Origin of the Proton Mass?
Heavy Quarkonium Production at Threshold from JLab to EIC

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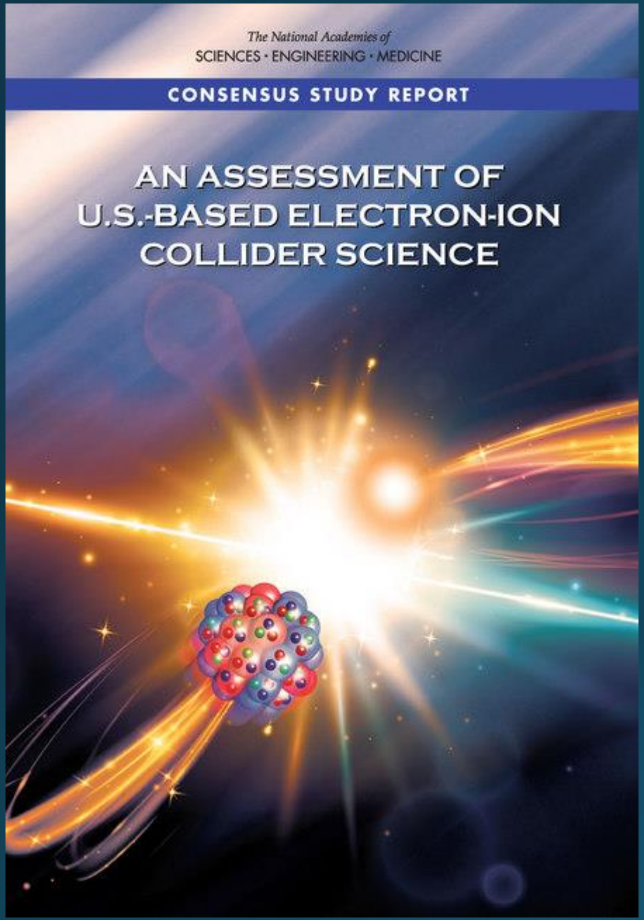
in collaboration with Sylvester Joosten, Temple U.

S. Joosten and Z. E. Meziani, PoS QCDEV 2017, 017 (2018) [arXiv:1802.02616 [hep-ex]]

Outline:

- The science enabled by heavy quarkonia in the threshold region
- Elastic threshold production of Charm (J/Psi) on the nucleon experiments a JLab
- Elastic threshold production of Beauty (Upsilon) on the nucleon at an EIC

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?

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?

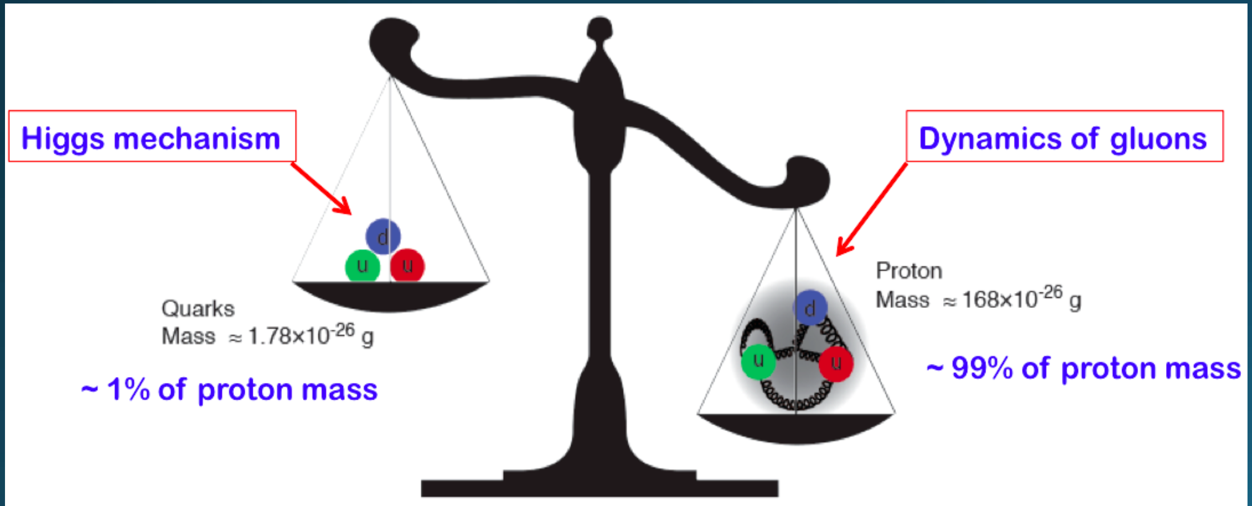
- Are bound states of quarkonia in nuclei possible?

Threshold electro-photoproduction of quarkonium can probe the mass distribution inside the proton and nuclei

How does QCD generate its mass?

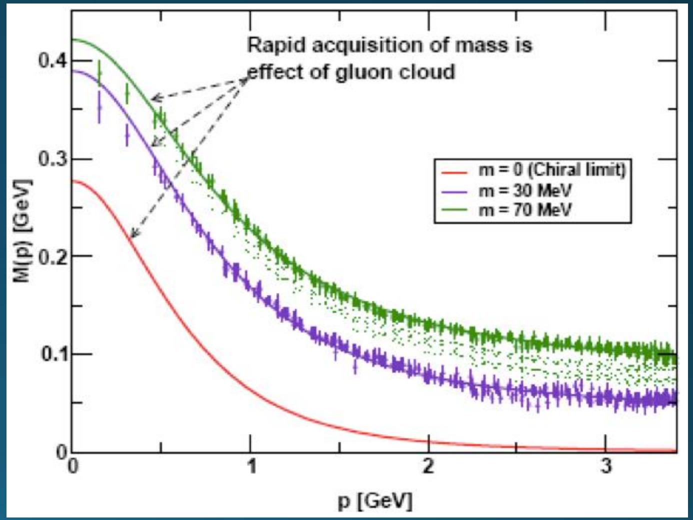
"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass   Frank Wilczek (1999, Physics Today)

✧ Massless, yet, responsible for nearly all visible mass



Examples in nature: proton, blackhole

"Mass without mass!"

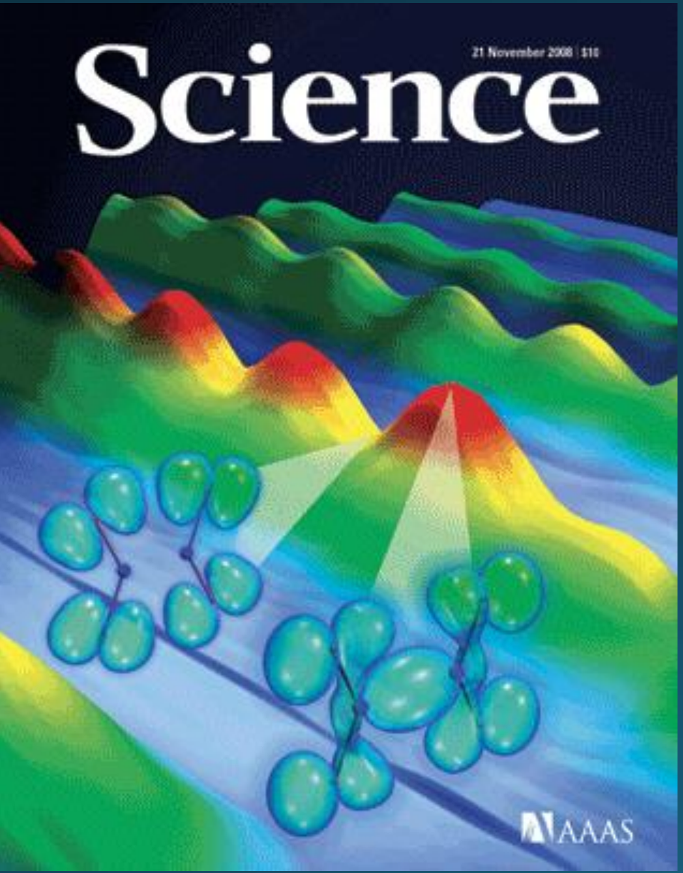


Bhagwat & Tandy/Roberts et al

How does QCD generate the nucleon mass?

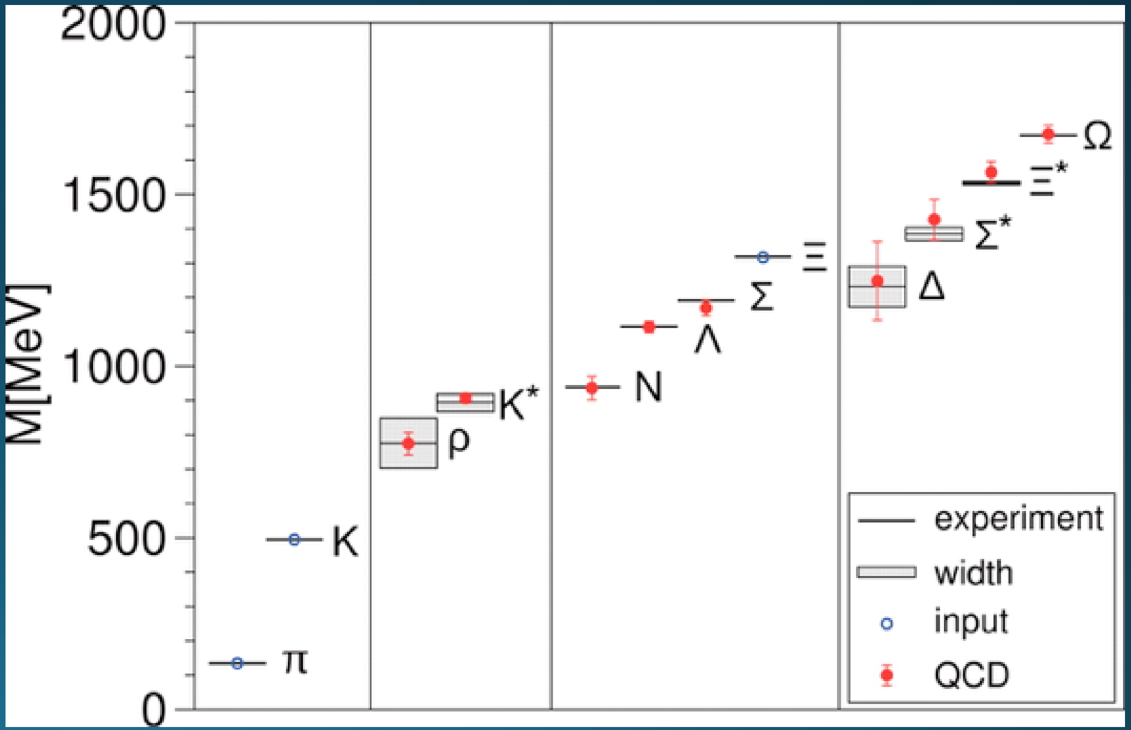
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" ***The 2015 Long Range Plan for Nuclear Science***

❑ Hadron mass from Lattice QCD calculation:



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



How does QCD generate this? The role of quarks and 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

- 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, …**

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

In the chiral limit we have a finite number for the nucleon and zero for the pion

Proton Mass Decomposition
useful to find the role the constituents but not unique

- Trace decomposition
  - see, e.g., [M. Shifman et al., Phys. Lett. 78B (1978), D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130 (1996)]

- Rest frame decomposition
- [X.D. Ji, Phys. Rev. Lett. 74, 1071 (1995), X. D. Ji, Phys. Rev. D 52, 271 (1995)]

- Decomposition with Pressure effects
  - [C. Lorce´, Eur. Phys. J. C78 (2018) 2, arXiv:1706.05853]

Scale Anomaly in QCD; Trace Decomposition

D. Kharzeev Proc. Int. Sch. Phys. Fermi 130 (1996)

$$T^{\mu}_{\mu} = +\frac{\beta(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{q}_h q_h$$

with

$$\beta(g) = -b \frac{g^3}{16\pi^2} + \ldots, \quad b = 9 - \frac{2}{3} n_h$$

At small momentum transfer, heavy quarks decouple:

$$\sum_h \bar{q}_h q_h \rightarrow -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}{}_{\alpha\beta} + \ldots$$

M. Shifman et al., Phys. Lett. 78B (1978),

Only light quarks enter the expression

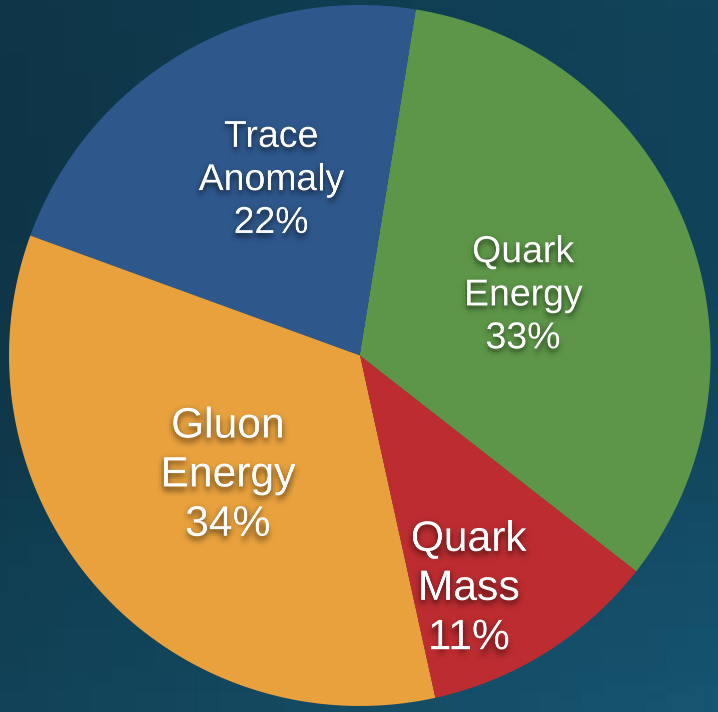
$$T^{\mu}_{\mu} = +\frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l$$

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:

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

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

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

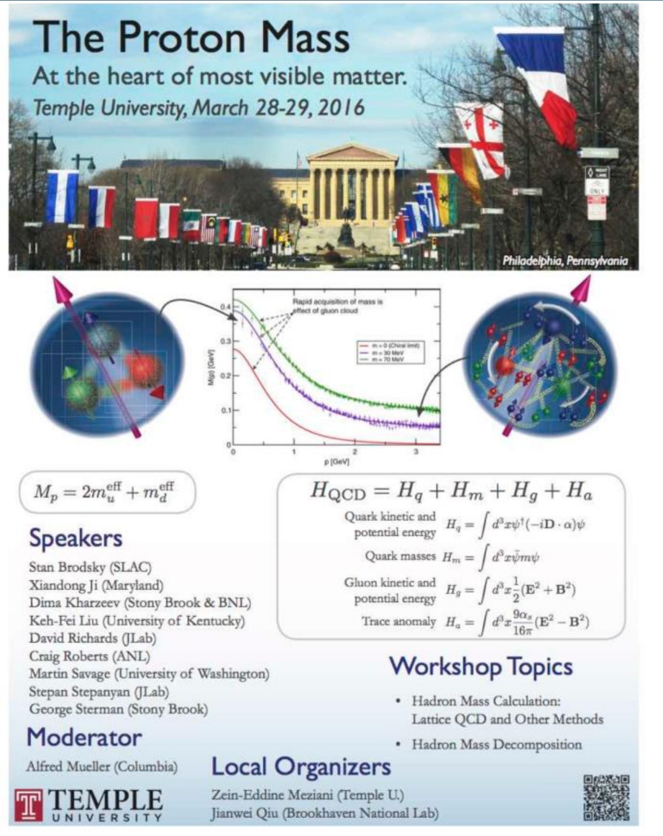
$$M_a = \frac{1}{4}(1-b)M$$

- *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**

The proton mass … a hot topic!

Three-pronged approach to explore the origin of proton/hadron mass:



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

What can lattice QCD do to explore the role of "individual" constituents in making up the proton mass? Such as role of quark mass, in particular, strange and heavy quark mass, …

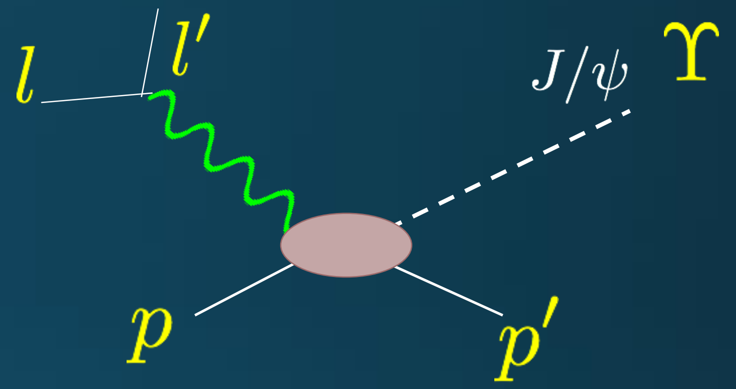
What can the mass decomposition teach us? Taking advantage of the non-uniqueness of the decomposition? Physical meaning and measurability of various terms?

How well can we control the approximation of the analytical or model approaches? Proton wave function? How to quantify or improve the approximations? Hints from the success of model calculations?

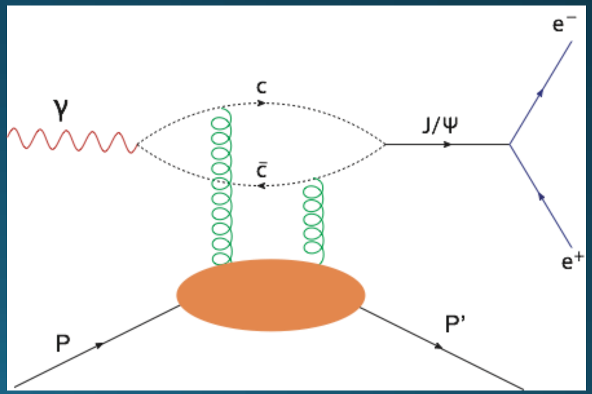
Access the trace anomaly through elastic J/psi and Upsilon production near threshold

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

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



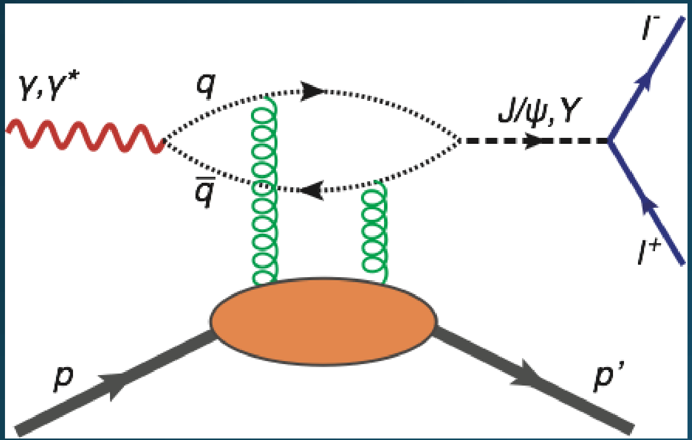
- At JLab we can measure the threshold region in photo and electro-production of J/ ψ in fixed target experiments in 4 halls.
- Depending on the experimental set-up we have:
  - A fully exclusive measurement with the detection of all final state particles in some cases.
  - Detection of the J/ψ decay 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?

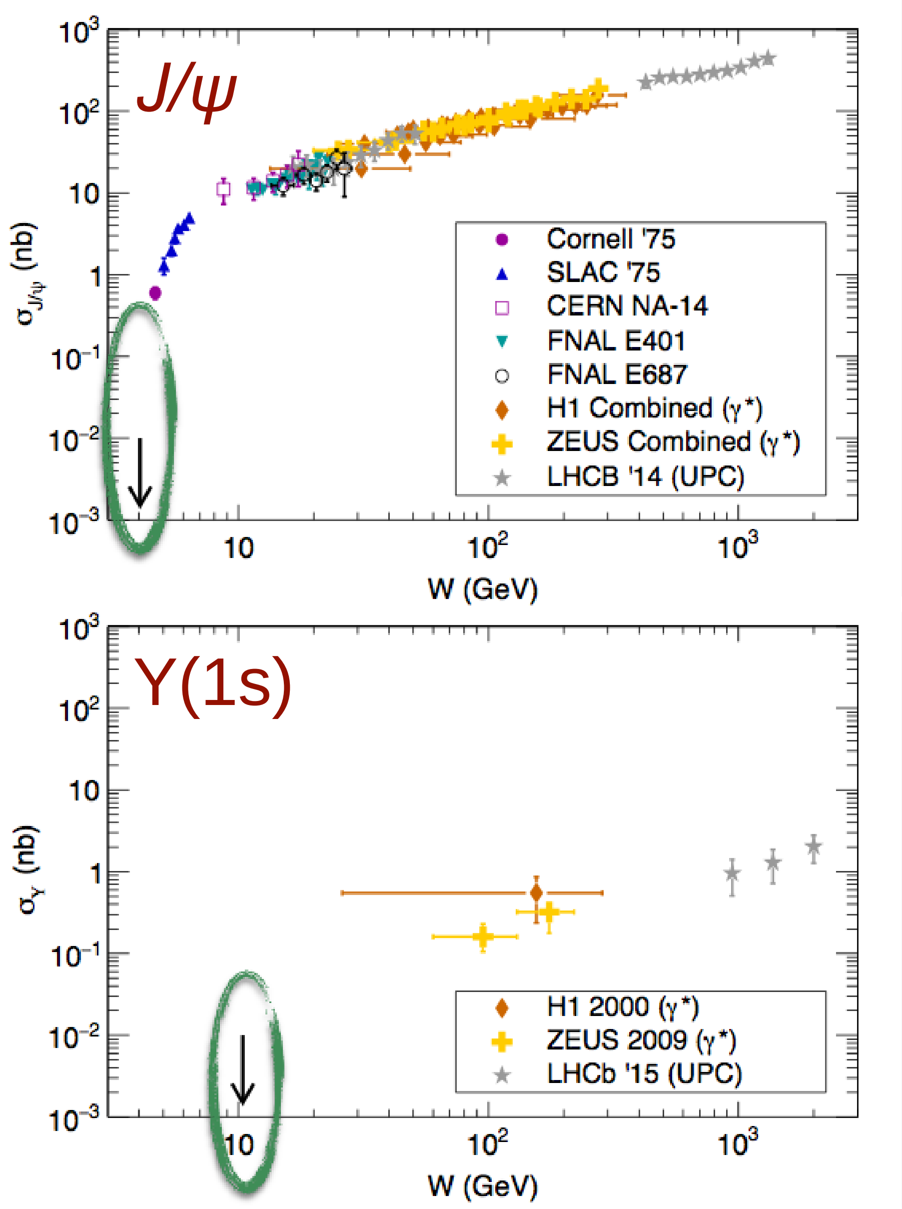
J/ψ photo-production:

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



Υ(1s) photo-production:

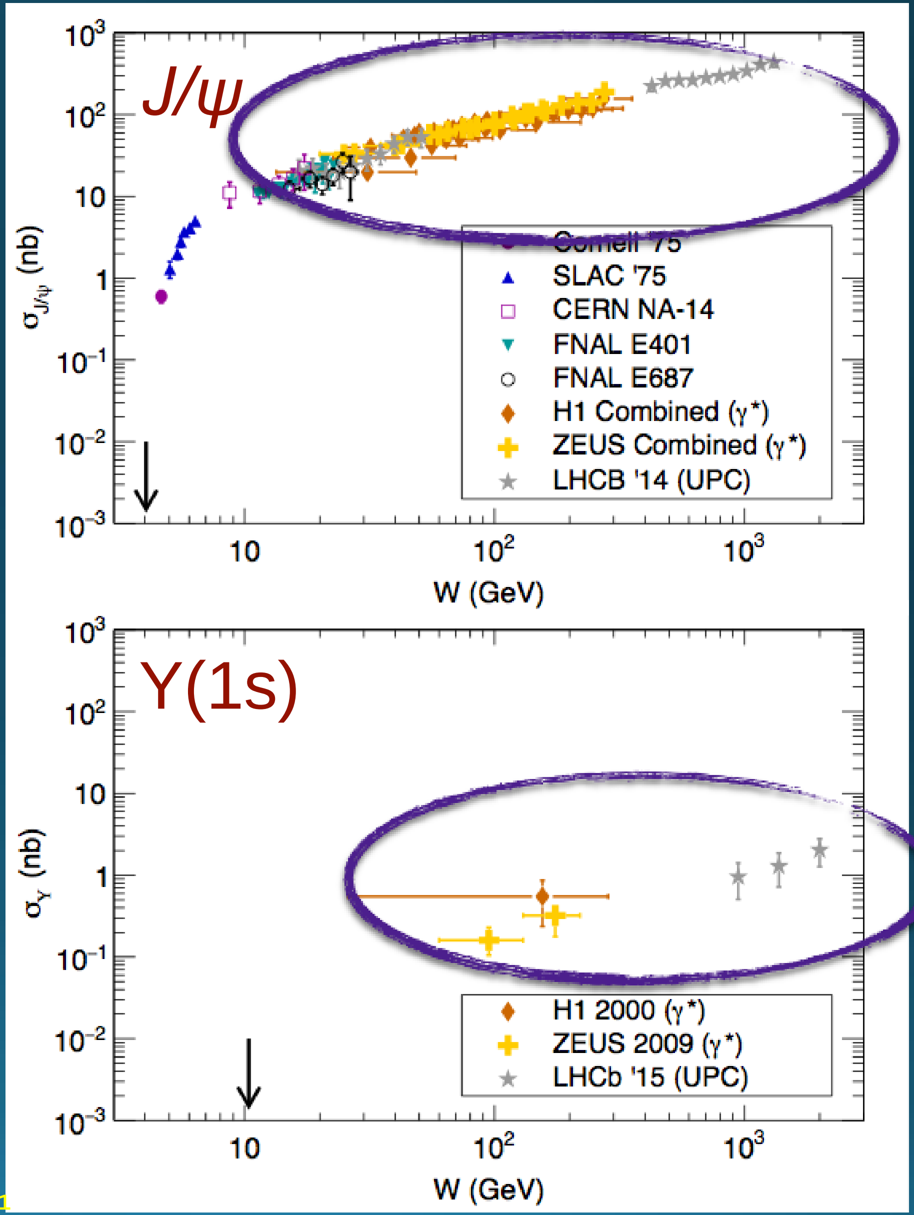
- Not much available
  - ZEUS measured 62 ± 12 events total!



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



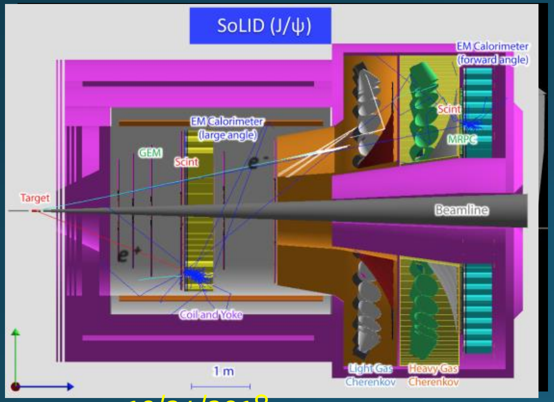
An EIC is ideal for sea-quarks and gluons in the nucleon studies

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***

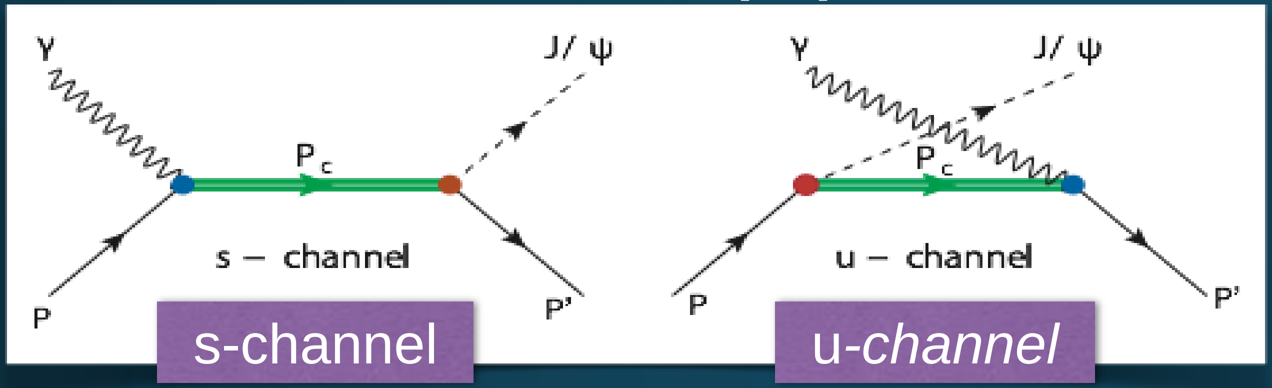
*Hall C – has an approved proposal **to search for the LHCb pentaquark E12-16-007***



*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

J/ψ–007

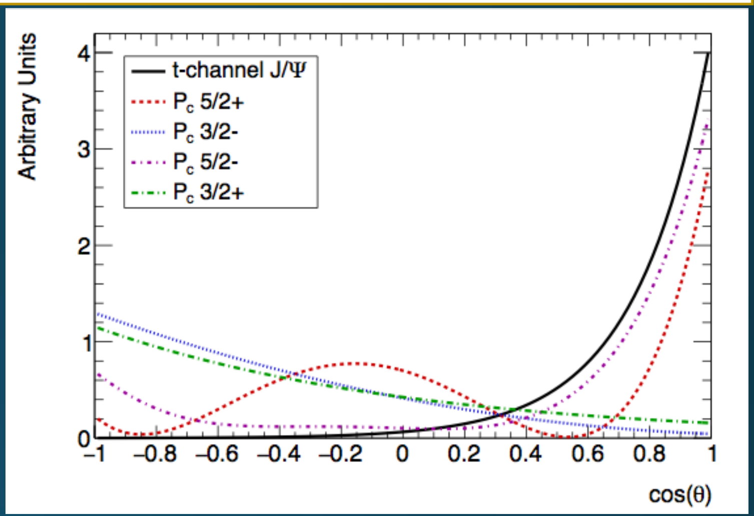


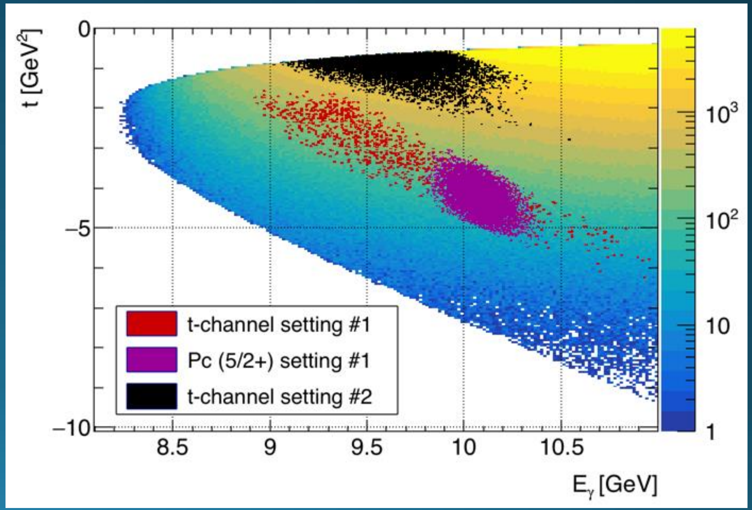
- Cross section depends on coupling of P_c to (J/ψ, p) channel
- J/ψ angular distribution differs between t-channel and $s(u)$-channel

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

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

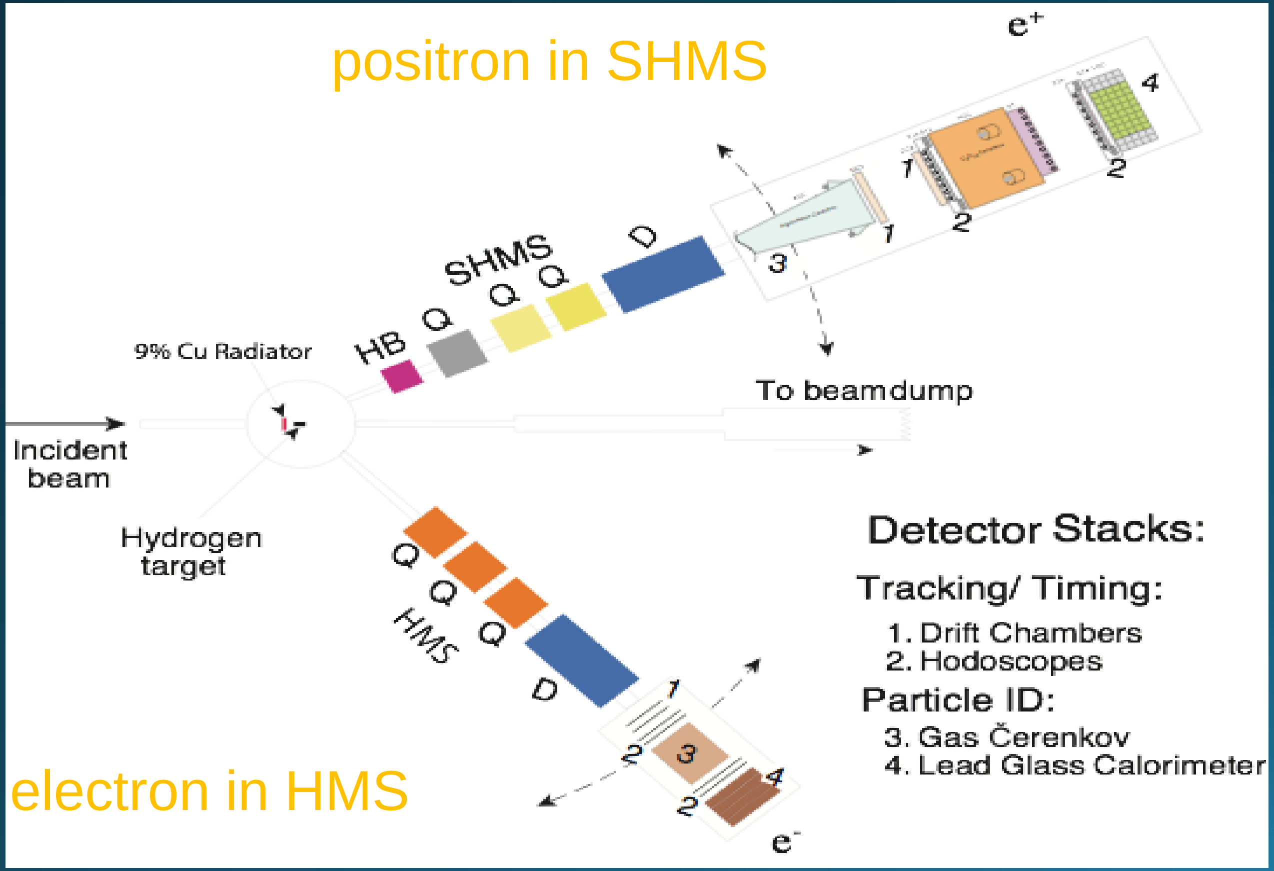




Search for the LHCb pentaquark

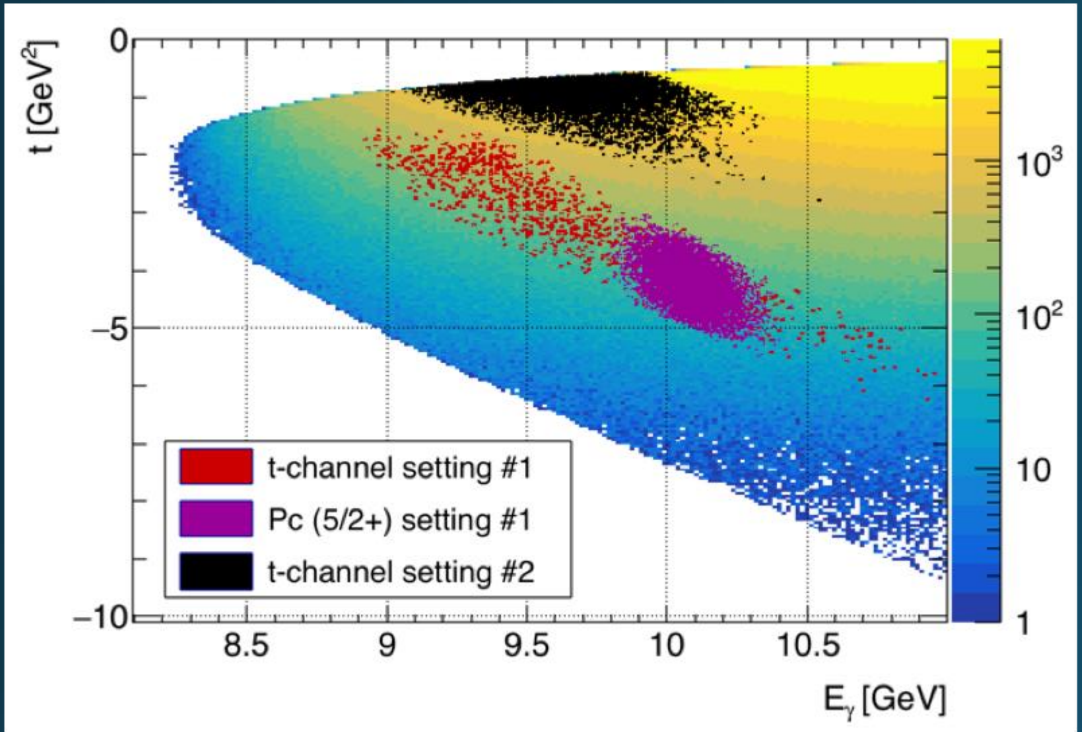
- 50μA electron beam at 10.7 GeV (or 11 GeV)
- 9% copper radiator
- 15cm liquid hydrogen target
  - total 10% RL

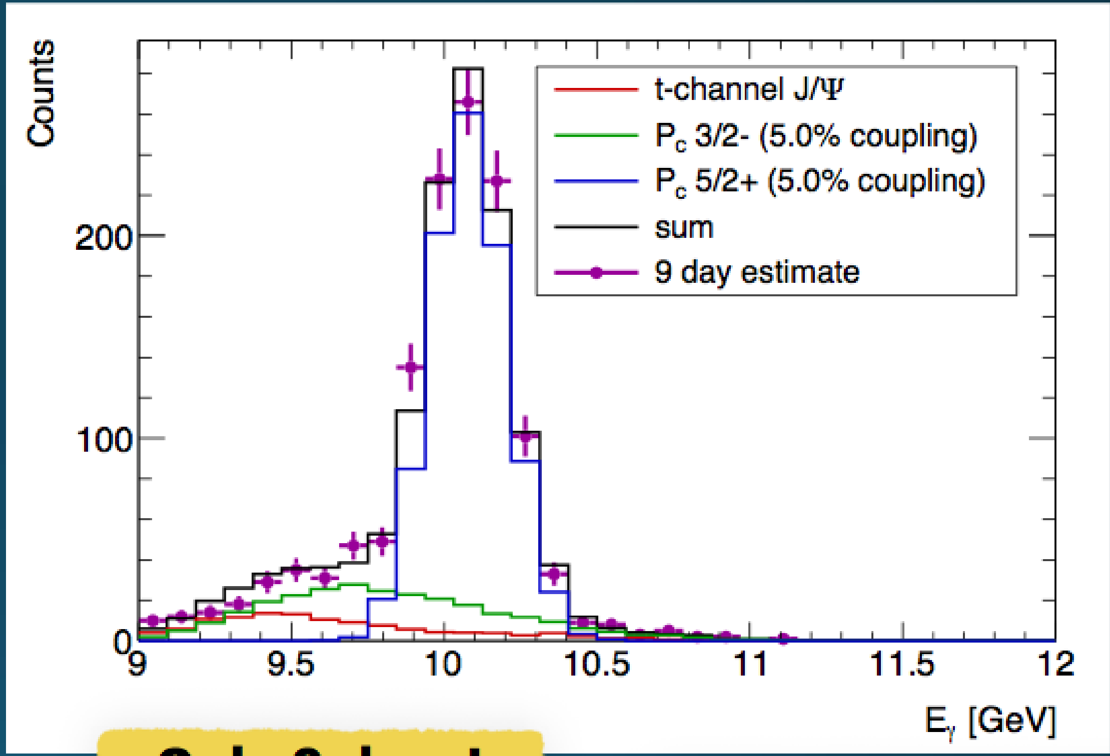
JLab Experiment 12-16-007 in Hall C



- 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

Search for the LHCb pentaquark





Only 9 days!

Significance > 20σ!

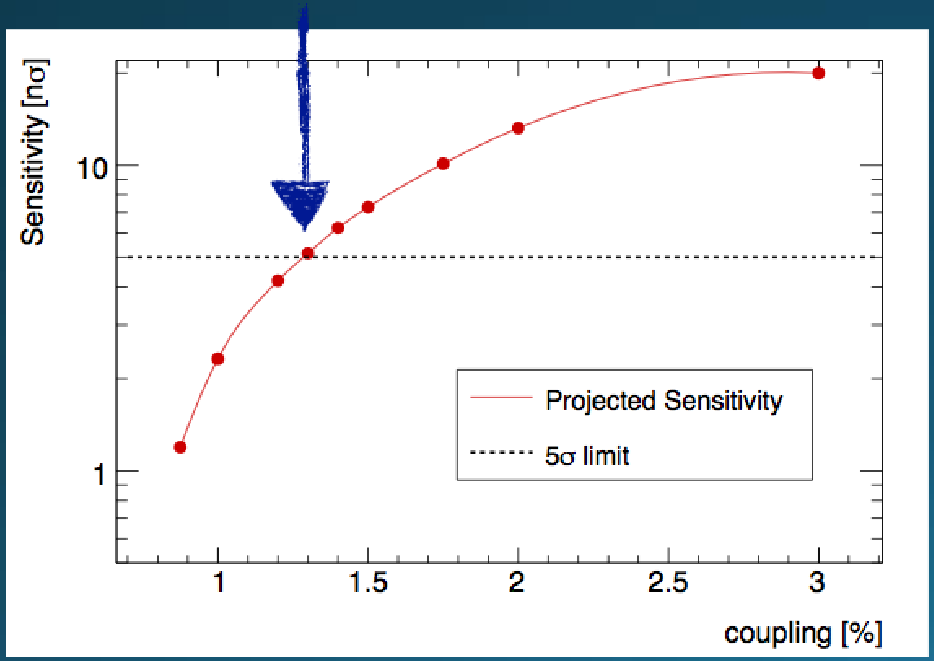
t-channel: 120 events
5/2+: 881 events
3/2-: 266 events

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

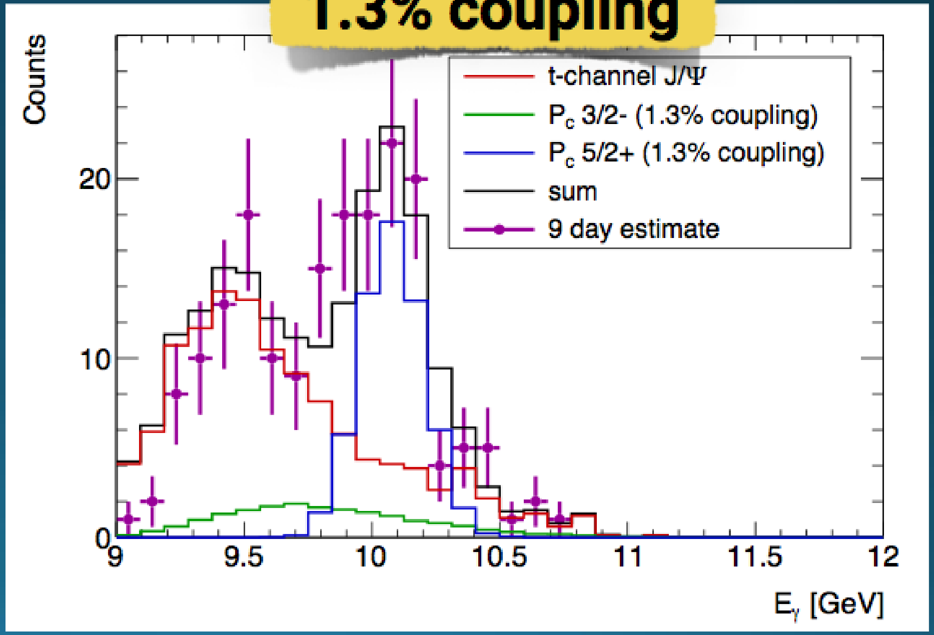
Wang Q., *et al.*, PRD 92-3 (2015) 034022-7

Sensitivity for Discovery

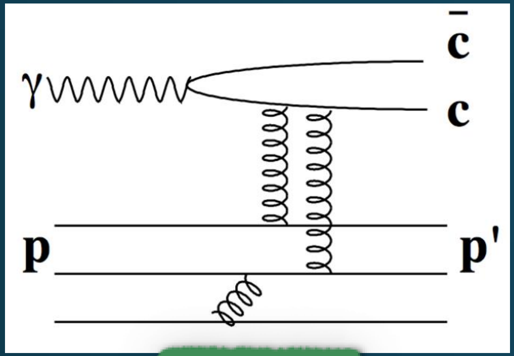
- sensitivity calculated using a Δ-log-likelihood formalism
- 5 standard deviation level of sensitivity starting from 1.3% coupling!



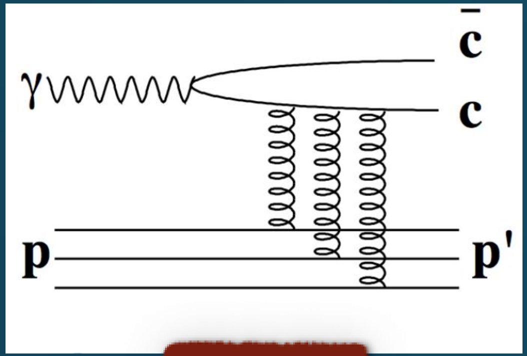
Projection for 1.3% coupling



Production mechanism near threshold unknown

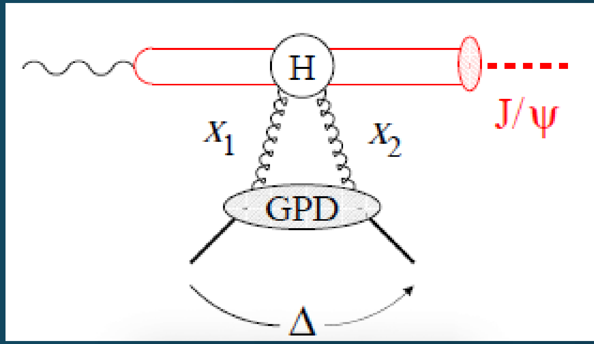


2-gluon



3-gluon

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



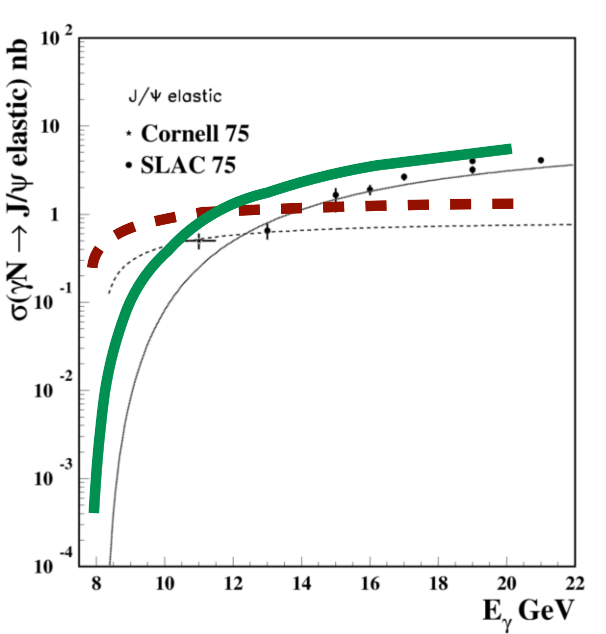
partonic soft

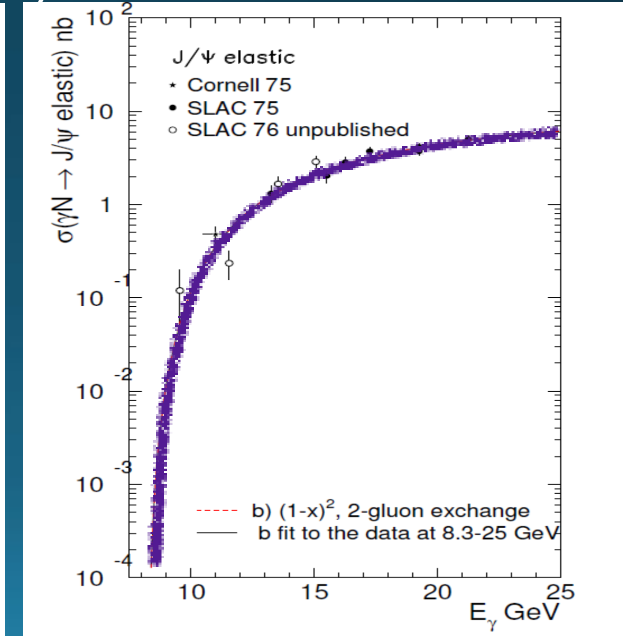
Frankfurt and Strikman., PRD66 (2002), 031502

- 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





Y.~Hatta and D.~L.~Yang, ``Holographic J/ψ production near threshold and the proton mass problem,''
Phys.Rev. D 98}, no. 7, 074003 (2018)

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

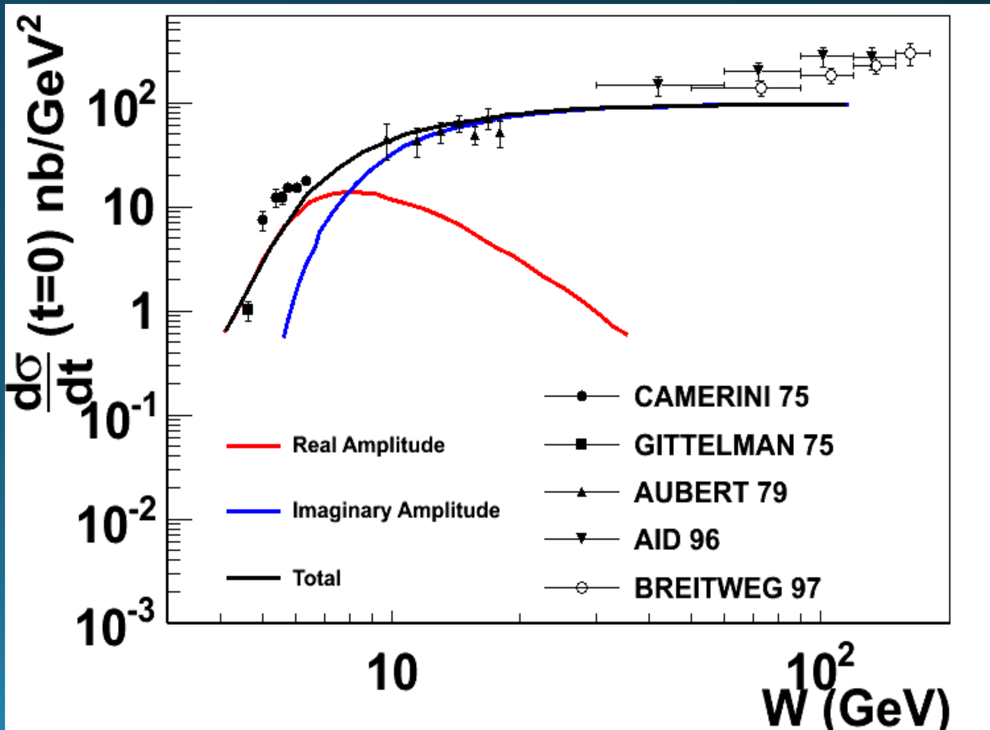
$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

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

- VMD relates photo-production cross section to quarkonium-nucleon scattering a ude $M_{\psi p}$
- **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)!



Binding energy of the *J/ψ* - nucleon potential

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

$$\mathcal{R}eT_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{el}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\mathcal{I}mT_{\psi p}(\nu')}{\nu'^2 - \nu^2}$$

- 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 $a_{\psi p}$

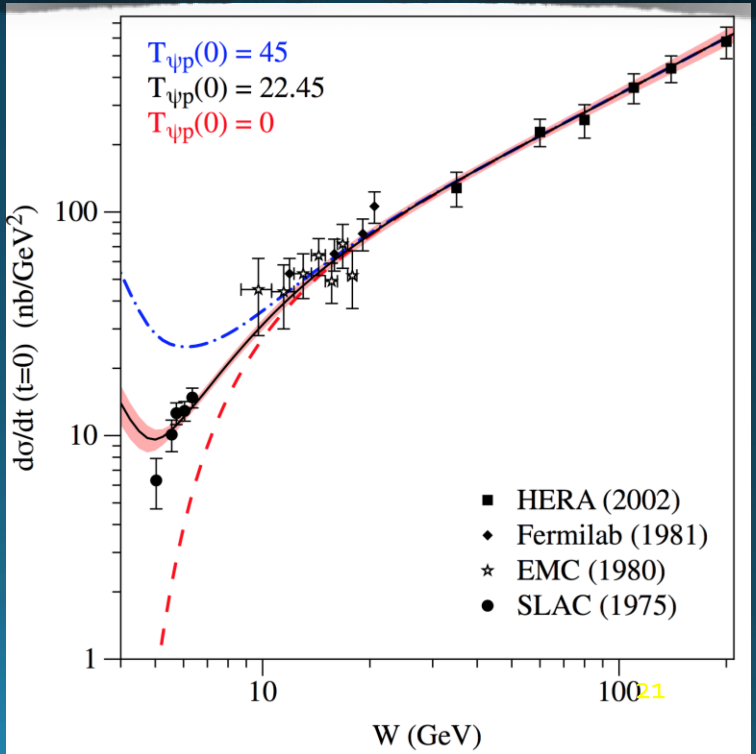
$$T_{\psi p} = 8\pi(M + M_{\psi})a_{\psi p}$$

- 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)

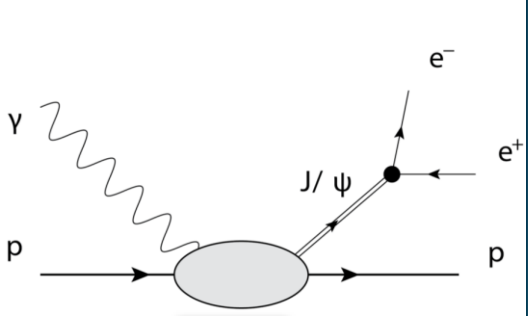
- Recent fit to existing data in a dispersive framework:
  - $a_{\psi p}$ ~ 0.05 fm translated to ($B_{\psi p}$ ~ 3 MeV) for nuclear matter

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

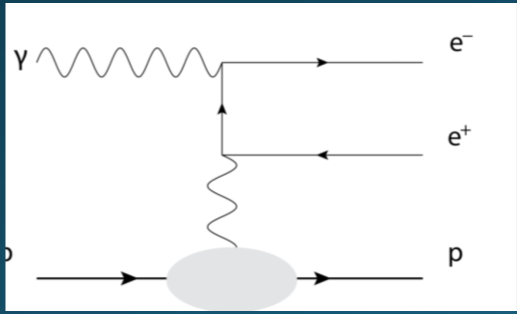


B-H asymmetry: access scattering length $a_{\psi p}$

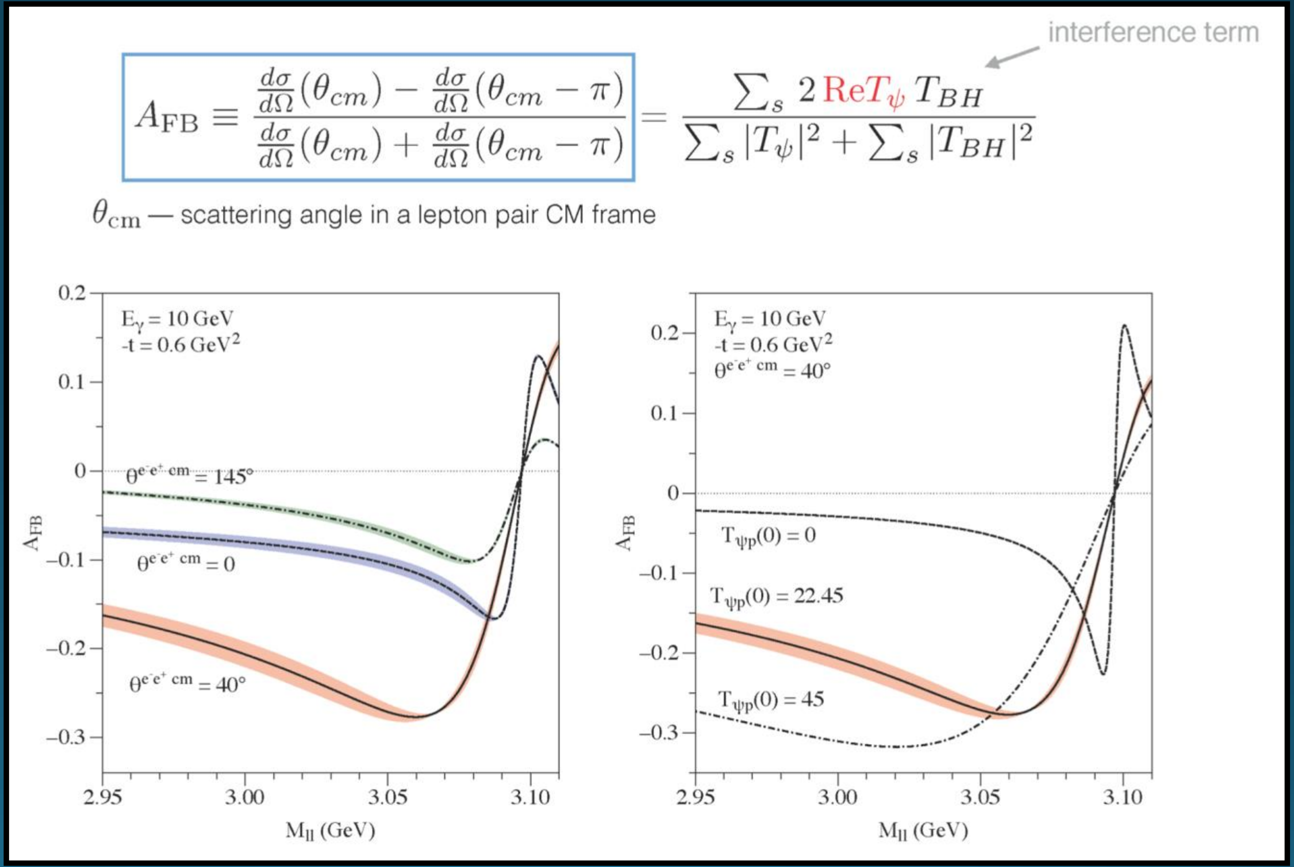
- Interference between elastic J/ψ production near threshold and Bethe-Heitler
- Forward-backward asymmetry near the J/ψ invariant mass peak
- Sensitive to real part of the scattering amplitude, hence $a_{\psi p}$ and $B_{\psi p}$



J/ψ

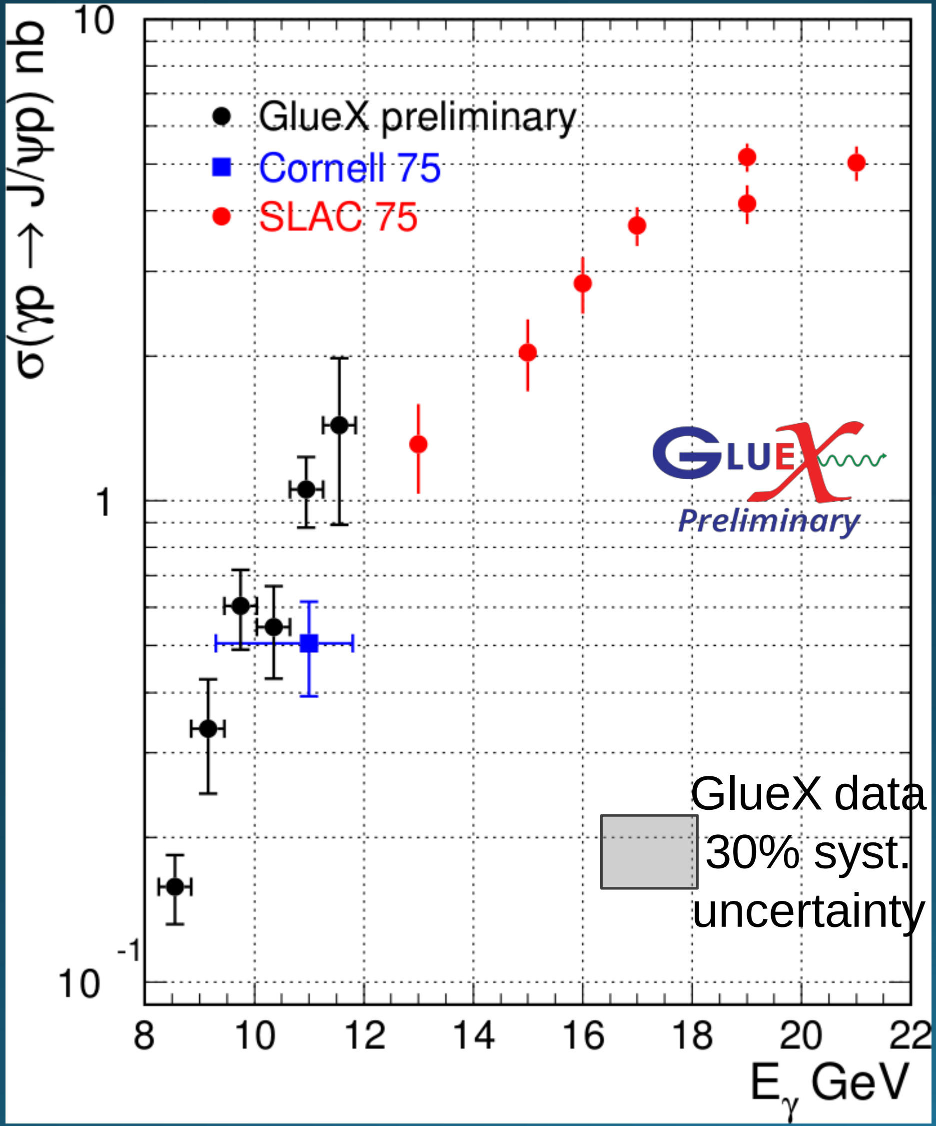


B-H



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

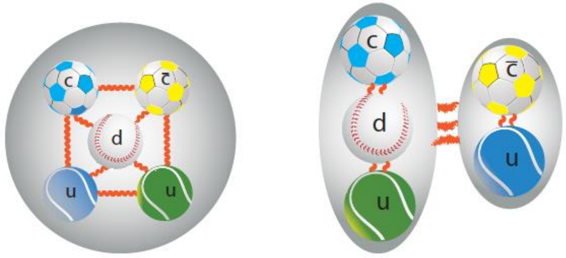
Slide from Penchev at the 2018 JLab Users Group Meeting

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

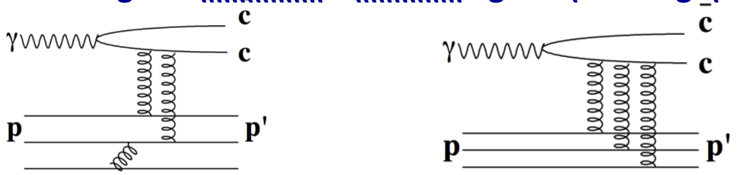
$$P_c \rightarrow J/\psi\ p$$

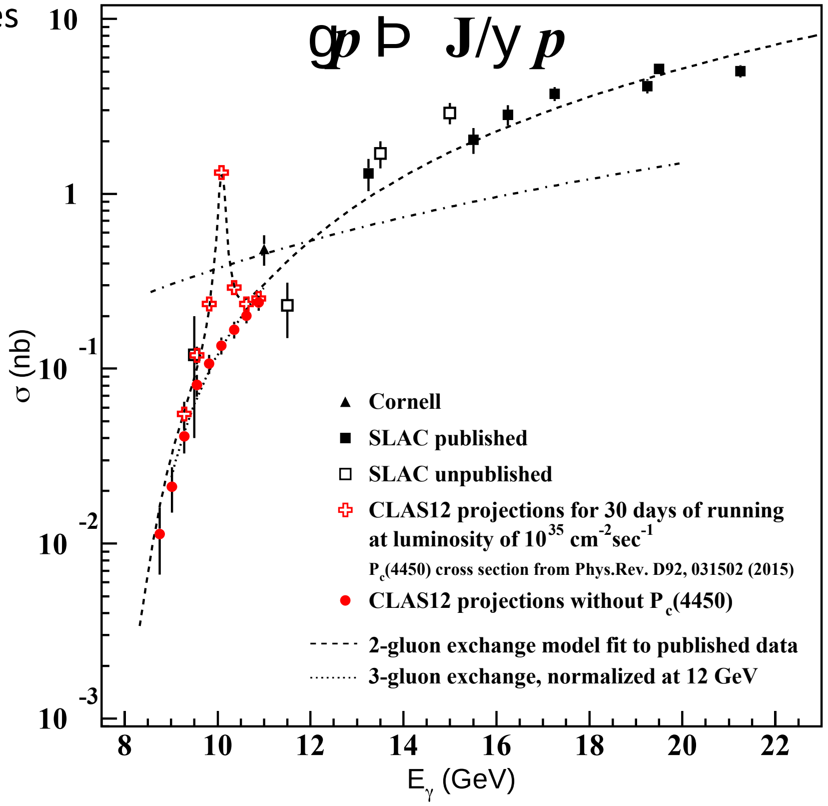
5-quark(bound(state((((((or((((((Hadronic(molecule(



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***

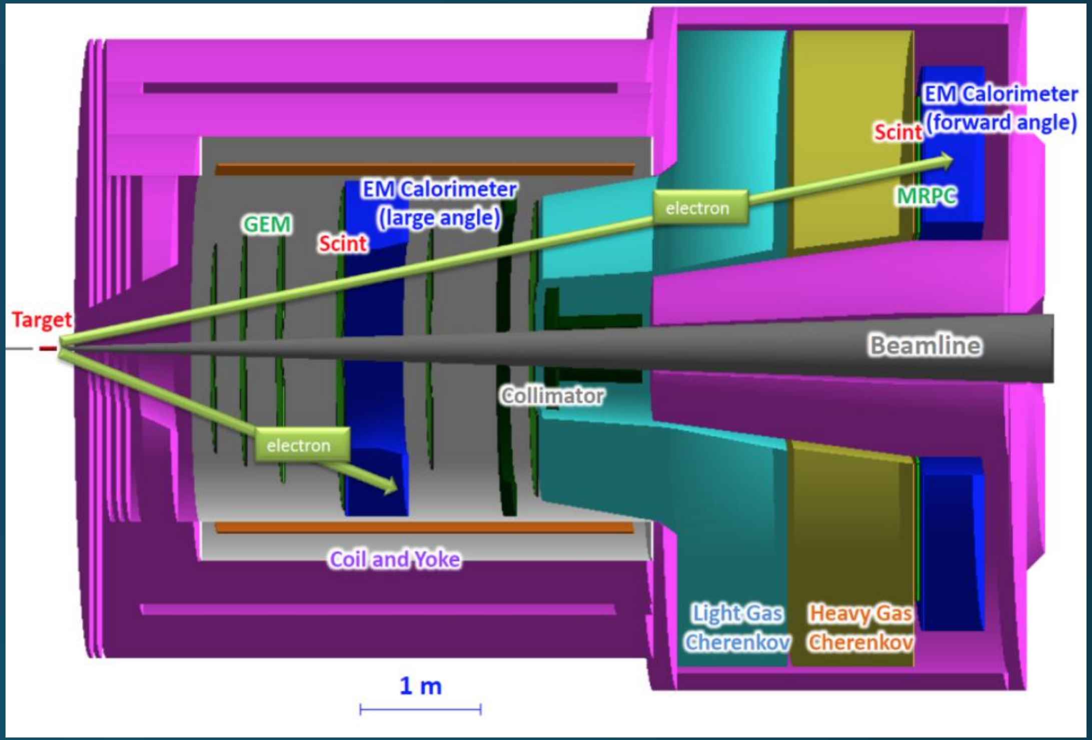
JLAB experiment E12-12-001

J/ψ experiment E12-12-006 at SoLID

ATHENNA Collaboration

- 3μA 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

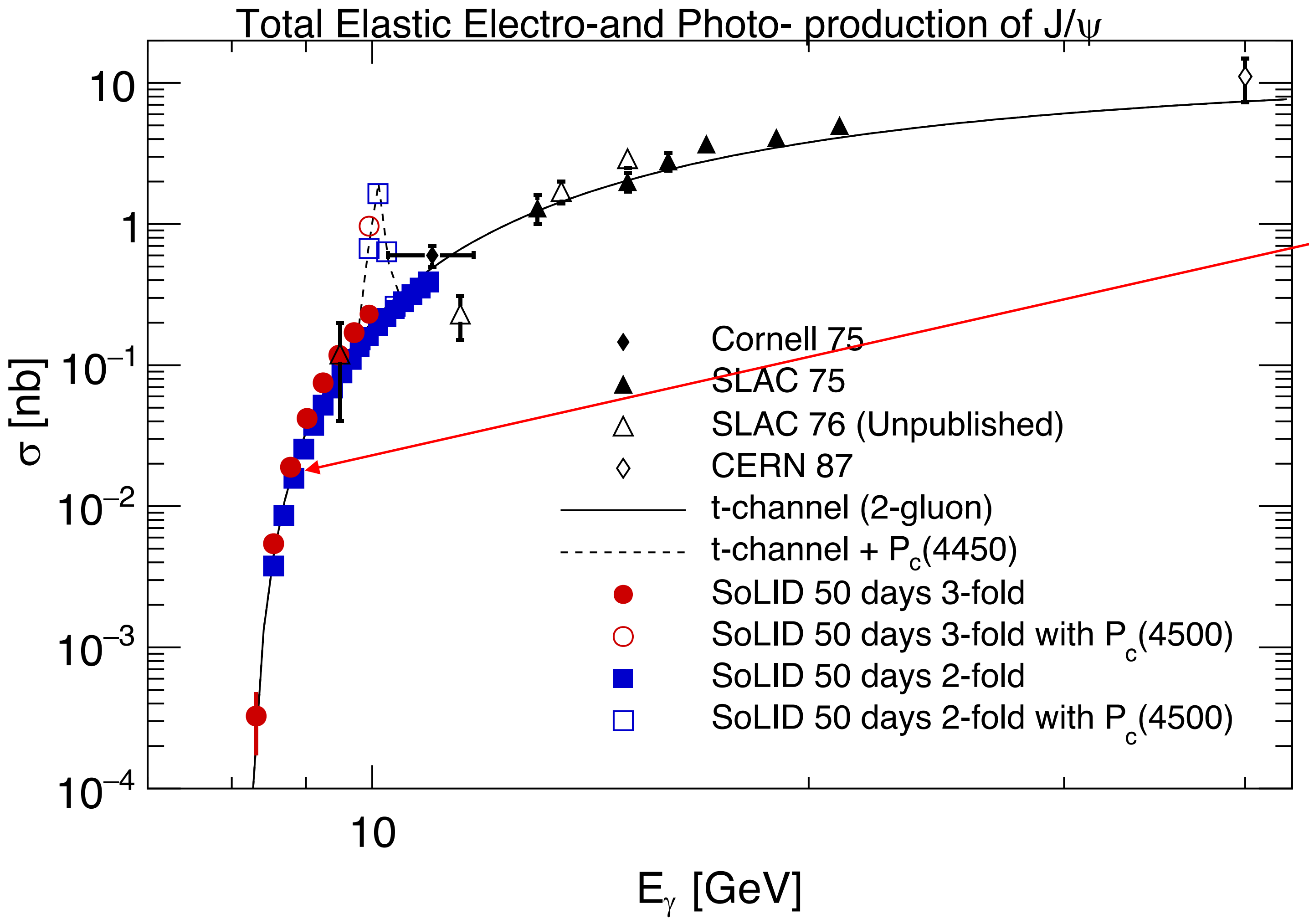
- **Photo-production**
  - **2-fold** coincidence + **recoil** proton
  - *t*-channel J/ψ rate: **1627 per day**
  - **Advantage over electro-production**
    - Energy reach in charmed pentaquark region
    - High rate
- **Electro-production**
  - **3-fold** coincidence (3 leptons)
  - *t*-channel J/ψ rate: **86 per day**
  - **Advantage over photo-production:**
    - Less background
    - Closer to threshold

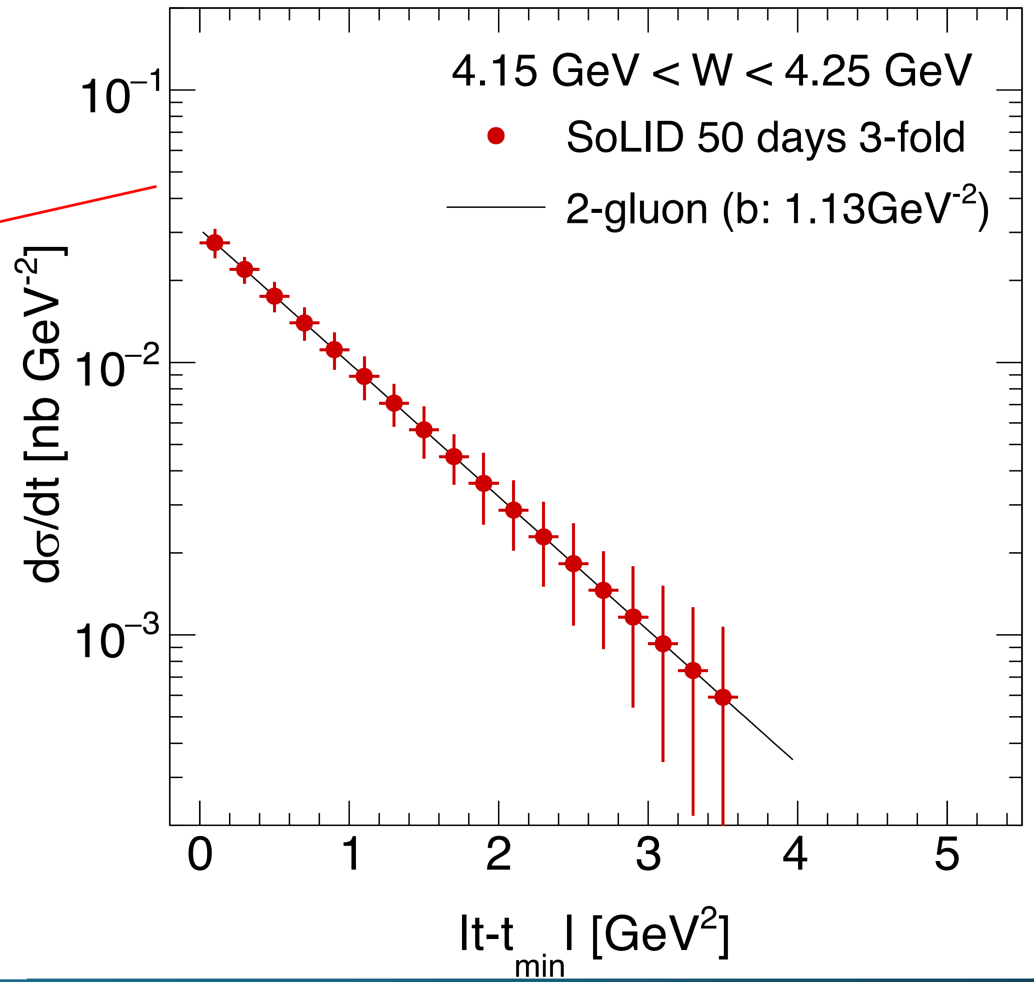


$$\gamma/\gamma^* + N \rightarrow N + J/\psi$$

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

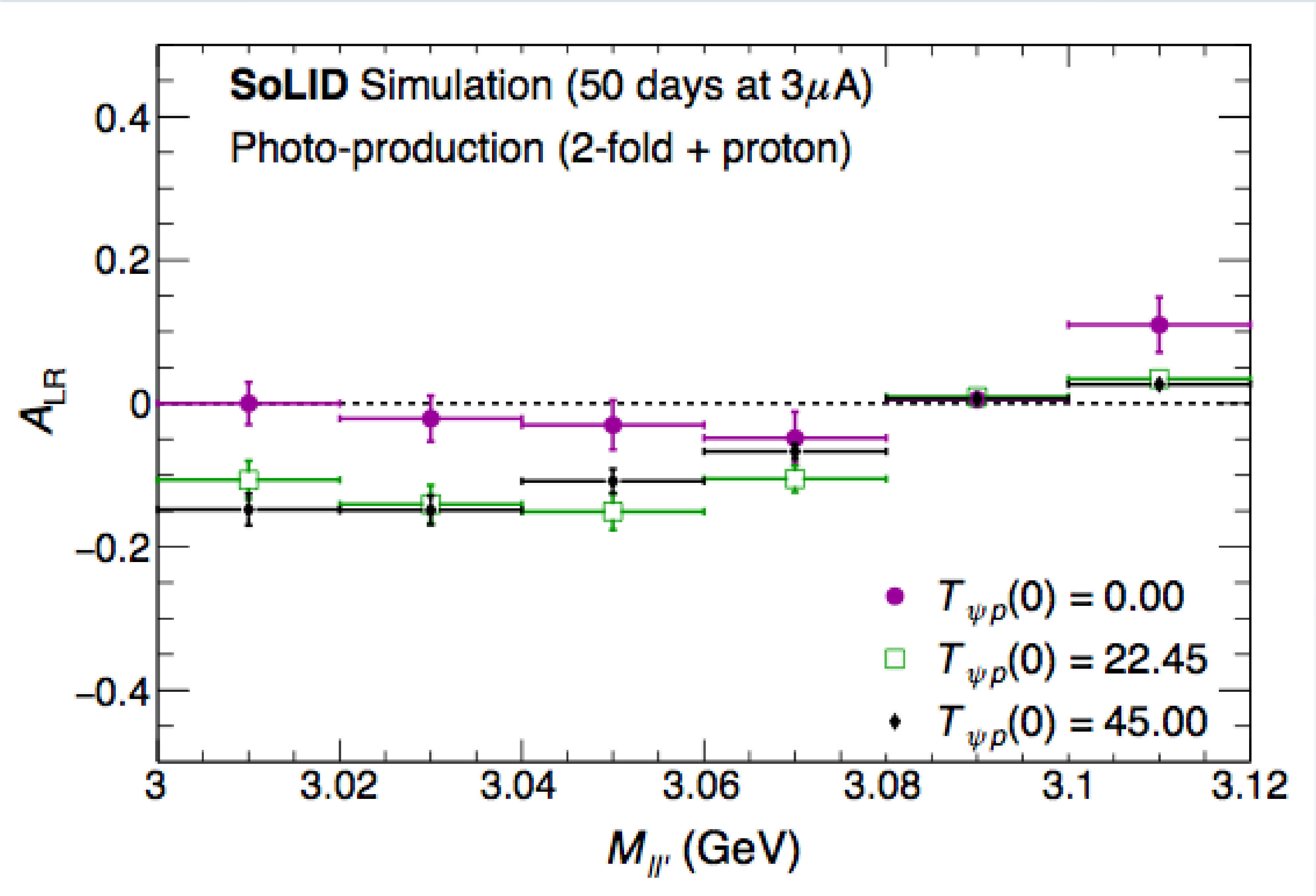
J/Psi Experiment E12-12-006 @ SoLID





Sensitivity below 10^{-3} nb!

Projected Results: all together



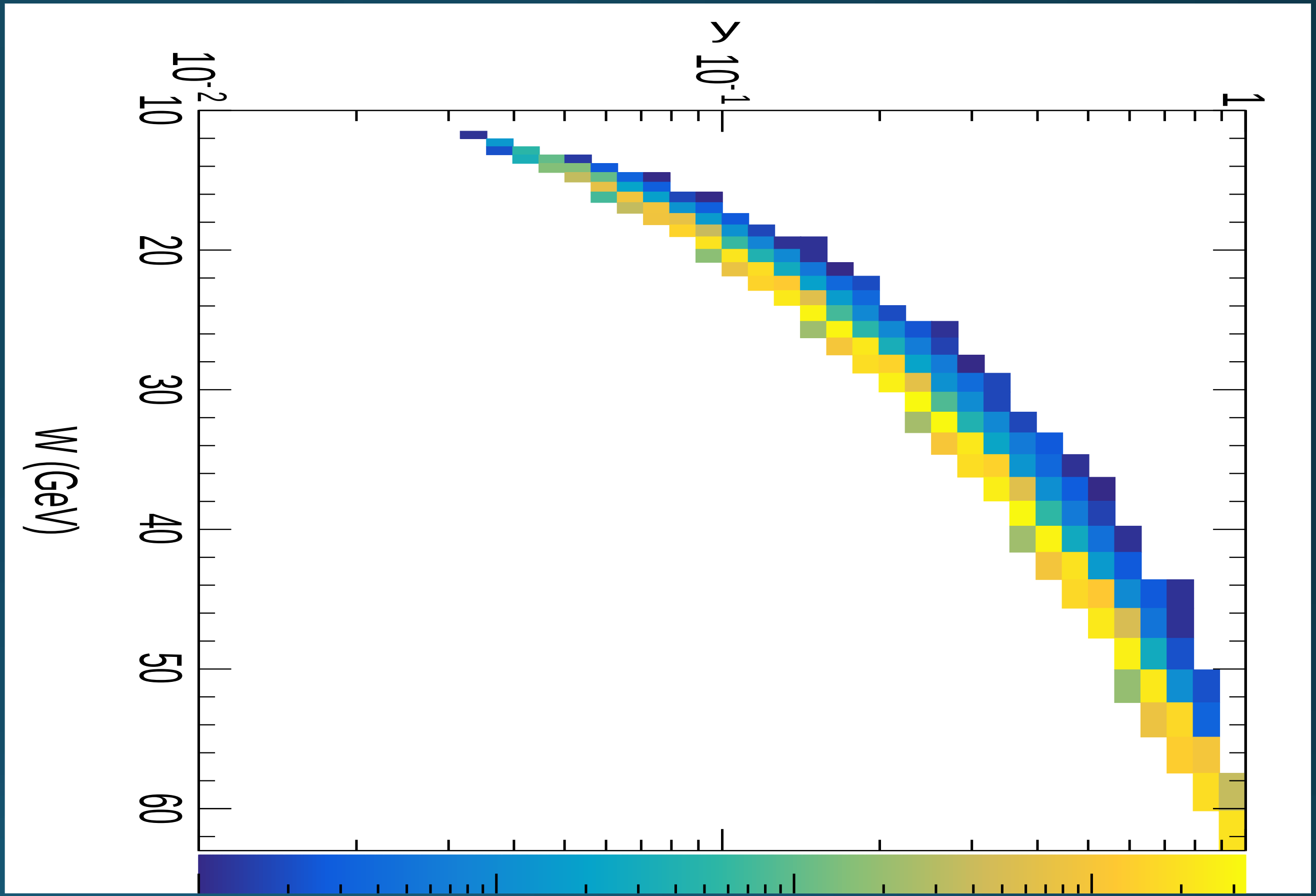
Quarkonia at an EIC

- 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.

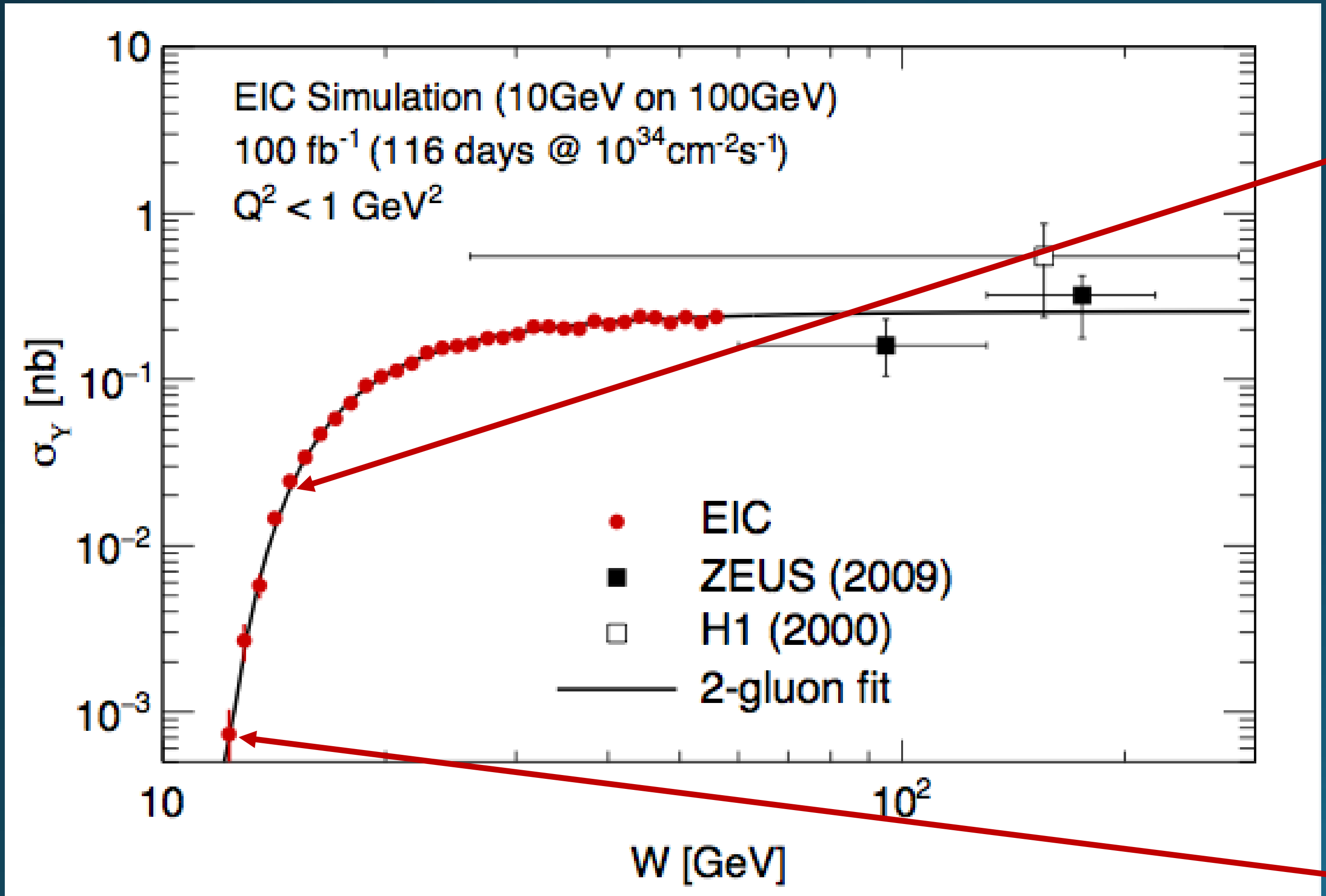
Υ photo-production at an EIC

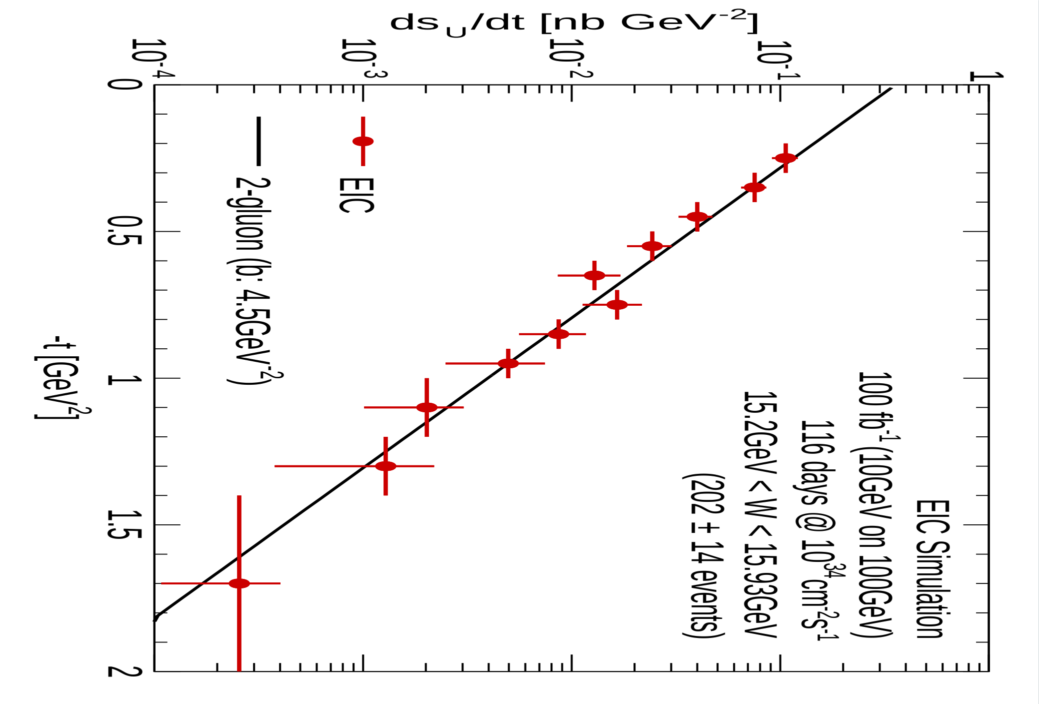
- Quasi-real production at an EIC
- Using nominal EIC detector (consistent with white paper)
  - Both electron and muon channel
- Fully exclusive reaction
- Can go to near-threshold region

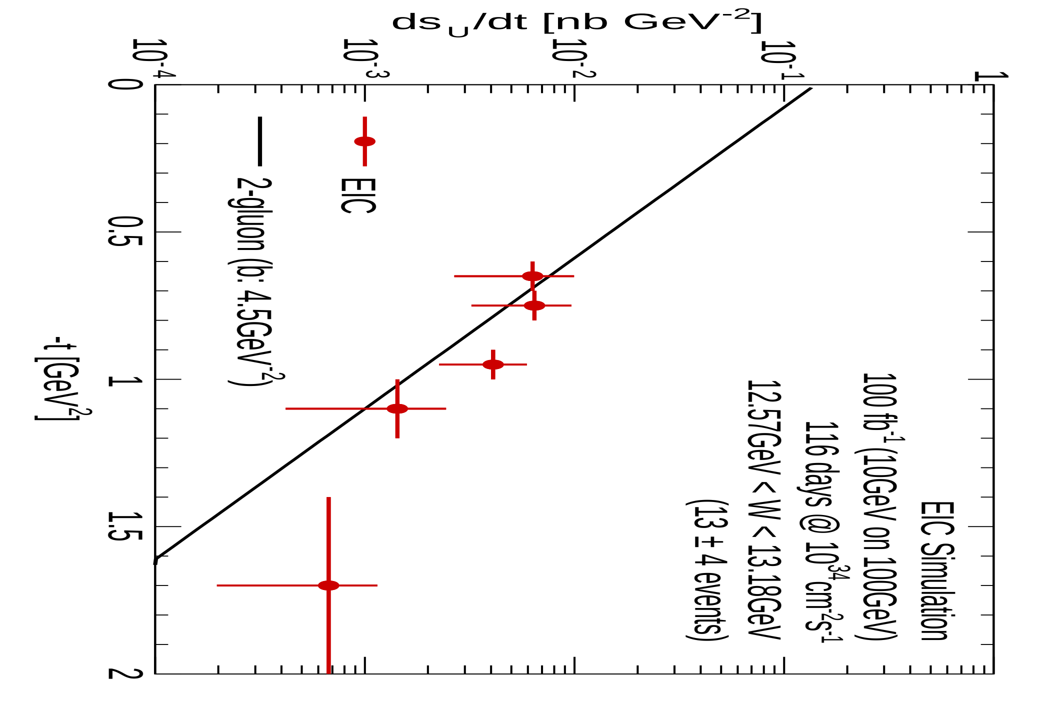


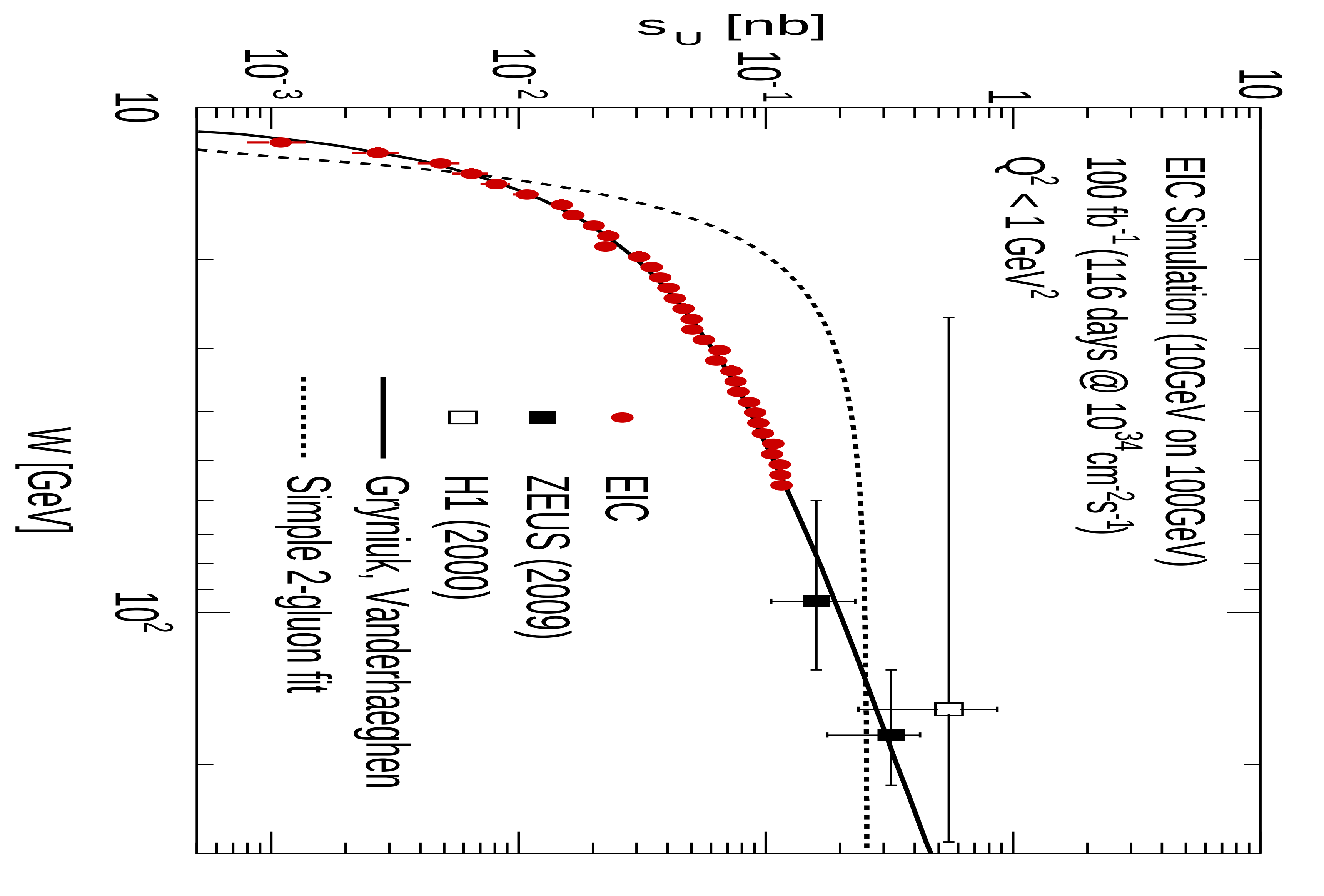
- *Υ(1s)* production possible at threshold!
  - Provides measure for universality, complimentary to threshold *J/ψ* program at JLab12
  - Is there a “beautiful” pentaquark?
- Sensitivity down to ~10^{-3} nb!

Elastic Upsilon production at an EIC









EIC Simulation (10GeV on 100GeV)
100 fb^{-1} (116 days @ 10^{34} cm^{-2}s^{-1})
Q^2 < 1 GeV^2
EIC
ZEUS (2009)
H1 (2000)
Gryniuk, Vanderhaegen
Simple 2-gluon fit
s$_U$ [nb]
W [GeV]
10
10^2
10^{-3}
10^{-2}
10^{-1}
1
10

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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