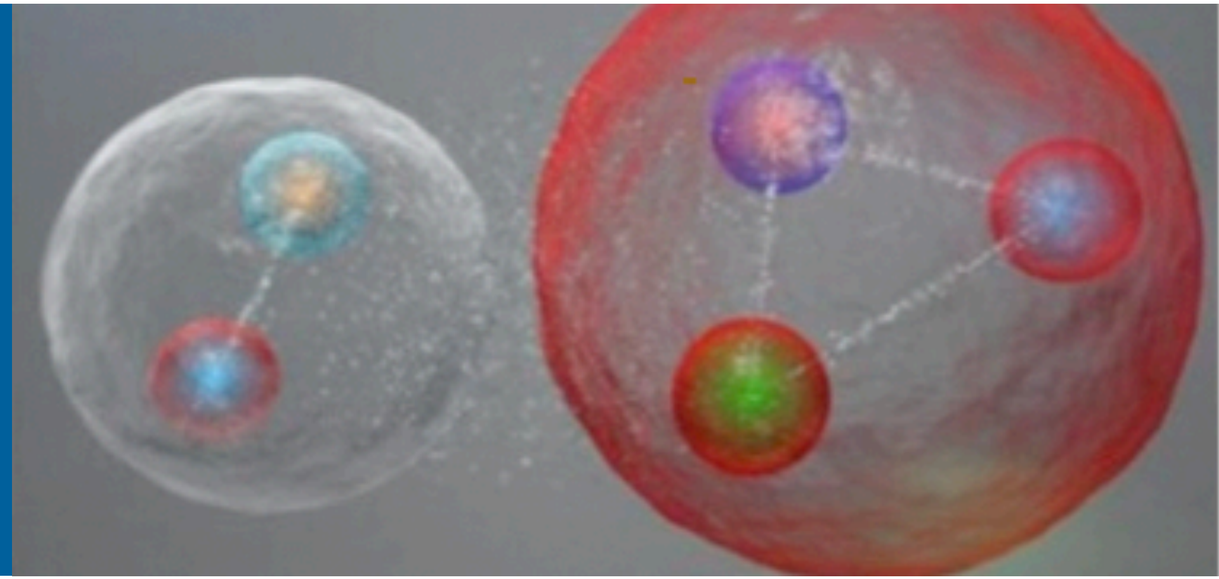
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY

E12-12-006 JEOPARDY REVIEW

Near-threshold Electroproduction of J/ψ at 11 GeV



SYLVESTER JOOSTEN
sjoosten@anl.gov

ON BEHALF OF SOLID-J/Ψ

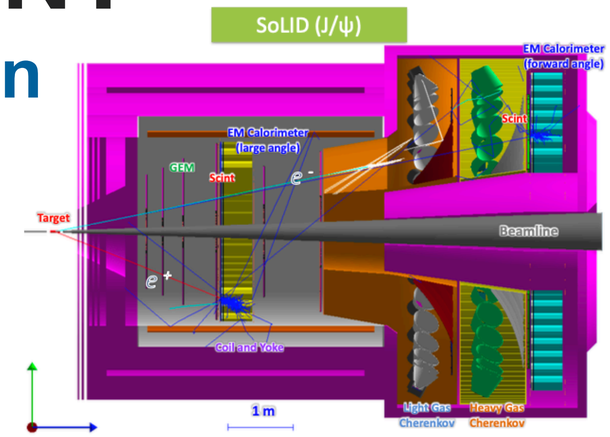
SOLID
SOLENOIDAL LARGE INTENSITY DEVICE

PAC50
Jefferson Lab, July 13, 2022

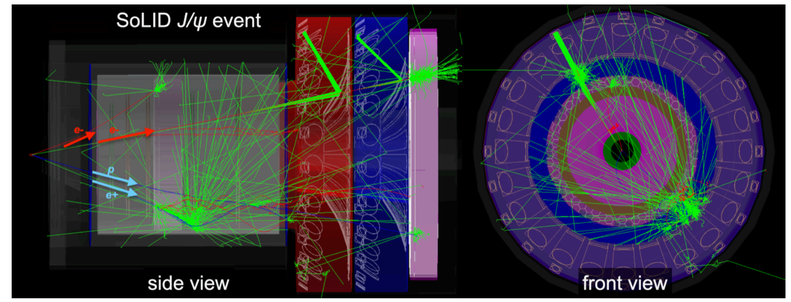
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

THE UPDATED SOLID-J/Ψ EXPERIMENT

Ultimate experiment for near-threshold J/ψ production



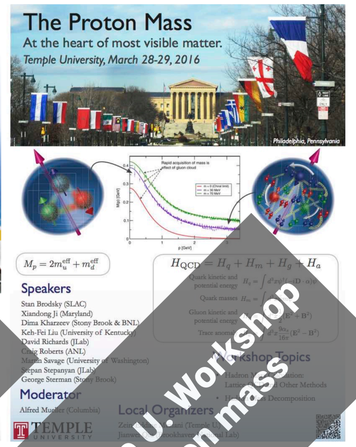
- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target ($10^{37}/cm^2/s$)
- **Ultra-high luminosity**: $43.2ab^{-1}$
- **Open 2-particle trigger,** covering J/ψ production in four channels:
  Electroproduction (e,e^-e^+), photoproduction (p,e^-e^+), inclusive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

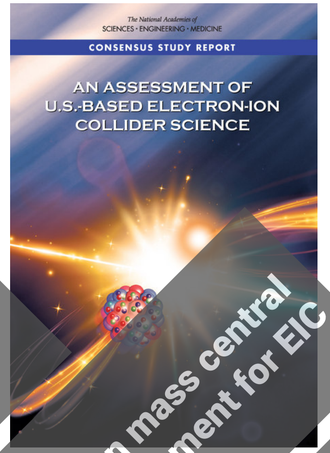


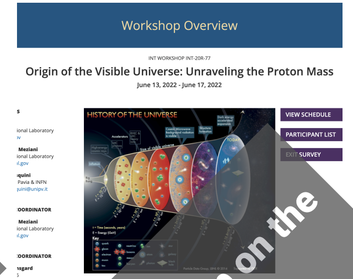
SoLID-J/ψ was originally approved by the PAC in 2012 with A-
We request you consider upgrading the grade to A, as the scientific impact has become much more prominent and the instrumentation is more mature and powerful.

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

LOTS HAS HAPPENED IN 10 YEARS!







2012 Temple U. Workshop on heavy quarkonia

Featured in the 2015 Long Range plan

2016 Temple U. Workshop on the proton mass

2017 ECT* Workshop on the proton mass

2018 Proton mass central in NAS assessment for EIC

2021 Remote Workshop on the proton mass

2022 INT Workshop on the proton mass

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

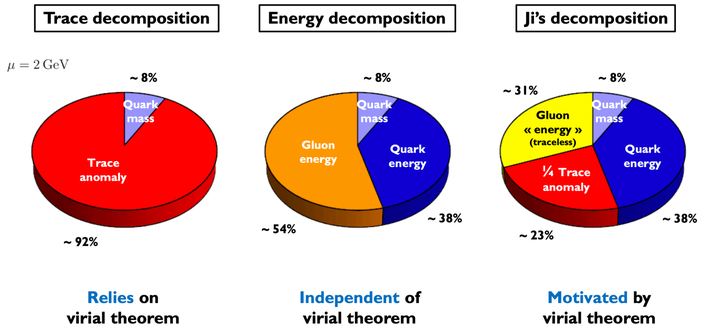
2016 Proposal for Hall C Pentaquark search

2019 First GlueX near-threshold J/ψ results

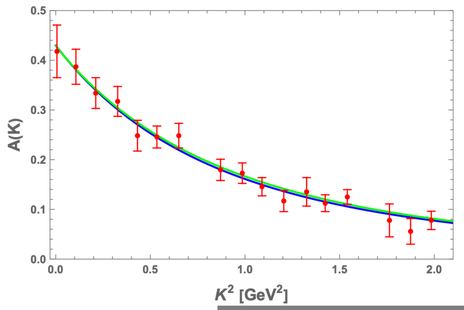
2021 First Hall C results on the pentaquark search

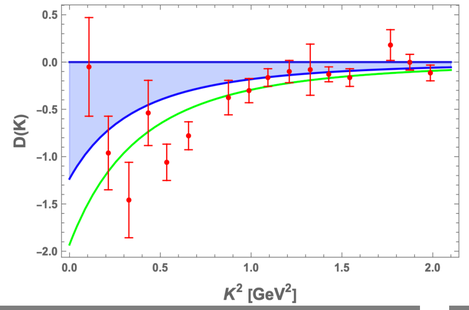
2022 First 2D near-threshold J/ψ results from Hall C

Subject not intrinsically changed, but science case strongly enhanced
PROMINENT NEW DEVELOPMENTS

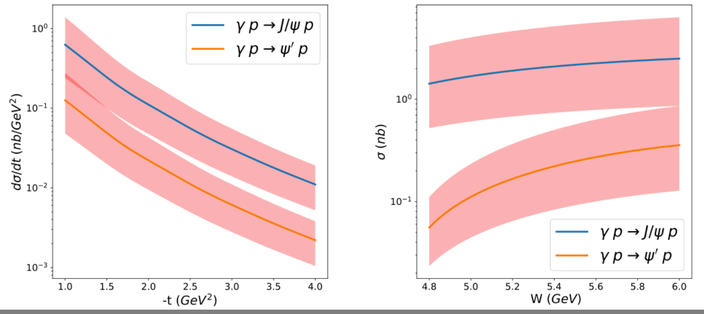


Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)



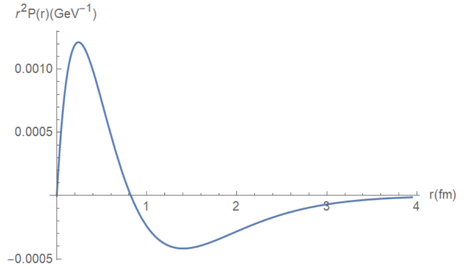


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

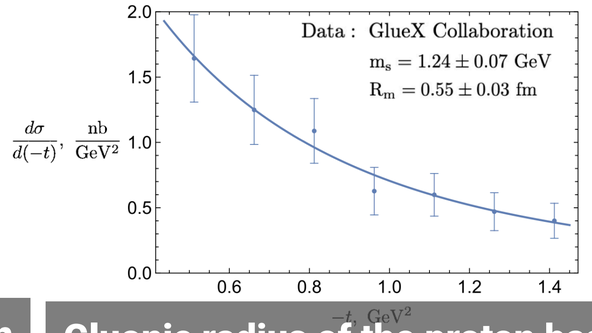


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

- 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)

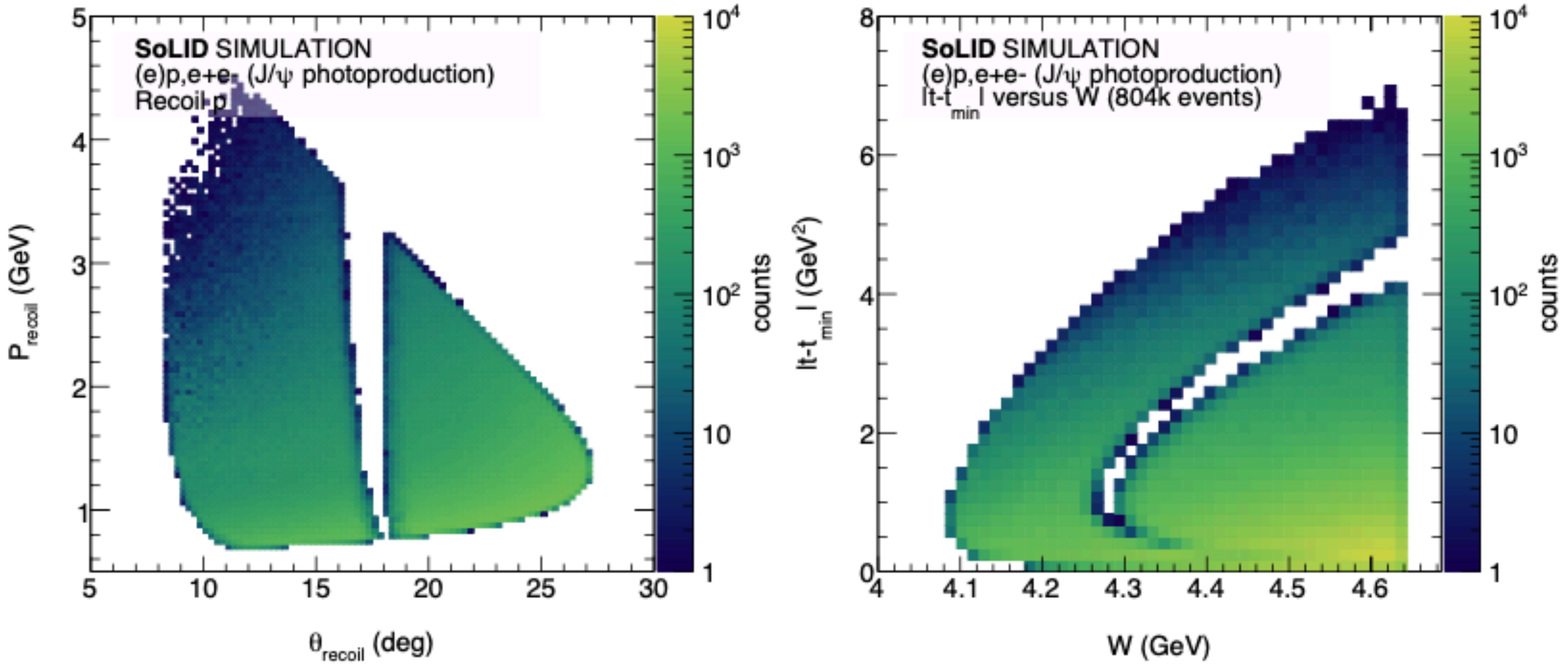


Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)

PHOTOPRODUCTION

Ultra-high statistics and best reach to high energies

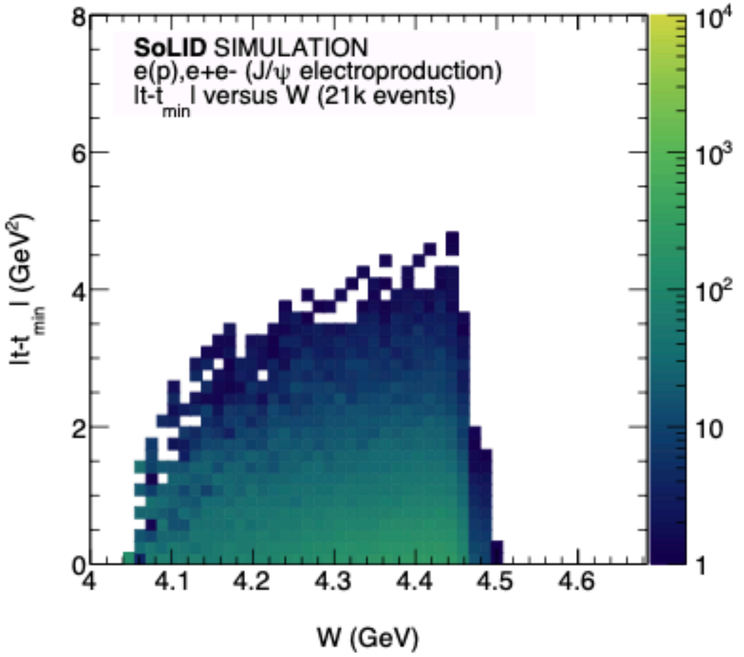
- Production through quasi-real photons, and bremsstrahlung in the extended target.
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify recoil proton (which is slow) through time-of-flight with the SPDs and MRPCs.
- Can make measurement up to very large values of *t*.

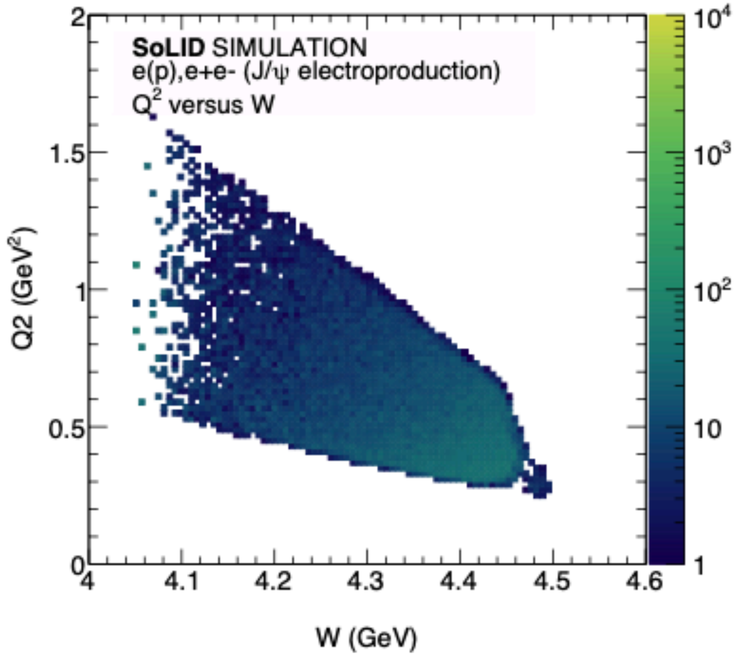


ELECTROPRODUCTION

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

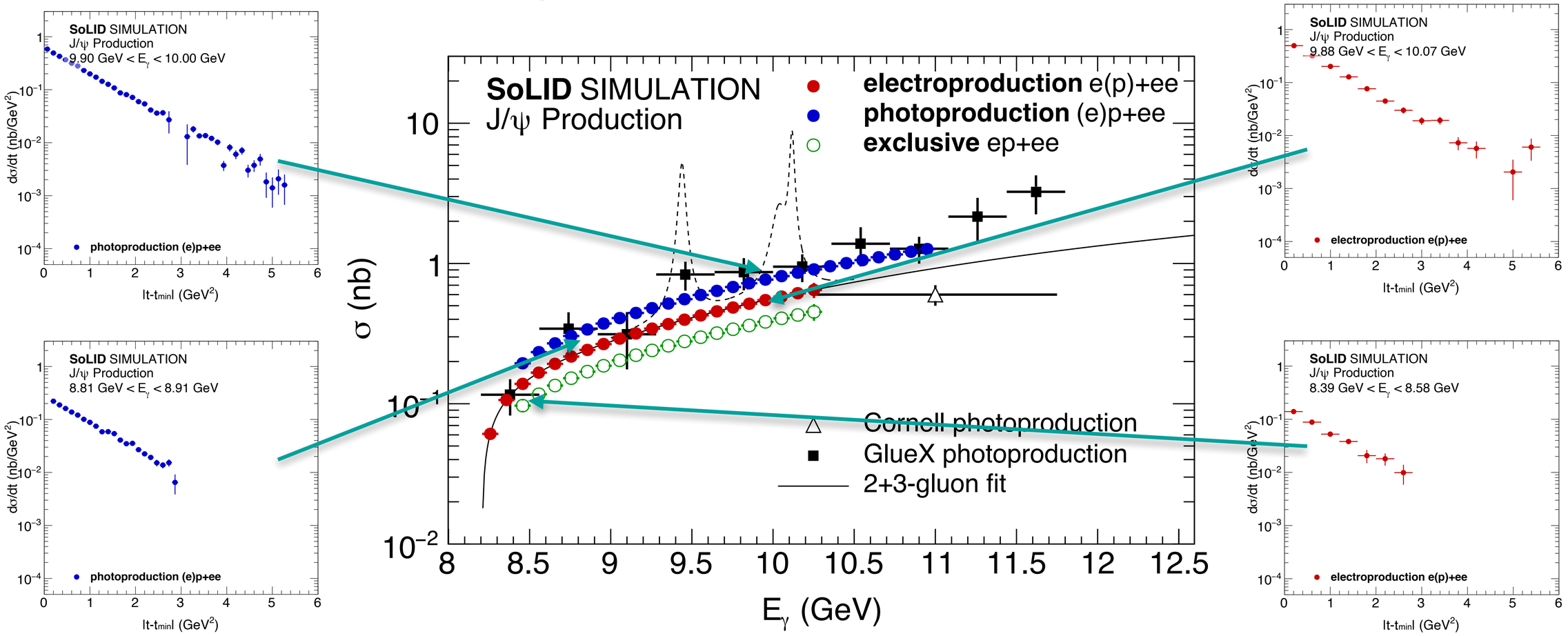
- Production through virtual photons
- Measure J/ψ decay pair in forward and/or wide-angle detectors
- Identify scattered electron in the forward spectrometer.
- Coverage up to larger values of t very close to threshold.



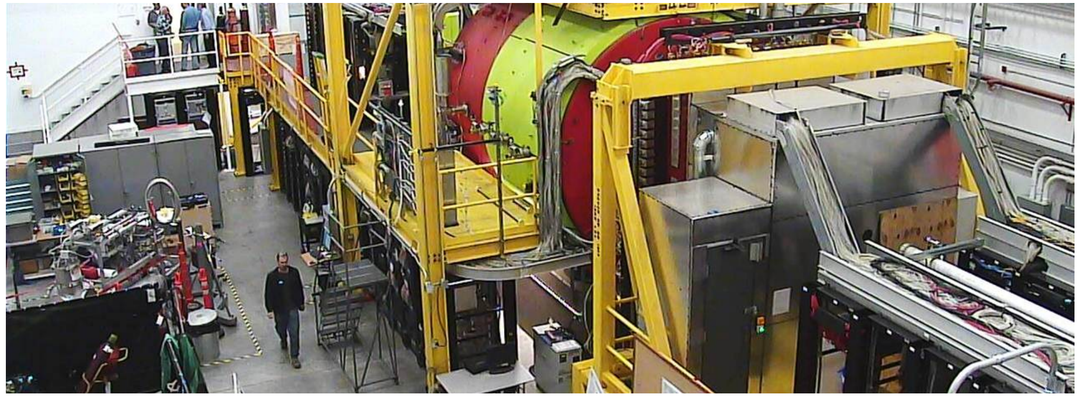


SOLID-J/Ψ PROJECTIONS

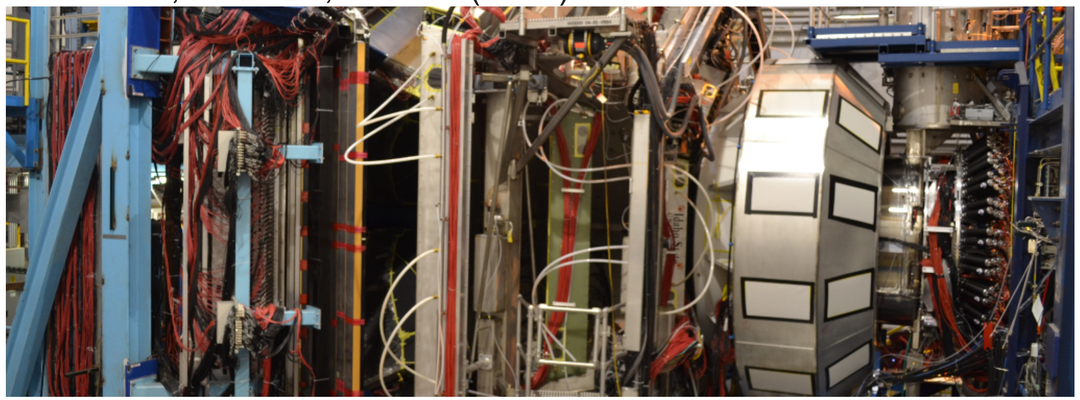
Precision at high t crucial for extrapolations to the forward limit (exponential, dipole, triple, …)



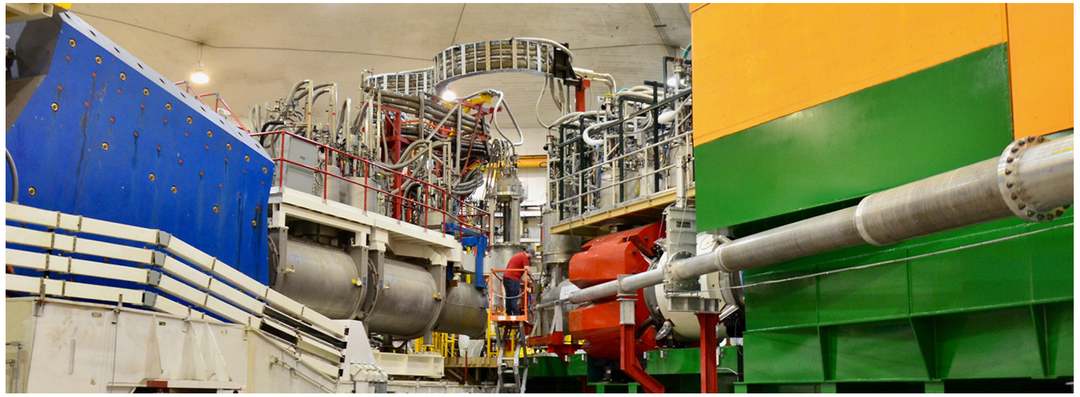
J/Ψ EXPERIMENTS IN THE 12 GEV ERA



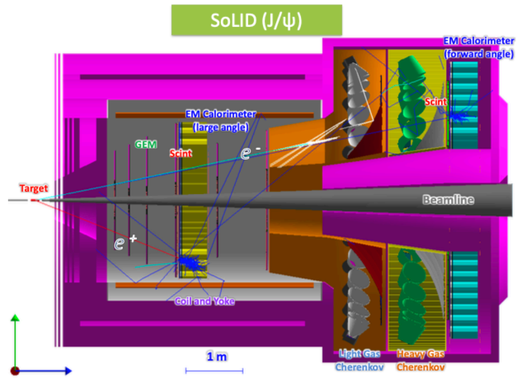
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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

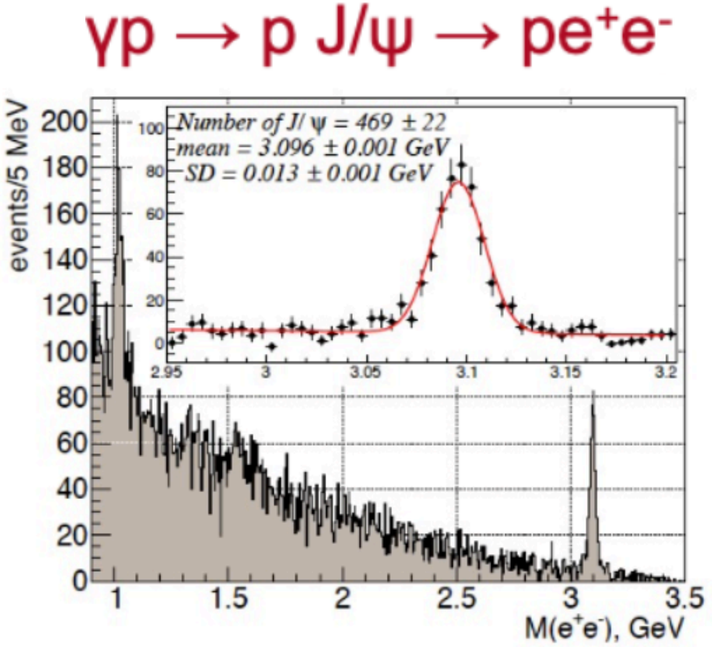


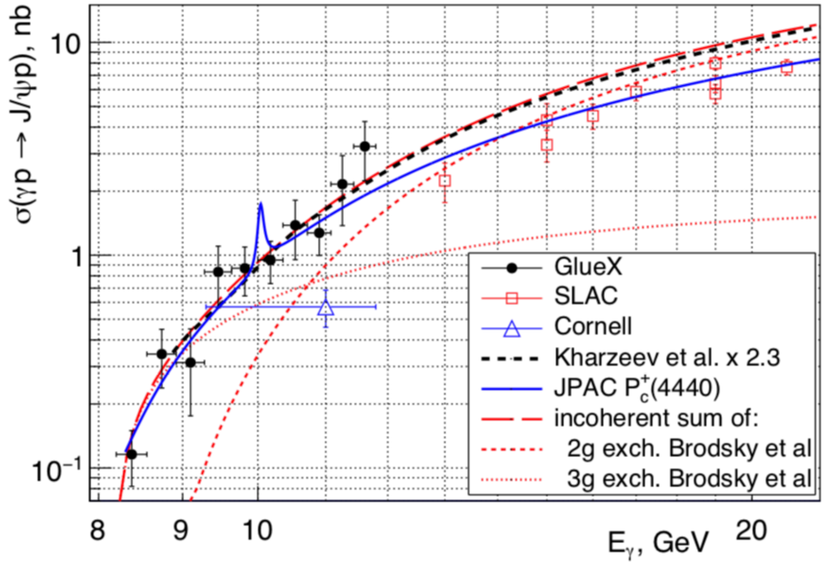
Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

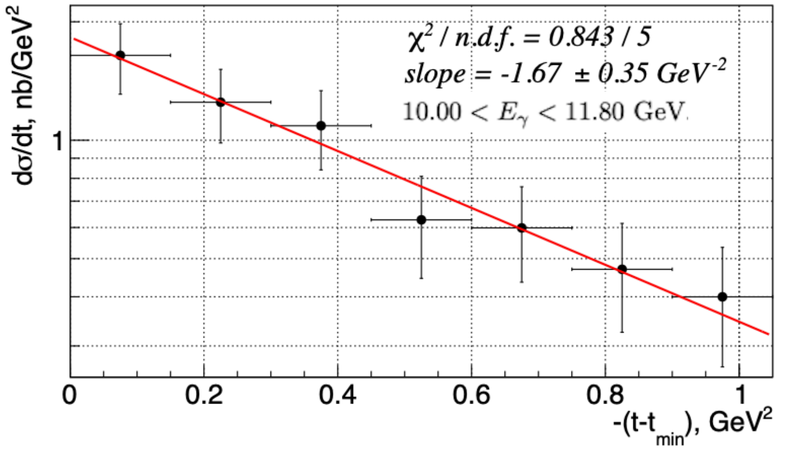
J/Ψ NEAR THRESHOLD IN HALL D

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

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



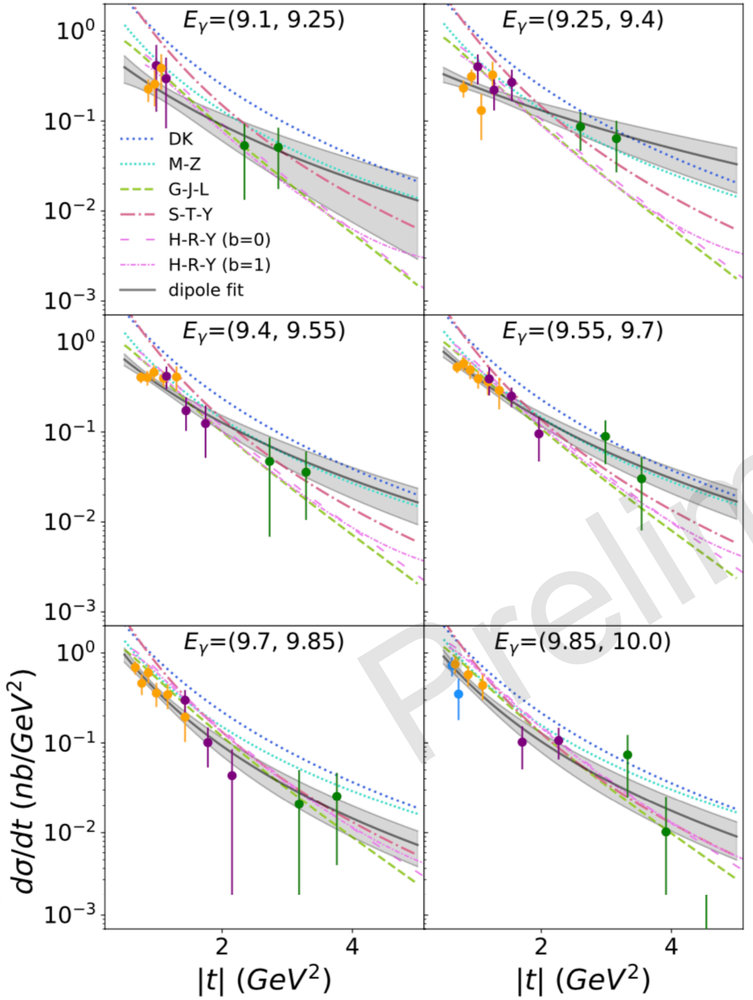


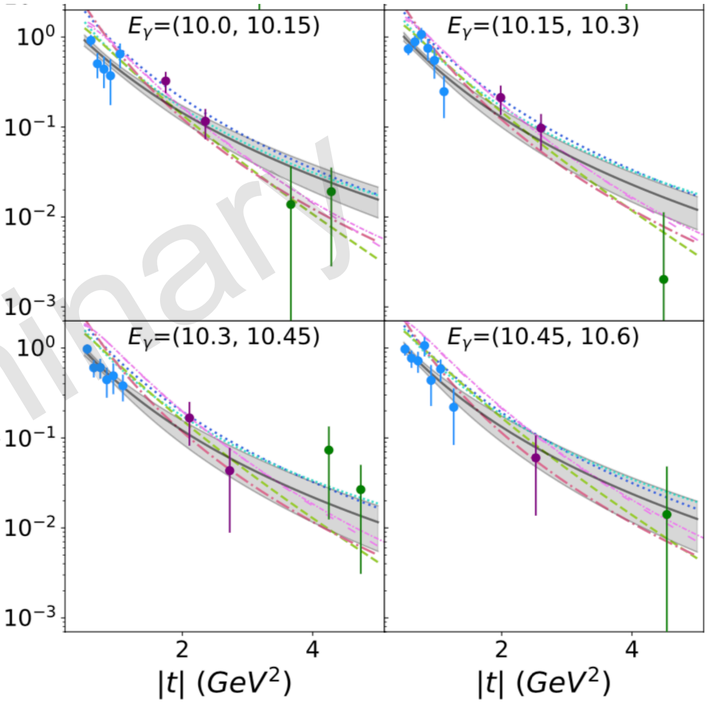


NEW DEVELOPMENTS: HALL C

First 2D cross section measurement

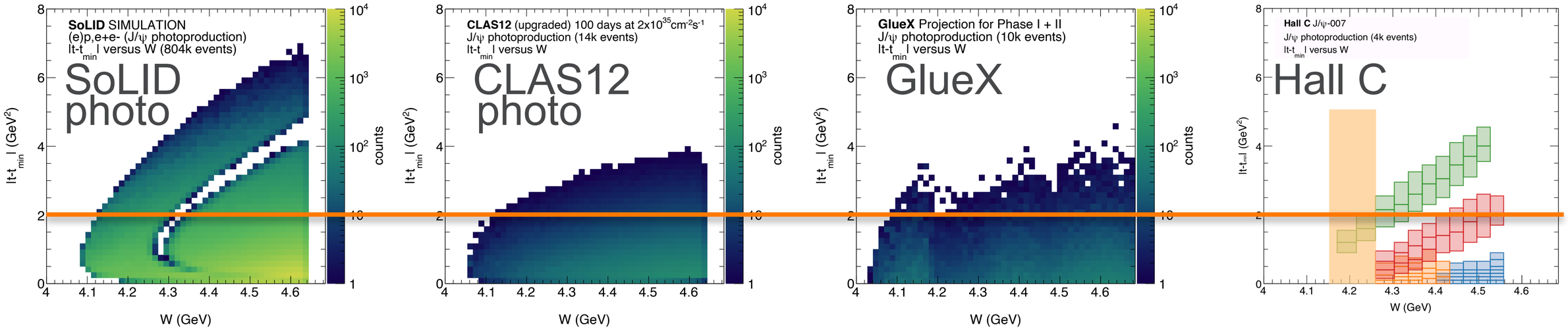
- The **Hall C J/ψ-007 experiment has the first near-threshold 2D J/ψ cross section results** in this area, currently under peer review.
  - Stringent exclusion limit for the LHCb charmed pentaquarks in photoproduction
  - New window on the gluonic GFFs in the proton.
  - Based on 2000 events (extra 2000 muon channel events to come).
  - Reaches high t (but with low statistics).

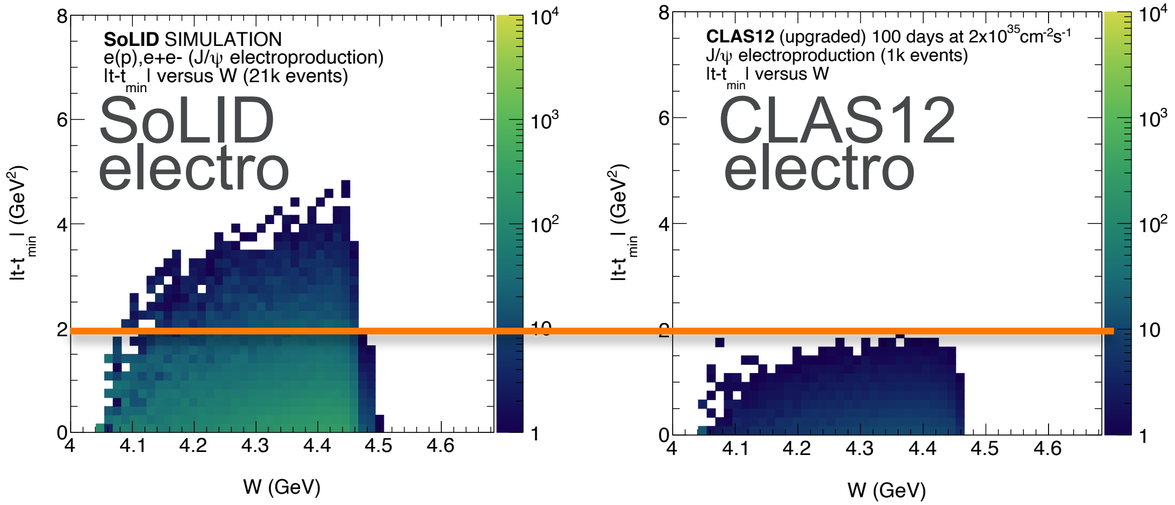




No substitute for SoLID-J/ψ

COMPARISON WITH FUTURE RESULTS





- Reaching higher values of $|t - t_{\min}| > 2\ \text{GeV}^2$ near threshold impossible with other projected experiments.
- Precision electroproduction only possible at SoLID.

J/Ψ EXPERIMENTS AT JLAB COMPARED

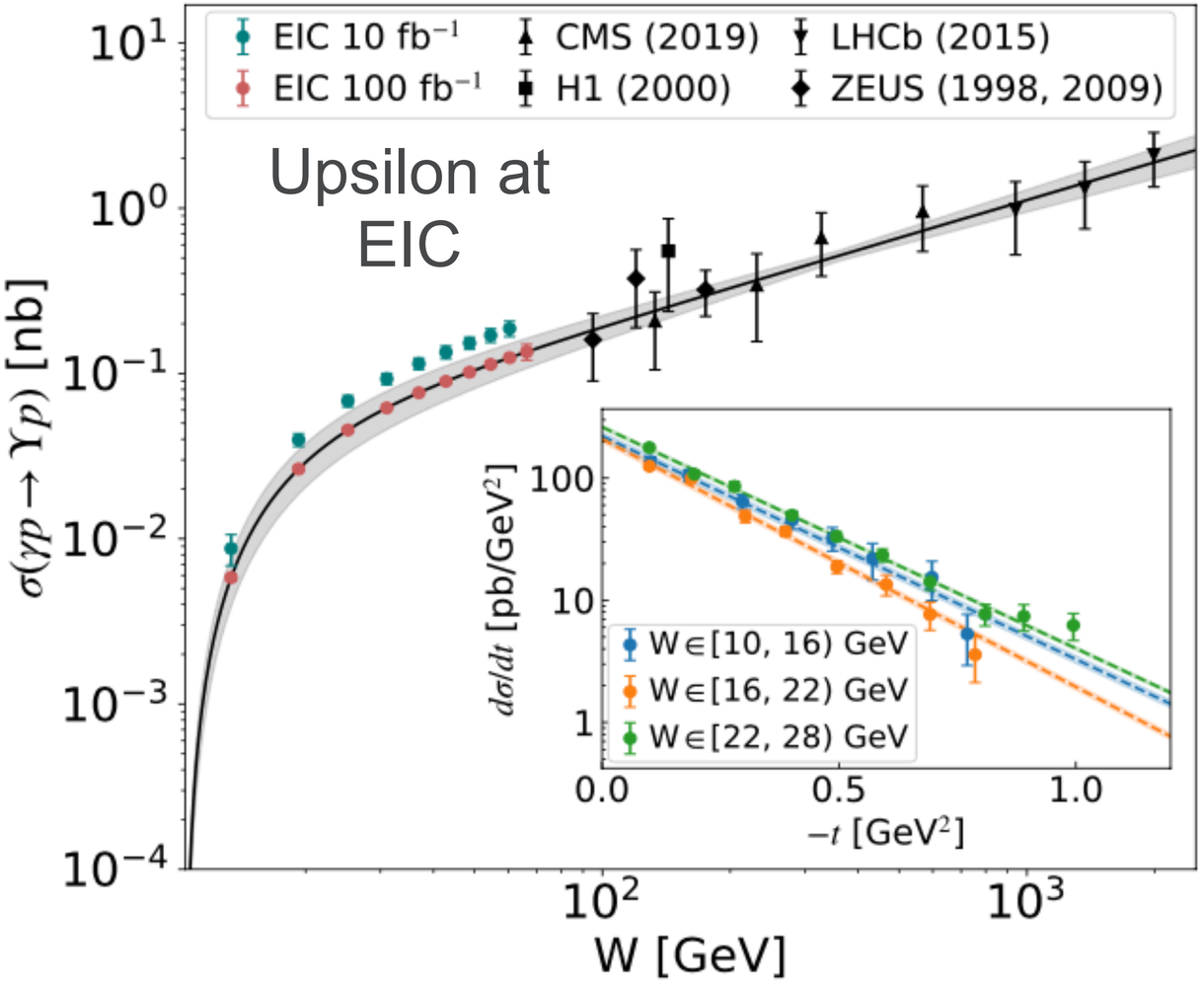
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 with upgrade[1] HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	**469 published ~10k phase I + II**	**2k electron channel 2k muon channel**	**14k**	**804k**
J/ψ Rate (electro-prod.)	**N/A**	**N/A**	**1k**	**21k**
Features	Good reach to threshold. No high-t reach.	Can 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 $2x10^{35}/cm^2/s$

COMPLEMENTARITY WITH EIC

J/ψ at SoLID and Y at EIC

- Y(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



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

COLLABORATION

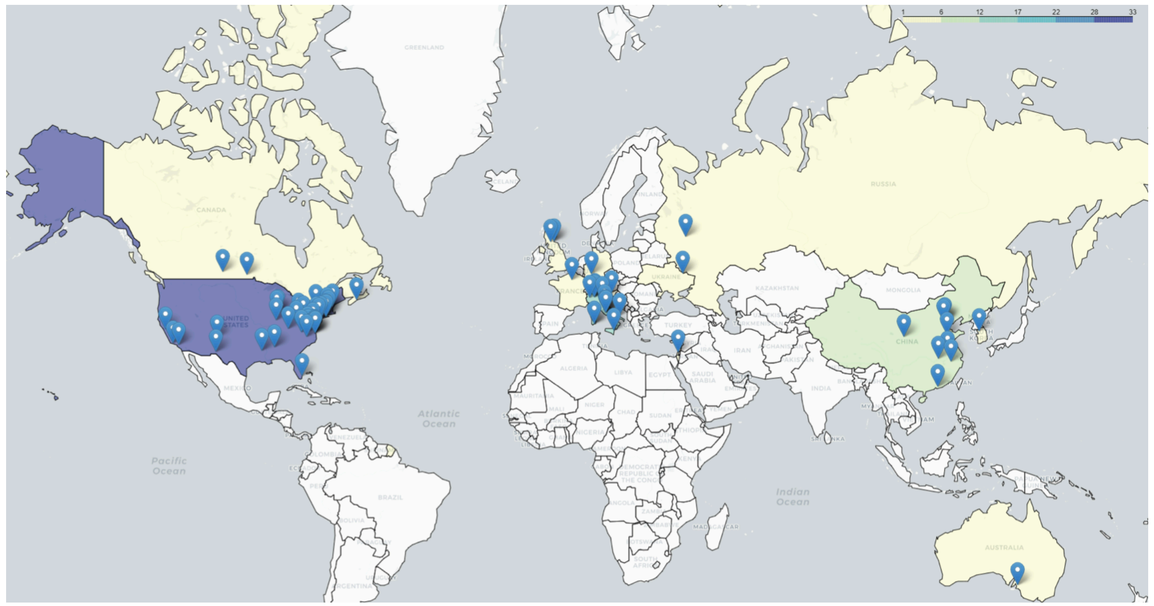
SoLID: a large collaboration!

SOLENOIDAL LARGE INTENSITY DEVICE

270+ collaborators from 70+ institutions in 13 countries

SoLID-J/ψ Spokespeople

Sylvester Joosten (ANL)
Zein-Eddine Meziani (ANL)
Xin Qian (BNL)
Nikos Sparveris (Temple University)
Zhiwen Zhao (Duke University)



$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$

RUN GROUP: TIMELIKE COMPTON SCATTERING AT SOLID

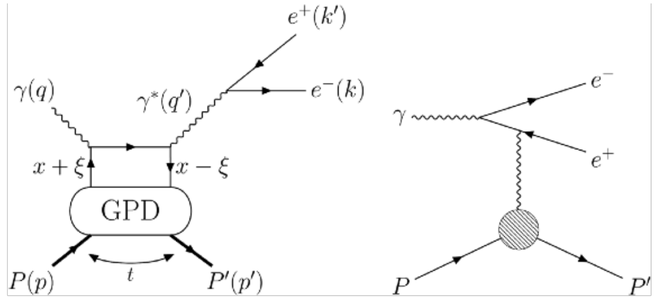
Run group proposal E12-12-006A, approved in 2015

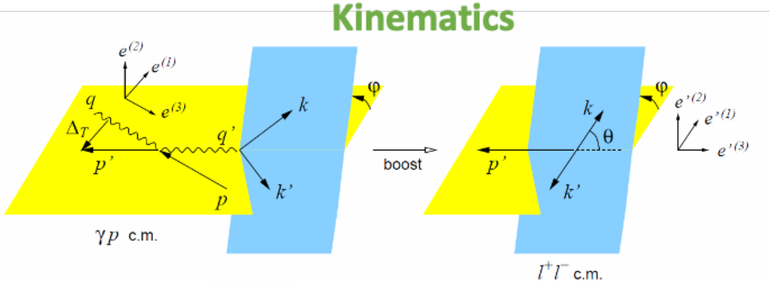
Motivation

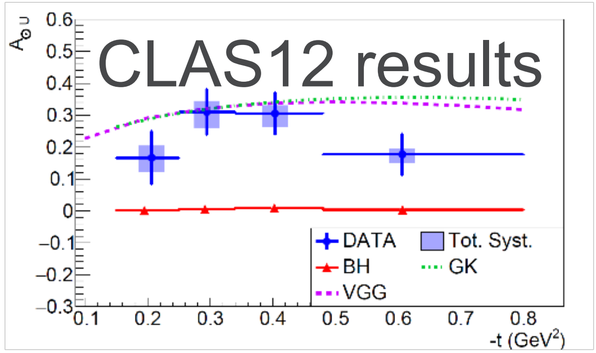
- Channel to access GPDs complimentary to DVCS, can test universality
- New observables to better constrain global GPD fits

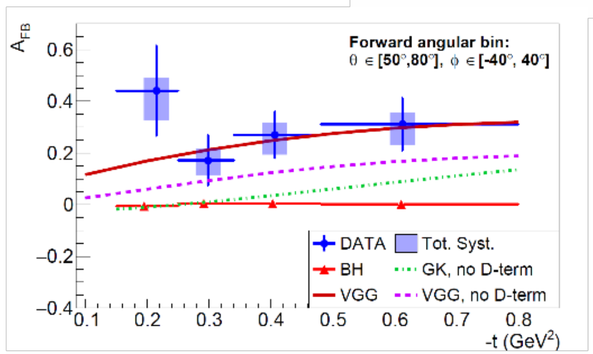
Current experimental status

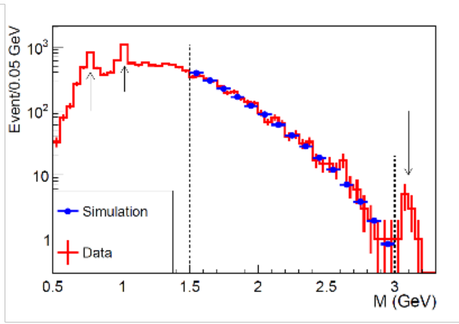
- Channel explored at CLAS6
- First results from CLAS12 published in PRL 127, 262501 (2021)
  - Used TCS and Bethe-Heitler interference to obtain nonzero beam polarized asymmetry A_{LU} and forward backward asymmetry A_{FB}
  - Consistent with DVCS-data-constrained GPD model predictions for the imaginary and real parts of GPD H and support universality
  - Limited by statistical precision











TCS Spokespeople: Marie Boer, Pawel Nadel-Turonski, Jixie Zhang, Zhiwen Zhao

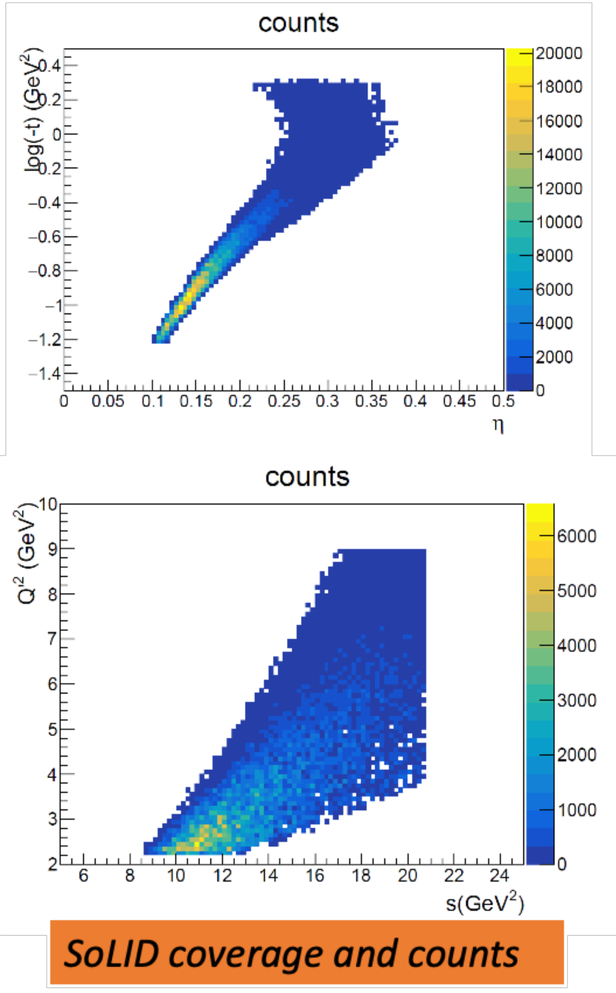
$\gamma\, p \rightarrow \gamma^*(e^- e^+)\, p'$

RUN GROUP: TIMELIKE COMPTON SCATTERING AT SOLID

Run group proposal E12-12-006A, approved in 2015

Advantages of measuring TCS at SoLID

- At least 1 order larger statistics than CLAS12
- Usher TCS study into precision era with multi-dimensional binning
  - SoLID TCS has 250 times more integrated luminosity than the CLAS12 TCS published result
  - SoLID acceptance for TCS events is about ¼ of CLAS12, But with full azimuthal symmetry
- SoLID TCS will allow NLO corrections to be studied and is in synergy with EIC at low x



SoLID coverage and counts

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

CONCLUSION

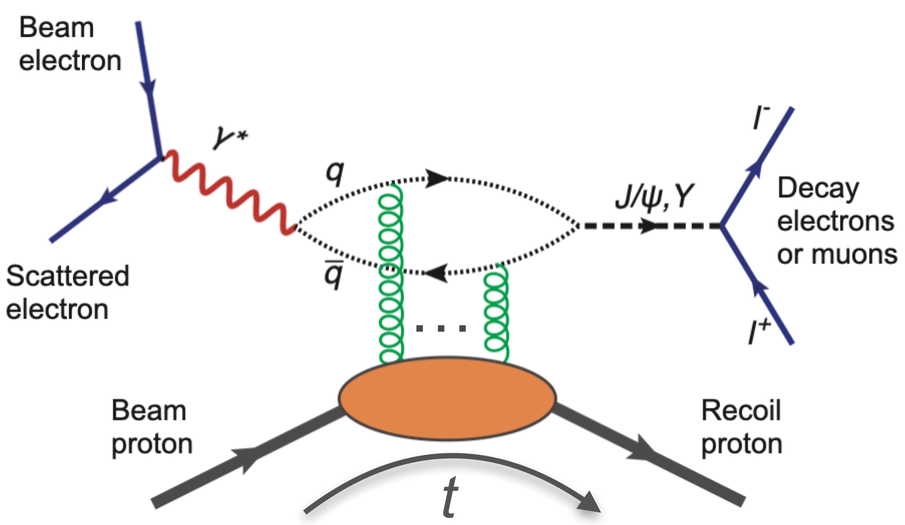
- The science case for SoLID-J/ψ has become much more compelling:
  - Covers once of the most important topics in contemporary hadronic physics.
  - Strong synergy between SoLID and at the EIC.
- SoLID apparatus design much more mature and realistic:
  - Greatly expanded experimental reach (2-particle trigger).
  - SoLID can reach observables that cannot be achieved anywhere else.
  - Flexible for other impactful measurements, e.g. TCS, …
- Collaboration has grown since the original proposal - we have the people to do this measurement!

Bottom-line: We ask to re-approve the time (50+10 days) with the highest scientific rating.

QUESTIONS?

EXCLUSIVE QUARKONIUM PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

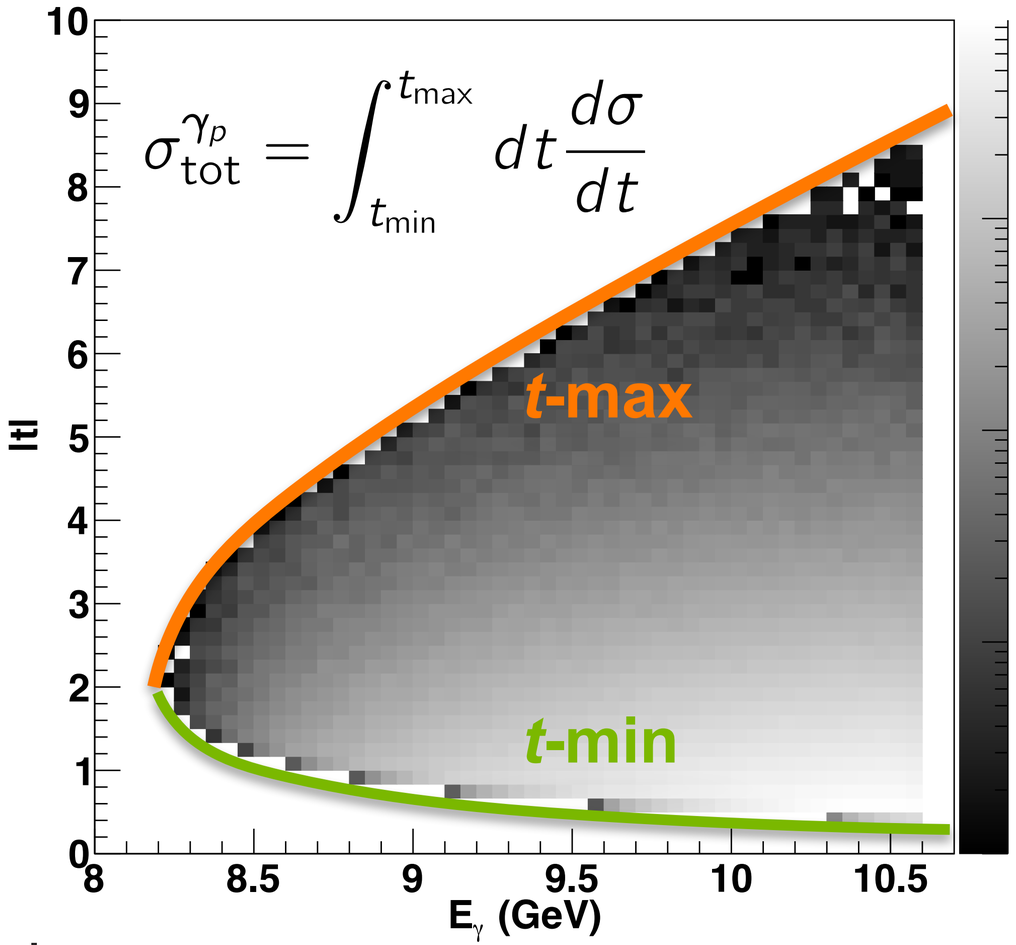
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

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

Y(1S) threshold:

$W \approx 10.4\text{GeV}$

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

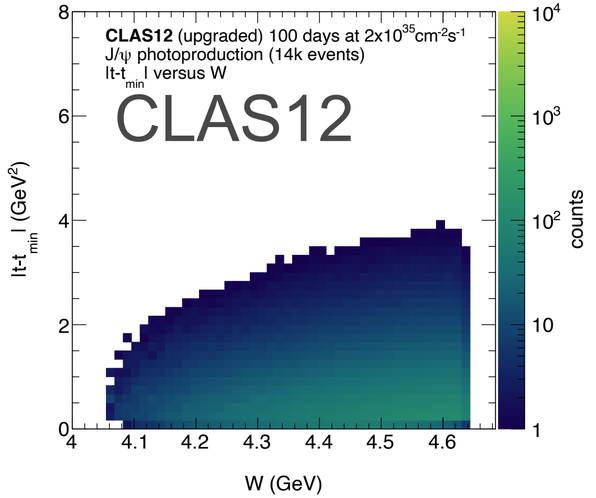


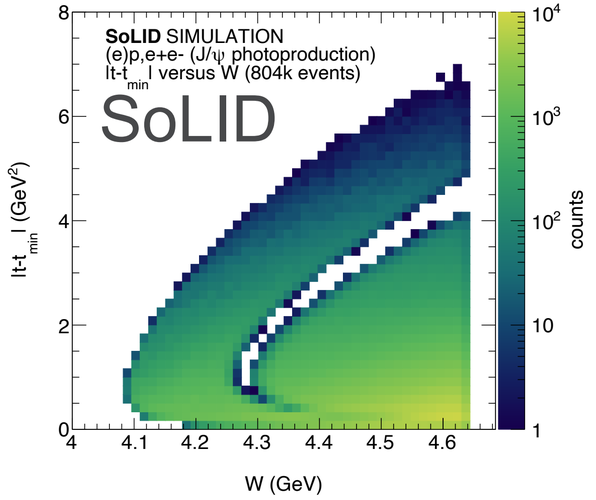
- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\text{min}}$
  - Backward (with proton): $t = t_{\text{max}}$
- Forward direction preferred: *t*-dependence ~exponential

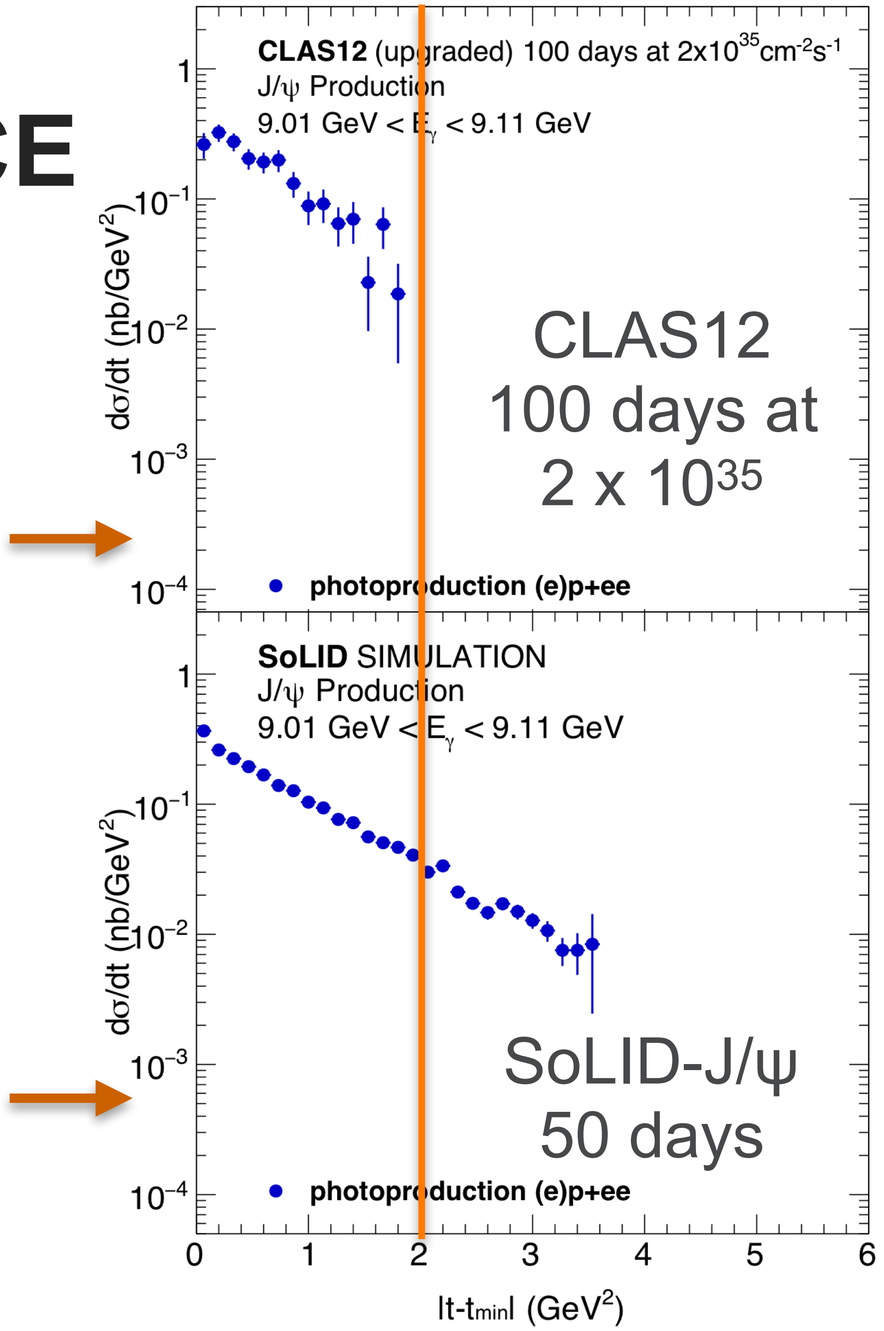
No substitute for SoLID-J/ψ

DIFFERENCE IN T-DEPENDENCE

- Reaching higher values of $|t - t_{\text{min}}| > 2\,\text{GeV}^2$ only way to experimentally constrain the the functional form of the *t*-dependence.
- This avoids systematic uncertainties on the theoretical interpretation of the results, allowing for a better understanding of the underlying physics of the process
- **This is a unique contribution only SoLID-J/ψ can make**



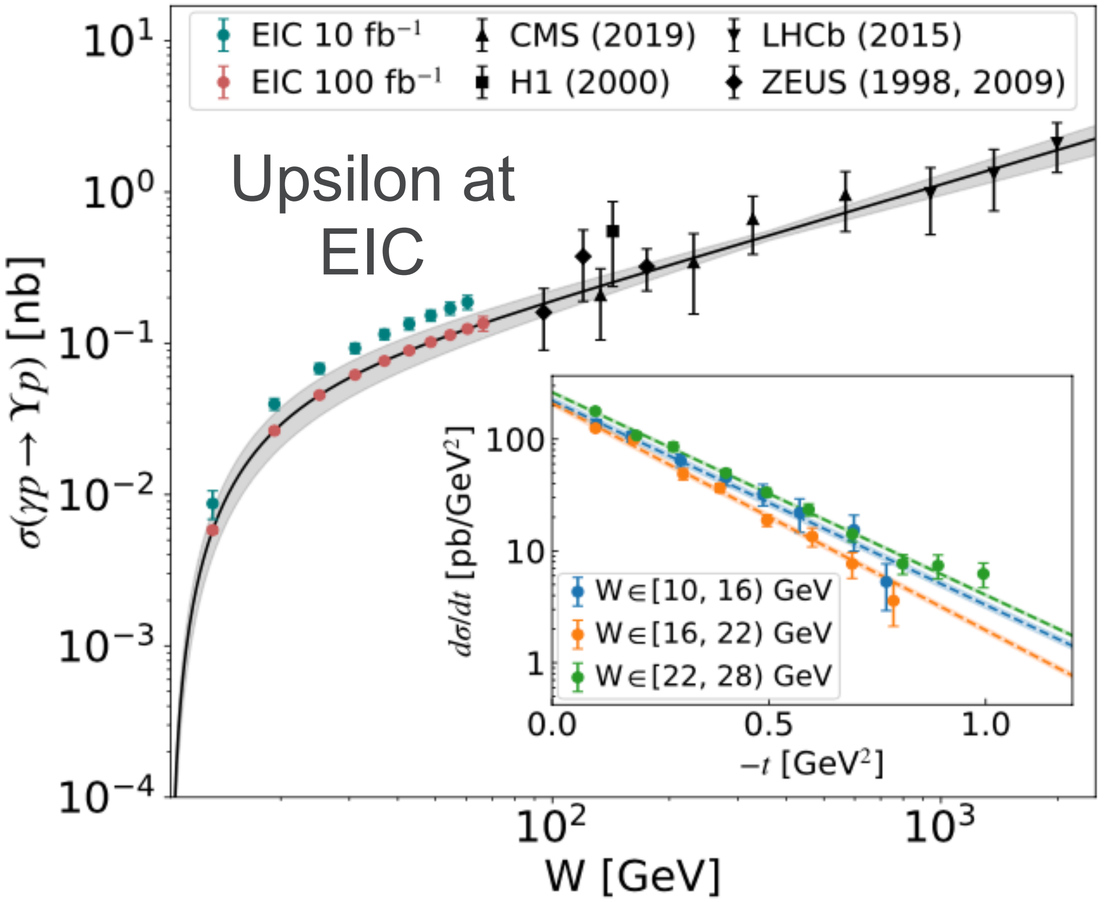




COMPLEMENTARITY WITH EIC (LONG)

J/ψ at SoLID and Y 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. Y(1S)) can be measured much more precisely.
- Y(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).



Schedule and milestones: *Please let us know your anticipated schedule and milestones toward the realization of the experiment.*

	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY30+
CDR		X								
PED			X	X						
Constr-uction				X	X	X	X	X		
Pre-ops								X	X	

CD: Critical Decision
PED: Project Engineering and Design
CDR: Conceptual Design Report

Presentation from Science Review; schedule to be shifted by one year.

Tentative run plan (address C4)

10/1/2028- 6/30/2029 Polarized He3 run (90+35 PAC Days)

7/1/2029-10/30/2029 de-install polarized He3, install LH2 target

11/1/2029-3/30/2030 J/Psi run (60 PAC day)

4/1/2030-8/30/2030 de-install LH2 target, install polarized NH3

9/1/2030-5/30/2031 Polarized proton run (120 PAC days)

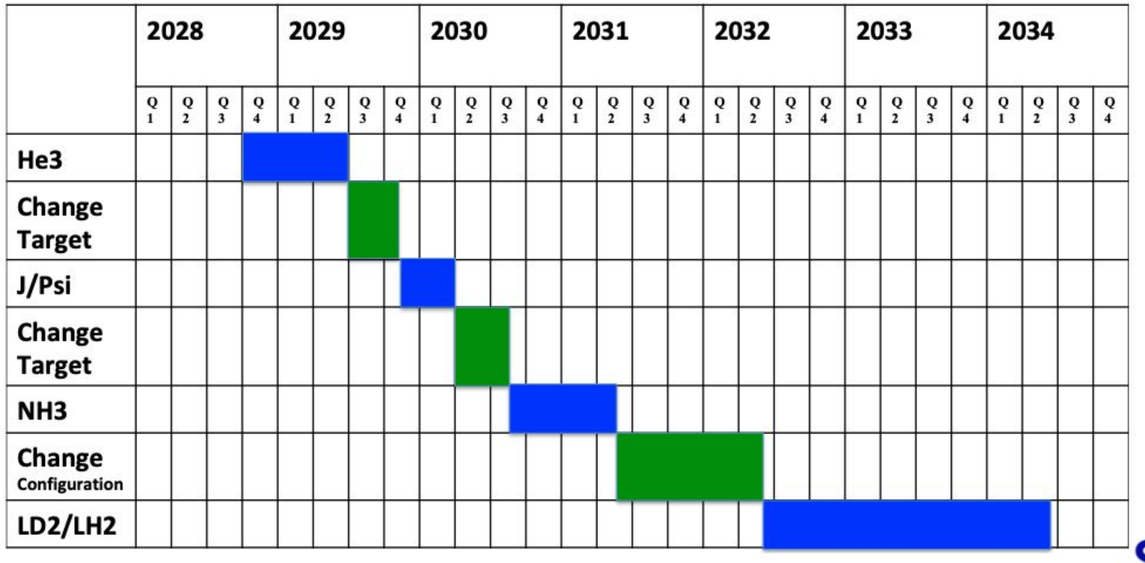
6/1/2031-5/30/2032 de-install polarized NH3, reconfigure SoLID for PVDIS, install LD2/LH2 targets

6/1/2032-5/30/2034 PVDIS run (169 PAC days)

- Start with standard dependencies (polarized ^3He, LH_2)
- Minimize switchover time (radiation level)

Assuming starting data taking from FY2029

Assuming ~ 50% efficiency



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Answers to the issues raised from previous PAC meetings*: Please let us know the answers to the issues raised from previous two PAC meetings, PAC39 and PAC43. The PAC39 report said "The PAC is concerned about the proposed modifications of the SoLID setup and strongly recommends trying to come up with a common solution appropriate for the whole SoLID program, if possible."* (*Continued on the next slide)*

Yes, we have a common solution as described in the pCDR:

Since the original proposal, we have optimized the SoLID-J/psi experiment to use the SoLID SIDIS setup without any detector changes. The only difference with the SIDIS setup is the LH2 target position, which is placed further downstream compared to the SIDIS 3He target to optimize the acceptance. This was discussed with the target group and found to not be a problem. Furthermore, we optimized the trigger design based around the two decay leptons only, allowing both electroproduction and photoproduction data to be collected simultaneously, while the trigger rate remains below the SoLID SIDIS setup limit of 100kHz.

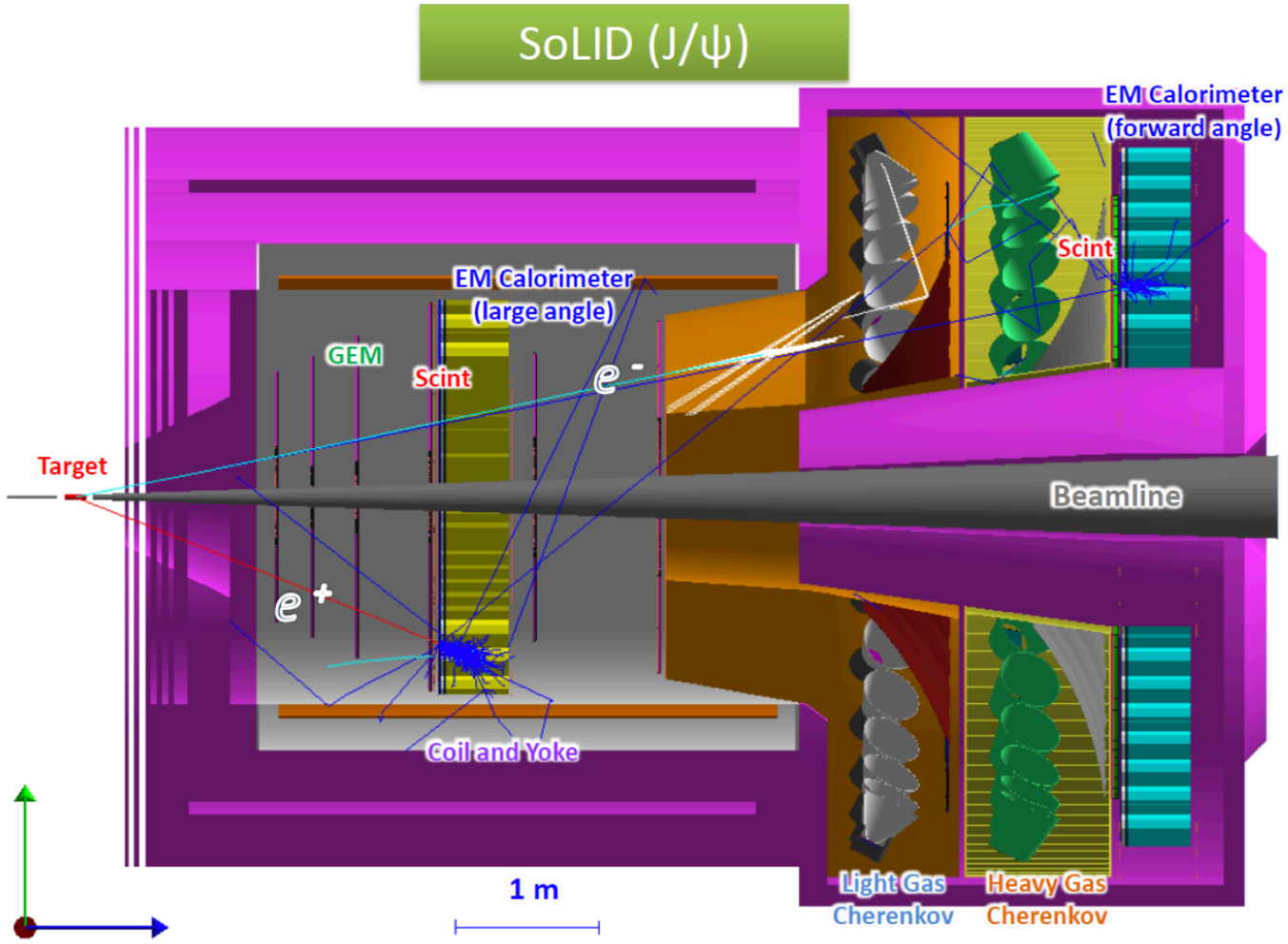
Answers to the issues raised from previous PAC meetings (continued)*: The PAC43 report said that the TAC raised issues on the trigger rate which would be solved by the Level-3 trigger. The PAC 43 report also pointed out that better background estimates would be needed. These issues might have already been solved with the pre-CDR, but I would like to have summarized answers for clear discussions at the PAC50.*

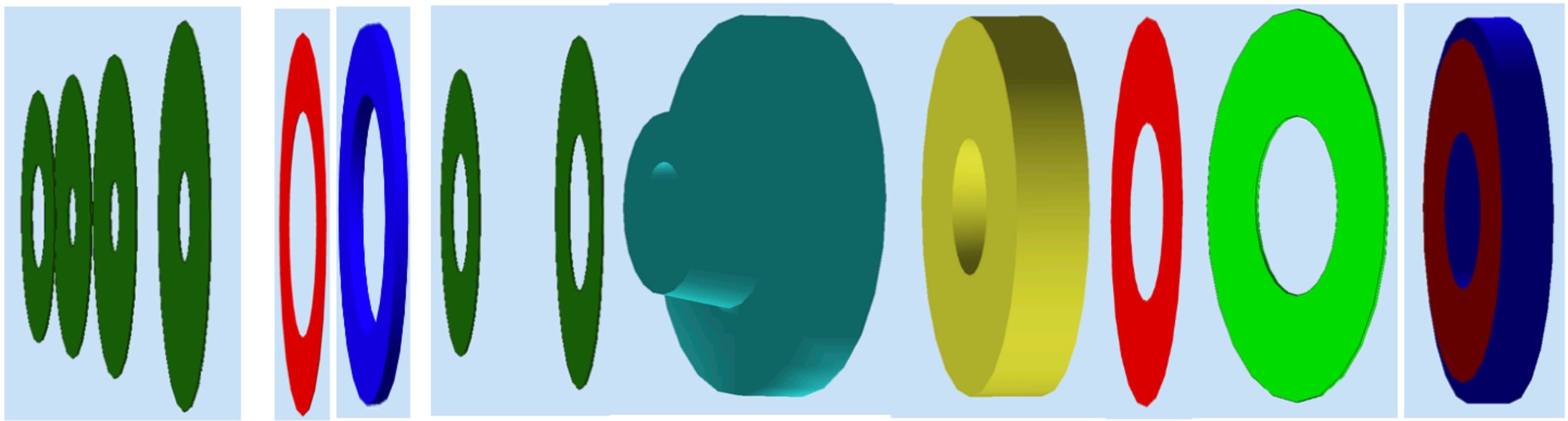
After careful consideration, we found that SoLID-J/psi does not need a L3 trigger, only a L1 trigger. This was verified by more realistic background simulations for the Director's Review and the Science Review, and then confirmed with pre-R&D activities. This is with the new VMM readout for the GEMs, as described in the latest pCDR. The total trigger rate for the J/psi experiment assuming the two-particle trigger required for TCS is below the trigger capabilities of the SIDIS setup. The rates are below 40 kHz, which is why no higher-level trigger is needed.

Regarding backgrounds for TCS, the recently published CLAS12 analysis has demonstrated that the pion background can be controlled below 1% for the majority of their data set. SoLID TCS has a similar kinematic coverage and similar Cherenkov and calorimetry for electron-pion separation, and thus we expect a similar level of background suppression.

Instrumentation update

- No need to change any SoLID existing detector hardware
- Target position optimized at z=-325cm
- Triggering on two decay leptons allows both electroproduction and photoproduction data collected at the same time and the trigger rate is below SoLID SIDIS limit at 100kHz





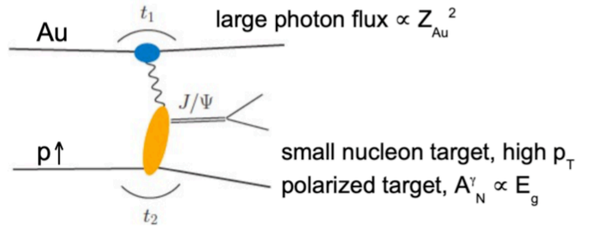
J/ψ : 4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC

	Time (Hour)	Time (Day)
LH_2 at 11 GeV	**1200**	**50**
Dedicated Al dummy run	**72**	**3**
Optics and detector check out	**72**	**3**
Special low luminosity	**96**	**4**
Total	**1440**	**60**

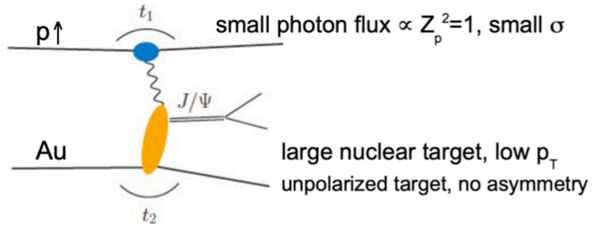
UPC Process → p↑+Au at STAR BNL

UPC processes in p↑+Au

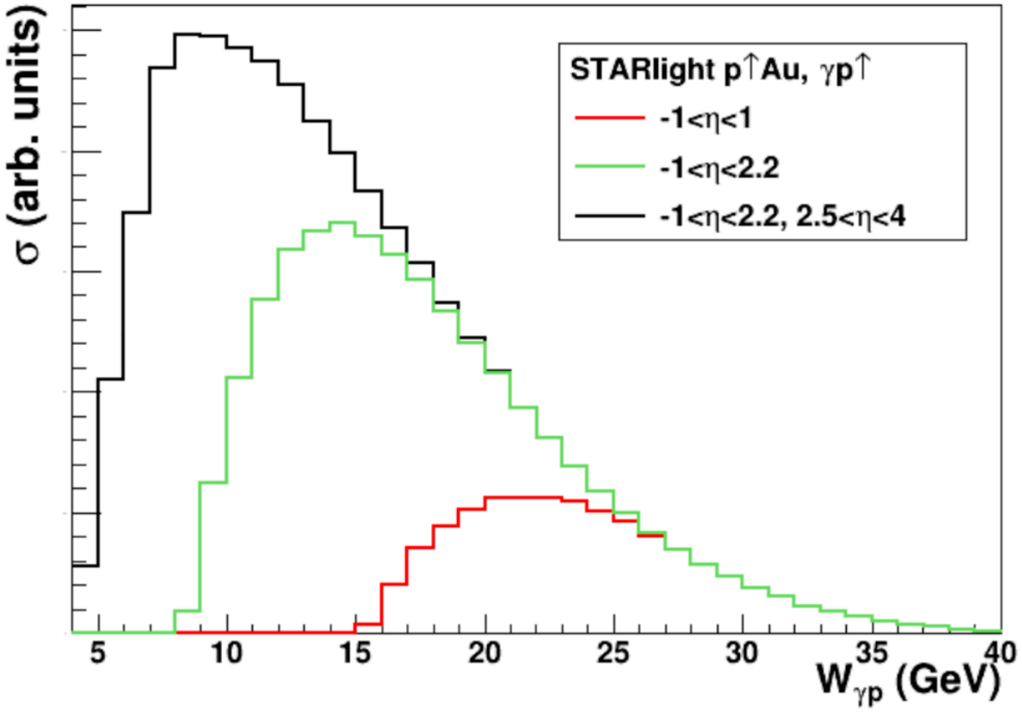
γp↑ J/ψ photoproduction:
- Au photon source, p↑ target



γAu J/ψ photoproduction:
- p↑ photon source, Au target



W. Schmidke (BNL), Private communication



- The STAR detector UPC J/ψ in polarized p↑+Au so far was limited to rapidity |y|<1. This limited the γ-p center of mass energy to ~15-35 GeV.
- STAR's Forward Upgrade is finishing installation and will be commissioned later this year.
- We anticipate only ~75 J/Psi events <5 GeV in the final RHIC runs in the next few years; it's not clear how much information that will provide on threshold features.

Systematic uncertainties on the measured cross sections

- Acceptance effect: 5% for triple coincidence
- Detector and trigger efficiency: <2%
- Target luminosity: < 2%
- Contribution from Al wall <1%
  - Dummy run (scheduled) + vertex cut
- Background contamination: ~0.5%
  - B-H background + Random coincidences (measured directly)

We intend to validate the cross section at the 5% level by measuring other vector mesons channels and relying on comparisons with smaller acceptance measurements in Hall C

- With the Hall C J/psi (HMS, SHMS) measurement
- ep elastic channel: (2.2 and 4.4 GeV beam)
  - SoLID optics calibration channel for electrons
- SIDIS charged pion and DIS
  - SIDIS program compared with Hall C

$$e + p \rightarrow e' + V(e^- + e^+) + p$$

	Bethe-Heitler	ω	ρ	ϕ	η
Cross Section	0.1 ub	1ub	1ub	50 nb	10 ub
Decay Channel and BR	e^+e^- 1.0	e^+e^- $7.30\ 10^{-5}$	e^+e^- $4.71\ 10^{-5}$	e^+e^- $2.97\ 10^{-4}$	γγ 0.39
Compared to J/ψ	>10	x2	x1	x1	Large
SoLID capability	good	good	good	good	good

Requirements for the J/ψ Measurements (C3)

$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-) \qquad W^2 = 2\nu \cdot M_p + M_p^2 - Q^2 = 2E_\gamma^{eff} \cdot M_p + M_p^2$$

- 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