Quarkonium production at threshold from JLab to EIC

Image credit: Z.-E. Meziani

ZEIN-EDDINE MEZIANI

Argonne National Laboratory

With thanks to S. Joosten, C. Peng

01/16/2021

Outline

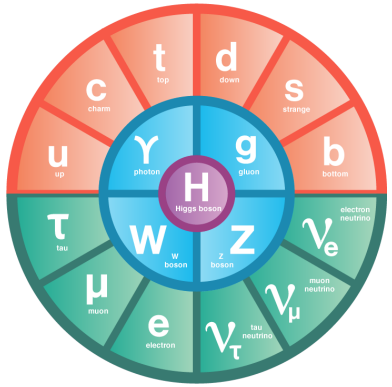
1. Motivation
2. Science questions enabled by the J/psi production at threshold
3. Status and future of J/ψ threshold production experiments at Jefferson Lab
4. Projections for what is possible with Y at EIC
5. Summary

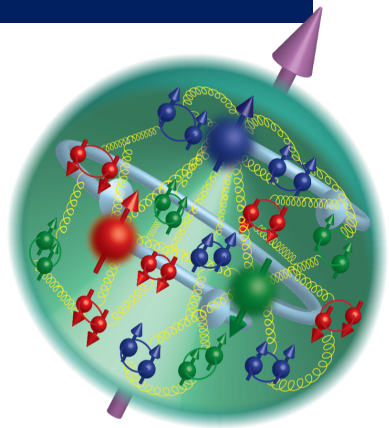
Science of J/Psi Production at Threshold

- Hadron masses
  - How do hadron masses emerge?
  - Can we learn something deeper about nucleon dynamics and confinement?

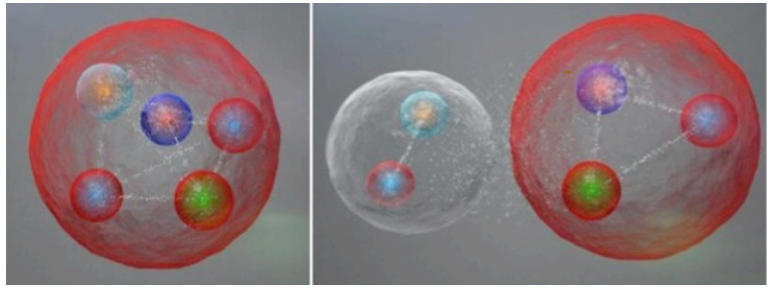
- Color Van der Waal Forces and heavy quarkonium-nuclei binding
  - A unique case of strong force from QCD degrees of freedom in nuclear physics

- Existence of heavy pentaquarks
  - Do heavy pentaquark exits?
  - Can we confirm/refute their existence?



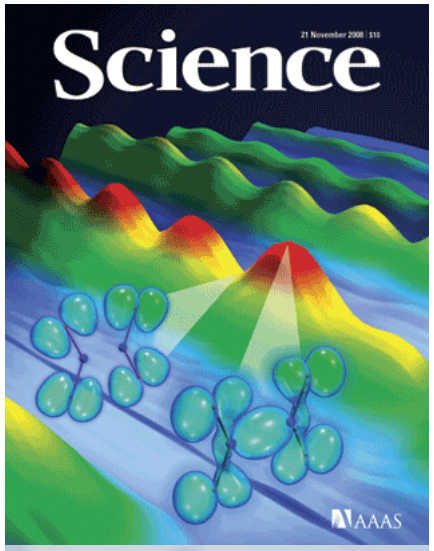


Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass to nucleons and nuclei through the "trace anomaly" a consequence of broken scale invariance



Cartoon of different configurations of 3 light -2 heavy quarks system. Courtesy of Daniel Domingez/CERN

Hadron Masses from Lattice QCD

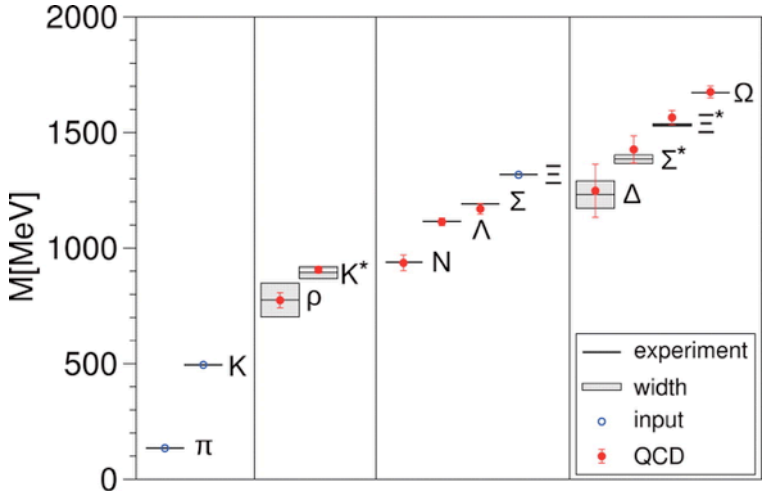


(2008)

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

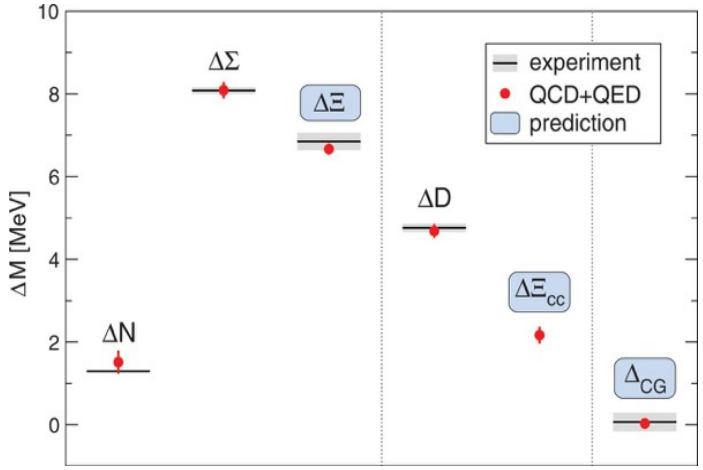
589 citations



(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

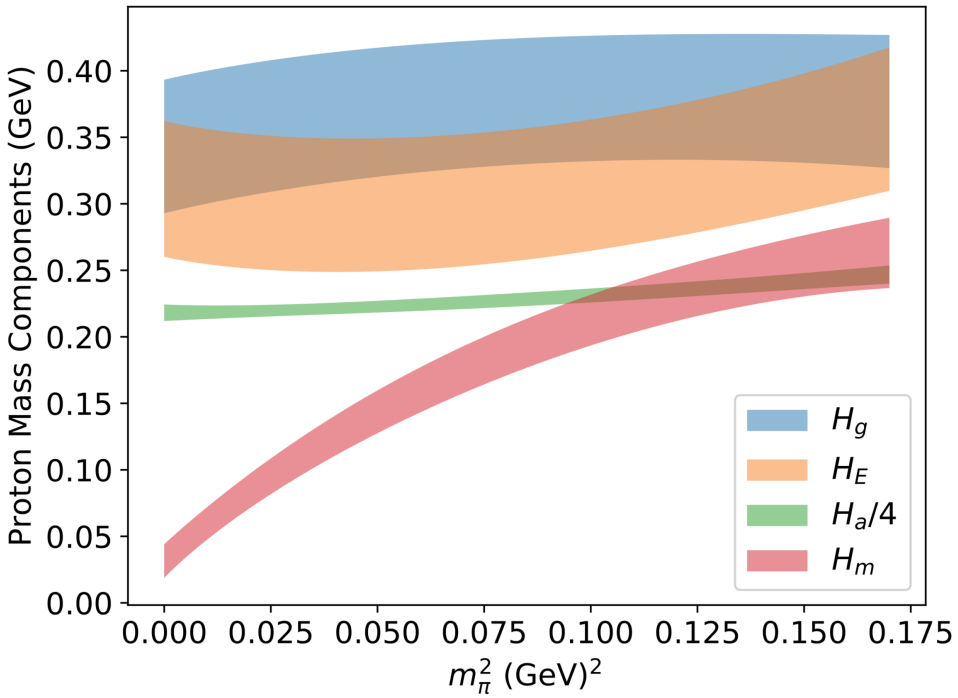
Science **347** (6229), 1452-1455
DOI: 10.1126/science.1257050



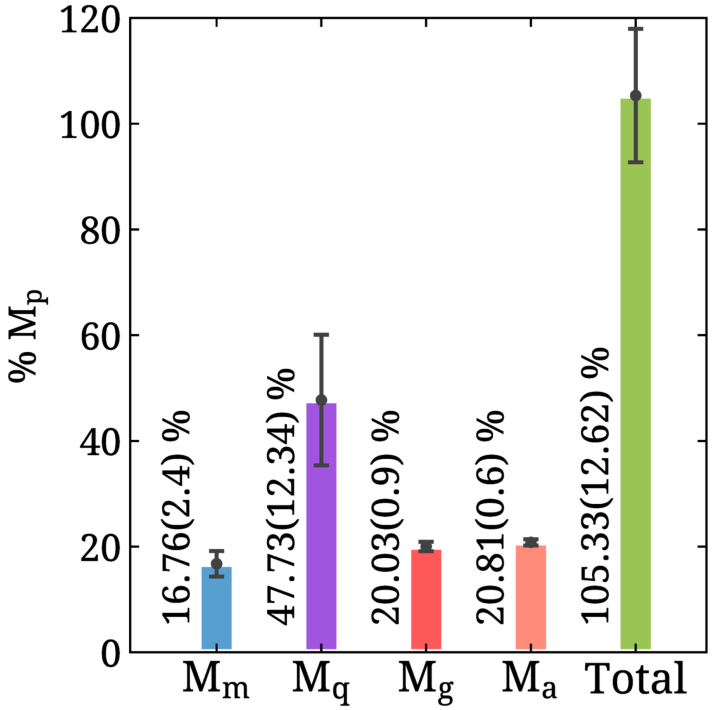
How does QCD generate this? The role of quarks and of gluons?

Proton mass on the lattice

To date no direct calculation of the trace anomaly



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



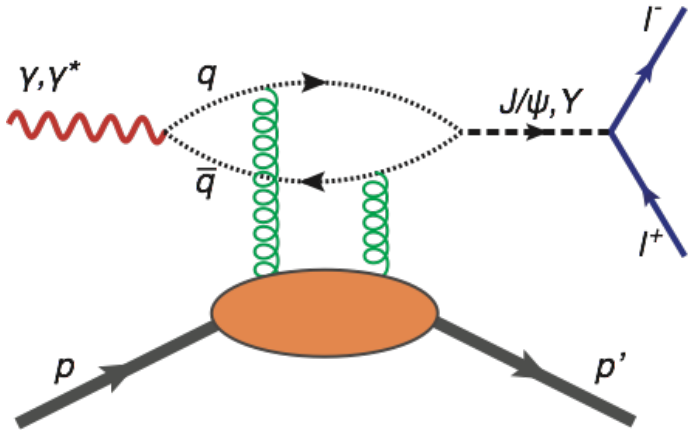
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

Trace anomaly only constrained through sum-rules not calculated directly.

Heavy-Quarkonium photo-production: **what do we know?**

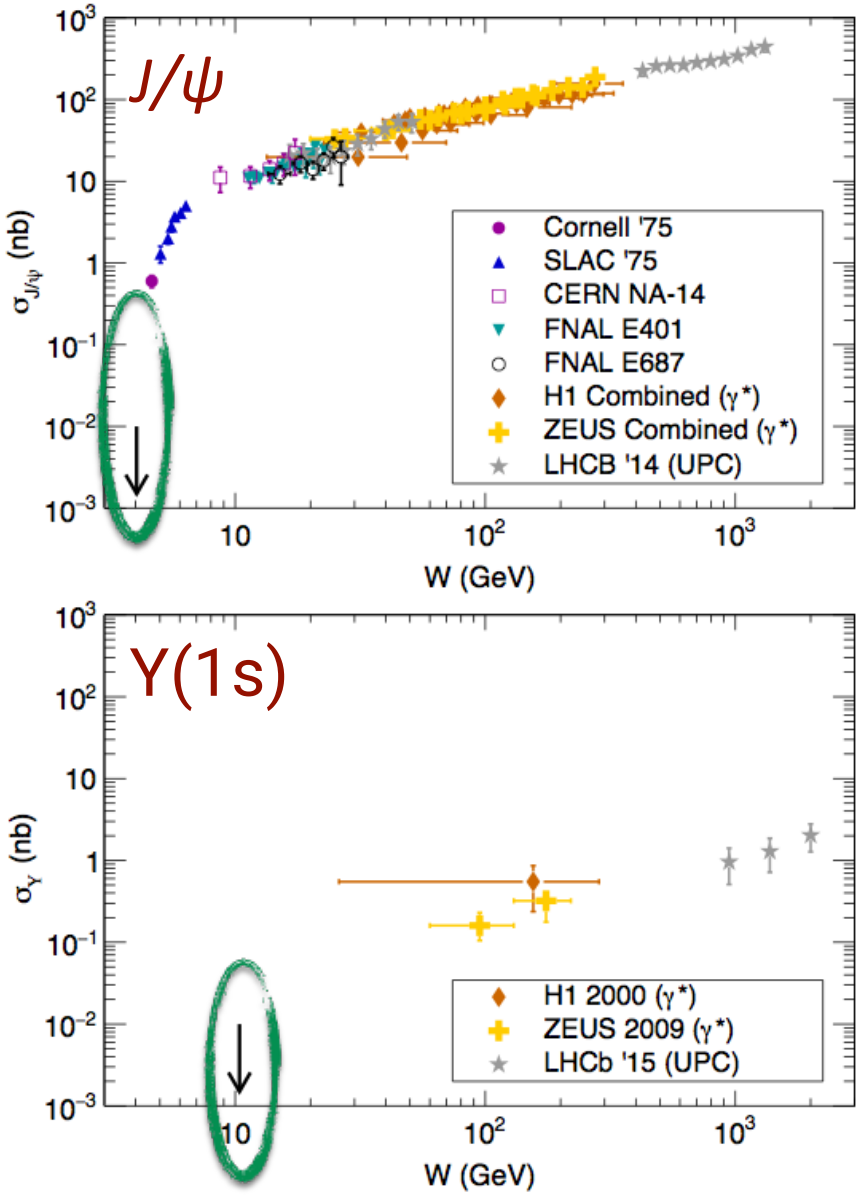
J/ψ photo-production:

- **Well constrained above W > 15 GeV**
  - **Dominated by t-channel 2-gluon exchange**
- **Almost no data near threshold**



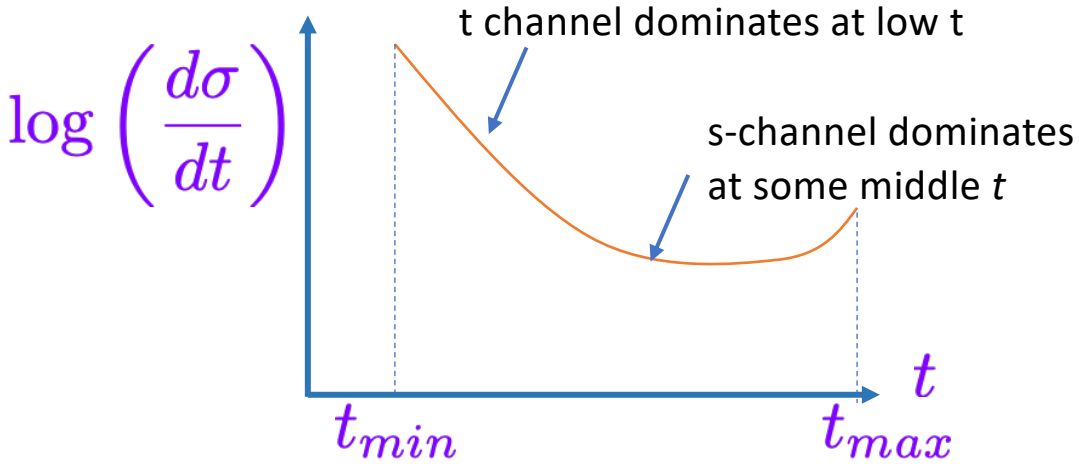
Υ(1s) photo-production:

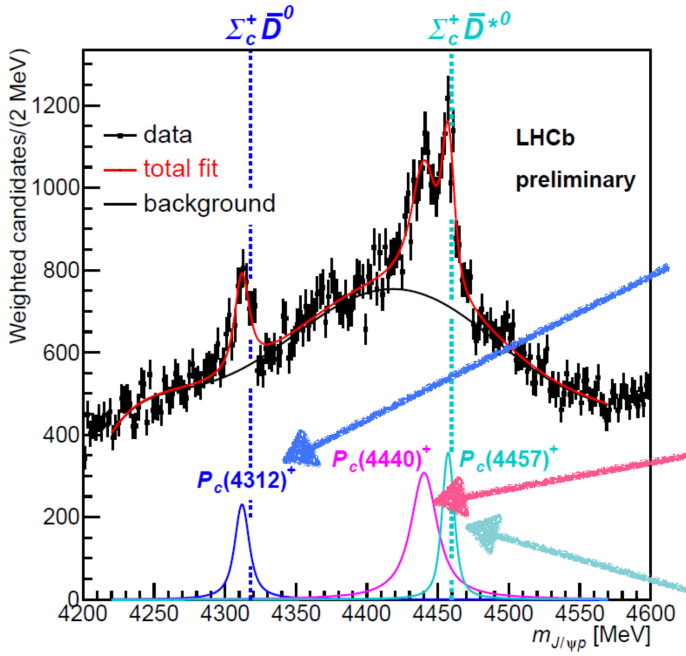
- **Not much available**
  - **ZEUS measured 62 ± 12 events total!**



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 in the s-channel.





- **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

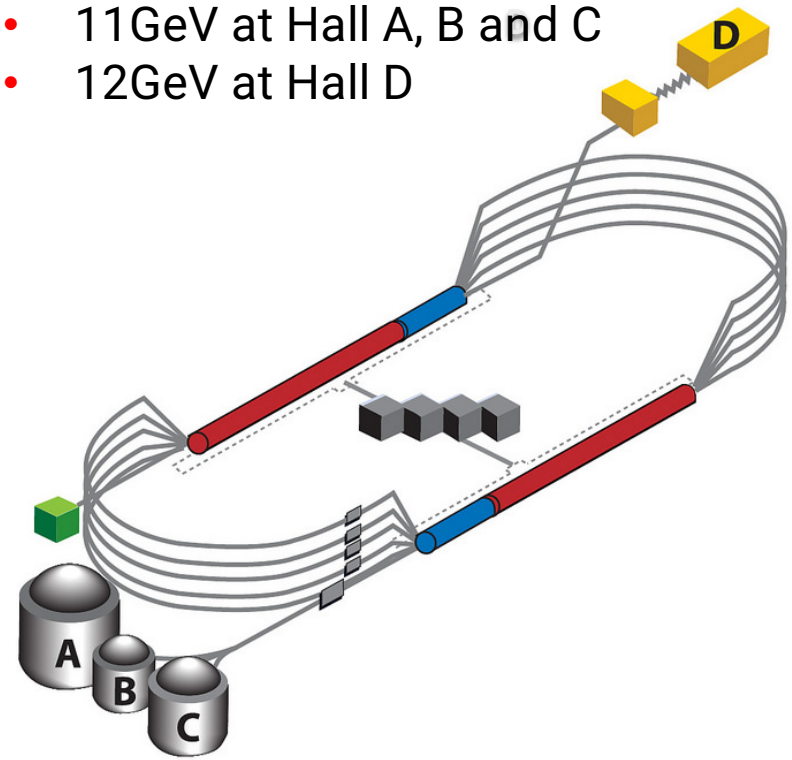
★ ***Pc⁺(4457)***

M: 4457.3±0.6+4.1/-1.7 MeV

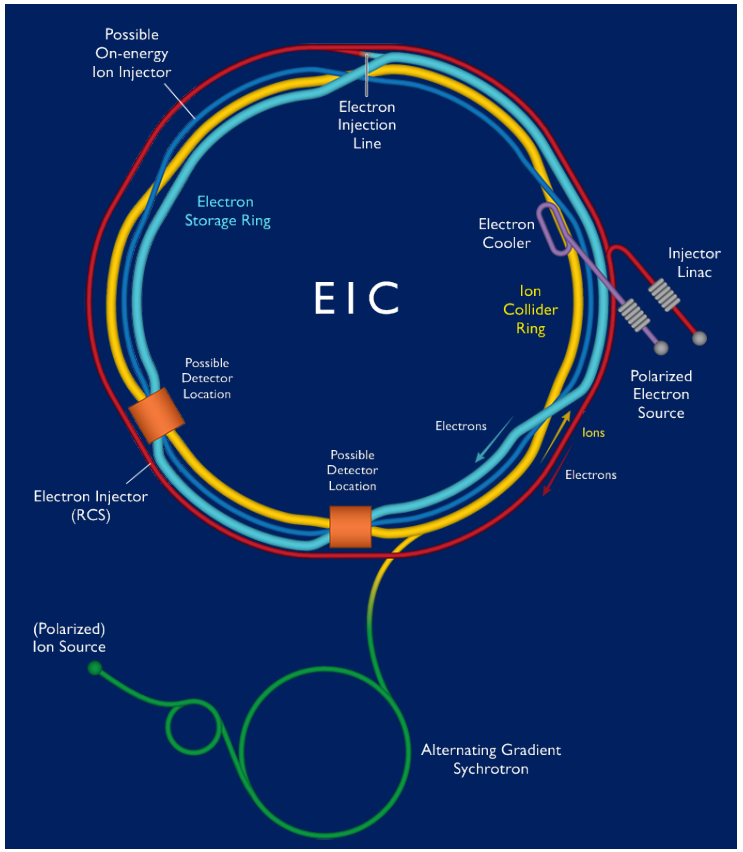
Γ = 6.4±2.0+5.7/-1.9 MeV

J/ψ at JLab in **the 12GeV era** and *Υ* at a future **EIC**

- CEBAF: High-luminosity continuous electron beam
- 4 Experimental Halls
- 11GeV at Hall A, B and C
- 12GeV at Hall D



- EIC: Luminosity up to 10^{33}-10^{34} $cm^{-2}s^{-1}$
- polarized electron beam
- polarized light ion beams
- Center-of-mass energies 20-100 GeV upgradable to 140 GeV
- 1 or 2 Interaction regions

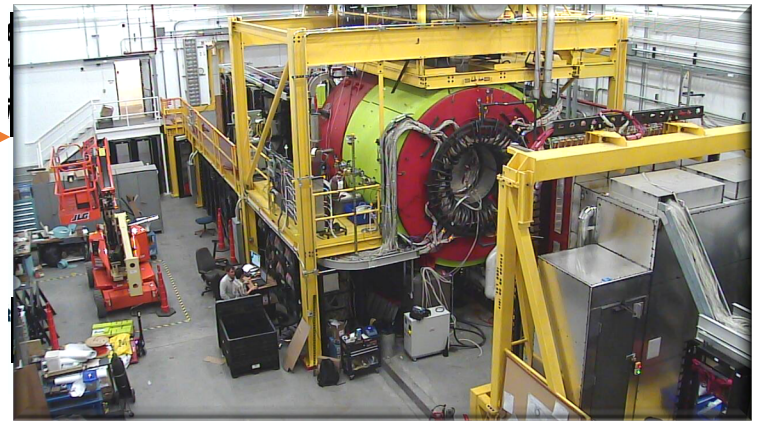


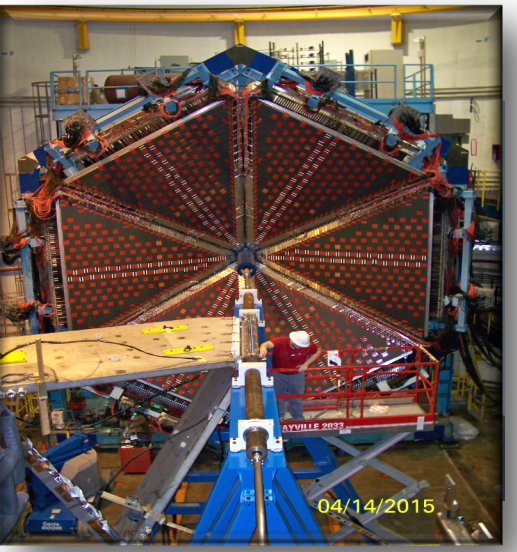
JLab is the ideal laboratory to measure J/psi near threshold, due to luminosity, resolution and energy reach but Upsilon is for the EIC

Argonne NATIONAL LABORATORY

12 GeV J/Ψ experiments at JLab Overview

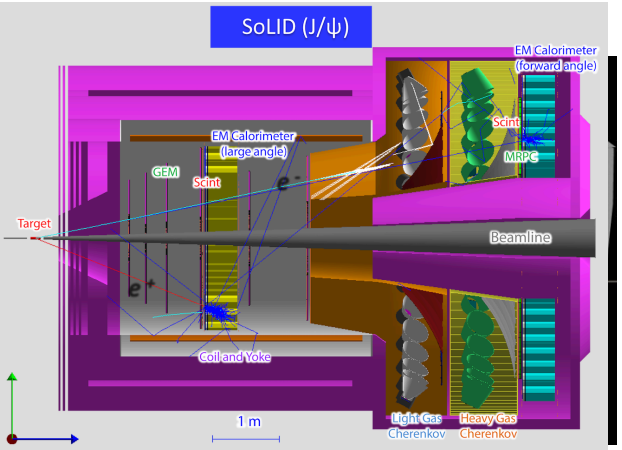
A. ***Hall D – GlueX has observed the first J/ψs at Jlab and a publication,*** Ali *et al.* [GlueX Col, Phys. Rev. Lett. 123, no. 7, 072001 (2019)





Hall B – has an approved experiment to measure Time like Compton Scattering+ J/psi in photo-production E12-12-001 and E12-001, and for deuterium E12-11003B: data taken

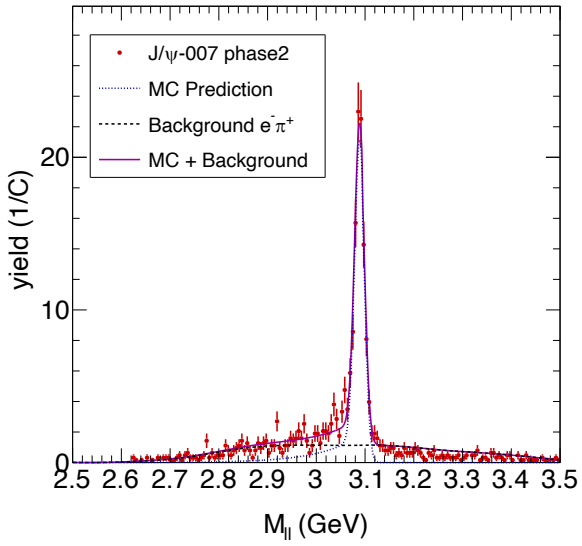
Hall C –took data to search for the LHCb pentaquark E12-16-007:data taken and imminent results



Hall A-has an approved experiment involving a future detector of large acceptance and high luminosity capability -SoLID - E12-12-006 + 1 LOI on double polarization using SBS

In search of the LHCb Pentaquark at JLab

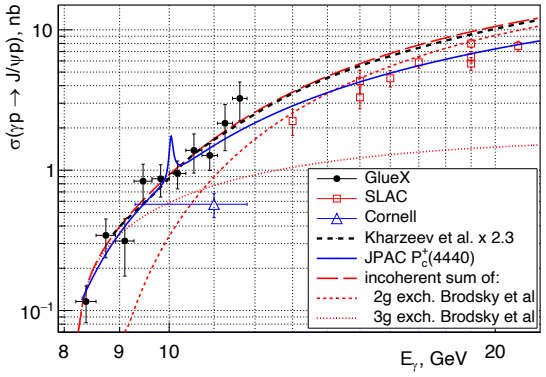
Hall C-E12-16-007 (online results)

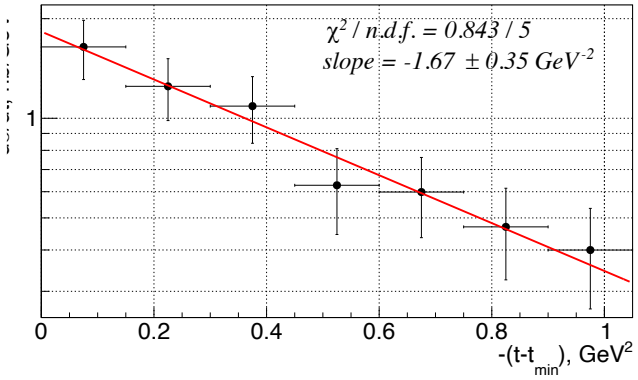


Hall B-CLAS12- E12-12-001A & B (deuterium)

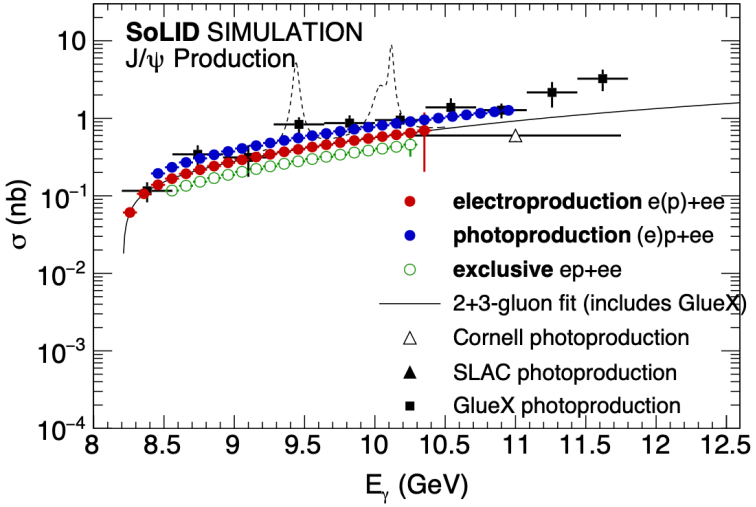
Data taken analysis in progress?

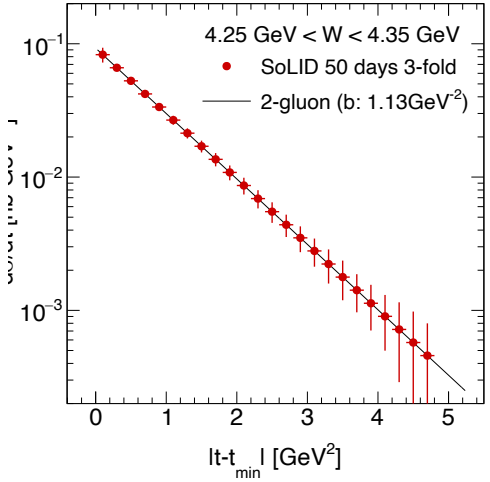
Hall D- GLUE-X results





- *Hall A-SoLID (projected)*





J/ψ experiments in JLab in a nutshell

Why SoLID for J/ψ near threshold!

	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?

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

From the Cross section to the Trace Anomaly

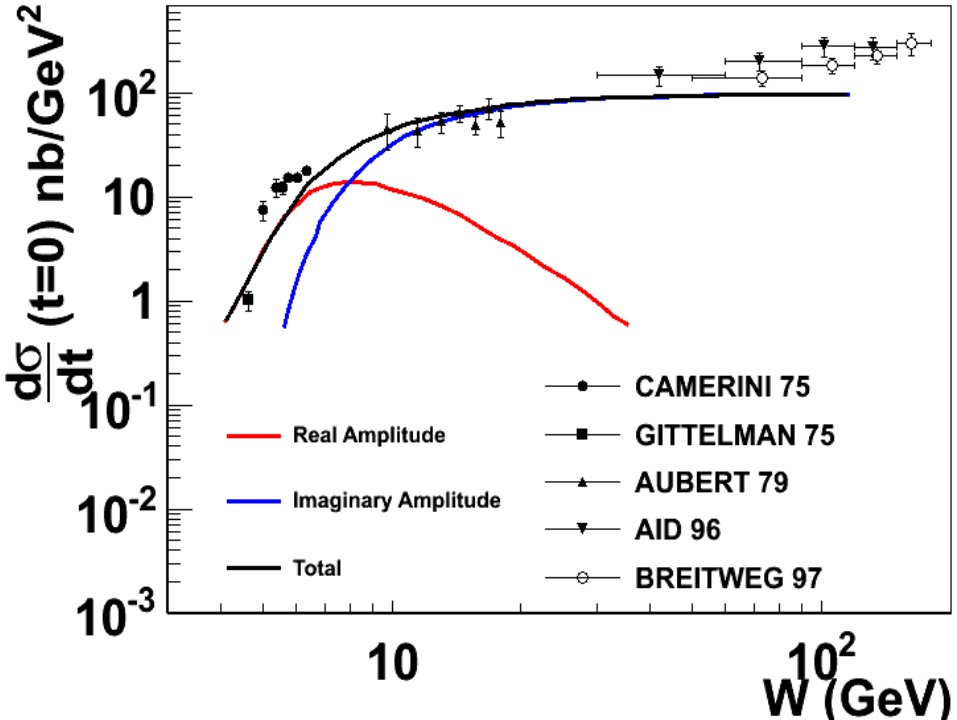
D. Kharzeev. Quarkonium interactions in QCD, 1995
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

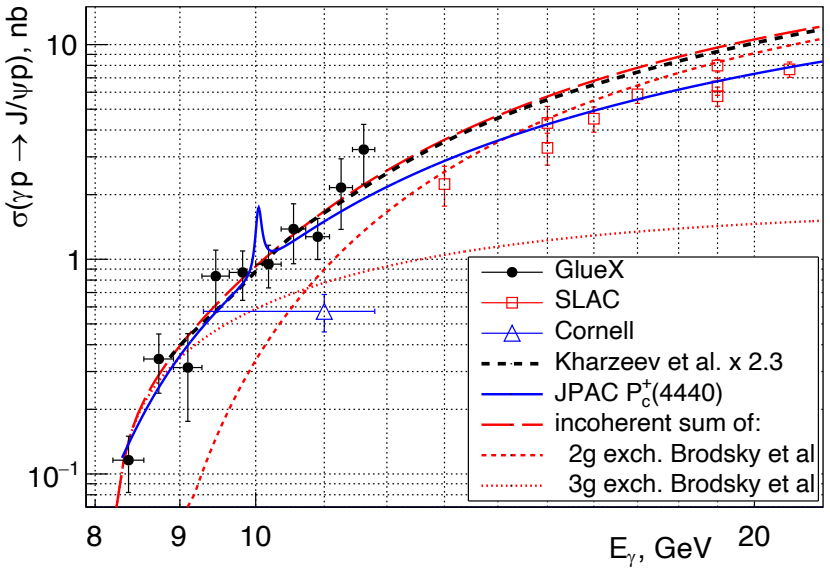
$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

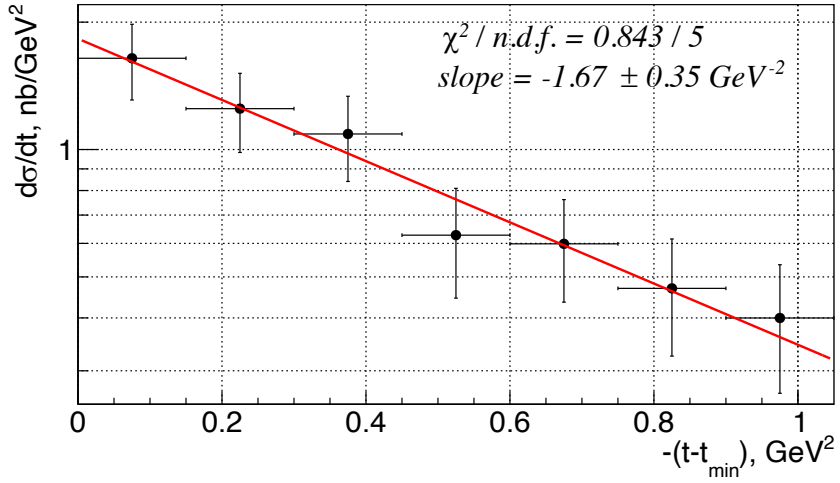
- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $M_{\psi p}$
- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region and constrained through dispersion relation

A measurement near threshold could allow access to the trace anomaly



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.

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)

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

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

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

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

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

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

Trace anomaly

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

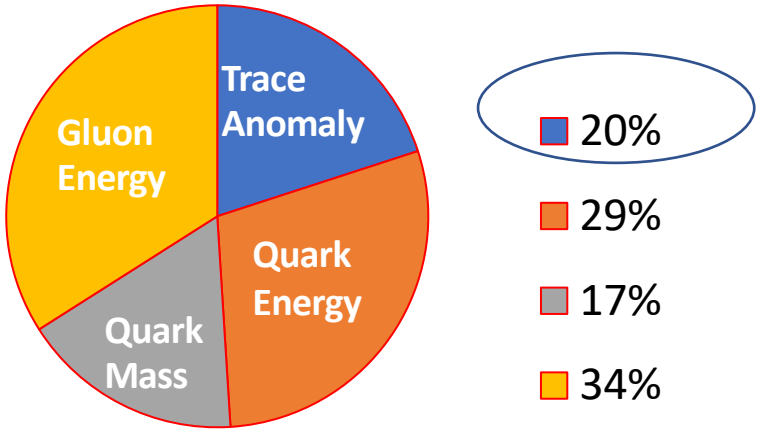
$$M_N = M_q + M_m + M_g + M_a$$

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

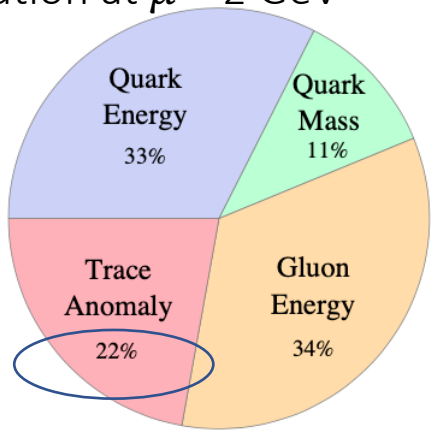
Trace Anomaly Inferences from Data

- In Ji's original work μ =1 GeV

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



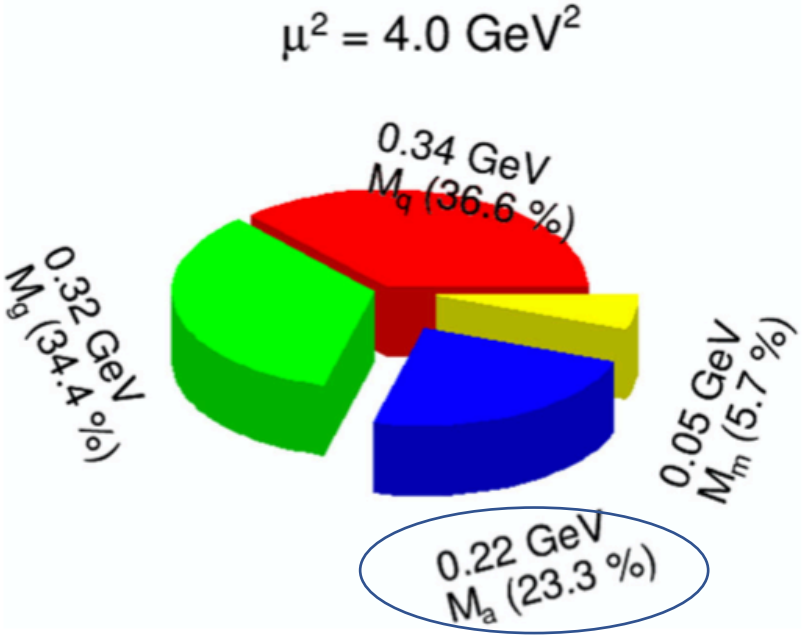
- An updated data analysis due to an update on the pion-nucleon sigma term and the strange quark contribution at μ = 2 GeV



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: $M_a = 23.3\% \pm 0.08\%$

Impact of SoLID on the trace anomaly determination

D. Kharzeev. Quarkonium interactions in QCD, 1995
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

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

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

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

Nucleon energy in the charmonium rest frame

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

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

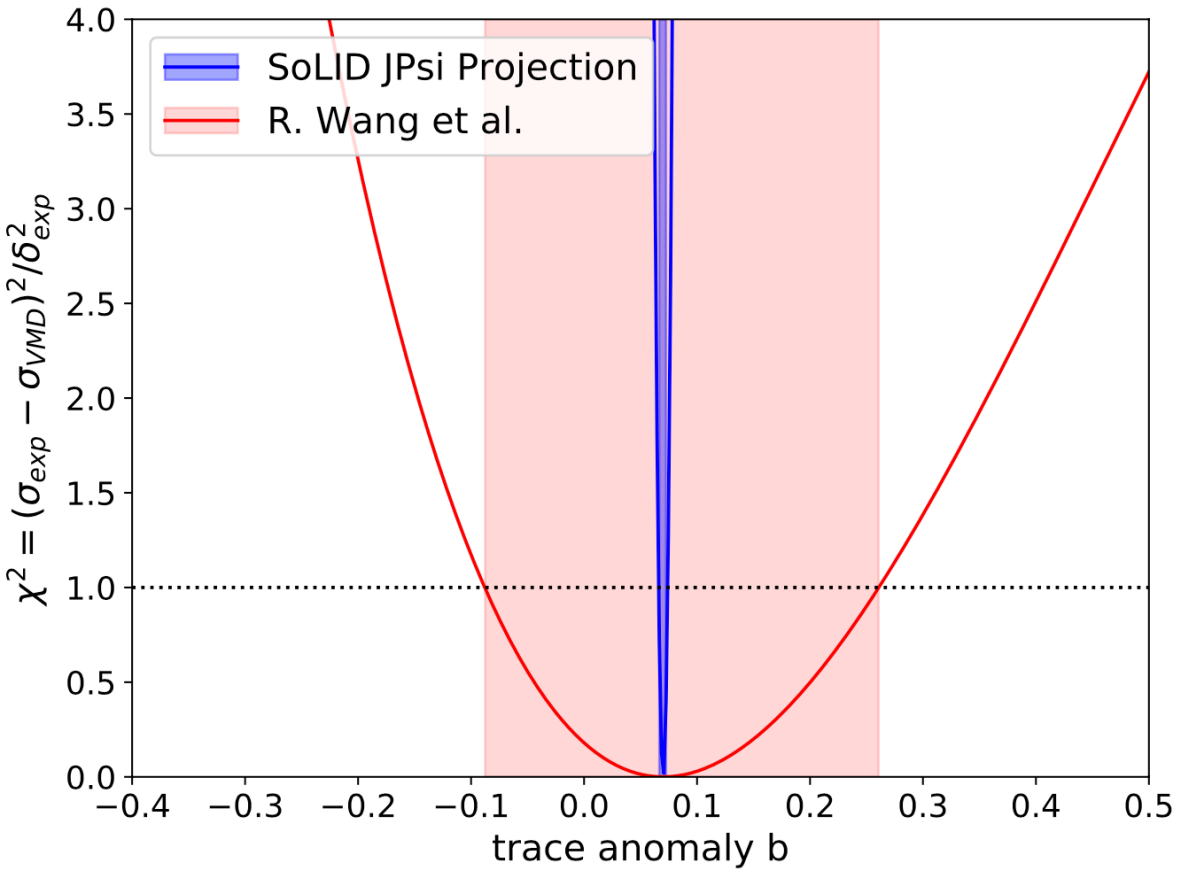
Bohr radius of charmonium

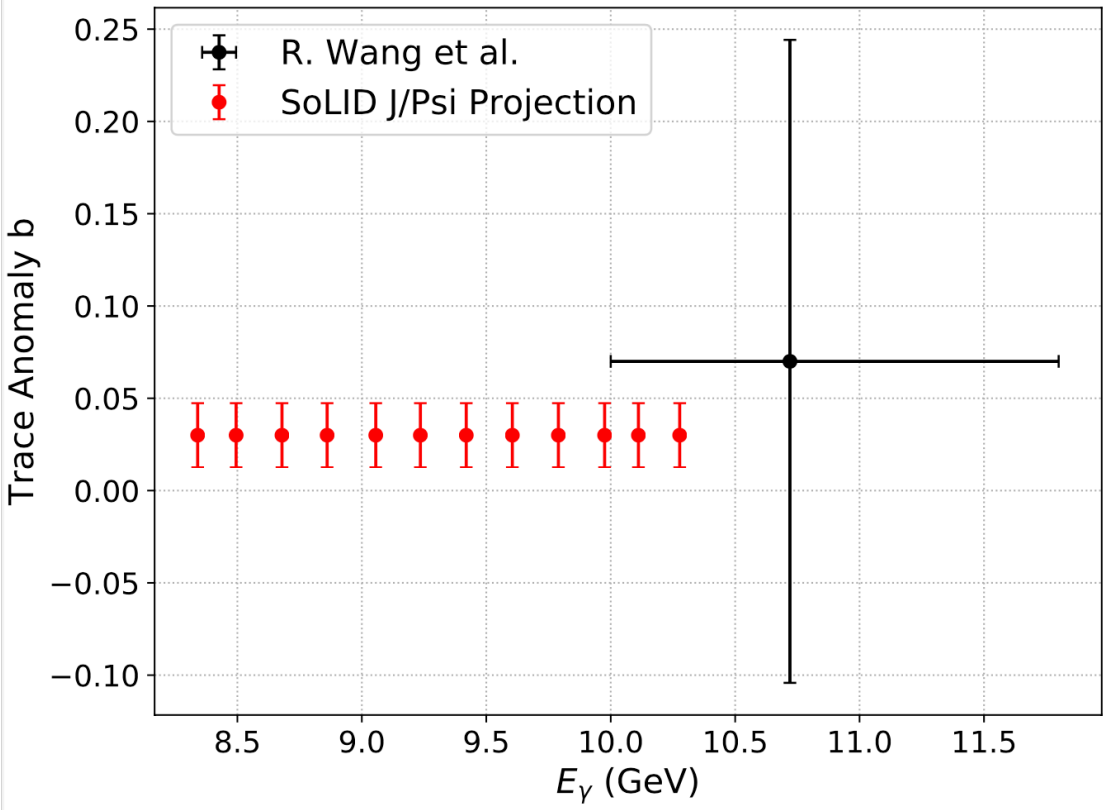
$$d_2^{(1S)} = \left(\frac{32}{N_c}\right)^2 \sqrt{\pi}\frac{\Gamma(n+5/2)}{\Gamma(n+5)}$$

Wilson coefficient

Rydberg energy squared = μ^2

Impact on the trace Anomaly Extraction

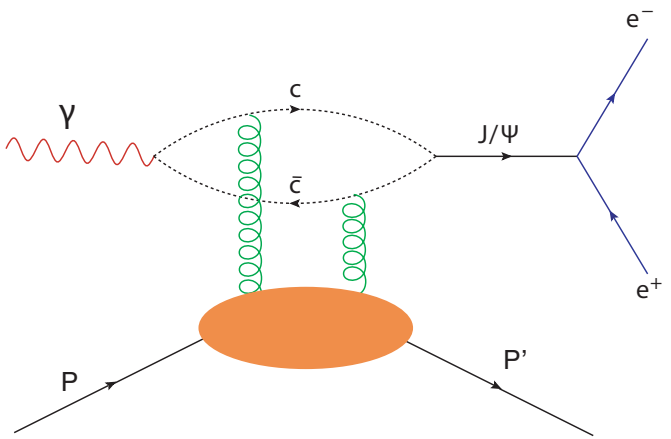




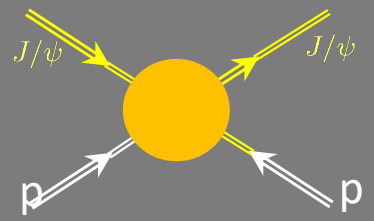
C. Peng, S. Joosten

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

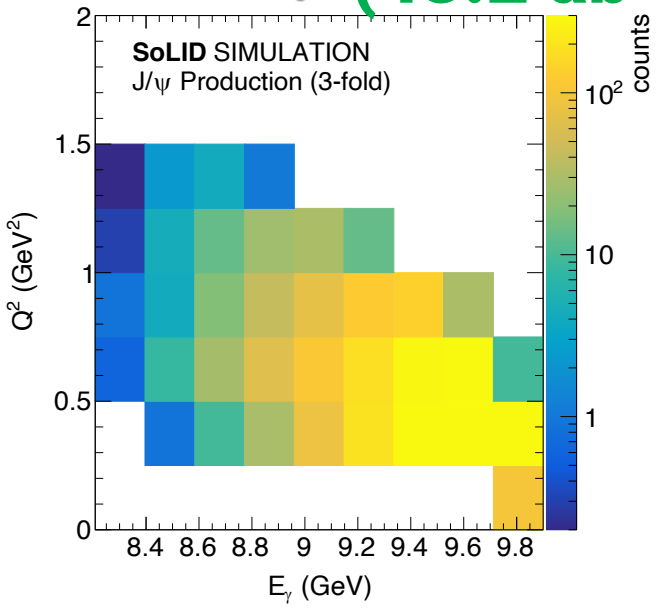
$$\sigma^{tot}_{\psi p} = \sigma^{el}_{\psi p} + \sigma^{inel}_{\psi p}$$

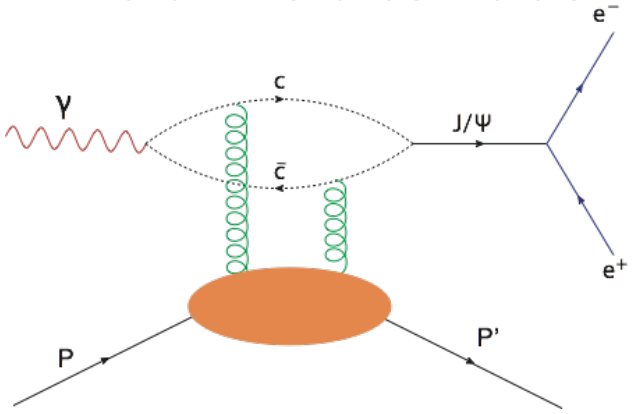
$$\sigma^{el}_{\psi p} \propto C_{el}\left(1 - \frac{\nu_{el}}{\nu}\right)^{b_{el}}\left(\frac{\nu_{el}}{\nu}\right)^{a_{el}}$$

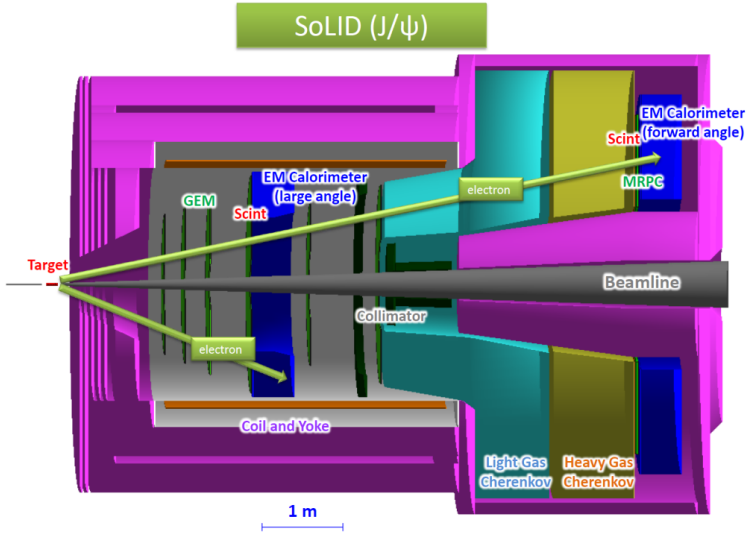
$$\sigma^{inel}_{\psi p} \propto C_{in}\left(1 - \frac{\nu_{in}}{\nu}\right)^{b_{in}}\left(\frac{\nu_{in}}{\nu}\right)^{a_{in}}$$

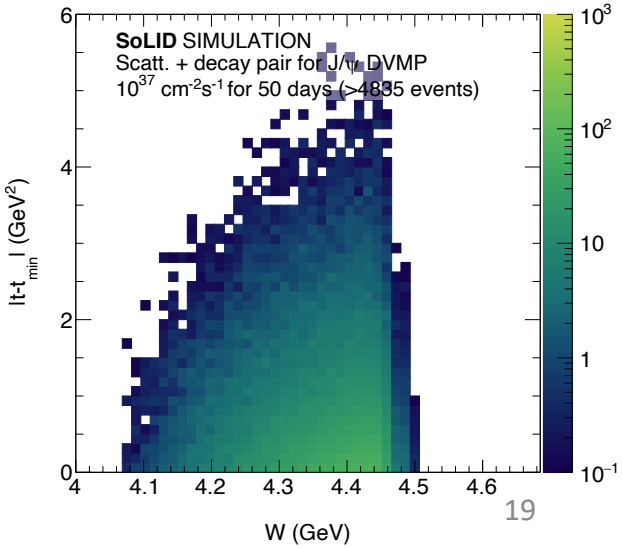
J/ψ experiment E12-12-006 at SoLID

- 50 days of $3\,\mu\mathrm{A}$ beam on a 15 cm long LH_2 target at $1 \times 10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ **(43.2 ab^{-1})**
  - 10 more days include calibration/background run
- SoLID configuration overall compatible with SIDIS with small changes
- 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^-)









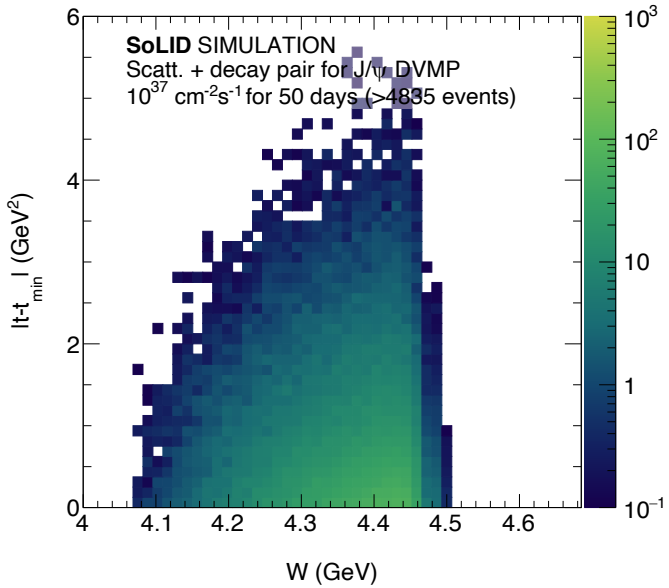
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

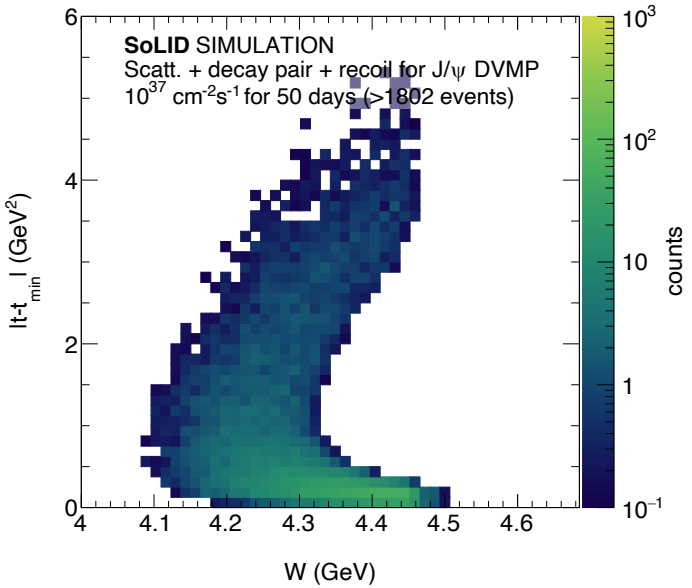
Event Counts @ $1x10^{37}$ in 50 days

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

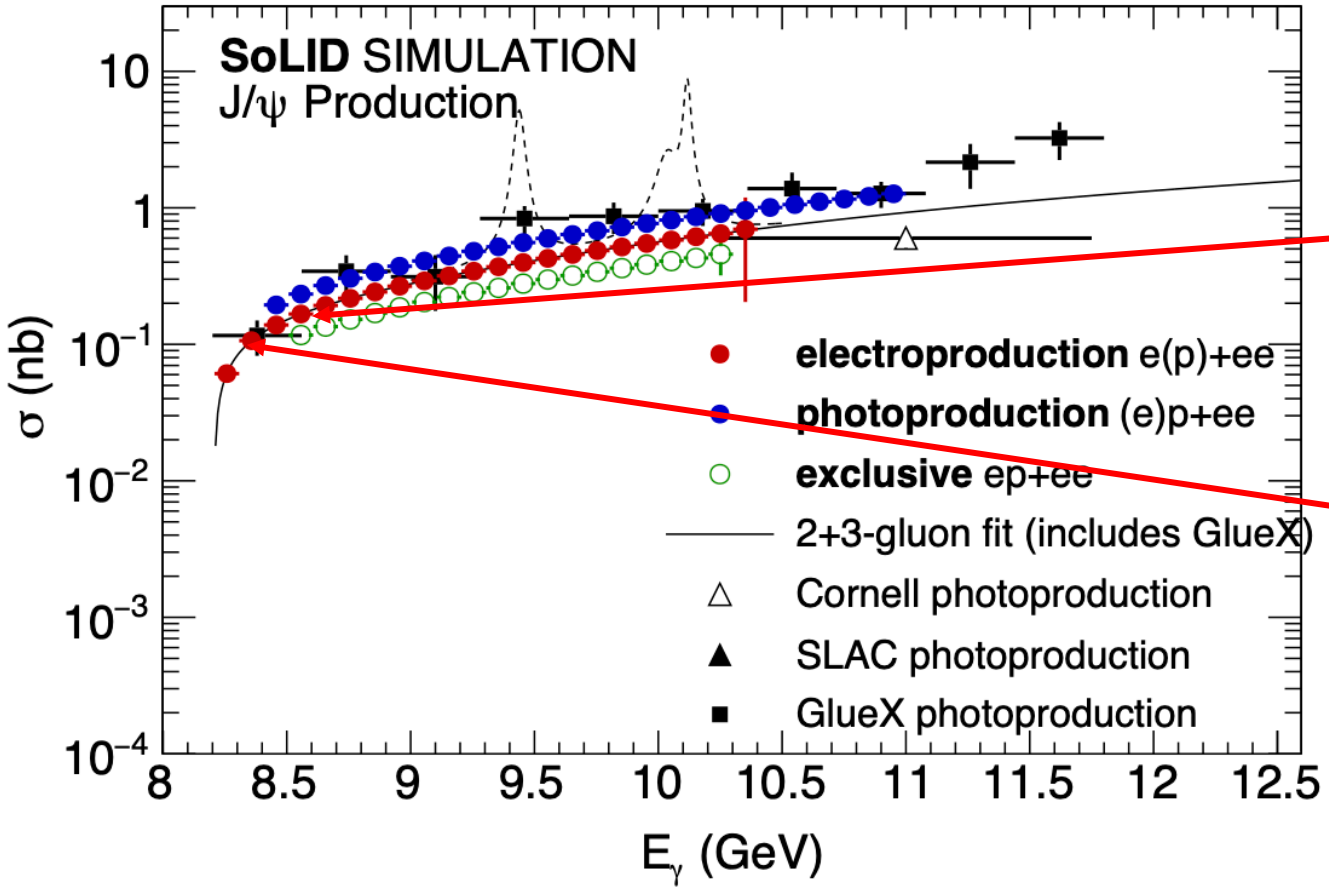


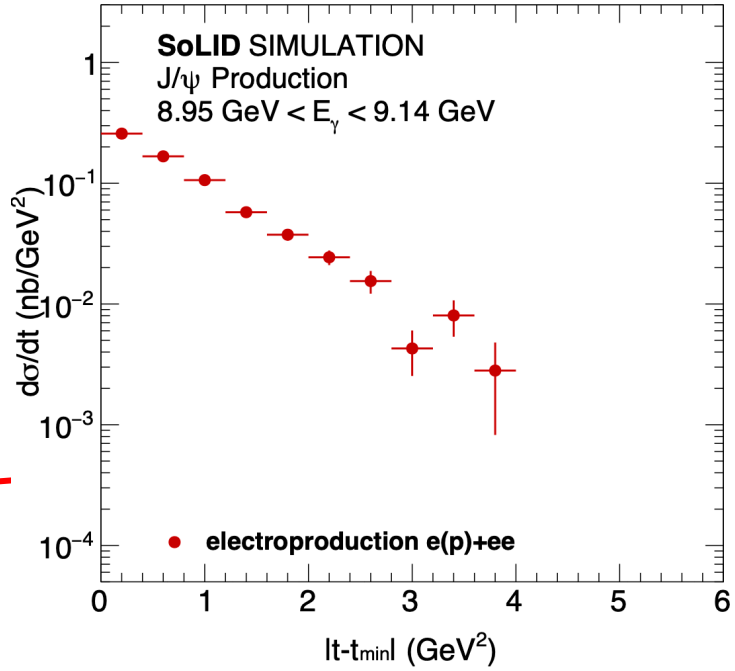


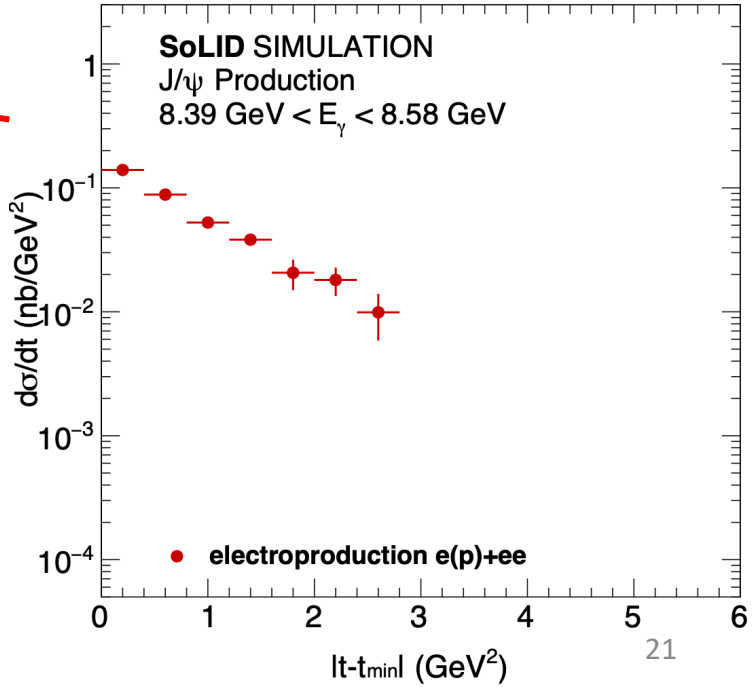
4-fold

Argonne NATIONAL LABORATORY

J/Psi Experiment E12-12-006 @ SoLID





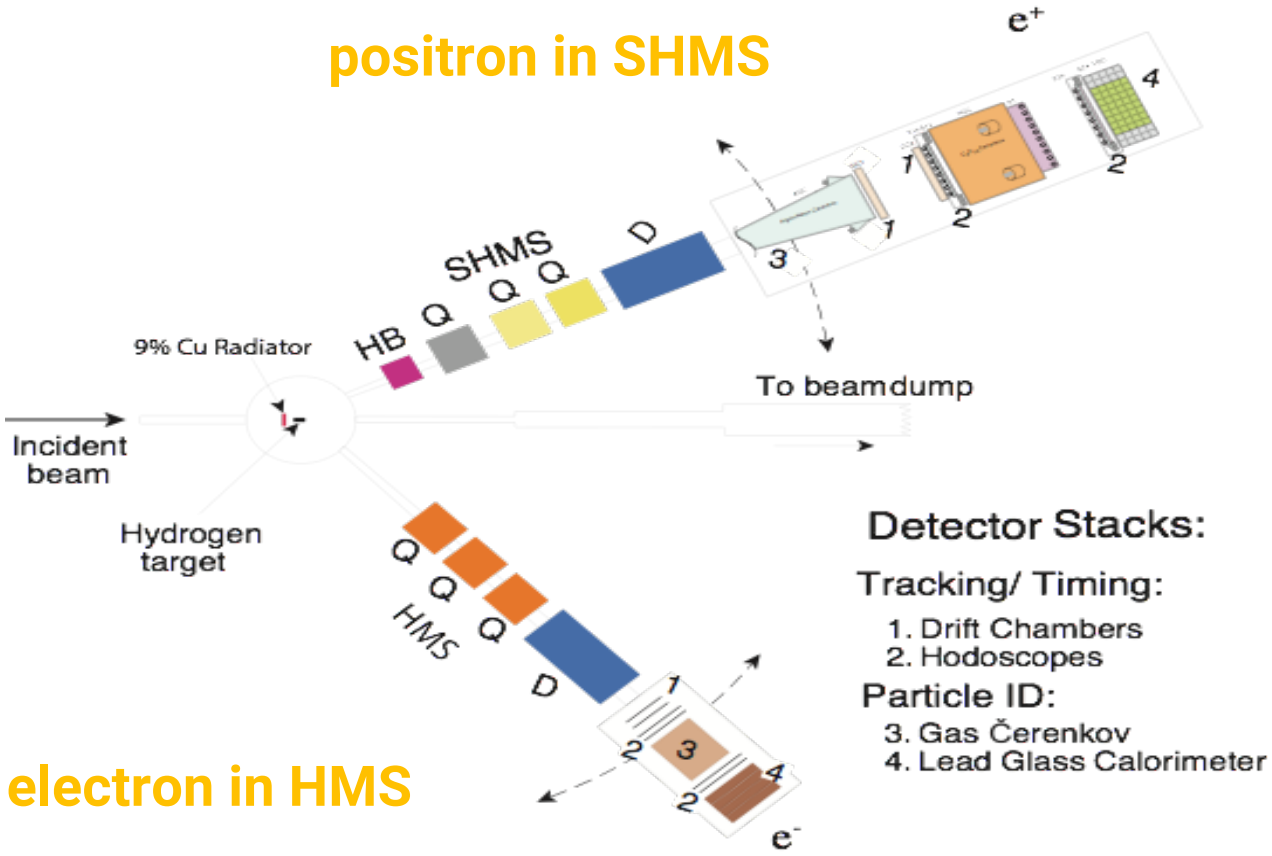


Sensitivity at about 10^{-3} nb!

Search for the LHCb pentaquark

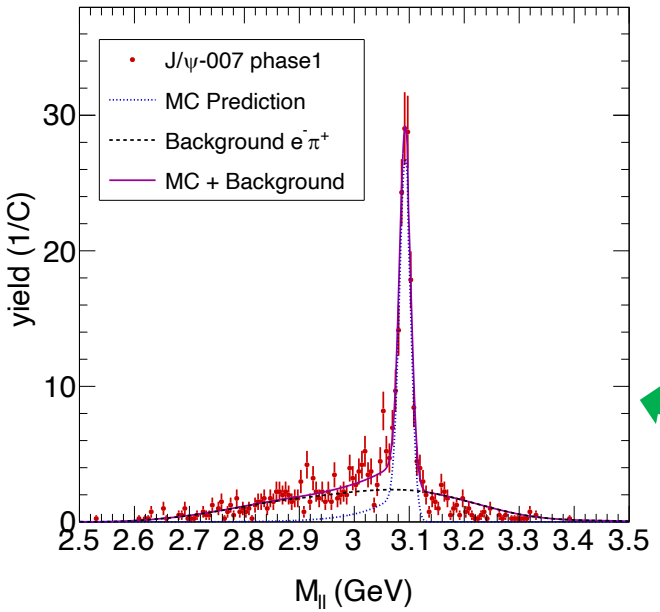
- 50μA electron beam at 10.7 GeV (or 11 GeV)
- 9% copper radiator
- 15cm liquid hydrogen target
  - **total 10% RL**

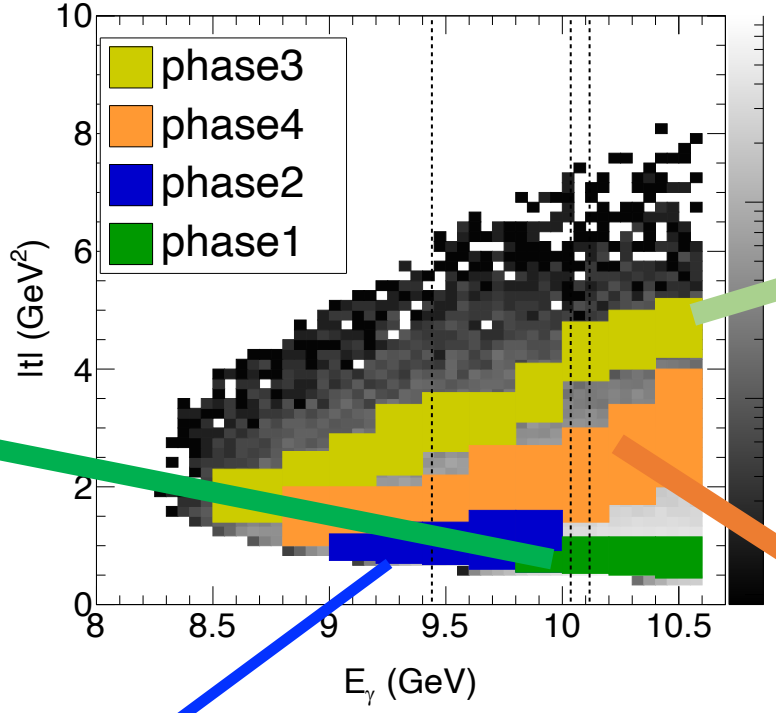
JLab Experiment 12-16-007 in **Hall C**

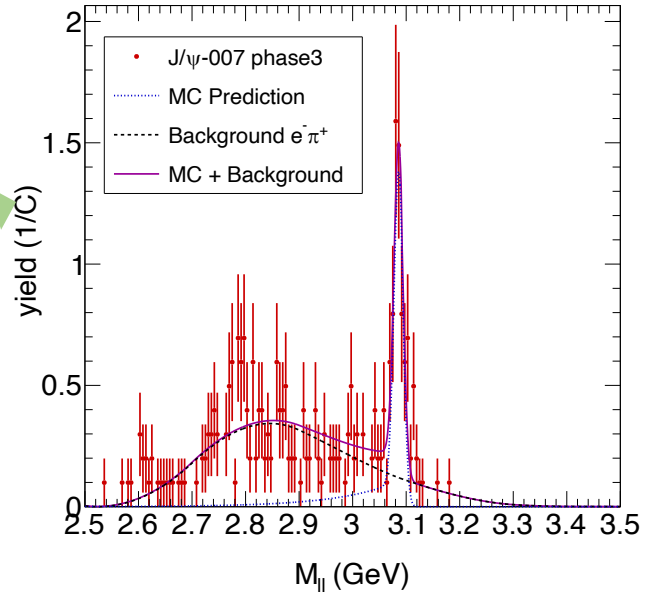


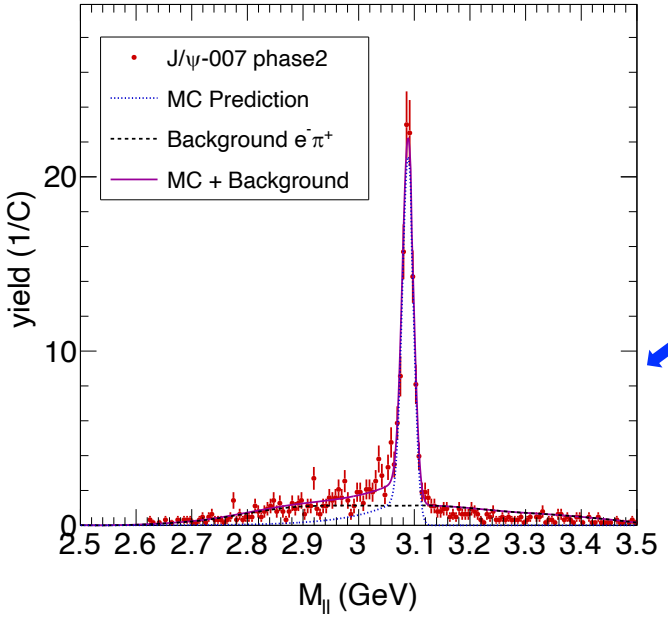
- **Run with 2 settings:**
  - **"SIGNAL" Setting** (9 days): minimizes accidentals and **maximizes signal/background**:
    - HMS: 34°, 3.25 GeV electrons
    - SHMS: 13°, 4.5 GeV positrons
  - **"BACKGROUND" Setting:** (2 days): precise determination of the ***t*-channel background**
    - HMS: 20°, 4.75 GeV electrons
    - SHMS: 20°, 4.25 GeV positrons

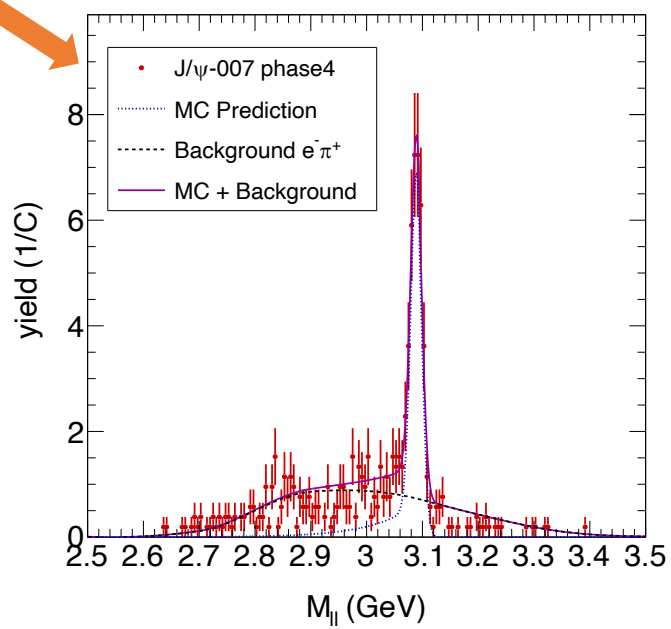
Leptons pair invariant mass





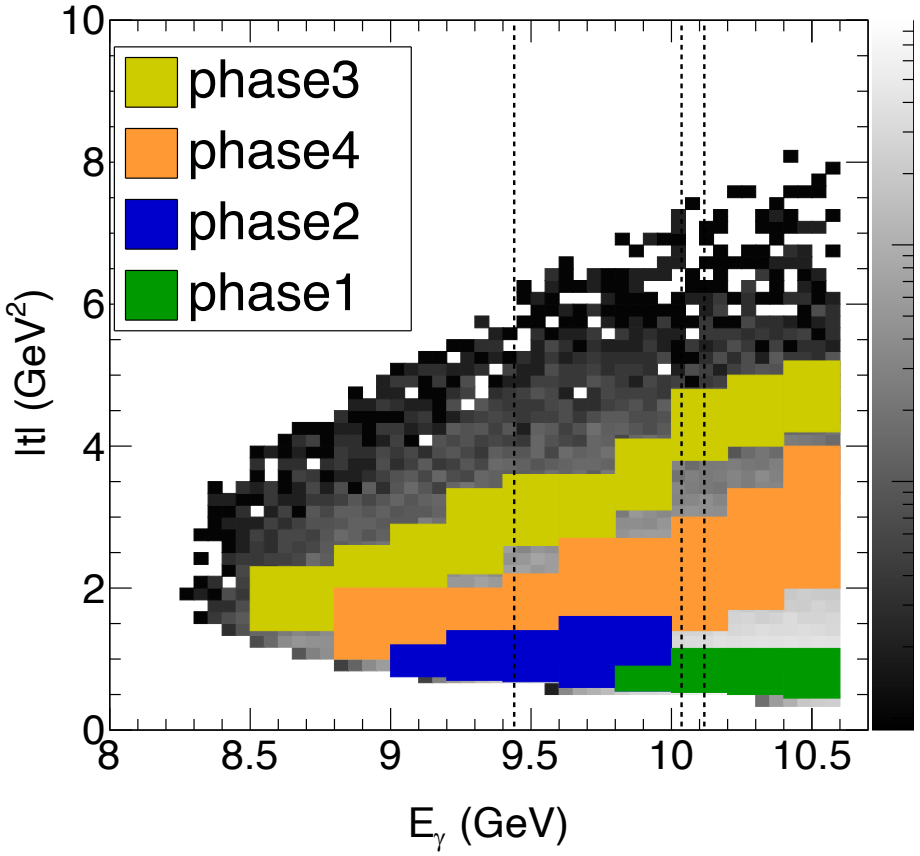


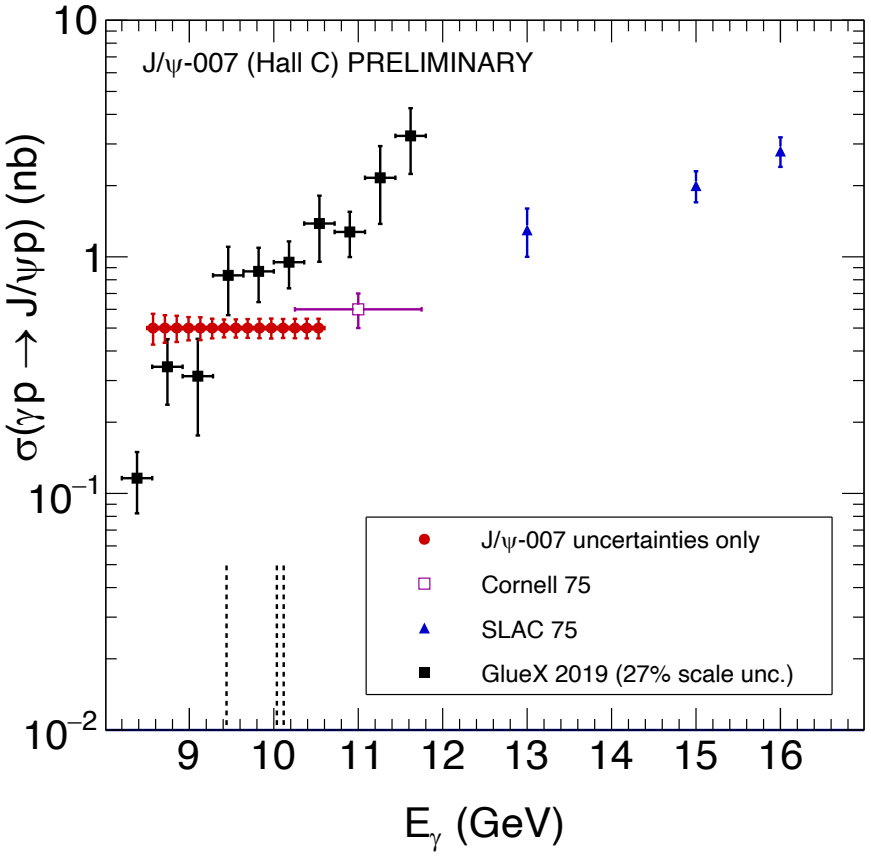




- Experiment ran in February 2019
- Good coverage of *t* dependence
- Largest dataset of J/psi produced with a real photon beam

Kinematic phase space and expected precision





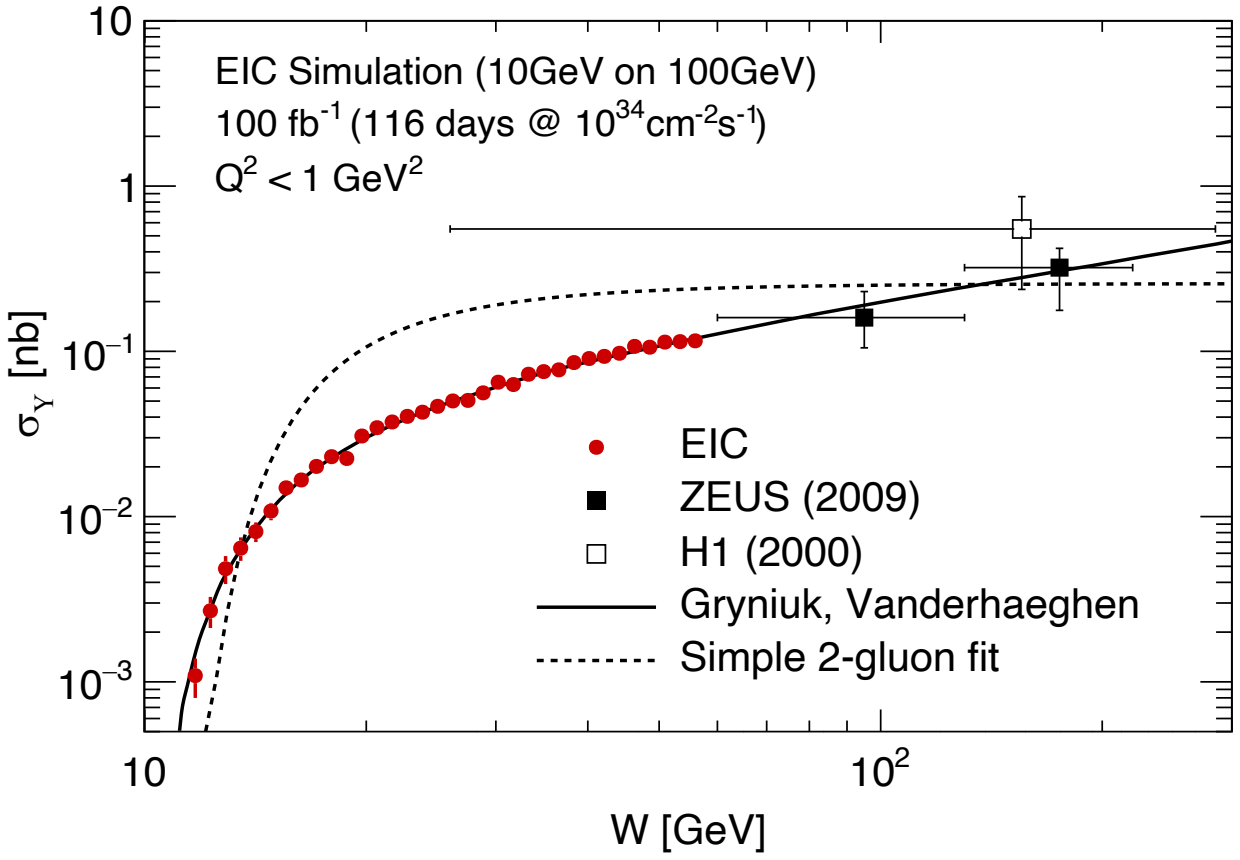
Quarkonia at an EIC

- J/Psi production at large W is used as a tool for gluon imaging
  - NLO calculations exist but point to large corrections, further work is underway
  - It would be important to use Upsilon to access gluons, the heavier mass of the bottom helps suppress NLO corrections.

- What an EIC offers in the threshold region using upsilon is unique and complementary to JLab12.
  - Q^2 dependence study in electroproduction of *Upsilon* at threshold is possible with an EIC allowing an easier interpretation
  - Direct search for “bottom pentaquarks” if they exist.

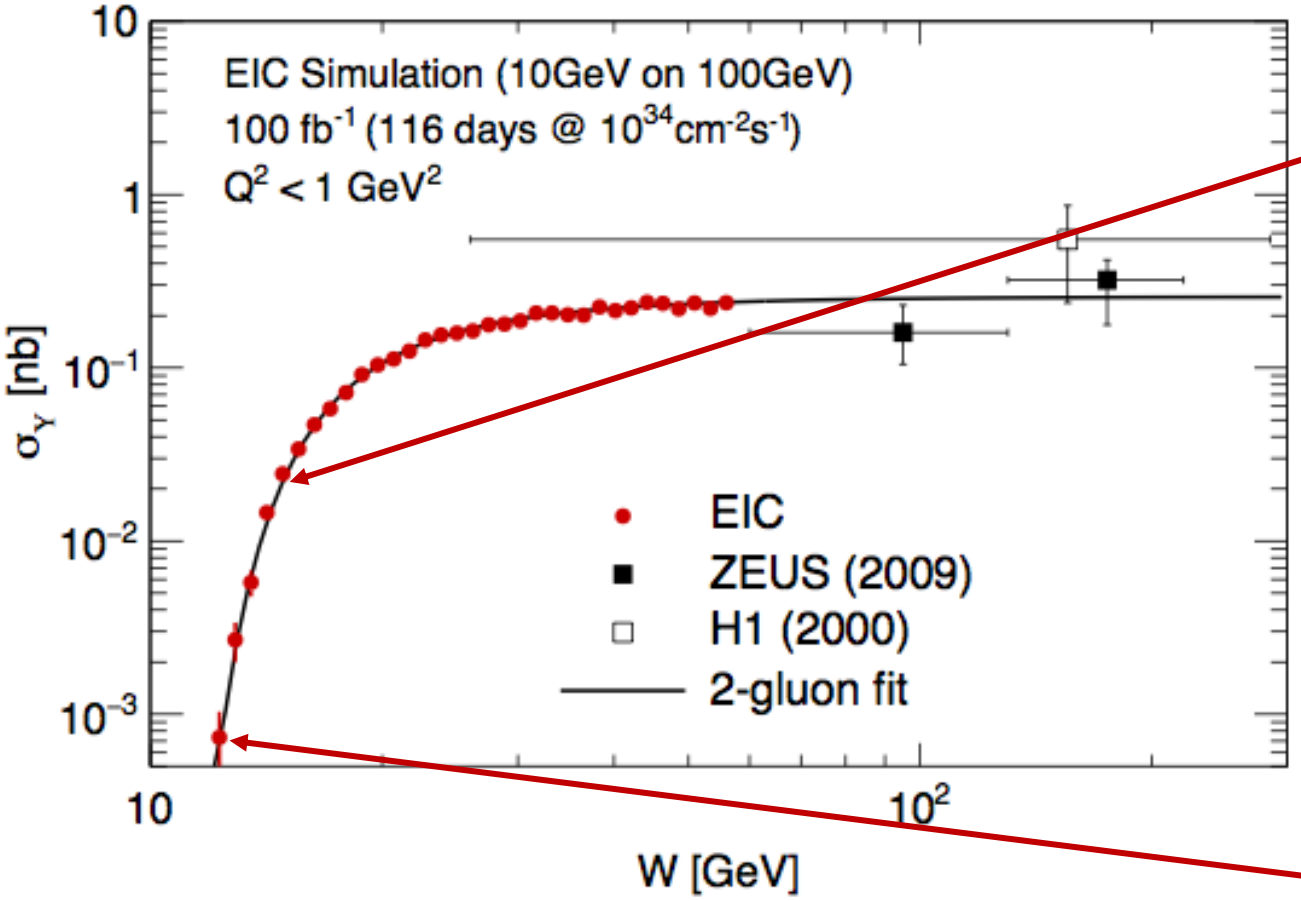
Y photo-production at an EIC

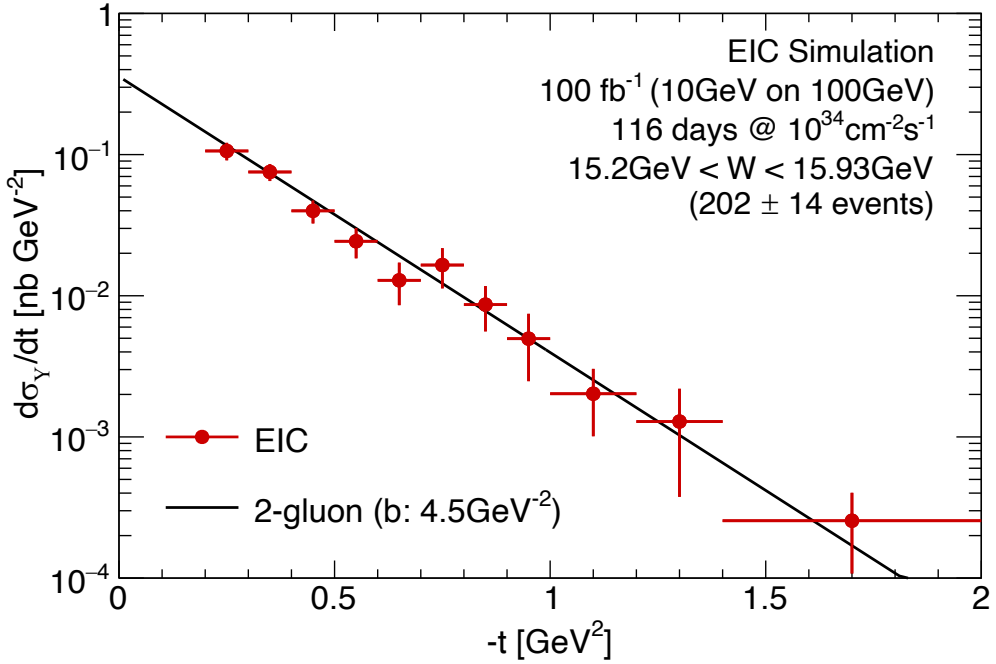
- **Quasi-real production at an EIC**
- **Using nominal EIC detector (consistent with white paper)**
  - **Both electron and muon channel**
- **Fully exclusive reaction**
- **Can go to near-threshold region**

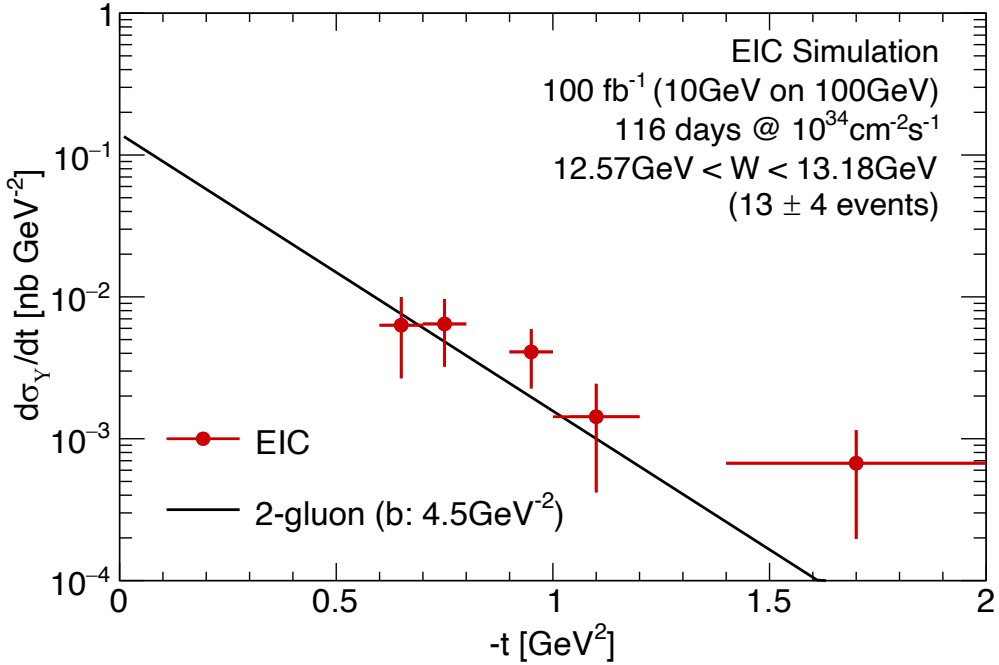


- ***Y(1s)*** production possible at threshold!
  - Provides measure for **universality**, complimentary to threshold *J/ψ* program at JLab12
  - Is there a "beautiful" pentaquark?
- **Sensitivity down to ~10^{-3} nb!**

Elastic Upsilon production at an EIC







S. Jossten

Conclusions

- Heavy quarkonia production is an important tool for probing the gluonic fields in the nucleon
- It enables the exploration of possible existence of charm and bottom pentaquarks and heavy quarkonia bound states in nuclei.
- At large W it allows access to the gluonic GPDs, at threshold it might shed light on the trace anomaly thus the proton mass
- Direct lattice calculations of the two independent parts of the trace anomaly are an important step towards understanding the proton mass
- JLab 12 and the EIC are poised to contribute significantly to these topics