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

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Emergence of Hadron Mass and Structure

Emergence of Hadron Mass

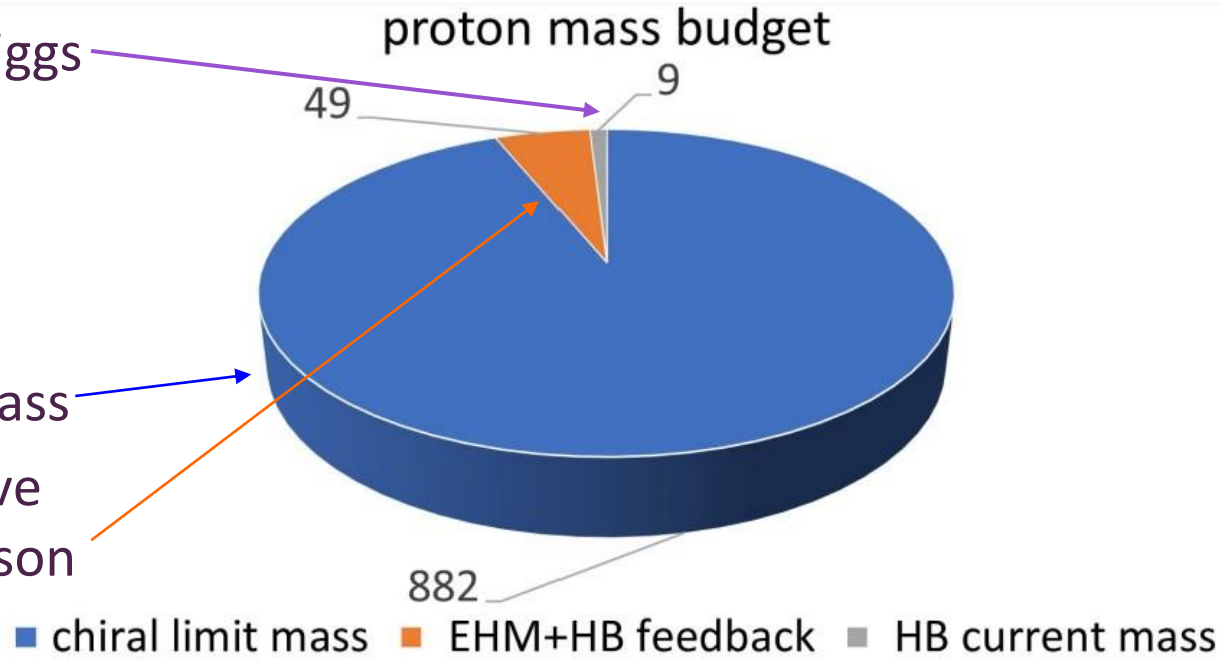
- Standard Model of Particle Physics has one *known* mass-generating mechanism

  = 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 the Standard Model, i.e., 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?
  - Critically, without Higgs mechanism of mass generation, π and K would be indistinguishable
- Whence mass?

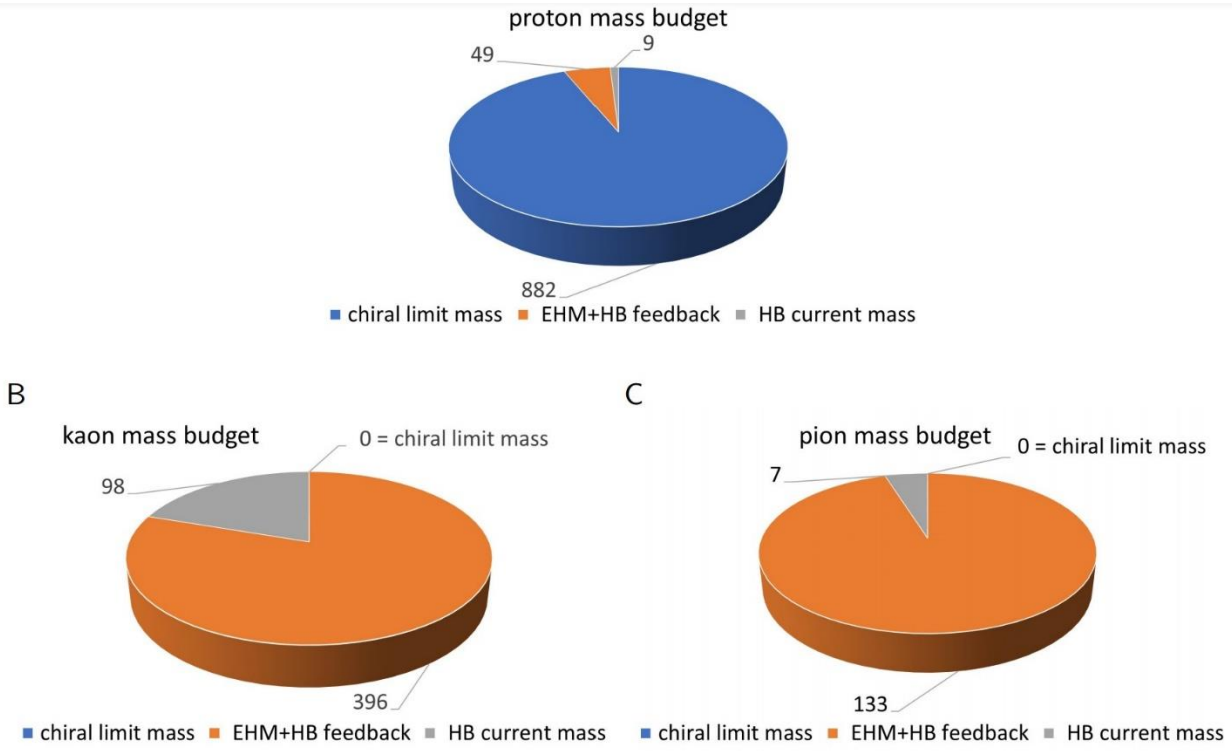


FIG. 1.1. Mass budgets for A – proton, B – kaon and C – pion, drawn using a Poincaré invariant decomposition. There are crucial differences. The proton's mass is large in the chiral limit, *i.e.* even in the absence of Higgs couplings into QCD. This nonzero chiral-limit component is an expression of emergent hadronic mass (EHM) in the SM. Conversely and yet still owing to EHM via its dynamical chiral symmetry breaking (DCSB) corollary, the kaon and pion are massless in the chiral limit – they are the SM's Nambu-Goldstone modes [24–27]. (See Eq. (2.22) below.) (Units MeV, separation at $\zeta = 2\,\mathrm{GeV}$, produced using information from Refs. [8, 21–23].)

All mass is interaction.

— Richard P. Feynman —

[redacted]

Quantum Chromodynamics

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

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

- One-line Lagrangian – expressed in terms of gluon and quark partons
- Which are NOT the degrees-of-freedom measured in detectors

Questions

- What are the asymptotic detectable degrees-of-freedom?
- How are they built from the Lagrangian degrees-of-freedom?
- Is QCD really the theory of strong interactions?
- Is QCD really a theory? ⇒ Implications far beyond Standard Model

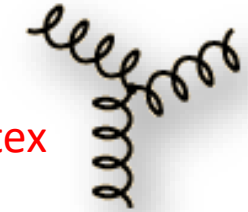
G E N E S I S

Modern Understanding Grew Slowly from Ancient Origins

- More than 40 years ago

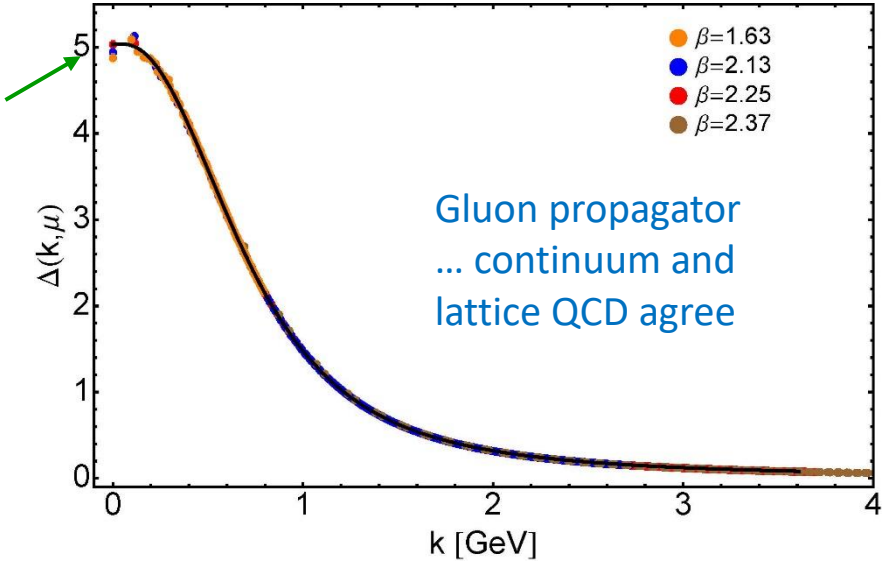
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1050 citations

3-gluon vertex



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

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



Gluon propagator … continuum and lattice QCD agree

4-gluon vertex

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

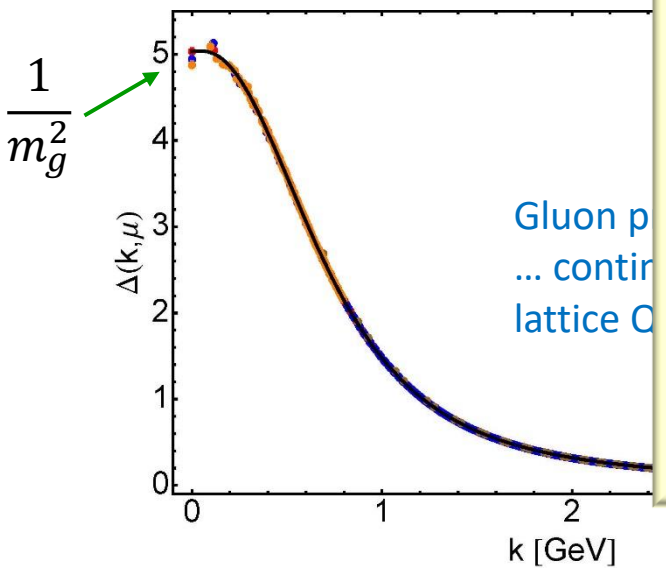
- ✓ *QCD fact*
- ✓ *Continuum theory and lattice simulations agree*
- ✓ *Empirical verification?*

Modern Understanding
Grew Slowly from [illegible] Origins

- More than 40 year[illegible]

  Dynamical mass ger[illegible]mics,
  J.M. Cornwall, Phys.[illegible]

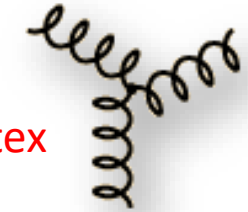
- Owing to strong se[illegible]uasiparticles,
  described by a[illegible]omenta



Gluon p[illegible]
... contir[illegible]
lattice Q[illegible]

[illegible]t
[illegible]ion

3-gluon vertex



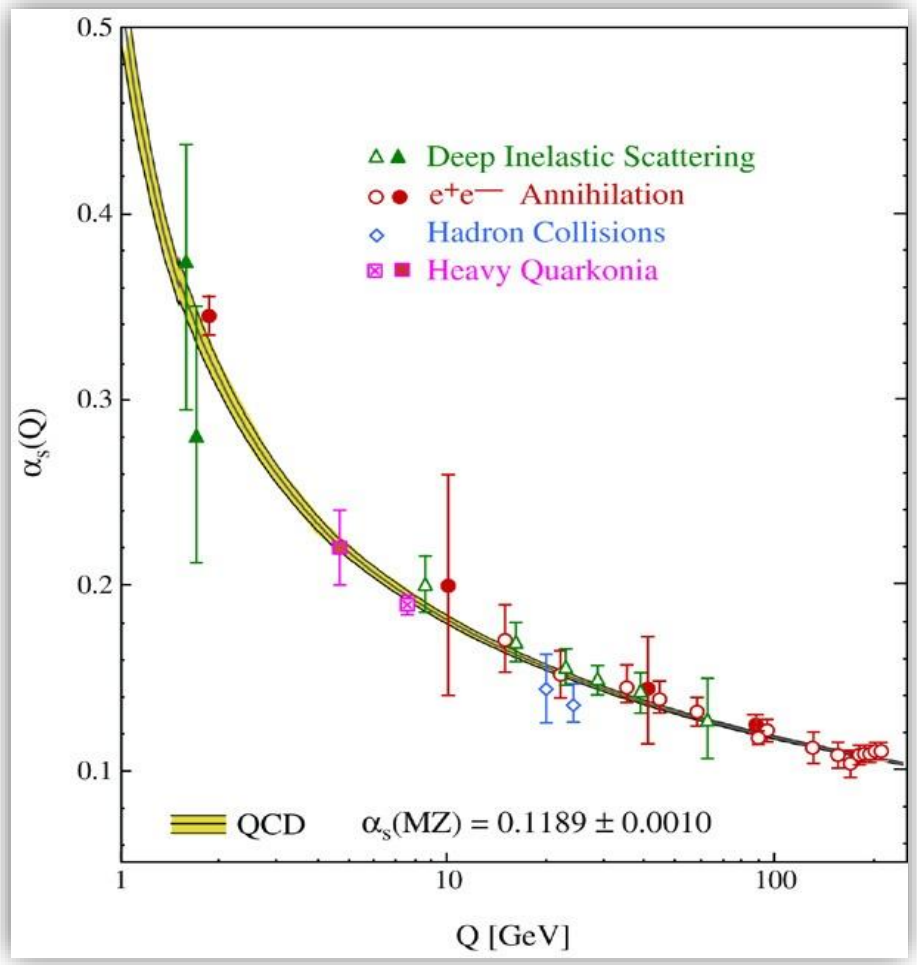
4-gluon vertex

EHM means Gluons are massive

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

This is where we live

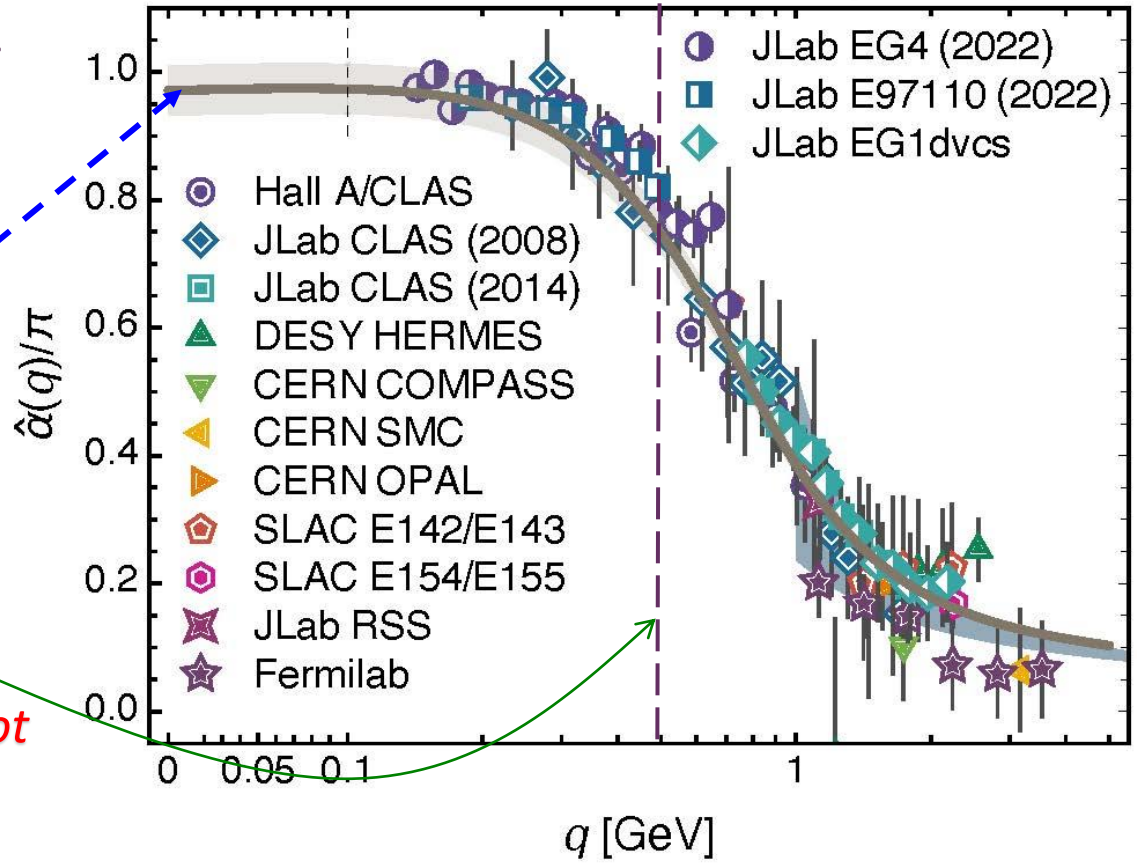
⇐
What's happening out here?!



QCD's Running Coupling

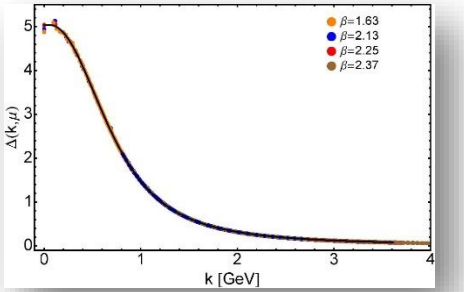
Process independent effective charge = running coupling

- 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

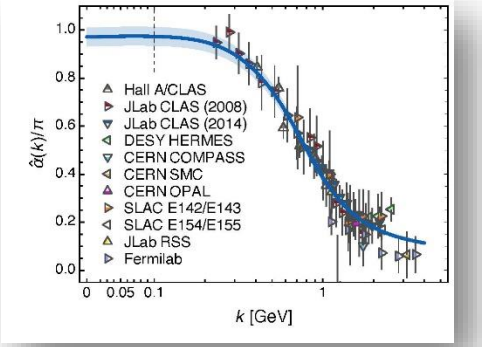


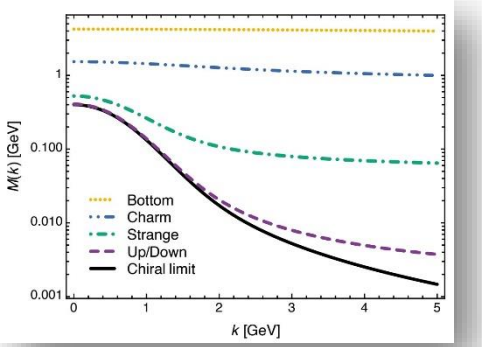
The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process independent strong running coupling
Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
Effective charge from lattice QCD, Zhu-Fang Cui et al., NJU-INP 014/19, arXiv:1912.08232 [hep-ph], Chin. Phys. C **44** (2020) 083102/1-10

EHM Basics



- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent scale-expressing 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

QCD Fact Pion (Nambu-Goldstone modes) and mass

- Higgs boson couplings → 0
- Pion exists and is massless
- Pion Bethe-Salpeter amplitude

EHM demands equivalence between one-body mass and two-body correlation strength in Nature's most fundamental Nambu-Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

Pion wave function quark mass function

- **This identity is the most basic expression of the Nambu-Goldstone Theorem in the Standard Model**

QCD Fact Pion (Nambu-Goldstone modes) and mass

- Higgs boson couplings → 0
- Pion exists and is massless
- Pion Bethe-Salpeter amplitude

EHM demands equivalence between one-body mass and two-body correlation strength in Nature's most fundamental Nambu-Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

Pion wave function quark mass function

- Entails, enigmatically, properties of the nearly massless pion are the cleanest expression of EHM in the Standard Model !

All mass is interaction.

— Richard P. Feynman —

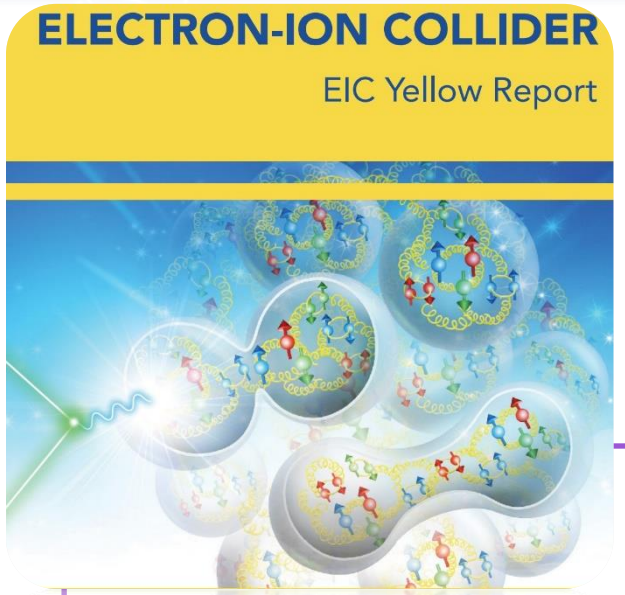
In QCD, so is the absence of mass

[redacted]

AMBER

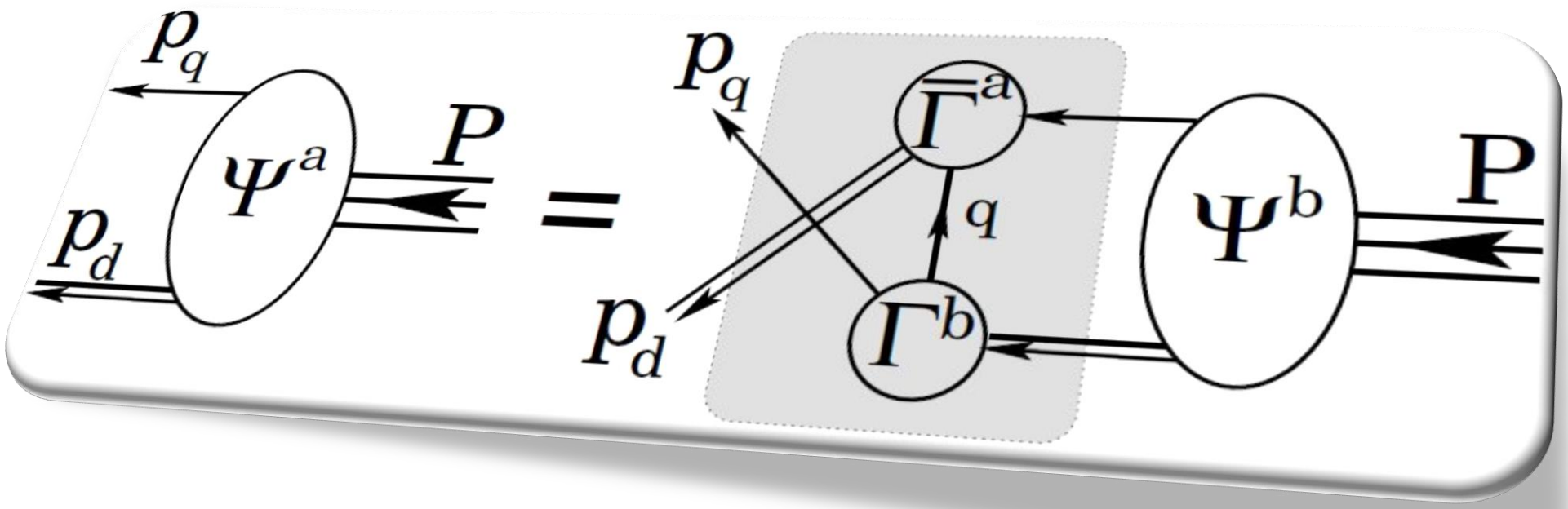
A new QCD facility at the M2 beam line of the CERN SPS

Jefferson Lab
Thomas Jefferson National Accelerator Facility



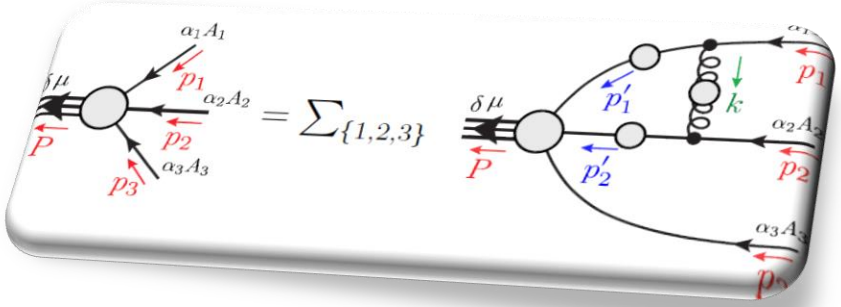
EHM at Existing and Future Facilities

Baryon Structure and QCD
R.T. Cahill, C. D. Roberts, J. Praschifka
Austral. J. Phys. **42** (1989) 129-145

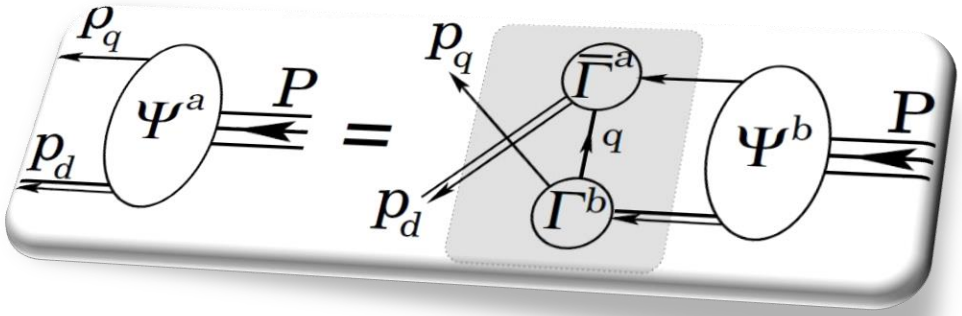


Structure of Baryons - diquark correlations

Structure of Baryons

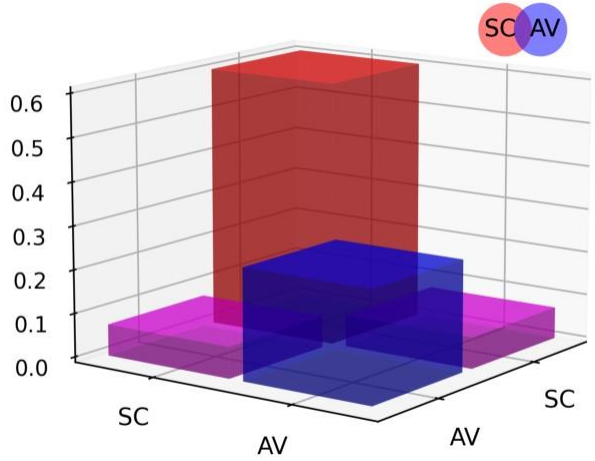


- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain



Structure of Baryons

- 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



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

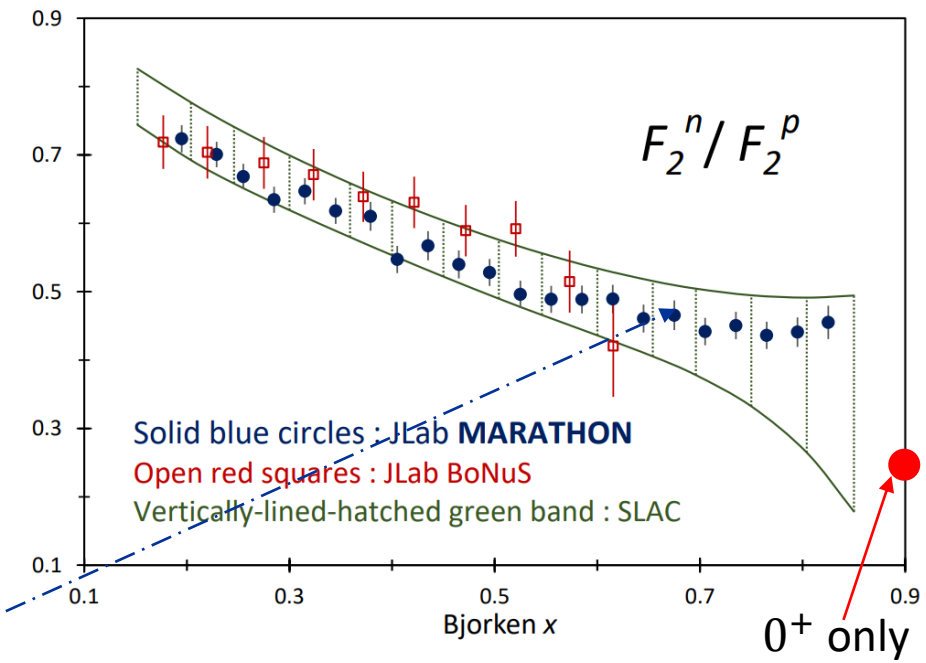
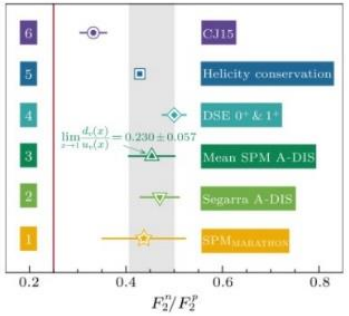


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics $[Q^2 = 14 \cdot x\ (\mathrm{GeV}/c)^2]$ (see text). All three experimental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



Valence Quark Ratio in the Proton

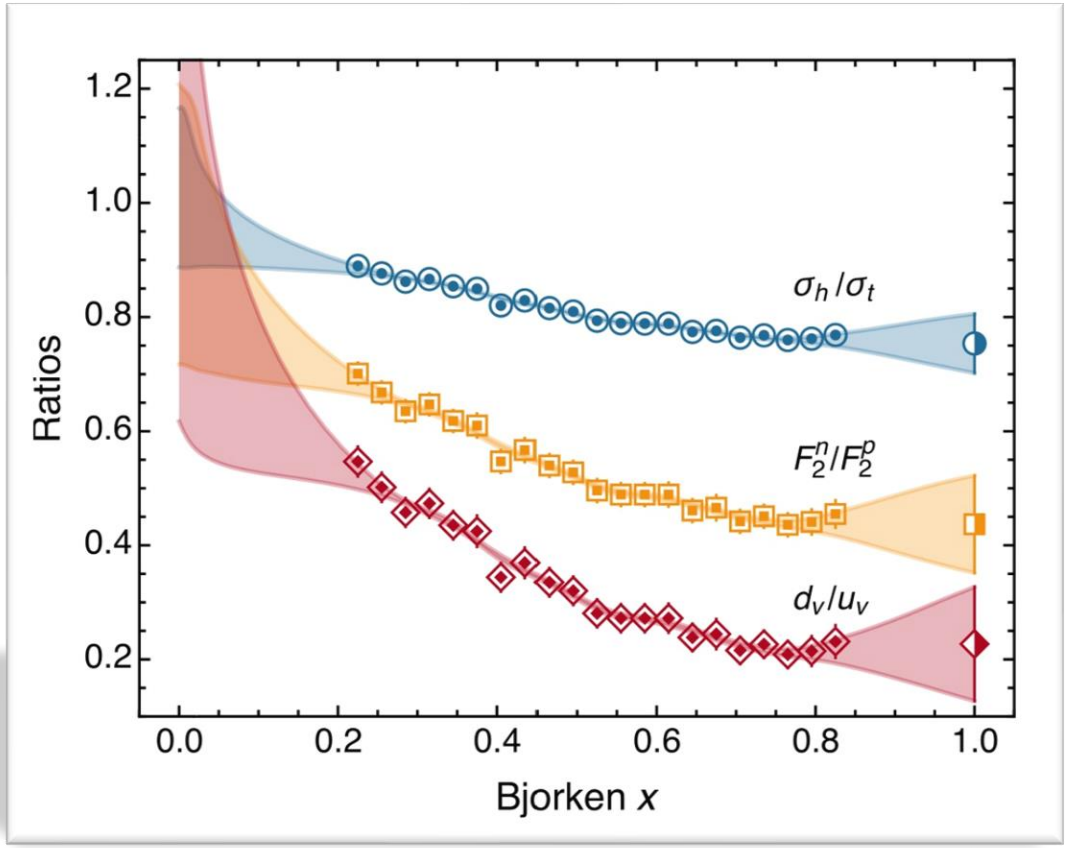
Zhu-Fang Cui, Fei Gao, Daniele Binosi, Lei Chang, Craig D. Roberts, and Sebastian M. Schmidt

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*

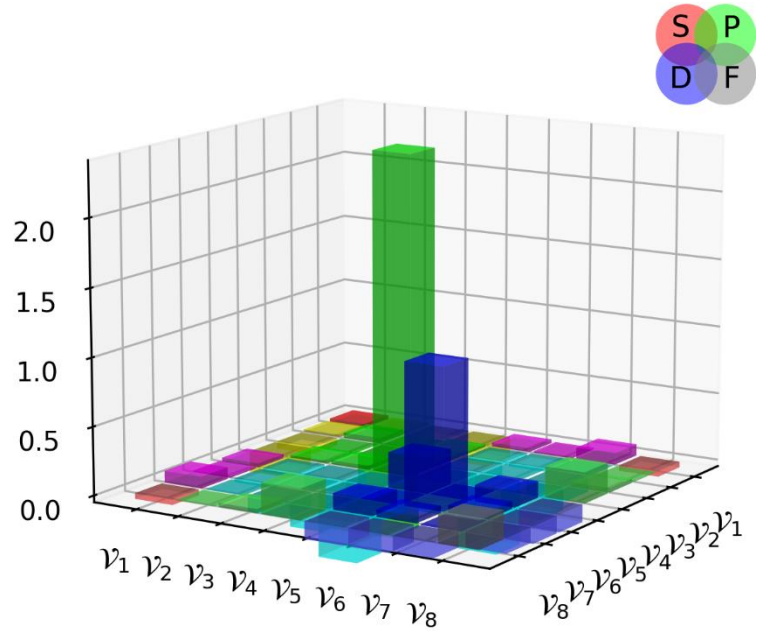


Composition of low-lying $\mathbf{J} = \frac{3}{2}^{\pm}$ Δ-baryons

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

Wave functions of (I, J^P) = (1/2,3/2$^{\mp}$) baryons
Langtian Liu (刘浪天), Chen Chen (陈晨) and Craig D. Roberts, NJU-INP 064/22, e-Print: 2208.12353 [hep-ph]

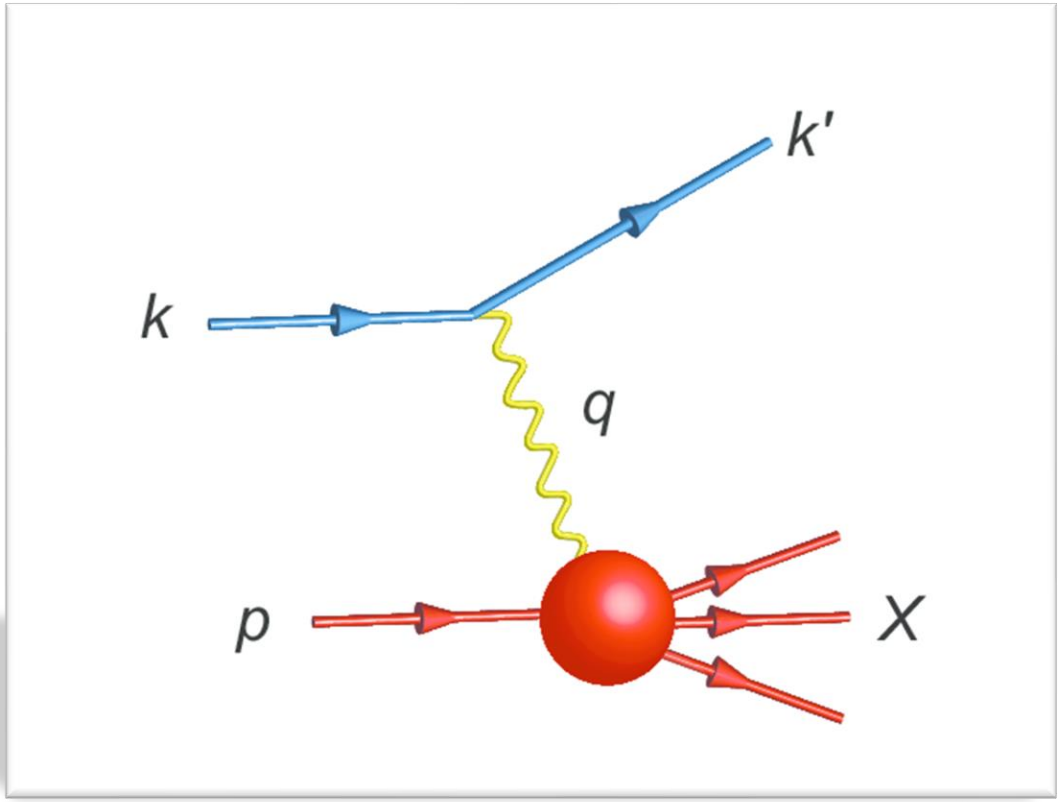
Electroexcitation of baryon resonances



Exposing orbital angular momentum structure of, e.g., $\Delta(1700)\frac{3}{2}^{-}$ … providing motivation and support for extensive baryon resonance programme at JLab

- *The ground state proton is not enough*
- Ground state of the hydrogen atom did not give us QED
- Studies of the proton alone cannot reveal all the wonders of QCD, if QCD is truly the theory of strong interactions in the Standard Model
- Modern and planned high-luminosity facilities provide unprecedented opportunities to move beyond the 100-year focus on the structure of just one (or two = neutron) hadron(s)
- Insights into the full array of Nature's hadrons will greatly enrich our store of knowledge!
- Poincaré-covariant Faddeev equation is shedding new light on the structure of ALL baryons

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



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?

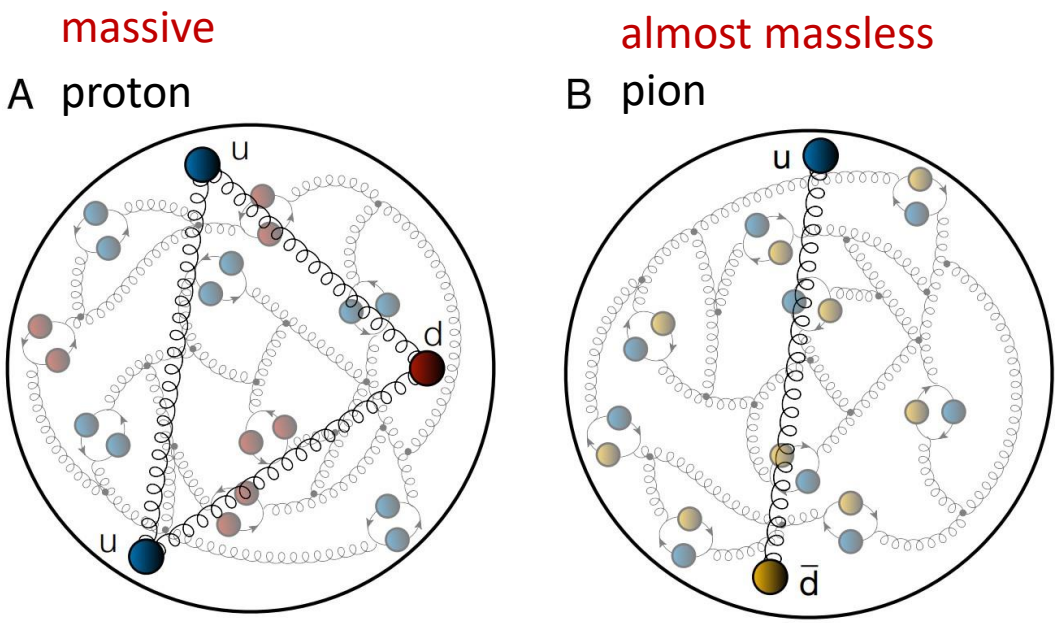


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

- Valence-quark domain: there is a scale $\zeta_H < m_p$ at which $\left\{ \begin{array}{l} d^p(x;\zeta_{\mathcal{H}}), u^p(x;\zeta_{\mathcal{H}}) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_{\mathcal{H}}), u^\pi(x;\zeta_{\mathcal{H}}) \overset{x\simeq 1}{\propto} (1-x)^2 \end{array} \right.$
- $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p$, $\beta_\pi = 2 + \gamma_\pi$
  - Gluon DFs: $\beta_{p,\pi}^{\text{glue}} \geq \beta_{p,\pi}^{\text{val}} + 1$
  - Sea DFs: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$
- Further, no simultaneous global fits to proton and pion data have ever been performed
  - Largely because pion data are scarce
- Existing approaches are unlikely to yield definitive answers because practitioners typically ignore QCD constraints

✓ These are simple consequences of DGLAP equations.

✓ Argument can be reversed:

if large-x glue or sea DF exponent is smaller than that of valence DF at any given scale, then it is smaller at all lower scales.

✓ DF with lowest exponent defines the valence degree-of-freedom.

✓ Proton is supposed to be a stable bound-state of three valence-quarks

❽ Yet, modern global analyses of proton DIS and related data encompass fits with role of glue and valence-quarks reversed!

❽ Proton has valence glue but no valence quarks!

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

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✓ These are simple consequence of DGLAP equations.

❽ CT18: large-x power of glue distribution at the scale ζ = $\text{mass}_{\text{charm}}$ is (almost) identical to that of valence-quarks.

❽ With this behavior, proton has valence-gluon degrees of freedom at all scales. That would make the proton a hybrid baryon, which it is not.

❽ CT18Z: large-x power of glue distribution is a_2=1.87, whereas that on the valence quarks is a_2=3.15,

❽ *i.e.*, at ζ = $\text{mass}_{\text{charm}}$ valence-quarks are subleading degrees-of-freedom. Instead, gluons dominate on what is typically called the valence-quark domain.

Proton and pion distribution functions in counterpoint

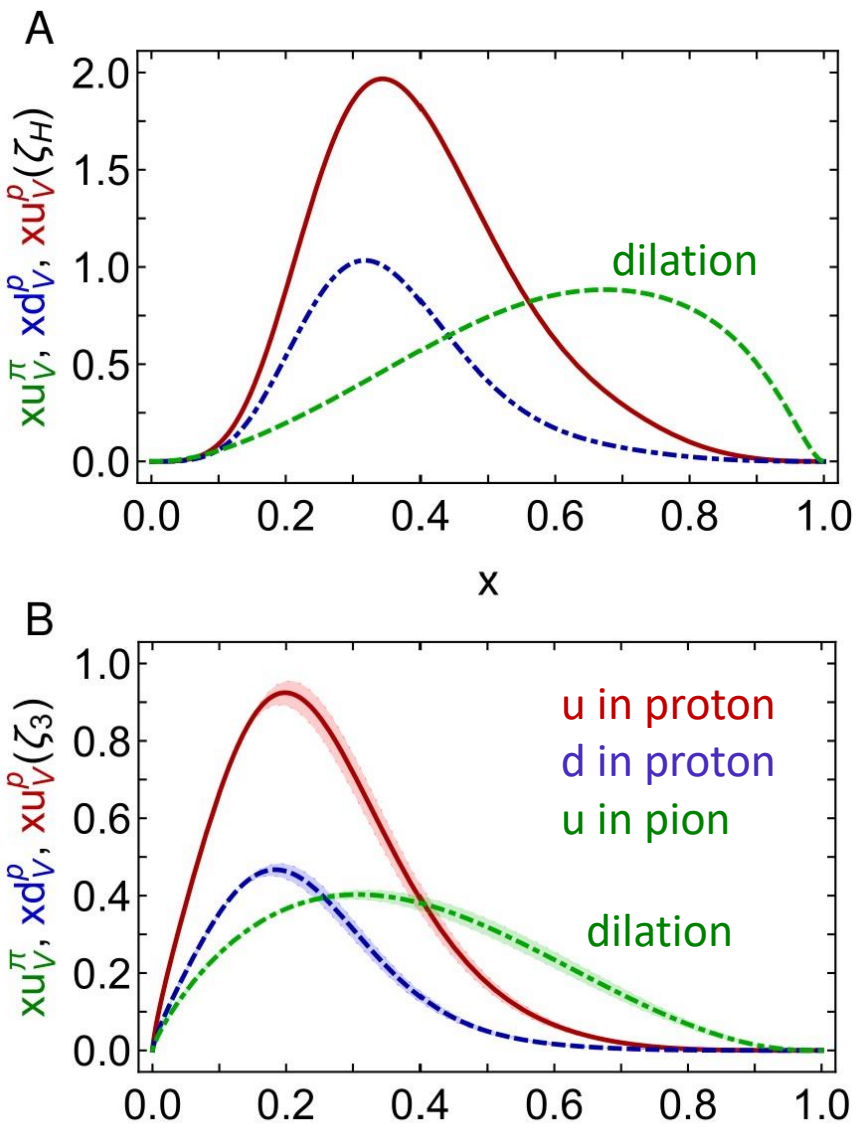
Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) *et al.*,
NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130

- 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: $\langle x\rangle_{u_p}^{\zeta_{\mathcal{H}}} = 0.687$, $\langle x\rangle_{d_p}^{\zeta_{\mathcal{H}}} = 0.313$, $\langle x\rangle_{u_\pi}^{\zeta_{\mathcal{H}}} = 0.5$
- Diquark correlations in proton, induced by EHM

  $\Rightarrow u_V\ (x) \neq 2d_V(x)$
- Proton and pion valence-quark DFs have markedly different behaviour
  - $u^\pi(x;\zeta_H)$ is Nature's most dilated DF

  i. "Obvious" because $(1-x)^2$ vs. $(1-x)^3$ behaviour & preservation of this unit difference under evolution

  ii. Also "hidden" = strong EHM-induced broadening

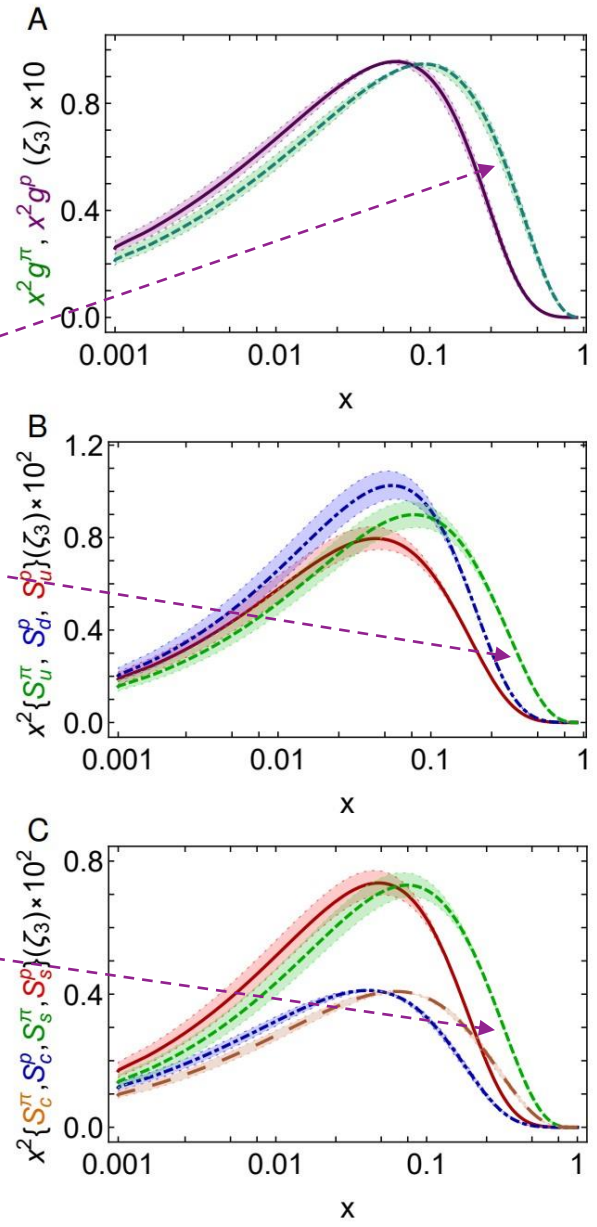


Proton and pion distribution functions in counterpoint - glue and sea

- 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



Proton and pion distribution functions in counterpoint

- CSMs have delivered 1st ever unified body of predictions for all proton and pion DFs
  – valence, glue, and four-flavour-separated sea.
- Within mesons & baryons that share familial flavour structure, light-front momentum fractions carried by identifiable, distinct parton classes are identical at any scale.
- On the other hand, *x*-dependence of DFs is strongly hadron dependent

  Smoking gun for EHM

  – At any resolving scale, ζ, those in the pion are the hardest (most dilated).
- All CSM DFs comply with QCD constraints on endpoint (low- and high-x) scaling behaviour.
- However, existing global fits ignore QCD constraints, so:
  – Fail to deliver realistic DFs, even from abundant proton data
  – Meson data almost nonexistent and controversial results from fits
- *Only after imposing QCD constraints on future phenomenological data fits will it be possible to draw reliable pictures of hadron structure.*
- *Especially important for attempts to expose and understand differences between Nambu-Goldstone bosons and seemingly less complex hadrons.*

Many, Many Other Expressions of EHM

- EHM ⇒ formation of nonpointlike diquark correlations within baryons
  - All baryons, including those with one or more heavy quarks
- Proton possess 0^+ isoscalar & 1^+ isovector correlations
  - Marathon data ⇒ Probability that proton contains scalar-diquark-only = $\frac{1}{7{,}000{,}000}$
- Nucleon resonances contain more correlations … 0^- isoscalar, 1^- isoscalar & 1^- isovector
- Nucleon-elastic & nucleon-to-resonance transition form factors can test these and other structural predictions
- Electroweak transitions: heavy+light systems (Higgs boson dominant mass mechanism) to light (lighter) final states (in which EHM dominates) – interference between Nature's two mass-generating mechanisms
- Progress demands Synergy between Experiment + Phenomenology + Theory

0^+ only

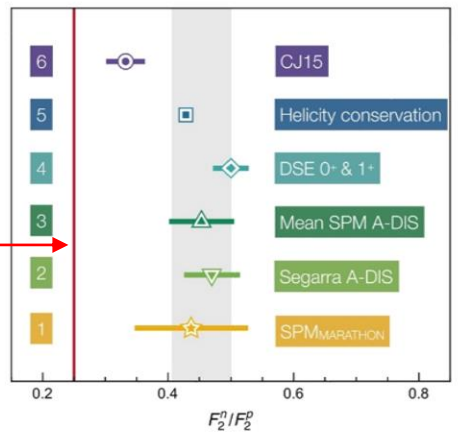


FIG. 3. $\lim_{x\to 1} F_2^n(x)/F_2^p(x)$. MARATHON-based SPM prediction compared with results inferred from: nuclear DIS [35]; Dyson-Schwinger equation analyses (DSE) [57, 58]; quark counting (helicity conservation) [59]; and a phenomenological fit (CJ15) [53]. The vertical red line marks the Nachtmann lower-limit, Eq. (3); and row 3 is the average in Eq. (8).

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Emergent Hadron Mass

- QCD is unique amongst known fundamental theories of natural phenomena
  - The degrees-of-freedom used to express the scale-free Lagrangian are not directly observable
  - Massless gauge bosons become massive, with no "human" interference
  - Gluon mass ensures a stable, infrared completion of the theory through the appearance of a running coupling that saturates at infrared momenta, being everywhere finite
  - Massless fermions become massive, producing
    - Massive baryons and simultaneously Massless mesons
- These emergent features of QCD are expressed in every strong interaction observable
- They can also be revealed via

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

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

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

There are theories of many things,

But is there a theory of everything?


Thankyou
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But is there a theory of everything?