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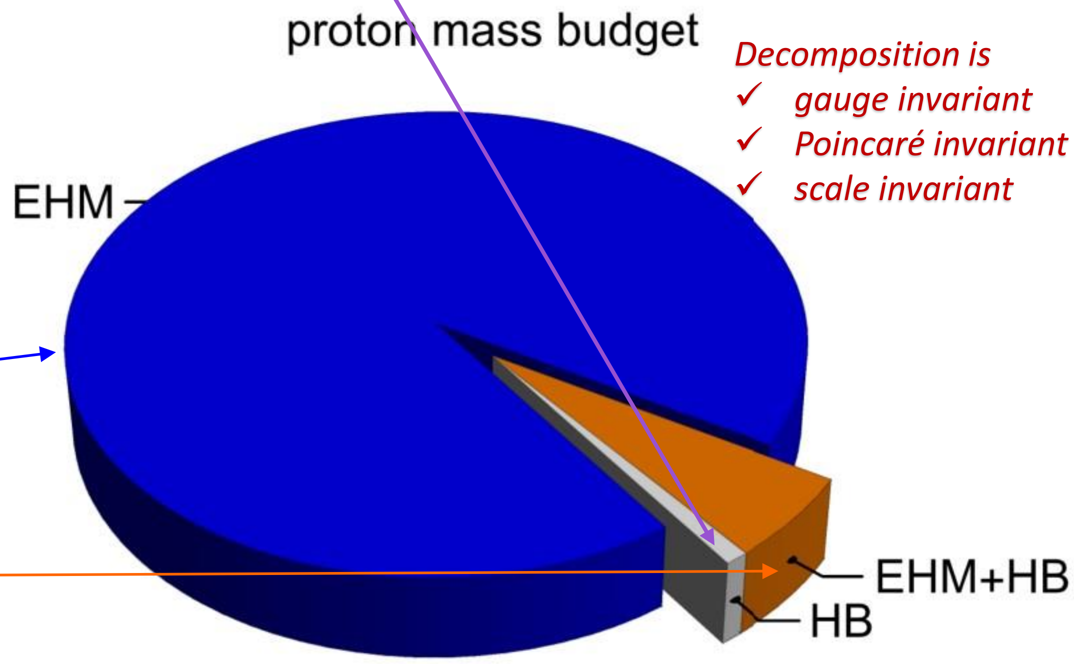
Emergent Hadron Mass ⇔ Pion and Kaon Structure

Emergence of Hadron Mass

- Standard Model of Particle Physics has one obvious mass-generating mechanism

  = Higgs Boson … impacts are critical to evolution of Universe as we know it
- However, Higgs boson alone is responsible for just ~ 1% of the visible mass in the Universe
- Proton mass budget … only 9 MeV/939 MeV is directly from Higgs
- Evidently, Nature has another very effective mechanism for producing mass:

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



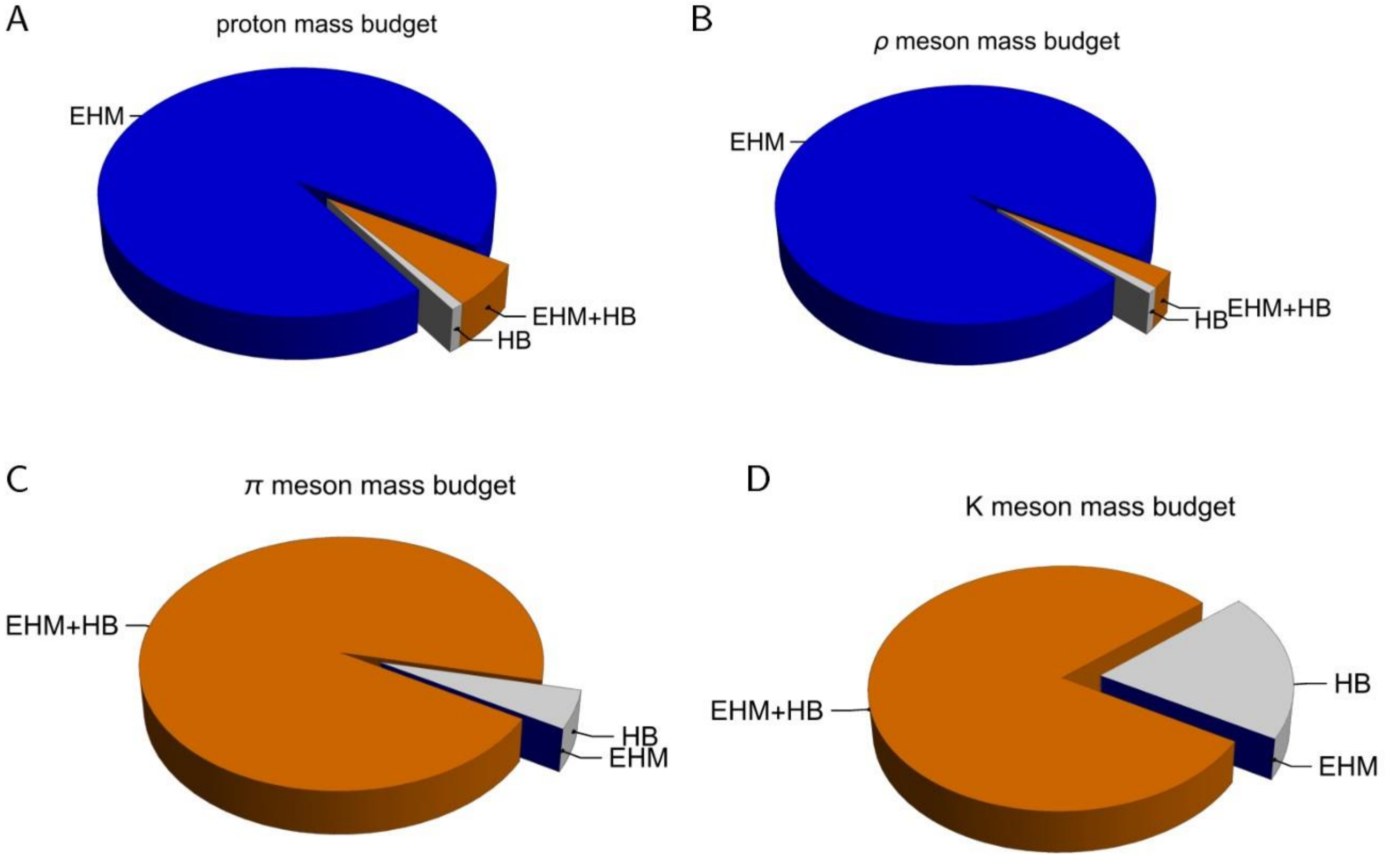
Decomposition is
- ✓ *gauge invariant*
- ✓ *Poincaré invariant*
- ✓ *scale invariant*

Emergence of Hadron Mass - Basic Questions

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

- ➢ What is the origin of EHM?
- ➢ Does it lie within QCD?
- ➢ What are 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?

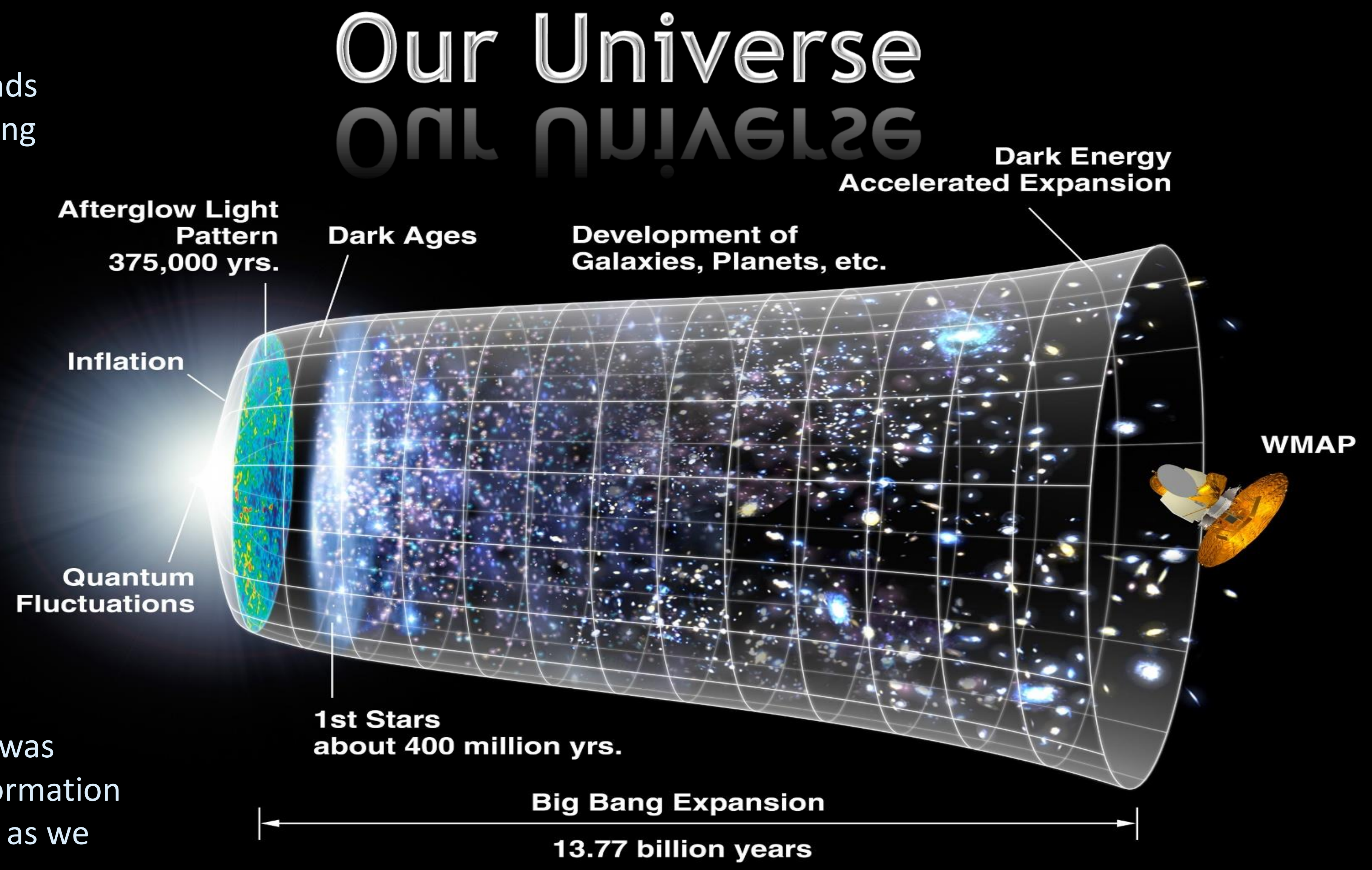
Proton and ρ-meson mass budgets are practically identical



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

The Frontier of Physics: Emergence of m_{Nature}

Mass emerged
0.000001 seconds
after the Big Bang



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

Quantum Chromodynamics

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

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

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

Questions

- What are the (asymptotic) detectable degrees-of-freedom?
- How are they built from the Lagrangian degrees-of-freedom?
- Is QCD really the theory of strong interactions?
- Is QCD really a theory … or just another EFT?

  ⇒ Implications far beyond Standard Model

G E N E S I S

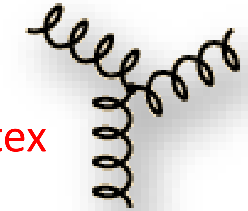
GLUON

Modern Understanding
Grew Slowly from *Ancient* Origins

- More than 40 years ago

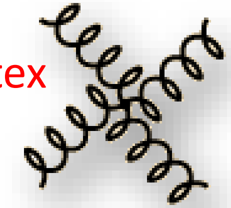
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … > 1100 citations

3-gluon vertex

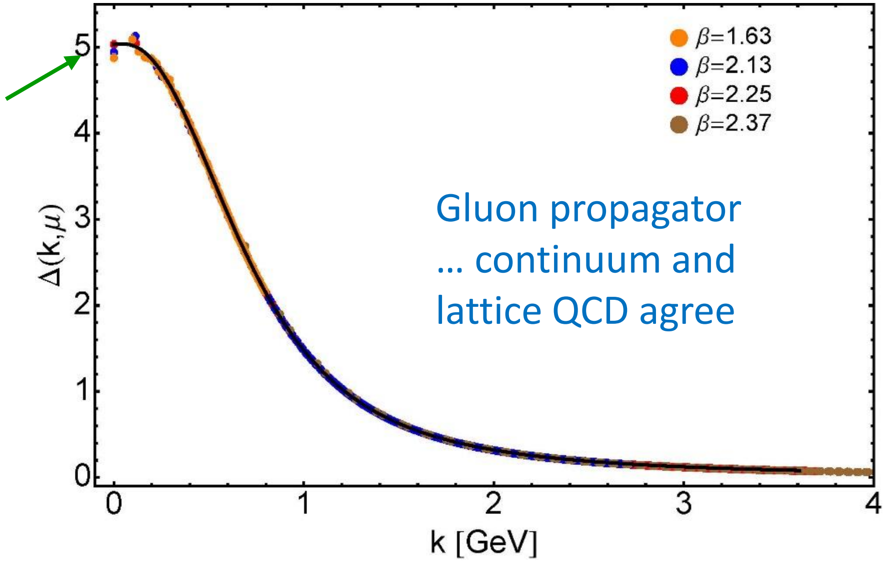


- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

4-gluon vertex



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



Gluon propagator
… continuum and
lattice QCD agree

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

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

D. Binosi, *Emergent Hadron Mass in Strong Dynamics*, Few Body Syst. **63** (2022) 42.

M. N. Ferreira, J. Papavassiliou, *Gauge Sector Dynamics in QCD*, Particles **6** (1) (2023) 312–363.

Modern Understanding Grew Slowly from Ancient Origins

- More than 40 years a

  Dynamical mass gene *ics,*

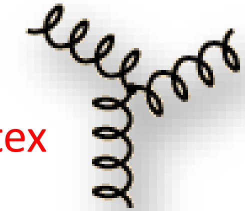
  J.M. Cornwall, Phys. R

- Owing to strong self- siparticles,

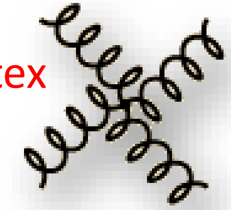
  described by a r menta

EHM means Gluons are massive – Schwinger Mechanism

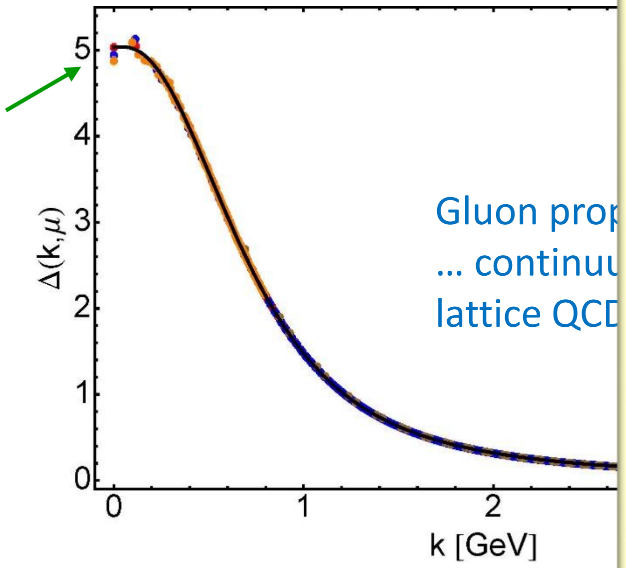
3-gluon vertex



4-gluon vertex



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



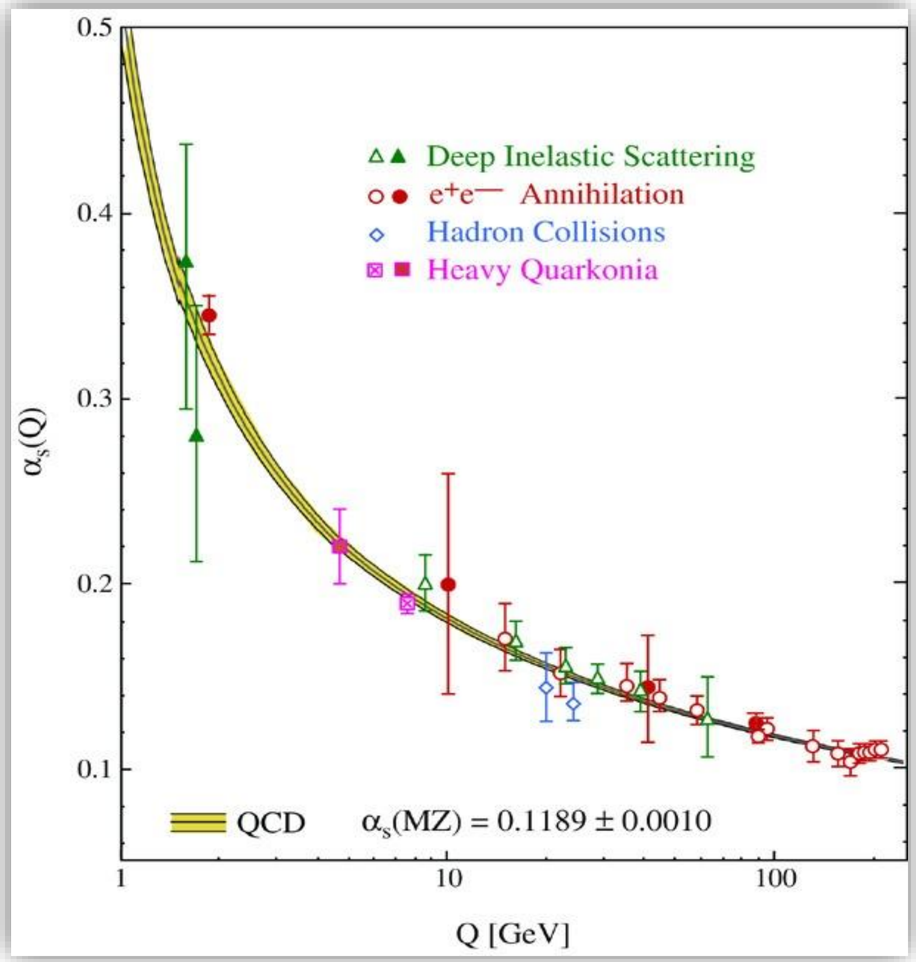
Gluon prop
… continuu
lattice QCD

n

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

This is where we live

⇐
What's happening out here?!



Asymptotic Freedom

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

QCD's Running Coupling

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 134, January 2024, 104081

Review

QCD running couplings and effective charges

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

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https://doi.org/10.1016/j

May 2024

SCIENTIFIC AMERICAN

Abstract

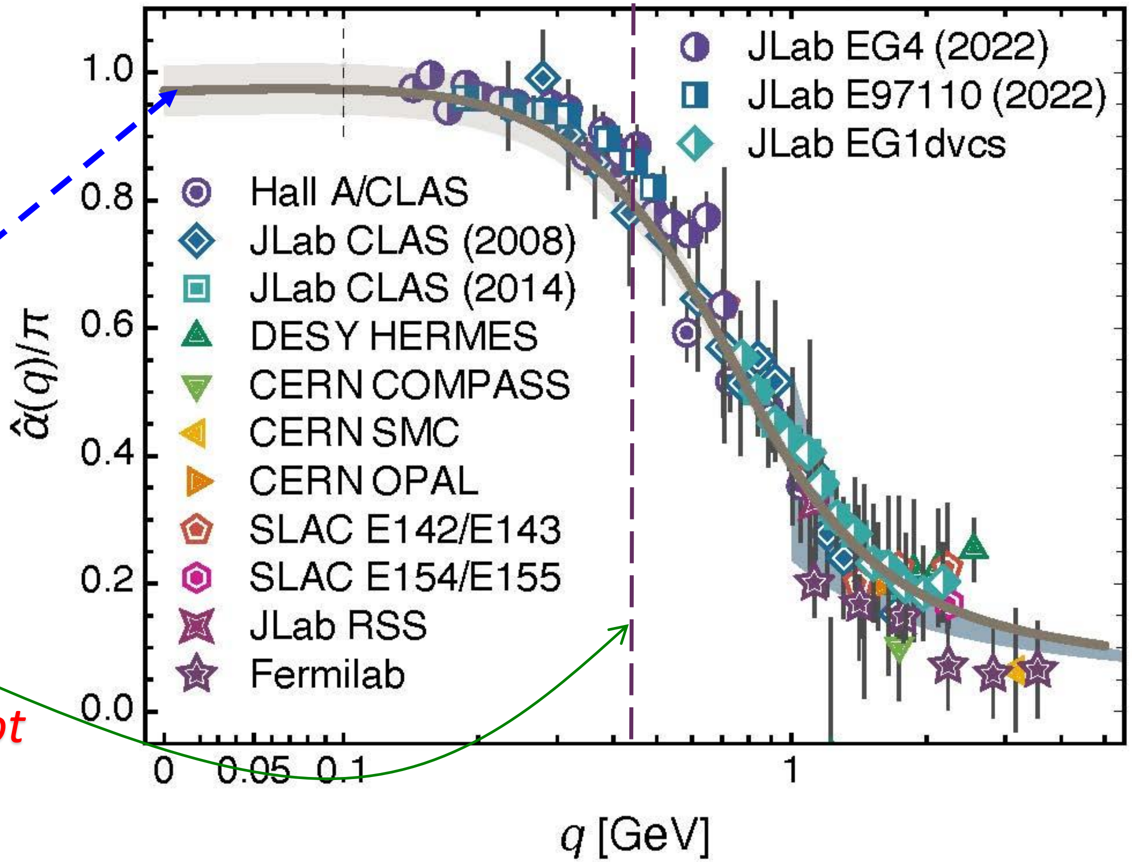
We discuss our present knowledge of α_s, the fundamental running coupling or effective charge of Quantum Chromodynamics (QCD). A precise understanding of the running of $\alpha_s\,(Q^2)$ at high momentum transfer, Q, is necessary for any perturbative QCD calculation. Equally important, the behavior of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

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

~**2500 total downloads**

Process independent effective charge = running coupling

- Modern theory enables unique QCD analogue of "Gell-Mann – Low" running charge to be rigorously defined and calculated
- Analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$
- No Landau Pole
  - *"Infrared Slavery" picture – linear potential – is not viable explanation of real-world confinement*
- Below $k \sim \widehat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again

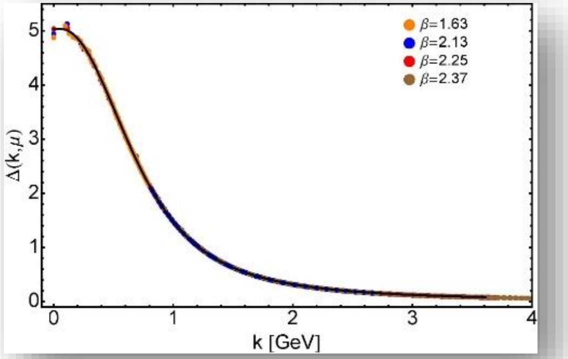


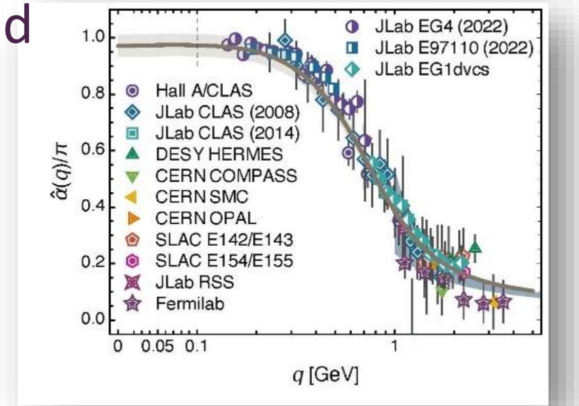
- ✓ *Process independent strong running coupling*
  Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.*
  A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running Couplings and Effective Charges,* Alexandre Deur, Stanley J. Brodsky and Craig Roberts, e-Print: 2303.00723 [hep-ph], Prog. Part. Nucl. Phys. **134** (2024) 104081

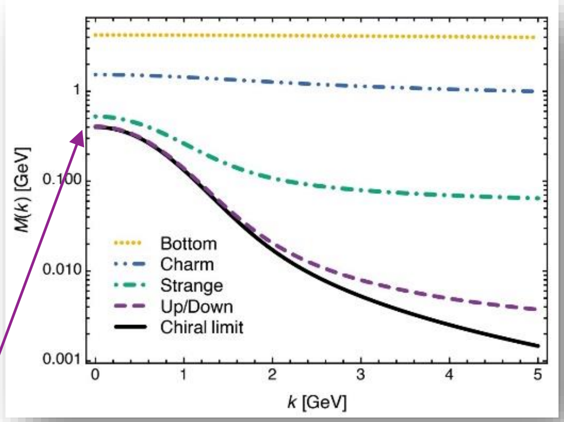
EHM Basics

- Absent Higgs boson couplings, QCD Lagrangian is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- Challenge to Experiment =
  Test the theory predictions so that
  the boundaries of the Standard Model can finally be drawn

THREE PILLARS OF EHM







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

✓ Meson-loops provide 20% quantum corrections

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: 2 body problem quark mass function: one body problem

- 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: 2 body problem

quark mass function: one body problem

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

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 120, September 2021, 103883

Review

Insights into the emergence of mass from studies of pion and kaon structure

Craig D. Roberts [a b], David G. Richards [c], Tanja Horn [d c], Lei Chang [e]

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https://doi.org/10.1016/j.ppnp.2021.103883

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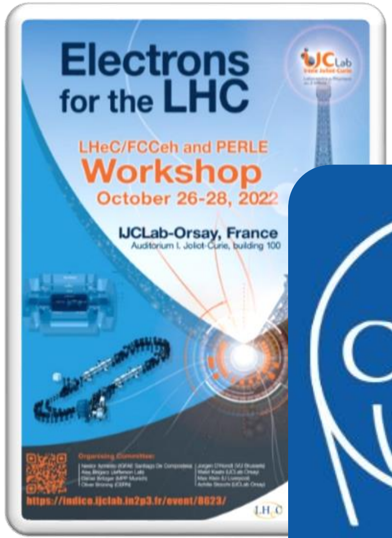
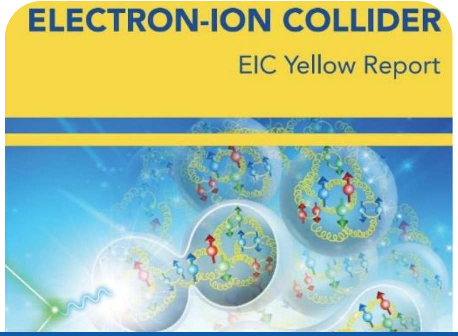
Abstract

There are two mass generating mechanisms in the standard model of particle physics (SM). One is related to the Higgs boson and fairly well understood. The other is embedded in quantum chromodynamics (QCD), the SM's strong interaction piece; and although responsible for emergence of the roughly 1 GeV mass scale that characterises the proton and hence all observable matter, the source and impacts of this emergent hadronic mass (EHM) remain puzzling. As bound states seeded by a valence-quark and -antiquark, pseudoscalar mesons present a simpler problem in quantum field theory than that associated with the nucleon. Consequently, there is a large array of robust predictions for pion and kaon properties whose empirical validation will provide a clear window onto many effects of both mass generating mechanisms and the constructive interference between them. This has now become significant because new-era experimental facilities, in operation, construction, or planning, are capable of conducting such tests and thereby contributing greatly to resolving the puzzles of EHM. These aspects of experiment, phenomenology, and theory, along with contemporary successes and challenges, are reviewed herein. In addition to providing an overview of the experimental status, we focus on recent progress made using continuum Schwinger function methods and lattice-regularised QCD. Advances made using other theoretical tools are also sketched. Our primary goal is to highlight the potential gains that can accrue from a coherent effort aimed at finally reaching an understanding of the character and structure of Nature's Nambu–Goldstone modes.

Jefferson Lab
Thomas Jefferson National Accelerator Facility





CERN

AMBER

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

Charting EHM using High Intensity, High Luminosity Facilities

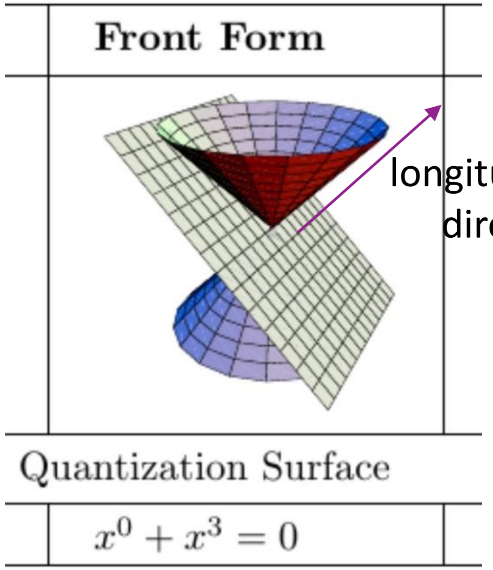
$$\Psi(x,t)$$

Measuring π & K *Wave Functions*

Wave Functions of Nambu Goldstone Bosons

- Physics Goals:
  - Pion and kaon distribution amplitudes (DAs – $\varphi_{\pi,K}$)
  - Nearest thing in quantum field theory to Schrödinger wave function
  - Consequently, fundamental to understanding π and K structure.
- Scientific Context:
  - For 40 years, the *x*-dependence of the pion's dominant distribution amplitude (DA) has been controversial.
  - Modern theory ⇒ EHM expressed in *x*-dependence of $\varphi_{\pi,K}(x)$
  - $\varphi_{\pi}(x)$ is direct measure of dressed-quark running mass in chiral limit.
  - Kaon DA = asymmetric around midpoint of its domain of support (0<x<1)
    - Degree of asymmetry is signature of constructive interference between EHM and HB mass-generating mechanisms

DAs are 1D projection of hadron's light-front wave function, obtained by integration $\sim \int d^2k_\perp \Psi(x, k_\perp)$



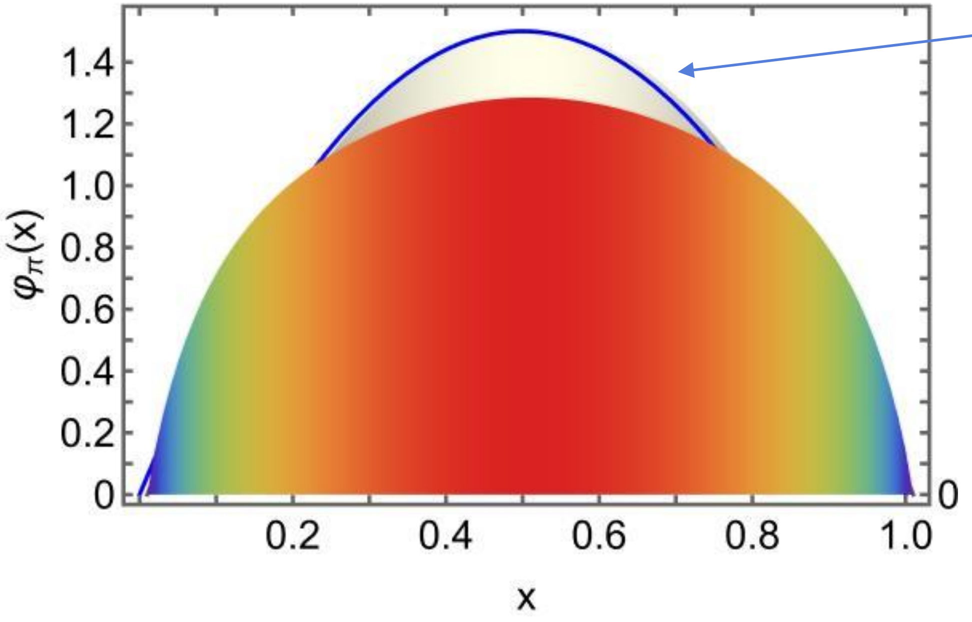
LF longitudinal direction

Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

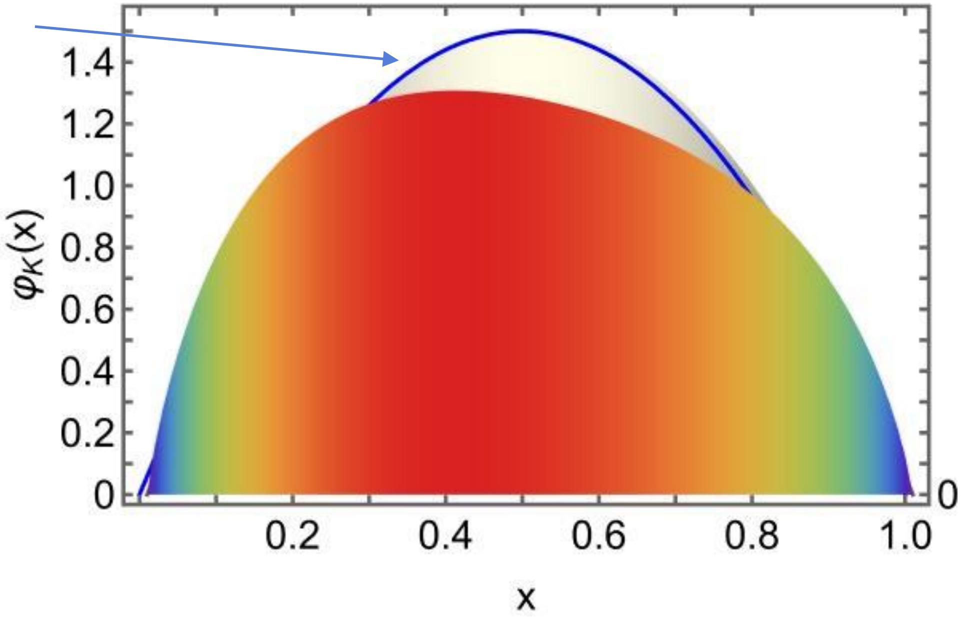
Exposing strangeness: projections for kaon electromagnetic form factors, Fei Gao *et al.*, arXiv:1703.04875 [nucl-th], Phys. Rev. D **96** (2017) 034024/1-8

Constraining the pion DA using Drell-Yan reactions on a proton, H.-Y. Xing (邢惠瑜) *et al.*, NJU-INP 077/23, e-Print: 2308.13695 [hep-ph], Phys. Lett. B **849** (2024), 138462/1-7

π & K DAs
cf. asymptotic profile



$\varphi_{\text{asymptotic}}$



- EHM generates broadening in both π & K
- EHM + Higgs-boson interference responsible for skewing in kaon
  - HB-only ⇒ peak shifted to $\frac{m_u^{\text{HB}}}{m_s^{\text{HB}}} \times \frac{1}{2} \approx 0.02$ … *wrong*
  - Instead, EHM*HB for u and s quarks … $\frac{\text{EHM } m_u \to M_u}{\text{EHM } m_s \to M_s} \times \frac{1}{2} \approx 0.4$

These features have widespread impact in studies of (hard) exclusive processes.

Broadening can be verified, e.g.,

- ✓ *in measurements of π and K electric charge distributions (elastic form factor measurements at large Q^2)*
- ✓ *in $\pi + p$ Drell-Yan measurements*

Possibility discussed throughout the series of teleworkshops: Perceiving EHM through AMBER @ CERN

Crystalised during EHM AMBER @ CERN VI 2021 Sept 27-29

Large part of Hui-Yu's PhD thesis

Phys. Lett. B 849 (2024) 138462

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PHYSICS LETTERS B

Letter

Constraining the pion distribution amplitude using Drell-Yan reactions on a proton

Check for updates

H.-Y. Xing [a,b], M. Ding [c], Z.-F. Cui [a,b], A.V. Pimikov [b], C.D. Roberts [a,b,*], S.M. Schmidt [c,d]

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Dyson-Schwinger equations
Emergence of mass
Pion structure
Quantum chromodynamics

ABSTRACT

Using a reaction model that incorporates pion bound state effects and continuum results for proton parton distributions and the pion distribution amplitude, φ_π, we deliver parameter-free predictions for the μ^+ angular distributions in $\pi N \to \mu^+\mu^- X$ reactions on both unpolarised and polarised targets. The analysis indicates that such angular distributions are sensitive to the pointwise form of φ_π and suggests that unpolarised targets are practically more favourable. The precision of extant data is insufficient for use in charting φ_π; hence, practical tests of this approach to charting φ_π must await data with improved precision from new-generation experiments. The reaction model yields a nonzero single-spin azimuthal asymmetry, without reference to T-odd parton distribution functions (DFs). This may necessitate additional care when attempting to extract such T-odd DFs from data.

Pion Distribution Amplitude

Pion DA

H.-Y. Xing, M. Ding, Z.-F. Cui et al. — Physics Letters B 849 (2024) 138462

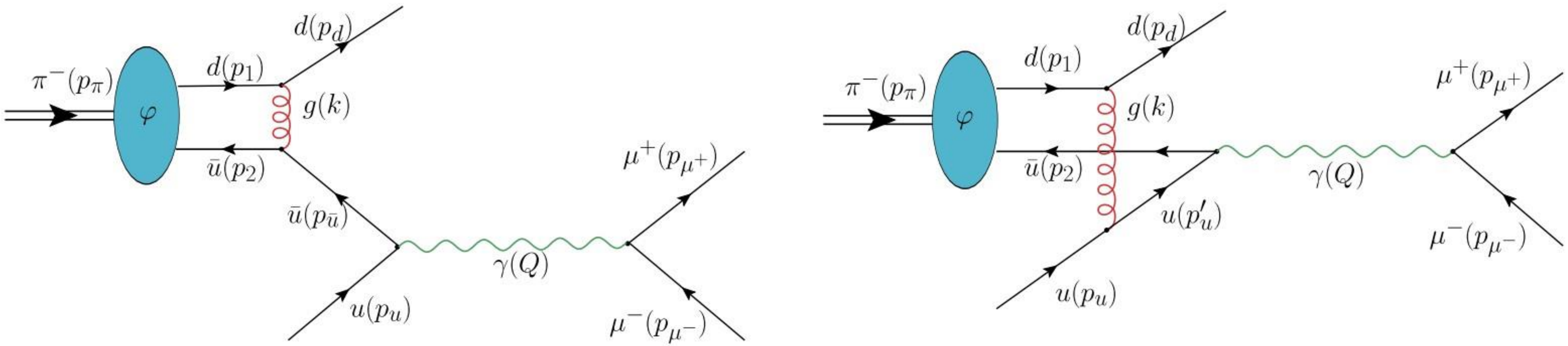


Fig. 1. Contributions supposed to describe the production of $\mu^+\mu^-$ pairs with large invariant mass, Q^2, and longitudinal-momentum fraction, x_L, in the process $\pi^-(p_\pi)N(p_N) \to \mu^+\mu^- X$. With $s = (p_\pi + p_N)^2$, $\tau = Q^2/s$, and $Q_{L/T}$ being the components of the (virtual) photon momentum that are parallel/perpendicular to p_π, then the $\mu^+\mu^-$ longitudinal momentum fraction is $x_L = 2Q_L/\sqrt{s}$. x_L takes the maximum value $x_L^{\max} = 1 - (Q^2 + Q_T^2)/s$, which is typically slightly less than unity on the relevant kinematic domain. π and N longitudinal momentum fractions are $x_{\pi,N} = [\pm x_F + (x_F^2 + 4\tau^2)^{1/2}]/2$: $x_F = x_\pi - x_N$; $x_\pi x_N = \tau$.

- Hard gluon exchange between annihilating valence antiquark in pion and spectator valence quark (and the partner process)

  $\Rightarrow$ associated cross-section is sensitive to pion leading-twist two-particle DA φ_π

Pion DA

- Angular distribution coefficients in unpolarised DY cross-section
- Uncertainties on all NA10 data are too large for meaningful assessment
- Comparison with **E615** is meaningful
  - Dilated DA

    χ^2/dof = 2.7
  - Asymptotic

    χ^2/dof = 4.8
- Dilated DA is supported

H.-Y. Xing, M. Ding, Z.-F. Cui et al. *Physics Letters B 849 (2024) 138462*

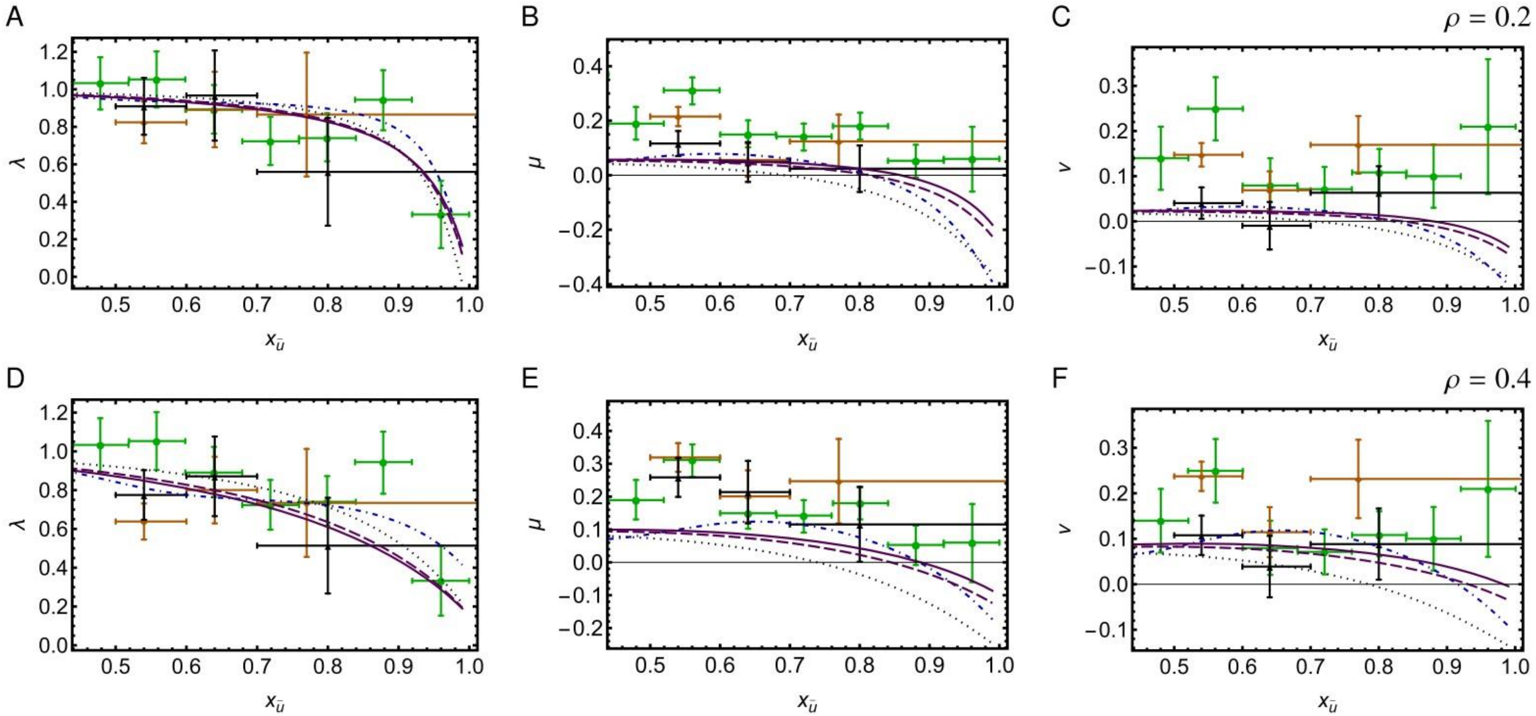
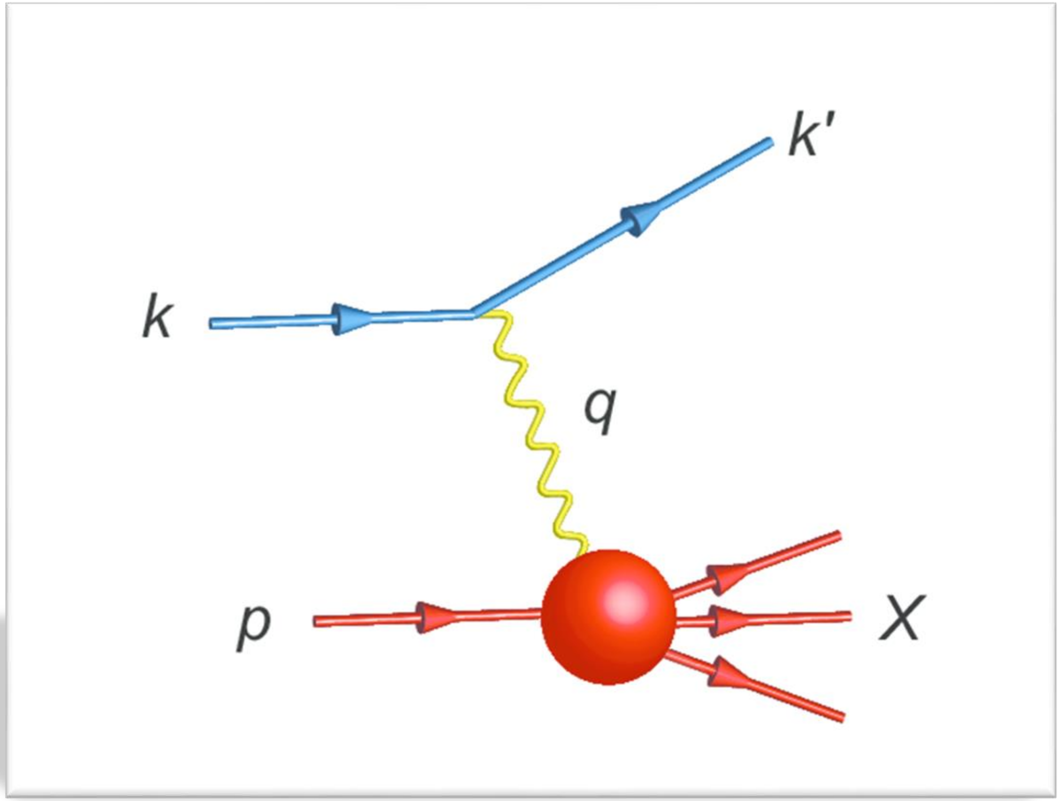


Fig. 2. Results for the unpolarised-target angular distribution coefficients in Eq. (3). Row 1 (panels A, B, C) – $\rho = 0.2$; Row 2 (panels D, E, F) – $\rho = 0.4$. The predictions are insensitive to the proton DFs, which cancel via normalisation. *Legend*. Solid purple curve: our predictions with CSM pion DA evolved from $\zeta_2 = 2$ GeV to ζ_5. Long-dashed purple: our predictions with pion DA evolved from $\zeta_1 = 1$ GeV. Dot-dashed blue: results obtained using the pion DA discussed in Ref. [50, BMS], which is associated therein with initial scale ζ_1. Dotted black: results obtained with $\varphi_{as}(x)$. Results inferred from data, all associated with $Q^2 = \zeta_5^2$: orange diamonds – Ref. [51, NA10] – 194 GeV π^- beams; black triangles – Ref. [51, NA10] – 286 GeV π^-; green circles – Ref. [52, E615] – 252 GeV π^-.

- Plainly, however, modern experiment with precise data is needed to make a strong case.



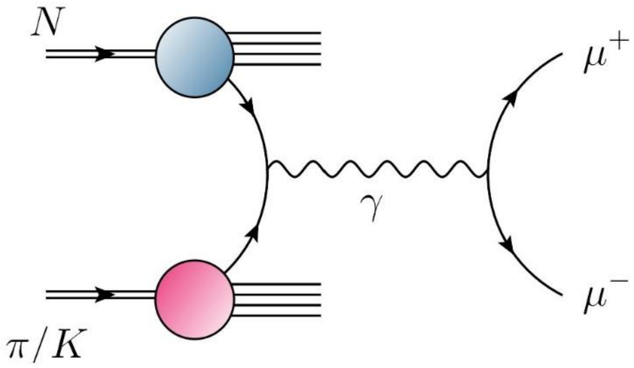
Parton Distribution Functions

NG Boson Distribution Functions

Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

- Physics Goals:
  - Precise data that can be used to determine
    Pion and Kaon Distribution Functions – valence, sea and glue
  - Provide the first complete charts of the internal structure of Nature's most fundamental Nambu-Goldstone bosons.
- Today:
  - Existing pion data are more than 40-years-old
  - That data only covers the valence-quark domain
  - A forty-year controversy, with doubts persisting over whether the data agree with QCD predictions or challenge the truth of QCD
  - Regarding the kaon, worldwide, only 8 points of data exist

NG Boson Distribution Functions



- Physics Goals:
  - Precise data that can be used to determine
    Pion and Kaon Distribution Functions – valence, sea and glue
  - Provide the first complete charts of the internal structure of Nature's most fundamental Nambu-Goldstone bosons.
- Future:
  - JLab, EIC, EicC
    ⇒ pion and kaon elastic electromagnetic form factors … reveal and quantify scaling violations in hard exclusive processes … hard prediction of QCD, never seen
    ⇒ pion and kaon valence quark distribution functions at large x_B
  - AMBER
    → precision data to chart π and K structure: DFs of valence, sea and glue.
    → Glue is particularly important … because controversial, yet prominent theory predicts that pions contain (almost) zero glue.

Craig Roberts: cdroberts@nju.edu.cn 447 .. 24/03/19 ... "Emergent Hadron Mass and Pion and Kaon Structure"

Controversy over pion valence DF

- QCD theory leads to the following statement:
  At any $\zeta > \zeta_{\mathrm{H}}$ for which experiment can be interpreted through parton distributions, then

$$x \simeq 1 \Rightarrow q^{\pi}(x;\zeta) \propto (1-x)^{\beta=2+\gamma}, \gamma > 0$$

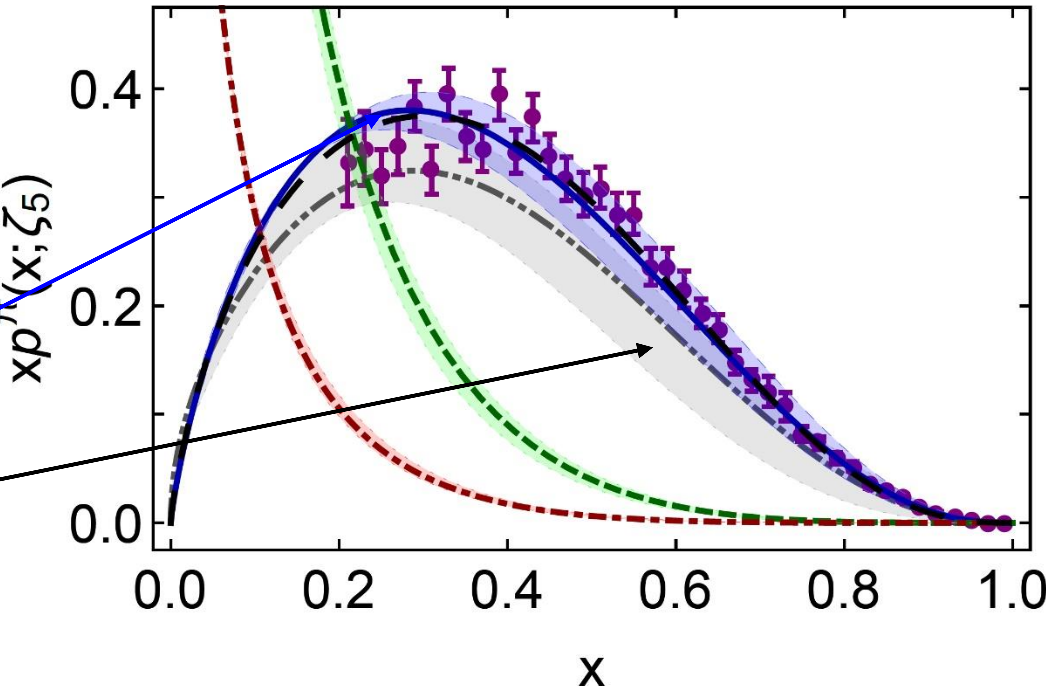
- Consequence
  - Any analysis of DY, DIS, etc. experiment which returns β <2 conflicts with QCD.
- Observations
  - All existing internally-consistent calculations preserve connection between large-k^2 behaviour of interaction and large-x behaviour of DF: J=0 … $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$
- No existing calculation with n=1 produces anything other than $(1-x)^2$
- Internally-consistent calculation that preserve RG properties of QCD,
  then 2 → 2+γ, γ>0, at any factorisation-valid scale
- Controversy:
  - Some contemporary data fits yield $(1-x)^{1+\gamma}$
  - Result depends on assumptions about hard scattering kernel

  - Is QCD wrong?
  - Is existing large-x data a true measure of $q^{\pi}(x;\zeta)$?
  - Are fitter-favoured analysis methods correct/complete?

π valence-quark distributions
25 Years of Theory Evolution → 2024

$\beta^{contm}(\zeta_5)$ = 2.66(12)
$\beta^{lattice}(\zeta_5)$ = 2.45(58)

- Developments in continuum-QCD enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^{\pi}(x;\zeta)$ is dilated by EHM, yet remains consistent with pQCD endpoint behaviour
- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^{\pi}(x;\zeta)$
- Agreement between new continuum prediction for $u^{\pi}(x;\zeta)$ [Ding:2019lwe] and lattice-QCD result [Sufian:2019bol]



- Real strides toward understanding pion structure.
- Standard Model prediction: stronger than ever before
- *After 30 years – new era dawning in which the ultimate experimental checks can be made:*
  M2 beam-line @ CERN … JLab12 … EIC … EicC

π valence-quark di
25 Years of Theory

- Developments in contin
  enabled 1st parameter-
  valence, glue and sea di
  – Reveal that $u^\pi(x;\zeta)$
    consistent with pQC
- Novel lattice-QCD algori
  pointwise behaviour of u
- Agreement between
  new continuum predict
  and lattice-QCD result
- Real strides toward ur
- Standard Model predi
- *After 30 years – new e ... cks can be made:*
  M2 beam-line @

Physics Letters B
Volume 850, March 2024, 138534

Letter

Pion distribution functions from low-order Mellin moments

Ya Lu (陆亚) [a], Yin-Zhen Xu (徐胤禛) [b c], Khépani Raya [b], Craig D. Roberts [d e], José Rodríguez-Quintero [b]

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https://doi.org/10.1016/j.physletb.2024.138534

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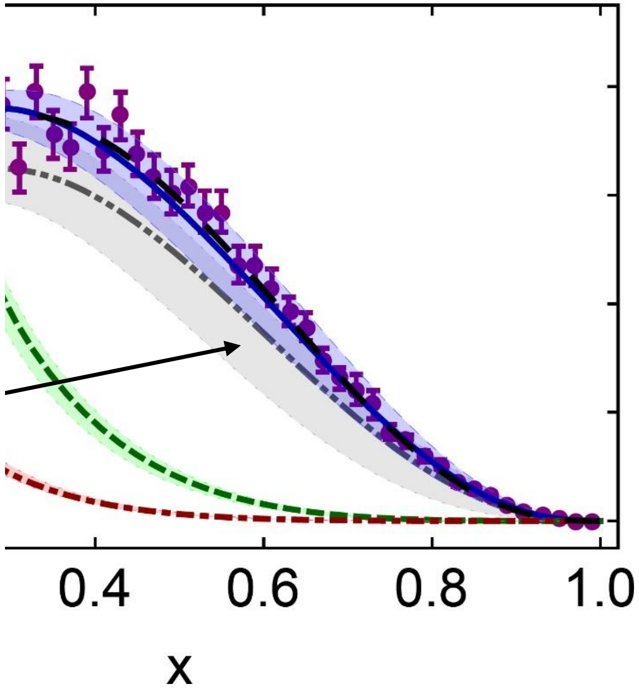
Abstract

Exploiting an evolution scheme for parton distribution functions (DFs) that is all-orders exact, contemporary lattice-QCD (lQCD) results for low-order Mellin moments of the pion valence quark DF are shown to be mutually consistent. The analysis introduces a means by which key odd moments can be obtained from the even moments in circumstances where only the latter are available. Combining these elements, one arrives at parameter-free lQCD-based predictions for the pointwise behaviour of pion valence, glue, and sea DFs, with sound uncertainty estimates. The behaviour of the pion DFs at large light-front momentum fraction, $x \gtrsim 0.85$, is found to be consistent with QCD expectations and continuum analyses of pion structure functions, *i.e.*, damping like $(1-x)^{\beta_{\rm parton}}$, with $\beta_{\rm valence} \approx 2.4$, $\beta_{\rm glue} \approx 3.6$, $\beta_{\rm sea} \approx 4.6$. It may be possible to test these predictions using data from forthcoming experiments.

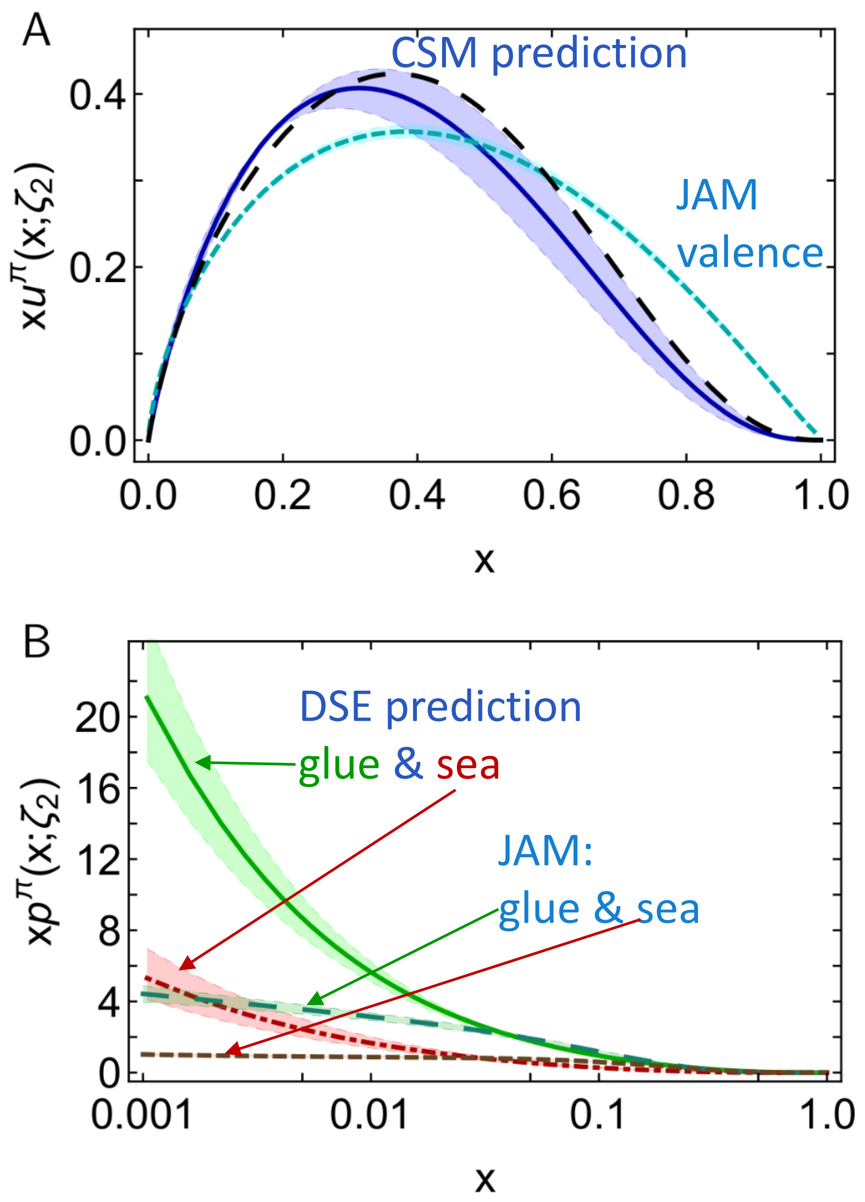
$\beta^{\rm contm}(\zeta_5) = 2.66(12)$

$\beta^{\rm lattice}(\zeta_5) = 2.45(58)$



π DFs … Modern Theory Predictions vs Traditional Phenomenological Fits to Data

- **Valence:**
  - momentum fraction similar
  - Phenomenological Fits … profile much harder & inconsistent with QCD prediction
- **Glue:**
  - Qualitative similarities on x ≥ 0.05, but marked quantitative disagreement, especially on complementary domain
  - Both continuum prediction and fit are very different from early phenomenology
  - Should be tested in new experiments that are directly sensitive to the pion's gluon content.
  - E.g., prompt photon & J/Ψ production
- **Sea:**
  - Prediction and fit disagree on entire x-domain
  - If pion's gluon content is considered uncertain, then fair to describe sea-quark distribution as empirically unknown
  - Motivation for the collection and analysis of DY data with $\pi^{\pm}$ beams on isoscalar targets

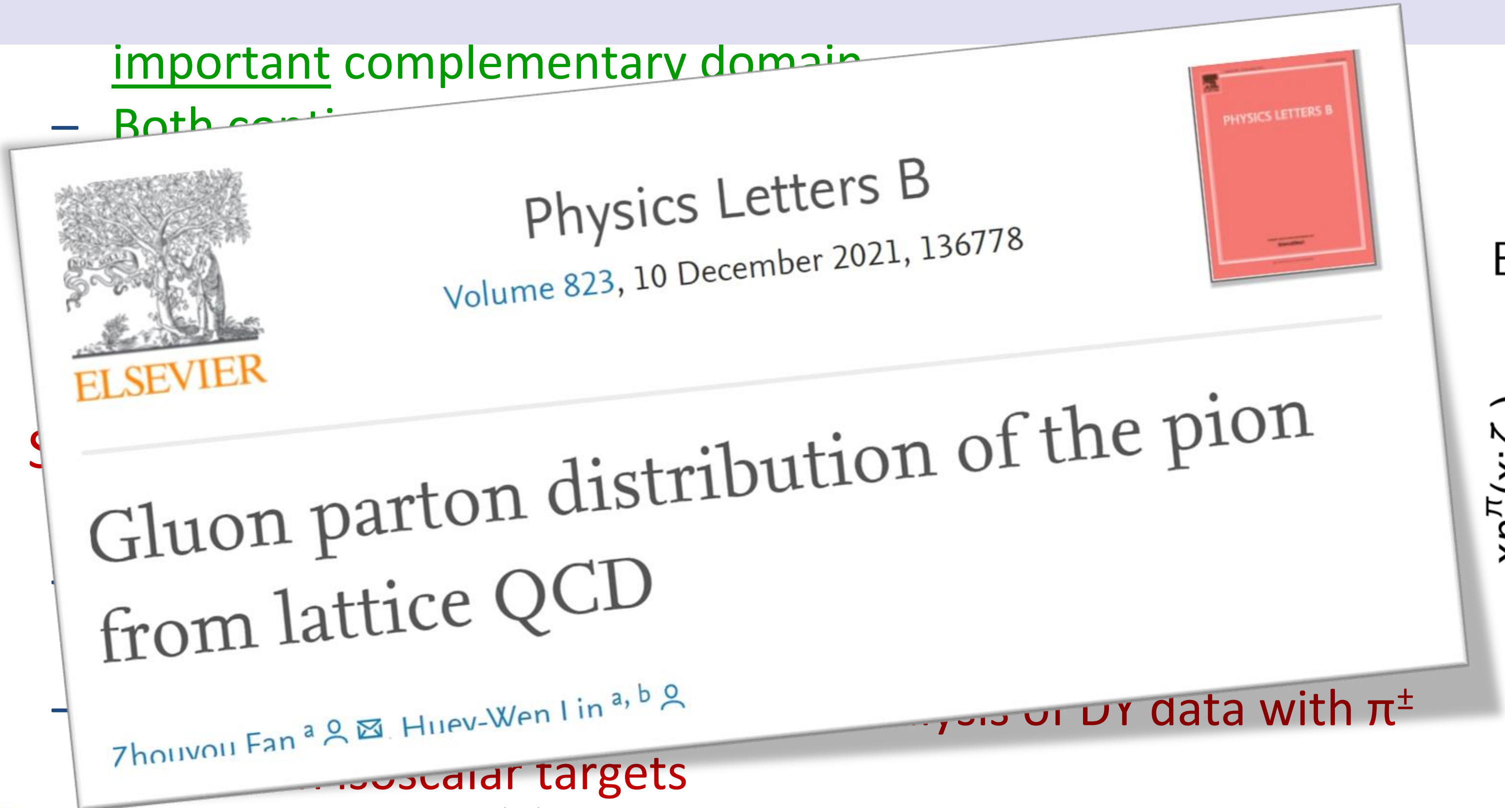


π DFs … Modern Theory Predictions vs Traditional Phenomenological Fits to Data

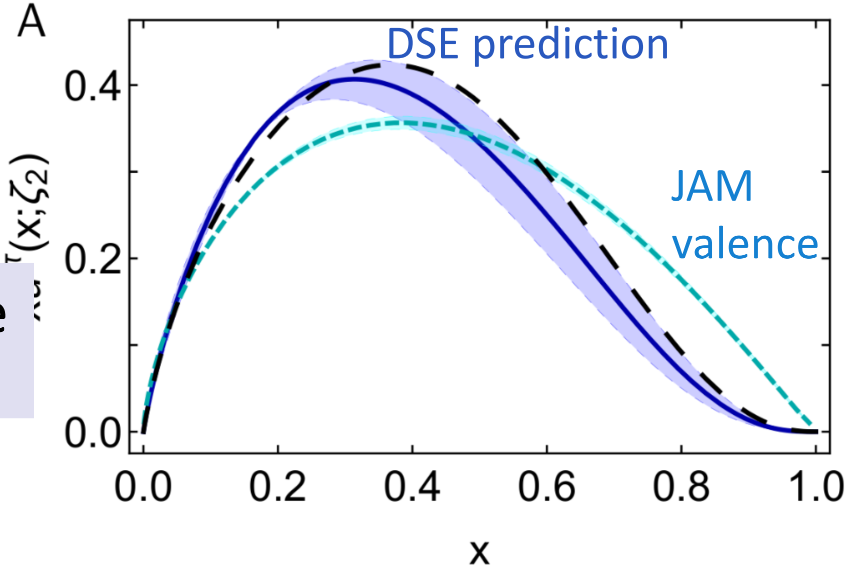
- Valence:
  - momentum fraction similar
  - JAM … publication ignores NLL resummation … profile much harder & inconsistent with QCD prediction

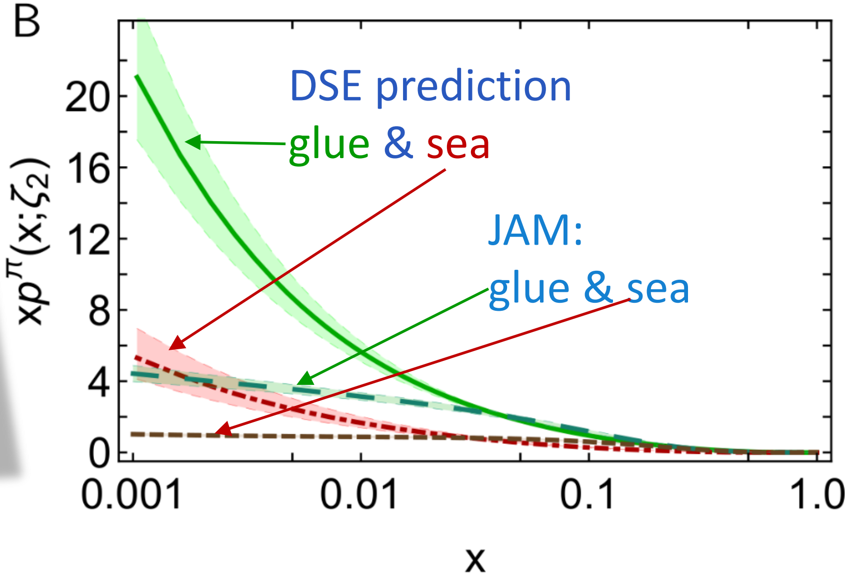
Exploratory lQCD results for pion's glue DF are now available

important complementary domain
- Both conti…


Physics Letters B
Volume 823, 10 December 2021, 136778
ELSEVIER
Gluon parton distribution of the pion from lattice QCD
Zhouyou Fan [a], Huey-Wen Lin [a,b]

- S…
  - … of DY data with π±
  - … isoscalar targets

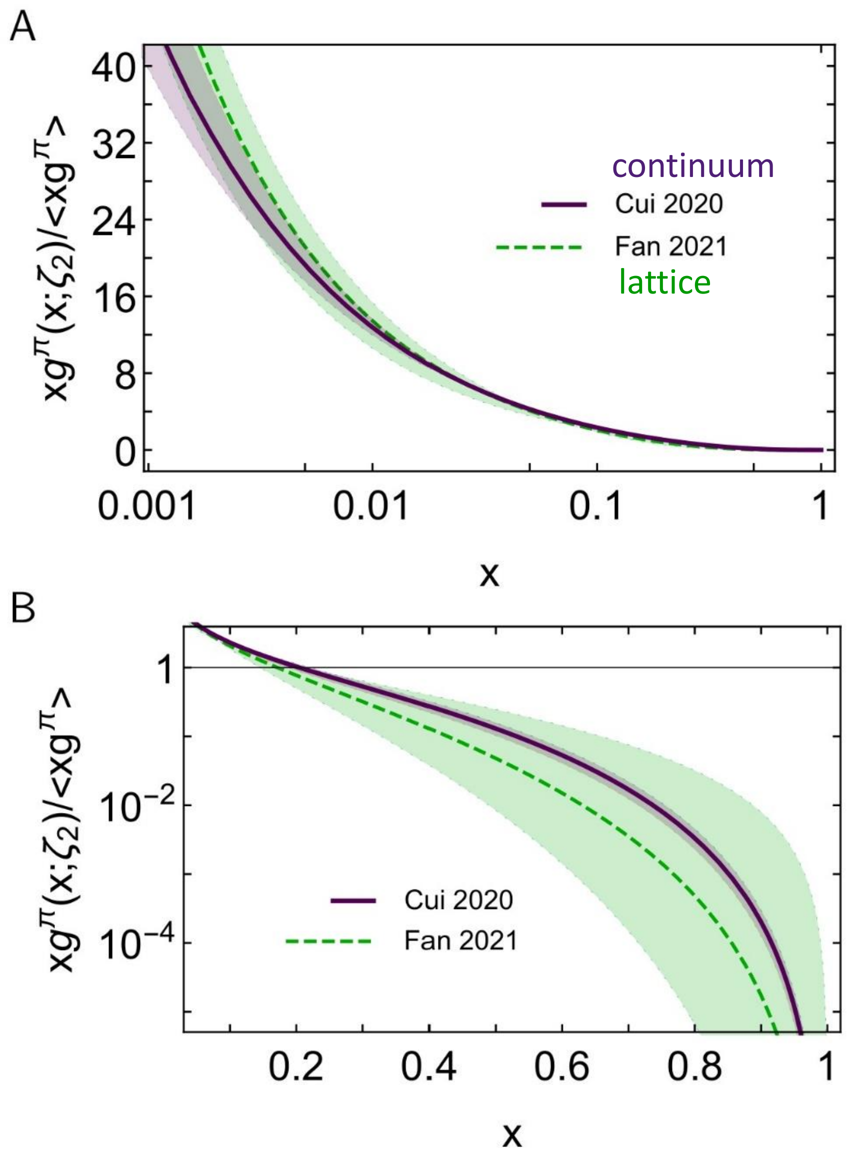




Glue in π: Continuum (Eur. Phys. J. C 80 (2020) 1064/1-20) & Lattice Predictions (arXiv: Phys.Lett.B 823 (2021) 136778)

Two distinct methods for tackling QCD
Agree quantitatively on $g^{\pi}(x)$

- Phenomenological analyses
  exhibit qualitatively different behaviour
- Highlights need for new data and improved phenomenology in order to turn that data into a real test of QCD and our understanding of Nambu-Goldstone modes.
- AMBER @ CERN can provide the necessary precise data.



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 - Editors' Suggestion

Status: Kaon

- Little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no results
- One piece of available experimental information:

$$u_K(x)/u_\pi(x)$$

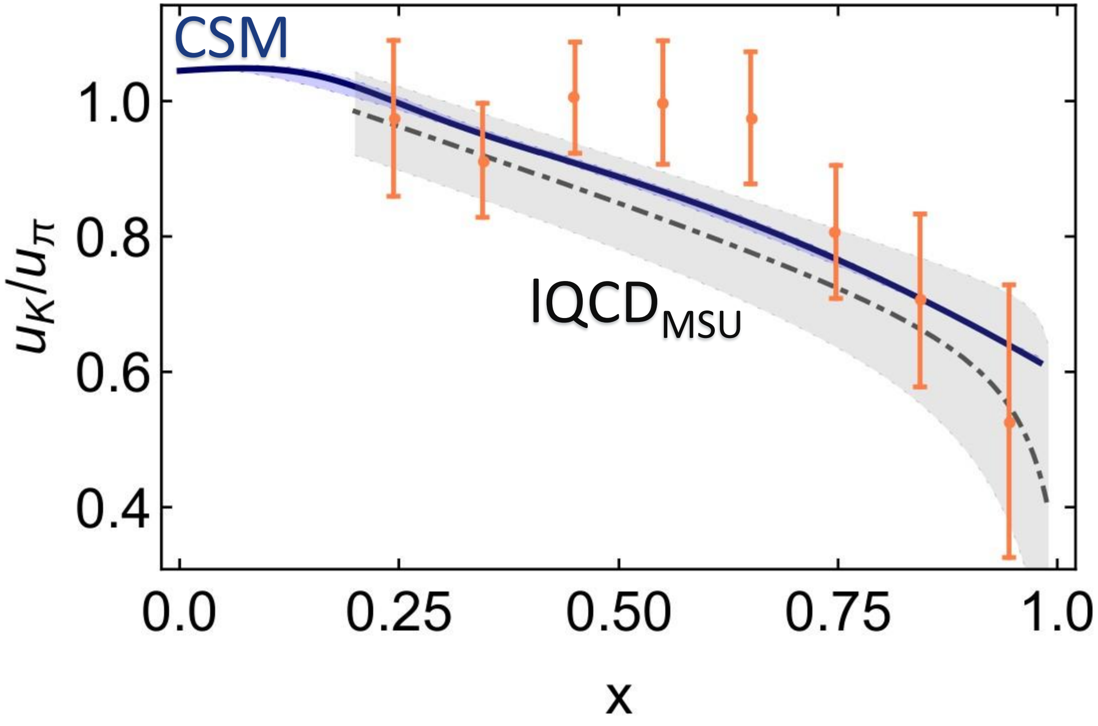
  - Continuum prediction for ratio is consistent with data.
  - But, given large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - New, precise data critical if this ratio to be used as path to understanding the Standard Model's Nambu-Goldstone modes;
    - Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately = better.

Programmes at JLab, AMBER

Proposals at EIC and EicC

Tackling the kaon structure function at EicC
Gang Xie *et al.* e-Print: 2109.08483 [hep-ph].
Chin. Phys. C 46 (2022) 6, 064107

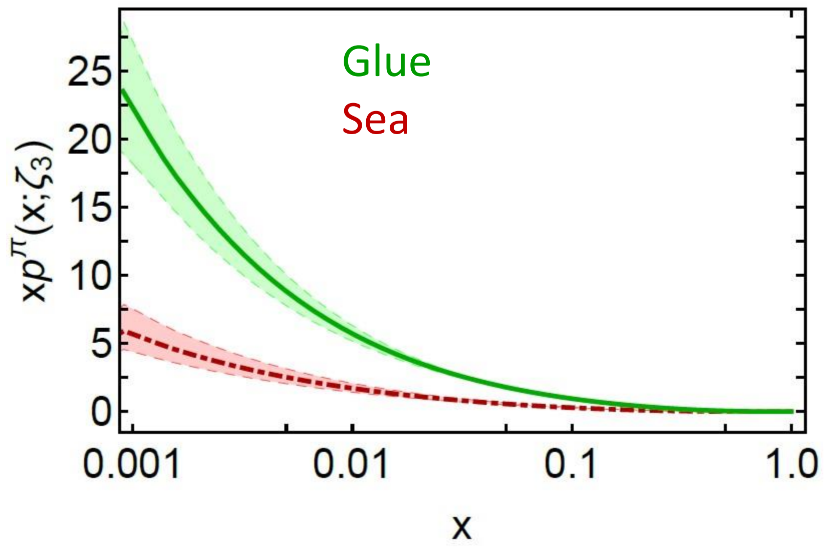
Entirety of human history
– only 8 kaon data in existence
CERN … *Phys. Lett. B* 93 (1980) 354-356

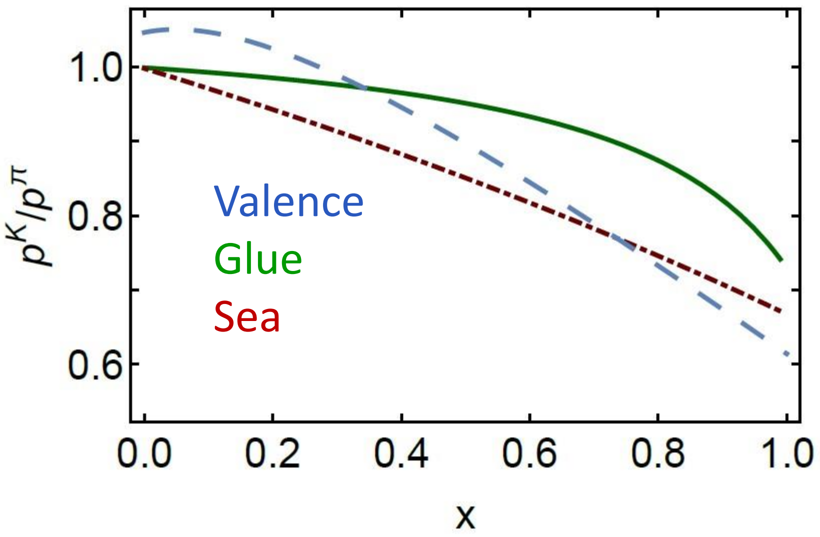


Status: Kaon

Kaon parton distributions, Z.-F. Cui et al., arXiv:2006.14075 [hep-ph], Eur. Phys. J. C 80 (2020) 1064/1-20

- Little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no predictions … until now
- Glue and Sea – Predictions:
  - DFs similar to those in the pion
  - Detailed comparison requires use of mass-dependent splitting functions.
  - Conclusions:
    i. Light-front momentum fraction carried by s-quarks in the kaon increases by ~ 5%;
    ii. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).





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?

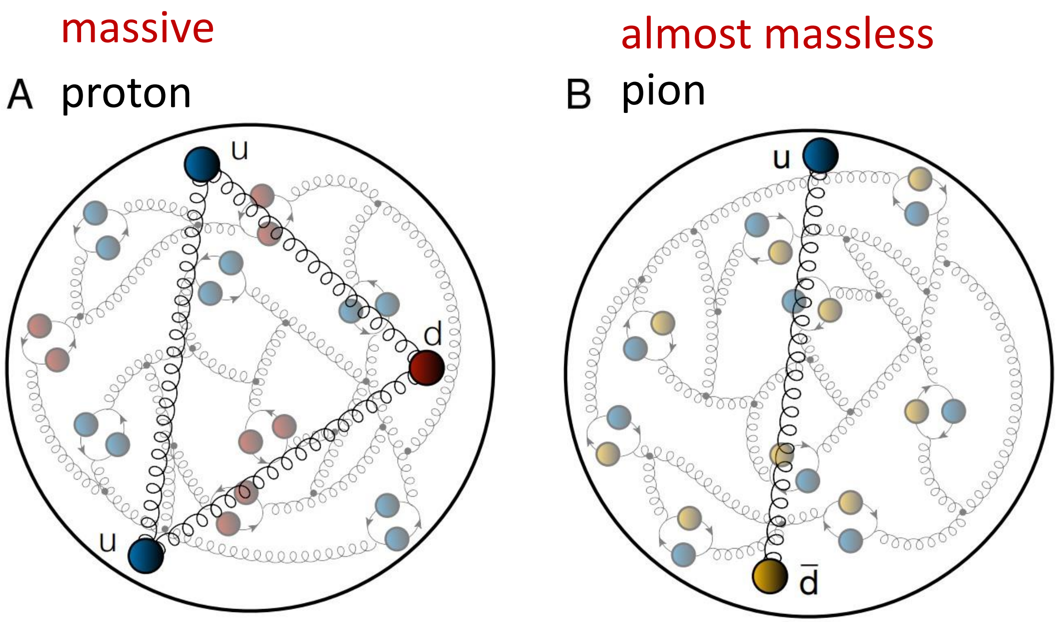


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

skip

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

$$\begin{cases} d^p(x;\zeta_H), u^p(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_H), u^\pi(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^2 \end{cases}$$

- $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p$, $\beta_\pi = 2 + \gamma_\pi$
  - Gluon DFs: $\beta_{p,\pi}^{\rm glue} \geq \beta_{p,\pi}^{\rm val} + 1$
  - Sea DFs: $\beta_{p,\pi}^{\rm sea} \geq \beta_{p,\pi}^{\rm val} + 2$

✓ 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

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

8 Proton has valence glue but no valence quarks!

- 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 fitting practitioners typically overlook QCD constraints

Proton Spin Crisis

- Long story … 35+ years … $-billions …
- Future … Electron Ion Collider
  … Total project cost is expected to range from $1.7-2.8 billion
  … First beam ~ 2034

USA NAS Report

Hearing from experts on the science that an EIC would be able to carry out, the committee finds that

Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

EHM is the keystone for future experiments in hadroparticle physics

Proton Spin

Polarised parton distribution functions and proton spin, Peng Cheng (程鹏), Yang Yu (俞杨), Hui-Yu Xing (邢惠瑜) *et al.*, e-print: 2304.12469 [hep-ph], Phys. Lett. B **844** (2023) 138074/1-7

- CSMs predict

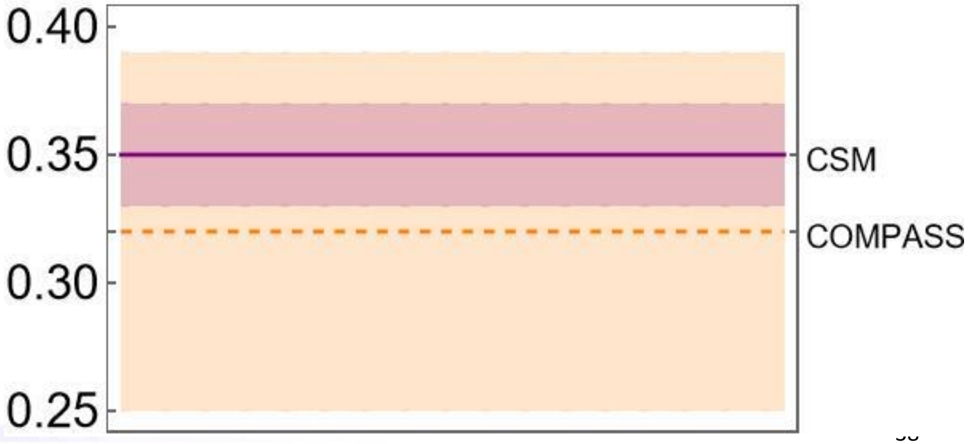
  $a_0 \approx 65\%$ of proton spin
  carried by valence quark
  quasiparticle degrees of freedom at the hadron scale.
- Under **P1** evolution, this value is independent of scale.
- However, measurements of the proton spin are sensitive to

  non-Abelian anomaly corrected combination $(n_f = 4)$

$$a_0^{\rm E}(\zeta) = a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \int_0^1 dx\, \Delta G(x;\zeta) =: a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \Delta G(\zeta)\,,$$

- CSM prediction: $a_0^E(\zeta = \sqrt{3}\mathrm{GeV}) = 0.35(2)$
- COMPASS: $a_0^{\mathrm{COMPASS}}(\zeta = \sqrt{3}\mathrm{GeV}) = 0.32(7)$
- *Parameter-free explanation*

  of proton spin measurement



Theory Predictions

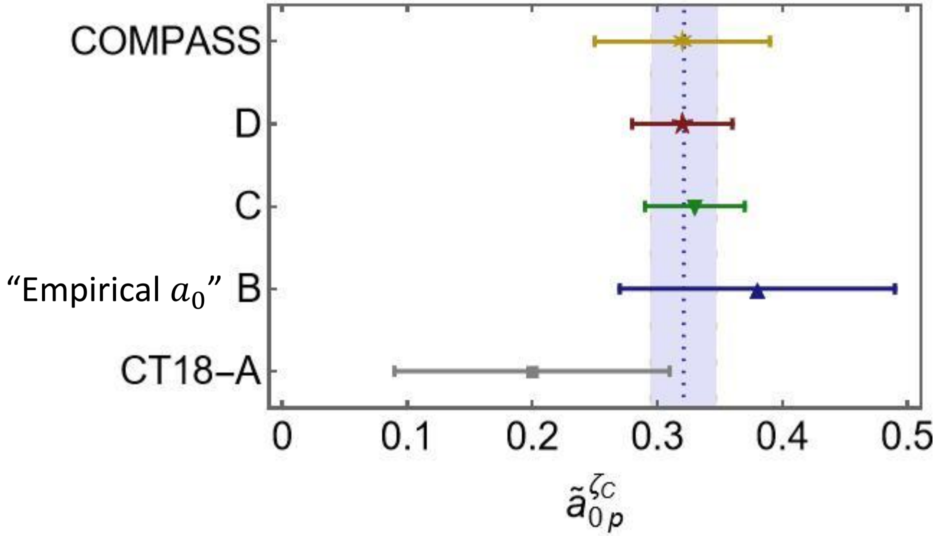
Viable parameter-free explanation of proton spin measurement

- Novel approach to understanding character of proton internal structure has enabled derivation of algebraic formula for the gluon contribution to the proton spin

- ✓ *Symmetry, symmetry breaking, and pion parton distributions,* Minghui Ding, Khépani Raya *et al*., arXiv:1905.05208 [nucl-th], Phys. Rev. D **101** (2020) 054014/1-14
- ✓ *Parton distributions of light quarks and antiquarks in the proton*, Lei Chang (常雷), Fei Gao (高飞) and Craig D. Roberts, e-Print: 2201.07870 [hep-ph], Phys. Lett. B 829 (2022) 137078/1-7
- ✓ *All-Orders Evolution of Parton Distributions: Principle, Practice, and Predictions,* Pei-Lin Yin (尹佩林), Yin-Zhen Xu (徐胤禛), Zhu-Fang Cui (崔著钫) *et al*., e-Print: 2306.03274 [hep-ph], Chin. Phys. Lett. *Express* **40** (2023) 091201/1-8. Express Letter.

$$a_{0H}^{\zeta} := \langle x^0 \rangle_{\Delta\Sigma_H}^{\zeta} = \langle x^0 \rangle_{\Delta\Sigma_H}^{\zeta_{\mathcal{H}}} ,$$

$$\Delta G_H^{\zeta} := \langle x^0 \rangle_{\Delta g_H}^{\zeta} = a_0^{\zeta} \, \frac{12}{25} \left[[\langle x \rangle_{\mathcal{V}_H}^{\zeta}]^{-75/32} - 1 \right]$$



- Reveals that gluon contribution is positive and grows as resolving scale of the probe increases, removing measurable spin from the quarks
- Prediction for valence-quark part of proton spin: $a_0^E(\zeta = \sqrt{3}\text{GeV}) = 0.32(3)$
- COMPASS (CERN) measurement (2016): $a_0^{\text{COMPASS}}(\zeta = \sqrt{3}\text{GeV}) = 0.32(7)$

Proton Spin Budget

Contact interaction study of proton parton distributions,
Yang Yu (俞杨), Peng Cheng (程鹏), Hui-Yu Xing (邢惠瑜),
Fei Gao (高飞) and Craig D. Roberts,
NJU-INP 083/24, e-Print: 2402.06095 [hep-ph]

- Consider a light-front separation of the proton spin into contributions from quark and gluon spin and angular momenta:

$$\frac{1}{2} = \frac{1}{2}a_0 + L_q(\zeta) + \Delta G(\zeta) + L_g(\zeta)$$

- At hadron scale:
  - ✓ $a_0 = 0.55, L_q(\zeta_H) = 0.23$
  - ✓ $\Delta G(\zeta_H) = 0, L_g(\zeta_H) = 0$

  all proton spin is lodged with valence quark helicity and orbital angular momentum
- Evolved to COMPASS scale

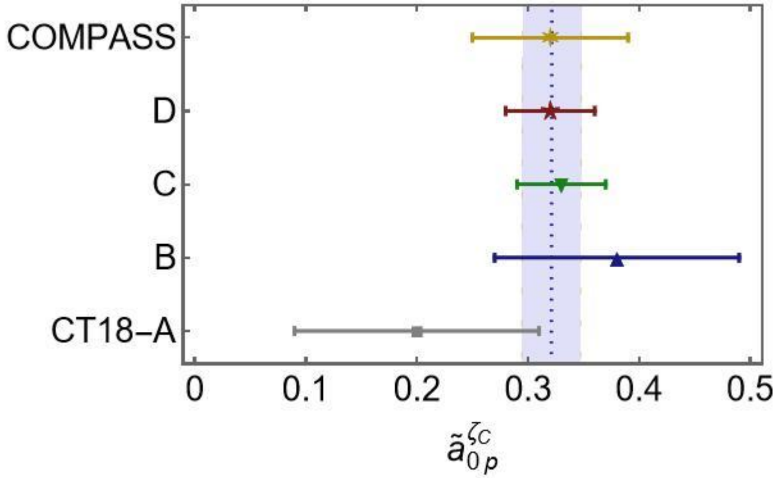
$$a_0 = 0.54, L_q(\zeta) = 0.03, \Delta G(\zeta) = 1.07, L_g(\zeta) = -0.87$$

- Including calculation uncertainties
  - ✓ Valence quark helicity: $(50 \pm 12)\%$,
  - ✓ glue: $\approx 40\%$,
  - ✓ sign and magnitude of valence quark light-front orbital angular momentum is uncertain

Proton and pion distribution functions in counterpoint

- CSMs delivered 1st ever

  unified body of predictions for all proton and pion DFs
  - valence, glue, and 4-flavour-separated sea, unpol. and pol.
  - explain COMPASS measurement of quark helicity



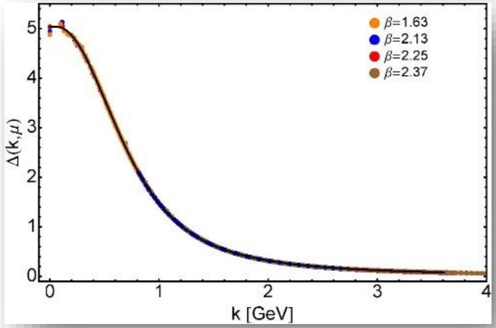
- x-dependence of DFs is strongly hadron dependent

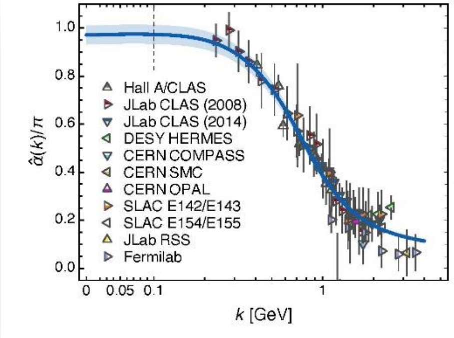
  Smoking gun for EHM
  - At any resolving scale, ζ, those in the pion are the hardest (most dilated).
- All CSM DFs comply with QCD constraints on endpoint (low- and high-x) scaling behaviour.
- However, existing global fits ignore QCD constraints, so:
  - Fail to deliver realistic DFs, even from abundant 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.*

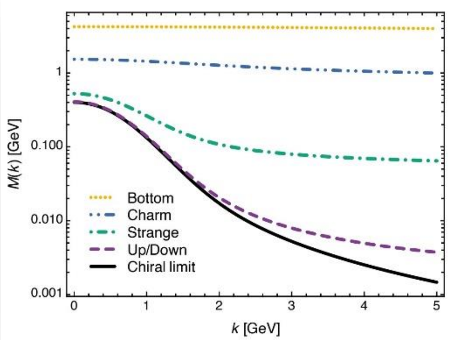
Synergy of Experiment, Phenomenology, Theory

- *Drawing detailed map of the proton is important because proton is Nature's only absolutely stable bound state.*
  - ✓ *However, while QCD is the proton, the proton is not QCD*
- *Strong interaction theory is maturing*
  - ✓ *Expanding array of parameter-free predictions for the proton – yes*
  - ✓ *And all the other hadrons whose properties express the full meaning of QCD*
- *Understanding how QCD's simplicity explains the emergence of hadron mass and structure requires investment in facilities that can deliver precision data on much more than one of Nature's hadrons.*
- *AMBER@CERN, EIC, EicC, STCF, CEPC, JLab22, LHeC could …*
  - ✓ *Deliver precise structure data on a wide range of hadrons with distinctly different quantum numbers*
  - ✓ *Thereby move Science into a new realm of understanding.*

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







Craig Roberts: cdroberts@nju.edu.cn 447 .. 24/03/19 ..."Emergent Hadron Mass and Pion and Kaon Structure"

Grant no. 12135007
国家自然科学基金委员会
National Natural Science Foundation of China

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*

Grant no. 12135007

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National Natural Science Foundation of China

Emergent Hadron Mass

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

- QCD is unique amongst known fundamental theories of n
  - The degrees-of-freedom used to express the scale-free Lag
  - Massles
  - Gluon r … e of a running
  - Massles
    - Massive baryons and simultaneously Massless mesons

There are theories of many things,

But is there a theory of everything?

- 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*

Thankyou

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

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

CERN

AMBER

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

New Paradigm

All-orders ζ-evolution

- **P1** – *In the context of Refs. [73, 74], there exists at least one effective charge, $\alpha_{1\ell}(k^2)$, which, when used to integrate the leading-order perturbative evolution (DGLAP) equations, defines an evolution scheme for parton DFs that is all-orders exact.*
- CSM Process-Independent charge serves this purpose

ELSEVIER
Physics Letters B
Volume 95, Issue 1, 8 September 1980, Pages 70-74

Renormalization group improved perturbative QCD

G. Grunberg [1]

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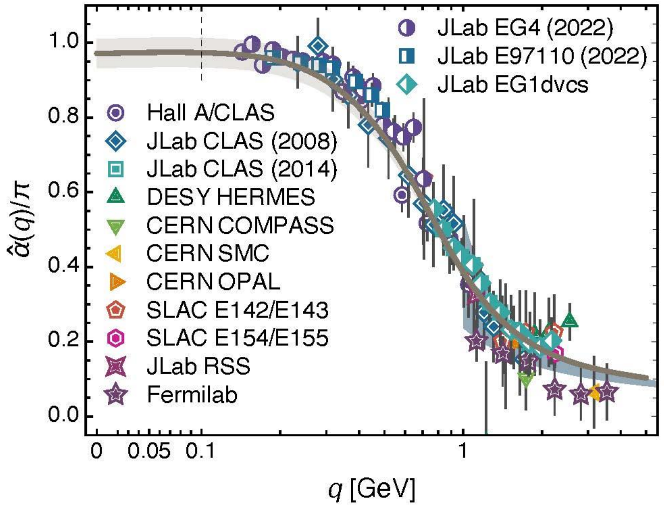
https://doi.org/10.1016/0370-2693(80)90402-5 Get rights and content

Abstract

The results of perturbative QCD calculations are reformulated as renormalization-scheme independent predictions; in so doing, we obtain a renormalization group improvement of perturbation theory. As an application, we show that asymptotic freedom alone does not give the correct quantitative relation between pseudoscalar charmonium decay and the scaling violations in deep inelastic scattering.

- *Hadron scale, ζ_H*
  Scale at which all properties of a given hadron are carried by valence degrees-of-freedom



[73] G. Grunberg, Renormalization Group Improved Perturbative QCD, Phys. Lett. B 95 (1980) 70, [Erratum: Phys. Lett. B 110, 501 (1982)].
[74] G. Grunberg, Renormalization Scheme Independent QCD and QED: The Method of Effective Charges, Phys. Rev. D 29 (1984) 2315.
[75] A. Deur, S. J. Brodsky, G. F. de Teramond, The QCD Running Coupling, Prog. Part. Nucl. Phys. 90 (2016) 1–74.
[76] A. Deur, V. Burkert, J. P. Chen, W. Korsch, Experimental determination of the QCD effective charge $\alpha_{g_1}(Q)$, Particles 5 (2) (2022) 171–179.
[77] A. Deur, S. J. Brodsky, C. D. Roberts, QCD Running Couplings and Effective Charges – arXiv:2303.00723 [hep-ph] .

Proton and pion distribution functions in counterpoint

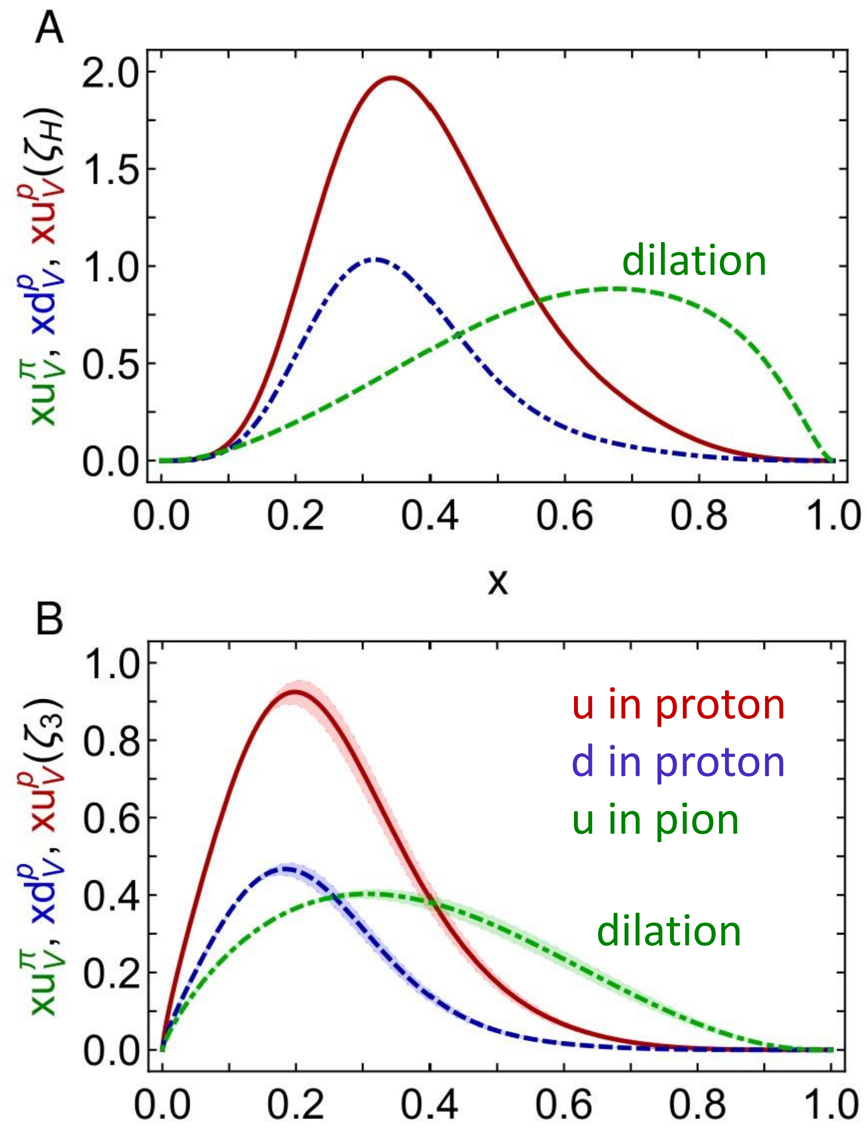
Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) *et al.*,
NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130

- 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

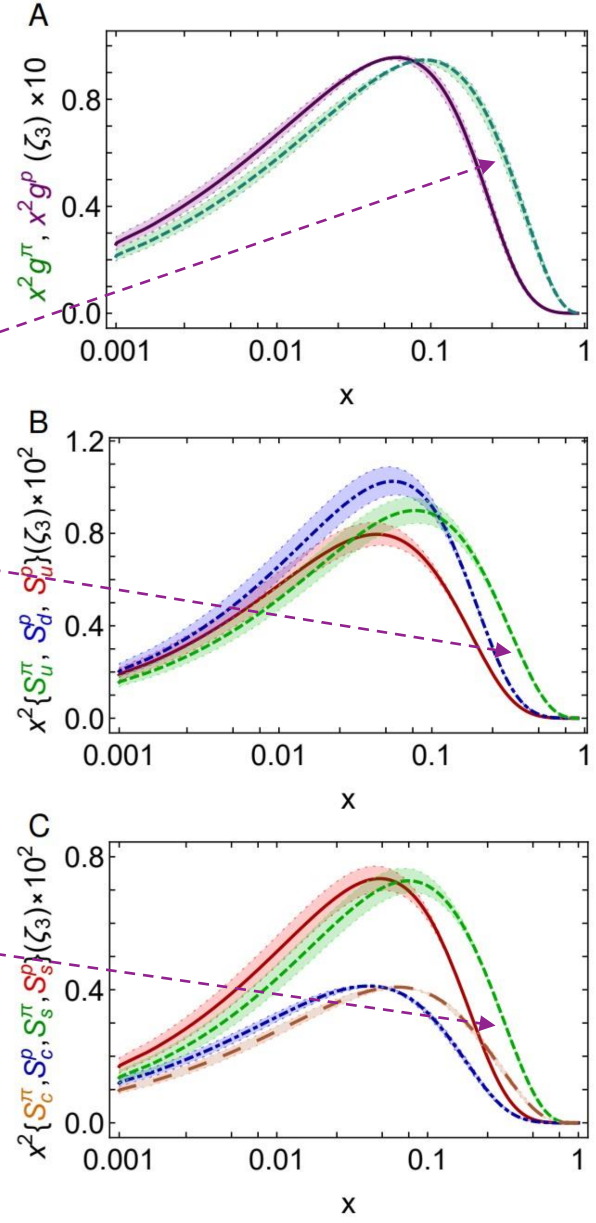
  i. "Obvious" because $(1-x)^2$ vs. $(1-x)^3$ behaviour & preservation of this unit difference under evolution

  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



Proton Spin Crisis

- Long story … 35+ years … $-billions …
- Future … Electron Ion Collider
  … Total project cost is expected to range from $1.7-2.8 billion
  … First beam ~ 2034

USA NAS Report

Hearing from experts on the science that an EIC would be able to carry out, the committee finds that

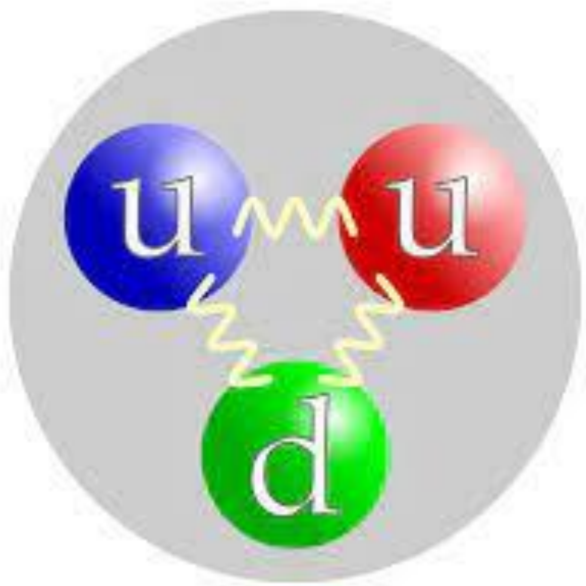
Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

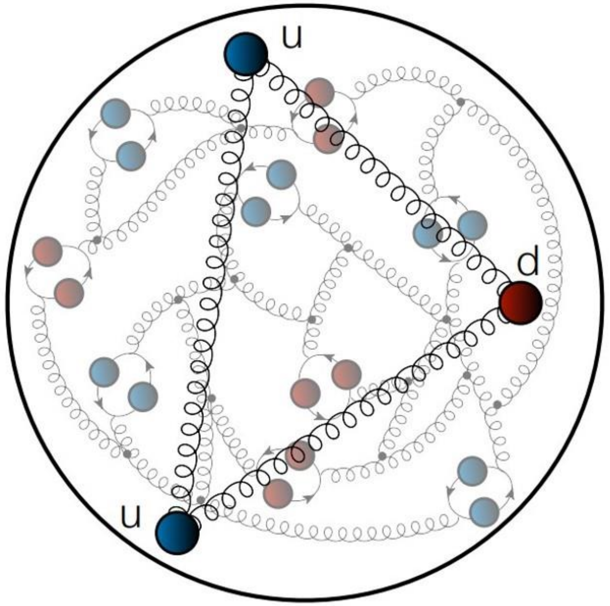
EHM is the keystone for future experiments in hadroparticle physics

Origin of Proton Spin

- Basic answer
- This is **NOT** the proton



- In relativistic quantum non-Abelian gauge field theory (QCD), this is the proton



A. ∃orbital angular momentum in every frame

B. *Infinitely many spin $(J)=1$ gluons can potentially carry a lot of the proton spin*

- 2 valence u quarks + 1 valence d quark + sea of infinitely many quarks and antiquarks and gluons

Polarised quark distribution functions at $\zeta = \sqrt{3}$GeV

- Continuum predictions for helicity-dependent quark DFs deliver quantitative agreement with all available world data
- COMPASS $\Delta u(x)$ lead to underestimate of g_A by 25%
  - Explains why COMPASS data lie below prediction

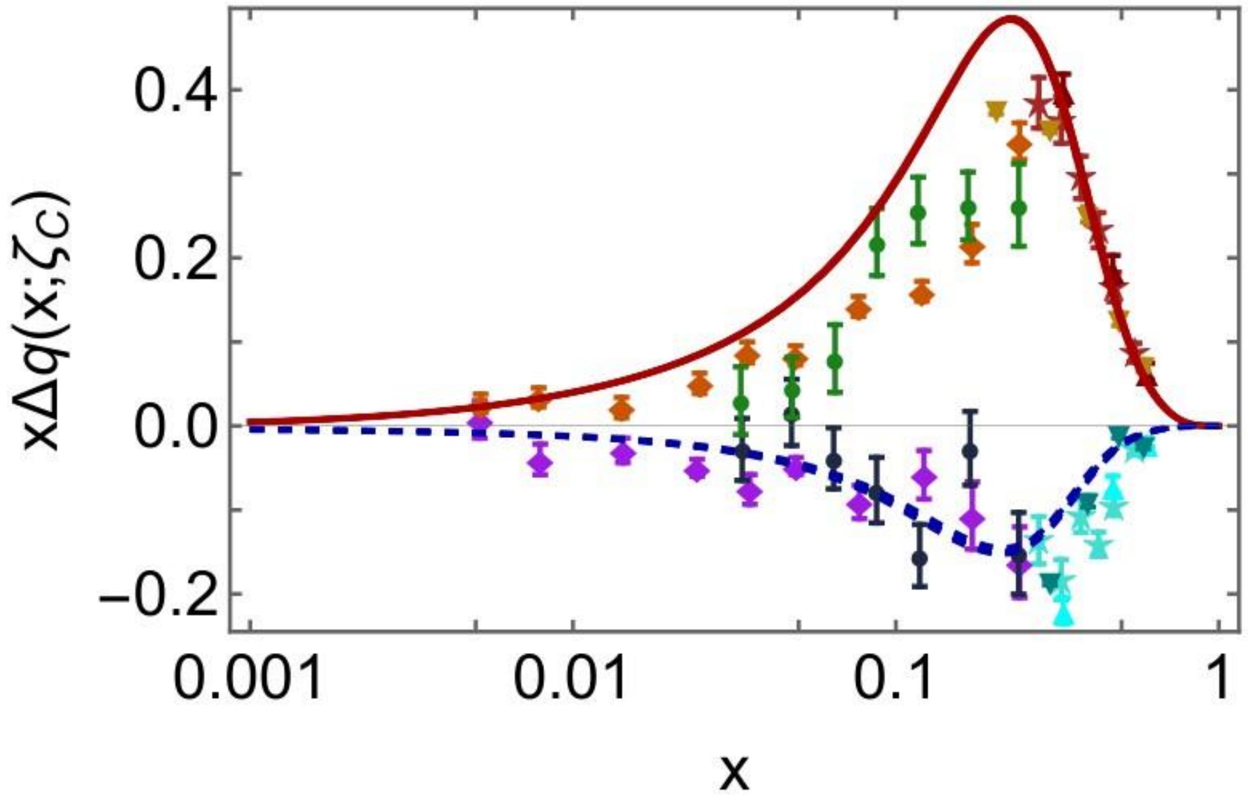


Figure 2: Polarised quark DFs: $\Delta u(x;\zeta_C)$ – solid red curves; and $\Delta d(x;\zeta_C)$ – dashed blue curves. Data: [48, HERMES] – circles; [49, COMPASS] – diamonds; filled down-triangles – [50–53, CLAS EG1]; five-pointed stars – [54, E06-014]; filled up-triangles –[55, 56, E99-117].

Polarised parton distribution functions and proton spin, Peng Cheng (程鹏), Yang Yu (俞杨), Hui-Yu Xing (邢惠瑜) *et al*., e-print: 2304.12469 [hep-ph], Phys. Lett. B **844** (2023) 138074/1-7

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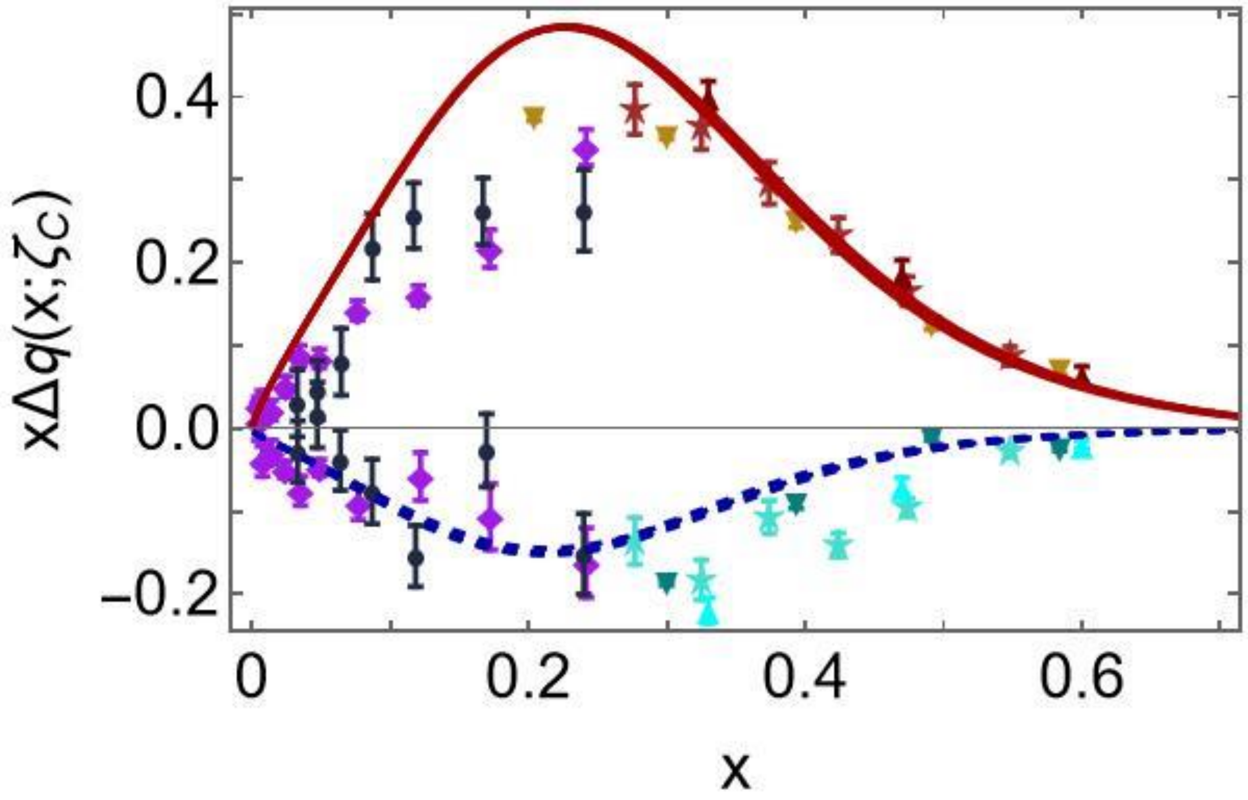
  - Explains why COMPASS data lie below prediction
- Predictions for sea are consistent with available data



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Polarised glue distribution functions at $\zeta = \sqrt{3}\text{GeV}$

- Parameter-free CSM prediction

  compared with COMPASS data

  C. Adolph, *et al.*, *Leading-order determination of the gluon polarization from semi-inclusive deep inelastic scattering data*, Eur. Phys. J. C 77 (4) (2017) 209

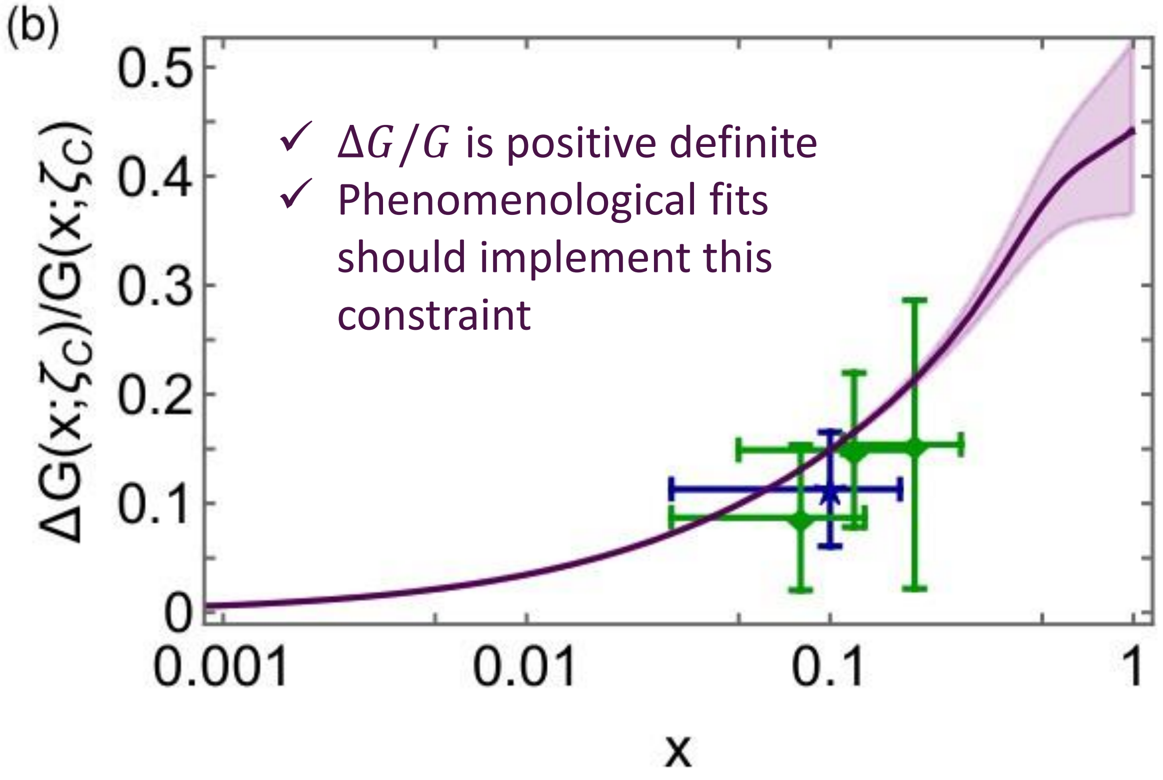
  e.g. average value over data window

  $0.167(3)_{\text{CSM}}$ *cf.* $0.113 \pm 0.038 \pm 0.036_{\text{COMPASS}}$

- Comparison with phenomenological global fits

$$\int_{0.05}^{1} dx\, \Delta G(x;\zeta = 10\text{GeV}) = 0.199(3)_{\text{CSM}}$$

cf. DSSV14: $0.19(6)$



Proton Spin

Polarised parton distribution functions and proton spin, Peng Cheng (程鹏), Yang Yu (俞杨), Hui-Yu Xing (邢惠瑜) *et al*., e-print: 2304.12469 [hep-ph], Phys. Lett. B **844** (2023) 138074/1-7

- Recall page 19, which records

  $a_0 \approx 65\%$ of proton spin
  carried by valence quark
  quasiparticle degrees of freedom at the hadron scale.

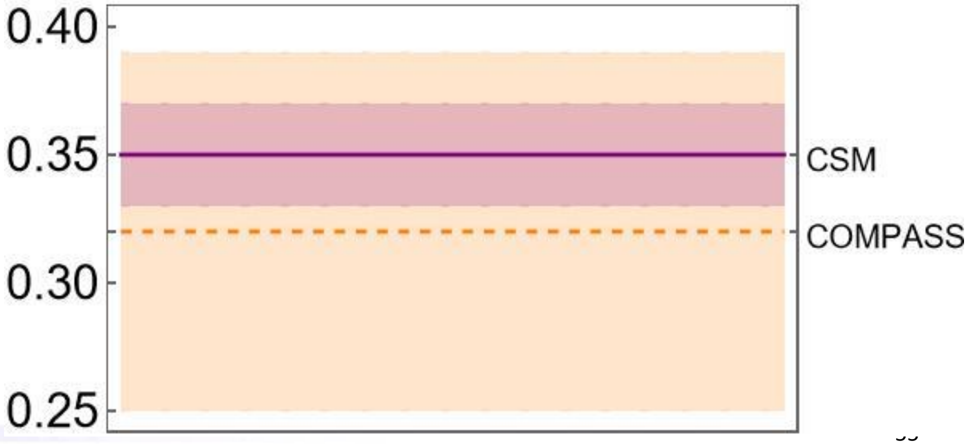
- Under **P1** evolution, this value is independent of scale.
- However, measurements of the proton spin are sensitive to

  non-Abelian anomaly corrected combination $(n_f = 4)$

$$a_0^{\rm E}(\zeta) = a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \int_0^1 dx\, \Delta G(x;\zeta) =: a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \Delta G(\zeta)\,,$$

- CSM prediction: $a_0^E(\zeta = \sqrt{3}\text{GeV}) = 0.35(2)$
- COMPASS: $a_0^{\text{COMPASS}}(\zeta = \sqrt{3}\text{GeV}) = 0.32(7)$
- ***Parameter-free explanation***

  of proton spin measurement



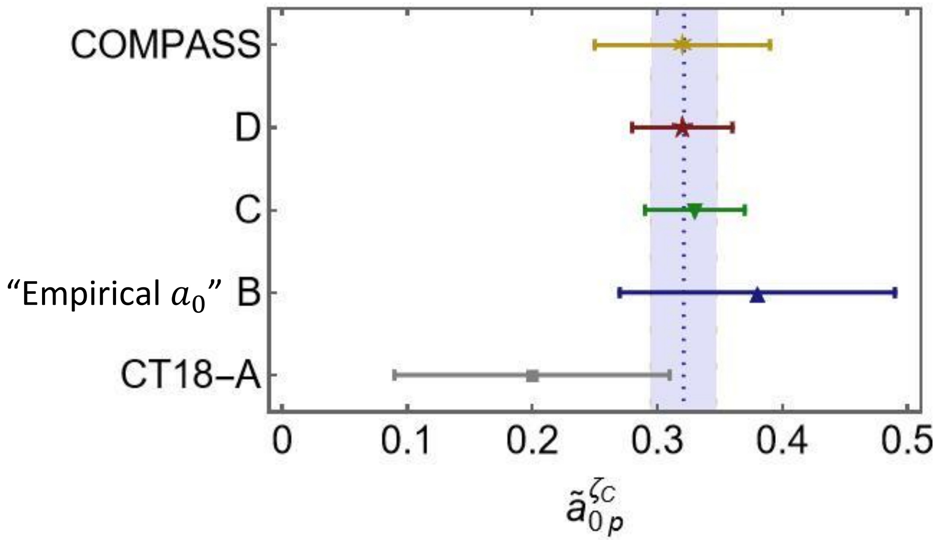
Theory Predictions

Viable parameter-free explanation of proton spin measurement

- Novel approach to understanding character of proton internal structure has enabled derivation of algebraic formula for the gluon contribution to the proton spin

✓ *Symmetry, symmetry breaking, and pion parton distributions,* Minghui Ding, Khépani Raya *et al*., arXiv:1905.05208 [nucl-th], Phys. Rev. D **101** (2020) 054014/1-14
✓ *Parton distributions of light quarks and antiquarks in the proton*, Lei Chang (常雷), Fei Gao (高飞) and Craig D. Roberts, e-Print: 2201.07870 [hep-ph], Phys. Lett. B 829 (2022) 137078/1-7
✓ *All-Orders Evolution of Parton Distributions: Principle, Practice, and Predictions,* Pei-Lin Yin (尹佩林), Yin-Zhen Xu (徐胤禛), Zhu-Fang Cui (崔著钫) *et al*., e-Print: 2306.03274 [hep-ph], Chin. Phys. Lett. *Express* **40** (2023) 091201/1-8. Express Letter.

$$a_{0H}^{\zeta} := \langle x^0 \rangle_{\Delta\Sigma_H}^{\zeta} = \langle x^0 \rangle_{\Delta\Sigma_H}^{\zeta_{\mathcal{H}}},$$
$$\Delta G_H^{\zeta} := \langle x^0 \rangle_{\Delta g_H}^{\zeta} = a_0^{\zeta} \frac{12}{25} \left[[\langle x \rangle_{\mathcal{V}_H}^{\zeta}]^{-75/32} - 1 \right]$$



- Reveals that gluon contribution is positive and grows as resolving scale of the probe increases, removing measurable spin from the quarks
- Prediction for valence-quark part of proton spin: $a_0^E(\zeta = \sqrt{3}\mathrm{GeV}) = 0.32(3)$
- COMPASS (CERN) measurement (2016): $a_0^{\mathrm{COMPASS}}(\zeta = \sqrt{3}\mathrm{GeV}) = 0.32(7)$

Proton Spin Budget

Contact interaction study of proton parton distributions,
Yang Yu (俞杨), Peng Cheng (程鹏), Hui-Yu Xing (邢惠瑜),
Fei Gao (高飞) and Craig D. Roberts,
NJU-INP 083/24, e-Print: 2402.06095 [hep-ph]

- Consider a light-front separation of the proton spin into contributions from quark and gluon spin and angular momenta:

$$\frac{1}{2} = \frac{1}{2}a_0 + L_q(\zeta) + \Delta G(\zeta) + L_g(\zeta)$$

- At hadron scale:
  - ✓ $a_0 = 0.55, L_q(\zeta_H) = 0.23$
  - ✓ $\Delta G(\zeta_H) = 0, L_g(\zeta_H) = 0$

  all proton spin is lodged with valence quark helicity and orbital angular momentum
- Evolved to COMPASS scale

$$a_0 = 0.54, L_q(\zeta) = 0.03, \Delta G(\zeta) = 1.07, L_g(\zeta) = -0.87$$

- Including calculation uncertainties
  - ✓ Valence quark helicity: $(50 \pm 12)\%$,
  - ✓ glue: $\approx 40\%$,
  - ✓ sign and magnitude of valence quark light-front orbital angular momentum is uncertain