Near threshold J/ψ and Υ production and the proton mass problem

Yoshitaka Hatta

(Brookhaven National Laboratory)

Based on 1906.00894 with Abha Rajan and Dilun Yang
1810.05116 with A.Rajan and Kazuhiro Tanaka
1808.02163 with D.Yang

07/24/2018

An Assessment of U.S.-Based Electron-Ion Collider Science

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of

SCIENCES · ENGINEERING · MEDICINE

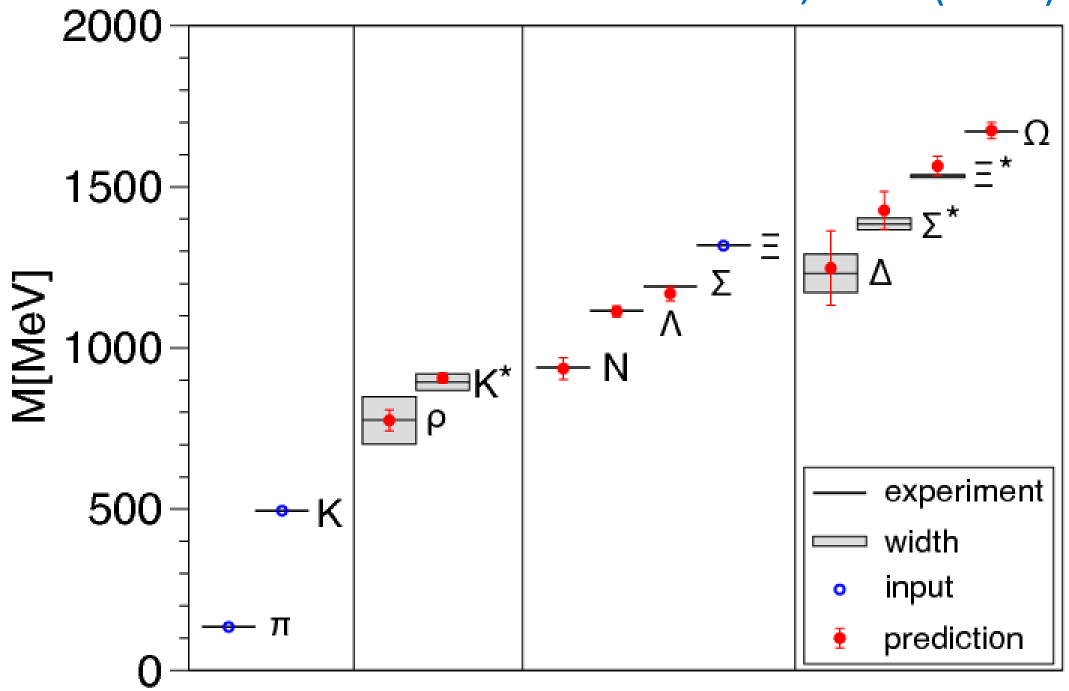
Finding 1: An EIC can uniquely address three profound questions about nucleons-protons—and how they are assembled to form the nuclei of atoms:

- 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?

Nucleon mass: What’s the issue?

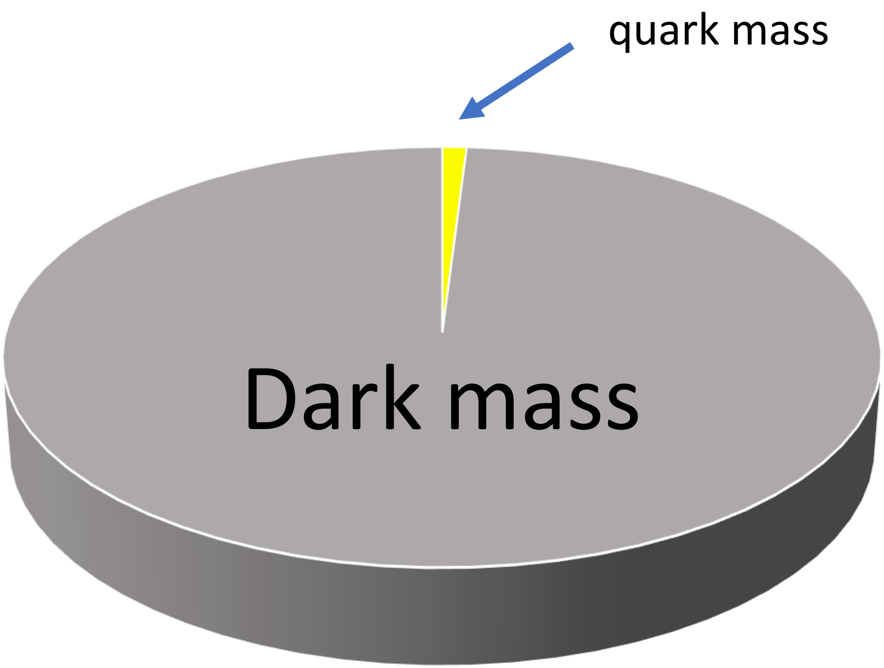
What’s mysterious about proton mass? Lattice QCD can explain it.

Durr, et al. (2009)



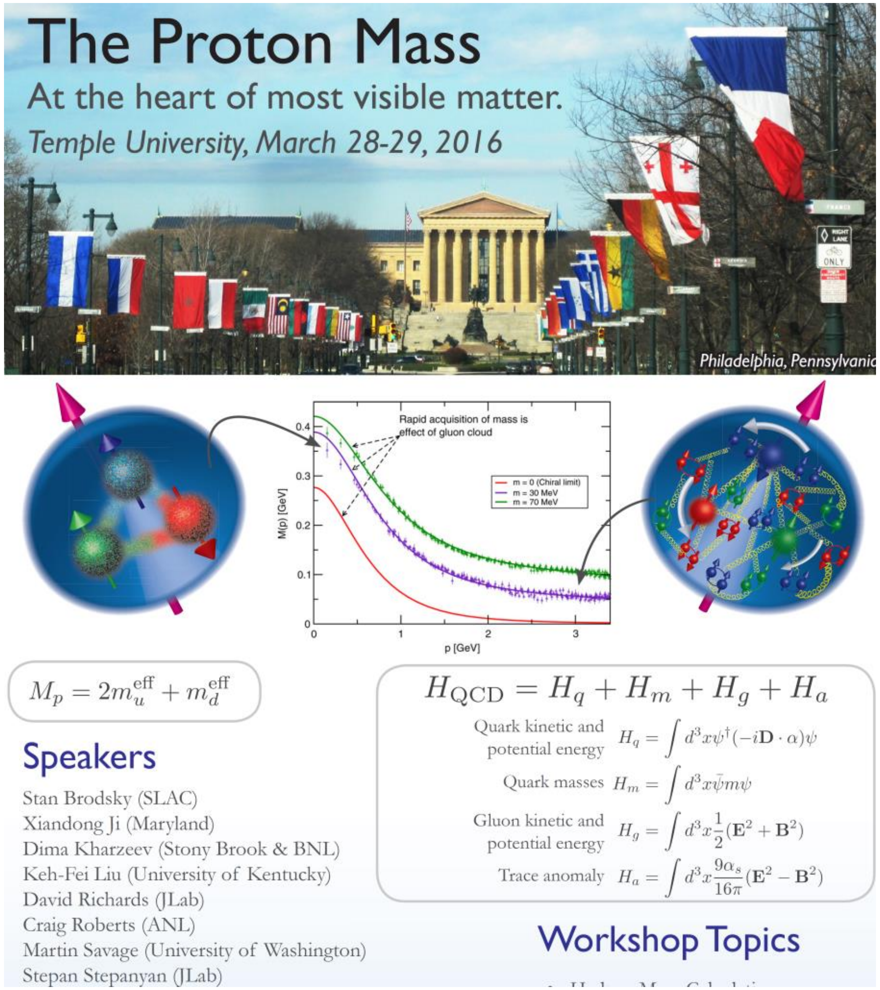
Proton mass crisis

u,d quark masses add up to ~10MeV, only 1 % of the proton mass!



Higgs mechanism explains quark masses, but not hadron masses!

c.f. talk by C. Roberts


The Proton Mass
At the heart of most visible matter.
Temple University, March 28-29, 2016
Philadelphia, Pennsylvania
Rapid acquisition of mass is effect of gluon cloud
m = 0 (Chiral limit)
m = 30 MeV
m = 70 MeV
M(p) [GeV]
p [GeV]
$M_p = 2m_u^{\rm eff} + m_d^{\rm eff}$
$H_{\rm QCD} = H_q + H_m + H_g + H_a$
Quark kinetic and potential energy $H_q = \int d^3x \psi^\dagger(-i\mathbf{D}\cdot\alpha)\psi$
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 $H_a = \int d^3x \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$
Speakers
Stan Brodsky (SLAC)
Xiandong 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)
Workshop Topics


ECT*
ECT*
ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC
TEMPLE UNIVERSITY
INFN
Istituto Nazionale di Fisica Nucle
Jefferson L
Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,
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:

Origin of the proton mass

QCD Lagrangian approximately scale (conformal) invariant.
Why is the proton mass nonvanishing in the first place?

Conformal symmetry is explicitly broken by the trace anomaly.

QCD energy-momentum tensor

$$T^{\mu\nu} = -F^{\mu\lambda}F^{\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4}F^2 + i\bar{q}\gamma^{(\mu}D^{\nu)}q$$

$$\langle P|T^{\mu\nu}|P\rangle = 2P^\mu P^\nu$$

$$T^\mu_\mu = \frac{\beta(g)}{2g}F^2 + m(1+\gamma_m(g))\bar{q}q \qquad \langle P|T^\mu_\mu|P\rangle = 2M^2$$

Proton mass decomposition

Traceless and trace parts of EMT in $d = 4 - 2\epsilon$ dimensions.

$$T^{\mu\nu} = \left(T^{\mu\nu} - \frac{\eta^{\mu\nu}}{d} T^\alpha_\alpha\right) + \frac{\eta^{\mu\nu}}{d} T^\alpha_\alpha$$

$$\frac{\beta(g)}{2g} F^2 + m(1 + \gamma_m(g))\bar{q}q$$

Work in the rest frame. Mass is the eigenvalue of the Hamiltonian $H = \int d^3x T^{00}$

quark/gluon kinetic energy — trace anomaly — quark mass

$$M = M_q + M_g + M_a + M_m$$

Ji (1995)

Lattice calculation→ talk by Y. Yang

Difficult to calculate $M_a \sim \langle P|F^2|P\rangle$ directly.

Alternative decomposition

YH, Rajan, Yang (2019)

$$T^{\mu\nu} = \underbrace{-F^{\mu\lambda}F^{\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4}F^2}_{T_g^{\mu\nu}} + \underbrace{i\bar{q}\gamma^{(\mu}D^{\nu)}q}_{T_q^{\mu\nu}}$$

$$T^{\mu}_{\mu} = (T_q)^{\mu}_{\mu} + (T_g)^{\mu}_{\mu} = \frac{\beta}{2g}F^2 + m(1+\gamma_m)\bar{\psi}\psi$$

If it makes sense to compute $(T_q)^{\mu}_{\mu}$ and $(T_g)^{\mu}_{\mu}$ separately,

$$M^2 = M_q^2 + M_g^2 \qquad\qquad M_{q,g}^2 \equiv \frac{1}{2}\langle P|(T_{q,g})^{\mu}_{\mu}|P\rangle$$

Quark and gluon contributions to the trace anomaly

YH, Rajan, Tanaka (2018)

two-loops, $\overline{\mathrm{MS}}$ scheme

$$\eta_{\mu\nu}\left(T_g^{\mu\nu}\right)_R = \frac{\alpha_s}{4\pi}\left(\frac{14}{3}C_F\left(m\bar{\psi}\psi\right)_R - \frac{11}{6}C_A\left(F^2\right)_R\right) + \left(\frac{\alpha_s}{4\pi}\right)^2 \times\left[\left(C_F\left(\frac{812C_A}{27} - \frac{22n_f}{27}\right) + \frac{85C_F^2}{27}\right)\left(m\bar{\psi}\psi\right)_R + \left(\frac{28C_An_f}{27} - \frac{17C_A^2}{3} + \frac{5C_Fn_f}{54}\right)\left(F^2\right)_R\right]$$

$$\eta_{\mu\nu}\left(T_q^{\mu\nu}\right)_R = \left(m\bar{\psi}\psi\right)_R + \frac{\alpha_s}{4\pi}\left(\frac{4}{3}C_F\left(m\bar{\psi}\psi\right)_R + \frac{1}{3}n_f\left(F^2\right)_R\right) + \left(\frac{\alpha_s}{4\pi}\right)^2 \times\left[\left(C_F\left(\frac{61C_A}{27} - \frac{68n_f}{27}\right) - \frac{4C_F^2}{27}\right)\left(m\bar{\psi}\psi\right)_R + \left(\frac{17C_An_f}{27} + \frac{49C_Fn_f}{54}\right)\left(F^2\right)_R\right]$$

Result in $\overline{\mathrm{MS}}$ at three-loops

Tanaka, JHEP 1901 (2019) 120

$$\eta_{\mu\nu}\left(T_g^{\mu\nu}\right)_R = \frac{\alpha_s}{4\pi}\left(\frac{14}{3}C_F\left(m\bar{\psi}\psi\right)_R - \frac{11}{6}C_A\left(F^2\right)_R\right) + \left(\frac{\alpha_s}{4\pi}\right)^2$$
$$\times\left[\left(C_F\left(\frac{812C_A}{27} - \frac{22n_f}{27}\right) + \frac{85C_F^2}{27}\right)\left(m\bar{\psi}\psi\right)_R + \left(\frac{28C_An_f}{27} - \frac{17C_A^2}{3} + \frac{5C_Fn_f}{54}\right)\left(F^2\right)_R\right]$$
$$+\left(\frac{\alpha_s}{4\pi}\right)^3\left[\left\{n_f\left(\left(\frac{368\zeta(3)}{9} - \frac{25229}{729}\right)C_F^2 - \frac{2}{243}(4968\zeta(3)+1423)C_AC_F\right)\right.\right.$$
$$+\left(\frac{32\zeta(3)}{3} - \frac{91753}{1458}\right)C_AC_F^2 + \left(\frac{294929}{1458} - \frac{32\zeta(3)}{9}\right)C_A^2C_F - \frac{554}{243}C_Fn_f^2$$
$$\left.+\left(\frac{95041}{729} - \frac{64\zeta(3)}{9}\right)C_F^3\right\}\left(m\bar{\psi}\psi\right)_R$$
$$\left.+\left\{n_f\left(\left(\frac{1123}{162} - \frac{52\zeta(3)}{9}\right)C_AC_F + \left(4\zeta(3) + \frac{293}{36}\right)C_A^2 + \frac{16}{729}(81\zeta(3) - 98)C_F^2\right) + n_f^2\left(\frac{655C_A}{2916} - \frac{361C_F}{729}\right) - \frac{2857C_A^3}{108}\right\}\left(F^2\right)_R\right]$$

$$\eta_{\mu\nu}\left(T_q^{\mu\nu}\right)_R = \left(m\bar{\psi}\psi\right)_R + \frac{\alpha_s}{4\pi}\left(\frac{4}{3}C_F\left(m\bar{\psi}\psi\right)_R + \frac{1}{3}n_f\left(F^2\right)_R\right) + \left(\frac{\alpha_s}{4\pi}\right)^2$$
$$\times\left[\left(C_F\left(\frac{61C_A}{27} - \frac{68n_f}{27}\right) - \frac{4C_F^2}{27}\right)\left(m\bar{\psi}\psi\right)_R + \left(\frac{17C_An_f}{27} + \frac{49C_Fn_f}{54}\right)\left(F^2\right)_R\right]$$
$$+\left(\frac{\alpha_s}{4\pi}\right)^3\left[\left\{n_f\left(\left(\frac{64\zeta(3)}{9} - \frac{8305}{729}\right)C_F^2 - \frac{2}{243}(864\zeta(3)+1079)C_AC_F\right)\right.\right.$$
$$-\frac{8}{729}(972\zeta(3)+143)C_AC_F^2 + \left(\frac{32\zeta(3)}{9} + \frac{6611}{729}\right)C_A^2C_F - \frac{76}{243}C_Fn_f^2$$
$$\left.+\frac{8}{729}(648\zeta(3)-125)C_F^3\right\}\left(m\bar{\psi}\psi\right)_R$$
$$+\left\{n_f\left(\left(\frac{52\zeta(3)}{9} - \frac{401}{324}\right)C_AC_F + \left(\frac{134}{27} - 4\zeta(3)\right)C_A^2 + \left(\frac{2407}{1458} - \frac{16\zeta(3)}{9}\right)C_F^2\right)\right.$$
$$\left.\left.+n_f^2\left(-\frac{697C_A}{729} - \frac{169C_F}{1458}\right)\right\}\left(F^2\right)_R\right],$$

In terms of the parameter b introduced in Ji, PRL (1995)

$$M_m = \frac{1}{4}\frac{\langle P|m(1+\gamma_m)\bar{\psi}\psi|P\rangle}{2M} \equiv \frac{b}{4}M \qquad M_a = \frac{1}{4}\frac{\langle P|\frac{\beta}{2g}F^2|P\rangle}{2M} \equiv \frac{1-b}{4}M$$

$$\frac{M_g^2}{M^2} = 1.23 - 1.04b$$

$\overline{\mathrm{MS}}$, three-loop, $\mu = 2\mathrm{GeV}$

This is larger than unity when $b < 0.22$

From the nucleon sigma term and lattice, $b \sim 0.12$

$$M_g^2 < 0$$

Can we measure the gluon condensate $\langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle$ in experiments?

The operator $F^{\mu\nu}F_{\mu\nu}$ is twist-four,
highly suppressed in high energy scattering.
QCD factorization difficult to establish.

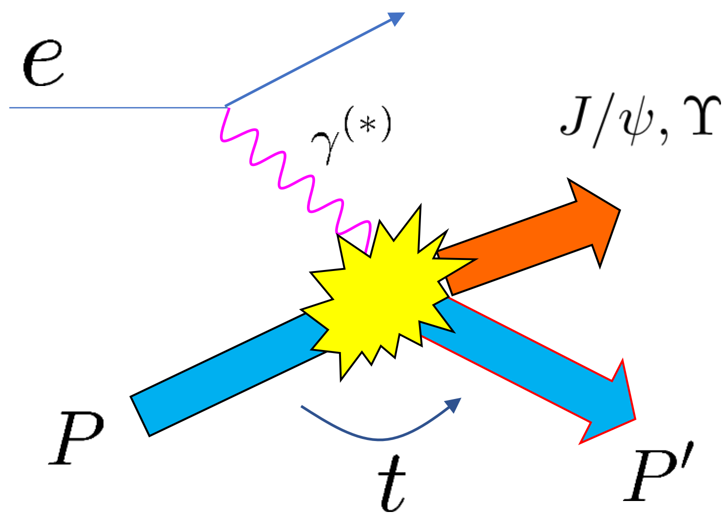
Instead, we should look at low-energy scattering.

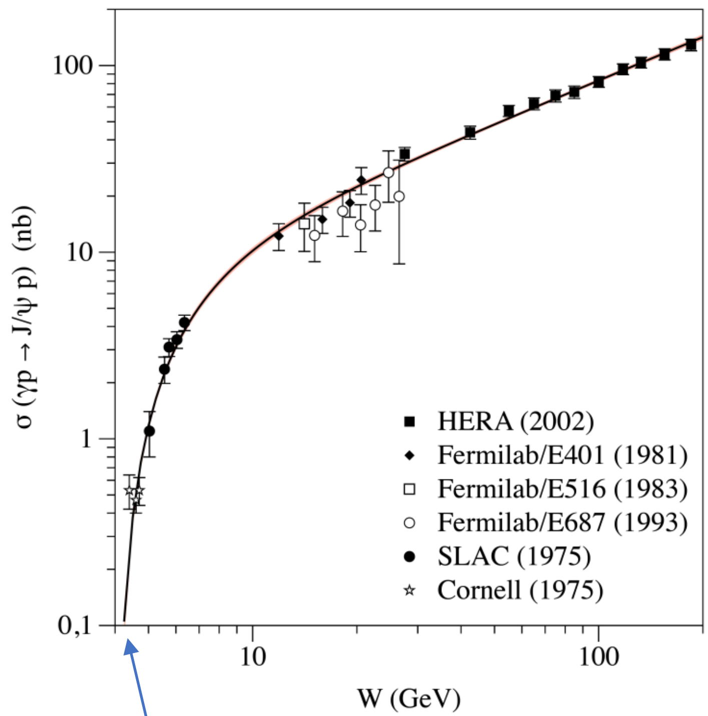
Purely gluonic operator. Use quarkonium as a probe.

Near-threshold photo-production of $J/\psi, \Upsilon$

Sensitive to the non-forward matrix element $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$

Kharzeev, Satz, Syamtomov, Zinovjev (1998)
Brodsky, Chudakov, Hoyer, Laget (2000)





$$\sigma_{tot}^{\gamma p} = \int_{t_{min}}^{t_{max}} dt \frac{d\sigma}{dt}$$

$$W_{th} \approx 4.04\text{GeV} \quad (E_\gamma^{lab} = 8.2\text{GeV})$$

Experiments going on at Jlab → talks by A. Somov, S. Joosten
Possibly at EIC in China in future

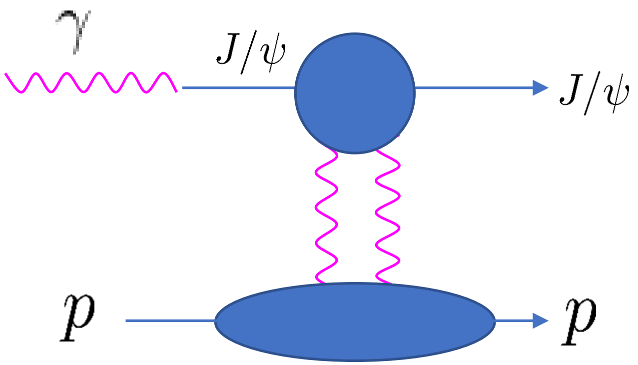
Previous approaches

Kharzeev, Satz, Syamtomov, Zinovjev (1998);

Assume vector meson dominance to relate $\gamma p \to J/\psi p$ to forward $J/\psi p \to J/\psi p$

Compute $\mathrm{Im} T^{J/\psi p}(t=0) \sim \sigma_{tot}^{J/\psi p}$

Reconstruct $\mathrm{Re} T^{J/\psi p}(t=0)$ via dispersion relation. $\langle P|F^2|P\rangle$ enters as a subtraction constant.

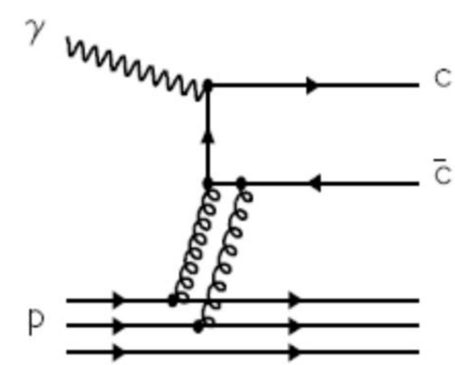


Brodsky, Chudakov, Hoyer, Laget (2001)

Two-gluon, three-gluon exchanges
Amplitude from quark counting rule

Frankfurt, Strikman (2002)

t-dependence not exponential but power-law,
and comes from 2-gluon form factors
(Which form factors?)



The nucleon gravitational form factors

`anomalous gravitomagnetic moment'

The D-term $C_{q,g} = D_{q,g}/4$
`radial force' inside the proton

$$\langle P'S|T^{\mu\nu}_{q,g}|PS\rangle = \bar{u}(P'S)\left[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + C_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{q,g}Mg^{\mu\nu}\right]u(PS)$$

$$A_q = \int_0^1 dx x(q(x) + \bar{q}(x))$$

$$A_g = \int_0^1 dx x g(x)$$

Momentum fraction of quarks and gluons $\Delta = 0$

Related to the trace anomaly

$A_{q,g}(t), B_{q,g}(t), C_{q,g}(t)$ has been calculated in lattice QCD. Typically fitted by the dipole form

$$A_g(t) = \frac{A_g(0)}{(1-t/\Lambda^2)^2}$$

Form factor $\bar{C}_g$

Least understood among the four gravitational form factors.

Related to the nonconvervation of energy momentum tensor in quark and gluon subsystems.

$$\langle \partial_\mu T^{\mu\nu}_{q,g} \rangle \sim \Delta^\nu \bar{C}_{q,g} \qquad \bar{C}_q + \bar{C}_g = 0$$

Related to the trace anomaly in the forward limit.

$$\langle P | (T^R_{q,g}(\mu))^\alpha_\alpha | P \rangle = 2M^2 (A^R_{q,g}(\mu) + 4\bar{C}^R_{q,g}(\mu))$$

Related to the radial `pressure' in the quark and gluon subsystems
Polyakov, Schweitzer (2018)

$$p_{q,g}(r) = \frac{1}{6Mr^2} \frac{d}{dr} r^2 \frac{d}{dr} D_{q,g}(r) - M\bar{C}_{q,g}(r)$$

Relation between $\langle P'|F^2|P\rangle$ and $\bar{C}_g$

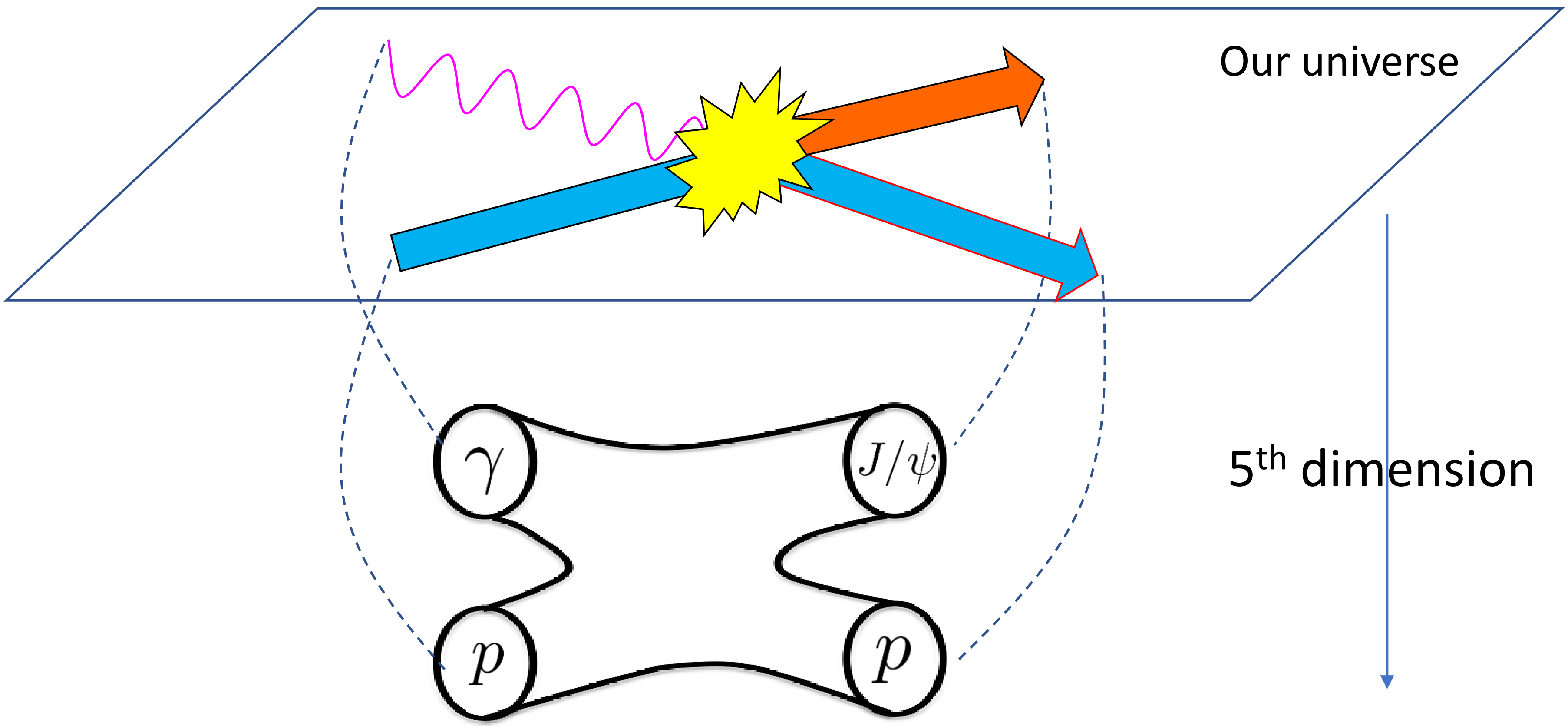
$$\langle P'|F_R^2|P\rangle = \bar{u}(P')\Big[(K_g A_g^R + K_q A_q^R)M + \frac{K_g B_g^R + K_q B_q^R}{4M}\Delta^2 - 3\frac{\Delta^2}{M}(K_g C_g^R + K_q C_q^R) + 4(K_g \bar{C}_g^R + K_q \bar{C}_q^R)M\Big]u(P),$$

Nonforward amplitude of F^2 completely given by the gravitational form factors.
Coefficients $K_{q,g}$ perturbatively calculable to 3 loops.

Holographic approach

YH, Yang (2018)

Need nonperturbative methods.
Use AdS/CFT, or more generally, gauge/string duality
QCD amplitude $\approx$ string amplitude in asymptotically AdS_5.



The AdS/CFT correspondence

Maldacena, `97

N=4 super Yang-Mills at strong coupling, large-Nc

↕ equivalent

Type IIB superstring theory on $AdS_5 \times S^5$

$$ds^2 = R^2 \frac{dz^2 - dx^\mu dx_\mu}{z^2} + R^2 d\Omega_5^2$$

Field theory	string
operators $T^{\mu\nu}, F^2, \cdots$	string state $G_{\mu\nu}, \phi, \cdots$
(anomalous) dimension	mass
`t Hooft coupling λ	curvature radius R
number of colors $1/N_c$	string coupling constant g_s

Application of AdS/CFT to high/low energy scattering

High energy : Disaster

Polchinski, Strassler; Brower, Polchinski, Strassler, Tan
Hatta, Iancu, Mueller; Cornalba, Costa, Penedones,…

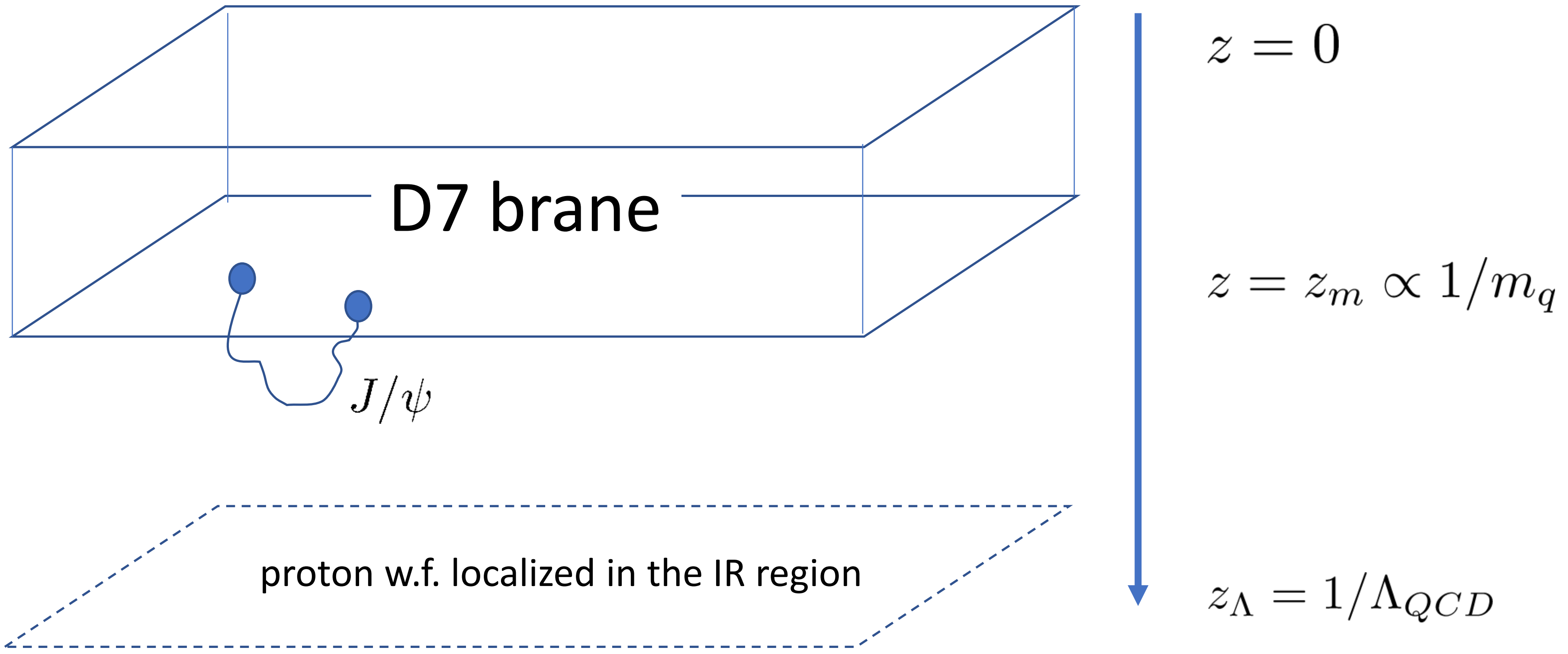
Scattering amplitudes dominantly real, in stark contrast to QCD
Graviton exchange gives too strong rise of the cross section $\sigma_{tot} \propto s$
Finite-coupling corrections/modified geometry essential for reasonable phenomenology.

Low-energy : Some hope

QCD amplitudes dominantly real near threshold.
Energy momentum tensor shows up naturally (=graviton exchange)

Setup

Quarkonium: open string excitation on a D7 brane Karch, Katz (2002)

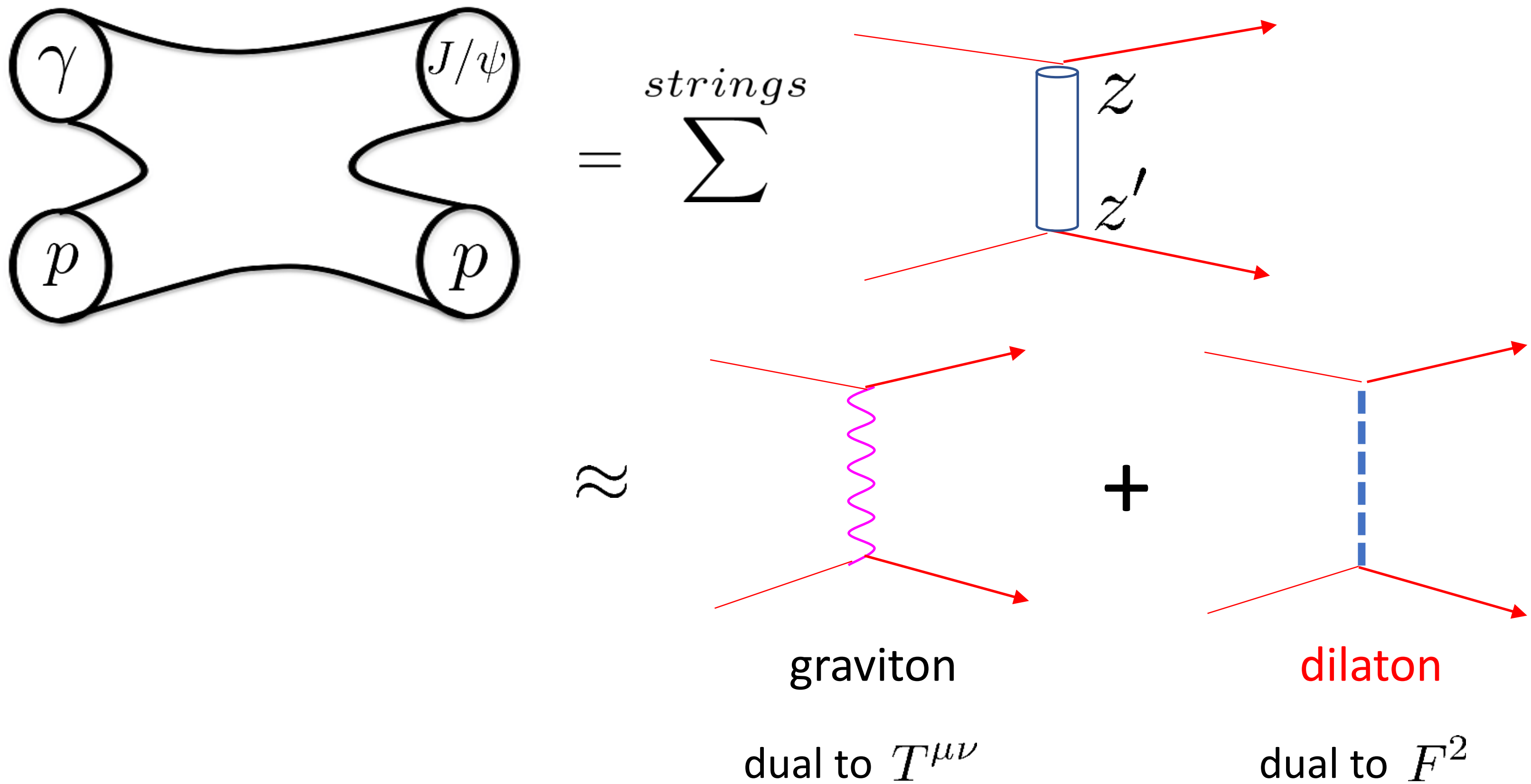


Born-Infeld action on the D7 brane.

dilaton

$$S_{D7} = -T_{D7} \int d^8\xi e^{-\phi} \sqrt{-\det \left[G_{ab} + 2\pi\alpha' (F^{\gamma}_{ab} + F^{J/\psi}_{ab}) \right]}$$

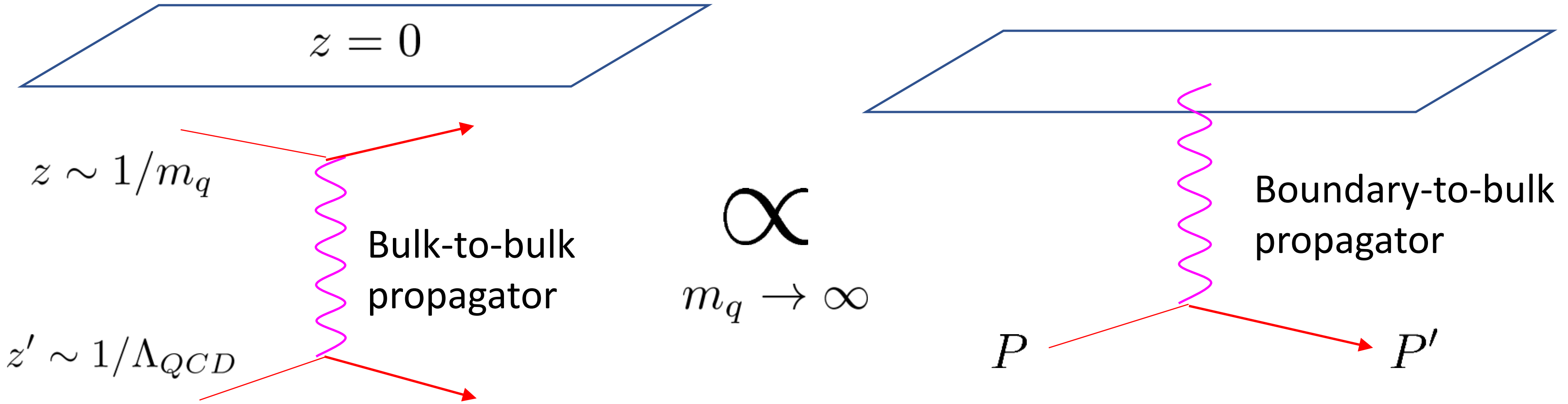
Scattering amplitude in AdS



$$\langle P|\epsilon \cdot J|P'k\rangle \sim \int d^4x dz \sqrt{-G} \int d^4x' dz' \sqrt{-G'} \Phi_\gamma \Phi_{J/\psi} G(zx, z'x') \Phi_P \Phi_{P'}$$

Connection to gravitational form factors

In the heavy-quark limit, one can make connection with the gravitational form factors

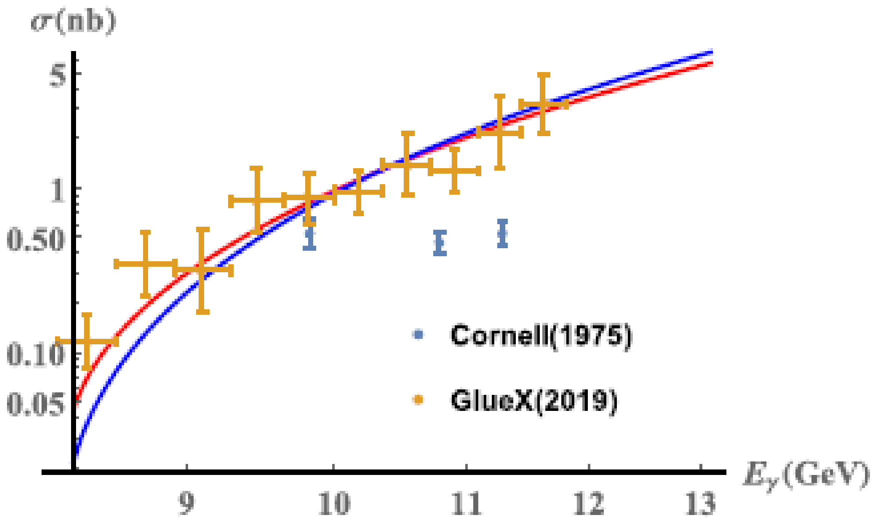


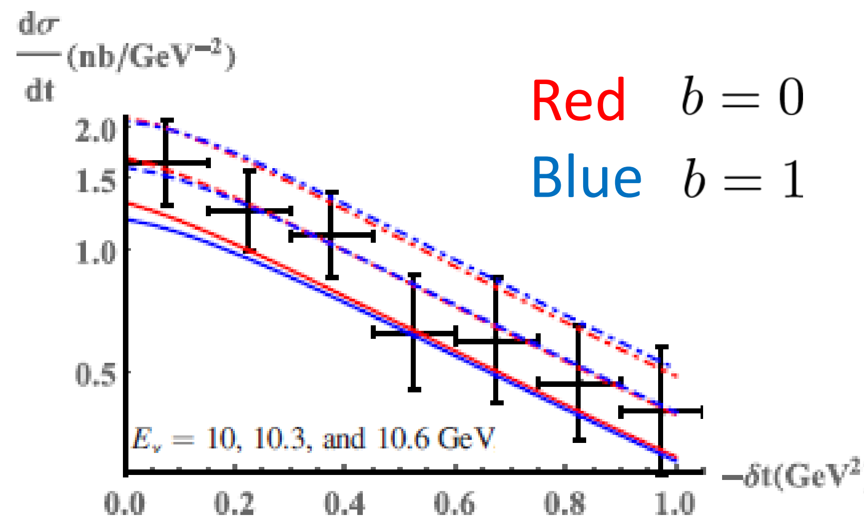
$$\langle P|\epsilon\cdot J(0)|P'k\rangle \approx -\frac{2\kappa^2}{f_\psi R^3}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}}\frac{z^2R^2}{4}\langle P|T^{gTT}_{\mu\nu}|P'\rangle + \frac{2\kappa^2}{f_\psi R^3}\frac{3}{8}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta\phi}\frac{z^4}{4}\langle P|\frac{1}{4}F^{\mu\nu}_a F^a_{\mu\nu}|P'\rangle$$

Fitting the latest GlueX result

c.f. talk by A. Somov

$$M_m = \frac{1}{4}\frac{\langle P|m(1+\gamma_m)\bar{\psi}\psi|P\rangle}{2M} \equiv \frac{b}{4}M \qquad M_a = \frac{1}{4}\frac{\langle P|\frac{\beta}{2g}F^2|P\rangle}{2M} \equiv \frac{1-b}{4}M$$





Comments:

Normalization fitted to the data.

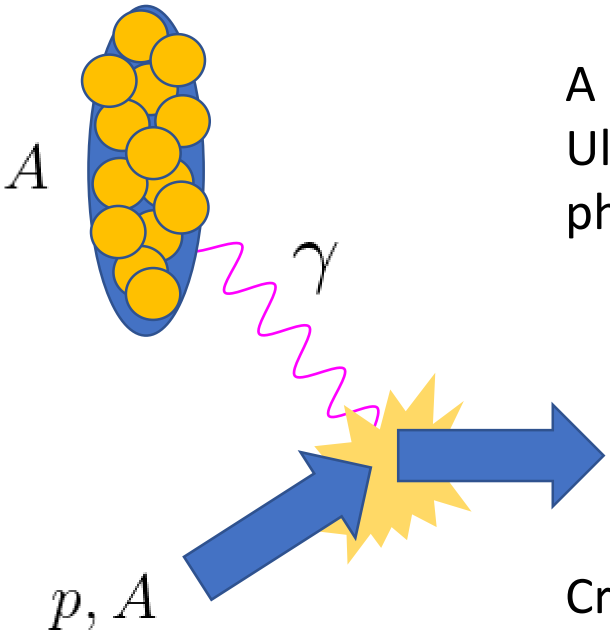
Amplitude purely real

Model does not work at high energy

$A_g(\Delta^2), D_g(\Delta^2)$ from lattice Shanahan, Detmold (2018)

Small-b favored, b=1 disfavored→ Gluon condensate important for the proton mass!

Ultraperipheral collisions at RHIC



A heavy ion is an abundant source of real photons. Ultrapheripheral collisions (UPC) closely mimic the photoproduction limit of DIS.

Cross section enhanced by $Z^2 = 6241$ (for gold nucleus)
Can study Υ photo-production

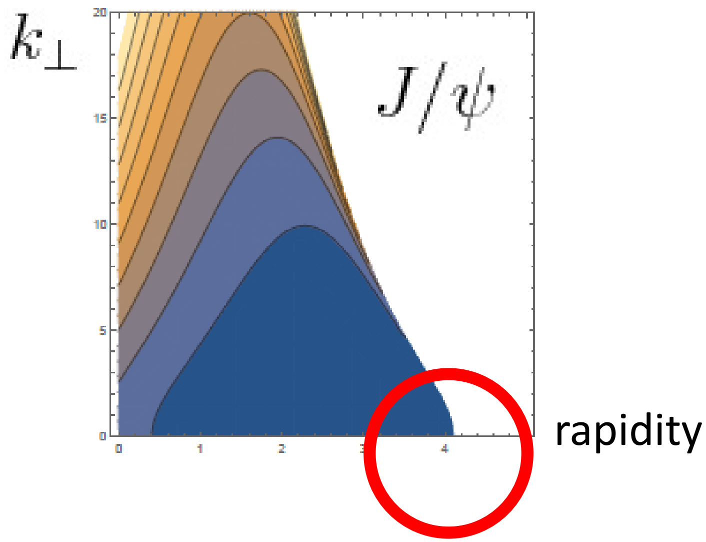
Typical photon energy at 200GeV runs $\omega = 2 \sim 3\,\mathrm{GeV}$, $\sqrt{(P+q)^2} \sim 28\,\mathrm{GeV}$

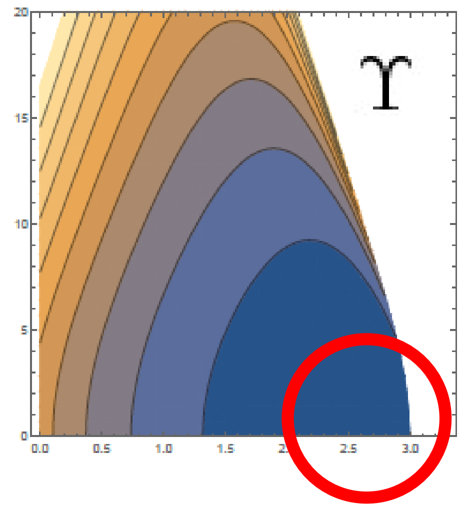
Enough to produce Υ , but they are produced in the forward rapidity region

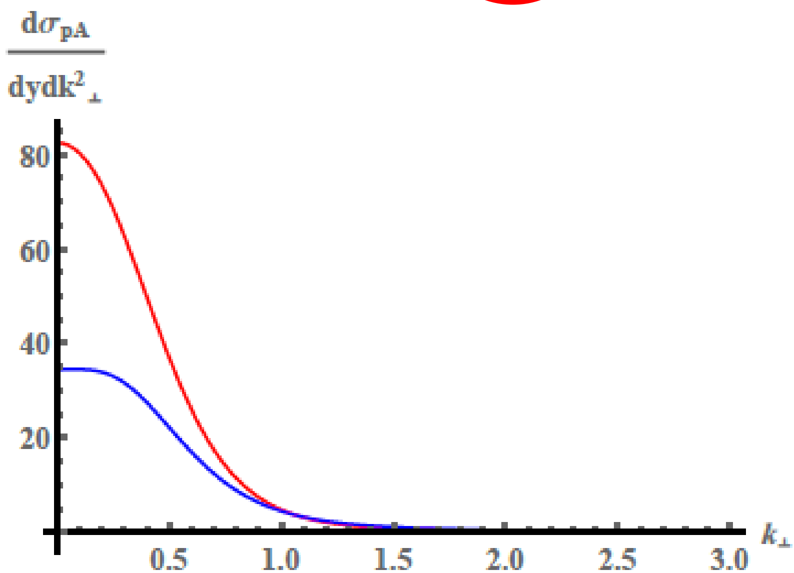
→ Measurable after the completion of STAR forward upgrades.

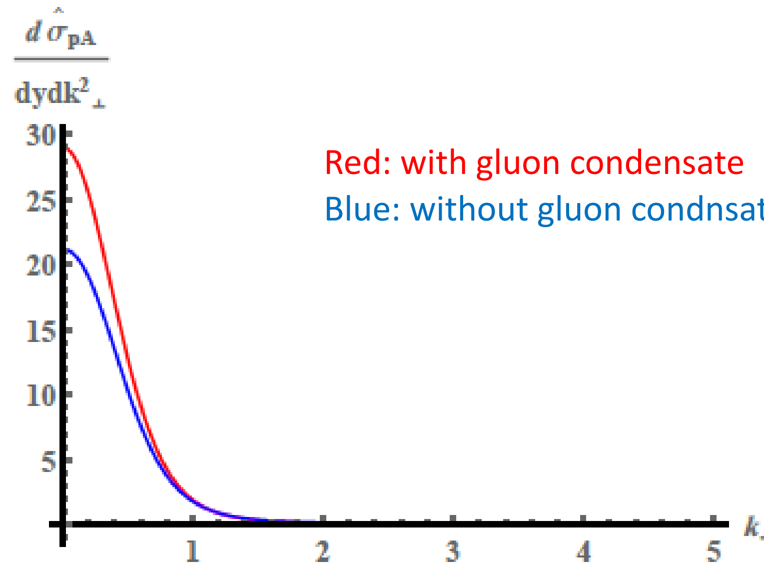
Near threshold production in UPC pA collisions at RHIC

YH, Rajan, Yang, 1906.00894









Red: with gluon condensate

Blue: without gluon condnsate

Conclusion

- Near-threshold J/ψ , Υ-production
  → An interesting physics case at EIC in China
  Lower energy helps.
- Cross section sensitive to $\langle P|F^2|P'\rangle$ and the gluon D-term
- Precise t-dependence of gravitational form factors very welcome ← models, lattice
- Use more realistic AdS/QCD models
- First principle/model independent approach?