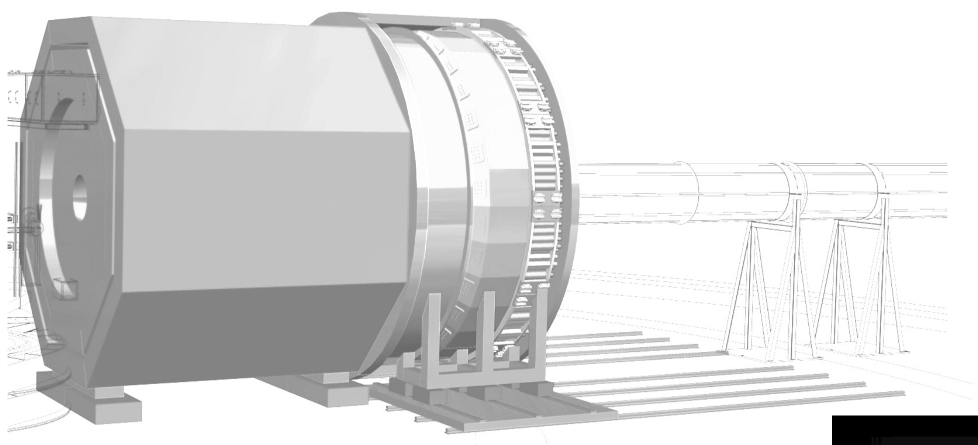
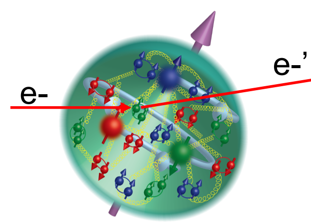
J/ψ Science Program with SoLID



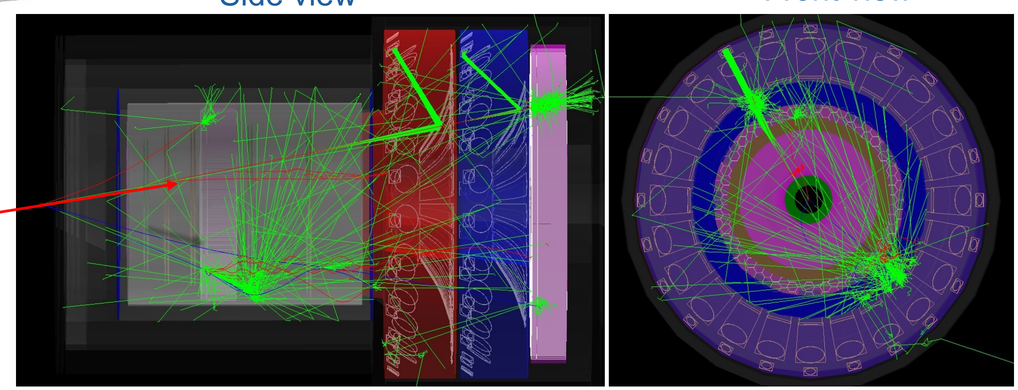
SoLID Collaboration Meeting
December 15-16, 2021

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Zein-Eddine Meziani
Argonne NATIONAL LABORATORY



Side view | Front view

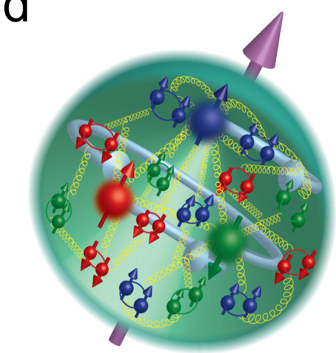


A charmonium event in SoLID

JSA | U.S. DEPARTMENT OF ENERGY | Office of Science | SoLID | Jefferson Lab

Outline

1. Science questions enabled by the J/ψ production at threshold
   - Origin of Hadron Masses
   - Charm Pentaquark Search
   - Color Vander Waals Force
2. SoLID J/ψ electro- and photo- production experiment
3. Measurements and impact on the science questions
4. Landscape of J/ψ production at JLab, BNL and Upsilon at EIC.
5. Summary



Science Questions Enabled by J/ψ at Threshold with SoLID

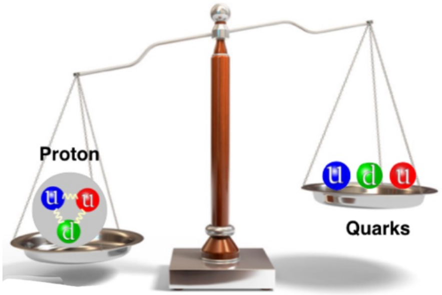
- What is the origin of hadron masses?
  - A case study: the proton.

"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass

Frank Wilczek (1999, Physics Today)

The 2015 Long Range Plan for Nuclear Science

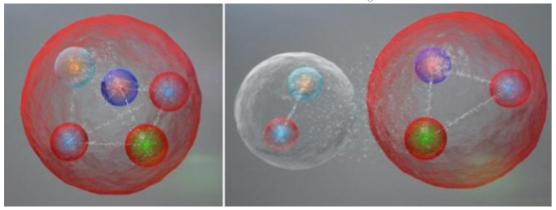
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"



- Do heavy quarkonia enable pentaquarks to exist?

- What is the size of the interaction between a quarkonium and a proton, dubbed Color Van der Waals force?

Credit: Daniel Dominguez/ CERN

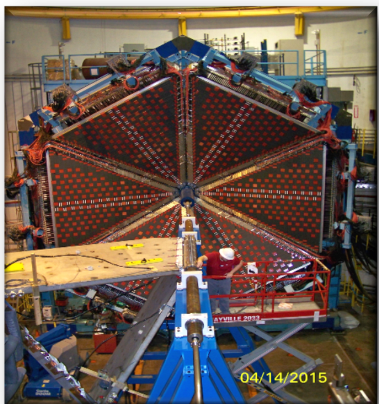


Charm pentaquark? Molecule?

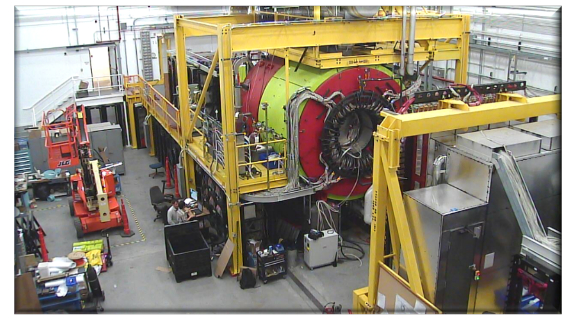
- Are bound states of quarkonia in nuclei possible?

Threshold electro- & photoproduction of quarkonium can probe the energy distribution of gluonic fields inside the proton and nuclei

12 GeV J/Ψ experiments at Jlab: Overview

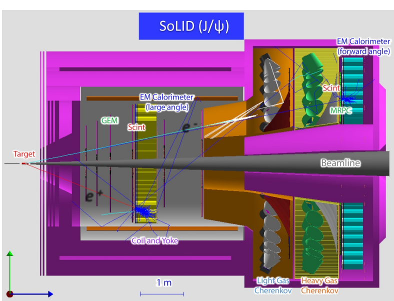


Hall D – GlueX has observed the first J/ψs at JLab A. Ali *et al.*, Phys. Rev. Lett. 123, 072001(2019)



Hall B – Has approved proposals to measure TCS + J/ψ in photo-production E12-12-001 and E12-12-001A and for deuterium in E12-11-003B. Data taken and under analysis

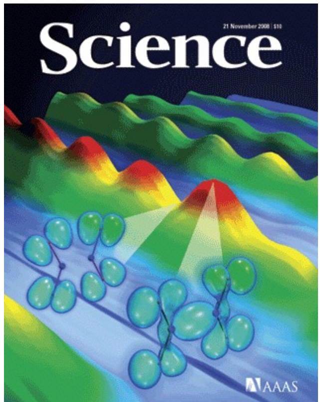
Hall C –took data to search for the LHCb pentaquark E12-16-007 –experiment completed and analysis is complete



Hall A-has an approved experiment requiring a large acceptance, high luminosity detector, namely -SoLID - E12-12-006 and 1 LOI on double polarization measurement using SBS

ORIGIN OF HADRON MASSES
FOCUS: PROTON

Hadron Masses from Lattice QCD

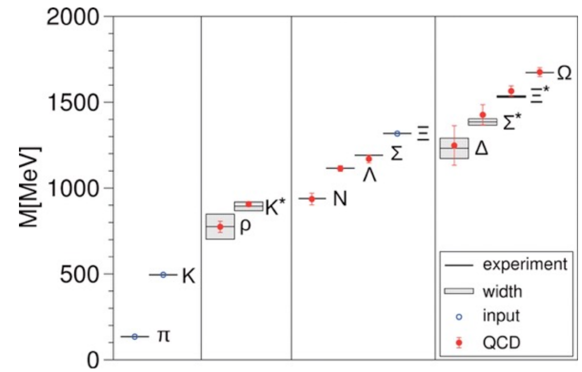


(2008)

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

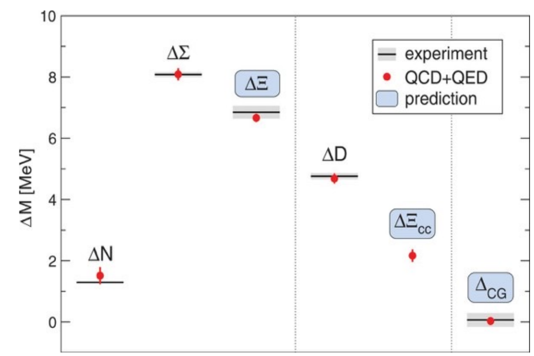
589 citations



(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



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

How does QCD generates the nucleon mass? Breaking of scale Invariance

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

$$T^\alpha_\alpha = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta}}_{\text{QCD trace anomaly}} + \sum_{l=u,d,s} m_l \bar{q}_l q_l + \sum_{c,b,t} m_h \bar{Q}_h Q_h$$

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

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

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

$$\sum_h \bar{Q}_h Q_h \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^a_{\alpha\beta} + ...$$

$$T^\alpha_\alpha = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta}}_{\text{Field energy}} + \underbrace{\sum_{l=u,d} m_l \bar{q}_l q_l + m_s \bar{q}_s q_s}_{\text{Pion-nucleon sigma term}} + ...$$

✧ **Trace anomaly, chiral symmetry breaking, …**

$$M^2 \propto \langle P | T^\alpha_\alpha | P \rangle \xrightarrow{\text{Chiral limit}} \frac{\beta(g)}{2g} \langle P | G^2 | P \rangle$$

In the chiral limit we have a finite number for the nucleon and zero for the pion 7

Higgs Mass Contribution to the proton mass

Pion-Nucleon Sigma Term

$$\sigma_{\pi N} = \langle N(P)|m_u \bar{u}u + m_d \bar{d}d|N(P)\rangle = (59.1 \pm 3.5)\ \mathrm{MeV}$$

Strangeness content

$$\sigma_s = \langle N(P)|m_u \bar{s}s|N(P)\rangle = 41.0(8.4)\ \mathrm{MeV}$$

A talk by Ulf-G Meißner at the 3rd Proton Mass WorkshopS, Jan 14-2021

https://indico.phy.anl.gov/event/2/

Consequence for the proton mass: About 100 MeV from the Higgs, the rest is gluon field energy

Hoferichter, Ruiz de Elvira, Kubis, Ulf-GMeißner Phys. Rev. Lett. 115 (2015) 092301 [arXiv:1506.04142]
Phys. Rev. Lett. 115 (2015) 192301 [arXiv:1507.07552] Phys. Rept. 625 (2016) 1 [arXiv:1507.07552]

Ji's Nucleon Mass Decomposition: A Hamiltonian Approach

Quarks, anti-Quarks , Gluons and Trace Anomaly in the nucleon rest frame

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

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

$$M_N = \frac{\langle P|H_{QCD}|P\rangle}{\langle P|P\rangle}$$

$$H_q = \int d^3x \; \psi^\dagger \left(-iD \cdot \alpha\right) \psi$$

Quarks & anti-quarks kinetic and potential energy

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

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

Quarks masses

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

$$H_g = \int d^3x \; \frac{1}{2}\left(E^2 + B^2\right)$$

Gluons kinetic and potential energy

$$M_g = \frac{3}{4}\left(1-a\right) M_N$$

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

Trace anomaly

$$M_a = \frac{1}{4}\left(1-b\right) M_N$$

$$M_N = M_q + M_m + M_g + M_a$$

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

An ongoing debate: Anomalous Quantum Energy or Not

- C. Lorcé, H. Moutarde and A. P. Trawinski, ``Revisiting the mechanical properties of the nucleon,'' Eur. Phys. J. C 79 (2019) no.1, 89, arXiv:1810.09837 [hep-ph]
- A. Metz, B. Pasquini and S. Rodini, ``Revisiting the proton mass decomposition,'' Phys. Rev. D 102, 114042 (2020) arXiv:2006.11171 [hep-ph]
- C. Lorcé, A. Metz, B. Pasquini and S. Rodini, %``Energy-momentum tensor in QCD: nucleon mass decomposition and mechanical equilibrium,'' JHEP 11 (2021), 121, arXiv:2109.11785 [hep-ph]

These references claim you do not need M_a = ¼ M in their mass decomposition. Depend on renormalization scheme.

Mathematically both are right but:

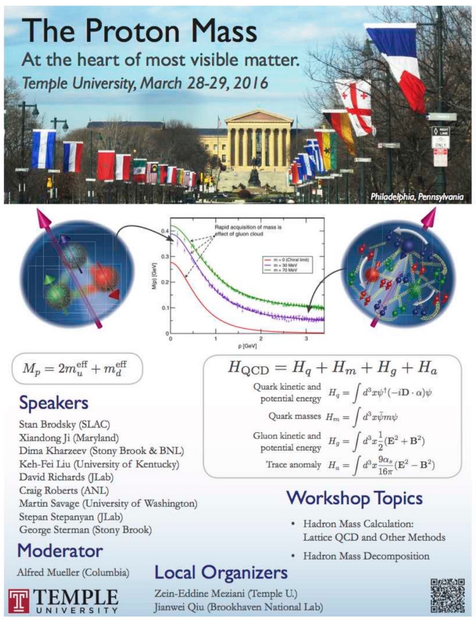
From an experimental viewpoint the question is: Can we connect all the terms in a given mass decomposition to a measurement?

it appears that Ma must be there is we want to extract the quark and gluon kinetic and potential energy from DIS.

The proton mass… a hot topic!

A precursor workshop before PR12-12-006 proposal was submitted was held in 2012: http://quarks.temple.edu/~npcfiqcd

2016



2017

Jan. 2021

Credit: Z.-E Meziani

https://indico.phy.anl.gov/event/2/

Due to COVID-19 a 2020 INT proton mass workshop has been postponed to June 2022 to become the 4th workshop in the series

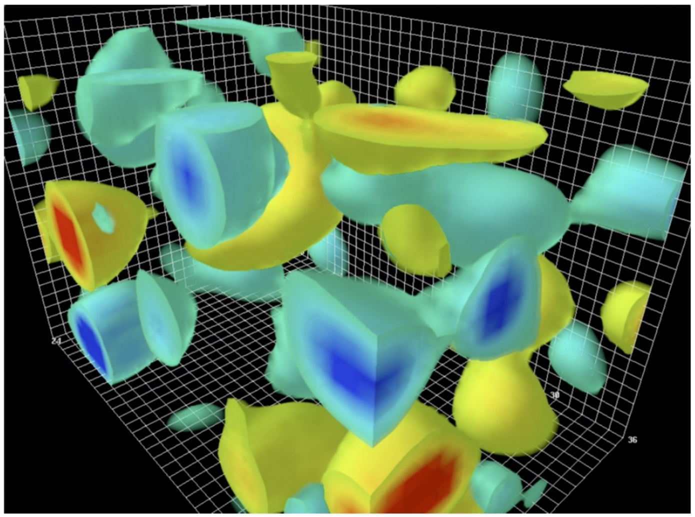
- lattice QCD
- mass decomposition – roles of the constituents
- approximated analytical or model approaches

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

A holographic Approach to the Origin of the Nucleon Mass

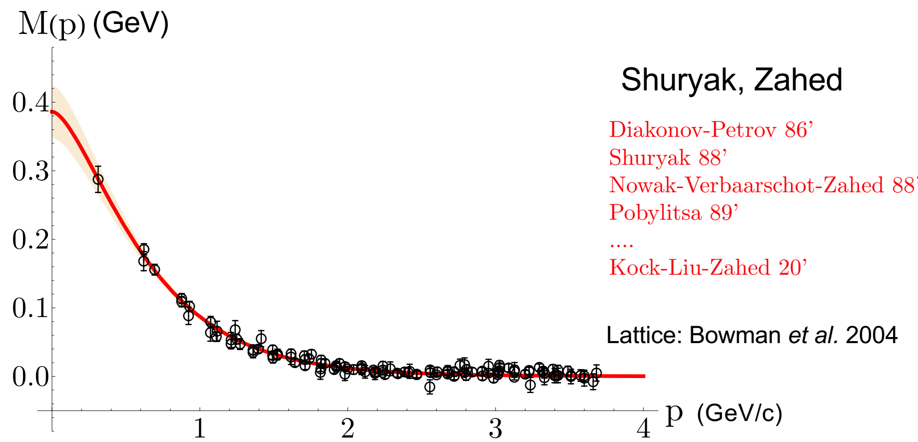
- Holography provides a string-based approach dual to Yang-Mills (YM)

Instantons (yellow) and anti-instantons (blue)



Leinweber et al. 2003
Cooled Yang Mills vacuum filled with topological gauge fields

Vacuum: a liquid on instantons
Gluon condensate in the nucleon is linked to the QCD vacuum compressibility which measures the diluteness of the QCD instanton vacuum as a topological liquid.



Momentum dependence of the instanton induced effective quark mass in singular gauge at LO compared to the effective quark mass measured on the lattice in Coulomb gauge. M(0)=383±39 MeV

- Topological origin of mass
  - Vacuum conformal symmetry breaking by density of instantons and the rate of vacuum tunneling
  - Spontaneous chiral symmetry breaking follows simultaneously from the delocalization of the light quarks zero modes!

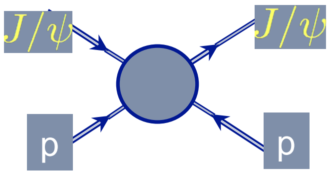
Active field of research

- L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meissner, ``Deciphering the mechanism of near-threshold J/psi photoproduction,'' *Eur. Phys. J. C* **80***, no.11, 1053 (2020),* arXiv:2009.08345 [hep-ph]
- R. Boussarie and Y. Hatta, ``QCD analysis of near-threshold quarkonium leptoproduction at large photon virtualities,'' Phys. Rev. D **101** (2020) no.11, 114004, arXiv:2004.12715 [hep-ph].
- X. Ji, Y. Liu and I. Zahed, ``Mass structure of hadrons and light-front sum rules in t' Hooft model,'' arXiv:2010.06665 [hep-ph] *Phys.Rev.D* 103 (2021) 7, 074002
- X. Ji and Y. Liu, ``Quantum anomalous energy effects on the nucleon mass,'' arXiv:2101.04483 [hep-ph] *Sci.China Phys.Mech.Astron.* 64 (2021) 8, 281012
- D. E. Kharzeev, ``The mass radius of the proton,'' arXiv:2102.00110 [hep-ph] *Phys.Rev.D* 104 (2021) 5, 054015
- I. Zahed, ``Mass sum rule of hadrons in the QCD instanton vacuum,'' arXiv:2102.08191[hep-ph] *Phys.Rev.D* 104 (2021) 5, 054031
- Fangcheng He, Peng Sun and Yi-Bo Yang, [χQCD Collaboration] ``A demonstration of hadron mass origin from QCD trace anomaly,'' [arXiv:2101.04942 [hep-lat] *Phys.Rev.D* 104 (2021) 7, 074507
- R. Wang, W. Kou and X. Chen, ``Extraction of the proton mass radius from the vector meson photoproductions near thresholds,'' arXiv:2102.01610 [hep-ph] *Phys.Rev.D* 103 (2021) 9, L091501
- Y. Guo, X. Ji and Y. Liu, ``QCD Analysis of Near-Threshold Photon-Proton Production of Heavy Quarkonium, arXiv:2103.11506 [hep-ph]. '' Phys. Rev. D 103 (2021) 9, 096010

Photoproduction a path towards the trace anomaly

- To determine *b* we need the *t* distribution of SoLID at a given photon beam energy.

D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, **1999**



$$\left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0} = \frac{\alpha_{em} m_{J/\psi}}{3\Gamma(J/\psi\to e^+e^-)}\left(\frac{k_{\gamma N}}{k_{J/\psi N}}\right)^2 \left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=0}$$

Photoproduction cross section at *t=0* linked to the forward elastic scattering amplitude of J/psi-N through VMD

$$\left|F_{J/\Psi N}\right| = \left[64\pi [m^2_{J/\psi}(\lambda^2 - m_N^2)] \left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0}\right]^{1/2}$$

$$\lambda = (p_N p_{J/\psi}/m_{J/\psi})$$

Nucleon energy in the charmonium rest frame

$$\left|F_{J/\Psi N}\right| \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b) = r_0^3 d_2 \frac{16\pi^2}{27} M_N M_a$$

$$r_0 = \left(\frac{4}{3\alpha_s(\mu^2)}\right)\frac{1}{m_c(\mu^2)}$$

Bohr radius of charmonium

$$d_2^{(1S)} = \left(\frac{32}{N_c}\right)^2 \sqrt{\pi}\,\frac{\Gamma(n+5/2)}{\Gamma(n+5)}$$

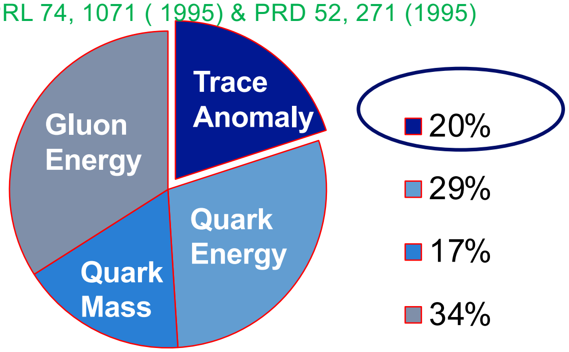
Wilson coefficient

Rydberg energy squared = μ^2

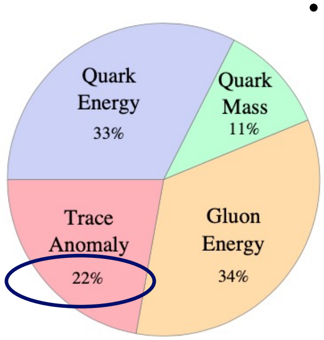
Trace Anomaly Inferences from Data

- In Ji's original work μ =1 GeV

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



- Anomaly contribution inferred
  - Deep Inelastic Scattering (DIS)
  - Pi-Nucleon Sigma term
  - Up, down and strange quark contributions

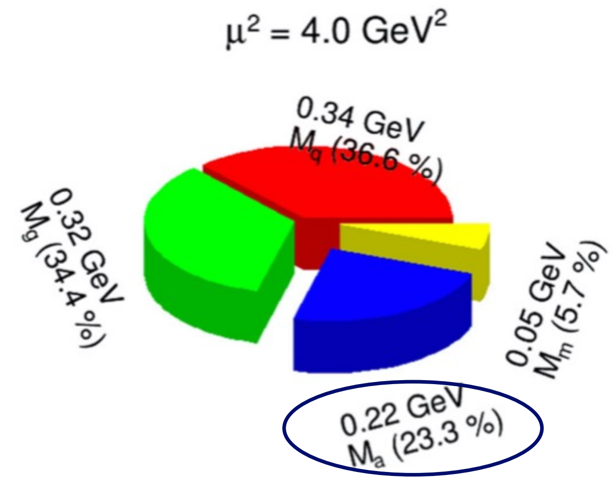


- An updated data analysis due to an update o the pion-nucleon sigma term and the strange quark contribution at μ = 2 GeV

H. Gao, T. Liu, C. Peng, Z. Ye and Z. Zhao, The Universe Vol. 3, No. 2, 18 (2015)

- A recent update using threshold J/psi data from GlueX at Jefferson Lab

R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)



Wang et al. :

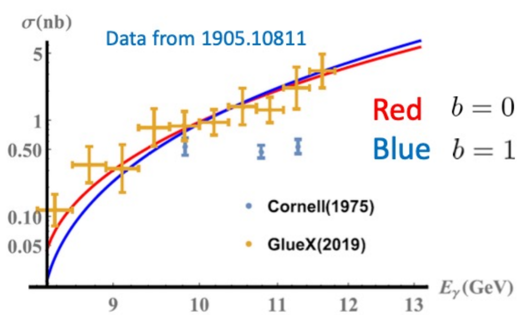
$$M_a = 23.3\% \pm 4.25\%$$

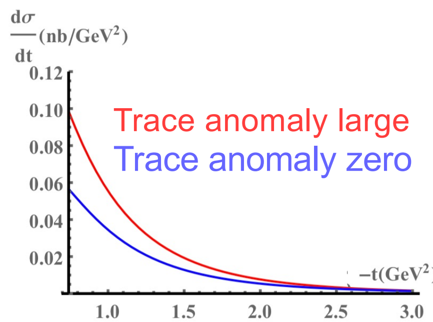
SoLID J/psi:

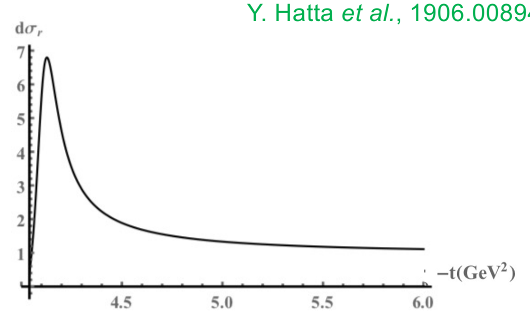
$$M_a = 23.3\% \pm 0.02\%(stat.) + 0.5\%(sys.)$$

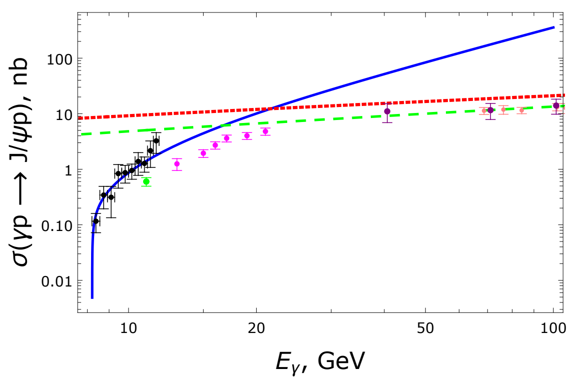
Holographic approaches; AdS/CFT

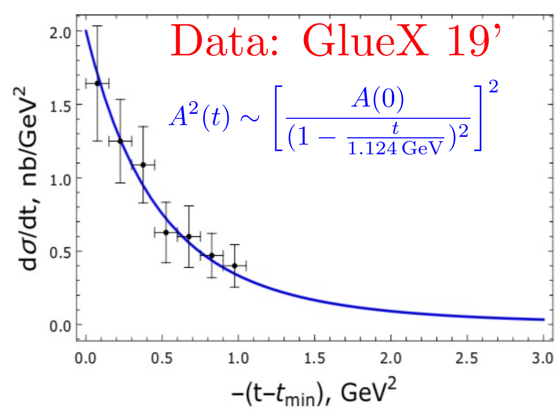
Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2019)

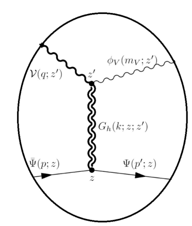






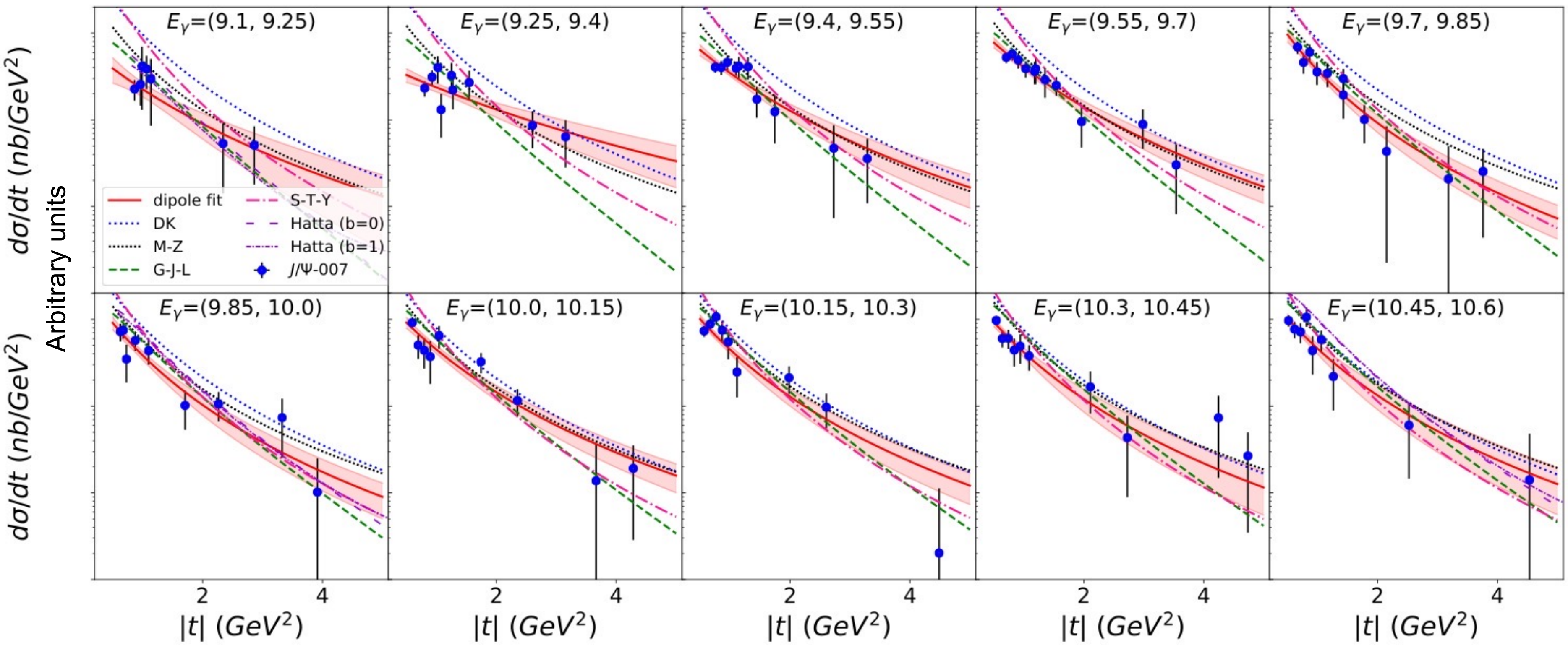






K. Mamo & I. Zahed Phys. Rev. D 101, 086003 (2020)

Hall C J/psi-007 differential cross sections

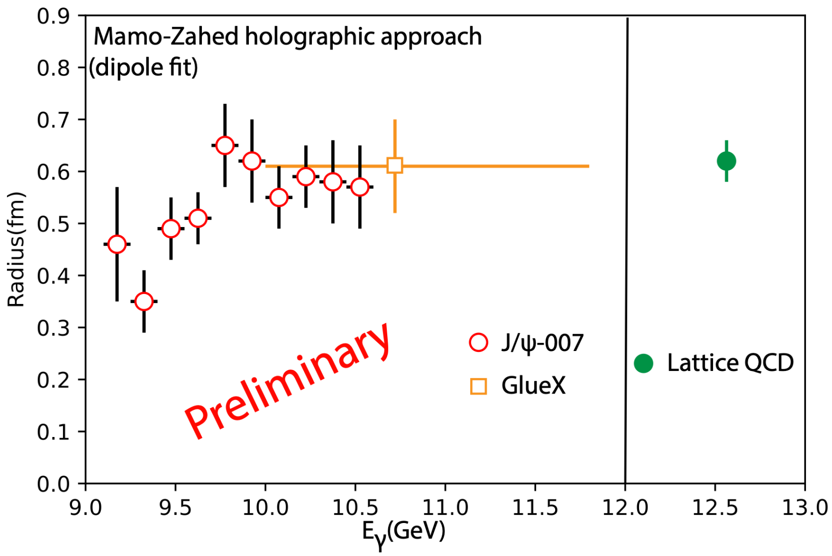


An energy scan of the gluon radius

007 J/ψ

NEW

First ever access of the energy dependence of the gluon radius in two models

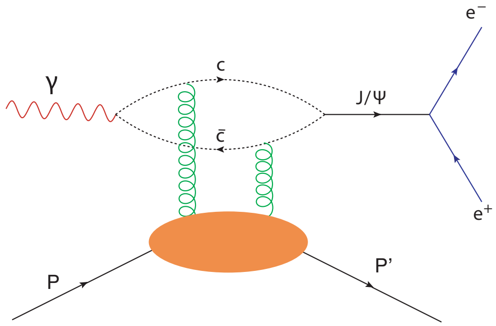


- Mass radii can be extracted for each of the 10 energy bins by means of a dipole fit
- Figure shows results following the approach from Mamo-Zahed (Phys. Rev. D 101, 086003, 2020).
- Similar results are obtained following D. Kharzeev's approach (Phys. Rev. D 104, 054015, 2021)
- Data can also be used to constrain the gravitational form factors falling the approach from Guo-Ji-Liu (Phys. Rev. D 103, 096010, 2021)
- The results can also be used to study the energy-momentum tensor of QCD following the approach from Hatta-Rajan-Yang (Phys. Rev. D 100, 014032, 2019)
- Lattice from Shanahan & Detmold (*Phys.Rev.D* 99 (2019) 1, 014511)

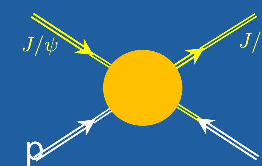
COLOR VAN-DER WAALS FORCE (SCATTERING LENGTH)

Extracting the scattering length 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

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

- Unitarity lead to:

$$\mathrm{Im}T_{\psi p}(\nu) = 2\sqrt{s}q_{\psi p}\sigma^{tot}_{\psi p}(\nu)$$

- Causality and crossing lead to the dispersion relation:

$$\mathrm{Re}T_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{el}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\mathrm{Im}T_{\psi p(\nu')}}{\nu'^2 - \nu^2}$$

Cross section is parametrized

$$\sigma^{tot}_{\psi p} = \sigma^{el}_{\psi p} + \sigma^{inel}_{\psi p}$$

$$\sigma^{el}_{\psi p} \propto C_{el}\left(1 - \frac{\nu_{el}}{\nu}\right)^{b_{el}}\left(\frac{\nu_{el}}{\nu}\right)^{a_{el}}$$

$$\sigma^{inel}_{\psi p} \propto C_{in}\left(1 - \frac{\nu_{in}}{\nu}\right)^{b_{in}}\left(\frac{\nu_{in}}{\nu}\right)^{a_{in}}$$

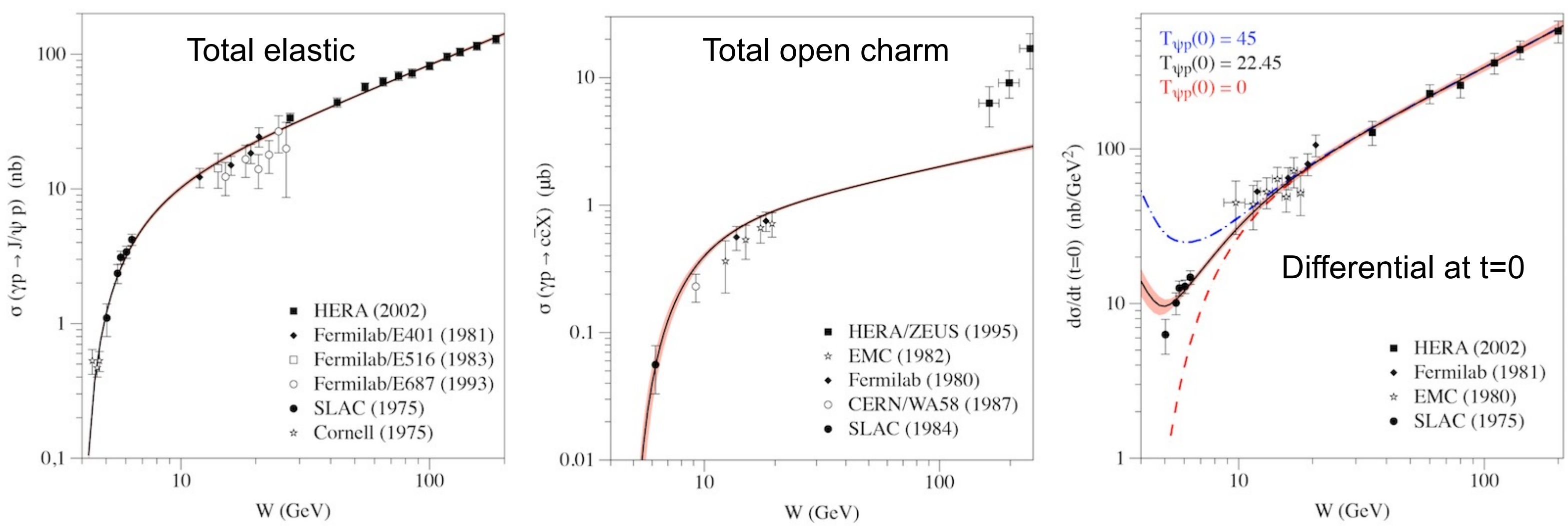
Forward J/ψ -p scattering in relation to γ -p scattering

Vector Dominance Model (VDM) Assumption

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

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

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

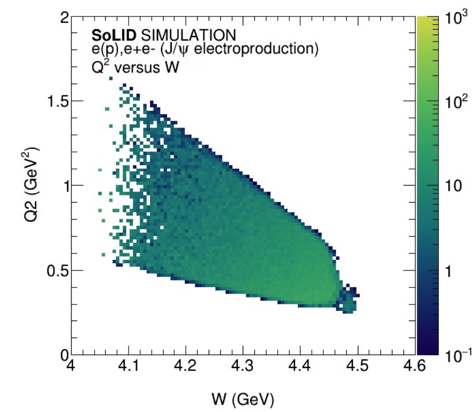


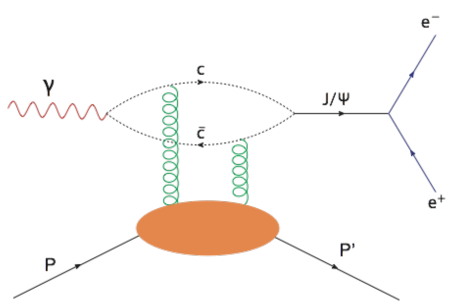
Simultaneous fitting $T(0) = 22.5 \pm 2.5$ ⇨ $a_{\psi p} \sim 0.05\text{fm}$ ⇨ $B_\psi \sim 3\text{MeV}$

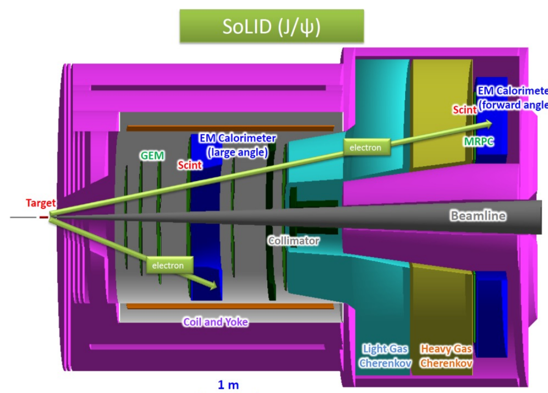
THE SoLID J/ψ EXPERIMENT

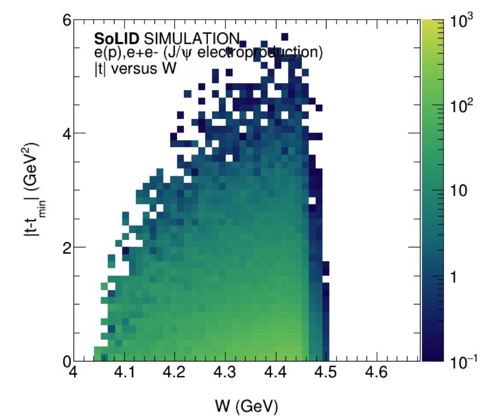
SoLID Experiment Overview

- 50 days of 3 $\mu\mathrm{A}$ 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 configuration overall compatible with SIDIS
  - **Electroproduction trigger**: 3-fold coincidence of e, e^-e^+
  - **Photoproduction trigger:** 3-fold coincidence of p, e^-e^+
  - **Additional trigger:** 4-fold coincidence of ep, e^-e^+
  - And (inclusive) 2-fold coincidence e^+e^-







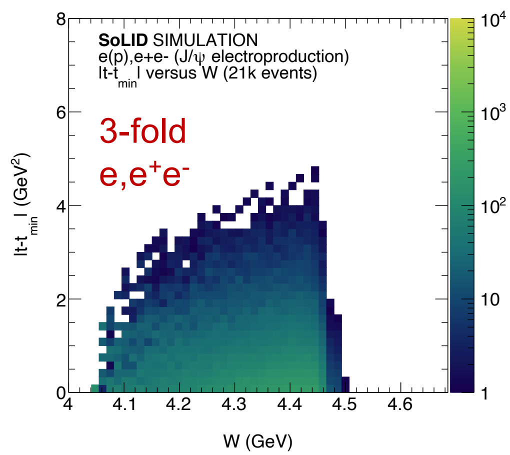


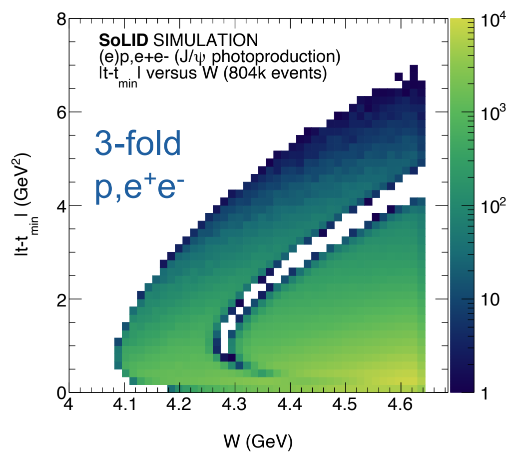
$$e^- + p \longrightarrow e^- + p + J/\psi\left(e^+ + e^-\right)$$

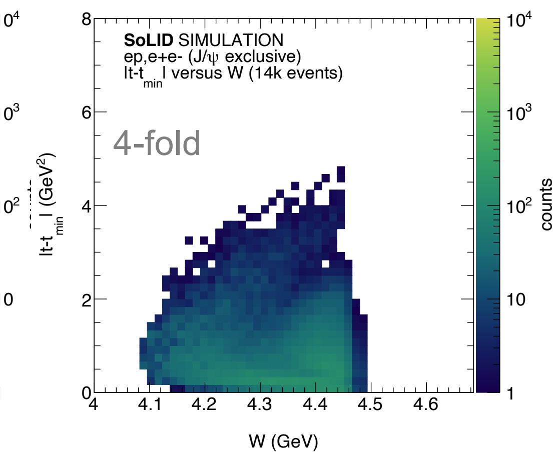
Event Counts @ 1×10^{37} in 50 days

- 4-fold coincidence: ep,e^+e^-
  - **280-400** events/day
- 3-fold (electroproduction): e,e^+e^-
  - **415-594** events/day
- 3-fold (photoproduction): p,e^+e^-
  - **16k-23k** events/day
- 2-fold (inclusive): e^+e^-
  - 26k-37k events/day

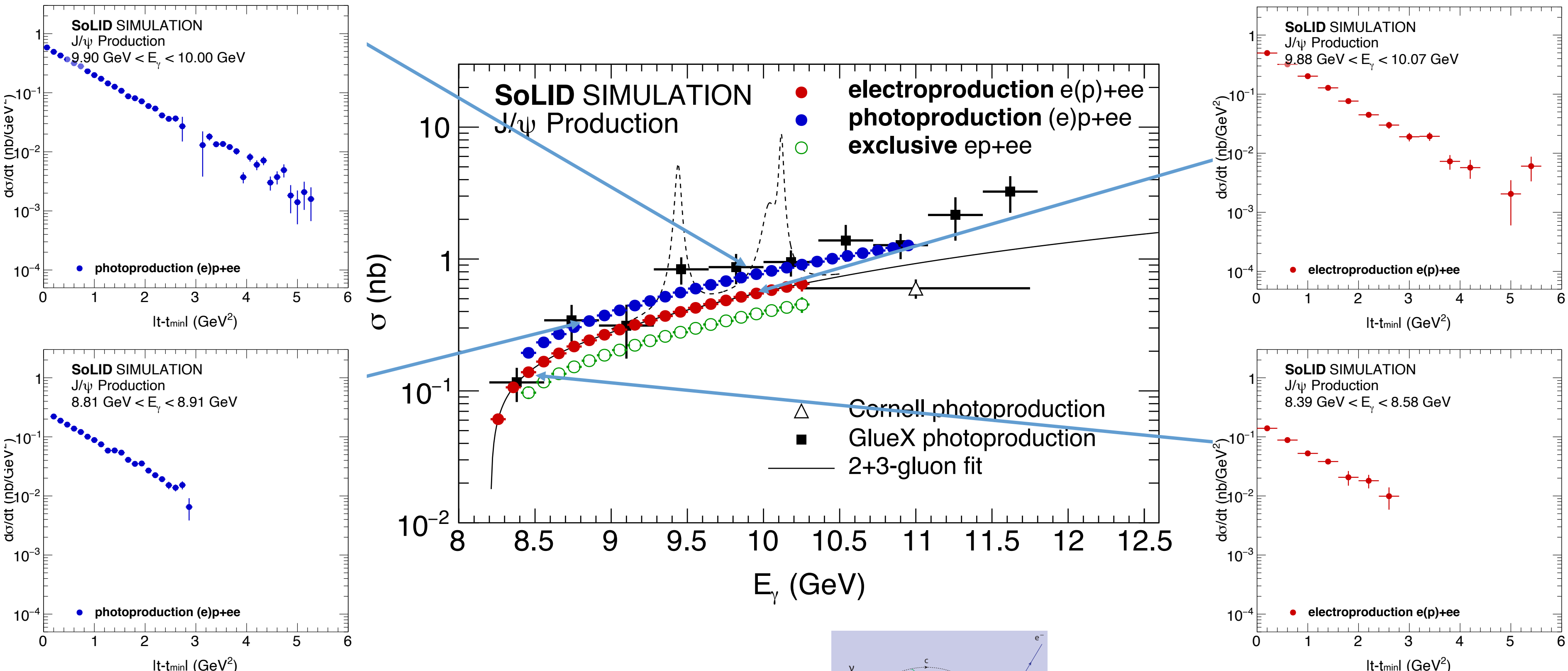
	Time (Hour)	Time (Day)
LH_2 at 11 GeV	**1200**	**50**
Dedicated Al dummy run	**72**	**3**
Optics and detector check out	**72**	**3**
Special low luminosity	**96**	**4**
Total	**1440**	**60**



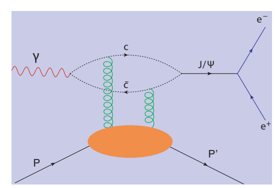




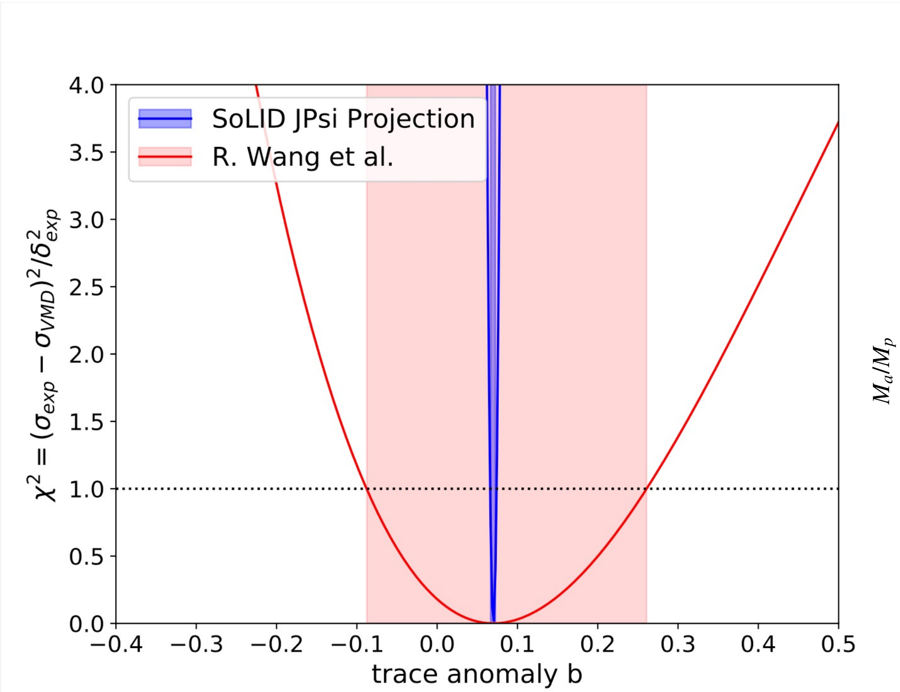
J/Psi Experiment E12-12-006 @ SoLID (C4)

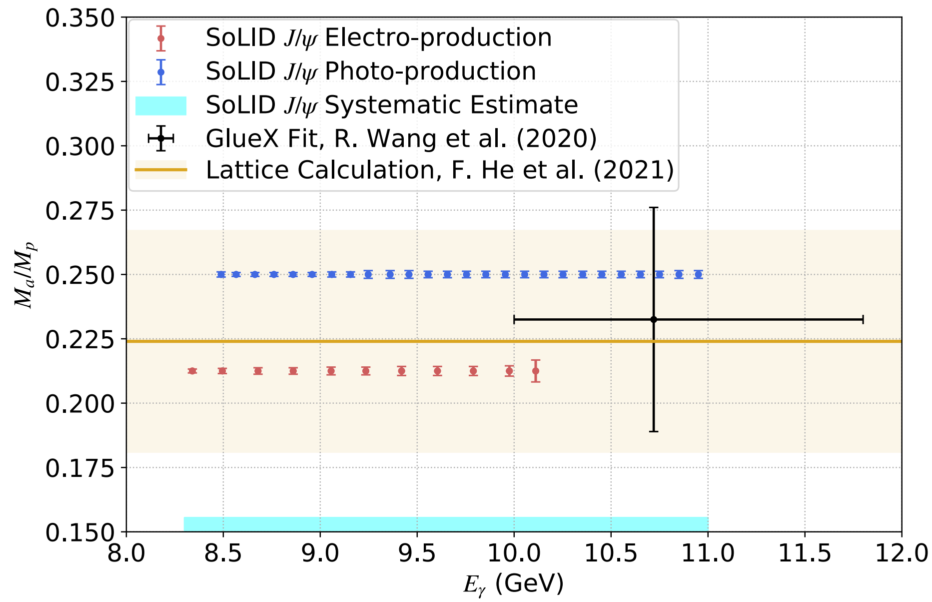


Sensitivity at threshold at about 10^{-3} nb!



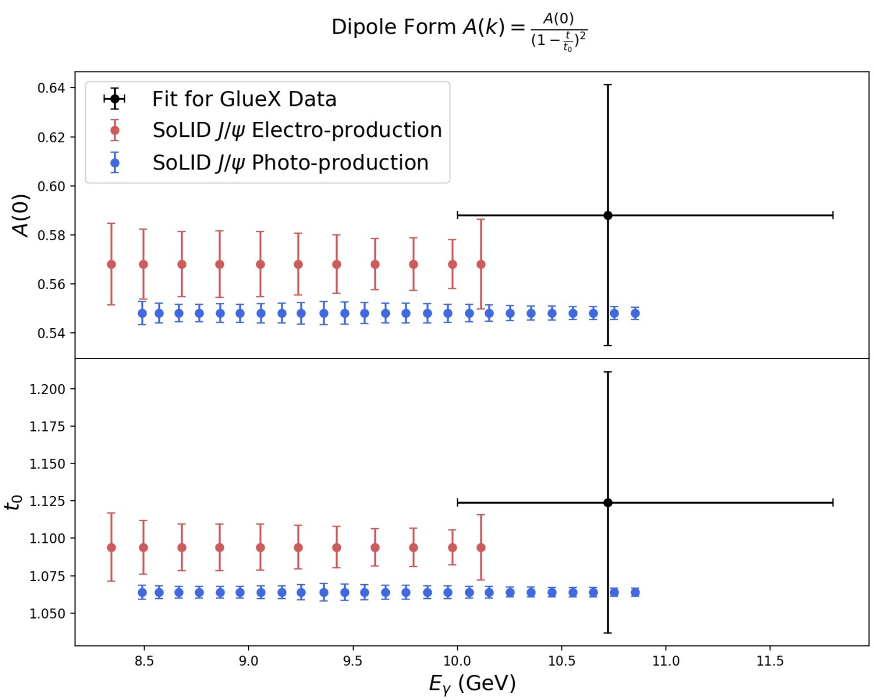
Impact on the trace Anomaly Extraction

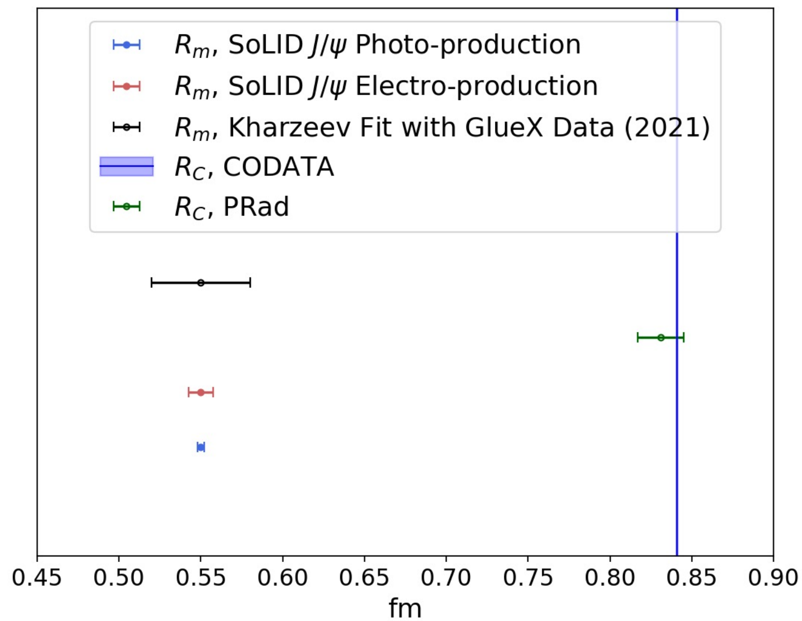




Impact on the mass radius

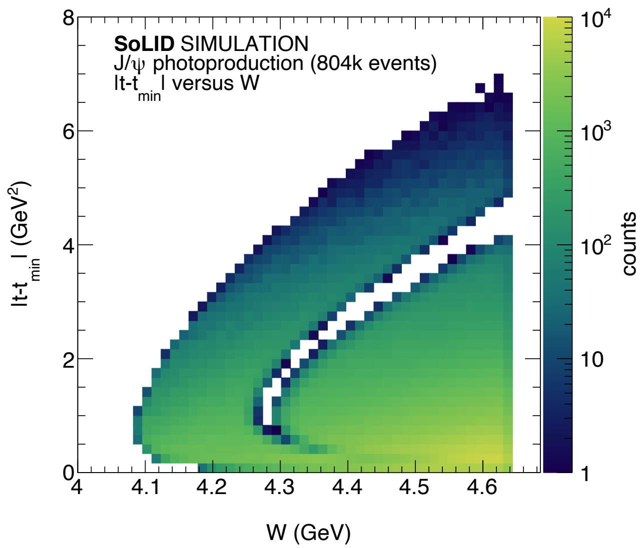
D. E. Kharzeev, ``The mass radius of the proton,"
arXiv:2102.00110 [hep-ph]



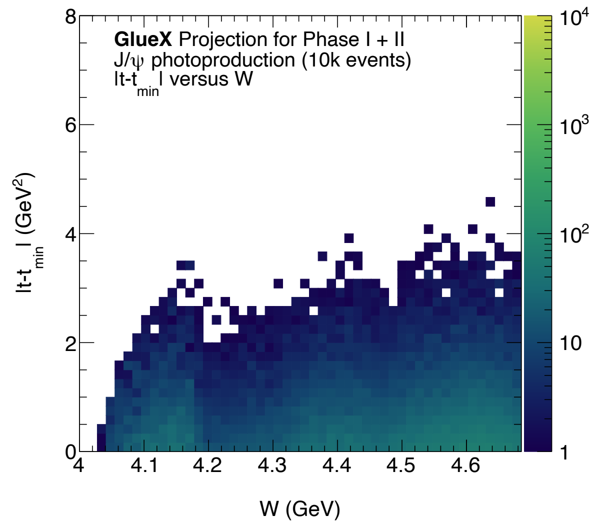


Why SoLID? An unprecedented luminosity with large acceptance

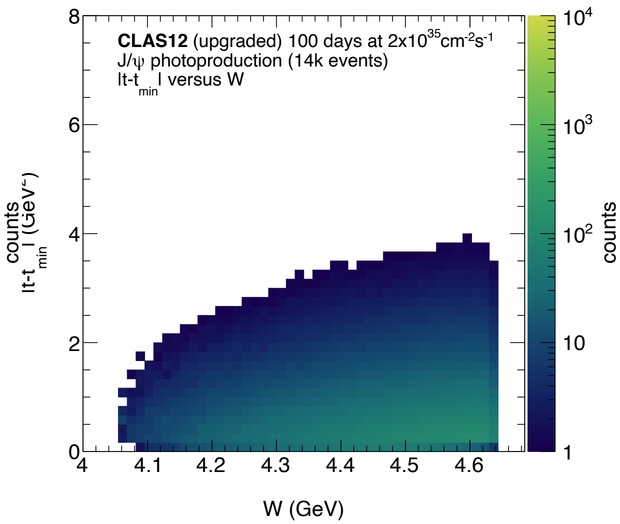
Photoproduction case: SoLID (p,e^+e^-), GlueX (p,e^+e^-), CLAS12 upgrade (p,e^+e^-)



Integrated photon-proton luminosity
25 fb^{-1}
Acceptance:~2π

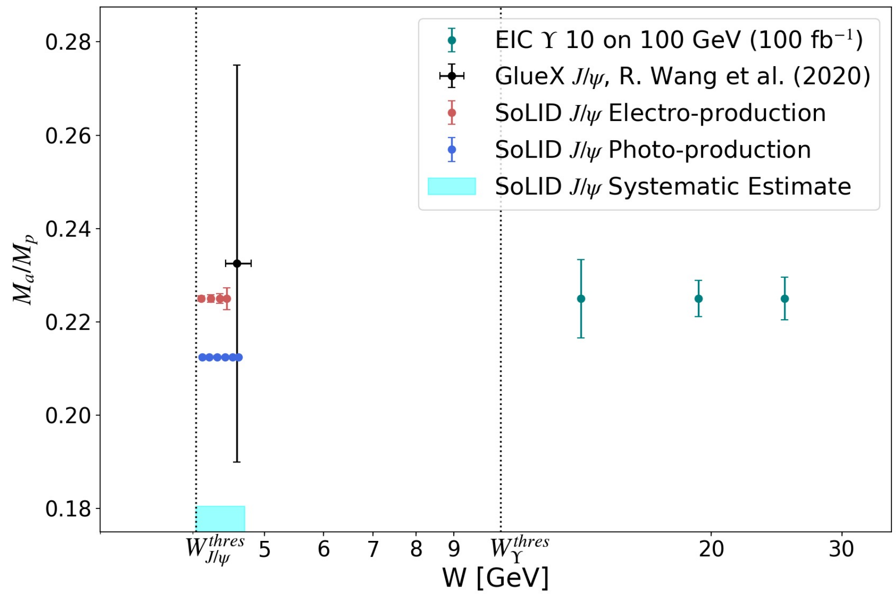


Integrated photon-proton luminosity
Phase I+II: **~0.4 fb-^{1}**
Acceptance:~2π



Integrated photon-proton luminosity:
~0.5 fb-1
Acceptance:< 2π

Complementary impact: SoLID (J/ψ) and EIC (Υ)



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?

- Direct lattice calculation of the trace anomaly is an important step toward understanding the proton mass different decompositions. Precision data will be able to benchmark these ab initio calculations.
- Statistical precision will help to understand the systematic uncertainties in the extractions of the anomaly, the mass radius and the scattering length.
- The origin of hadron masses is an active field of QCD. A 3rd Workshop was held in 14-16 January 2021 (see: https://indico.phy.anl.gov/event/2/)
- A 4th workshop on the proton mass will be held at the INT in June 2022 to continue explore the different important observables SoLID can and should cover.
- SoLID and the EIC, using heavy quarkonia, are truly complementary to address these questions.