NANJING UNIVERSITY

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

Grant no. 12135007

国家自然科学基金委员会
National Natural Science Foundation of China

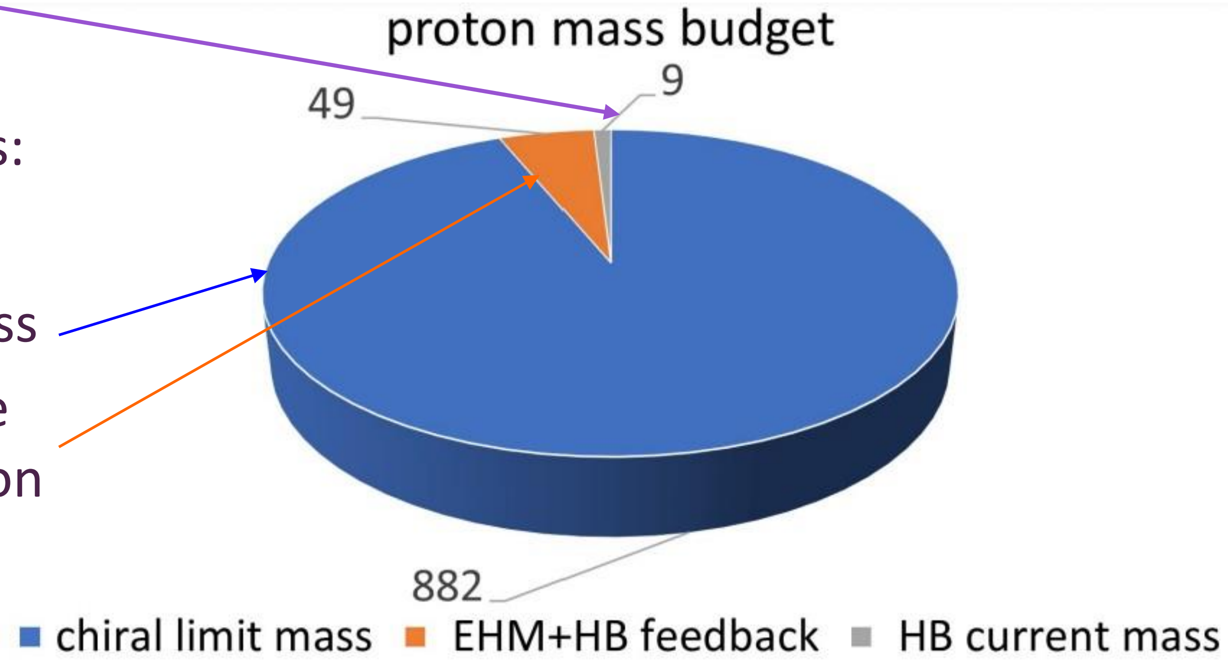
Insights into N Resonances using CSMs

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
- But … Proton mass budget … only 9 MeV/939 MeV is directly from Higgs
- Evidently, there is another phenomenon in Nature that is *very* effective in producing mass:

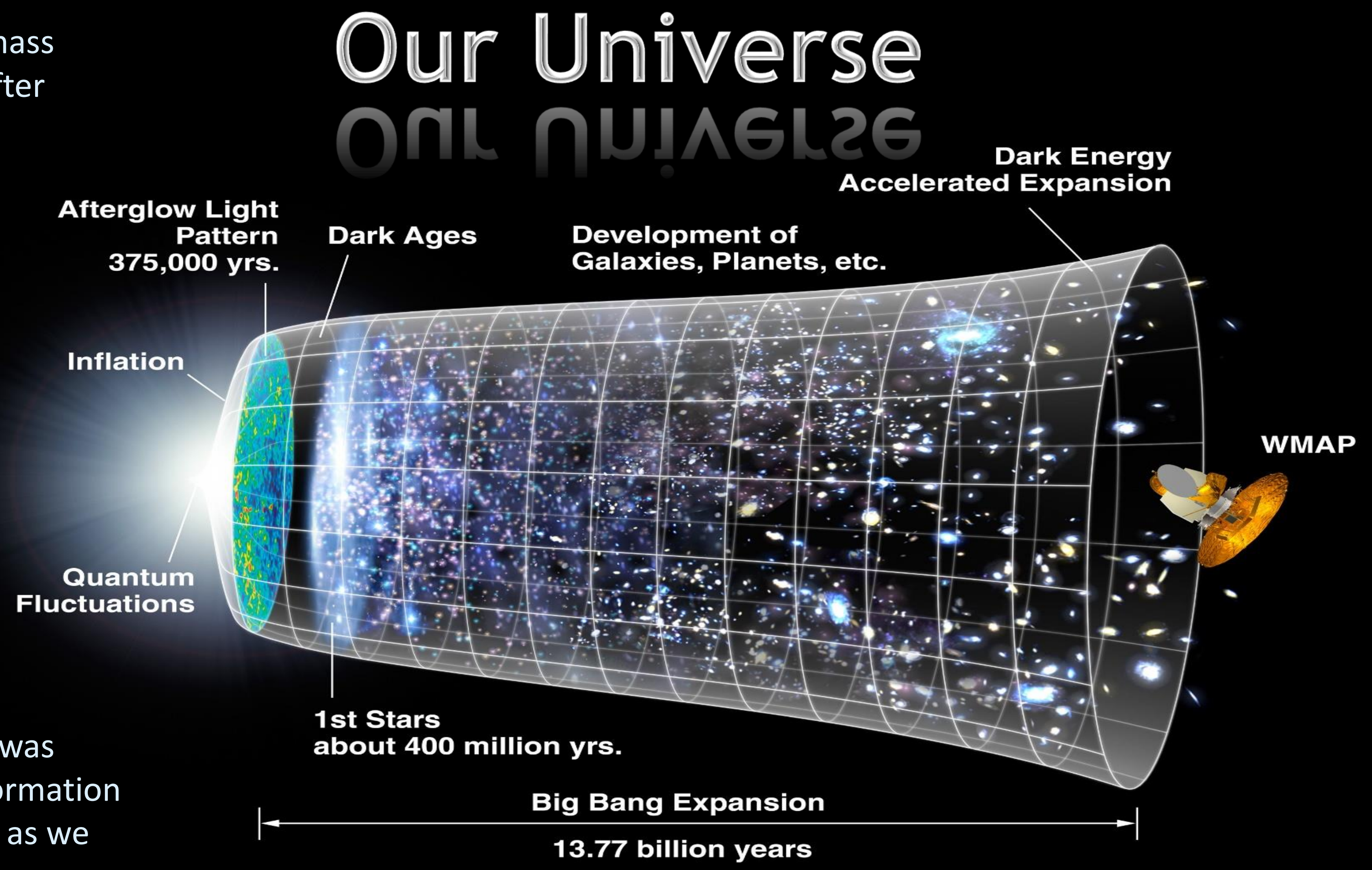
  Emergent Hadron Mass (EHM)

  - ✓ Alone, it produces 94% of the proton’s mass
  - ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



- ✓ What is EHM?
- ✓ Does it have a reductionist explanation,
  i.e. like a Swiss watch, can it be explained by mere “mechanics”
- ✓ If so, what is it and does it lie within the Standard Model?

Nuclear-scale mass emerged 1μs after Big Bang



Its appearance was crucial to the formation of the Universe as we know it

NASA/WMAP Science Team

Fundamental Science Questions for 21st Century

- How do Hadron Masses Emerge?
- How do Hadron Spins Emerge?
- What role, if any, do gluons play in producing emergent features of strong interactions?
- To answer these questions

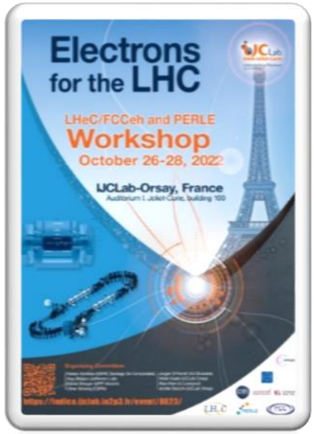
  International community is operating, building, and planning an array of high-intensity facilities with the potential for delivering answers

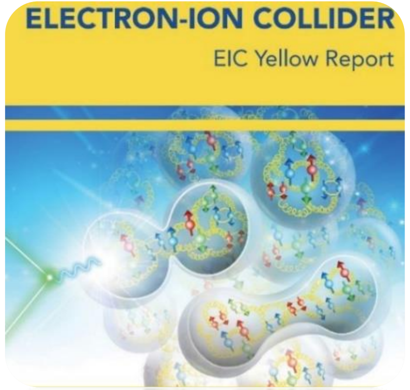
Can't build a Theory of Everything before status of QCD is decided

Jefferson Lab
Thomas Jefferson National Accelerator Facility

QCD at FAIR

BESIII





AMBER
Apparatus for Meson and Baryon Experimental Research

CEPC

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

Origin of Mass: The Frontier of Physics

GENESIS

GLUON

In the Beginning…

Ancient History

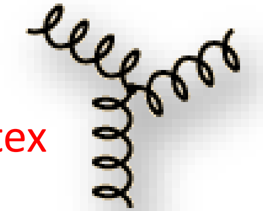
Cornwall's estimate: $\mathrm{m_g} = 0.5(2)\mathrm{GeV} \approx \frac{1}{2} m_p$

- $\approx$ 45 years ago

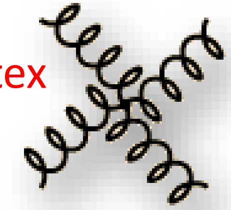
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … $>$ 1100 citations

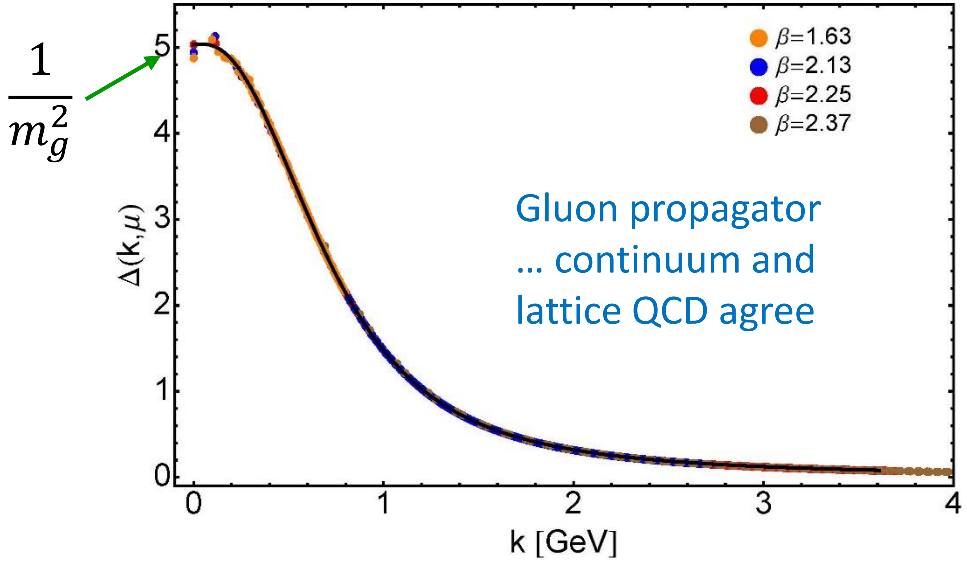
- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

3-gluon vertex



4-gluon vertex





Truly *mass from nothing*
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?*

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.

D. Binosi, *Gauge Symmetry Beyond Perturbation Theory: BRST and anti-BRST Structure, Background Fields, and Infrared Dynamics of Yang--Mills Theory*, Particles 9 (2026) 2, 59

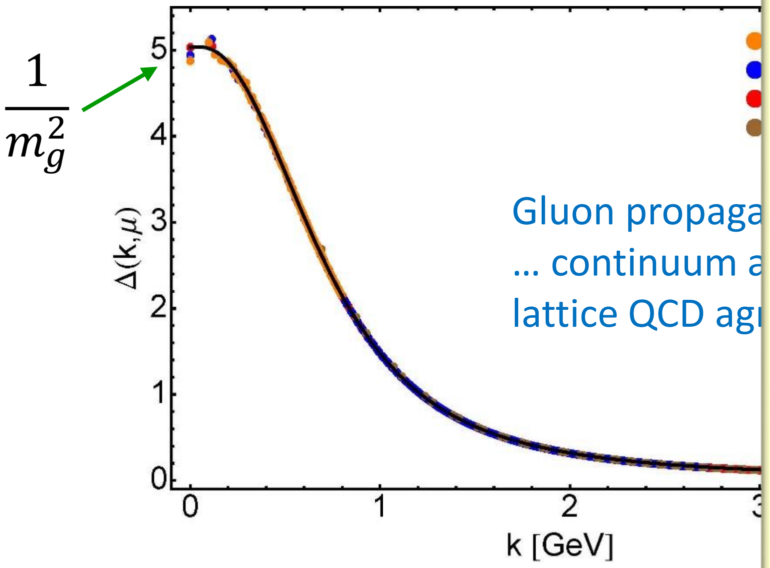
Ancient History

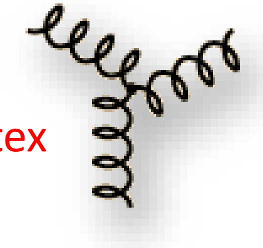
Today's best estimate: $m_g^{\mathrm{RGI}} = 0.43(1)\mathrm{GeV}$

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.

EHM means Gluons are massive via Schwinger Mechanism





articles,
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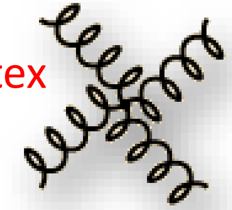


QCD fact

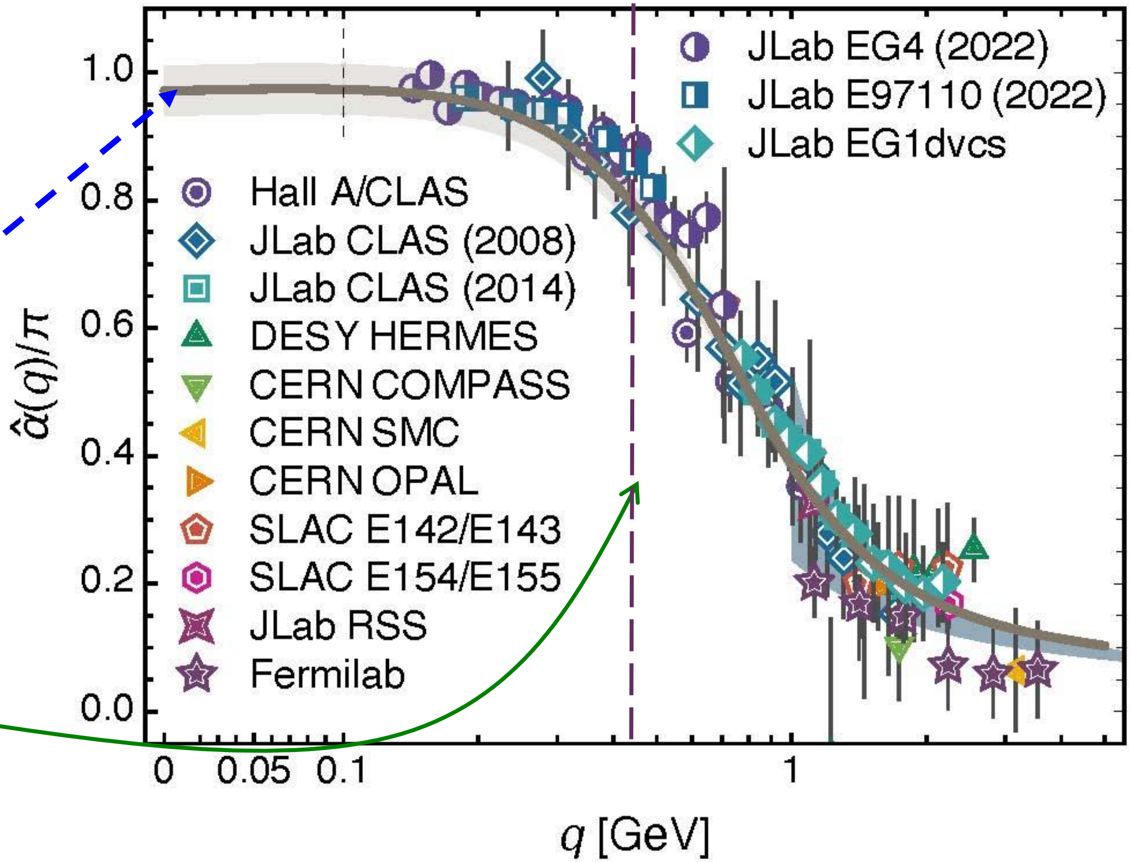
Continuum theory and lattice simulations agree

Empirical verification?

Effective charge from lattice QCD, *Jin-Li Zhang et al.*, *NJU-INP 014/19*, *arXiv:1912.08232 [hep-ph]*, *Chin. Phys. C 44 (2020) 083102/1-10*

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 $k \approx ½\, m_p$
- 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

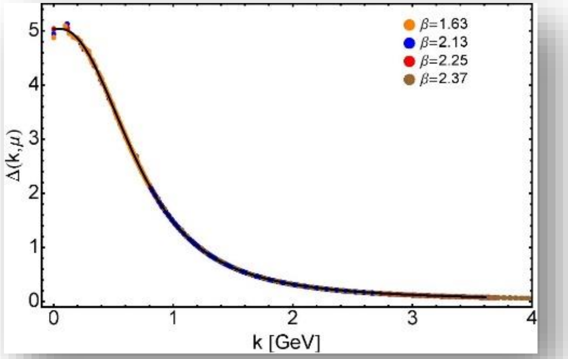


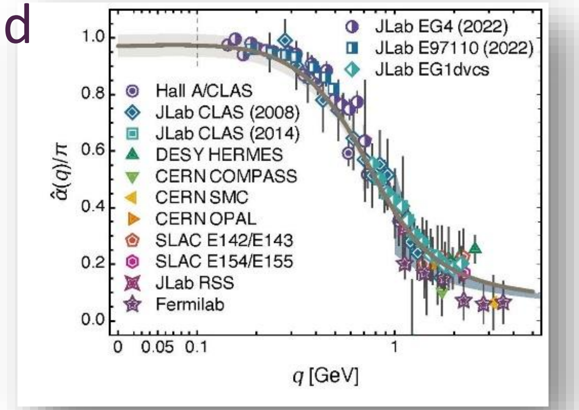
- ✓ *Process independent strong running coupling* Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.* A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig Roberts, e-Print: 2303.00723 [hep-ph], Prog. Part. Nucl. Phys. **134** (2024) 104081

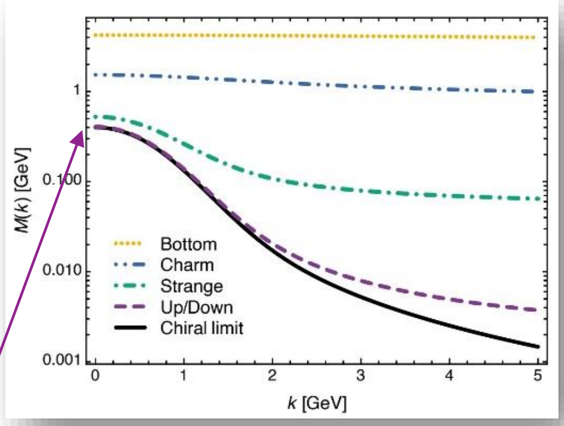
EHM Basics

- Absent Higgs boson couplings, QCD Lagrangian is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- Challenge to Experiment =
  Test the theory predictions so that
  the boundaries of the Standard Model can finally be drawn

THREE PILLARS OF EHM



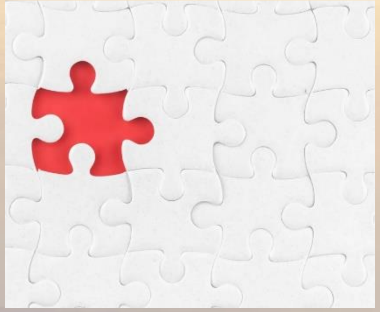




- ✓ $3 \times M(0)$ sets the scale of the proton mass.
- ✓ Meson-loops provide 20% quantum corrections

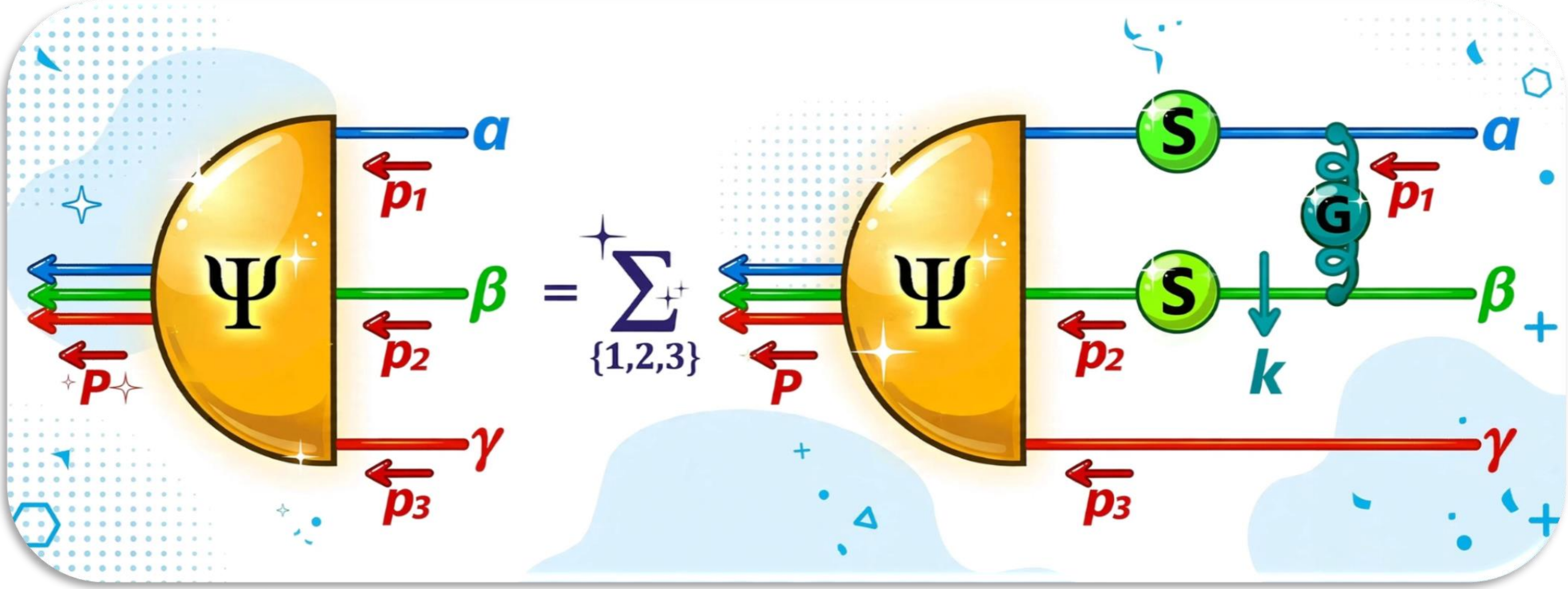
Charting EHM

- Proton was discovered 100 years ago … It is stable; hence, an ideal target in experiments
- But just as studying the hydrogen atom ground state didn't give us QED,
  focusing on the ground state of only one form of hadron matter will not solve QCD
- New era is dawning … high energy + high luminosity
  ⇒ Science can move beyond the focus on the proton
- Precision studies of the structure of
  - Nature's most fundamental Nambu-Goldstone bosons (π & K) will become possible
  - Baryon excited states
    - ✓ Baryons are the most fundamental three-body systems in Nature
    - ✓ If we don't understand how QCD, a Poincaré-invariant quantum field theory, builds each of the baryons in the complete spectrum, then we don't understand Nature.
- EHM is not immutable
  - its manifestations are manifold
  - experience ⇒ each hadron reveals different facets
  - One piece does not complete a puzzle



AMBER @ CERN
EIC
EicC & SCT & CEPC
JLab12 & JLab20+
QCD @ FAIR

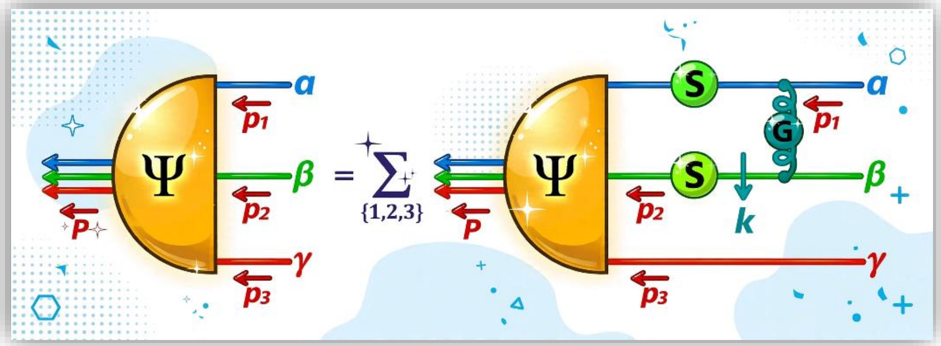
- ✓ *Nucleon mass from a covariant three-quark Faddeev equation*
  G. Eichmann *et al.*, Phys. Rev. Lett. 104 (2010) 201601
- ✓ *Poincaré-covariant analysis of heavy-quark baryons*
  Si-Xue Qin (秦思学) *et al.*, Phys.Rev. D 97 (2018) 114017/1-13
- ✓ *Nucleon Gravitational Form Factors,*
  Z.-Q. Yao (姚照千) et al., Eur. Phys. J. A 61 (2025) 92/1-13



Faddeev Equation for Baryons

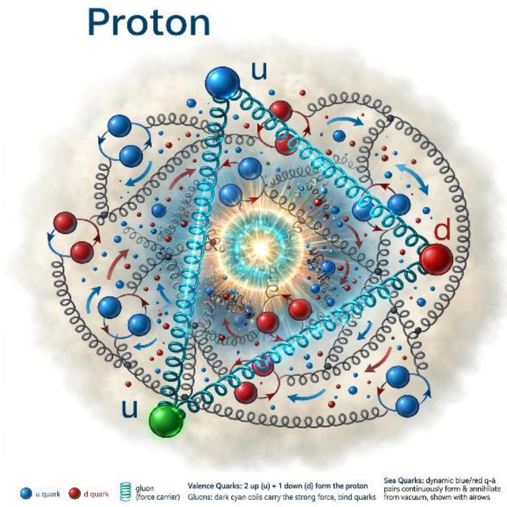
Nucleon as a Bound State

Nucleon charge and magnetisation distributions: flavour separation and zeroes,
Zhao-Qian Yao (姚照千) *et al.*, e-Print: 2403.08088 [hep-ph], *Fund. Res. 6 (2026) 1409-1416*



- 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
- Modern such analyses use precisely 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.

Baryon Structure



Physically Meaningless

- Poincaré covariance ⇒ irrespective of quark model assignments $n^{2s+1}\ell_J$, every hadron contains orbital angular momentum, *e.g.*,
  - π contains two S-wave components and two P-wave components
  - Few systems are simply radial excitations of another
- No separation of J into $L + S$ is Poincaré invariant
  - Consequently, *e.g.*, negative parity states are <u>not</u> simply orbital angular momentum excitations of positive parity ground states
- In quantum field theory, NO direct connection between parity and orbital angular momentum
  - Parity is a Poincaré invariant quantum number
  - L is not Poincaré invariant = value depends on the observer's frame of reference
- QCD structure of hadrons – mesons and baryons – is far richer than can be produced by quark models, relativized or not
  - ✓ *Baryons are the most fundamental three-body systems in Nature*
  - ✓ *If we don't understand how QCD, a <u>Poincaré-invariant quantum field theory</u>, builds each and every one of the baryons in the complete spectrum, then we don't understand Nature.*

EHM Measurements: How does nucleon mass arise? … Trace Anomaly Form Factor

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

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

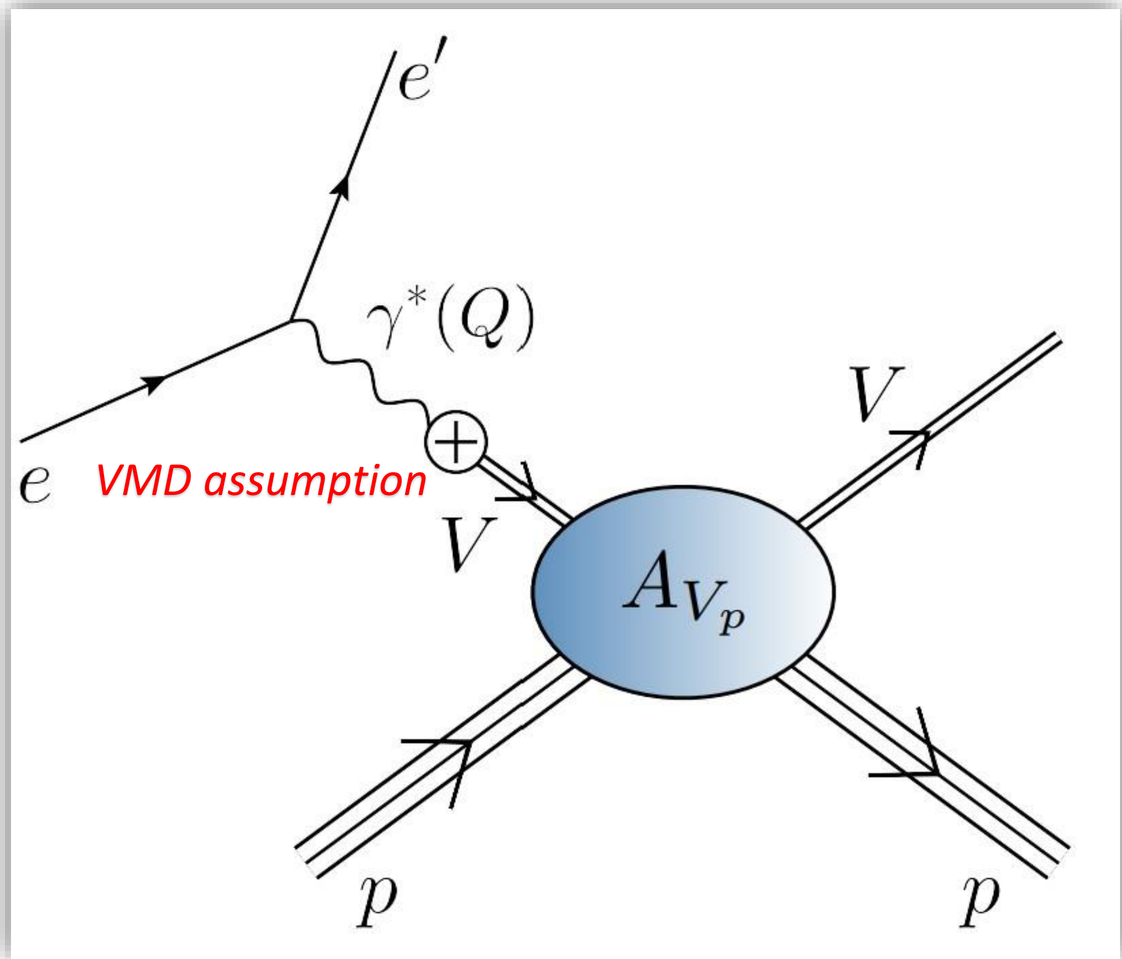
  possible via photoproduction from proton of vector mesons that share no valence degrees of freedom in common with the proton

- Consequently, extensive new data available on

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

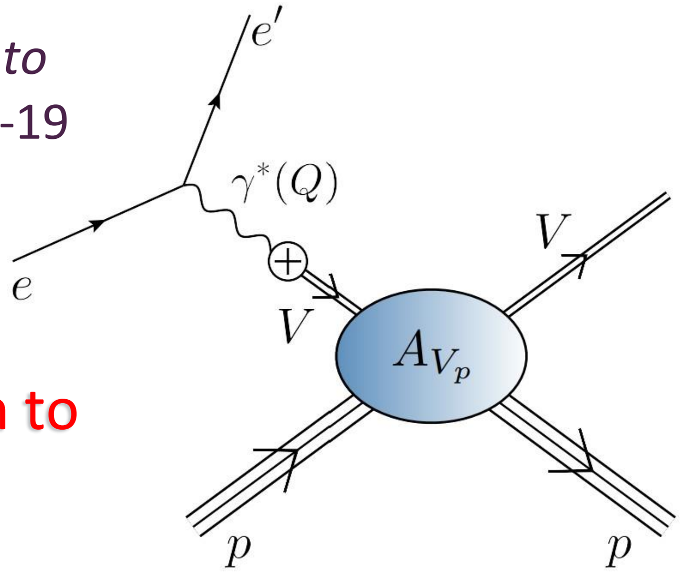
- Desire to calculate/predict the trace anomaly form factor

- Also, its species decomposition
  - In misguided attempt to decide whether the gluon parton density extends further than the proton charge radius



EHM Measurements: How does nucleon mass arise?

- But …
  - *Deciphering the mechanism of near-threshold J/ψ photoproduction*, M.-L. Du *et al*., Eur. Phys. J. C **80**, 1053 (2020)
  - *Vector-meson production and vector meson dominance*, Yin-Zhen Xu *et al*., Eur. Phys. J. C **81** (2021) 895/1-11
  - *Near threshold heavy quarkonium photoproduction at large momentum transfer*, P. Sun *et al*., Phys. Rev. D **105** (2022) 5, 054032
  - *Exclusive photoproduction of light and heavy vector mesons: thresholds to very high energies*, Lin Tang (唐淋) *et al*., Eur. Phys. J. C 86 (2026) 284/1-19
- 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)



EHM Measurements: How does nucleon mass arise?

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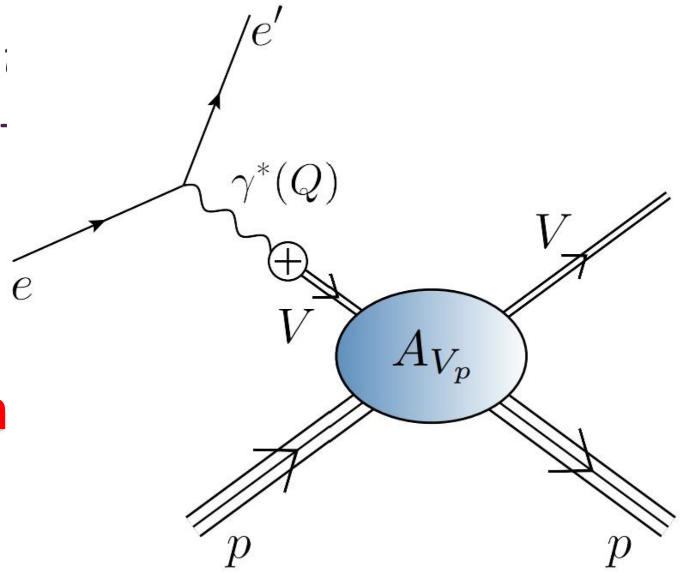
  - *Near threshold heavy quarkonium pho… …tum transfer*, P. Sun *et al.*, Phys. R…
  - *Exclusive photopr… …'s … very high…*
- There is no … …by which to connect $e +$ … $V + p$
- Hence, vector … …production does not provide a path … the QCD trace a…maly (or anything else)

Notwithstanding, hadron GFFs might be accessible via DVCS and GPDs



Hadron Gravitational Form Factors

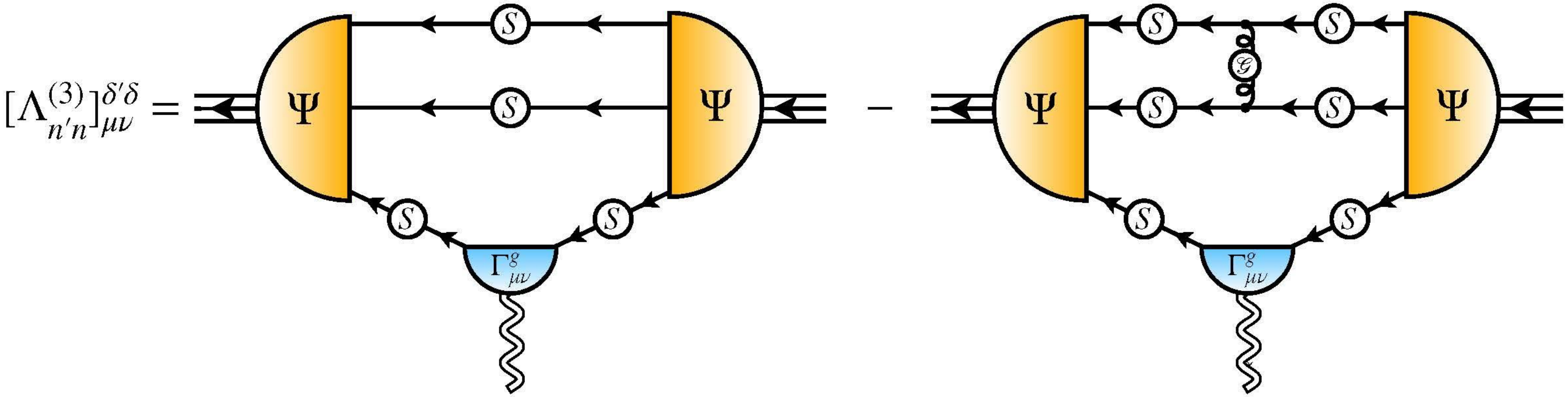
- *Forces inside hadrons: pressure, surface tension, mechanical radius, and all that,*
  M. V. Polyakov, P. Schweitzer, Int. J. Mod. Phys. A 33 (2018) 26

  "The physics related to the form factors of the energy momentum tensor spans a wide spectrum of problems, and includes
  - ✓ gravitational physics,
  - ✓ hard exclusive reactions,
  - ✓ hadronic decays of heavy quarkonia,
  - ✓ and the physics of exotic hadrons described as hadroquarkonia.

  It also provides access to the "last global unknown property:" the D-term.

  We review the physics associated with the form factors of the energy-momentum tensor and the D-term, their interpretations in terms of mechanical properties, their applications, and the current experimental status."

Nucleon Gravitational Form Factors



- Current … completing solution of Faddeev equation, then all elements are known
- Current …

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

- $A(Q^2)$ 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

Nucleon Gravitational Form Factors, Z.-Q. Yao (姚照千) *et al.*, e-Print: 2409.15547 [hep-ph], Eur. Phys. J. A **61** (2025) 92/1-13

Predicted GFFs

- Solid curves … CSM predictions
- Points lQCD results [Hackett:2023rif]
  - Agreement within (large) lattice uncertainties
- Symmetry-preserving character of CSM analysis is evident in values of
  - $A(0) = 1$
  - $J(0) = 1/2$
- With $J(0) = 1/2$, confirm that the anomalous gravitomagnetic moment of a spin-1/2 system is zero [Kobzarev:1962wt, Teryaev:1999su, Brodsky:2000ii].
- *nucleon "D-term" … prediction $D(0) = -3.11(1)$*

  analogue for pion is symmetry constrained $D_\pi(0) \approx -1$

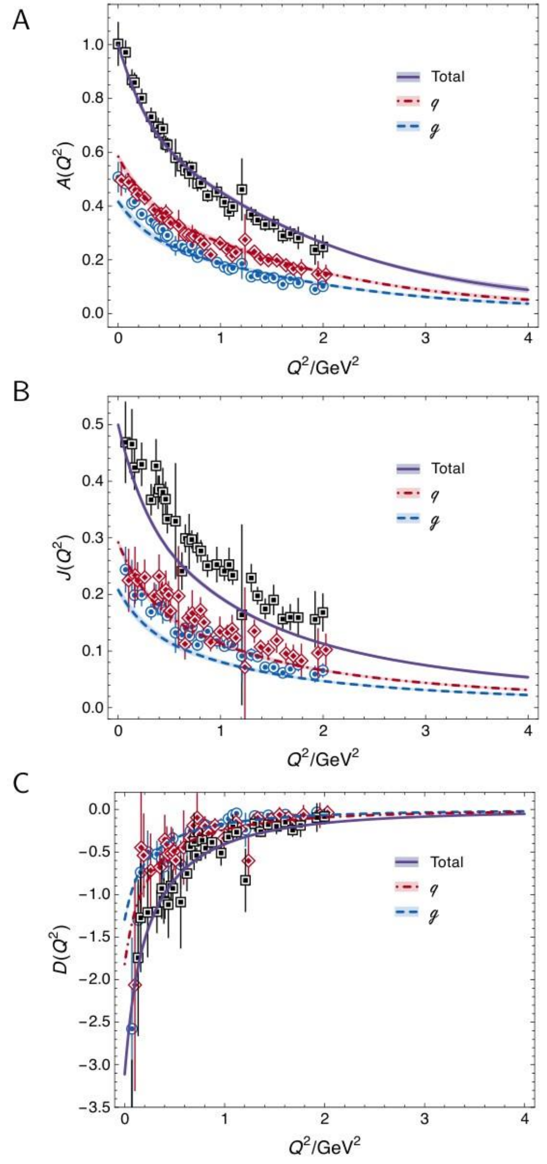


FIG. 1. Nucleon gravitational form factors. Curves – predictions herein: bracketing bands mark the extent of 1σ SPM uncertainty. In each case, the overall (species-summed) result is independent of resolving scale, ζ. The species decompositions evolve with ζ. The lQCD points in each panel are reproduced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

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

- CSM prediction – species decomposition,

  for each form factor:

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

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

  namely, the ratio of glue:quark contributions is the same Q^2-independent number for each form factor

  Important to test this prediction … *entails that no species decomposition contains new information: everything that can be known is already contained in the scale-invariant observable form factors*

- lQCD results … see figure
  - Consistent with prediction
  - $\text{constant}_{\text{lQCD}}(\zeta_2) = 0.82(18)$

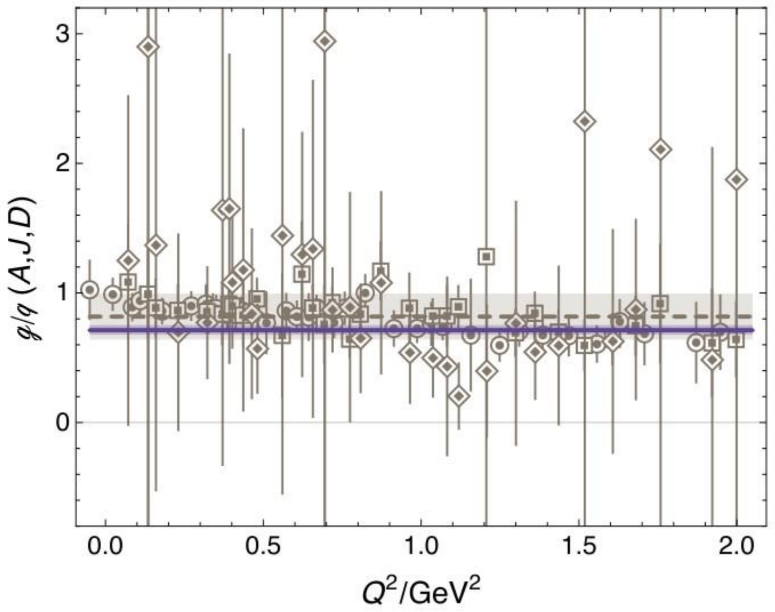


FIG. S.8. Combined A, J, D lQCD g/q results (grey points): grey line – uncertainty weighted average of all points; and grey band – 1σ around the central value: 0.82(18). Prediction herein: $g/q = 0.71(4)$ (purple line and band).

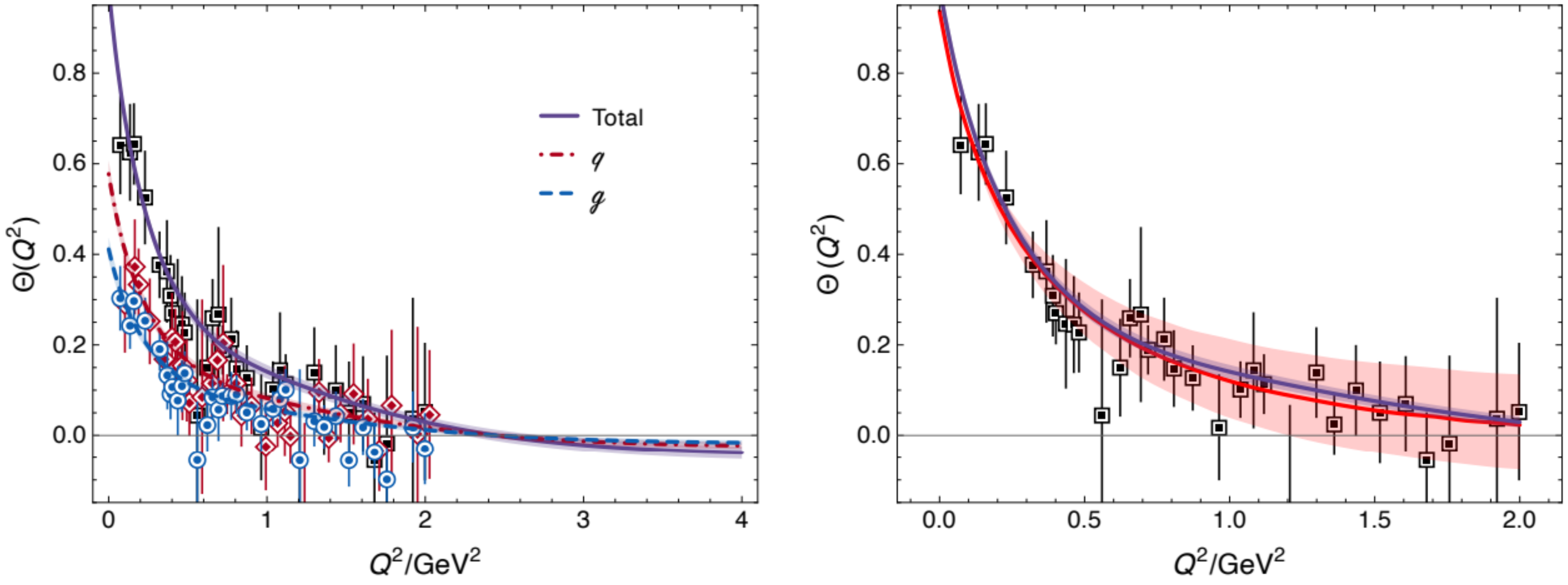
Trace Anomaly Form Factor

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

Nonnegative function = good for a mass distribution

- In-proton expectation value of QCD trace anomaly:

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



- $\theta(Q^2)$ 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 $M: D \rightarrow \theta: 3D$

Trace Anomaly Form Factor

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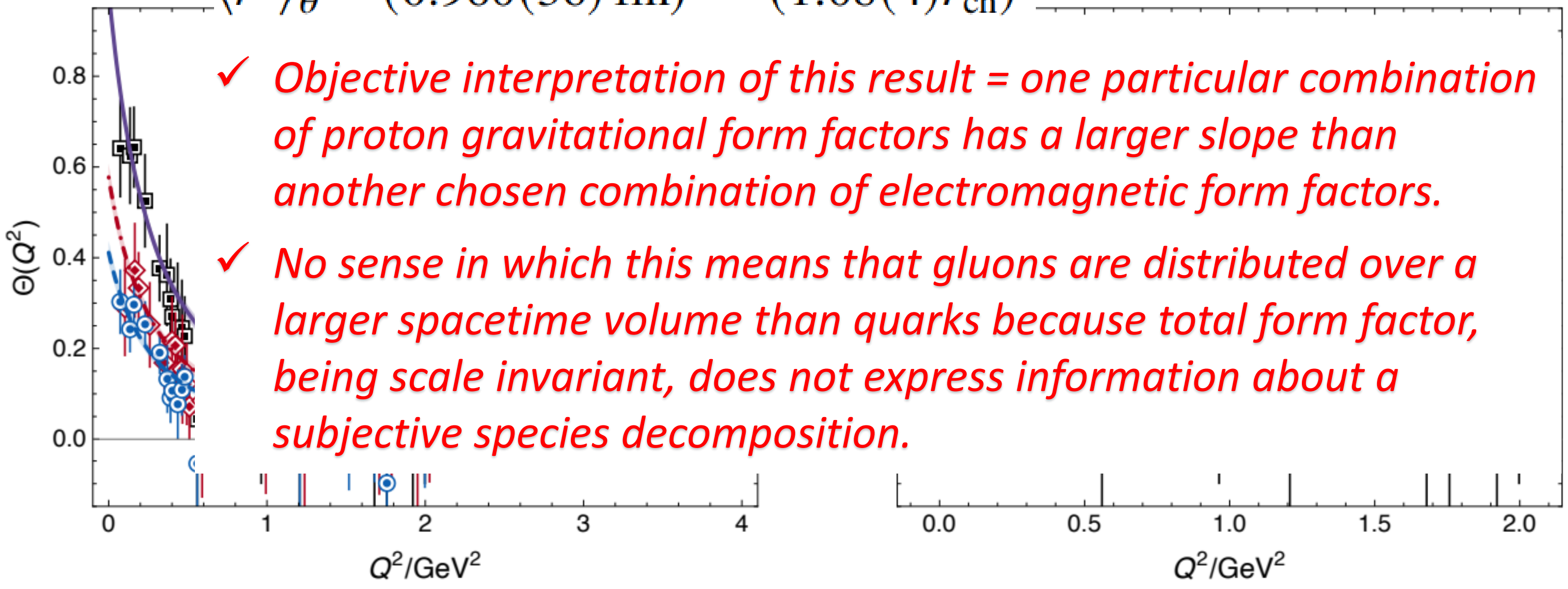
$$\theta(Q^2) = A(Q^2) + \frac{Q^2}{4m_p^2}[A(Q^2) - 2J(Q^2) + 3D(Q^2)]$$

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



✓ *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.*

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  - 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
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- Somewhat arbitrary outcome: just $D_M \to 3D_\theta$

Proton Pressure Profiles

- 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
- $r_{\rm mass} = 0.81(5) r_{\rm ch} > r_{\rm mech} = 0.72(2) r_{\rm ch}$
- Species decomposition (ζ_2)
  - $r^q_{\rm mass} = 0.62(4) r_{\rm ch} > r^g_{\rm mass} = 0.52(3) r_{\rm ch}$
  - $r^q_{\rm mech} = 0.55(4) r_{\rm ch} > r^g_{\rm mech} = 0.47(3) r_{\rm ch}$
- *Contrary to practitioner desires … no existing experiment provides information on glue contributions to proton GFFs*

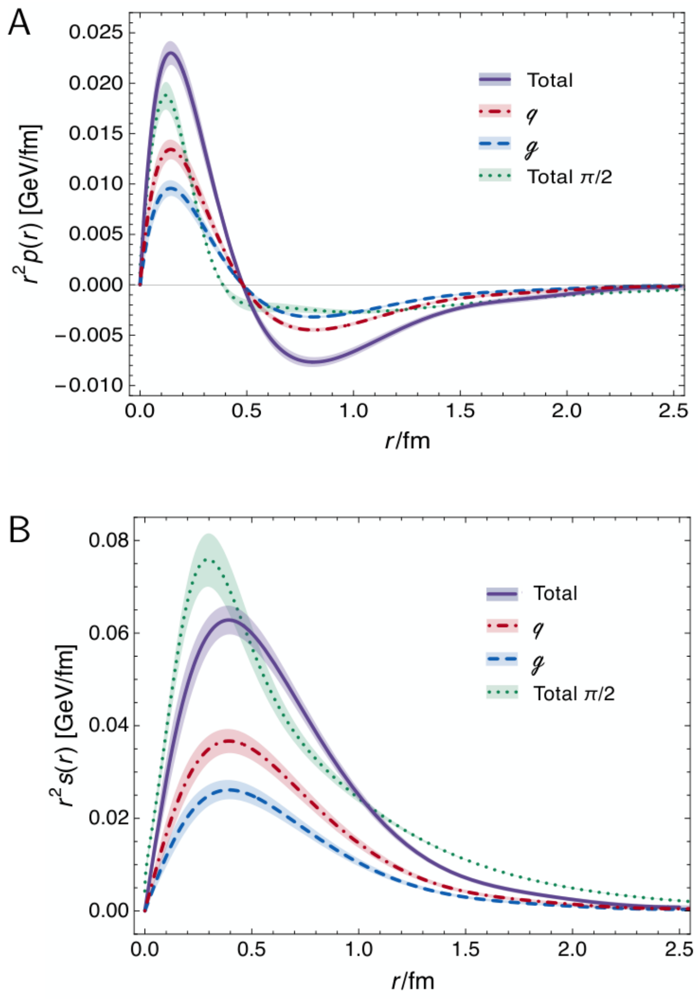
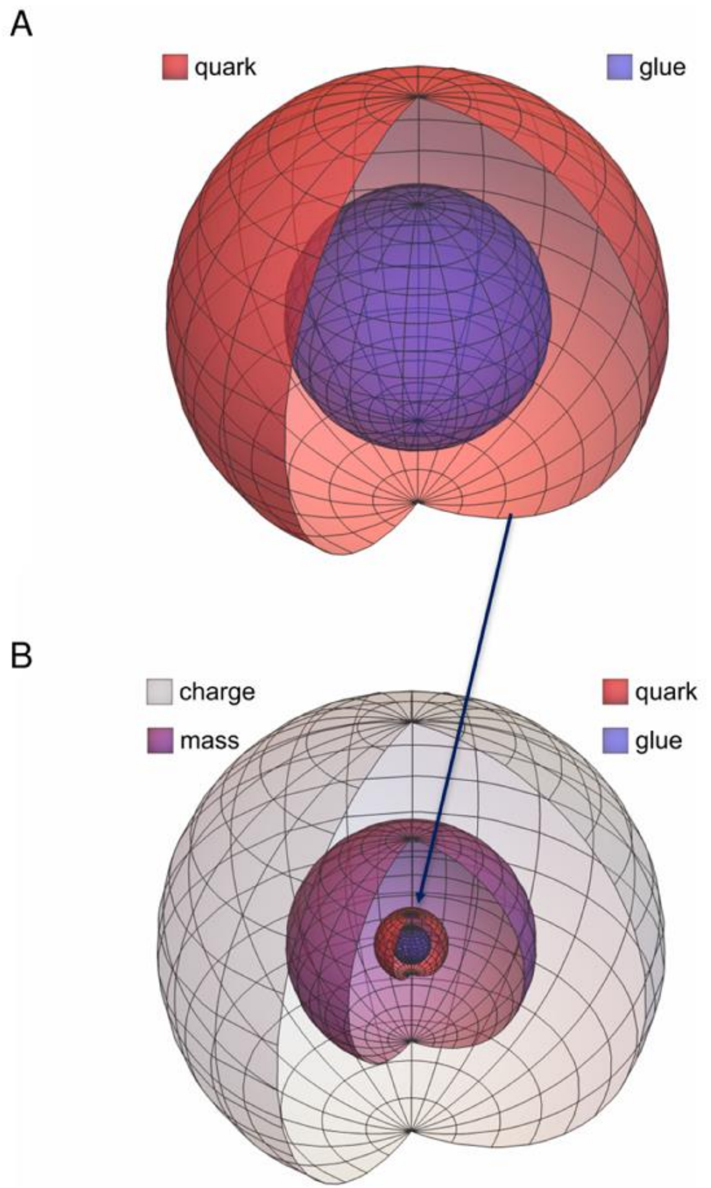


FIG. 3. Nucleon pressure, $p(r)$, and shear force, $s(r)$, distributions, along with total-quark and glue species decompositions at ζ_2. Like pion distributions are drawn in green. *N.B.* The pion distributions are divided by 2. In all cases, the like-coloured band marks the extent of 1σ SPM uncertainty.

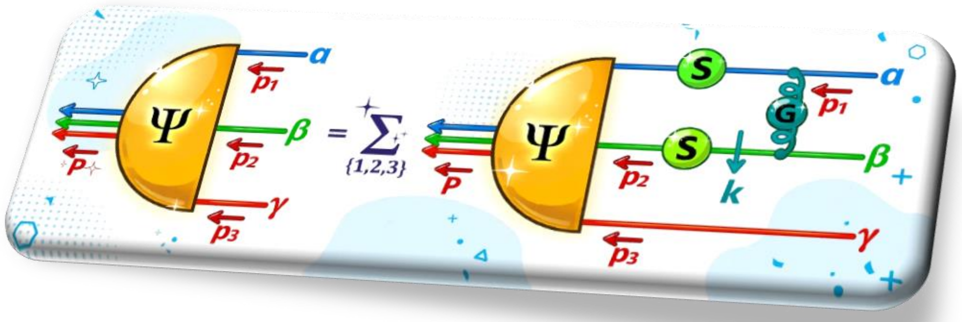
Exclusive photoproduction of light and heavy vector mesons: thresholds to very high energies, Lin Tang (唐淋) *et al.*, e-Print: 2510.08845 [hep-ph], Eur. Phys. J. C 86 (2026) 284/1-19.

Relative Spacetime Volumes

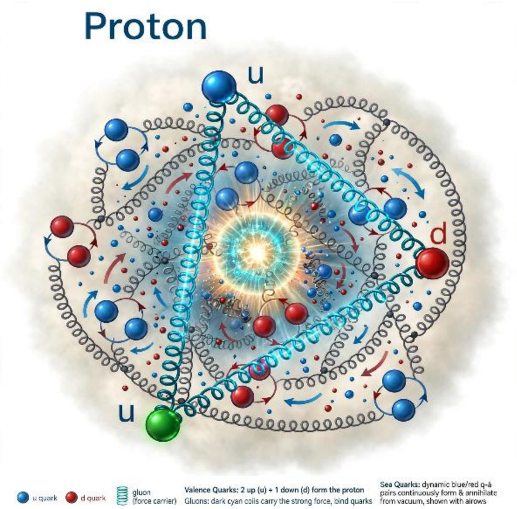
- Panel A. … Relative sizes of in-proton spacetime volumes occupied by quark and gluon mass-energy distributions at resolving scale $\zeta_2 = 2$ GeV.
- Panel B. Combined as required, the scale-dependent distributions in the upper panel yield the scale-invariant (observable) mass-energy distribution (purple 3/4-sphere) in this image.
- Plainly, the spacetime volume occupied by the proton mass-energy distribution is far smaller than that occupied by the charge distribution (grey 3/4-sphere).

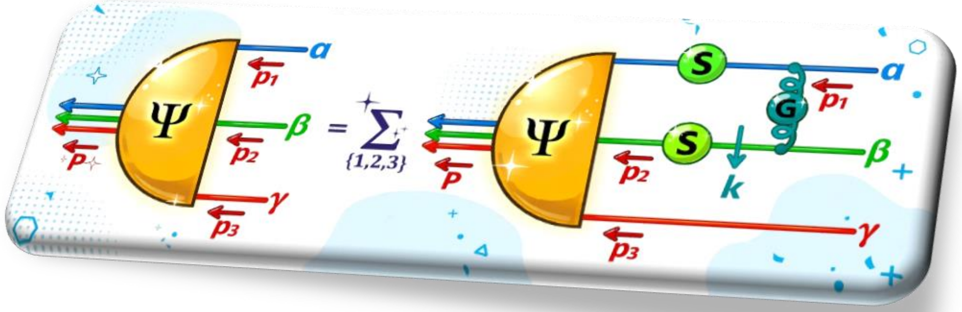


Structure of Baryons



- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- As seen … direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but remains challenging problem – algorithms and numerical analysis



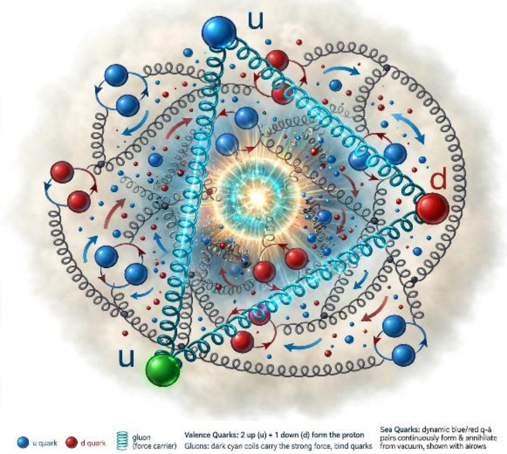


Solution delivers Poincaré-covariant proton wave function

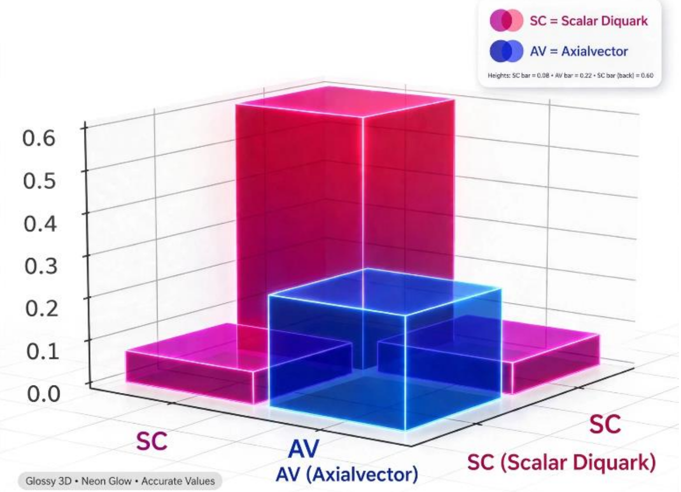
Structure of Baryons

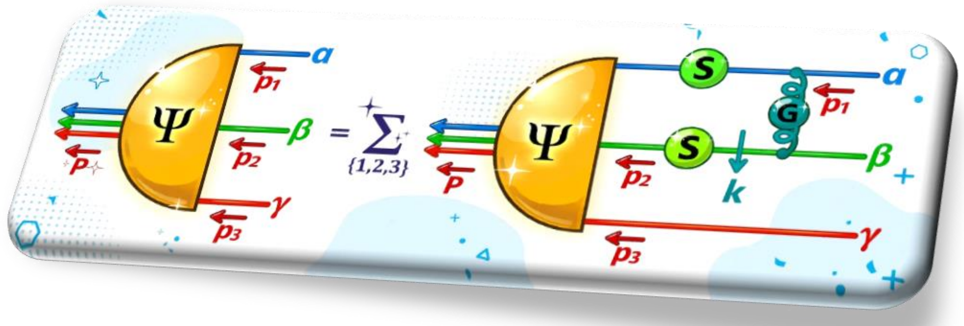
- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- As seen … direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but remains challenging problem – algorithms and numerical analysis
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM, *strong diquark (quark + quark) correlations exist within baryons* - proton & neutron … both scalar and axial-vector diquarks are present

Proton



- ✓ CSM prediction = presence of axialvector (AV) diquark correlation in the proton
- ✓ AV Responsible for ≈ 40% of proton charge





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- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
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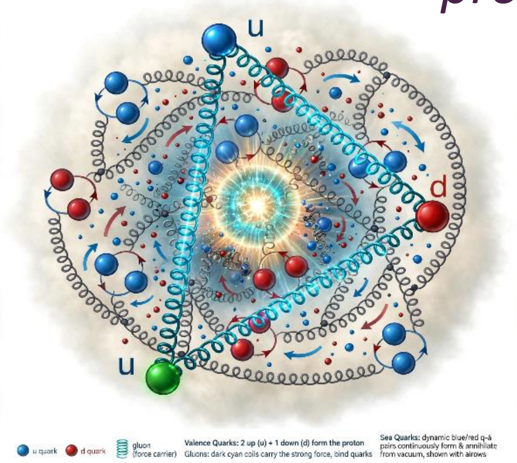
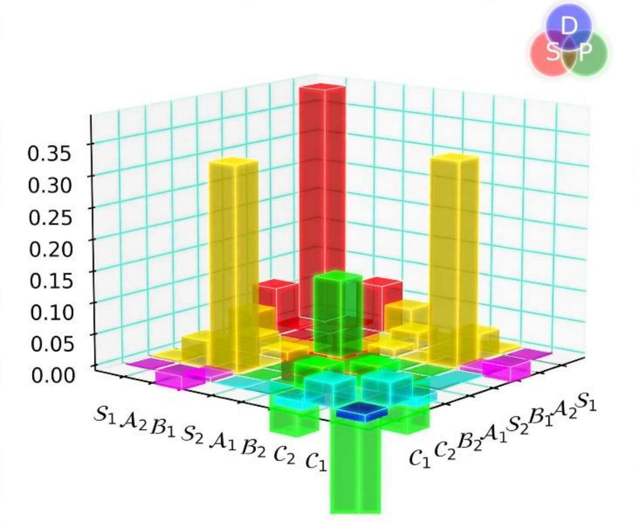


proton wave function is not just S-wave, but contains strong P-wave contributions

baryon wave functions necessarily contain orbital angular momentum

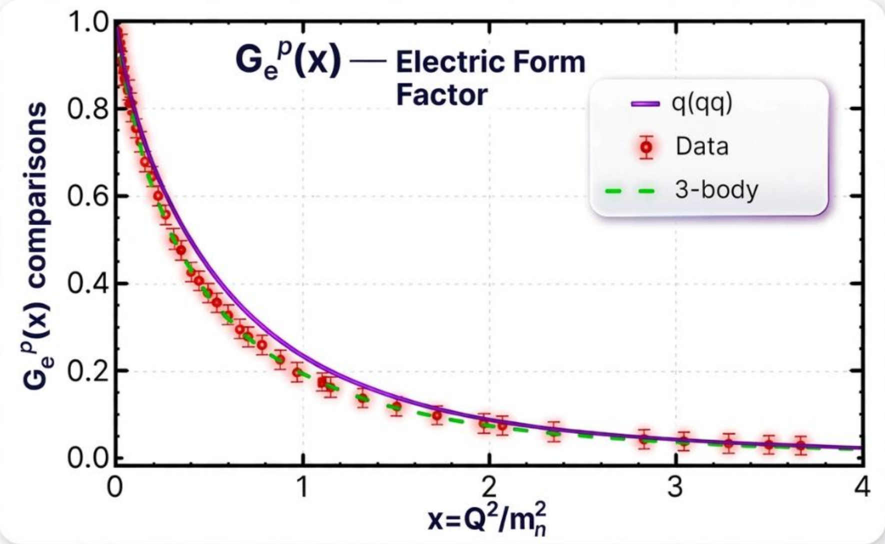


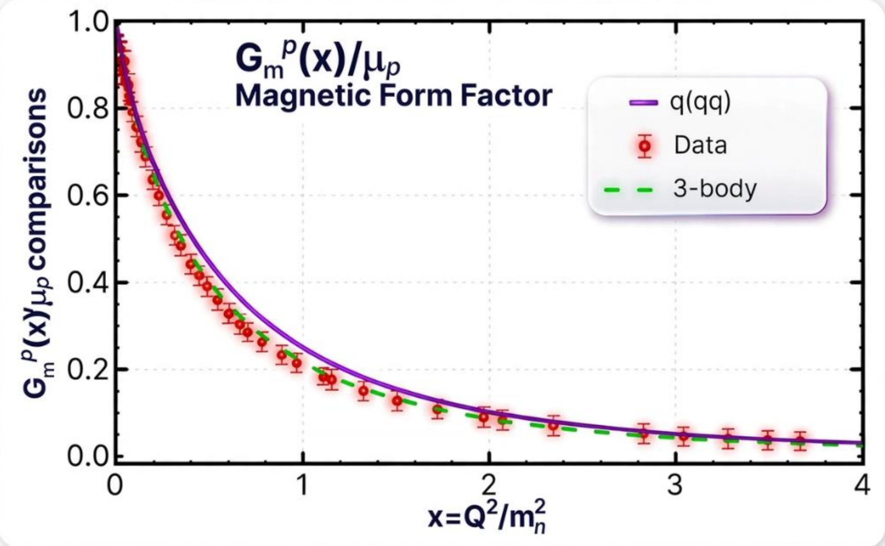
- ✓ CSM prediction = canonical normalization dominated by $S \otimes S$, but receives large $S \otimes P$ and $P \otimes P$ contributions
- ✓ Non-$S \otimes S$ make-up 60% of proton charge

Modern $q(qq)$ formulation of baryon problem

Quark + Diquark Description of Nucleon Elastic Electromagnetic Form Factors, Peng Cheng (程鹏) *et al.*, e-Print: 2507.13484 [hep-ph], Eur. Phys. J. A (2025) 61:255/1-20

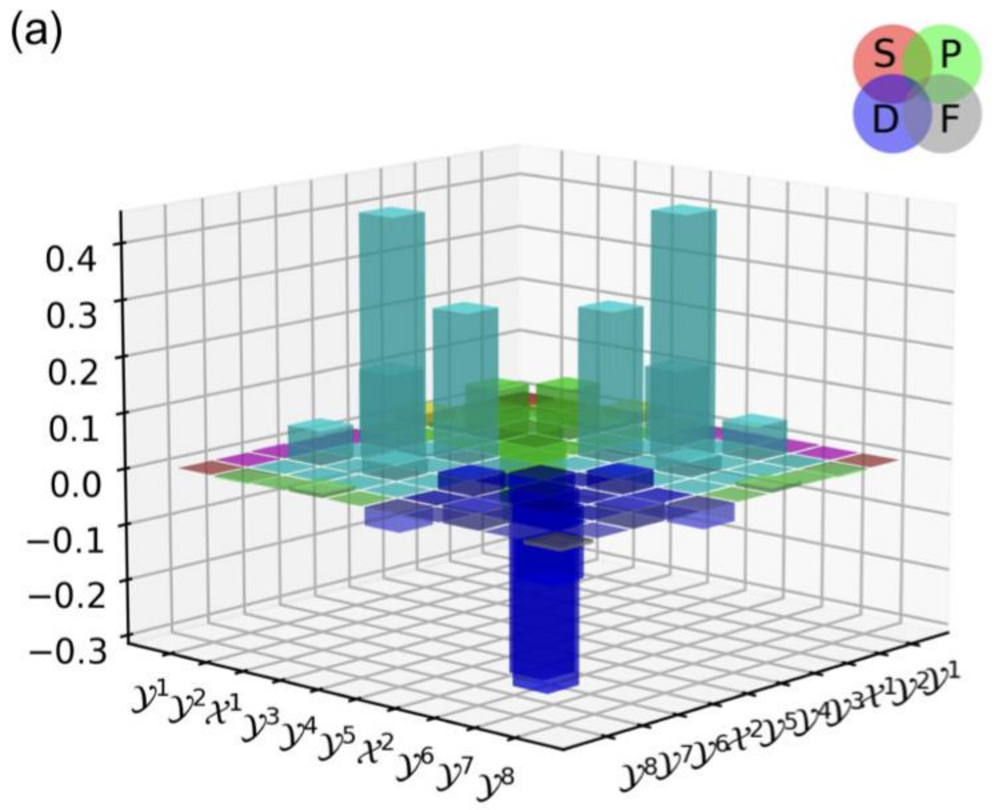
- Modern $q(qq)$ results for nucleon form factors are practically identical with those obtained in qqq picture
- qqq has not yet been applied to resonance excitation form factors
- $q(qq)$ approach has been applied to many such transitions
- New example $N \to N(1520)\ I = \frac{1}{2}, J = \frac{3}{2}^{-}$





CSMs & $N(1520)\frac{3}{2}^{-}$ Structure

- Rest Frame $L_{q(qq)}$ decomposition of $N(1520)\frac{3}{2}^{-}$ canonical normalization constant
  - ✓ Most prominent positive contributions are provided by constructive P ⊗ D-wave interference terms
  - ✓ Contributions from purely P-wave components are visible, but interfere destructively
  - ✓ Pure D-wave terms are responsible for largely destructive interference.
- Plainly, Poincaré-covariant wave function is structurally complex
- Test picture via comparison with $N \to N(1520)$ electroproduction data



This picture is very different from that obtained from quark models built upon (weakly broken) SU(6) spin-flavour symmetry …

Constituent-quark orbital angular $L_{QQQ} = 1$ & three constituent-quark spins being coupled to $S_{QQQ} = \frac{1}{2}$

Insights into Nucleon Resonances via Continuum Schwinger Function Methods, Peng Cheng (程鹏), Langtian Liu (刘浪天), Ya Lu (陆亚) and Craig D. Roberts, e-Print: 2512.09160 [hep-ph], Acta Physica Polonica B 57 (2026) 2-A13. Contribution to a special issue of Acta Physica Polonica that celebrates the 90th birthday of L. David Roper

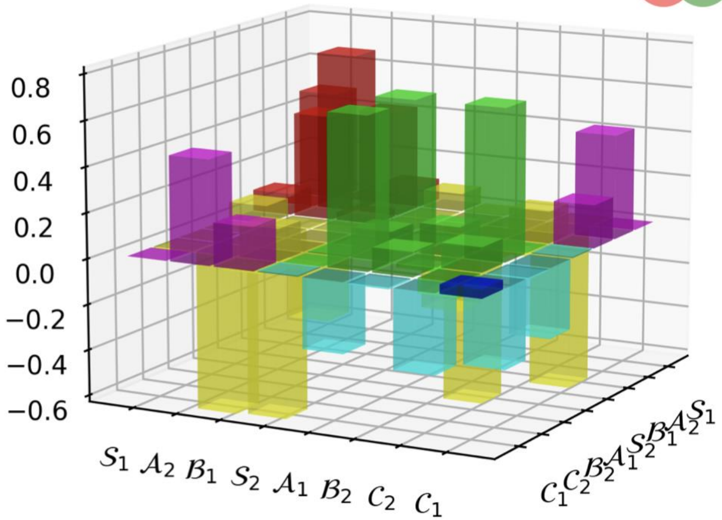
Peng Cheng (程鹏) *et al.*, in progress

$$N \to N(1520)\ I = \frac{1}{2}, J = \frac{3}{2}^-$$

- Transition to $J = \frac{3}{2}$ final state is described by 3 form factors

  Magnetic G_M^*, Electric G_E^*, Coulomb G_C^*

- Data are available from the CLAS Collaboration
  - ✓ extracted assuming that imaginary part of the form factors at the resonance pole position is small
  - ✓ some DCC models find this to be the case (Argonne-Osaka), others do not (BonnJ)



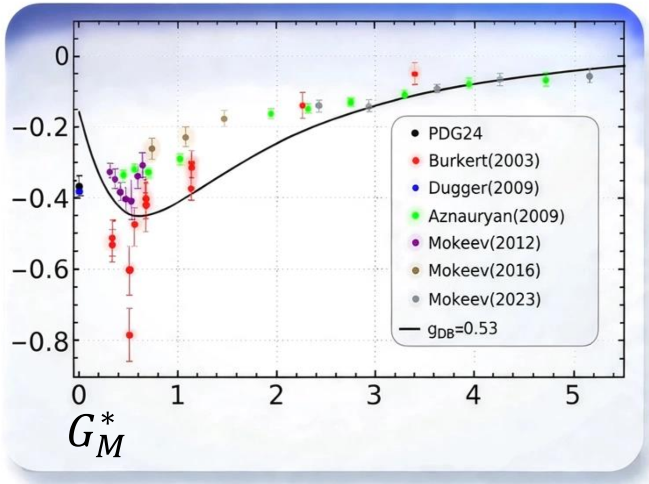
- Test … which (if any) data inference do continuum-QCD results favour?
- In case of $N \to N(1440)\ I = \frac{1}{2}, J = \frac{1}{2}^+$, answer is unambiguous
  - ✓ on domain beyond meson-cloud reach, $q(qq)$ predictions agree with CLAS extraction
  - ✓ Roper resonance is well understood as the first radial excitation of the nucleon, dominated by its three-quark core, yet dressed by a substantial meson cloud

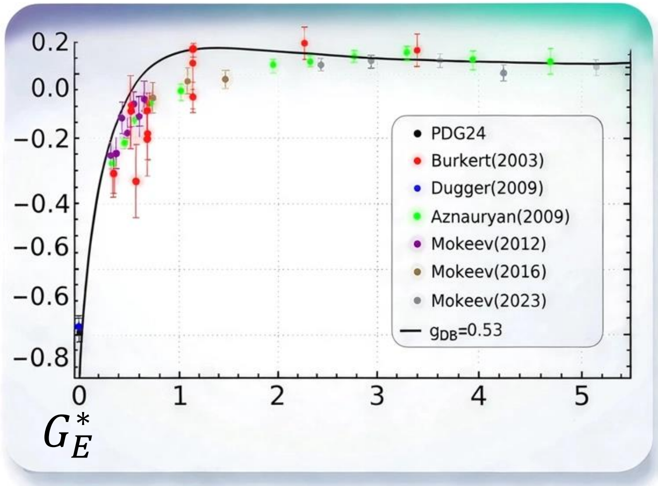
Insights into Nucleon Resonances via Continuum Schwinger Function Methods, Peng Cheng (程鹏), Langtian Liu (刘浪天), Ya Lu (陆亚) and Craig D. Roberts, [e-Print: 2512.09160 [hep-ph]], [Acta Physica Polonica B 57 (2026) 2-A13]. Contribution to a special issue of Acta Physica Polonica that celebrates the 90th birthday of L. David Roper

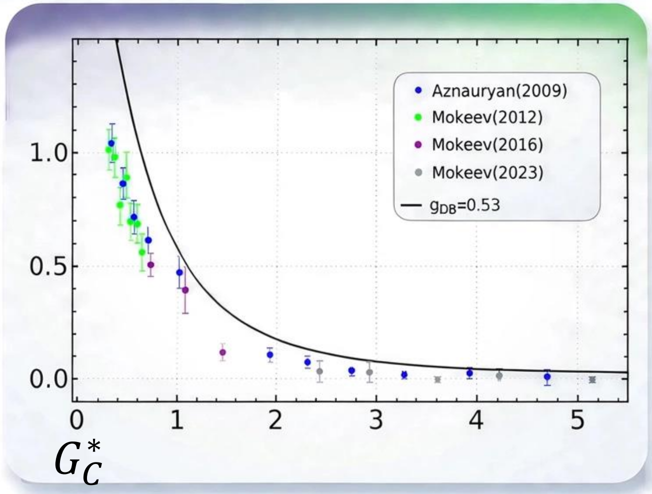
Peng Cheng (程鹏) *et al.*, in progress

$N \to N(1520)\ I = \frac{1}{2}, J = \frac{3}{2}^-$

- Using precisely same framework as used for $N \to N(1440)\ I = \frac{1}{2}, J = \frac{1}{2}^+$
  - ✓ Built upon the Three Pillars of Emergent Hadron Mass
  - ✓ Extensively benchmarked
- **Parameter-free predictions**
- Fair agreement with CLAS extractions
  - ✓ Including zero in G_E^*
  - ✓ As with Roper, ∃ room for meson-baryon FSIs on $x \lesssim 2$
- Validation of structurally complex Faddeev amplitude for $N(1520)\ (\frac{1}{2}, \frac{3}{2}^-)$







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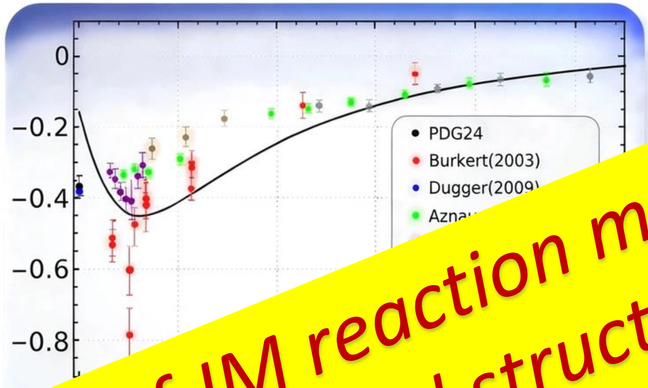
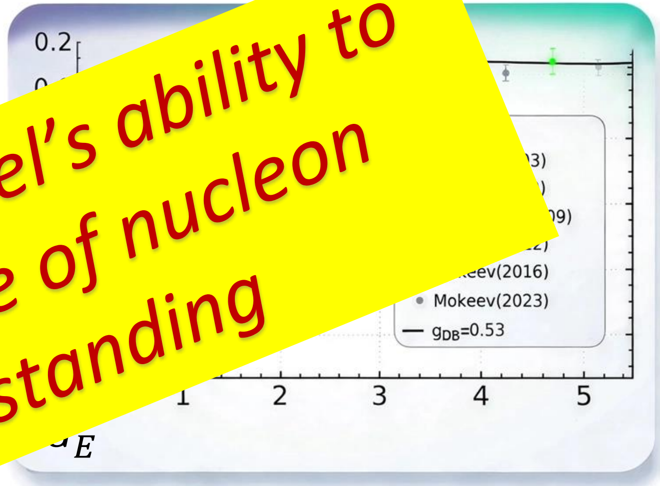
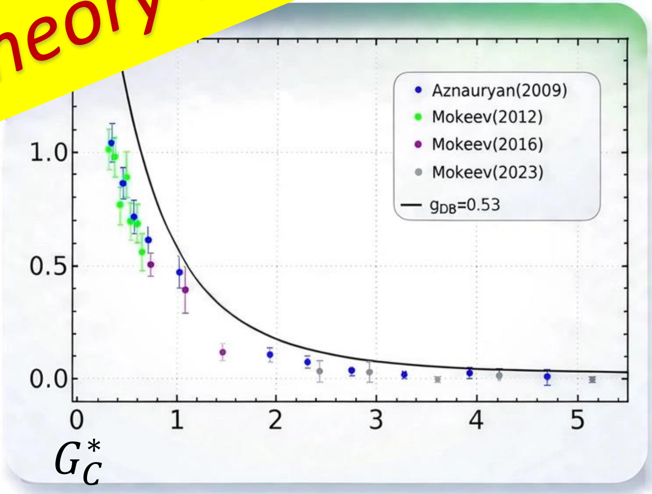
- Va ... turally complex Fad ... amplitude for $N(1520)\ (\frac{1}{2}, \frac{3}{2}^-)$

✓ Strong evidence in support of JM reaction model's ability to deliver empirical access to internal structure of nucleon resonances and, so, test theory understanding



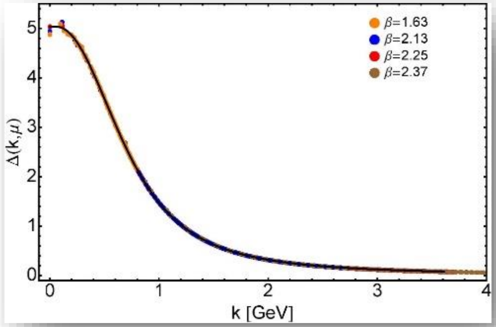


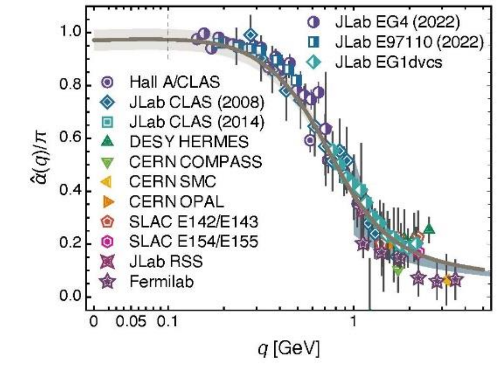


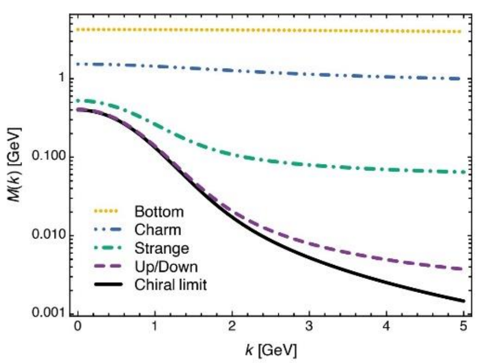
Gather all pieces of the puzzle … Reveal the source of Nature's basic mass-scale

Synergy of Experiment, Phenomenology, Theory

- Continuum strong interaction theory is maturing
  - ✓ Expanding array of parameter-free predictions for the nucleon
  - ✓ And all the other hadrons whose properties express the full meaning of QCD
    - Structure of Nature's most fundamental Nambu-Goldstone bosons
    - Structure of baryons, e.g., Q^2-dependence of nucleon resonance transition form factors
      - ✓ Spectrum is insufficient – many models give same spectrum, but transition form factors discriminate between pictures.
- Understanding how QCD's simplicity explains the emergence of hadron mass and structure requires investment in facilities that can deliver precision data on much more than one of Nature's hadrons.
- AMBER@CERN, CEPC, EIC, EicC, JLab22, LHeC, QCD@FAIR, STCF, could …
  - ✓ Deliver precise structure data on a wide range of hadrons with distinctly different quantum numbers
  - ✓ Thereby move Science into a new realm of understanding.







Grant no. 12135007
国家自然科学基金委员会
NSFC
National Natural Science Foundation of China

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 1st well-defined four-dimensional quantum field theory ever contemplated
- *This may open doors that lead far beyond the Standard Model*

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

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

$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) - f^{abc} A^b_\mu(x) A^c_\nu(x)$$

Current mass generated by Higgs boson couplings into QCD

No mass term for gluons

- One-line Lagrangian – expressed in terms of massless gluon (A^a_μ) and Higgs-mass quark (ψ) partons
- Which are NOT the degrees-of-freedom measured in detectors

Gluon and Quark Confinement

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.”*

Quantum Chromodynamics

Current mass generated by Higgs boson couplings into QCD

100-times smaller than proton mass

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

No mass term for gluons

$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) - f^{abc} A^b_\mu(x) A^c_\nu(x)$$

- One-line Lagrangian – expressed in terms of massless gluon (A^a_μ) and Higgs-mass quark (ψ) partons
- Which are NOT the degrees-of-freedom measured in detectors

Gluon and Quark Confinement

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

Hadrons

= protons, pions, etc.

All-orders evolution

- **P1** – *In the context of Refs. [73, 74], there exists at least one effective charge, $\alpha_{1\ell}(k^2)$, which, when used to integrate the leading-order perturbative DGLAP equations, defines an evolution scheme for parton DFs that is all-orders exact.*
- CSM Process-Independent charge serves this purpose

Physics Letters B
Volume 95, Issue 1, 8 September 1980, Pages 70-74

Renormalization group improved perturbative QCD

G. Grunberg [1]

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https://doi.org/10.1016/0370-2693(80)90402-5

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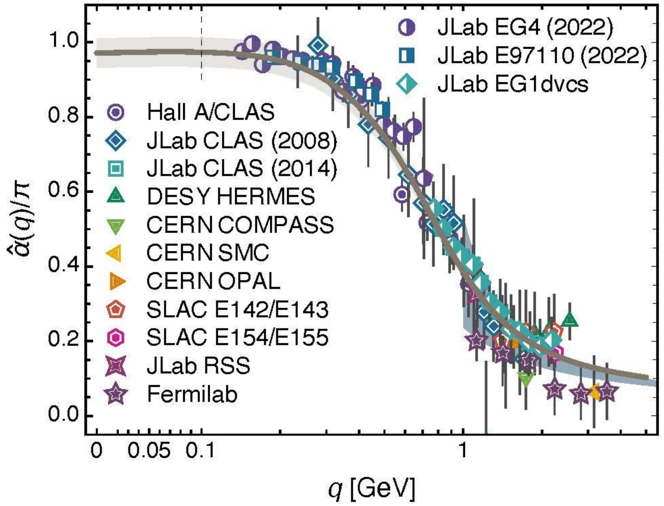
Abstract

The results of perturbative QCD calculations are reformulated as renormalization-scheme independent predictions; in so doing, we obtain a renormalization group improvement of perturbation theory. As an application, we show that asymptotic freedom alone does not give the correct quantitative relation between pseudoscalar charmonium decay and the scaling violations in deep inelastic scattering.

- *Hadron scale, ζ_H*

  Scale at which all properties of a given hadron are carried by valence degrees-of-freedom



[73] G. Grunberg, Renormalization Group Improved Perturbative QCD, Phys. Lett. B 95 (1980) 70, [Erratum: Phys. Lett. B 110, 501 (1982)].
[74] G. Grunberg, Renormalization Scheme Independent QCD and QED: The Method of Effective Charges, Phys. Rev. D 29 (1984) 2315.
[75] A. Deur, S. J. Brodsky, G. F. de Teramond, The QCD Running Coupling, Prog. Part. Nucl. Phys. 90 (2016) 1–74.
[76] A. Deur, V. Burkert, J. P. Chen, W. Korsch, Experimental determination of the QCD effective charge $\alpha_{g_1}(Q)$, Particles 5 (2) (2022) 171–179.
[77] A. Deur, S. J. Brodsky, C. D. Roberts, QCD Running Couplings and Effective Charges – arXiv:2303.00723 [hep-ph] .

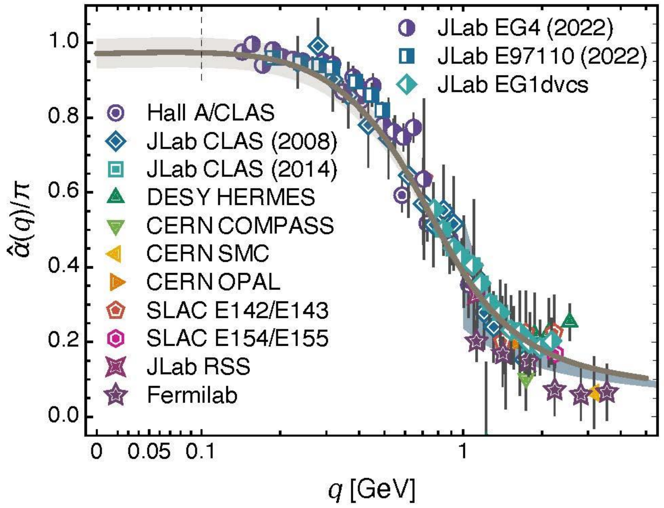
AO Evolution

- Principle
  - Hadron scale, ζ_H, is rigorously defined in connection with a Grunberg charge, in terms of which leading-order DGLAP evolution is promoted to the status of an all-orders exact procedure.
  - The AO scheme is not a model, and neither is ζ_H.
  - Instead, the AO approach, involving and defining ζ_H, is complete by definition.
- As explained by Grunberg, there is always an effective (process-dependent) effective charge for which the AO propositions are true.
  - Consequently, there is no room for doubt about the existence of ζ_H.
- Crucially, such a Grunberg effective charge is
  - consistent with the renormalization group;
  - renormalization scheme independent;
  - everywhere analytic and finite;
  - and supplies an infrared completion of any standard running coupling.

AO Evolution

- Crucially, such a Grunberg effective charge is
  - ✓ consistent with the renormalization group;
  - ✓ renormalization scheme independent;
  - ✓ everywhere analytic and finite;
  - ✓ and supplies an infrared completion of any standard running coupling.
- These features entail that all calculations of a DF at a scale within a domain of pQCD applicability are compatible with this effective charge.
- Moreover, and especially important, is the fact that one does not need to know the pointwise form of the effective charge
  - ✓ Its existence alone is sufficient to deliver the definition of ζ_H and all attendant consequences
  - ✓ *N.B.* glue and sea DFs are identically zero at ζ_H

AO Evolution

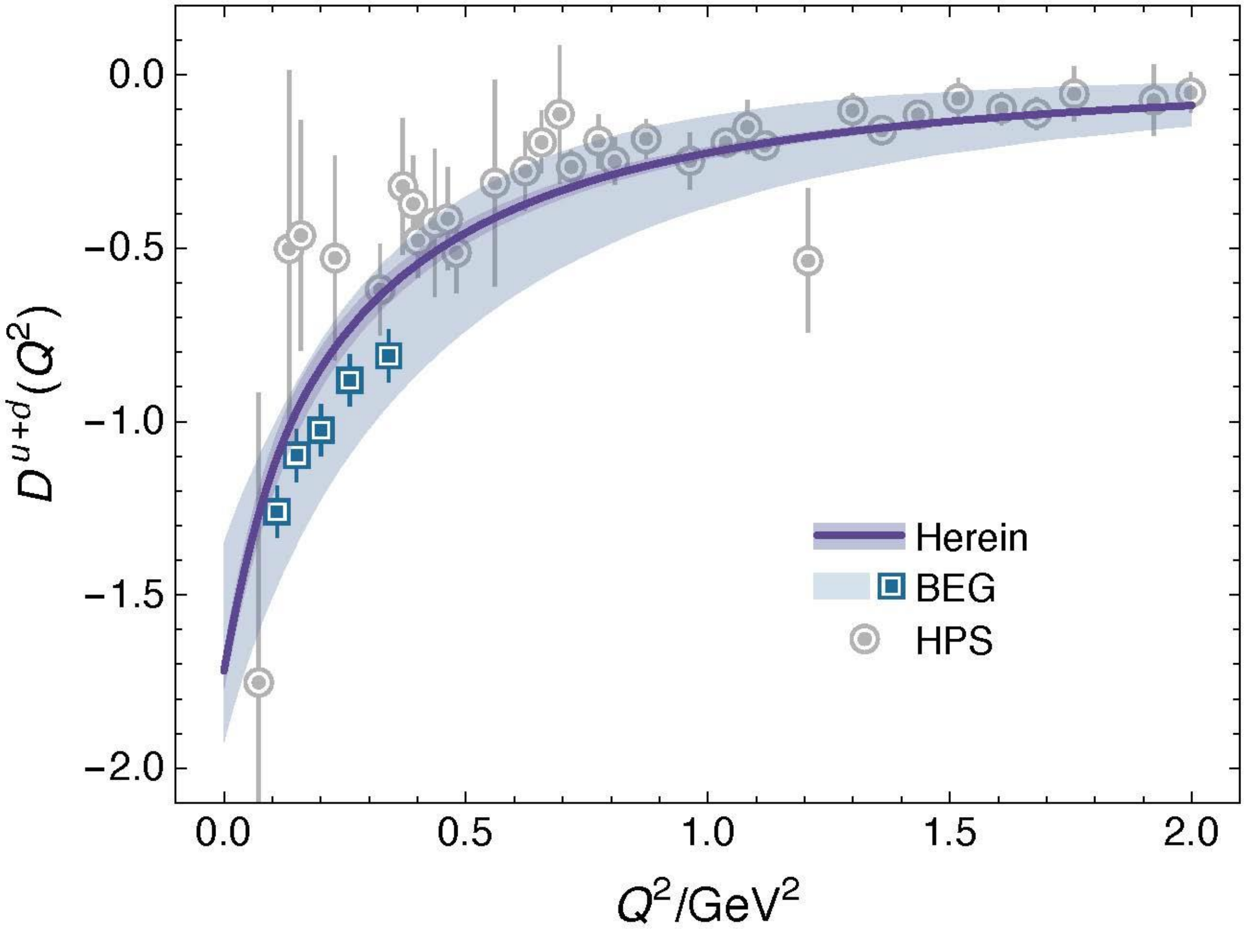


- The potential issue with a Grunberg effective charge is that reference to a specific process may make it globally useless
- We know that is not the case
  - The class of process-dependent (Grunberg) charges, defined in connection with the AO scheme, may be characterized by our unique, predicted process-independent effective charge
- Thus far, the AO class of charges – in particular, our PI charge – has served in the same form for all known parton DFs
  - ✓ Namely, for a large array of structure functions and fragmentation processes.

✓ This is a very broad domain of applicability for one single Grunberg charge.

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

- Considering light quarks alone:
  $$D^{u+d}(0;\zeta_2) = -1.73(5)$$
- Inference from available DVCS data
  $$D^{u+d}_{\text{DVCS}}(0;\zeta_2) = -1.63(29)$$
- 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.

Exclusive photoproduction of light and heavy vector mesons: thresholds to very high energies, Lin Tang (唐淋), Hui-Yu Xing (邢惠瑜) et al., NJU-INP 105/25, e-Print: 2510.08845 [hep-ph], Eur. Phys. J. C 86 (2026) 284/1-19.

Exclusive photoproduction of light and heavy vector mesons

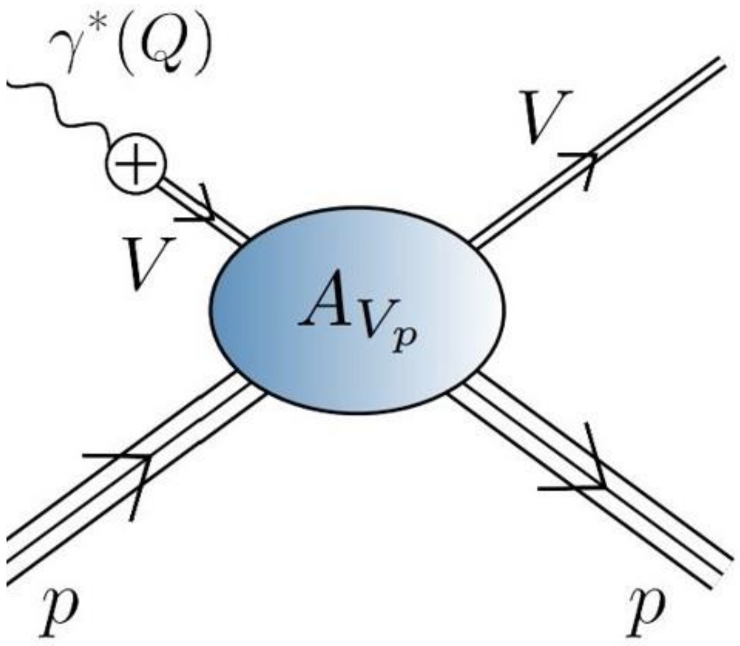
- $e + p \to e' + V + p$
- If one cannot reasonably use the VMD model, what alternative is there?
- Proposal
  - Diffractive, so use Pomeron

$$\gamma \to q\bar{q} + \mathbf{P} \to V \text{ transition}$$

i. Photon Fluctuation: incoming photon fluctuates into a (virtual) $q\bar{q}$ pair.

ii. Diffractive Scattering: $q\bar{q}$ pair interacts with proton via exchange of Pomeron

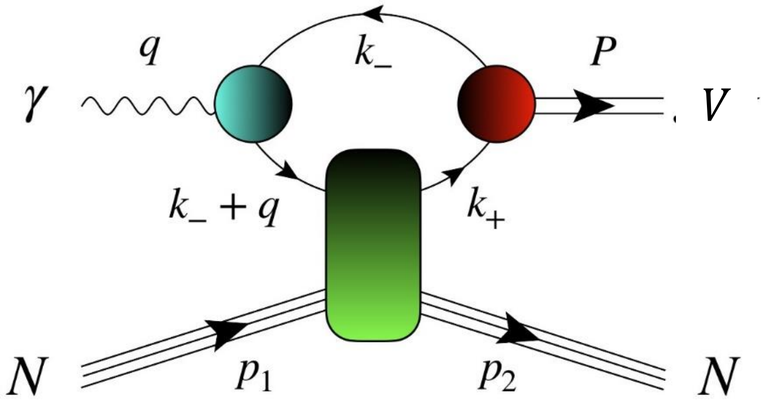
iii. Meson Formation: $q\bar{q}$ subsequently coalesces into the final-state, on-shell vector meson



V photoproduction: from threshold to very high energies

- Parameter-free CSM calculation of quark 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 Pomeron parameters
  - Pomeron trajectory: α_0, α_1

    ... fixed 20 years ago by high-W data from HERA
  - Pomeron – valence-quark coupling:
    - β_ℓ ... fixed by HERA high-W $\gamma p \to \rho^0 p$ photoproduction differential cross-section
    - β_c ... fixed by HERA high-W $\gamma p \to J/\psi p$ forward differential cross-section
- Hereafter, all predictions



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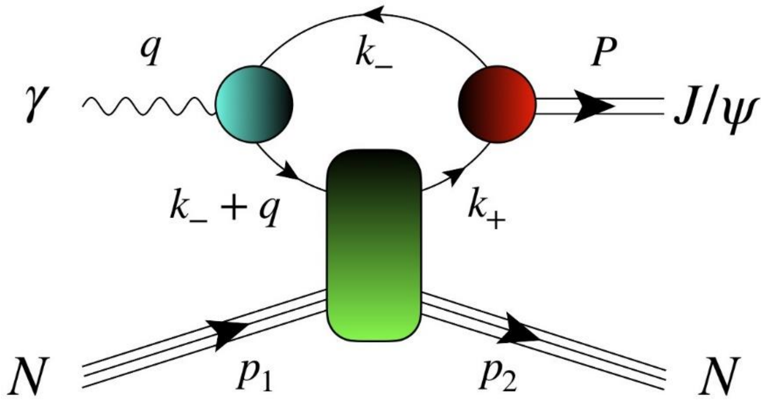
J/ψ photoproduction: from threshold to very high energies

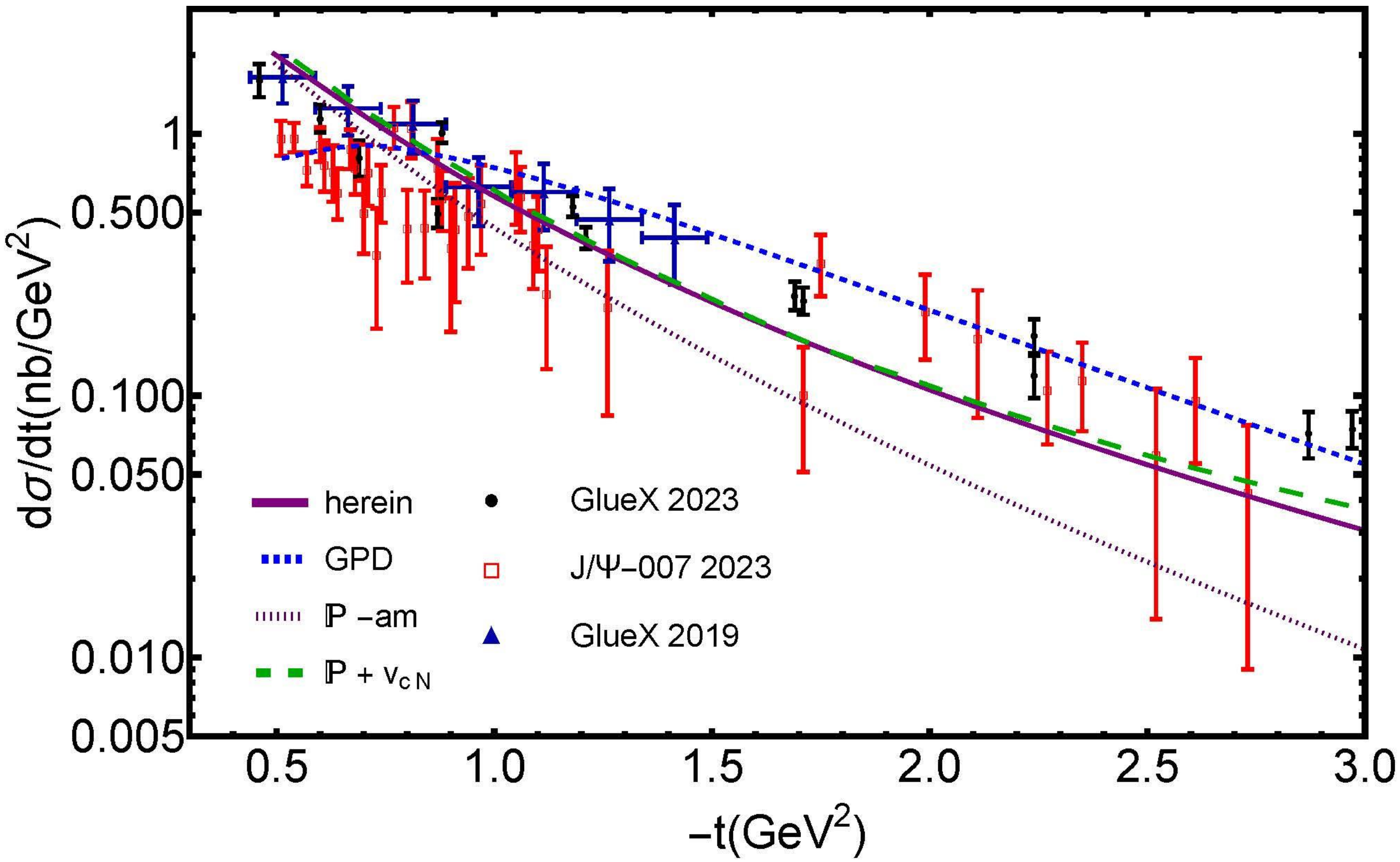


- Some modern proposals for reaction model:
  - $\gamma + p \to c + \bar{c} + P + p \to J/\psi + p$
    - Exposes $c + \bar{c}$ content of the dressed photon
    - Couples the intermediate $c + \bar{c}$ system to proton's valence quarks via Pomeron exchange
  - ~~VMD-based GPD treatment … desire to gain access to in-proton gluon gravitational form factors~~

    If GPD scheme valid at all, then only very near threshold. All W unification impossible
  - 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.

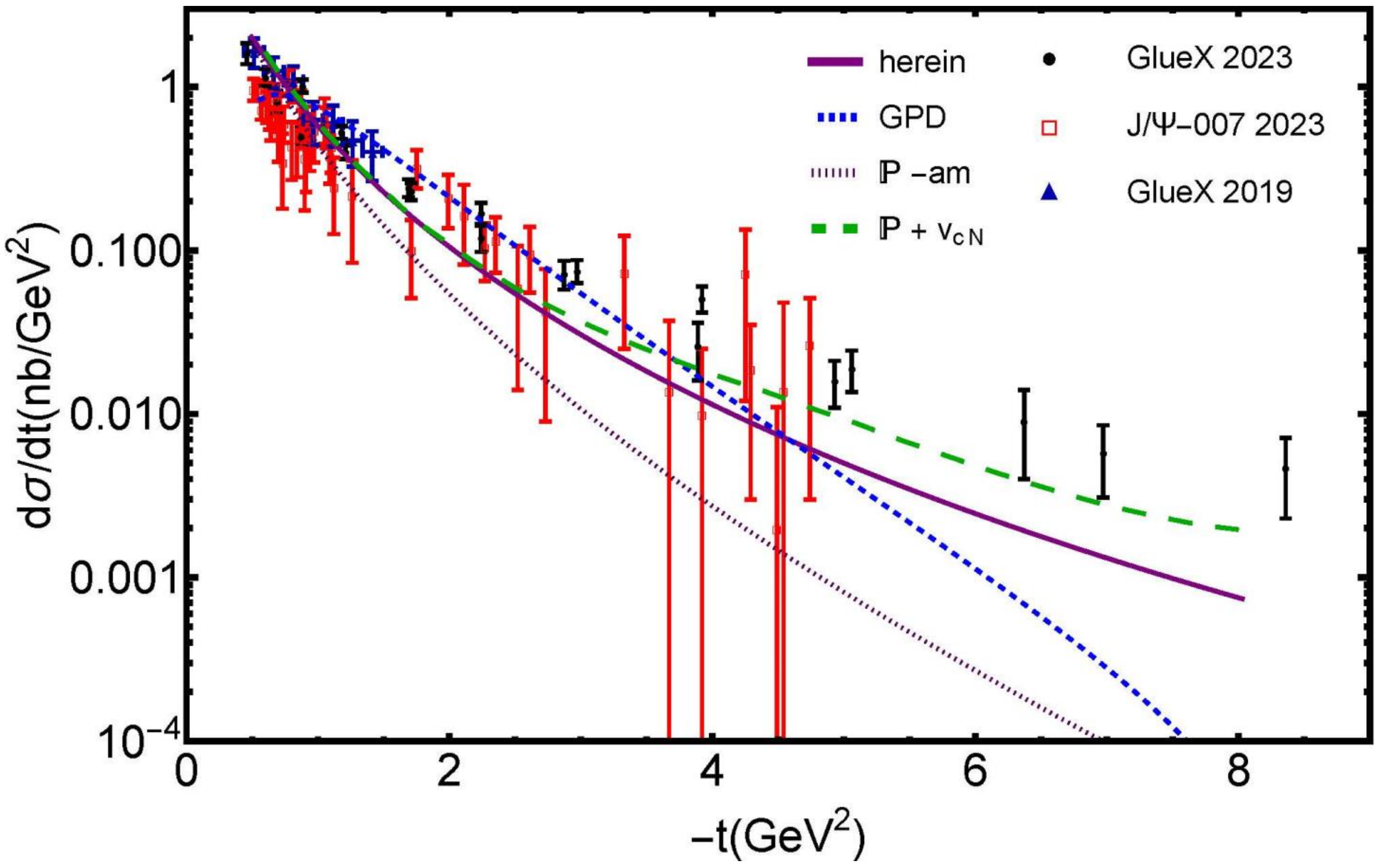
J/ψ photoproduction: threshold differential cross-section

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



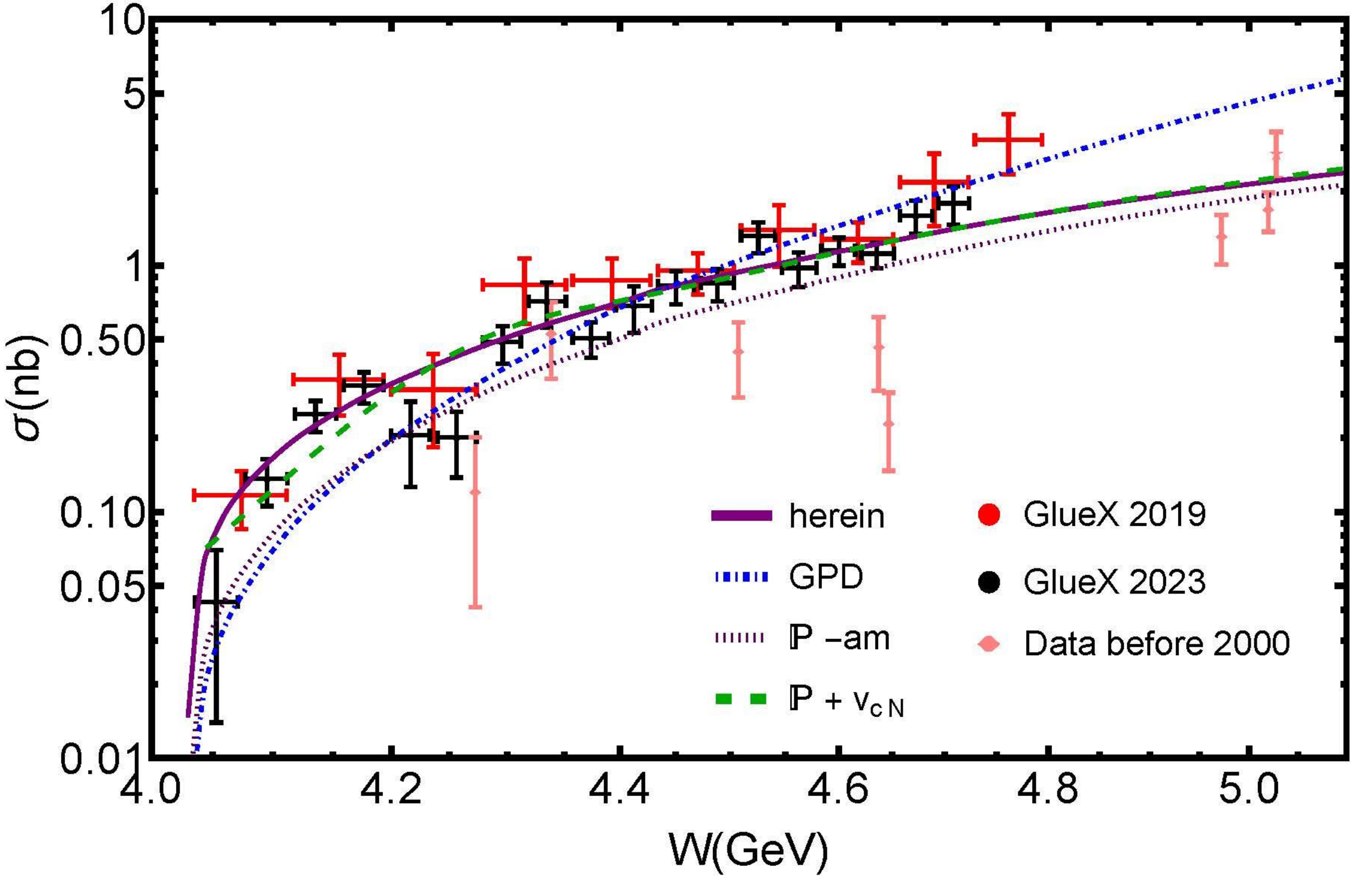
J/ψ photoproduction: threshold differential cross-section

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



J/ψ photoproduction: total cross-section, threshold to high-W

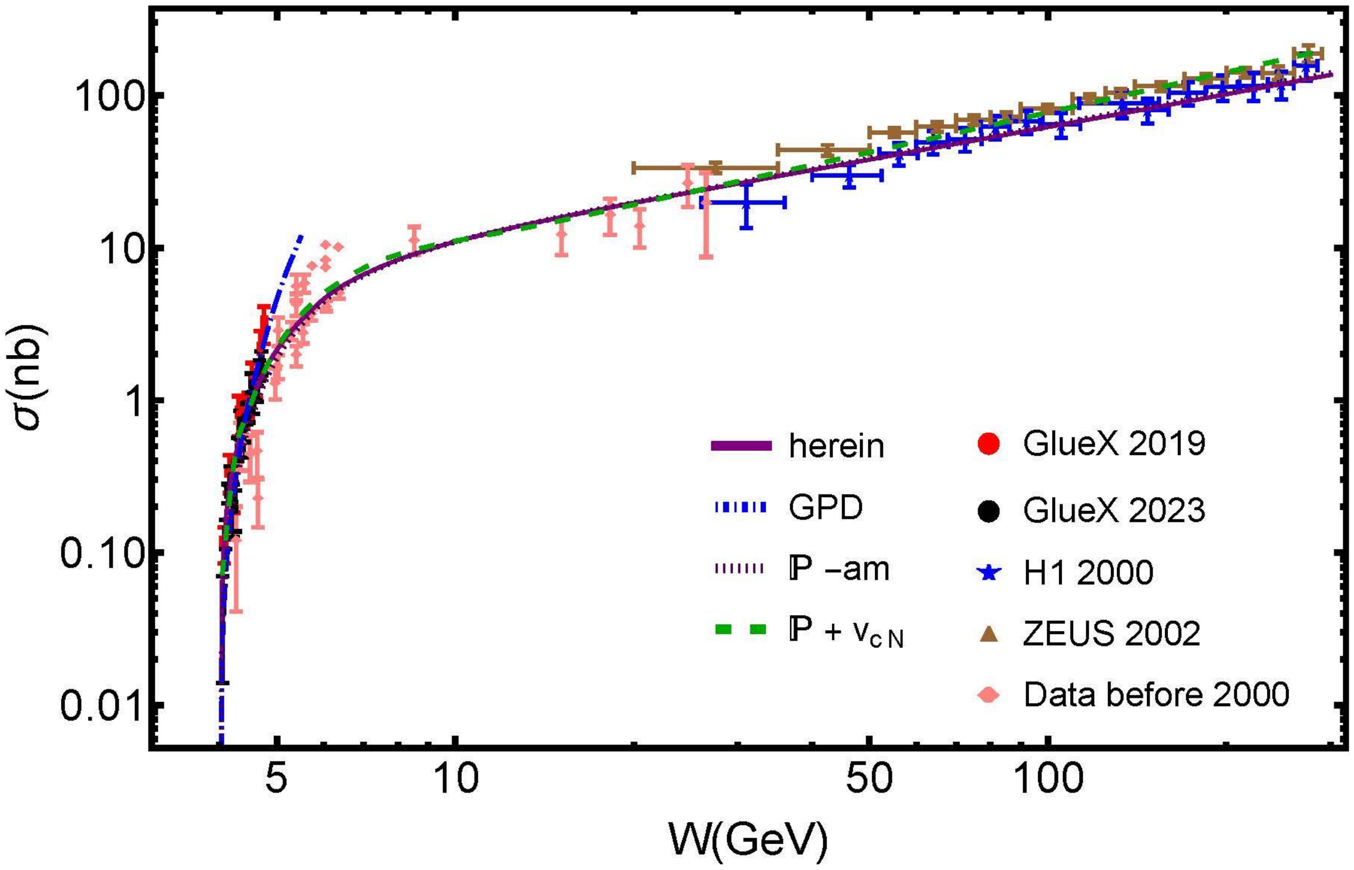
- GPD model (dotted blue)
  - Inapplicable on $W > 5$ GeV
  - $\chi^2_{\rm dof} = 2.5$ near threshold
- $\mathbf{P} + J/\psi\, p$ rescattering
  - dashed green – $\chi^2_{\rm dof} = 1.7$
- $\mathbf{P}$ + quark loop
  - solid purple – $\chi^2_{\rm dof} = 1.4$



J/ψ photoproduction: total cross-section, threshold to high-W

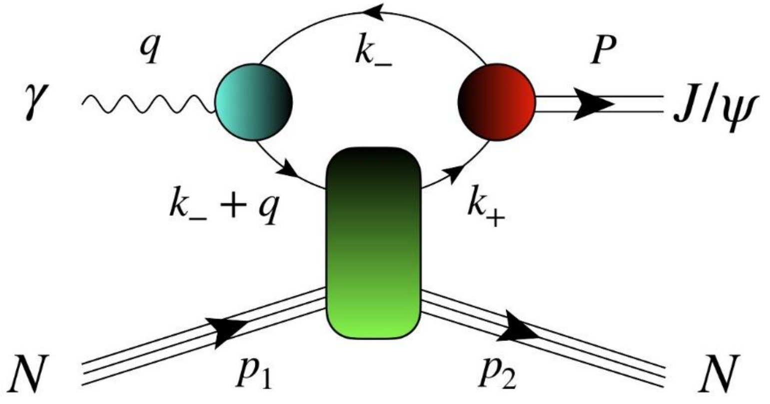
Reported ZEUS uncertainty in W is large, but uncertainty in σ is small
Distorts χ^2

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



J/ψ 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/ψ controls reaction
    - No sensitivity to glue in proton

J/ψ 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.