Heavy Quarkonia Production at Threshold from Jlab to EIC

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with thanks to Jianwei Qiu, Barbara Pasquini, Marc Vanderhaeghen

Outline:

- The science enabled by heavy quarkonia
- Threshold production of quarkonia on the nucleon
- Summary

What are some of the science questions?

- What is the origin of hadron masses?
  - A case study: the proton together with the pion
- What is the size of the interaction between a quarkonium and a proton
- Do heavy quarkonia enable pentaquarks to exist?
- Are bound states of quarkonia in nuclei possible?

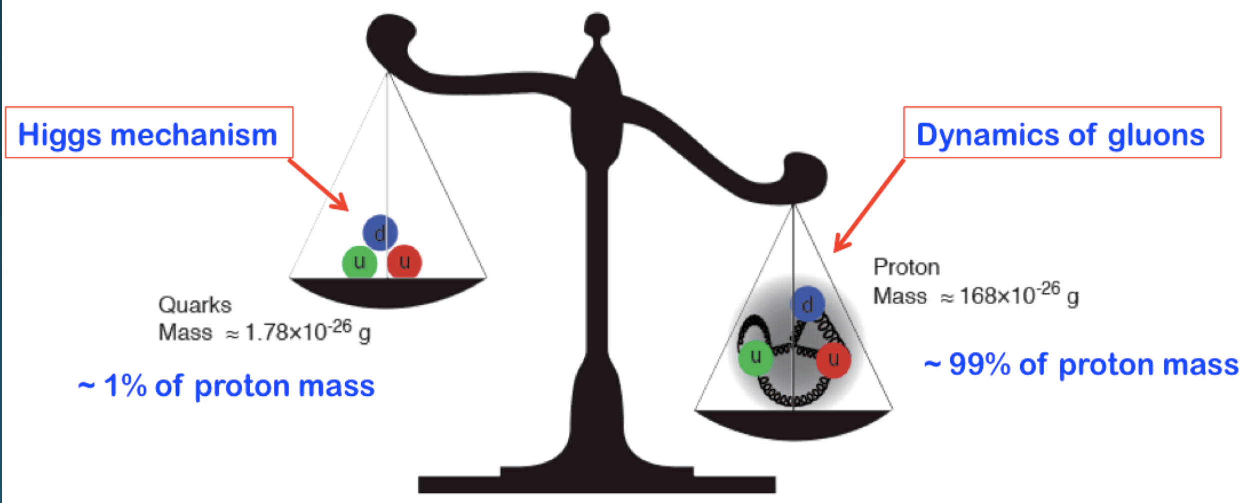
How does QCD generate its Mass & Spin?

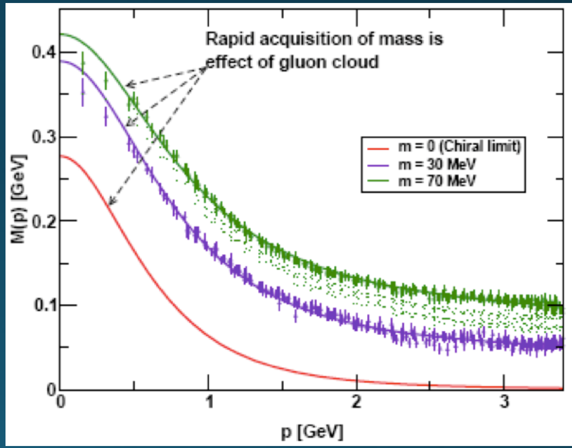
"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass Frank Wilczek (1999, Physics Today)

Close examples in nature: proton, blackhole

✧ Massless, yet, responsible for nearly all visible mass

"Mass without mass!"





Bhagwat & Tandy/Roberts et al

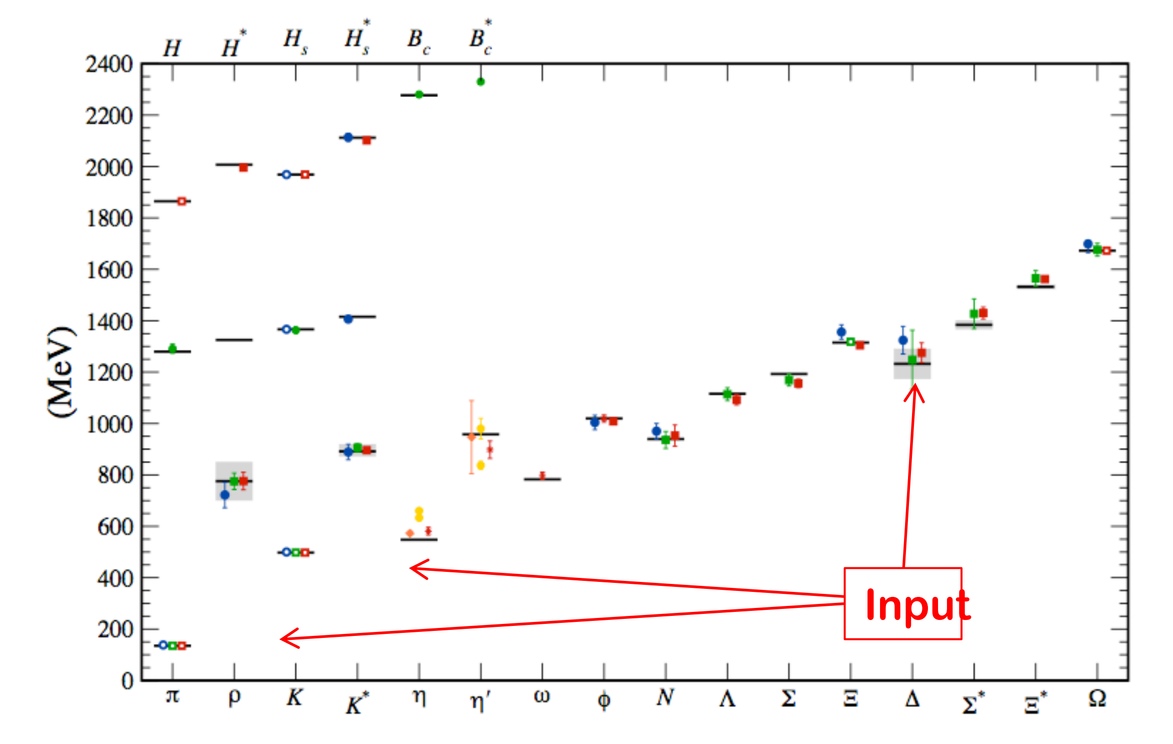
What Susskind has to say about proton mass and the Higgs mechanism.

- https://youtu.be/JqNg819PiZY?t=2403

How does QCD generate the nucleon mass?

"… 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. …" ***The 2015 Long Range Plan for Nuclear Science***

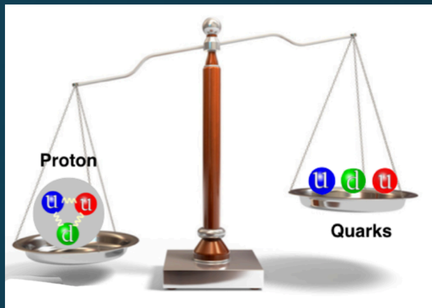
❑ Hadron mass from Lattice QCD calculation:



How does QCD generate this? The role of quarks vs that of gluons?

If we do not understand proton mass, we do not understand QCD

How does QCD generates the nucleon mass?



❑ Role of quarks and gluons?

✧ **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \frac{1}{2}\bar{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4}g^{\mu\nu}F^2 - F^{\mu\alpha}F^{\nu}_{\alpha}$$

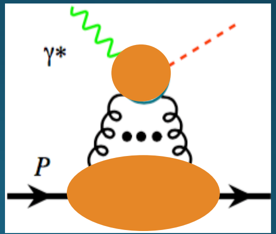
✧ Trace of the QCD energy-momentum tensor:

$$T^{\alpha}_{\alpha} = \underbrace{\frac{\beta(g)}{2g}F^{\mu\nu,a}F^{a}_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q$$

$$\beta(g) = -(11 - 2n_f/3)g^3/(4\pi)^2 + \ldots$$

✧ **Mass, trace anomaly, chiral symmetry breaking, …**

$$m^2 \propto \langle p|T^{\alpha}_{\alpha}|p\rangle \xrightarrow{\text{Chiral limit}} \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$



➡ Heavy quarkonium production near the threshold, from JLab12 to EIC

How does QCD generate nucleon mass?

- **Four-pronged approach to explore the origin of hadron mass**
  - Lattice QCD
  - Mass decomposition – roles of the constituents
  - Model calculation – approximated analytical approach
  - Measurements of the parts in a decomposition

https://phys.cst.temple.edu/~meziani/proton-mass-workshop-2016/

How does QCD generate its Mass & Spin?

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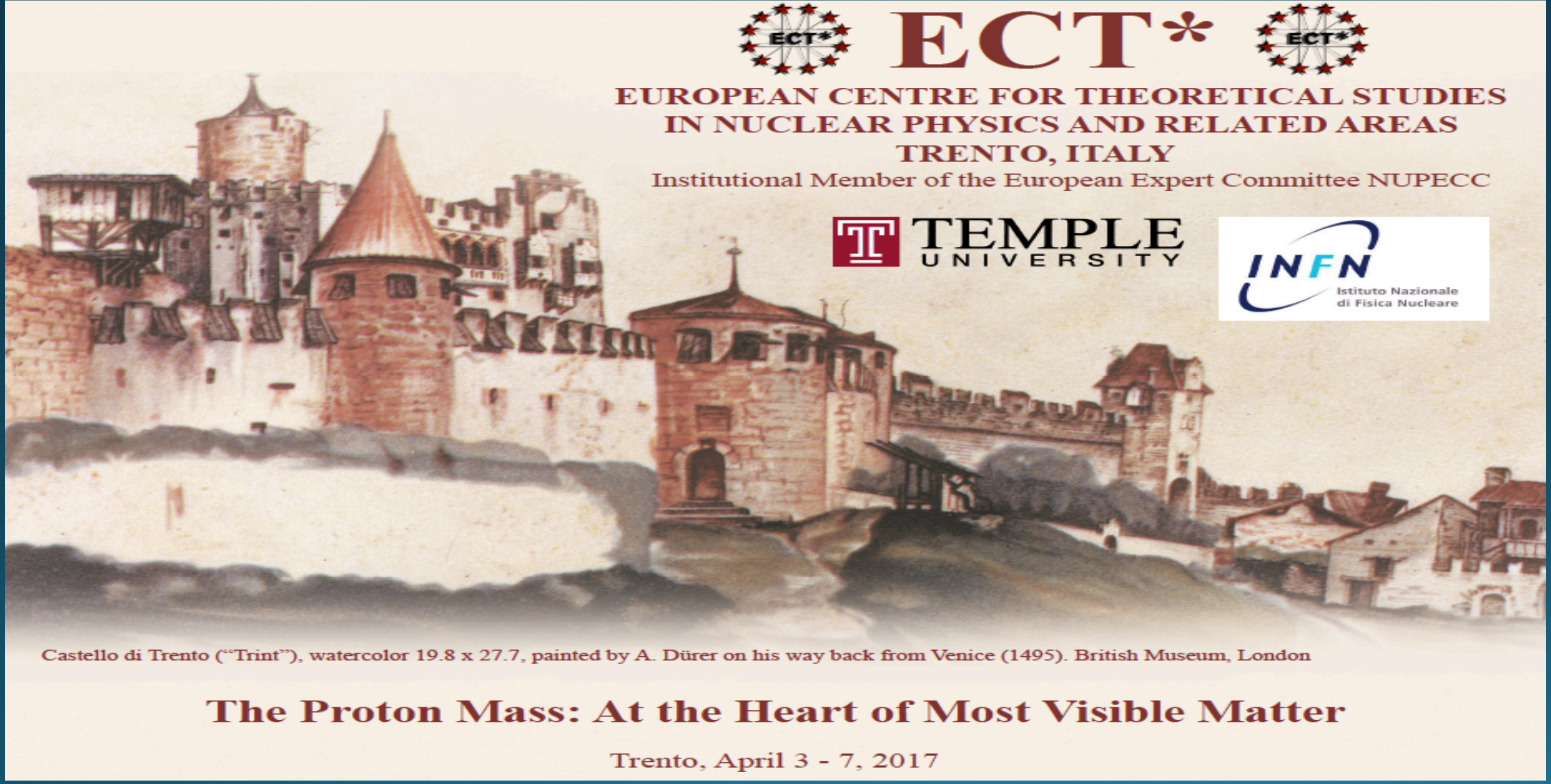
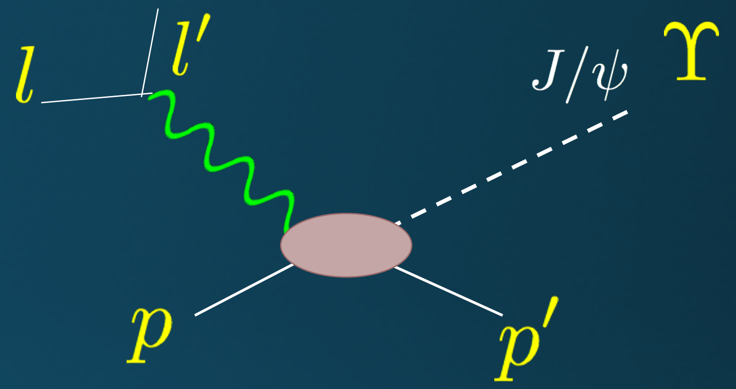


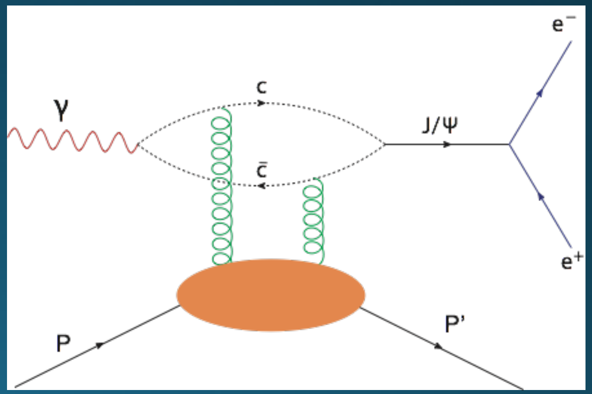
http://www.ectstar.eu/node/2218

Experimental Tools: Exclusive Production of Quarkonia at Jlab and an EIC

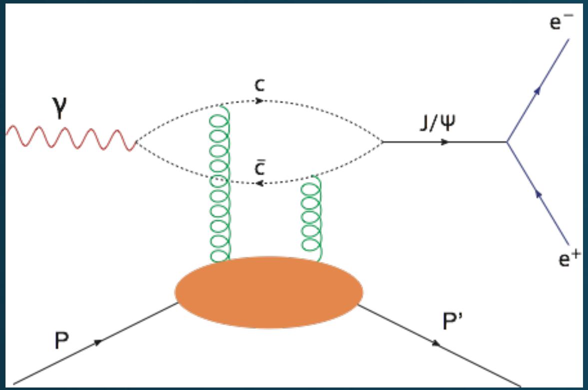
Virtual Meson Production of J/Psi and Upsilon at Threshold (VMP)



- At JLab we can measure the threshold region in photo and electro-production of J/ ψ in fixed target experiments in 4 halls.
- Depending on the experimental set-up we have:
  - A fully exclusive measurement with the detection of all final state particles in some cases.
  - Detection of the J/ψ decay lepton pair alone with the scattered electron in case of electroproduction or the decay pair together with the proton
  -
- At an EIC we can detect the the scattered lepton and the J/ψ decay pair of leptons. Detecting the proton is challenging.



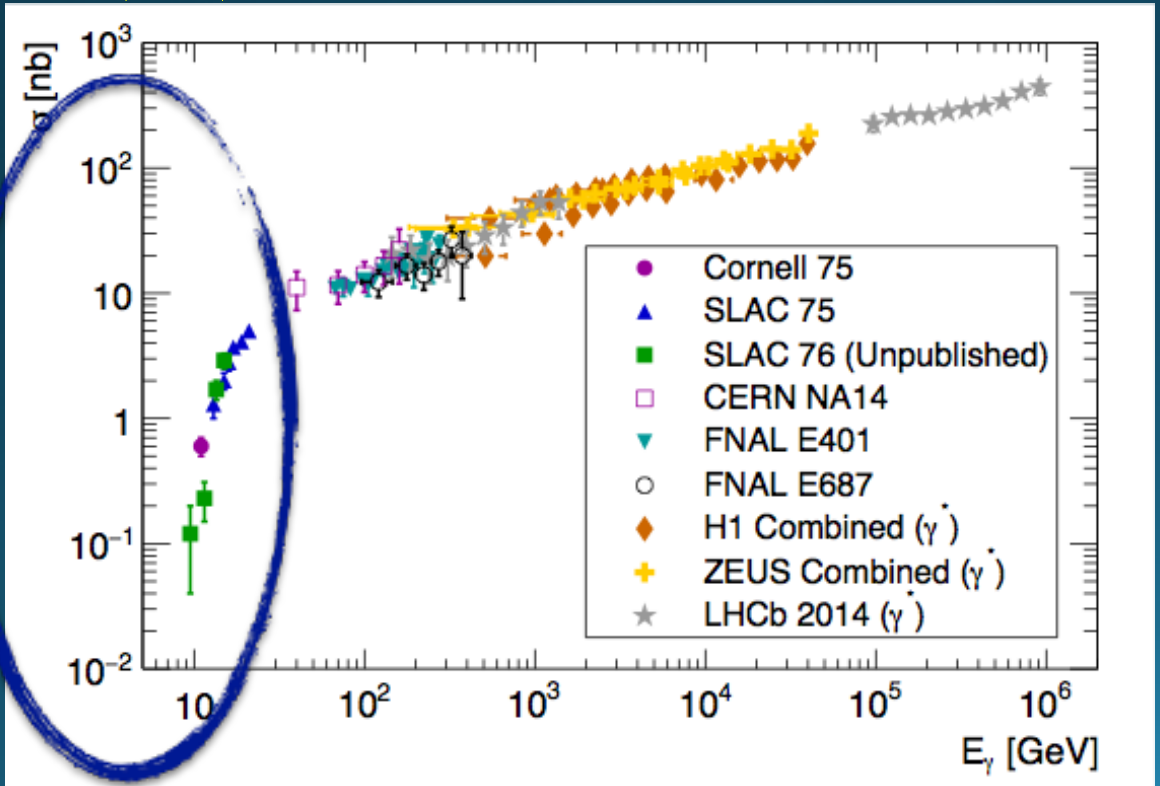
J/ψ Photo-production: What do we know?

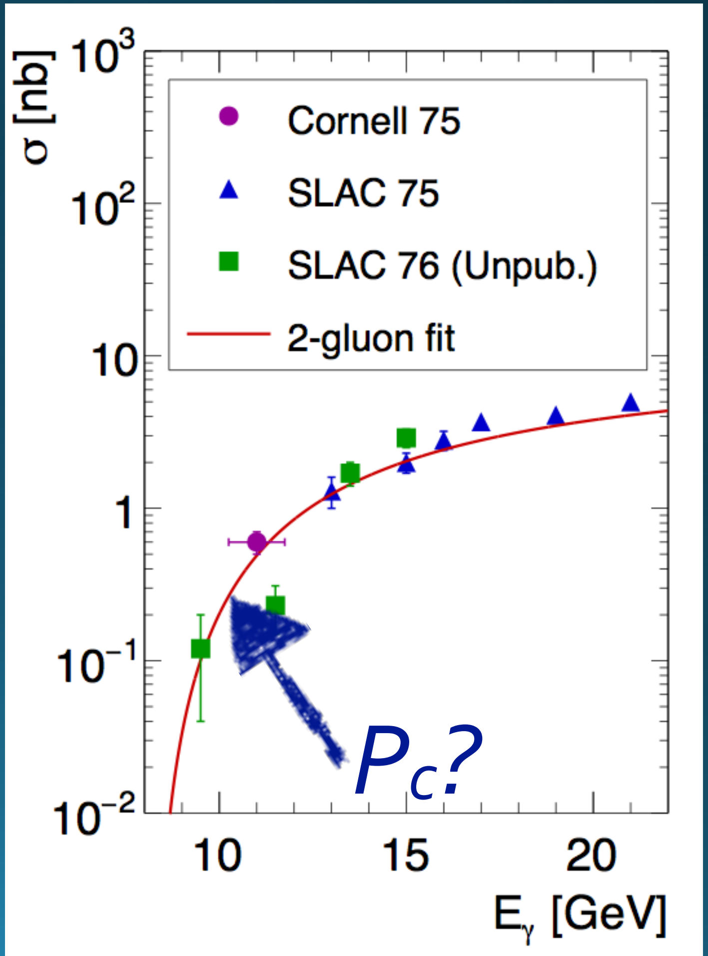


t-channel

Brodsky S J, *et al.*, PLB 498-1 (2001), p23

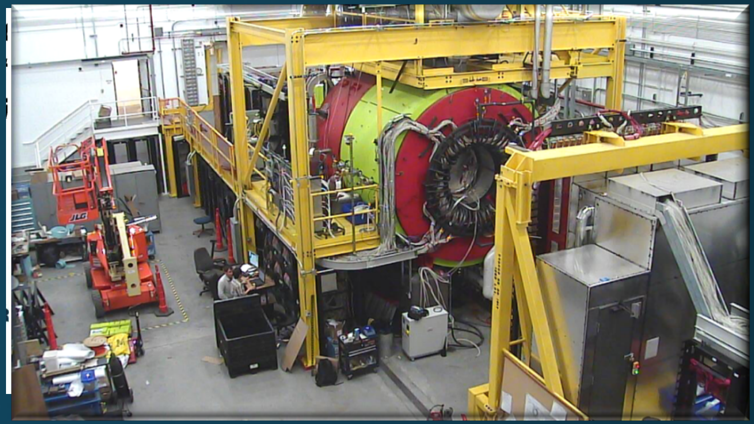
- Cross section well constrained above 100 GeV
- **Almost no data near-threshold**
- Resolution of the existing measurements too low
- 2 of the 3 lowest points unpublished!

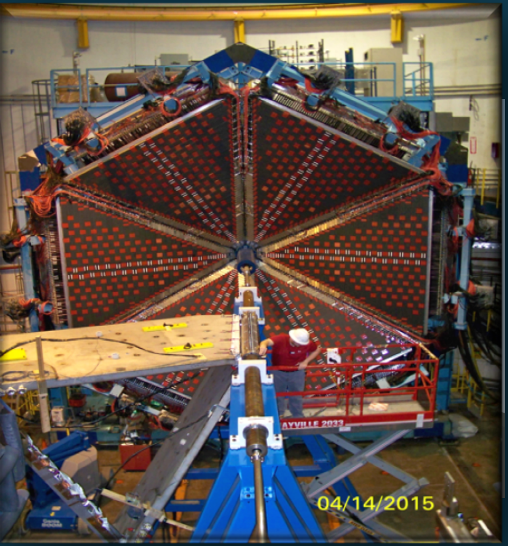




12 GeV J/Ψ experiments at JLab Overview

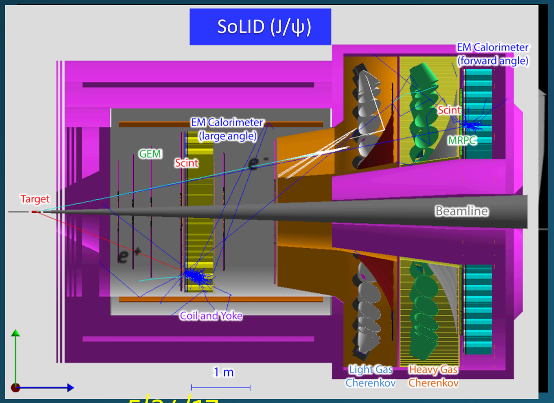
*Hall D – GlueX has observed the **first** J/ψs at Jlab*





*Hall B – Has an approved proposal to measure TCS + J/psi in phot-production **E12-12-001***

*Hall C – has an approved proposal **to search for the LHCb pentaquark E12-16-007***



*Hall A-has an approved proposal involving a future detector of high luminosity capabilities -**SoLID** **E12-12-006***

Interaction between J/ψ-N

- New scale provided by the charm quark mass and size of the J/ψ
  - OPE, Phenomenology, Lattice QCD …
- High Energy region: Pomeron picture …
- Medium/Low Energy: 2-gluon exchange
- Very low energy: QCD color Van der Waals force
  - Prediction of J/ψ-Nuclei bound state
    - Brodsky et al. ….
- LHCb charm pentaquark?….

- Experimentally no free J/ψs are available
  - Challenging to produce close to threshold!
  - **Photo/electro-production of J/ψ at JLab is a special opportunity**

Some references

Q. Wang, X.-H. Liu, and Q. Zhao, "Photoproduction of hidden charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$," *Phys. Rev.* **D92** (2015) 034022, arXiv:1508.00339 [hep-ph].

M. Karliner and J. L. Rosner, "Photoproduction of Exotic Baryon Resonances," *Phys. Lett.* **B752** (201 329–332, arXiv:1508.01496 [hep-ph].

V. Kubarovsky and M. B. Voloshin, "Formation of hidden-charm pentaquarks in photon-nucleon collisions," *Phys. Rev.* **D92** no. 3, (2015) 031502, arXiv:1508.00888 [hep-ph].

F.-K. Guo, U.-G. Meiner, W. Wang, and Z. Yang, "How to reveal the exotic nature of the $\mathrm{P}_c(4450)$," *Phys. Rev.* **D92** no. 7, (2015) 071502, arXiv:1507.04950 [hep-ph].

A. N. H. Blin, C. Fernndez-Ramrez, A. Jackura, V. Mathieu, V. I. Mokeev, A. Pilloni, and A. P. Szczepaniak, "Studying the $\mathrm{P}_c(4450)$ resonance in J/ψ photoproduction off protons," *Phys. Rev.* **D94** no. 3, (2016) 034002, arXiv:1606.08912 [hep-ph].

Jefferson Lab Experiment E12-12-006, Co-spokespersons, K. Hafidi, Z.-E. Meziani (contact person), X. Qian, N. Sparveris and Z. Zhao, PAC40 https://www.jlab.org/exp_prog/proposals/12/PR12-12-006.pdf.

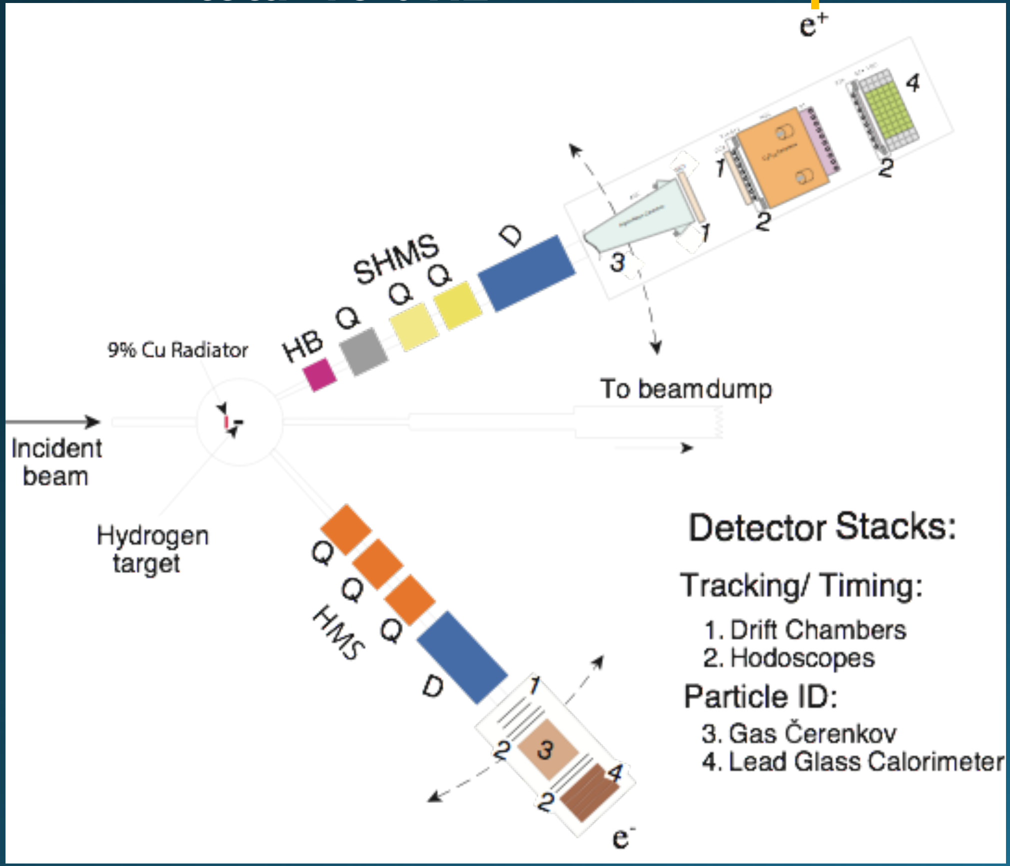
Y. Huang, J. He, H.-F. Zhang, and X.-R. Chen, "Discovery potential of hidden charm baryon resonances via photoproduction," *J. Phys.* **G41** no. 11, (2014) 115004, arXiv:1305.4434 [nucl-th].

CERN Press Office, "CERN's LHCb experiment reports observation of exotic pentaquark particles," *http://press.cern/press-releases/2015/07/cerns-lhcb-experiment-reports-observation-exotic-pentaquark-particles* (2015) .

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**

positron in SHMS

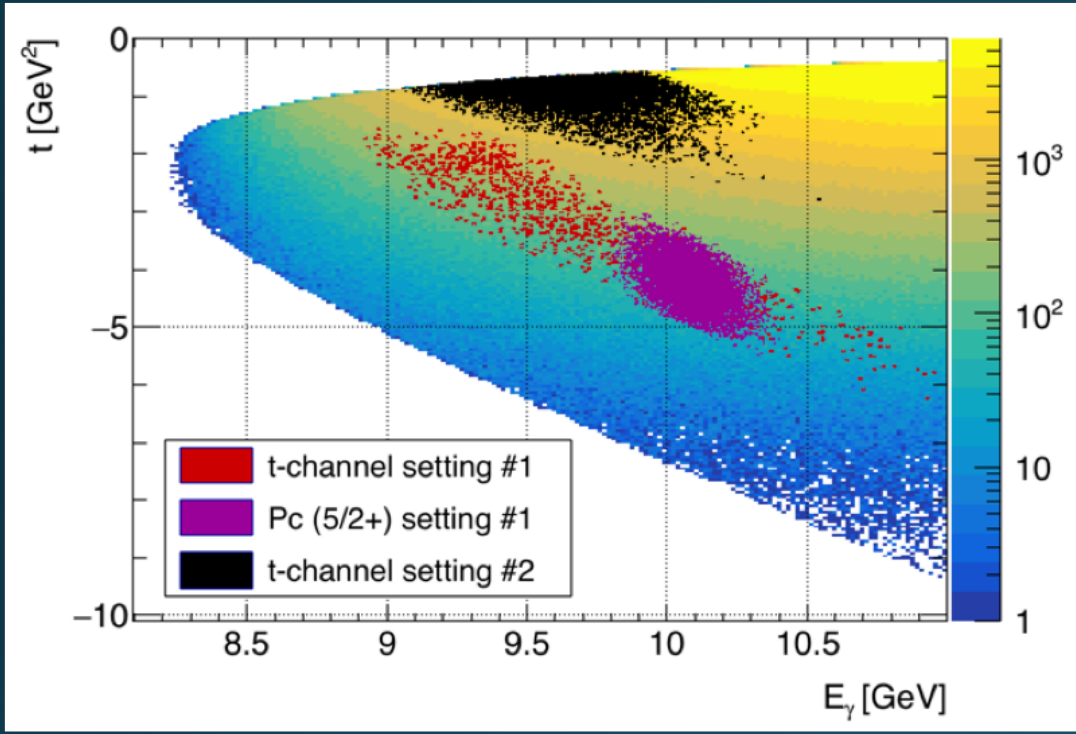


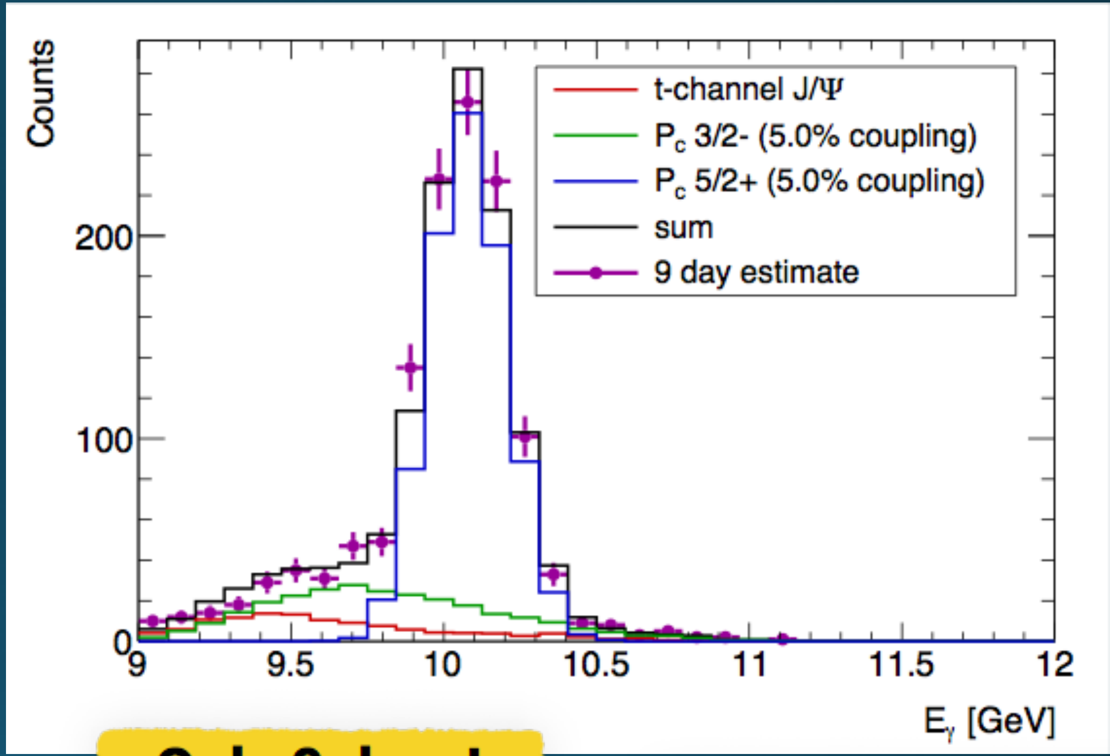
electron in HMS

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

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

Search for the LHCb pentaquark





Only 9 days!

Significance > 20σ!

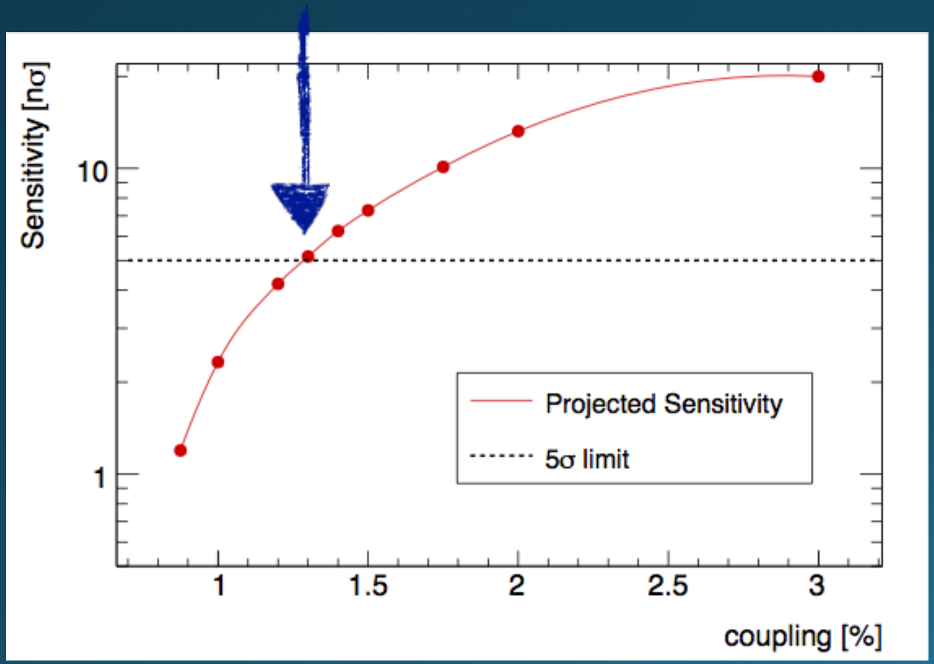
t-channel: 120 events
5/2+: 881 events
3/2-: 266 events

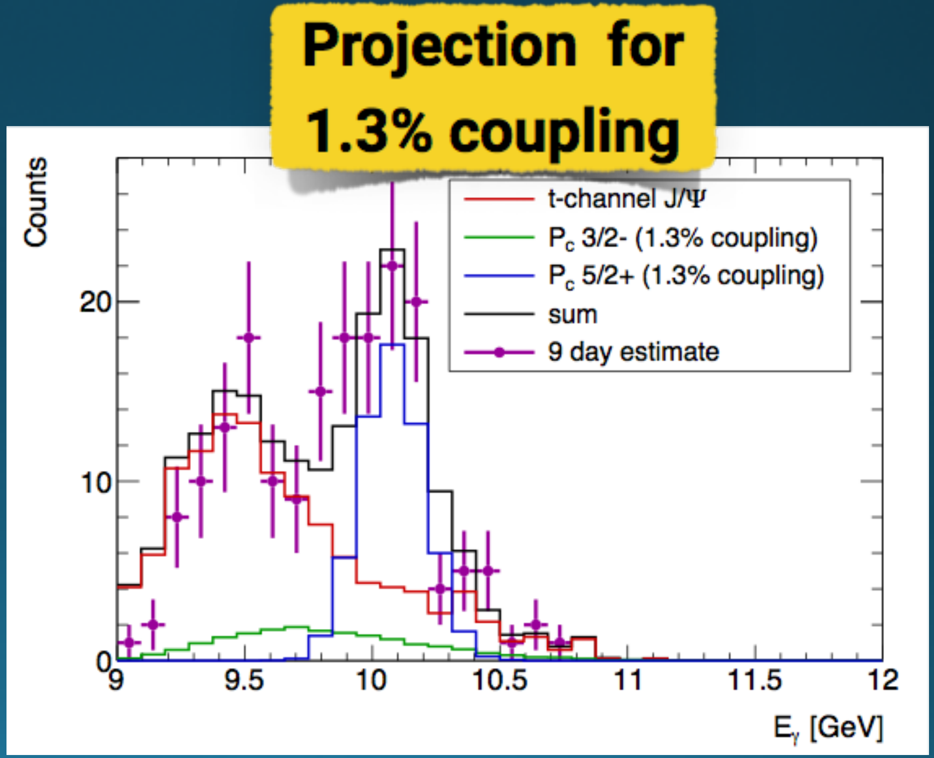
- **assuming 5% coupling** (value favored by existing photo-production data)
- 9 days of beam time at 50μA
- 5/2+ peak **dominates the spectrum**

Wang Q., *et al.*, PRD 92-3 (2015) 034022-7

Sensitivity for **Discovery**

- sensitivity calculated using a Δ-log-likelihood formalism
- **5 standard deviation** level of sensitivity **starting from 1.3% coupling!**



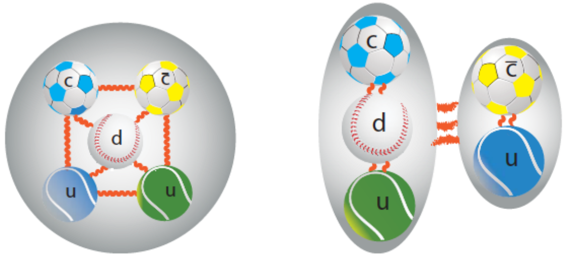


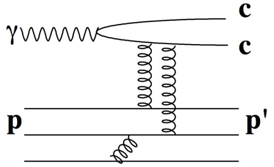
Search for *hidden charmed pentaquarks* and study of *gluonic structure* of the nucleon

What is the exact nature of *charmed pentaquark* states discovered by LHCb collaboration at CERN

$$P_c \Rightarrow J/\psi\, p$$

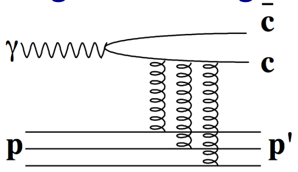
5-quark bound state or **Hadronic molecule**

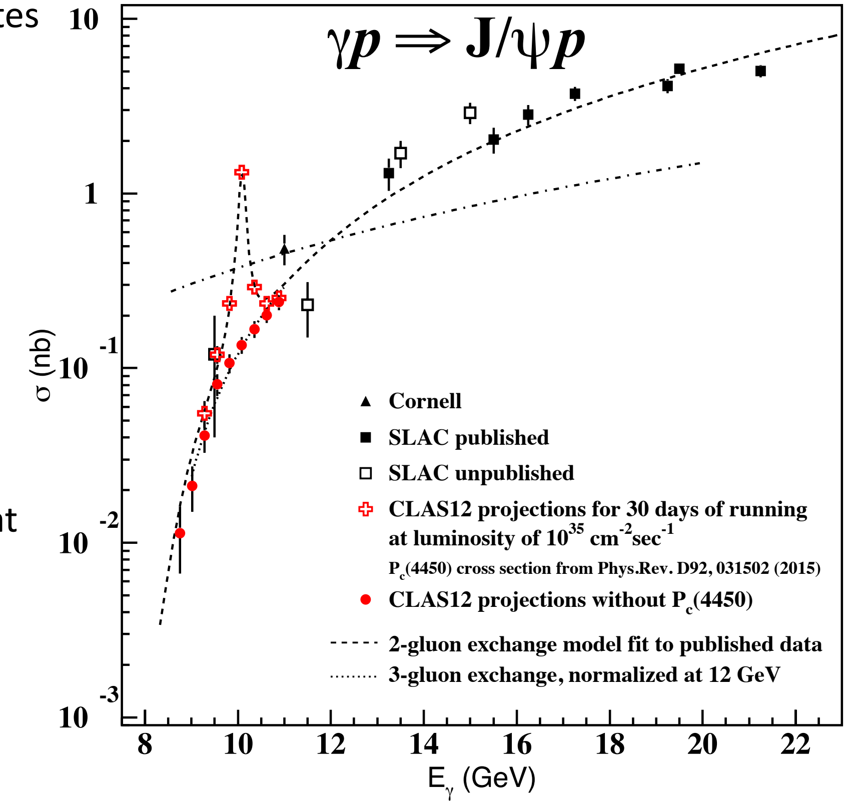




What is the mechanism of charmonium production at the threshold

2-gluon or **3-gluon exchange**



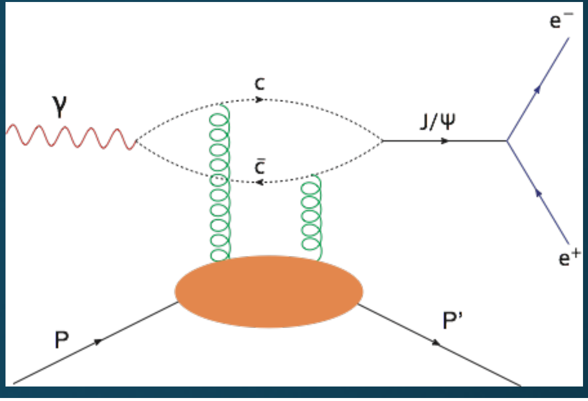


Experiment E12-12-001 measures J/ψ production on the proton near threshold – will verify existence of the ***charmed pentaquarks*** and will study ***the gluon field of the nucleon***

JLAB experiment E12-12-001

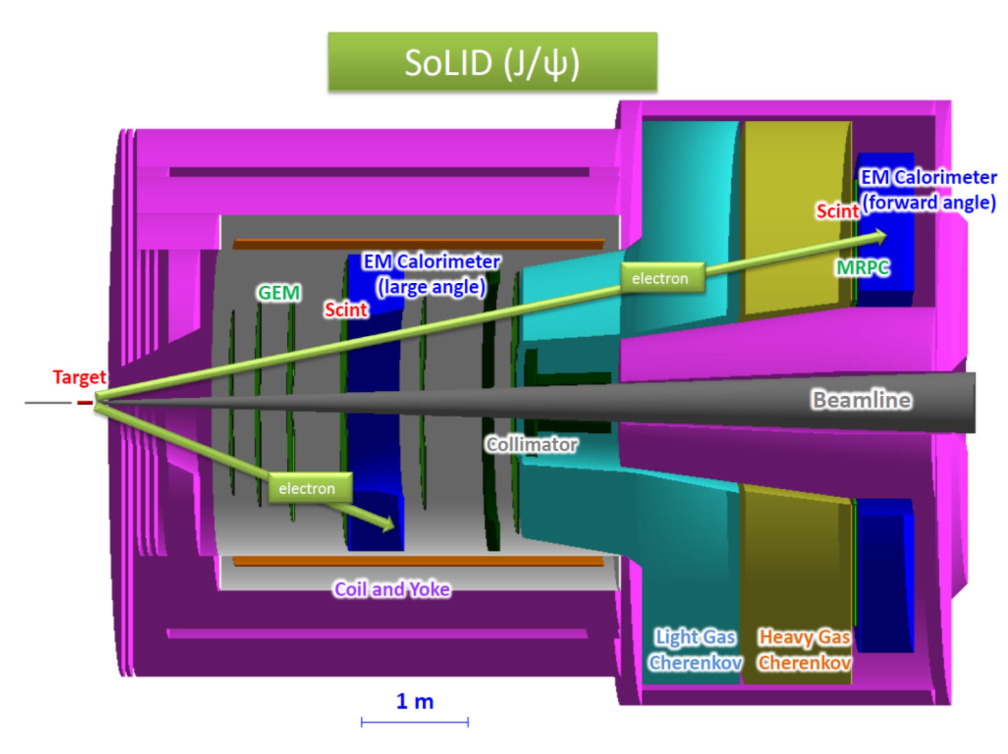
J/ψ @ SoLID E12-12006

$$\gamma^* + N \to N + J/\psi$$



Threshold J/Ψ production, probing strong color field in the nucleon, QCD trace anomaly (important to proton mass budget)

e p → e′ p′ J/ψ(e⁻ e⁺)
γ p → p′ J/ψ(e⁻ e⁺)



Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly

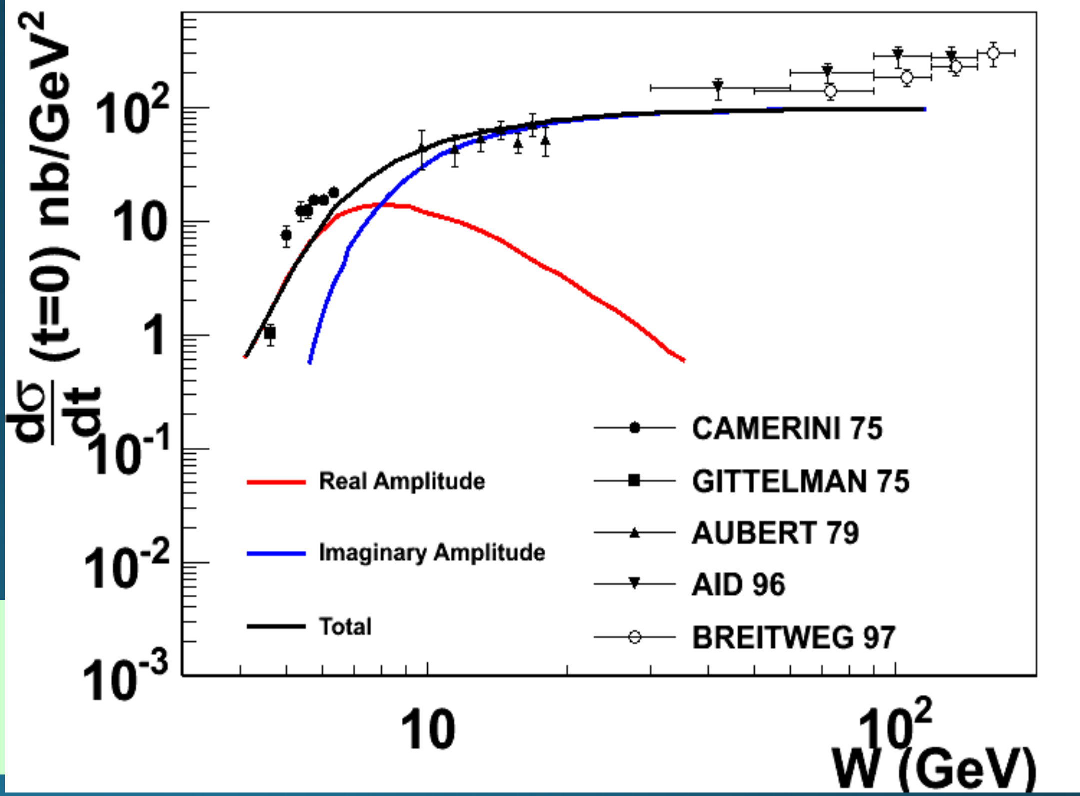
Another view: Reaction mechanism with FSI?

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

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

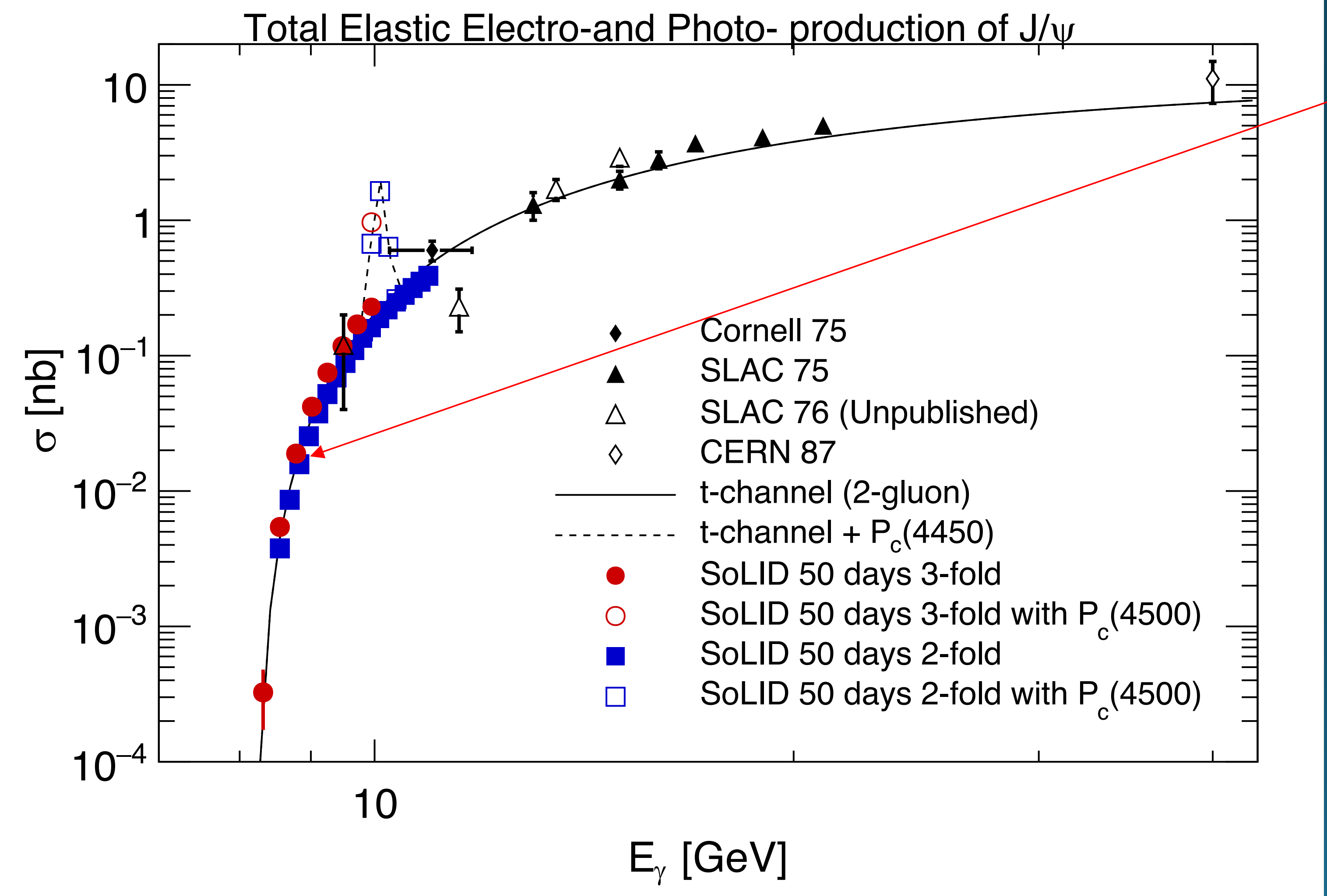
$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

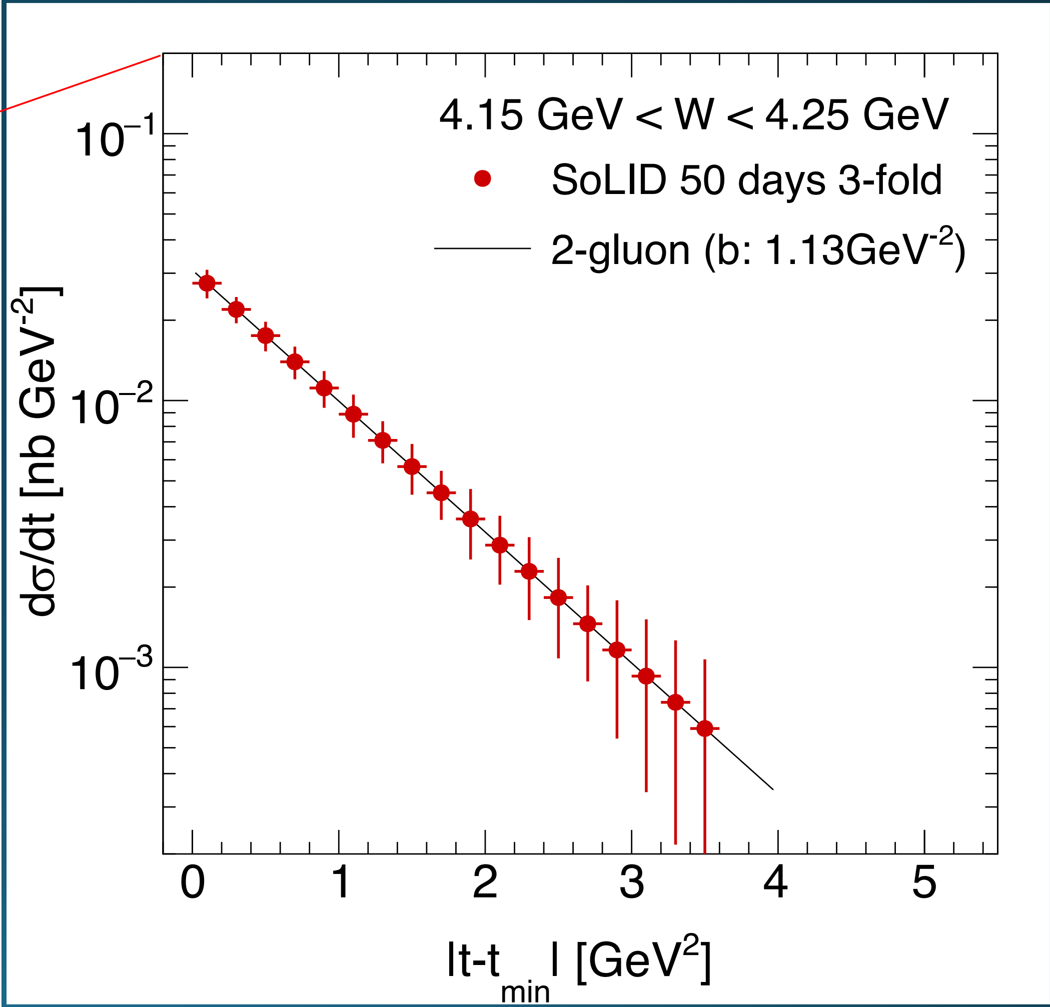
- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region



A measurement near threshold could shed light on the conformal anomaly

J/Psi@ SoLID E12-12006





Quarkonia at an EIC

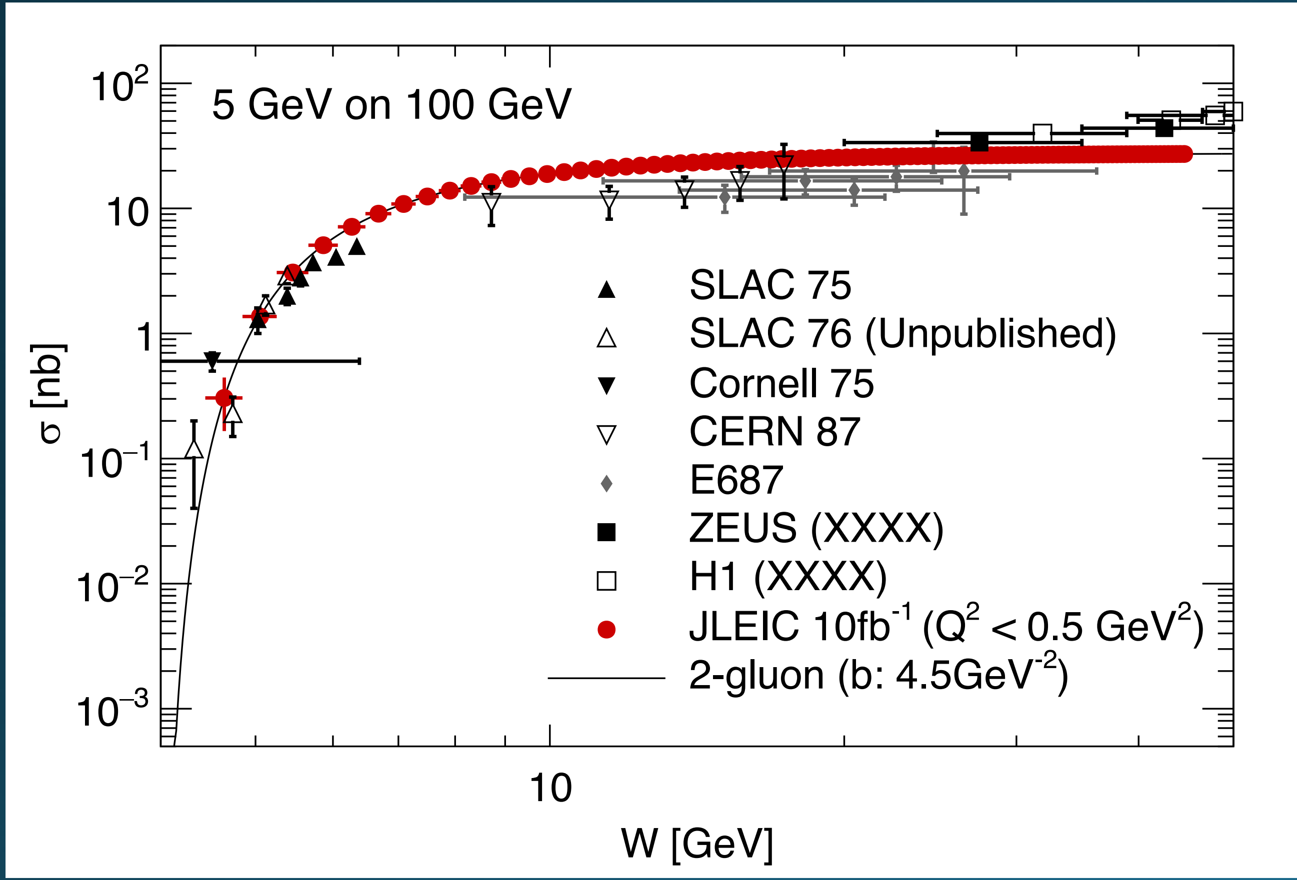
- J/Psi production at large W is used as a tool for gluon imaging
  - NLO calculations exist but point to large corrections, further work is underway
  - Would be important to use the Upsilon to access gluons, the heavier mass of the bottom helps suppress NLO corrections.

- Our focus here is what an EIC offers in the threshold region that is unique and complementary to JLab12.
  - Q^2 dependence study in electroproduction of J/ψ at threshold is possible with an EIC
  - Upsilon production is also possible at threshold allowing an easier interpretation
  - Direct search for "bottom pentaquarks" if they exist.

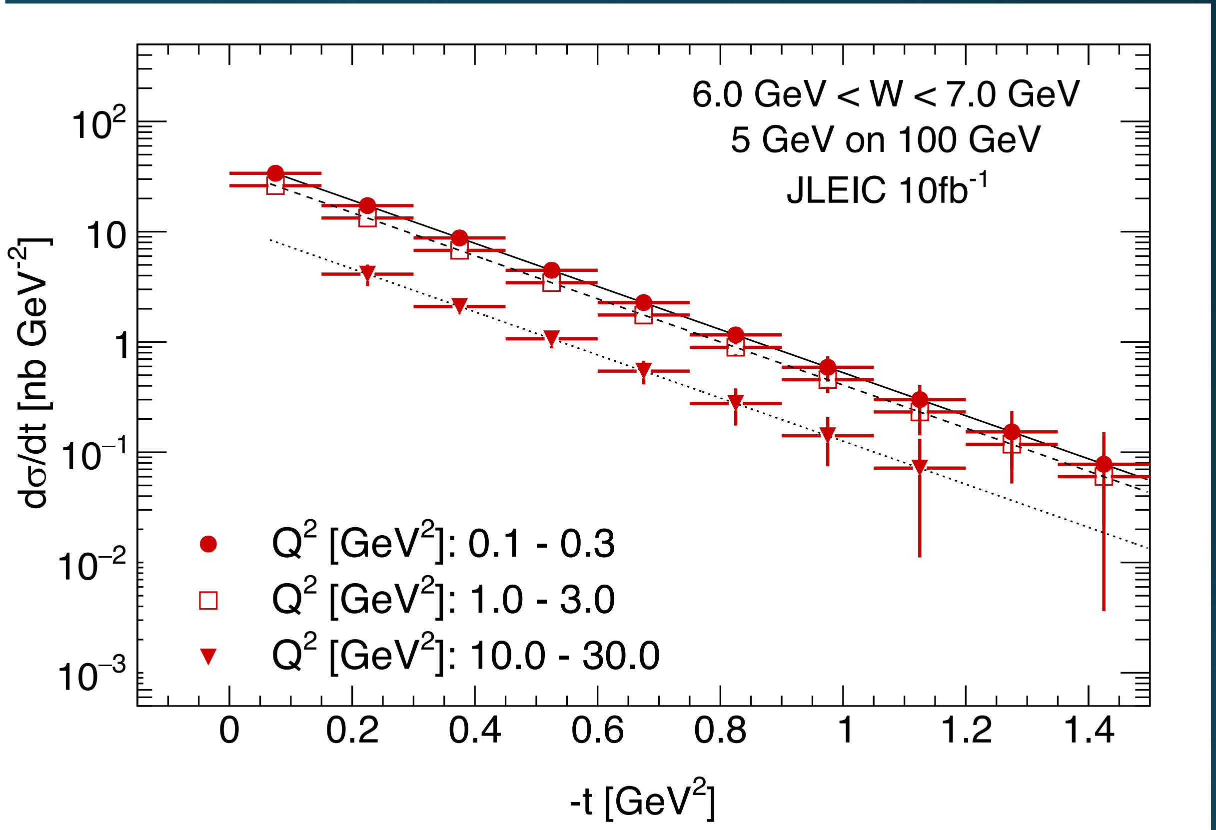
Elastic J/ψ production near threshold at an EIC

At an EIC a study of the Q² dependence in the threshold region is possible

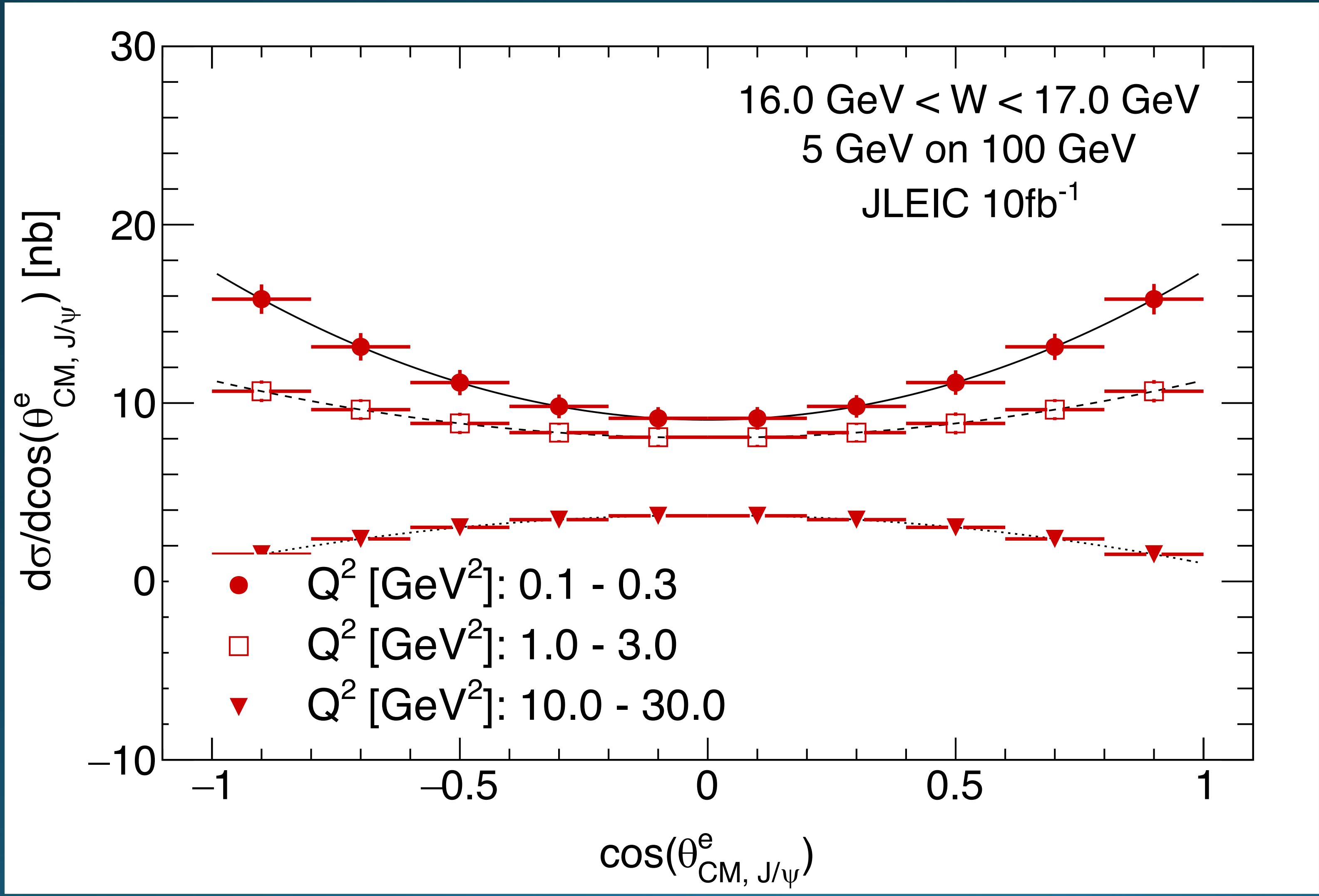
Total electroproduction cross section



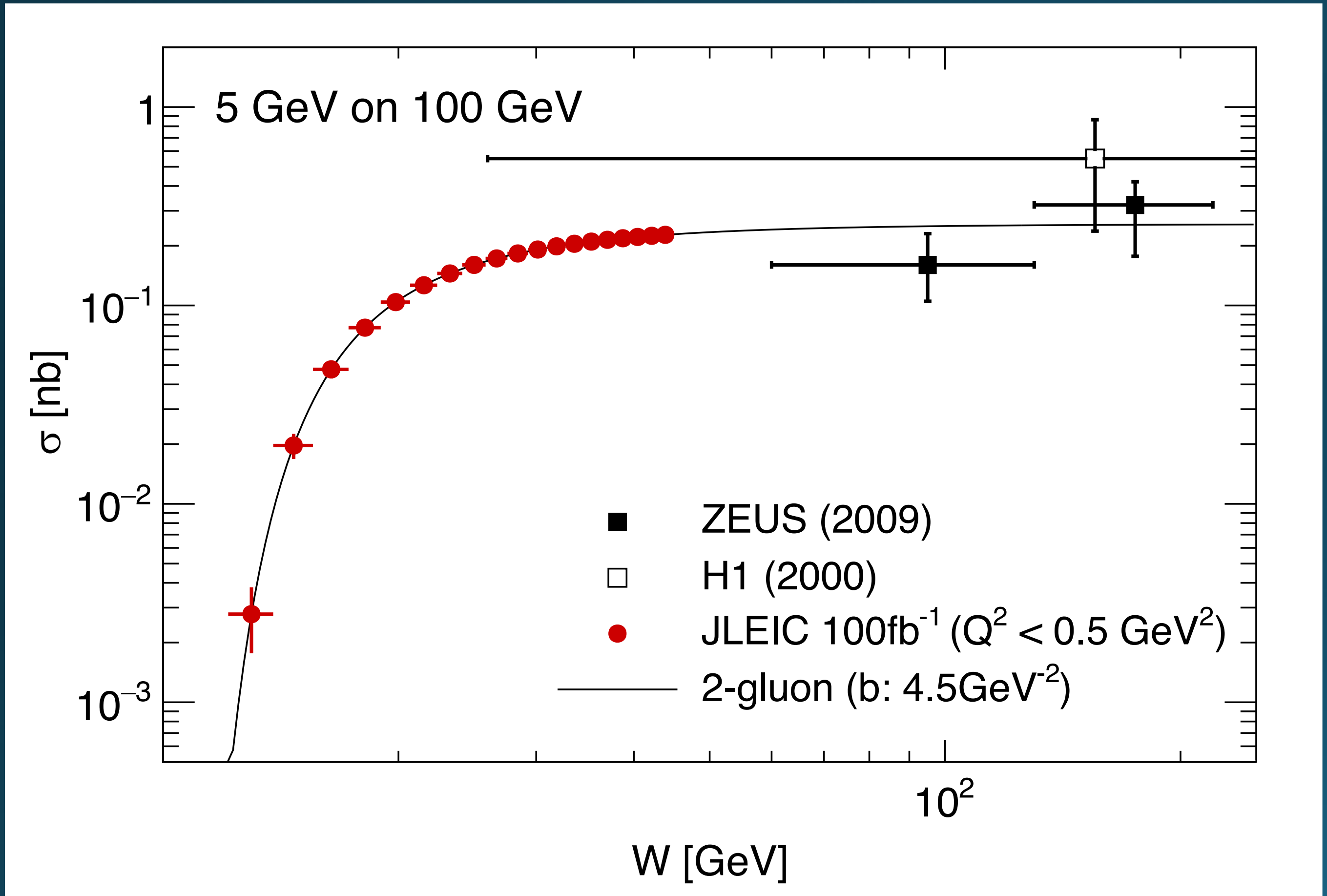
t distribution

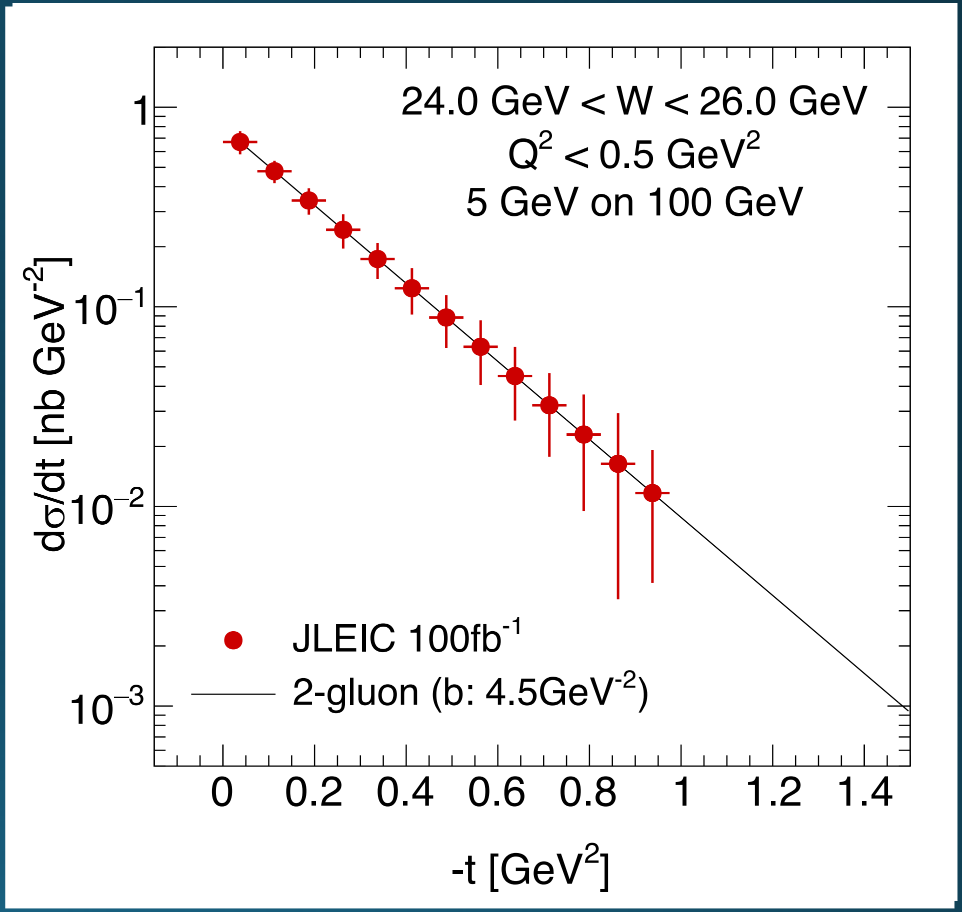


Angular distribution of the decays



Elastic Upsilon production at an EIC





Conclusions

- Heavy Quarkonia production is an important tool for probing the gluonic fields in the nucleon
- It enable the exploration of possible existence of charm and bottom pentaquarks
- 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

Acknowledgments

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- This work is partially supported by the Department of Energy Contract DE-FG02-94ER40844