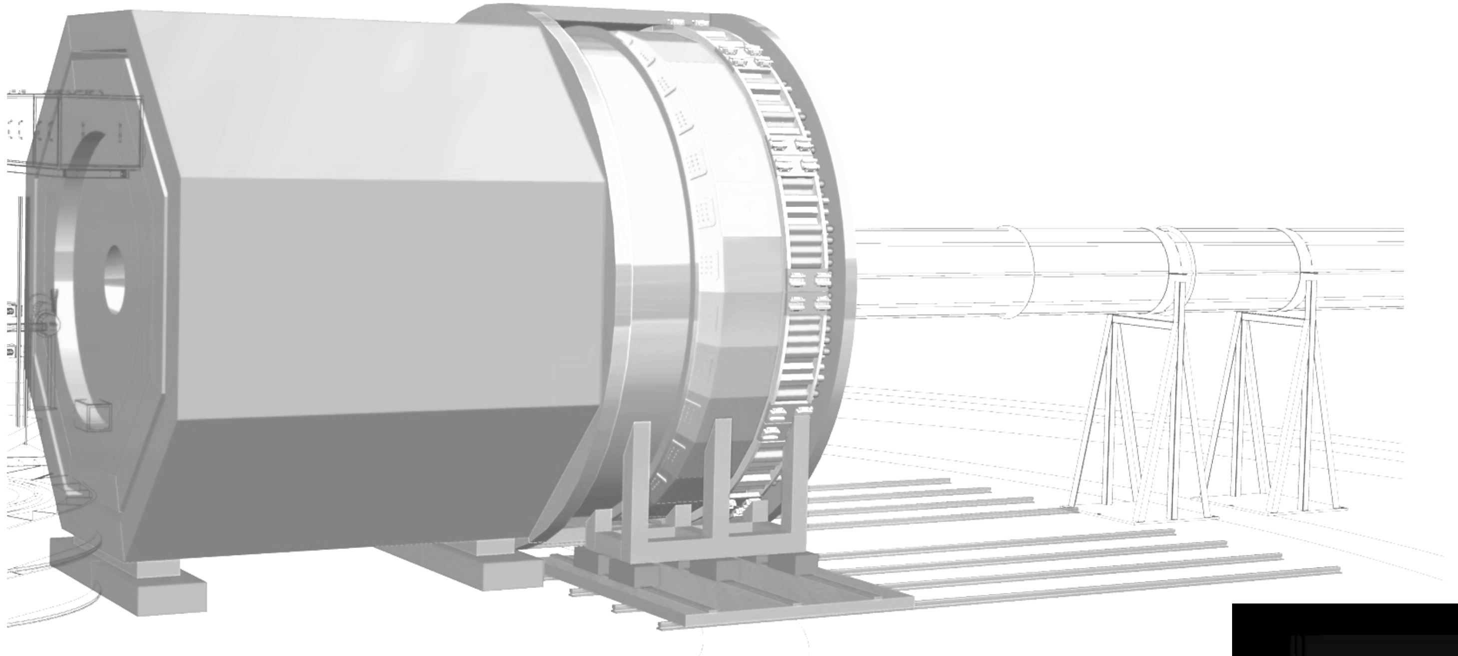
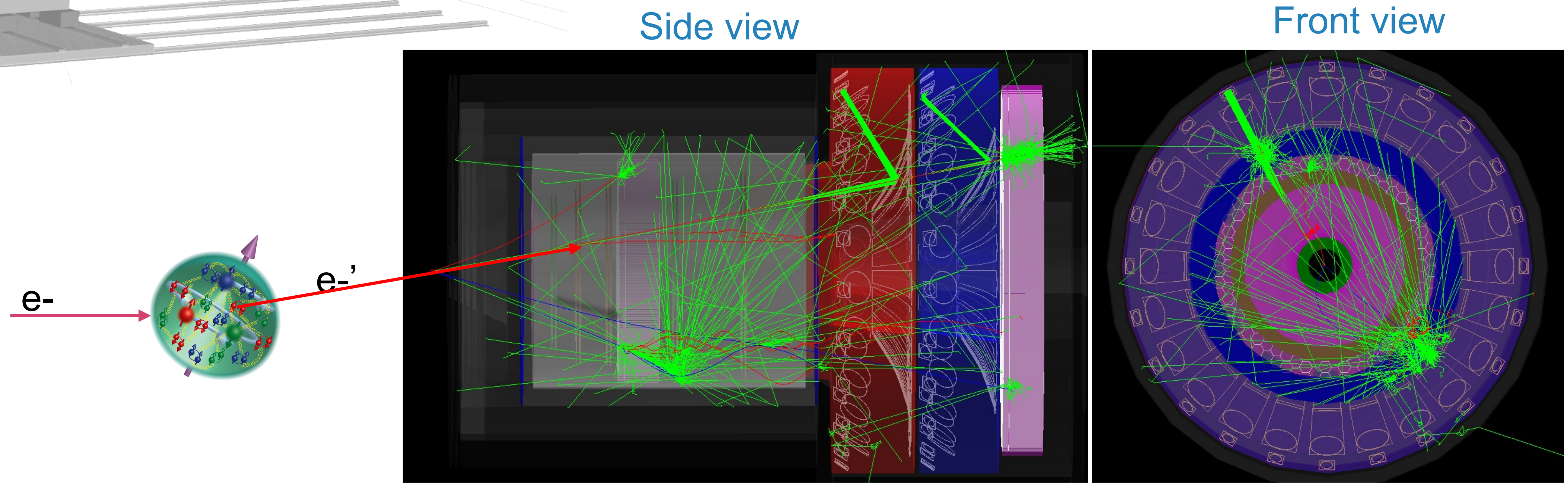
J/ψ Science Program with SoLID



SoLID Director's Review
February 9-10, 2021

Zein-Eddine Meziani
SoLID collaboration
Argonne NATIONAL LABORATORY

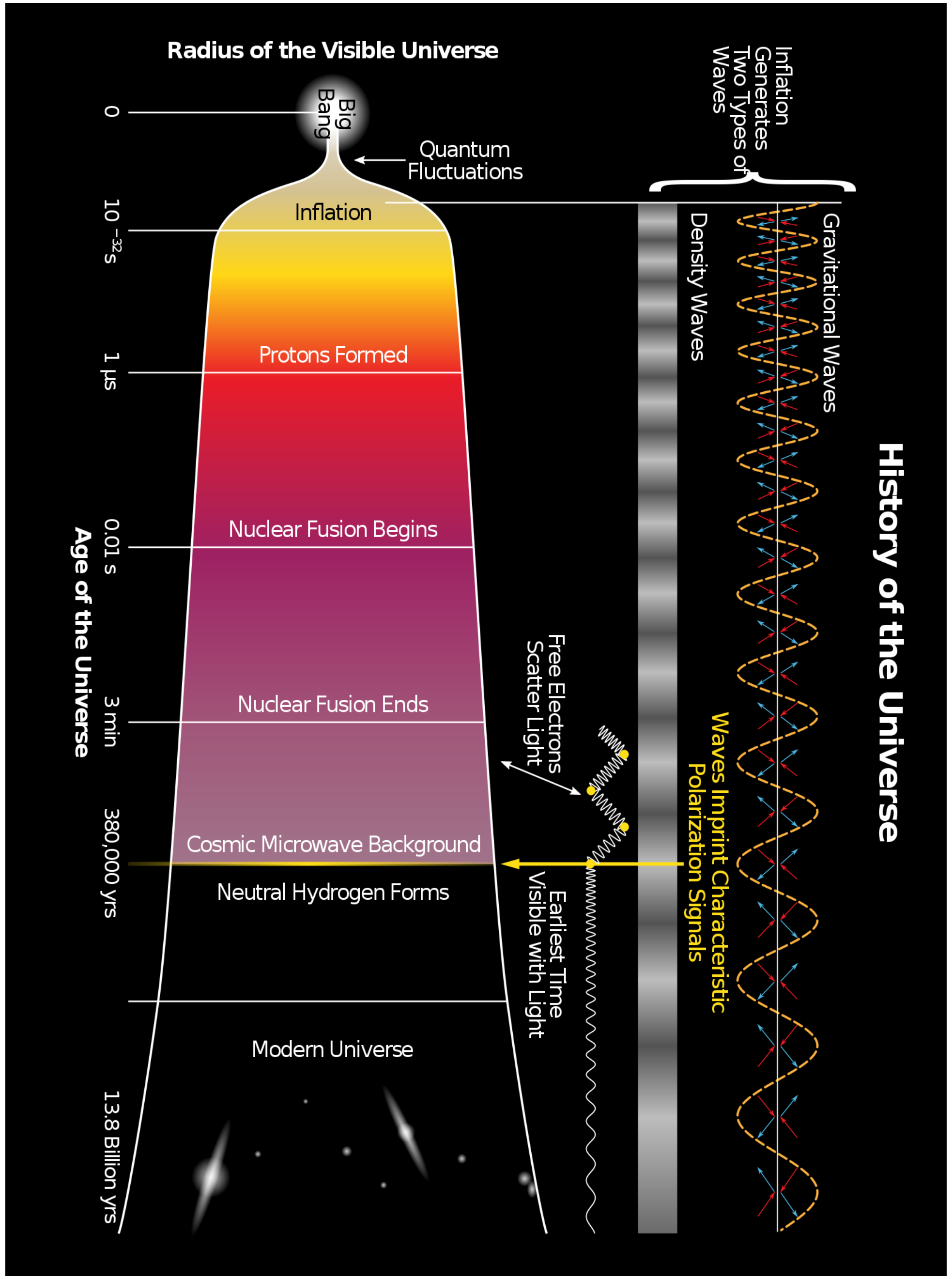


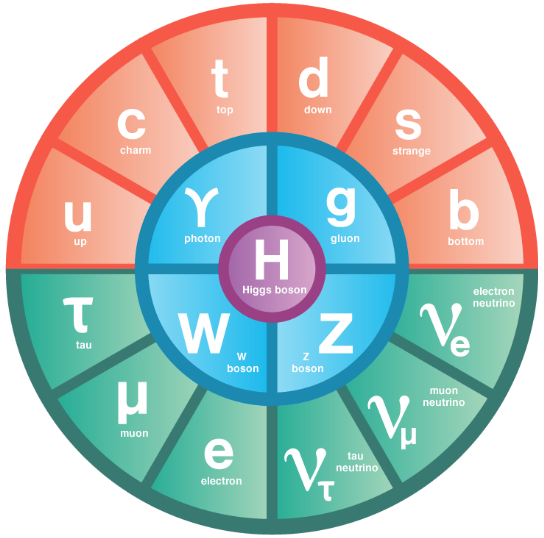
A charmonium event in SoLID

Outline

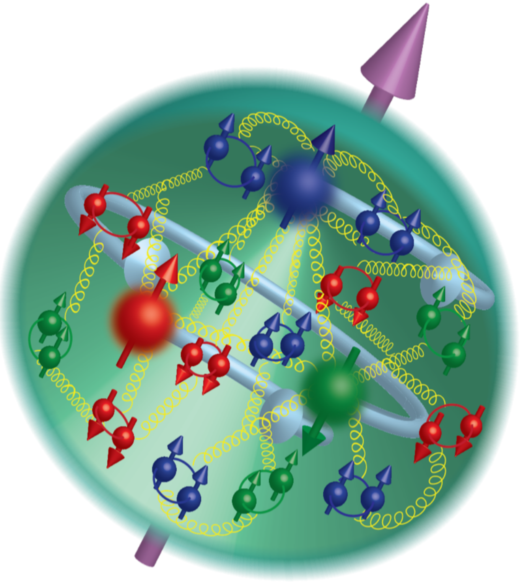
1. Motivation
2. Science questions enabled by the J/ψ production at threshold
3. Current status of J/ψ threshold production experiments at Jefferson Lab
4. The SoLID J/ψ electro- and photo- production experiment
5. Summary

Introduction: QCD in the Standard Model of Particle Physics and Mass





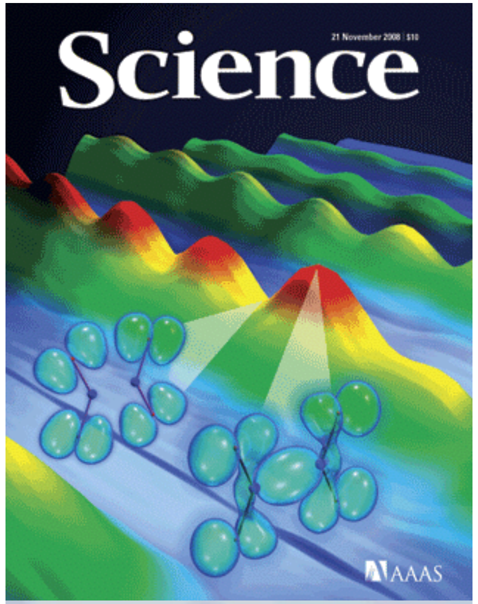
Standard Model of Particle Physics



Nucleon

- The Higgs mechanism is responsible for the mass of elementary particles but not of nucleons and nuclei thus the visible universe.
- Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass to nucleons and nuclei through the "trace anomaly" a consequence of broken scale invariance and accessible in threshold J/ψ production.
- Gravitational form factors (GFFs) with info, on energy/mass distribution in the nucleon and nuclei can be accessed through the second Mellin moments of leading-twist GPDs.

Hadron Masses from Lattice QCD

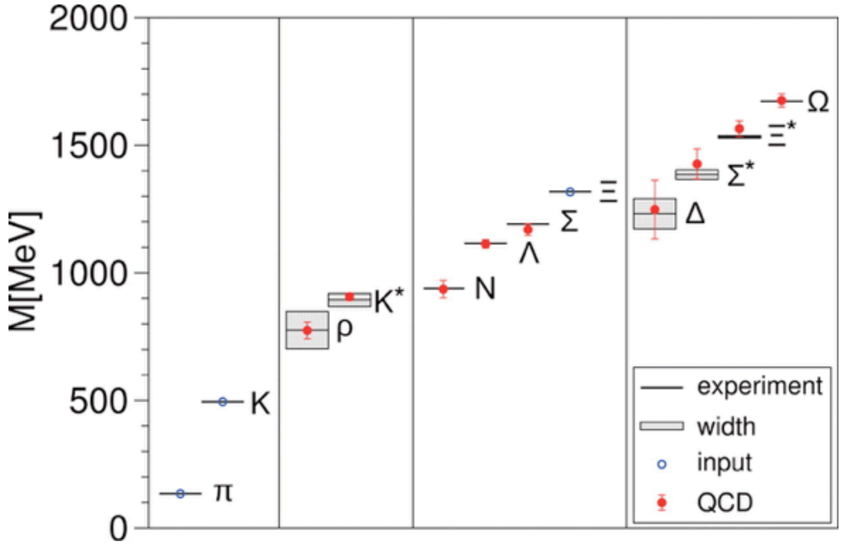


(2008)

Ab Initio Determination of Light Hadron Masses
S. Dürr, Z. Fodor, C. Hoelbling,
R. Hoffmann, S.D. Katz, S. Krieg, T. Kuth, L. Lellouch, T. Lippert, K.K. Szabo and G. Vulvert

Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233

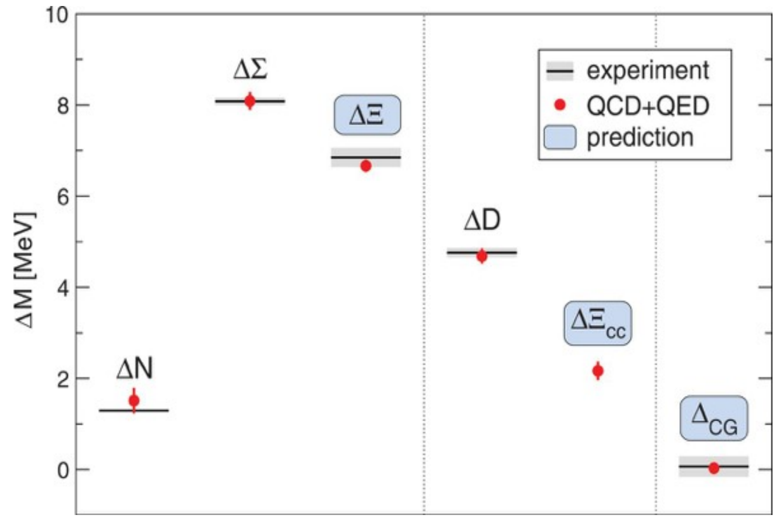
589 citations



(2015)

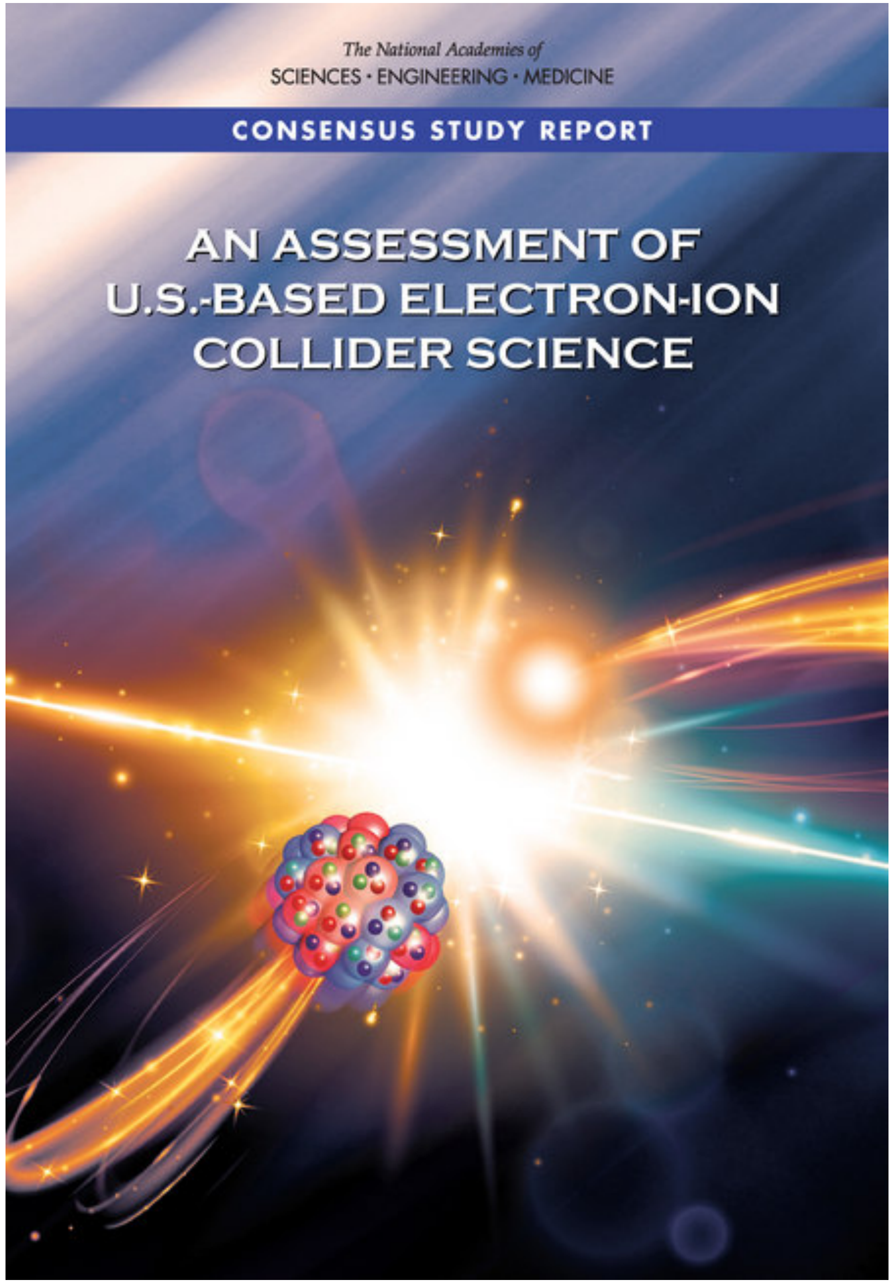
Ab initio calculation of the neutron-proton mass difference
Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S.D. Katz,S. Krieg,
L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo, and B.C. Toth

Science **347** (6229), 1452-1455
DOI: 10.1126/science.1257050



How does QCD generate this? The role of quarks and of gluons?

EIC Science Assessment by NAS



Finding 1:

An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

SoLID will address in an important but complementary way to the EIC the first two questions

Science Questions Enabled by J/ψ at Threshold with SoLID

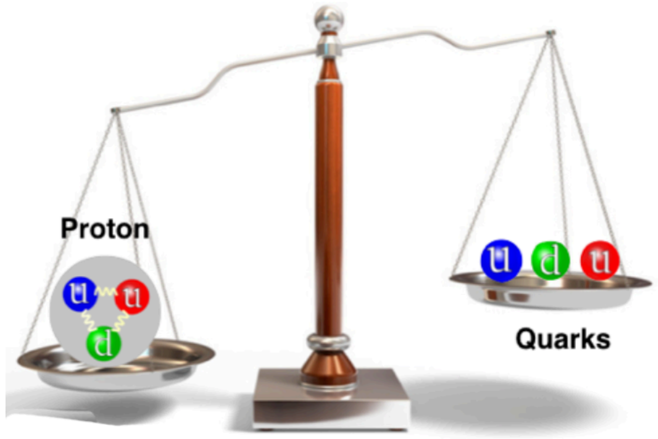
- What is the origin of hadron masses?
  - A case study: the proton.

"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass

Frank Wilczek (1999, Physics Today)

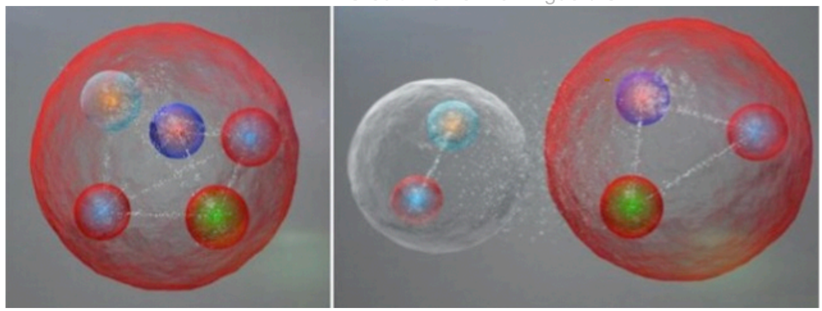
The 2015 Long Range Plan for Nuclear Science

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"



- What is the size of the interaction between a quarkonium and a proton, dubbed Color Van der Waals force?

Credit: Daniel Dominguez/ CERN



Charm pentaquark? Molecule?

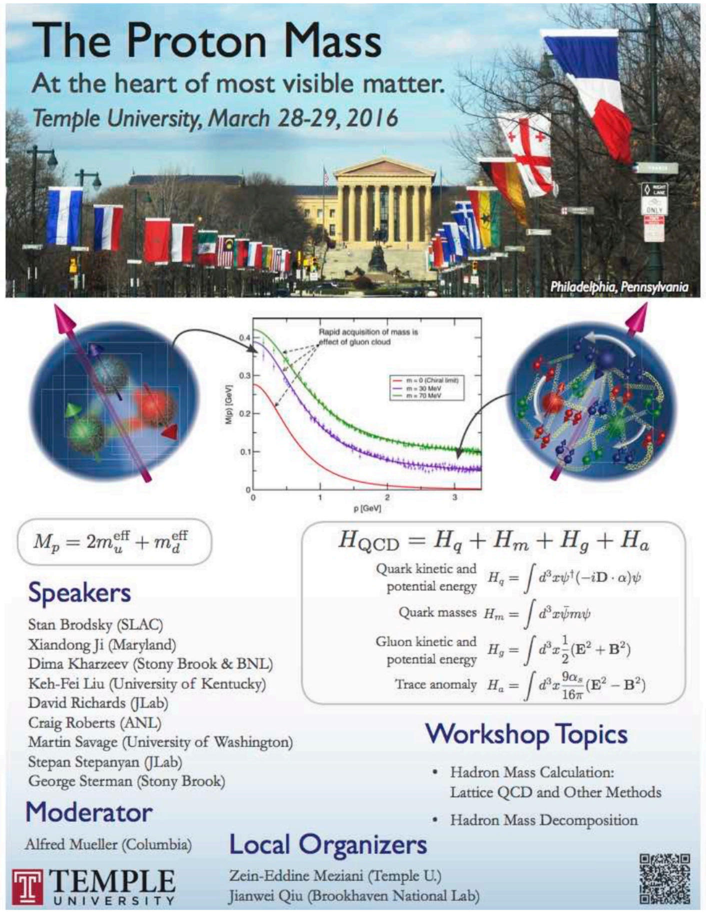
- Do heavy quarkonia enable pentaquarks to exist?

- Are bound states of quarkonia in nuclei possible?

Threshold electro-photoproduction of quarkonium can probe the energy distribution of gluonic fields inside the proton and nuclei

The proton mass… a hot topic since 2012!

2016



2017

Jan. 2021

Credit: Z.-E Meziani

https://indico.phy.anl.gov/event/2/

Due to COVID-19 a 2020 INT proton mass workshop has been postponed to Dec. 2021to become the 4th workshop in the series

- lattice QCD
- mass decomposition – roles of the constituents
- approximated analytical or model approaches

Access the trace anomaly through elastic J/psi and Upsilon production near threshold

Ji's Nucleon Mass Decomposition: A Hamiltonian Approach

Quarks, anti-Quarks , Gluons and Trace Anomaly in the nucleon rest frame

X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

$$H_{QCD} = \int d^3x T^{00}(0, \vec{x})$$

$$M_N = \frac{\langle P|H_{QCD}|P\rangle}{\langle P|P\rangle}$$

$$H_q = \int d^3x\, \psi^\dagger\, (-iD\cdot\alpha)\,\psi$$

Quarks & anti-quarks kinetic and potential energy

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) M_N$$

$$H_m = \int d^3x\, \psi^\dagger m \psi$$

Quarks masses

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b M_N$$

$$H_g = \int d^3x\, \frac{1}{2}\left(E^2 + B^2\right)$$

Gluons kinetic and potential energy

$$M_g = \frac{3}{4}(1-a)\, M_N$$

$$H_a = \int d^3x\, \frac{9\alpha_s}{16\pi}\left(E^2 - B^2\right)$$

Trace anomaly

$$M_a = \frac{1}{4}(1-b)\, M_N$$

$$\boxed{M_N = M_q + M_m + M_g + M_a}$$

- $a(\mu)$ related to PDFs, well constrained
- **$b(\mu)$ related to quarkonium-proton scattering amplitude $T_{\psi p}$ near-threshold**

Impact of SoLID on the trace anomaly determination

- To determine *b* we need the *t* distribution of SoLID at a given energy.

$$\left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0} = \frac{\alpha_{em} m_{J/\psi}}{3\Gamma(J/\psi \to e^+e^-)}\left(\frac{k_{\gamma N}}{k_{J/\psi N}}\right)^2 \left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=0}$$

Photoproduction cross section at t=0 linked to the forward elastic scattering amplitude of J/psi-N through VMD

$$\left|F_{J/\Psi N}\right| = \left[64\pi[m^2_{J/\psi}(\lambda^2 - m^2_N)]\left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0}\right]^{1/2}$$

$$\lambda = (p_N p_{J/\psi}/m_{J/\psi})$$

Nucleon energy in the charmonium rest frame

$$\left|F_{J/\Psi N}\right| \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b) = r_0^3 d_2 \frac{16\pi^2}{27} M_N M_a$$

$$r_0 = \left(\frac{4}{3\alpha_s(\mu^2)}\right)\frac{1}{m_c(\mu^2)}$$

Bohr radius of charmonium

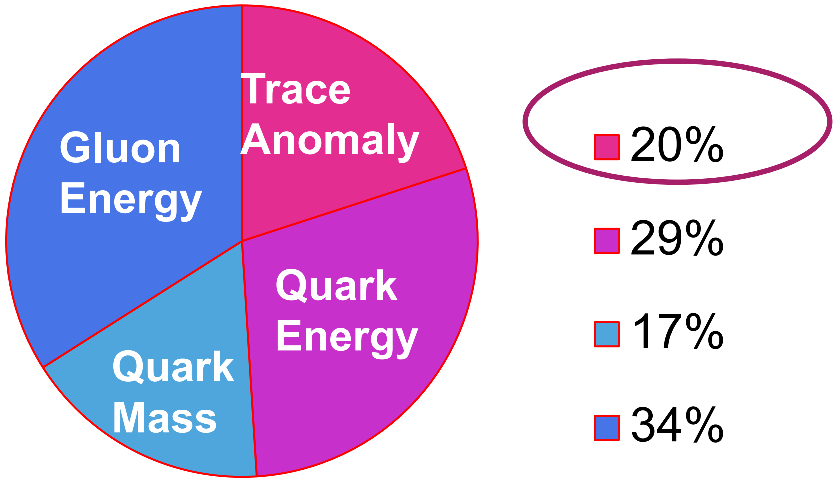
$$d_2^{(1S)} = \left(\frac{32}{N_c}\right)^2 \sqrt{\pi}\frac{\Gamma(n+5/2)}{\Gamma(n+5)}$$

Wilson coefficient

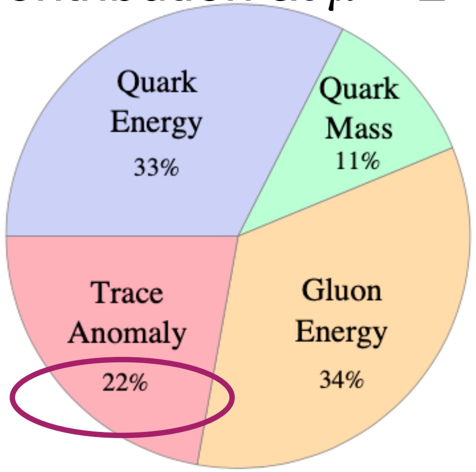
Rydberg energy squared = μ^2

Trace Anomaly Inferences from Data

- In Ji's original work μ =1 GeV
  X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

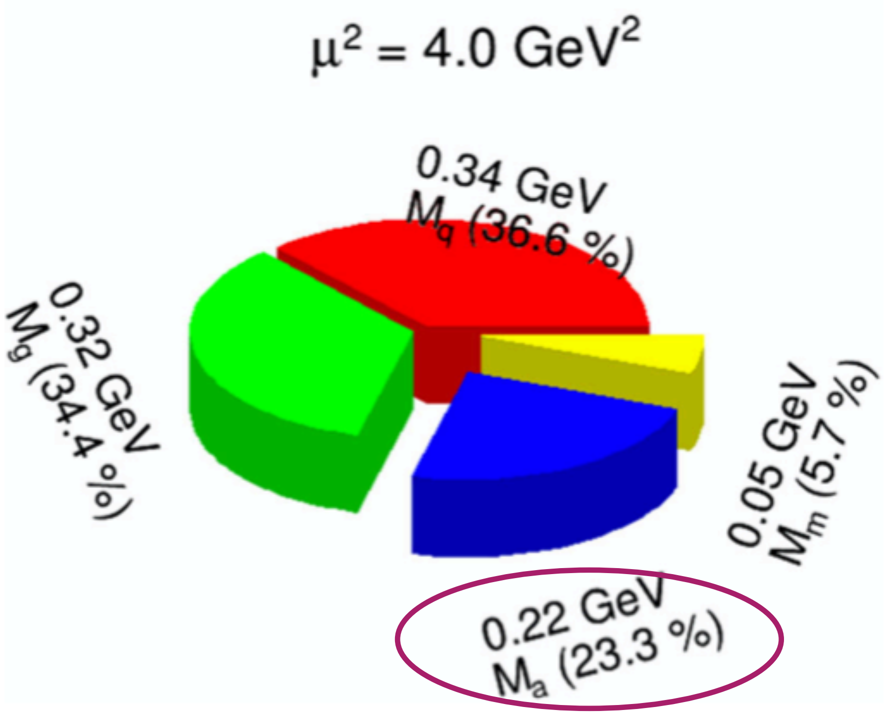


- An updated data analysis due to an update on the pion-nucleon sigma term and the strange quark contribution at μ = 2 GeV



H. Gao, T. Liu, C. Peng, Z. Ye and Z. Zhao, The Universe Vol. 3, No. 2, 18 (2015)

- A recent update using threshold J/psi data from GlueX at Jefferson Lab
  R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

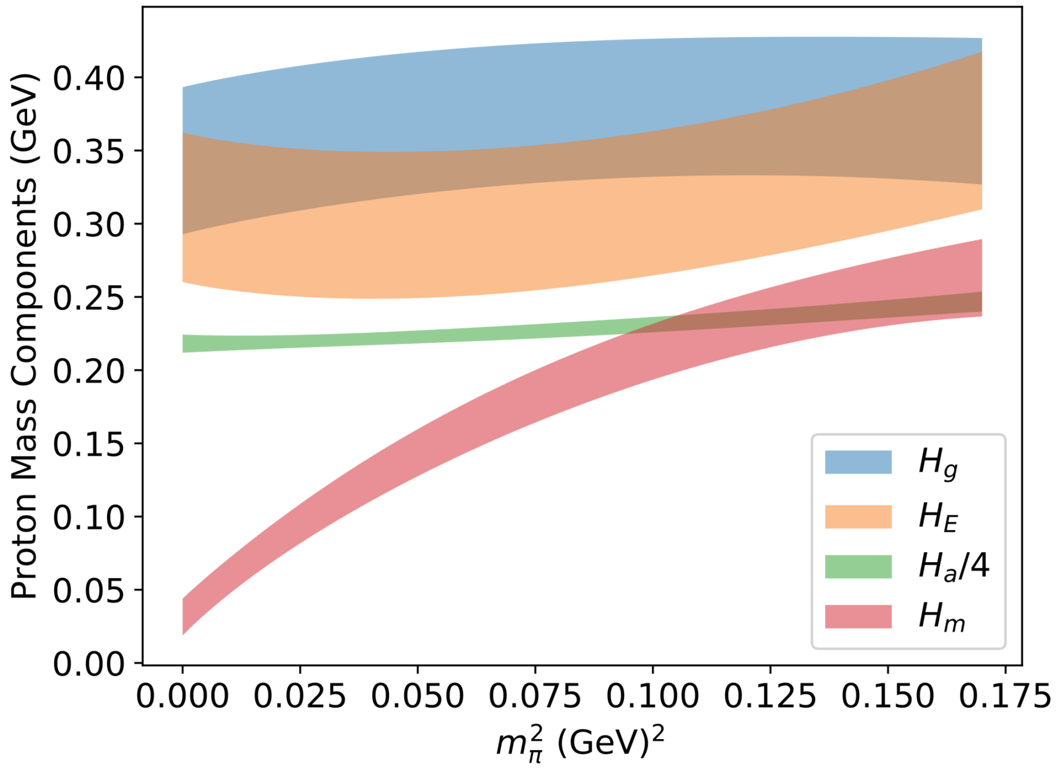


Wang et al. : $M_a = 23.3\% \pm 4.25\%$

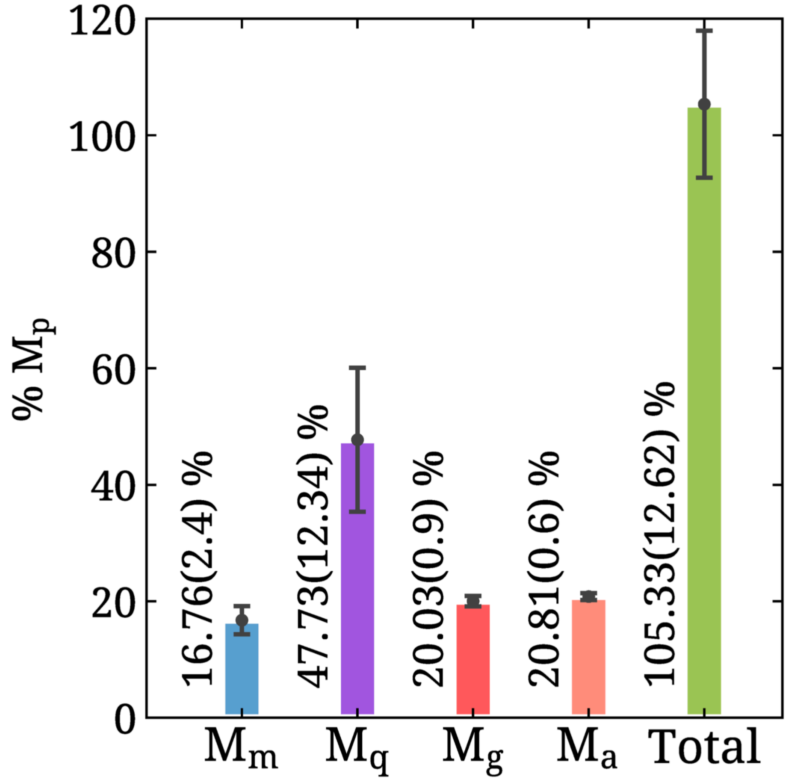
SoLID J/psi: $M_a = 23.3\% \pm 0.08\%$

Proton mass on the lattice

Direct calculations of the trace anomaly were still missing



Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

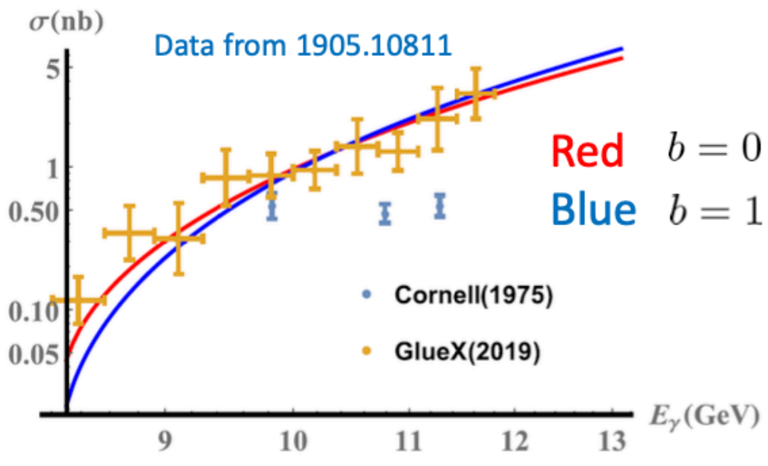


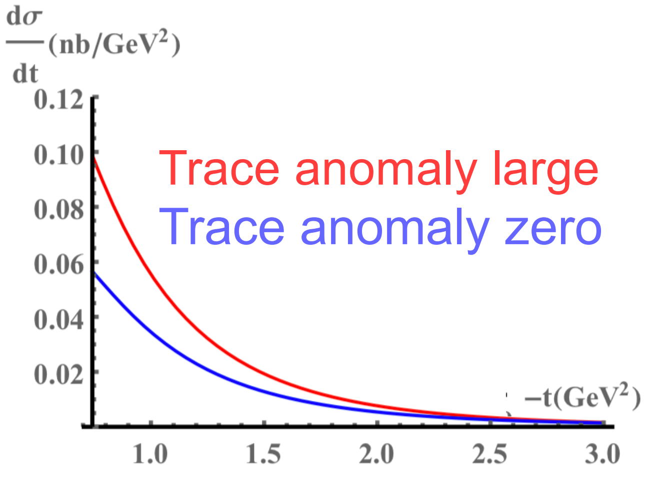
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

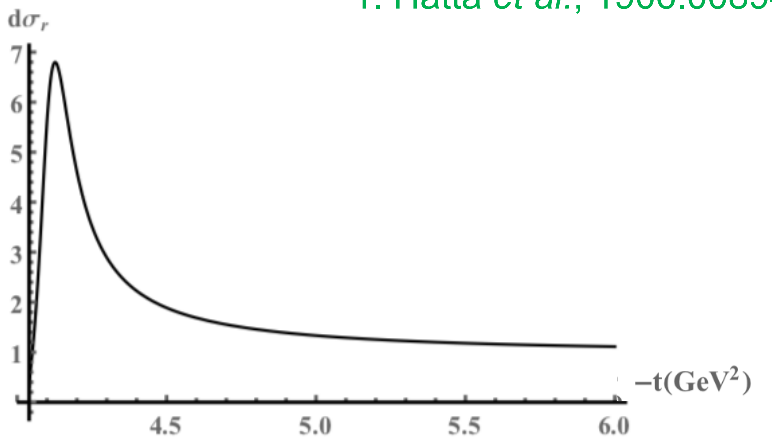
There is change with a recent eprint posted on Jan 13, 2021:
He, Fangcheng and Sun, Peng and Yang, Yi-Bo, [χQCD Collaboration] "A Demonstration of Hadron Mass Origin from QCD Trace Anomaly", eprint = "2101.04942[hep-lat],

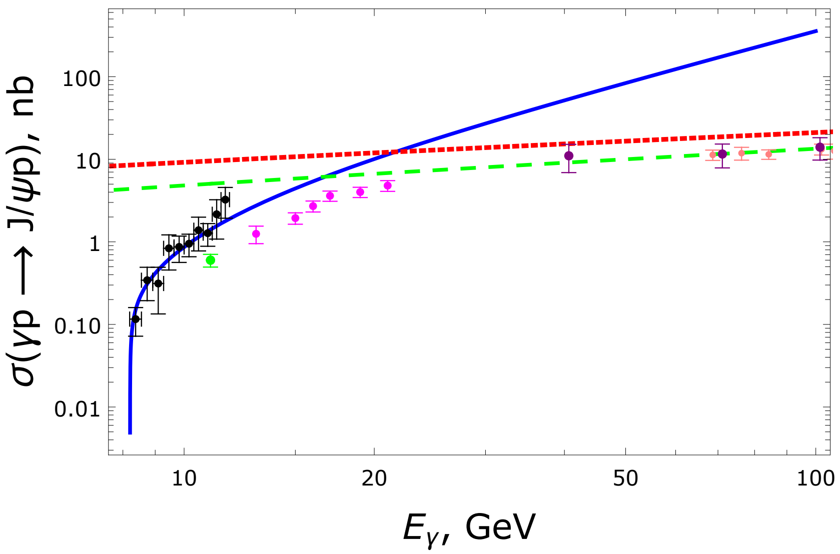
Holographic approaches; AdS/CFT

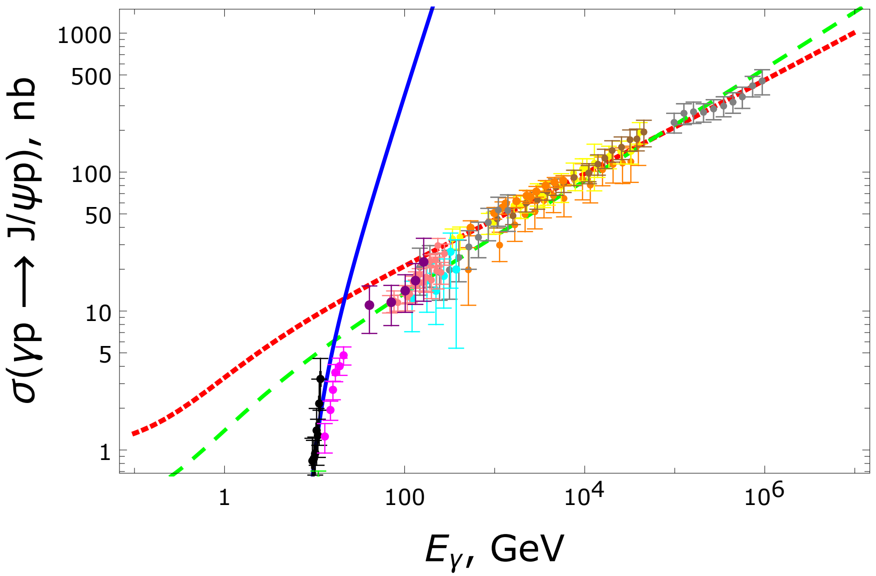
Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2019)



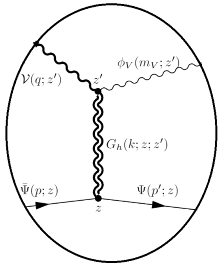






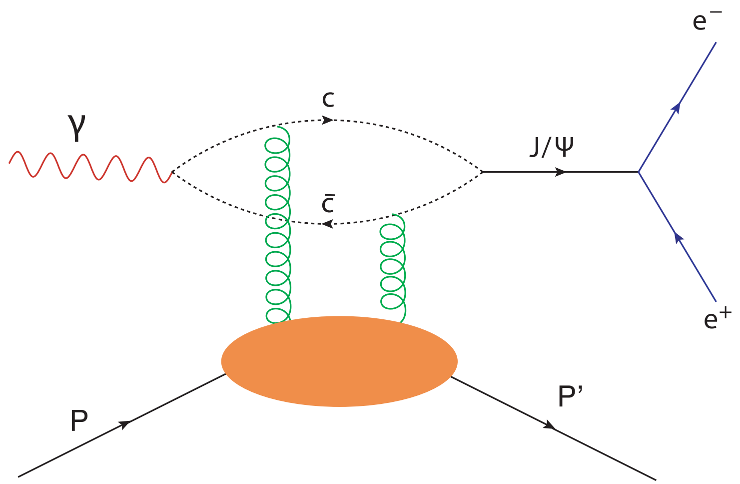


K. Mamo & I. Zahed, Phys. Rev. D 101, 086003 (2020)

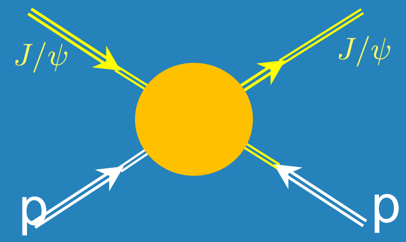


Extracting the scattering length of the J/Psi-Nucleon interaction

Oleksii Gryniuk, M. Vanderhaeghen, PRD 94, 074001 (2016)



- Spin averaged $J/\psi - p$ scattering amplitude related to scattering length $a_{\psi p}$



$$\nu \equiv pq = \frac{s-u}{4}$$

$$T_{\psi p}(\nu = \nu_{el}) = 8\pi(M + M_\psi)a_{\psi p}$$

- Binding is related to the scattering length for a nucleus by

$$B_{\psi p} \simeq \frac{8\pi(M + M_\psi)a_{\psi p}}{4MM_\psi}\rho_{nm}$$

- Unitarity lead to:

$$\mathrm{Im}T_{\psi p}(\nu) = 2\sqrt{s}q_{\psi p}\sigma^{tot}_{\psi p}(\nu)$$

- Causality and crossing lead to the dispersion relation:

$$\mathrm{Re}T_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{el}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\mathrm{Im}T_{\psi p(\nu')}}{\nu'^2 - \nu^2}$$

Cross section is parametrized

$$\sigma^{tot}_{\psi p} = \sigma^{el}_{\psi p} + \sigma^{inel}_{\psi p}$$

$$\sigma^{el}_{\psi p} \propto C_{el}\left(1 - \frac{\nu_{el}}{\nu}\right)^{b_{el}}\left(\frac{\nu_{el}}{\nu}\right)^{a_{el}}$$

$$\sigma^{inel}_{\psi p} \propto C_{in}\left(1 - \frac{\nu_{in}}{\nu}\right)^{b_{in}}\left(\frac{\nu_{in}}{\nu}\right)^{a_{in}}$$

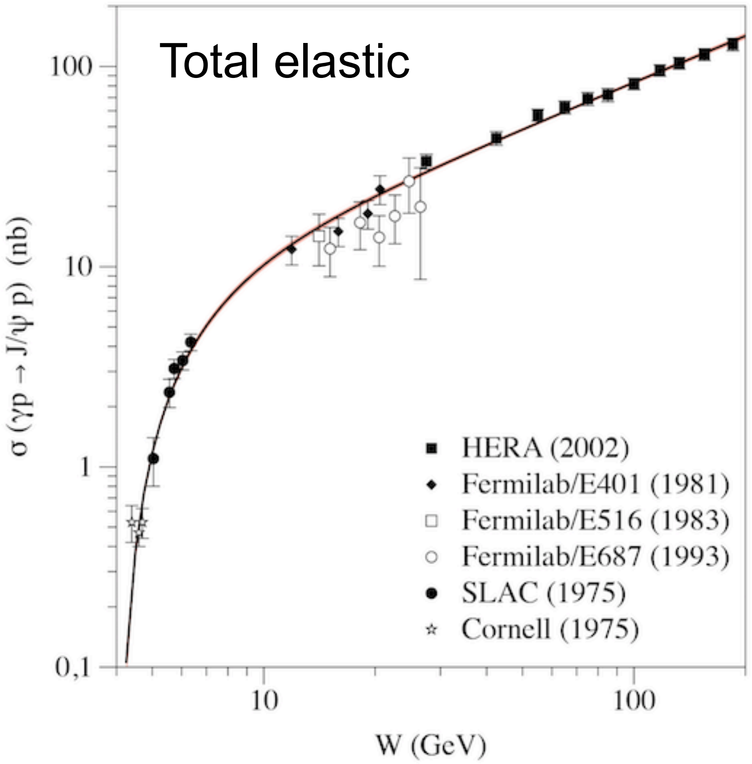
Forward J/ψ -p scattering in relation to γ -p scattering

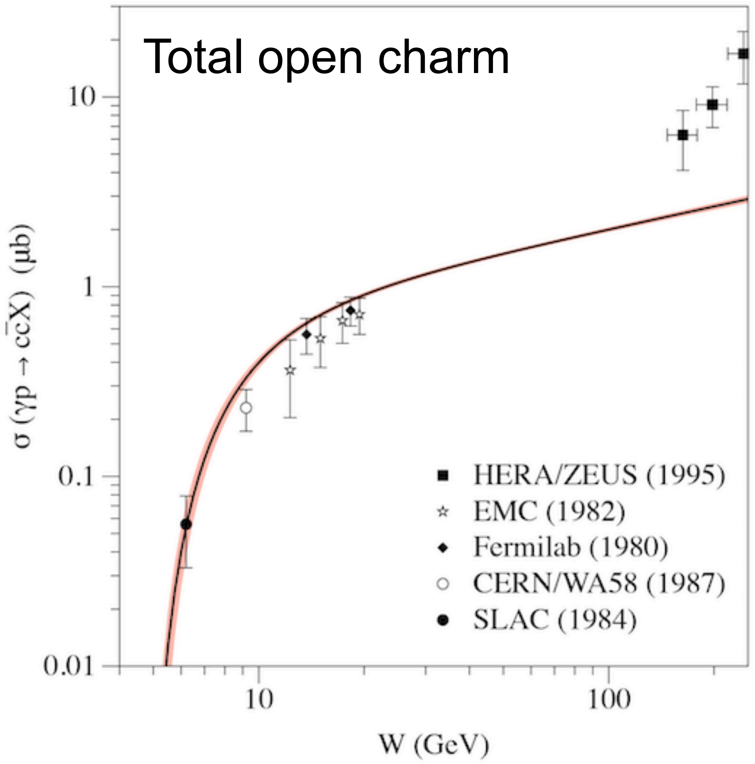
Vector Dominance Model (VDM) Assumption

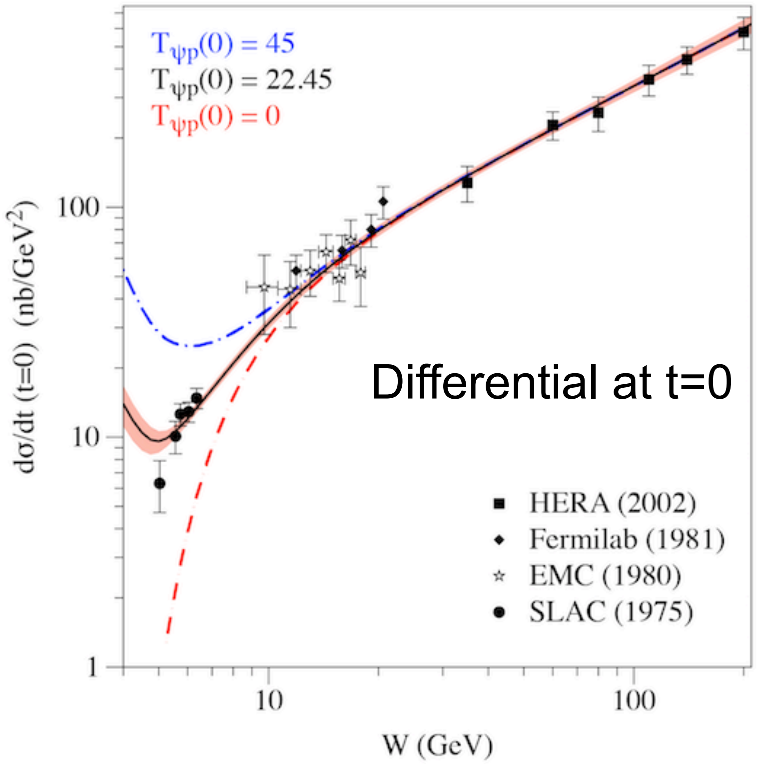
$$\sigma^{el}_{\psi p} = \left(\frac{M_\psi}{f_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to \psi p)$$

$$\sigma^{inel}_{\psi p} = \left(\frac{M_\psi}{e f_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to c\bar{c}X)$$

$$\frac{d\sigma}{dt}\Big|_{t=0}(\gamma p \to \psi p) = \left(\frac{e f_\psi}{M_\psi}\right)^2 \left(\frac{q \psi p}{q_{\gamma p}}\right)^2 \frac{d\sigma}{dt}\Big|_{t=0}(\psi p \to \psi p)$$



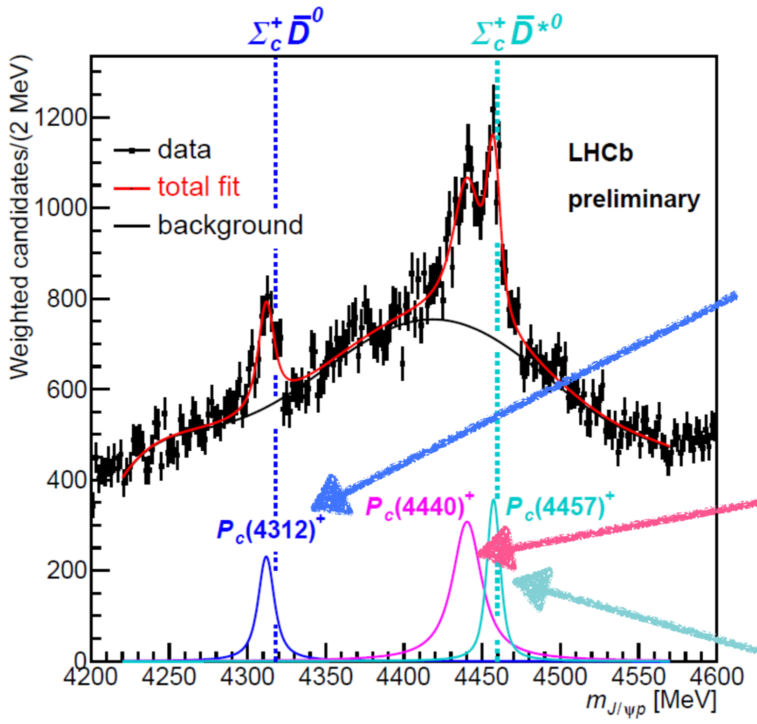




Simultaneous fitting $T(0) = 22.5 \pm 2.5$ ⇨ $a_{\psi p} \sim 0.05\text{fm}$ ⇨ $B_\psi \sim 3\text{MeV}$

Charm pentaquark search

- It was suggested in many early papers, that if the LHCb pentaquark is a true resonance it should be observed in a direct s-channel photoproduction of J/psi on the nucleon.
- As a consequence the differential cross section at intermediate *t* might be very different from the typical exponential drop of the t-channel production.
- At Jefferson Lab experiments have been performed in 3 different Halls in search of the LHCb pentaquark. Precision & accuracy in the *t* distributions is important for high sensitivity to the Charm pentaquark if it is produced.



R. Aaij et al. (LHCb) (2019) PRL 22, 222001

2

- 9x more data than 2015 paper
- Previous results are consistent
- New state discovered: $Pc^+(4312)$

M: 4311.9±0.7+6.8/-0.6 MeV

Γ: 9.8±2.7+3.7/-4.5 MeV

- $Pc^+(4450)$ is resolved into 2 narrow peaks

★ $Pc^+(4440)$

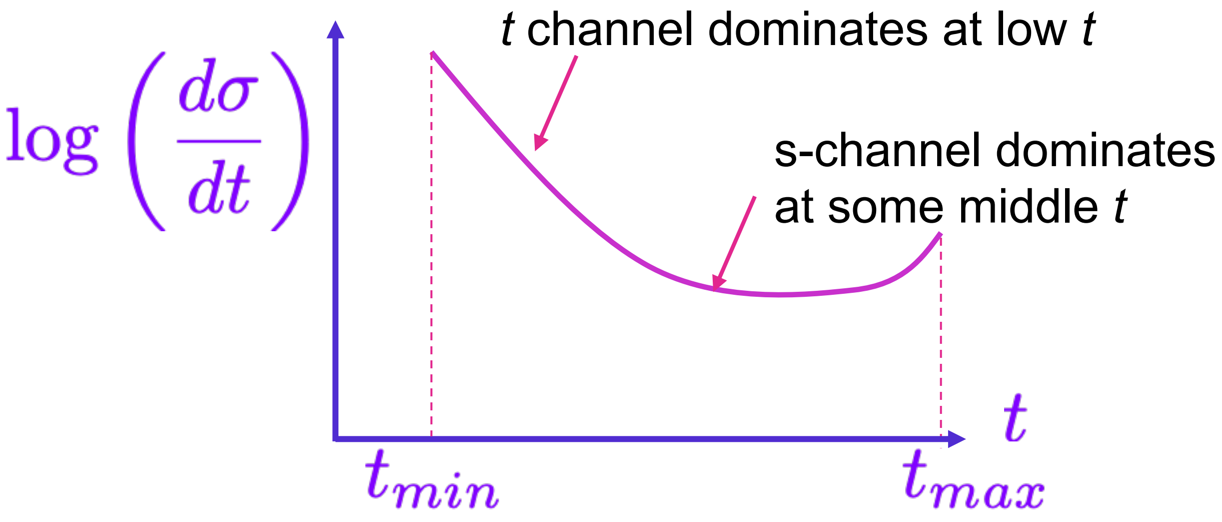
M: 4440.3±1.3+4.1/-4.7 MeV

Γ = 20.6±4.9+8.7/-10.1 MeV

★ $Pc^+(4457)$

M: 4457.3±0.6+4.1/-1.7 MeV

Γ = 6.4±2.0+5.7/-1.9 MeV



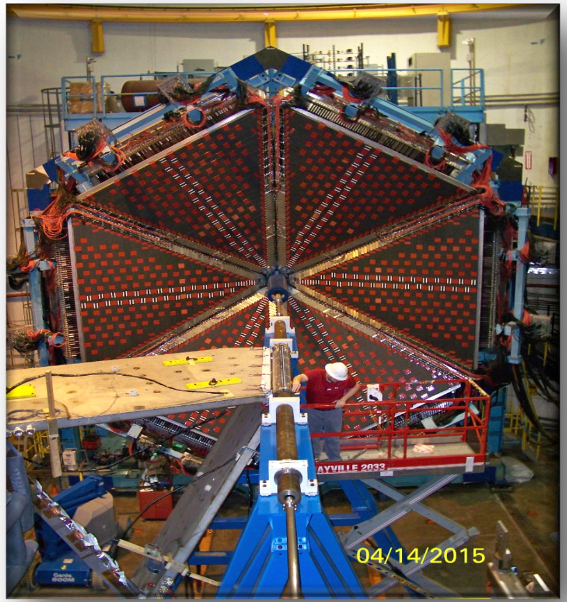
Active field of research

- Y. Hatta, A. Rajan and K. Tanaka, ``Quark and gluon contributions to the QCD trace anomaly,'' JHEP 1812, 008 (2018)
- Y. Hatta and D. L. Yang, ``Holographic J/psi production near threshold and the proton mass problem,'' Phys. Rev. D 98, no. 7, 074003 (2018)
- C. Lorcé, H. Moutarde and A. P. Trawiński, ``Revisiting the mechanical properties of the nucleon,'' Eur. Phys. J. C 79, no.1, 89 (2019), doi:10.1140/epjc/s10052-019-6572-3
- W. Cosyn, S. Cotogno, A. Freese and C. Lorcé, ``The energy-momentum tensor of spin-1 hadrons: formalism,'' Eur. Phys. J. C 79, no. 6, 476 (2019) doi:10.1140/epjc/s10052-019-6981-3
- T. F. Caramés, C. E. Fontoura, G. Krein, J. Vijande and A. Valcarce, ``Charmed baryons in nuclear matter,'' Phys. Rev. D 98, no. 11, 114019 (2018)
- K. Mamo & I. Zahed, Phys. Rev. D 101, 086003 (2020)

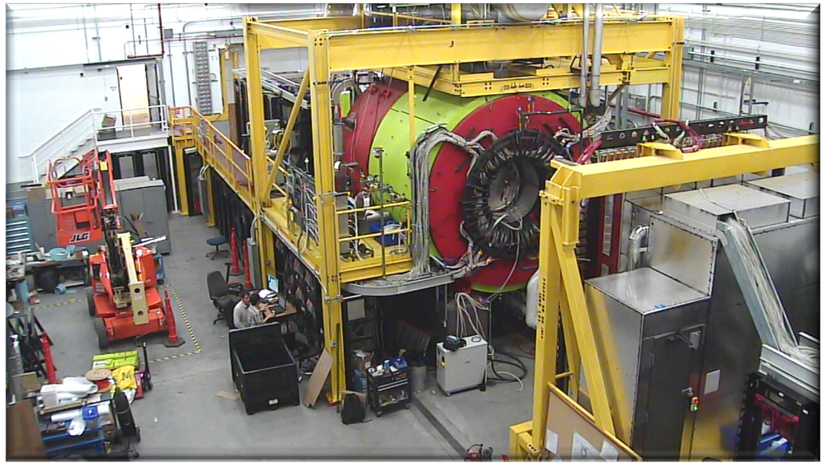
Active field of research

- Wang, R., Chen, X. and Evslin, J. The origin of proton mass from J/Ψ photo-production data. *Eur. Phys. J. C* **80,** *no.* 507 (2020), doi:10.1140/epjc/s10052-020-8057-9
- F. Zeng, X.Y. Wang, L. Zhang, Y.P. Xie, R. Wang and X. Chen, ``Near-threshold photoproduction of J/psi in two-gluon exchange model,'' *Eur. Phys. J. C* **80***, no.11, 1027 (2020)* doi:10.1140/epjc/s10052-020-08584-6, arXiv:2008.13439 [hep-ph]
- A. Metz, B. Pasquini and S. Rodini, ``Revisiting the proton mass decomposition,'' Phys. Rev. D **102** (2021) no.11,114042 doi:10.1103/PhysRevD.102.114042 arXiv:2006.11171 [hep-ph]
- L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meissner, ``Deciphering the mechanism of near-threshold J/psi photoproduction,'' *Eur. Phys. J. C* **80***, no.11, 1053 (2020)* doi:10.1140/epjc/s10052-020-08620-5, arXiv:2009.08345 [hep-ph]
- R. Boussarie and Y. Hatta, ``QCD analysis of near-threshold quarkonium leptoproduction at large photon virtualities,'' Phys. Rev. D **101** (2020) no.11, 114004 doi:10.1103/PhysRevD.101.114004, arXiv:2004.12715 [hep-ph].
- X. Ji, Y. Liu and I. Zahed, ``Mass structure of hadrons and light-front sum rules in t' Hooft model,'' arXiv:2010.06665 [hep-ph]
- X. Ji and Y. Liu, ``Quantum Anomalous Energy Effects on the Nucleon Mass,'' arXiv:2101.04483 [hep-ph]
- D. E. Kharzeev, ``The mass radius of the proton,'' arXiv:2102.00110 [hep-ph]

12 GeV J/Ψ experiments at JLab Overview

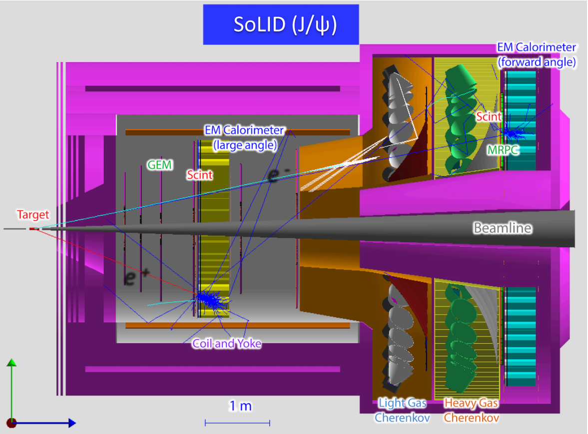


Hall D – GlueX has observed the first J/ψs at JLab A. Ali et al., [GlueX Collaboration], 'arXiv:1905.10811 [nucl-ex].PRL



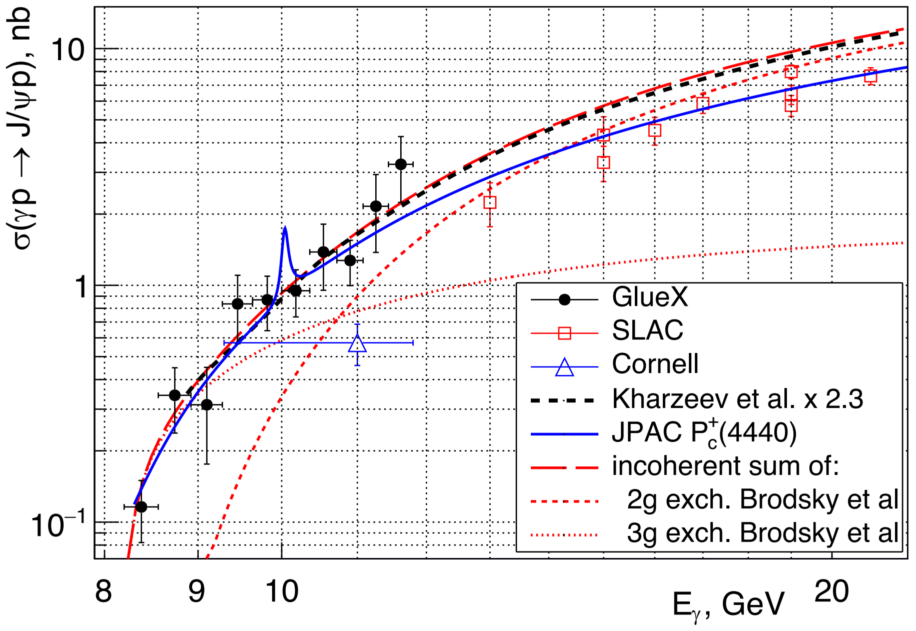
Hall B – Has approved proposals to measure TCS +Jpsi in phot-production E12-12-001 and E12-12-001A and for deuterium in E12-11-003B

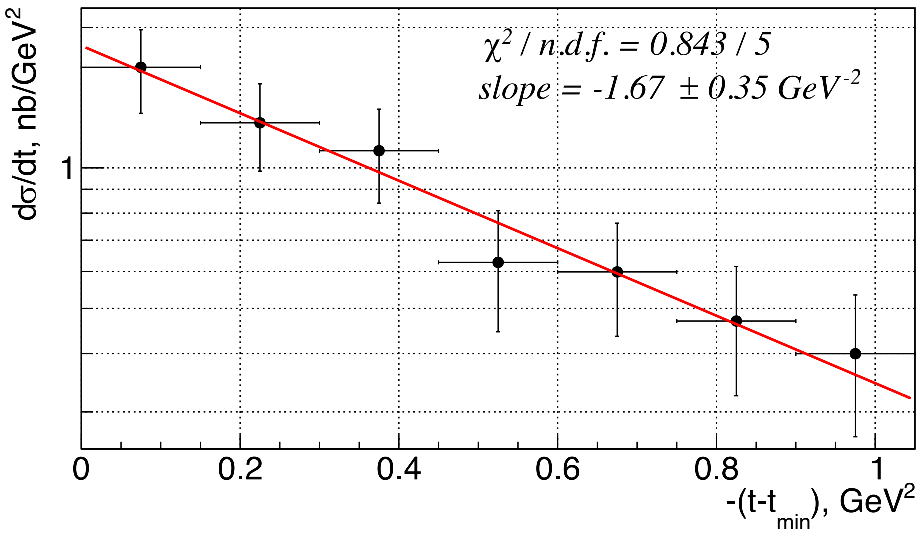
Hall C –took data to search for the LHCb pentaquark E12-16-007 –experiment completed and analysis underway



Hall A-has an approved experiment requiring a large acceptance, high luminosity detector, namely -SoLID - E12-12-006 and 1 LOI on double polarization measurement using SBS

J/ψ photoproduction cross-section near threshold-GlueX results





A. Ali *et al.*, Phys. Rev. Lett. 123, 072001(2019)

SLAC results calculated from $d\sigma/dt(t=t_{min})$ using t-slope of 2.9 ± 0.3 GeV^{-2} (measured at 19 GeV)

Cornell data:

- t-slope 1.25 ± 0.2 GeV^{-2}
- horizontal errors represent acceptance

SoLID is critical to provide

- A precise *t* distribution is required for each bin in photon energy for any pentaquark search or trace anomaly determination.
- The electroproduction Q^2 is important very close to threshold to test the production mechanism.

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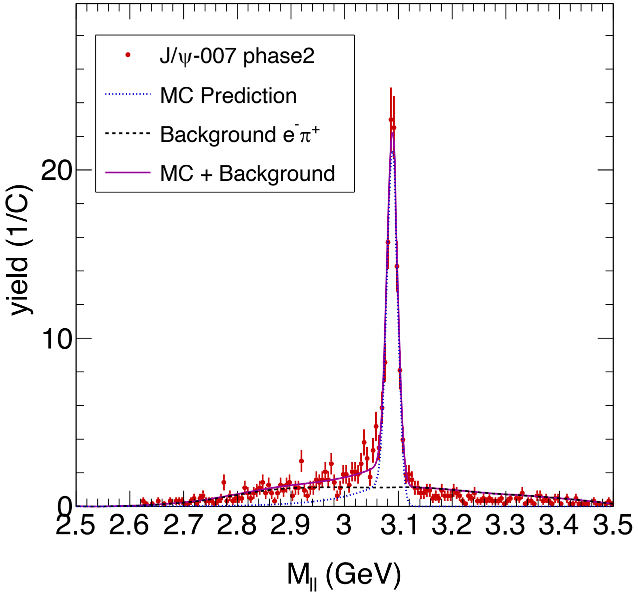
In search of the LHCb Pentaquark at JLab

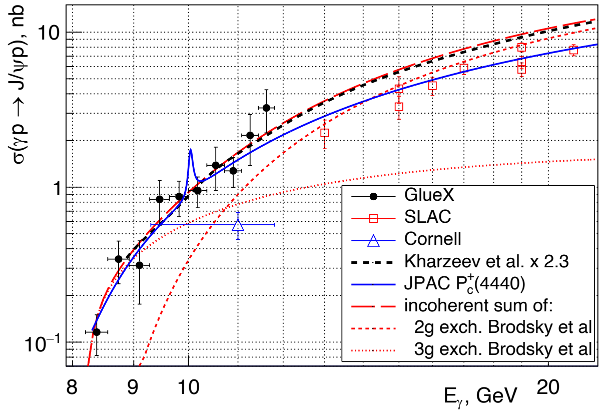
Hall C-E12-16-007 (online results)

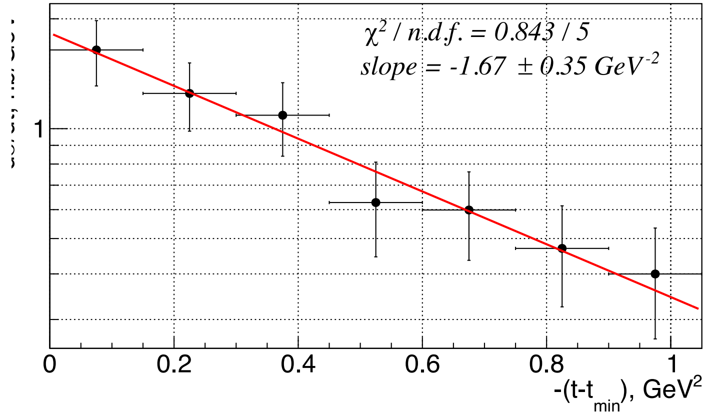


Hall B-CLAS12- E12-12-001A & E12-11-003B (deuterium)

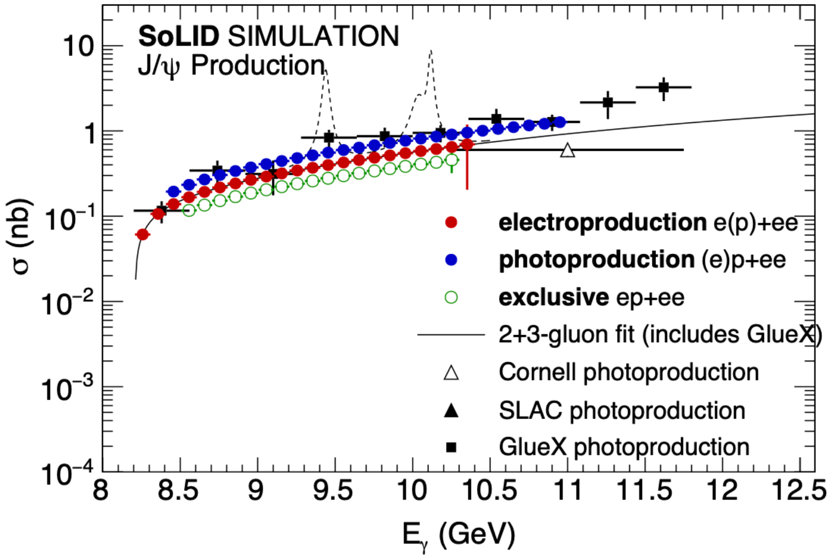
Data taken, analysis in progress?

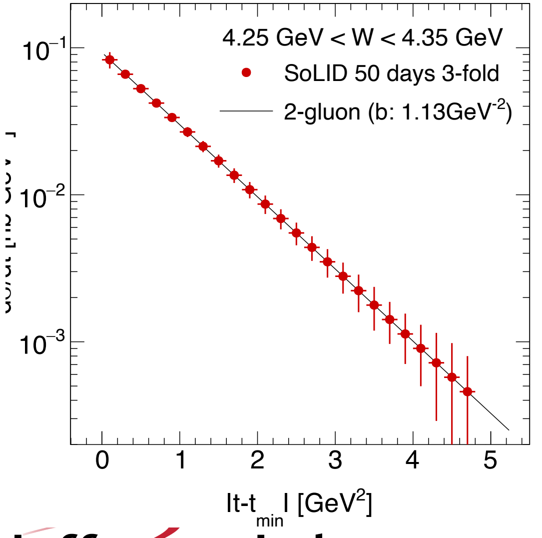
Hall D- GLUE-X results





- ## *Hall A-SoLID (projected)*





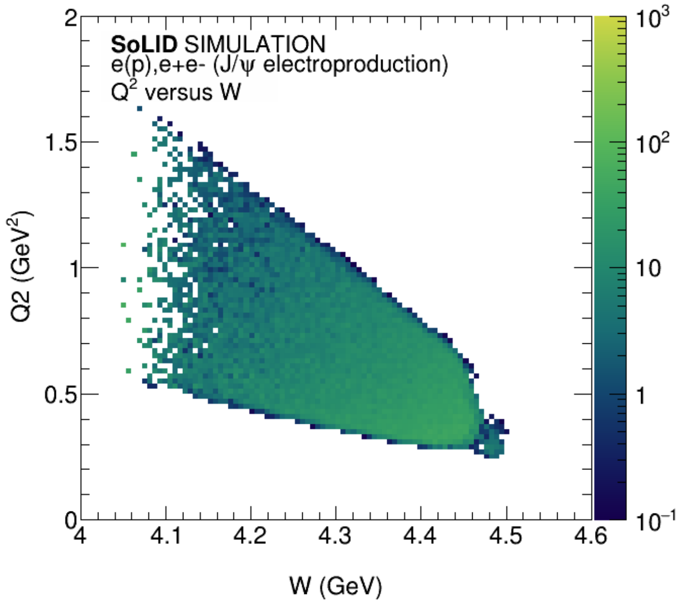
J/ψ experiments at JLab in a nutshell. Why SoLID?

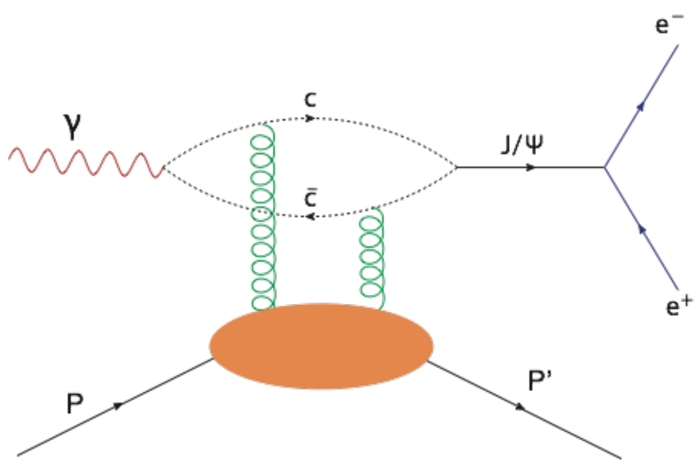
	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	~400 published, 4k on tape	2100 electrons 2100 muons	45-180/day	6974/day
J/ψ Rate (electro-prod.)				529/day
Experiment		E12-16-007	E12-12-001 E12-11-003B	E12-12-006
PAC days		9+2	130	50
When?	Finished	Finished	Ongoing	~8 years?

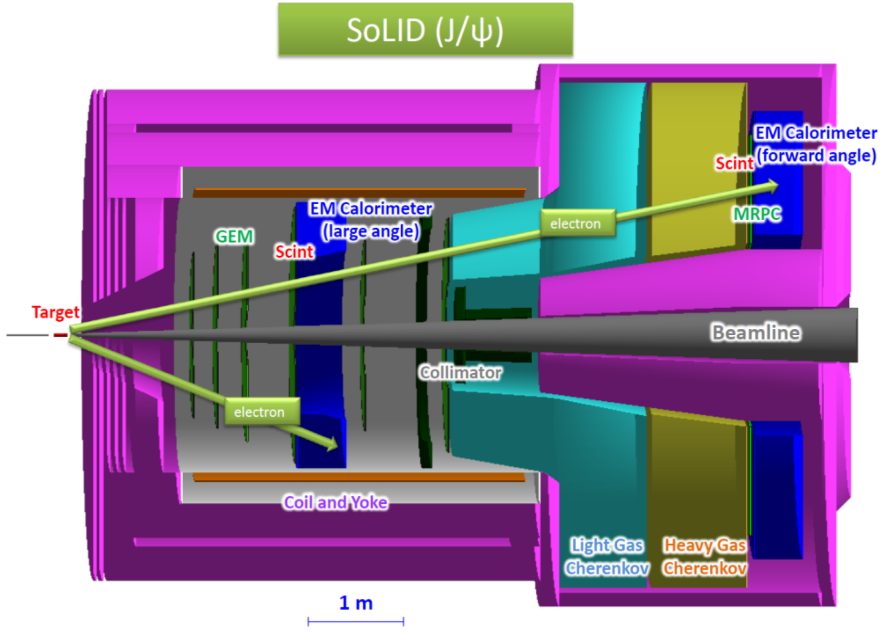
+ letter-of-intent to measure J/ψ double polarization with SBS in Hall A

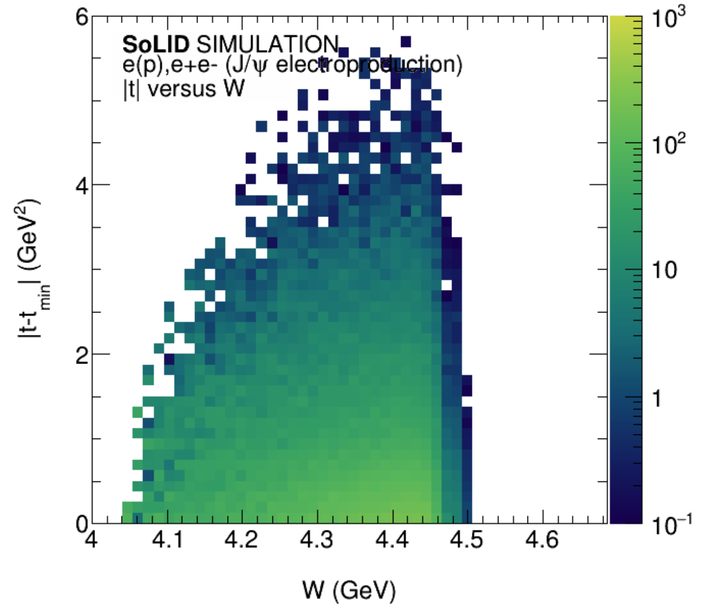
Experimental Overview

- 50 days of $3\,\mu A$ beam on a 15 cm long LH_2 target at $1 \times 10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include calibration/background run
- SoLID configuration overall compatible with SIDIS
- Main Trigger: 3-fold coincidence of $e^-e^-e^+$
  - Additional trigger 4-fold coincidence ($e^-e^+e^-\,p$)
  - And a 2-fold coincidence (e^+e^-)









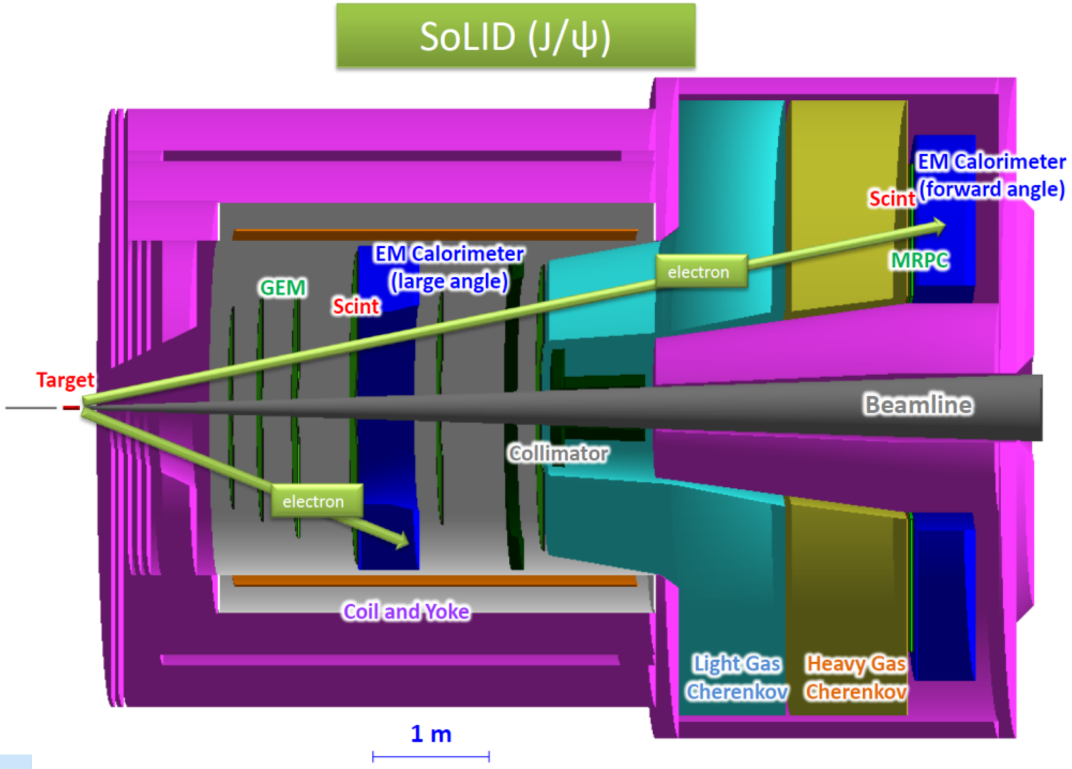
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

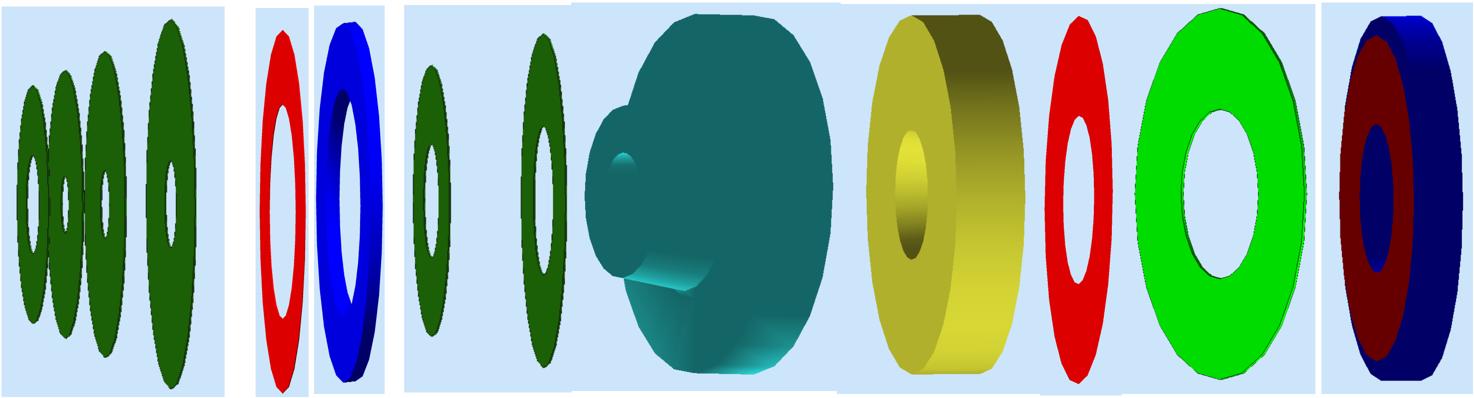
SoLID Jefferson Lab

J/psi - detector configuration similar to SIDIS

- Main trigger is 3-fold coincidence (LGC+LAEC+FAEC)
  - Gas Č + Calorimeter at forward angle (scattered e-)
  - Calorimeter only for large angle decay e+e- pair (slow J/ ψ)
  - Gas Č + Calorimeter at forward angle (decay pair) (fast J/ ψ)

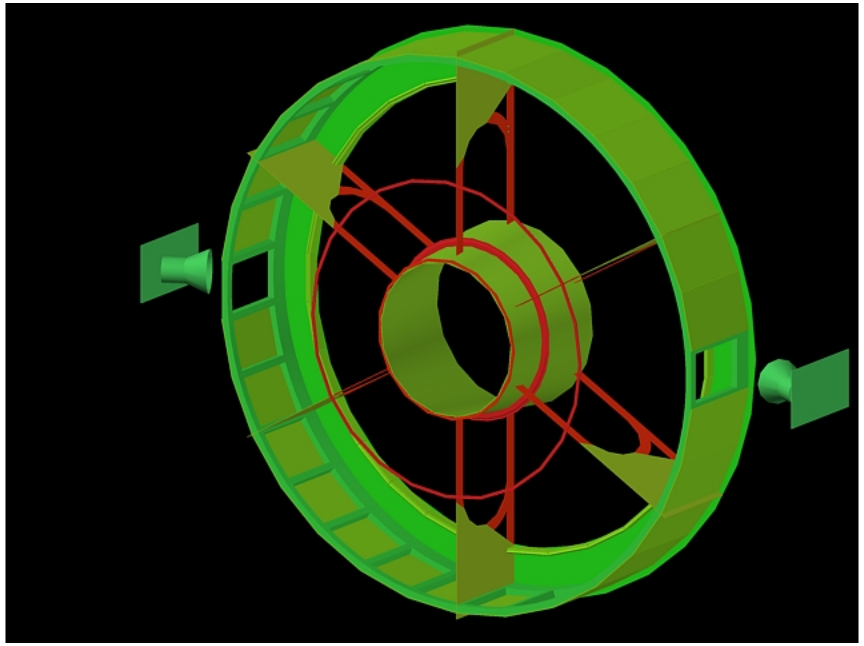
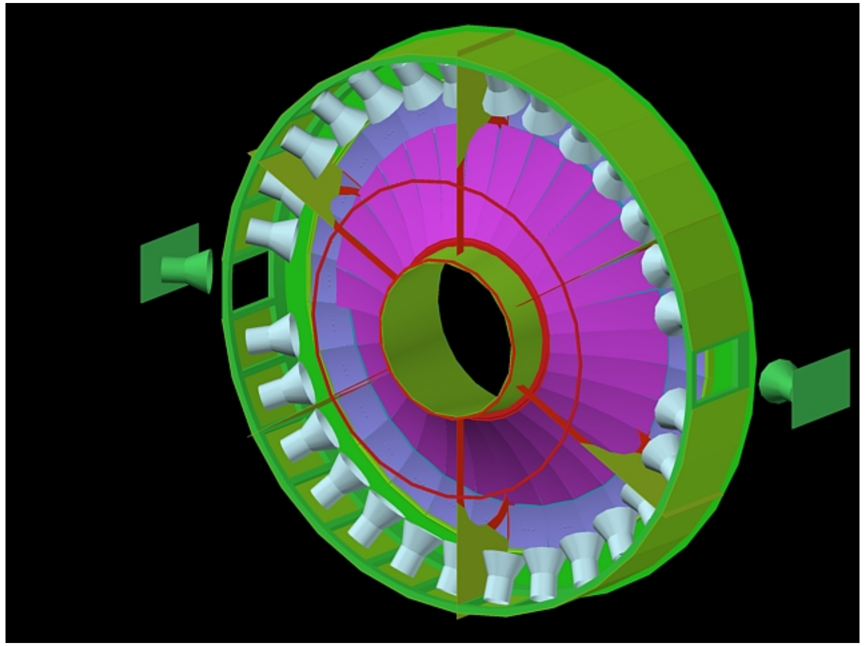
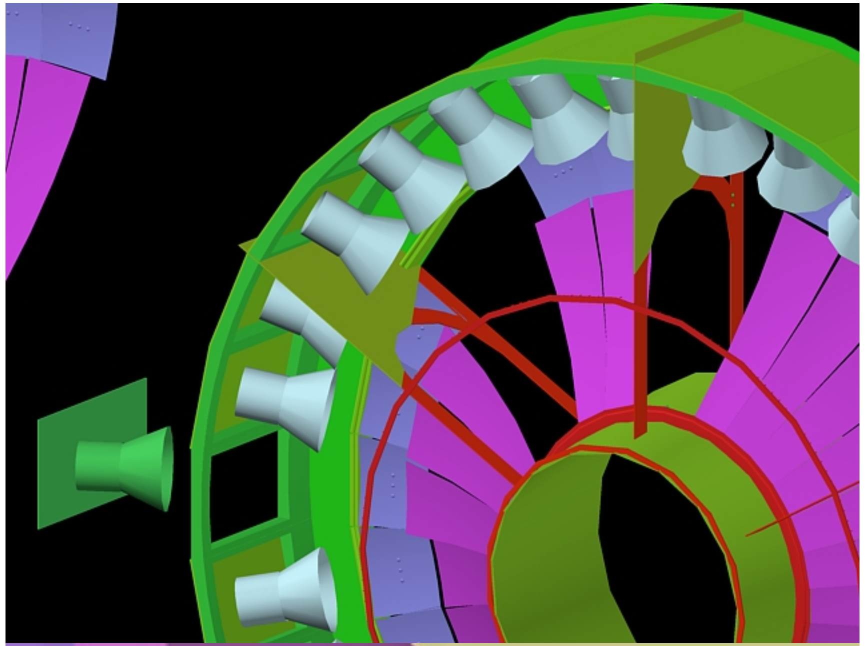
Full exclusivity - 4-fold coincidence (includes proton) with MRPC or FASPD





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

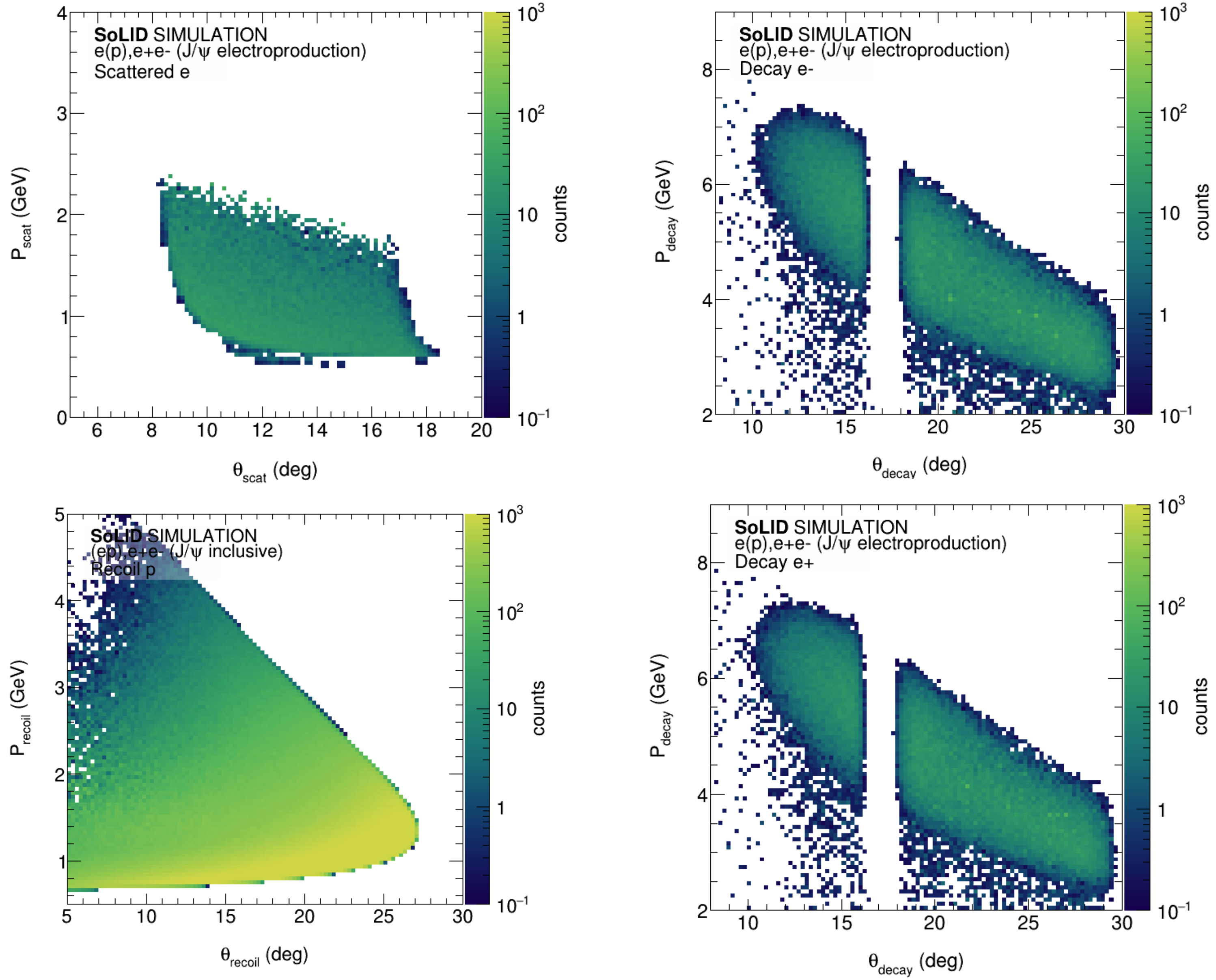
Light Gas Cherenkov for J/psi-SIDIS includes snout


- Operates at slightly above atmospheric pressure
- A snout is added to increase the radiator length compared to PVDIS.
- 2 sets of mirrors with one set inclined for SIDIS-J/psi configurations
- > 98% efficient for electrons.
- Reject pions at 500:1 level below 4.2 GeV.
- Shielded photosensors must operate in moderate magnetic field normal to the face of the sensors.
- Segmentation imposed by PVDIS

PID and Acceptance

- Scattered electron:
  - Gas Č + Calorimeter @ forward angle
- Decay electron/positron:
  - Calorimeter only at large angle
  - Gas Č + Calorimeter at forward angle
- Recoil proton:
  - 50-150 ps TOF MRPC/SPD: 2 ns separation between p/K @ 2 GeV/c
  - ~ 8m flight path



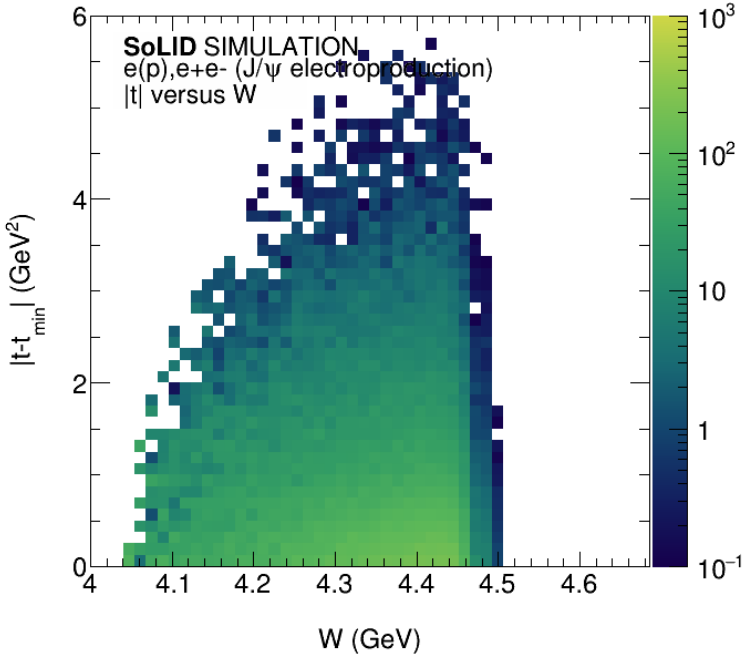
Main trigger rate **~60kHz** with 50 ns coincidence window. Comparing to **~100 kHz** design trigger rate for SIDIS.

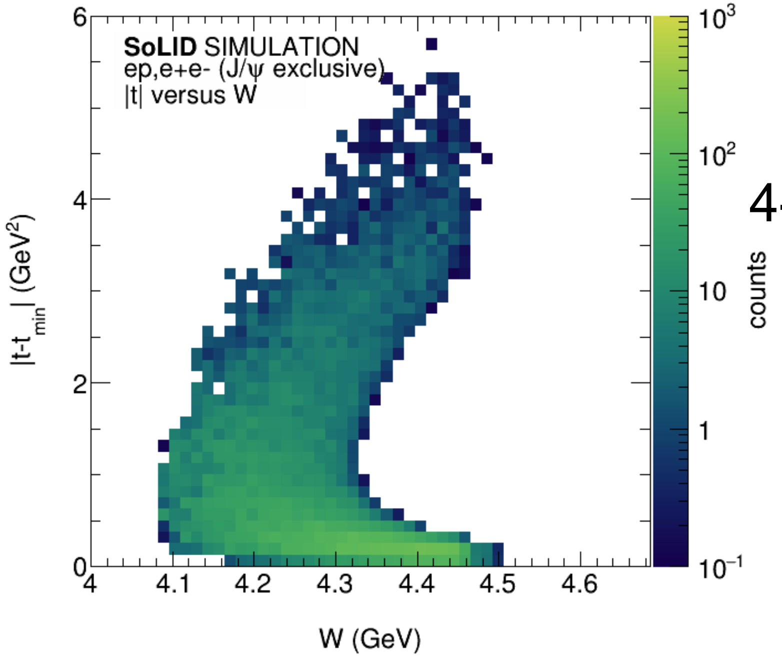
Event Counts @ 1×10^{37} in 50 days

- 4-fold coincidence: epe+e-
  - **164-234** events/day
- 3-fold no proton: e-e+e-
  - 370-529 events/day
- 3-fold coincidence pe+e-
  - 4882-6974 events/day
- 2-fold coincidence e+e-
  - 21517-30739 events/day

	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**

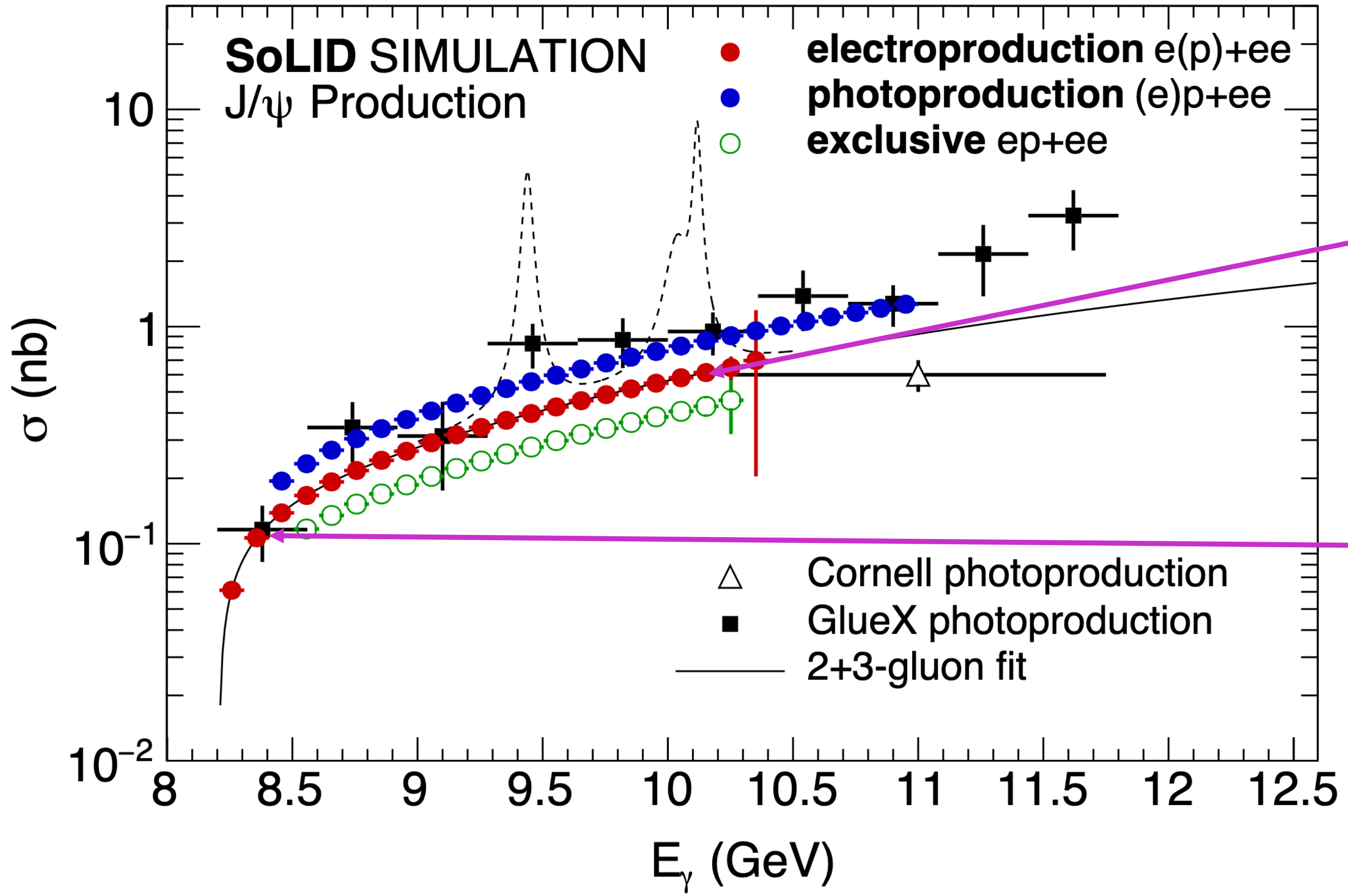
3-fold

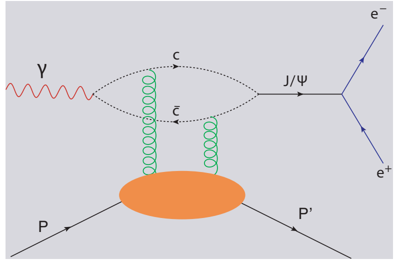


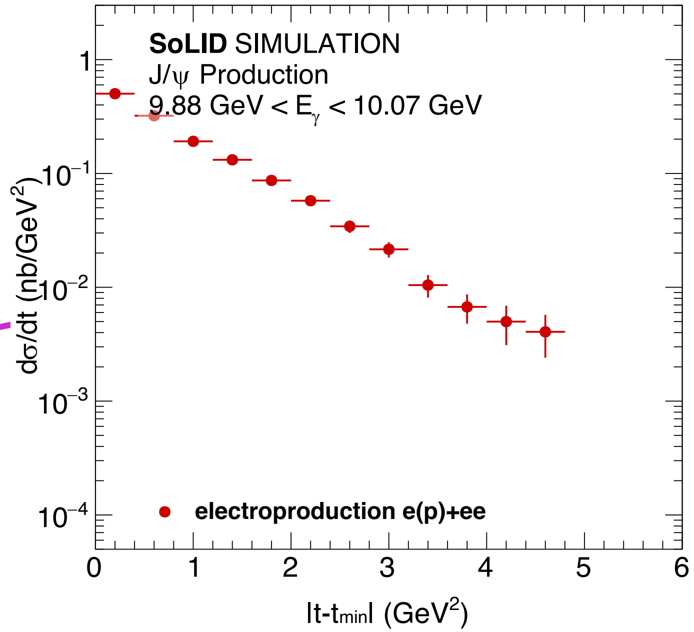


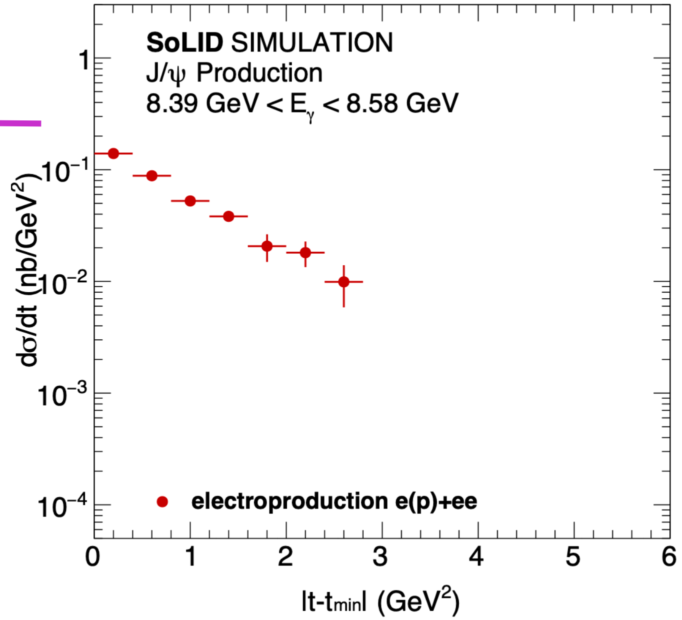
4-fold

J/Psi Experiment E12-12-006 @ SoLID



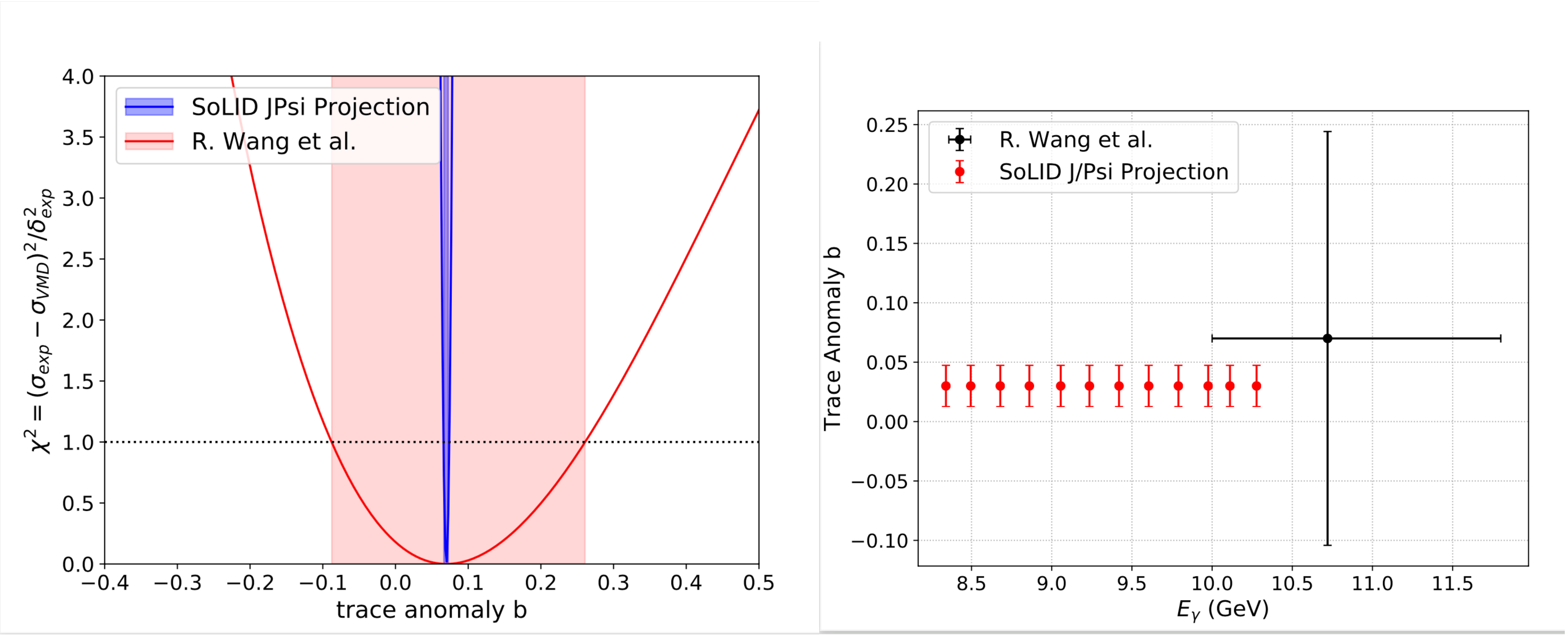






Sensitivity at threshold at about 10^{-3} nb!

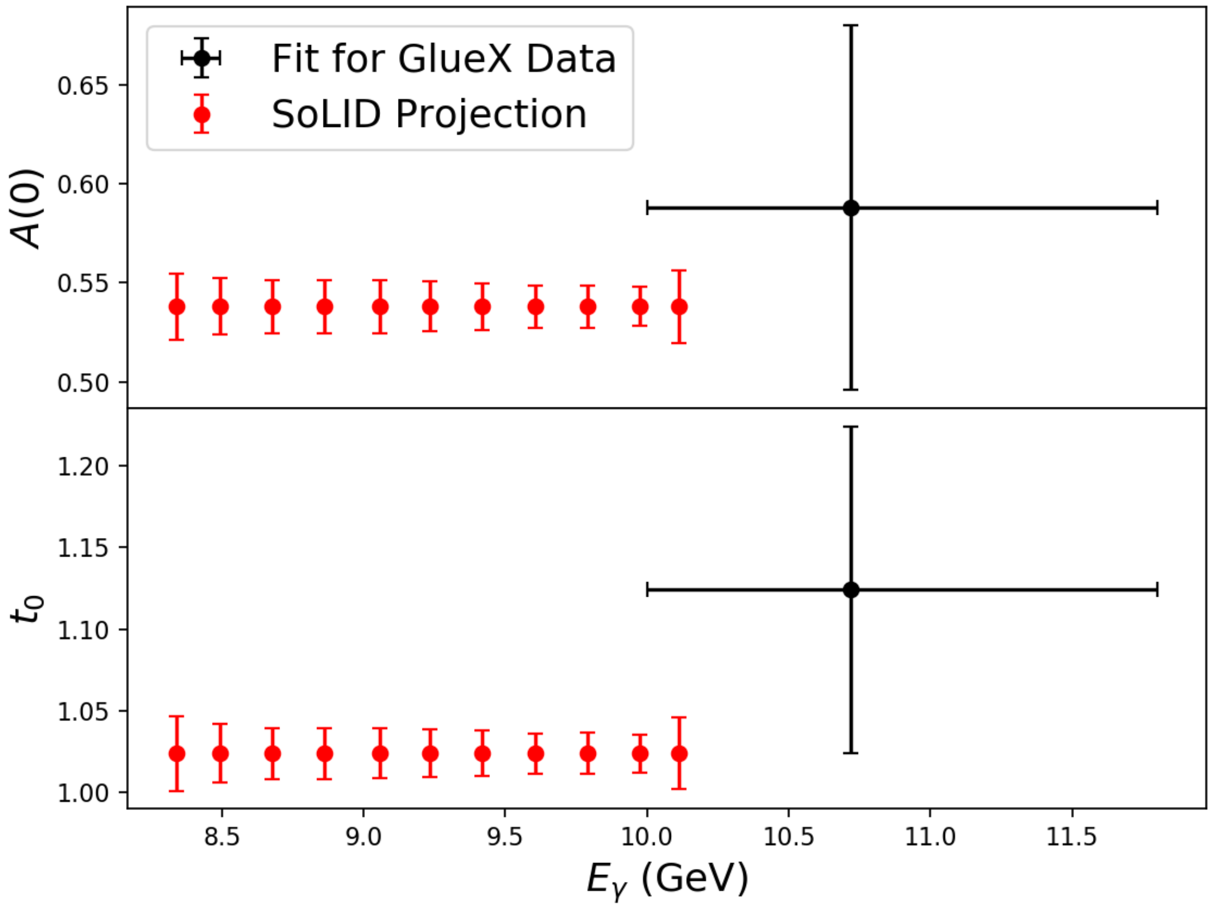
Impact on the trace Anomaly Extraction

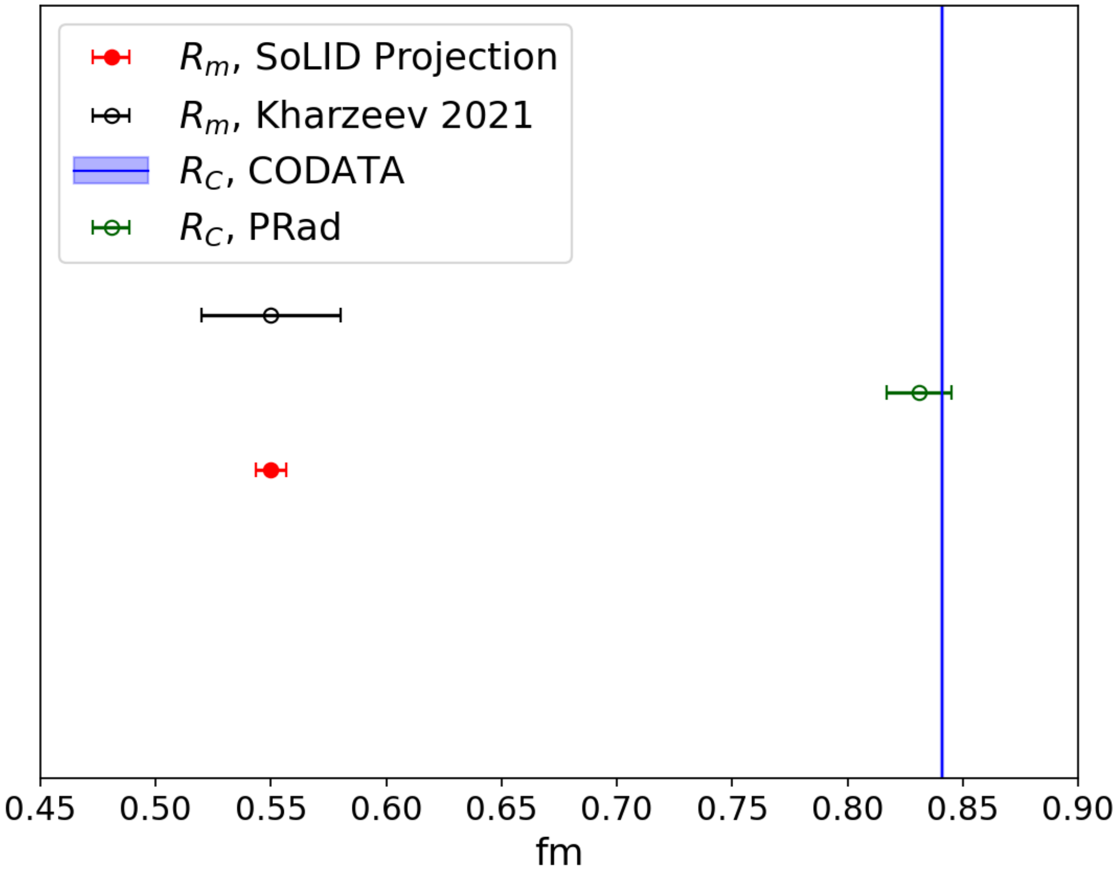


Impact on the mass radius

D. E. Kharzeev, ``The mass radius of the proton,'' arXiv:2102.00110 [hep-ph]

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

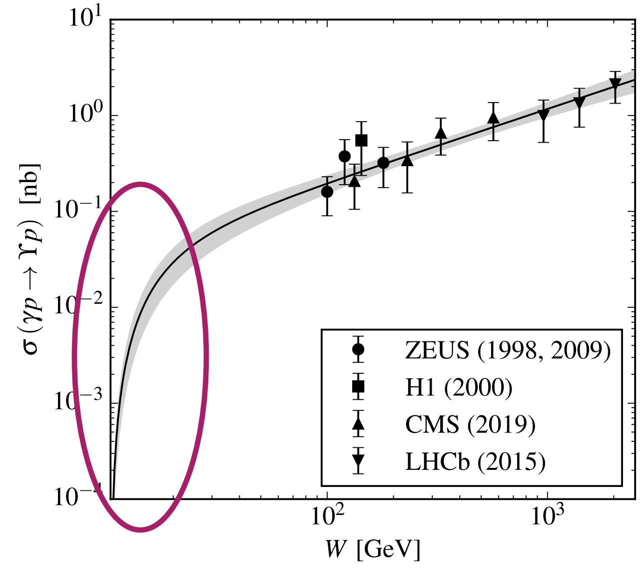




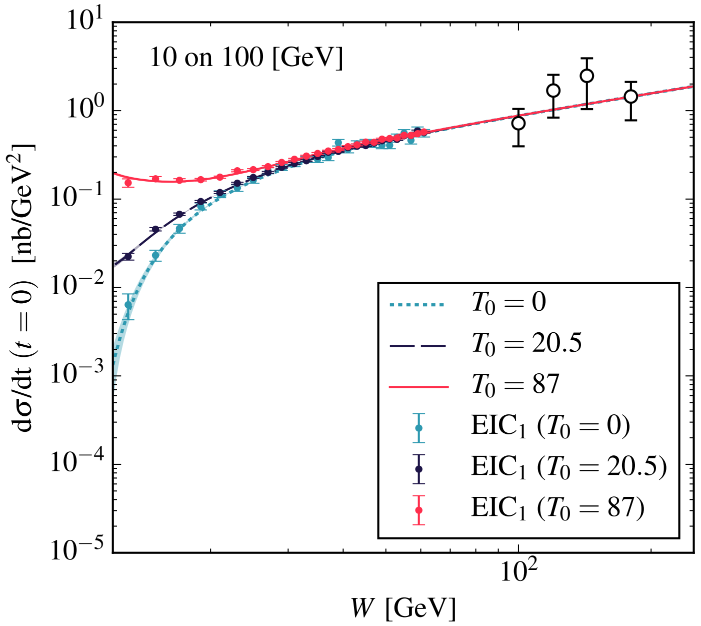
From JLab charm (J/ψ) to the EIC beauty (Υ)

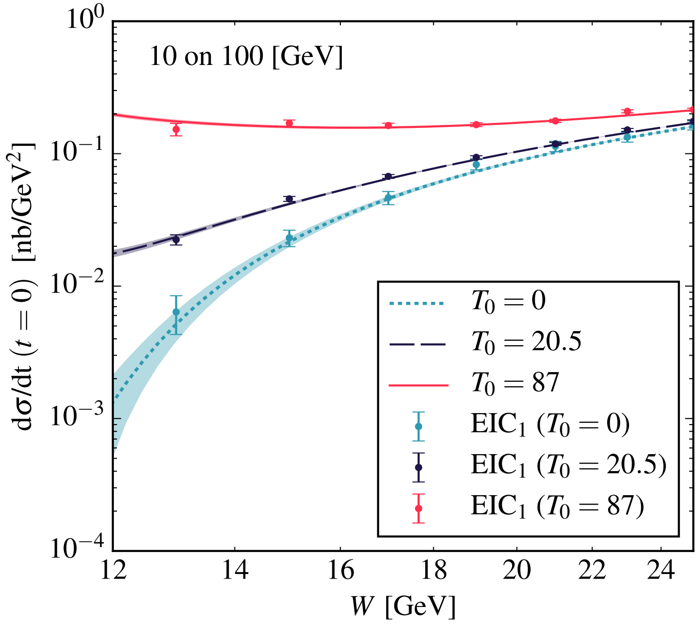
- SoLID and EIC are truly complementary in this science endeavor.
- It is essential to use the mass of the heavy quarks and the Q^2 range as nobs for our theoretical understanding of the reaction mechanism at threshold and the extraction of the anomaly, or the mass radius of the proton.

Present data on Elastic Upsilon photoproduction



Result of simulations for a measurement at 100 fb^{-1}





$T_{\Upsilon p}(0)$	$a_{\Upsilon p}$(in fm)	B_{Υ}(in MeV)
0	≈0	≈0
25± 0.9	0.016± 0.001	0.78±0.03
87±2	0.066±0.001	3.23±0.06

O. Grynyuk, S. Joosten, Z.-E. M., Vanderhaeghen
Phys. Rev. D 102, 014016 (2020)

Summary

- SoLID is crucial to acquire precision data in electroproduction and photoproduction to answer the questions
  - ✓ **What is the origin of hadron masses**?
  - ✓ What is the strength of the interaction between charmonium and a proton, dubbed color Van der Waals force?
  - ✓ Does charmonium enable pentaquarks to exist?
  - ✓ Are bound states of charmonium-nuclei possible?
- Direct lattice calculation of the trace anomaly is an important step toward understanding the proton mass different decompositions. Precision data will be able to benchmark these ab initio calculations.
- Statistical precision will help to understand the systematic uncertainties in the extractions of the anomaly, the mass radius and the scattering length.
- The origin of hadron masses is an active field of QCD. A 3rd Workshop was held in 14-16 January 2021 (see: https://indico.phy.anl.gov/event/2/)
- A 4rd workshop on the proton mass will be held at the INT in Winter 2022 to continue explore the different important observables SoLID can and should cover.
- The case for bound states in nuclei is under investigation, tagging will need to be implemented.
- SoLID and the EIC using heavy quarkonia are truly complementary to address these questions.