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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

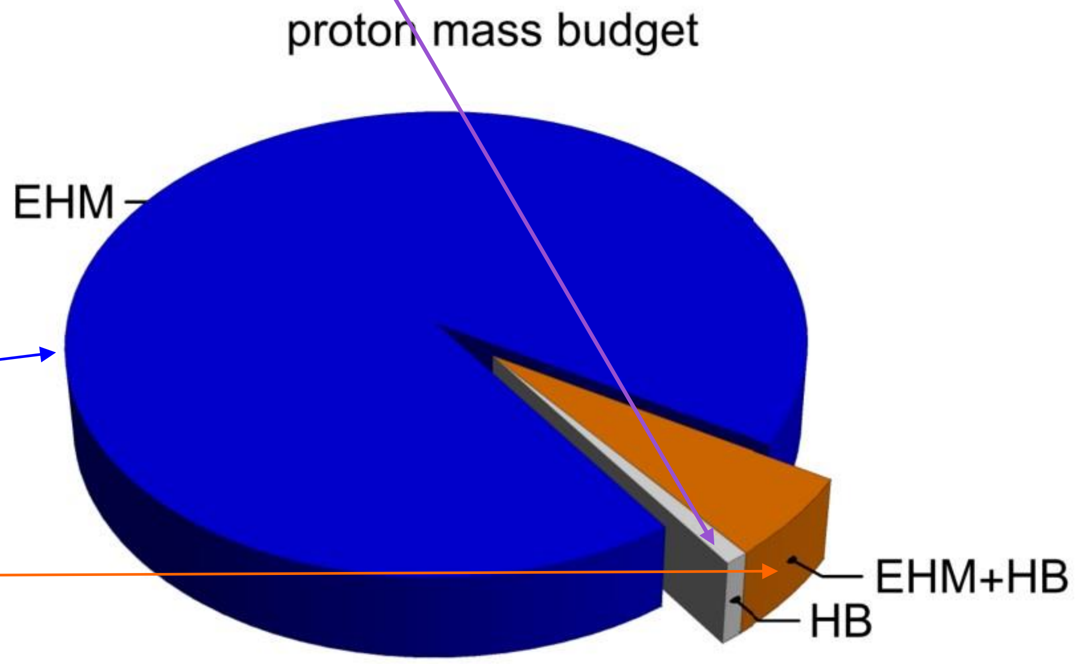
Revealing and Mapping EHM using High Luminosity and Energy

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 is alone 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:

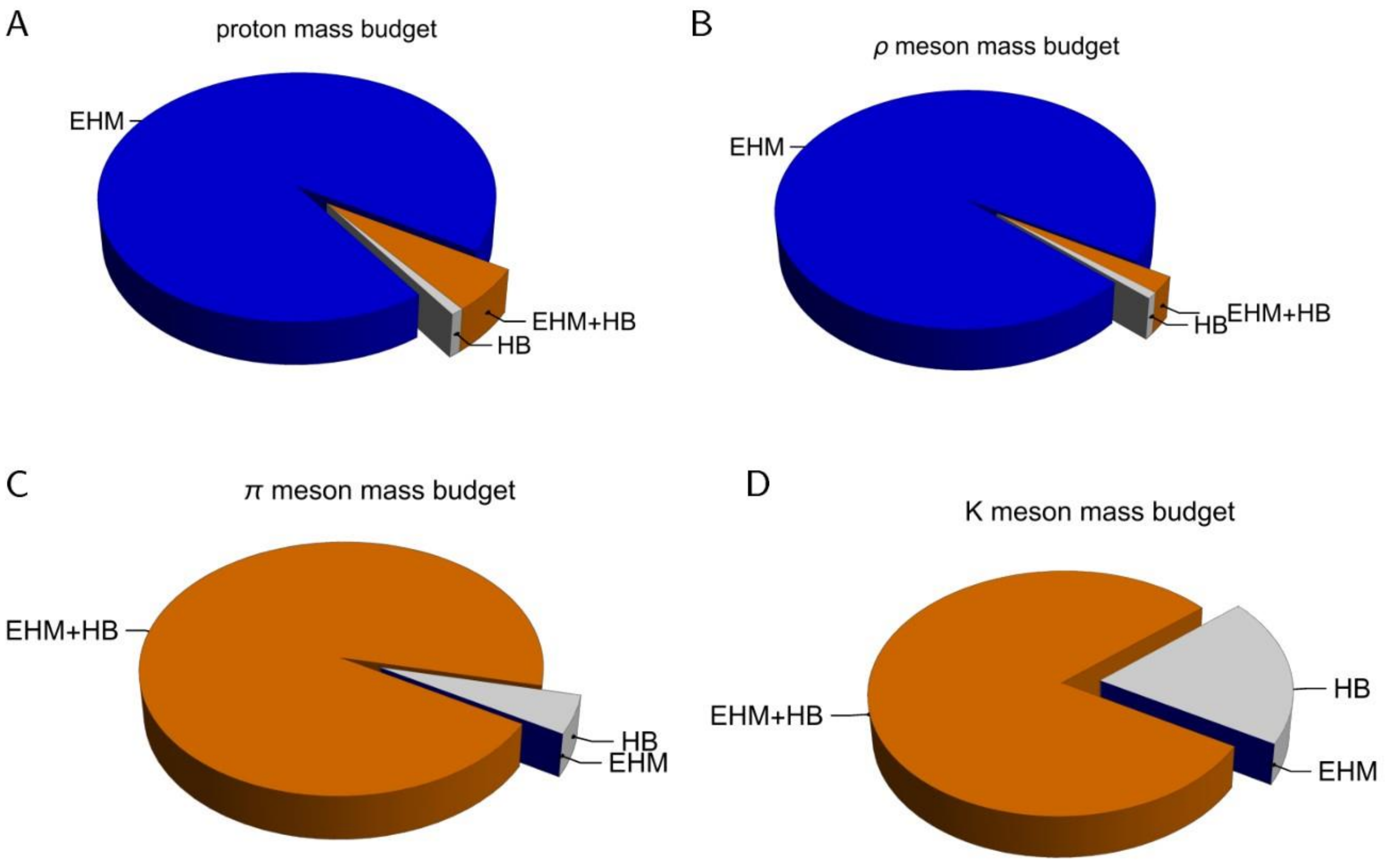
  Emergent Hadron Mass (EHM)
  - ✓ Alone, it produces 94% of the proton's mass
  - ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



Emergence of Hadron Mass - Basic Questions

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

Proton and ρ-meson mass budgets are practically identical



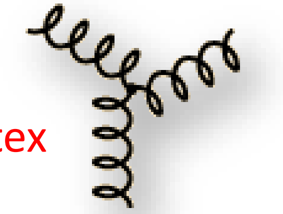
π- and K-meson mass budgets are essentially/completely different from those of proton and ρ

G E N E S I S

GLUON

Modern Understanding Grew Slowly from *Ancient* Origins

3-gluon vertex

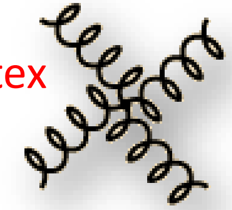


- More than 40 years ago

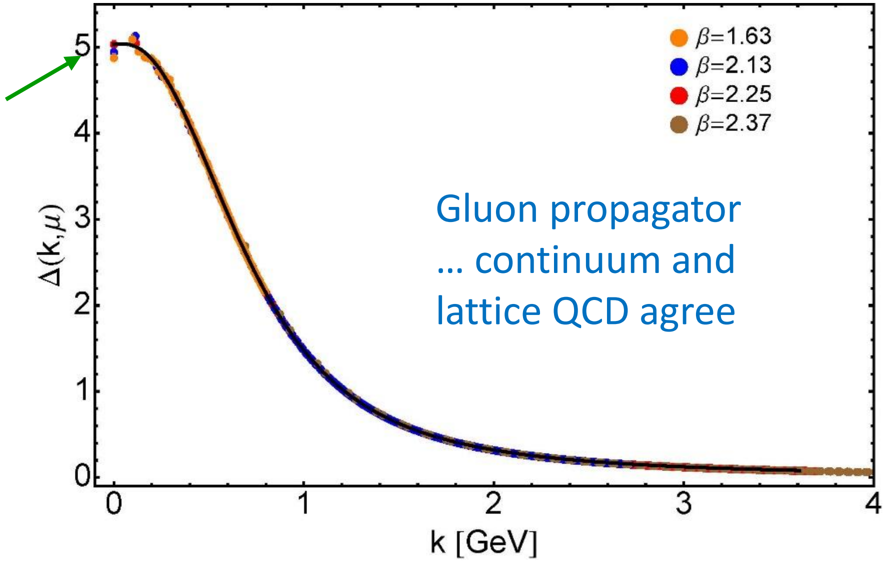
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1070 citations

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

4-gluon vertex



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



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?*

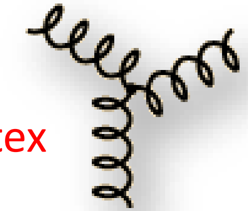
Modern Understanding
Grew Slowly from … Origins

- More than 40 year …

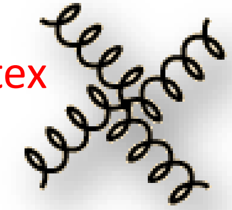
  Dynamical mass ger … mics,
  J.M. Cornwall, Phys. …

- Owing to strong se … uasiparticles,
  described by a … omenta

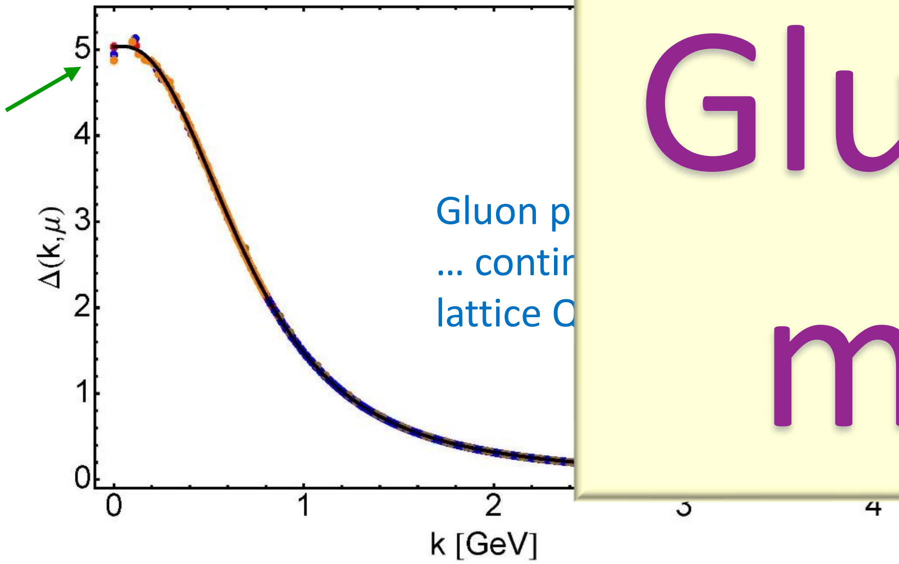
3-gluon vertex



4-gluon vertex



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

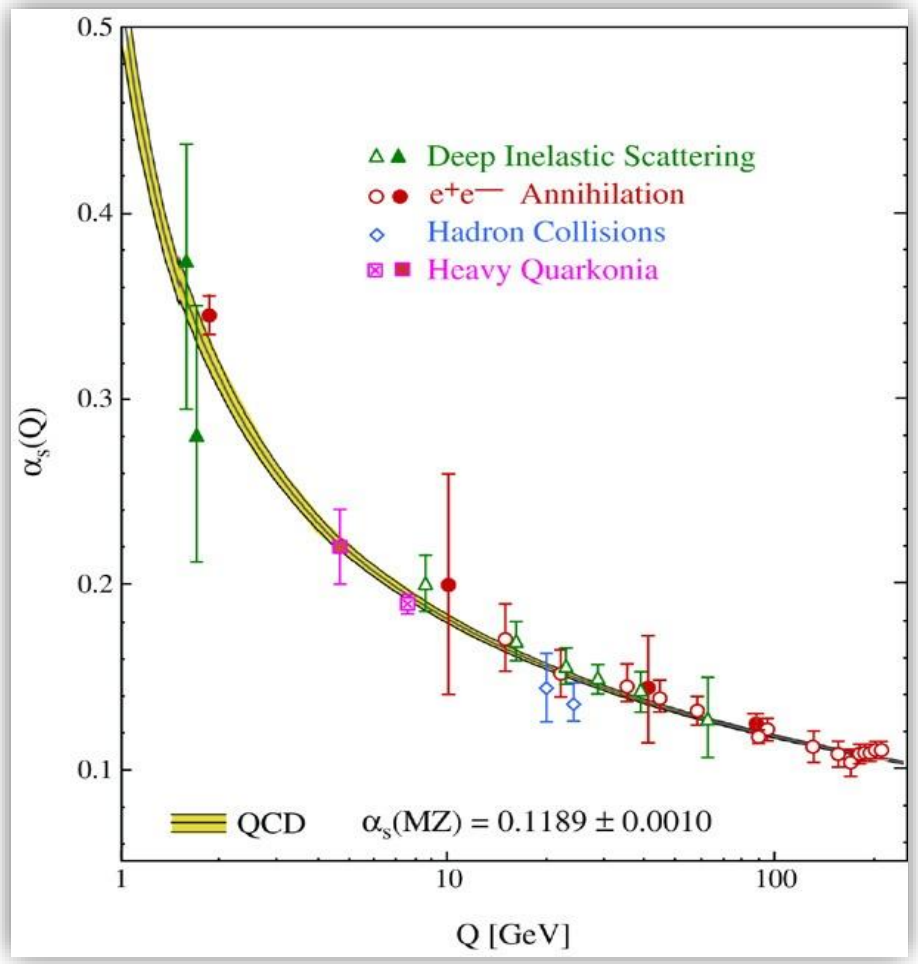


EHM means Gluons are massive

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

This is where we live

⇐
What's happening out here?!



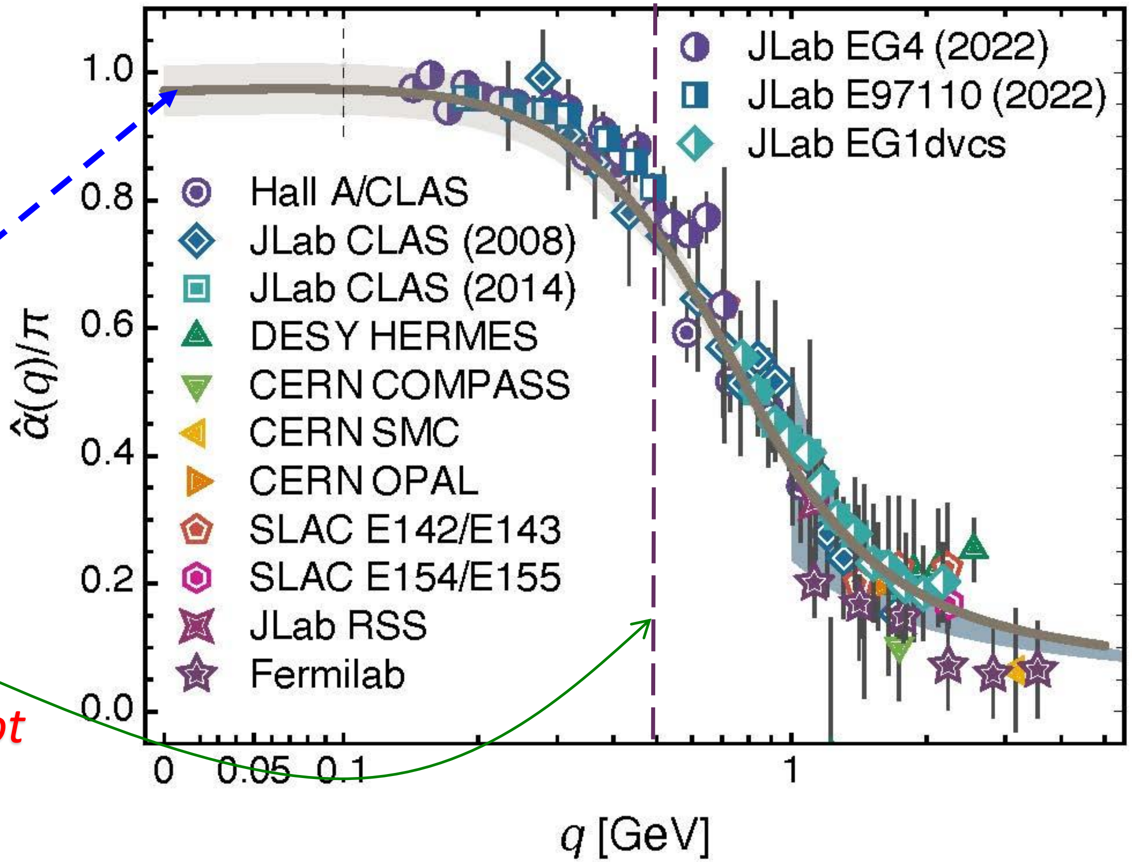
QCD's Running Coupling

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*

2199 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
  - *"Infrared Slavery" picture – linear potential – is not correct explanation of confinement*
- Below $k \sim \hat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



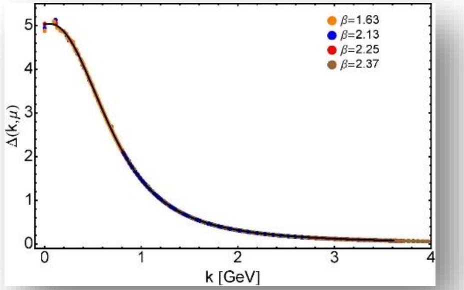
✓ *The QCD Running Coupling,* A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
✓ *Process independent strong running coupling* Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.* A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171

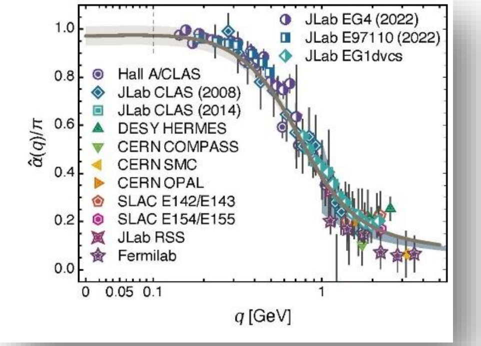
EHM Basics

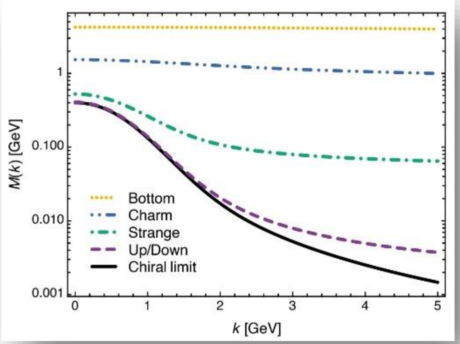
- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =

  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

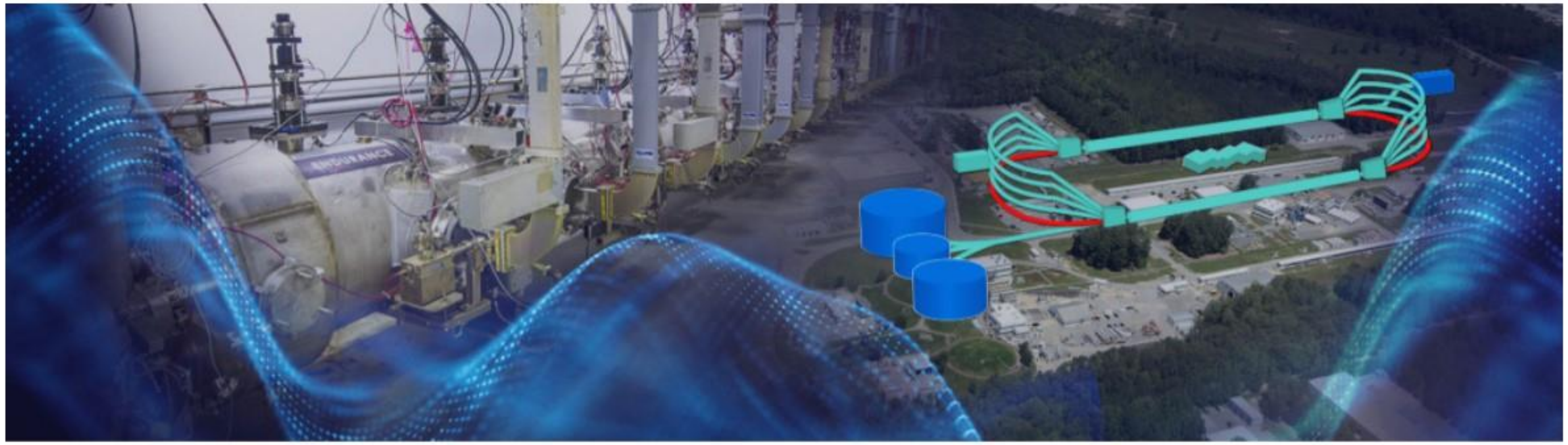






Beam Energy (GeV)	Fraction EHM mapped (%)
6	≈ 35
12	≈ 50
22	≈ 90

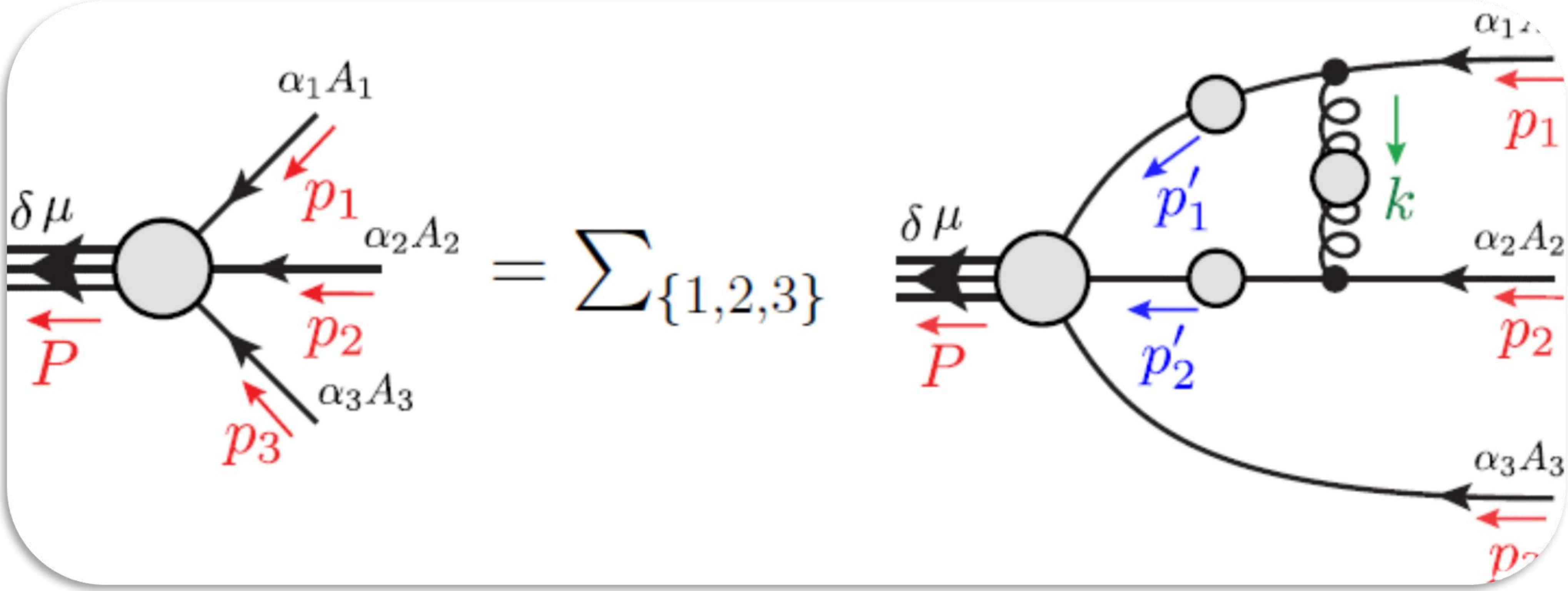
SCIENCE AT THE LUMINOSITY FRONTIER: JEFFERSON LAB AT 22 GEV



EHM at High Luminosity and Energy

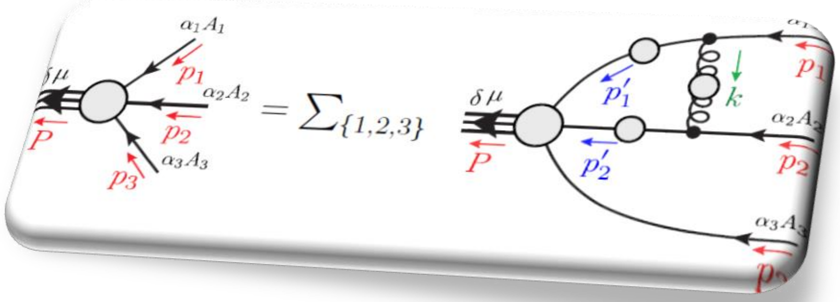
Charting EHM

- 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 monomaniacal 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



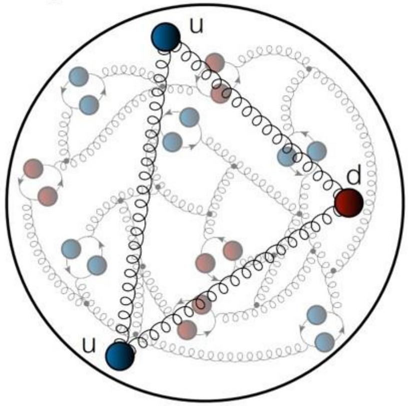
Faddeev Equation for Baryons

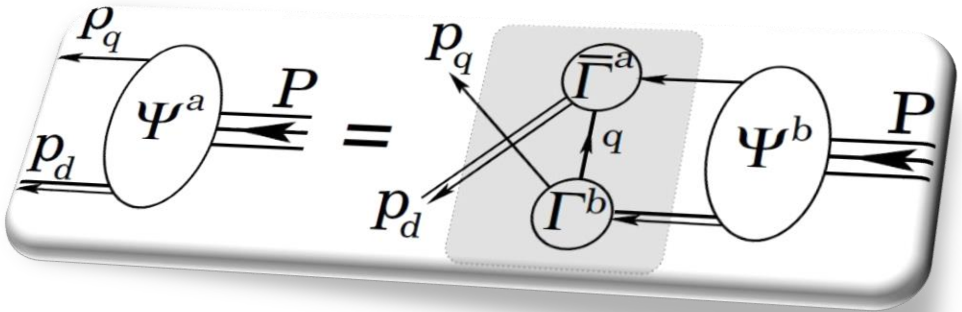
Structure of Baryons



- 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

A proton

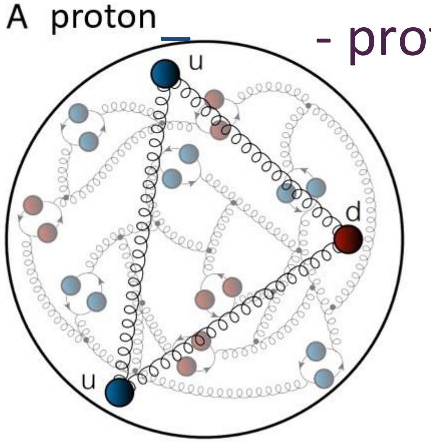




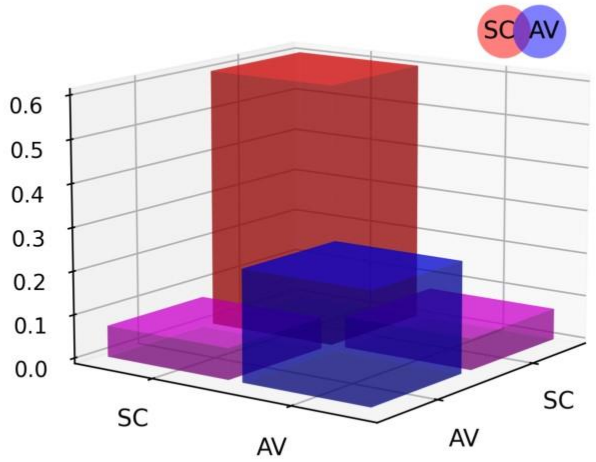
Solution delivers Poincaré-covariant proton wave function

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/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena, *strong diquark correlations exist within baryons*

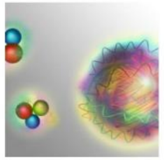


- proton and neutron … both scalar and axial-vector diquarks are present



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

Craig Roberts: cdroberts@nju.edu.cn 425 "Revealing and Mapping EHM using High-Energy and Lun



23 September 2019 — 27 September 2019

DIQUARK CORRELATIONS IN HADRON PHYSICS: ORIGIN, IMPACT AND EVIDENCE

Modern experimental facilities, new theoretical techniques for the continuum bound-state problem and progress with lattice-regularized QCD have provided strong indications that soft quarkquark (diquark) correlations play a crucial role in hadron physics.

More info

Diquarks - Facts

- Theory predicts experimental observables that would constitute unambiguous measurable signals for the presence of diquark correlations.
- Some connect with spectroscopy of exotics
  - ✓ tetraquarks and pentaquarks
- Numerous observables connected with structure of conventional hadrons, e.g.
  - ✓ existence of zeros in *d*-quark contribution to proton Dirac and Pauli form factors
  - ✓ Q^2-dependence of nucleon-to-resonance transition form factors
  - ✓ x-dependence of proton structure functions
  - ✓ deep inelastic scattering on nuclear targets (nDIS) … proton production described by direct knockout of diquarks, which subsequently form into new protons

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 116, January 2021, 103835

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6, 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10, 11], R. Ent [12], J. Ferretti [13] ✉, R.W. Gothe [14], T. Horn [15, 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18, 19] ✉ … B.B. Wojtsekhowski [12] ✉

PHYSICAL REVIEW D **105**, 094022 (2022)

Nucleon axial-vector and pseudoscalar form factors and PCAC relations

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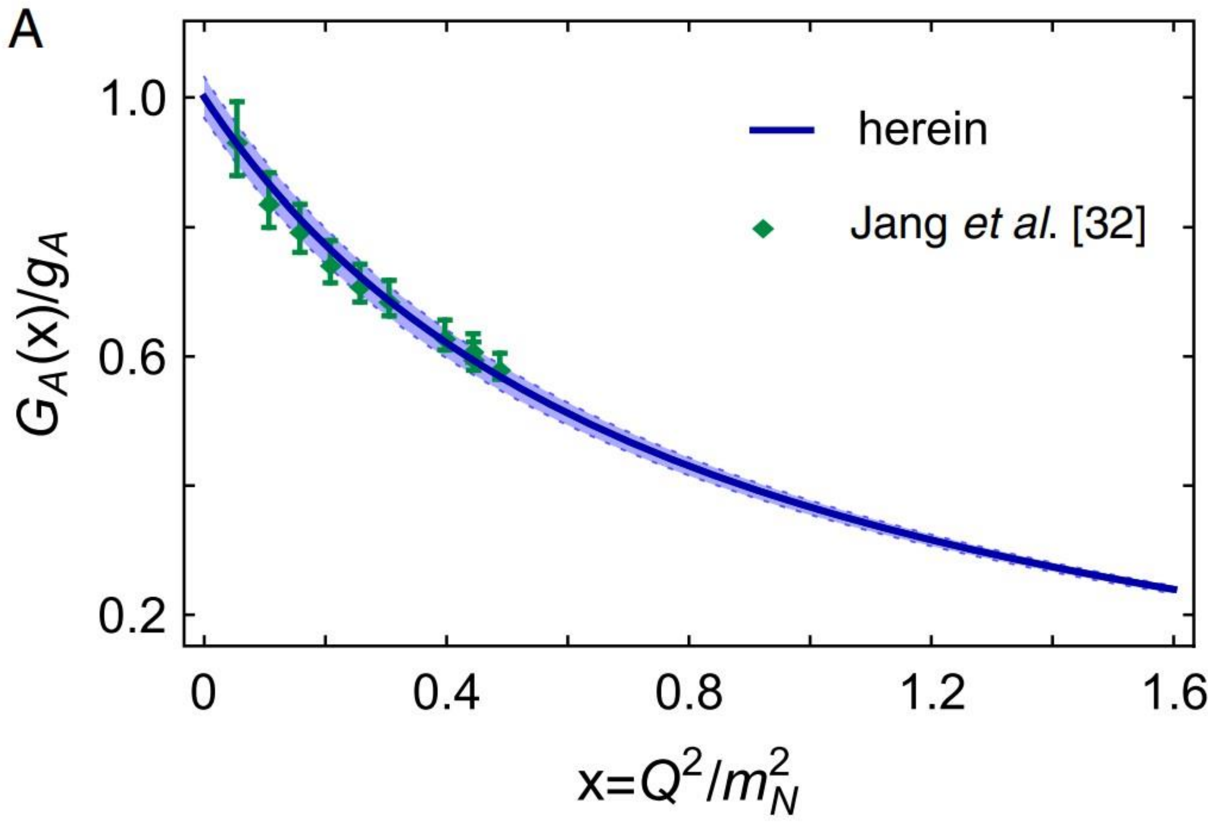
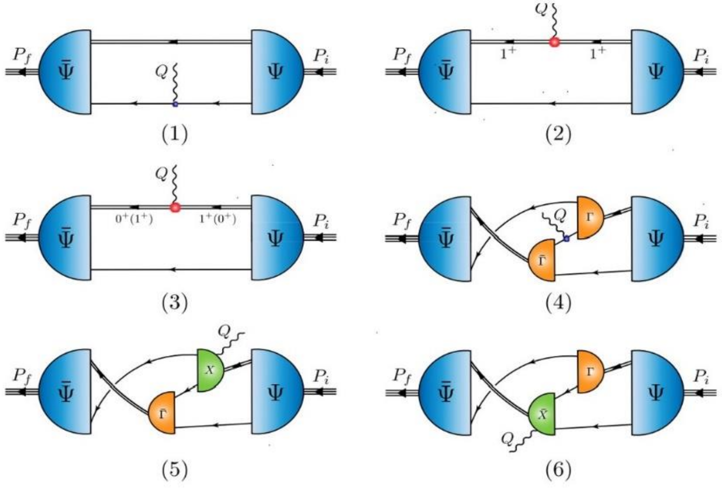
Nucleon axial form factor: $G_A(Q^2)$

- ✓ Parameter-free continuum quark+diquark prediction compared with up-to-date lattice result
- ✓ Mean χ^2= 0.27
- ✓ Q^2 reach of continuum prediction is unlimited
  - ✓ Now have results to 10 GeV^2
- ✓ “Precision” lattice result is constrained to the modest Q^2-window shown
- ✓ Contribution dissection:

  29% from $(I, J^P) = (1, 1^+)$ diquarks



	$\langle J\rangle^S_{\rm q}$	$\langle J\rangle^A_{\rm q}$	$\langle J\rangle^{AA}_{\rm qq}$	$\langle J\rangle^{SA+AS}_{\rm qq}$	$\langle J\rangle_{\rm ex}$	$\langle J\rangle_{\rm sg}$
$G_A(0)$	$0.71_{4_\mp}$	$0.064_{2_\pm}$	$0.025_{5_\pm}$	$0.13_{0_\mp}$	$0.072_{32_\pm}$	0
$G_P(0)$	$0.74_{4_\mp}$	$0.070_{5_\pm}$	$0.025_{5_\pm}$	$0.13_{0_\mp}$	$0.224_\pm$	$-0.19_{1_\mp}$
$G_5(0)$	$0.74_{4_\mp}$	$0.069_{5_\pm}$	$0.025_{5_\pm}$	$0.13_{0_\mp}$	$0.224_\pm$	$-0.19_{1_\mp}$



Eur. Phys. J. A (2022) 58:206
https://doi.org/10.1140/epja/s10050-022-00848-x

THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Theoretical Physics

Nucleon axial form factor at large momentum transfers

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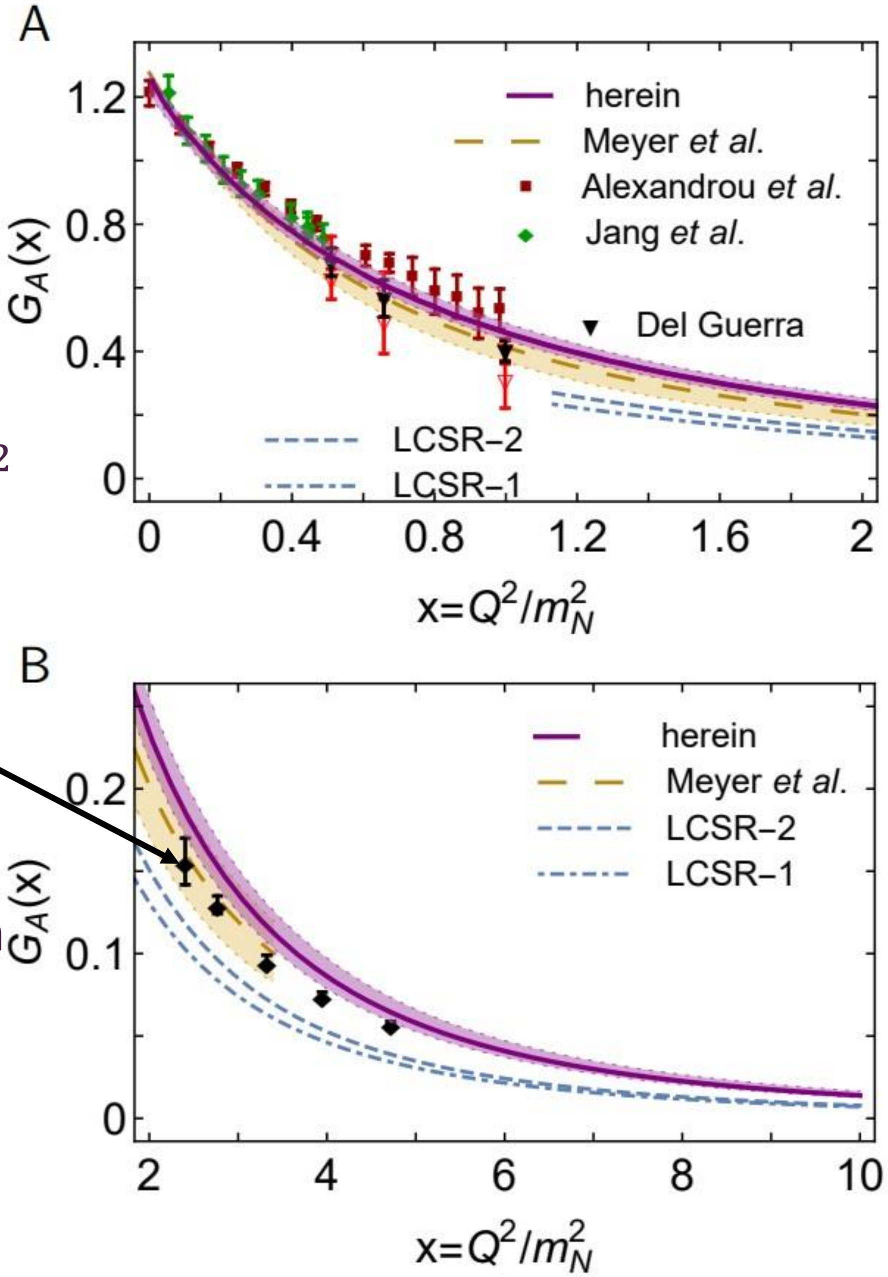
Large Q^2 Nucleon Axial Form Factor

- Parameter-free CSM predictions to $Q^2 = 10\, m_p^2$
- One other calculation, *viz*. LCSRs using different models for proton DA ... Only available on $Q^2 > 1\, m_p^2$
- CSM prediction agrees with available data: small & larger Q^2
- Larger Q^2 data from CLAS [K. Park *et al*., Phys. Rev. C 85 (2012) 035208], threshold pion electroproduction, extends $Q^2 \approx 5\, m_p^2$
  - ✓ This technique could be used to reach higher Q^2
- ✓ Regarding oft-used dipole *Ansatz*,
  - ✓ Fair representation of $G_A(x)$ on $x \in [0, 3]$ = fitting domain
  - ✓ But outside fitted domain, quality of approximation deteriorates quickly
  - ✓ dipole overestimates true result by 56% at x = 10



Large Q^2 Nucleon Axial Form Factor

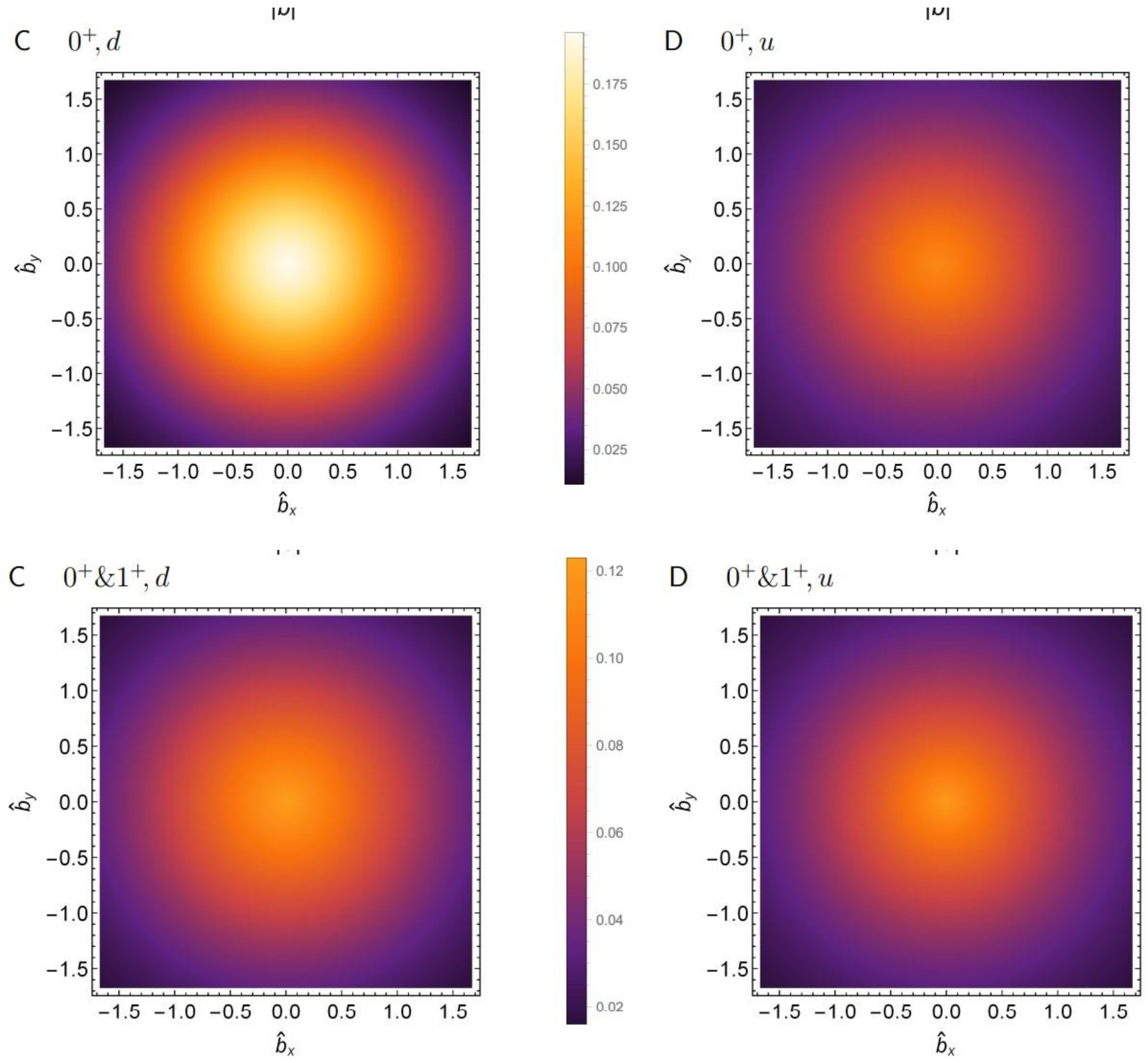
- Light-front transverse density profiles

- Omitting axialvector diquarks
  - ✓ magnitude of the d quark contribution to GA is just 10% of that from the u quark
  - ✓ d quark is also much more localized

$$r_{A_d}^{\perp} \approx 0.5\, r_{A_u}^{\perp}$$

- Working with realistic axialvector diquark fraction
  - ✓ d and u quark transverse profiles are quite similar

$$r_{A_d}^{\perp} \approx 0.9\, r_{A_u}^{\perp}$$



Proton Spin Structure

Table 1 Diagram and flavour separation of the proton axial charge: $g_A^u = G_A^u(0)$, $g_A^d = G_A^d(0)$; $g_A^u - g_A^d = 1.25(3)$. The listed uncertainties in the tabulated results reflect the impact of $\pm 5\%$ variations in the diquark masses in Eq. (3), *e.g.* $0.88 6_{\mp} \Rightarrow 0.88 \mp 0.06$.

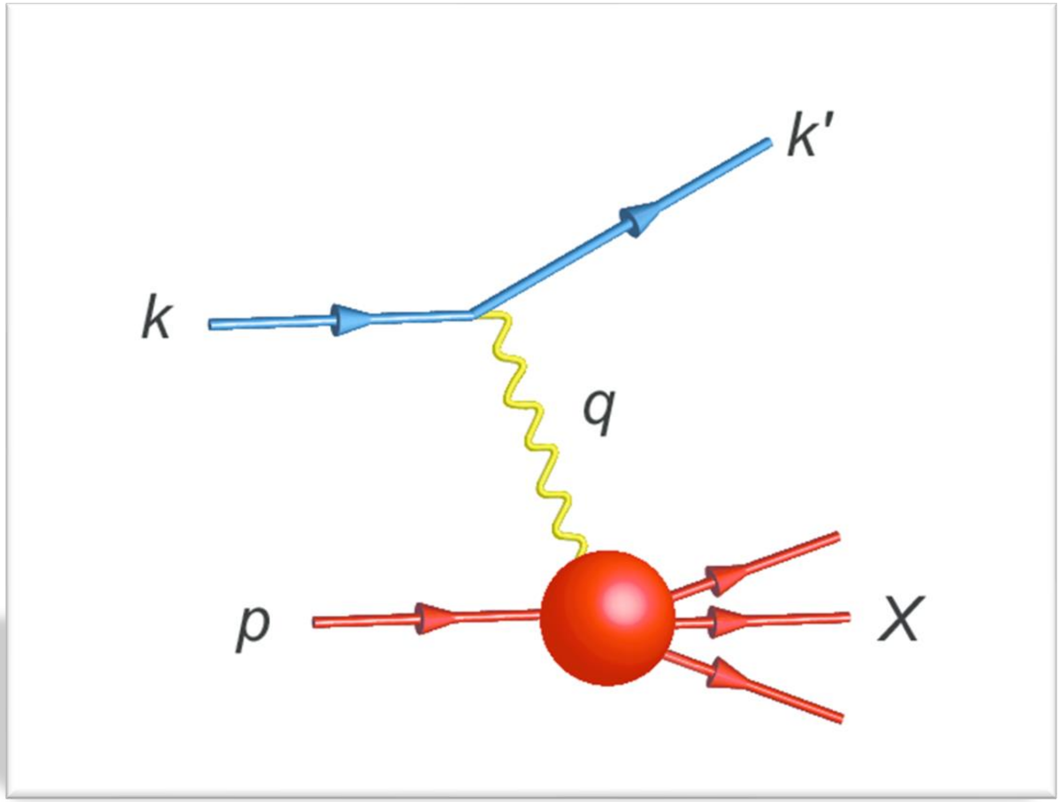
	$\langle J\rangle_{\rm q}^{S}$	$\langle J\rangle_{\rm q}^{A}$	$\langle J\rangle_{\rm qq}^{AA}$	$\langle J\rangle_{\rm qq}^{\{SA\}}$	$\langle J\rangle_{\rm ex}^{SS}$	$\langle J\rangle_{\rm ex}^{\{SA\}}$	$\langle J\rangle_{\rm ex}^{AA}$
g_A^u	$0.88 6_{\mp}$	$-0.08 0_{\pm}$	$0.03 0_{\pm}$	$0.08 0_{\mp}$	0	≈ 0	$0.03_{\pm 1}$
$-g_A^d$	0	$0.16 0_{\pm}$	0	$0.08 0_{\mp}$	$0.05 1_{\pm}$	≈ 0	$0.01_{\pm 0}$

- Flavour separation of proton axial charge
- d-quark receives large contribution from probe+quark in presence of axialvector diquark
  - $\frac{g_A^d}{g_A^u} =^{0^+ \& 1^+} -0.32(2)$
  - $\frac{g_A^d}{g_A^u} =^{0^+ \text{ only}} -0.054(13)$

Probability that scalar diquark only picture of proton is consistent with data = 1/7,100,000

- Experiment: $\frac{g_A^d}{g_A^u} =^{0^+ \& 1^+} -0.27(4) \Leftarrow$ strong pointer to importance of AV correlation
- Hadron scale: $g_A^u + g_A^d \; (+g_A^s = 0) = 0.65(2) \Rightarrow$ quarks carry 65% of the proton spin
- Poincaré-covariant proton wave function: remaining 35% lodged with quark+diquark orbital angular momentum
- Extended to entire octet of ground-state baryons: dressed-quarks carry 50(7)% of baryon spin at hadron scale

Contact interaction analysis of octet baryon axialvector and pseudoscalar form factors, Peng Cheng (程鹏), Fernando E. Serna, Zhao-Qian Yao (姚照千) et al., NJU-INP 063/22, e-Print: 2207.13811 [hep-ph], Phys. Rev. D **106**,(2022) 054031



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?

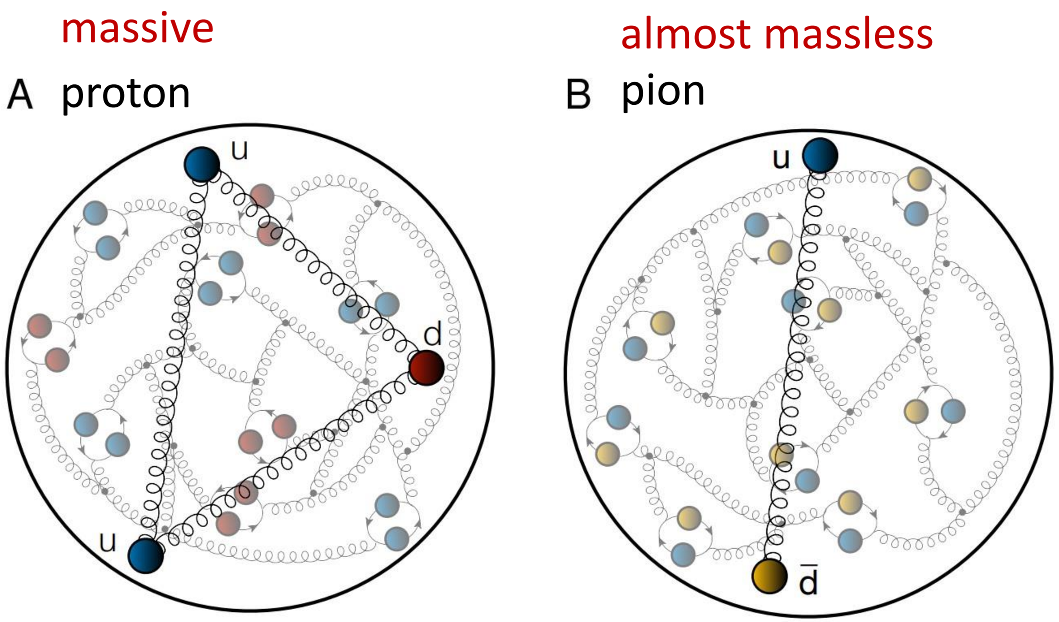


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

Proton and pion distribution functions in counterpoint

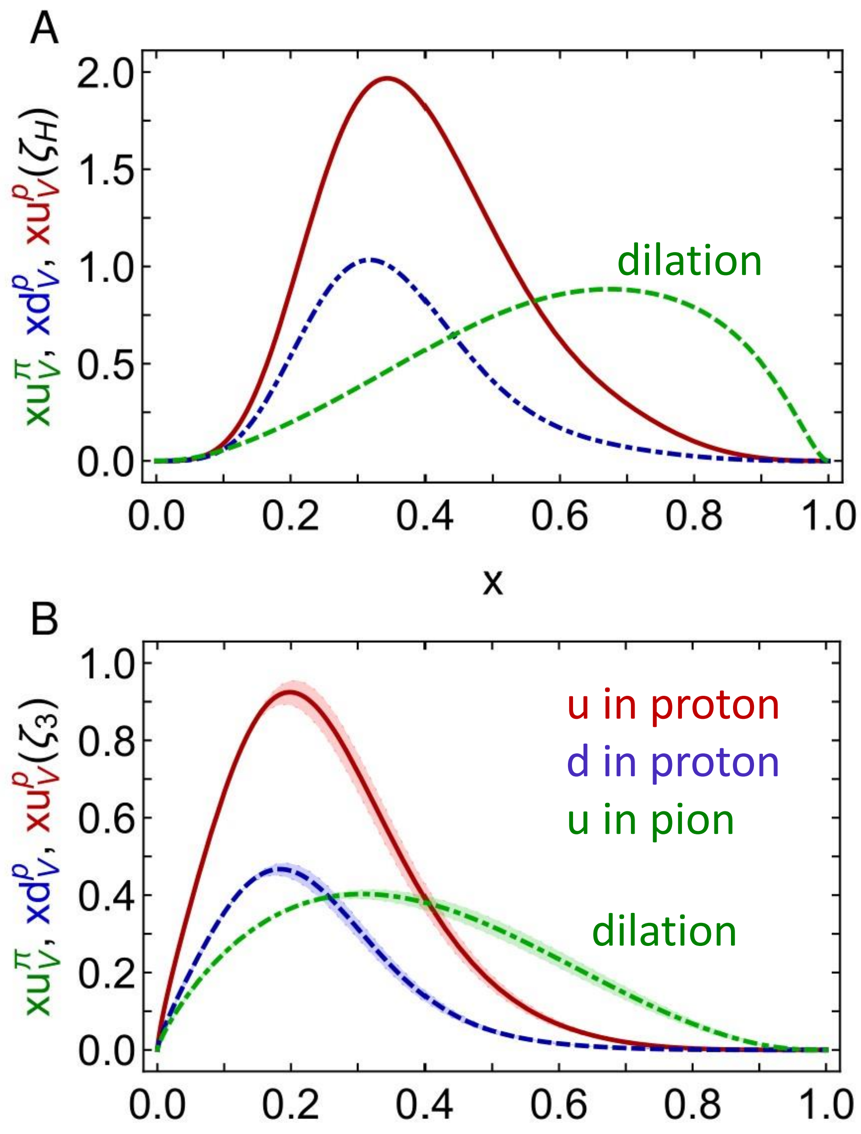
Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) *et al.*,
NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130

- Symmetry-preserving analyses using continuum Schwinger function methods (CSMs) deliver hadron scale DFs that agree with QCD constraints
- Valence-quark degrees-of-freedom carry all hadron's momentum at ζ_H: $\langle x\rangle_{u_p}^{\zeta_H} = 0.687$, $\langle x\rangle_{d_p}^{\zeta_H} = 0.313$, $\langle x\rangle_{u_\pi}^{\zeta_H} = 0.5$
- 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



Diquarks & Deep Inelastic Scattering

- The ratio of neutron and proton structure functions at large x is keen discriminator between competing pictures of proton structure
- Example:
  - Only scalar diquark in the proton (no axial-vector): $\lim_{x\to 1} \frac{F_2^n(x)}{F_2^p(x)} = \frac{1}{4}$
  - No correlations in the proton wave function (SU(4) spin-flavour) $\lim_{x\to 1} \frac{F_2^n(x)}{F_2^p(x)} = \frac{2}{3}$
- Experiments have been trying to deliver reliable data on this ratio for fifty years!
- MARATHON – a more-than ten-year effort, using a tritium target at JLab, has delivered precise results

D. Abrams, *et al., Measurement of the Nucleon Fn2/Fp2 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.

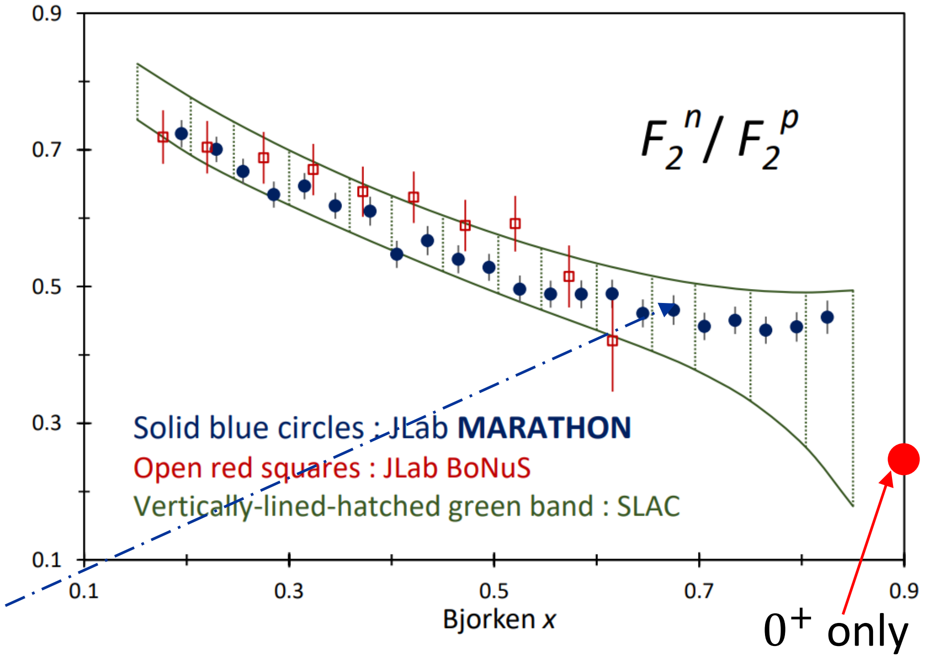


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14 \cdot x$ (GeV$/c)^2$] (see text). All three experimental data sets include statistical, point to point systematic, and normalization uncertainties.

Neutron/Proton structure function ratio

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

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

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

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

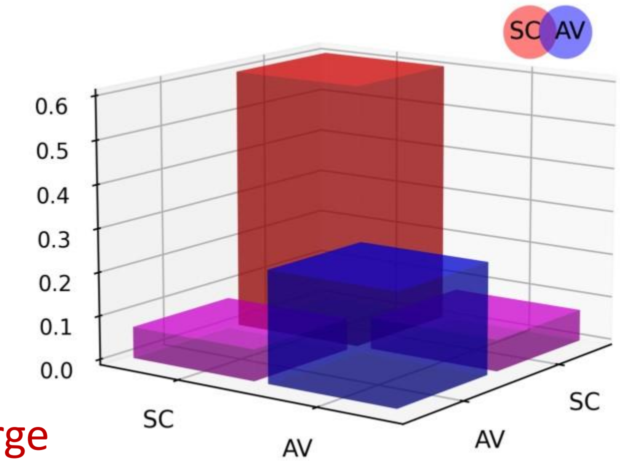
- ➢ Comparison with MARATHON data

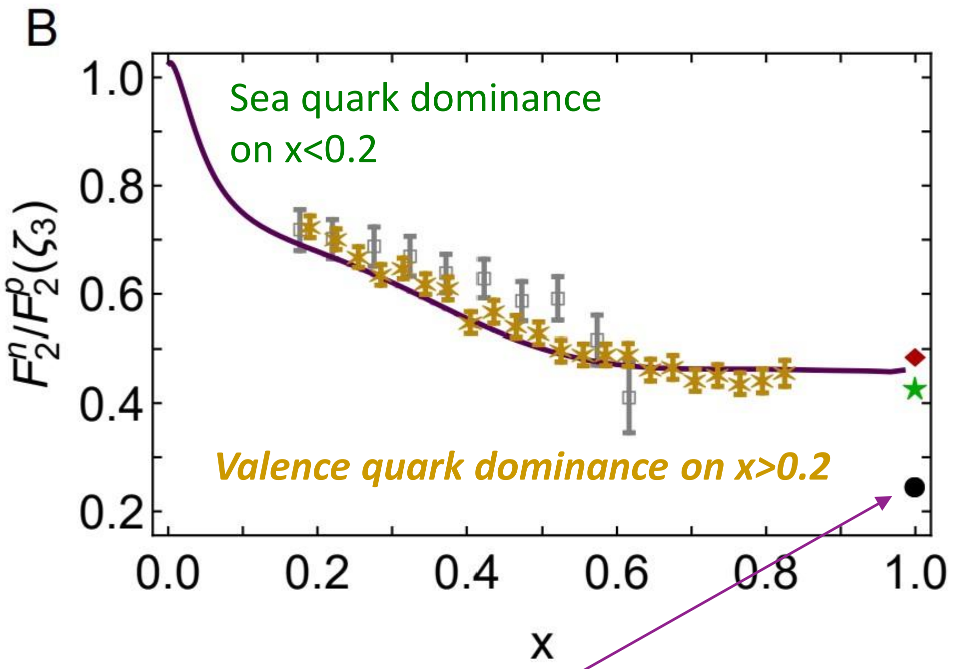
[D. Abrams, *et al.*, Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

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

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

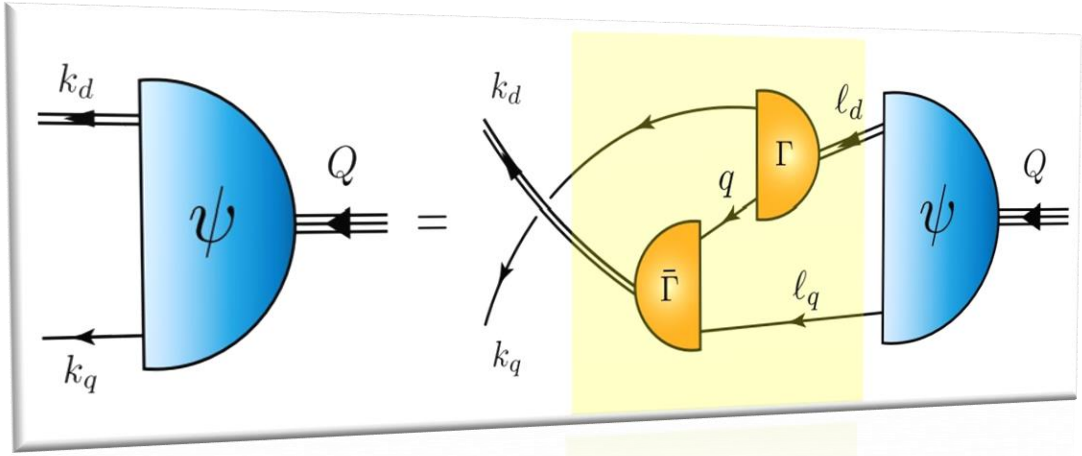
✓ Responsible for ≈ 40% of proton charge





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), Daniele Binosi, Lei Chang (常雷), Craig D. Roberts and Sebastian M. Schmidt, NJU-INP 049/21, e-print: 2108.11493 [hep-ph], Chin. Phys. Lett. *Express* **39** (04) (2022) 041401/1-5: Express Letter



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

Langtian Liu (刘浪天), Chen Chen (陈晨), Ya Lu (陆亚), Craig D. Roberts, and Jorge Segovia
Phys. Rev. D **105**, 114047 – Published 27 June 2022

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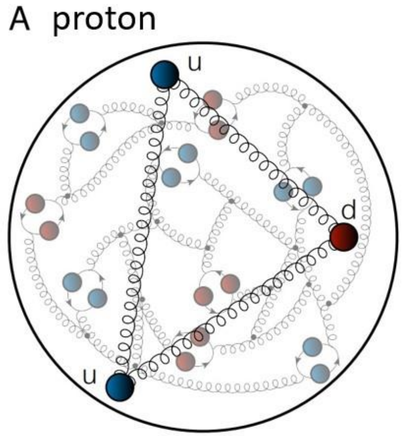
Baryon Structure



- 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 not 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 Poincaré-invariant quantum field theory, builds each of the baryons in the complete spectrum, then we don't understand Nature.*

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

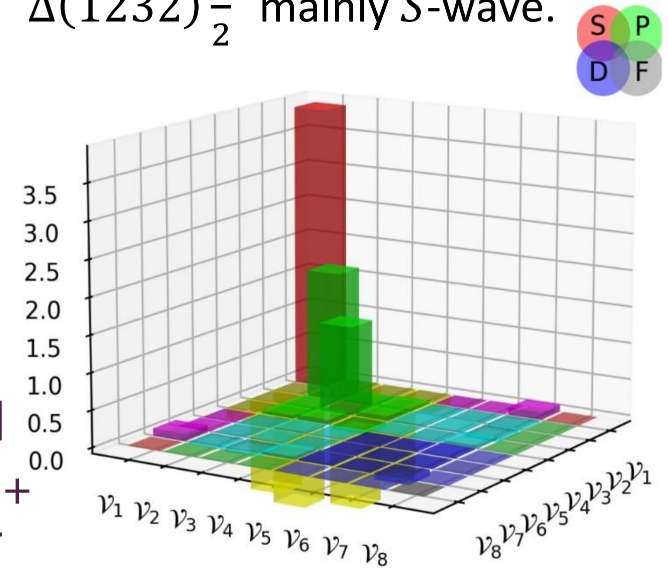
- Poincaré-covariant quark+diquark Faddeev equation

  $\Rightarrow$ insights into the structure of four lightest $(I, J^P) = (\frac{3}{2}, \frac{3}{2}^{\pm})$ baryon multiplets.

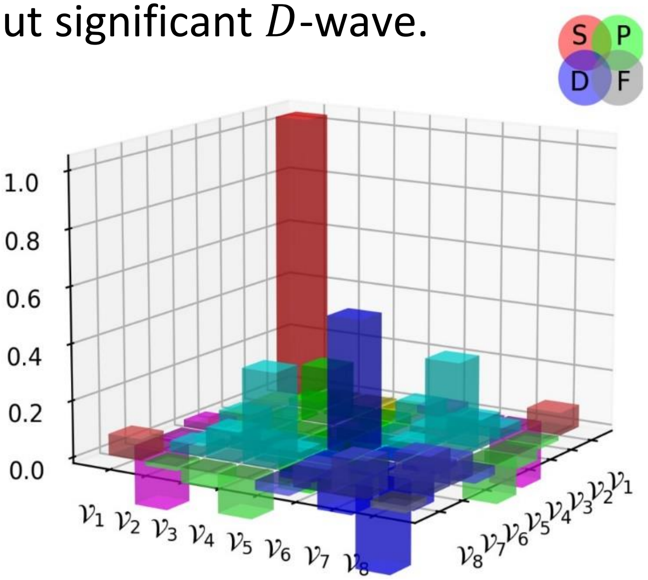
- Prediction: Whilst these systems can contain isovector-axialvector $(1,1^+)$ and isovector-vector $(1,1^-)$ diquarks, one may neglect the latter and still arrive at a reliable description.

- $(\frac{3}{2}, \frac{3}{2}^+)$ 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.



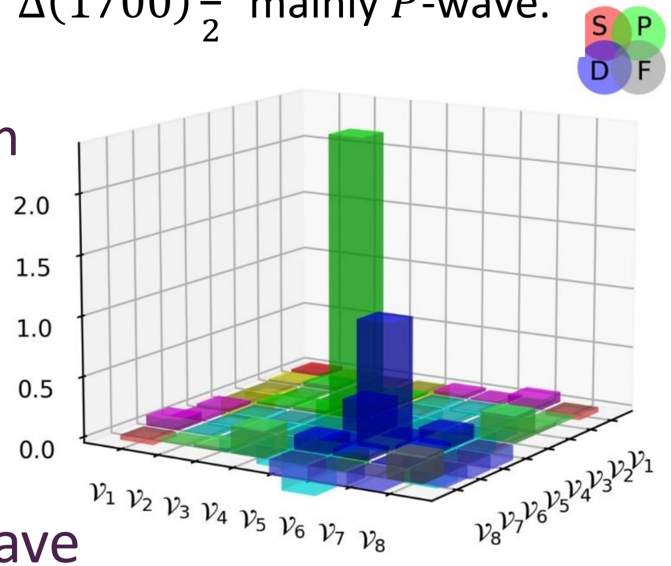
Rest-frame angular momentum decompositions

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

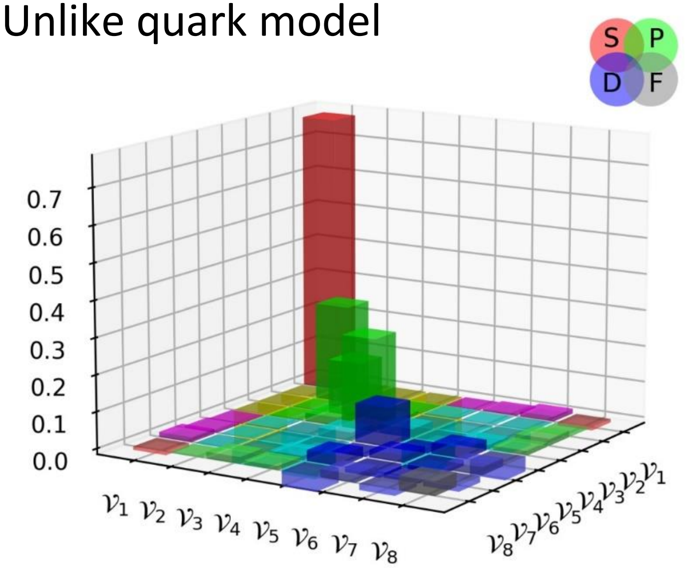
- Poincaré-covariant quark+diquark Faddeev equation

  $\Rightarrow$ 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.
- $(\frac{3}{2}, \frac{3}{2}^{-})$ states are more complex
  - $\Delta(1940)\frac{3}{2}^{-}$ doesn't look much like $\Delta(1700)\frac{3}{2}^{-}$ radial excitation
  - Rest-frame wave function of $\Delta(1700)\frac{3}{2}^{-}$ is predominantly P-wave
  - but $\Delta(1940)\frac{3}{2}^{-}$ is largely S-wave

$\Delta(1700)\frac{3}{2}^{-}$ mainly P-wave.



$\Delta(1940)\frac{3}{2}^{-}$ mainly S-wave!
Unlike quark model



Rest-frame angular momentum decompositions

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.

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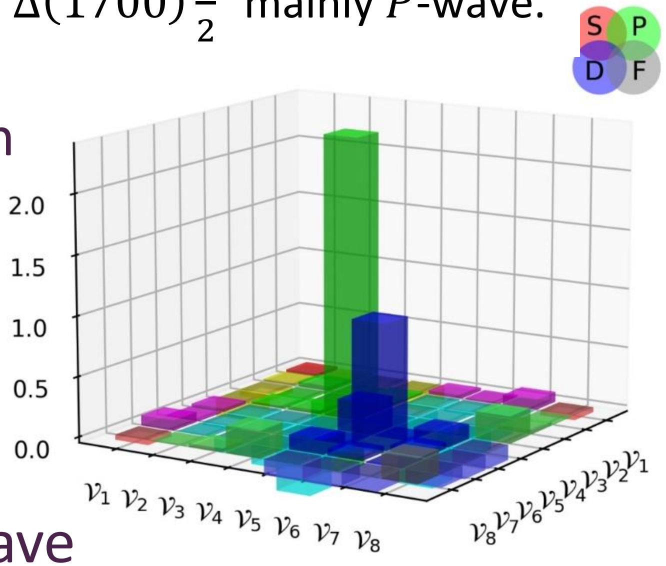

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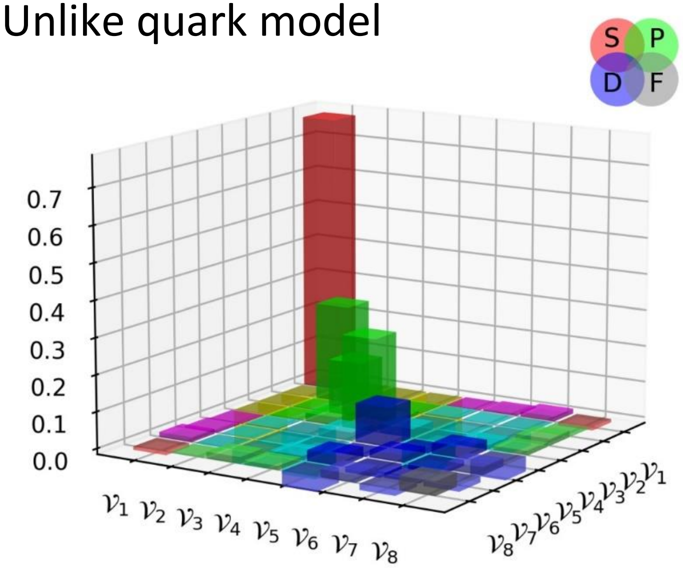
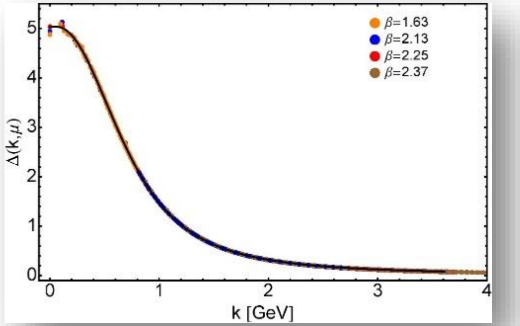


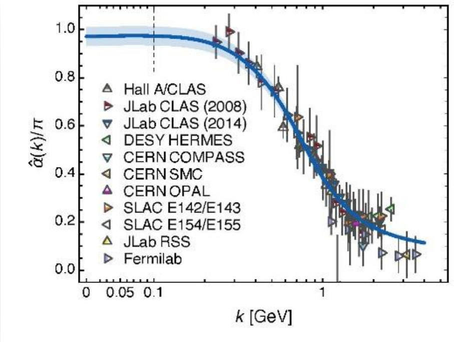
Rest-frame angular momentum decompositions

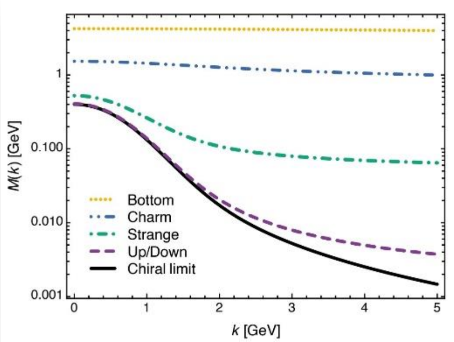
Synergy of Experiment, Phenomenology, Theory

- *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*
- *Understanding how QCD's simplicity explains the emergence of hadron mass and structure requires investment in a facility that can deliver precision data on much more than one of Nature's hadrons.*
- *An energy-upgraded Jlab complex is the only envisaged facility that 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.*

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







Craig Roberts: cdroberts@nju.edu.cn 425 "Revealing and Mapping EHM using High-Energy and Luminosity"

Grant no. 12135007

国家自然科学基金委员会
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Emergent Hadron Mass

- QCD is unique amongst known fundamental theories of natural phenomena
  - 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 appearance of a running coupling that saturates at infrared momenta, being everywhere finite
  - Massless fermions become massive, producing
    - Massive baryons and simultaneously Massless mesons
- 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
- High energy and high luminosity facilities are the key to validating these concepts

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

Grant no. 12135007

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

Emergent Hadron Mass

There are theories of many things,

But is there a theory of everything?

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

- QCD is uniq
  - Degrees … ɔservable
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There are theories of many things,
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$$\mathcal{L}_{Nature} = ?$$

Thankyou