Holographic J/ψ production near threshold and the proton mass problem

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Reference :
Yoshitaka Hatta, Di-Lun Yang, Phys. Rev. D 98, 074003 (2018), preprint:1808.02163

Mystery of proton mass & spin

- Proton is not an elementary particle : quarks + gluons

- Proton spin crisis : $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

quarks' helicity gluons' helicity orbital angular momentum

From polarized DIS : $\Delta\Sigma = 0.25 \sim 0.3$

EMC 1987

- Proton mass ~1 GeV v.s. u, d quark masses ~10 MeV

- What contribute to the 99% mass of protons ? kinetic energy of quarks & gluons, chiral condensate, conformal anomaly.

QCD EM tensor

- QCD energy-momentum tensor :

$$T^{\mu\nu} = -F_a^{\mu\lambda} F^{a\nu}{}_{\lambda} + \frac{\eta^{\mu\nu}}{4} F_a^{\alpha\beta} F^a{}_{\alpha\beta} + i\bar{\psi}\gamma^{(\mu} D^{\nu)}\psi$$

- Trace anomaly : $T^{\alpha}{}_{\alpha} = \frac{\beta(g)}{2g} F_a^{\alpha\beta} F^a{}_{\alpha\beta} + m(1+\gamma_m)\bar{\psi}\psi$

- Decomposition : $T^{\mu\nu} = \boxed{T^{\mu\nu}_{q,\mathrm{kin}} + T^{\mu\nu}_{g,\mathrm{kin}}} + \boxed{T^{\mu\nu}_{m} + T^{\mu\nu}_{a}}$

traceless :kinetic energy

trace : quark mass + anomaly

- Matrix elements :

$$\langle P|T^{\mu\nu}|P\rangle = 2P^{\mu}P^{\nu}, \quad \langle P|T^{\alpha}{}_{\alpha}|P\rangle = 2M^2$$

from quark condensate

$$\left\{ \begin{array}{ll} \langle P|T^{\mu\nu}_{q,\mathrm{kin}}|P\rangle = 2a(\mu^2)\left(P^{\mu}P^{\nu} - \frac{\eta^{\mu\nu}}{4}M^2\right), & \boxed{\langle P|T^{\mu\nu}_{m}|P\rangle} = \frac{1}{2}b(\mu^2)\eta^{\mu\nu}M^2, \\ \langle P|T^{\mu\nu}_{g,\mathrm{kin}}|P\rangle = 2(1-a(\mu^2))\left(P^{\mu}P^{\nu} - \frac{\eta^{\mu\nu}}{4}M^2\right), & \boxed{\langle P|T^{\mu\nu}_{a}|P\rangle} = \frac{1}{2}(1-b(\mu^2))\eta^{\mu\nu}M^2 \end{array} \right.$$

from (gluonic) trace anomaly

Proton mass decomposition

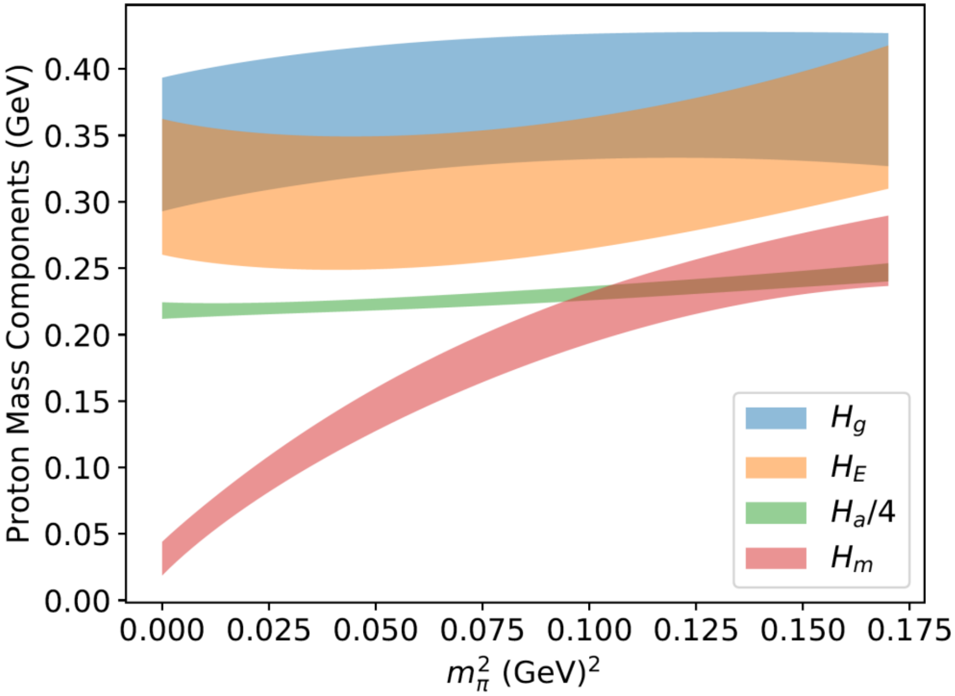
- In the proton rest frame $\mathcal{H} = \int d^3x T^{00}$:

quark/gluon kinetic energy trace anomaly quark mass

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

X.-D. Ji, 1995

- Mass decomposition from lattice :



Y. B. Yang, et.al. 18
χQCD collaboration

$$H_a = H_g^a + H_m^\gamma$$

Measuring trace anomaly from DIS?

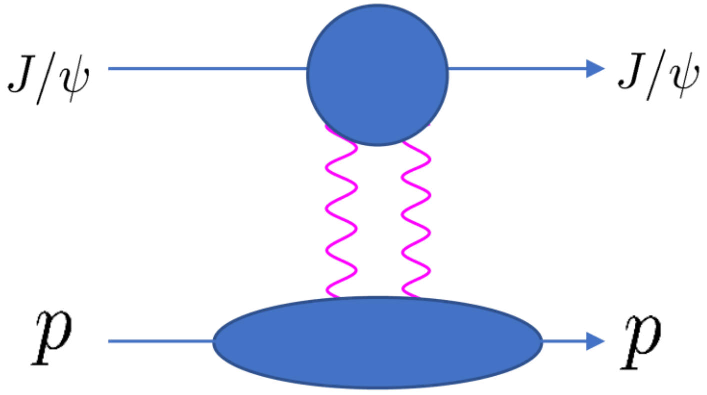
- Could we measure $\langle P|F_{\mu\nu}F^{\mu\nu}|P\rangle$ from experiment?

(gluonic contribution for the trace anomaly)

- $\langle P|F_{\mu\nu}F^{\mu\nu}|P\rangle$ is twist four :
  - Highly suppressed in high energy scattering
  - Low-energy scattering
  - Using heavy quarkonia as the probe

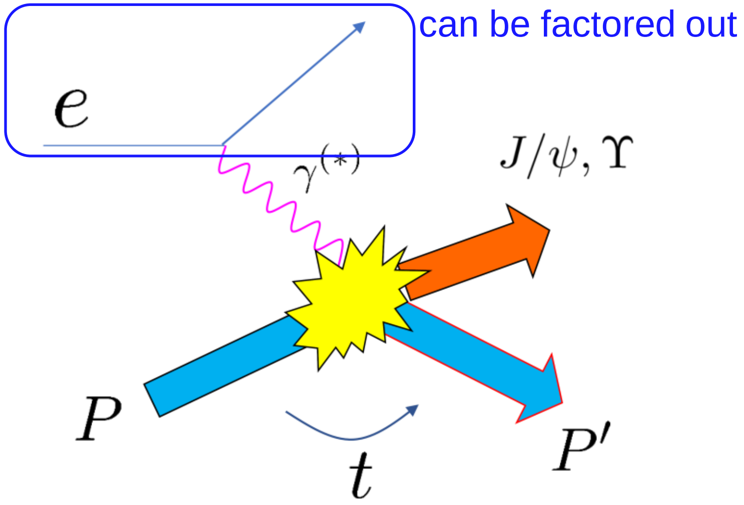
M. Luke, A. Manohar, and M. Savage, 92

D. Kharzeev, 96



- Initial motivation is instead to study the $c\bar{c}$ bound state in nuclei.

J/ψ photoproduction



can be factored out

- Relation to J/ψ photoproduction :
  - Assuming vector meson dominance :

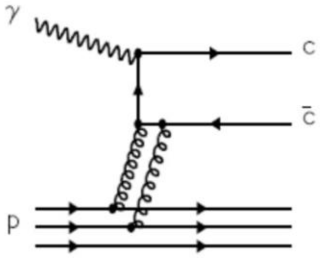
$$J/\psi + P \to J/\psi + P \quad \longleftrightarrow \quad \gamma + P \to J/\psi + P'$$

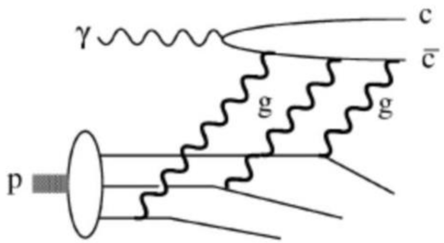
  - The trace anomaly enters the subtraction const. of $\mathrm{Re}(T_{\psi P})(t=0)$ reconstructed from $\mathrm{Im}(T_{\psi P})(t=0)$.

Kharzeev, Satz, Syamtomov, Zinovjev (98)

- Other theoretical studies :
  - 2/3 gluons hard scattering

Brodsky, Chudakov, Hoyer, Laget (2001)





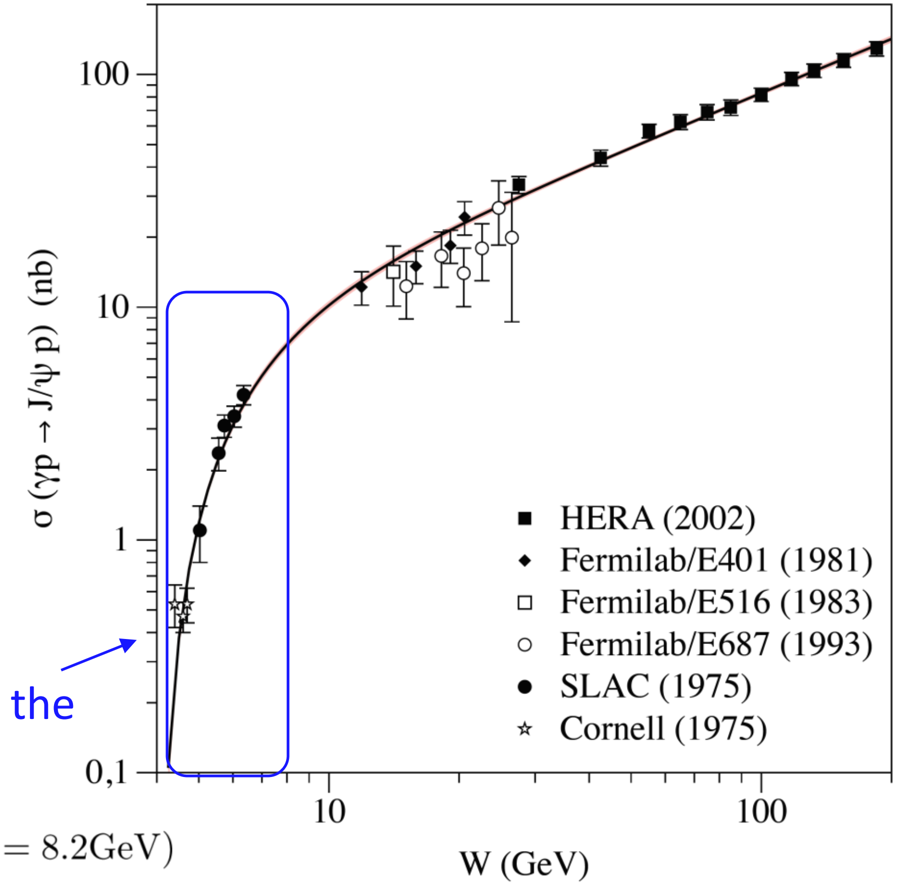
  - t-dependence from 2-gluon form factor

Frankfurt, Strikman (2002)

(No connection to anomaly !)

Present data in experiments

- Experimental data for J/ψ photoproduction :



Gryniuk, Vanderhaeghen (16) : Following the approach of Kharzeev, et.al.

No discussion about the anomaly

Very old data near the threshold

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

$$W^2 = (P+q)^2$$

- The new measurement is ongoing in Jlab.   (or EIC in the future !)

- What we want to study?
- To construct $\frac{d\sigma}{dt}(\gamma + P \to J/\psi + P')$ which explicitly depends on $\langle P | F_{\mu\nu}F^{\mu\nu} | P \rangle$.
- Fitting the data near threshold by tuning the value of the trace anomaly.

Nonforward proton matrix element

- In practice, $\langle P|T^{\mu\nu}|P\rangle$ is kinematically inaccessible in the scattering process $ep \to e'p'J/\psi$.

- Measuring $\langle P'|T^{\mu\nu}|P\rangle \xrightarrow{\text{extrapolation}}$ the forward limit $\Delta^\mu = P'^\mu - P^\mu \to 0$

- Parameterization of the nonforward matrix element : X.-D. Ji, 1997

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

- Gravitational form factors : $A,\ B,\ C,\ \bar{C}$ (depend on $\Delta^2 = t,\ \mu$)
- (gluonic) trace anomaly term :

$$\begin{aligned}\langle P'|\frac{\beta(g)}{2g}F^a_{\mu\nu}F^{\mu\nu}_a|P\rangle = \bar{u}(P')\Big[&(A_g - \gamma_m A_q)M + (B_g - \gamma_m B_q)\frac{\Delta^2}{4M} \\ &- 3\frac{\Delta^2}{M}(C_g - \gamma_m C_q) + 4(\bar{C}_g - \gamma_m \bar{C}_q)M\Big]u(P)\end{aligned}$$

Kinematics

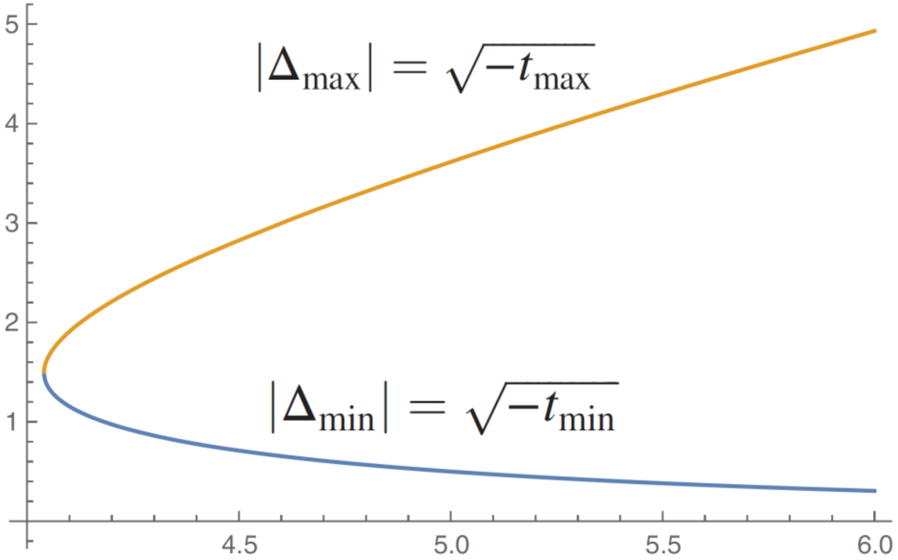
- Photoproduction cross section :

$$\sigma(\gamma p \to p' J/\psi) = \frac{e^2}{16\pi(W^2-M^2)^2}\frac{1}{2}\sum_i^{1,2}\int dt \boxed{\langle P|\epsilon_i \cdot J(0)|P'k\rangle} \langle P'k|\epsilon_i^* \cdot J(0)|P\rangle$$

(in the photoprodction limit $q^2 \to 0$)

The matrix element
we would like to compute.

- The kinematically allowed region :



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

$$M = 0.94 \text{ GeV},$$
$$M_\psi = 3.1 \text{ GeV}$$

photon energy in the proton rest frame :

$$\frac{W_{th}^2 - M^2}{2M} \approx 8.2 \text{ GeV} \le E_\gamma \lesssim 20 \text{ GeV}$$

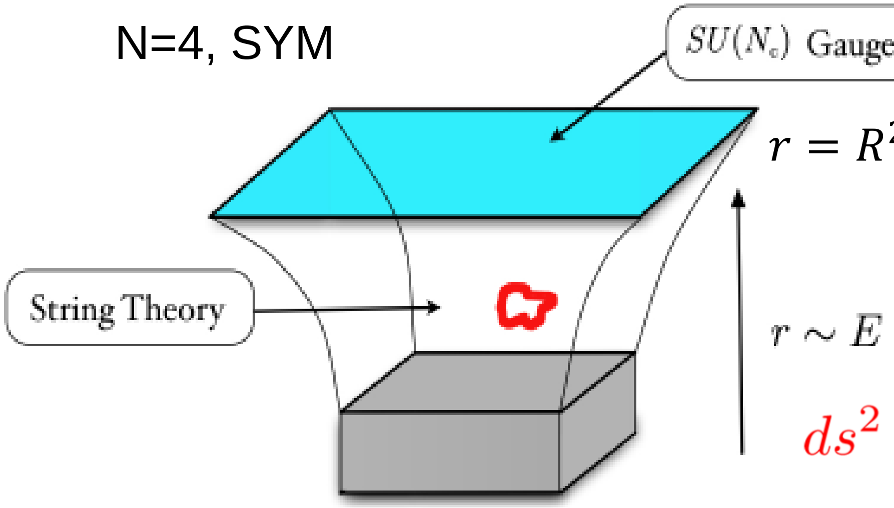
$$W_{th} \le W \lesssim 6 \text{ GeV}$$

AdS/CFT

- To establish the factorization with the trace anomaly is difficult with the perturbative approach.
- Non-perturbative approach : holography (AdS/CFT correspondence)
- n-dim strongly coupled gauge theory ↔ (n+1)-dim supergravity
- Operators $(T^{\mu\nu}, F^2)$ ↔ bulk fields on the boundary $(\delta g_{\mu\nu}, \phi)$
- Limitations : conjecture, large N_c, conformal, supersymmetric.

N=4, SYM

Maldacena, 97



$r = R^2/z$

$AdS_5 \times S^5$

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

Hard scattering in holography

- High-energy scattering in AdS/CFT : too steep rise of cross section due to the spin-2 nature of gravitons

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

- Low-energy scattering :
  - The rise due to gravitons is more comparable with experiments
  - Dilatons play a more important role

Theoretical setup

- Introduce heavy quarks : D3/D7 model

M. Kruczenski, D. Mateos, R. Myers, D. Winters (03)

DBI action : $S_{D7} = -T_{D7}\int d^8\bar{\xi} e^{-\phi}\sqrt{-\det(G_{ab}+2\pi\alpha'\mathcal{F}_{ab})}$

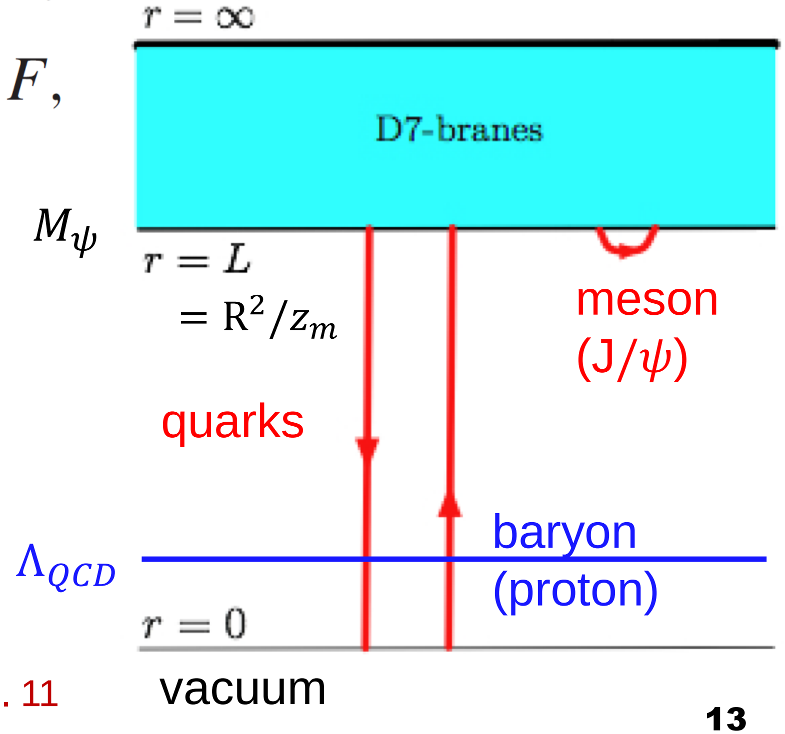
$$ds^2_{D7} = \frac{R^2}{z^2}\eta_{\mu\nu}dx^\mu dx^\nu - \frac{R^2}{z^2(1-\frac{z^2}{z_m^2})}dz^2 - \left(1-\frac{z^2}{z_m^2}\right)R^2 d\Omega_3^2$$

- Gauge-field fluctuations : $\mathcal{F} = \bar{F} + F,$

photons : $A_\mu \propto \epsilon_\mu e^{iq\cdot x}$

J/ψ : $\bar{A}_\mu \propto \xi_\mu e^{-ik\cdot x}\frac{z^2}{z_m^2}$

$$M_\psi = \frac{2\sqrt{2}}{z_m} = \frac{4\sqrt{2}\pi m_q}{\sqrt{g^2 N_c}}$$



review : J. Casalderrey-Solana, et.al. 11

Calculations for the matrix element

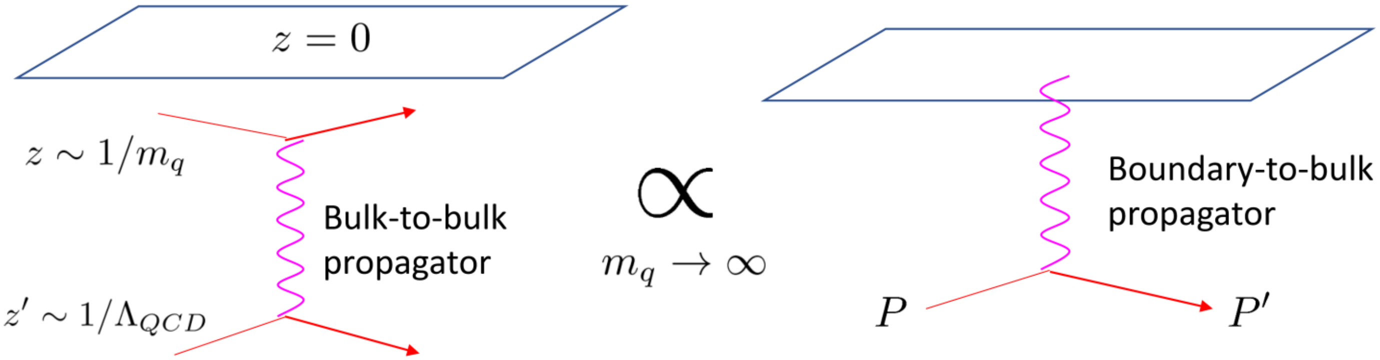
- Evaluate the matrix element in holography :

proton states

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

bulk to bulk propagators
(gravitons & dilatons)

- Heavy-quark limit : matching



e.g. $$\langle P|\frac{1}{4}F^2|P'\rangle \approx \frac{cR^3}{2\kappa^2}\frac{4}{z^4}\int d^4x'dz' iD(xz,x'z')\frac{\delta S_B}{\delta\phi}$$

Holographic results

- The matrix element :

work in the transverse-traceless (TT) gauge $\delta g_{Mz} = 0,\ \delta g^\mu_\mu = \nabla_\mu \delta g^{\mu\nu} = 0$

utilize Ji's parameterization

$$\langle P|\epsilon\cdot J(0)|P'k\rangle$$

$$\approx -\boxed{\frac{2\kappa^2}{f_\psi R^3}}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}}\frac{z^2R^2}{4}\boxed{\langle P|T^{gTT}_{\mu\nu}|P'\rangle}$$

$$+\boxed{\frac{2\kappa^2}{f_\psi R^3}}\frac{3}{8}\int_0^{z_m} dz\,\frac{\delta S_{D7}(q,k,z)}{\delta \phi}\frac{z^4}{4}\boxed{\langle P|\frac{1}{4}F^{\mu\nu}_a F^a_{\mu\nu}|P'\rangle}$$

treated as an overall const.

- Results : $\langle P|\epsilon\cdot J|P'k\rangle = \bar{u}(P')(X\Pi^{\mu\nu}\boxed{\Gamma_{\mu\nu}} + Y\Pi^\mu_\mu\boxed{\Gamma})u(P),$

depend on gravitational from factors

D3/D7
$$\begin{cases} Y = -\dfrac{11}{80}X \\ \Pi^{\mu\nu}(q,k) \equiv q^{(\mu}k^{\nu)}\epsilon\cdot\xi + \epsilon^{(\mu}\xi^{\nu)}q\cdot k - q^{(\mu}\xi^{\nu)}k\cdot\epsilon - k^{(\mu}\epsilon^{\nu)}q\cdot\xi \end{cases}$$

Gravitational form factors

- Revisit the parameterization :

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

$$\bar{P}^\mu \equiv \frac{P^\mu + P'^\mu}{2}.$$

- Some constraints : $A_q(0) + A_g(0) = 1,$ $\bar{C}_q(t) = -\bar{C}_g(t)$

(forward limit)

(energy-momentum conservation)

- Dipole form (assumption) : $A_{q,g}(t) = \dfrac{A_{q,g}(0)}{(1-t/\Lambda^2)^2},$

Frankfurt, Strikman (2002)
(fit exp)
EM : $\Lambda^2 = 0.71\ \mathrm{GeV}^2$

(gluonic) trace anomaly-related parameter →

$b = 1$: no (gluonic) anomaly
$b = 0$: maximal anomaly

$$\bar{C}_g(t) = \frac{\frac{\boxed{1-b}+\gamma_m}{1+\gamma_m} - A_g(0)}{4\boxed{(1-t/\Lambda^2)^2}} = -\bar{C}_q(t),$$

(assuming the same suppression at large t as A)

Neglect $B_{q,g}$ (exp & lattice)

- Gluon D term : $D_g(t) = 4C_g(t)$

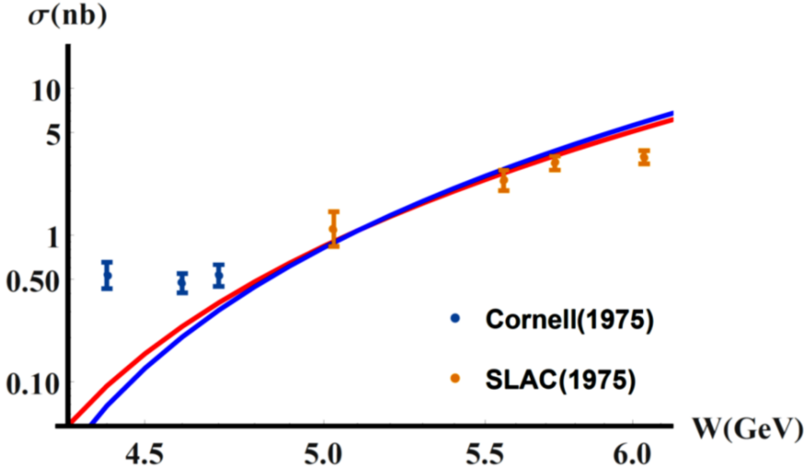
$$C_g(t) = \frac{16}{3n_f}C_q(t) = \frac{16}{3n_f}\frac{-0.4}{(1-t/\Lambda^2)^3}$$

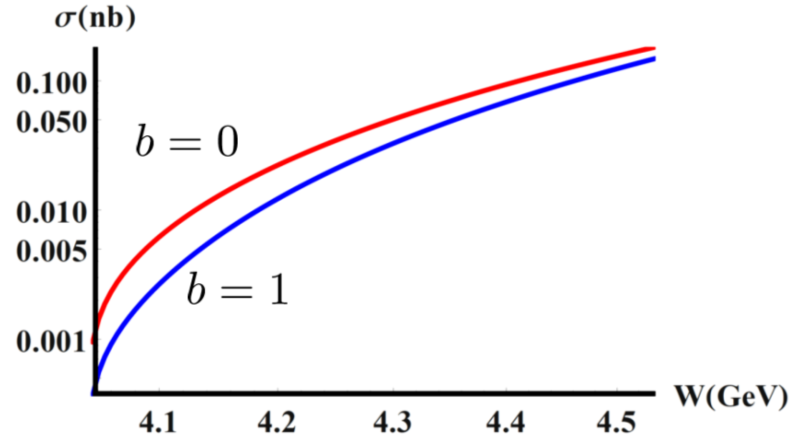
model, Tanaka(18)

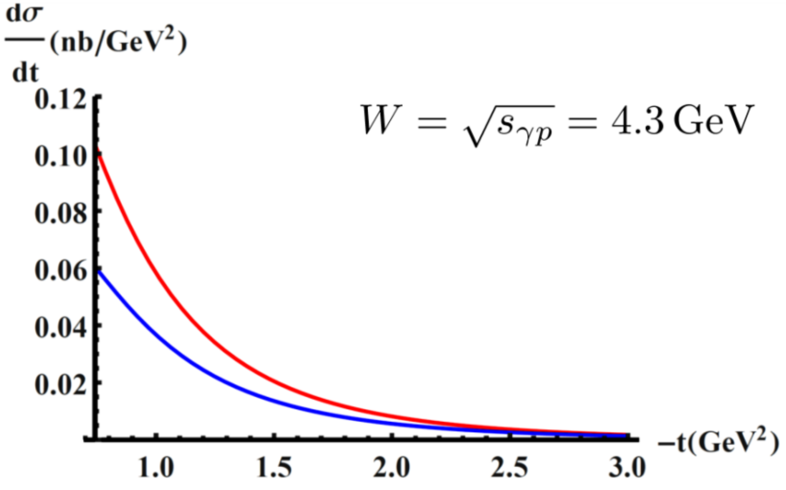
Numerical results

$$M_m = \frac{1}{4}\frac{\langle P|m(1+\gamma_m)\bar{\psi}\psi|P\rangle}{2M} \equiv \frac{b}{4}M$$

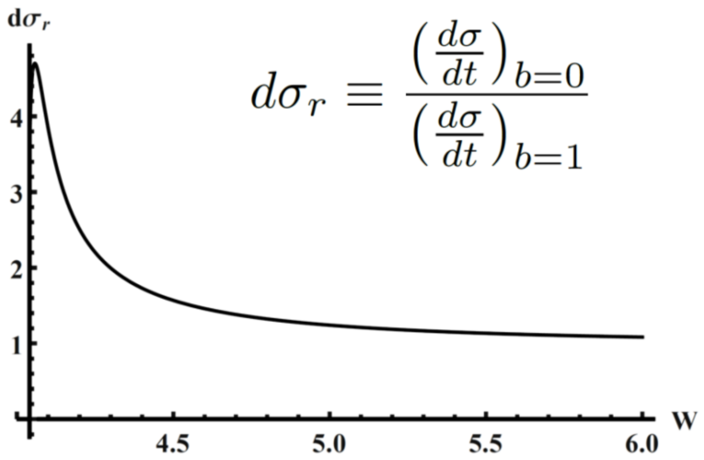
$$M_a = \frac{1}{4}\frac{\langle P|\frac{\beta}{2g}F^2|P\rangle}{2M} \equiv \frac{1-b}{4}M$$







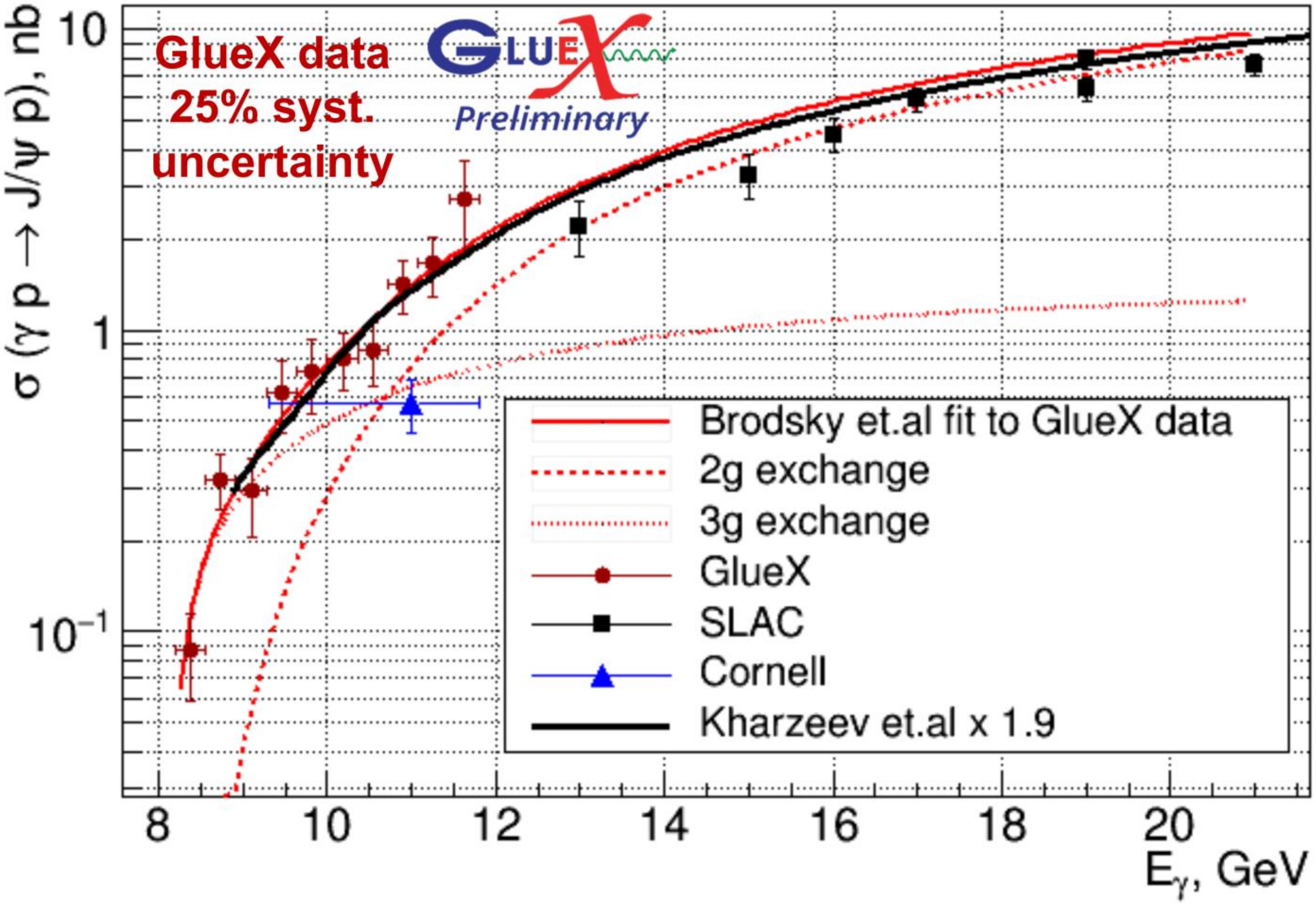
$$W = \sqrt{s_{\gamma p}} = 4.3\,\text{GeV}$$



$$d\sigma_r \equiv \frac{\left(\frac{d\sigma}{dt}\right)_{b=0}}{\left(\frac{d\sigma}{dt}\right)_{b=1}}$$

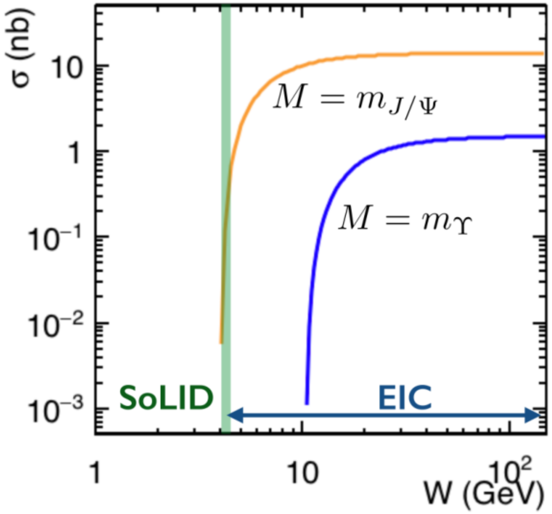
Preliminary data from Jlab

- Lubomir Pertchev’s talk in QNP2018



Conclusions & outlook

- Quarkonium photoproduction near threshold is sensitive to $\langle P'|F^2|P\rangle$.
- Toward EIC : higher energy $\longrightarrow$ Υ production



Talk by A. Deshpande
@Proton mass workshop (2017)

- In our present work, we only use the bare operators.
- How about using the renormalized one? Y. Hatta, A. Rajan, K. Tanaka, 18
  - The parameterization of $\langle P'|F_R^2|P\rangle$ is nontrivial
  - We need renormalized gravitational form factors
- t-dependence of gravitational form factors from models or lattice are welcome!

Thank you!

$$\langle P|T^{\mu\nu}_{q,\mathrm{kin}}|P\rangle = 2a(\mu^2)\left(P^\mu P^\nu - \frac{\eta^{\mu\nu}}{4}M^2\right),$$

$$\langle P|T^{\mu\nu}_{g,\mathrm{kin}}|P\rangle = 2(1-a(\mu^2))\left(P^\mu P^\nu - \frac{\eta^{\mu\nu}}{4}M^2\right),$$

$$\langle P|T^{\mu\nu}_{m}|P\rangle = \frac{1}{2}b(\mu^2)\eta^{\mu\nu}M^2,$$

$$\langle P|T^{\mu\nu}_{a}|P\rangle = \frac{1}{2}(1-b(\mu^2))\eta^{\mu\nu}M^2,$$

$$M_q = \frac{\langle P|H_q|P\rangle}{\langle P|P\rangle} = \frac{3a}{4}M,$$

$$M_g = \frac{\langle P|H_g|P\rangle}{\langle P|P\rangle} = \frac{3(1-a)}{4}M,$$

$$M_m = \frac{\langle P|H_m|P\rangle}{\langle P|P\rangle} = \frac{b}{4}M,$$

$$M_a = \frac{\langle P|H_a|P\rangle}{\langle P|P\rangle} = \frac{1-b}{4}M.$$

X.-D. Ji, 1995 : $\widetilde{M}_q = \frac{\langle P|H_q|P\rangle}{\langle P|P\rangle} = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M,$

$$\widetilde{M}_g = \frac{\langle P|H_g|P\rangle}{\langle P|P\rangle} = \frac{3(1-a)}{4}M,$$

$$\widetilde{M}_m = \frac{\langle P|H_m|P\rangle}{\langle P|P\rangle} = \frac{b}{4}\frac{4+\gamma_m}{1+\gamma_m}M,$$

$$\widetilde{M}_a = \frac{\langle P|H_a|P\rangle}{\langle P|P\rangle} = \frac{1-b}{4}M.$$