



Charting EHM using High Luminosity and Energy

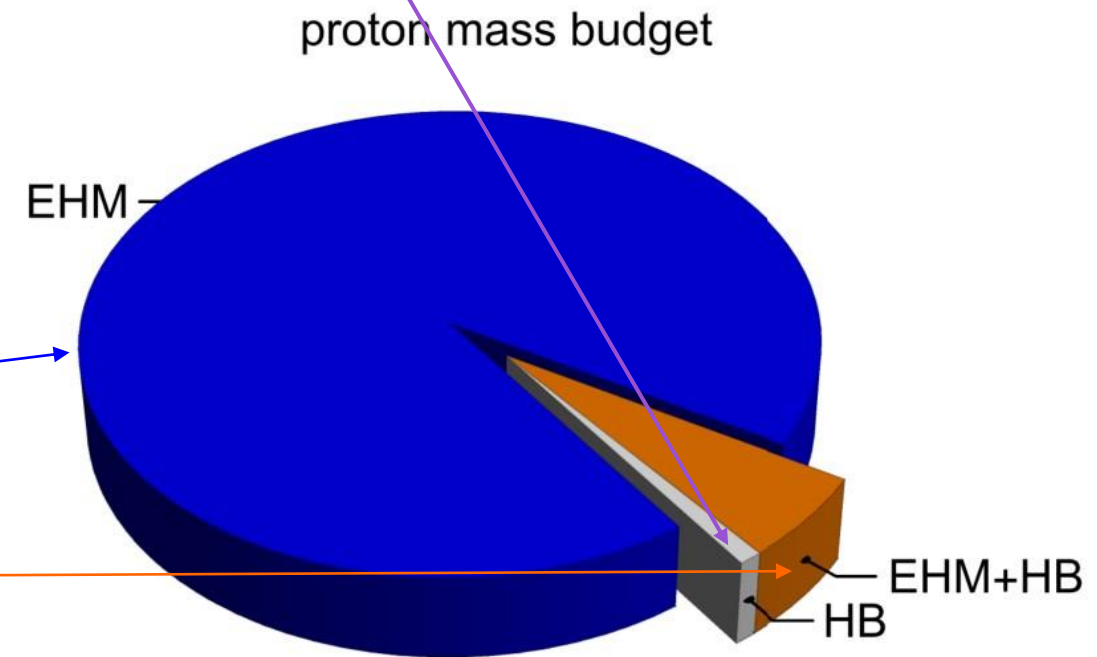
Emergence of Hadron Mass

- 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 $\sim 1\%$ 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)

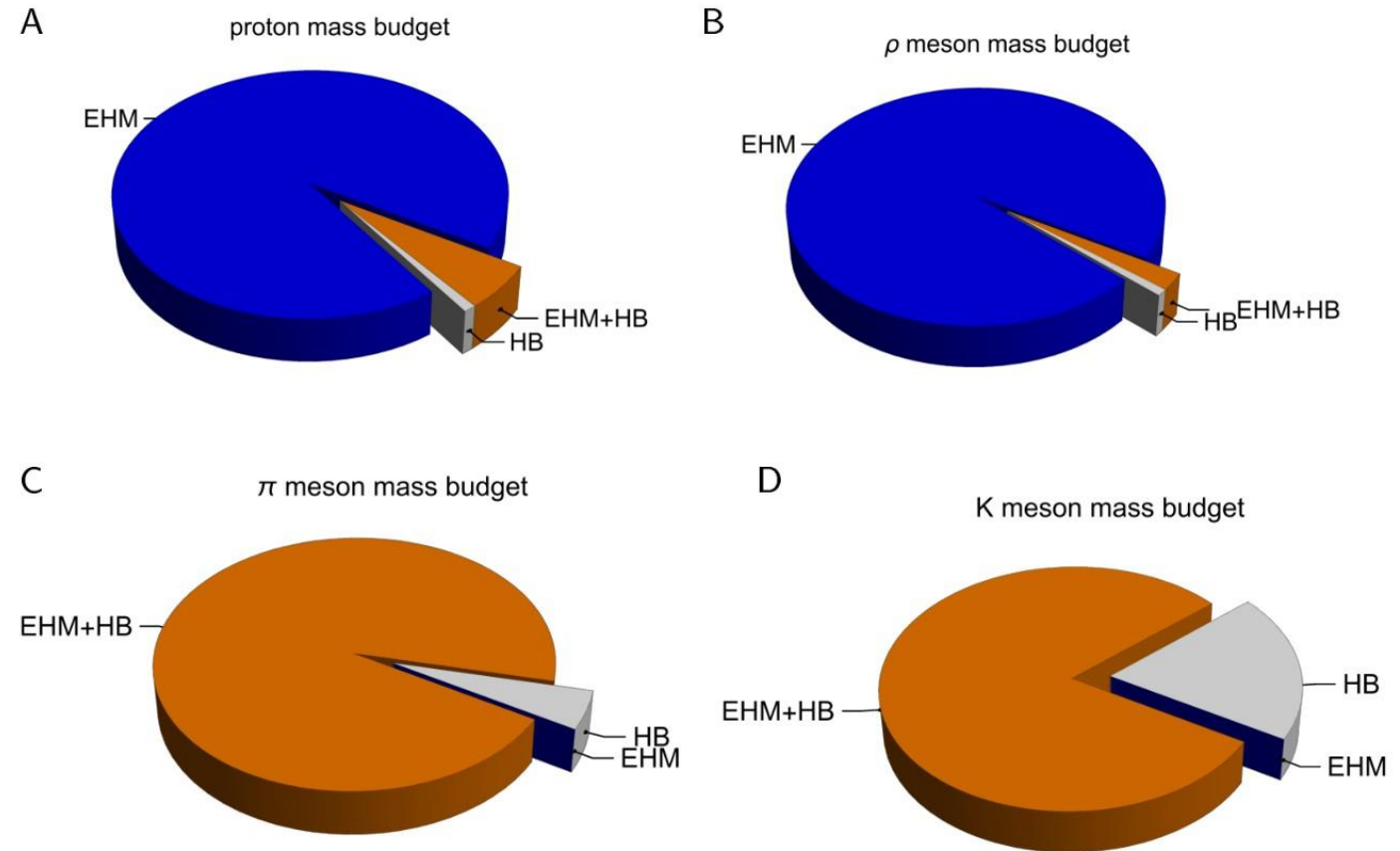
- ✓ Alone, it produces **94%** of the proton's mass
- ✓ Remaining **5%** is generated by constructive interference between EHM and Higgs-boson



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



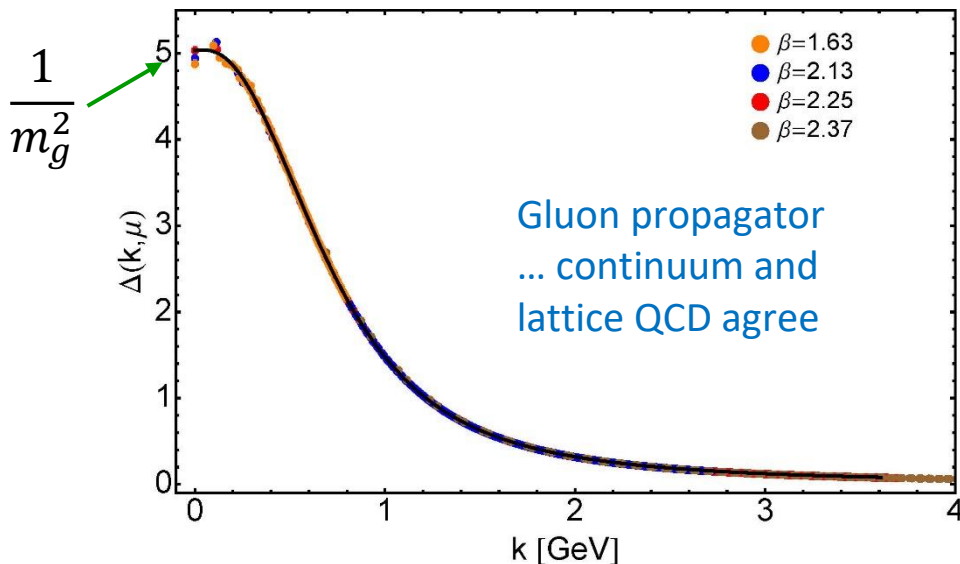
π - and K -meson mass budgets are essentially/completely different from those of proton and ρ

G E N E S I S



Modern Understanding Grew Slowly from *Ancient* Origins

- 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 \Rightarrow gluon quasiparticles,
described by a mass function that is large at infrared momenta



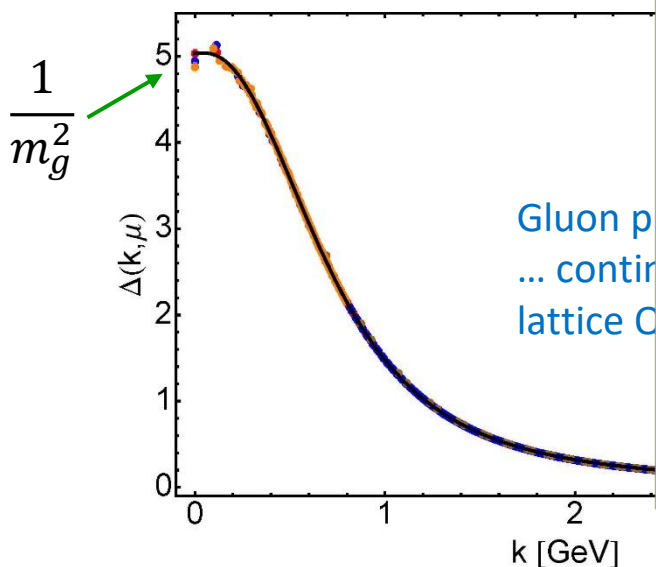
Truly mass from nothing
An interacting theory, written in
terms of massless gluon fields,
produces dressed gluon fields that
are characterised by a mass function
that is large at infrared momenta

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

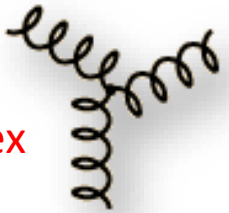
Modern Understanding Grew Slowly from @ Origins

EHM
means
Gluons are
massive

- More than 40 years
Dynamical mass generation
J.M. Cornwall, Phys.
- Owing to strong self-interactions,
described by a



3-gluon vertex



4-gluon vertex



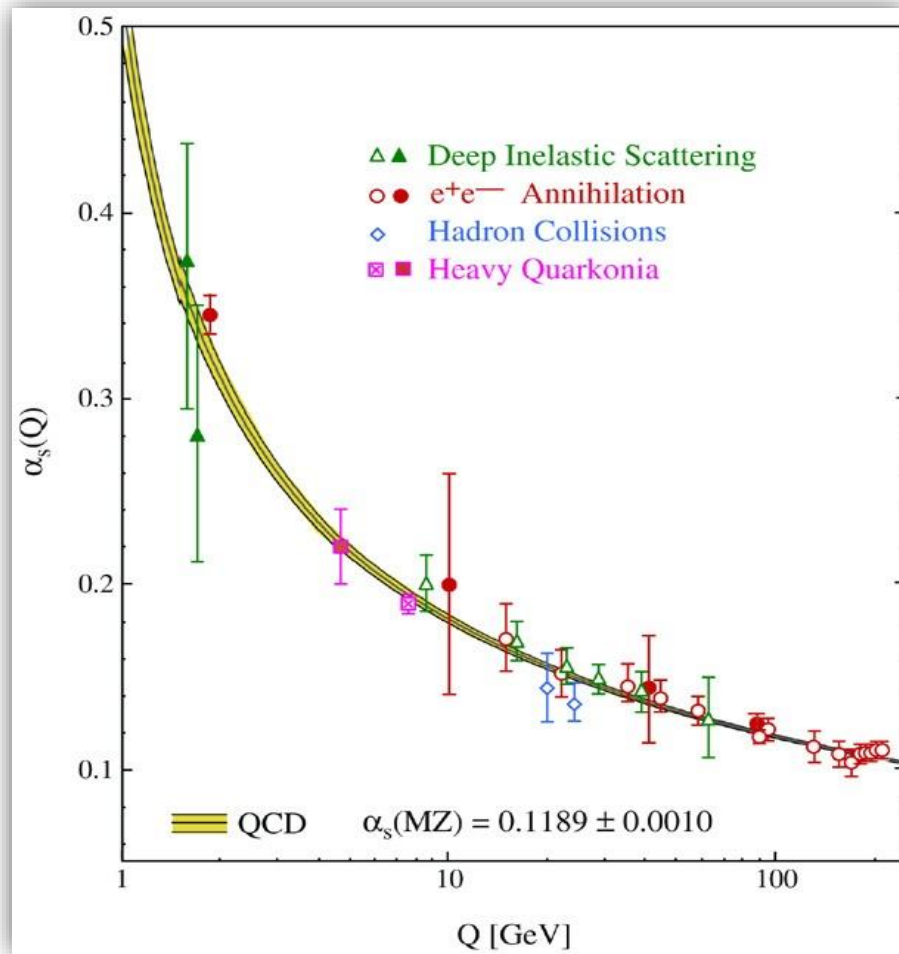
- ✓ QCD fact
- ✓ Continuum theory and lattice simulations agree
- ✓ Empirical verification?



This is where we live



What's happening
out here?!



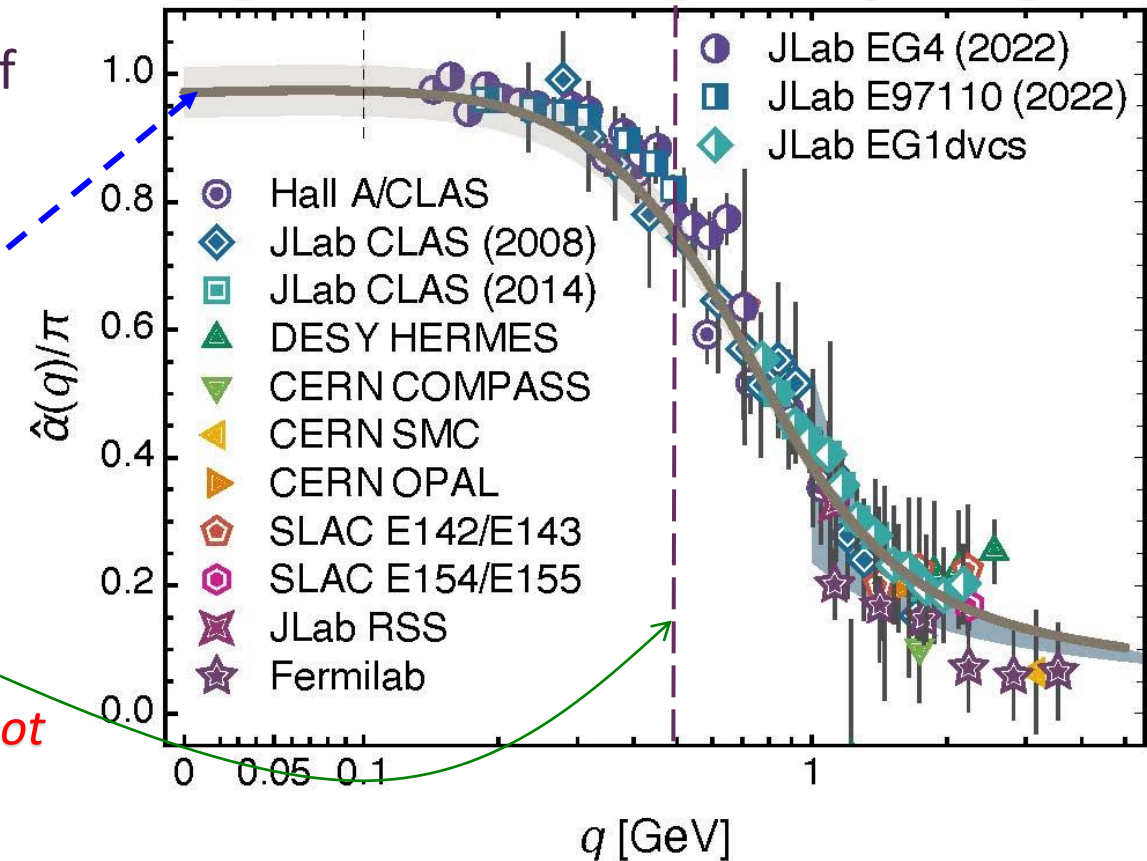
QCD's Running Coupling

Effective charge from lattice QCD, Zhu-Fang Cui, Jin-Li Zhang et al.,
NJU-INP 014/19, [arXiv:1912.08232 \[hep-ph\]](https://arxiv.org/abs/1912.08232), [Chin. Phys. C 44 \(2020\) 083102/1-10](https://doi.org/10.1088/1674-7580/44/10/083102)

2064 total downloads

Process independent effective charge = running coupling

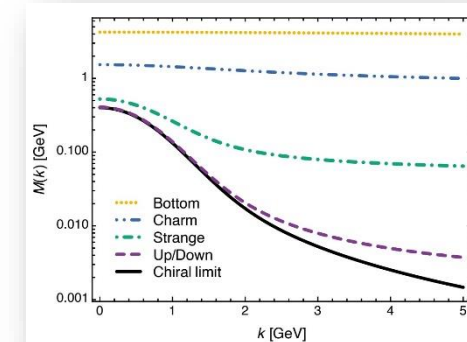
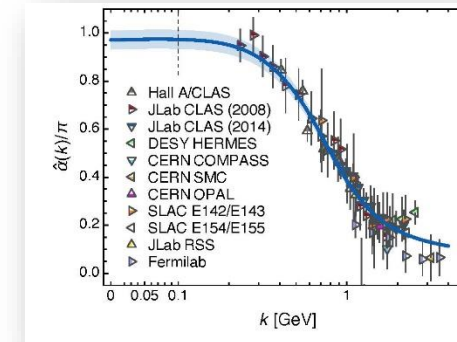
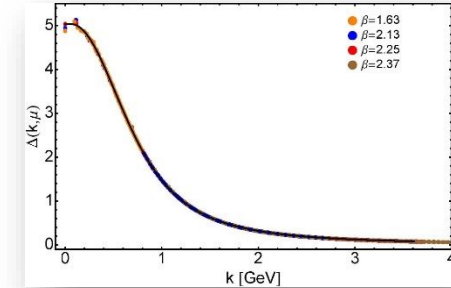
- Modern theory enables unique QCD analogue of “Gell-Mann – Low”
running charge to be rigorously defined and calculated
- Analysis of QCD’s gauge sector
yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx \frac{1}{2} m_p$
- No Landau Pole
 - “Infrared 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 \[nucl-th\]](https://arxiv.org/abs/1612.04835), *Phys. Rev. D* **96** (2017) 054026/1-7

EHM Basics

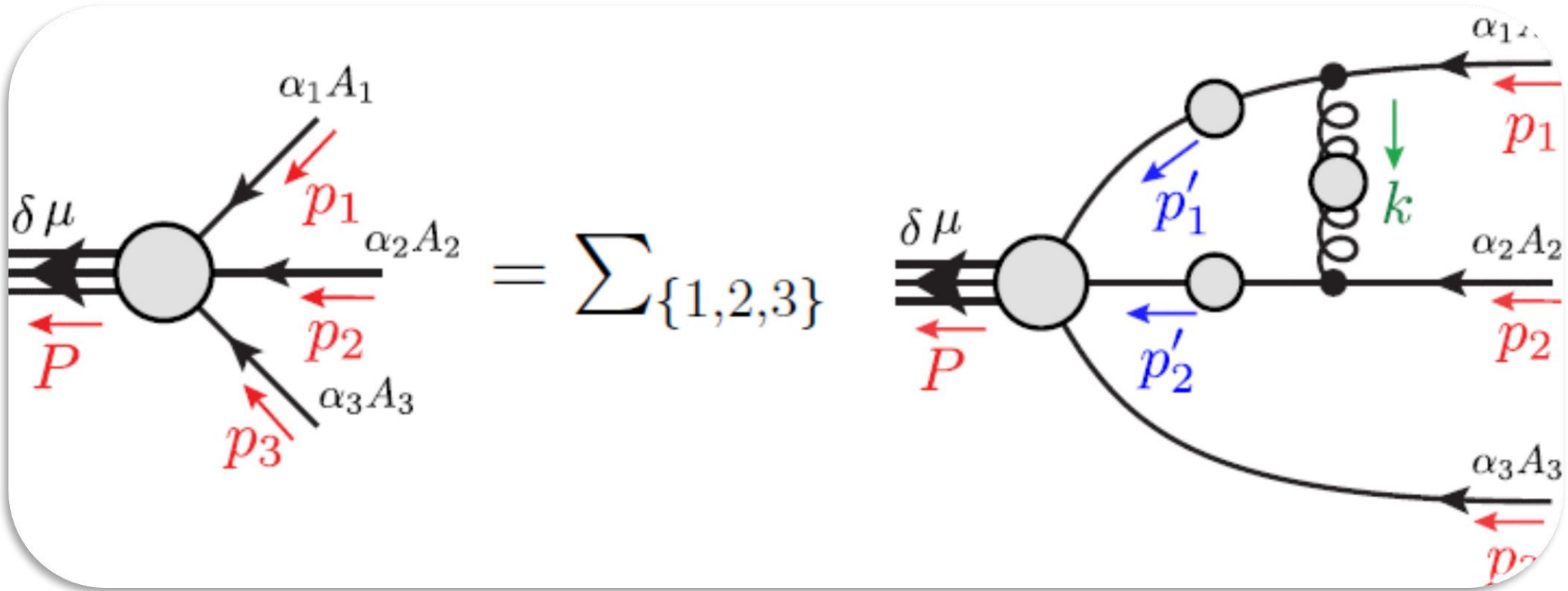
- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet ...
 - Massless gluons become massive
 - A momentum-dependent charge is produced
 - Massless quarks become massive
- EHM is expressed in
EVERY strong interaction observable
- Challenge to Theory =
Elucidate all observable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



EHM at High Energy and Luminosity Facilities

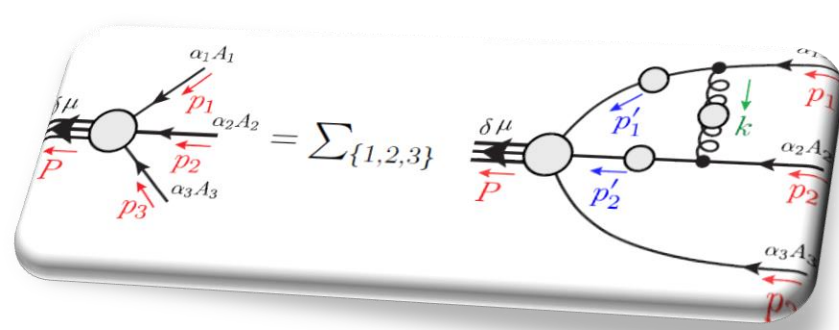
Charting EHM

- 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.



Faddeev Equation for Baryons

Structure of Baryons

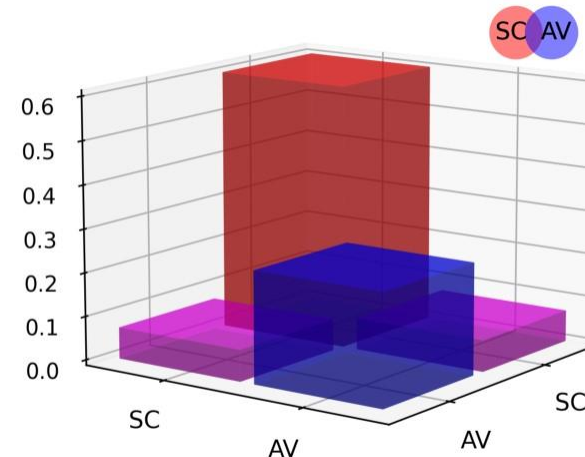


- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain

Structure of Baryons

*Solution delivers
Poincaré-covariant
proton wave function*

- 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 $\approx 40\%$ of proton charge

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](#)

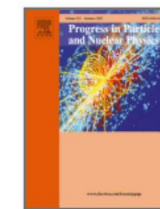
- Theory predicts experimental observables that would constitute unambiguous measurable signals for the presence of diquark correlations.
- Some connect with spectroscopy of exotics
 - ✓ tetraquarks and pentaquarks
- Numerous observables connected with structure of conventional hadrons, e.g.
 - ✓ existence 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

Diquarks - Facts



Progress in Particle and Nuclear Physics

Volume 116, January 2021, 103835







Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov¹, M.A. Bedolla², W.K. Brooks³, G.D. Cates⁴, C. Chen⁵, Y. Chen^{6, 7}, E. Cisbani⁸, M. Ding⁹, G. Eichmann^{10, 11}, R. Ent¹², J. Ferretti¹³
 ✉, R.W. Gothe¹⁴, T. Horn^{15, 12}, S. Liuti⁴, C. Mezrag¹⁶, A. Pilloni⁹, A.J.R. Puckett¹⁷, C.D. Roberts^{18, 19} ✉ ... B.B. Wojtsekhowski¹² ✉

Nucleon axial-vector and pseudoscalar form factors and PCAC relations

Chen Chen (陈晨)^{1,2,3,4,*} Christian S. Fischer^{3,4,†} Craig D. Roberts^{5,6,‡} and Jorge Segovia^{7,6,§}

¹*Interdisciplinary Center for Theoretical Study, University of Science and Technology of China,
Hefei, Anhui 230026, China*

²*Peng Huanwu Center for Fundamental Theory, Hefei, Anhui 230026, China*

³*Institut für Theoretische Physik, Justus-Liebig-Universität Gießen, D-35392 Gießen, Germany*

⁴*Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum
für Schwerionenforschung, Campus Gießen, D-35392 Gießen, Germany*

⁵*School of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*

⁶*Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China*

⁷*Dpto. Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, E-41013 Sevilla, Spain*

Nucleon Electroweak Form Factors and Pion-Nucleon Coupling

- Symmetry preserving current for realistic nucleon = quark + nonpointlike diquark
- Probe strikes
 - Quark – (1)
 - Diquark elastic – (2)
 - Diquark transition – (3)
 - Quark in-flight – (4)
 - Seagull terms – (5) & (6)
- Guarantees PCAC and all related identities
- Parameter-free predictions

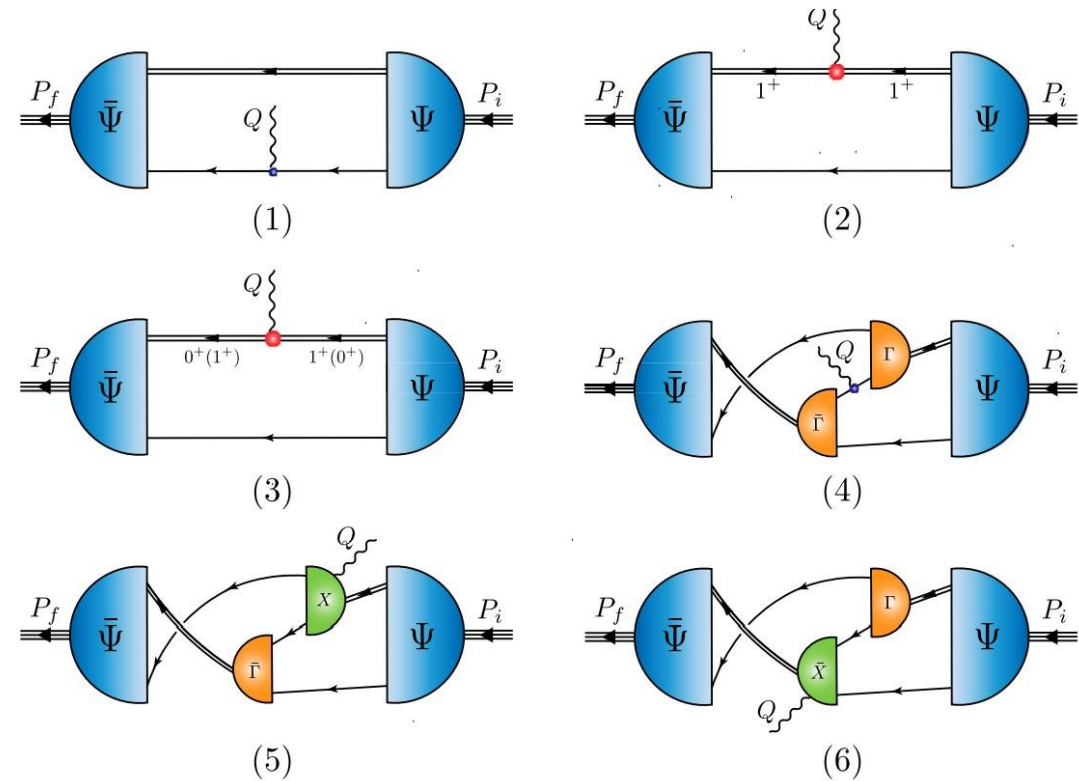
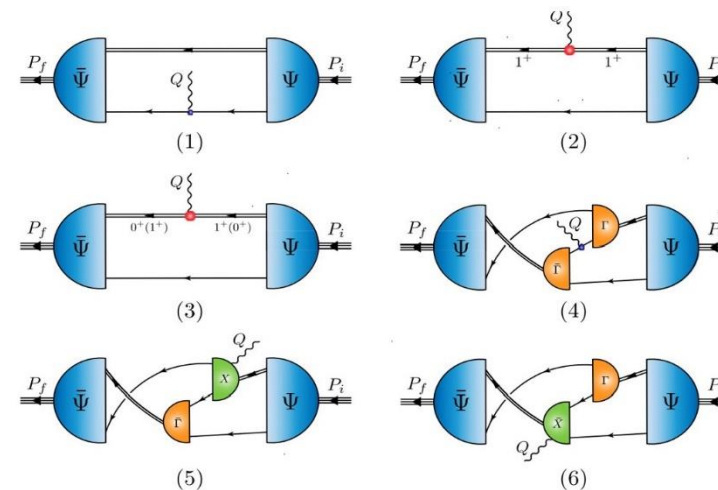
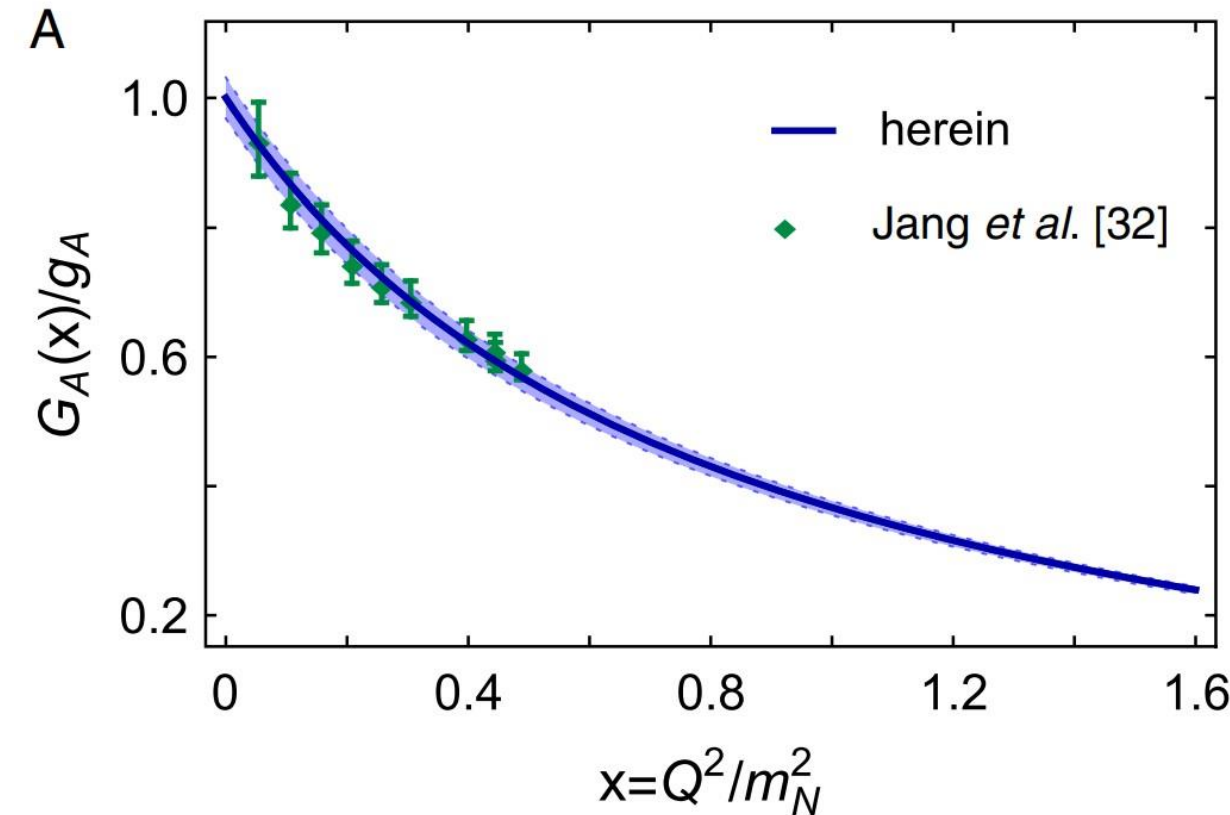


FIG. 3. Axial or pseudoscalar currents that ensure PCAC for on-shell baryons that are described by the Faddeev amplitudes produced by the equation depicted in Fig. 2. Single line: dressed-quark propagator; undulating line: the axial or pseudoscalar current; Γ : diquark correlation amplitude; double line: diquark propagator; and χ : seagull terms. Diagram 1 is the top-left image, the top-right is Diagram 2, and so on, with Diagram 6 being the bottom-right image.



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

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

	$\langle J \rangle_q^S$	$\langle J \rangle_q^A$	$\langle J \rangle_{qq}^{AA}$	$\langle J \rangle_{qq}^{SA+AS}$	$\langle J \rangle_{\text{ex}}$	$\langle J \rangle_{\text{sg}}$
$G_A(0)$	$0.71_{4\mp}$	0.064_{2+}	0.025_{5+}	$0.13_{0\mp}$	0.072_{32+}	0
$G_P(0)$	$0.74_{4\mp}$	$0.070_{5\pm}$	$0.025_{5\pm}$	$0.13_{0\mp}$	$0.22_{4\pm}$	$-0.19_{1\mp}$
$G_5(0)$	$0.74_{4\mp}$	$0.069_{5\pm}$	$0.025_{5\pm}$	$0.13_{0\mp}$	$0.22_{4\pm}$	$-0.19_{1\mp}$



Nucleon axial form factor at large momentum transfers

Chen Chen^{1,2}  and Craig D. Roberts^{3,4} 

¹Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei, Anhui 230026, China

²Peng Huanwu Center for Fundamental Theory, Hefei, Anhui 230026, China

³School of Physics, Nanjing University, Nanjing, Jiangsu 210093, China

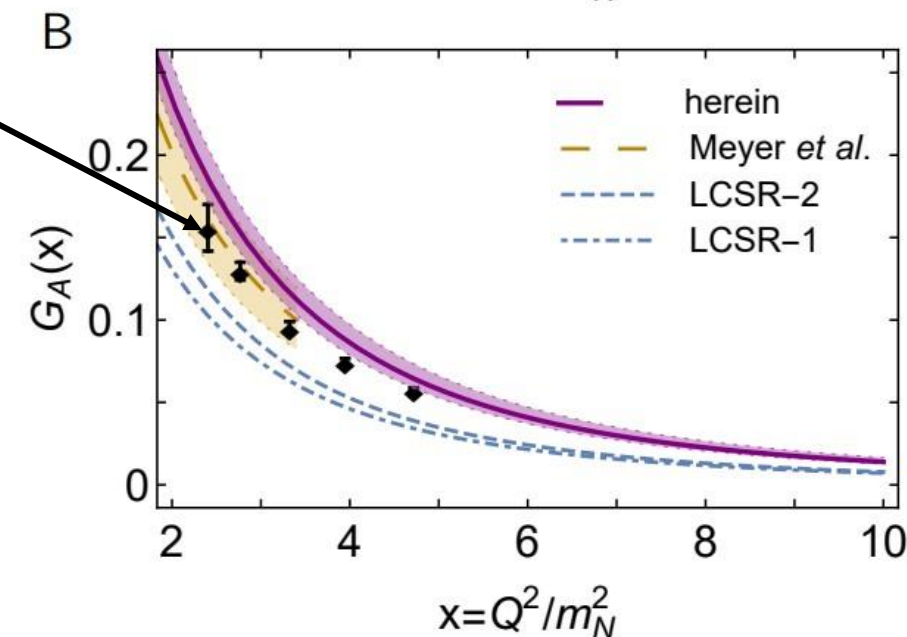
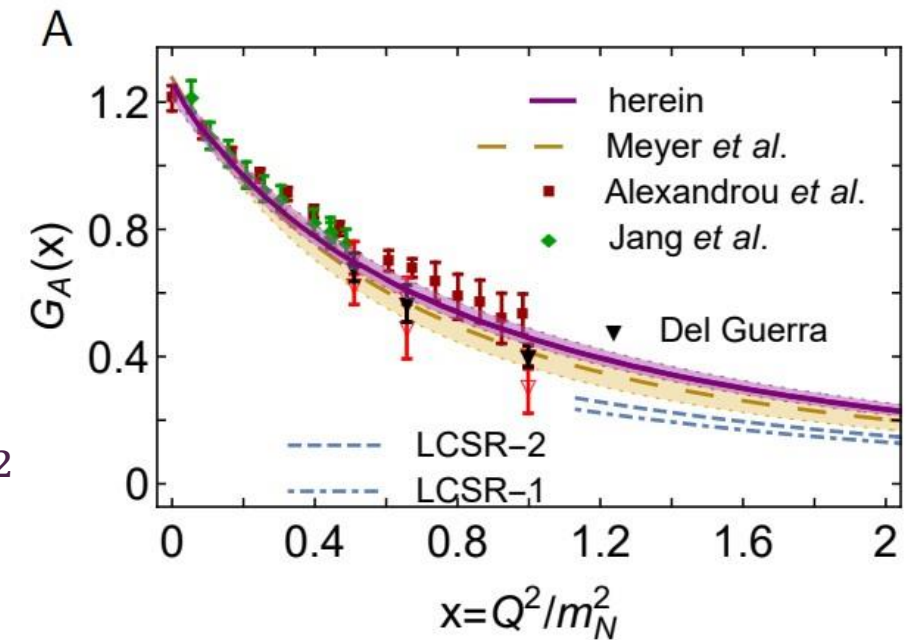
⁴Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China

Email: chenchen1031@ustc.edu.cn (C. Chen); cdroberts@nju.edu.cn (C. D. Roberts).



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 & large Q^2
- Large 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 $x = 10$



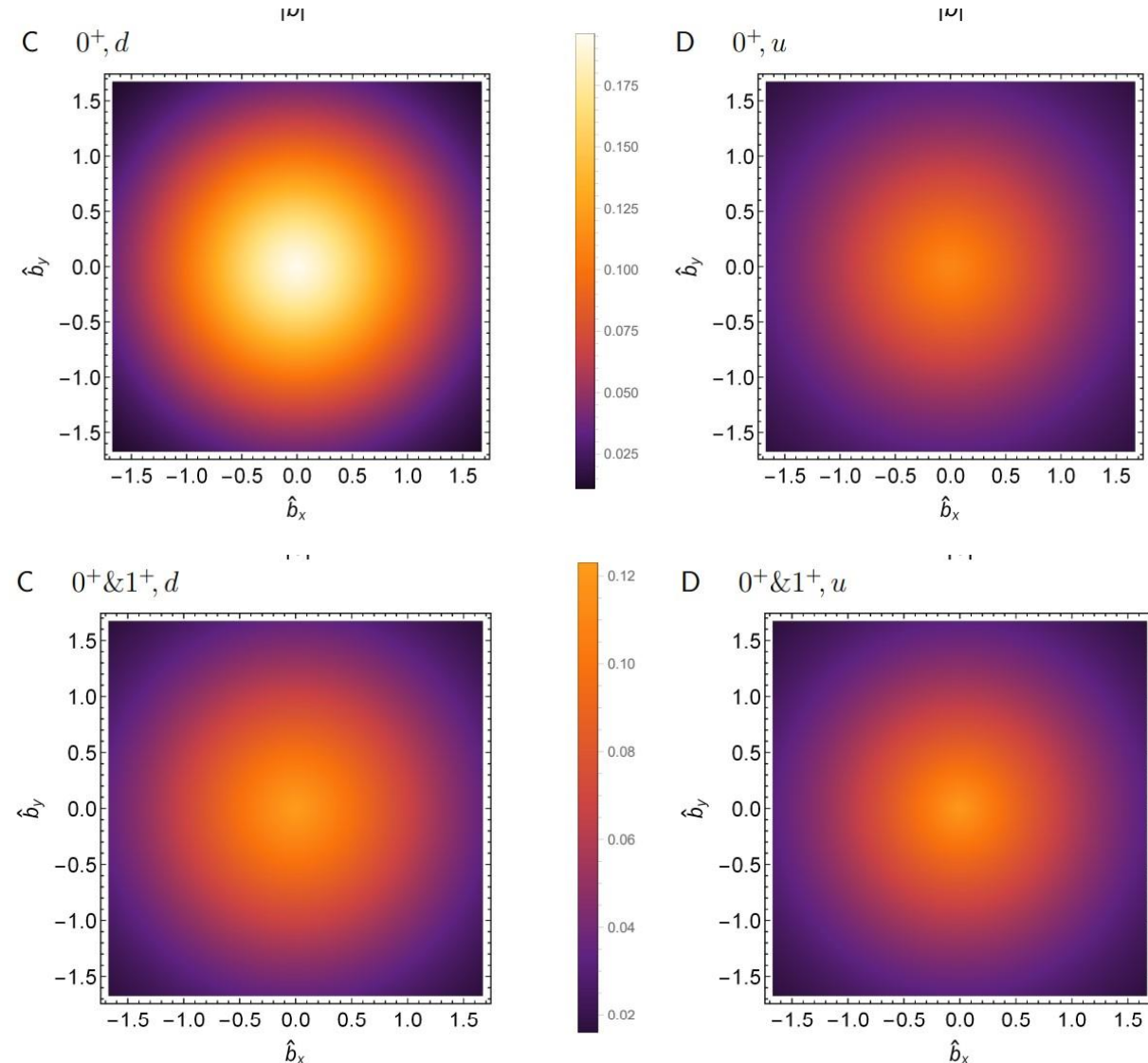
Large Q^2 Nucleon Axial Form Factor

- 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

$$r_{Ad}^\perp \approx 0.5 r_{Au}^\perp$$

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

$$r_{Ad}^\perp \approx 0.9 r_{Au}^\perp$$



Proton Spin Structure

- Flavour separation of proton axial charge
- d-quark receives large contribution from probe+quark in presence of axialvector diquark

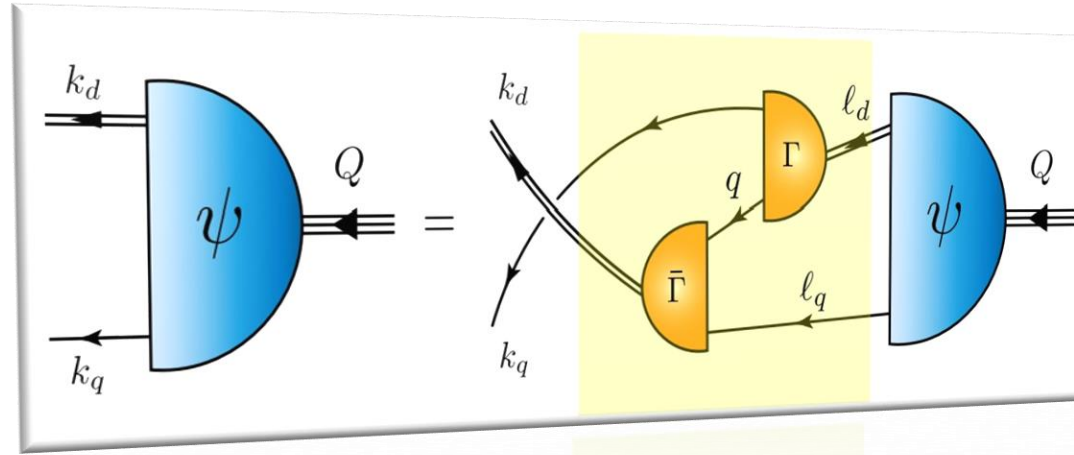
- $\frac{g_A^d}{g_A^u} = 0^+ \& 1^+ -0.32(2)$

- $\frac{g_A^d}{g_A^u} = 0^+ \text{ only } -0.054(13)$

- Experiment: $\frac{g_A^d}{g_A^u} = 0^+ \& 1^+ -0.27(4) \Leftarrow$ strong pointer to importance of AV correlation
- Hadron scale: $g_A^u + g_A^d (+g_A^s = 0) = 0.52(1) \Rightarrow$ quarks carry 52% of the proton spin
- Poincaré-covariant proton wave function: remaining 48% lodged with quark+diquark orbital angular momentum
- Extended to entire octet of ground-state baryons: dressed-quarks carry 50(7)% of proton spin at hadron scale

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. $0.88_{6\mp} \Rightarrow 0.88 \mp 0.06$.

	$\langle J \rangle_q^S$	$\langle J \rangle_q^A$	$\langle J \rangle_{qq}^{AA}$	$\langle J \rangle_{qq}^{\{SA\}}$	$\langle J \rangle_{ex}^{SS}$	$\langle J \rangle_{ex}^{\{SA\}}$	$\langle J \rangle_{ex}^{AA}$
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	$0.01_{\pm 0}$



Preprint nos. NJU-INP 057/22, USTC-ICTS/PCFT-22-11

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

Langtian Liu,^{1,2} Chen Chen,^{3,4,*} Ya Lu,^{1,2,5} Craig D. Roberts,^{1,2,†} and Jorge Segovia^{6,2}

¹*School of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*

²*Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China*

³*Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei, Anhui 230026, China*

⁴*Peng Huanwu Center for Fundamental Theory, Hefei, Anhui 230026, China*

⁵*Department of Physics, Nanjing Tech University, Nanjing 211816, China*

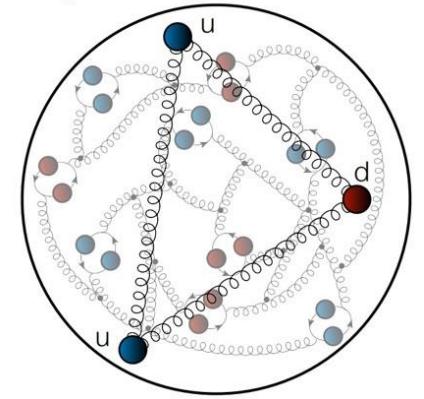
⁶*Dpto. Sistemas Físicos, Químicos y Naturales, Univ. Pablo de Olavide, E-41013 Sevilla, Spain*

(Dated: 2022 March 22)

Baryon Structure

- Poincaré covariance \Rightarrow 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.*

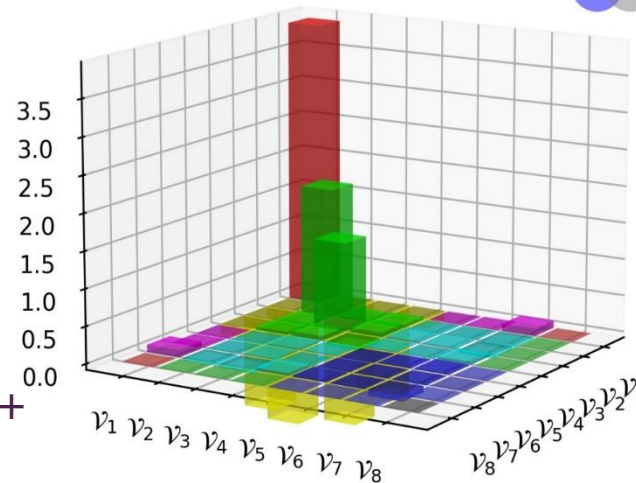
A proton



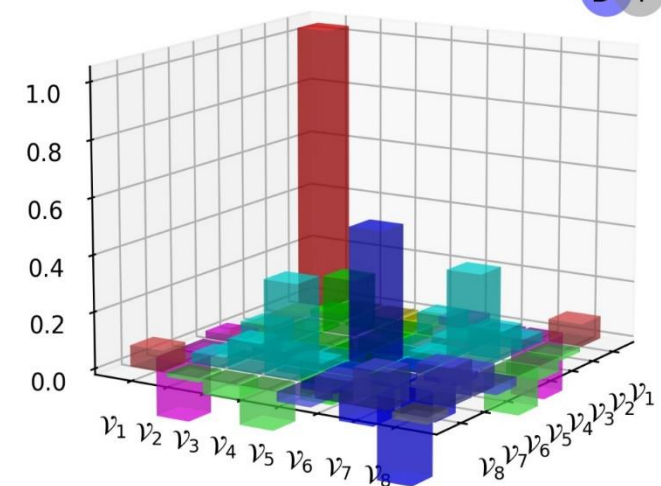
Composition of low-lying $J=\frac{3}{2}^{\pm}$ Δ -baryons

- Poincaré-covariant quark+diquark Faddeev equation
 - ⇒ 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.
- $(\frac{3}{2}, \frac{3}{2}^{\pm})$ 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.

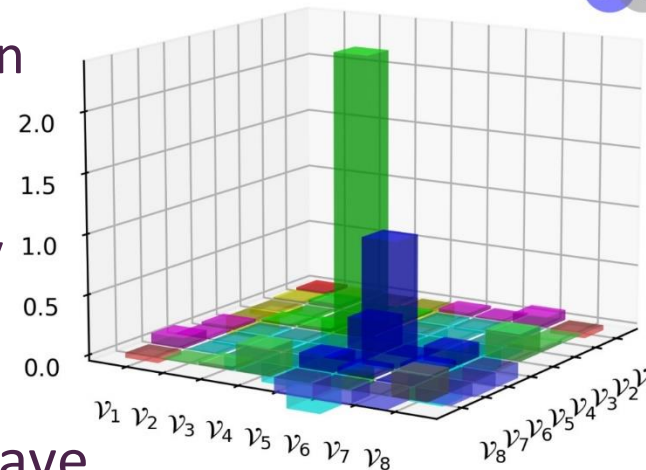


Rest-frame angular momentum decompositions

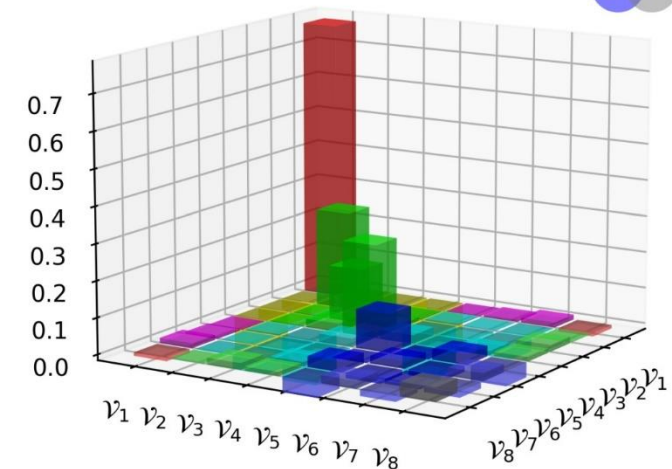
Composition of low-lying $J=\frac{3}{2}^{\pm}$ Δ -baryons

- Poincaré-covariant quark+diquark Faddeev equation
 - ⇒ 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

⇒ insight

- Prediction vector (

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

vector-
description.

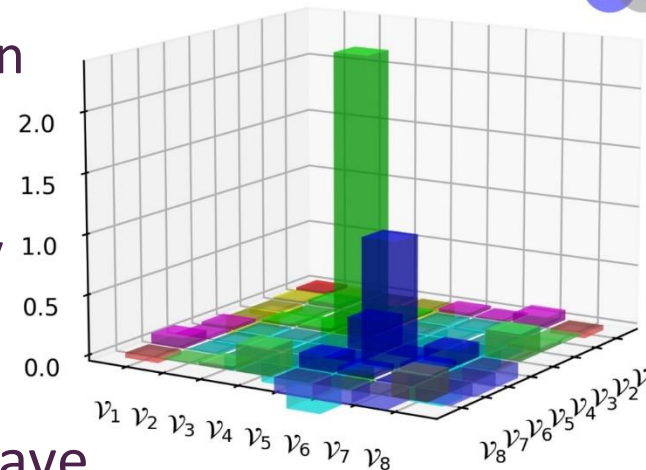
- $(\frac{3}{2}, \frac{3}{2}^-)$ states are more complex

- $\Delta(1940) \frac{3}{2}^-$ 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

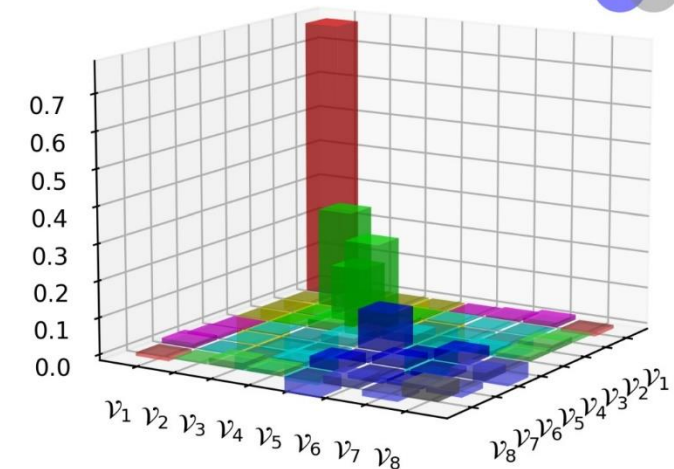
- but $\Delta(1940) \frac{3}{2}^-$ is largely S -wave

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

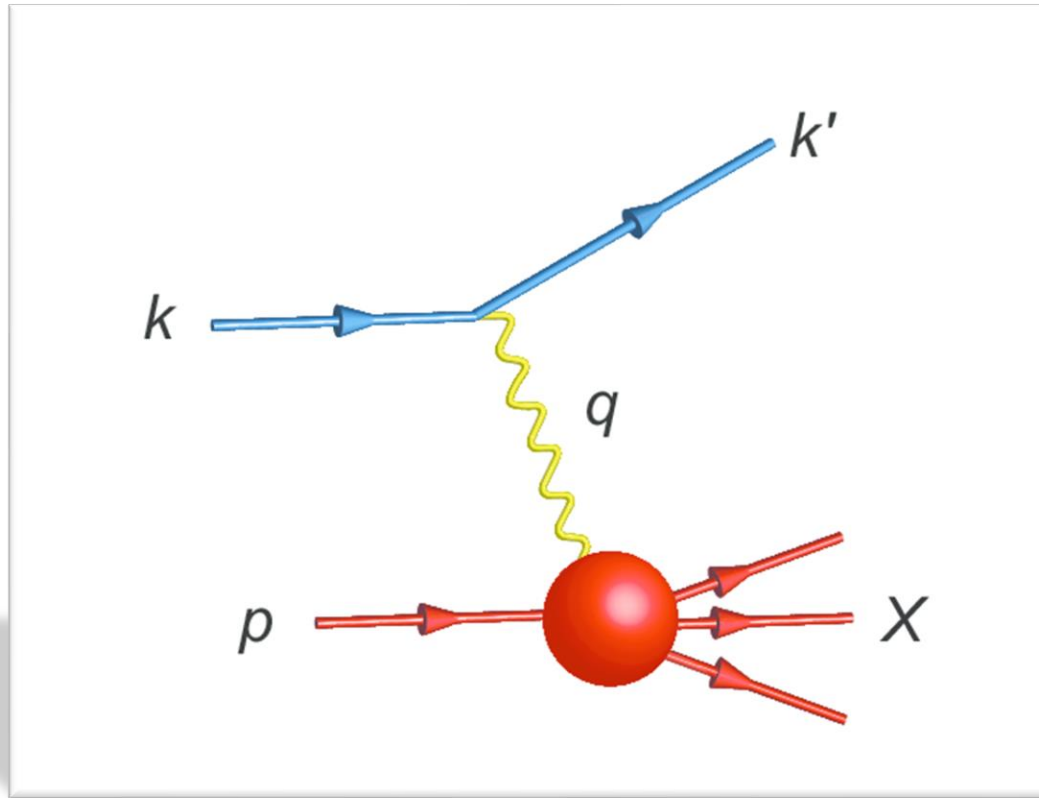


$\Delta(1940) \frac{3}{2}^-$ mainly S -wave!

Unlike quark model



Rest-frame angular momentum decompositions



Parton Distribution Functions

Diquarks & Deep Inelastic Scattering

- The ratio of neutron and proton structure functions at large x is kept as a discriminator between competing pictures of proton structure

➤ Example:

- Only scalar diquark in the proton (no axial-vector):

$$\lim_{x \rightarrow 1} \frac{F_2^n(x)}{F_2^p(x)} = \frac{1}{4}$$

- No correlations in the proton wave function (SU(4)

$$\text{spin-flavour) } \lim_{x \rightarrow 1} \frac{F_2^n(x)}{F_2^p(x)} = \frac{2}{3}$$

- 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 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.

Craig Roberts: cdroberts@nju.edu.cn 417 "Charting EHM using High-Energy and Luminosity"

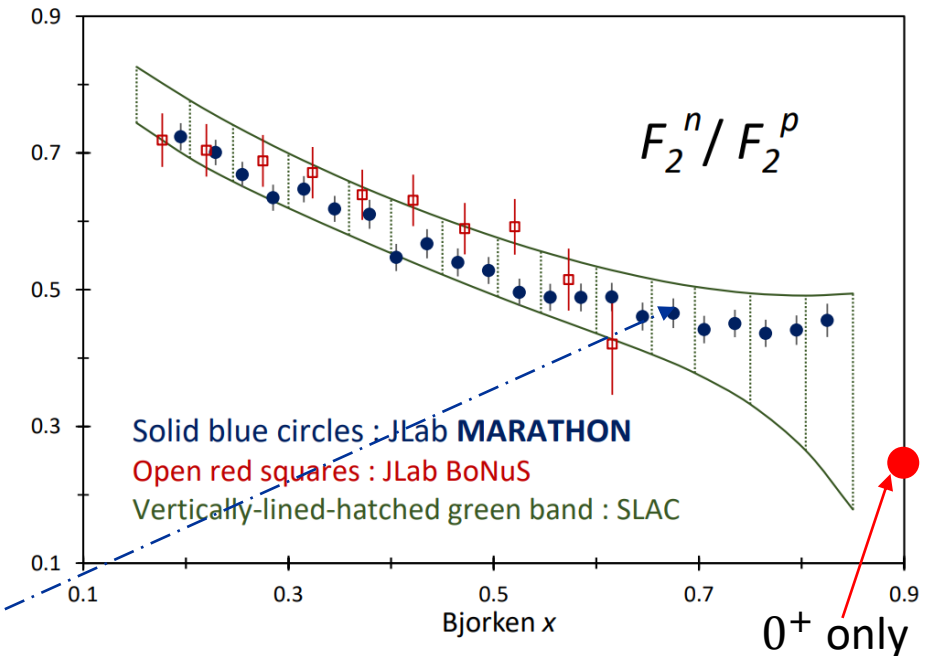


FIG. 2: The F_2^n / F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14 \cdot x$ (GeV/c)²] (see text). All three experimental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

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

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

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

- Comparison with MARATHON data

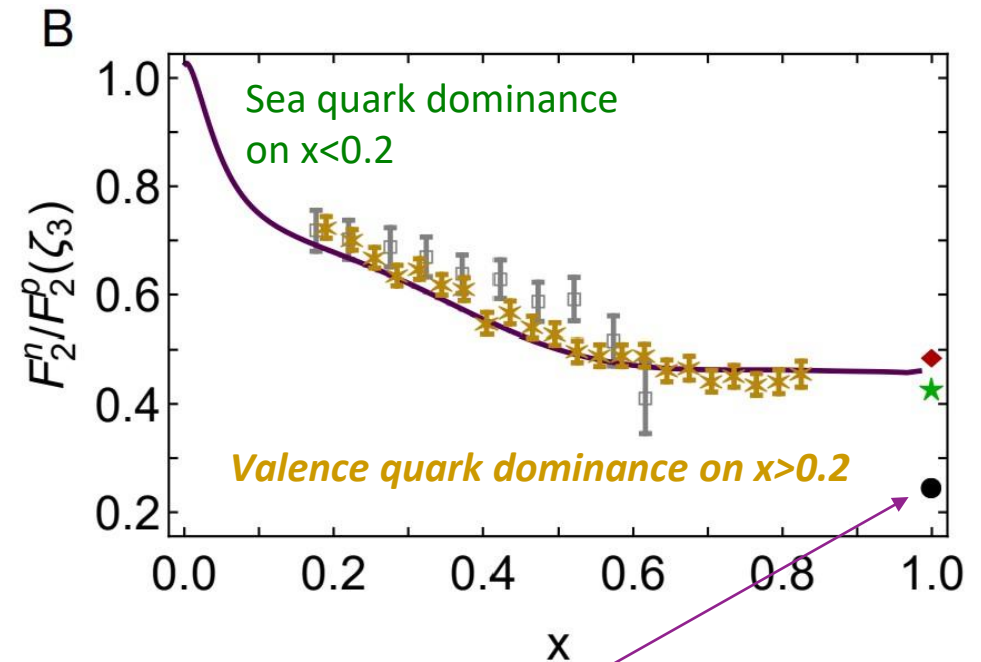
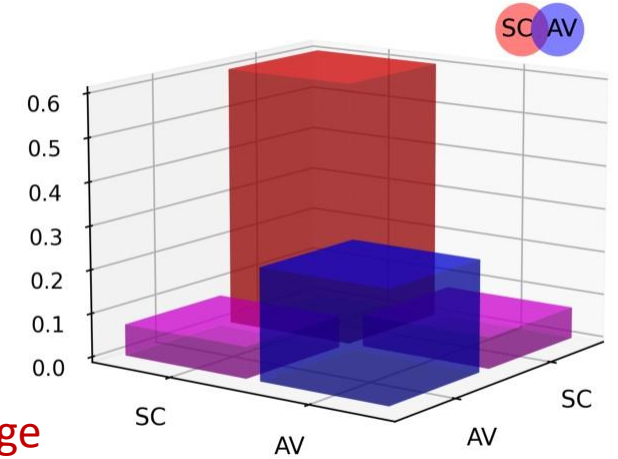
[D. Abrams, *et al.*, Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

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

☀ *Valence quark ratio in the proton*, Zhu-Fang Cui, (崔著钊), 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](#)

Craig Roberts: cdroberts@nju.edu.cn 417 "Charting EHM using High-Energy and Luminosity"

- ✓ CSM prediction = presence of axial-vector diquark correlation in the proton
- ✓ Responsible for $\approx 40\%$ of proton charge

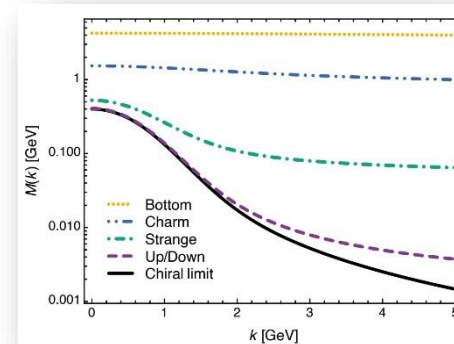
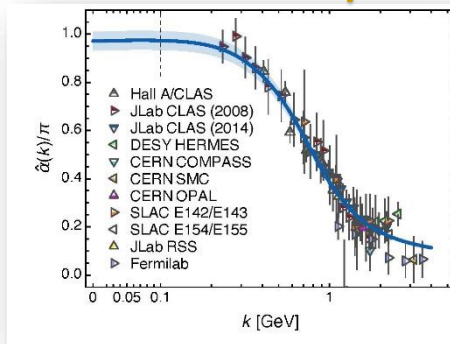
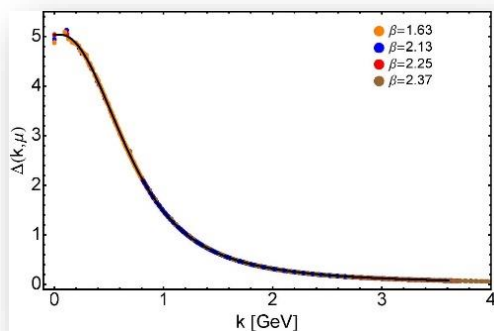


Probability that scalar diquark only models of nucleon might be consistent with available data is 1/7,000,000

Expanding array of parameter-free predictions, including

- **Transition form factors: $\gamma^* + p \rightarrow \Delta(1232), \Delta(1600)$** , Ya Lu, Chen Chen, Zhu-Fang Cui, Craig D Roberts, Sebastian M Schmidt, Jorge Segovia and Hong Shi Zong, [arXiv:1904.03205 \[nucl-th\]](https://arxiv.org/abs/1904.03205), Phys. Rev. D **100** (2019) 034001/1-13
 - Predictions confirmed in recent months following analysis of large- Q^2 CLAS data
- **Nucleon-to-Roper electromagnetic transition form factors at large- Q^2** , Chen Chen et al., [arXiv:1811.08440 \[nucl-th\]](https://arxiv.org/abs/1811.08440), Phys. Rev. D **99** (2019) 034013/1-13
- **Nucleon elastic form factors at accessible large spacelike momenta**, Zhu-Fang Cui et al., NJU-INP 017/20, [arXiv:2003.11655 \[hep-ph\]](https://arxiv.org/abs/2003.11655), Phys. Rev. D **102** (2020) 014043/1-14
- **Dynamical diquarks in the $\gamma^* p \rightarrow N(1535)1/2^-$ transition**, Khépani Raya et al., [NJU-INP 046/21](https://arxiv.org/abs/2108.02306), [arXiv:2108.02306 \[hep-ph\]](https://arxiv.org/abs/2108.02306), Eur. Phys. J. A **57** (2021) 266/1-16
- **Revealing pion and kaon structure via generalised parton distributions**, Khépani Raya et al., NJU-INP 051/21, e-Print: [2109.11686 \[hep-ph\]](https://arxiv.org/abs/2109.11686), Chin. Phys. C **46** (01) (2022) 013107/1-22
- **Proton and pion distribution functions in counterpoint**, Ya Lu (陆亚) et al., [NJU-INP 056/22](https://arxiv.org/abs/2203.00753), e-Print: [2203.00753 \[hep-ph\]](https://arxiv.org/abs/2203.00753), Phys. Lett. B **830** (2022) 137130/1-7

Validate the EHM paradigm



Craig Roberts: cdroberts@nju.edu.cn 417 "Charting EHM using High-Energy and Luminosity"



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*



Emergent Hadron Mass

- QCD is unique *There are theories of many things,*
 But is there a theory of everything?
- Degrees of freedom
 - Masses
 - Gluon mass ensures a static theory through the appearance of a running coupling that is 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*

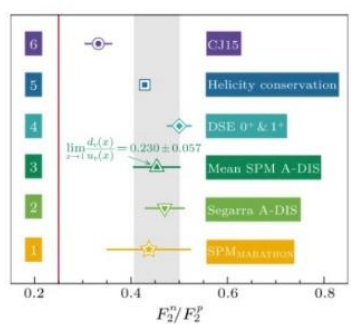
Nature = ?

A photograph of a stone path lined with large elephant statues in a park-like setting. The path is paved with rectangular stones and leads into the distance. On either side of the path are large, grey stone statues of elephants, each with a circular emblem on its side. The background is filled with lush green trees and foliage. The text "There are theories of many things, But is there a theory of everything?" is overlaid in a yellow, cursive font at the top. Below it, the text "Nature = ?" is overlaid in the same font. At the bottom, the word "Thankyou" is overlaid in a white, cursive font. At the very bottom, there is a small line of text: "Craig Roberts: cdroberts@nju.edu.cn 417 "Charting EHM using High-Energy and Luminosity"".

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

Nature = ?

Thankyou



Valence Quark Ratio in the Proton

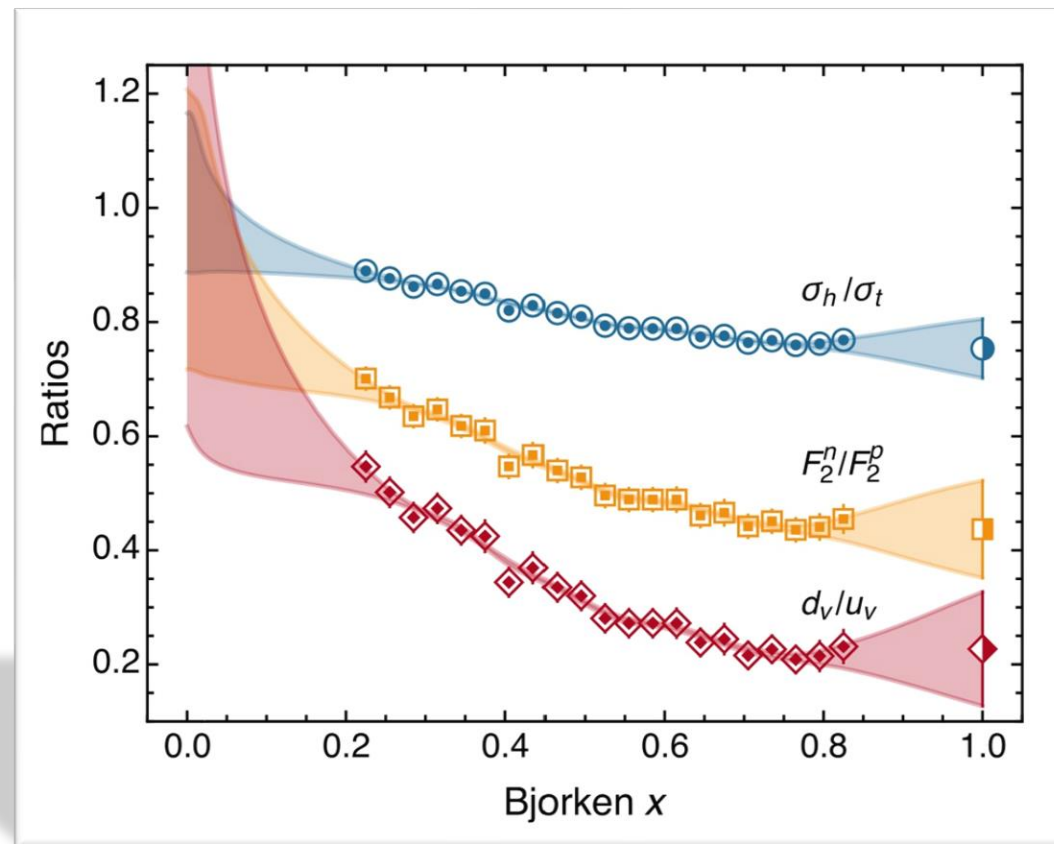
Zhu-Fang Cui, Fei Gao, Daniele Binosi, Lei Chang, Craig D. Roberts, and Sebastian M. Schmidt

Chin. Phys. Lett. 2022, 39 (4): 041401 . DOI: 10.1088/0256-307X/39/4/041401

[Abstract](#) [HTML](#) [PDF \(571KB\)](#)

MARATHON EXPERIMENT Schlessinger point method

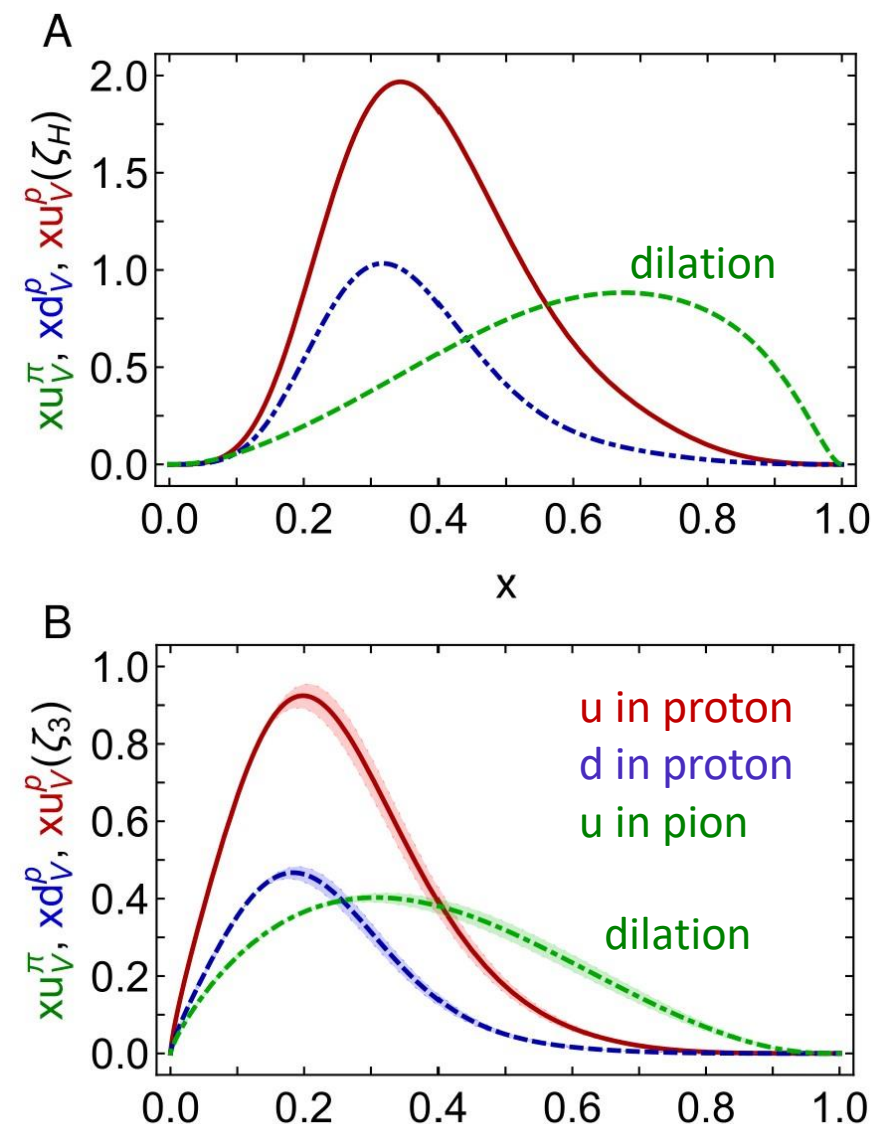
- New mathematical method for interpolation and extrapolation of data
 - based on continued-fraction representation of functions, augmented by statistical sampling
- Delivers model-independent prediction for all ratios
 - No reference to models or physics theories
- Provides benchmark against which all pictures of nucleon structure can be measured
- *Probability that scalar diquark only models of nucleon might be consistent with available data is 1/7,000,000*



Proton and pion distribution functions in counterpoint

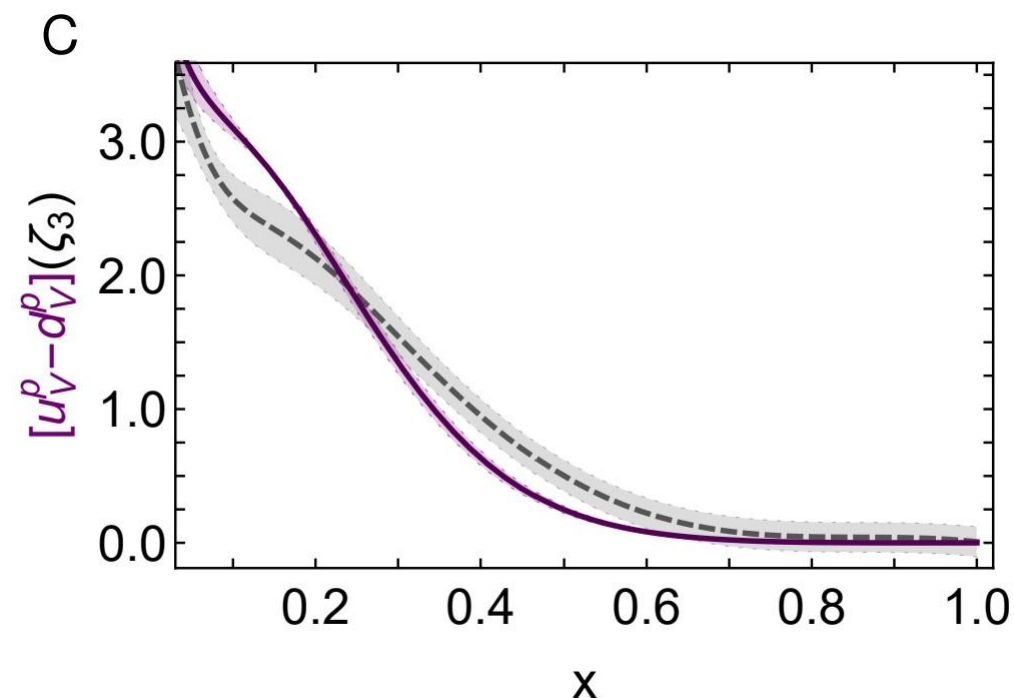
Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) et al.,
 NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130

- 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



Proton valence-quark DFs: Continuum cf. Lattice

- Owing to difficulties in handling so-called disconnected contributions, the calculation of individual proton valence DFs using lattice-regularised QCD (IQCD) is problematic
- IQCD results are typically only available for isovector distributions, from which disconnected contributions vanish in the continuum limit.
- Comparison of isovector distributions
$$u^p(x; \zeta_3) - d^p(x; \zeta_3)$$
- Completely different approaches; yet good agreement, especially since refinements of both calculations may be anticipated.



- ✓ Continuum: *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚) et al., NJU-INP 056/22, e-Print: 2203.00753 [hep-ph]
- ✓ Lattice: *Nucleon Isovector Unpolarized Parton Distribution in the Physical-Continuum Limit*, H.-W. Lin et al., arXiv:2011.14971 [hep-lat]

Asymmetry of antimatter in the proton

- Pauli blocking: gluon splitting produces

$d + \bar{d}$ in preference to $u + \bar{u}$

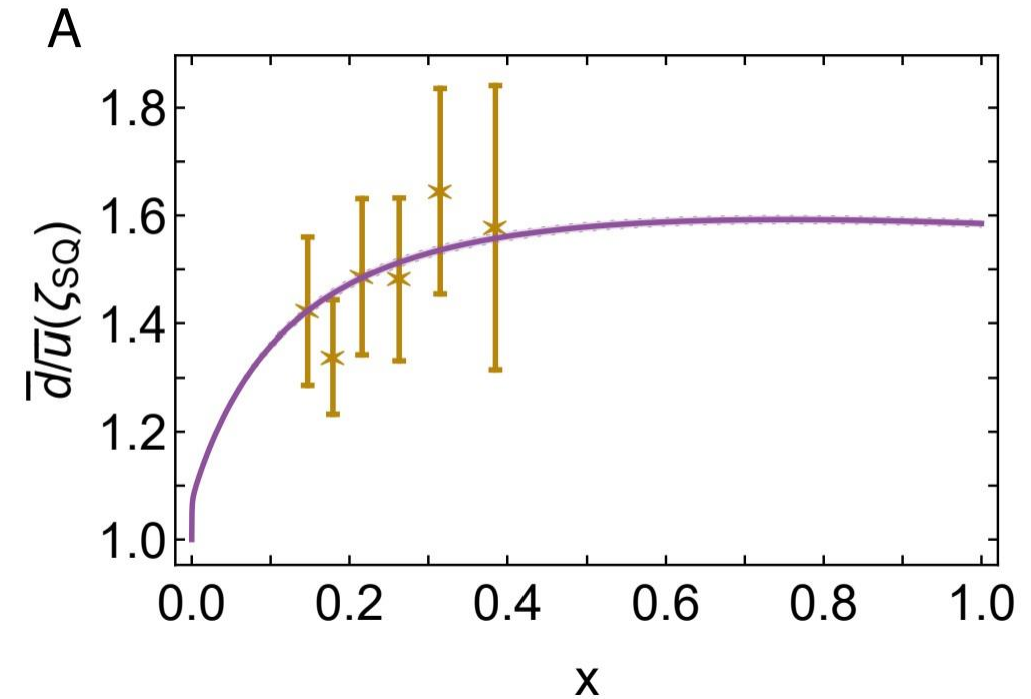
- Comparison with SeaQuest data

[J. Dove, et al., *The asymmetry of antimatter in the proton*, Nature 590 (7847) (2021) 561–565.]

- Gottfried sum rule

$$\int_{0.004}^{0.8} dx [\bar{d}(x; \zeta_3) - \bar{u}(x; \zeta_3)] = 0.116(12)$$

- ✓ Most recent result from global fits [CT18]:
0.110(80)



- ✓ *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚), Lei Chang (常雷), Khépani Raya, Craig D. Roberts and José Rodríguez-Quintero, [NJU-INP 056/22](#), e-Print: [2203.00753 \[hep-ph\]](#), [Phys. Lett. B 830 \(2022\) 137130/1-7](#)
- ✓ *Parton distributions of light quarks and antiquarks in the proton*, Lei Chang (常雷), Fei Gao (高飞) and Craig D. Roberts, [NJU-INP 055/22](#), e-Print: [2201.07870 \[hep-ph\]](#), [Phys. Lett. B 829 \(2022\) 137078/1-7](#)