Gluonic structure of the nucleon at Jlab20+GeV

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Gluonic structure of hadrons

- Gluons generated from valence quarks are an important part of hadron structure,
  - Mass
  - Momentum
  - Spin
  - Gravitational form factors
  - Gluon PDFs, GPDs, TMDs, etc
- However, their effects are mostly known through high-energy scattering, jets, Q^2 evolution etc.

Questions for Jlab 20+ GeV upgrade

- Can one learn something about gluonic structure of the nucleon at Jlab 20+ GeV?
- Can one measure the energy-momentum tensor form factors?
- What are the theory predictions?
- Why the physics is important?

Questions for Jlab 20+ GeV upgrade

- Can one learn something about gluonic structure of the nucleon at Jlab 20+ GeV? (X. Ji)
- Can one measure the energy-momentum tensor form factors? (Y. Guo)
- What are the theory predictions? (Y. Guo)
- Why the physics is important? (X. Ji)

Can one learn something about gluonic structure of the nucleon at Jlab 20+ GeV?

Heavy-quarkonium production

- J/psi etc
- Gluon physics? problems:
  - J/Ψ may be produced through intrinsic heavy quarks.
    - Question of scale?
  - J/Ψ formation and final-state interactions (non-perturbative)
  - Large radiative corrections and higher-twist effects.

Limit of $m_Q \to \infty$

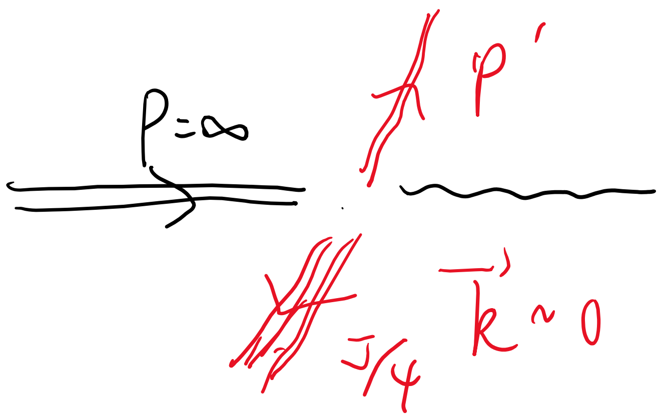
- Infinity m_Q limit might be a clean case.
- Conjectures:
    - Intrinsic contribution is suppressed.
    - At a reasonable flying out velocity v, the heavy quarkonium might have negligible FSI

      (Color transparency)
    - Heavy-quarkonium formation might is perturbative.
- One can organize an expansion in this limit.

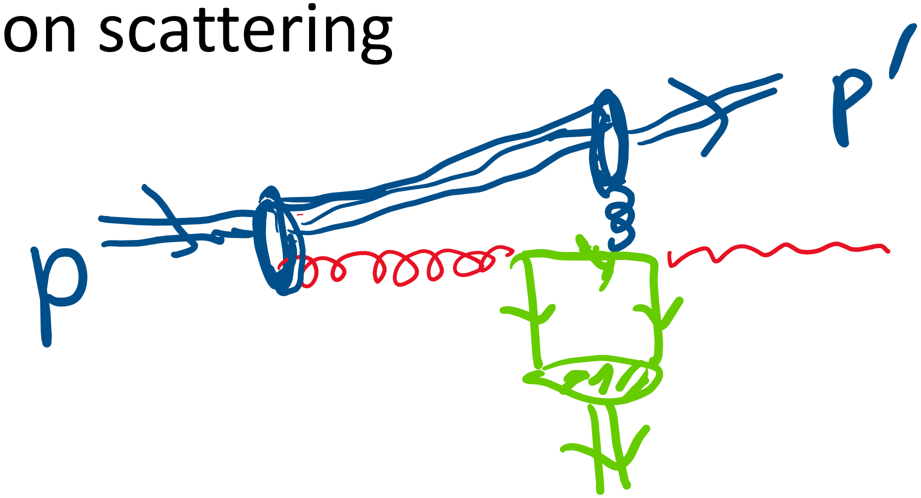
Y. Guo, X. Ji and Y. Liu, *Phys.Rev.D* 103 (2021) 9, 096010

Light-cone dominated process

- In the COM frame, the proton comes in Pz = ∞



- Parton scattering



Threshold J/psi production: new QCD factorization formula

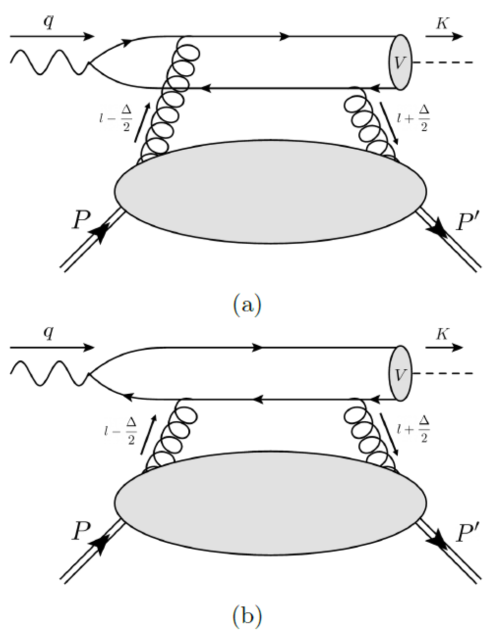


FIG. 4: Examples of leading Feynman diagrams that contribute to heavy vector meson photoproduction.

$$\frac{d\sigma}{dt} = \frac{e^2 e_Q^2}{16\pi\,(W^2 - M_N^2)^2}\frac{1}{2}\sum_{\text{polarization}} |\mathcal{M}(\varepsilon_V,\varepsilon)|^2 \;,$$

$$= \frac{\alpha_{\rm EM} e_Q^2}{4\,(W^2 - M_N^2)^2}\frac{(16\pi\alpha_S)^2}{3M_V^3}|\psi_{\rm NR}(0)|^2|G(t,\xi)|^2$$

$$G(t,\xi) = \frac{1}{2\xi}\int_{-1}^{1}\mathrm{d}x\mathcal{A}(x,\xi)F_g(x,\xi,t)\;. \qquad (14)$$

where the hard kernel $\mathcal{A}(x,\xi)$ reads

$$\mathcal{A}(x,\xi) \equiv \frac{1}{x+\xi-i0} - \frac{1}{x-\xi+i0}\;. \qquad (15)$$

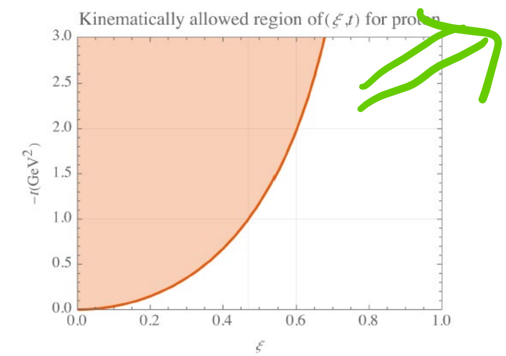
The standard gluon GPD F_g is defined as [40]

$$F_g(x,\xi,t) \equiv$$
$$\frac{1}{(\bar{P}^+)^2}\int\frac{\mathrm{d}\lambda}{2\pi}e^{i\lambda x}\left\langle P'\left|\mathrm{Tr}\left\{F^{+i}\left(-\frac{\lambda n}{2}\right)F_i^+\left(\frac{\lambda n}{2}\right)\right\}\right|P\right\rangle \qquad (16)$$

Compare with other factorization theorems

- Standard factorization in GPDs happens either in
  - Deeply virtual limit
    $Q^2 \to \infty$
    independent of meson mass
    J. Collins et al, Radyushkin (1996)
  - Real photon diffractive limit for heavy quarkonium,
    (FSI negligible due to high-energy final state)
    Ivanov et al, EJPC, **34** (2004) 297.

In Guo et al work, the factorization is due to small dipole size in the limit of heavy quark mass.



Large skewness

- Two gluons have very different light-cone momentum fraction

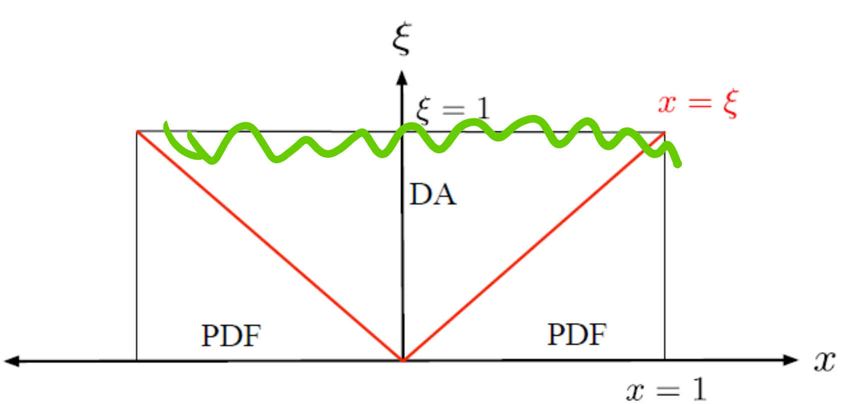
$$m_Q \to \infty,\ t \to \infty,\ \xi \to 1$$

(also Hatta & Strikman, 2021 in $Q^2 \to \infty$ limit, near threshold)

dominated by Distribution Amplitude (DA limit)

region, a very differ

$\xi \to 0$ (PDF limit)



Large-ξ expansion

- One might consider expand the gluon propagators in the large ξ limit

$$G(t,\xi) = \sum_{n=0}^{\infty} \frac{1}{\xi^{2n+2}} \int_{-1}^{1} dx x^{2n} F_g(x,\xi,t) \ .$$

- Leading contribution: leading-twist gluon energy momentum tensor form factors

$$G(t,\xi) = \frac{1}{\xi^2(\bar{P}+)^2} \langle P' | \frac{1}{2} \sum_{a,i} F^{a,+i}(0) F^{a,+}{}_i(0) | P \rangle$$

$$= \frac{1}{2\xi^2(\bar{P}+)^2} \langle P' | T_g^{++} | P \rangle \ , \qquad (2$$

Gravitations form factors

- Form factors of EMT for quarks and gluons (Ji, 1996)

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

Twist-2, A, B, C, twist-4, C-bar

- Form factors for the total EMT (Pagels, 1966)

$$\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\Big[A(Q^2)\gamma^{(\mu}\bar{P}^{\nu)} + B(Q^2)\bar{P}^{(\mu}i\sigma^{\nu)\alpha}q_\alpha/2M + C(Q^2)(q^\mu q^\nu - g^{\mu\nu}q^2)/M\Big]u(P),$$

$A = A_q + A_g,\ B\ \&\ C\ etc.,\ \ \bar{C}_q + \bar{C}_g = 0$

Why the physics is important?

Physics of EMT form factors

- Mass radius
- Momentum current form factor C & Tensor monopole moment
- Scalar fields and radius
- Anomalous contribution to proton mass

Mass form factor/radius

$$\langle P' | T^{00} | P \rangle = \bar{u}(P') u(P) G_m(Q^2) \ .$$

where

$$G_m(Q^2) = \left[M A(Q^2) - B(Q^2) \frac{Q^2}{4M} + C(Q^2) \frac{Q^2}{M} \right]$$

$$\langle r^2 \rangle_{s,m} = -6 \frac{dG_{s,m}(Q^2)}{dQ^2} \ ,$$

$$\langle r^2 \rangle_m \ = \ -6 \frac{dA(Q^2)}{dQ^2} - 6 \frac{C(0)}{M^2} \ ,$$

- Is Mass radius bigger or smaller than the charge radius?
- How much comes from the gluons?

C(q): momentum current FF

- The physics of this form factor is best seen in the Breit frame in which it is the form factor for momentum current.

$$\langle T^{ij} \rangle \sim \left(q^i q^j - \delta^{ij} q^2\right) C(q)$$

which generates gravitational field according to Einstein's equation.

- Tensor-monopole moment,

$$\tau \sim \int d^3r \, (Y_2 \times T)\text{^}0 \sim C(0)/M$$

which generates a particular type of gravitationl potential (Ji & Liu, e-Print: 2110.14781)

Tensor monopole moment of hydrogen atom

- Zero-th order

$$\tau_0 = \hbar^2/4m_e$$

positive!

for proton, it might be negative, $\tau_p = D(0)\hbar^2/4M_p$

- Radiative correction

$$\tau = \tau_0\left(1 + \frac{4\alpha}{3\pi} ln\alpha\right)$$

X. ji & Y. Liu, hep-ph/2208.05029

Trace anomaly, mass scale, and scalar form factor

- Form factor of the scalar density

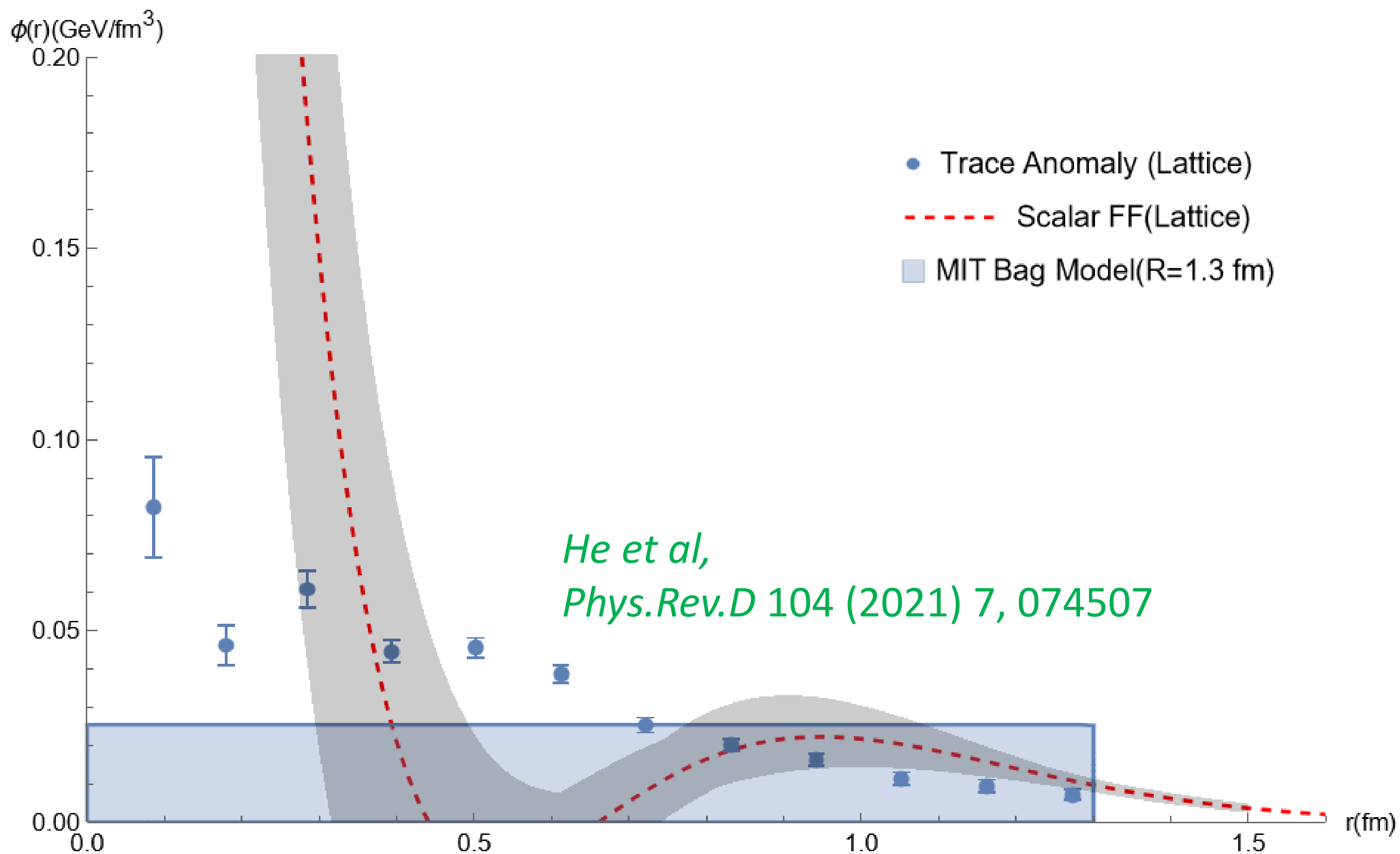
$$\langle P' | T^{\mu}_{\mu} | P \rangle = \bar{u}(P') u(P) G_s(Q^2) \ ,$$

where,

$$G_s(Q^2) = \left[M A(Q^2) - B(Q^2) \frac{Q^2}{4M} + C(Q^2) \frac{3Q^2}{M} \right]$$

- Fourier transformation of Gs gives us the scalar field distribution inside the Nucleon
- Dynamical MIT "bag constant".
- One can determine the mass scale without directly measuring F^2 matrix element! (EMT conservation)

Scalar field (QAE) distribution inside the proton



Scalar and mass radii

- Scalar radius

$$\langle r^2 \rangle_s = -6 \frac{dA(Q^2)}{dQ^2} - 18 \frac{C(0)}{M^2}$$

- The difference

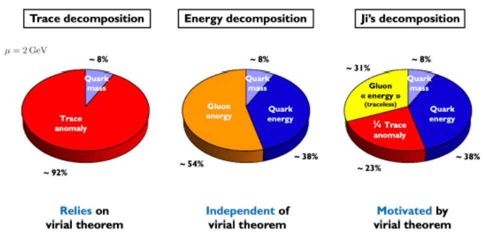
$$\langle r^2 \rangle_s - \langle r^2 \rangle_m = -12 \frac{C(0)}{M^2}$$

- Conjecture $\langle r^2 \rangle_s > \langle r^2 \rangle_m$ or $C(0)<0$

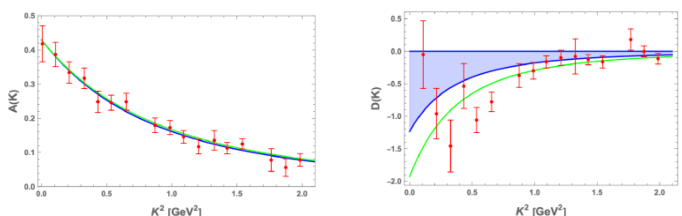
Mass decomposition

Science case rapidly evolving

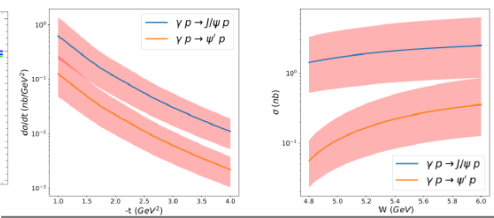
PROMINENT NEW DEVELOPMENTS



Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)

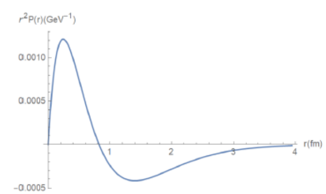


Proton gravitational form factors holographic QCD compared with Lattice, K. Mamo & I. Zahed (2022)

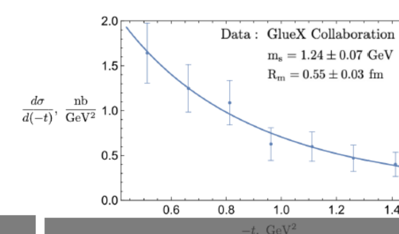


Near-threshold heavy quarkonium production at large momentum transfer, P. Sun, X-B. Tong, F. Yuan (PRD 2022)

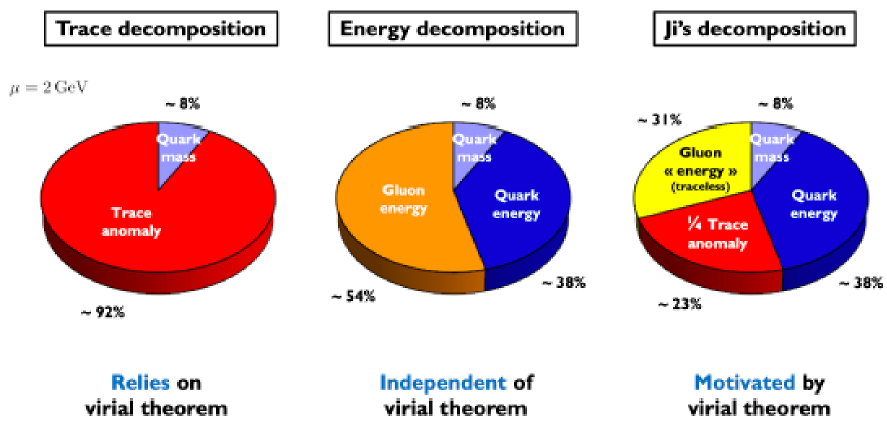
- A hot topic: many theoretical developments, and pace of publications only speeding up!
- Many extractions depend on extrapolating to the forward limit (t=0), which introduces theoretical systematic uncertainties. Best way to mitigate is high-precision data at high-t.



Gluon contribution to pressure in GPD formalism, Y. Guo, X. Ji, Y. Liu, (PRD 2021)



Gluonic radius of the proton based on 1D GlueX results, D. Kharzeev (PRD 2021)



Proton mass budget decompositions, C. Lorce (from 2022 INT workshop)

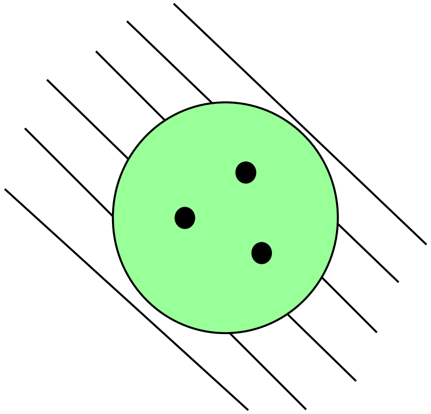
- Trace decomposition is not a proper mass sum rule.
- The so-called "energy decomposition" fails to recognize there are two types of the gluon energy contributions (although it is obtained by explicit sum)
  - Gluon energy as seen in Higgs production at LHC
  - Gluon scalar field response to the valence quarks (quantum anomalous energy!)

Quantum anomalous energy (QAE) contribution to the proton mass:

- The scalar field has a VEV: $\langle 0|F^2|0\rangle$
- QAE comes from the scalar response to the presence of the quarks.

$$\phi = F^2 - \langle 0|F^2|0\rangle$$

- QCD Higgs mechanism, with gluon scalar as a dynamical Higgs field.
- This contribution is like bag constant in MIT bag model.
- Instanton susceptibility (I. Zahed, *Phys.Rev.D* 104 (2021) 5, 054031)



Final comments

- It might be possible to learn something interesting about gluon content of the nucleon at Jlab
- 20+ GeV opens up a lot of more phase space
  - to test reaction mechanism (near & away from threshold)
  - to make precision measurements.
- A lot of theory work to do