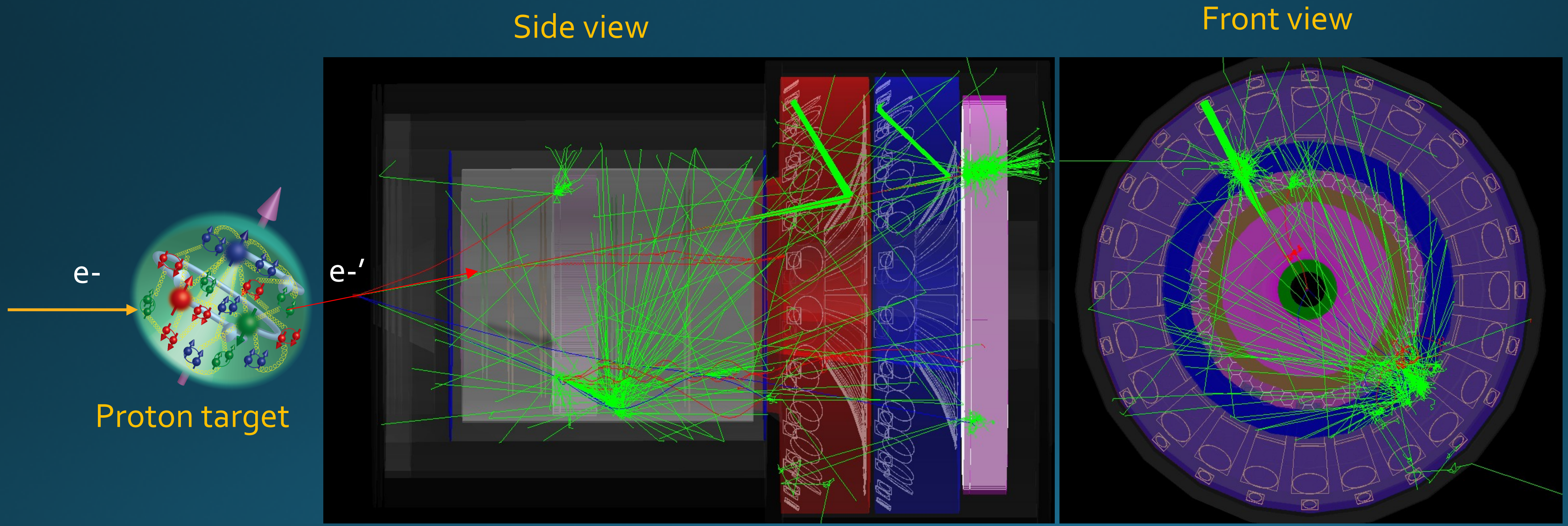
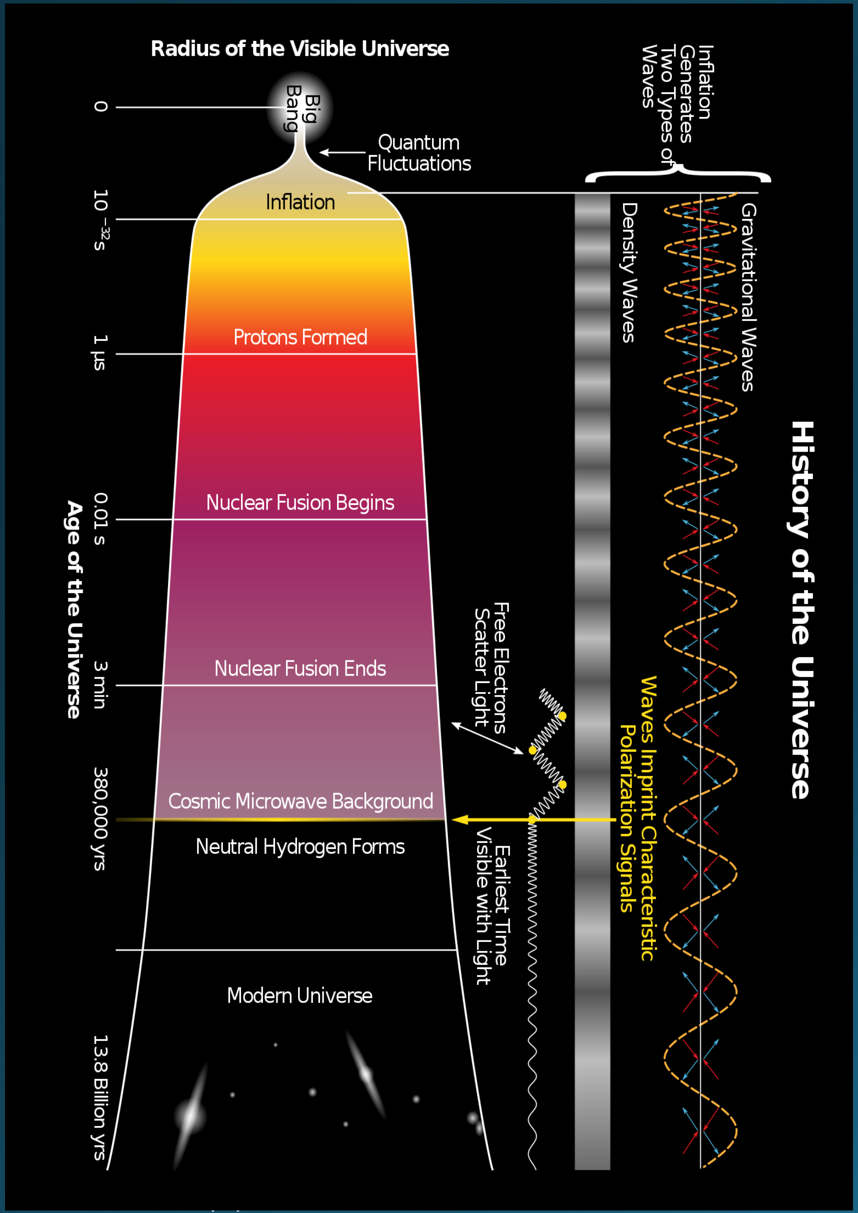
J/ψ-Nucleon Science with SoLID

Zein-Eddine Meziani
October 08-09, 2020

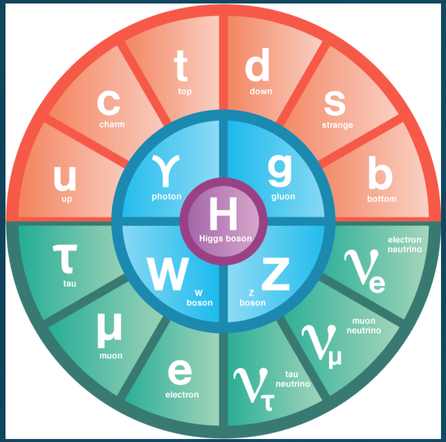


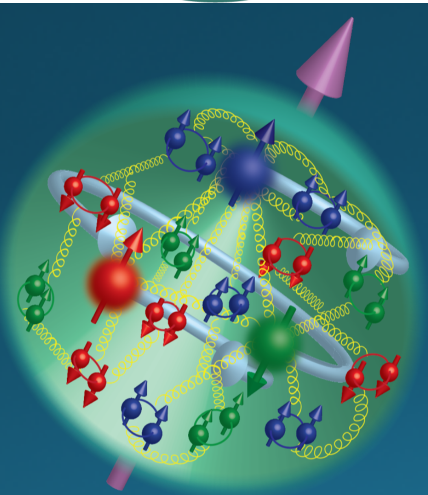
A charmonium event in SoLID

QCD in the Standard Model of Particle Physics



Standard Model of Particle Physics





Nucleon

- The Higgs mechanism is responsible for the mass of elementary particles but not of nucleons and nuclei thus the visible universe.
- Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass to nucleons and nuclei through the "trace anomaly" a consequence of scale invariance
- Gravitational form factors (GFFs) with info, on energy/mass distribution in the nucleon and nuclei can be accessed through the second Mellin moments of leading-twist GPDs.

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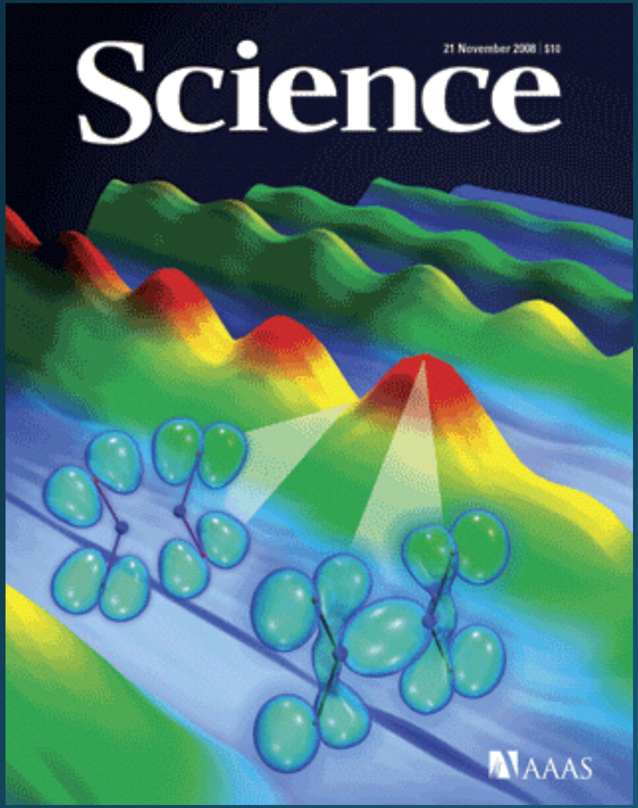
How does QCD generate the nucleon mass?

"… 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***

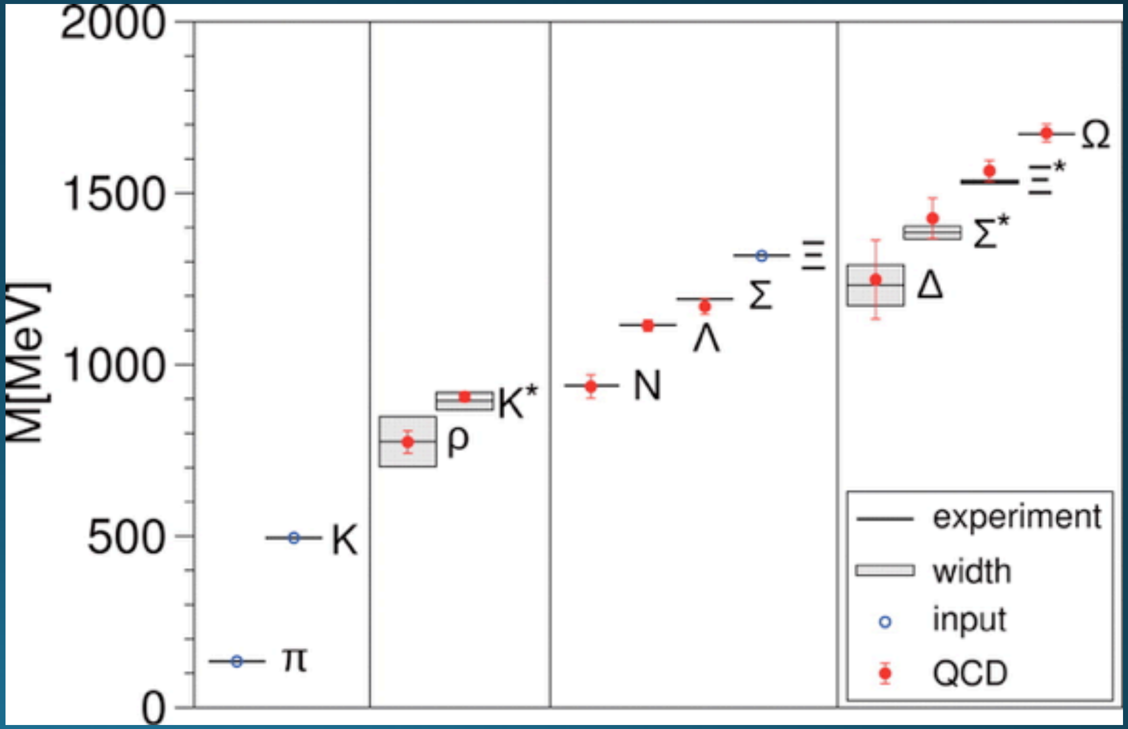
❑ Hadron mass from Lattice QCD calculation:



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

2008
Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233

568 citations



How does QCD generate this? The role of quarks and of gluons?

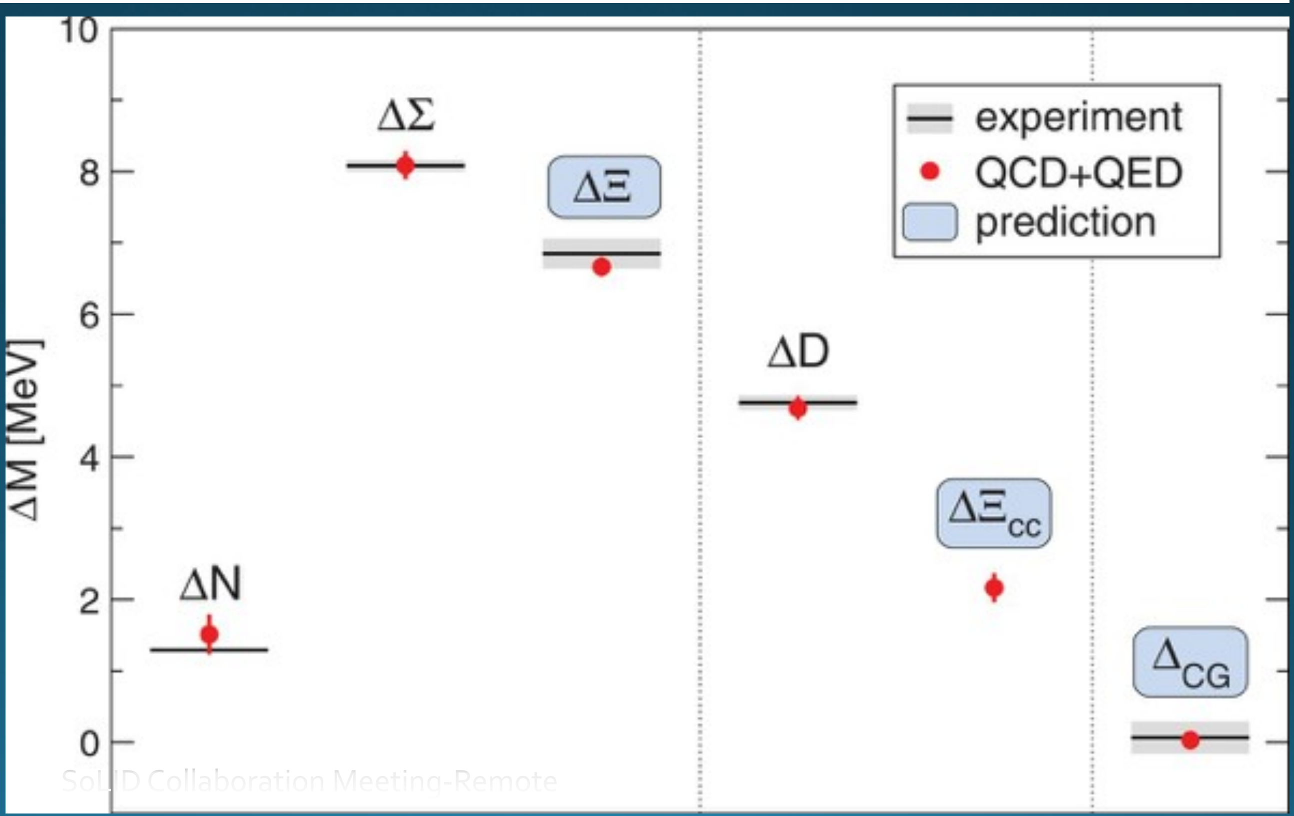
Science

2015

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo and B. C. Toth

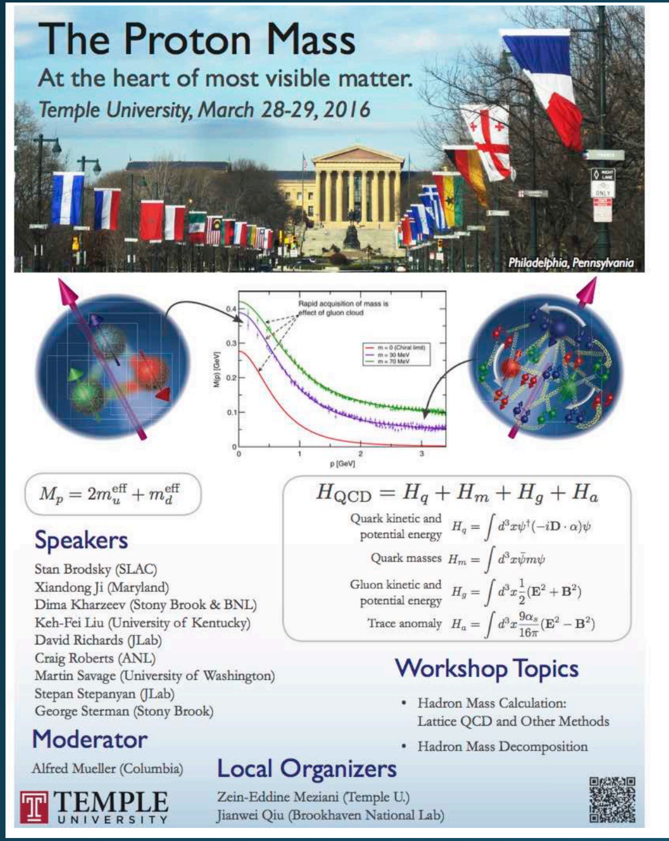
Science **347** (6229), 1452-1455.
DOI: 10.1126/science.1257050



261 Citations

The proton mass … **a hot topic!**

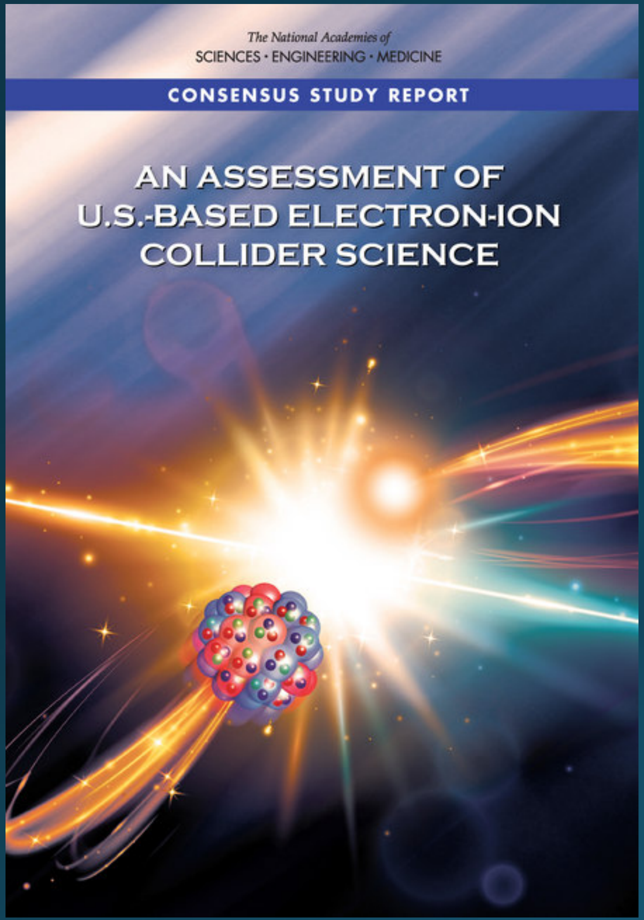
Due to COVID-19 a 2020 INT proton Mass workshop has been postponed to Dec. 2021



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

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

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 the Science Questions Enabled by J/ψ at Threshold in SoLID

- What is the origin of hadron masses?
  - A case study: the proton

- What is the size of the interaction between a quarkonium and a proton, dubbed 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 energy distribution of gluonic fields inside the proton and nuclei

Proton Mass Decomposition

What is the role the constituents

- Covariant 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/ Revisiting the Mechanical Properties of the Nucleon
  - [C. Lorce´, Eur. Phys. J. C78 (2018) 2, arXiv:1706.05853]
  - [C. Lorcé, H. Moutarde and A. Trawińsk, Eur. Phys. J C79 (2019)

Covariant decomposition

- At small momentum transfer the heavy quarks decouple

$$\sum_q m_q \bar{\psi}_q \psi_q \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\mu\nu,a} G^a_{\mu\nu} + \ldots$$

- So only light quarks enter the expression.

$$T^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\mu\nu,a} G^a_{\mu\nu} + \sum_{q=u,d,s} m_q \left(1 + \gamma_m\right) \bar{\psi}_q \psi_q$$

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

Ji's mass decomposition or Rest frame decomposition

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

$$H_{QCD} = H_q + H_m + H_g + H_a$$

$$H_q = \int d^3x \psi^\dagger \left(-i\mathbf{D} \cdot \alpha\right) \psi$$ Quarks kinetic and potential energy

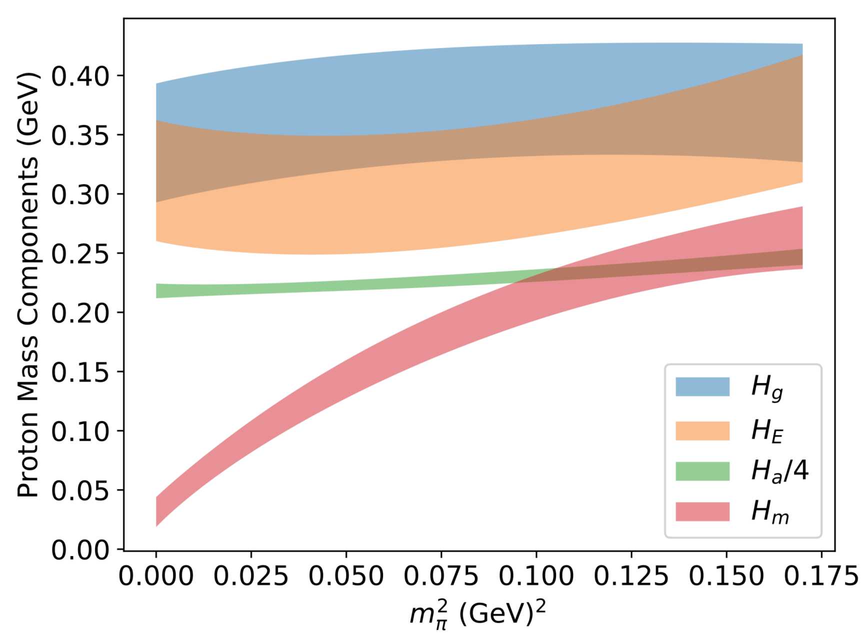
$$H_m = \int d^3x \psi^\dagger m \psi$$ Quarks masses

$$H_g = \int d^3x \frac{1}{2} \left(\mathbf{E^2} + \mathbf{B^2}\right)$$ Gluons kinetic and potential energy

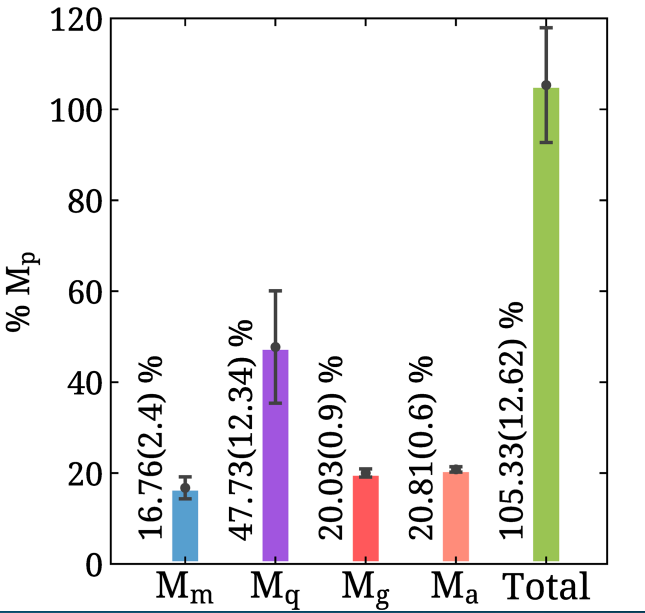
$$H_a = \int d^3x \frac{9\alpha_s}{16\pi} \left(\mathbf{E^2} - \mathbf{B^2}\right)$$ Trace anomaly

Proton mass on the lattice

No direct calculation of trace anomaly to date.



Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

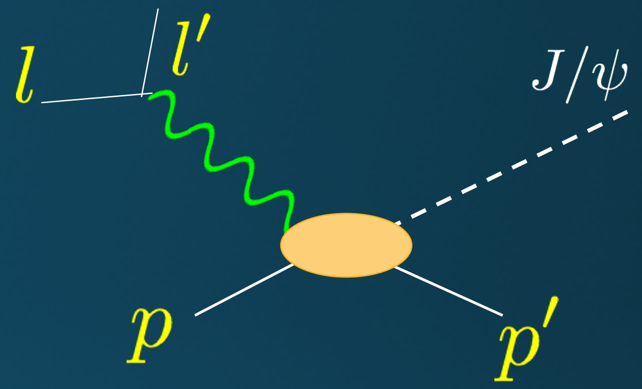


C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

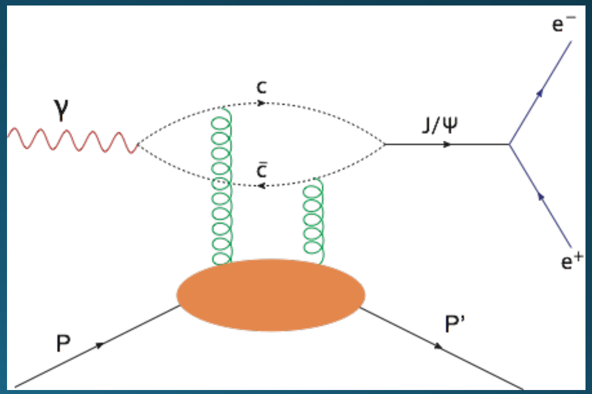
Trace anomaly only constrained through sum-rules not calculated directly.

Experimental Tools: Exclusive Production of Charmonium at JLab12 near Threshold

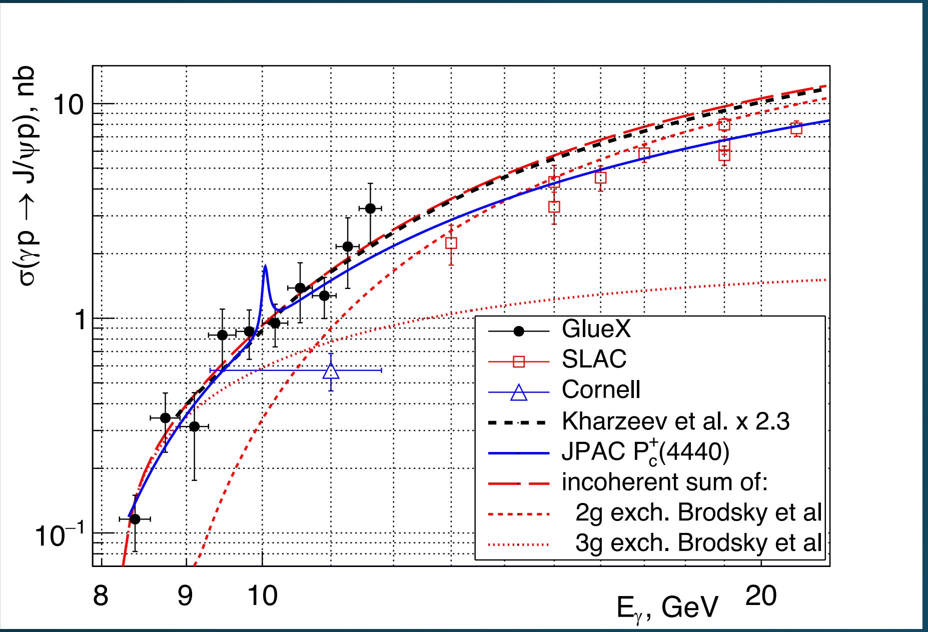
Virtual Meson Production of J/Psi (Charm) at Threshold (VMP)



- At JLab we can measure the threshold region in photo and electro-production of J/ ψ in fixed target experiments in 4 halls, however, SoLID is superior due to a combined high luminosity and large acceptance



J/ψ photoproduction cross-section near threshold-GlueX results

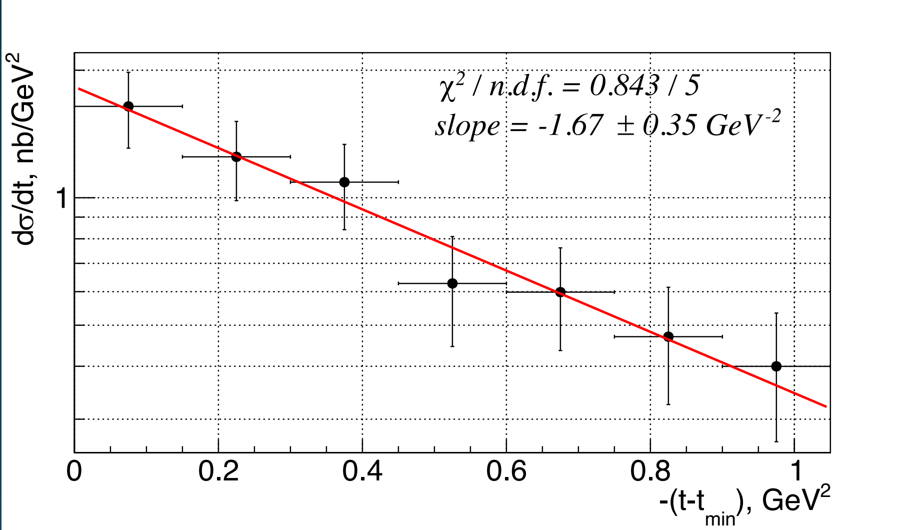


A. Ali *et al.*, Phys. Rev. Lett. 123, 072001(2019)

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



SoLID is critical to provide

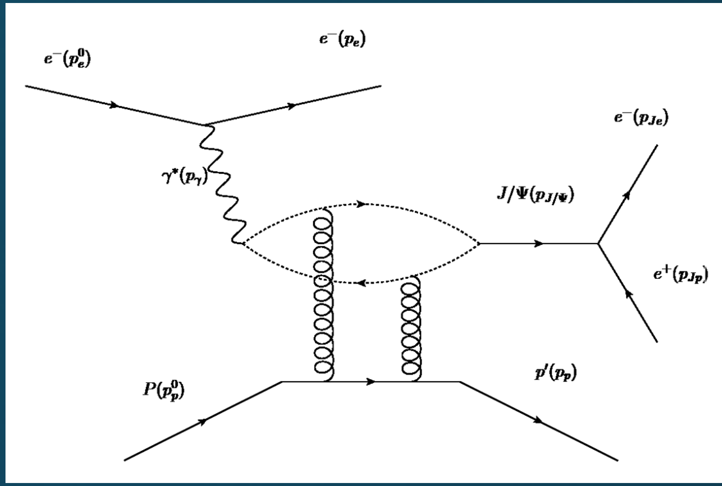
- A precise t distribution is required for each bin in photon energy
- The electroproduction is important at threshold to test the production mechanism. Close to threshold Q2

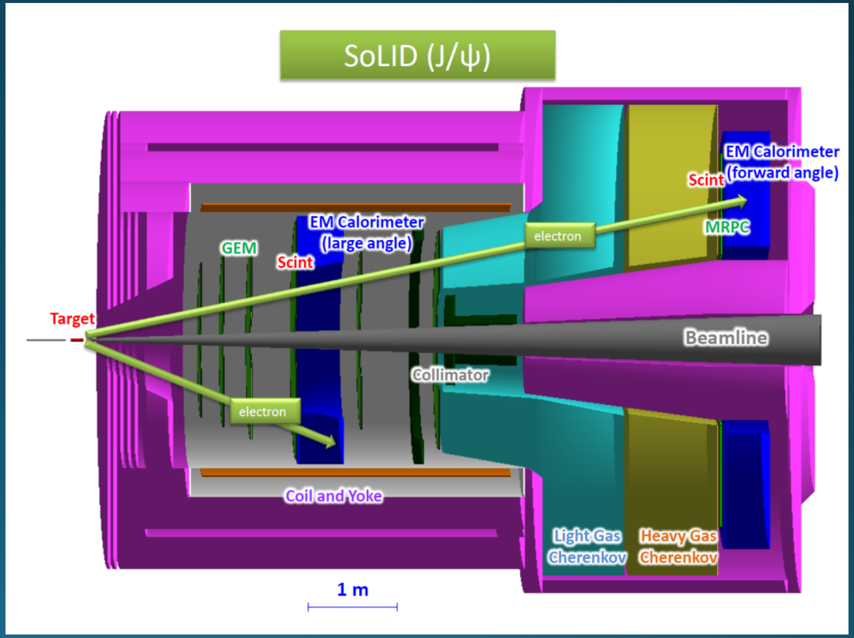
J/ψ @ SoLID

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

$e\ p \rightarrow e'\,p'\ J/\psi(e^-\ e^+)$

$\gamma\ p \rightarrow p'\ J/\psi(e^-\ e^+)$





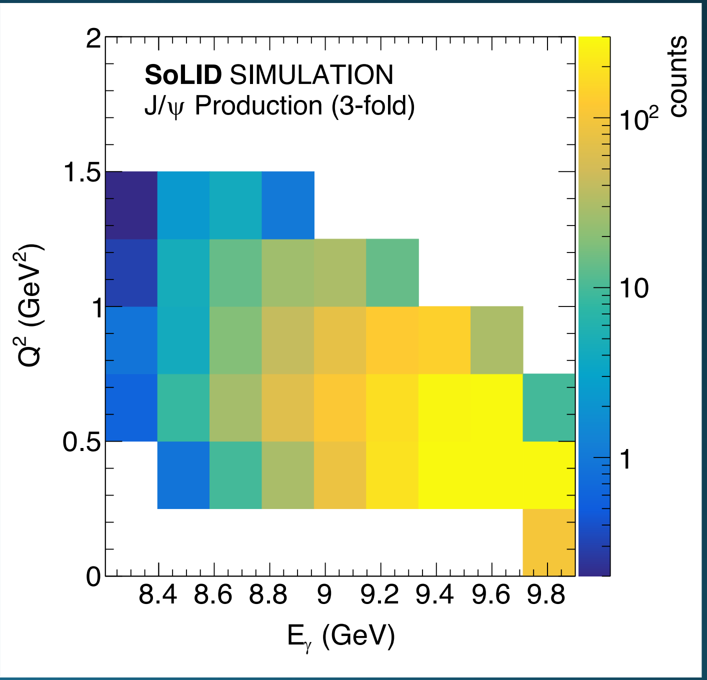
Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly

Experimental Overview

- 50 days of 3 μA beam on a 15 cm long LH_2 target at $1 \times 10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include calibration/background run
- SoLID configuartion overall compatible with SIDIS with slight changes
- Main Trigger: Triple coincidence of $e^-e^-e^+$
  - Additional trigger double coincidence (e^+e^-)

$$e^- + p \longrightarrow e^- + p + J/\psi(e^+ + e^-)$$



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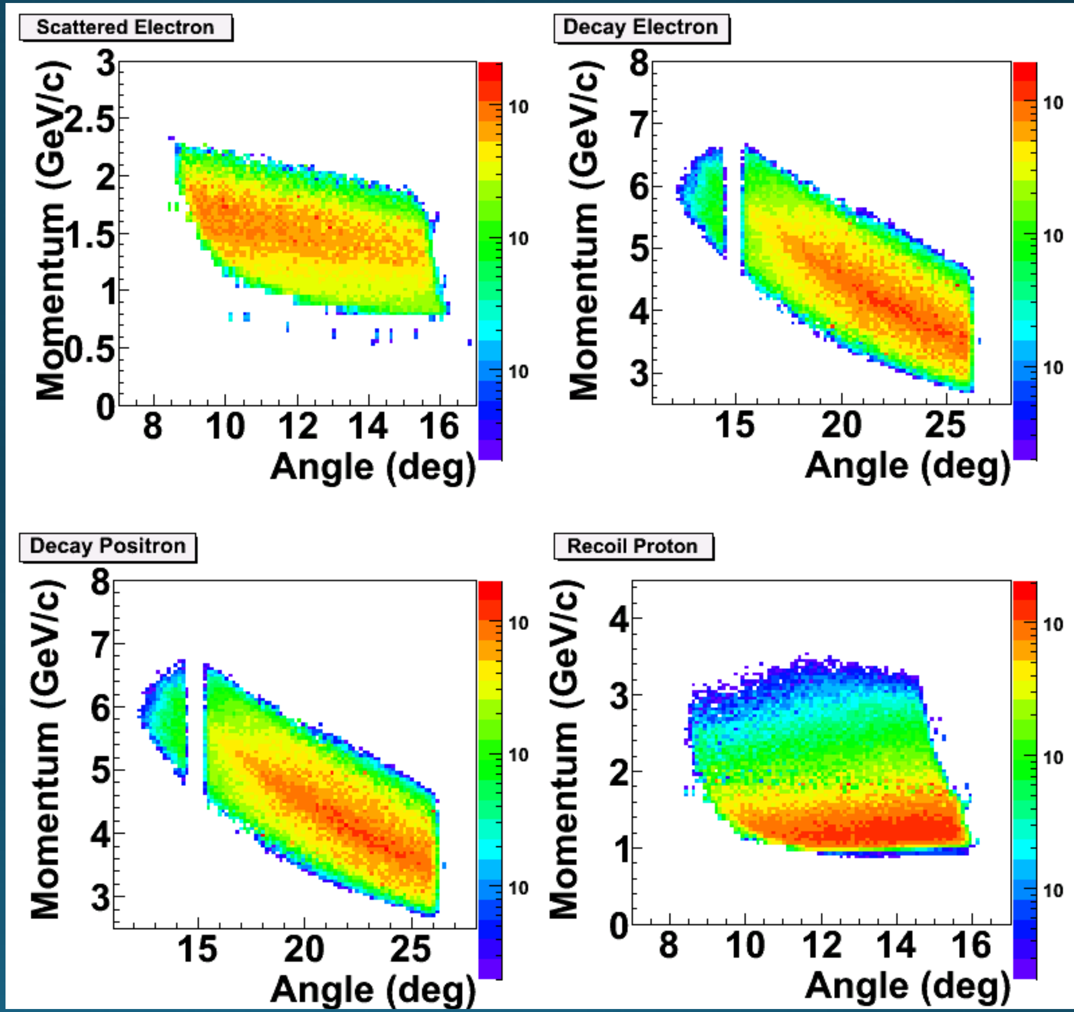
PID and Acceptance

- Scattered electron:
  - Gas Č + Calorimeter @ forward angle
- Decay electron/Positron:
  - Calorimeter only at large angle
  - Gas Č + Calorimeter at forward angle
- Recoil proton:
  - 100 ps TOF: 2 ns separation between p/K @ 2 GeV/c
  - ~ 8m flight path



Main trigger rate is below **1 kHz** with 50 ns coincidence window.
Comparing to **~50 kHz** design trigger rate for SIDIS.

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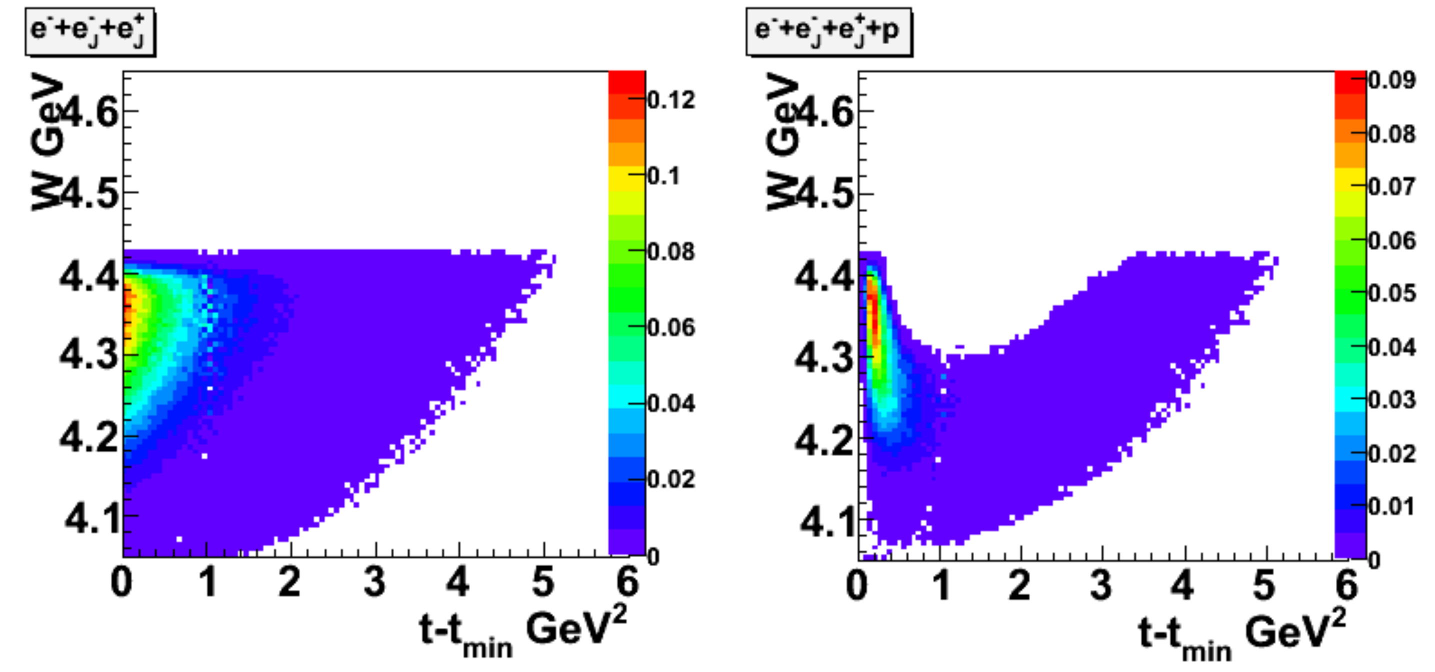
Event Counts @ 1×10^{37} in 50 days

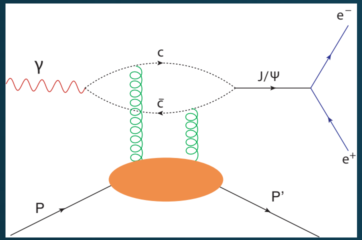
- 4-fold coincidence:
  - 2g-only: **0.68 k** events
  - 2g + 3g: **2.9 k** events
- 3-fold no proton:
  - 2g-only: **2.1 k** events
  - 2g + 3g: **8.08 k** events

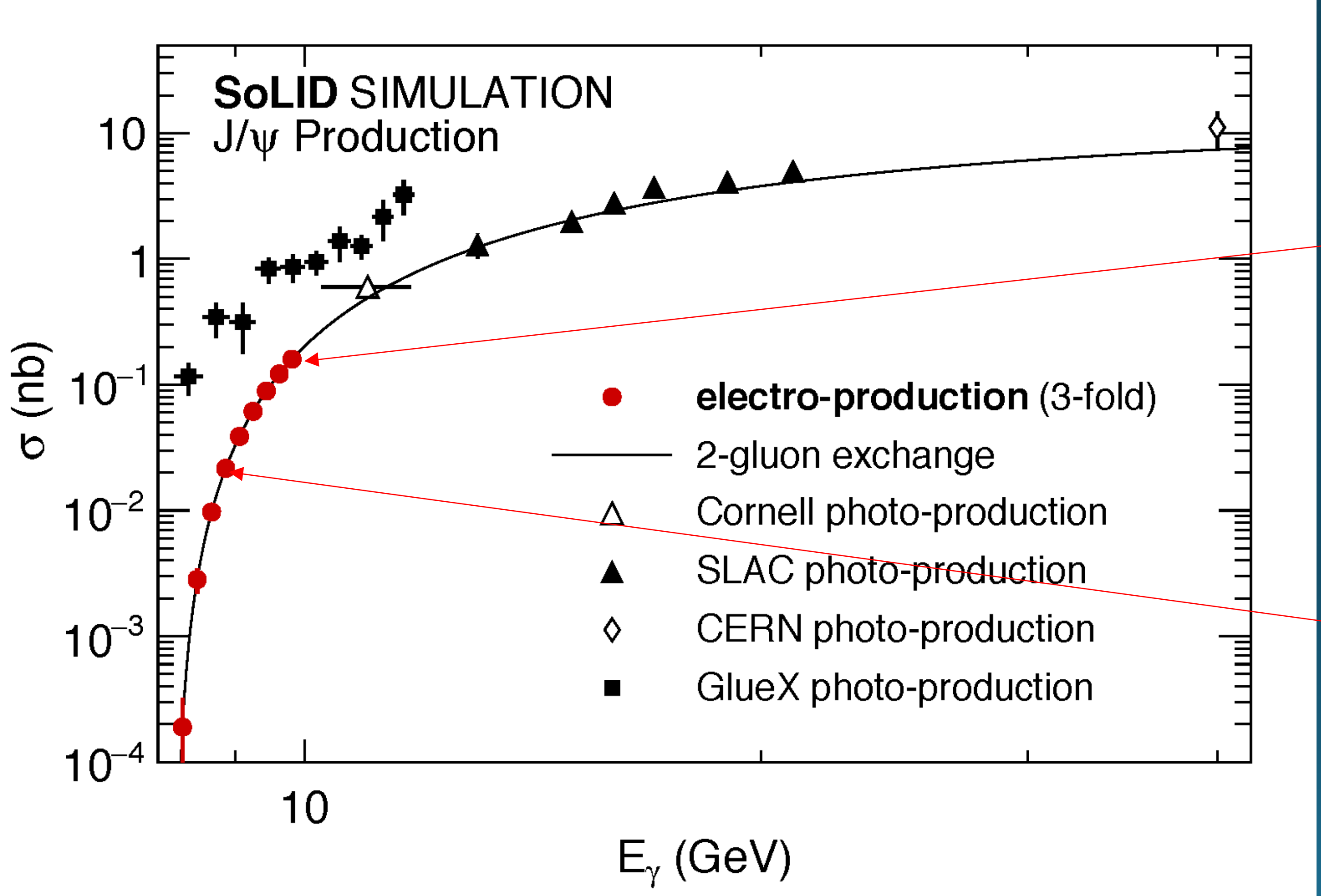
	Time (Hour)	Time (Day)
LH_2 at 11 GeV	**1200**	**50**
Dedicated Al dummy run	**72**	**3**
Optics and detector check out	**72**	**3**
Special low luminosity	**96**	**4**
Total	**1440**	**60**

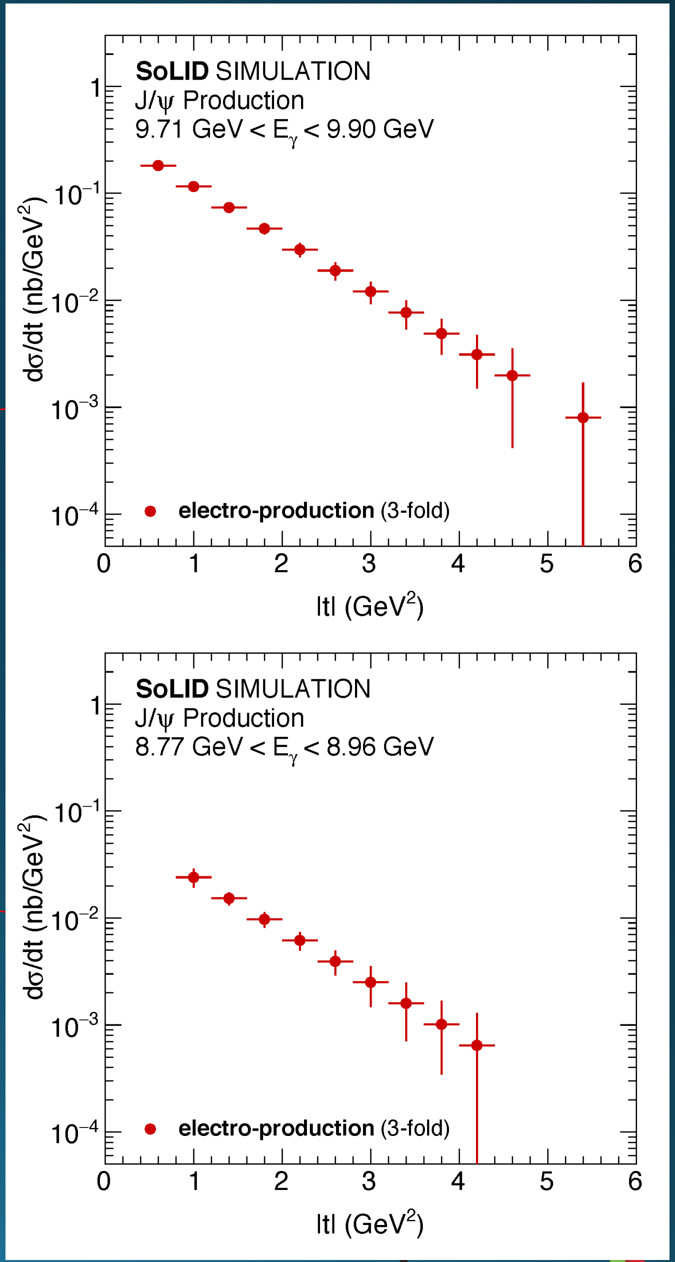


J/Psi Experiment E12-12-006 @ SoLID

S. Joosten







Sensitivity below 10^{-3} nb!

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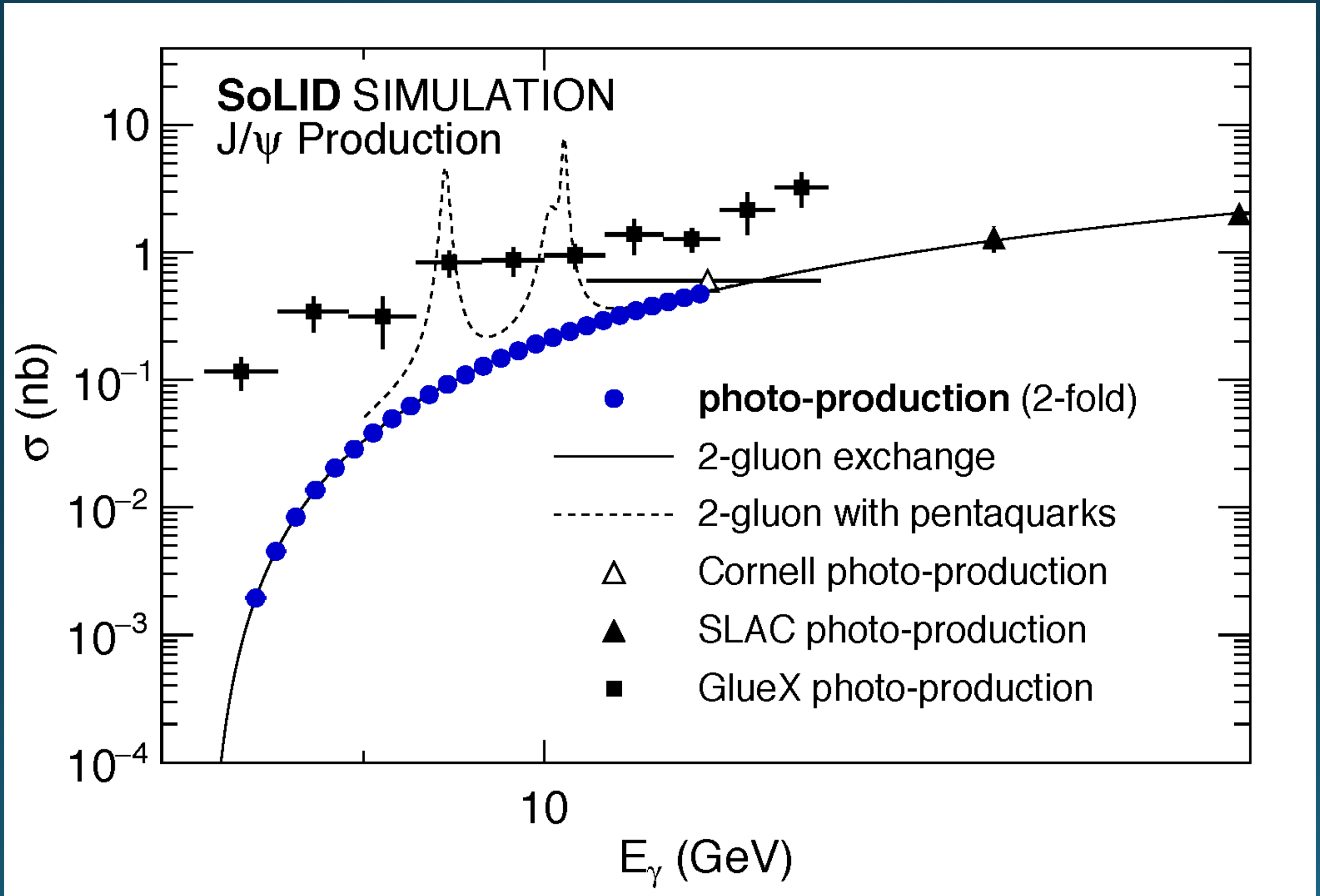
Quasi-real- & Photo-production



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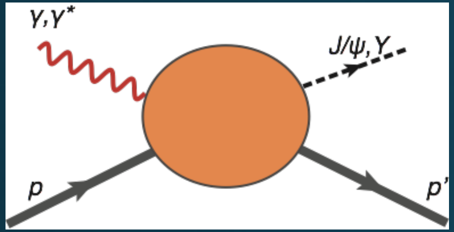
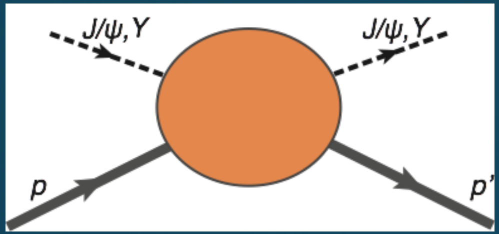
Forward J/ψ-p scattering in relation to γ -p scattering

Vector Dominance Model (VDM) Assumption



VDM



$$\frac{d\sigma}{dt}\Big|_{t=0}(\gamma p \to \psi p) = \left(\frac{ef_\psi}{M_\psi}\right)^2 \left(\frac{q\psi p}{q_{\gamma p}}\right)^2 \frac{d\sigma}{dt}\Big|_{t=0}(\psi p \to \psi p)$$

$$\sigma^{el}_{\psi p} = \left(\frac{M_\psi}{f_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to \psi p)$$

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

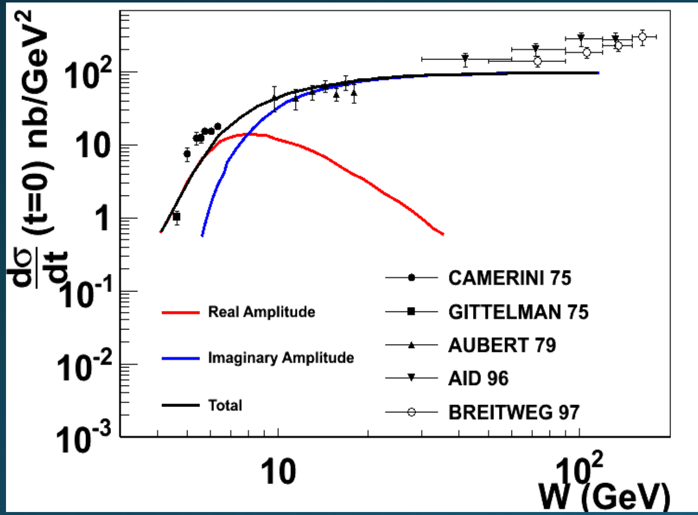
$$\sigma^{inel}_{\psi p} = \left(\frac{M_\psi}{ef_\psi}\right)^2 \left(\frac{q_{\gamma p}}{q_{\psi p}}\right)^2 \sigma(\gamma p \to c\bar{c}X)$$

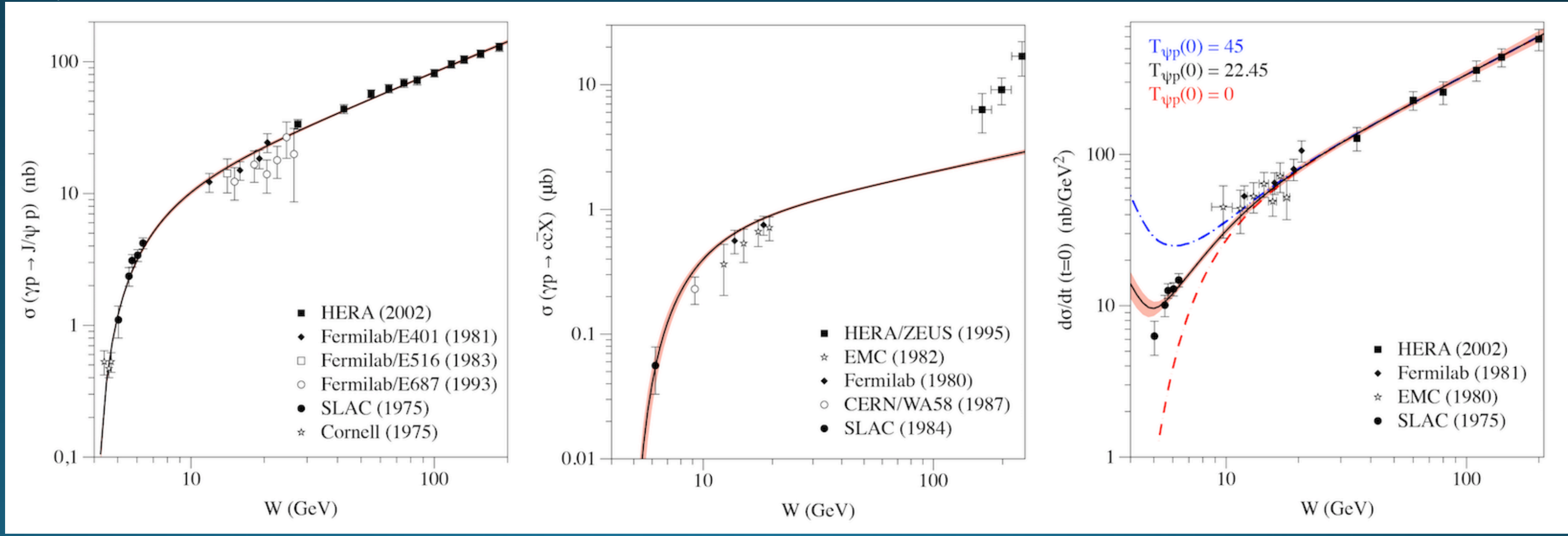
D. Kharzeev. Quarkonium interactions in QCD, 1995

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

Oleksii Gryniuk, M. Vanderhaeghen, PRD 94, 074001 (2016)

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





Simultaneous fitting $T(0) = 22.5 \pm 2.5 \Rightarrow a_{\psi p} \sim 0.05\text{fm} \Rightarrow B_\psi \sim 3\text{MeV}$

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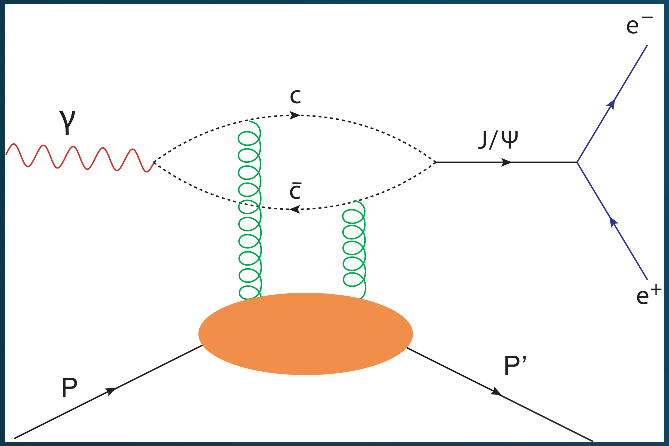
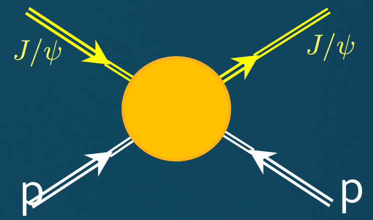
Extracting the scattering length and binding energy of the J/Psi-Nucleon interaction



Oleksii Gryniuk, M. Vanderhaeghen, PRD 94, 074001 (2016)

- Spin averaged $J/\psi - p$ scattering amplitude related to scattering length $a_{\psi p}$



$$\nu \equiv pq = \frac{s-u}{4}$$

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

- Binding is related to the scattering length for a nucleus by

$$B_{\psi p} \simeq \frac{8\pi(M + M_\psi)a_{\psi p}}{4MM_\psi}\rho_{nm}$$

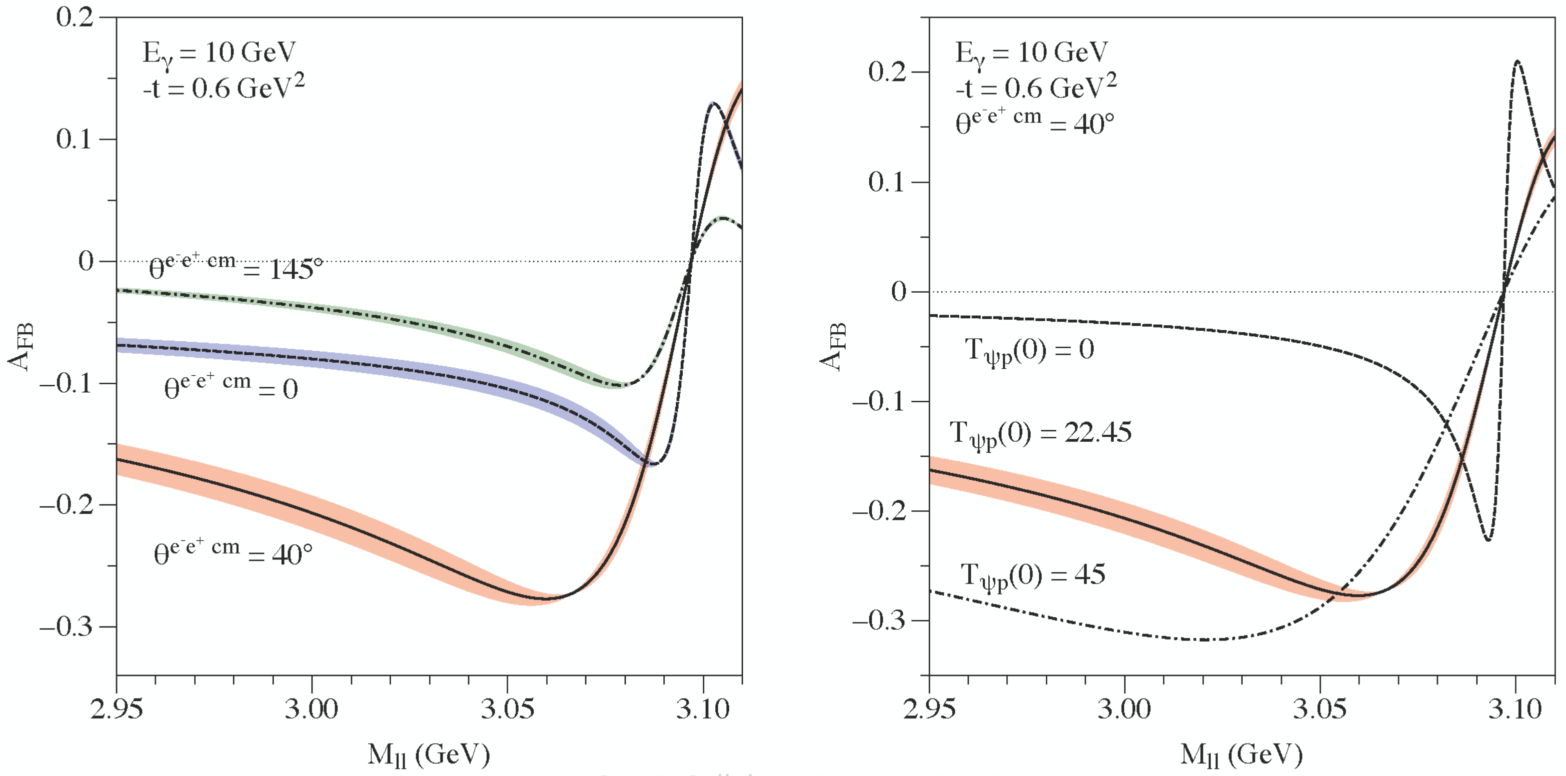
$$T(0) = 22.5 \pm 2.5 \Rightarrow \quad a_{\psi p} \sim 0.05\text{fm} \Rightarrow B_\psi \sim 3\text{MeV}$$

Asymmetry near the J/ψ peak

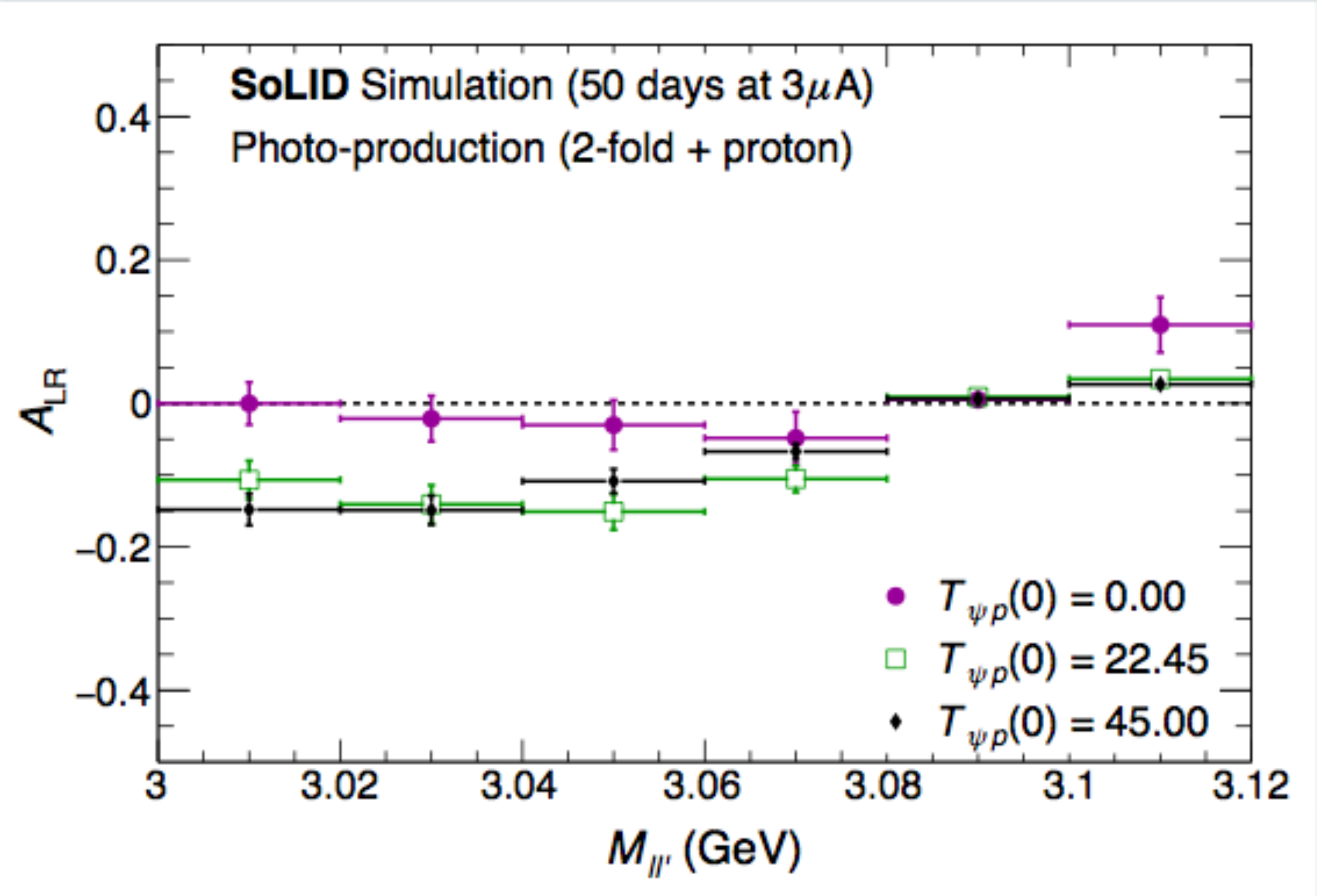
interference term

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

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



Projected Results: all together



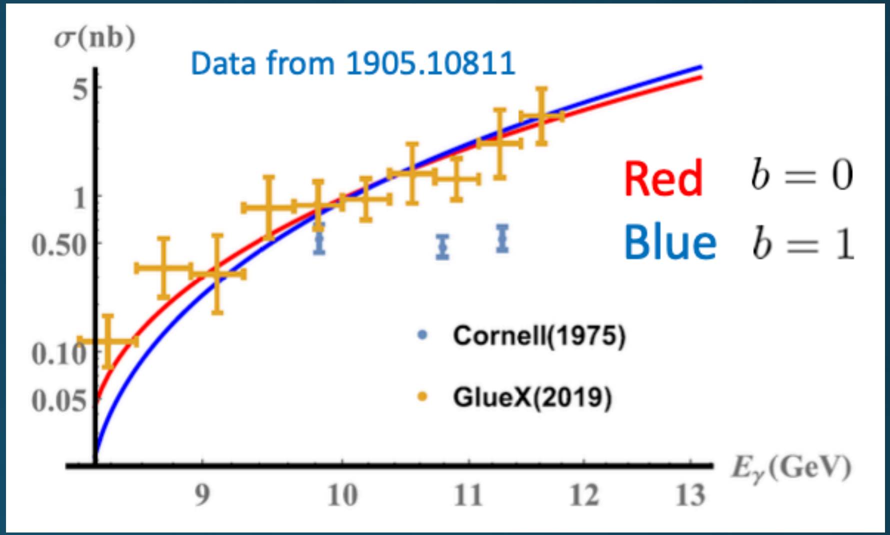
S. Joosten

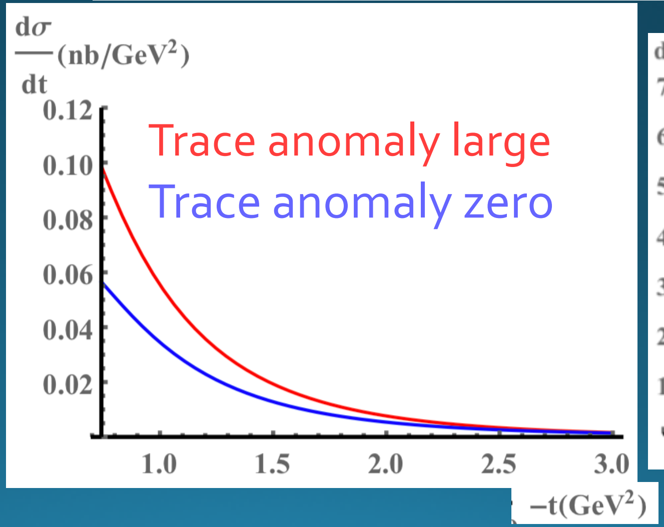
Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2019)

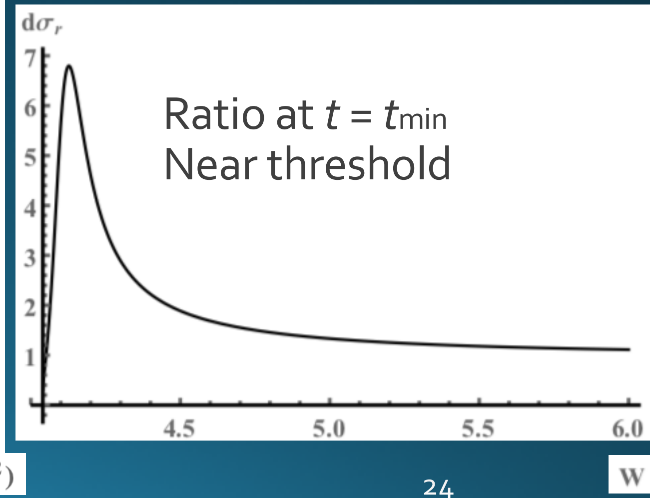
Sensitivity to Trace Anomaly near threshold?

Holographic approach (AdS/CFT)

- Perturbative approach difficult
(no factorization for twist-4 trace anomaly operator)
- Use non-perturbative method instead through AdS/CFT
(gauge-string duality: dilaton dual to $F^{\mu\nu}F_{\mu\nu}$)
- **No appropriate for high energies** (Amplitude should be imaginary in this approach it is real)
- **At low energies**: Scattering amplitudes are real as they should
- Predicts largest sensitivity to trace anomaly near threshold at low t
- New development, numerical predictions carry large model uncertainties





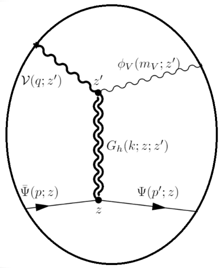


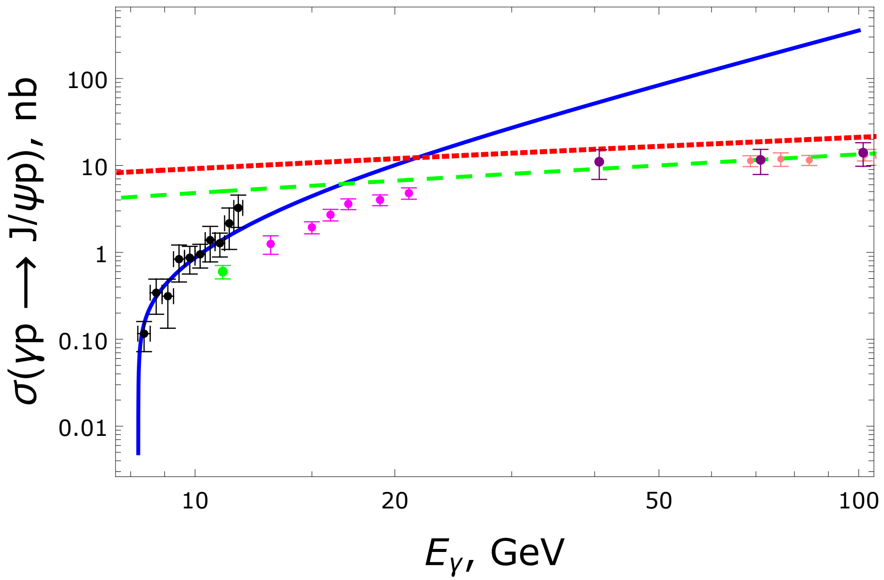
Another Holographic Approach

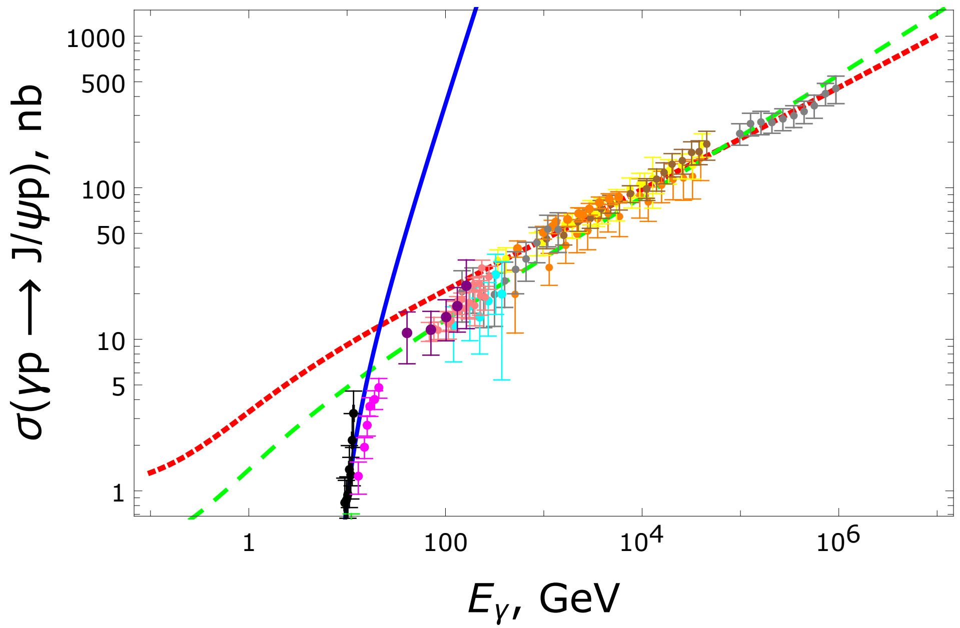
K. Mamo & I. Zahed, “Diffractive photoproduction of J/ψ and Υ using holographic QCD: Gravitational form factors and GPD of gluons in the proton” Phys. Rev. D 101, 086003 (2020)

Conclusion: We have analyzed heavy meson photoproduction for all sqrt(s), using a bottom-up approach holographic construction.

We have used the Witten diagrams in AdS_5 for diffractive photoproduction of J=ψ, shown in Fig. 2, and explicitly computed the differential cross section for the heavy meson production, first near threshold, where it is dominated by the exchange of massive 2^{++} glueballs as spin-2 gravitons in bulk, and second away from threshold, where the exchange involves a tower of spin-j states that transmute to the Pomeron.
Our construction is general, and carries readily to heavier meson production such as ϒ. We have presented direct predictions for this production near and away from threshold.







Since the Last June Collaboration Meeting

Active field

Wang, R., Chen, X. & Evslin, J. The origin of proton mass from J/Ψ photo-production data. *Eur. Phys. J. C* **80,** 507 (2020). https://doi.org/10.1140/epjc/s10052-020-8057-9

F. Zeng, X.Y. Wang, L.~Zhang, Y.P. Xie, R. Wang and X. Chen, ``Near-threshold photoproduction of J/psi in two-gluon exchange model,” arXiv:2008.13439 [hep-ph]

A.~Metz, B.~Pasquini and S.~Rodini, ``Revisiting the proton mass decomposition," arXiv:2006.11171 [hep-ph]

L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meissner, A. Nefediev and I. Strakovsky, ``Deciphering the mechanism of near-threshold J/psi photoproduction,” arXiv:2009.08345 [hep-ph]

Summary

- SoLID is crucial to acquire precision data in electroproduction and photoproduction to answer the questions
  - ✓ **What is the origin of hadron masses?**
  - ✓ What is the strength of the interaction between charmonium and a proton, dubbed color Van der Waals force?
  - ✓ Does charmonium enable pentaquarks to exist?
  - ✓ Are bound states of charmonium-nuclei possible?

- Direct lattice calculations of the two independent parts of the trace anomaly are an important step towards understanding the proton mass.

- A 3rd workshop on the proton mass will be held at the INT in Spring 2021 to continue explore the different important observables SoLID can and should cover.

- Covariant decomposition
  - Light quark mass contributions
    - π-N σ term
  - Heavy quarks mass contributions
    - Lattice QCD evaluations
  - Trace Anomaly
    - Lattice QCD evaluations
- Rest Frame Decomposition
  - Ji's decomposition
  - Lorcé's decomposition
  - Lattice QCD evaluations
- Non-Perturbative Interpretations
  - Dyson Schwinger approach
  - Holographic Approach
- Connections to experiments?
  - Threshold production of heavy quarkonia at threshold
  - Pentaquarks with ccbar and bbar
  - Quarkonium bound states in nuclei