Production of Heavy Quarkonium on the Nucleon at Threshold from JLab to EIC

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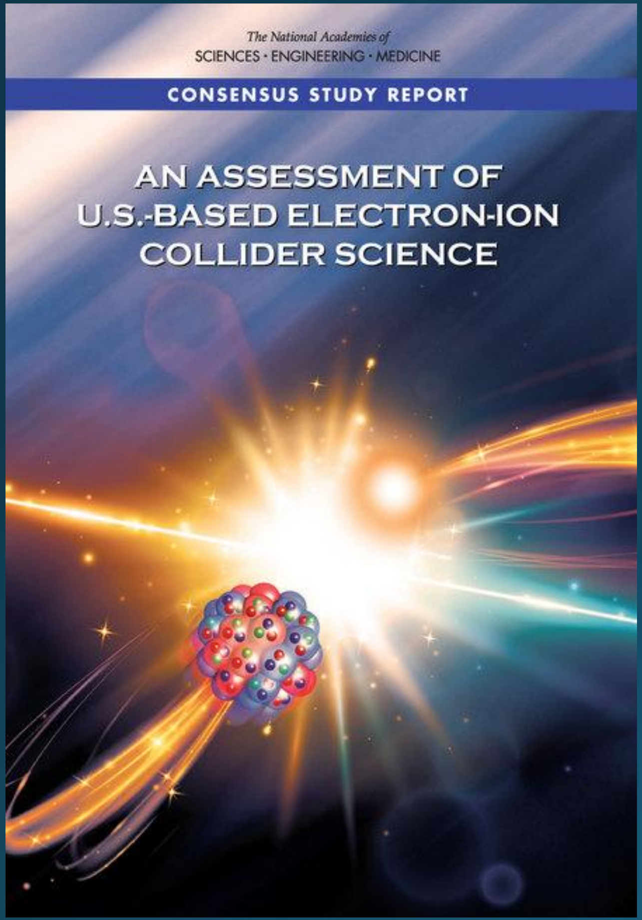
Outline:

- The science enabled by heavy quarkonia in the threshold region
- Threshold production of quarkonia on the nucleon experiments a JLab
- Outlook: Measurements at an EIC.

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-Color Van der Waals force.
- Do heavy quarkonia enable pentaquarks to exist?
- Are bound states of quarkonia in nuclei possible?

EIC Science Assessment by NAS



Finding 1:

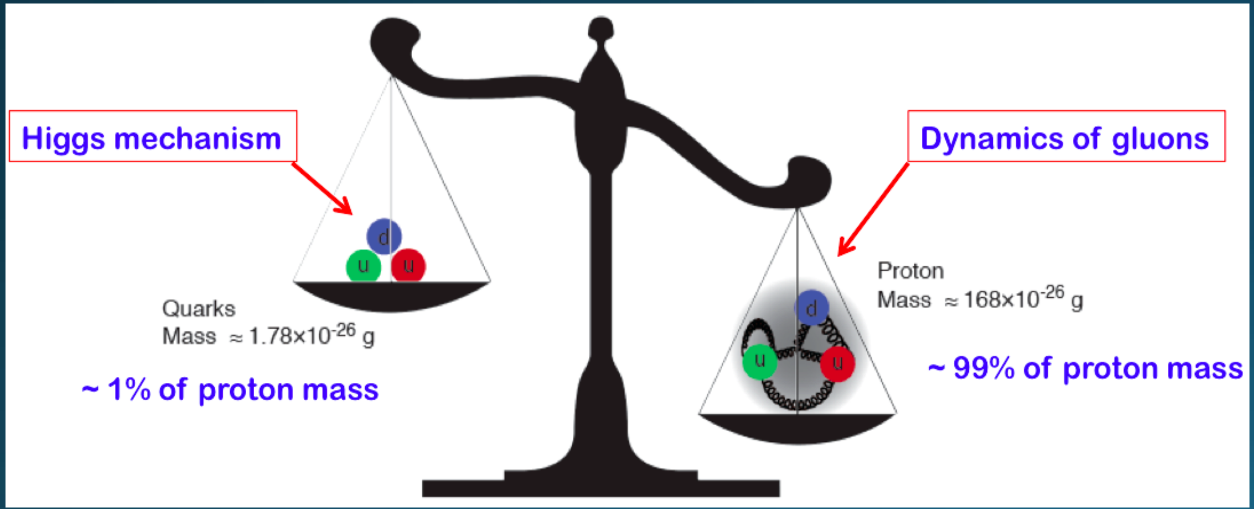
An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- 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?

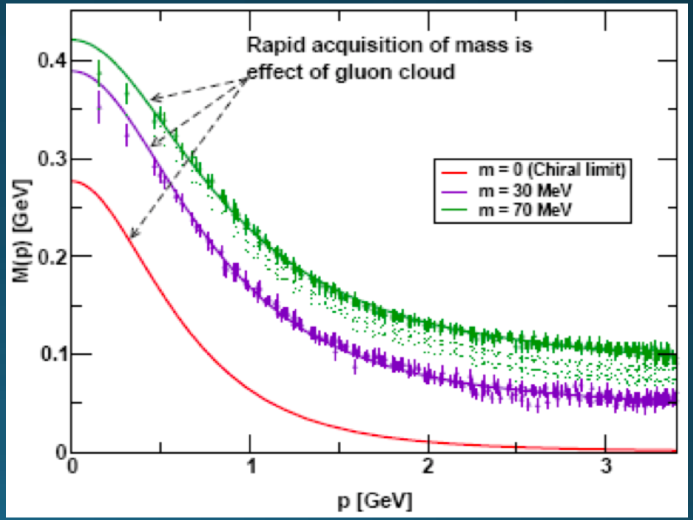
How does QCD generate its mass?

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

✧ Massless, yet, responsible for nearly all visible mass



"Mass without mass!"



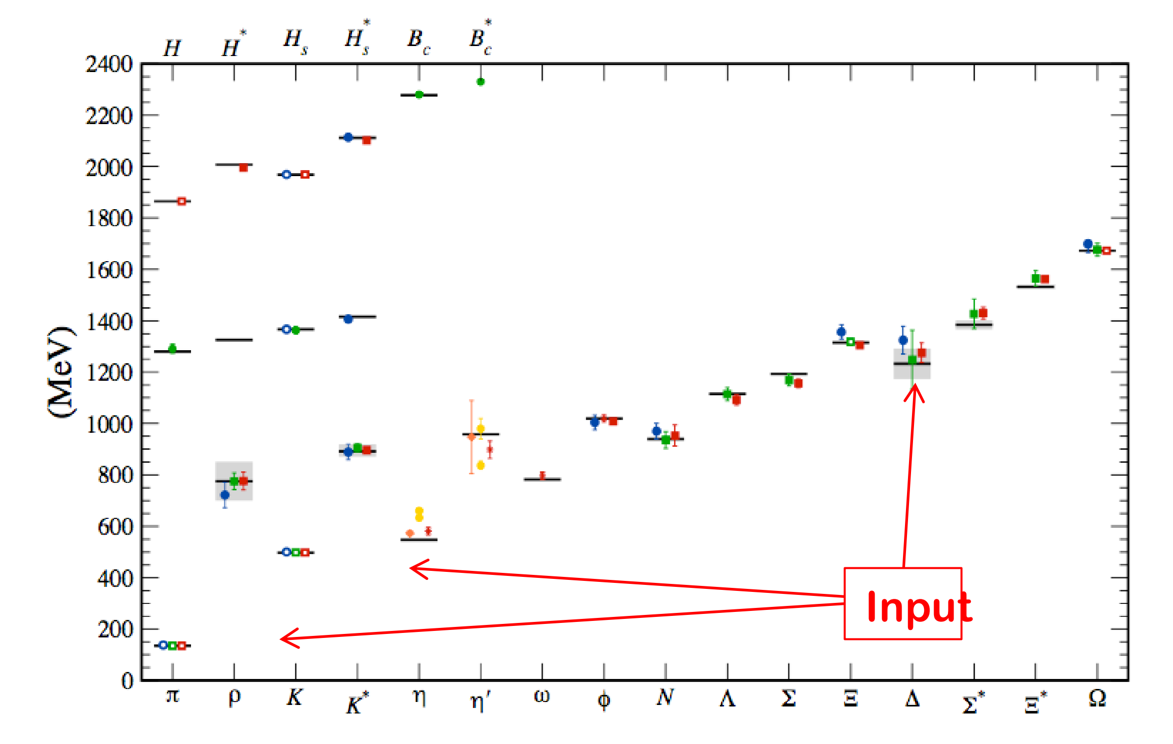
Bhagwat & Tandy/Roberts et al

Examples in nature: proton, blackhole

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***

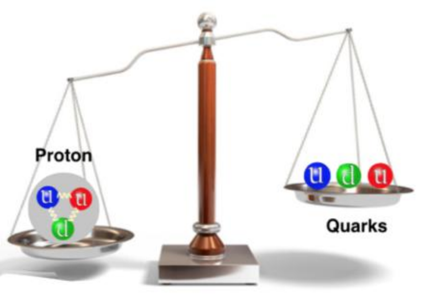
❑ Hadron mass from Lattice QCD calculation:



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

How does QCD generates the nucleon mass?

See for example, M. E. Peskin and D. V. Schroeder,
An Introduction to quantum field theory,
Addison-Wesley, Reading (1995), p. 682



- 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:

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

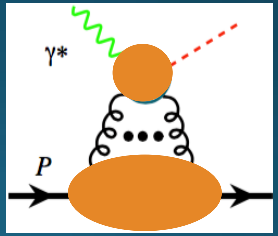
$$\beta(g) = -(11 - 2n_f/3)g^3/(4\pi)^2 + \ldots$$

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

$$m^2 \propto \langle p|T^{\alpha}_{\alpha}|p\rangle \;\Rightarrow\; \frac{\beta(g)}{2g}\langle p|F^2|p\rangle$$

Chiral limit

J/Ψ, Υ, …

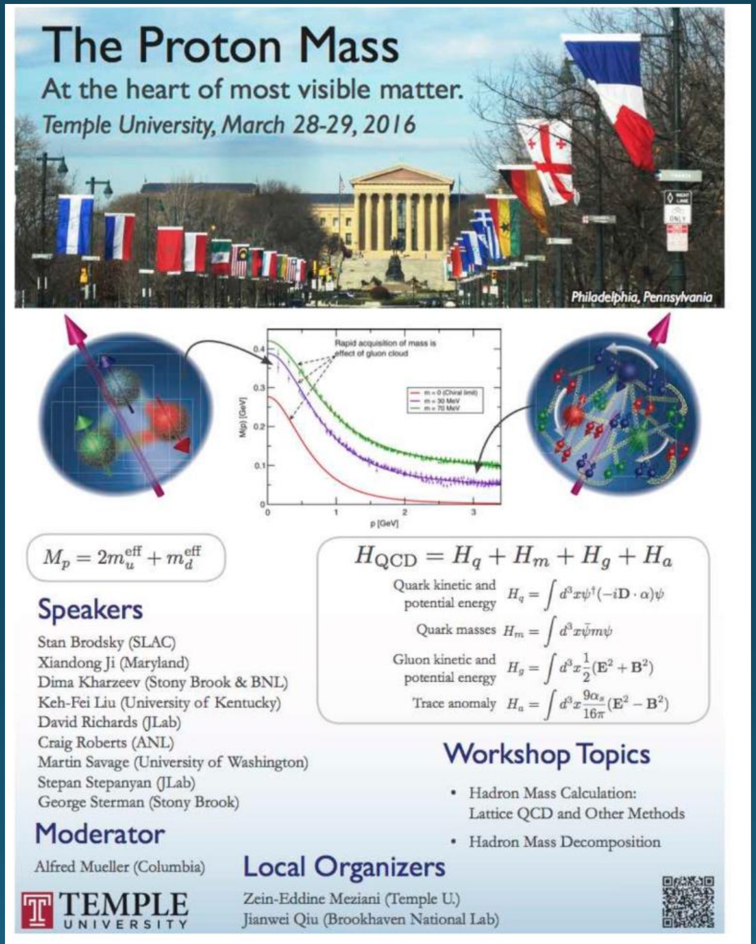


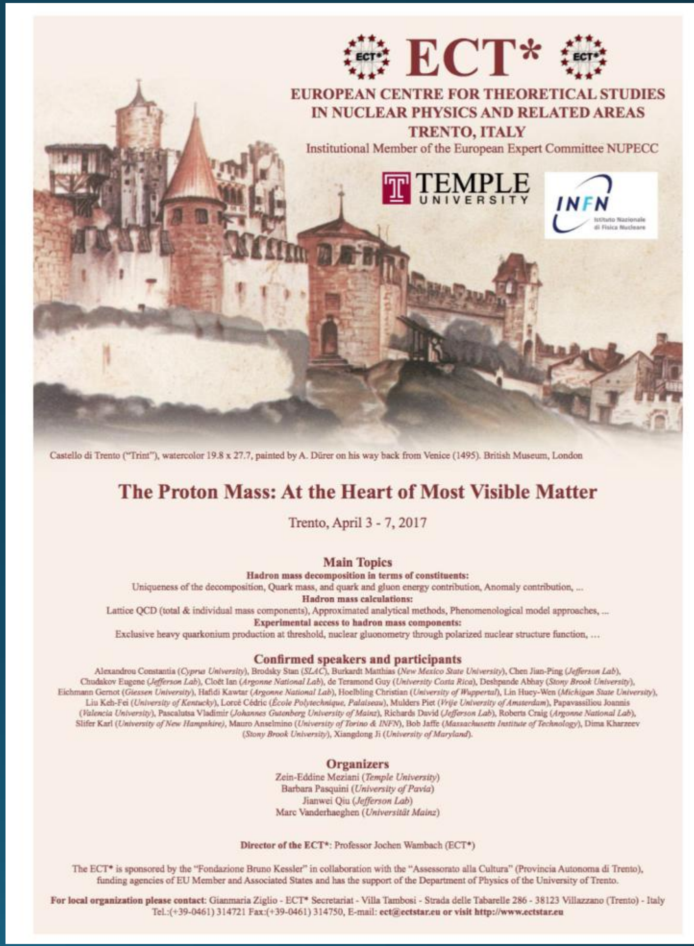
➡ Heavy quarkonium production near the threshold, from JLab12 to EIC

The proton mass … a hot topic!

"… 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)

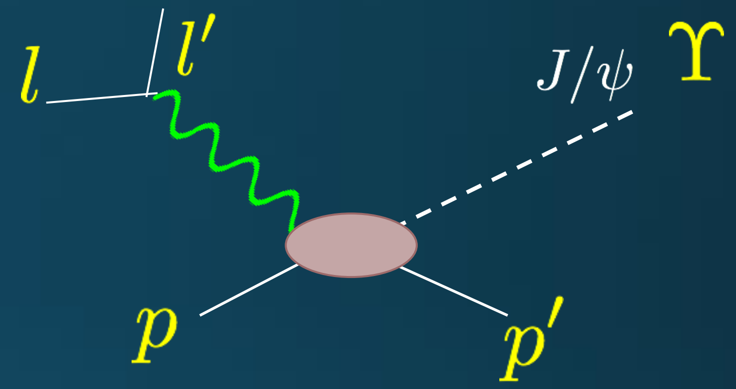




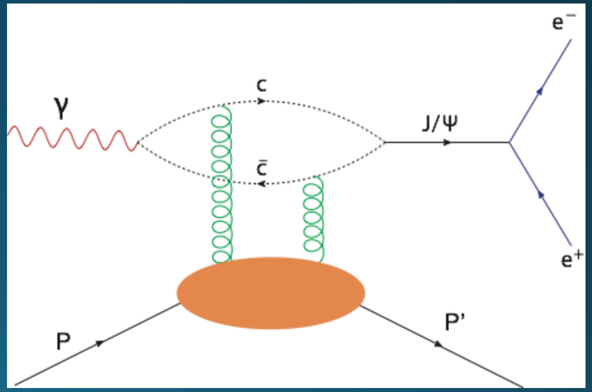
Access the trace anomaly through elastic J/psi and Upsilon production near threshold

Experimental Tools: Exclusive Production of Quarkonia at Jlab12 and an EIC

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



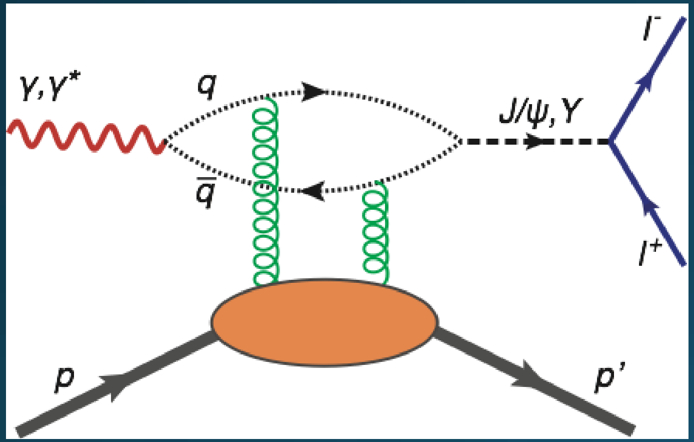
- At JLab we can measure the threshold region in photo and electro-production of J/ ψ in fixed target experiments in 4 halls.
- Depending on the experimental set-up we have:
  - A fully exclusive measurement with the detection of all final state particles in some cases.
  - Detection of the J/ψ decay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



Quarkonium photo-production: what do we know?

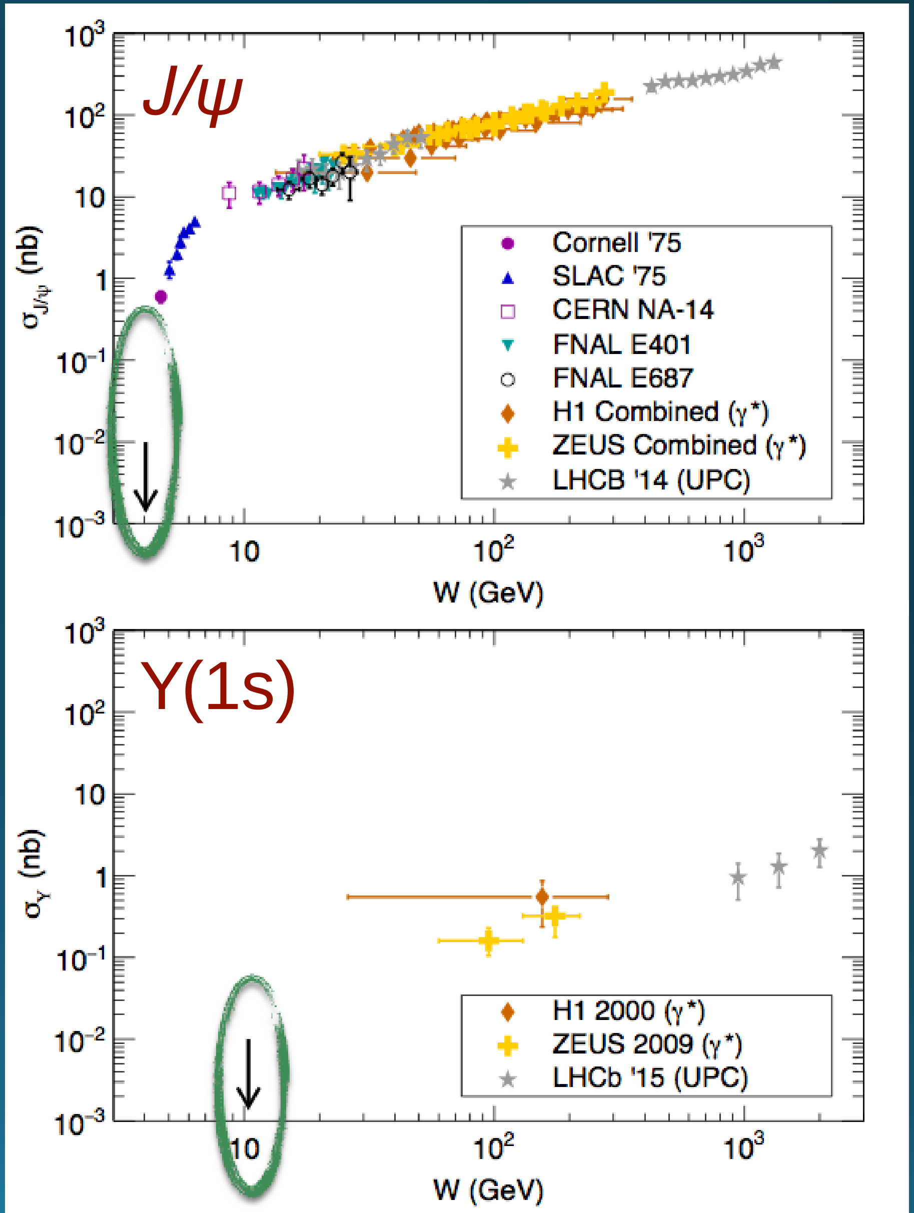
J/ψ photo-production:

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



Y(1s) photo-production:

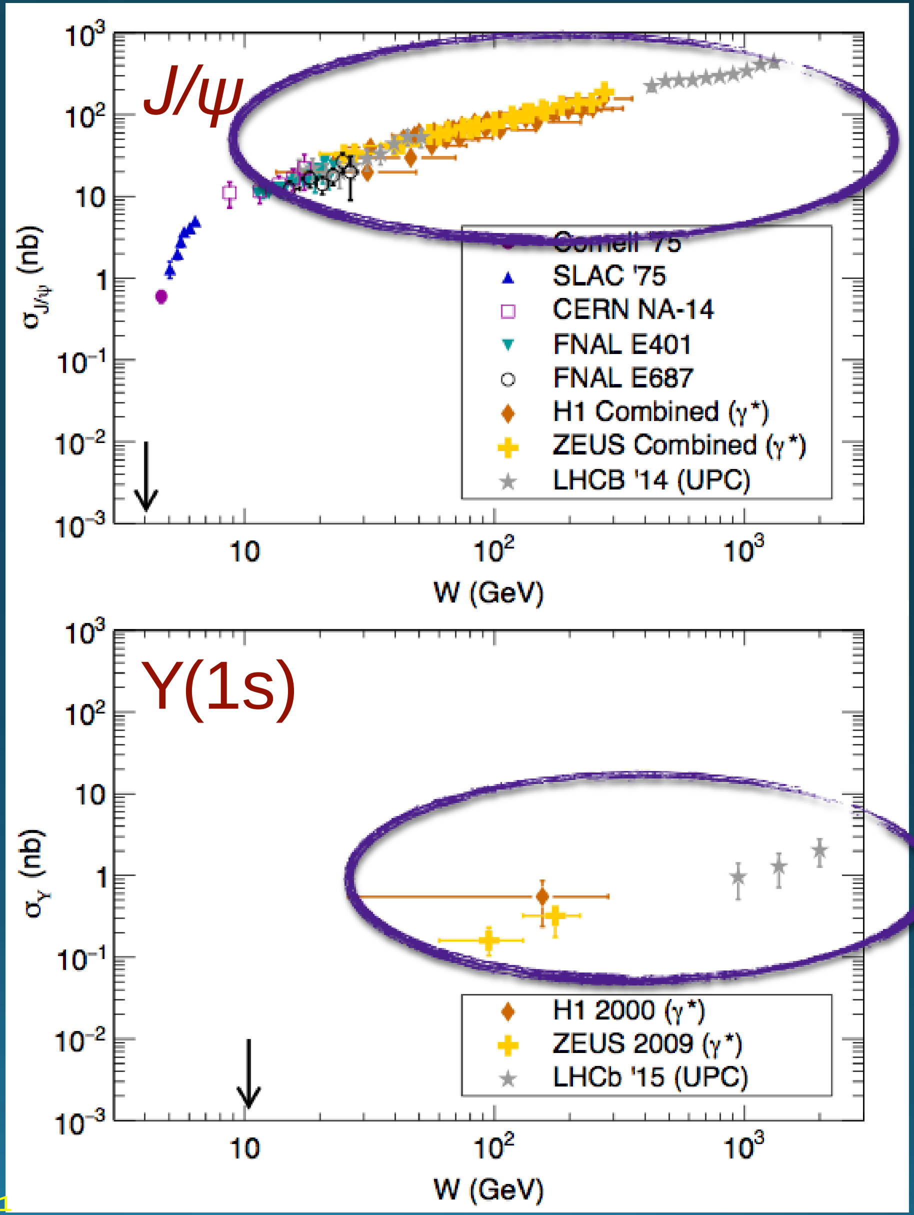
- Not much available
  - ZEUS measured 62 ± 12 events total!



Electro-production at high energies?

High Energies

- Access Gluon GPD: Full 3D tomography of the gluonic structure of the nucleon
- L-T separation and the Q^2 dependence of R for quarkonium production



An EIC is ideal for sea-quarks and gluons in the nucleon studies

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
  - ✓ LHCb charm pentaquark?....

Brodsky et al. ....

Gastao Krein

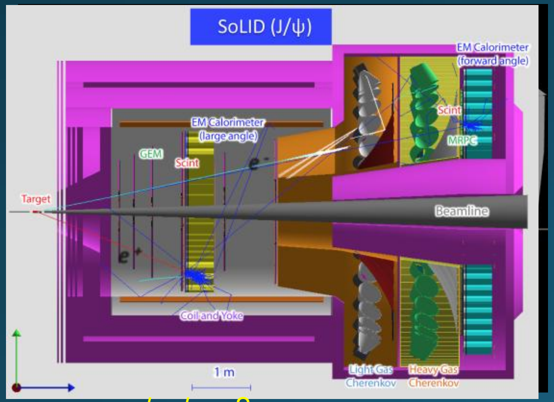
- Experimentally no free J/ψs or Upsilons are available
  - ✓ Challenging to produce very close to threshold!
  - ✓ Photo/electro-production of J/ψ at Jlab and Upsilon EIC are a special opportunity

12 GeV J/Ψ experiments at JLab Overview

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

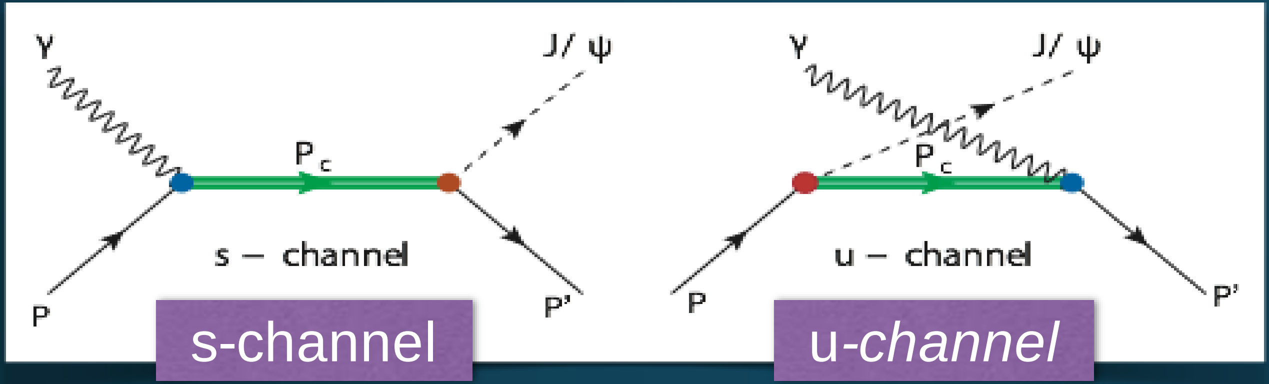
*Hall B – Has an approved proposal to measure TCS + J/psi in phot-production **E12-12-001***

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



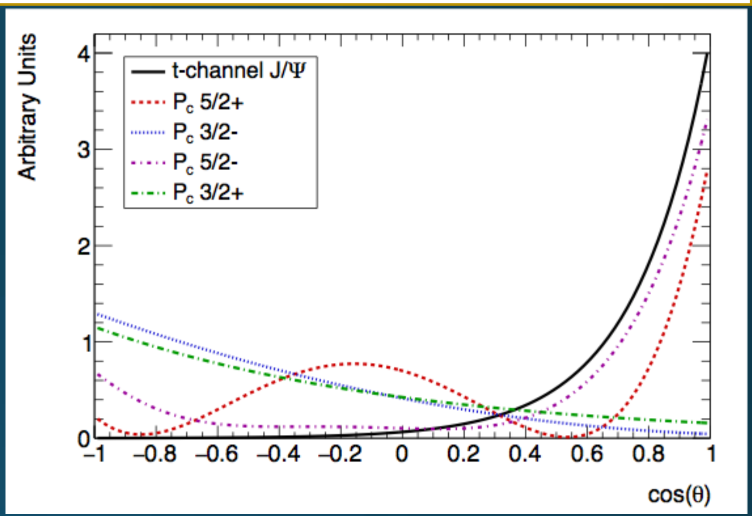
*Hall A-has an approved proposal involving a future detector of high luminosity capabilities -**SoLID** **E12-12-006***

Resonant J/ψ production through P_c decay

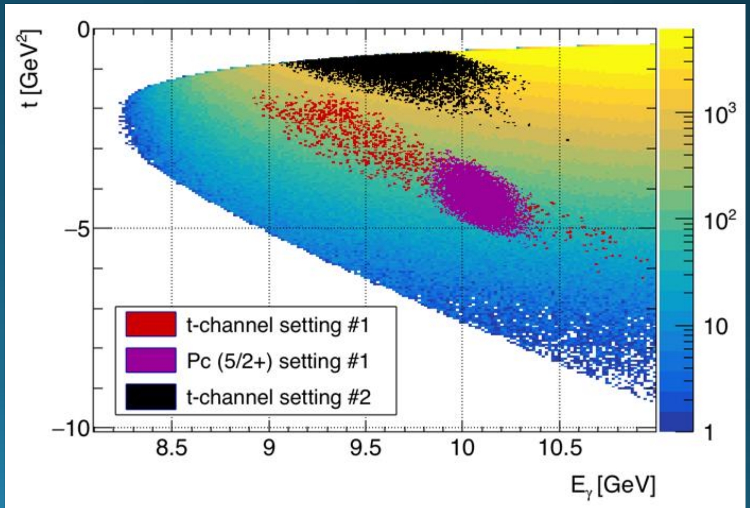


- Cross section depends on coupling of P_c to (J/ψ, p) channel
- J/ψ angular distribution differs between t-channel and $s(u)$-channel

$$\frac{d\sigma}{d\cos\theta_{J/\psi}}(\gamma p \to P_c \to J/\psi p)$$



Leverage angular dependence to maximize sensitivity at low coupling!

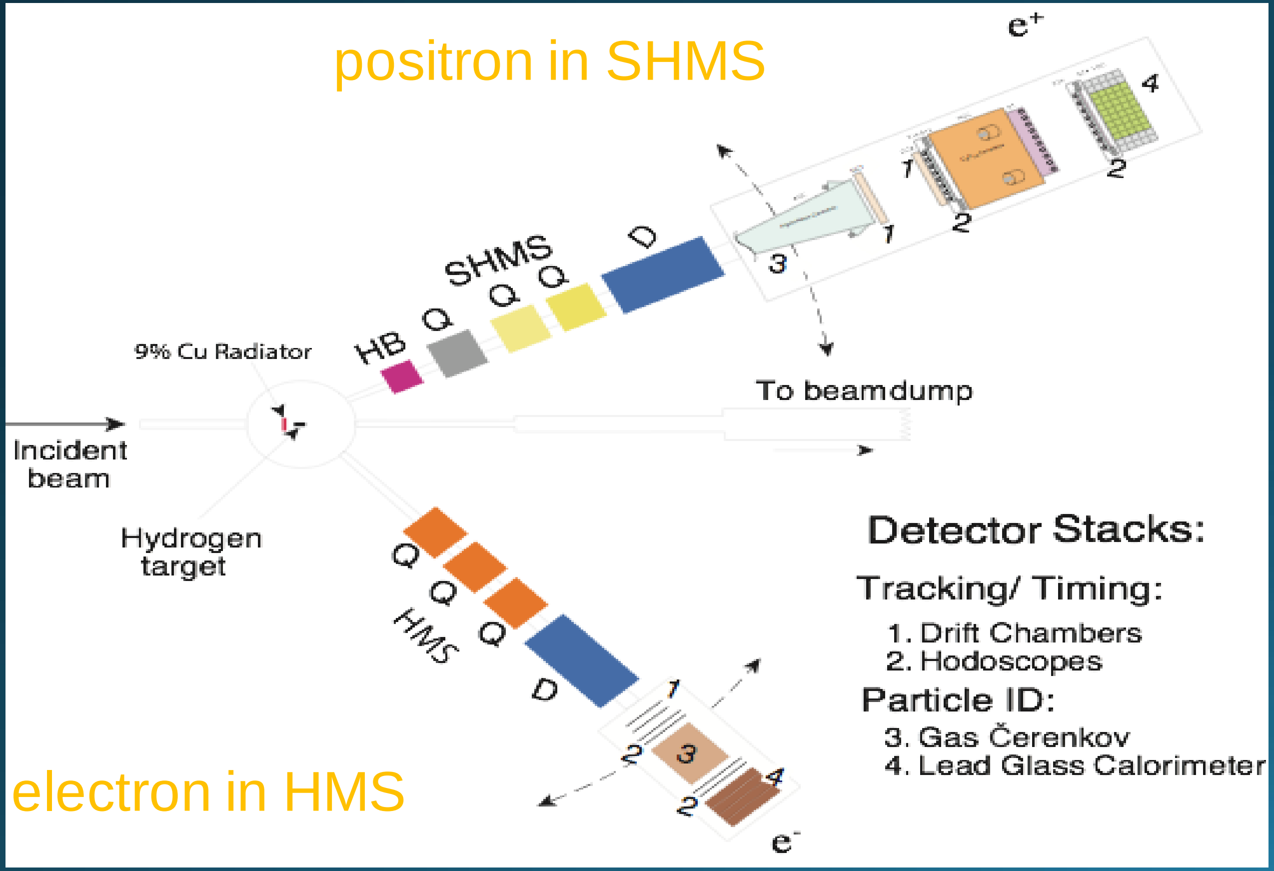


- 2 settings:
  - "SIGNAL" (#1) to maximize S/B
  - "BACKGROUND" (#2) to precisely determine t-channel J/ψ cross section

Search for the LHCb pentaquark

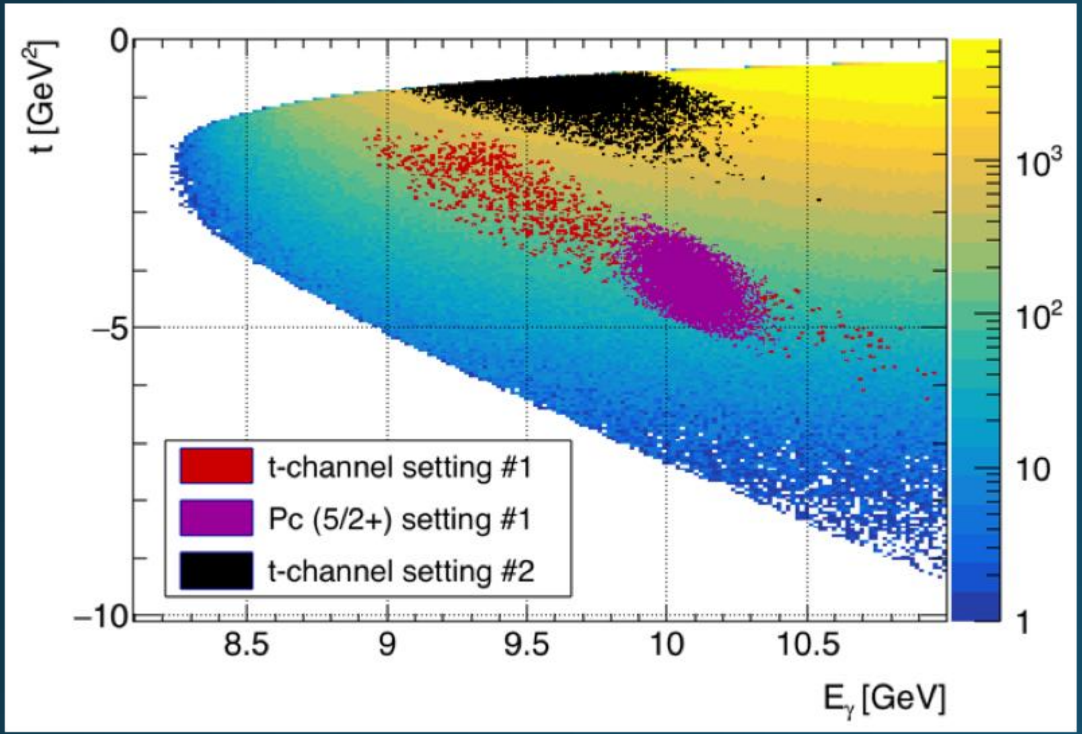
- 50μA electron beam at 10.7 GeV (or 11 GeV)
- 9% copper radiator
- 15cm liquid hydrogen target
  - total 10% RL

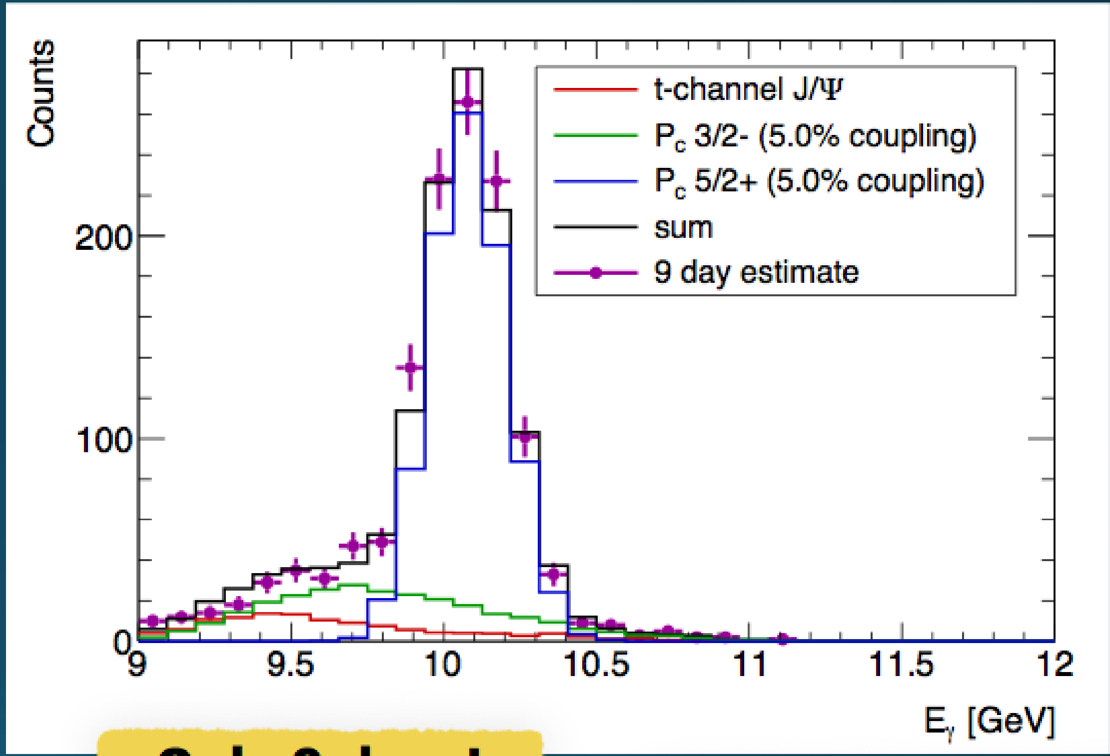
JLab Experiment 12-16-007 in Hall C



- Run with 2 settings:
  - "SIGNAL" Setting (9 days): minimizes accidentals and maximizes signal/background:
    - HMS: 34^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!

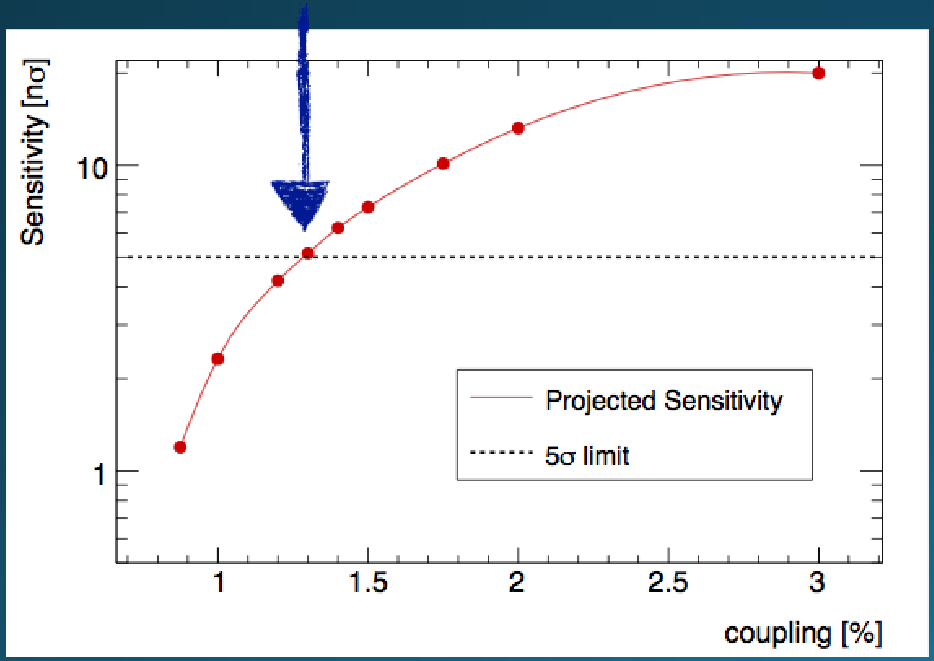
***t*-channel: 120 events**
5/2+: 881 events
3/2-: 266 events

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

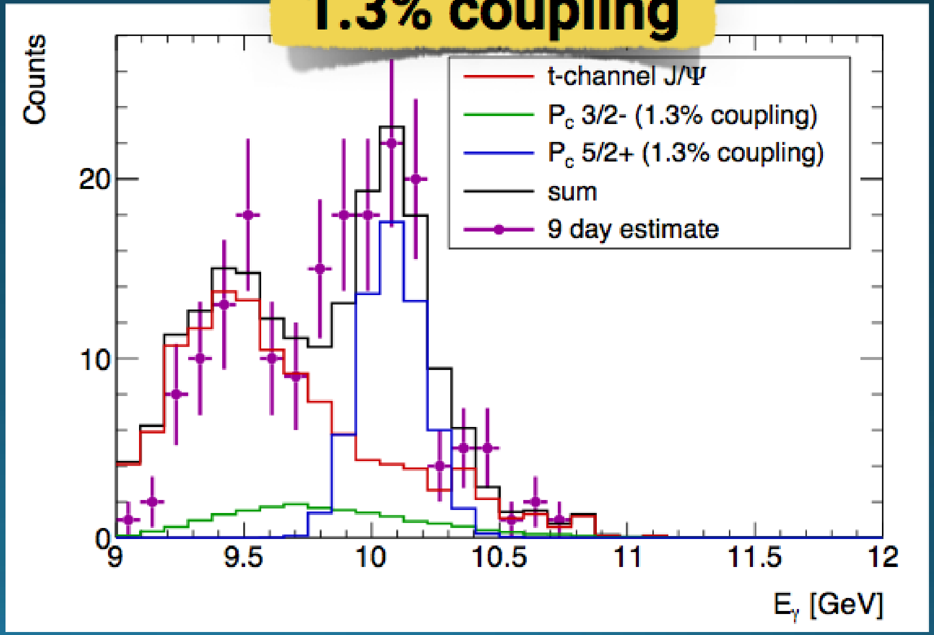
Wang Q., *et al.*, PRD 92-3 (2015) 034022-7

Sensitivity for Discovery

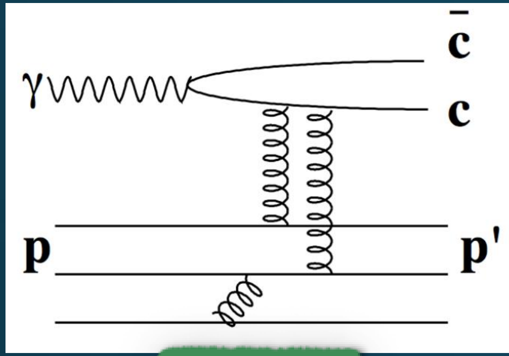
- sensitivity calculated using a Δ-log-likelihood formalism
- 5 standard deviation level of sensitivity starting from 1.3% coupling!

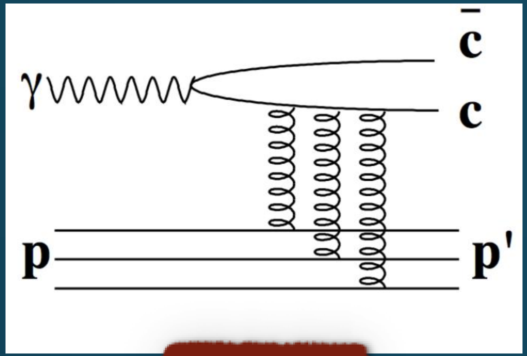


Projection for 1.3% coupling



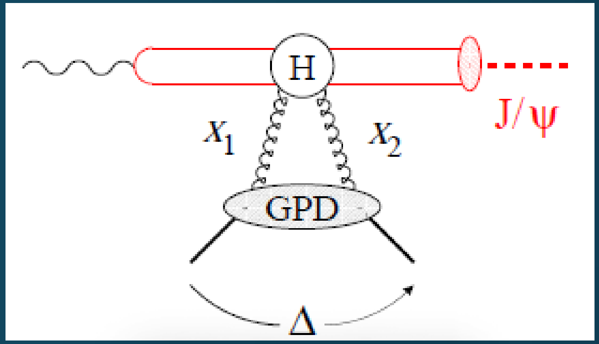
Production mechanism near threshold unknown





2-gluon **3-gluon**

S.J. Brodsky, *et al.*, Phys.Lett. B498, 23-28 (2001)



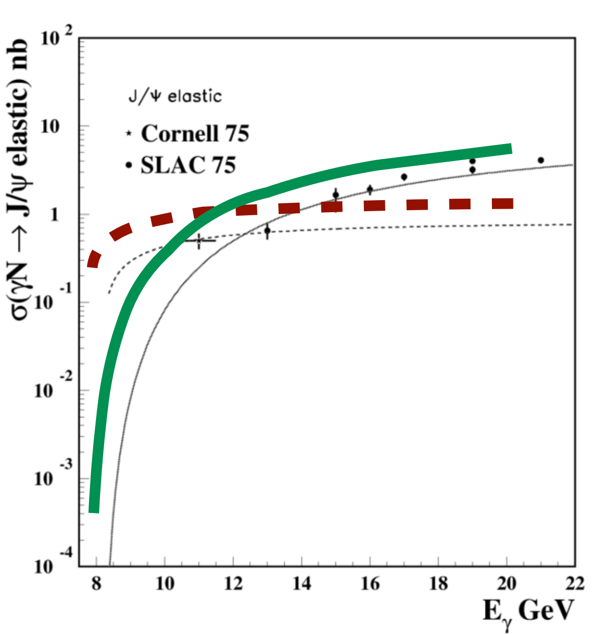
partonic soft

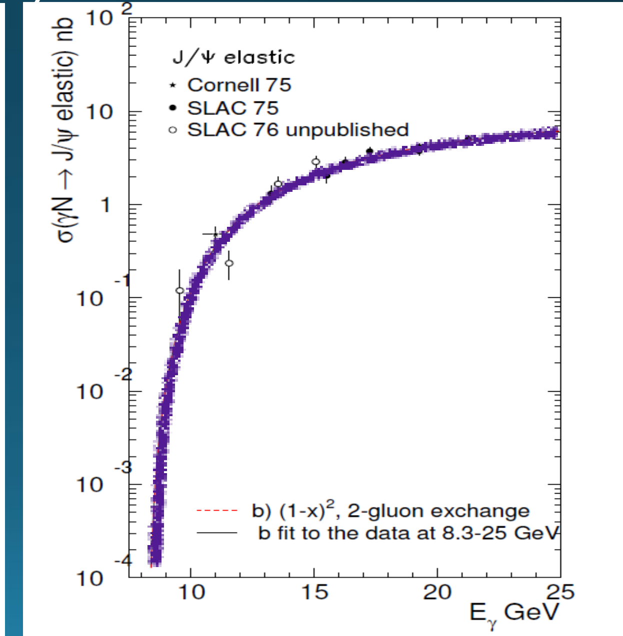
Frankfurt and Strikman., PRD66 (2002), 031502

- Same as high energies (2-gluon)?
- Maybe 3-gluon exchange dominant?

- Or a partonic soft mechanism (power law 2-gluon form-factor)?

- Orders of magnitude difference
- **2-gluon** fastest drop-off
  - **Drives required luminosity** for threshold measurement





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

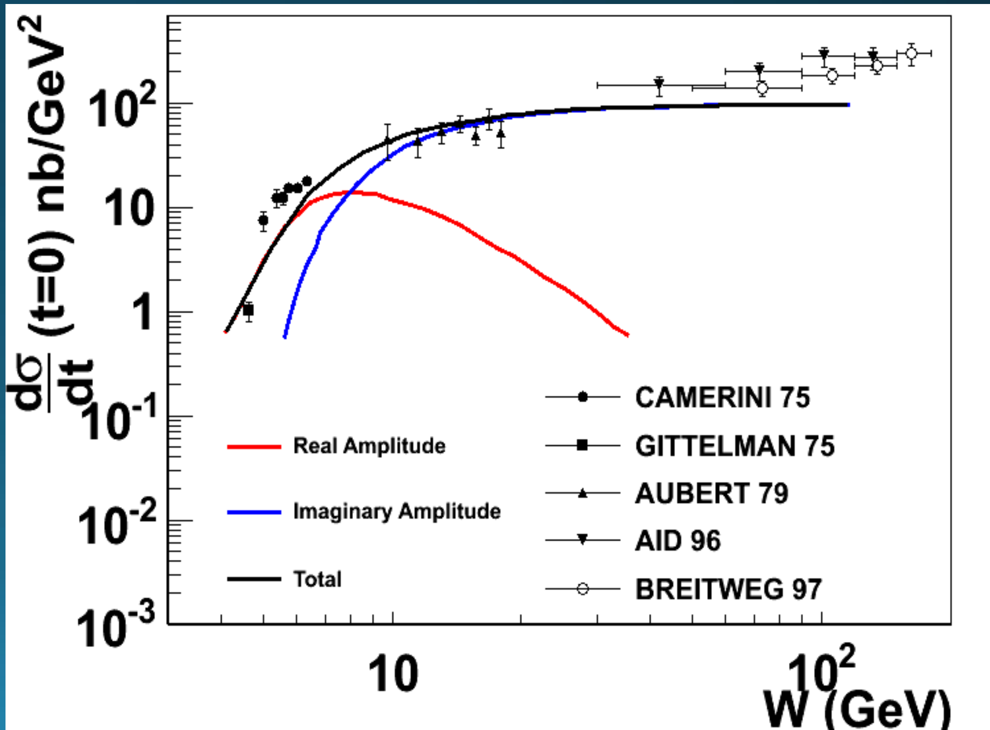
$$\frac{d\sigma_{\gamma N \to \psi N}}{dt}(s, t=0) = \frac{3\Gamma(\psi \to e^+e^-)}{\alpha m_\psi} \left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N \to \psi N}}{dt}(s, t=0)$$

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

- VMD relates photo-production cross section to quarkonium-nucleon scattering a… de $M_{\psi p}$
- **Imaginary part** is … total cross section through optical theorem
- **Real part contains the con… omaly**
  - Dominate the near threshold … trained through dispersion relation

A measurement near threshold could a… to the trace anomaly

WARNING LABEL: Keep in mind, no rigorous factorization theorem (yet)!

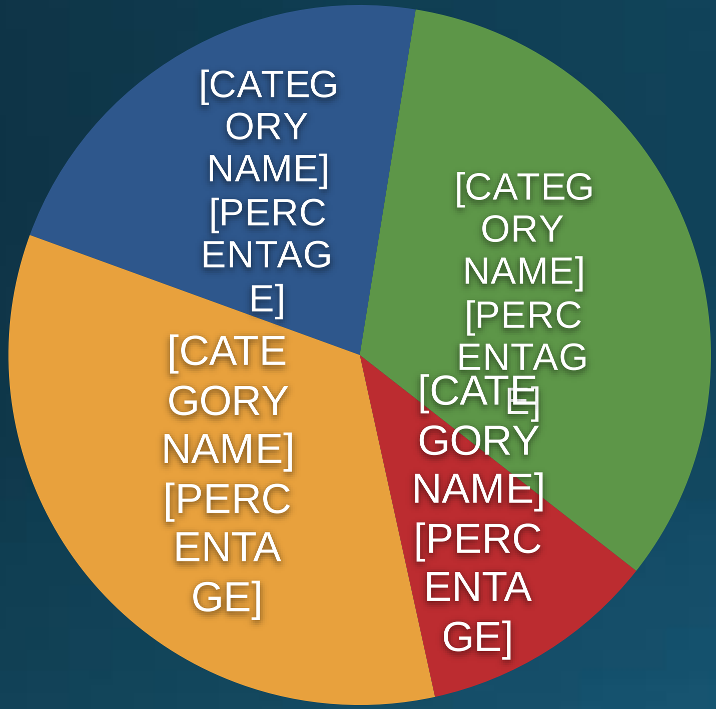


The proton mass: rest-frame decomposition

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

- Matrix element of the QCD Hamiltonian in the rest frame gives the proton mass

$$H_{\rm QCD} = \int d^3x T^{00}(0,\vec{x}) = H_q + H_m + H_g + H_a$$



- In leading order:

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

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

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

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

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

A more recent decomposition also in the rest frame including pressure effects : C. Lorcé, **Eur.Phys.J. C78 (2018) no.2, 120**

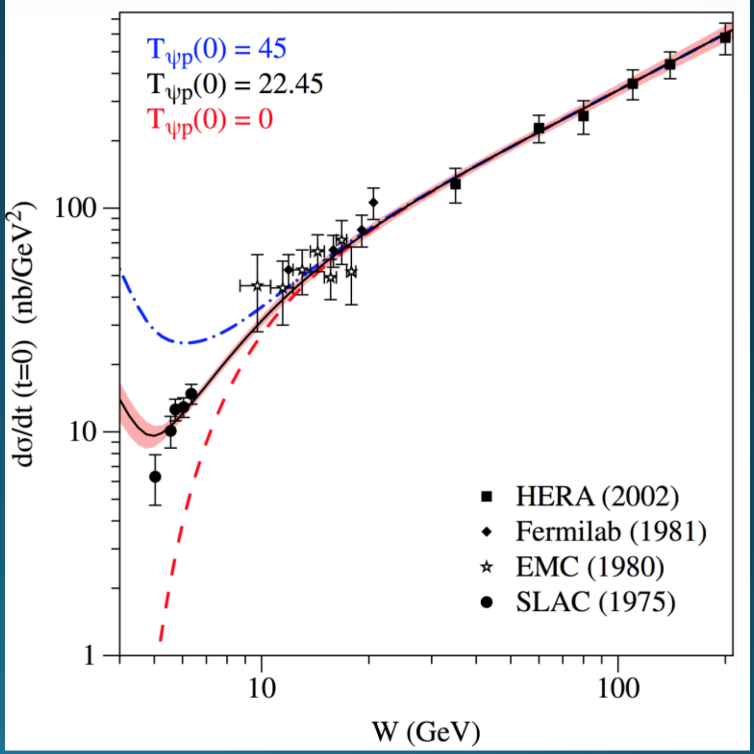
Binding energy of the J/ψ - nucleon potential

- Color neutral objects:
  gluonic Van der Waals force
  - At threshold, spin-averaged scattering amplitude related to s-wave scattering length $a_{\psi p}$
  - Binding $B_{\psi p}$ can be derived from $a_{\psi p}$

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

  - Estimates between 0.05-0.30 fm, corresponding to $B_{\psi p} < 20$ MeV
  - LQCD: $B_{\psi p} < 40$ MeV S. R. Beane *et al.*, Phys. Rev. D 91, 114503 (2015)
  - Recent fit to existing data in a dispersive framework:
    - $a_{\psi p} \sim 0.05$ fm ($B_{\psi p} \sim 3$ MeV)

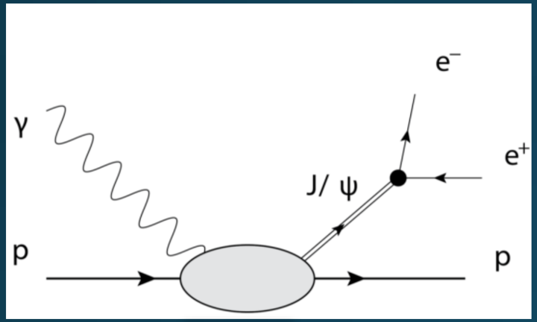
- Photo-production near threshold constrained through dispersion relations, not data
- **Threshold experiments needed!**



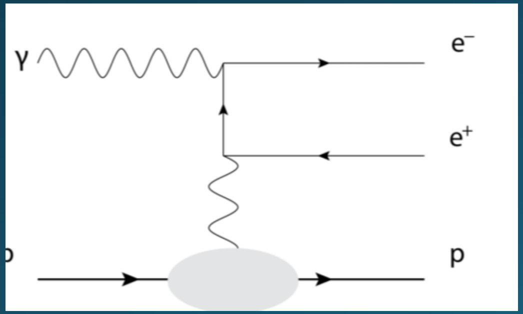
O. Gryniuk and M. Vanderhaeghen, Phys. Rev. D 94, 074001 (2016)

B-H asymmetry: access scattering length $a_{\psi p}$

- Interference between elastic J/ψ production near threshold and Bethe-Heitler
- Forward-backward asymmetry near the J/ψ invariant mass peak
- Sensitive to real part of the scattering amplitude, hence $a_{\psi p}$ and $B_{\psi p}$



J/ψ

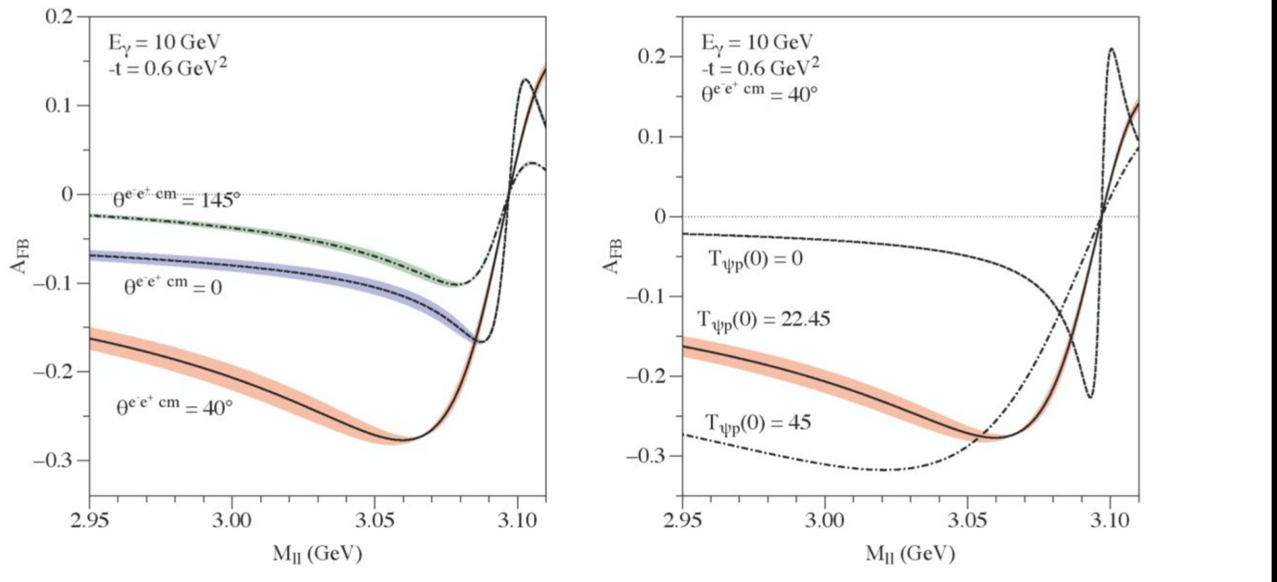


B-H

$$A_{\mathrm{FB}} \equiv \frac{\frac{d\sigma}{d\Omega}(\theta_{cm}) - \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}{\frac{d\sigma}{d\Omega}(\theta_{cm}) + \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)} = \frac{\sum_s 2\,\mathrm{Re}T_\psi\, T_{BH}}{\sum_s |T_\psi|^2 + \sum_s |T_{BH}|^2}$$

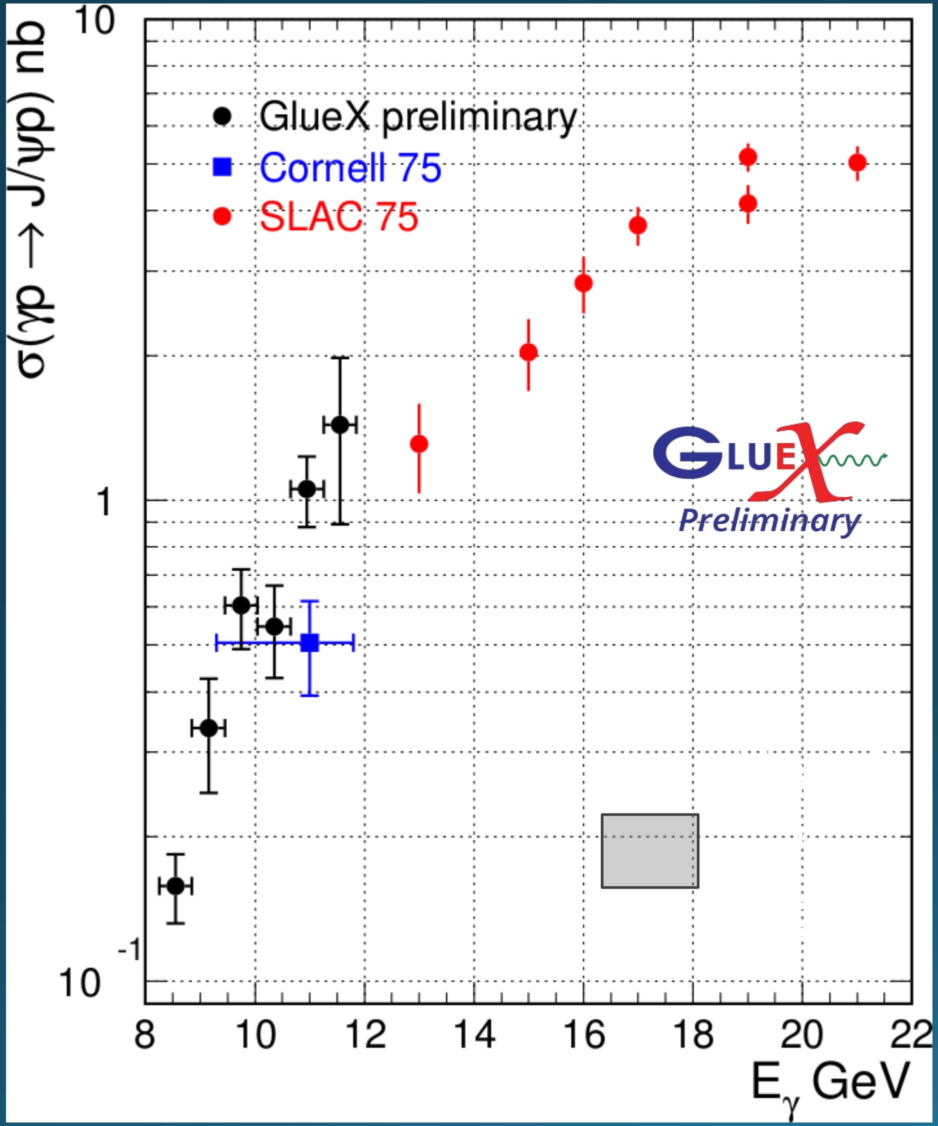
interference term

θ_{cm} — scattering angle in a lepton pair CM frame



Slide from O. Gryniuk

J/ψ cross-section – preliminary results



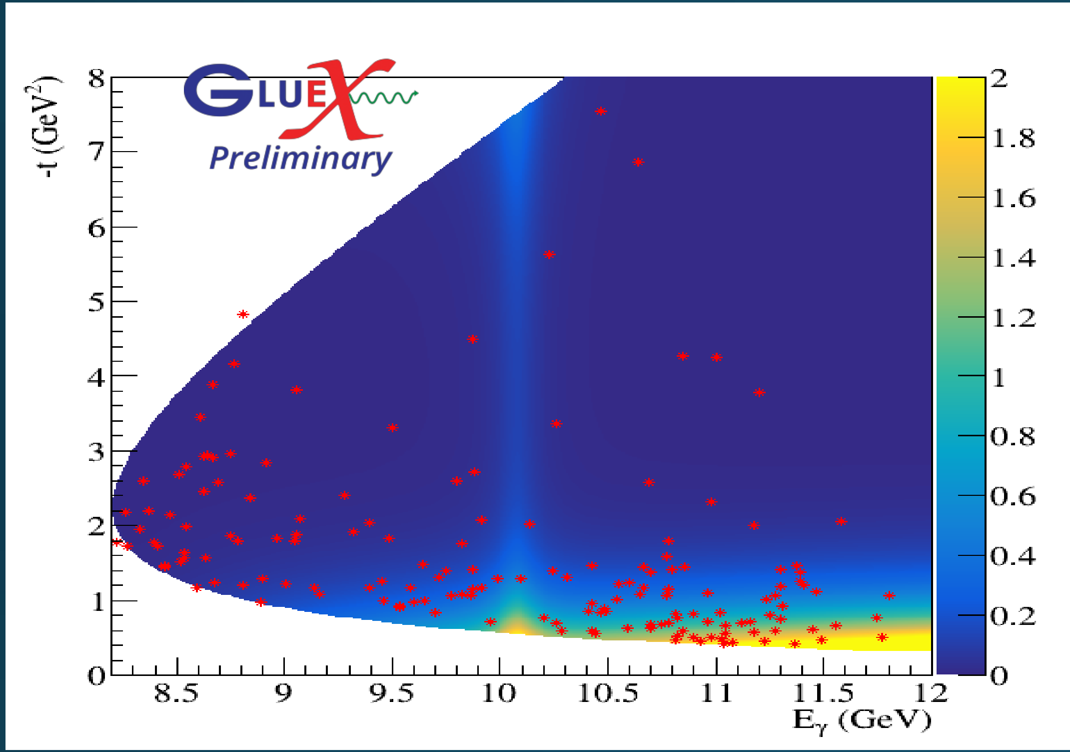
SLAC results calculated from $d\sigma/dt(t=t_{min})$ using t-slope of 2.9±0.3 GeV^{-2} (measured at 19 GeV)

Cornell data:

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

Slide from Penchev

t vs Eγ unbinned distribution for J/ψ events

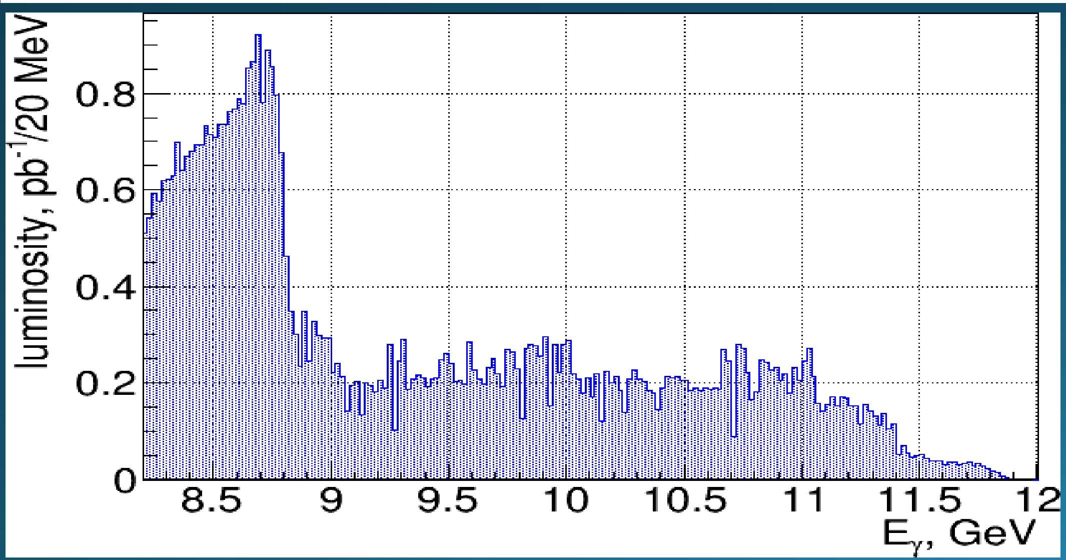


A.U

dots – GlueX data

color – model prediction from JPAC for 3%BR $P_c(4450)$ $5/2^+$

A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).



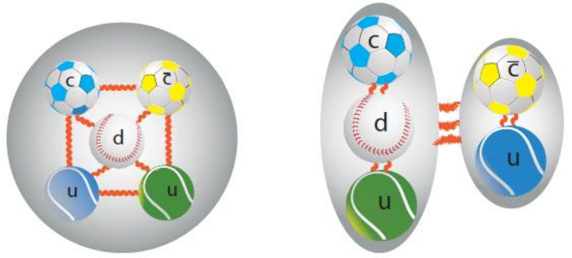
- Density of data points proportional to flux and efficiency
- No significant variations of flux (E_γ>9 GeV) and efficiency

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

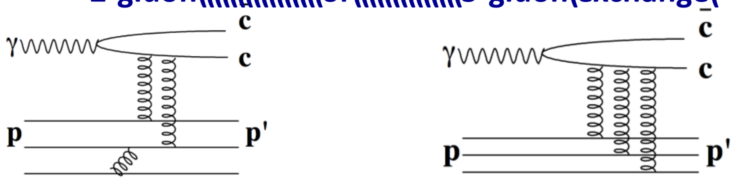
$$P_c \rightarrow J/\psi\ p$$

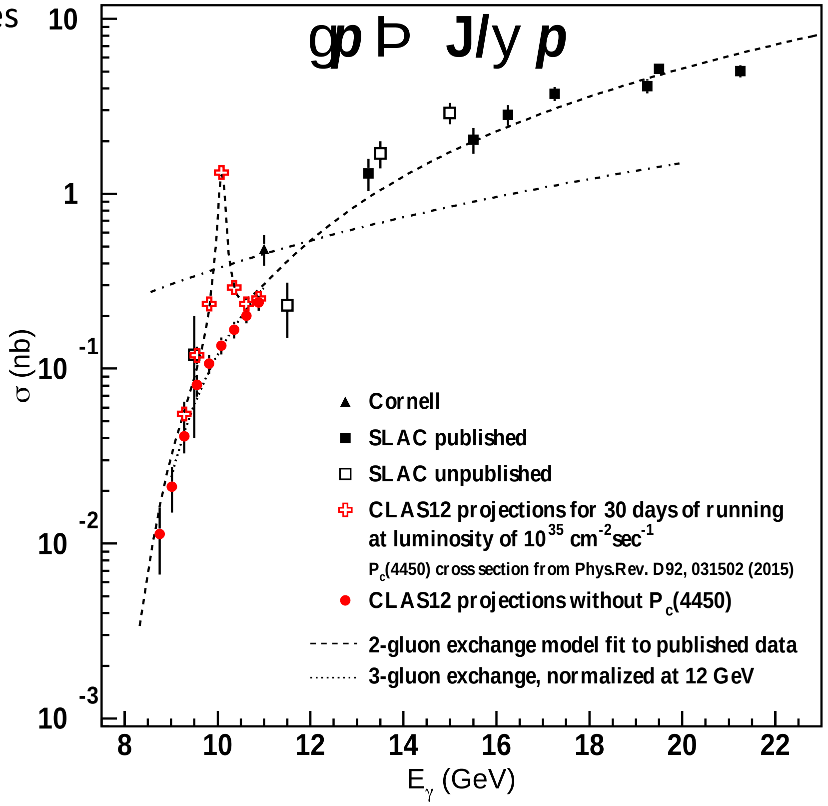
5-quark(bound(state((((((or(((((((Hadronic(molecule(



What is the mechanism of charmonium production at the threshold

2-gluon(((((((((((((((((or((((((((((((((3-gluon(exchange(





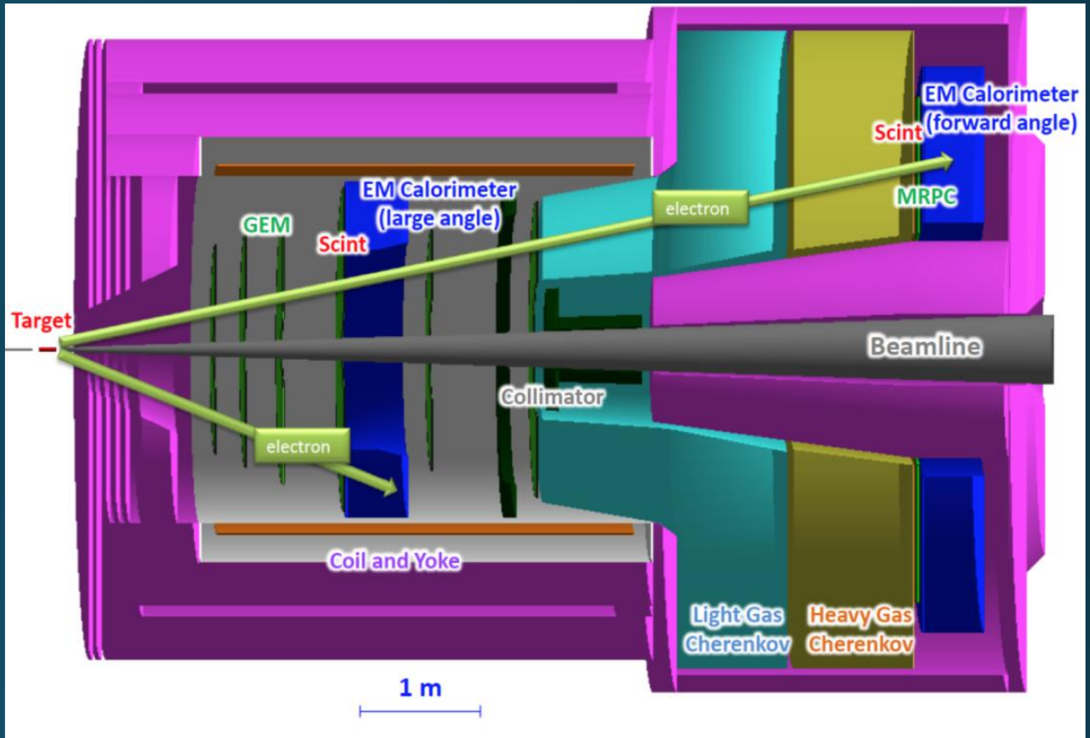
Experiment E12-12-001 measures J/ψ production on the proton near threshold – will verify existence of the ***charmed&pentaquarks***&and will study ***the&gluon&field&of&the&nucleon***

JLAB experiment E12-12-001

J/ψ experiment E12-12-006 at SoLID

ATHENNA Collaboration

- $3\mu A$ electron beam at 11 GeV for 50 days
- 11 GeV beam 15cm liquid hydrogen target
- Ultra-high luminosity (43.2 ab^{-1})
- General purpose large acceptance spectrometer
- Symmetric acceptance for electrons and positrons

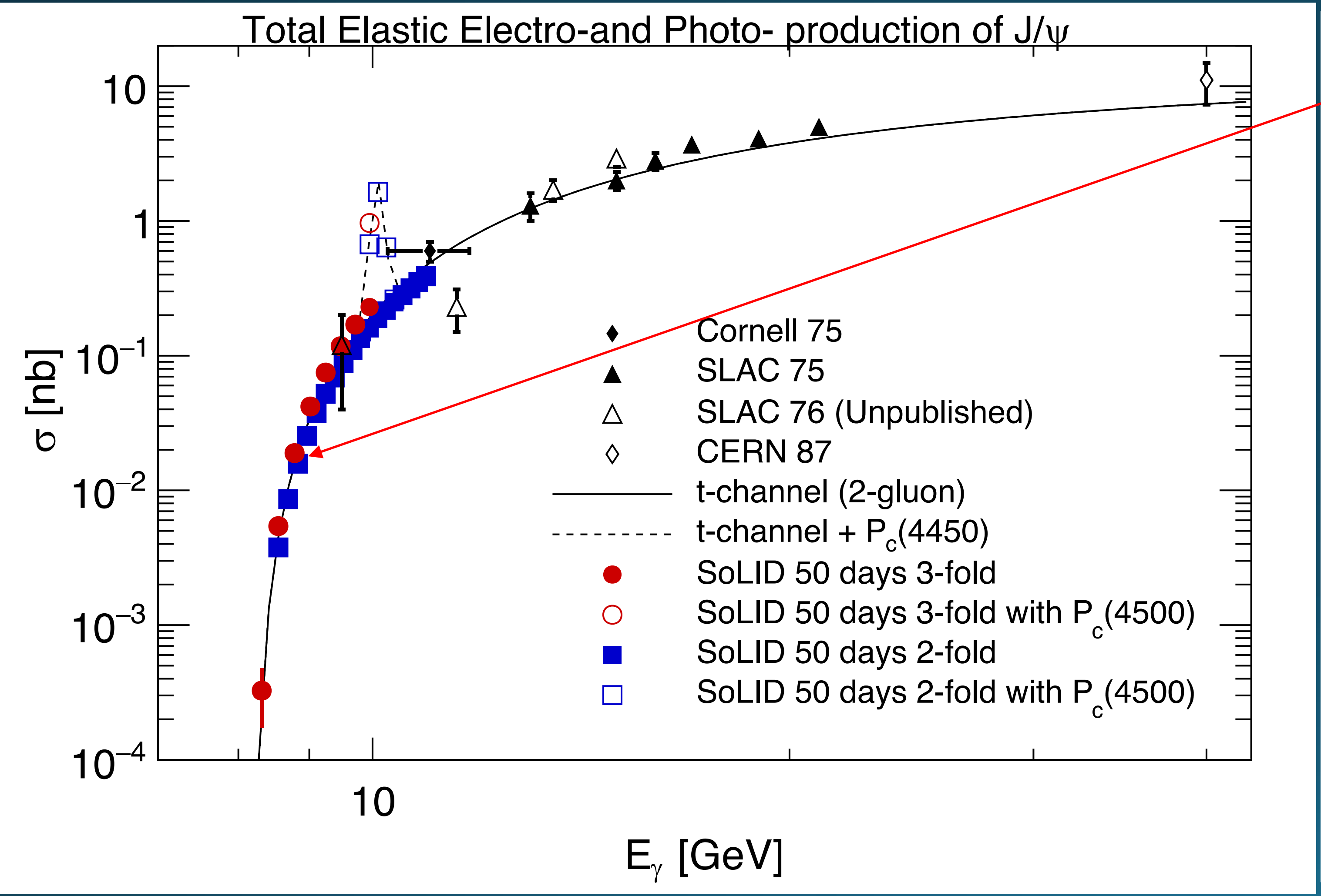


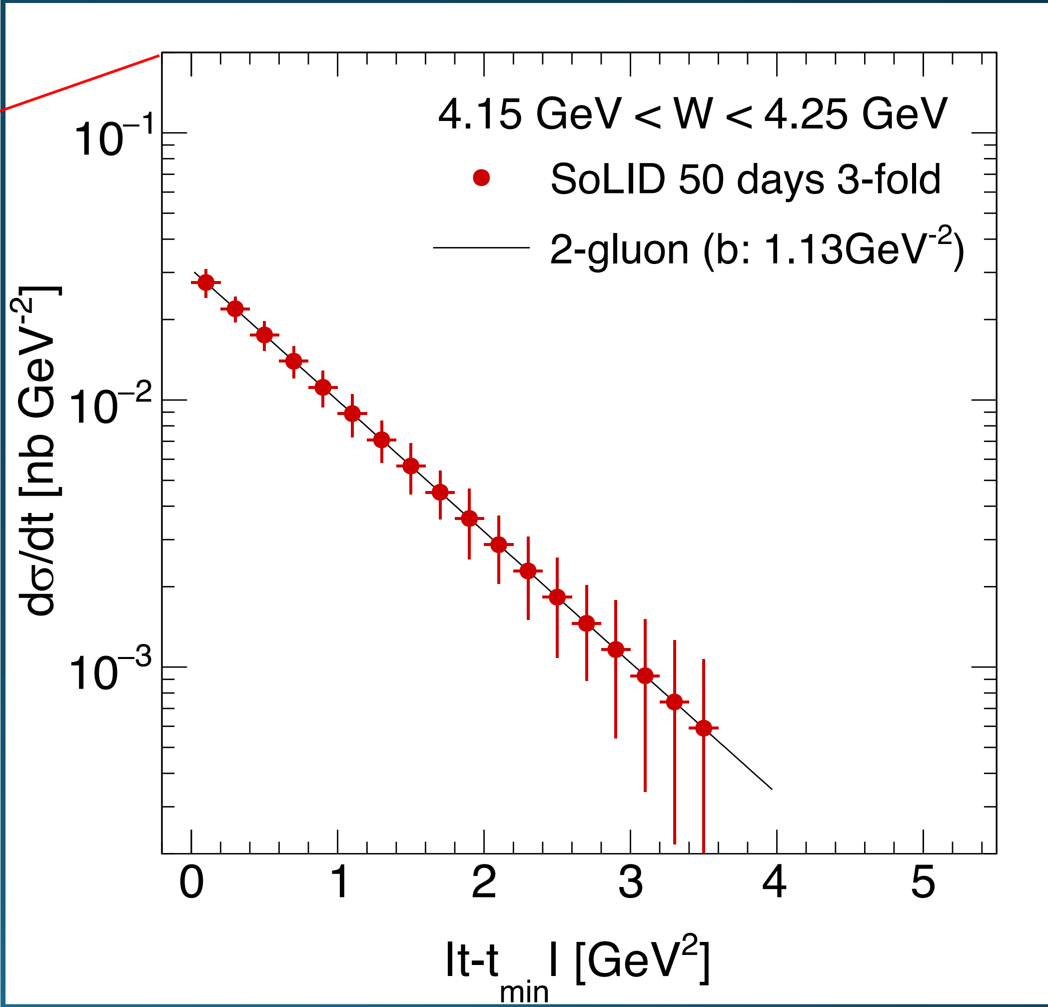
$$\gamma/\gamma^* + N \rightarrow N + J/\psi$$

- Electro-production
- Real photo-production through bremsstrahlung in the target cell

K. Hafidi, S. Joosten, Z.-E. Meziani & J.-W. Qiu, Few Body Syst. 58 (2017) no.4, 141 and references therein

J/Psi@ SoLID E12-12006





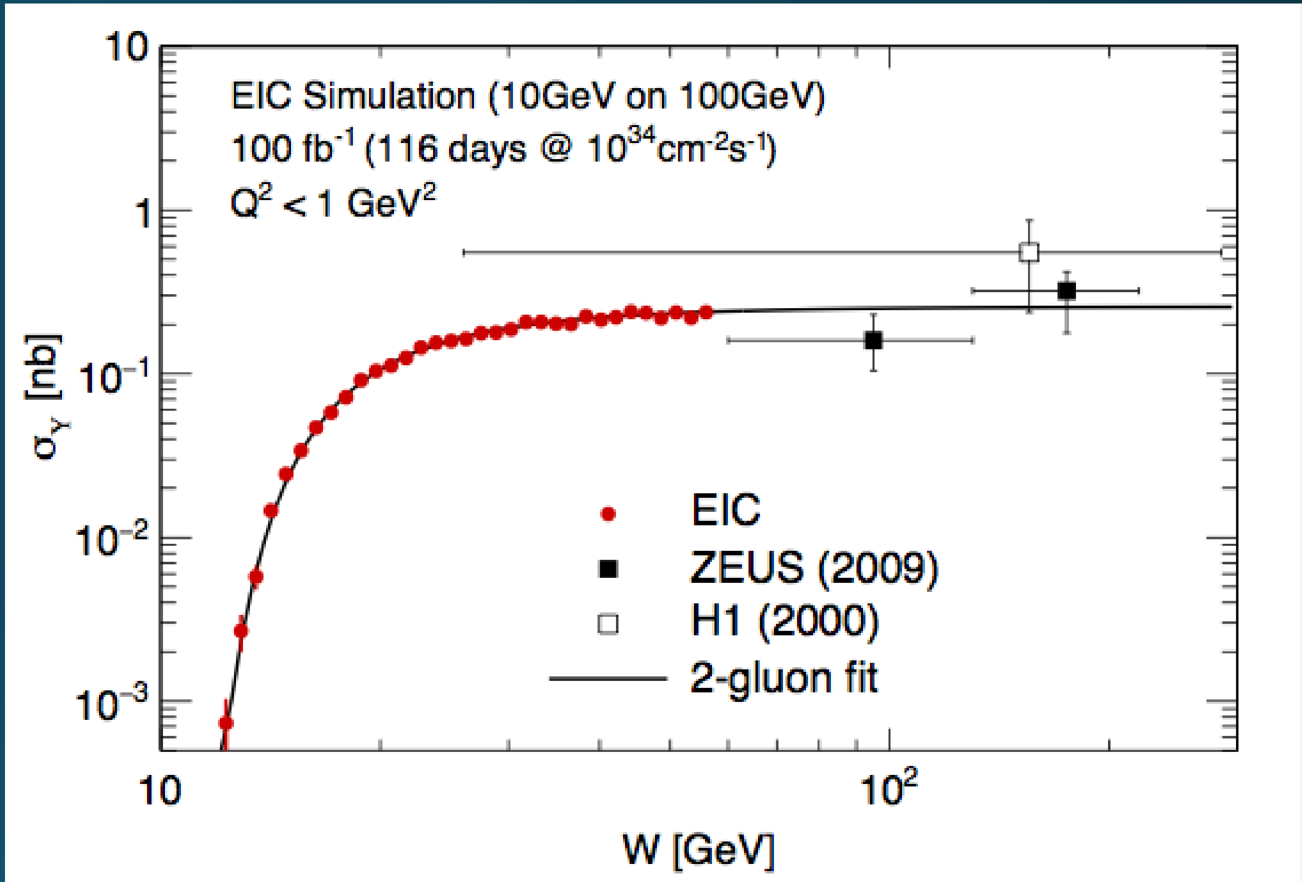
Quarkonia at an EIC

- 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
  - 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.

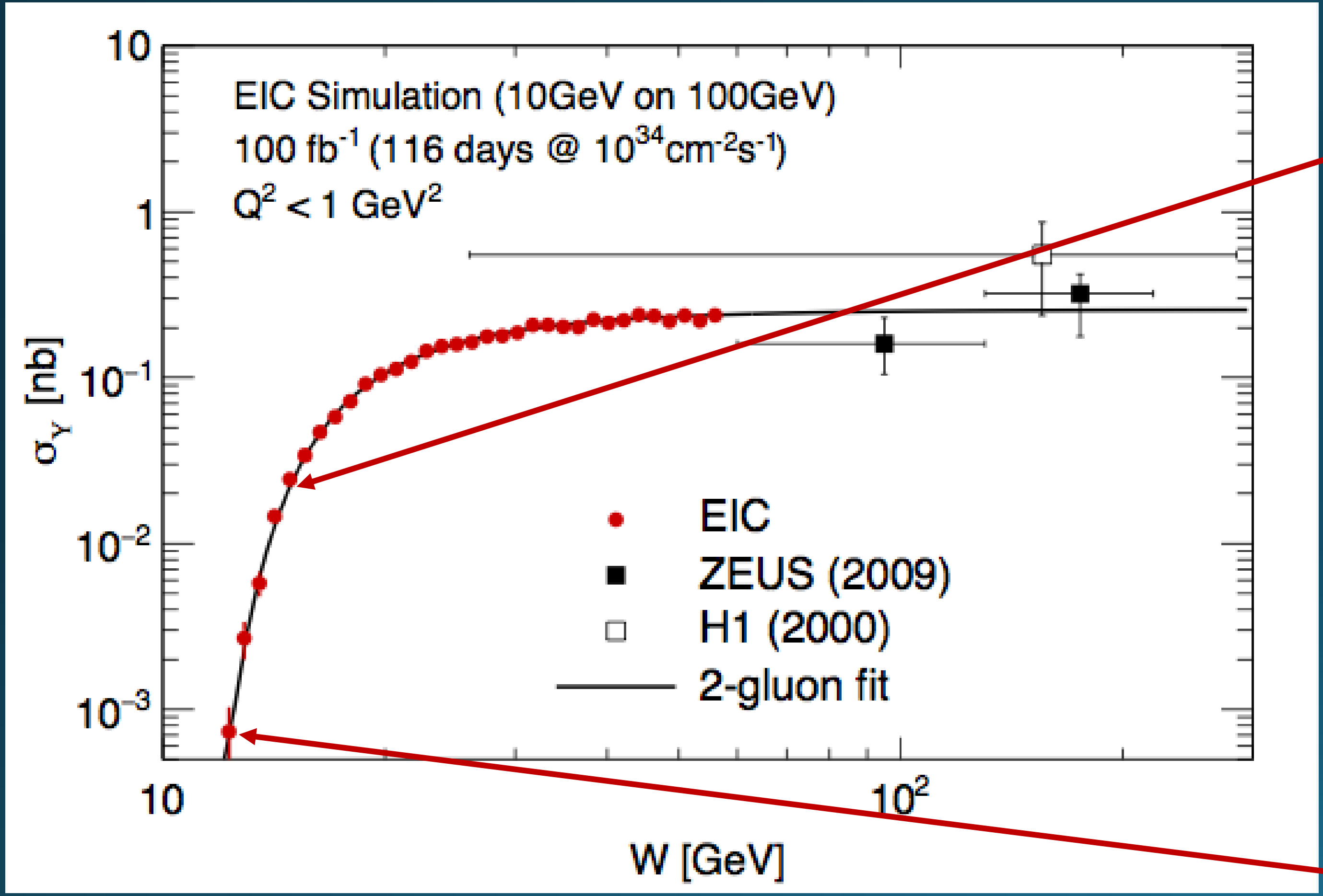
Υ photo-production at an EIC

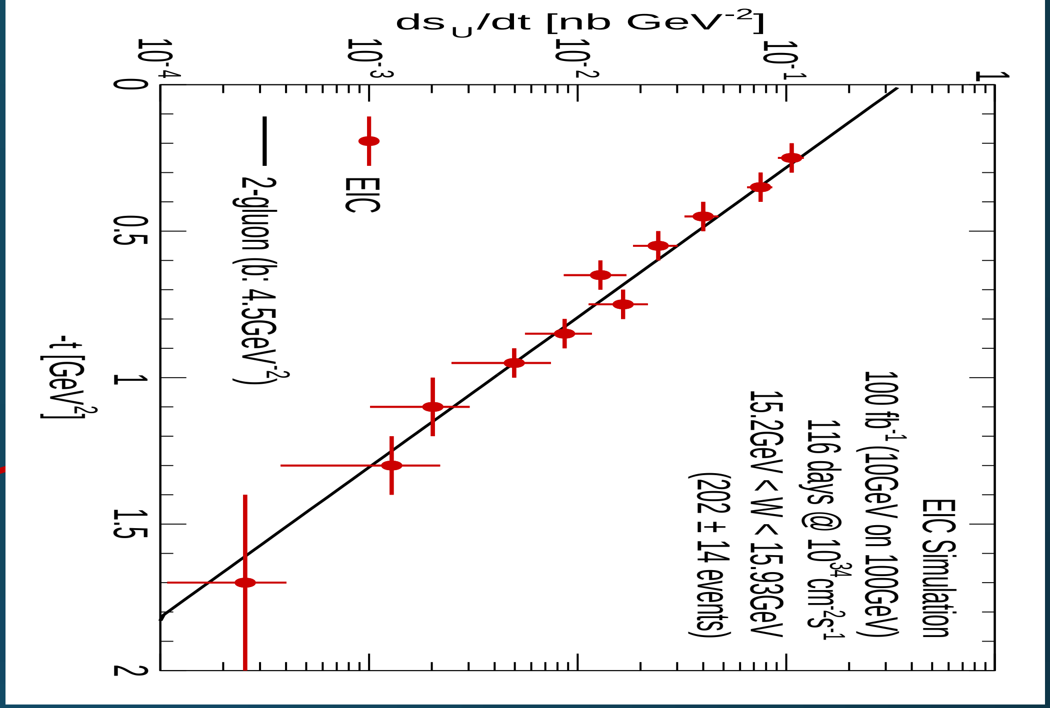
- Quasi-real production at an EIC
- Using nominal EIC detector (consistent with white paper)
  - Both electron and muon channel
- Fully exclusive reaction
- Can go to near-threshold region

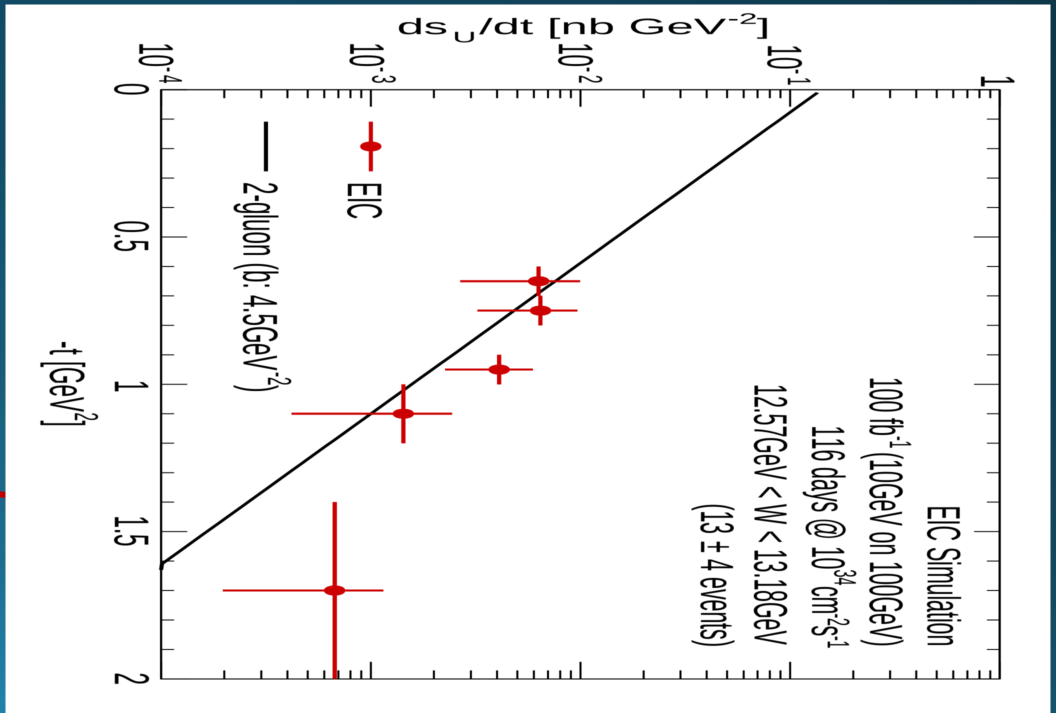


- *Υ(1s)* production possible at threshold!
  - Provides measure for universality, complimentary to threshold *J/ψ* program at JLab12
  - Is there a “beautiful” pentaquark?
- Sensitivity down to ~10^{-3} nb!

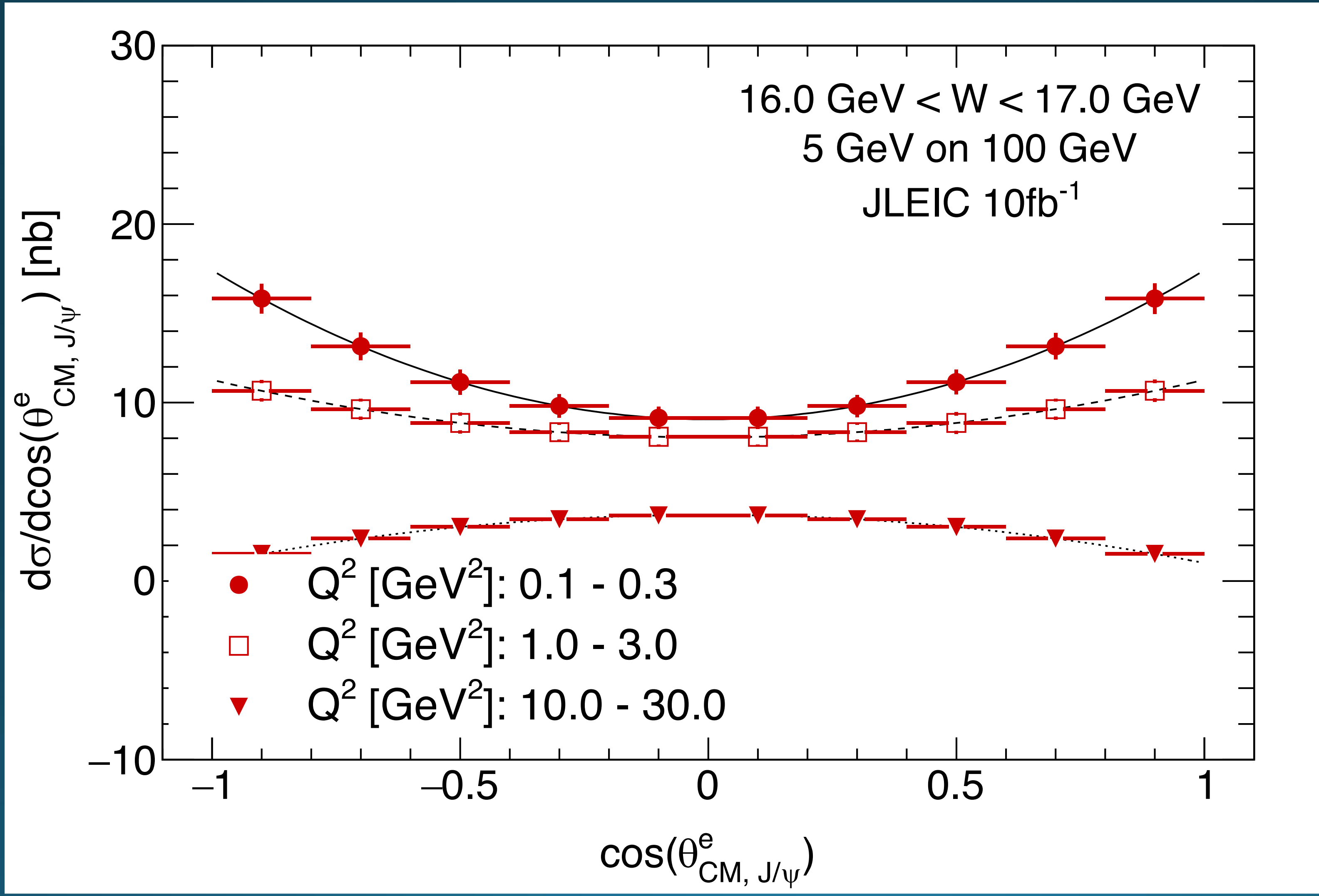
Elastic Upsilon production at an EIC







Angular distribution of the decays



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
- 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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