

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

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Argonne National Lab

&

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Temple University

Outline:

- The science enabled by heavy quarkonia in the threshold region
- Threshold production of quarkonia on the nucleon experiments at 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?

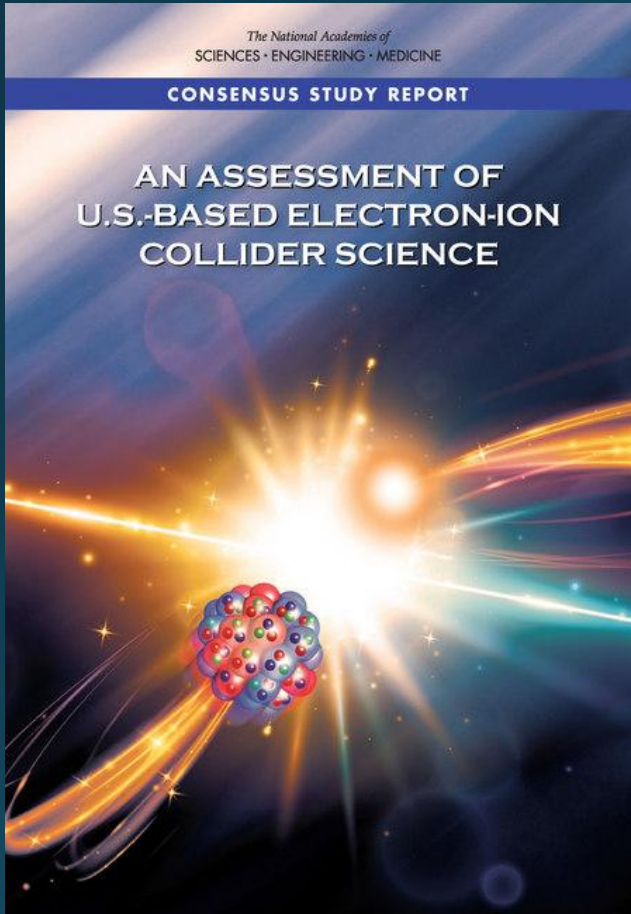
☀️ Are bound states of quarkonia in nuclei possible?

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:

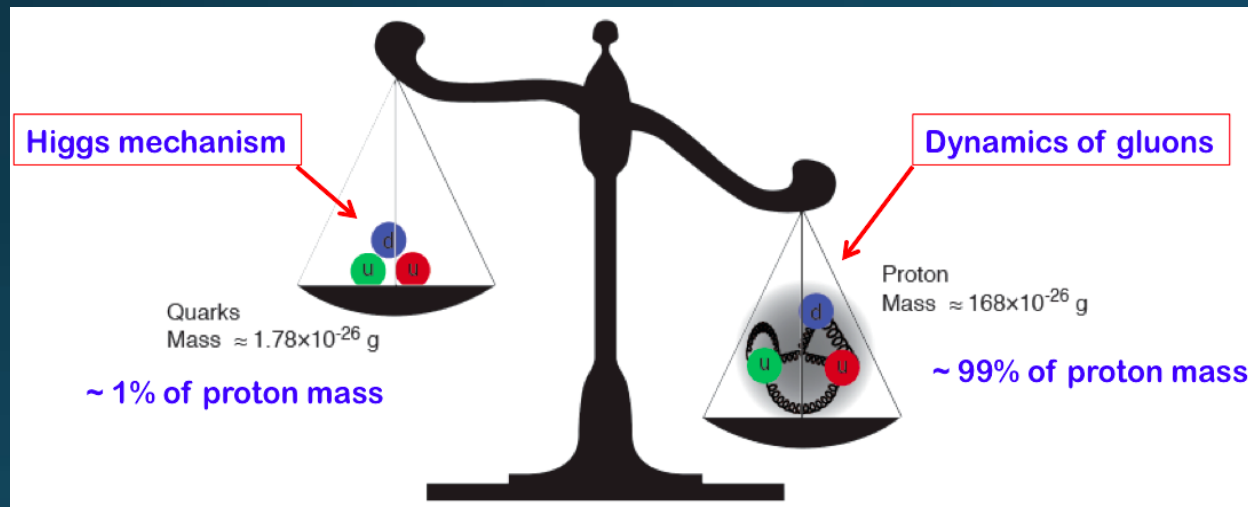
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?



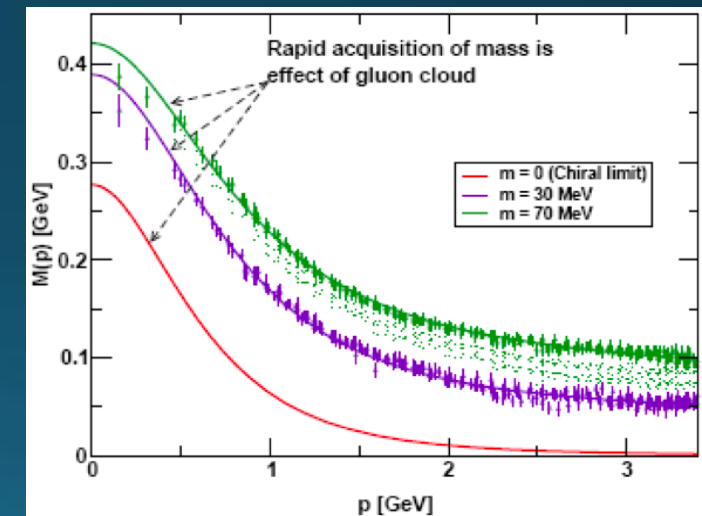
How does QCD generate its mass?

“...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!”



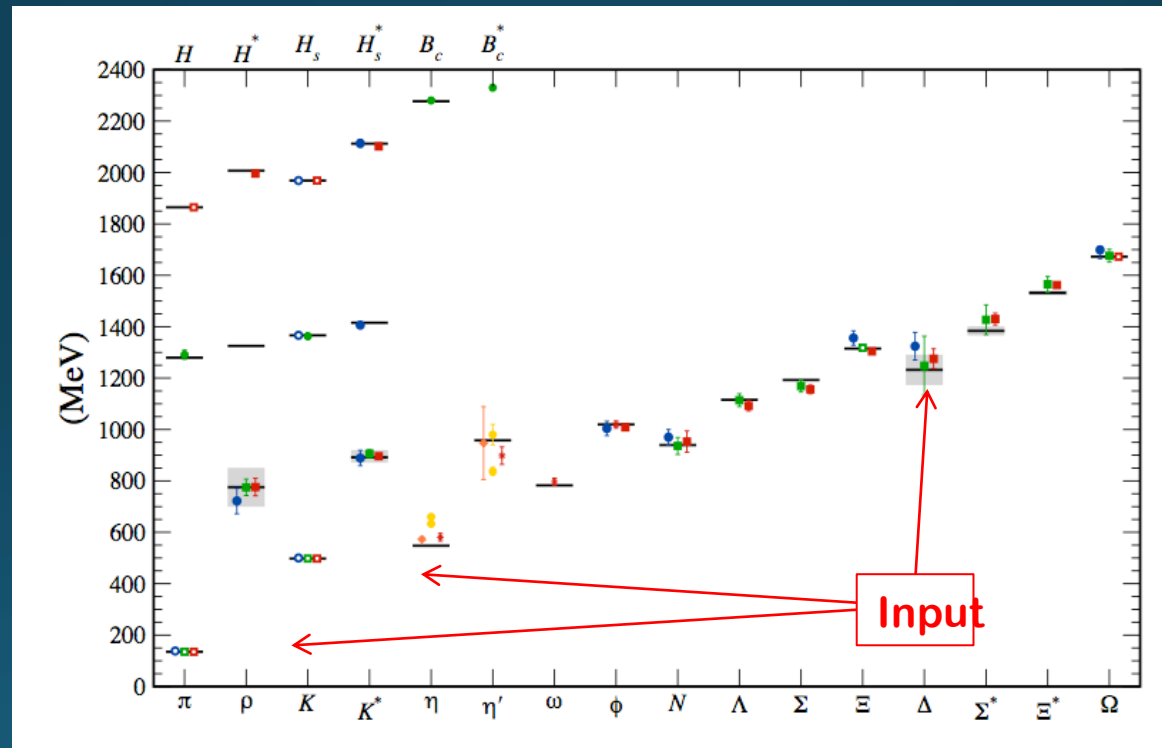
Bhagwat & Tandy/Roberts et al

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*

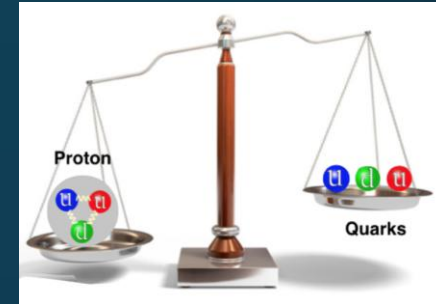
□ Hadron mass from Lattice QCD calculation:



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

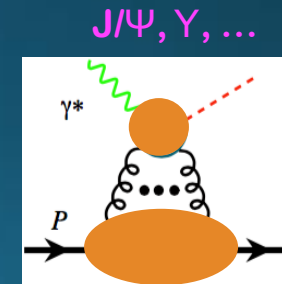
✧ Trace of the QCD energy-momentum tensor:

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

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

✧ 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

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)

The Proton Mass

At the heart of most visible matter.
Temple University, March 28-29, 2016
Philadelphia, Pennsylvania

$M_p = 2m_u^{\text{eff}} + m_d^{\text{eff}}$

Speakers
Stan Brodsky (SLAC)
Xiangdong Ji (Maryland)
Dima Kharzeev (Stony Brook & BNL)
Keh-Fei Liu (University of Kentucky)
David Richards (JLab)
Craig Roberts (ANL)
Martin Savage (University of Washington)
Stepan Stepanyan (JLab)
George Sterman (Stony Brook)

Moderator
Alfred Mueller (Columbia)

Local Organizers
Zein-Eddine Meziani (Temple U.)
Jianwei Qiu (Brookhaven National Lab)

Workshop Topics

- Hadron Mass Calculation: Lattice QCD and Other Methods
- Hadron Mass Decomposition

Equations:

$$H_{\text{QCD}} = H_q + H_m + H_g + H_a$$
 Quark kinetic and potential energy $H_q = \int d^3x \psi^\dagger (-i\mathbf{D} \cdot \boldsymbol{\alpha}) \psi$
 Quark masses $H_m = \int d^3x \bar{\psi} m \psi$
 Gluon kinetic and potential energy $H_g = \int d^3x \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2)$
 Trace anomaly $H_a = \int d^3x \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2)$

Graph: Mass (GeV) vs p (GeV). Legend: $m = 0$ (Green solid), $m = 10$ MeV (Red solid), $m = 10$ MeV (Blue dashed). Text: "Rapid acquisition of mass is effect of gluon cloud".

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IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC

TEMPLE UNIVERSITY INFN

Castello di Trento ("Trin"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum, London

The Proton Mass: At the Heart of Most Visible Matter

Trento, April 3 - 7, 2017

Main Topics
Hadron mass decomposition in terms of constituents:
 Uniqueness of the decomposition, Quark mass, and quark and gluon energy contribution, Anomaly contribution, ...
Hadron mass calculations:
 Lattice QCD (total & individual mass components), Approximated analytical methods, Phenomenological model approaches, ...
Experimental access to hadron mass components:
 Exclusive heavy quarkonium production at threshold, nuclear gluonometry through polarized nuclear structure function, ...

Confirmed speakers and participants
 Alexandros Contantinos (Cyprus University), Brodsky Stan (SLAC), Burkardt Matthias (New Mexico State University), Chen Jian-Ping (Jefferson Lab), Chudakov Eugene (Jefferson Lab), Chiu Han (Argonne National Lab), De Tommaso Guy (University of Catania), Deshpande Abhay (Stony Brook University), Eichmann Gerrit (GSI Helmholtz Centre for Heavy Ion Research), Haidt Klaus (Argonne National Lab), Haidt Klaus (University of Wuppertal), Lin Hsiang-Wei (Michigan State University), Liu Keh-Fei (University of Kentucky), Lovric Zdravko (Ecole Polytechnique, Palaiseau), Mankar Pooj (Purdue University of Amsterdam), Papavasiliou Ioannis (National University of Athens), Paschos Vladimir (Johannes Gutenberg University of Mainz), Richards David (Jefferson Lab), Roberts Craig (Argonne National Lab), Soffer Karl (University of New Hampshire), Mauro Asselmeier (University of Torino & INFN), Bob Jaffe (Massachusetts Institute of Technology), Dima Kharzeev (Stony Brook University), Xiangdong Ji (University of Maryland).

Organizers
 Zein-Eddine Meziani (Temple University)
 Barbara Pasquini (University of Pavia)
 Jianwei Qiu (Jefferson Lab)
 Marc Vanderhaeghe (Universität Mainz)

Director of the ECT*: Professor Jochen Wambach (ECT*)

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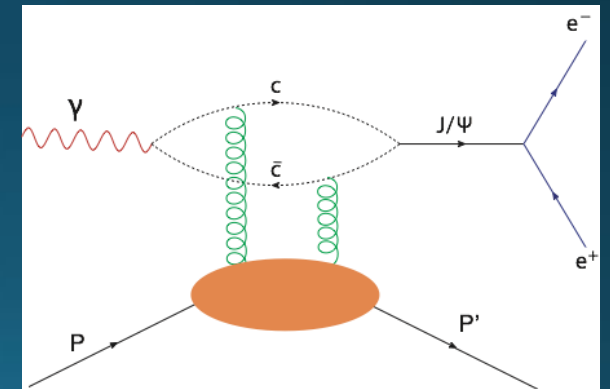
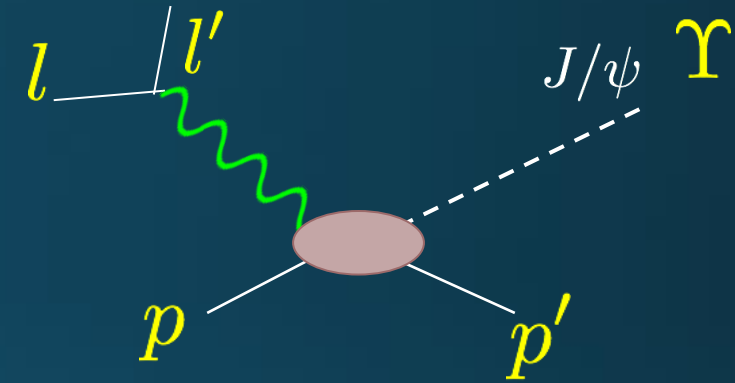
For local organization please contact: Giannaria Ziglio - ECT* Secretariat - Villa Tambosi - Strada delle Tobarèlle 286 - 38123 Villazano (Trento) - Italy
 Tel.:(+39-0461) 314721 Fax:(+39-0461) 314750, E-mail: ect@ectstar.eu or visit <http://www.ectstar.eu>

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)

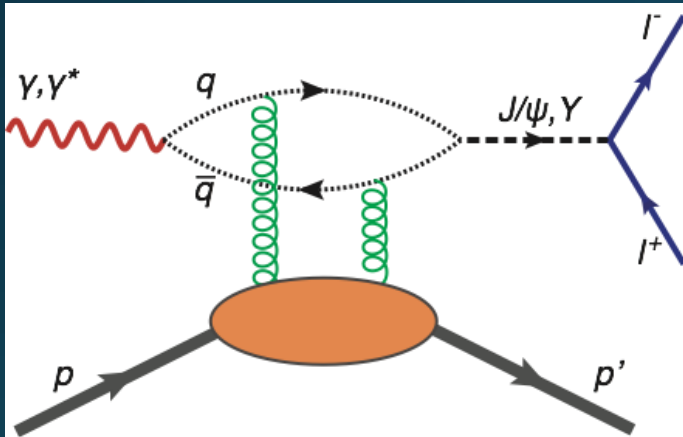
- At JLab we can measure the threshold region in photo and electro-production of J/ψ in fixed target experiments in 4 halls.
- Depending on the experimental set-up we have:
 - A fully exclusive measurement with the detection of all final state particles in some cases.
 - Detection of the J/ψ decay lepton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

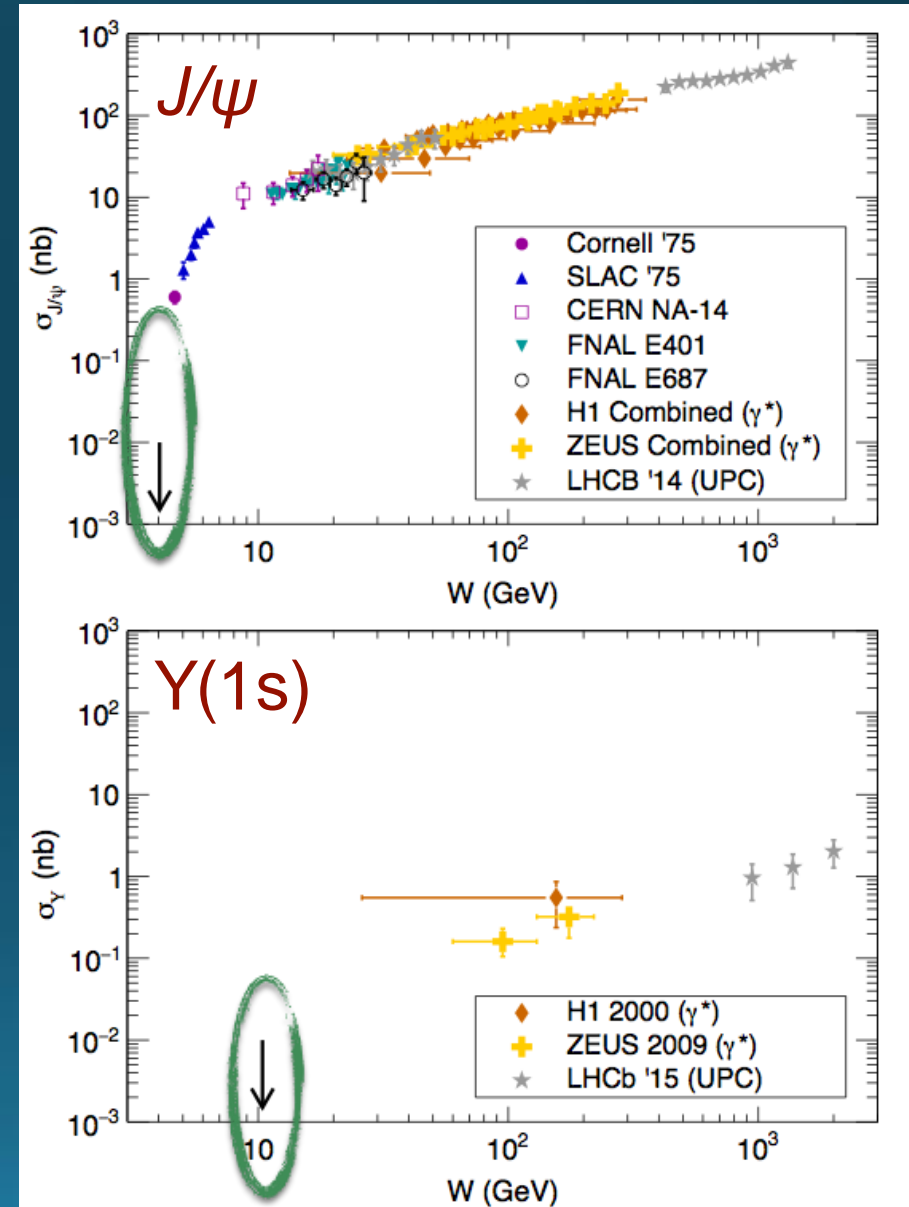
J/ψ photo-production:

- ★ 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!

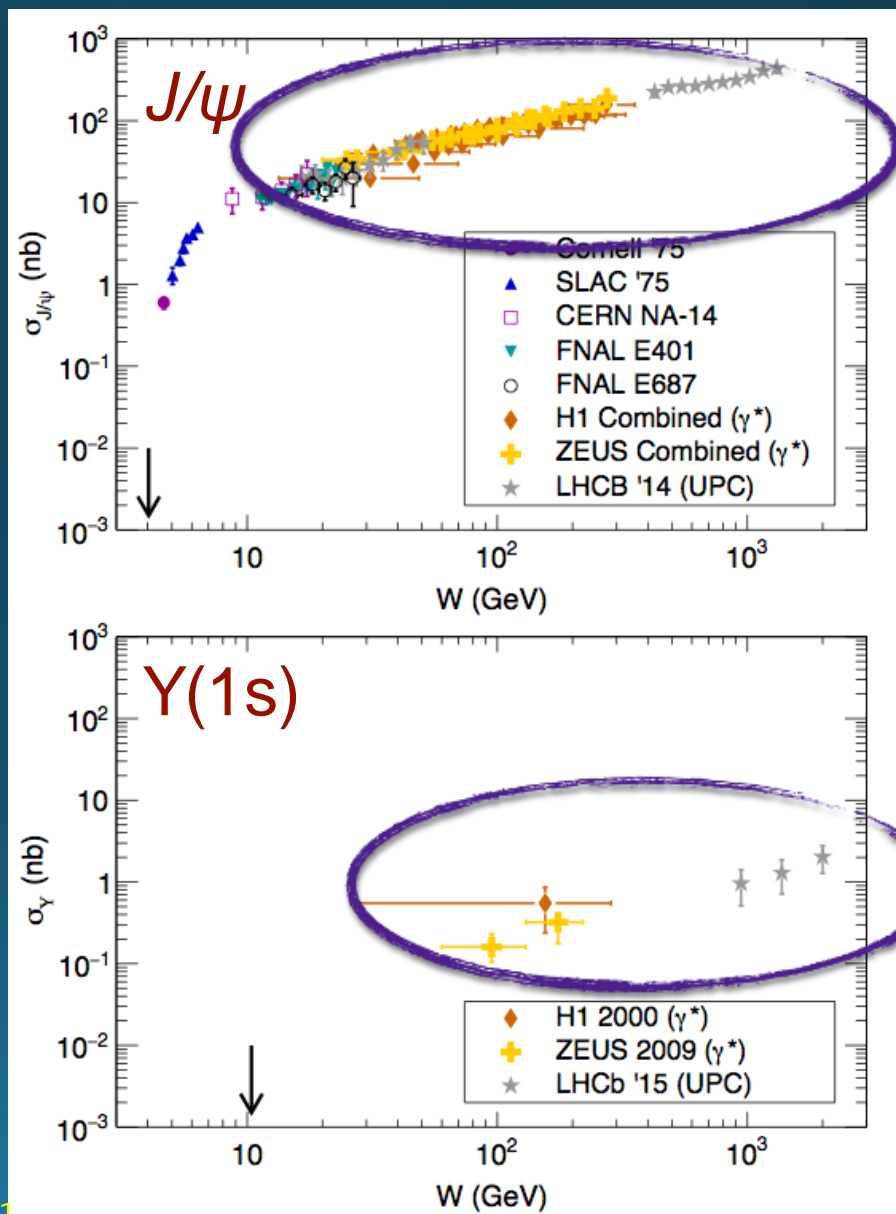


Electro-production at high energies?

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

Brodsky et al.

Gastao Krein

12 GeV J/ψ experiments at JLab Overview

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



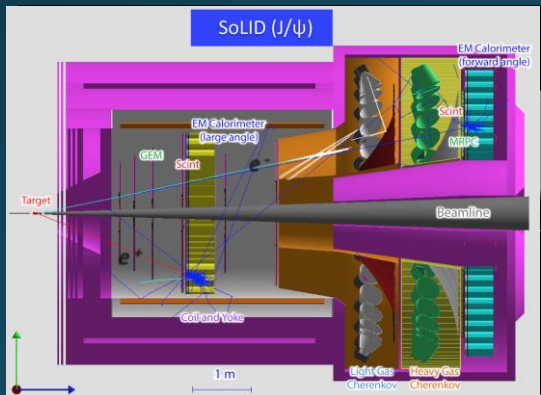
Hall B – Has an approved proposal to measure TCS + J/ψ in photoproduction **E12-12-001**



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**

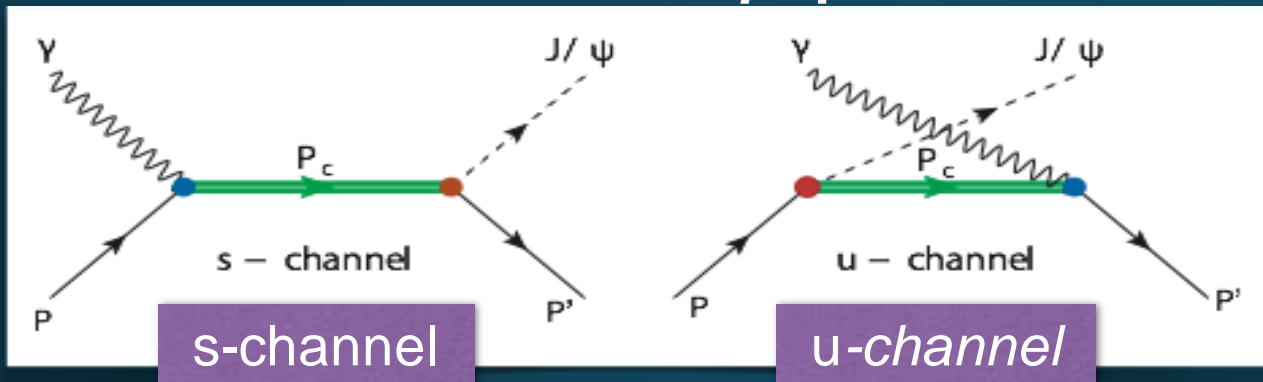


9/19/2018

ECT*, Trento, Italy

Resonant J/ψ production through P_c decay

$J/\psi-007^{\mathcal{F}}$

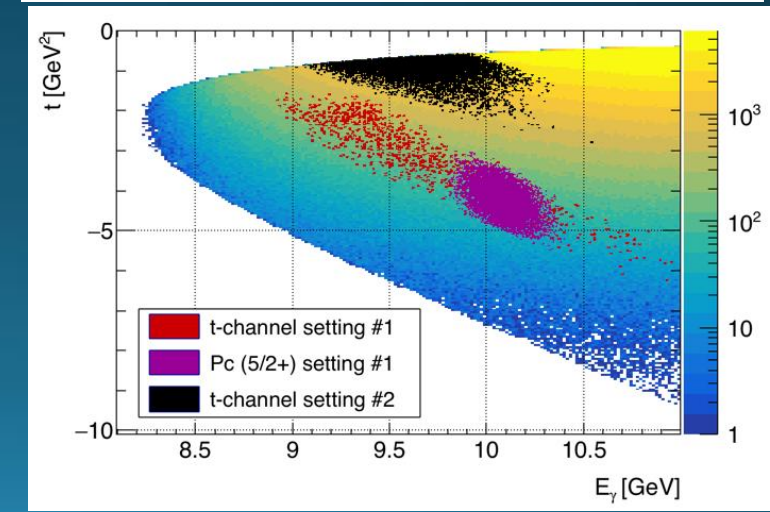
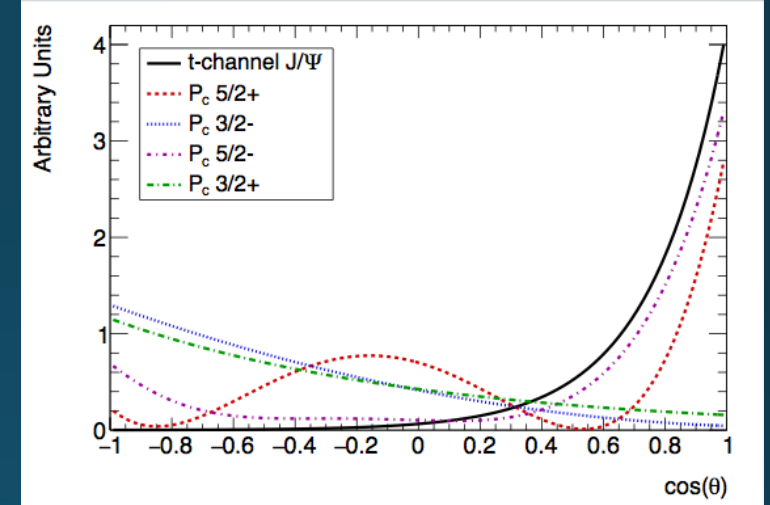


$$\frac{d\sigma}{d\cos\theta_{J/\psi}}(\gamma p \rightarrow P_c \rightarrow J/\psi p)$$

- ★ Cross section depends on coupling of P_c to $(J/\psi, p)$ 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

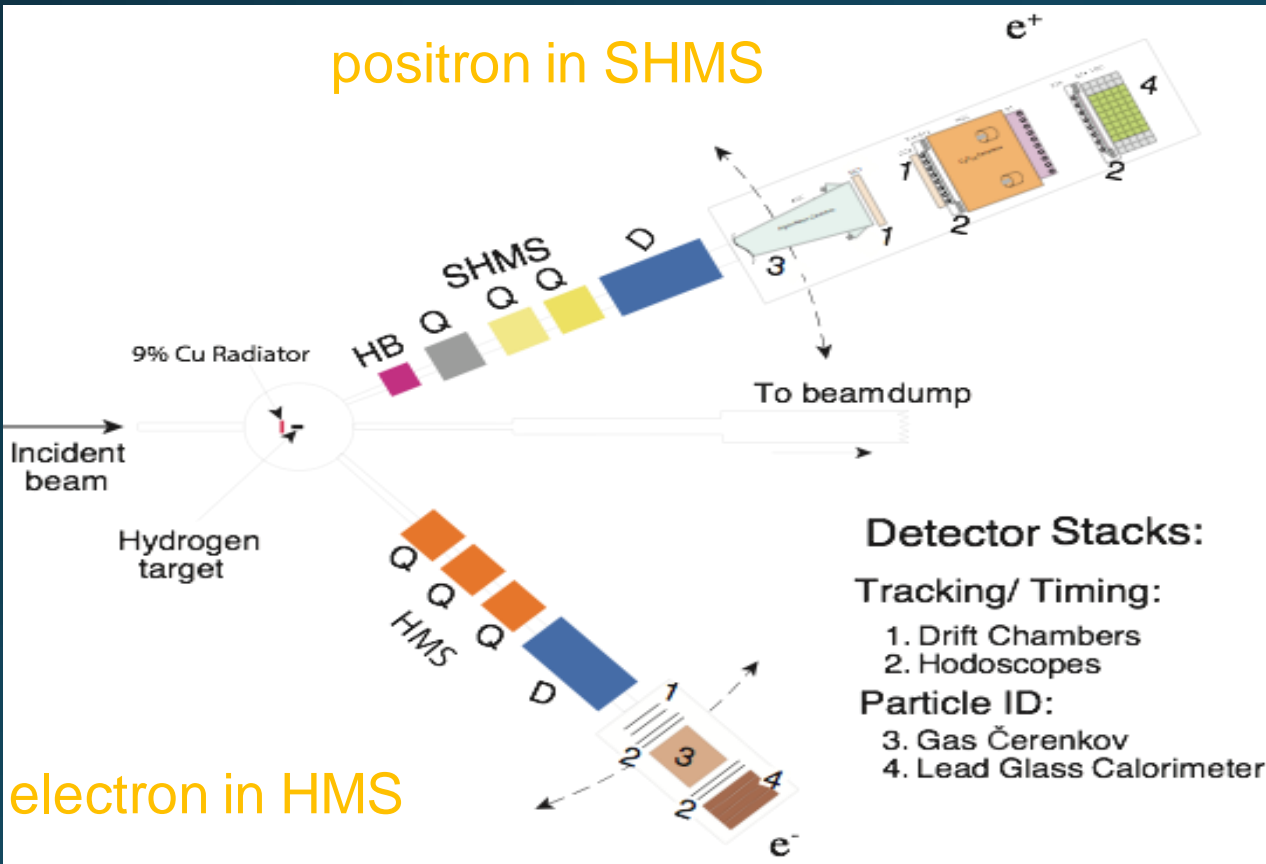


Search for the LHCb pentaquark

- ★ 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

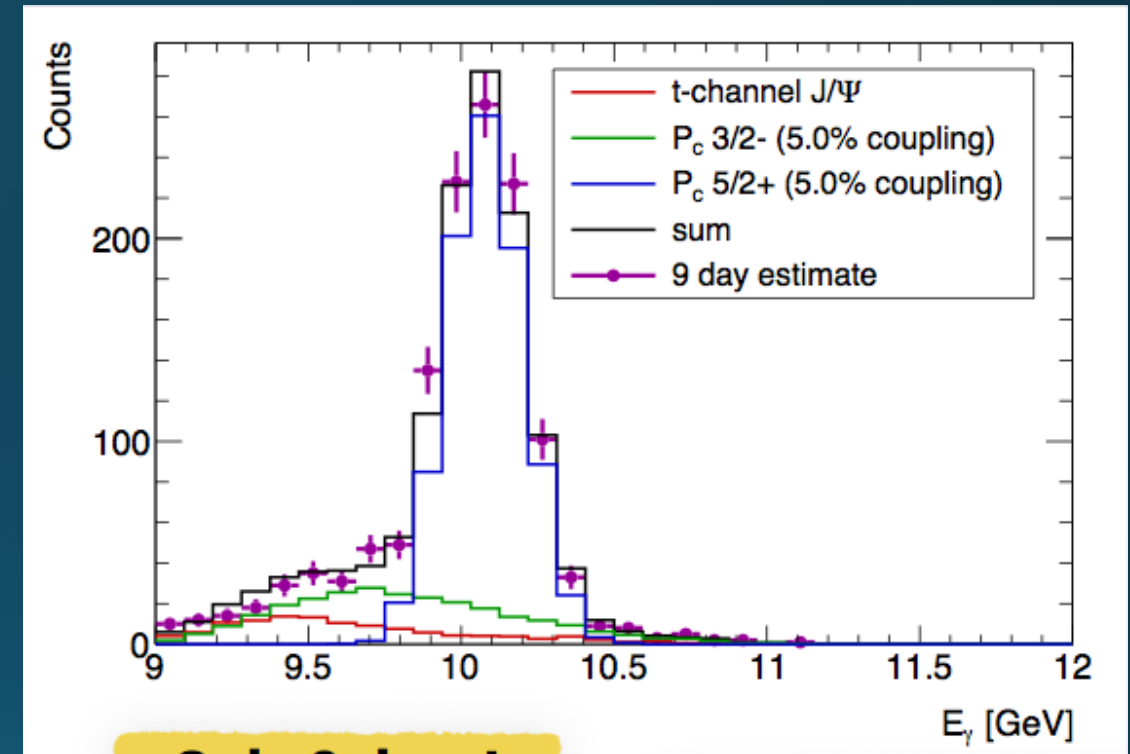
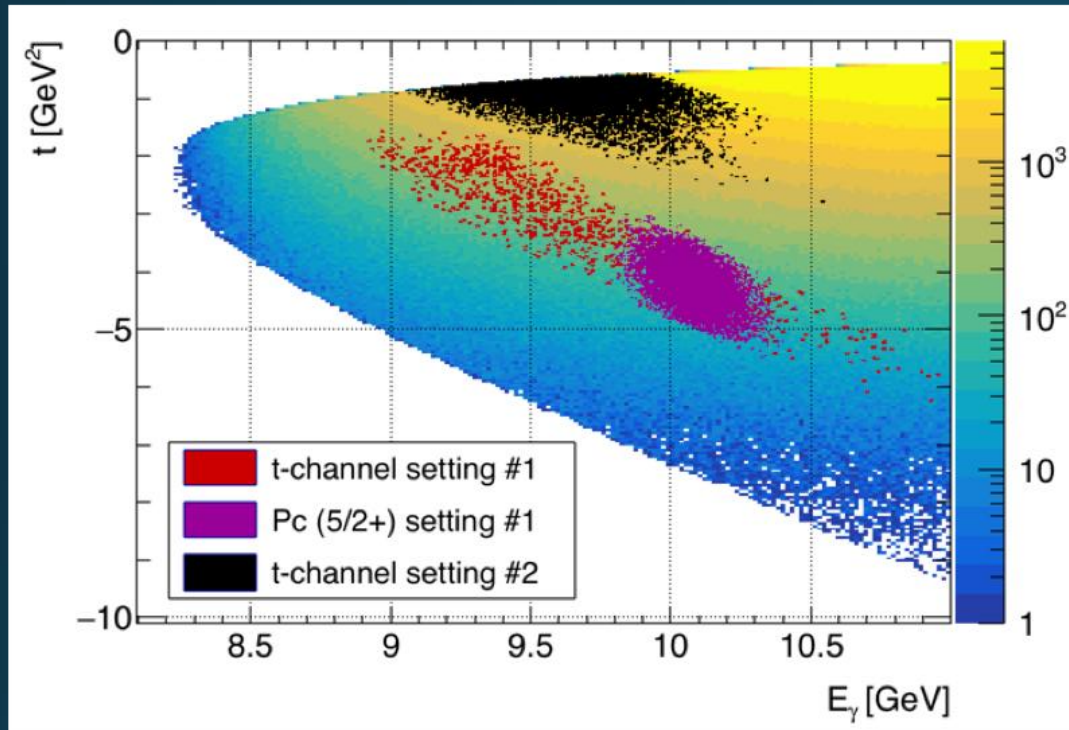
positron in SHMS



- 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



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

Only 9 days!

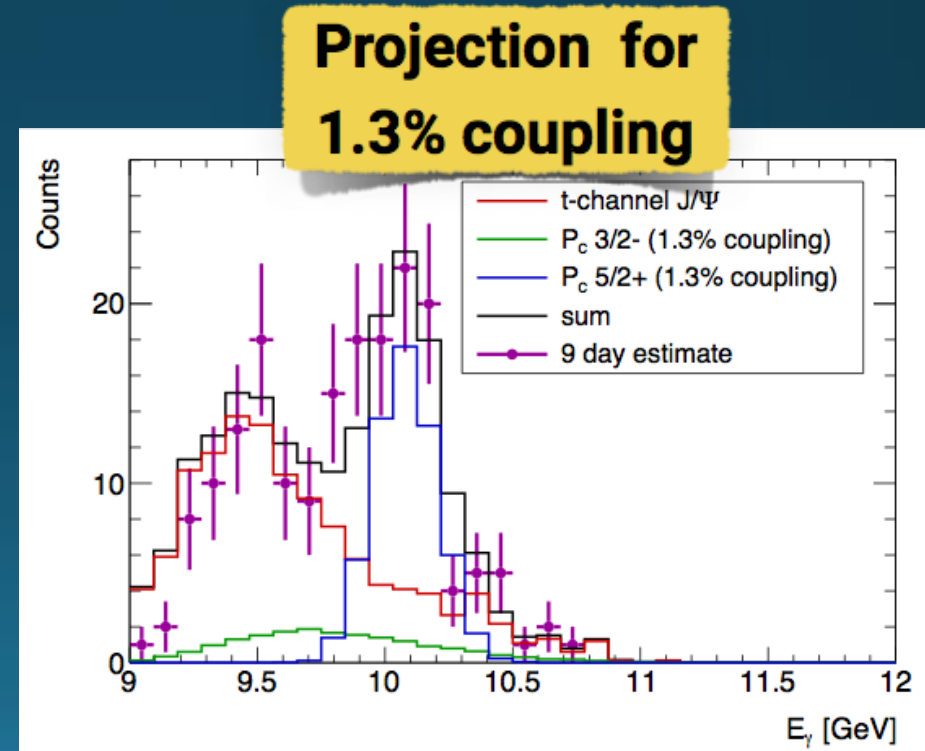
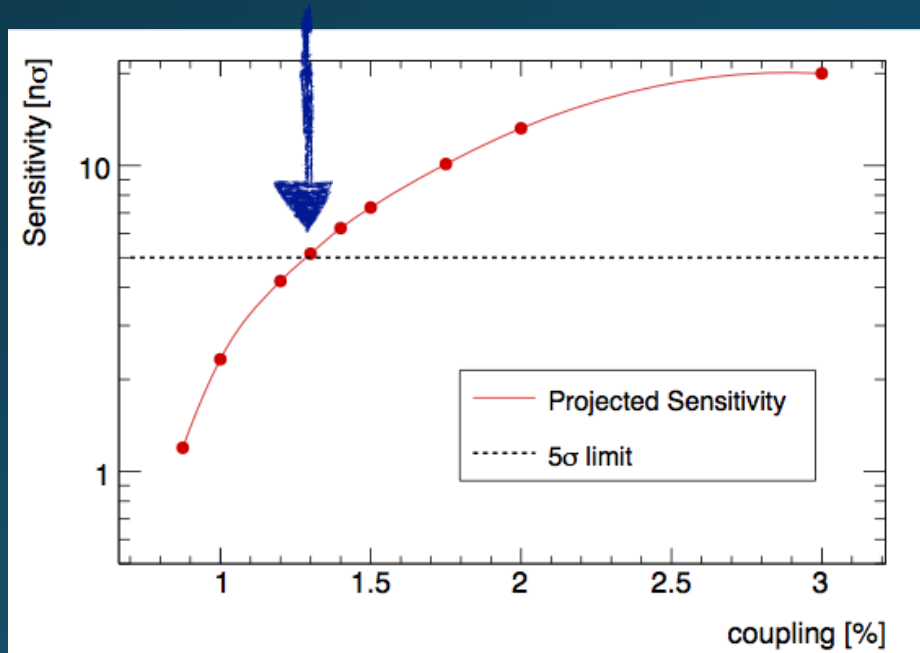
Significance > 20σ!

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

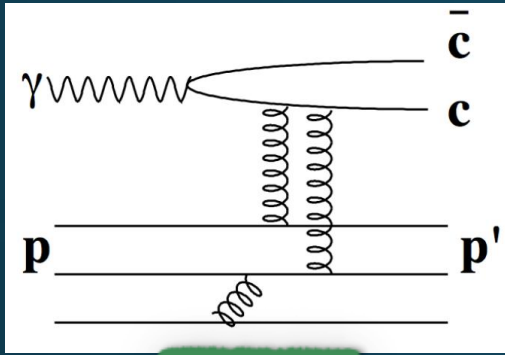
Wang Q., *et al.*, PRD 92-3 (2015) 034022-7

Sensitivity for Discovery

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

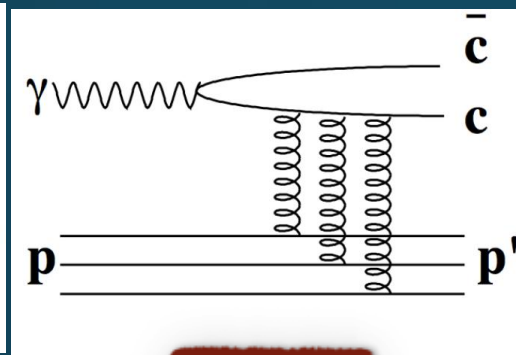


Production mechanism near threshold unknown

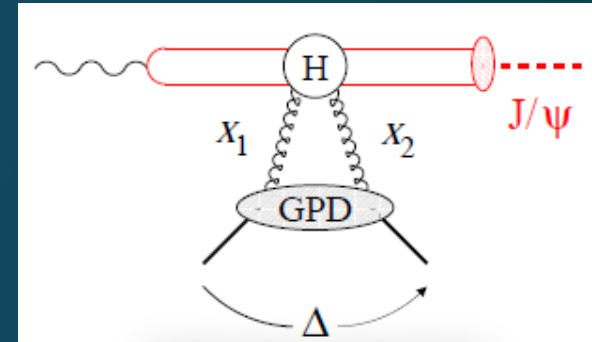


2-gluon

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



3-gluon



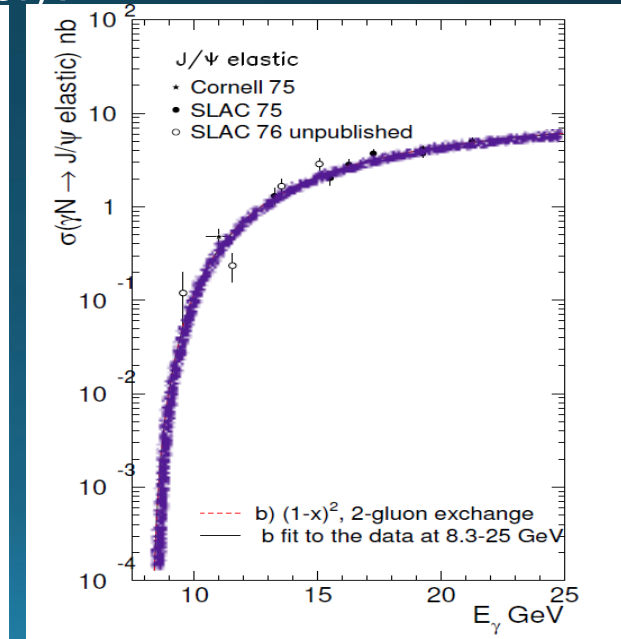
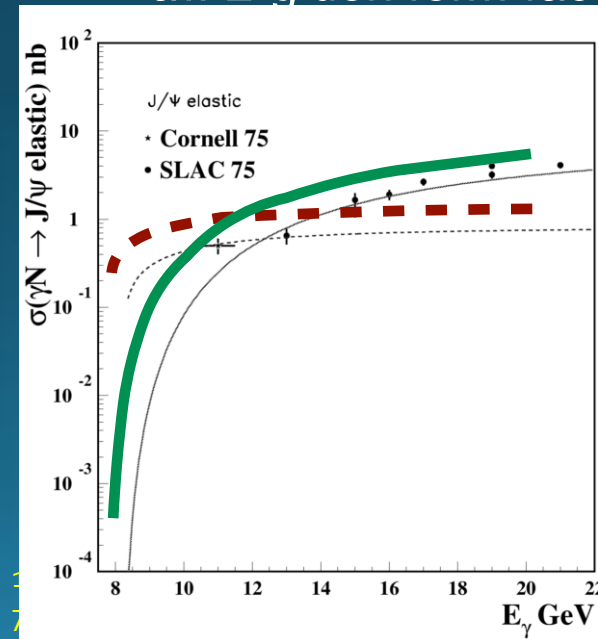
partonic soft

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



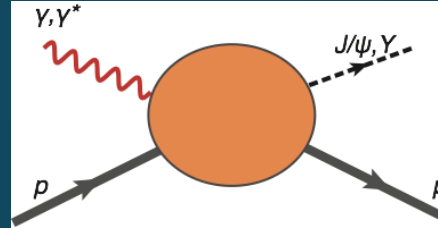
From the Cross section to the Trace Anomaly

D. Kharzeev. Quarkonium interactions in QCD, 1995

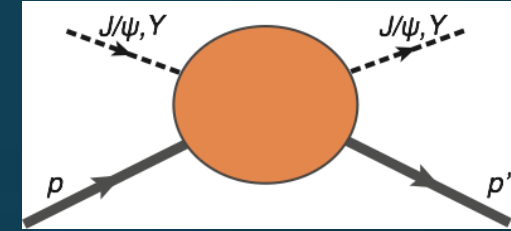
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459-462, 1999

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

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



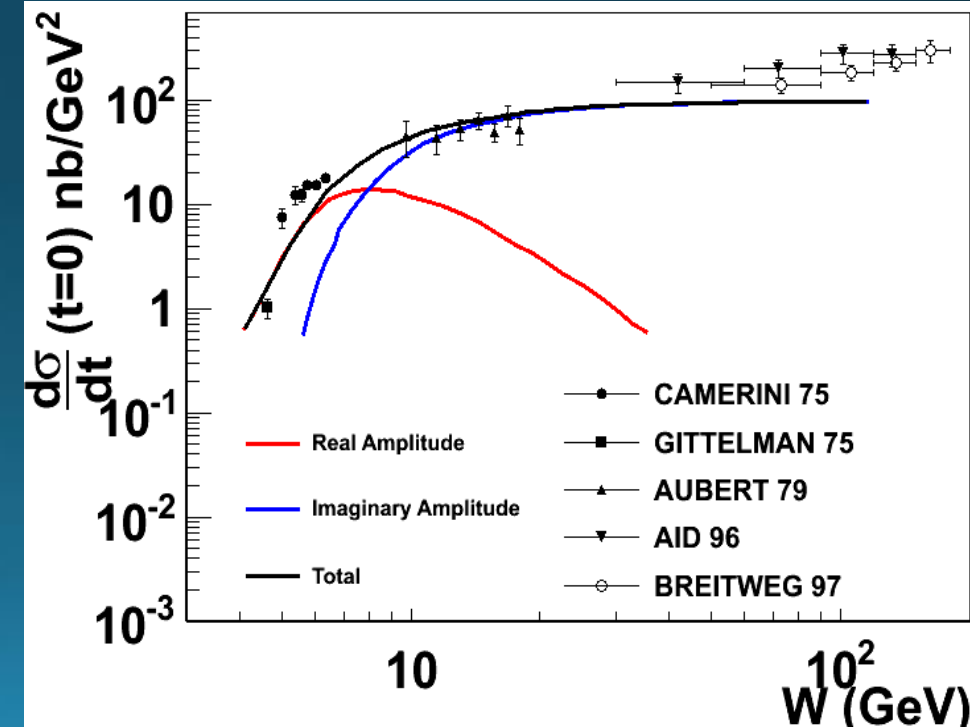
VDM



- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $\mathcal{M}_{\psi p}$
- **Imaginary part** is related to total cross section through optical theorem
- **Real part** contains the contribution of the trace anomaly
 - Dominate the near threshold region, constrained through dispersion relation

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

A measurement near threshold could lead to the trace anomaly



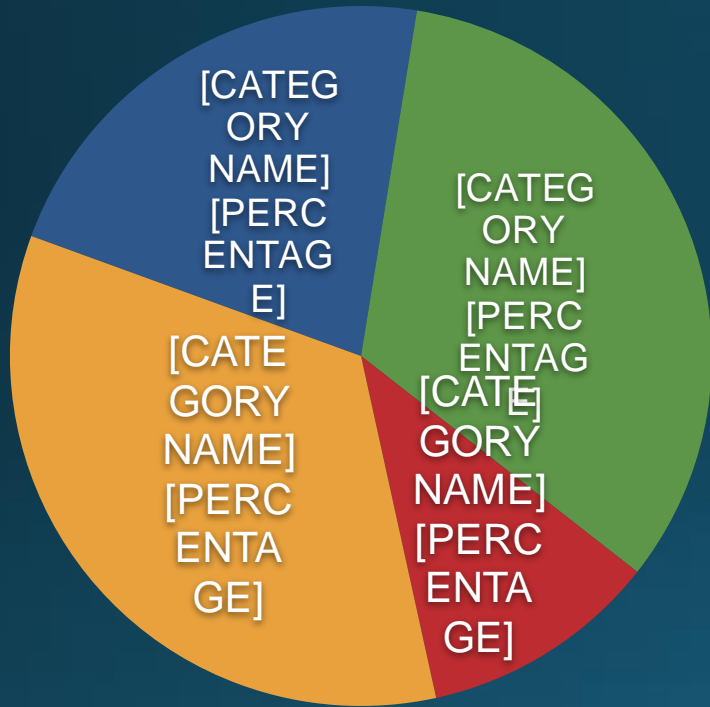
The proton mass: rest-frame decomposition

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

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

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

$$= H_q + H_m + H_g + H_a$$



- In leading order:

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

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

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

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

- $a(\mu)$ related to PDFs, well constrained
- $b(\mu)$ 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

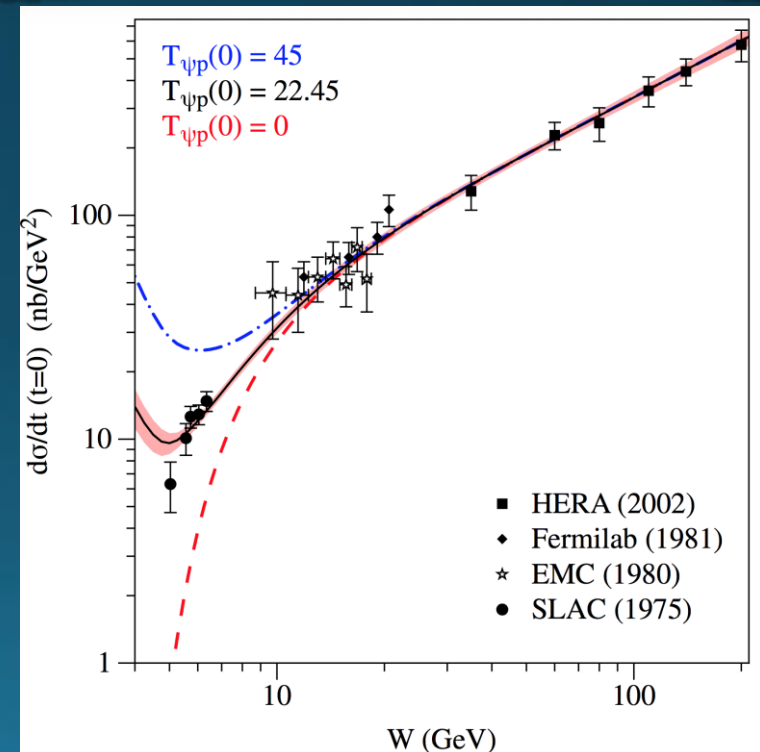
- ★ Color neutral objects:
gluonic Van der Waals force
- ★ **At threshold**, spin-averaged scattering amplitude related to **s-wave scattering length $a_{\psi p}$**

- ★ **Binding $B_{\psi p}$** can be **derived from $a_{\psi p}$**

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

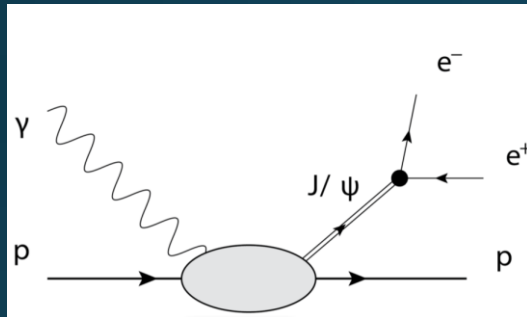
- ★ Estimates between 0.05-0.30 fm, corresponding to $B_{\psi p} < 20$ MeV
- ★ LQCD: $B_{\psi p} < 40$ MeV S. R. Beane *et al.*, Phys. Rev. D 91, 114503 (2015)
- ★ Recent fit to existing data in a dispersive framework:
 - ★ $a_{\psi p} \sim 0.05$ fm ($B_{\psi p} \sim 3$ MeV)

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

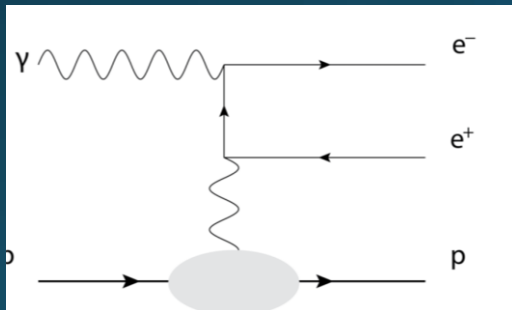


B-H asymmetry: access scattering length $a_{\psi\rho}$

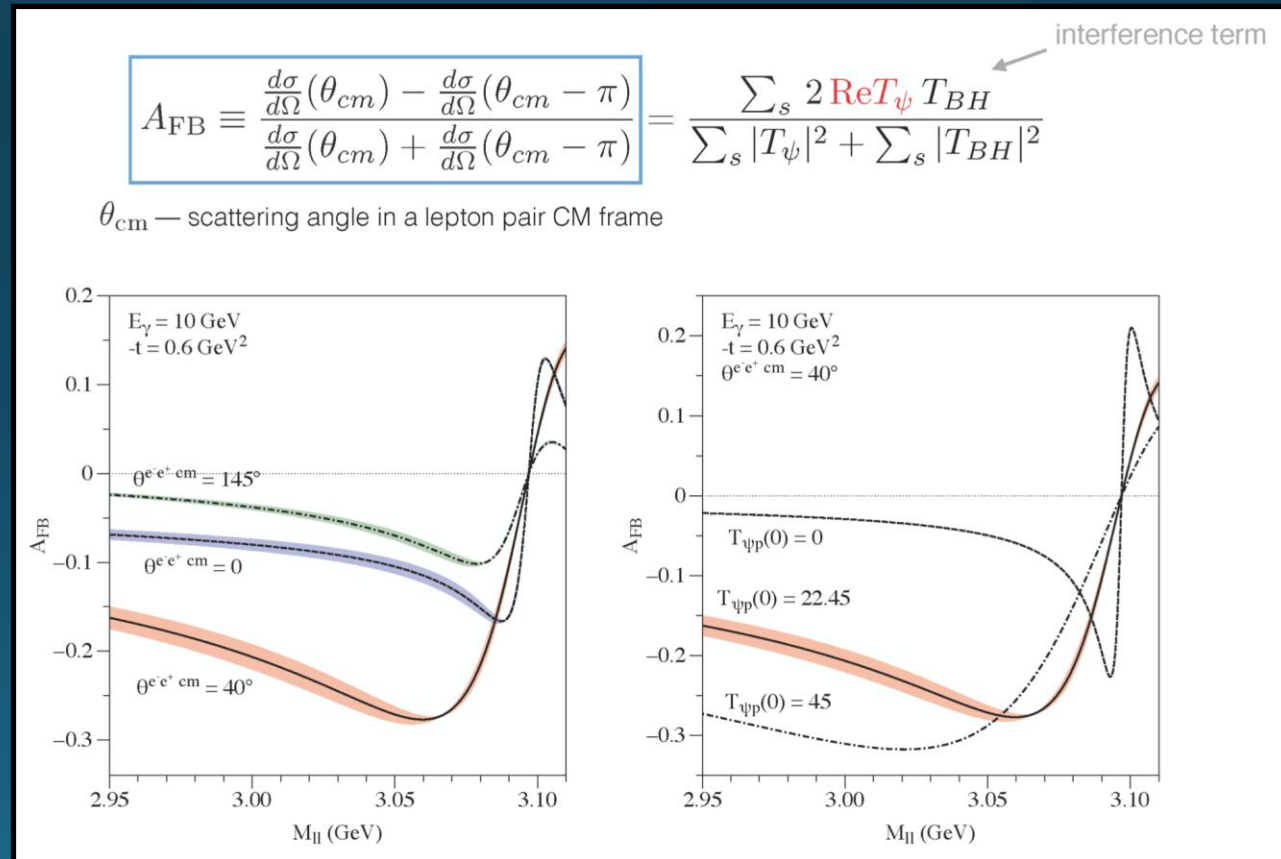
- ★ **Interference** between elastic J/ψ production near threshold and **Bethe-Heitler**
- ★ **Forward-backward asymmetry** near the J/ψ invariant mass peak
- ★ Sensitive to real part of the scattering amplitude, hence $a_{\psi\rho}$ and $B_{\psi\rho}$



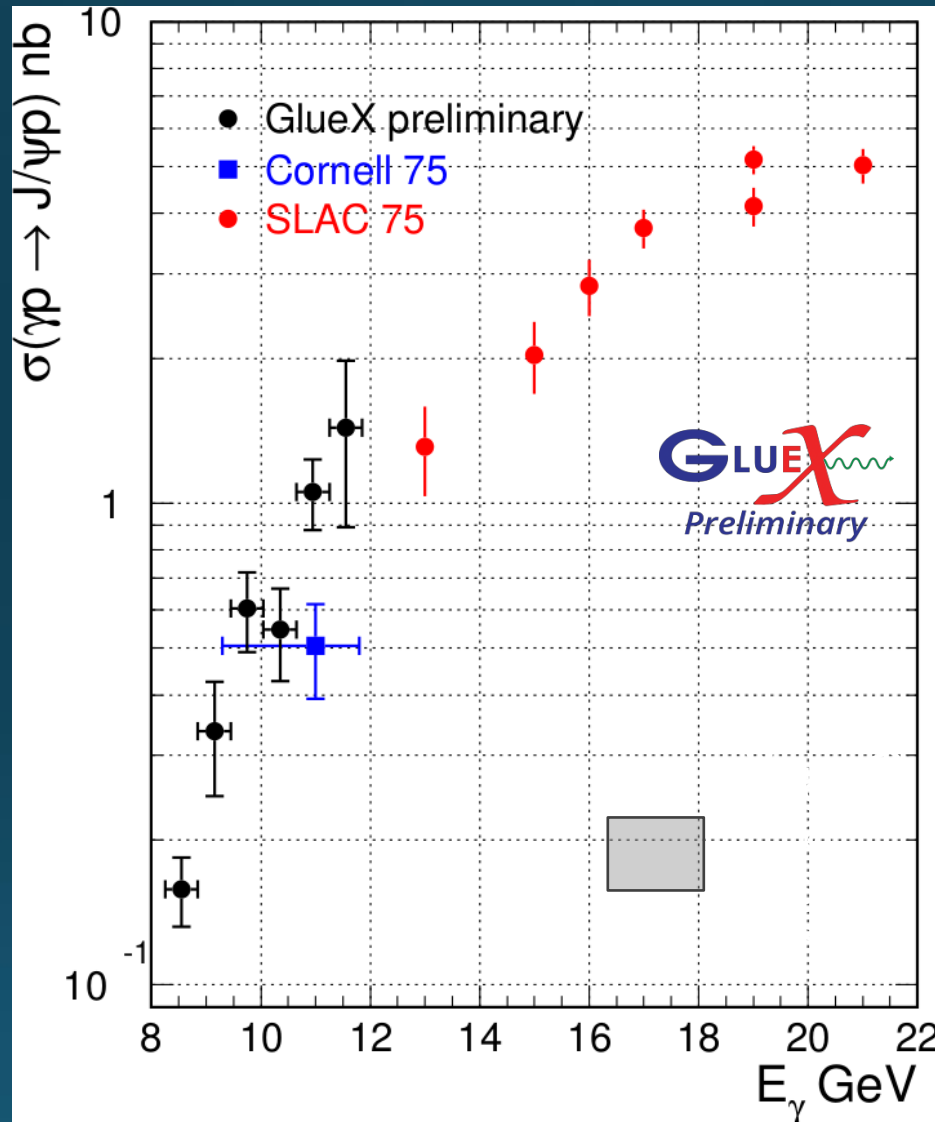
J/ψ



B-H



J/ ψ cross-section – preliminary results



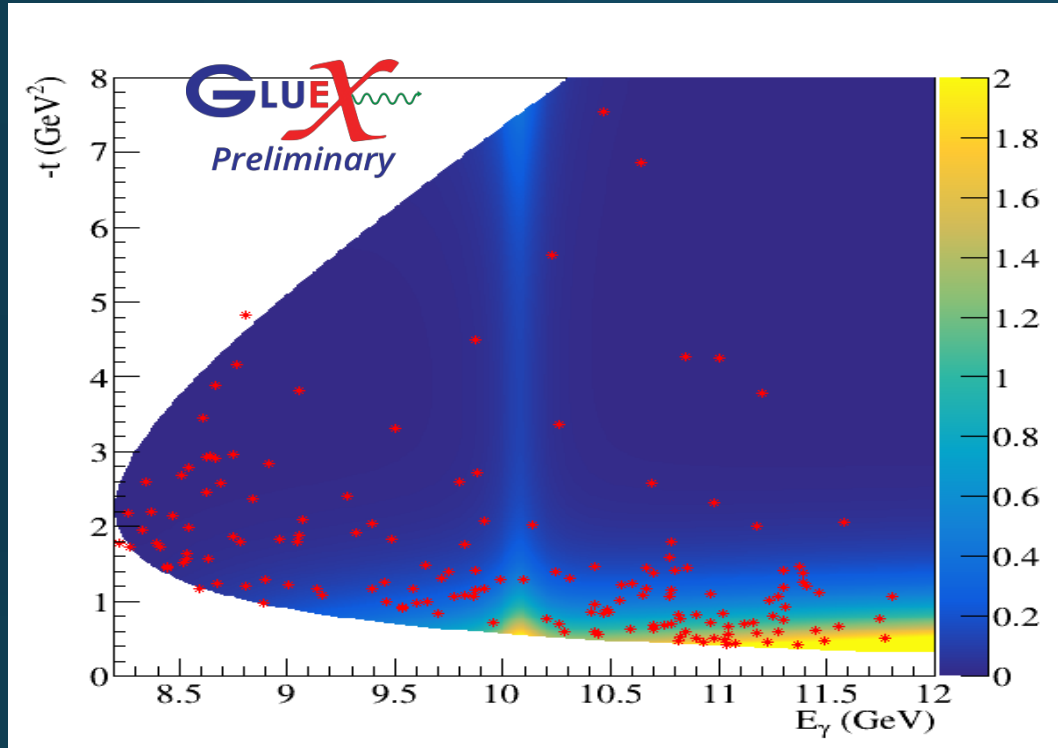
SLAC results calculated from $d\sigma/dt(t=t_{\min})$ using t -slope of $2.9 \pm 0.3 \text{ GeV}^{-2}$ (measured at 19 GeV)

Cornell data:

- t -slope $1.25 \pm 0.2 \text{ GeV}^{-2}$
- horizontal errors represent acceptance

Slide from Penchev

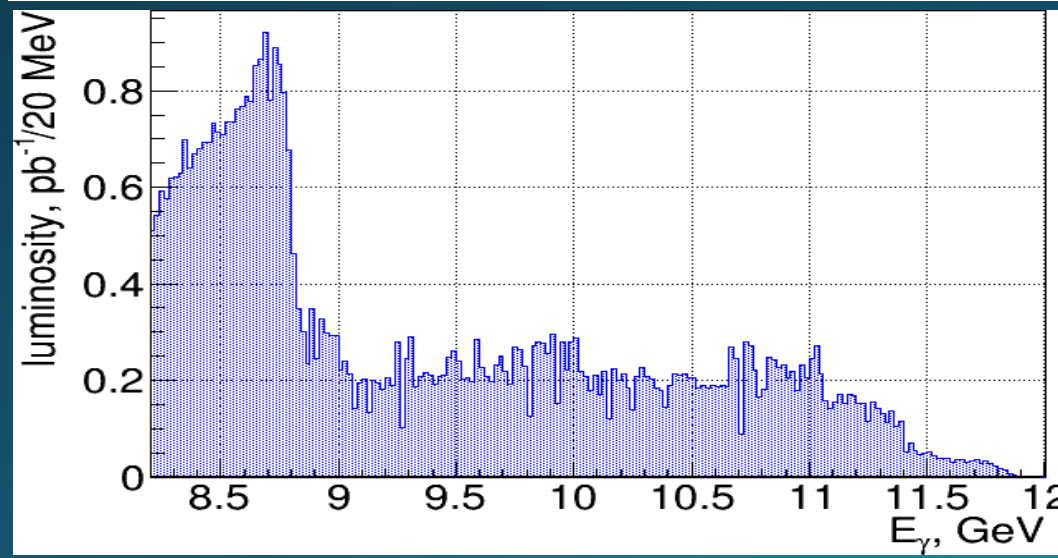
t vs E_γ unbinned distribution for J/ψ events



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).



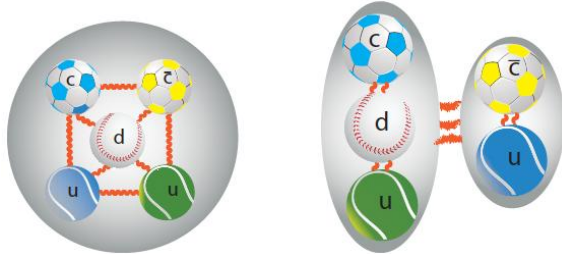
- Density of data points proportional to flux and efficiency
- No significant variations of flux ($E_\gamma > 9$ GeV) and efficiency

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

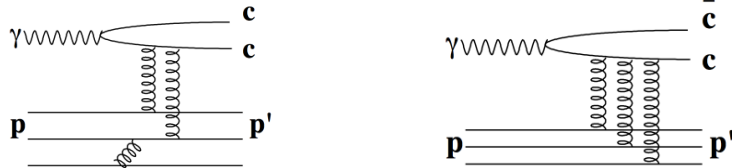
$$P_c \supset J/\psi p$$

5-quark bound state (or) Hadronic molecule

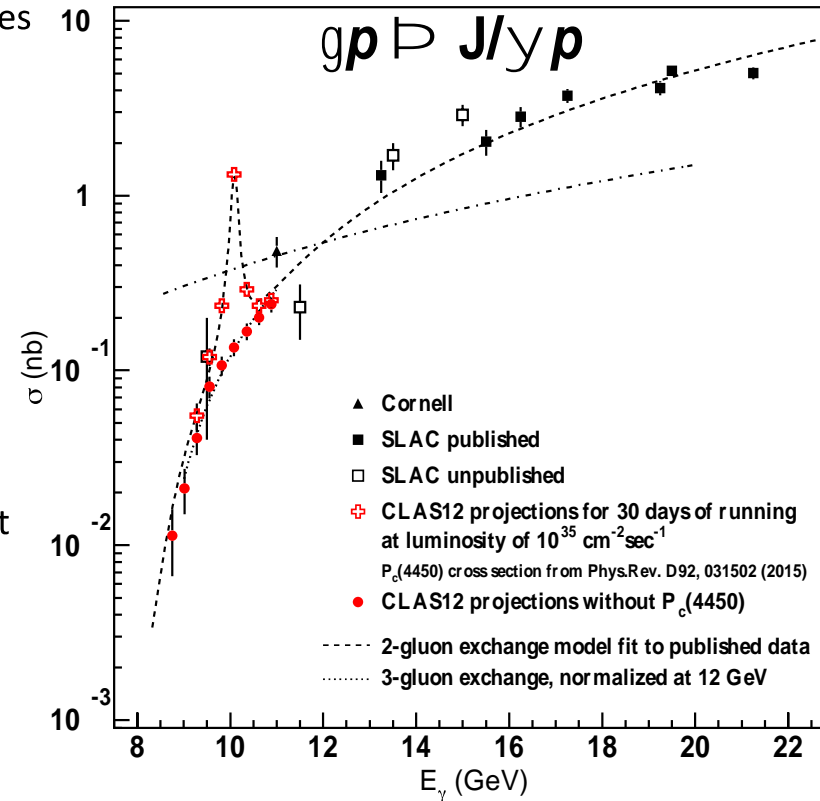


What is the mechanism of charmonium production at the threshold

2-gluon (or) 3-gluon exchange



Experiment E12-12-001 measures *J/psi* 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



Thomas Jefferson National Accelerator Facility

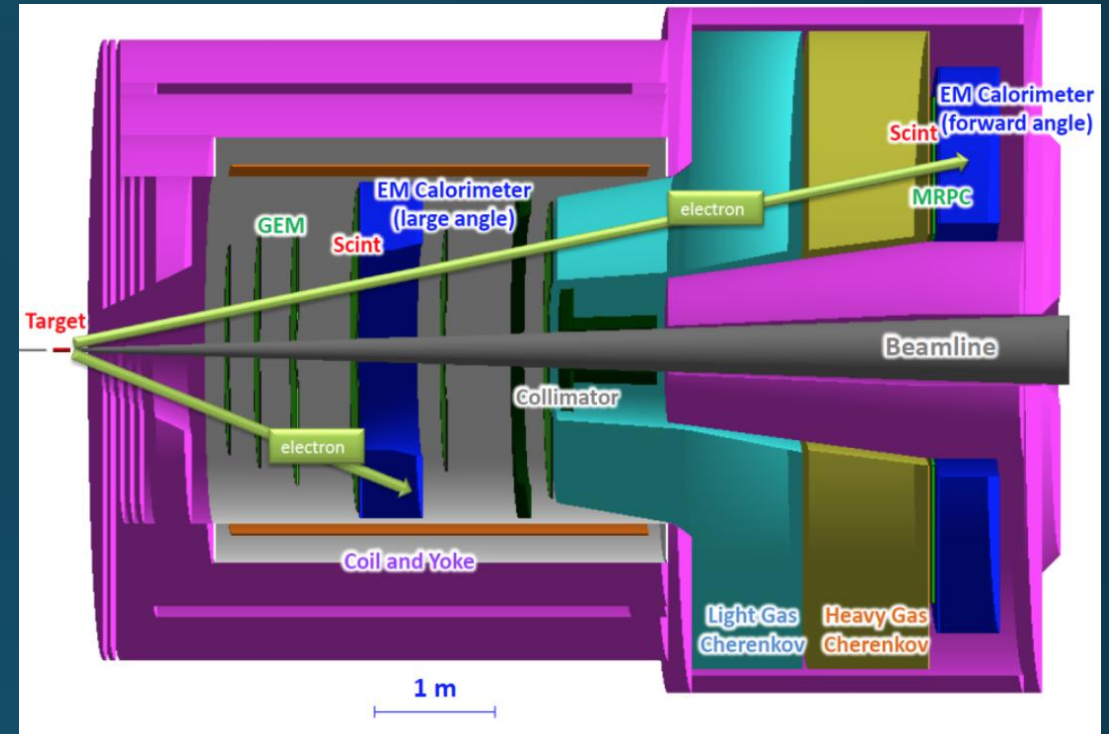


CERAF Large Acceptance Spectrometer

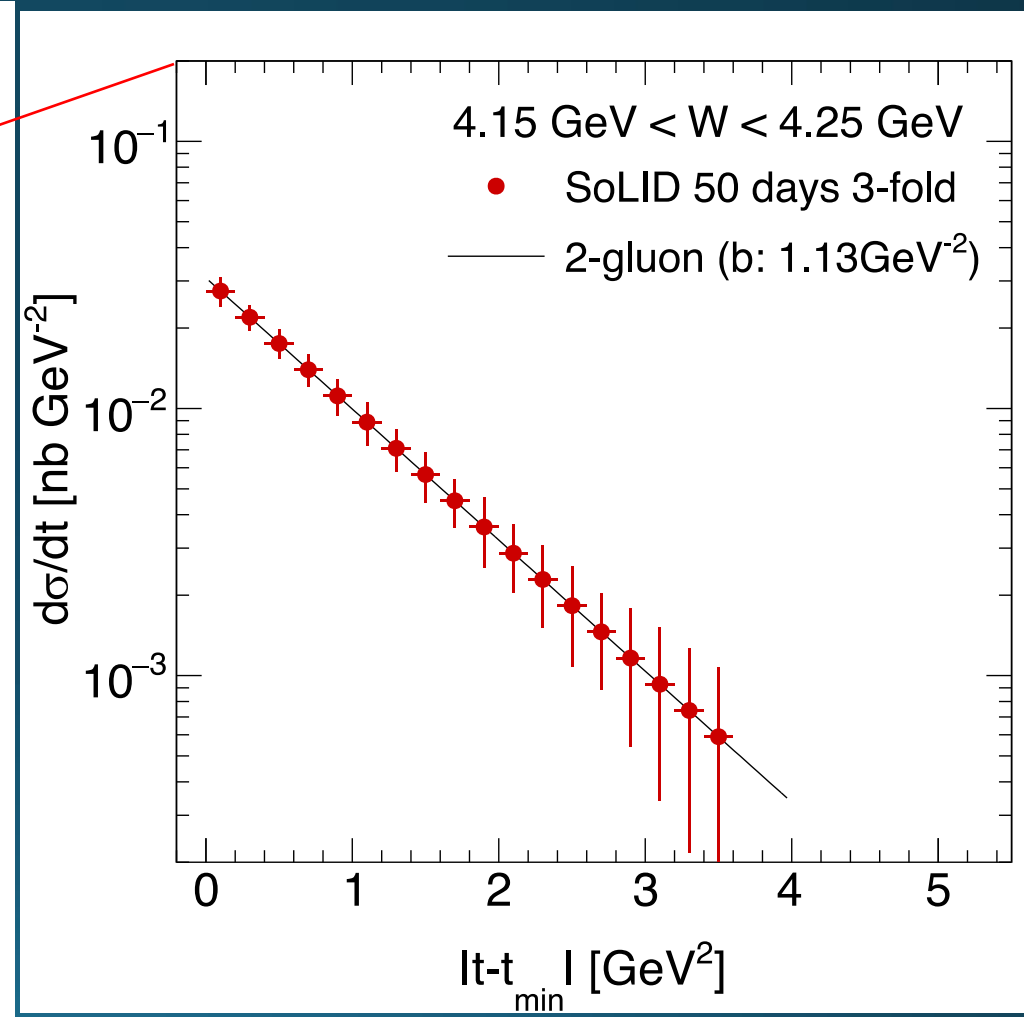
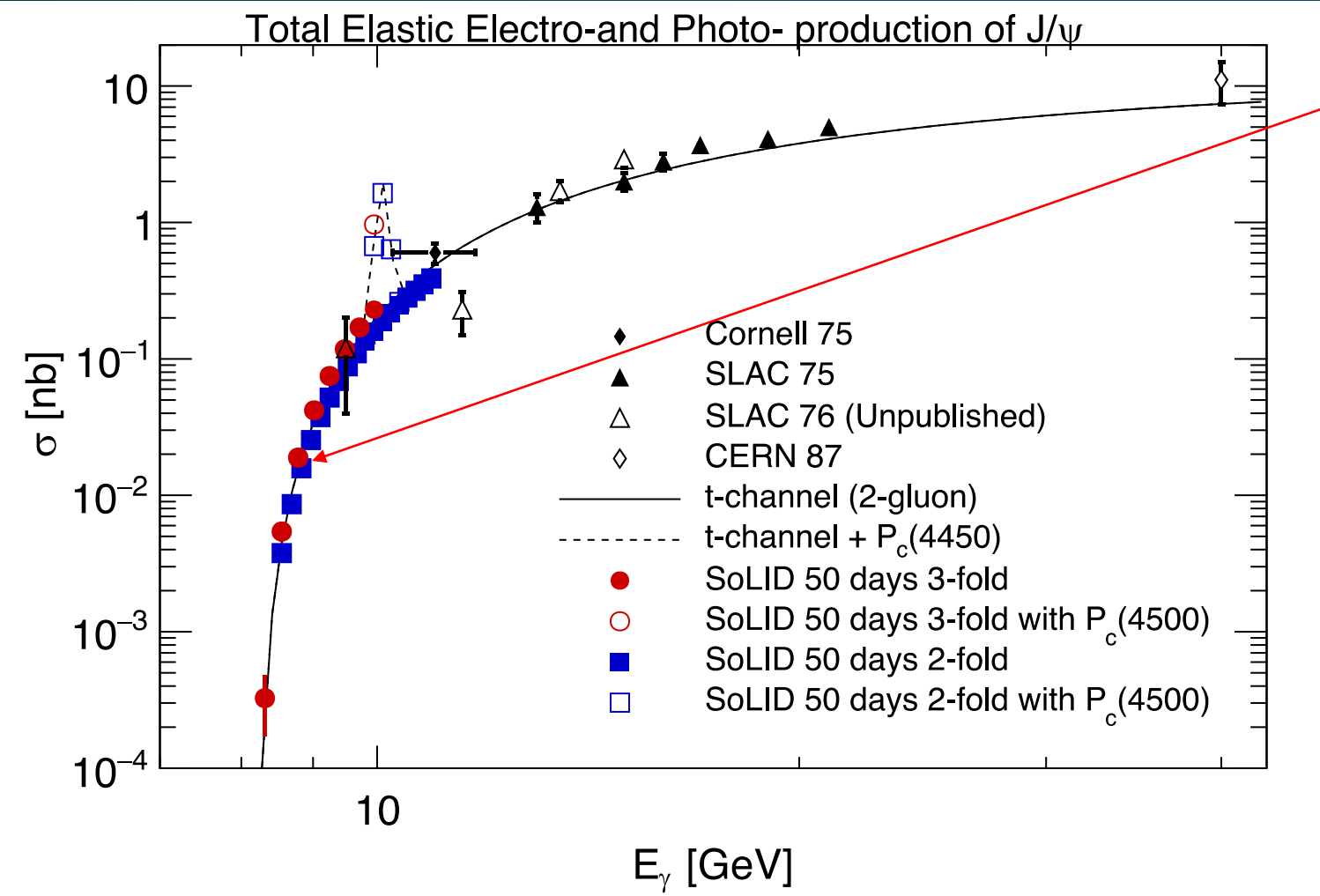
J/ψ experiment E12-12-006 at SoLID

ATHENNA Collaboration

- $3\mu\text{A}$ 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



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

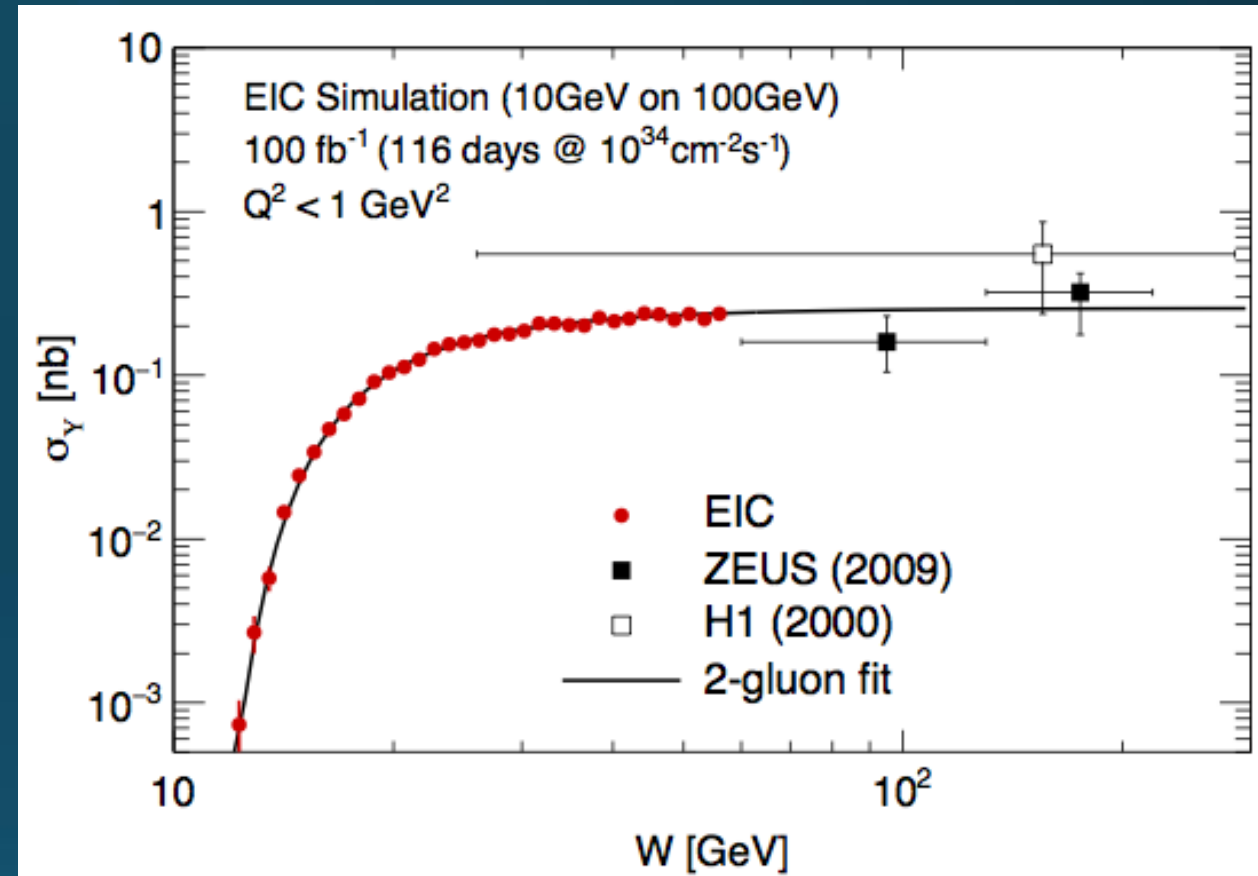


Quarkonia at an EIC

- J/Ψ 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.

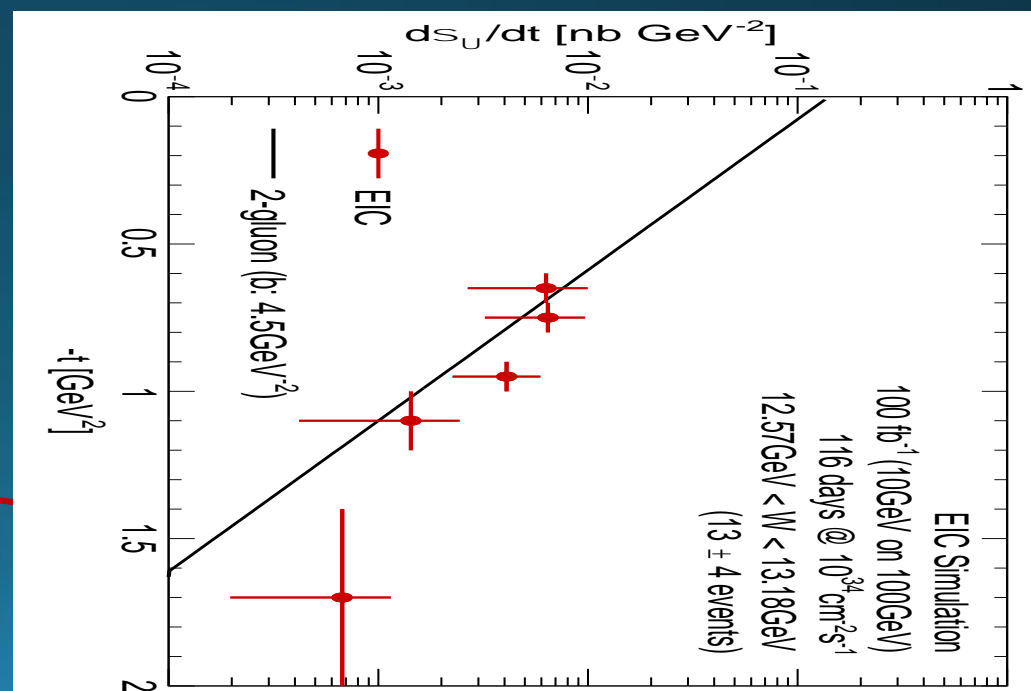
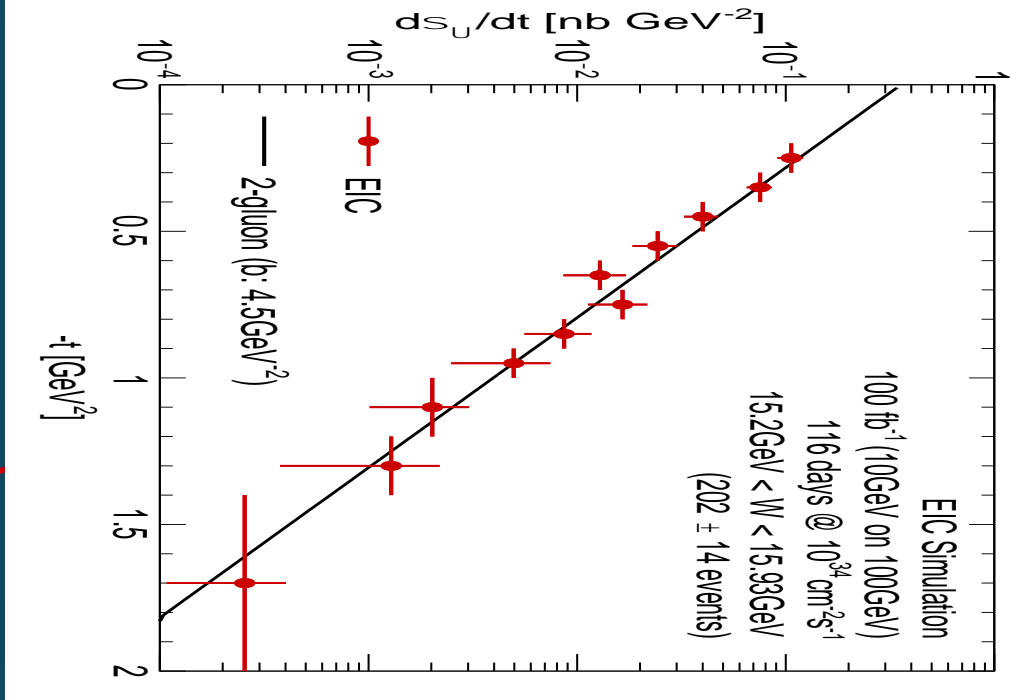
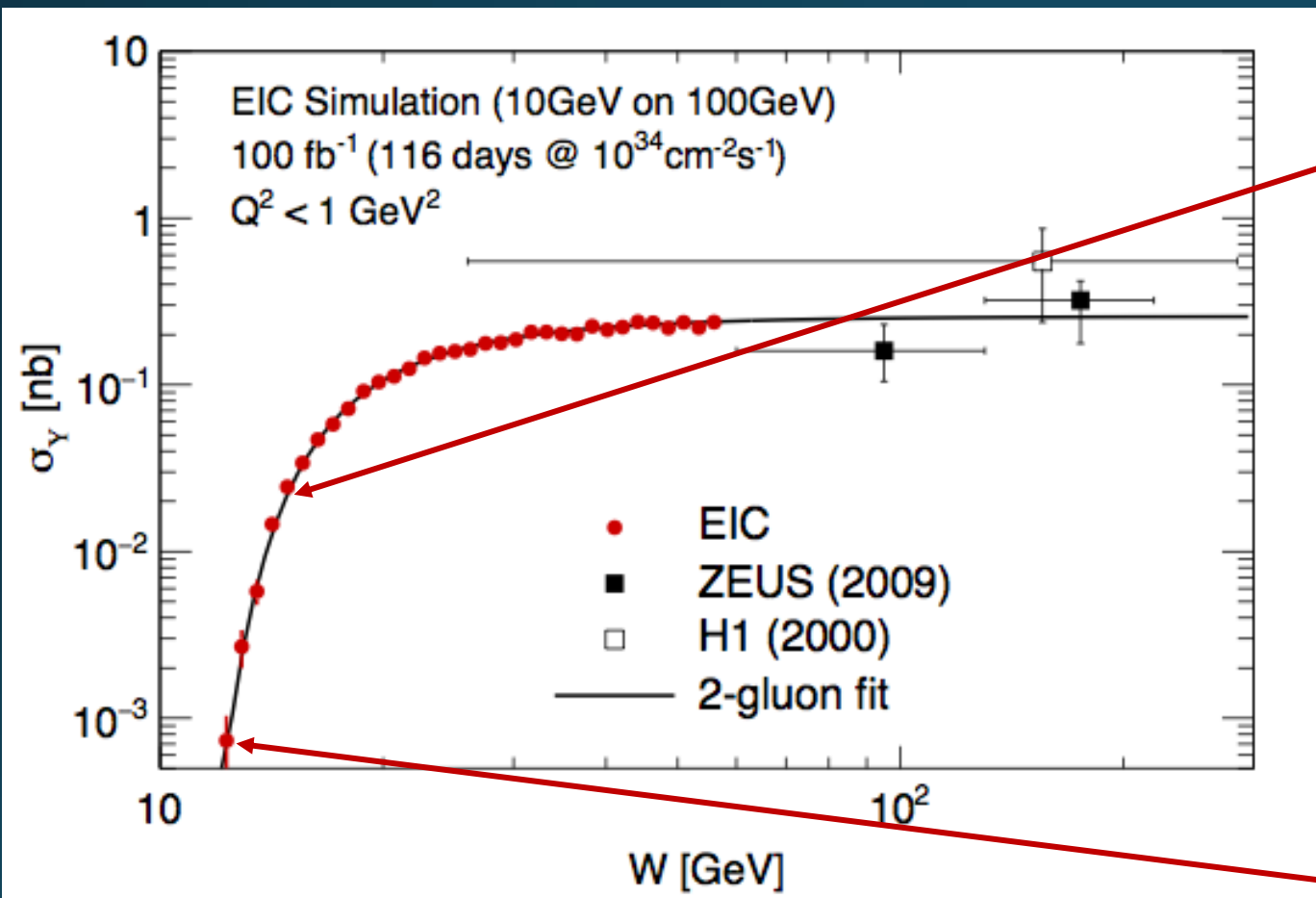
Υ photo-production at an EIC

- **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**

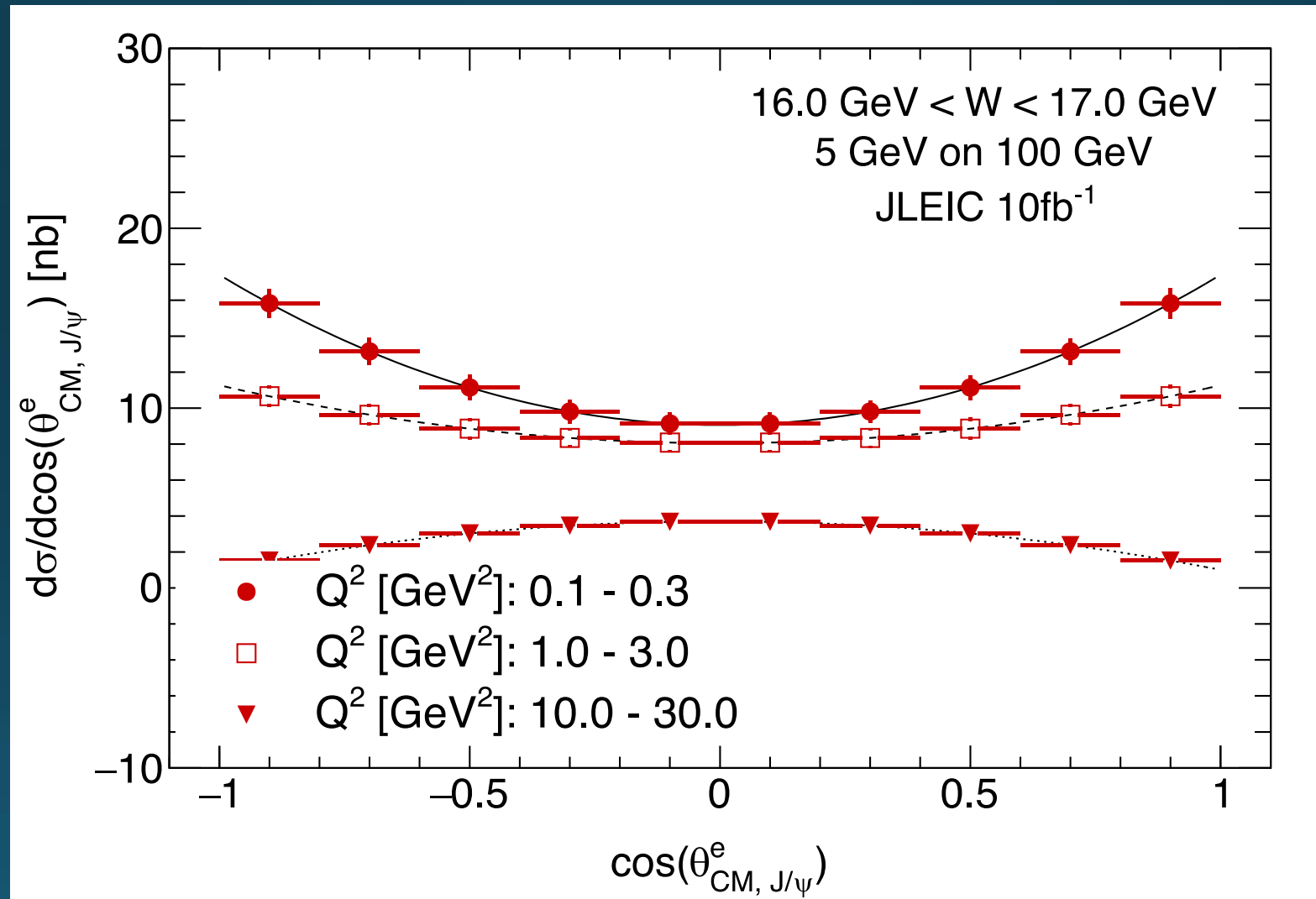


- $Y(1s)$ production possible at threshold!
 - Provides measure for **universality**, complimentary to threshold J/ψ program at JLab12
 - Is there a “beautiful” pentaquark?
- **Sensitivity down to $\sim 10^{-3}$ nb!**

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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