J/psi Production Near Threshold: from Heavy Pentaquarks to Hadron Mass Generation

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U.S. DEPARTMENT OF ENERGY

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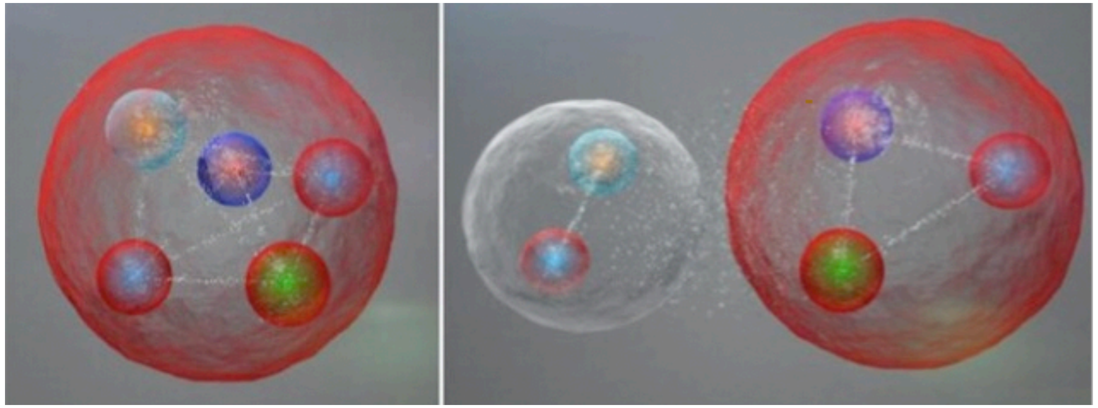
Science of J/Psi Production at Threshold

- Color Van der Waal Forces and binding
  - A unique case of strong force from QCD degrees of freedom in nuclear physics
- Existence of heavy pentaquarks
  - Do heavy pentaquark exits?
  - Can we predict their existence or non-existence?
- Hadron masses
  - How do hadron masses emerge?
  - Can we learn something deeper about nucleon dynamics and confinement?



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

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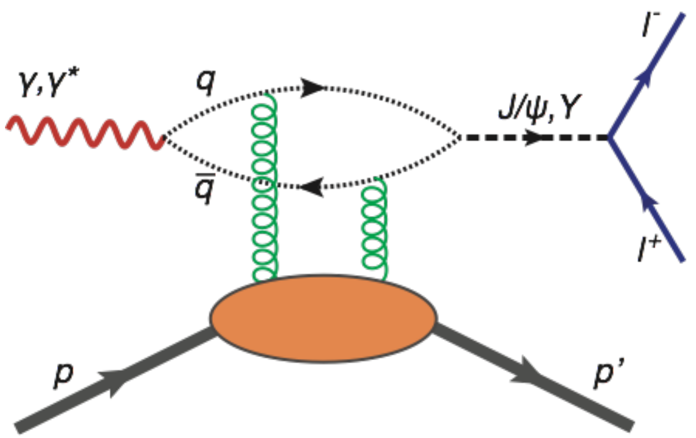
Heavy-Quarkonium photo-production: **what do we know?**

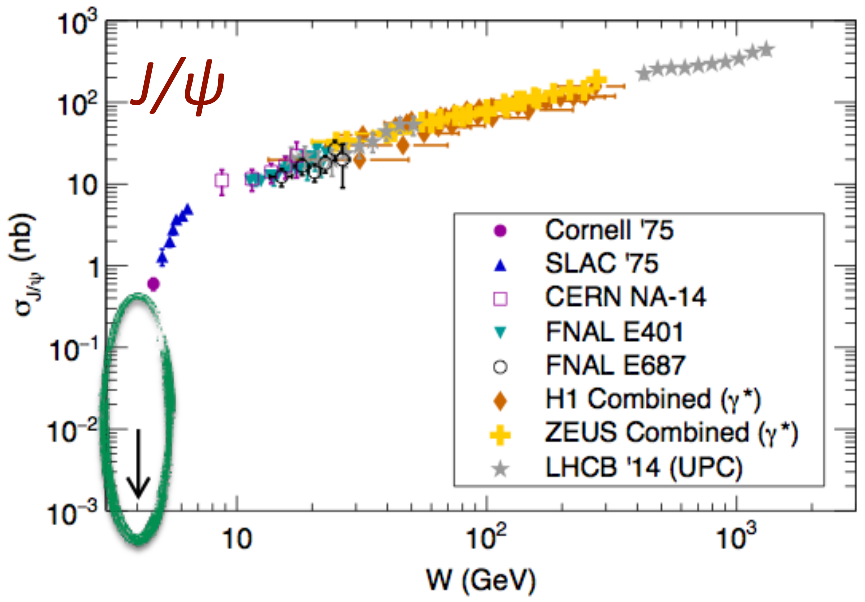
J/ψ photo-production:

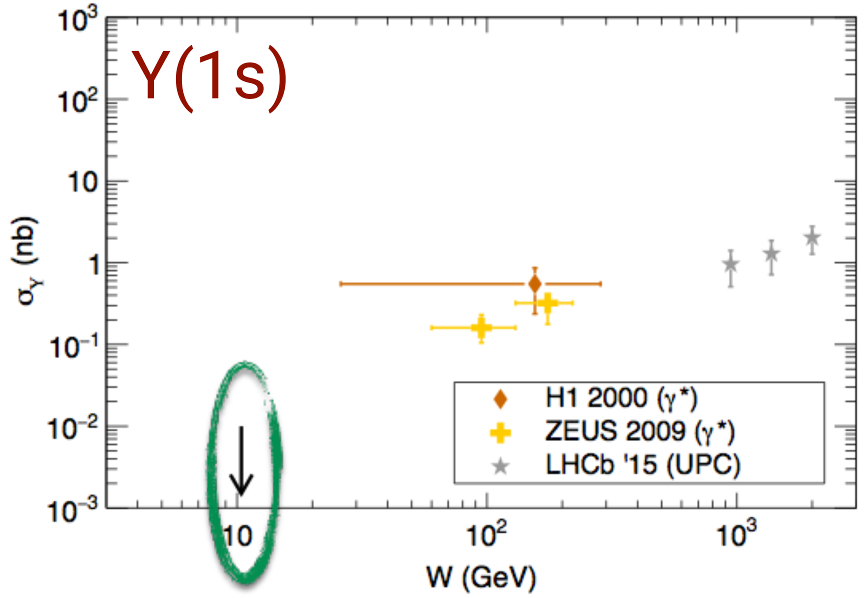
- Well constrained above W > 15 GeV
  - Dominated by t-channel 2-gluon exchange
- Almost no data near threshold



Υ(1s) photo-production:

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





Color Van der Waals Force and Binding

- Heavy quarkonium- nucleon system is unique
  - Not much quark exchange between the light quark system and heavy quark system
  - The force is attractive but its strength is no well determined
  - A consequence is the possible binding of J/psi in nuclei
  - Nuclear physics with the QCD basic degrees of freedom

- Suggestion made since 1990
  - **Nuclear-bound quarkonium,** Brodsky, de Téramond and Schmidt, **Phys. Rev. Lett. 64, 1011**
  - **A QCD Calculation of the interaction of quarkonium with nuclei,** Luke, Manohar and Savage, **Phys. Lett. B 288, 355 (1992)**
- Many theoretical estimates
  - Predicting weak binding of J/psi-Nucleon and possible binding in medium weight to heavy nuclei.
- Lattice calculations of Quarkonium nucleus bound states. S. Beane *et al.* **Phys.Rev. D91 (2015) no.11, 114503**
  - Pion masses are still large in these calculations

Sample of References Exploring Quarkonium-Nucleus Binding

1] S. J. Brodsky, I. Schmidt, and G. de Teramond, Phys. Rev. Lett. 64, 1011 (1990).
[2] D. Wasson, Phys. Rev. Lett. 67, 2237 (1991).
[3] M. E. Luke, A. V. Manohar, and M. J. Savage, Phys. Lett. B 288, 355 (1992).
[4] S. J. Brodsky and G. A. Miller, Phys. Lett. B 412, 125 (1997).
[5] G. F. de Teramond, R. Espinoza, and M. Ortega-Rodriguez, Phys. Rev. D 58, 034012 (1998).
[6] S. H. Lee and C. Ko, Phys. Rev. C 67, 038202 (2003).
[7] K. Tsushima, D. Lu, G. Krein, and A. Thomas, Phys. Rev. C 83, 065208 (2011).
[8] A. Yokota, E. Hiyama, and M. Oka, Prog. Theor. Exp. Phys. 2013, 113D01 (2013).

TABLE I. Estimates for the binding energies of charmonium to light nuclei and nuclear matter (in MeV) from selected models. A "$*$" indicates the system is predicted to be unbound, while entries with center dots indicate that the system was not addressed.

	Binding energy (MeV)			Binding energy (MeV)	
Ref.	^{3}He η_c	^{4}He η_c	NM η_c	^{4}He J/ψ	NM J/ψ
[1]	19	140	$*$		
[2]	0.8	5	27		
[3]			10		10
[5]	$*$	$*$	9		
[6]					5
[7]				5	18
[8]				15.7	

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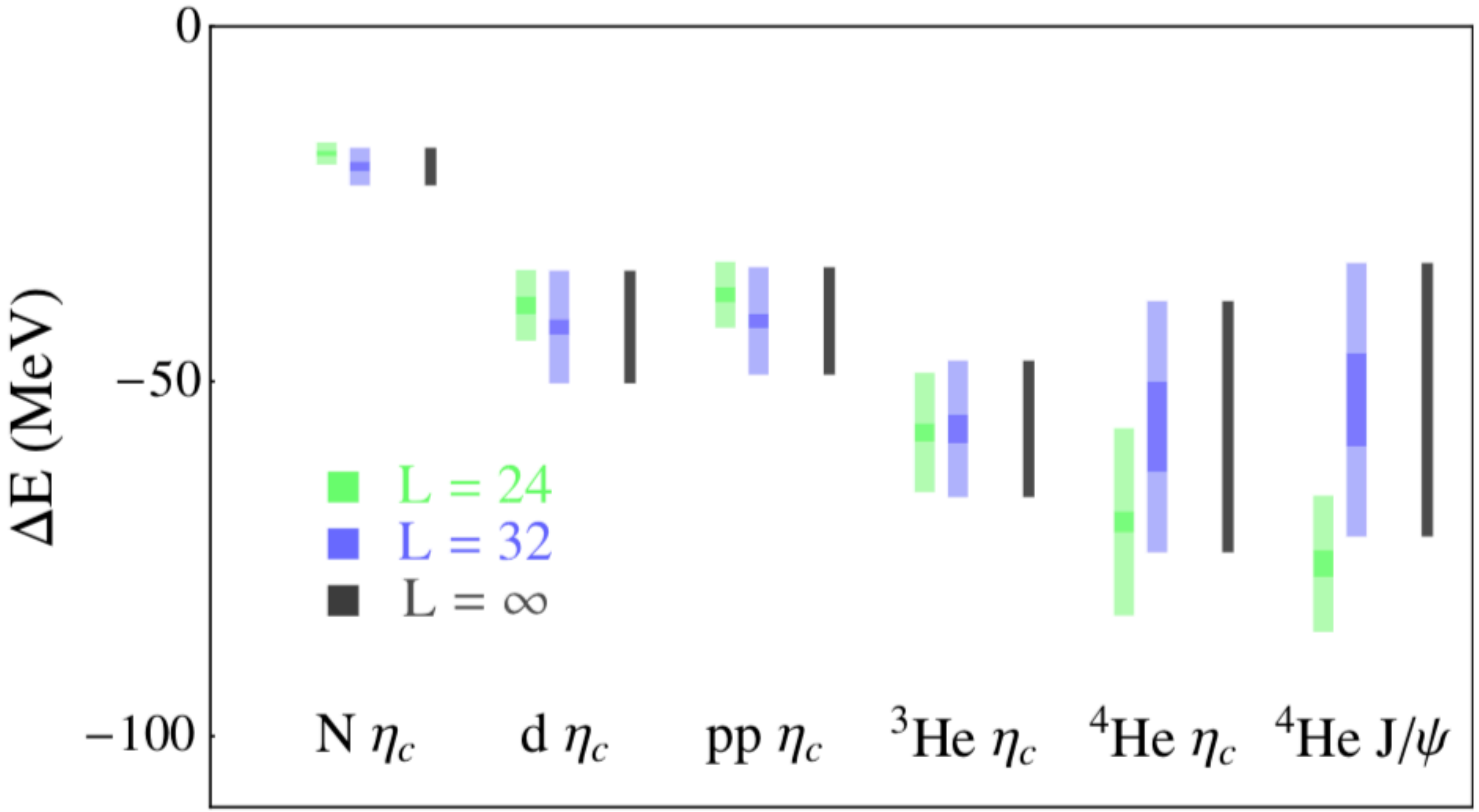
Lattice Exploration of Quarkonium-Nuclear Binding

S. Beane *et al.* **Phys.Rev. D91 (2015) no.11, 114503**



- Large pion mass ~800 MeV
- 1 lattice spacing

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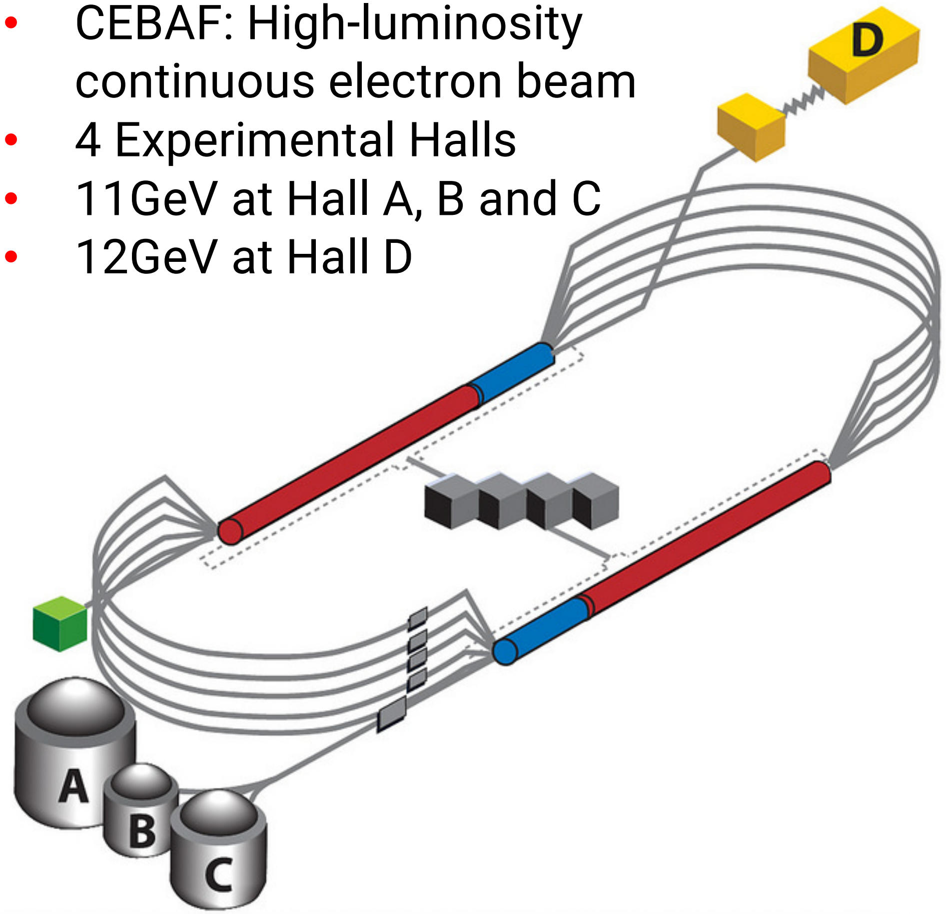
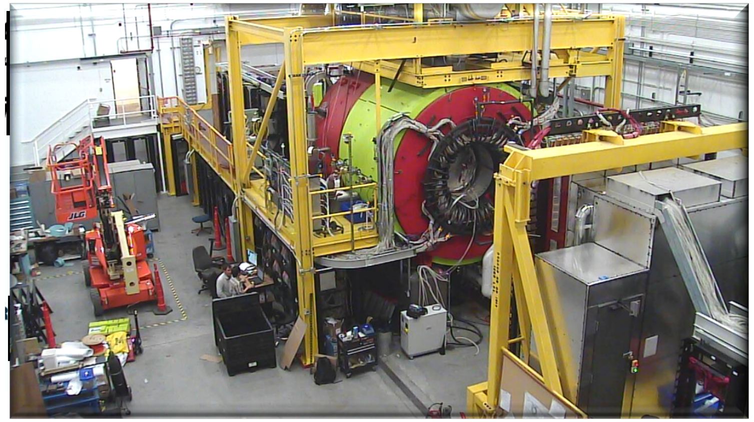
J/ψ at JLab in **the 12GeV era**

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



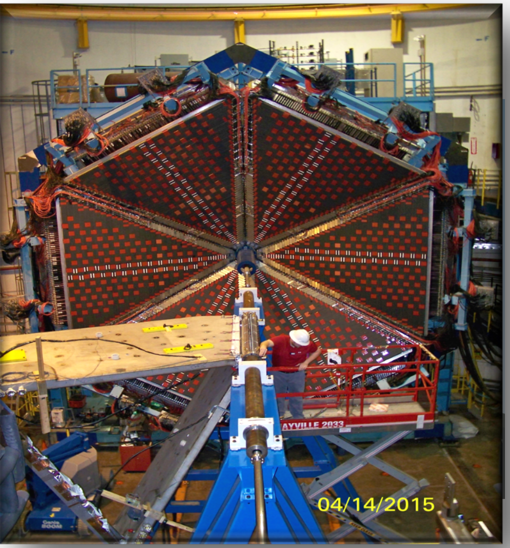
JLab is the ideal laboratory to measure J/ψ near threshold, due to luminosity, resolution and energy reach!

12 GeV J/Ψ experiments at JLab Overview



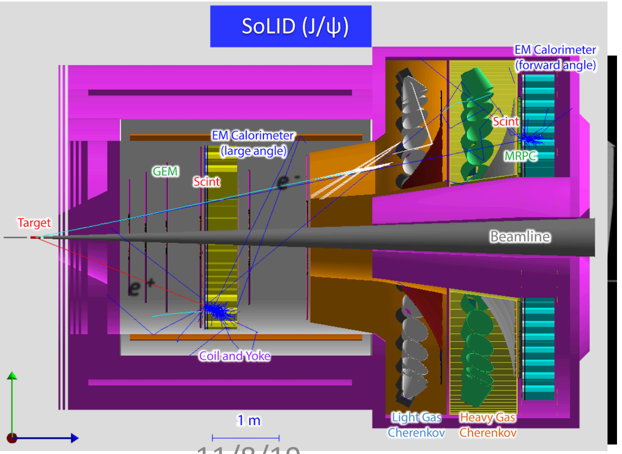
Hall D – GlueX has observed the first J/ψs at Jlab and a publication

A. Ali *et al.* [GlueX Collaboration], Phys. Rev. Lett. 123, no. 7, 072001 (2019)



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

Hall C – has an approved experiment to search for the LHCb pentaquark E12-16-007:data taken



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

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 $a_{\psi p}$**

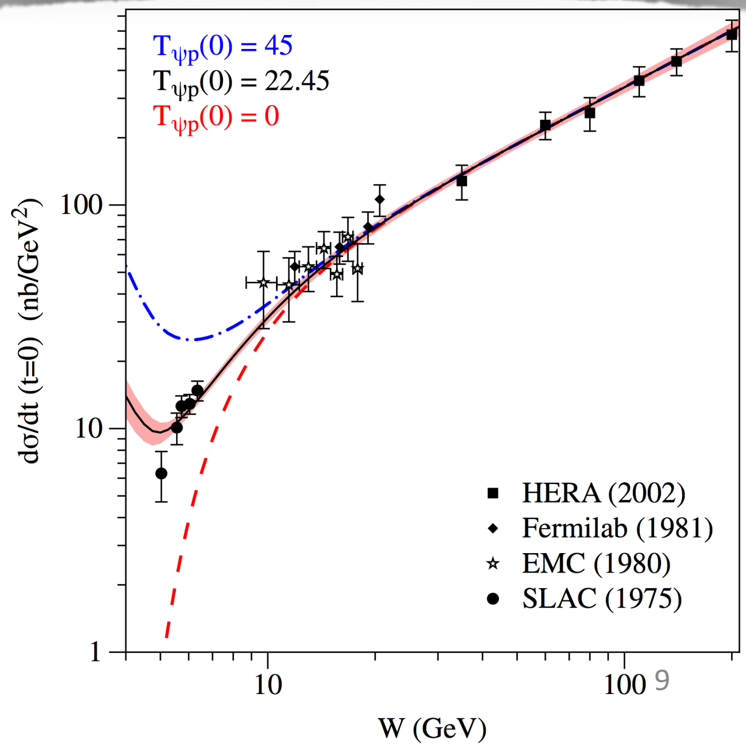
$$T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$$

- 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)

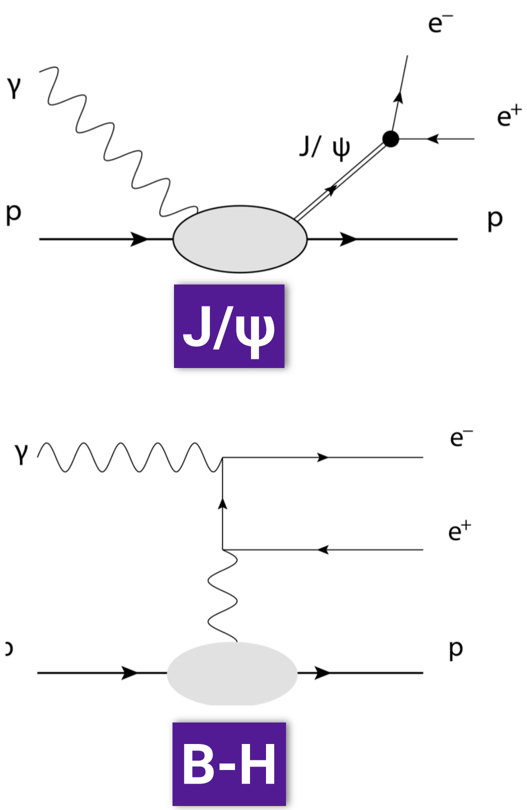
- Recent fit to existing data in a dispersive framework:
  - $a_{\psi p}$ ~ 0.05 fm translated to ($B_{\psi p}$ ~ 3 MeV) for nuclear matter

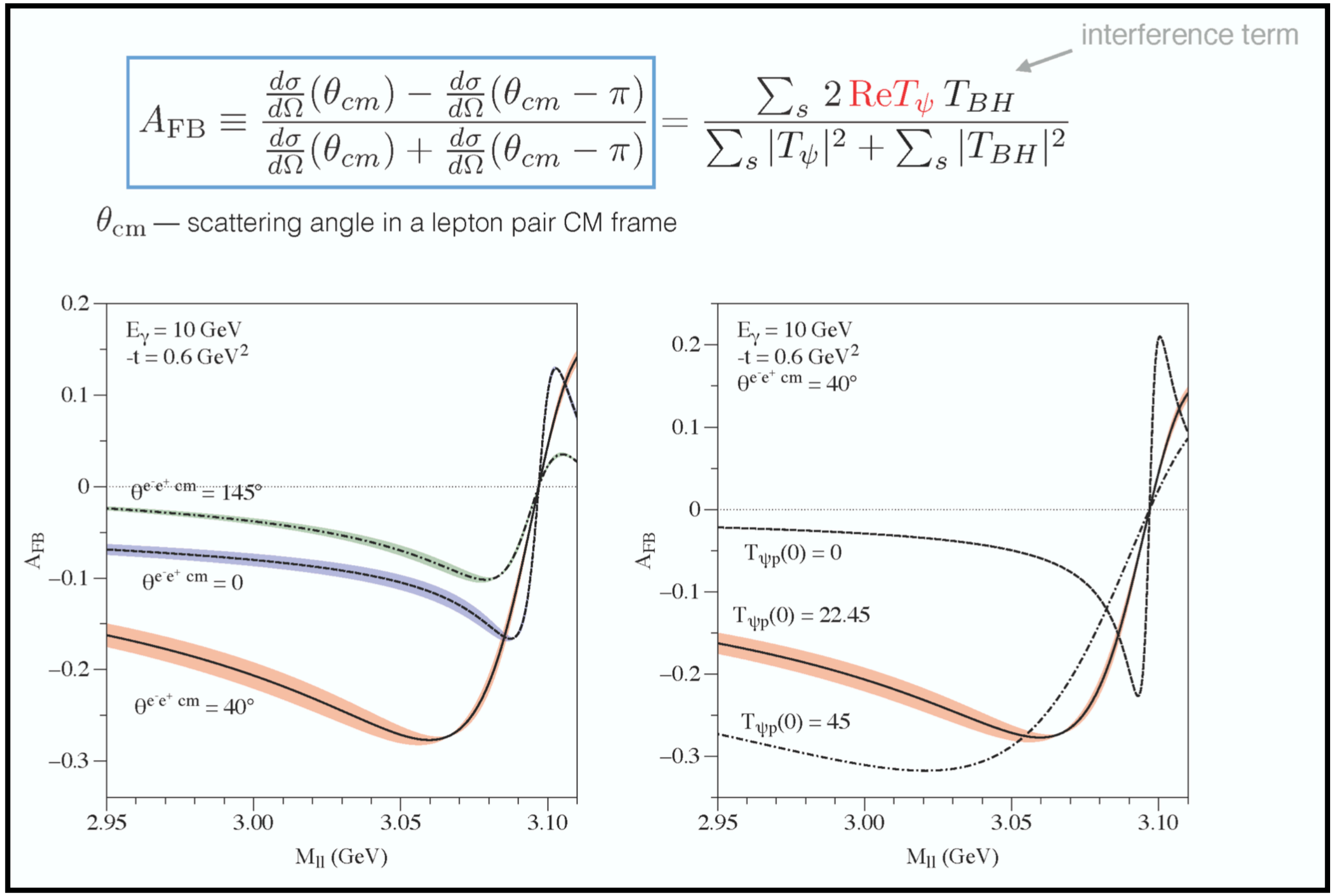
- Photo-production near threshold constrained through dispersion relations, not data
- **Threshold experiments needed!**



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 $B_{\psi p}$

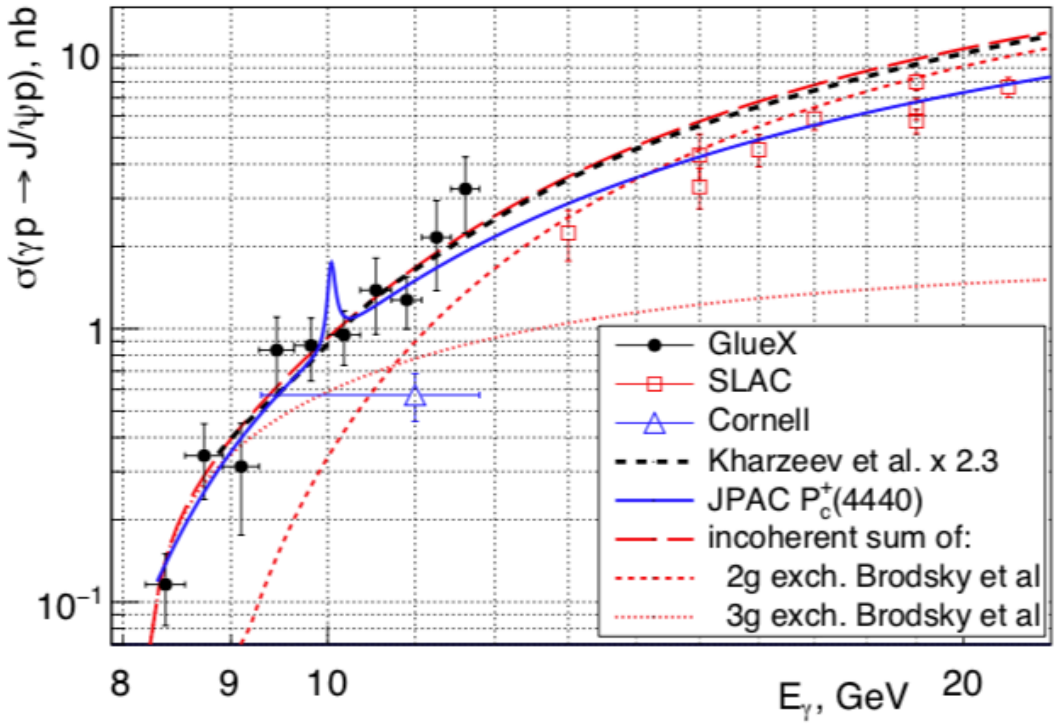




Slide from O. Gryniuk

Recent GlueX Results in the threshold region

GlueX photoproduction of J/psi data

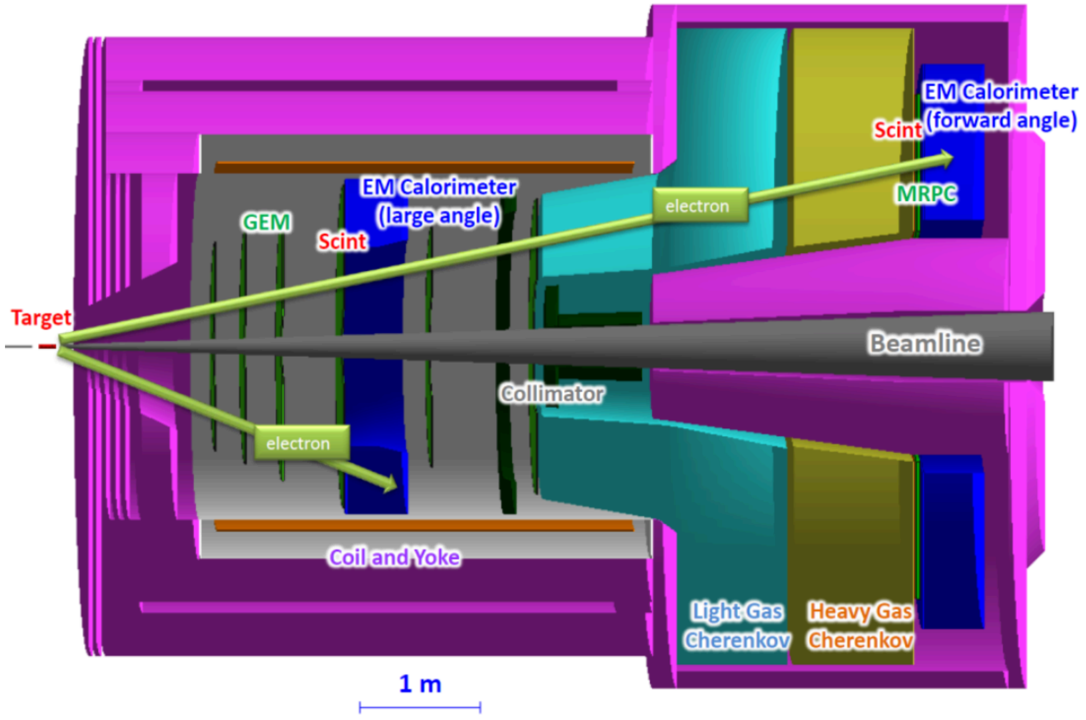


- Most world data are spread at large invariant mass
- Threshold region measurements date back to the 70s

- A. Ali *et al.* **Phys.Rev.Lett. 123 (2019) no.7, 072001**

J/ψ experiment E12-12-006 at SoLID

- 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

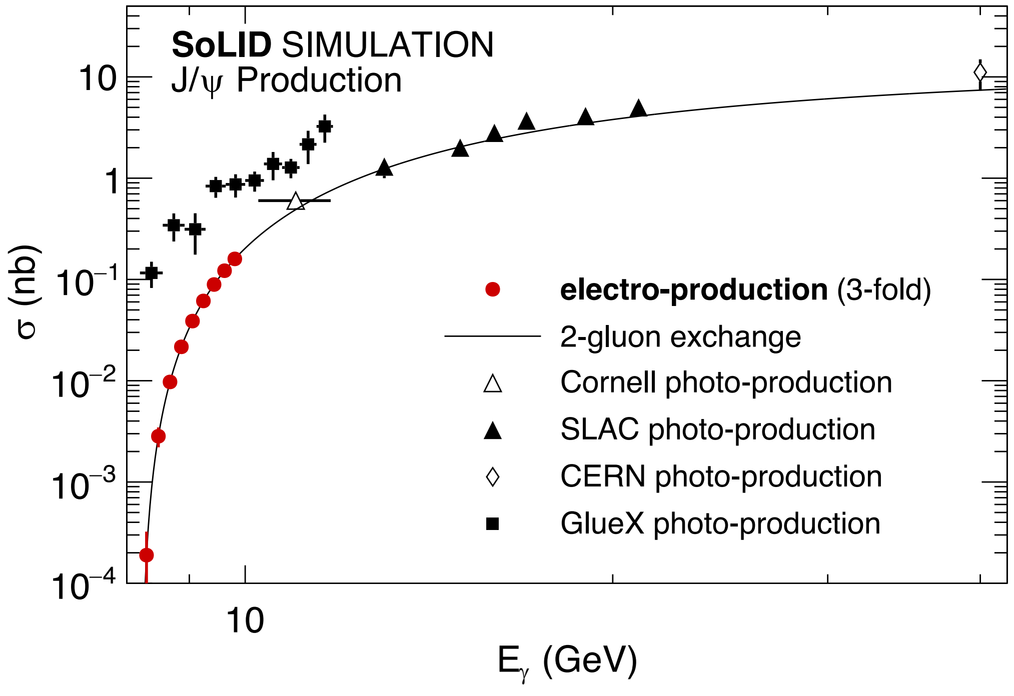


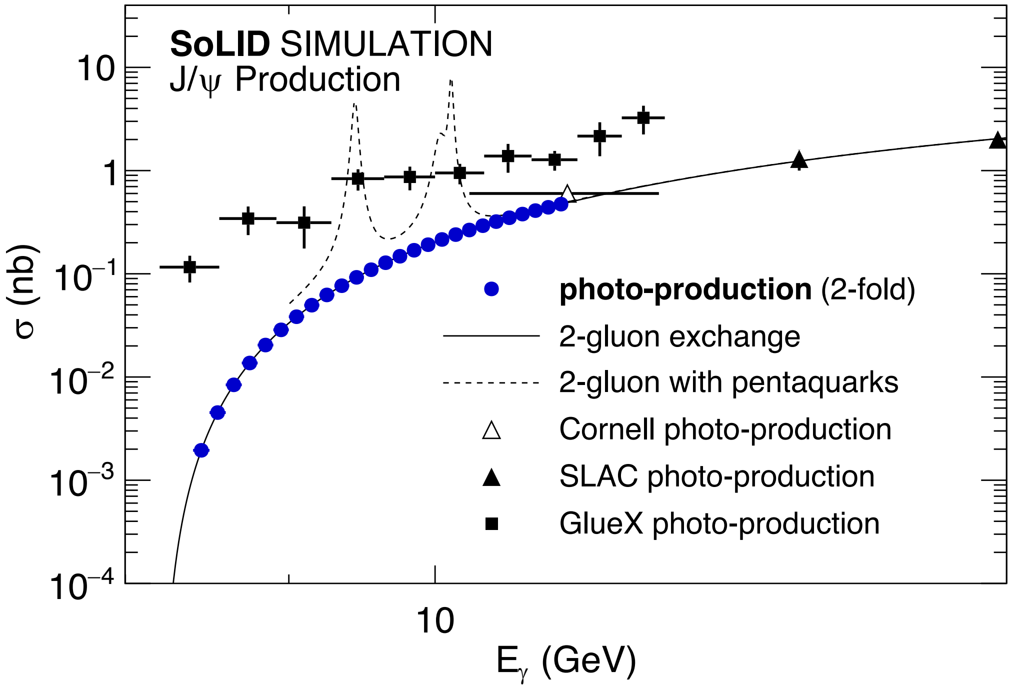
- **Photo-production**
  - **2-fold** coincidence + **recoil** proton
  - *t*-channel J/ψ rate: **1627 per day**
  - **Advantage over electro-production**
    - Energy reach in charmed pentaquark region
    - High rate
- **Electro-production**
  - **3-fold** coincidence (3 leptons)
  - *t*-channel *J/ψ*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

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

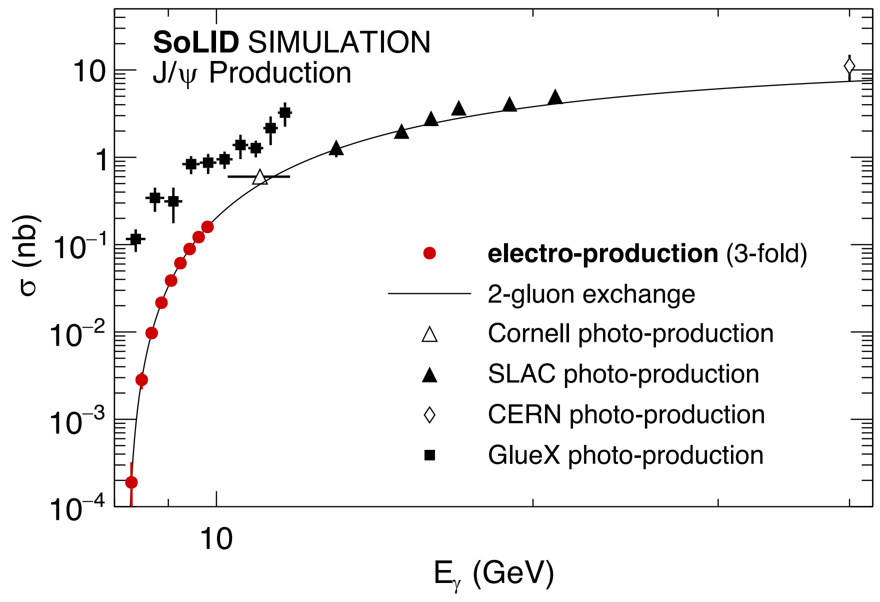
- Electro-production
- Photo-production through bremsstrahlung in the target cell

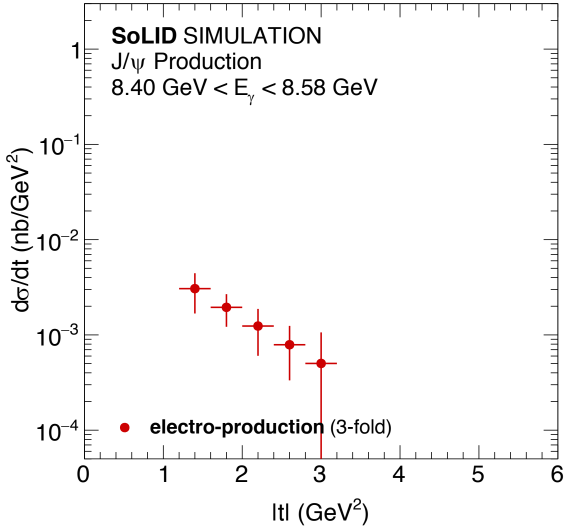
Projections of electroproduction and photoproduction

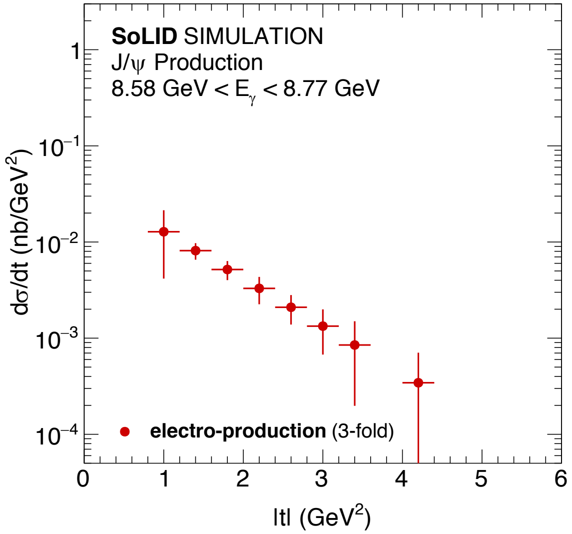


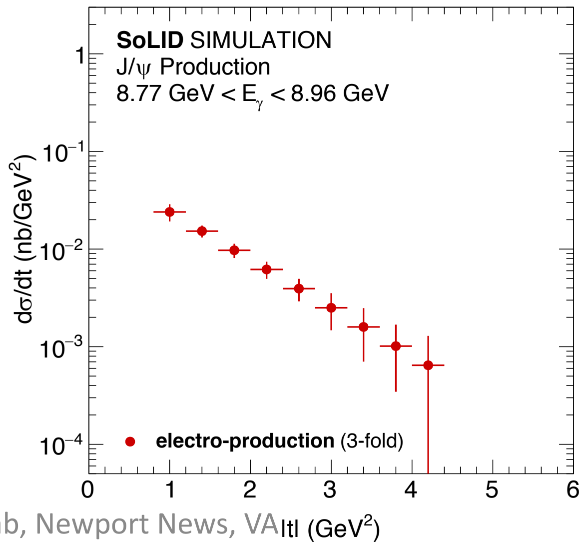


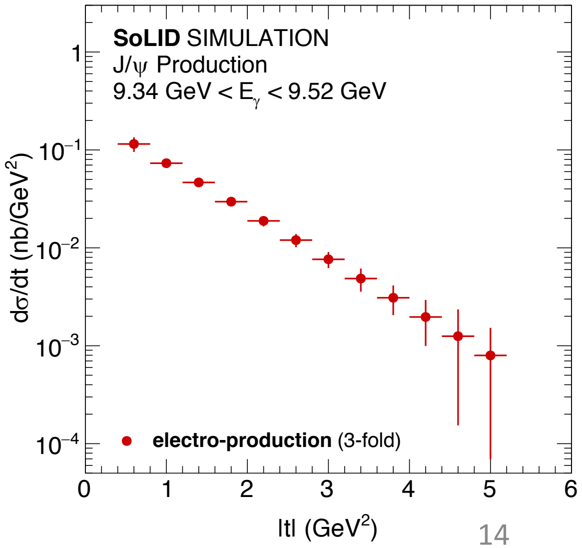
Total cross section and t distributions projections



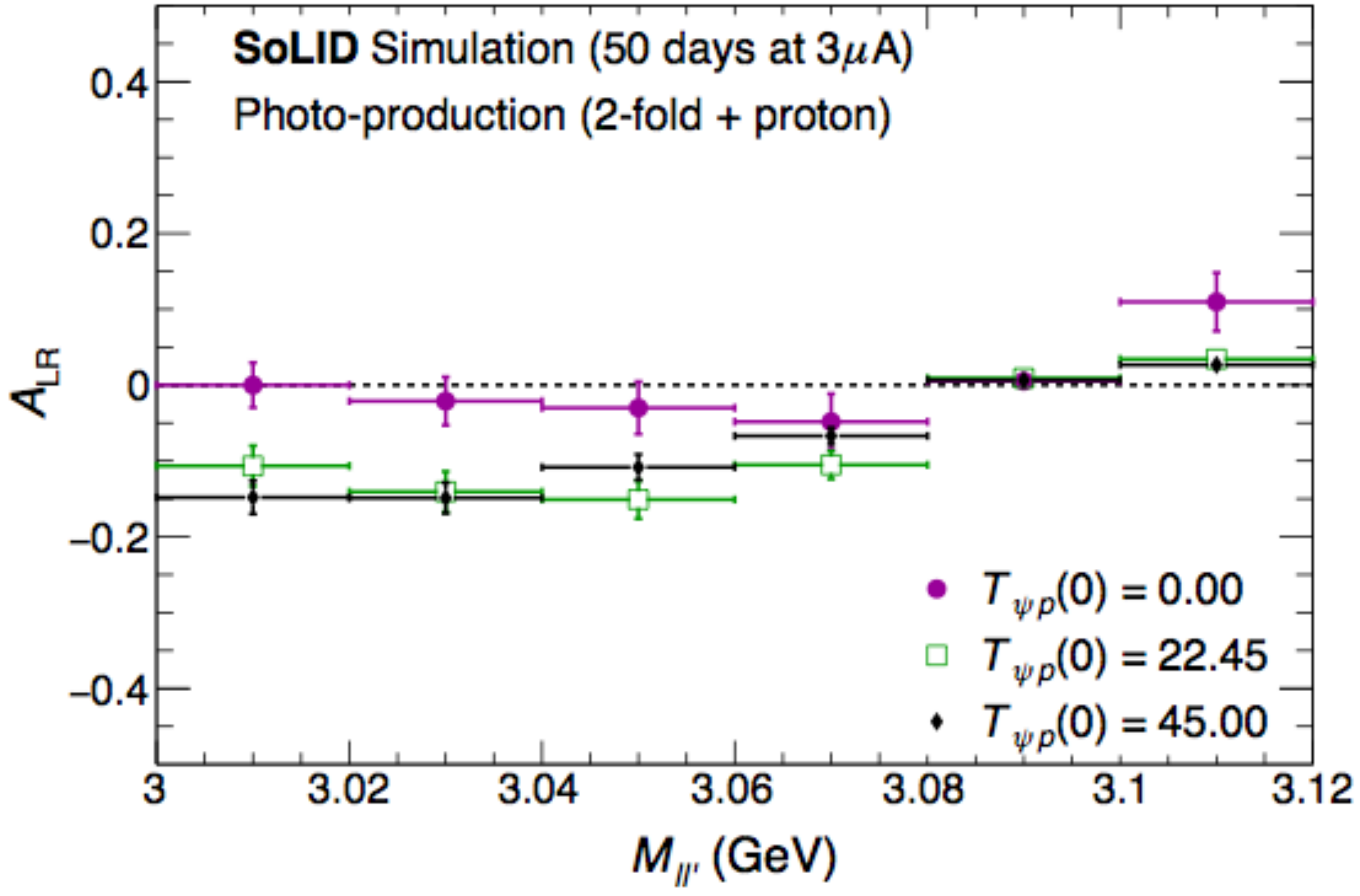








Projected Results: all together

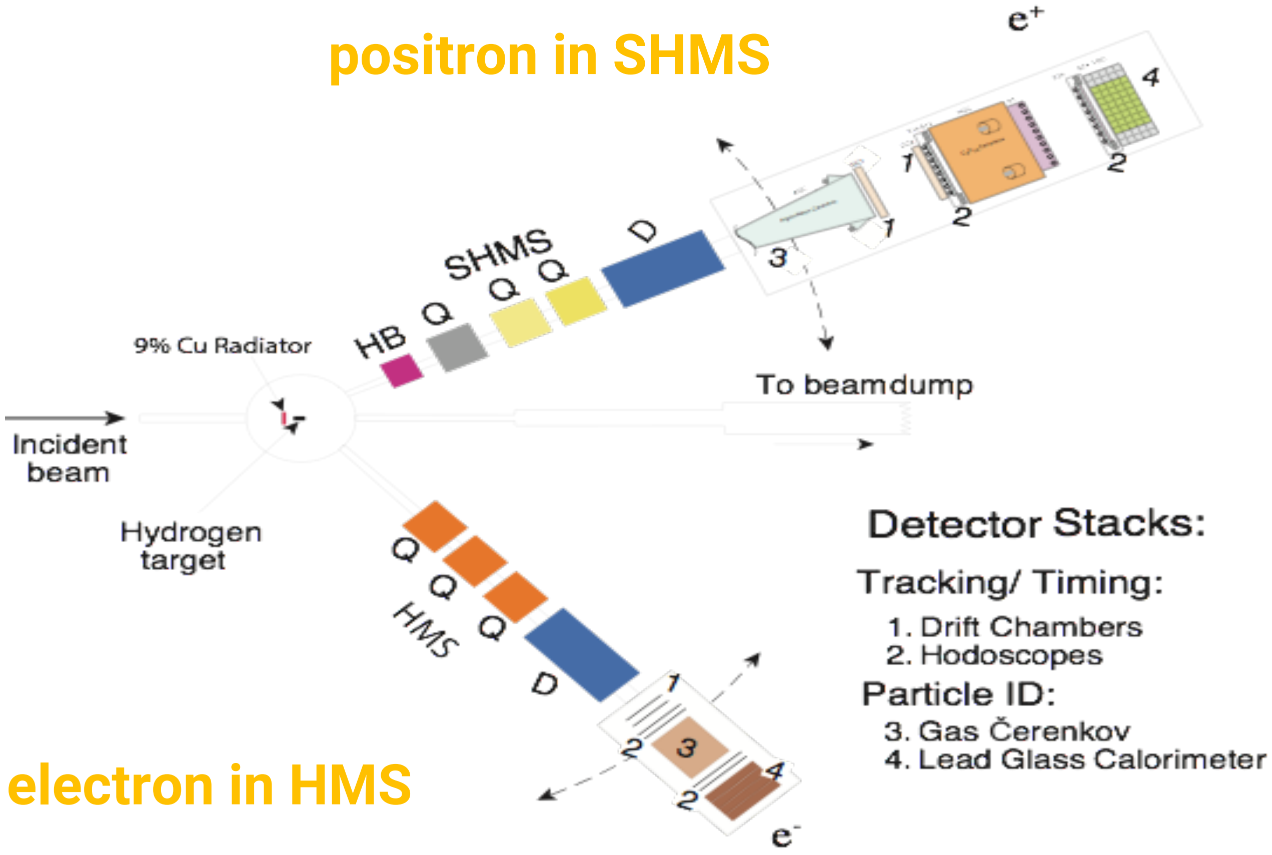


Search for the LHCb pentaquark

- 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**

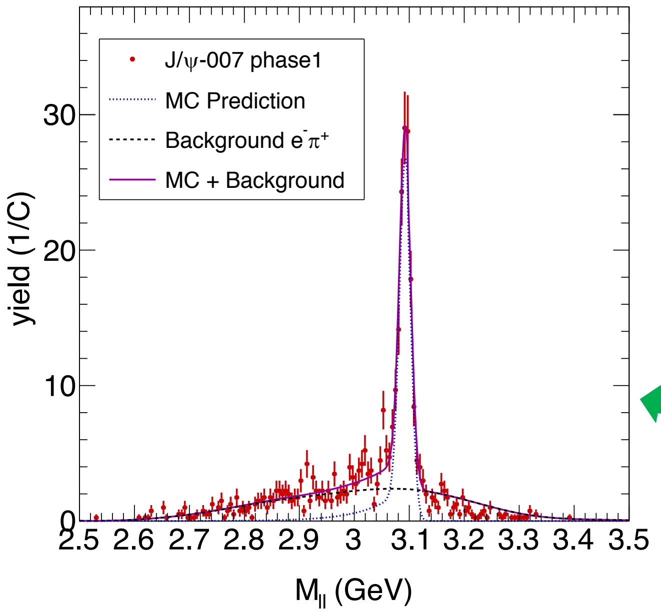
positron in SHMS

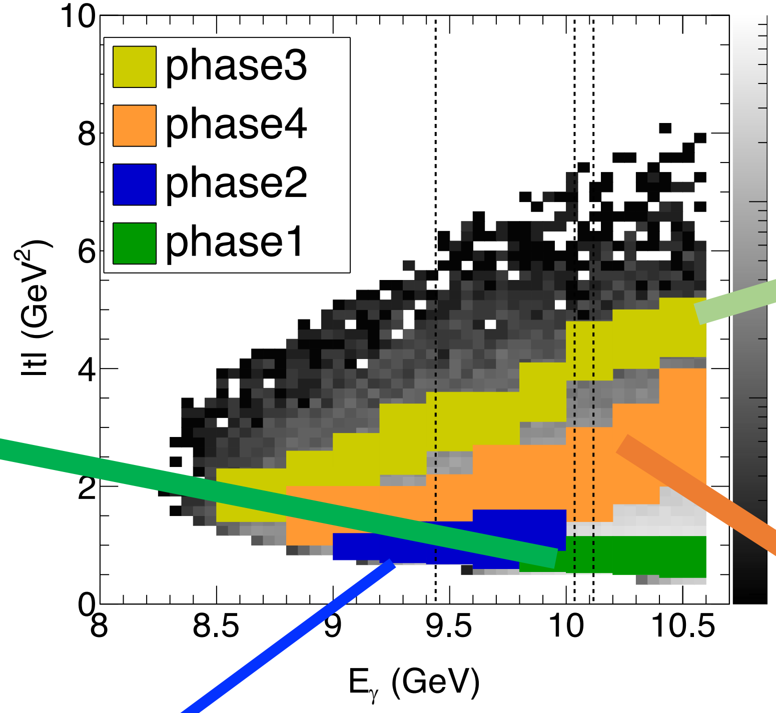


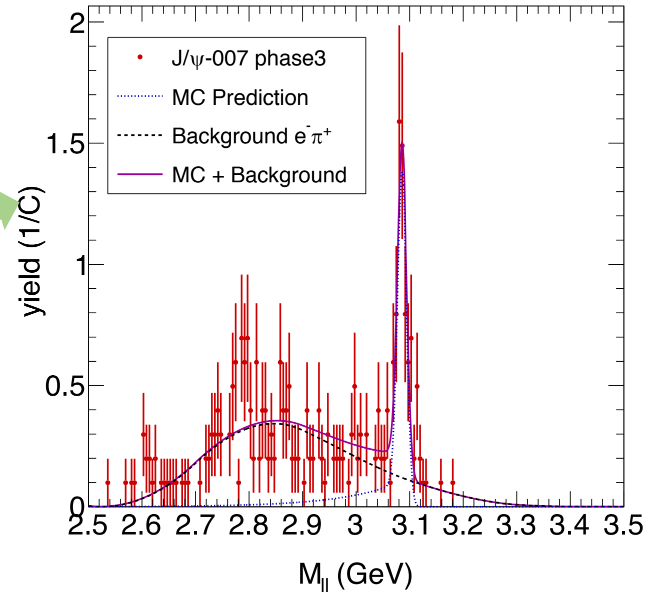
electron in HMS

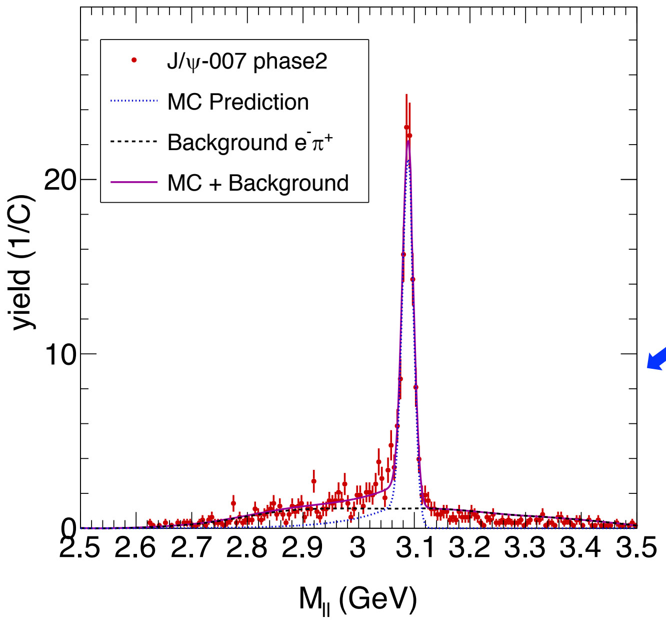
- **Run with 2 settings:**
  - **"SIGNAL" Setting** (9 days): minimizes accidentals and **maximizes signal/background**:
    - HMS: 34°, 3.25 GeV electrons
    - SHMS: 13°, 4.5 GeV positrons
  - **"BACKGROUND" Setting:** (2 days): precise determination of the ***t*-channel background**
    - HMS: 20°,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

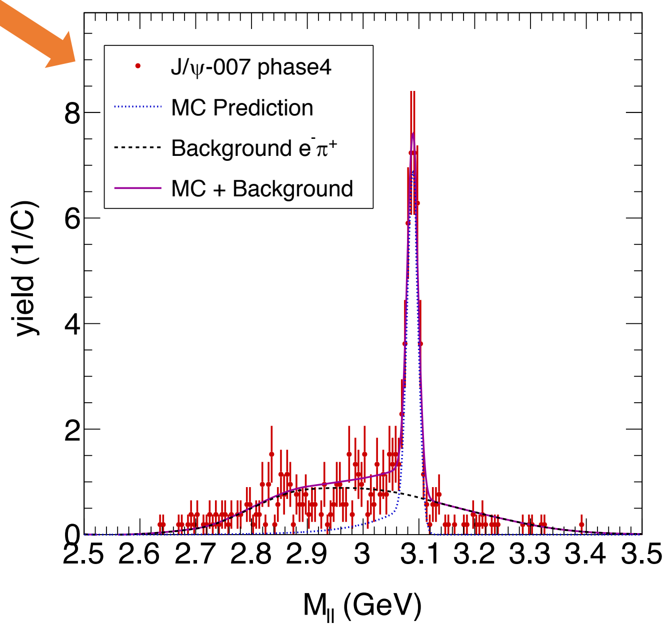
Leptons pair invariant mass





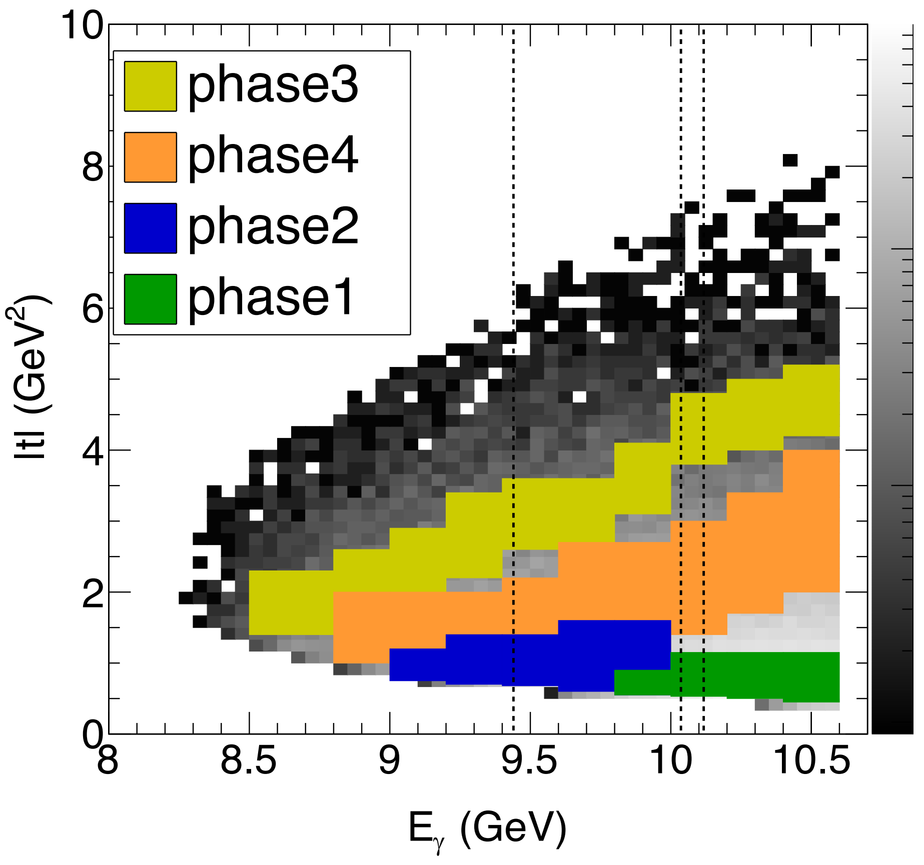


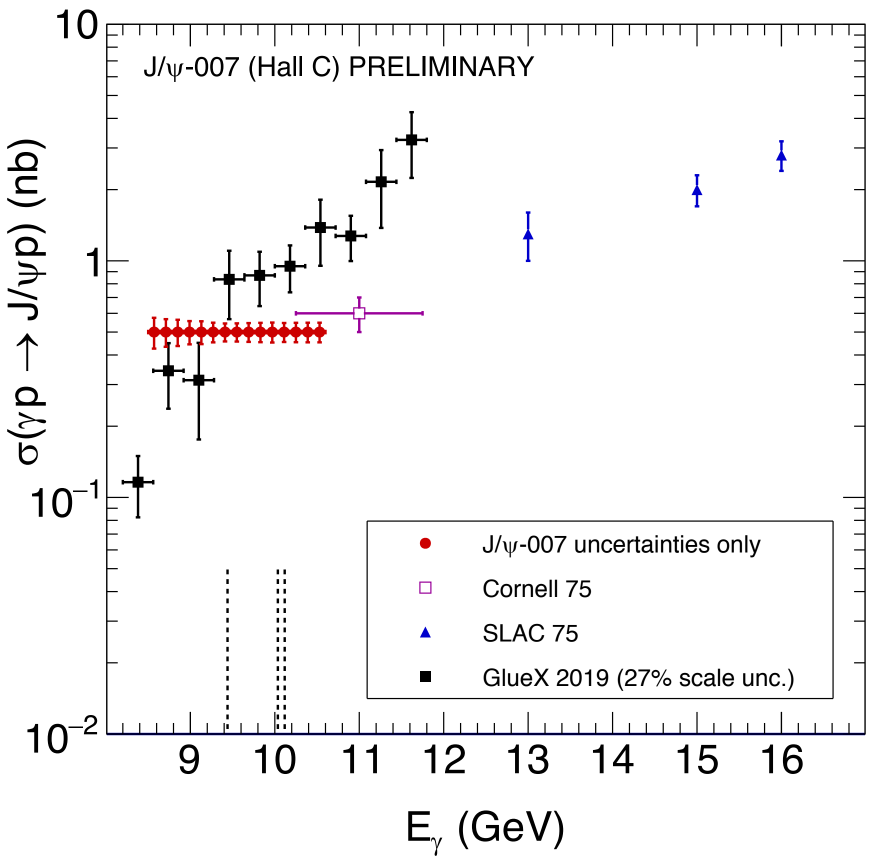




- Experiment ran in February 2019
- Good coverage of *t* dependence
- Largest dataset of J/psi produced with a real photon beam

Kinematic phase space and expected precision





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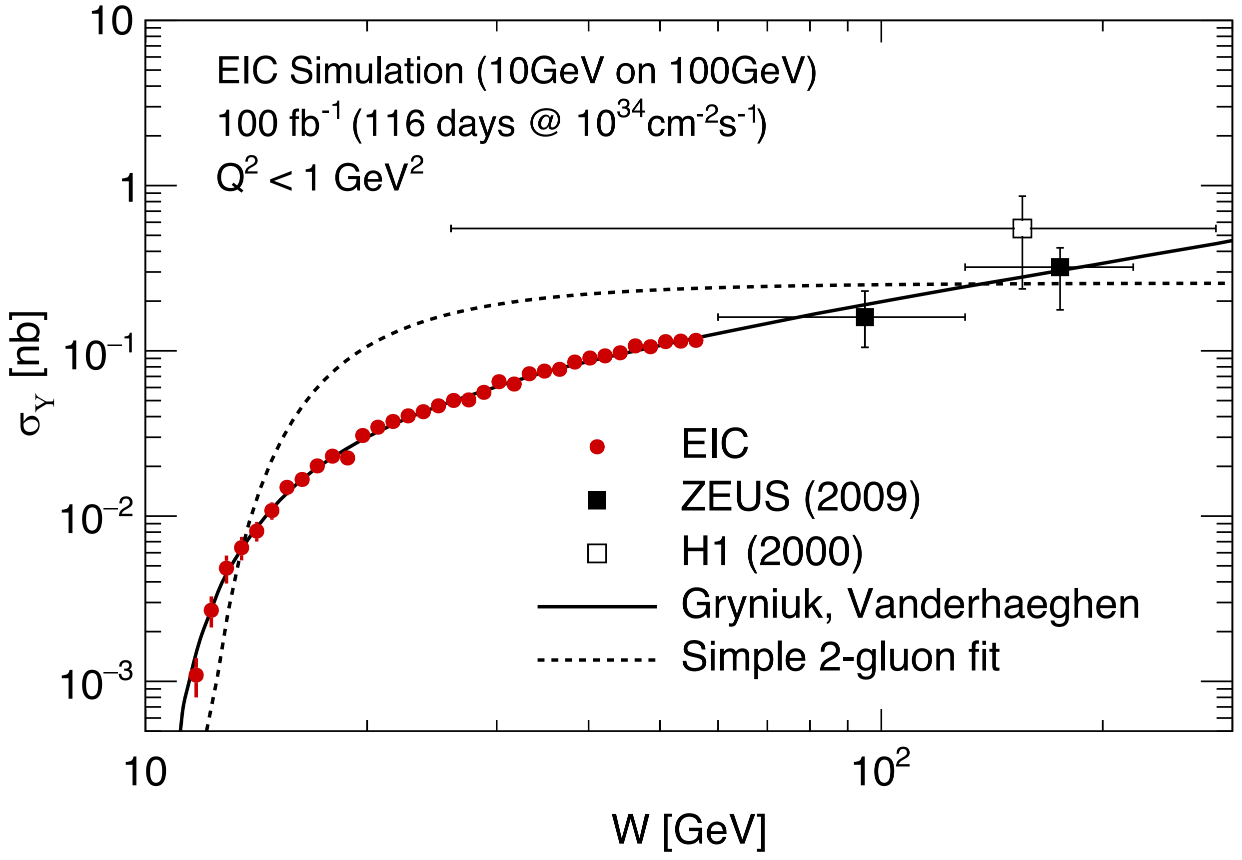
Quarkonia at an EIC

- 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.

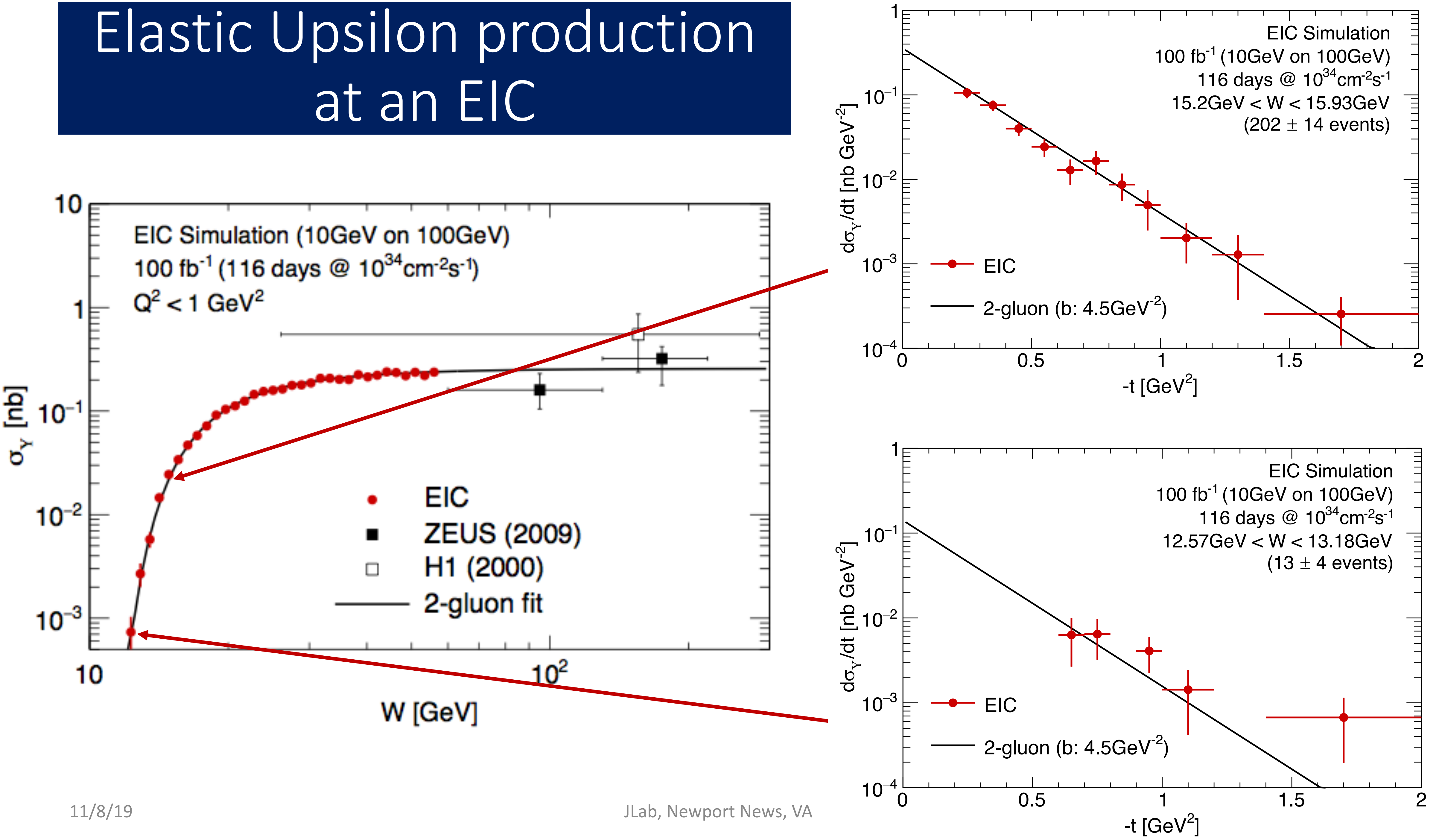
Υ photo-production at an EIC

- 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

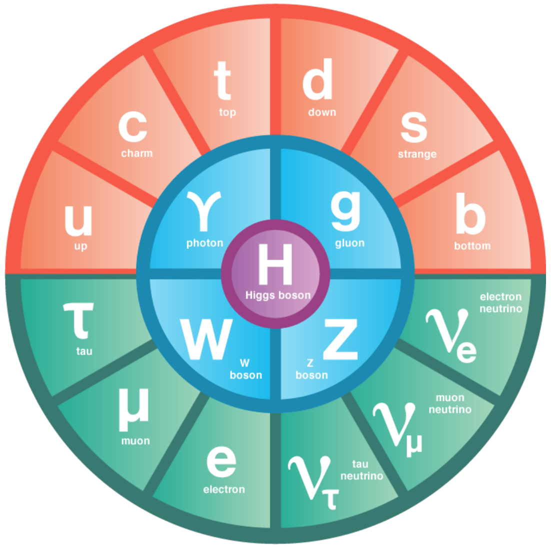


- ***Υ(1s)*** production possible at threshold!
  - Provides measure for **universality**, complimentary to threshold *J/ψ* program at JLab12
  - Is there a "beautiful" pentaquark?
- **Sensitivity down to ~10^{-3} nb!**

Elastic Upsilon production at an EIC

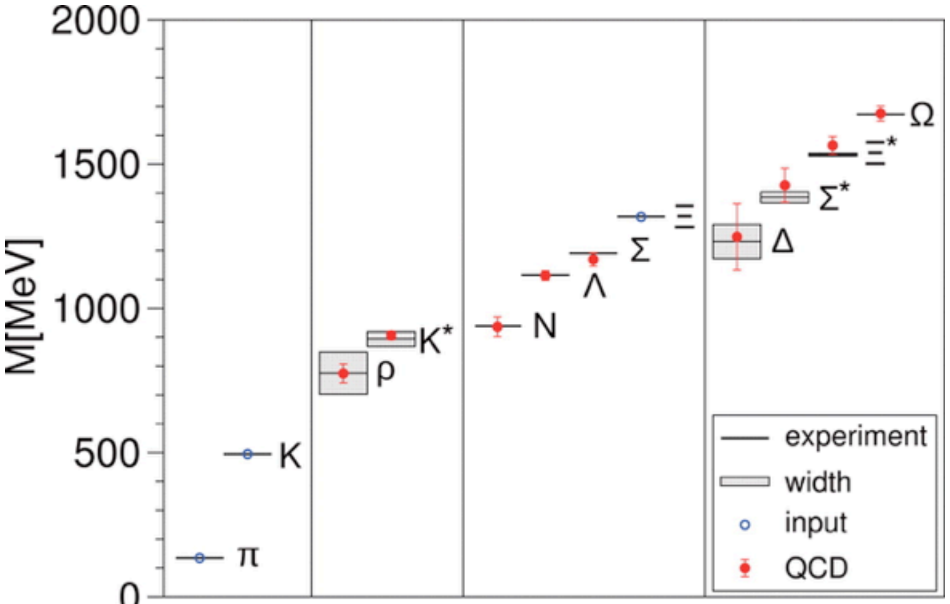


Emergence of Mass



- Mass of particles in the standard model is generated by the Higgs mechanism but not that of protons and neutrons.

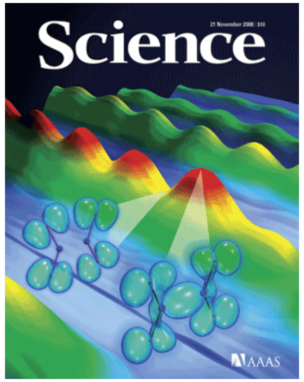
- Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass through the "trace anomaly"



Ab Initio Determination of Light Hadron Masses

S. Dürr, *et al.*

Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233



Proton Mass Decomposition

- 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:

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

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

Only light quarks enter the expression

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

$$m^2 \propto \langle P | T^\mu_\mu | P \rangle$$

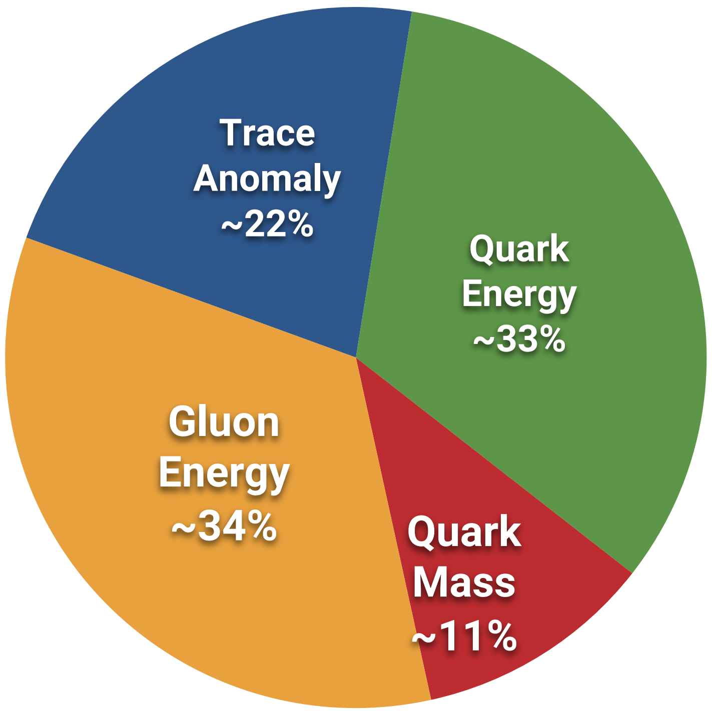
In the chiral limit the nucleon mass is non-zero
That of the pion is zero

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

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



- 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**

From the Cross section to the Trace Anomaly

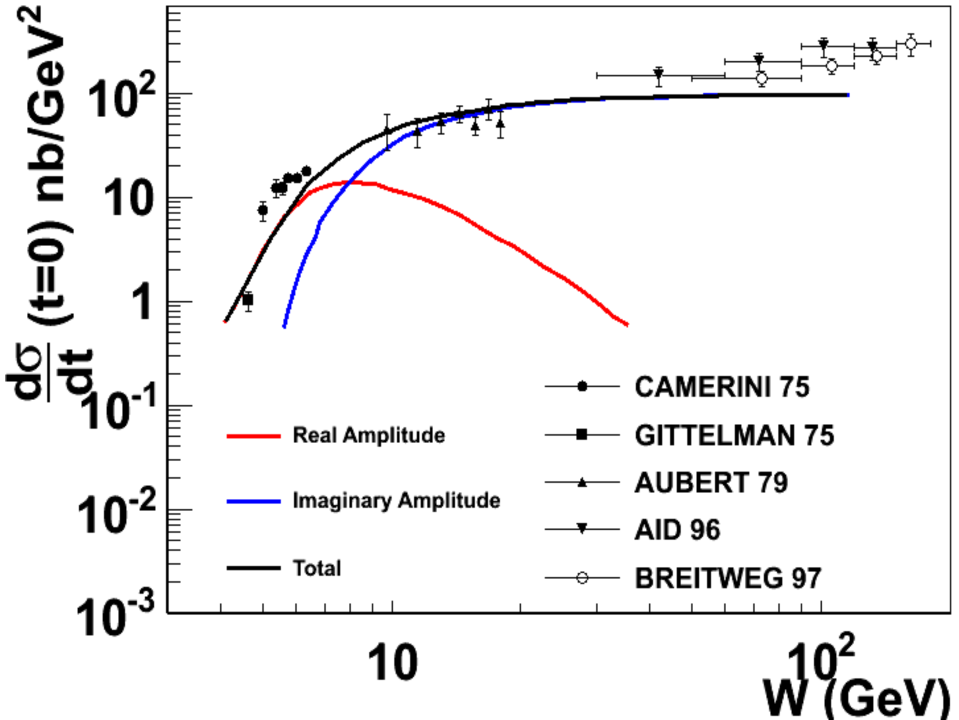
D. Kharzeev. Quarkonium interactions in QCD, 1995
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

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

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

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

A measurement near threshold could allow access to the trace anomaly



For completeness

- Y.~Hatta, A.~Rajan and D.~L.~Yang, Near threshold J/ψ and ϒ photoproduction at JLab and RHIC, Phys. Rev. D 100, no. 1, 014032 (2019) doi:10.1103/PhysRevD.100.014032

- K.~A.~Mamo and I.~Zahed, Diffractive photoproduction of J/ψ and Υ using holographic QCD: gravitational form factors and GPD of gluons in the proton,'' arXiv:1910.04707 [hep-ph].

- A.~Rajan, T.~Gorda, S.~Liuti and K.~Yagi,``Bounds on the Equation of State of Neutron Stars from High Energy Deeply Virtual Exclusive Experiments,'' arXiv:1812.01479 [hep-ph].

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

THANK YOU!