NANJING UNIVERSITY

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

Grant no. 12135007

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

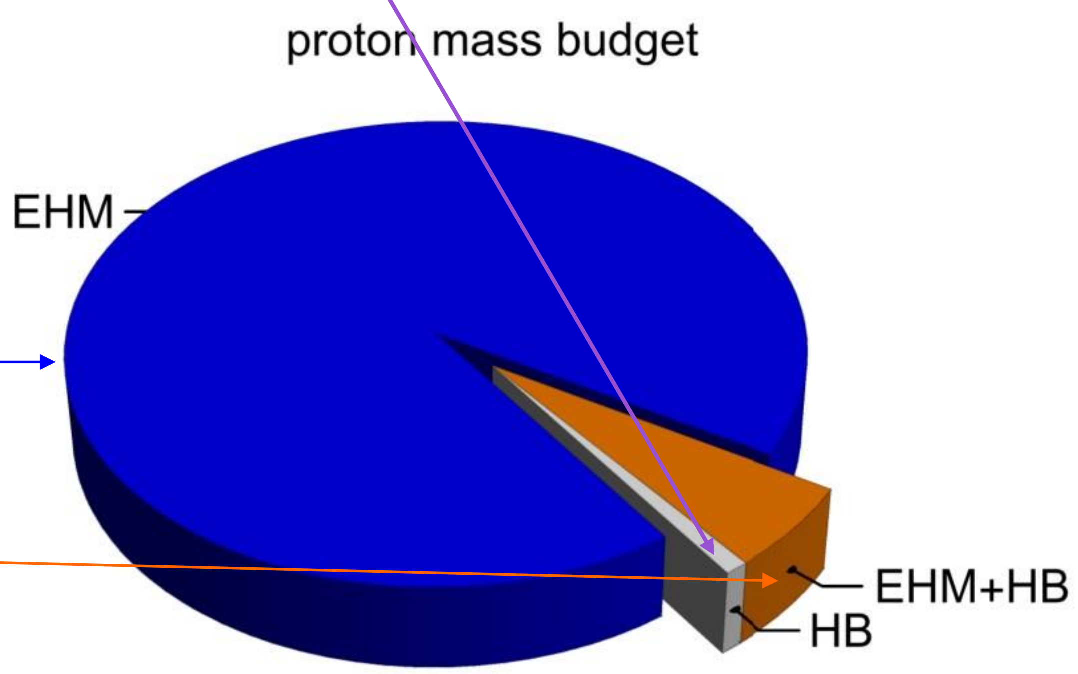
Hadron Structure using Continuum Schwinger Function Methods

Emergence of Hadron Mass … *and Structure*

- 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



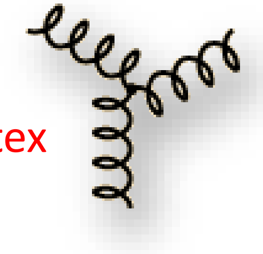
- What are the origins and expressions of EHM?

G E N E S I S

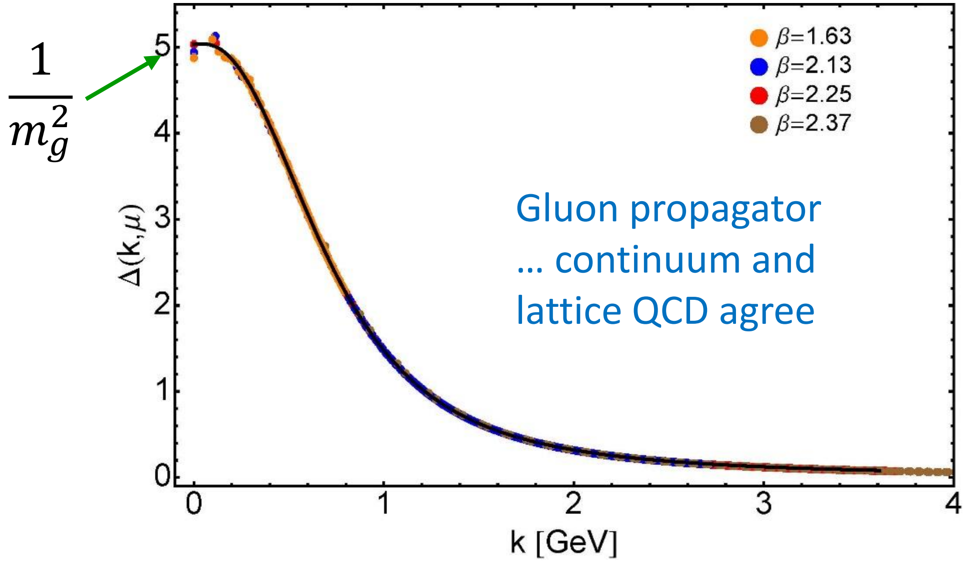
Modern Understanding Grew Slowly from Ancient Origins

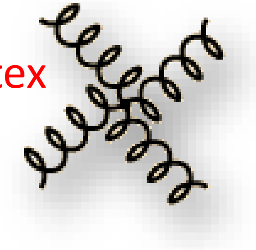
- More than 40 years ago

  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 ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta





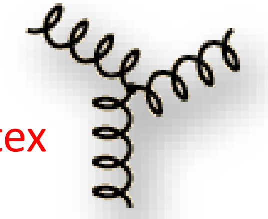
Truly mass from nothing
An interacting theory, written in terms of massless gluon fields, produces dressed gluon fields that are characterised by a mass function that is large at infrared momenta

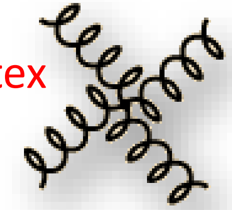
✓ *QCD fact*
✓ *Continuum theory and lattice simulations agree*
✓ *Empirical verification?*

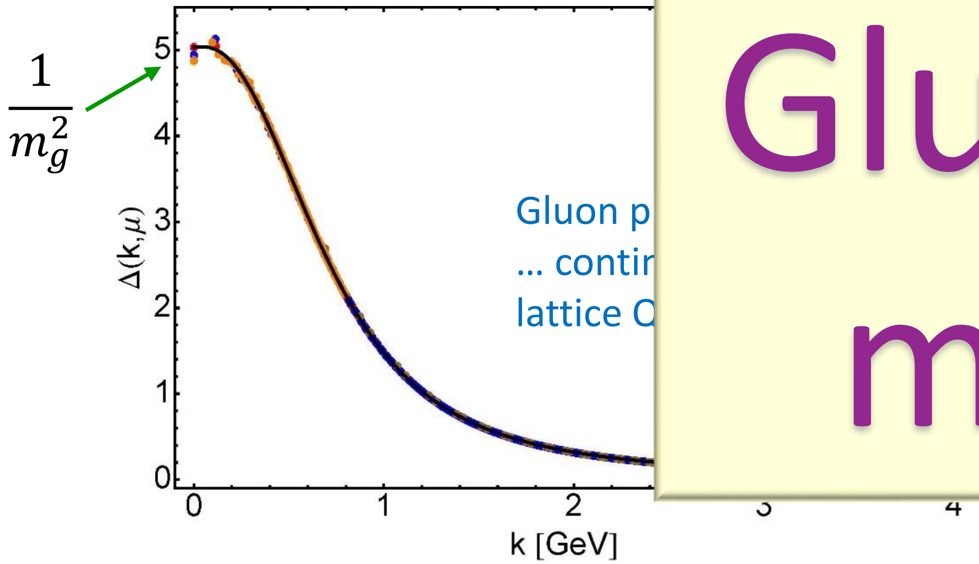
Modern Understanding
Grew Slowly from ... Origins

EHM means Gluons are massive

- More than 40 year
  Dynamical mass ger ... *mics,*
  J.M. Cornwall, Phys.
- Owing to strong se ... uasiparticles,
  described by a ... omenta







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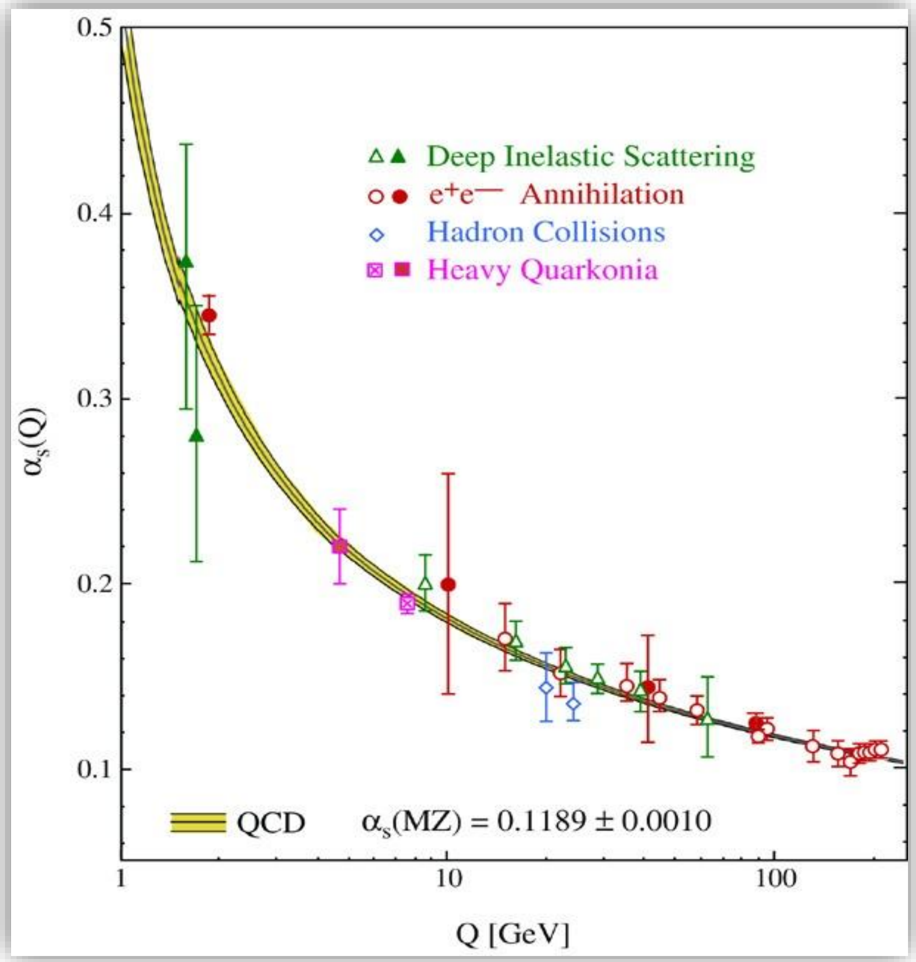
tion

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

Craig Roberts: cdroberts@nju.edu.cn 420 "Hadron Structure using Continuum Schwinger Function Methods"

This is where we live

⇐
What's happening out here?!

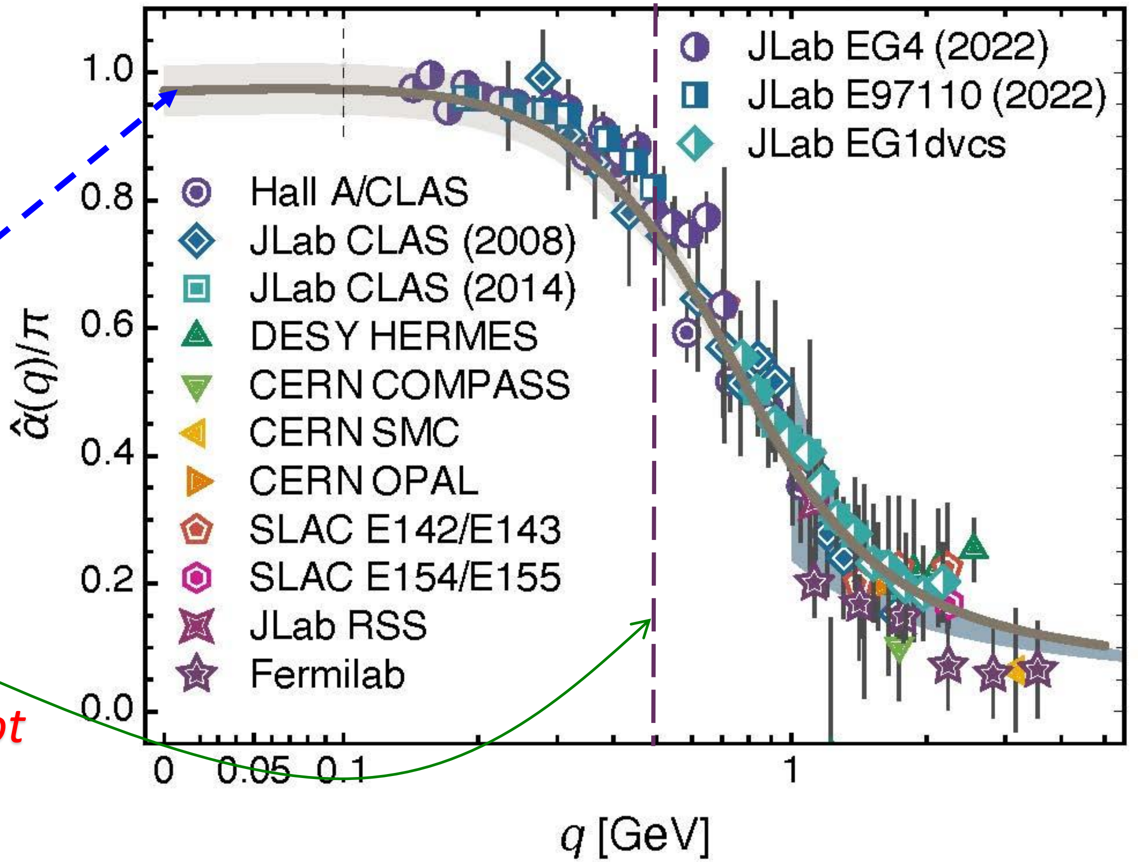


QCD's Running Coupling

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*

Process independent effective charge = running coupling

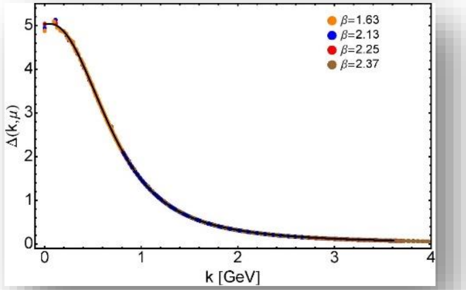
- Modern theory enables unique QCD analogue of "Gell-Mann – Low" running charge to be rigorously defined and calculated
- Analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$
- No Landau Pole
  - *"Infrared Slavery" 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



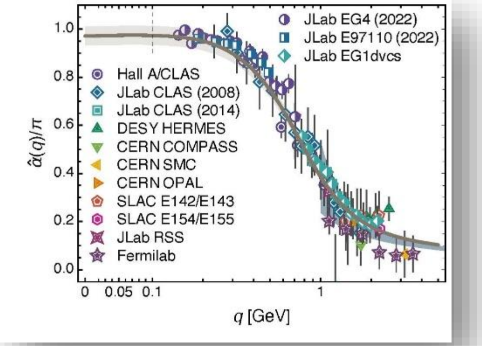
The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process independent strong running coupling
Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

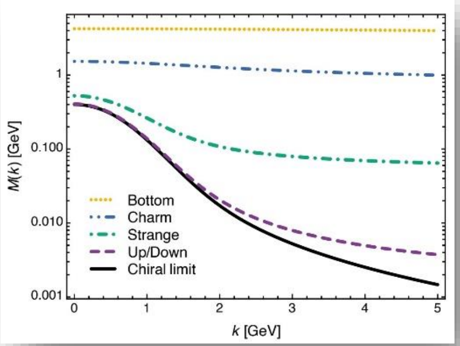
EHM Basics

- 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





EHM
and the Structure of Baryons

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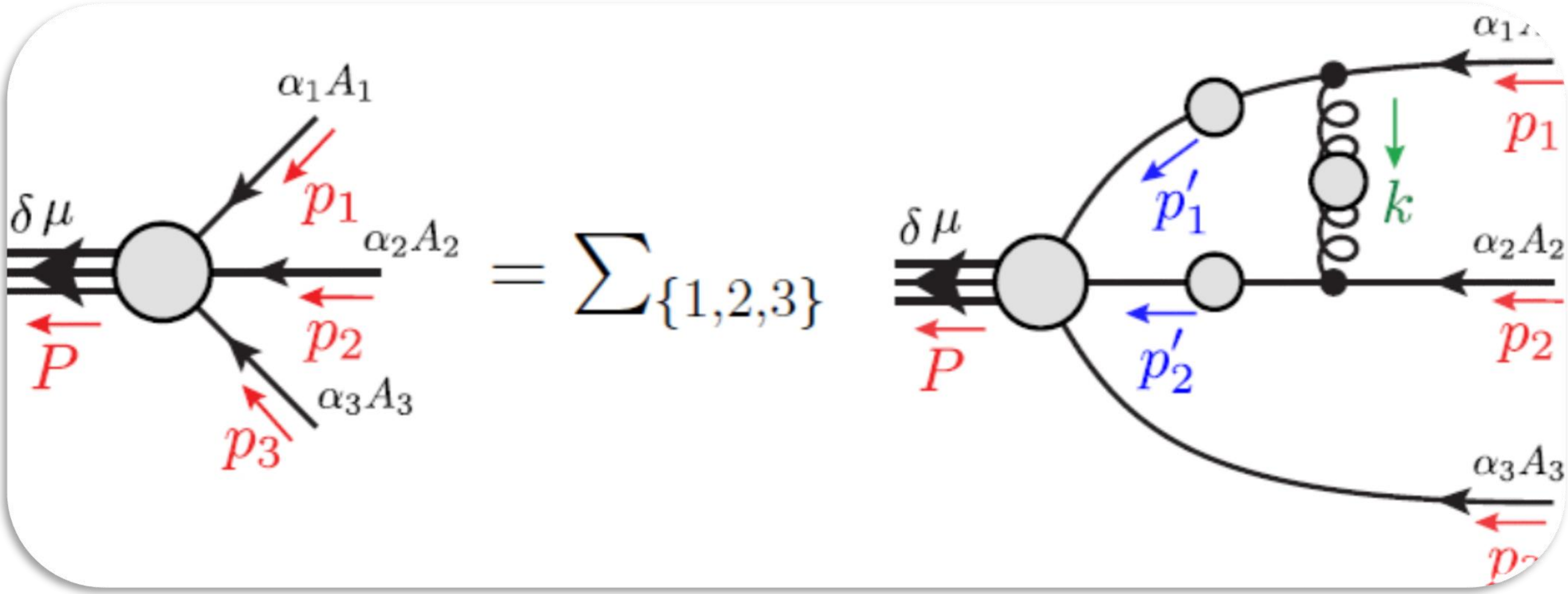
Exposing & Charting EHM

- 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 dawning
  High energy + high luminosity
  $\Rightarrow$ science can move beyond the monomaniacal focus on the proton

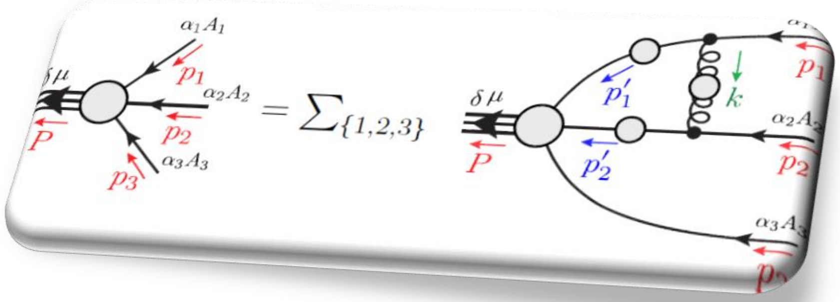
AMBER @ CERN
EIC
EicC
JLab12 & JLab20+

- 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.

Nucleon mass from a covariant three-quark Faddeev equation
G. Eichmann *et al*., Phys. Rev. Lett. 104 (2010) 201601
See plenary presentation on Wednesday

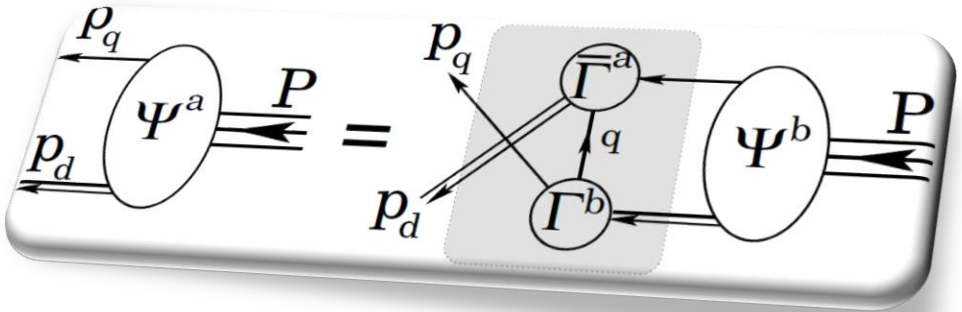


Faddeev Equation for Baryons



Structure of Baryons

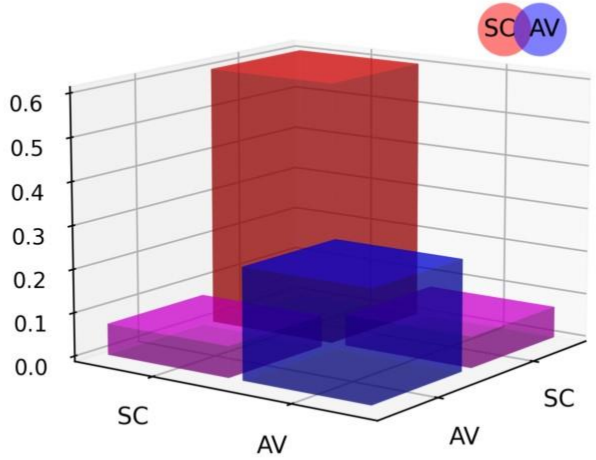
- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain



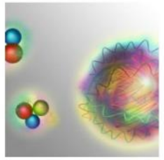
Solution delivers Poincaré-covariant proton wave function

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



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

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

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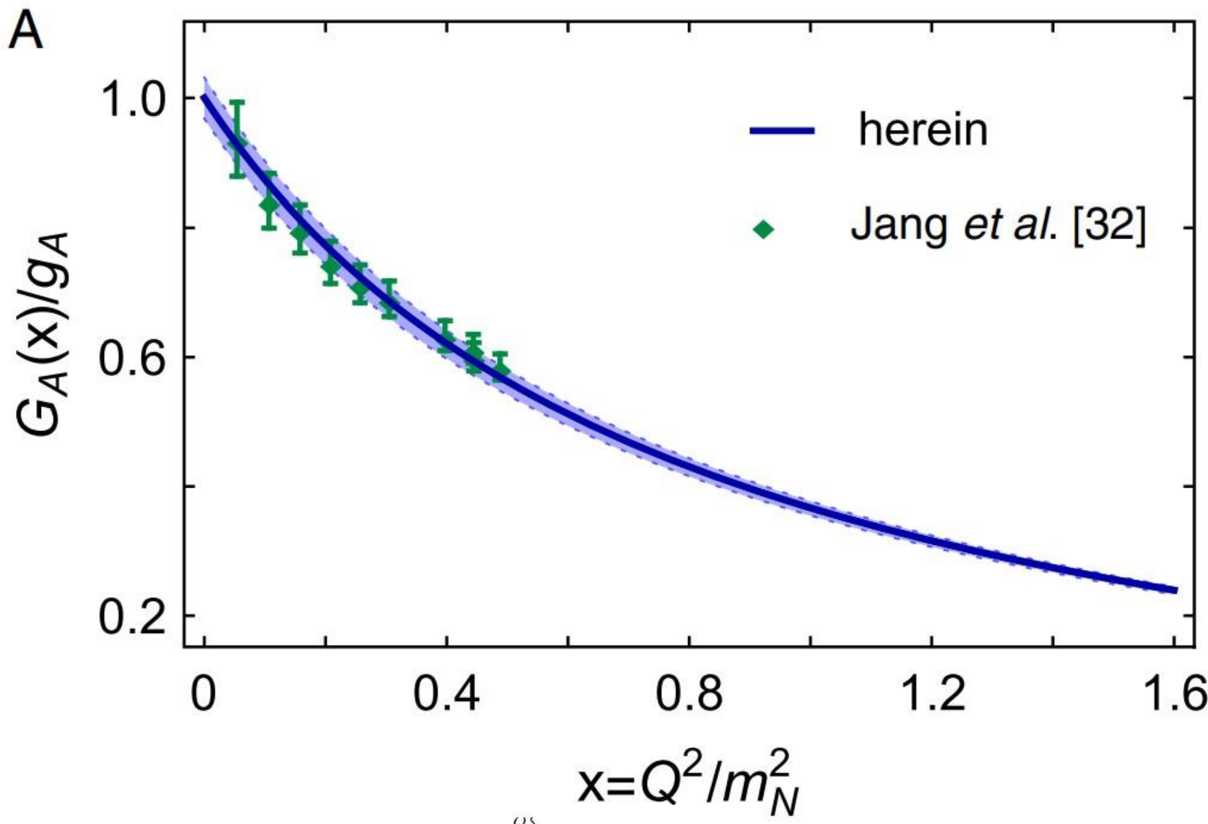
[4]*Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Gießen, D-35392 Gießen, Germany*
[5]*School of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
[6]*Institute for Nonperturbative Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
[7]*Dpto. Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, E-41013 Sevilla, Spain*

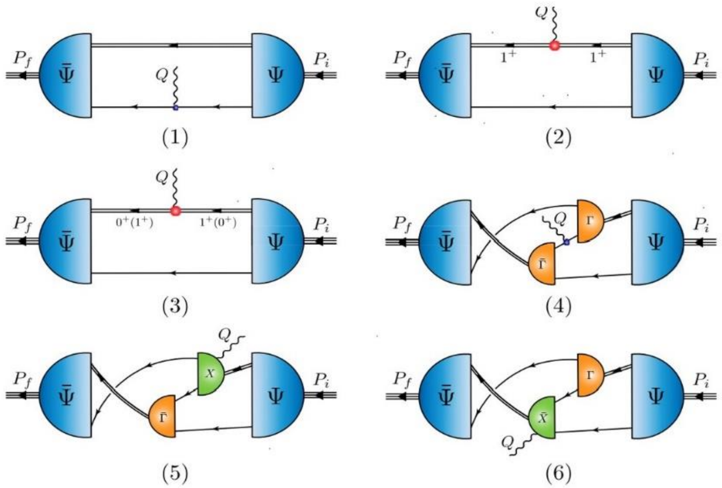
Nucleon axial form factor: $G_A(Q^2)$

Crucial for long-baseline ν experiments

- ✓ 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 small Q^2-window shown
- ✓ Contribution dissection:

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





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: $g_A^u + g_A^d\ (+g_A^s = 0) = 0.65(2) \Rightarrow$ 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 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.* $0.88_{6_\mp} \Rightarrow 0.88 \mp 0.06$.

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

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

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

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

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Theoretical Physics

Nucleon axial form factor at large momentum transfers

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[2] Peng Huanwu Center for Fundamental Theory, Hefei 230026, Anhui, China
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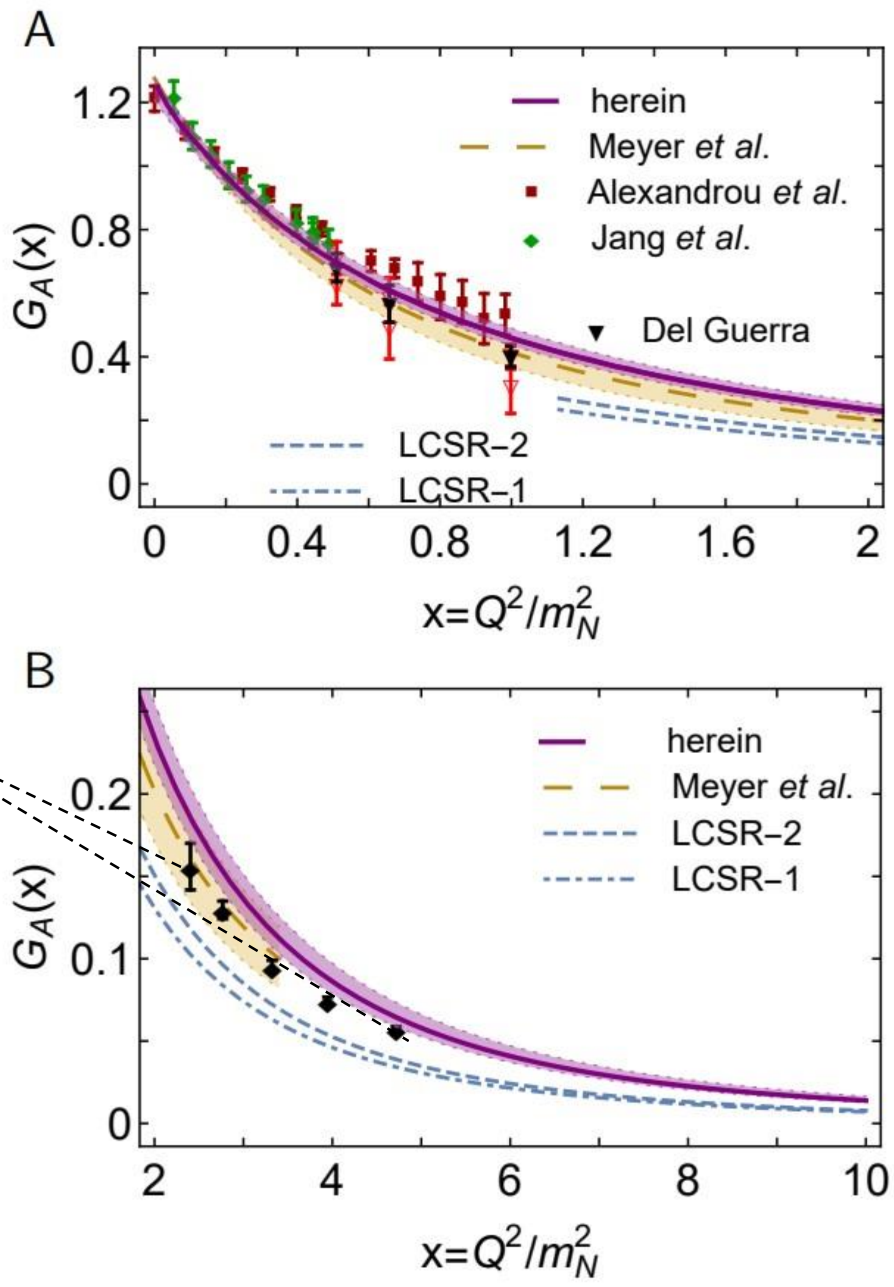
Received: 26 June 2022 / Accepted: 4 October 2022

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 [Park *et al*., Phys. Rev. C 85 (2012) 035208], threshold π electroproduction, $Q^2 \approx 5\, m_p^2$
  - ✓ 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

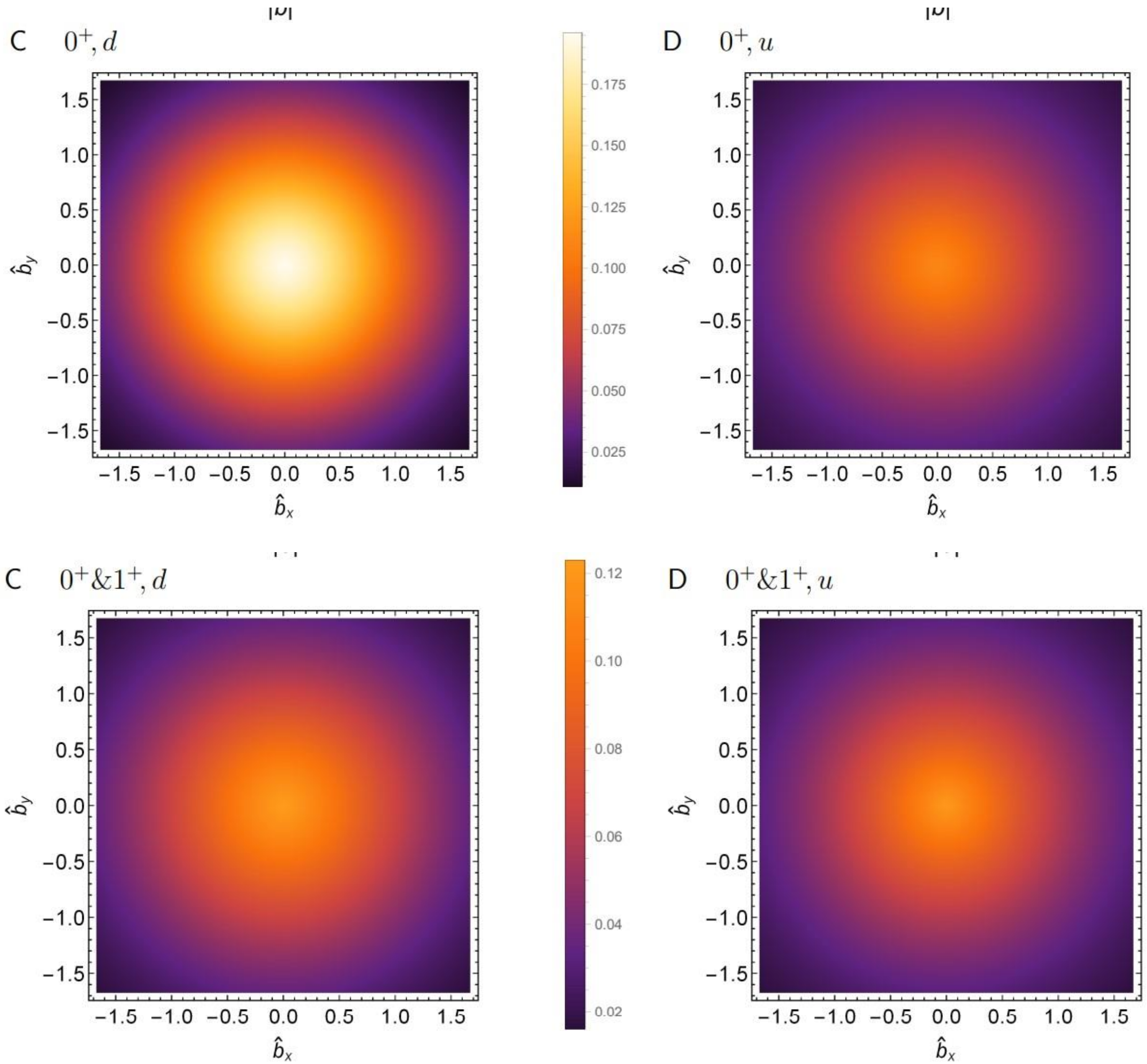
- Light-front transverse density profiles

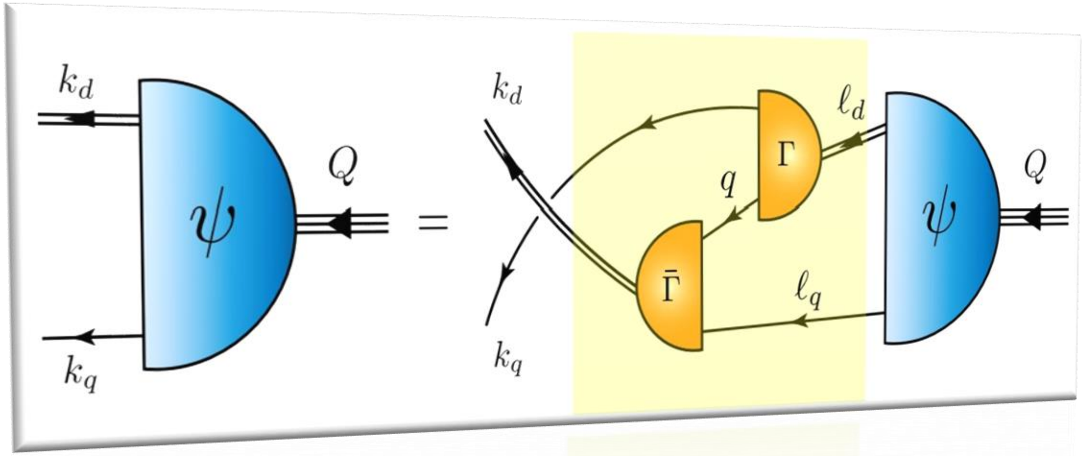
- Omitting axialvector diquarks
  - ✓ magnitude of the d quark contribution to GA is just 10% of that from the u quark
  - ✓ d quark is also much more localized

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

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

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





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

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

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

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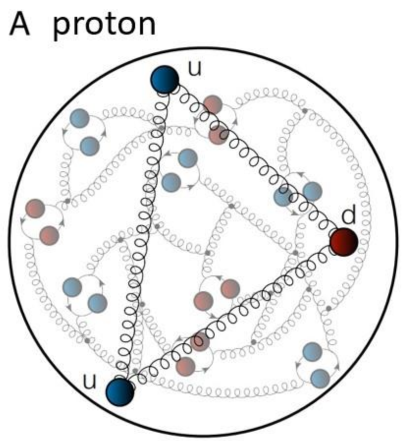
(Dated: 2022 March 22)

Baryon Structure

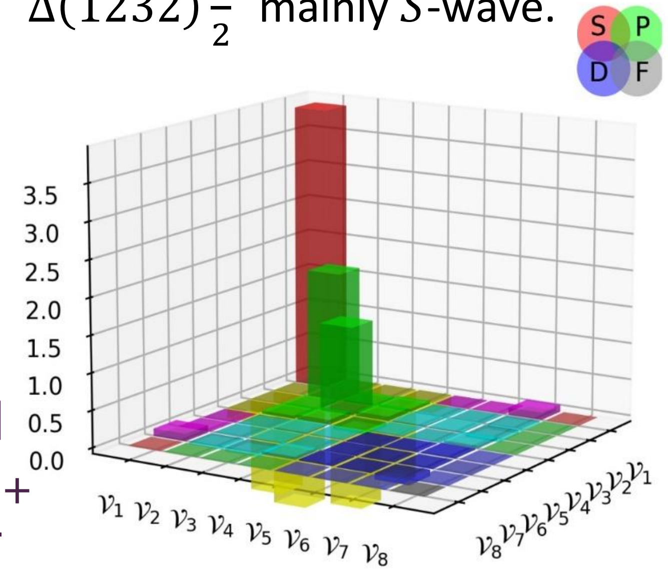


- Poincaré covariance ⇒ irrespective of quark model assignments $n^{2s+1}\ell_J$, every hadron contains orbital angular momentum, *e.g.*,
  - π contains two S-wave components and two P-wave components
  - Few systems are simply radial excitations of another
- No separation of J into $L+S$ is Poincaré 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.*

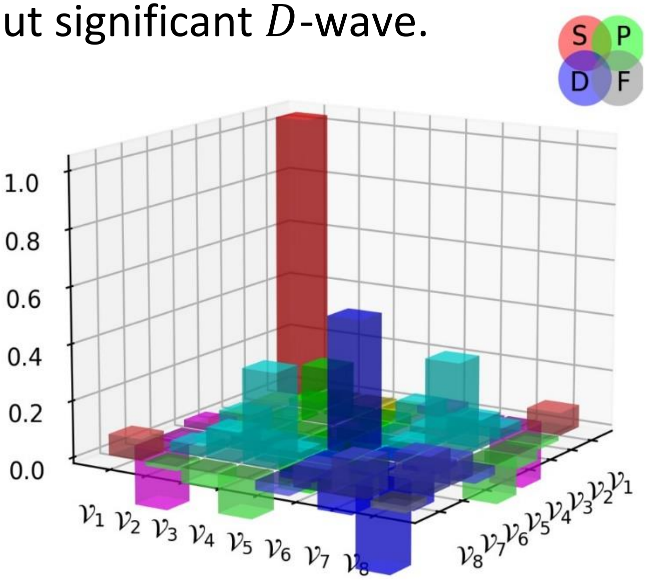
Composition of low-lying J=$\frac{3}{2}^{\pm}$ Δ-baryons

- 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.



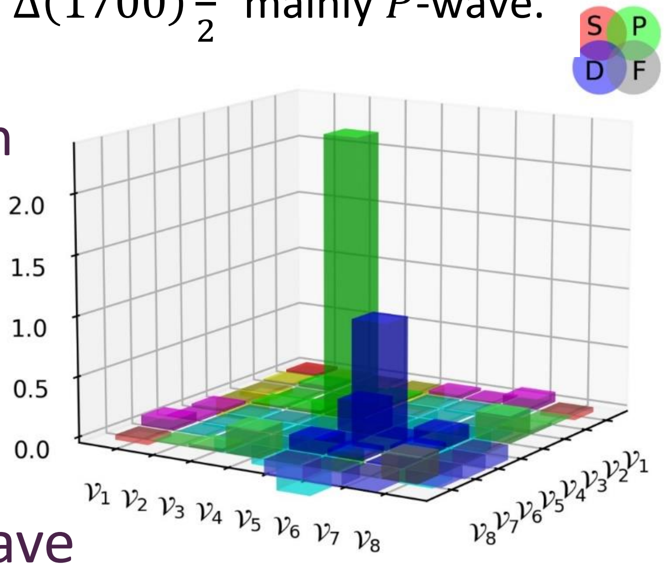
Rest-frame angular momentum decompositions

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

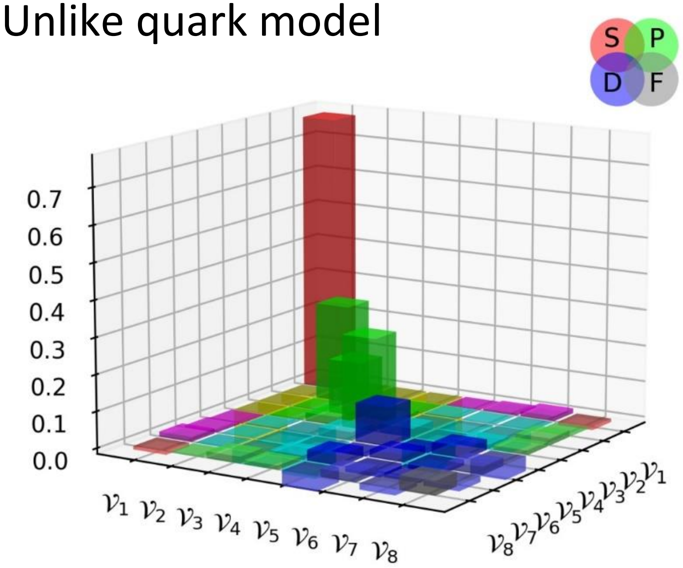
- Poincaré-covariant quark+diquark Faddeev equation

  $\Rightarrow$ 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

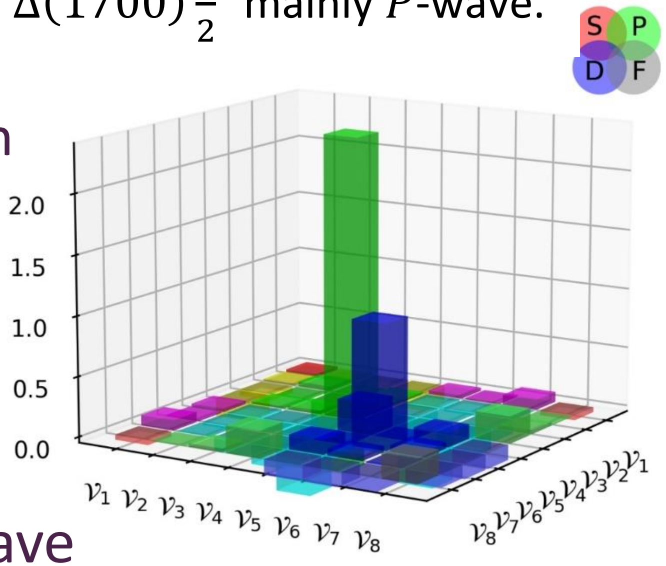
  $\Rightarrow$ insig

- Predicti ector-vector (ription.

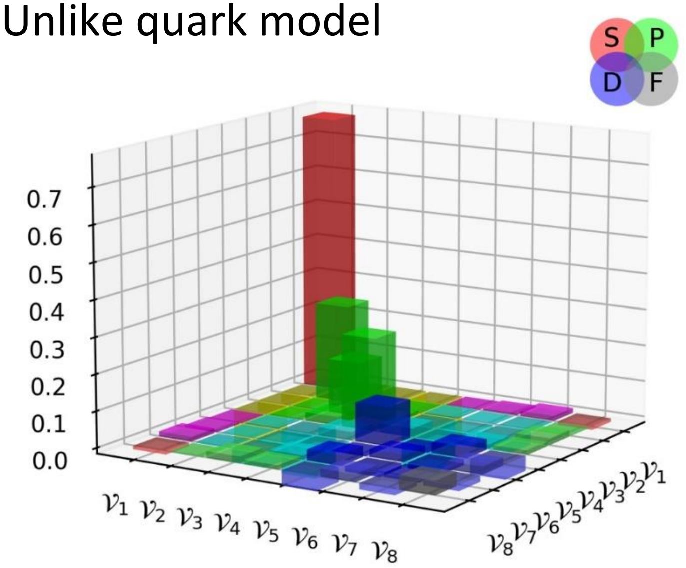
Large momentum transfer resonance electroexcitation experiments can test these predictions; so, will shed light on the nature of emergent hadron mass.

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

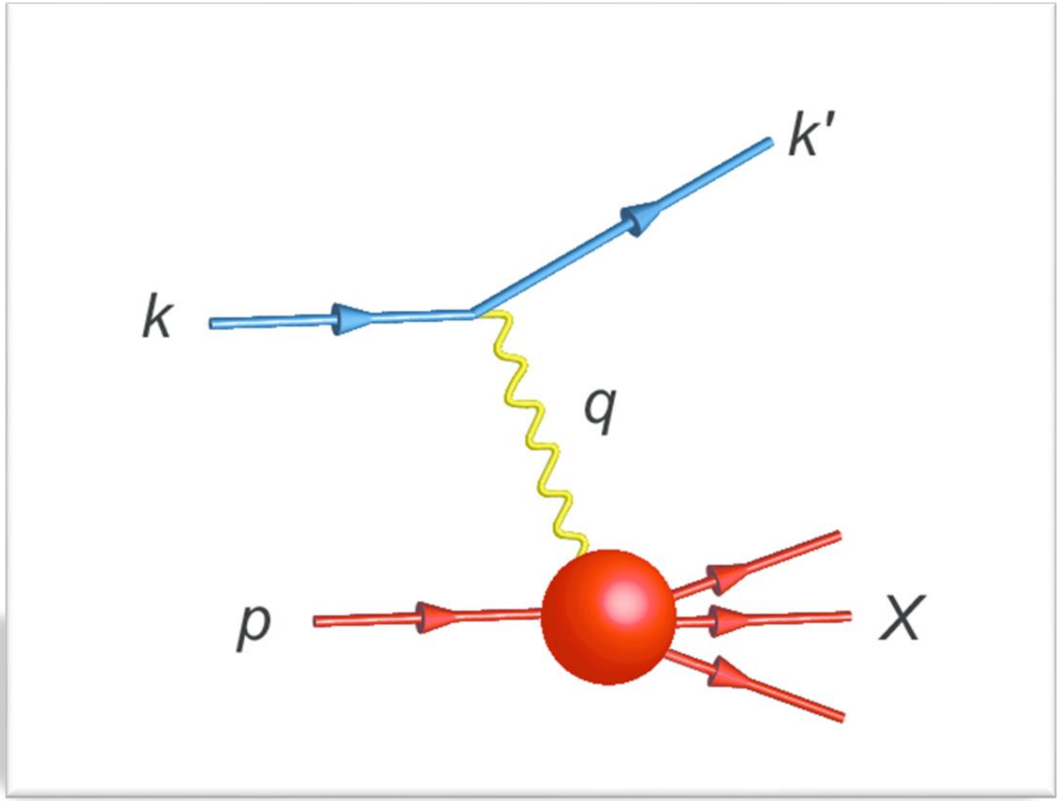
$\Delta(1700)\frac{3}{2}^{-}$ mainly P-wave.



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



Rest-frame angular momentum decompositions



Parton Distribution Functions

Proton and pion distribution functions in counterpoint

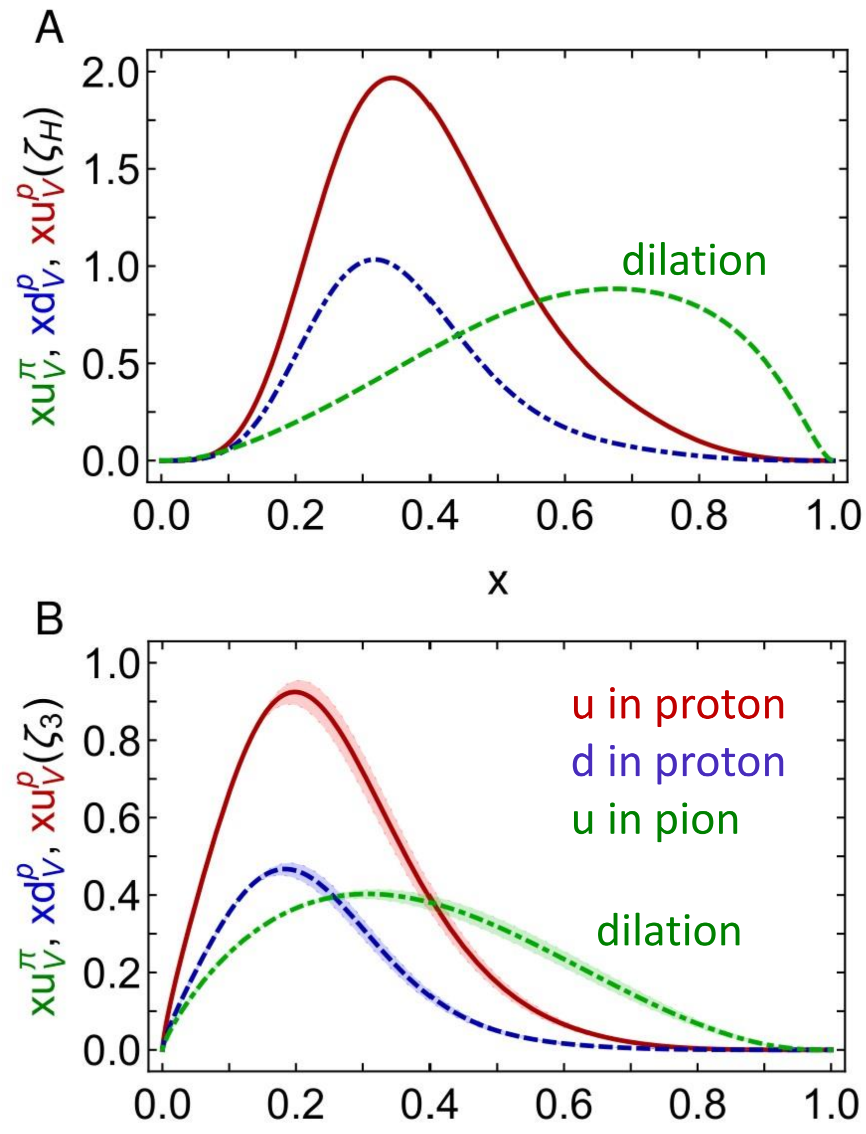
Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) *et al.*,
NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130

- 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

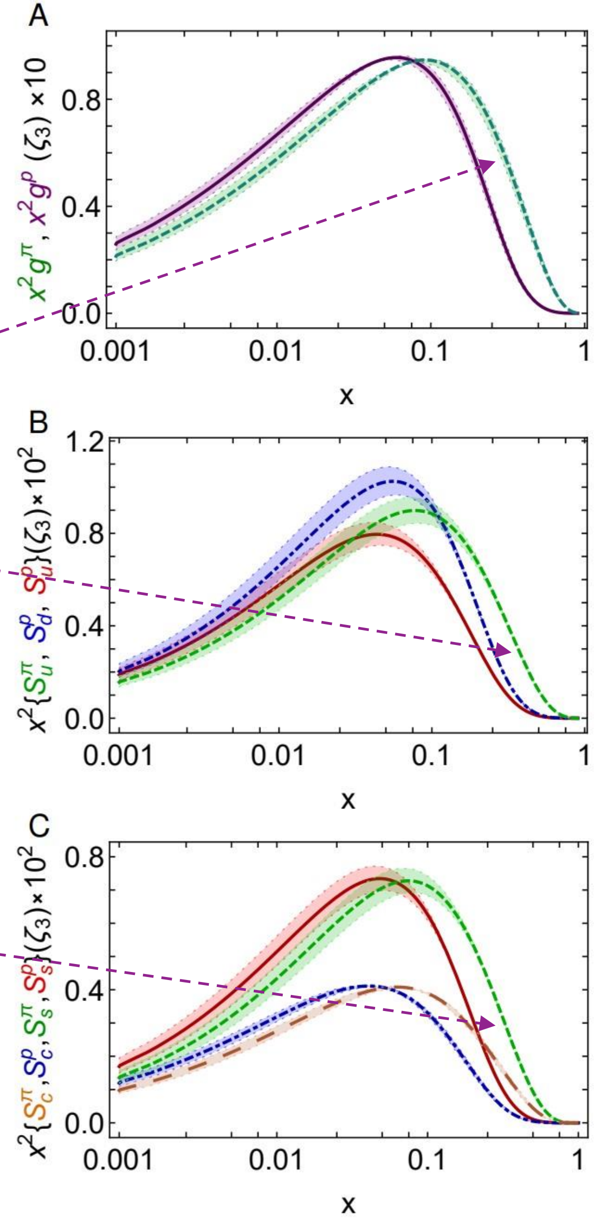


Proton and pion distribution functions in counterpoint - glue and sea

- CSM prediction for glue-in-pion DF confirmed by recent lQCD simulation

  [*Regarding the distribution of glue in the pion*, Lei Chang (常雷) and Craig D Roberts, e-Print: 2106.08451 [hep-ph], Chin. Phys. Lett. 38 (8) (2021) 081101/1-6]

- Glue-in-π DF possess significantly more support on the valence domain ($x \geq 0.2$) than the glue-in-p DF
- Sea-in-π DF possess significantly more support on the valence domain than sea-in-p DFs.
- *s* and *c* sea DFs are commensurate in size with those of the light-quark sea DFs
- For s-and c-quarks, too, the pion DFs possess significantly greater support on the valence domain than the kindred proton DFs.
- These outcomes are measurable expressions of EHM



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

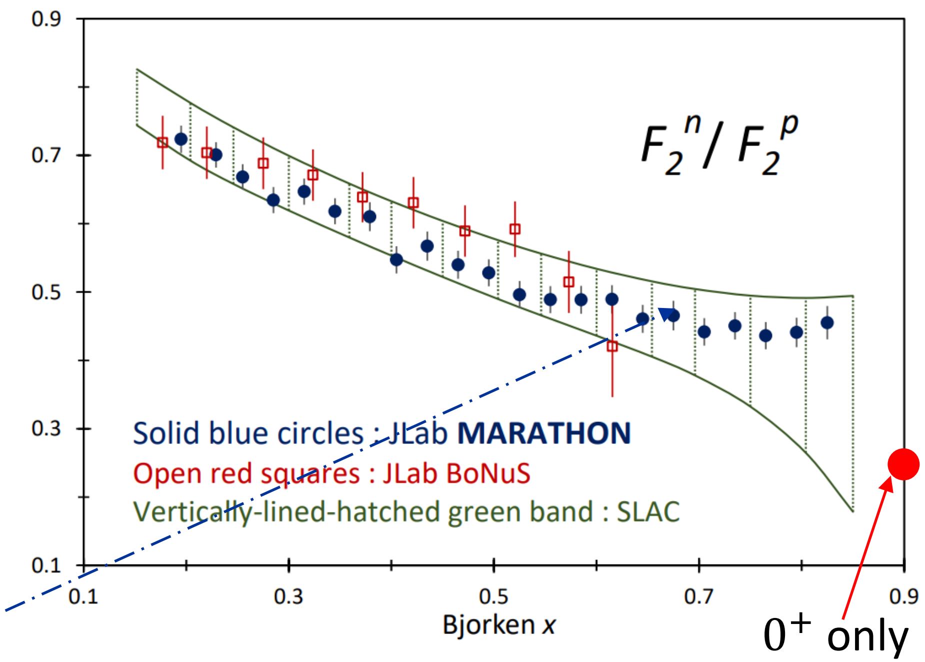


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14\cdot x$ (GeV/c)^2] (see text). All three experimental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

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.

Neutron/Proton structure function ratio

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

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

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

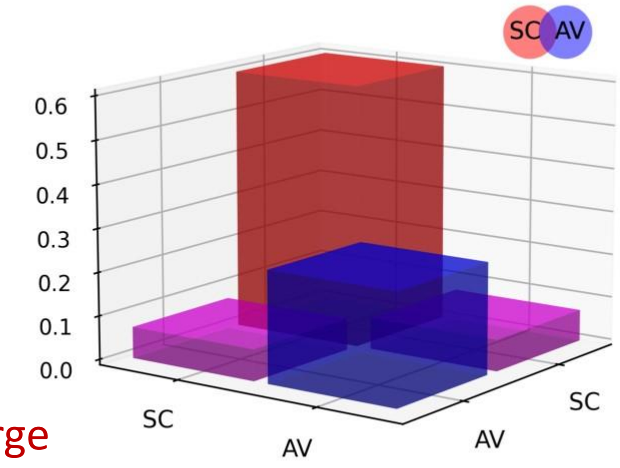
$$\Sigma(x;\zeta) = s(x;\zeta) + \bar{s}(x;\zeta) + c(x;\zeta) + \bar{c}(x;\zeta)$$

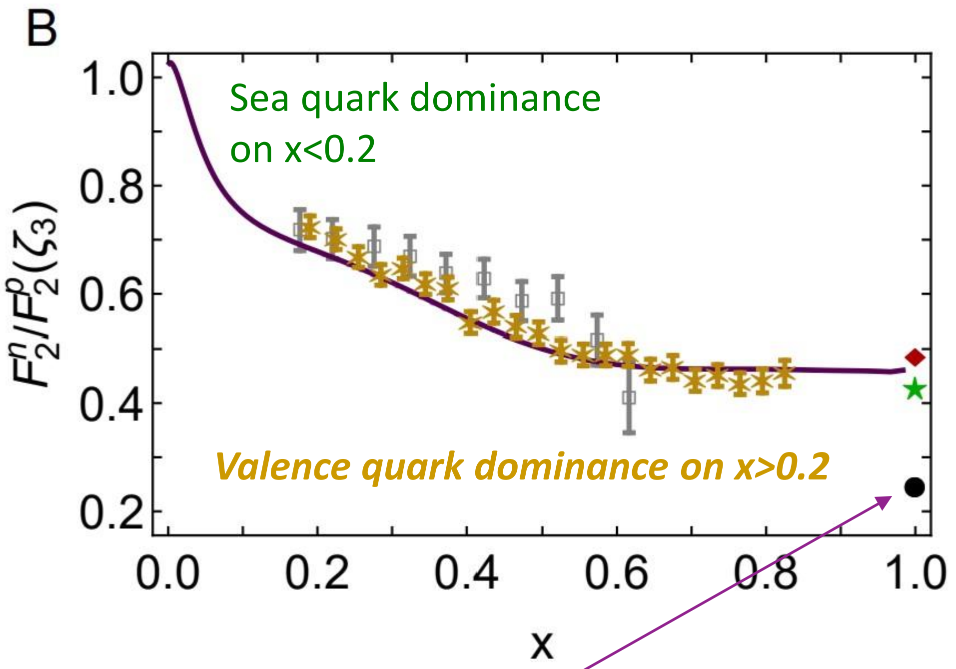
- Comparison with MARATHON data

[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

Asymmetry of antimatter in the proton

- Proton = u + u + d

  ⇒ Pauli blocking: gluon splitting produces

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

- Comparison with SeaQuest data

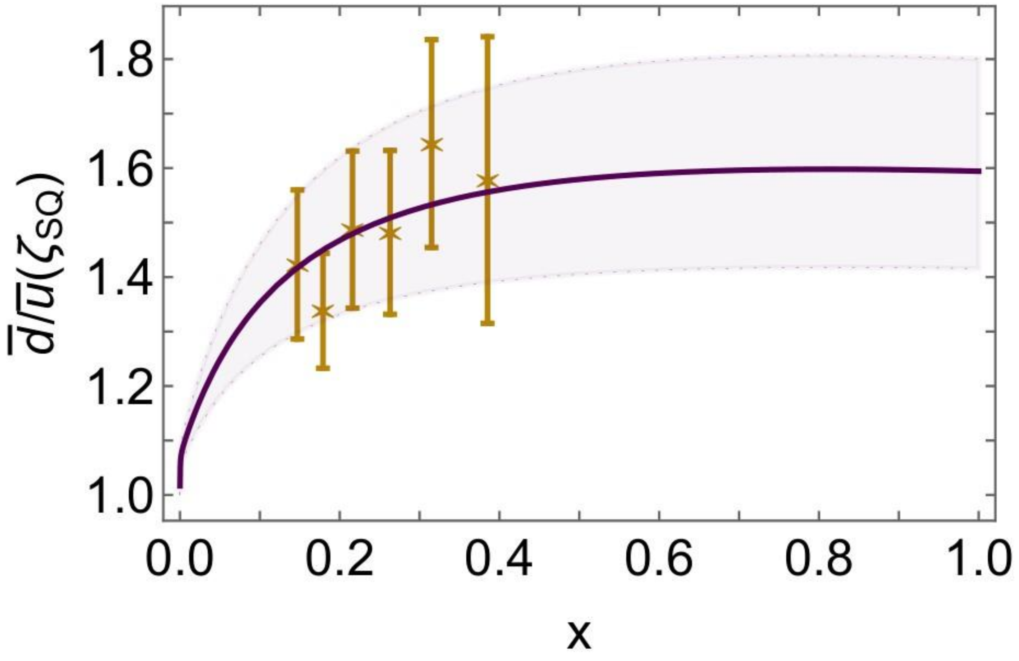
  [J. Dove, et al., *The asymmetry of antimatter in the proton*, Nature 590 (7847) (2021) 561–565.]

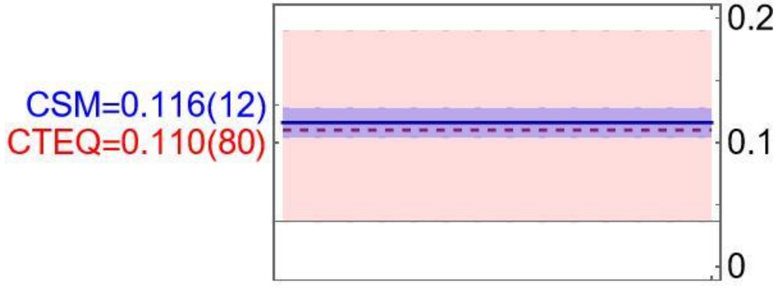
- Gottfried sum rule

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

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

$\zeta = 2$ GeV … $\langle x\rangle_{\bar{u}} \downarrow 25\%$ & $\langle x\rangle_{\bar{d}} \uparrow 25\%$





Gottfried Sum Rule

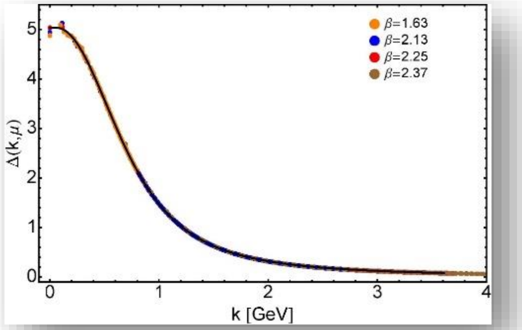
✓ *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚), Lei Chang (常雷), Khépani Raya, Craig D. Roberts and José Rodríguez-Quintero, NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130/1-7

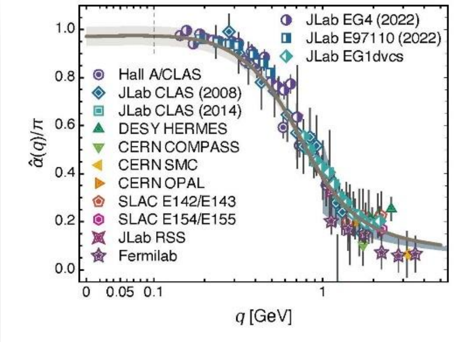
✓ *Parton distributions of light quarks and antiquarks in the proton*, Lei Chang (常雷), Fei Gao (高飞) and Craig D. Roberts, NJU-INP 055/22, e-Print: 2201.07870 [hep-ph], Phys. Lett. B 829 (2022) 137078/1-7

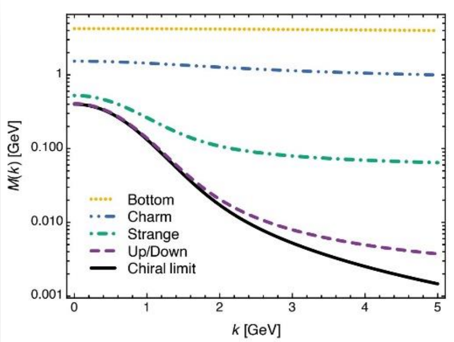
Expanding array of parameter-free predictions, including

- *Transition form factors: $\gamma * + p \to \Delta(1232), \Delta(1600)$*, Ya Lu, Chen Chen, Zhu-Fang Cui, Craig D Roberts, Sebastian M Schmidt, Jorge Segovia and Hong Shi Zong, arXiv:1904.03205 [nucl-th], Phys. Rev. D **100** (2019) 034001/1-13
  - *Predictions confirmed in recent months following analysis of large-Q^2 CLAS data – see Victor Mokeev's plenary presentation on Wednesday*
- *Nucleon-to-Roper electromagnetic transition form factors at large-Q^2*, Chen Chen *et al*., arXiv:1811.08440 [nucl-th], 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], Phys. Rev. D **102** (2020) 014043/1-14
- *Dynamical diquarks in the $\gamma^*p \to N(1535)1/2-$ transition*, Khépani Raya et al., NJU-INP 046/21, arXiv:2108.02306 [hep-ph], Eur. Phys. J. A **57** (2021) 266/1-16
- *Revealing pion and kaon structure via generalised parton distributions*, Khépani Raya et al., NJU-INP 051/21, e-Print: 2109.11686 [hep-ph], 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, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130/1-7

Validate the EHM paradigm & consequent appearance of diquark clusters







THREE PILLARS OF EHM

Grant no. 12135007

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

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*

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Emergent Hadron Mass

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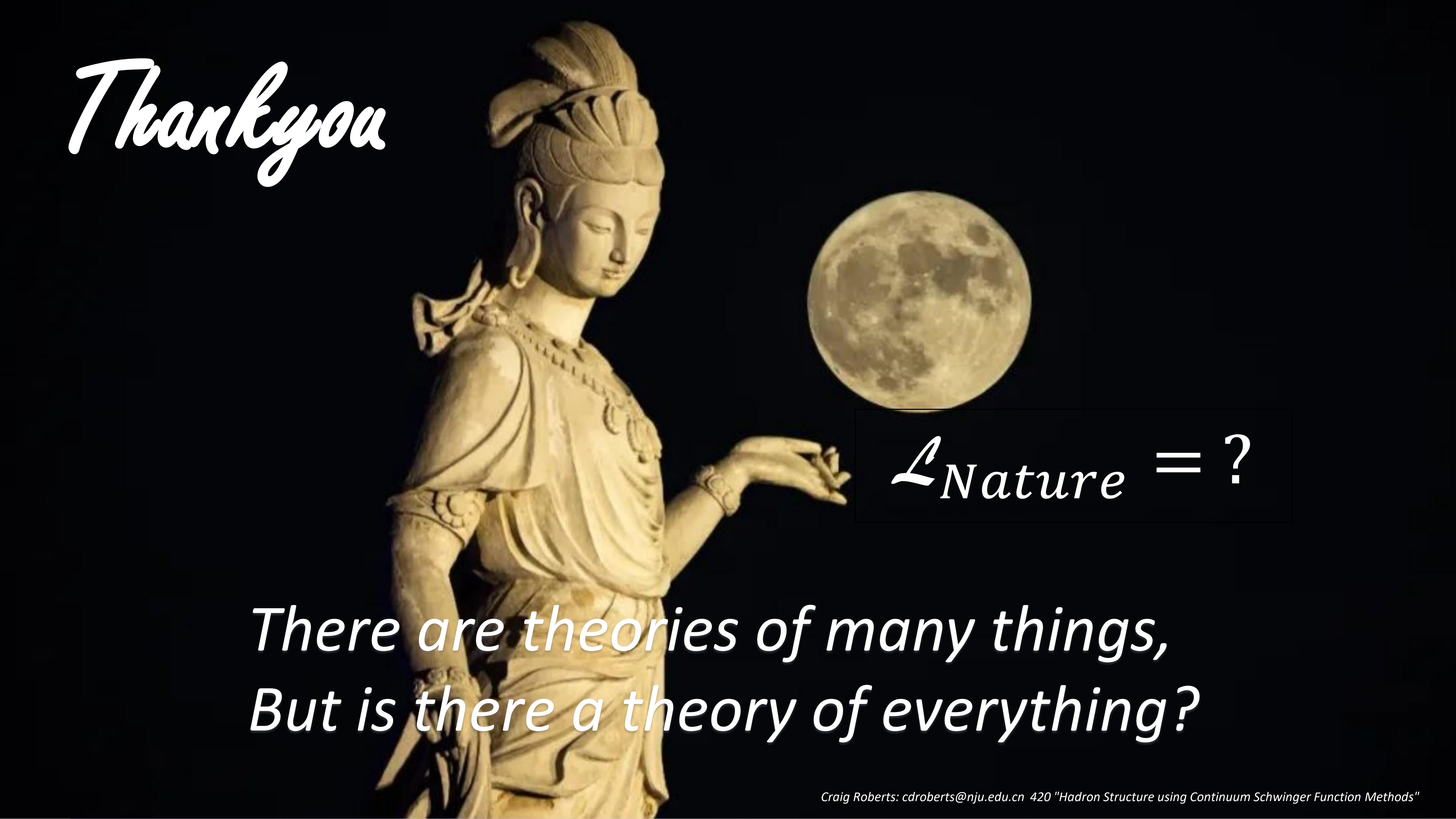
$\mathcal{L}_{Nature} = ?$

There are theories of many things,

But is there a theory of everything?

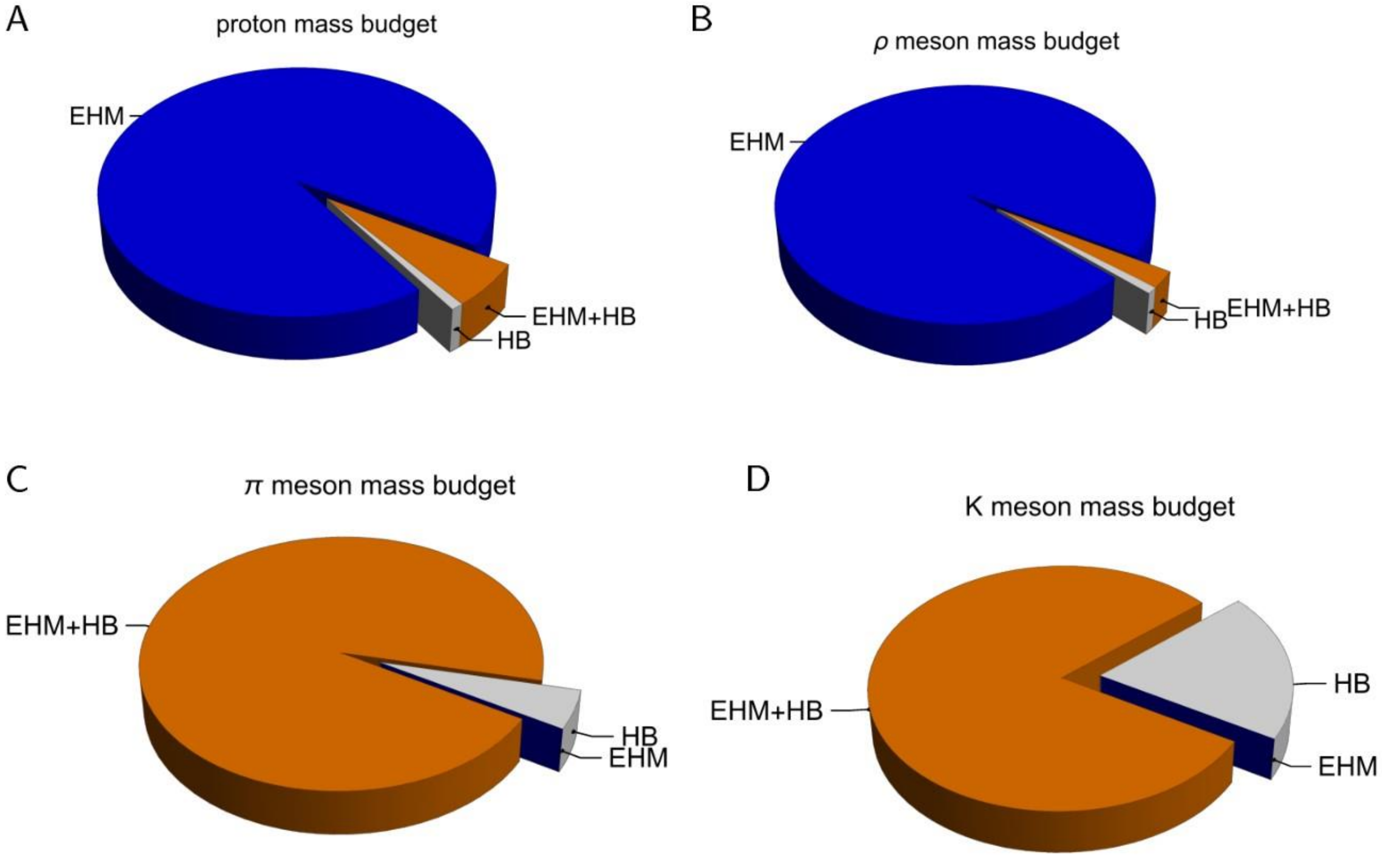
Craig Roberts: cdroberts@nju.edu.cn 420 "Hadron Structure using Continuum Schwinger Function Methods"


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

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