NANJING UNIVERSITY

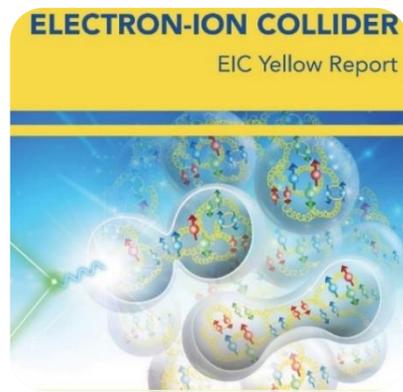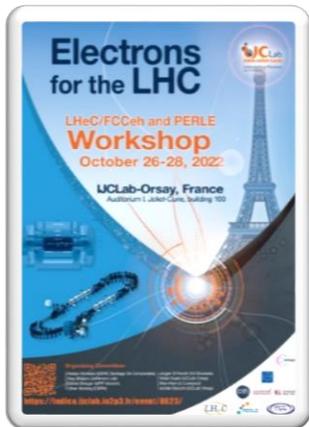Craig Roberts … http://inp.nju.edu.cn/

# Insights into Meson & Baryon Structure via Continuum Schwinger Function Methods

# *Basic Questions for 21ˢᵗ Century Science*

➢ 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?

➢ Response … International community is operating, building, and planning facilities with the potential for delivering answers

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# Quantum Chromodynamics

$$L = \frac{1}{4} G_{\mu\nu}^a(x) G_{\mu\nu}^a(x) + \bar{\psi}\left[\gamma \cdot \partial_x + m + ig\,\frac{\lambda^a}{2}\gamma \cdot A^a(x)\right]\psi(x)$$

$$G_{\mu\nu}^a(x) = \partial_\mu A_\nu^a(x) - \partial_\nu A_\mu^a(x) - f^{abc} A_\mu^b(x) A_\nu^c(x)$$

➢ One-line Lagrangian – expressed in terms of gluon and quark partons

➢ Which are NOT the degrees-of-freedom measured in detectors

## Questions

➢ What are the (asymptotic) detectable degrees-of-freedom?

➢ How are they built from the Lagrangian degrees-of-freedom?

➢ Is QCD really the theory of strong interactions?

➢ Is QCD really a theory … or just another EFT?
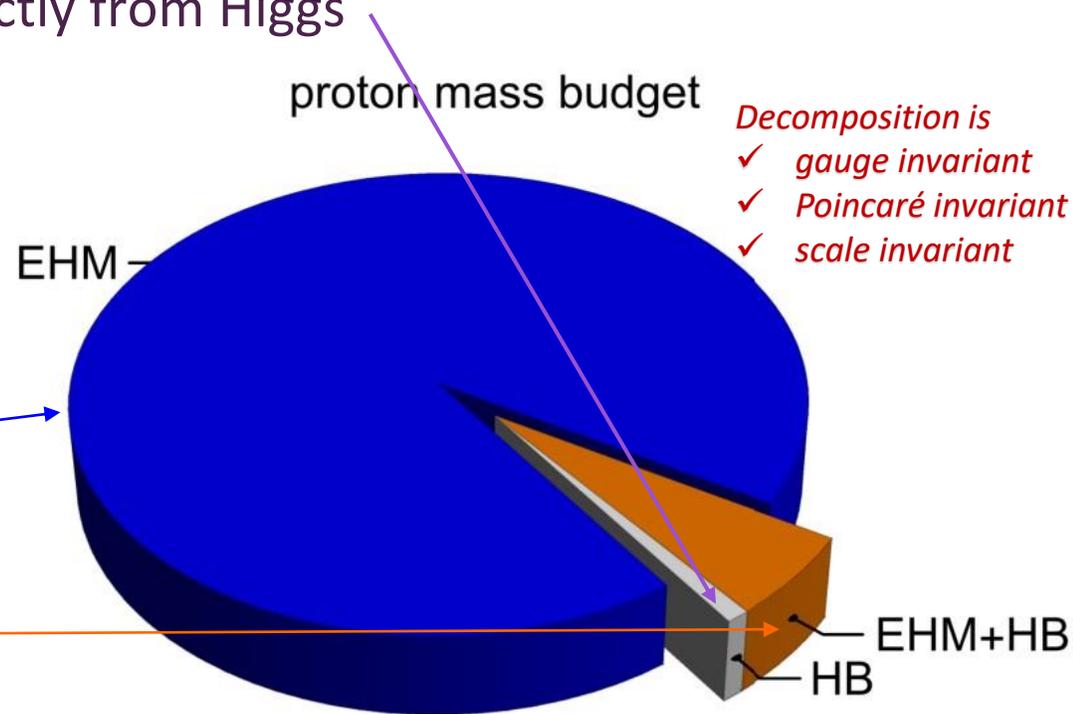
      ⇒ Implications far beyond Standard Model

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# Emergence of Hadron Mass

➤ Standard Model of Particle Physics has one obvious mass-generating mechanism

    = Higgs Boson … impacts are critical to evolution of Universe as we know it

➤ However, Higgs boson alone is responsible for just ~ 1% of the visible mass in the Universe

➤ Proton mass budget … only 9 MeV/939 MeV is directly from Higgs

➤ Evidently, Nature has another very effective mechanism for producing mass:

   Emergent Hadron Mass (EHM)

   ✓ Alone, it produces 94% of the proton's mass

   ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson

➤ *What is the origin of EHM?*



proton mass budget

EHM —

*Decomposition is*
✓ *gauge invariant*
✓ *Poincaré invariant*
✓ *scale invariant*

EHM+HB

HB

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GENESIS

GLUON

*In the Beginning…*

# Ancient History

Cornwall's estimate: $m_g = 0.5(2)\,\text{GeV} \approx \frac{1}{2}m_p$

➢ ≈ 45 years ago

*Dynamical mass generation in continuum quantum chromodynamics,*
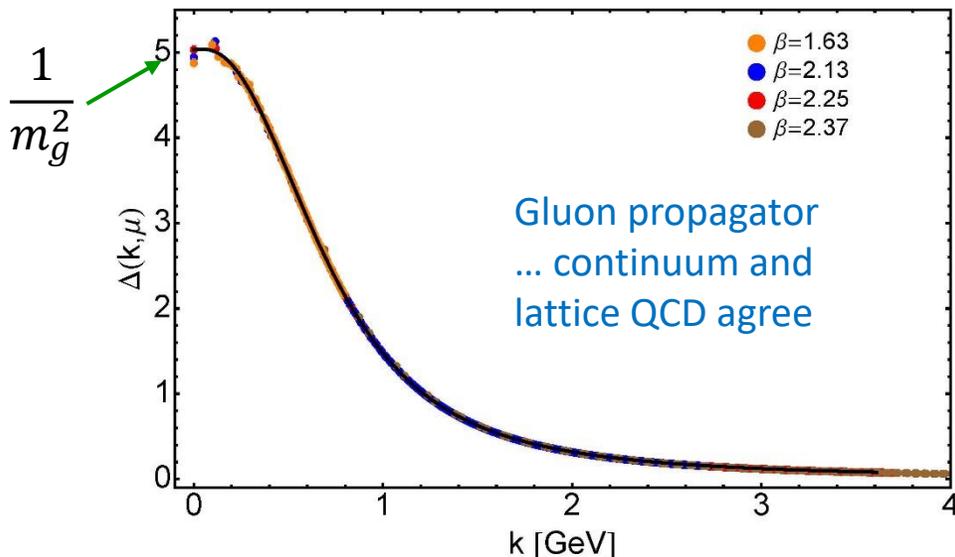J.M. Cornwall, Phys. Rev. D **26 (**1981) 1453 ... > 1100 citations

➢ Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles,
described by a mass function that is large at infrared momenta

3-gluon vertex

4-gluon vertex

$\frac{1}{m_g^2}$



Gluon propagator
... continuum and
lattice QCD agree

*Truly* <u>mass from nothing</u>
*An interacting theory, written in*
*terms of massless gluon fields,*
*produces dressed gluon fields that*
*are characterised by a mass function*
*that is large at infrared momenta*

✓ *QCD fact*
✓ *Continuum theory and*
*lattice simulations agree*

✓ *Empirical verification?*

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D. Binosi, *Emergent Hadron Mass in Strong Dynamics*, Few Body Syst. **63** (2022) 42.

M. N. Ferreira, J. Papavassiliou, *Gauge Sector Dynamics in QCD*, Particles **6** (1) (2023) 312–363.

## *Ancient History*
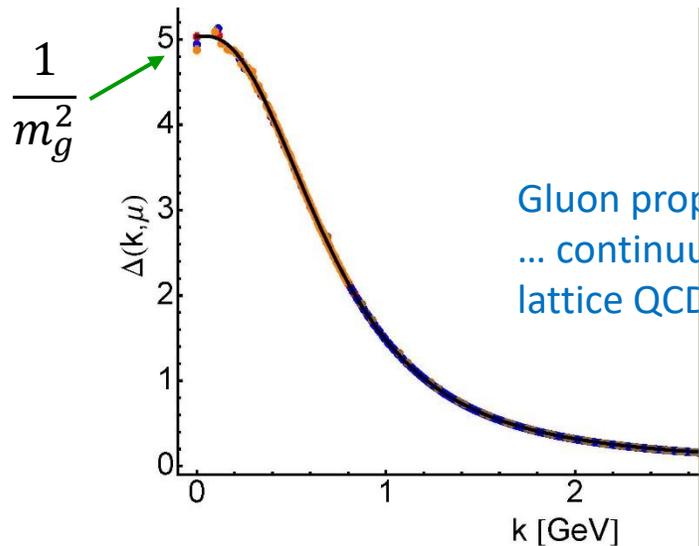
Today's best estimate: $m_g^{\mathrm{RGI}} = 0.43(1)\mathrm{GeV}$
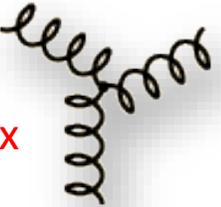
*Gauge Invariance and Mass*,
J. S. Schwinger
Phys. Rev. 125 (1962) 397-398
*It is argued that the gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong.*

3-gluon vertex

4-gluon vertex

# EHM means Gluons are massive via Schwinger Mechanism

...ics,

...siparticles,
...menta

Gluon prop
... continu
lattice QCD

$\dfrac{1}{m_g^2}$

$\Delta(k,\mu)$

k [GeV]

✓ *QCD fact*
✓ *Continuum theory and lattice simulations agree*
✓ *Empirical verification?*

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# *Process independent effective charge = running coupling*

- Modern theory – exploiting pinch technique and background field method – enables unique QCD analogue of

  "Gell-Mann – Low"

  running charge to be

  rigorously defined and calculated

- Analysis of QCD's gauge sector

  yields a *parameter-free prediction*

- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx \frac{1}{2} m_p$

- No Landau Pole

- Below $k \sim \hat{m}_0$ , interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again
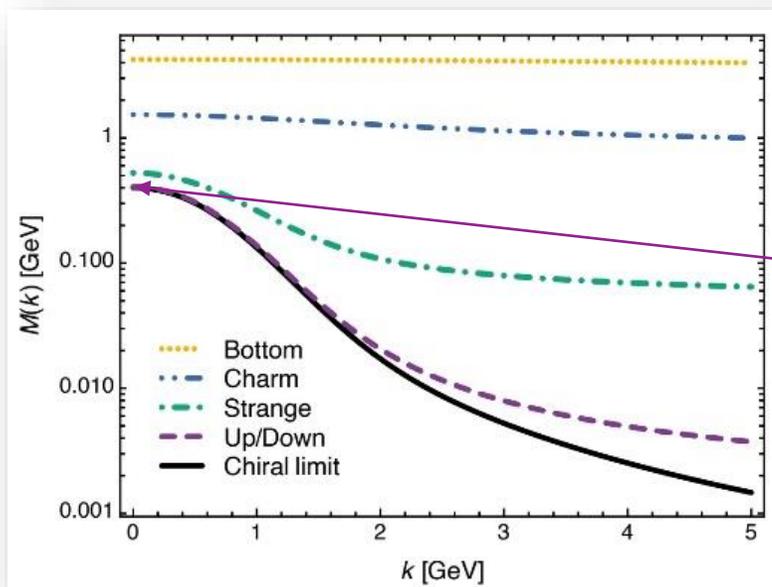
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✓ *Process independent strong running coupling*
  Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.*
  A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171

✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig Roberts, e-Print: 2303.00723 [hep-ph], Prog. Part. Nucl. Phys. **134** (2024) 104081

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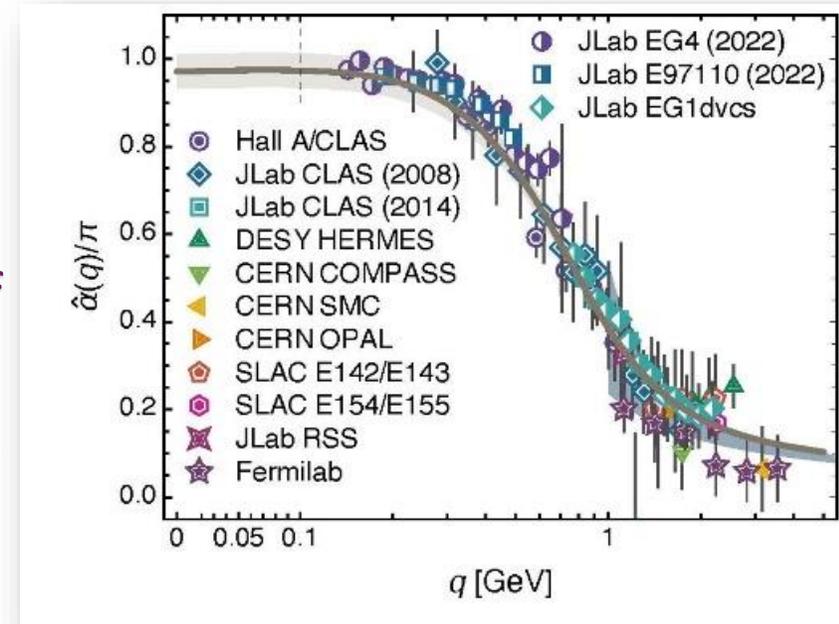*Intern. Conf. on Structure of Baryons (Baryons 2025) .. 2025/11/10-14*     (33)

# *EHM Basics*

➢ Absent Higgs boson couplings,
     QCD Lagrangian is scale invariant ... yet ...

  ✓ Massless gluons become massive

  ✓ A momentum-dependent, IR saturating charge is produced

  ✓ Massless quarks become massive

## THREE PILLARS OF EHM

✓ $3 \times M(0)$ sets the scale of the proton mass.

✓ Meson-loops provide 20% quantum corrections

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# *EHM Basics*

This result is the key to EHM in matter sector

Massless quark partons
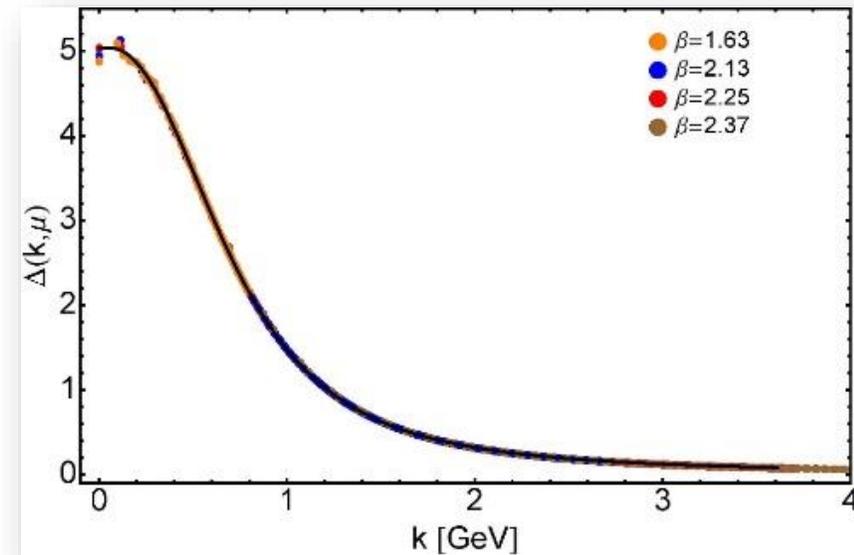become massive quark quasiparticles

$$f_\pi \sim M_0^{\bar{m}}(0)$$

➤ Absent Higgs boson couplings,
QCD Lagrangian is scale invariant … yet …

   ✓ Massless gluons become massive

   ✓ A momentum-dependent, IR saturating charge is produced

   ✓ Massless quarks become massive



## THREE PILLARS OF EHM



   ✓ $3 \times M(0)$ sets the scale of the proton mass.

   ✓ Meson-loops provide 20% quantum corrections



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# *One aspect of pseudoscalar meson physics*

# Era of Meson "Targets"



A — elastic form factors: $\gamma(q)$, $\pi$, $\pi^*$, $p(k)$, $t$, $n(k')$

B — parton distributions: $\gamma(q)$, $X$, $\pi^*$, $p(k)$, $t$, $n(k')$

➤ JLab & EIC & EicC

  – High luminosity electron ( + ion) beams

  – Access to meson targets via the Sullivan Process,

  i.e., a baryon's "meson cloud"

➤ AMBER @ CERN SPS

  – High-intensity beams of pions

  ( $\gtrsim 10^7$ pions/sec in Phase-1 = approved)
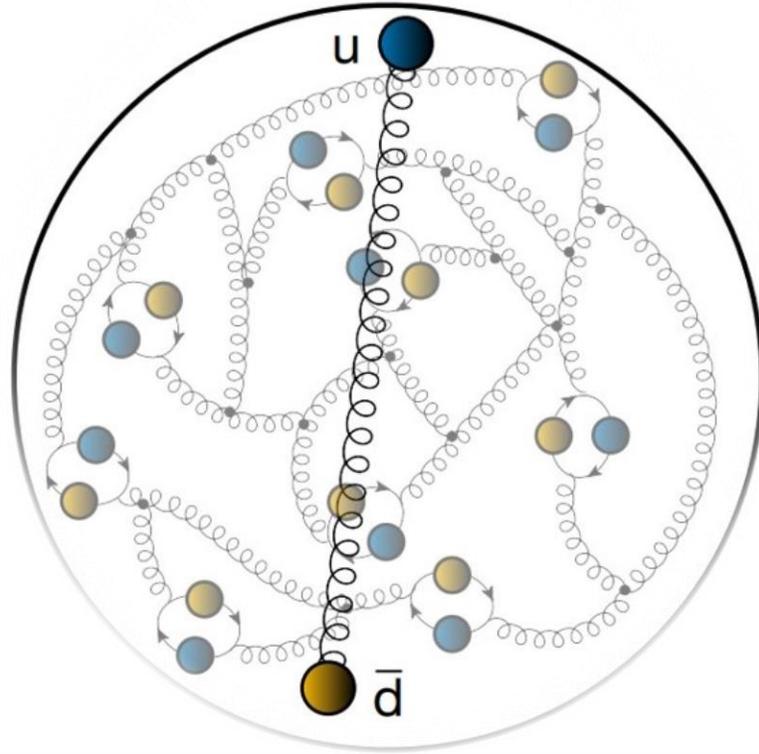
  and kaons ($5 \times 10^6$ kaons/sec Phase-2 = proposal

  being prepared)

  – Drell-Yan, J/ψ production, prompt photon production

  … from proton and nuclear targets





$N$, $\mu^+$, $\gamma$, $\mu^-$, $\pi/K$

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# Pseudoscalar Meson Electromagnetic Form Factors

➢ First precise data (beyond charge radius domain) obtained at JLab and published in 2001

> J. Volmer *et al.*, *Measurement of the Charged Pion Electromagnetic Form-Factor,* Phys. Rev. Lett. 86 (2001) 1713-1716

Obtained using Sullivan Process
= scattering electrons from pions in the proton's meson cloud

➢ Today, 9 precise data are available, out to $Q^2 \approx 2.5 \text{ GeV}^2$

➢ New results from JLab anticipated within 1 year, pushing coverage to $Q^2 \approx 9 \text{ GeV}^2$

➢ High-profile experiments planned and being developed for EIC and EicC

*Why?*

# Hard QCD Prediction

G. P. Lepage, S. J. Brodsky, Phys. Lett. B 87 (1979) 359–365.
A. V. Efremov, A. V. Radyushkin, Phys. Lett. B 94 (1980) 245–250.
G. P. Lepage, S. J. Brodsky, *Exclusive Processes in Perturbative Quantum Chromodynamics*, Phys. Rev. D 22 (1980) 2157–2198.

➢ Delivered $\approx 45$ years ago … positive-charge pseudoscalar meson $P$, constituted from valence $f, \bar{g}$ quarks:

$$\exists\, Q_0 \gg m_p \mid Q^2 F_P(Q^2) \overset{Q^2 > Q_0^2}{\approx} 16\pi\alpha_s(Q^2) f_P^2 w_{\varphi_P}^2(Q^2),$$

$$w_{\varphi_P}^2 = e_f w_{\varphi_{Pf}}^2 + e_{\bar{g}} w_{\varphi_{P\bar{g}}}^2$$

$$w_{\varphi_{Pf}} = \frac{1}{3} \int_0^1 dx \, \frac{1}{x} \varphi_P(x; Q^2),$$

$$w_{\varphi_{P\bar{g}}} = \frac{1}{3} \int_0^1 dx \, \frac{1}{1-x} \varphi_P(x; Q^2),$$

➢ $\alpha_s(Q^2)$ is QCD running coupling

➢ $f_P$ is pseudoscalar meson's leptonic decay constant

➢ $\varphi_P(x; Q^2)$ is meson's leading parton distribution amplitude (DA) – like a quantum field theory wave function – evaluated at the hard scale of the interaction

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# Hard QCD Prediction

$$\exists\, Q_0 \gg m_p \mid Q^2 F_P(Q^2) \overset{Q^2 > Q_0^2}{\approx} 16\pi\alpha_s(Q^2) f_P^2 w_{\varphi_P}^2(Q^2),$$

➤ Hard QCD prediction is remarkable.

- beyond some momentum scale, the meson form factor is precisely known
  - magnitude (normalisation) is set by meson leptonic decay constant, which is an order parameter for dynamical chiral symmetry breaking (DCSB) – a corollary of EHM
  - and scaling violations are apparent, with $Q^2$ dependence determined by that of the running coupling and evolution of the DA (wave function)
- Analogous proton equation – magnitude (normalization) is not known

➤ On domain $m_p^2/Q^2 \simeq 0 \Rightarrow \varphi_{P=\pi,K}(x) = 6\, x(1-x)$ and right-hand side $\Rightarrow 16\pi\alpha_s(Q^2) f_P^2$

➤ Two outstanding issues:

- what is value of $Q_0$ for which scaling violations become apparent?
- and what is pointwise form of $\varphi_P(x; Q^2)$ at scales for which terrestrial experiments are possible?

➤ These questions can only be answered using a nonperturbative approach to QCD.

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# *Pseudoscalar Meson Electromagnetic Form Factors*

- $(p_f + p_i)F_P(Q^2) = e\langle P(p_f)|\bar{\psi}\gamma_\mu\psi|P(p_i)\rangle$

  Hadron part of $e^- M \rightarrow e^- M$ matrix element defines meson form factor

- Leading order in systematically improvable, symmetry preserving truncation of QCD equations of motion (Dyson-Schwinger equations)

- Calculate the displayed matrix element using

  - ✓ 2-point Schwinger functions (propagators) and effective charge describe above

  - ✓ Poincaré-covariant Bethe-Salpeter equation to deliver

    - ✓ meson wave function
    - ✓ photon-quark vertex



Figure 1: Matrix element characterising the $f\bar{g}$ meson elastic electromagnetic form factor in rainbow-ladder (RL) truncation. Legend. $\Gamma^{f\bar{g}}$ – Bethe-Salpeter amplitude for the $f\bar{g}$ meson; $S^{f,g}$ – dressed quark propagators; $\mathcal{V}_\mu^{f,\bar{g}}$ – dressed photon–$f, \bar{g}$-quark vertex. All quantities calculated in RL truncation.

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# Pion Form Factor



A

➢ Low $Q^2$: CSM predictions for $Q^2 F_\pi(Q^2)$ – purple curve

– Charge radius agrees with experiment: 0.67 fm

– $Q^2$ dependence matches that JLab precision measurements [Horn:2007ug, Huber:2008id] (gold symbols)

➢ $Q^2 > 4\text{GeV}^2$

– *cf.* phenomenological – much loved, much used – vector meson dominance (VMD) result = dot-dashed red

  • VMD curve begins to deviate significantly from data and CSM prediction at upper bound of available JLab measurements

  • Best available lQCD (grey points) – pioneering work, pushing to high $Q^2$ … Heng-Tong Ding, *et al.*, Phys. Rev. Lett. **133** (2024) 181902

    – Desirable to improve precision

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# Pion Form Factor

- Salient feature of CSM predictions is existence of maximum in $Q^2 F_\pi(Q^2)$, which occurs on $Q^2 \simeq 4.6(5)\,\mathrm{GeV}^2$

- Thereafter, scaling violation apparent,

  $Q^2 F_\pi(Q^2)$ falls steadily toward zero as

  $\approx (1/\ln Q^2)^{\gamma_F}, \gamma_F \approx 1.1$

  consistent with hard QCD prediction

- *N.B.* Any model that expresses VMD must exhibit opposite trend, *viz.* result for $Q^2 F_\pi(Q^2)$ which rises steadily with increasing $Q^2$, without inflection, toward finite ultraviolet limit.

- Future: may see lattice-QCD reach and precision improved to (potentially) see breakaway from VMD and scaling violation

- green point farthest reach of anticipated JLab data

  – JLab is potentially capable of seeing breakaway from VMD

- black asterisks – anticipated EIC will see scaling violation

# *One aspect of baryon physics*

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- *Nucleon mass from a covariant three-quark Faddeev equation*
  G. Eichmann *et al.*, Phys. Rev. Lett. 104 (2010) 201601
- *Poincaré-covariant analysis of heavy-quark baryons*
  Si-Xue Qin (秦思学) *et al.*, Phys.Rev. D 97 (2018) 114017/1-13
- *Nucleon Gravitational Form Factors,*
  *Z.-Q. Yao (姚照干) et al., Eur. Phys. J. A 61 (2025) 92/1-13*



# Faddeev Equation for Baryons

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# Nucleon as a Bound State

*Nucleon charge and magnetisation distributions: flavour separation and zeroes,*
*Zhao-Qian Yao (姚照千), e-Print: 2403.08088 [hep-ph], Fund. Res. (2025) in press.*



➤ Nucleon bound-state problem can be addressed
  in any approach that provides access to the three-quark six-point Schwinger function

  – Using CSMs, one begins with the Poincaré-invariant Faddeev equation

  – Today, there are $\approx 5$ people in the world who can solve this problem

➤ The analysis to be described uses <u>precisely</u> the same approach (approximation and
  interaction) as that employed for pion and kaon electromagnetic form factors

  – Thus, one arrives at unifying set of parameter-free predictions for all pion and kaon and
    nucleon elastic electromagnetic and gravitational form factors and their species
    separations to large values of momentum transfer

  – All predictions link observables directly with fundamental QCD Schwinger functions and
    thereby expose novel expressions of emergent phenomena in QCD.

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# Electromagnetic Current

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# Nucleon charge and magnetisation distributions: zeroes and flavour separation

- ➢ Parameter-free unification of pion, kaon, nucleon electromagnetic form factors
  - – Equations: Gap + Bethe-Salpeter + 3-body Faddeev
- ➢ Proton electric form factor possesses a zero:
$$Q^2 = 8.86^{+1.93}_{-0.86} \text{ GeV}^2$$

- ➢ SPM ... working with the 29 available data on $\mu_p G_E^p / G_M^p$:
  - ✓ Predicts, with 50% confidence, data are consistent with existence of a zero on $Q^2 \leq 10.4 \text{GeV}^2$
  - ✓ Level of confidence increases to 99.9% on $Q^2 \leq 13.1 \text{GeV}^2$
  - ✓ Likelihood that existing data are consistent with absence of zero in ratio on $Q^2 \leq 14.5 \text{GeV}^2$ is 1/1-million

Figure 5: Final SPM prediction for the ratio $\mu_p G_E^p(Q^2)/G_M^p(Q^2)$. For comparison, the image also depicts the parameter-free Faddeev equation predictions [31, Fad-I, Fad-II] and the result obtained via a subjective phenomenological fit to the world's electron + nucleon scattering data [50, Ye]. The displayed data are from Refs. [21–25].

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# Nucleon charge and magnetisation distributions: zeroes and flavour separation

- Parameter-free unification of pion, kaon, nucleon electromagnetic form factors

  – Equations: Gap + Bethe-Salpeter + 3-body Faddeev

- Proton electric form factor possesses a zero:
$$Q^2 = 8.86^{+1.93}_{-0.86} \text{ GeV}^2$$

- Neutron electric form factor is positive definite
$$\Rightarrow G_E^n(Q^2) > G_E^p(Q^2) \text{ on } Q^2 \geq 4.7 \text{ GeV}^2$$

  – On this domain, electric form factor of charge-neutral neutron is larger than that of charge-one proton
  – Verification is within JLab reach



Prediction underestimates $G_E^n(Q^2)$ by 20%

FIG. 6.   Panel A: $\mu_p G_E^p / G_M^p$.  Panel B: $\mu_n G_E^n / G_M^n$.  SPM I – dashed orange curve within like-coloured band; and SPM II – solid red curve within like-coloured band.  Data: proton – Refs. [20–24]; and neutron – Refs. [87, 97].

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# *Nucleon Gravitational Form Factors*



$$[\Lambda^{(3)}_{n'n}]^{\delta'\delta}_{\mu\nu} = $$

➢ Current … complementing solution of Faddeev equation, then all elements are known

➢ Current …

$$m_N \Lambda^{Ng}_{\mu\nu}(Q) = -\Lambda_+(p_f)[K_\mu K_\nu A(Q^2)$$
$$+ iK_{\{\mu}\sigma_{\nu\}\rho}Q_\rho J(Q^2)$$
$$+ \frac{1}{4}(Q_\mu Q_\nu - \delta_{\mu\nu}Q^2)D(Q^2)]\Lambda_+(p_i) ,$$

- $A(Q^2)$ mass distribution form factor
  $$A(Q^2 = 0) = 1$$
- $J(Q^2)$ spin distribution form factor
  $$J(Q^2 = 0) = 1/2$$
- $D(Q^2)$ pressure distribution form factor
  $$D(Q^2 = 0) =?$$

Last unknown/unmeasured global property of nucleon

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# Predicted GFFs

➢ Solid curves … parameter-free CSM predictions

➢ Points lQCD results [Hackett:2023rif]

   – Agreement within (large) lattice uncertainties

➢ Symmetry-preserving character of CSM analysis is evident in values of

   – $A(0) = 1$

   – $J(0) = 1/2$

➢ nucleon "D-term" … prediction $D(0) = -3.11(1)$

➢ Is this big or small?  For the pion, answer = -1.



FIG. 1. Nucleon gravitational form factors. Curves – predictions herein: bracketing bands mark the extent of $1\sigma$ SPM uncertainty. In each case, the overall (species-summed) result is independent of resolving scale, $\zeta$. The species decompositions evolve with $\zeta$. The lQCD points in each panel are reproduced from Ref. [25]: black squares – total form factor; blue circles – glue component; red diamonds – quark.

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# Mass-energy density form factor

➤ Mass-energy density form factor

$$M(Q^2) = A(Q^2) + \frac{Q^2}{4m_p^2}[A(Q^2) - 2J(Q^2) + D(Q^2)]$$

$$\langle r^2 \rangle_{\text{mass}} = \left[ -6\frac{d}{dt}A(t)\Big|_{t=0} - 3\frac{D(0)}{2m_N^2} \right] \frac{1}{A(0)}$$

➤ Mechanical (normal force) radius, *viz*. force directed along 4-spherical radius vector

$$\langle r^2 \rangle_{\text{mech}} = \frac{6}{\int_0^\infty dt\,[D(t)/D(0)]}$$

➤ Poincaré- and scale-independent

   = *OBSERVABLES*

$$r_{\text{mass}} = 0.81(5)r_{\text{ch}}, \qquad r_{\text{mech}} = 0.72(2)r_{\text{ch}}$$

➤ $r_{\text{ch}} = 0.887(3)\text{fm}$

➤ On the other hand, species separated form factors are frame- and scale-dependent
   - Essentially subjective.

➤ No comparison between proton charge radius and quark-flavour radius or proton's gluon radius is objectively valid.

➤ Even a comparison between quark and glue radii is subjective
   - This ratio is different at different scales

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# GFF Species Decomposition (scale dependent, $\zeta_2 = 2\text{GeV}$)

➤ CSM prediction – species decomposition,

 for each form factor:

$$\frac{F^{\text{glue}}(Q^2; \zeta)}{F^{\text{quark}}(Q^2; \zeta)} = \text{constant}(\zeta)$$

➤ $\text{constant}(\zeta_2) = 0.71(4)$

<span style="color:red">namely, at a given scale, the ratio of glue:quark</span>

<span style="color:red">contributions is the same $Q^2$-independent number</span>

<span style="color:red">for each form factor</span>

Important to test this prediction

➤ lQCD results … see figure

   &ndash; Consistent with prediction

   &ndash; $\text{constant}_{\text{lQCD}}(\zeta_2) = 0.82(18)$
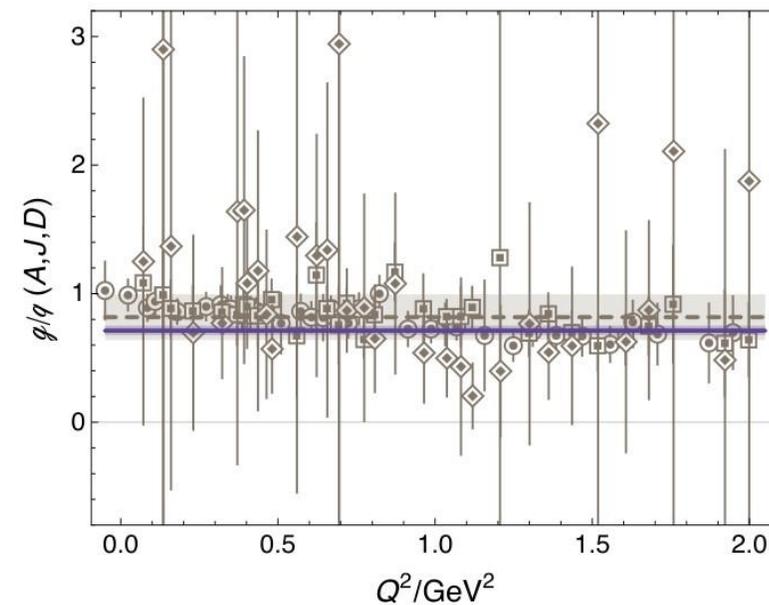


FIG. S.8. Combined $A$, $J$, $D$ lQCD $g/q$ results (grey points): grey line – uncertainty weighted average of all points; and grey band – $1\sigma$ around the central value: 0.82(18). Prediction herein: $g/q = 0.71(4)$ (purple line and band).

# Proton Pressure Profiles

A


- ➤ Pressure and shear-force density profiles: determined by $D(Q^2)$ for proton and $\theta_1(Q^2)$ for pion
- ➤ Pion (green) peak values are roughly twice those in the proton
  - – Expected because
    - • pressures $\sim \Psi^2$
    - • similar interior QCD dynamics + more compact object
    $$\Rightarrow \frac{p_\pi}{r_\pi^2} \approx p_p/r_p^2 \ \& \ r_p^2 \approx 2\,r_\pi^2$$
- ➤ Scale is order-of-magnitude greater than neutron star core
- ➤ $r_{\text{mass}} = 0.81(5)r_{\text{ch}} > r_{\text{mech}} = 0.72(2)r_{\text{ch}}$
- ➤ Species decomposition $(\zeta_2)$
  - – $r_{\text{mass}}^q = 0.62(4)r_{\text{ch}} > r_{\text{mass}}^g = 0.52(3)r_{\text{ch}}$
  - – $r_{\text{mech}}^q = 0.55(4)r_{\text{ch}} > r_{\text{mech}}^g = 0.47(3)r_{\text{ch}}$
- ➤ *No existing experiment provides objective information on glue contributions to proton GFFs*
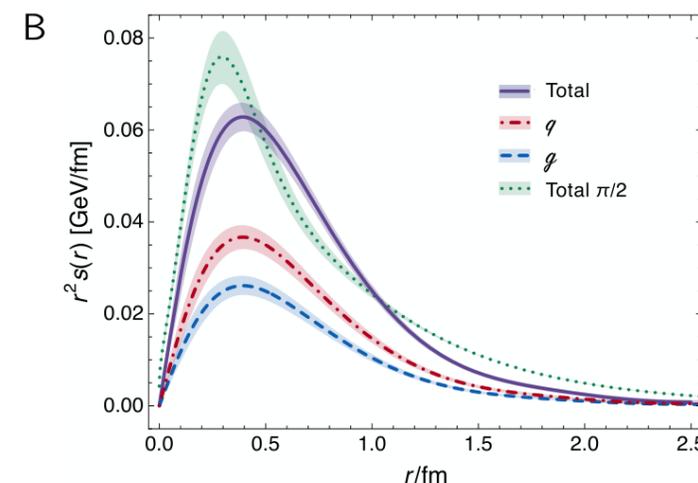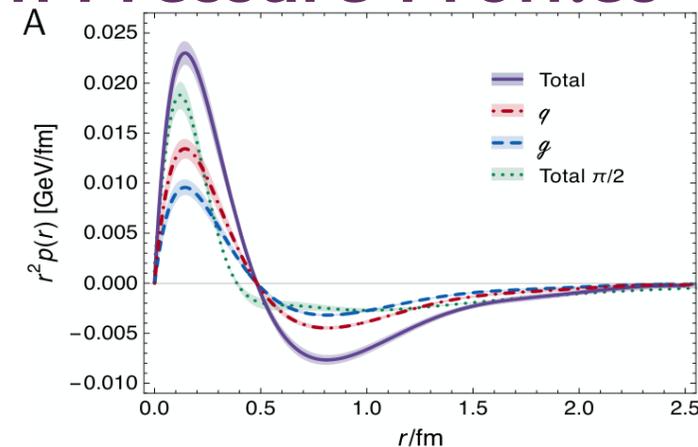
B


FIG. 3. Nucleon pressure, $p(r)$, and shear force, $s(r)$, distributions, along with total-quark and glue species decompositions at $\zeta_2$. Like pion distributions are drawn in green. *N.B.* The pion distributions are divided by 2. In all cases, the like-coloured band marks the extent of $1\sigma$ SPM uncertainty.

# Trace Anomaly Form Factor

- Some practitioners imagine that objective access to in-proton expectation value of trace of QCD energy momentum tensor

$$\langle p_{k_2}|T_{\mu\nu}(Q)|p(k_1)\rangle$$

  possible via photoproduction from proton of vector mesons that share no valence degrees of freedom in common with the proton

- Consequently, extensive new data available on

$$\gamma + p \rightarrow J/\psi + p$$

- Desire to calculate/predict the trace anomaly form factor

- Also, its species decomposition

  - ☐ In misguided attempt to decide whether the gluon parton density extends further than the proton charge radius



*VMD assumption*

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# Trace Anomaly Form Factor

➤ Mass-energy density form factor

$$M(Q^2) = A(Q^2) + \frac{Q^2}{4m_P^2}[A(Q^2) - 2J(Q^2) + \boxed{D(Q^2)}]$$

Nonnegative function = good for a mass distribution

➤ In-proton expectation value of QCD trace anomaly:

$$\theta(Q^2) = A(Q^2) + \frac{Q^2}{4m_P^2}[A(Q^2) - 2J(Q^2) + \boxed{3D(Q^2)}]$$

➤ $\theta(Q^2)$ is not positive definite
  – species decompositions have same feature.

➤ Unusual outcome for global property of a nucleon mass distribution

➤ Distributions of charge involve positive and negative charge carriers, hence can possess domains of negative support

➤ All physical mass is positive definite, so there is no good reason why a form factor definitive of mass should become negative.

➤ Somewhat arbitrary outcome: just
$$D_{\text{in } M} \rightarrow 3D_{\text{in } \theta}$$

# Trace Anomaly Form Factor

➢ Mass-energy density form factor   $M(Q^2) = A(Q^2) + \dfrac{Q^2}{4m_P^2}[A(Q^2) - 2J(Q^2) + D(Q^2)]$

Nonnegative function = good for a mass distribution

➢ In-proton expectation value of QCD trace anomaly:

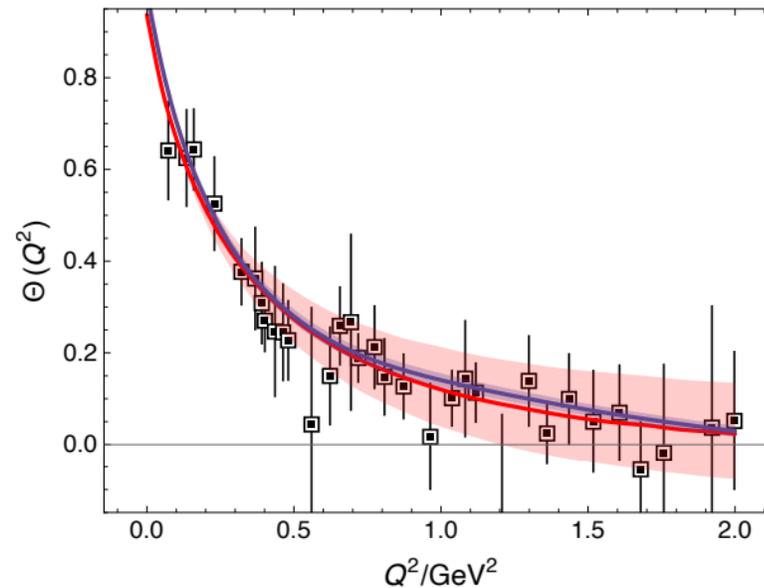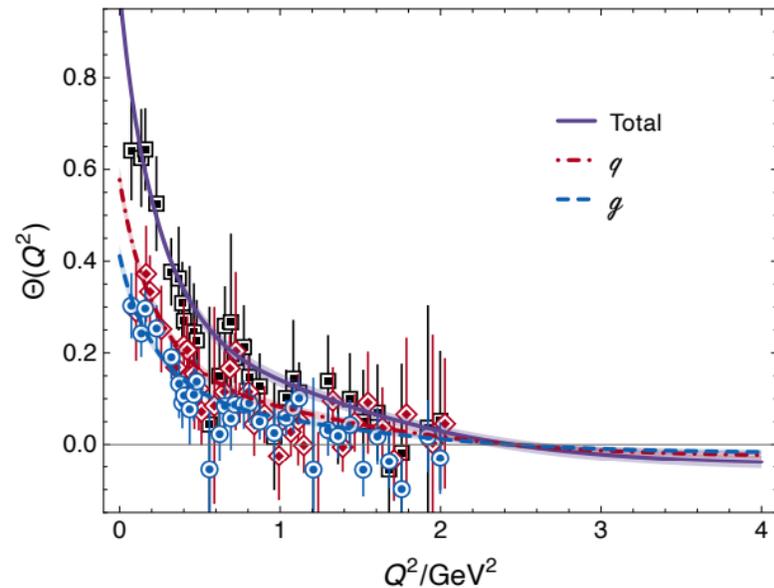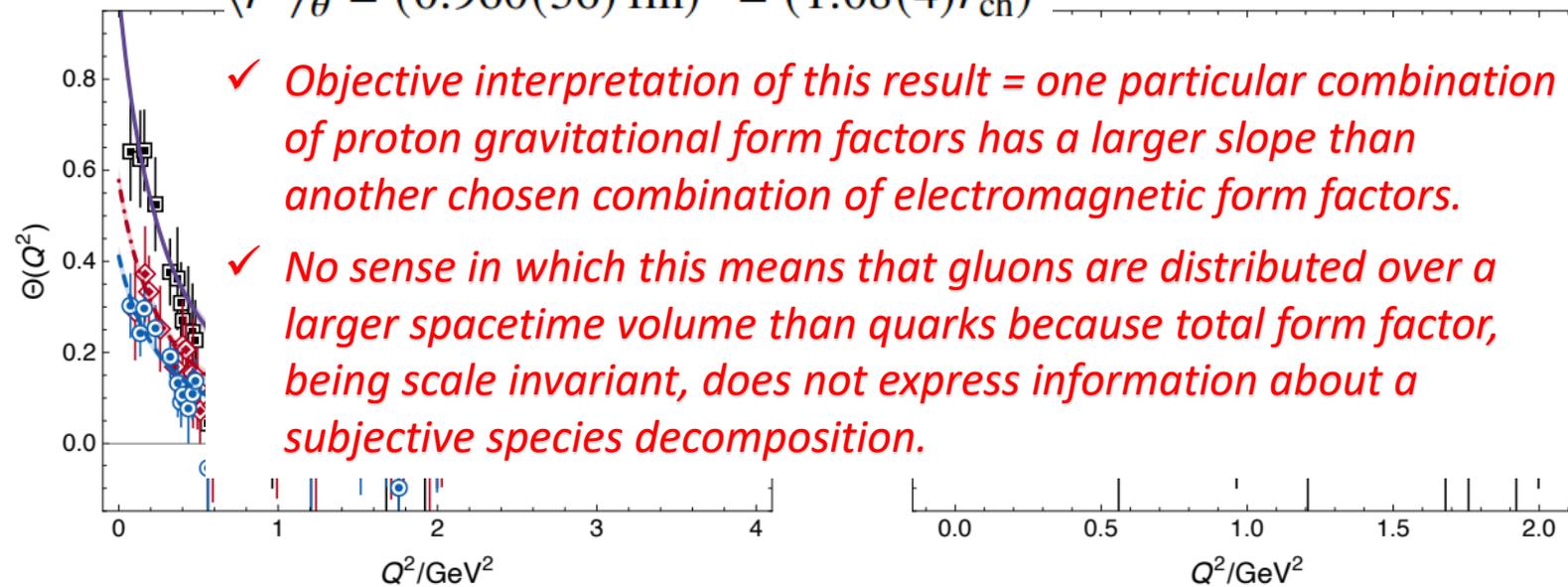$$\theta(Q^2) = A(Q^2) + \dfrac{Q^2}{4m_P^2}[A(Q^2) - 2J(Q^2) + 3D(Q^2)]$$

$$\langle r^2 \rangle_\theta = (0.960(36)\ \text{fm})^2 = (1.08(4)\,r_{\text{ch}})^2$$

✓ *Objective interpretation of this result = one particular combination of proton gravitational form factors has a larger slope than another chosen combination of electromagnetic form factors.*

✓ *No sense in which this means that gluons are distributed over a larger spacetime volume than quarks because total form factor, being scale invariant, does not express information about a subjective species decomposition.*

➢ $\theta(Q^2)$ is not positive definite
– species decompositions have same feature.

➢ Unusual outcome for global property of a nucleon mass distribution

➢ Distributions of charge involve positive and negative charge carriers, hence can possess domains of negative support

➢ All physical mass is positive definite, so there is no good reason why a form factor definitive of mass should become negative.

➢ Somewhat arbitrary outcome: just $D_M \rightarrow 3D_\theta$

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# *Emergent Hadron Mass*

➢ QCD is unique amongst known fundamental theories of natural phenomena

 – The degrees-of-freedom used to express the scale-free Lagrangian are not directly observable

 – Massless gauge bosons become massive, with no "human" interference

 – Gluon mass ensures a stable, infrared completion of the theory through the appearance of a running coupling that saturates at infrared momenta, being everywhere finite

 – Massless fermions become massive, producing

 • Massive baryons and simultaneously Massless mesons

➢ These emergent features of QCD are expressed in every strong interaction observable

➢ They can also be revealed via

  EHM interference with Nature's other known source of mass = Higgs

➢ We are capable of building facilities that can validate these concepts, proving QCD to be

  the 1$^{st}$ well-defined four-dimensional quantum field theory ever contemplated

➢ *This may open doors that lead far beyond the Standard Model*

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Can't build a Theory of Everything
before status of QCD is decided

$$\mathcal{L}_{Nature} = ?$$

There are theories of many things,
But is there a theory of everything?

*Thankyou*

# Quantum Chromodynamics

$$L = \frac{1}{4} G_{\mu\nu}^a(x) G_{\mu\nu}^a(x) + \bar{\psi}\left[\gamma \cdot \partial_x + m + ig\,\frac{\lambda^a}{2}\gamma \cdot A^a(x)\right]\psi(x)$$

$$G_{\mu\nu}^a(x) = \partial_\mu A_\nu^a(x) - \partial_\nu A_\mu^a(x) - f^{abc} A_\mu^b(x) A_\nu^c(x)$$

➤ One-line Lagrangian – expressed in terms of massless gluon ($A_\mu^a$) and Higgs-mass quark ($\psi$) partons

*Gluon and Quark Confinement*

➤ Which are NOT the degrees-of-freedom measured in detectors

*Advantages of the Color Octet Gluon Picture,*
*H. Fritzsch, Murray Gell-Mann, H. Leutwyler, Phys. Lett. B 47 (1973) 365-368*

➤ "The quarks come in three "colors," but all physical states and interactions are supposed to be singlets with respect to the SU(3) of color. Thus, we do not accept theories in which quarks are real, observable particles; nor do we allow any scheme in which the color non-singlet degrees of freedom can be excited."

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➤ The most important lessons to be learnt in modern hadron physics are …

*This is NOT a baryon*

➤ *This is NOT a meson*

*Three "constituent" quarks "confined" within some three-dimensional volume by an instantaneous potential*

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# Summary $F_\pi(Q^2)$

➤ Predictions also for flavour separation and neutral kaon form factors

  – Possibly accessible at EIC and EicC

➤ CSM analysis

  – $Q^2 F_P(Q^2)$ has maximum at $Q^2 \approx 5\text{GeV}^2$

  – So …

    • proposed experiments are capable of locating the peak

    • can, potentially, provide quantitative information on value of $\gamma_F$

➤ Crucial steps toward ultimate verification of hard QCD prediction

  (perhaps seen in $\gamma^*\pi \to \gamma$, but this is controversial – Phys. Rev. D**93** (2016) 074017/1-9)

  – Connecting hard scattering of leptons from mesons to expressions of emergent hadron mass, via QCD effective charge and meson leptonic decay constant

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# *Photoproduction of heavy vector mesons*

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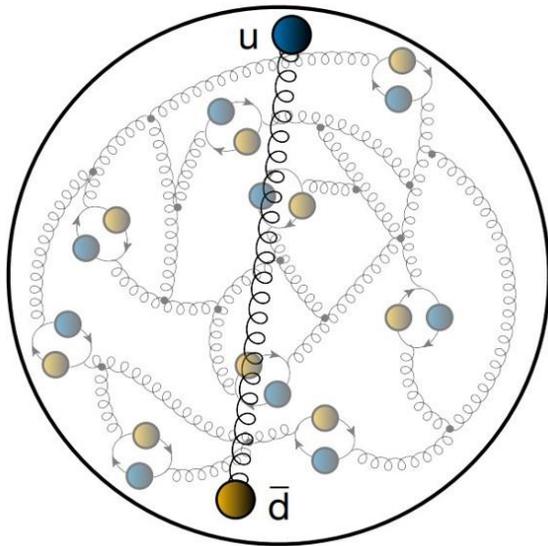
➢ The most important lessons to be learnt in modern hadron physics are …

*This IS a baryon*

➢ *This IS a meson*



B pion

A proton

*A few "valence" quark partons and/or antiquark partons, and infinitely many sea and glue partons confined by spacetime-dependent nonperturbative, nonlinear dynamics*

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# GFF Species Decomposition (scale dependent, $\zeta_2 = 2\,\mathrm{GeV}$)

- Considering light quarks alone:
  $$D^{u+d}(0; \zeta_2) = -1.73(5)$$

- Inference from available DVCS data
  $$D^{u+d}_{\mathrm{DVCS}}(0; \zeta_2) = -1.63(29)$$

- CSM prediction is also in pointwise agreement with curve inferred from that data … see figure



BEG: Inference from existing DVCS data
V. D. Burkert, L. Elouadrhiri, F.-X. Girod, *The pressure distribution inside the proton*, Nature 557 (7705) (2018) pp. 396–399.

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# EHM Measurements
## How does the mass of the nucleon arise?

➤ Once considered viable …

  Electromagnetic process $(V = J/\psi, \Upsilon) \dots e + p \to e' + V + p$

  to access purely hadronic process … $V + p \to V + p$

➤ But …

  – *Deciphering the mechanism of near-threshold J/ψ photoproduction*, M.-L. Du, V. Baru, F.-K. Guo *et al.*, Eur. Phys. J. C **80**, 1053 (2020)

  – *Vector-meson production and vector meson dominance*, Yin-Zhen Xu, Si-Yang Chen, Zhao-Qian Yao *et al.*, Eur. Phys. J. C **81** (2021) 895/1-11

  – *Near threshold heavy quarkonium photoproduction at large momentum transfer*, P. Sun, X.-B. Tong, F. Yuan, Phys. Rev. D **105** (2022) 5, 054032

➤ **There is no objective, model-independent means by which to connect** $e + p \to e' + V + p$ **with** $V + p \to V + p$

➤ **Hence, vector meson photoproduction**
   **does not provide a path to the QCD trace anomaly**
   **(or anything else)**



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# $J/\psi$ photoproduction: from threshold to very high energies

➢ Parameter-free CSM calculation of loop structure and momentum dependence

    – 9 independent Poincaré covariants; yet $q_\alpha[\delta_{\mu\nu} + P_\mu P_\nu/m_{J/\psi}^2]$ term is overwhelmingly dominant.

    – Nonetheless, keep all terms

➢ Four parameters

    – Pomeron trajectory: $\alpha_0, \alpha_1$

      … fixed 20 years ago by high-$W$ data from HERA

    – Pomeron + valence quark coupling:

       • $\beta_\ell$ … fixed by HERA high-$W$ $\gamma p \to \rho^0 p$ photoproduction differential cross-section

       • $\beta_c$ … fixed by HERA high-$W$ $\gamma p \to J/\psi p$ forward differential cross-section

➢ Hereafter, all predictions

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# $J/\psi$ photoproduction: from threshold to very high energies

<span style="color:red">If GPD scheme valid at all,
then only very near threshold.
All $W$ unification impossible</span>

➢ Some modern proposals for reaction model:

- ~~GPD treatment – gain access to in-proton gluon gravitational form factors~~

- Coupled channels treatment – $\mathbf{P} + J/\psi\, p$ rescattering

  - S. Sakinah, T. S. H. Lee, H.-M. Choi, *Dynamical Model of J/Ψ photoproduction on the nucleon* – arXiv:2403.01958 [nucl-th]

  - Suggestion = Final state interactions dominate cross-section near-threshold, so obscuring any connection with in-proton gluon distributions and/or gluon gravitational form factors.

- $\gamma + p \rightarrow c + \bar{c} + P + p \rightarrow J/\psi + p$

  - Lin Tang (唐淋) *et al*. NJU-INP 089/24

  - Exposes $c + \bar{c}$ content of the dressed photon

  - Couples the intermediate $c + \bar{c}$ system to proton's valence quarks via Pomeron exchange



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# $J/\psi$ photoproduction: threshold differential cross-section

- GPD model (dotted blue)
  - overfitting issue
  - concave differential cross-section with max. at low $|t|$
  - trying to reconcile GlueX and $J/\psi$-007 data (some tension)
  - all other reaction models produce convex $\frac{d\sigma}{dt}$
- $P + J/\psi p$ rescattering
  - dashed green $- \chi^2_{\text{dof}} = 8$
- $P +$ quark loop
  - solid purple $- \chi^2_{\text{dof}} = 7$

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# $J/\psi$ photoproduction: threshold differential cross-section

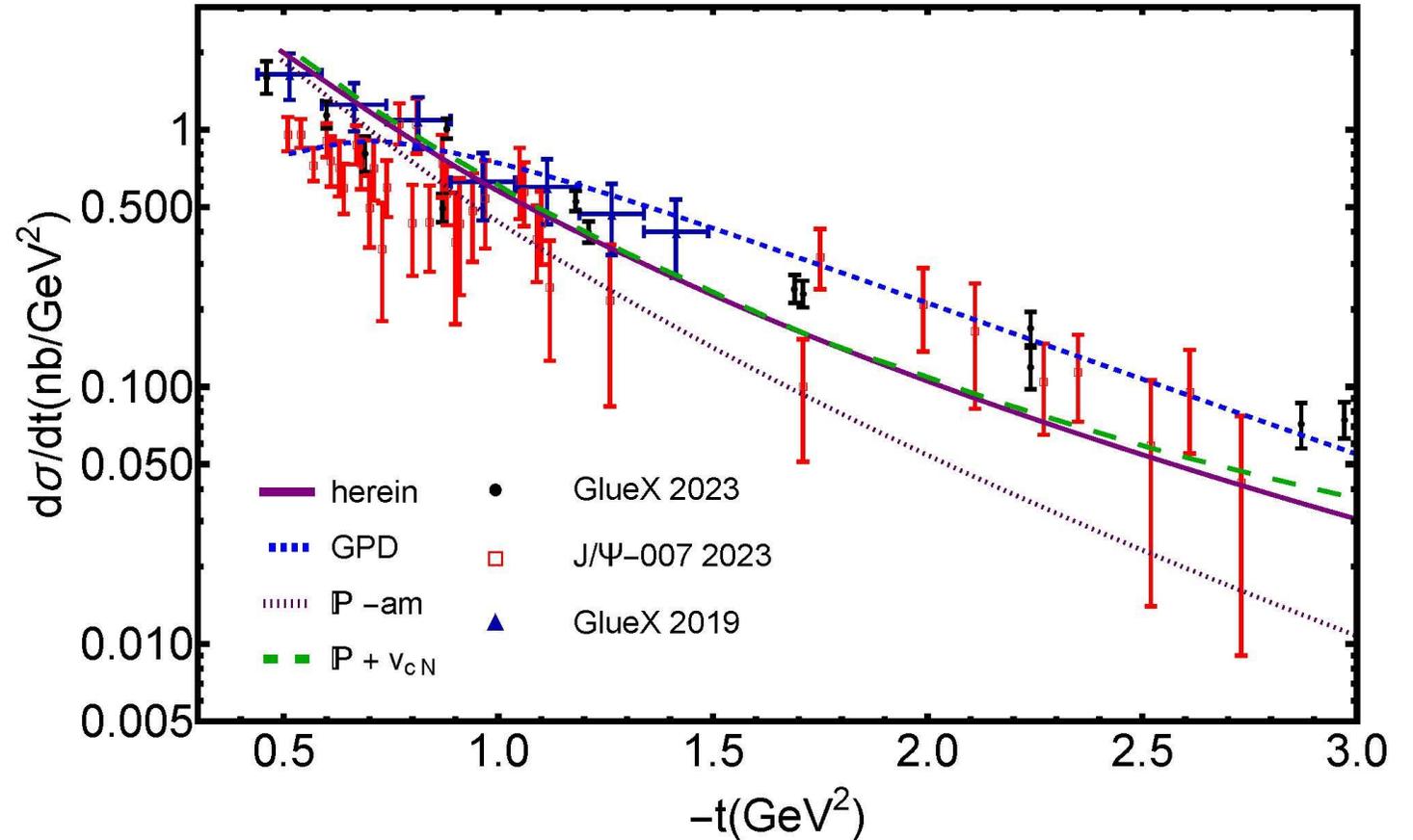- GPD model (dotted blue)
  - overfitting issue
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# $J/\psi$ photoproduction:
## total cross-section, threshold to high-$W$

- GPD model (dotted blue)
  - Inapplicable on $W > 5$ GeV
  - $\chi^2_{\text{dof}} = 2.5$ near threshold
- $P + J/\psi p$ rescattering
  - dashed green $- \chi^2_{\text{dof}} = 1.7$
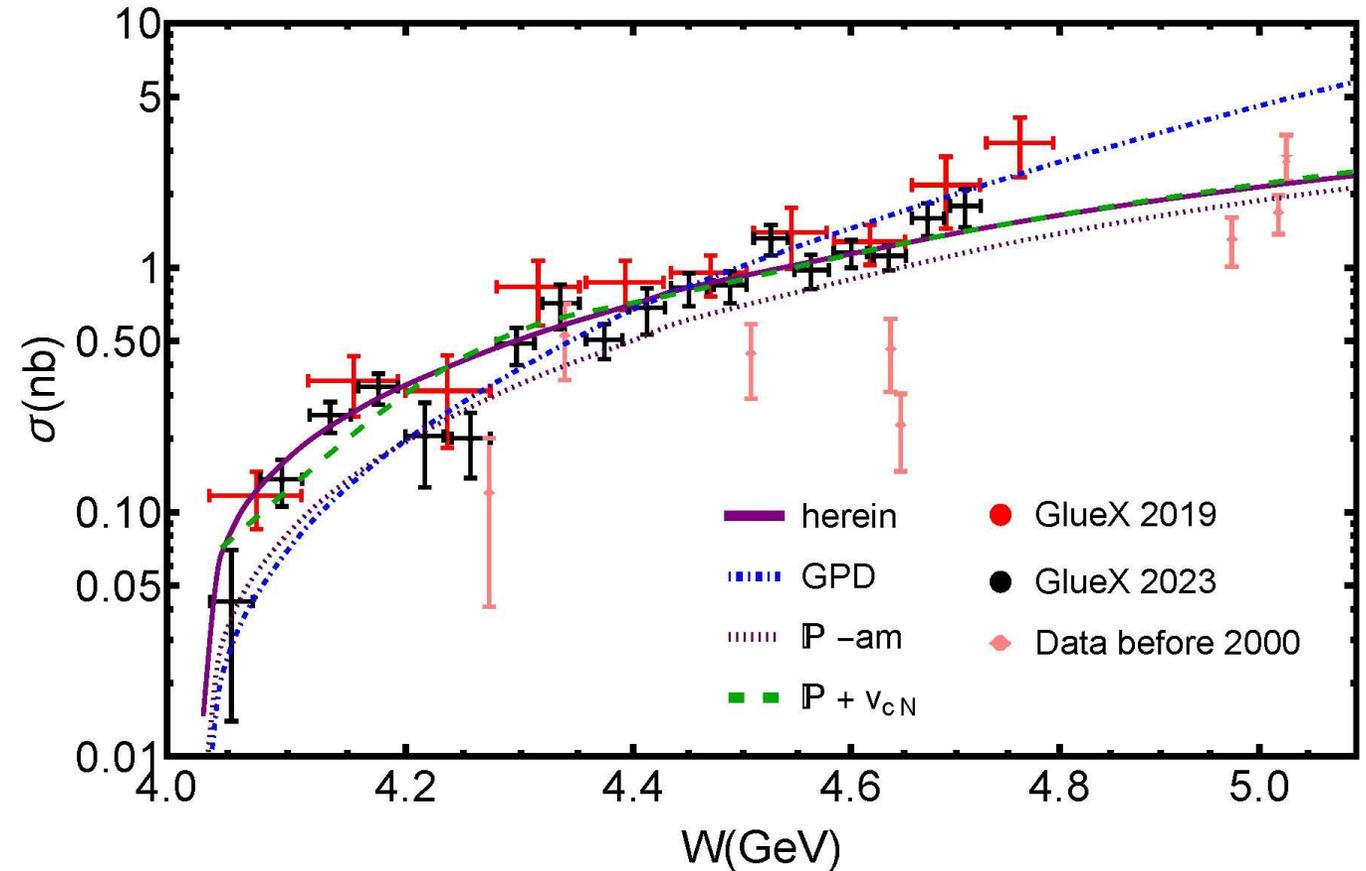- $P +$ quark loop
  - solid purple $- \chi^2_{\text{dof}} = 1.4$



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# $J/\psi$ photoproduction:
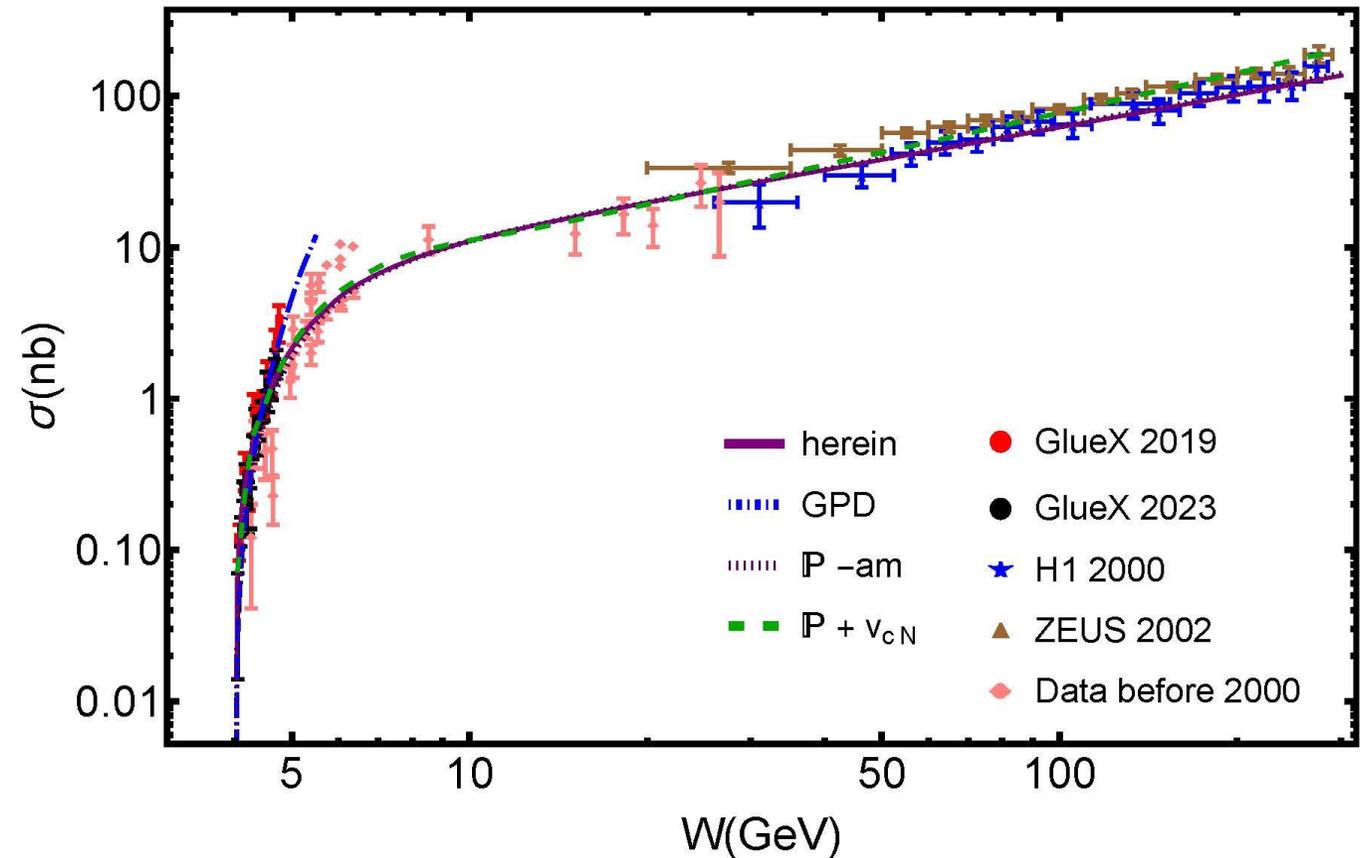## total cross-section, threshold to high-$W$

- GPD model (dotted blue)
  - Inapplicable on $W > 5$ GeV
  - $\chi^2_{\text{dof}}$ undefined
- $P + J/\psi p$ rescattering
  - dashed green
    - ZEUS+H1 $\chi^2_{\text{dof}} = 2.1$
    - H1 $\chi^2_{\text{dof}} = 1.6$
- $P + $ quark loop
  - solid purple
    - ZEUS +H1 $\chi^2_{\text{dof}} = 3.5$
    - H1 $\chi^2_{\text{dof}} = 1.0$



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# $J/\psi$ photoproduction: from threshold to very high energies

➤ Two reaction models provide viable unification

  – differential and total cross-section data

➤ GPD model does NOT

  – Premature to connect γ + p → J/ψ + p photoproduction data with anything derived from/connected with GPDs

  – Theory predicts that proton mass radius < proton charge radius – see *Empirical Determination of the Pion Mass Distribution*, Y-Z. Xu (徐胤禛) *et al.*, NJU-INP 070/23, e-Print: 2302.07361 [hep-ph], Chin. Phys. Lett. *Express* **40** (2023) 041201/1-7.

➤ Best description of data is provided by CSM reaction model

  – $(W, t)$ dependence of quark loop is important to differential cross-section near threshold

  – Quark structure of $J/\psi$ more important than glue in proton

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# $J/\psi$ photoproduction: from threshold to very high energies

➤ Do not pretend that reaction model described is complete

  – but it is viable because it is sufficient

➤ Analysis is valuable in highlighting that one should be wary of any attempts to over-interpret existing γ + p → J/ψ + p data in terms of desirable things

➤ Such desires should be tempered whilst more realistic reaction models are built, and higher precision data are accumulated

➤ Mutual feedback can lead to tightly constrained phenomenology, which may be used in understanding γ + p → J/ψ + p process & building solid bridge between data and proton properties.