NANJING UNIVERSITY

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

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

Hadron Structure: Perspective and Insights

Basic Questions in Nature …

Basic Questions in Nature …
… that physics might answer in the foreseeable future

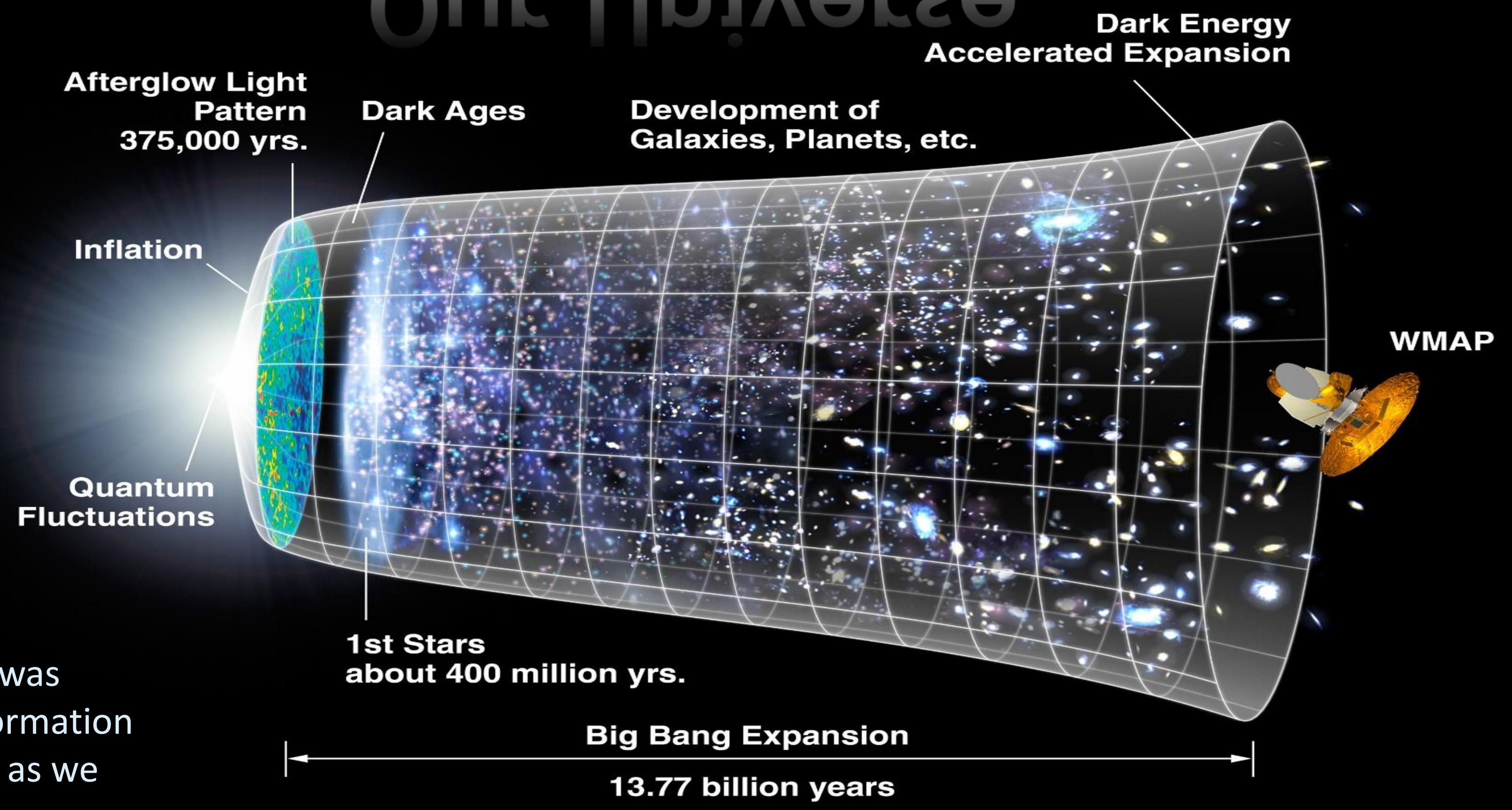
- What is the origin of the nuclear-physics mass scale

  $m_p =$ proton mass

  that characterises all visible matter?
- Whatever it is, why is the pion seemingly oblivious?
- How is this phenomenon expressed in measurable quantities?
  - ✓ The expressions are (almost) certainly system specific!

Our Universe

Mass emerged $1\mu s$ after the Big Bang



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

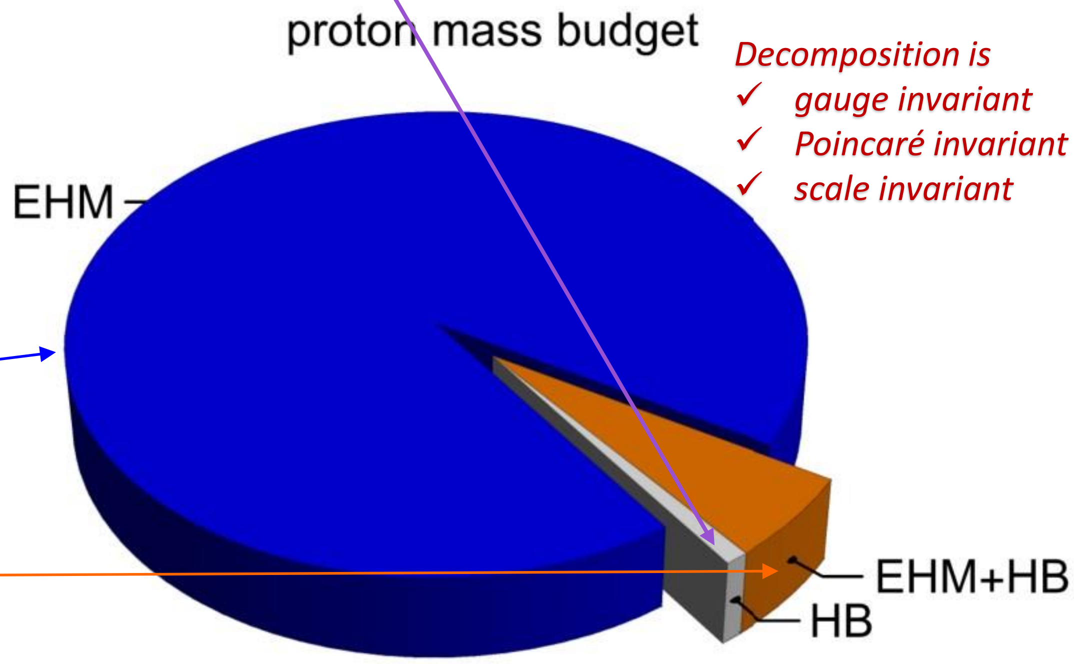
Emergence of Hadron Mass

- 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



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

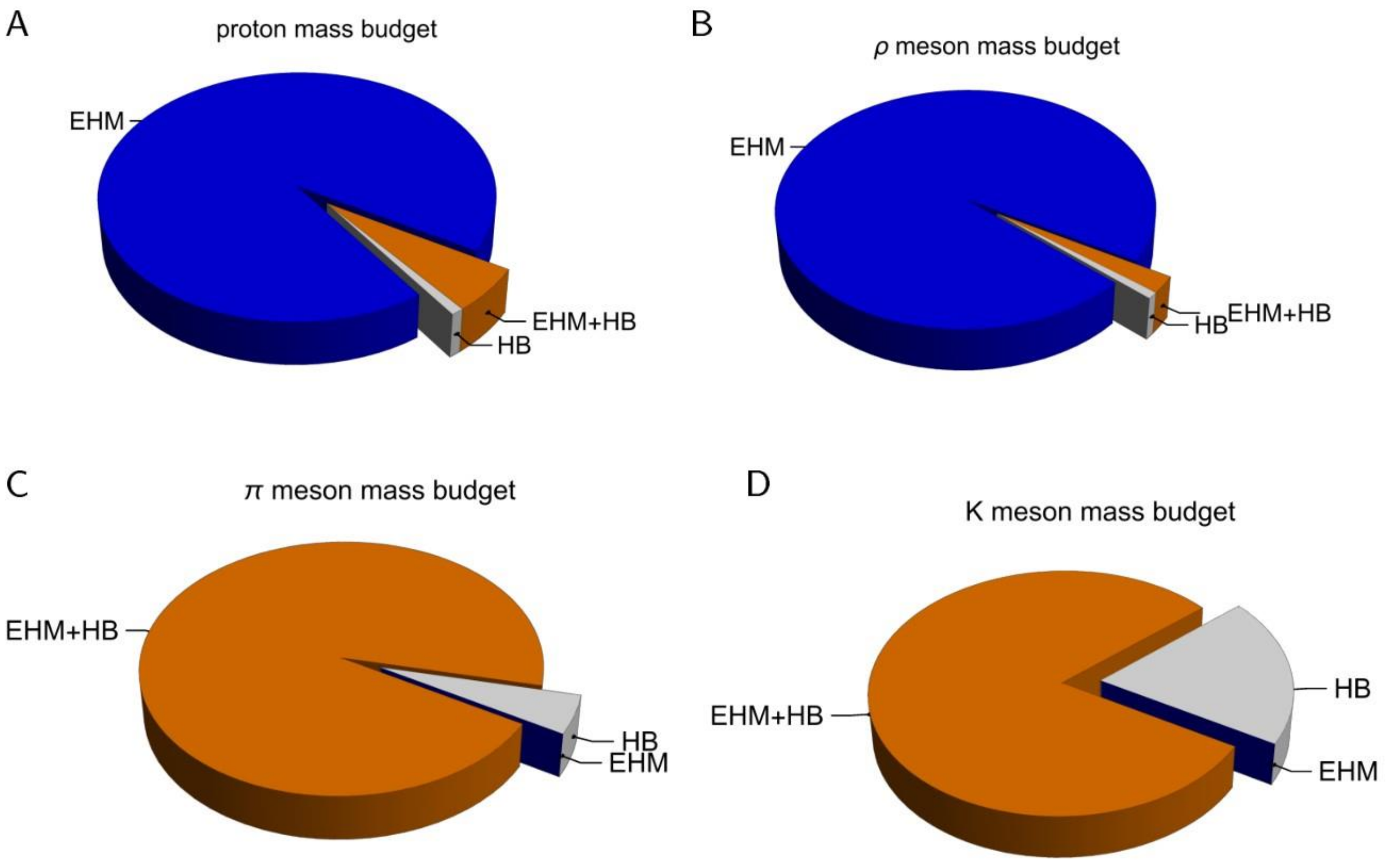
- *What is the origin of EHM?*

Emergence of Hadron Mass - Basic Questions

Decompositions are
- ✓ *gauge invariant*
- ✓ *Poincaré invariant*
- ✓ *scale invariant*

- What is the origin of EHM?
- Does it lie within QCD?
- What are EHM's connections with …
  - Gluon and quark confinement?
  - Dynamical chiral symmetry breaking (DCSB)?
  - Nambu-Goldstone modes = π & K?
- What is the role of Higgs in modulating EHM expressions in observable properties of hadrons?
  - Without Higgs mechanism of mass generation, π and K would be indistinguishable
- What and wherefrom is mass?

Proton and ρ-meson mass budgets are practically identical



π- and K-meson mass budgets
are completely different from those of proton and ρ

Quantum Chromodynamics

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

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

- 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

G E N E S I S

GLUON

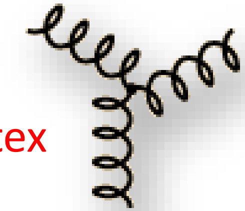
Modern Understanding Grew Slowly from Ancient Origins

- ≈ 45 years ago

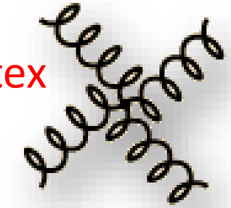
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … > 1100 citations

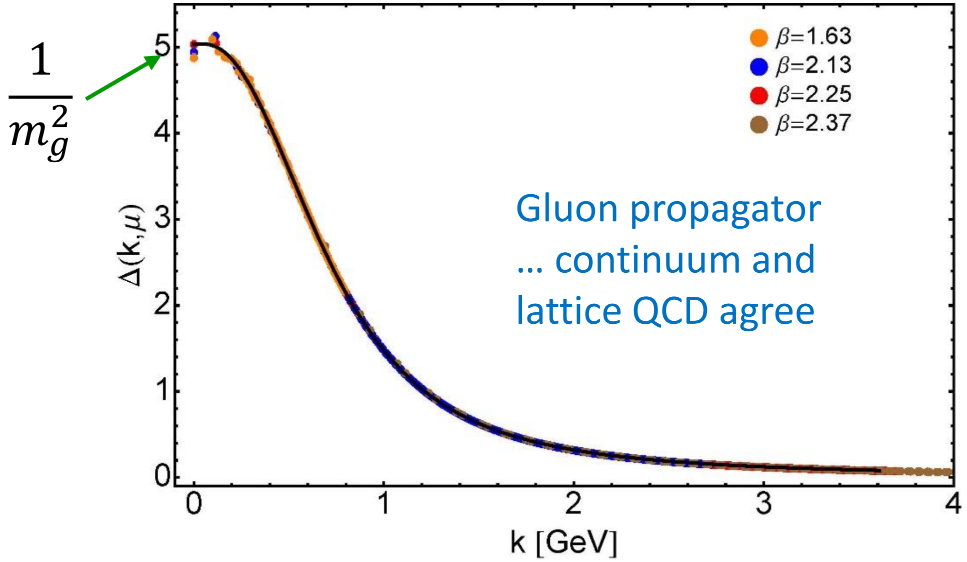
- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

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.

Modern Understanding Grew Slowly from Ancient Origins

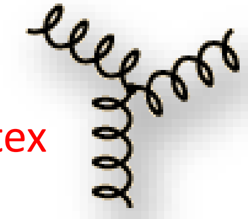
- More than 40 years a

  Dynamical mass gene *ics,*

  J.M. Cornwall, Phys. R

- Owing to strong self- siparticles, described by a r menta

3-gluon vertex



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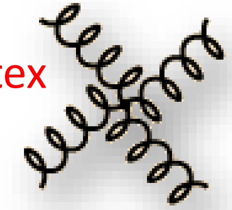
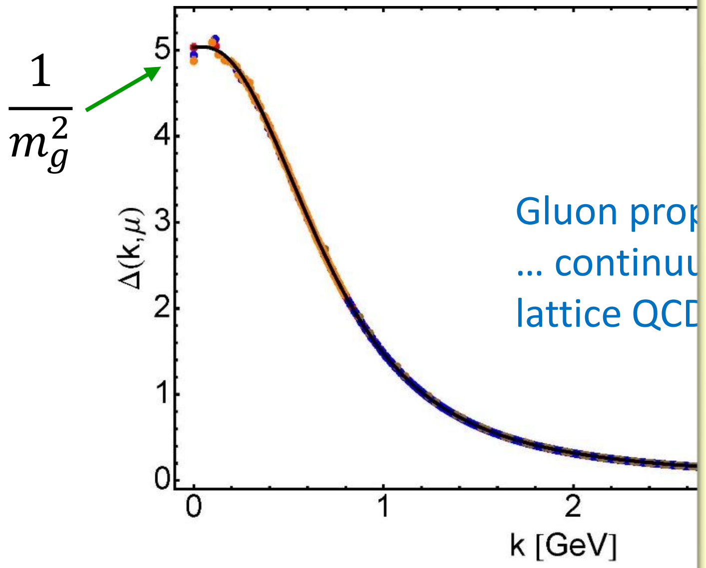




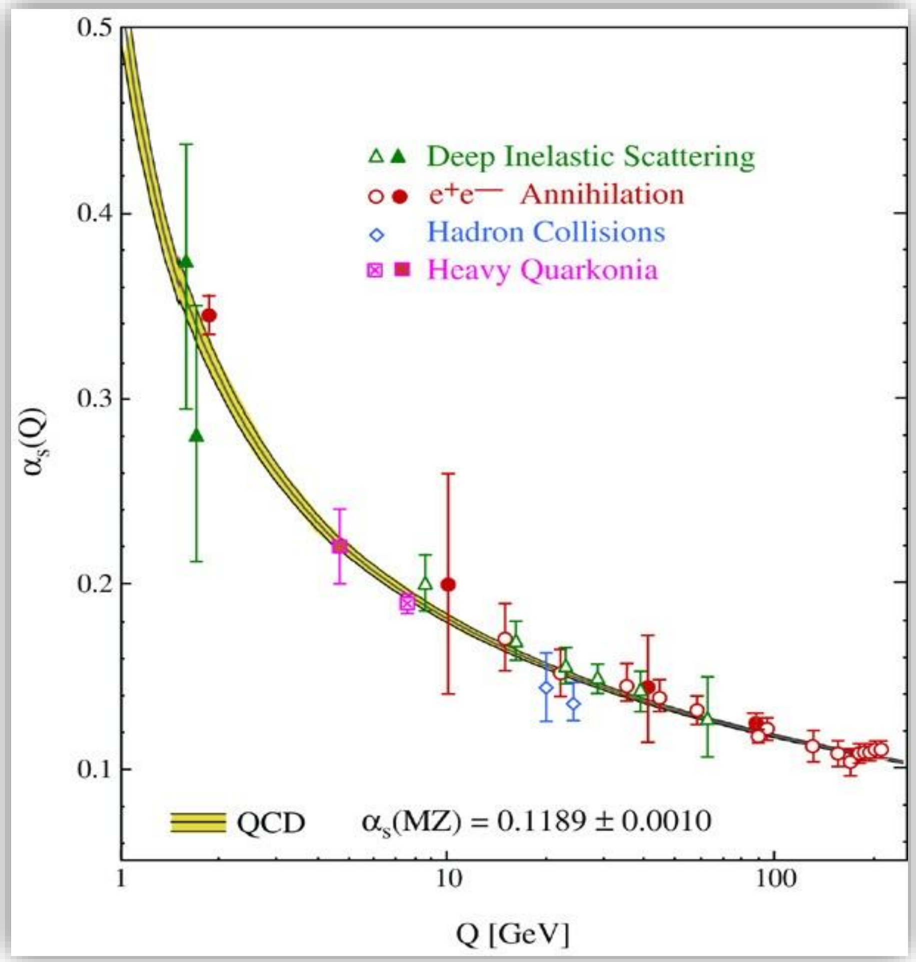
EHM means Gluons are massive via Schwinger Mechanism

n

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

This is where we live

⇐
What's happening out here?!



Asymptotic Freedom

Interaction becomes weaker as energy grows (as charges get closer together)

QCD's Running Coupling

Progress in Particle and Nuclear Physics
Volume 134, January 2024, 104081

Review

QCD running couplings and effective charges

Alexandre Deur [a], Stanley J. Brodsky [b], Craig D. Roberts [c d]

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https://doi.org/10.1016/j.ppnp.2023.104081

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Abstract

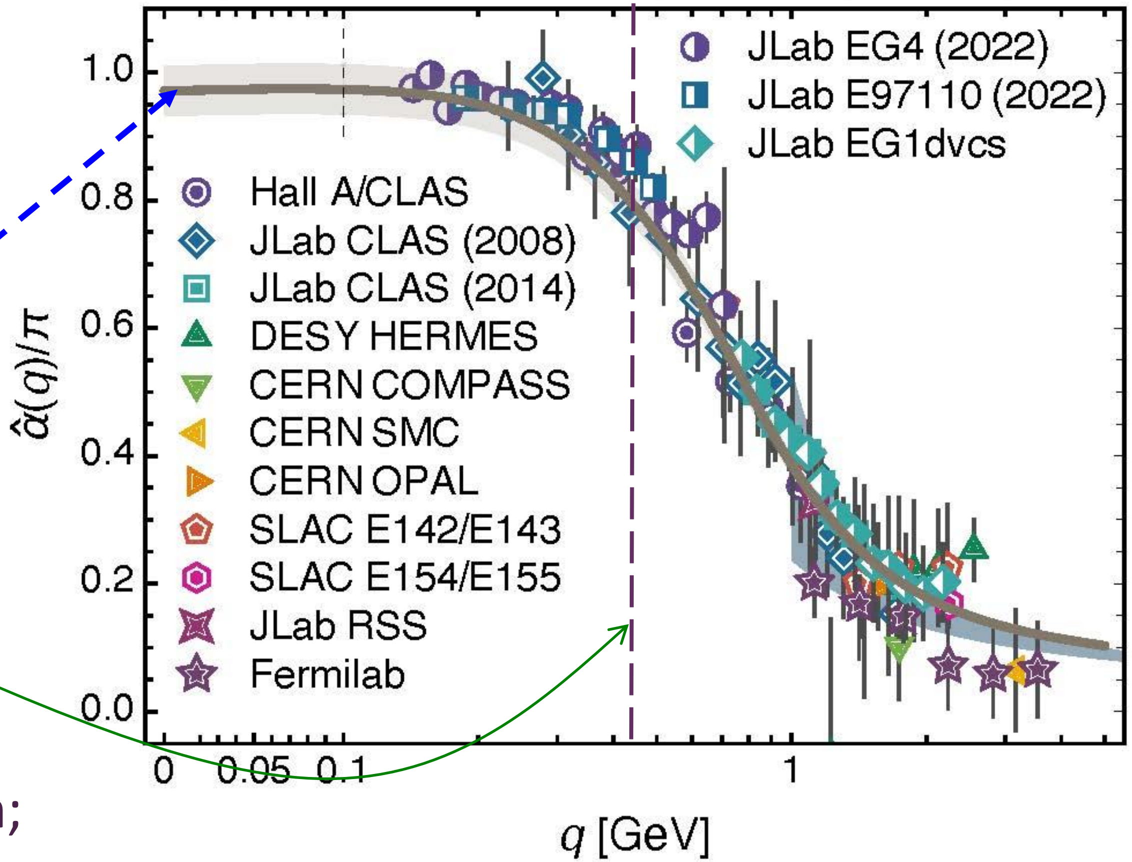
We discuss our present knowledge of α_s, the fundamental running coupling or effective charge of Quantum Chromodynamics (QCD). A precise understanding of the running of $\alpha_s(Q^2)$ at high momentum transfer, Q, is necessary for any perturbative QCD calculation. Equally important, the behavior of α_s at low Q^2 in the nonperturbative QCD domain is critical for understanding strong interaction phenomena, including the emergence of mass and quark confinement. The behavior of $\alpha_s(Q^2)$ at all momentum transfers also provides a connection between perturbative and nonperturbative QCD phenomena, such as hadron spectroscopy and dynamics. We first sketch the origin of the QCD coupling, the reason why its magnitude depends on the scale at which hadronic phenomena are probed, and the resulting consequences for QCD phenomenology. We then summarize latest measurements in both the perturbative and nonperturbative domains. New theory developments include the derivation of the universal nonperturbative behavior of $\alpha_s(Q^2)$ from both the Dyson–Schwinger equations and light-front holography. We also describe theory advances for the calculation of gluon and quark Schwinger functions in the nonperturbative domain and the relation of these quantities to α_s. We conclude by highlighting how the nonperturbative knowledge of α_s is now providing a parameter-free determination of hadron spectroscopy and structure, a central and long-sought goal of QCD studies.

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

2532 total downloads

Process independent effective charge = running coupling

- Modern theory 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 $k \sim \widehat{m}_0$, 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

Effective charge from lattice QCD, *Zhu-Fang Cui, Jin-Li Zhang et al.*,
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Process independent effective charge = running coupling

- Modern theory enables unique QCD analogue of “Gell-Mann – Low”

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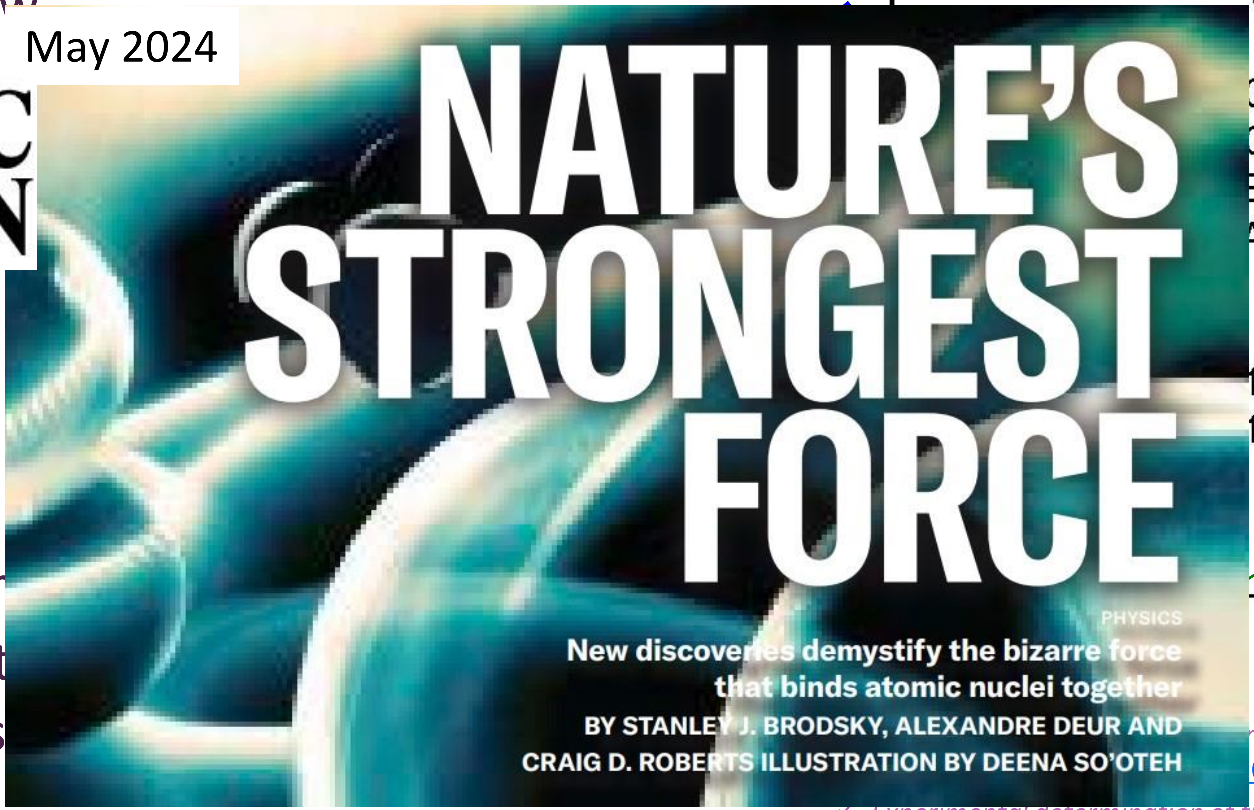
May 2024



yields a

- N.B. Qualitative c
- No Landau Pole
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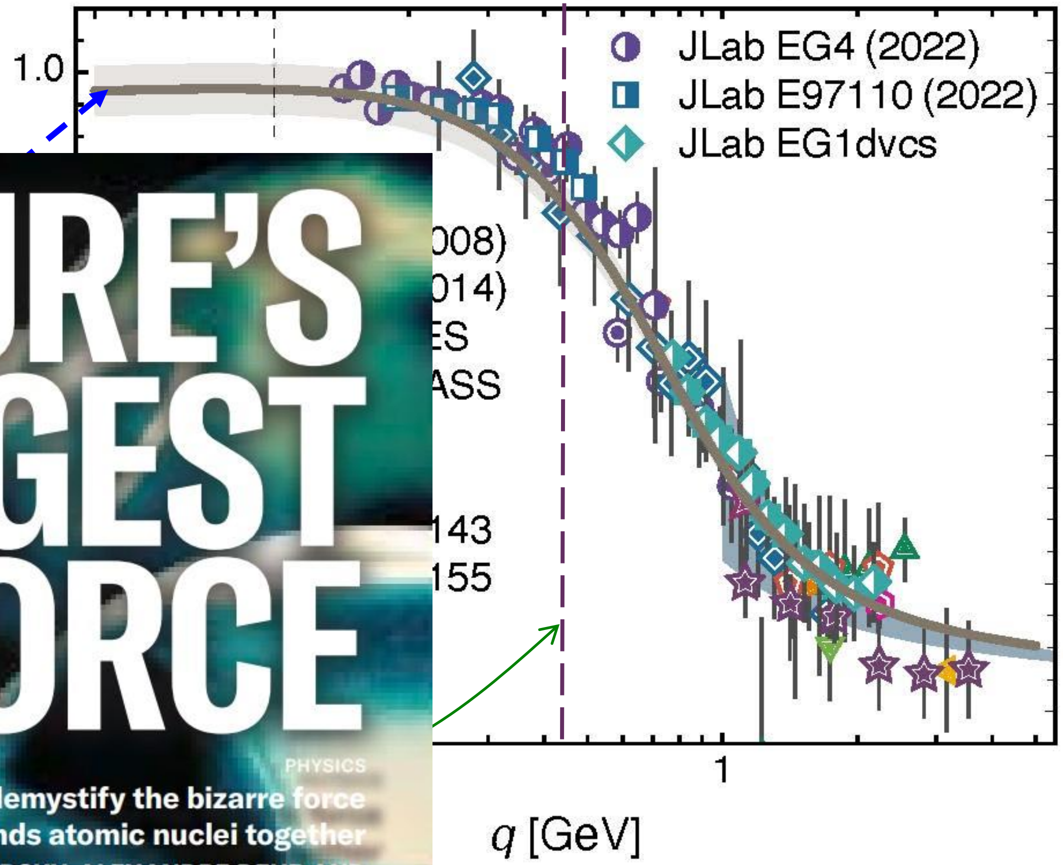

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  04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
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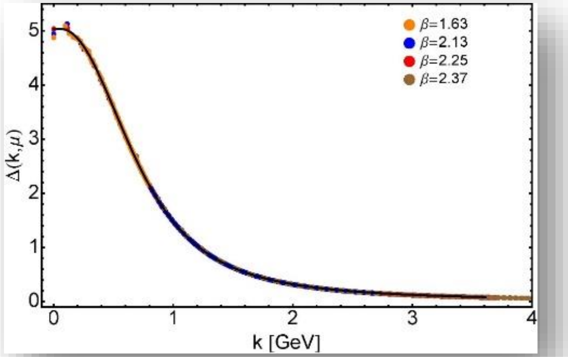
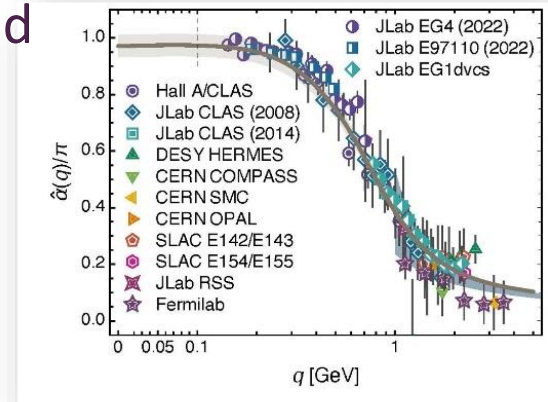
- ✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig Roberts, [e-Print: 2303.00723 [hep-ph]], Prog. Part. Nucl. Phys. **134** (2024) 104081

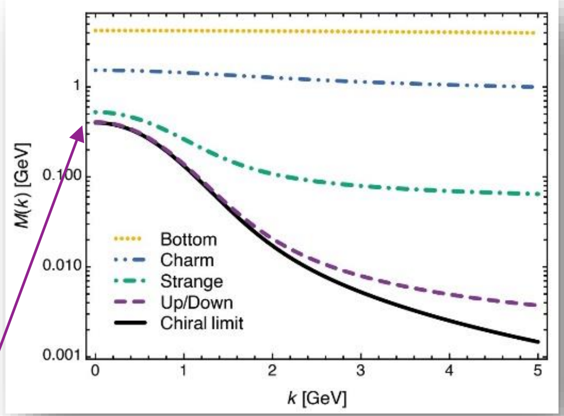
EHM Basics

- 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







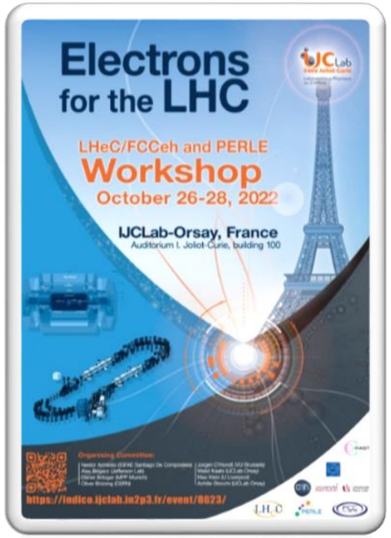
✓ $3 \times M(0)$ sets the scale of the proton mass.

✓ Meson-loops provide 20% quantum corrections

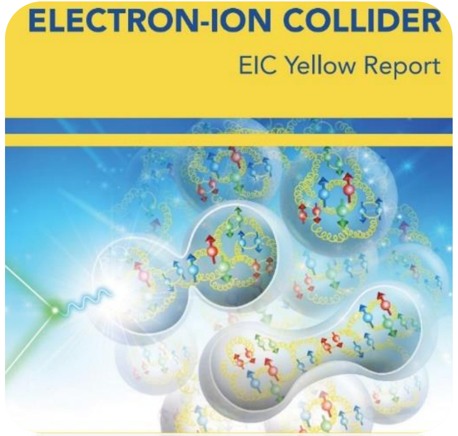
Jefferson Lab
Thomas Jefferson National Accelerator Facility

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

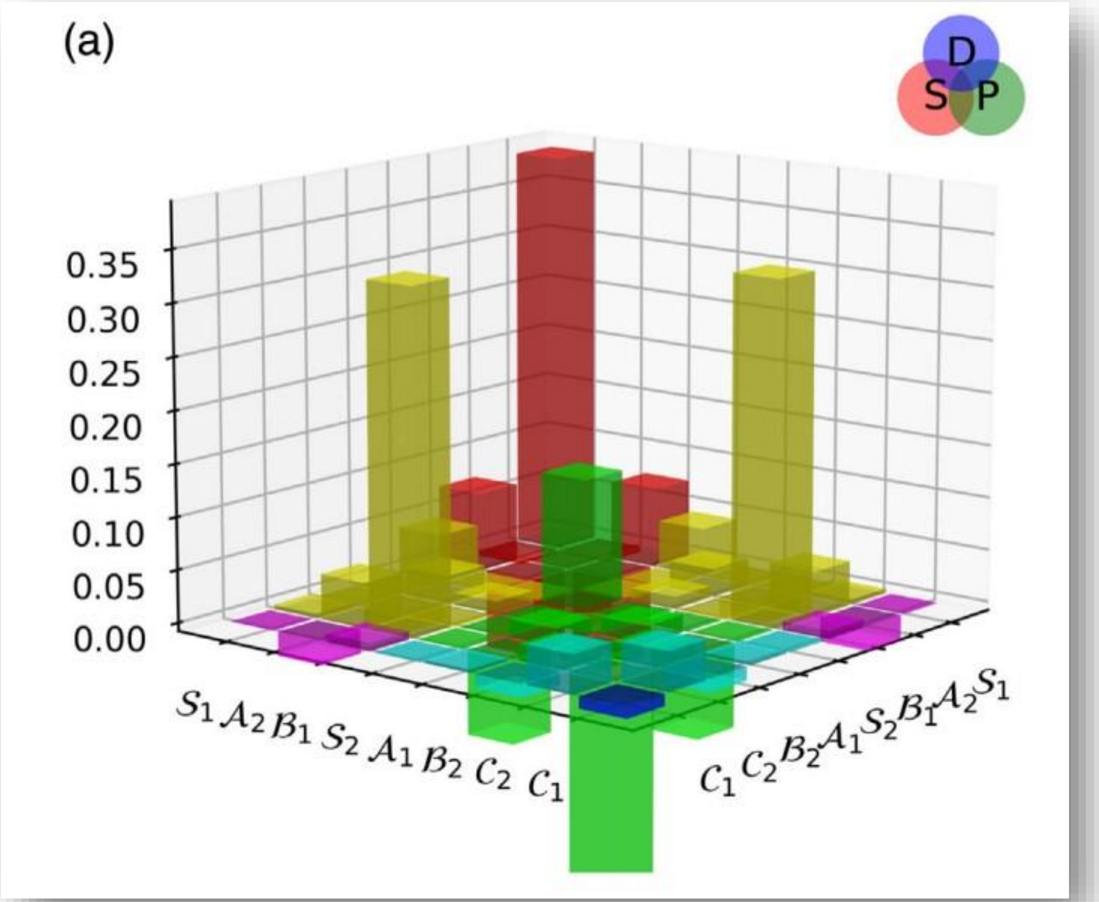
CERN
AMBER
A new QCD facility at the M2 beam line of the CERN SPS



BESIII

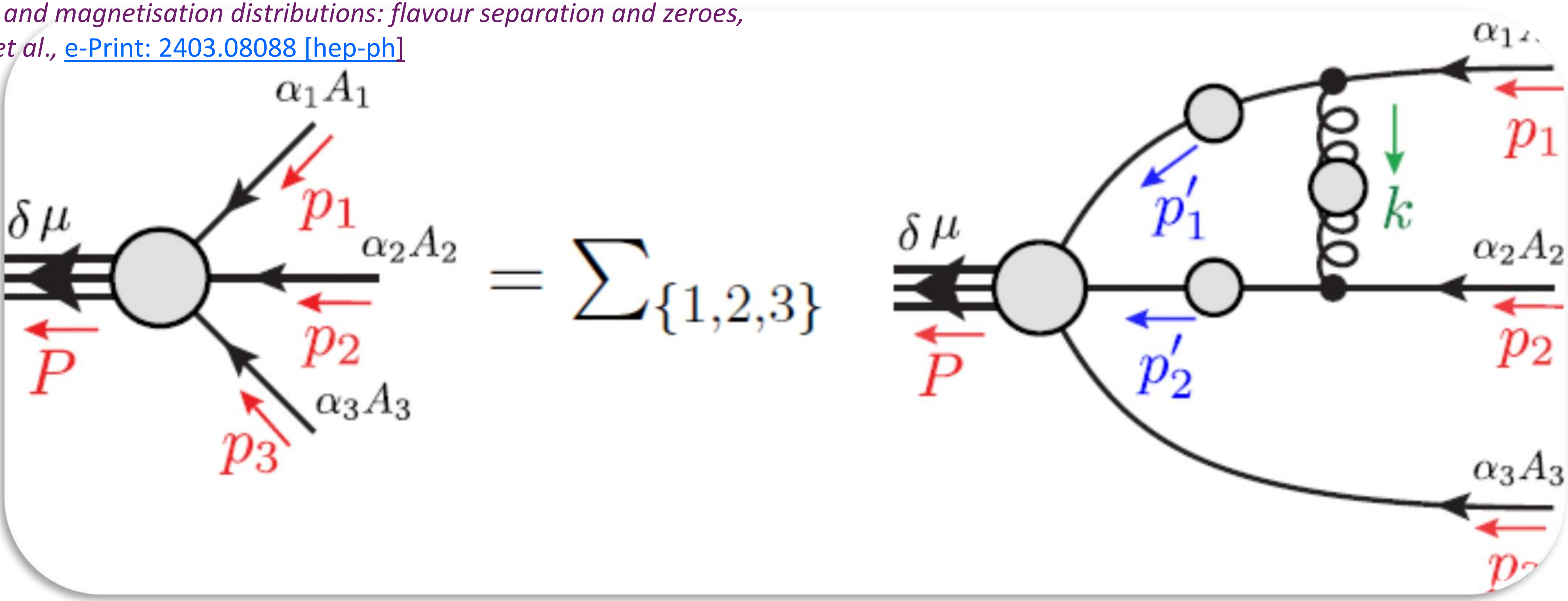


Charting EHM using High Intensity, High Luminosity Facilities



Nucleon & Its Resonances

Nucleon mass from a covariant three-quark Faddeev equation
G. Eichmann *et al*., Phys. Rev. Lett. 104 (2010) 201601
Nucleon charge and magnetisation distributions: flavour separation and zeroes,
Zhao-Qian Yao *et al*., e-Print: 2403.08088 [hep-ph]



Faddeev Equation for Baryons

Nucleon charge and magnetisation distributions: zeroes and flavour separation

- Parameter-free unification of pion, kaon, nucleon electromagnetic form factors
  - Gap equation + Bethe-Salpeter Equation + 3-body Faddeev Equation
- Proton electric form factor possesses a zero:
$$Q^2 = 8.86^{+1.93}_{-0.86}\ \mathrm{GeV}^2$$
- Neutron electric form factor is positive definite
$$\Rightarrow G_E^n(Q^2) > G_E^p(Q^2) \text{ on } Q^2 \geq 4.7\ \mathrm{GeV}^2$$
  - On this domain, electric form factor of charge-neutral neutron is larger than that of charge-one proton
- Verification within JLab reach

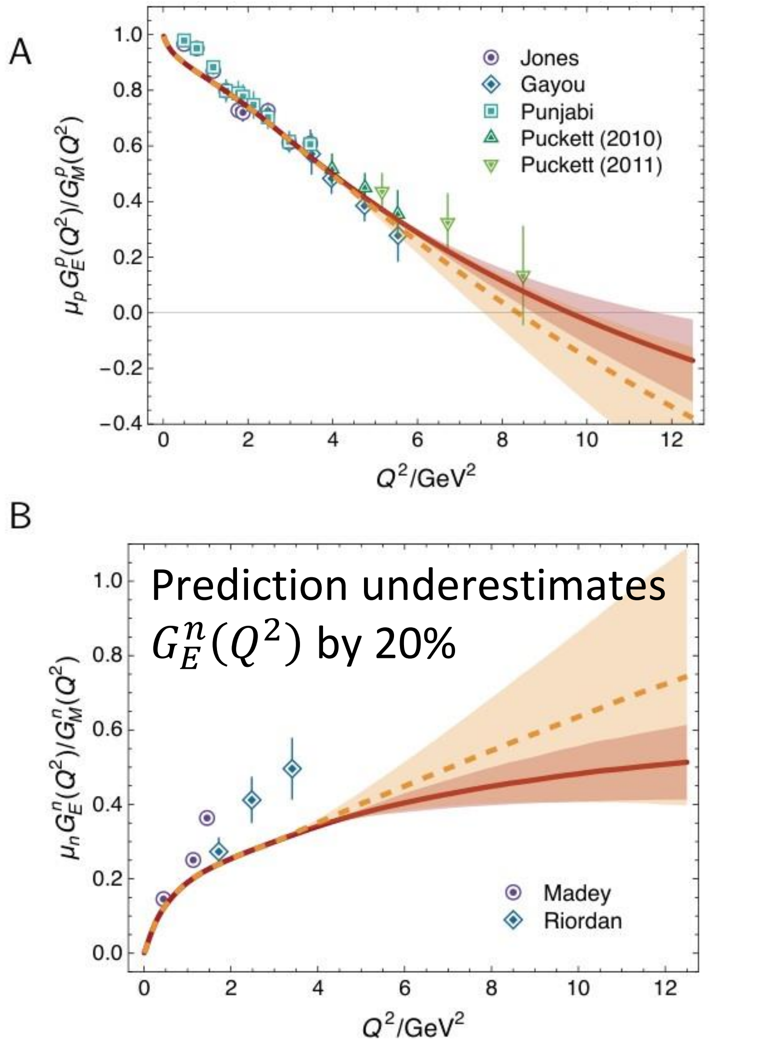
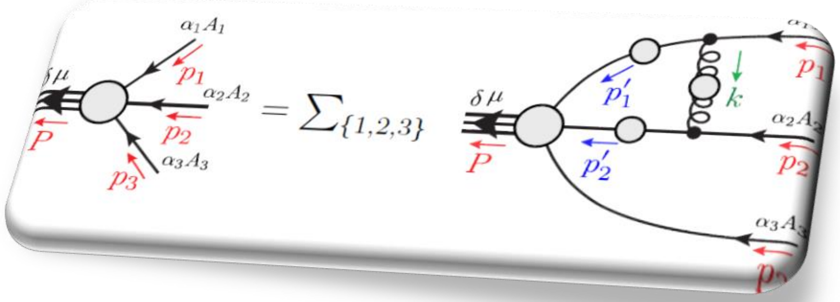


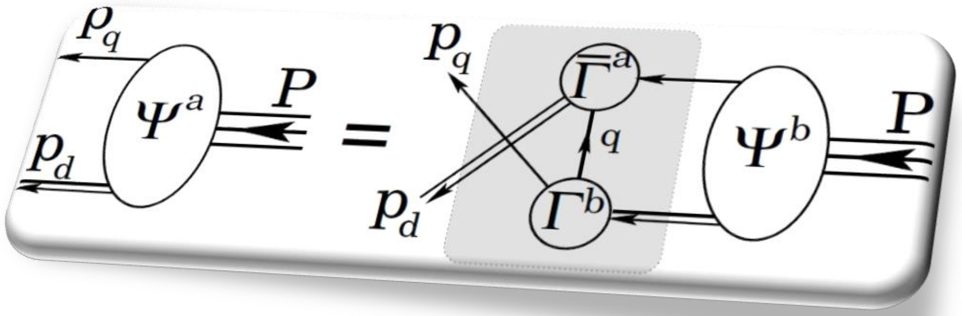
FIG. 6. Panel A: $\mu_p G_E^p/G_M^p$. Panel B: $\mu_n G_E^n/G_M^n$. SPM I – dashed orange curve within like-coloured band; and SPM II – solid red curve within like-coloured band. Data: proton – Refs. [20–24]; and neutron – Refs. [87, 97].

Nucleon charge and magnetisation distributions: flavour separation and zeroes,
Zhao-Qian Yao *et al.*, [e-Print: 2403.08088 [hep-ph]]
Onset of scaling violation in pion and kaon elastic electromagnetic form factors,
Zhao-Qian Yao (姚照千) et al., e-Print: 2405.04681 [hep-ph], Phys. Lett. B 855 (2024) 138823/1-7



Structure of Baryons

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

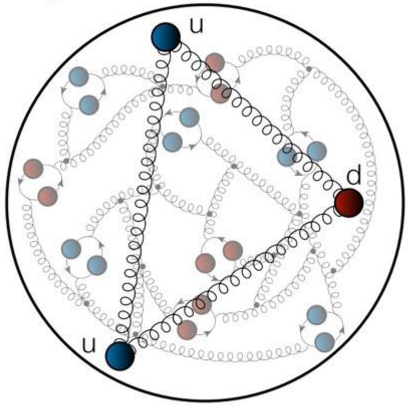


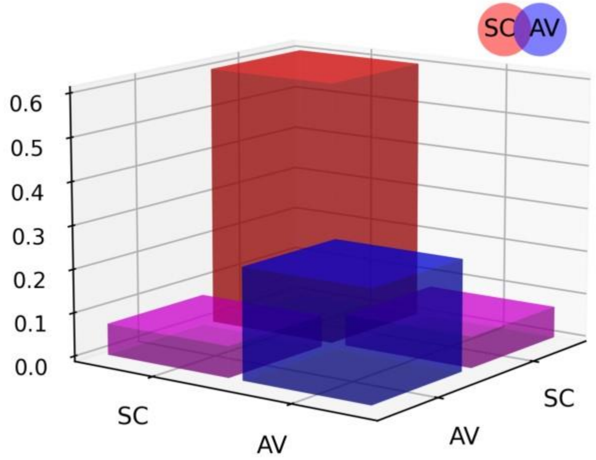
Solution delivers Poincaré-covariant proton wave function

Structure of Baryons

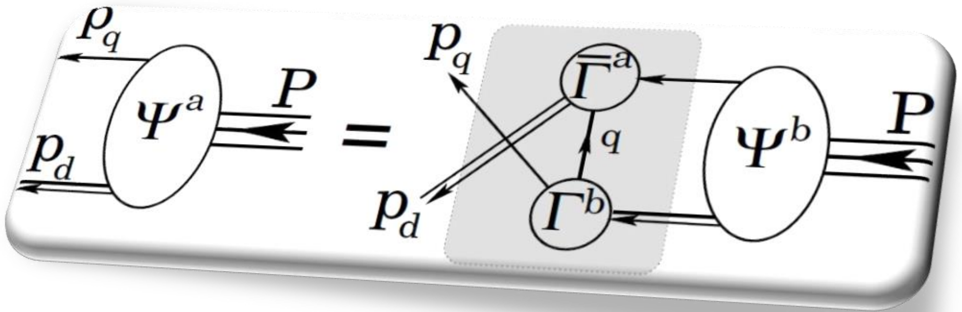
- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Evidently, direct solution of Faddeev equation using rainbow-ladder truncation is now possible … remains a challenging numerical problem
- For many applications, diquark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

A proton





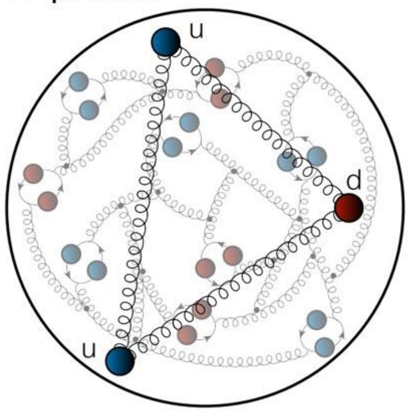
- ✓ CSM prediction = presence of axialvector (AV) diquark correlation in the proton
- ✓ AV Responsible for ≈ 40% of proton charge



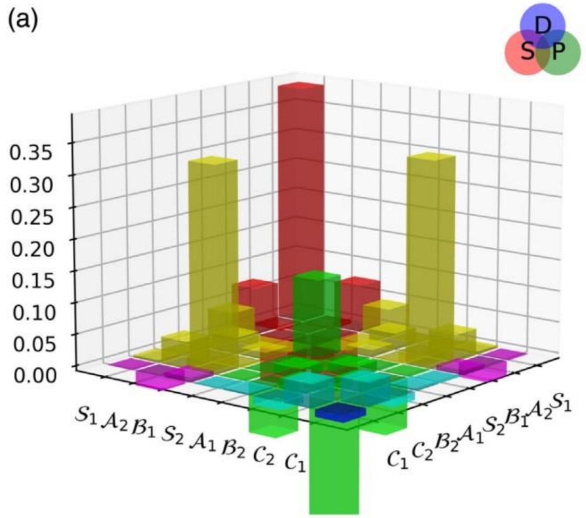
Solution delivers Poincaré-covariant proton wave function

Structure of Baryons

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain
- For many applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM*:*
- *proton wave function is not just S-wave, but contains strong P-wave contributions*



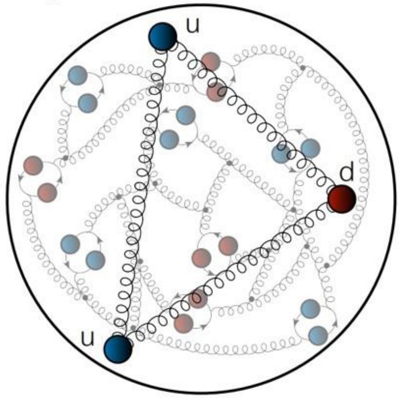
baryon wave functions necessarily contain orbital angular momentum



- ✓ 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

Baryon Structure

A proton



- 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, there is 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 of the baryons in the complete spectrum, then we don't understand Nature.*

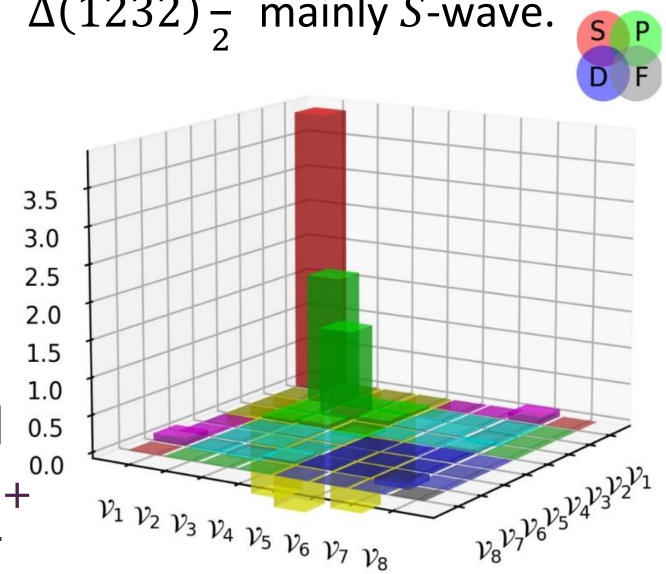
Composition of low-lying J = 3/2± Δ-baryons, Langtian Liu (刘浪天) *et al.*, NJU-INP 057/22, e-Print: 2203.12083 [hep-ph], Phys. Rev. D **105** (2022) 114047/1-13

Composition of low-lying J=$\frac{3}{2}^{\pm}$ Δ-baryons

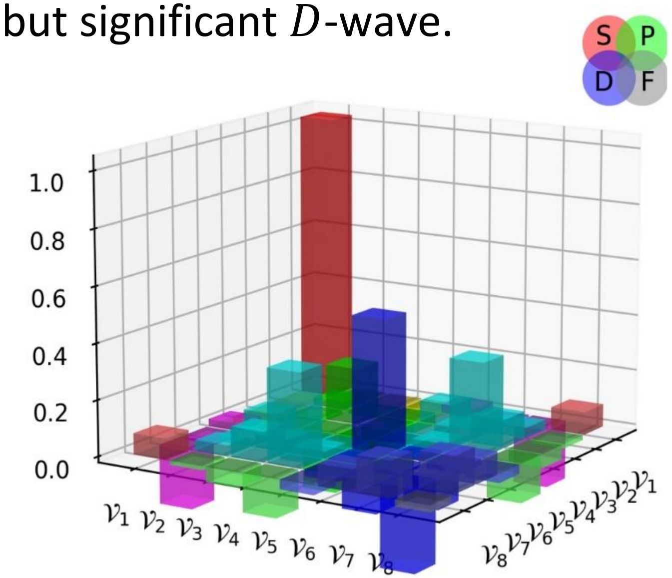
- Poincaré-covariant quark+diquark Faddeev equation

  $\Rightarrow$ insights into the structure of four lightest $(I,J^P) = (\frac{3}{2},\frac{3}{2}^{\pm})$ baryon multiplets.
- Prediction: Whilst these systems can contain isovector-axialvector $(1,1^+)$ and isovector-vector $(1,1^-)$ diquarks, one may neglect the latter and still arrive at a reliable description.
- $(\frac{3}{2},\frac{3}{2}^{+})$ are the simpler systems & features bear some resemblance to quark model pictures
  - Most prominent rest-frame orbital angular momentum component is S-wave
  - $\Delta(1600)\,\frac{3}{2}^{+}$ may fairly be viewed as radial excitation of $\Delta(1232)\,\frac{3}{2}^{+}$

$\Delta(1232)\,\frac{3}{2}^{+}$ mainly S-wave.



$\Delta(1600)\,\frac{3}{2}^{+}$ mainly S-wave, but significant D-wave.



Rest-frame angular momentum decompositions

Composition of low-lying J = 3/2± Δ-baryons, Langtian Liu (刘浪天) *et al*., NJU-INP 057/22, e-Print: 2203.12083 [hep-ph], Phys. Rev. D **105** (2022) 114047/1-13

Composition of low-lying J=$\frac{3}{2}^{\pm}$ Δ-baryons

- Poincaré-covariant quark+diquark Faddeev equation

  ⇒ insig

- Predicti … ector-vector (… ription.

Large momentum transfer resonance electroexcitation experiments can test these predictions; so, will shed light on the nature of emergent hadron mass.

- $(\frac{3}{2}, \frac{3}{2}^{+})$ are the simpler systems & features bear some resemblance to quark model pictures
  - Most prominent rest-frame orbital angular momentum component is S-wave
  - $\Delta(1600)\,\frac{3}{2}^{+}$ may fairly be viewed as radial excitation of $\Delta(1232)\,\frac{3}{2}^{+}$

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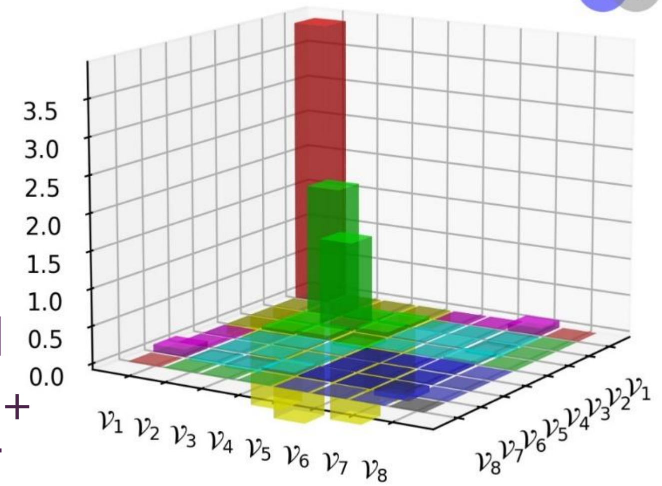

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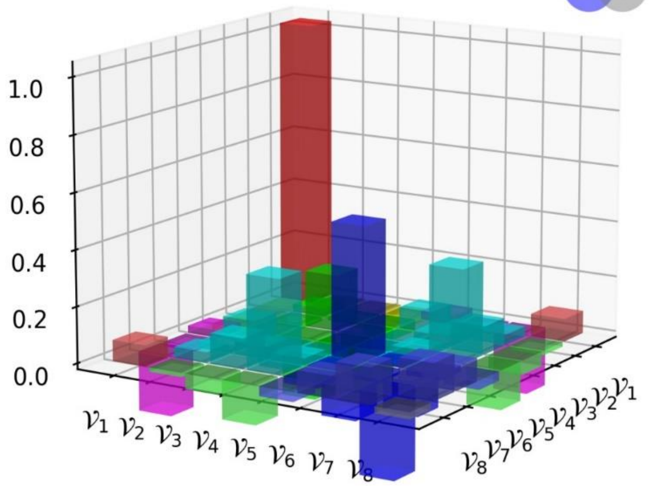
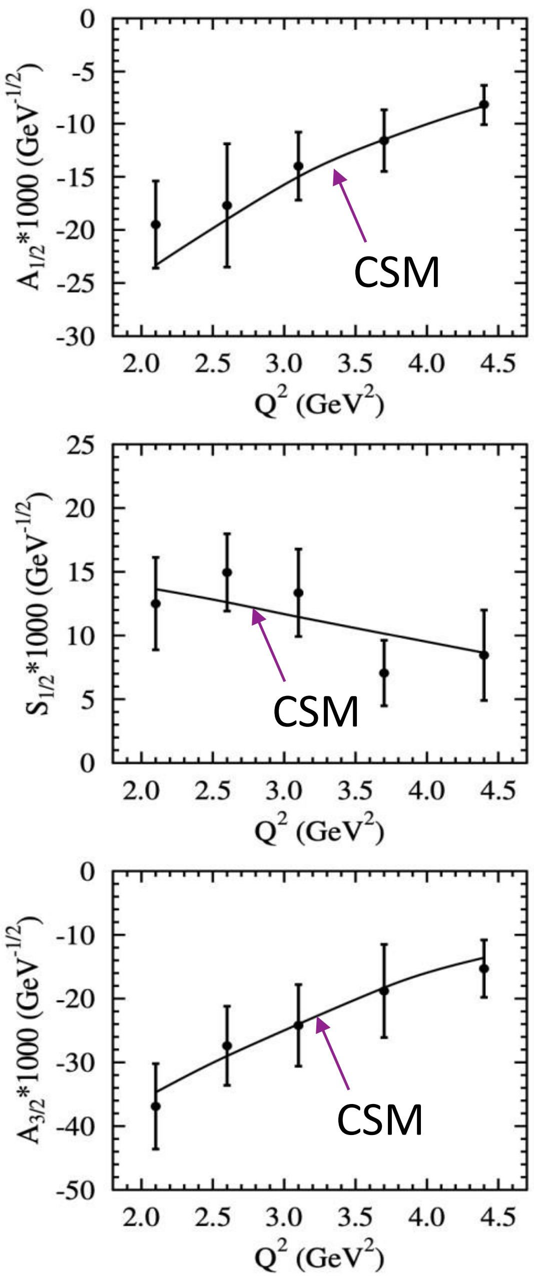


Rest-frame angular momentum decompositions

Composition of low-lying $J=\frac{3}{2}^{\pm}$ Δ-baryons



Example … recent progress

V. I. Mokeev *et al.*, Phys. Rev. C 108 (2023) 2, 025204 New analyses of CLAS $ep \to e'\pi^+\pi^-p'$ cross sections

Comparison with CSM predictions made 4 years before: Ya Lu *et al*. Phys. Rev. D 100 (2019) 034001/1-13

Remarkable agreement, suggesting confirmation of CSM predictions for structure of baryon wave functions

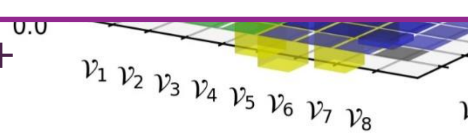
n multiplets.

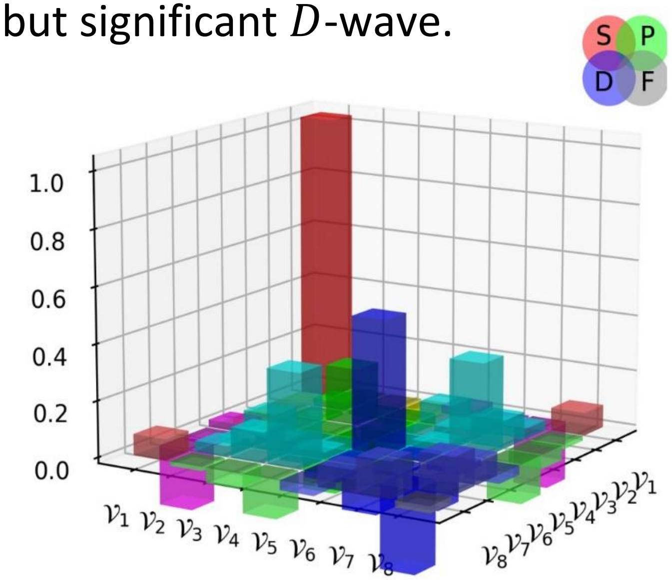
$(1,1^+)$ and isovector-

a reliable description.

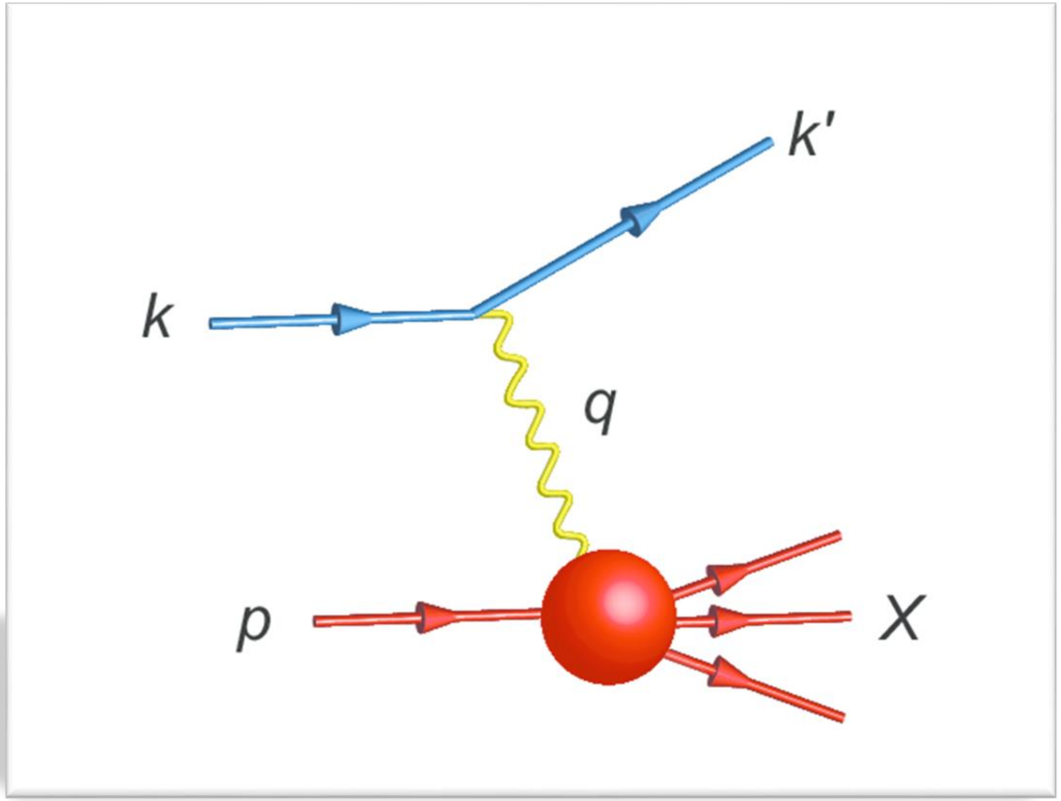
$\Delta(1600)\,\frac{3}{2}^+$ mainly S-wave, but significant D-wave.

tation of $\Delta(1232)\,\frac{3}{2}^+$





Rest-frame angular momentum decompositions



Parton Distribution Functions

Proton and pion distribution functions in counterpoint

- Today, despite enormous expense of time and effort, much must still be learnt before proton and pion structure may be considered understood in terms of DFs
- Most simply, what are the differences, if any, between the distributions of partons within the proton and the pion?
- The question of similarity/difference between proton and pion DFs has particular resonance today as science seeks to explain EHM
- How are obvious macroscopic differences between protons and pions expressed in the structural features of these two bound-states?

massive

almost massless

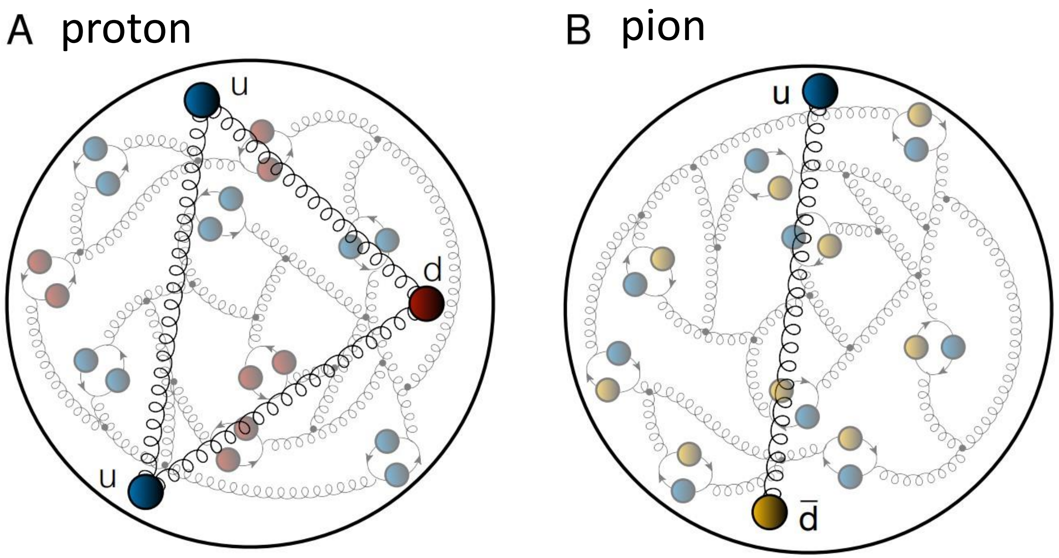
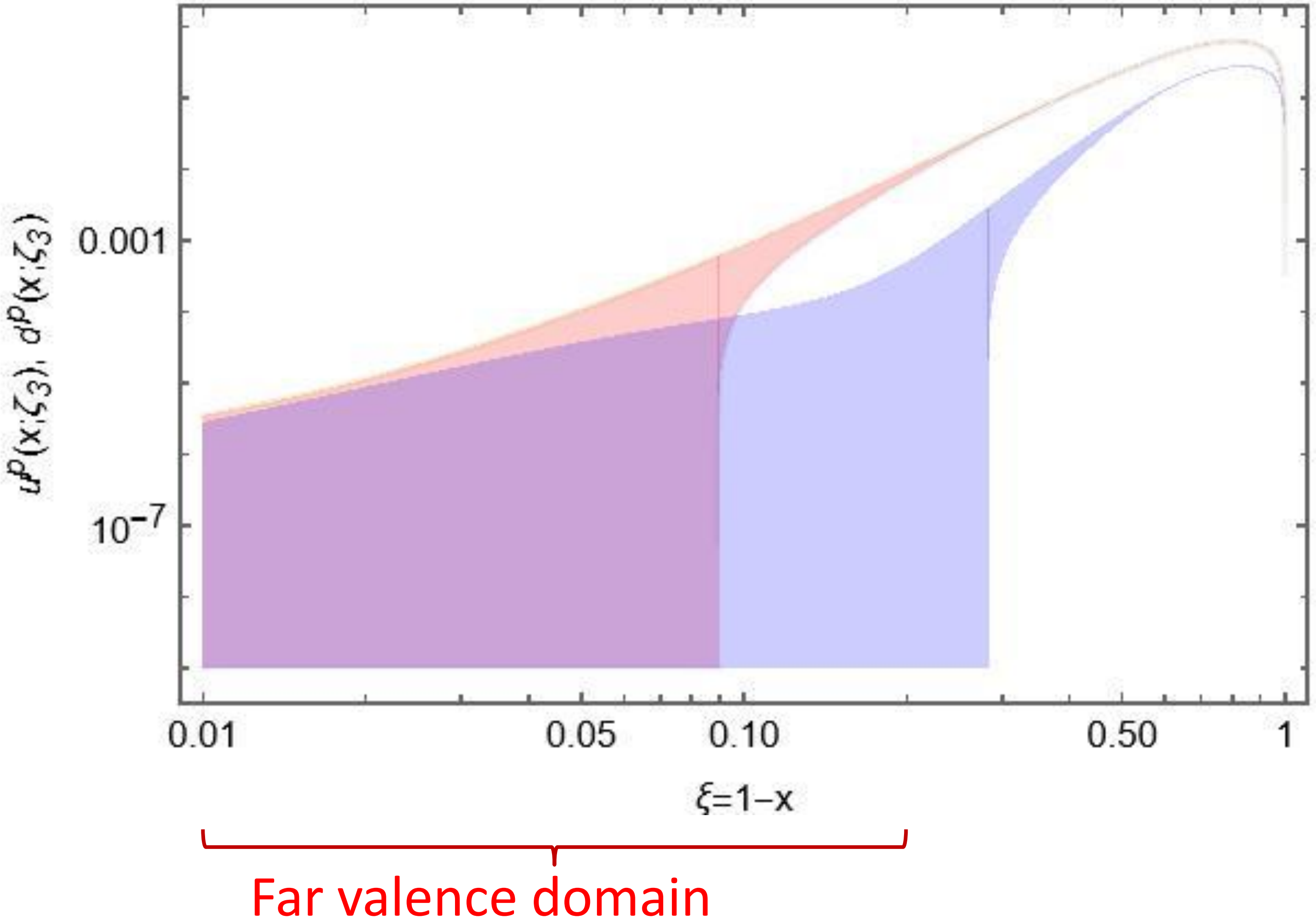


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined by one u and two d valence quarks. *Right panel* – B. The pion, π^+, contains one valence u-quark, one valence $\bar{d}$-quark, and, akin to the proton, infinitely many gluons and sea quarks. (In terms of valence quarks, $\pi^- \sim d\bar{u}$ and $\pi^0 \sim u\bar{u} - d\bar{d}$.)

Phenomenology – global fits – of proton valence quark DFs

- Example: NNPDF4.0 inferences of proton valence quark DFs
- $d(x)$ is unknown on $x > 0.7$

  $u(x)$ is unknown on $x > 0.9$
  - Fits can be negative on these domains
- Continuum strong interaction methods make firm predictions on valence-quark domain
  - Unpolarised DFs are non-negative
- Need combined effort in experiment, phenomenology, theory to arrive at QCD explanation of measurements
- Similar situation at low x

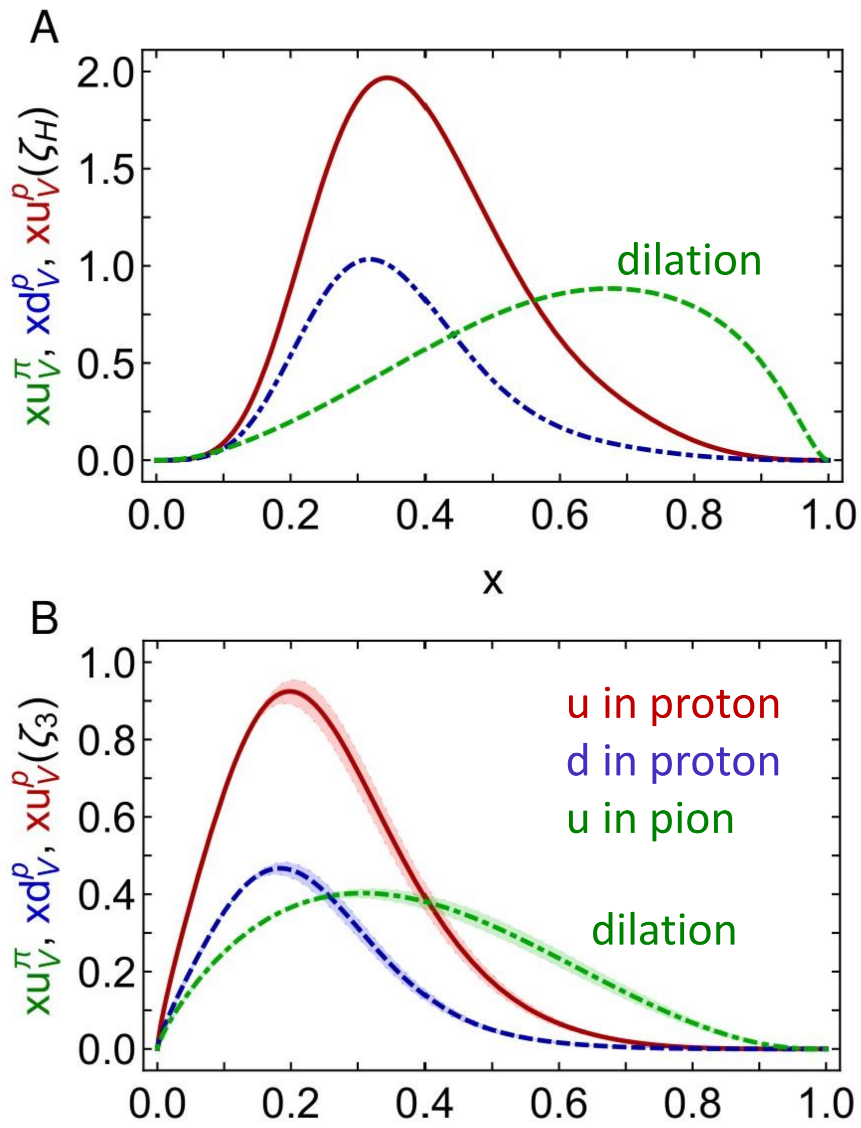


- ✓ *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚) *et al.*, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130
- ✓ *Pion distribution functions from low-order Mellin moments*, Ya Lu *et al.*, e-Print: 2311.01613 [hep-ph], Phys. Lett. B 850 (2024) 138534/1-6
- ✓ *Contact interaction study of proton parton distributions*, Yang Yu (俞杨) *et al.*, NJU-INP 083/24, e-Print: 2402.06095 [hep-ph], Eur. Phys. J. C **84** (2024) 7, 739/1-23

Proton and pion DFs in counterpoint

- Symmetry-preserving analyses using CSMs deliver hadron scale DFs that agree with known endpoint constraints
- Valence-quark degrees-of-freedom carry all hadron's momentum at ζ_H: $\langle x\rangle_{u_p}^{\zeta_{\mathcal{H}}} = 0.687\,,\ \langle x\rangle_{d_p}^{\zeta_{\mathcal{H}}} = 0.313\,,\ \langle x\rangle_{u_\pi}^{\zeta_{\mathcal{H}}} = 0.5$
- Diquark correlations in proton, induced by EHM

  $$\Rightarrow u_V\ (x) \neq 2d_V(x)$$
- Proton and pion valence-quark DFs have markedly different behaviour – $u^\pi(x;\zeta_H)$ is Nature's most dilated DF
  - i. "Obvious" because $(1-x)^2$ vs. $(1-x)^3$ behaviour & preservation of this unit difference under evolution
  - ii. Also "hidden" = strong EHM-induced broadening
  - iii. Dilation and endpoint power-law behaviour are consistent with analyses of modern lQCD results



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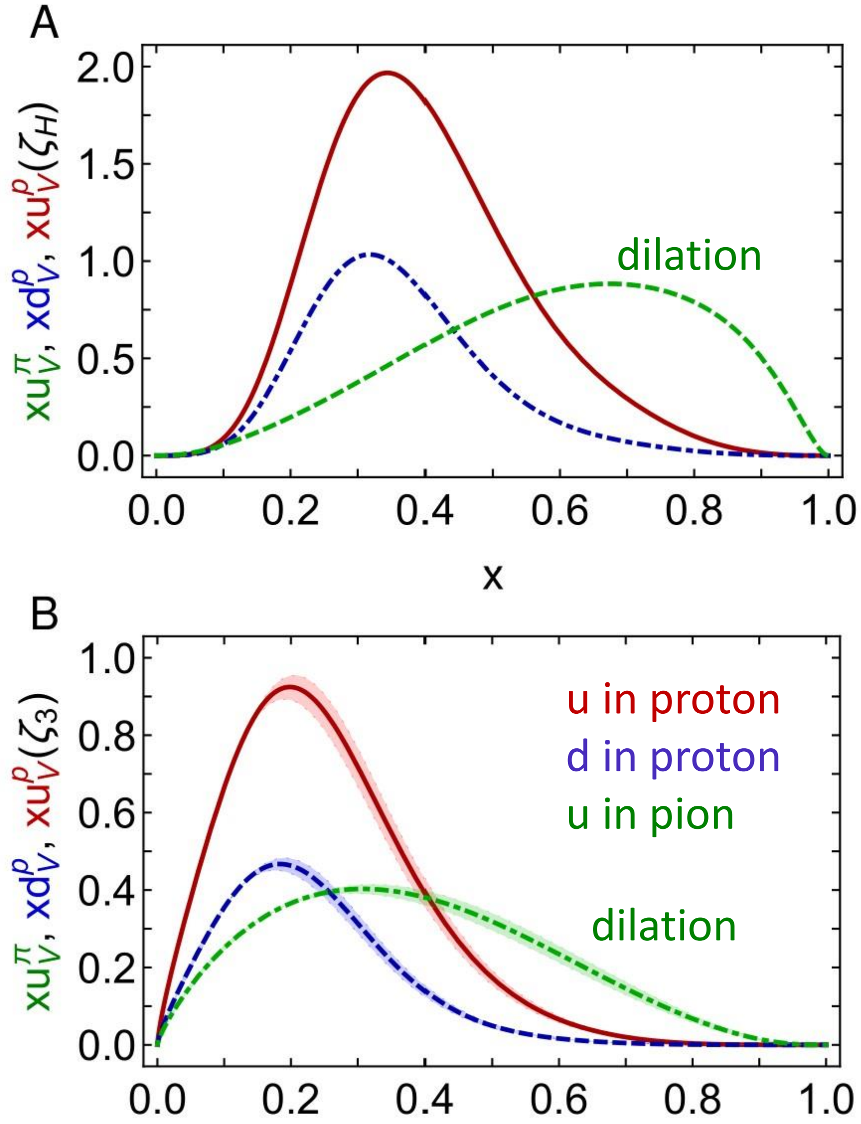
Proton and pion DFs in counterpoint

- Symmetry-preserving analyses using CSMs deliver hadron scale DFs that agree with known endpoint constraints
- Numerous π & p predictions – similarities and differences
- All of which can be tested with high-luminosity, high-energy facilities
- behaviour – $u^{\pi}(x;\zeta_H)$ is Nature's most dilated DF
  i. "Obvious" because $(1-x)^2$ vs. $(1-x)^3$ behaviour & preservation of this unit difference under evolution
  ii. Also "hidden" = strong EHM-induced broadening
  iii. Dilation and endpoint power-law behaviour are consistent with analyses of modern lQCD results

tum



Neutron/Proton structure function ratio

- Ratio $1^+/0^+$ diquarks in proton wave function is measure of EHM
- Structure function ratio is clear window onto $d_V(x)/u_V(x)$

$$\frac{F_2^n(x;\zeta)}{F_2^p(x;\zeta)} = \frac{\mathcal{U}(x;\zeta) + 4\mathcal{D}(x;\zeta) + \Sigma(x;\zeta)}{4\mathcal{U}(x;\zeta) + \mathcal{D}(x;\zeta) + \Sigma(x;\zeta)}$$

$$\mathrm{U}(x;\zeta) = u(x;\zeta) + \bar{u}(x;\zeta),\ \mathrm{D}(x;\zeta) = d(x;\zeta) + \bar{d}(x;\zeta)$$

$$\Sigma(x;\zeta) = s(x;\zeta) + \bar{s}(x;\zeta) + c(x;\zeta) + \bar{c}(x;\zeta)$$

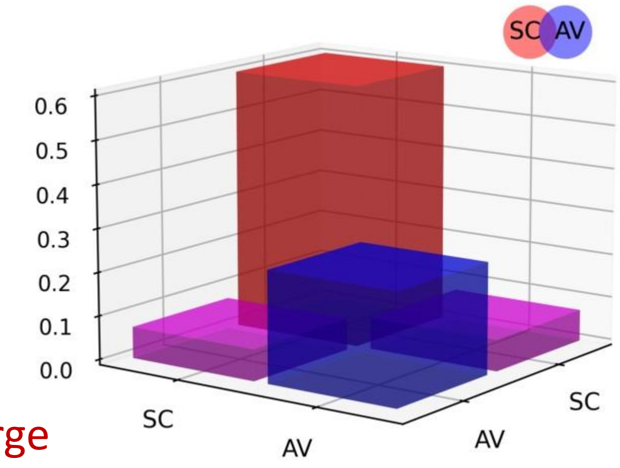
- Comparison with MARATHON data

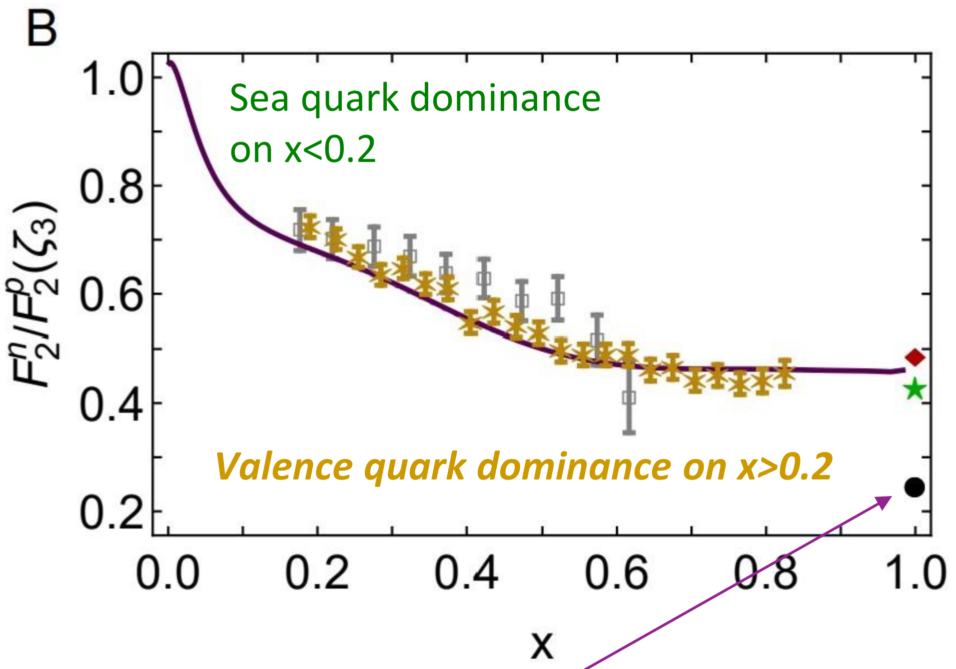
  [D. Abrams, *et al.*, Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- Agreement with modern data on entire x-domain – parameter-free prediction

✓ CSM prediction = presence of axial-vector diquark correlation in the proton

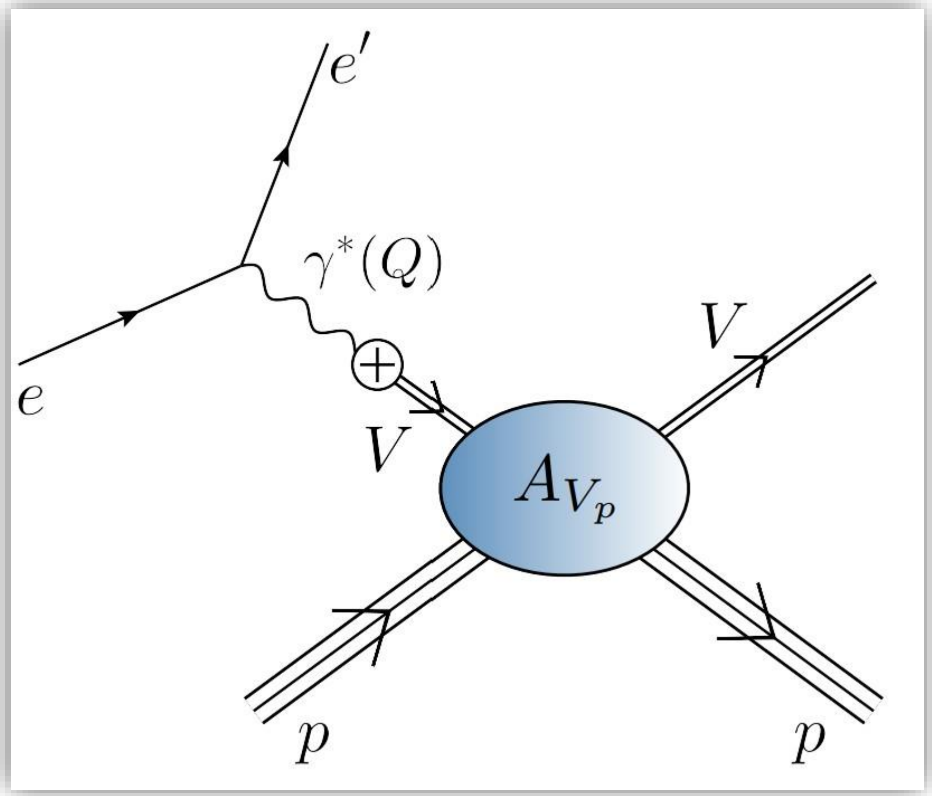
✓ Responsible for ≈ 40% of proton charge





Probability that scalar diquark only models of nucleon might be consistent with available data is 1/141,000

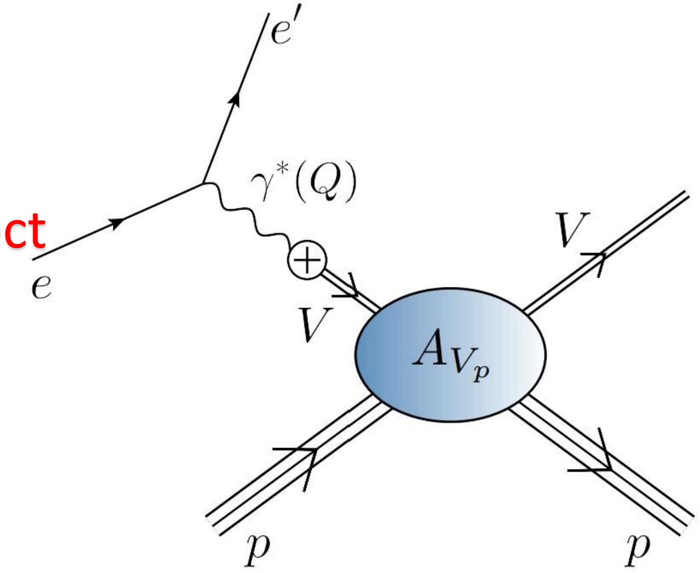
Valence quark ratio in the proton, Zhu-Fang Cui, (崔著钫), Fei Gao (高飞) *et al.*, NJU-INP 049/21, e-print: 2108.11493 [hep-ph], Chin. Phys. Lett. *Express* **39** (04) (2022) 041401/1-5



Photoproduction of heavy vector mesons

EHM Measurements
How does the mass of the nucleon arise?

- Once considered viable …
  Electromagnetic process ($V = J/\psi, \Upsilon$) … $e + p \to e' + V + p$
  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)

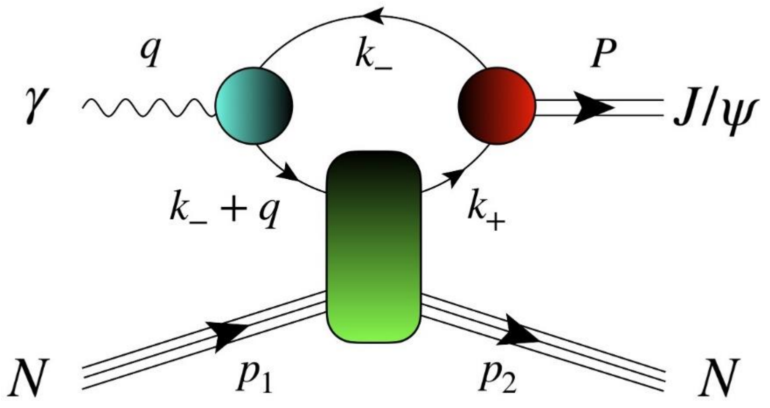


J/ψ photoproduction: from threshold to very high energies

J/ψ photoproduction: threshold to very high energy, Lin Tang (唐淋), Yi-Xuan Yang (杨逸轩), Zhu-Fang Cui (崔著钫) and Craig D. Roberts, NJU-INP 089/24, e-Print: 2405.17675 [hep-ph], Phys. Lett. B **856** (2024) 138904/1-7

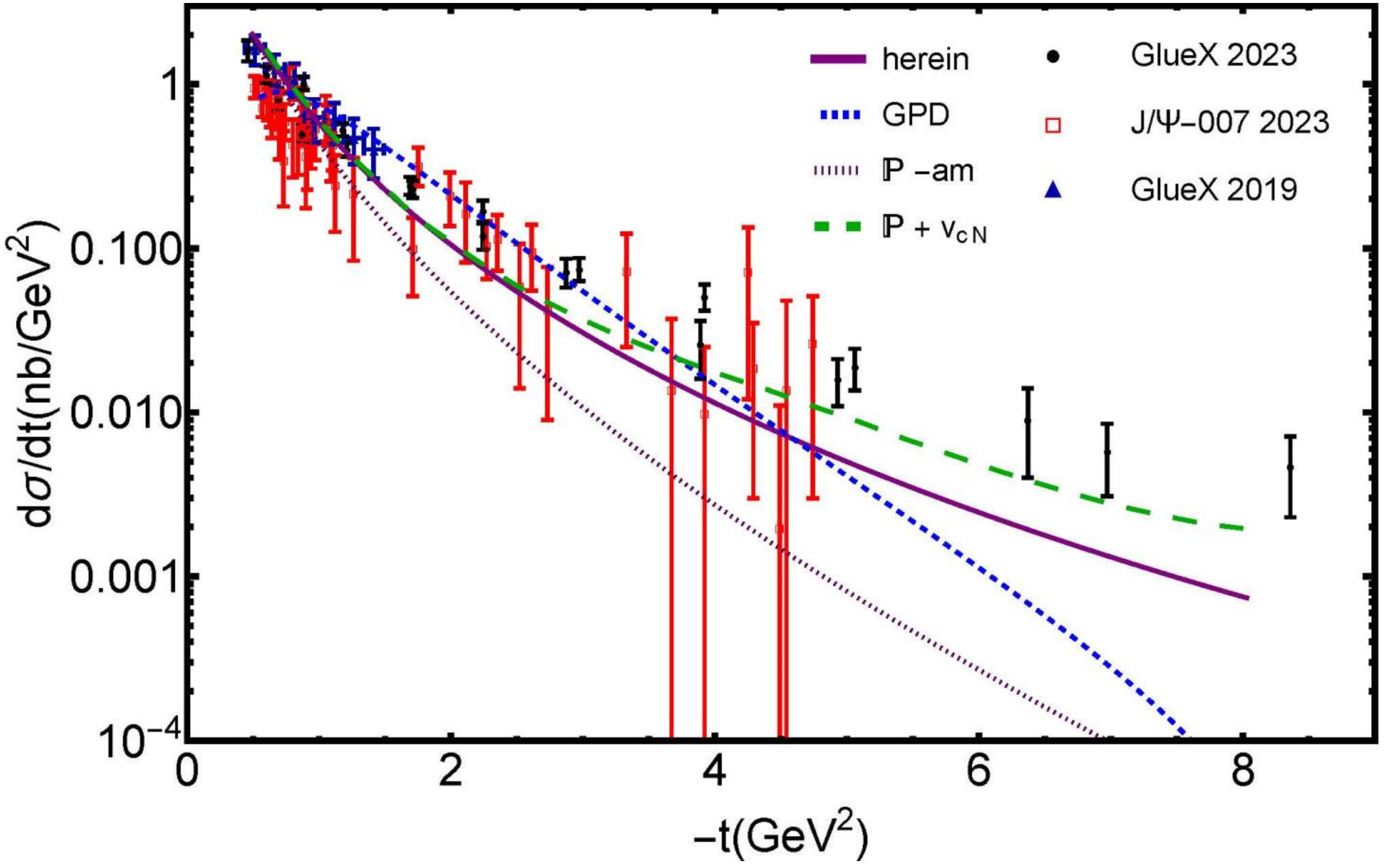
If GPD scheme valid at all,
then only very near threshold.
All W unification impossible

- 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] Phys. Rev. C **109** (2024) 6, 065204
    - Suggestion = Final state interactions dominate cross-section near-threshold, so obscuring any connection with in-proton gluon distributions and/or gluon gravitational form factors.
  - $\gamma + p \to c + \bar{c} + P + p \to J/\psi + p$
    - 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



J/ψ photoproduction: threshold differential cross-section

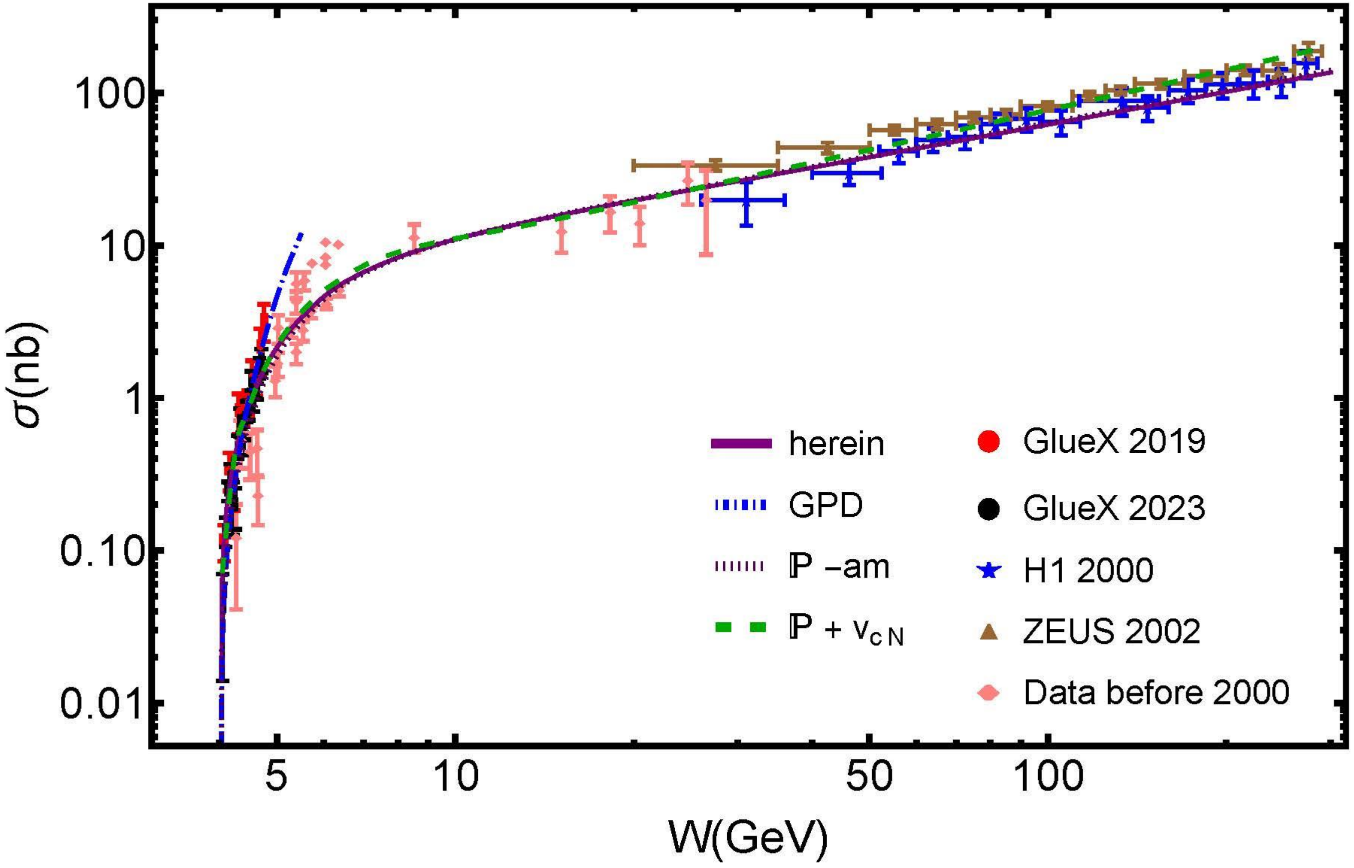
- GPD model (dotted blue)
  - overfitting issue
  - concave differential cross-section with max. at low $|t|$
  - trying to reconcile GlueX and J/ψ-007 data (some tension)
  - all other reaction models produce convex $\frac{d\sigma}{dt}$
- $P + J/\psi p$ rescattering
  - dashed green – $\chi^2_{\rm dof}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



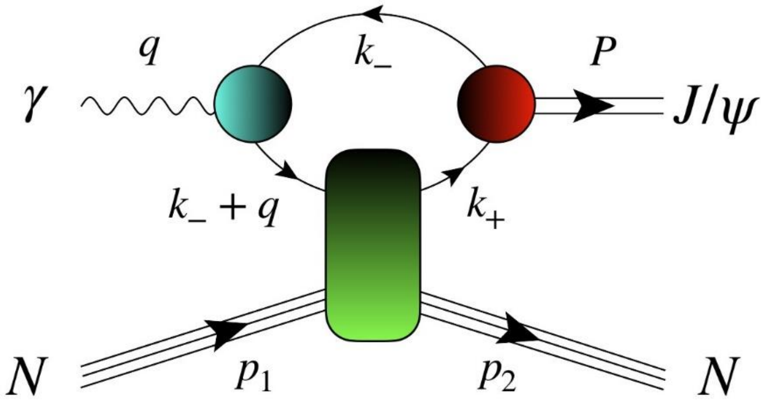
J/ψ photoproduction: total cross-section, threshold to high-W

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
- $P + J/\psi p$ rescattering
  - dashed green
    - ZEUS+H1 $\chi^2_{\rm dof} = 2.1$
    - H1 $\chi^2_{\rm dof} = 1.6$
- $P +$ 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
  - Photoproduction probes quark structure of $\gamma \to J/\psi$ not glue in proton

3-body Faddeev equation predictions

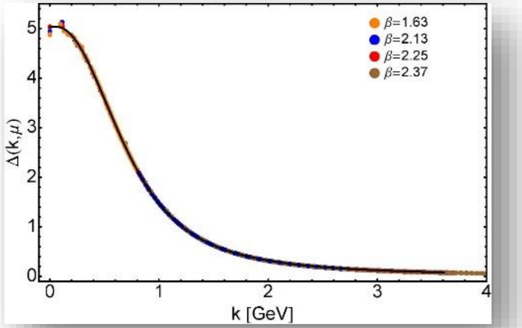
$$\frac{\langle r\rangle_{\rm mass}}{\langle r\rangle_{\rm E}} = 0.79 \pm 0.12 \text{ fm}$$

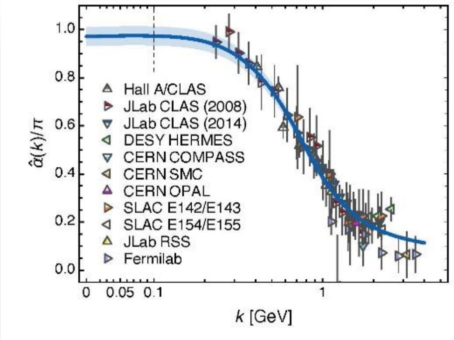
$$\frac{\langle r\rangle_{\rm mech}}{\langle r\rangle_{\rm E}} = 0.72 \pm 0.04 \text{ fm}$$

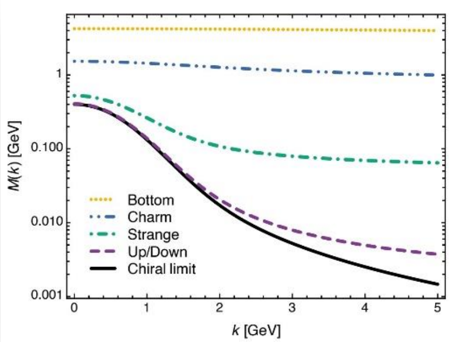
Gather all pieces of the puzzle … Reveal the source of Nature’s basic mass-scale

Synergy of Experiment, Phenomenology, Theory

- *Drawing detailed map of the proton is important because proton is Nature’s only absolutely stable bound state.*
  - ✓ *However, while QCD is the proton, the proton is not QCD*
- *Strong interaction theory is maturing*
  - ✓ *Expanding array of parameter-free predictions for the proton – yes*
  - ✓ *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, EIC, EicC, STCF, CEPC, JLab22, LHeC 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

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NSFC
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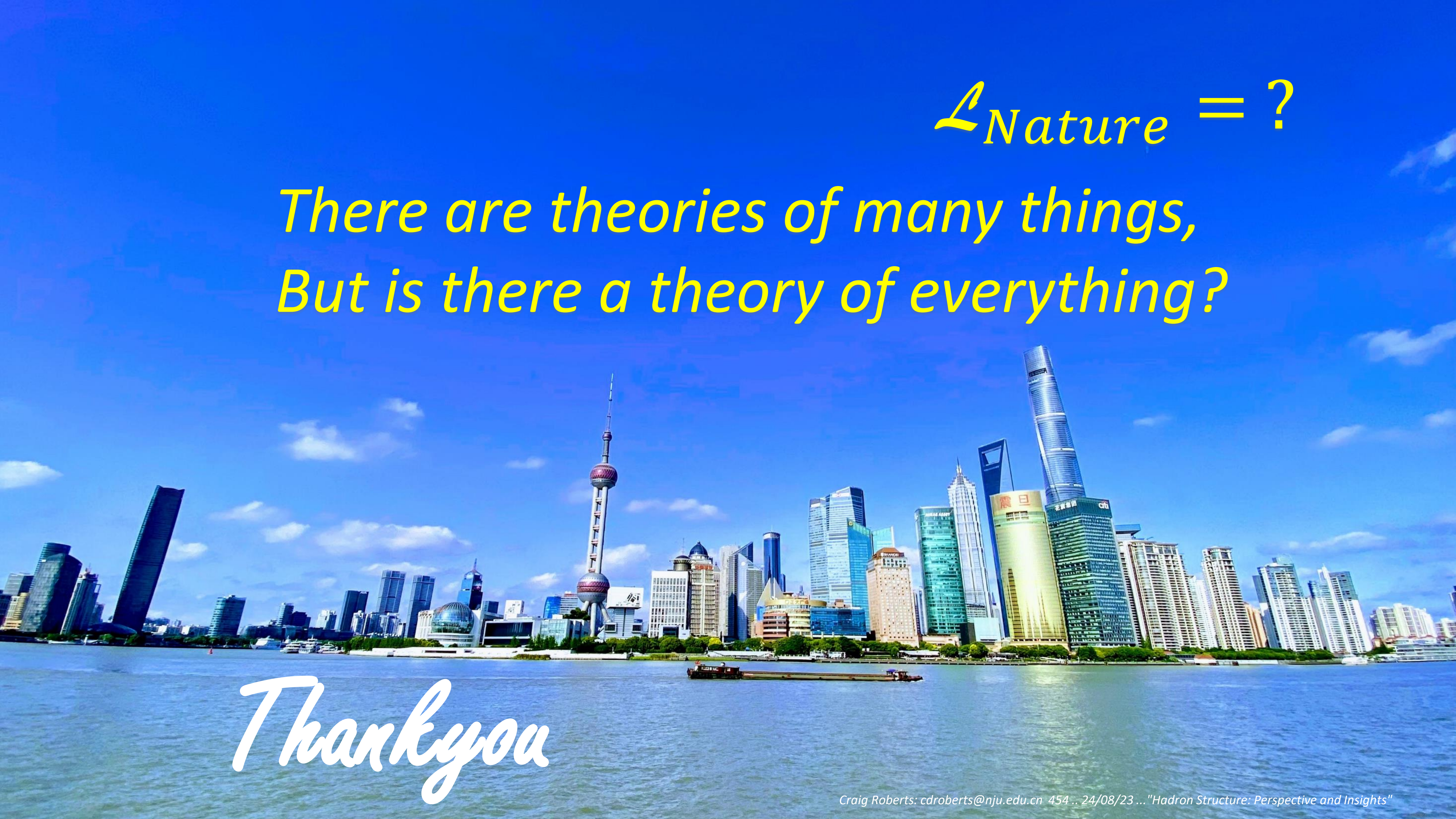
Emergent Hadron Mass

- 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

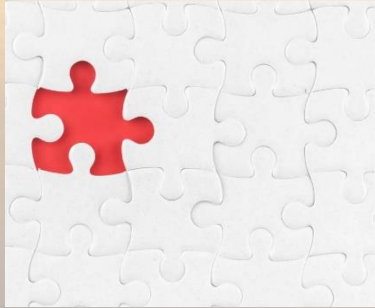
  EHM interference with Nature’s other known source of mass = Higgs
- We are capable of building facilities that can validate these concepts, proving QCD to be

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


$\mathcal{L}_{Nature} = ?$
There are theories of many things,
But is there a theory of everything?
Thankyou

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

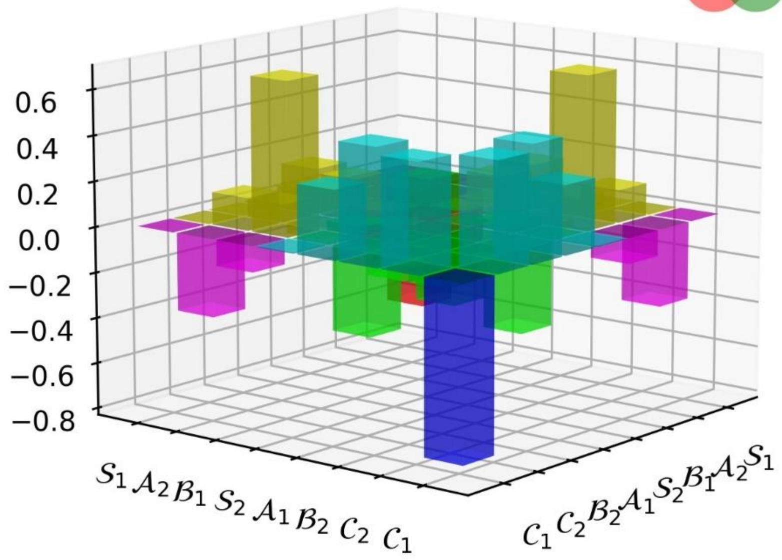


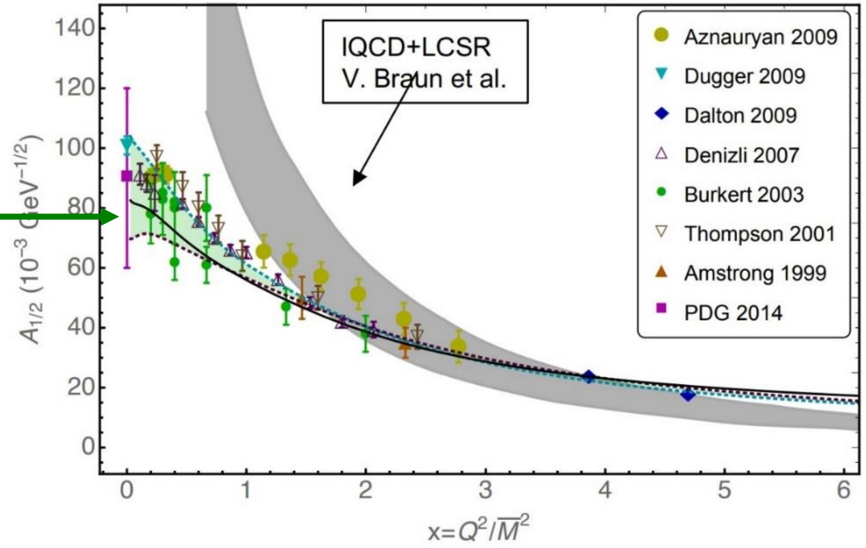
AMBER @ CERN
EIC
EicC & SCT & CEPC
JLab12 & JLab20+

Roper resonance: Toward a solution to the fifty year puzzle,
Volker D. Burkert and Craig D. Roberts,
arXiv:1710.02549 [nucl-ex], Rev. Mod. Phys. **91** (2019) 011003/1-18

Numerous other resonances

- CSM quark+diquark predictions exist
  for $\gamma^* p \to \Delta(1232)$ & $\gamma^* p \to N(1400)$
  - Good agreement with data on quark core domain, which varies from system to system
- $N(1535)$
  - CSM quark+diquark wave function available
  - Rest frame: complex angular momentum structure
    - strong P-wave & strong S⊗P, P ⊗ D, S ⊗ D interference
- $\gamma^* p \to N(1535)$
  - Contact interaction studies exist – qualitatively sound picture
  - Preliminary CSM quark+diquark results available
    promising ⇔ confirmation of complicated wave function

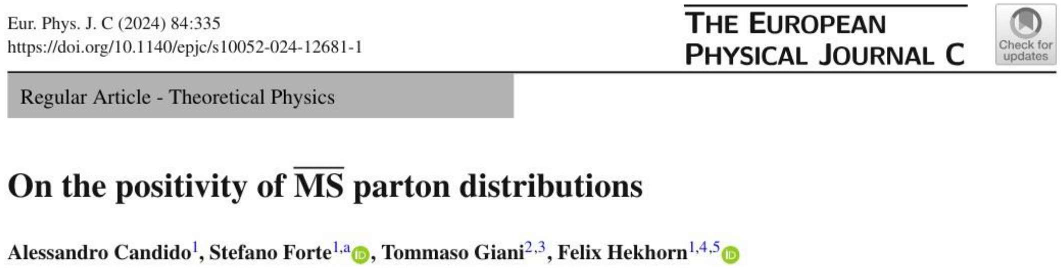




*Dynamical diquarks in the γ*p → N(1535)1/2− transition,*
Khépani Raya et al., NJU-INP 046/21, arXiv:2108.02306 [hep-ph],
Eur. Phys. J. A **57** (2021) 266/1-16

Positivity of unpolarised DFs

- The overlap representation of GPDs (hence, DFs) was introduced independently by Diehl *et al*. and Burkardt 24 years ago (2000): $p(x) \sim \int d^2k_\perp |\Psi(x, k_\perp)|^2$.
  - In all that time, no flaw has been found in the analysis
  - Objectively, available rigorous theoretical considerations ⇒ unpolarised DFs are positive definite
- Discussion Forte *et al*. *vs*. Collins *et al*. is readily summarised
  - At any factorisation scale for which O(α) pQCD is a valid tool for the description of cross-section data, the DF obtained is necessarily positive definite
  - As one lowers the factorisation scale, it cannot be guaranteed that O(α^2) corrections will preserve DF positivity.
    - Models exist in which that is not the case


Eur. Phys. J. C (2024) 84:335
https://doi.org/10.1140/epjc/s10052-024-12681-1

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

On the positivity of $\overline{\text{MS}}$ parton distributions

Alessandro Candido[1], Stefano Forte[1,a], Tommaso Giani[2,3], Felix Hekhorn[1,4,5]

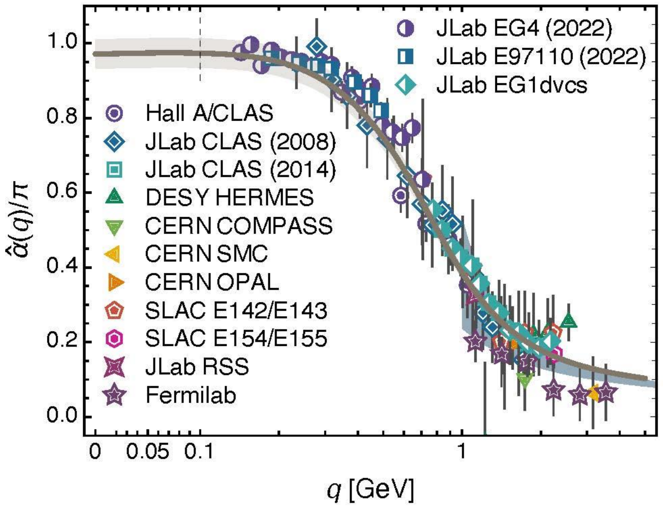
- An interpretation of F *v*. C:
  - Discussion does not demonstrate that QCD-connected DFs can be negative, only that attempts at a perturbative inference of DFs can yield results with domains of negative support
  - If O(α^2) changes physics, then O(α^2) is invalid tool and higher orders (in α and other corrections) should be included and tested to see whether they can restore the balance

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

- *Hadron scale, ζ_H*

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



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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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.

[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] .