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

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National Natural Science Foundation of China
NSFC

# Features of Parton Distribution and Fragmentation Functions


# Strong Interactions in the Standard Model

## THE DILEMMA OF ATTRIBUTION

Nobel Lecture, December 8, 2004

by

H. DAVID POLITZER

California Institute of Technology (Caltech), Pasadena, USA.

- The establishment by the mid-1970’s of QCD as the correct theory of the strong interactions completed what is now known prosaically as the Standard Model.
- It offers a description of all known fundamental physics except for gravity, and gravity is something that has no discernible effect when particles are studied a few at a time.
- However, the situation is a bit like the way that the Navier-Stokes equation accounts for the flow of water. The equations are at some level obviously correct, but there are only a few, limited circumstances in which their consequences can be worked out in any detail.
- Nevertheless, many leading physicists were inclined to conclude in the late 1970’s that the task of basic physics was nearly complete, and we’d soon be out of jobs.
- A famous example was the inaugural lecture of Stephen Hawking as Lucasian Professor of Mathematics, a chair first held by Isaac Barrow at Cambridge University.

  Hawking titled his lecture, “Is the End in Sight for Theoretical Physics?” And he argued strongly for “Yes”.

# The Higgs boson

Elementary particles gain their mass from a fundamental field associated with the Higgs boson

*Or so the story has gone*

# Emergence of Hadron Mass

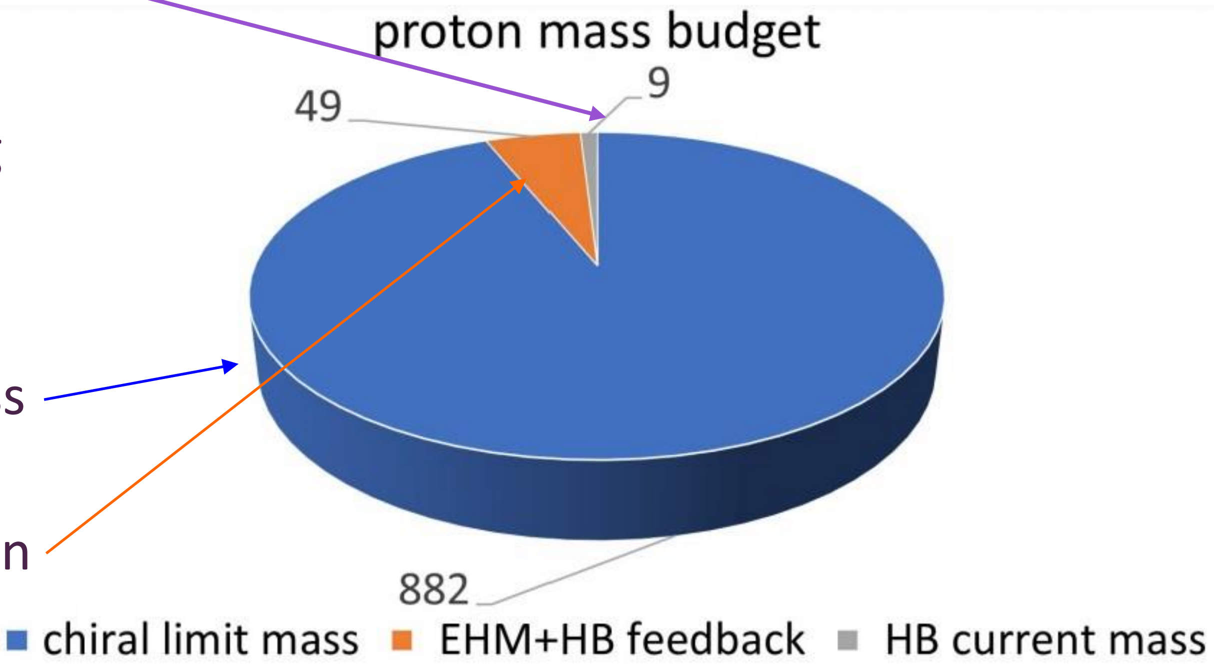
- Proton mass budget

  Only 9 MeV/939 MeV is directly from Higgs

- Evidently, there is another phenomenon in Nature that is extremely effective in 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 is EHM?
- ✓ Does it have a reductionist explanation,

  *i.e*. can it be explained by mere "mechanisms", like a Swiss watch?

- ✓ If so, what are they and do they lie within the Standard Model?

# 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?

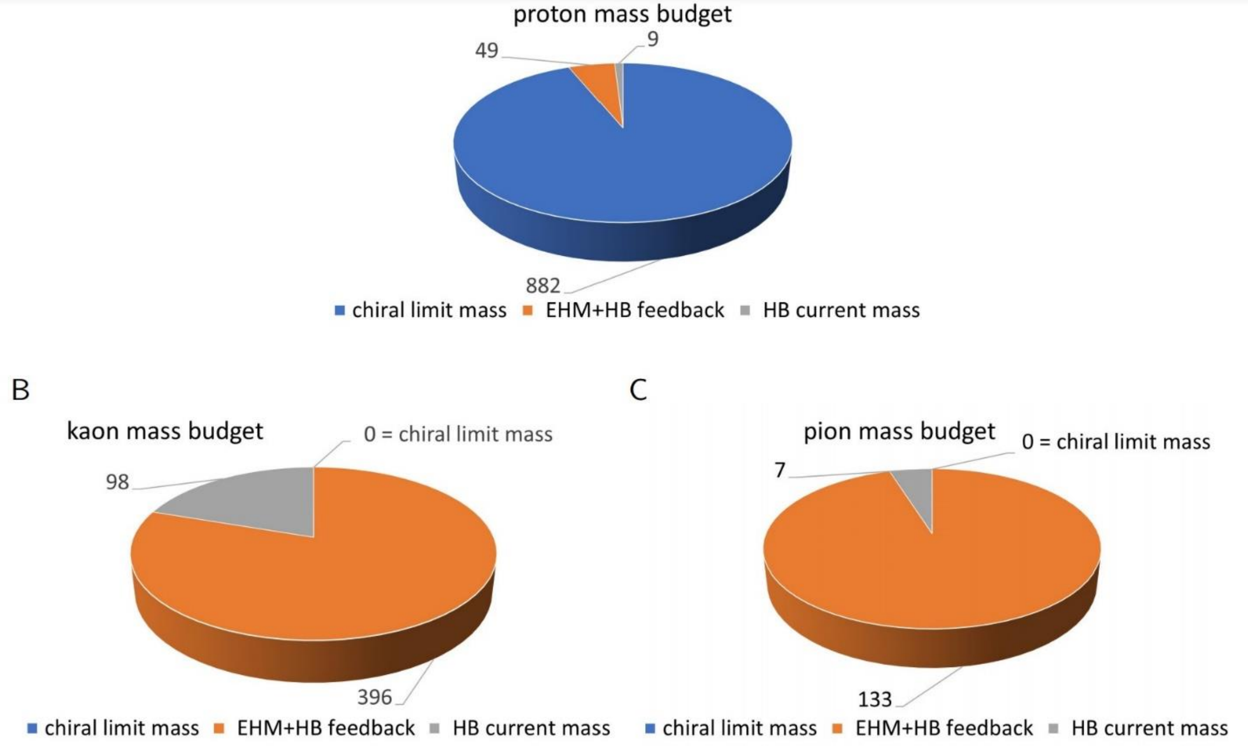



FIG. 1.1. Mass budgets for A – proton, B – kaon and C – pion, drawn using a Poincaré invariant decomposition. There are crucial differences. The proton's mass is large in the chiral limit, *i.e.* even in the absence of Higgs couplings into QCD. This nonzero chiral-limit component is an expression of 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 $\zeta = 2\,\text{GeV}$, produced using information from Refs. [8, 21–23].)

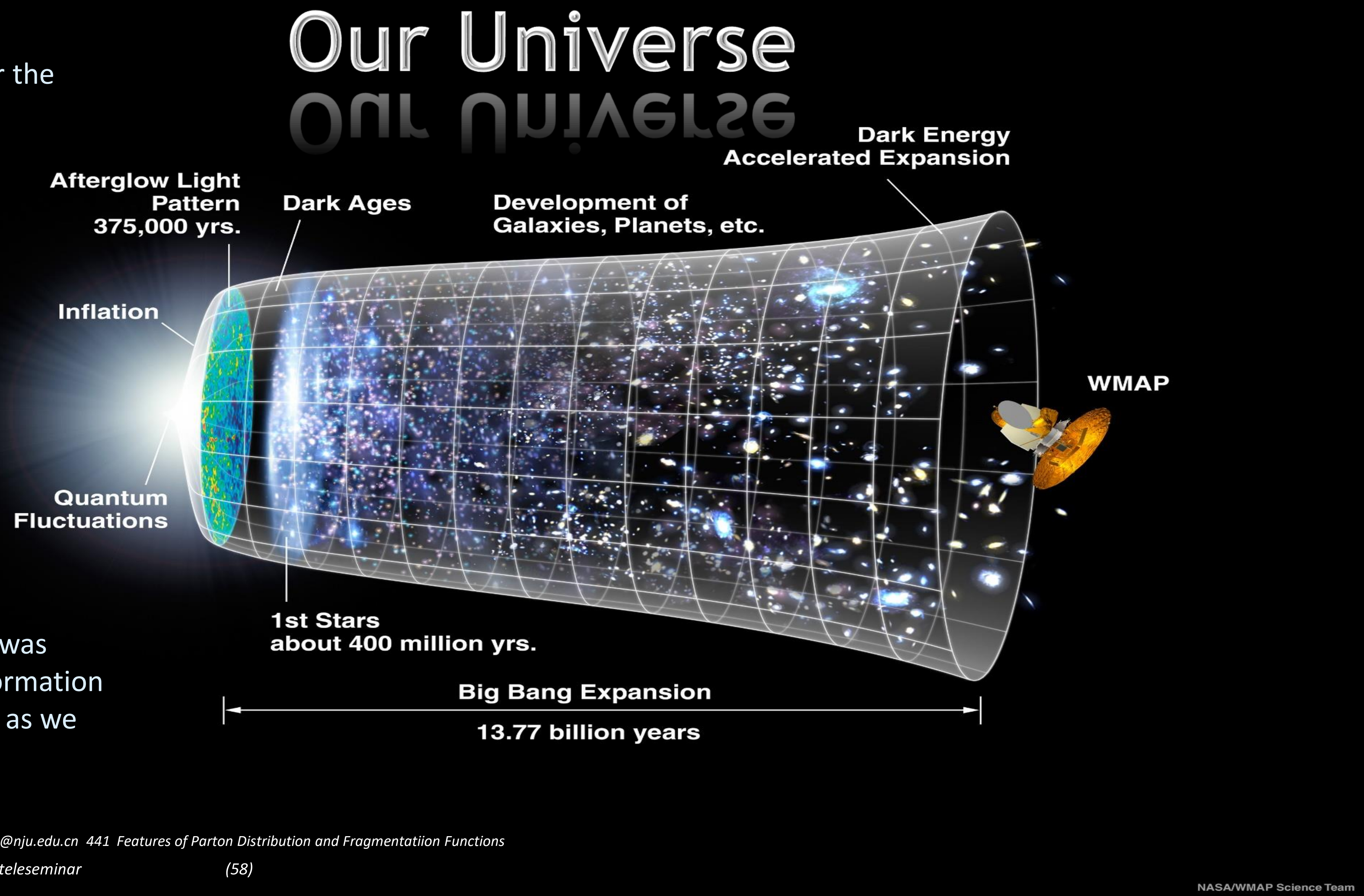
# Visible Mass


- More than 98% of visible mass is contained within nuclei.
- First approximation:
  - atomic weights = sum of the masses of all the nucleons they contain.
- Each nucleon has a mass $m_N \sim 1$ GeV ≈ 2000 $m_e$
- Higgs boson produces $m_e$, but what produces $m_N$ = remaining 1999 $m_e$?
- This question is basic to the whole of modern physics

**How can science explain the emergence of hadron mass (EHM)?**

# Origin of Mass:
# The Frontier of Physics

Mass emerged
$1\mu$ second after the
Big Bang




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

# Quantum Chromodynamics

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

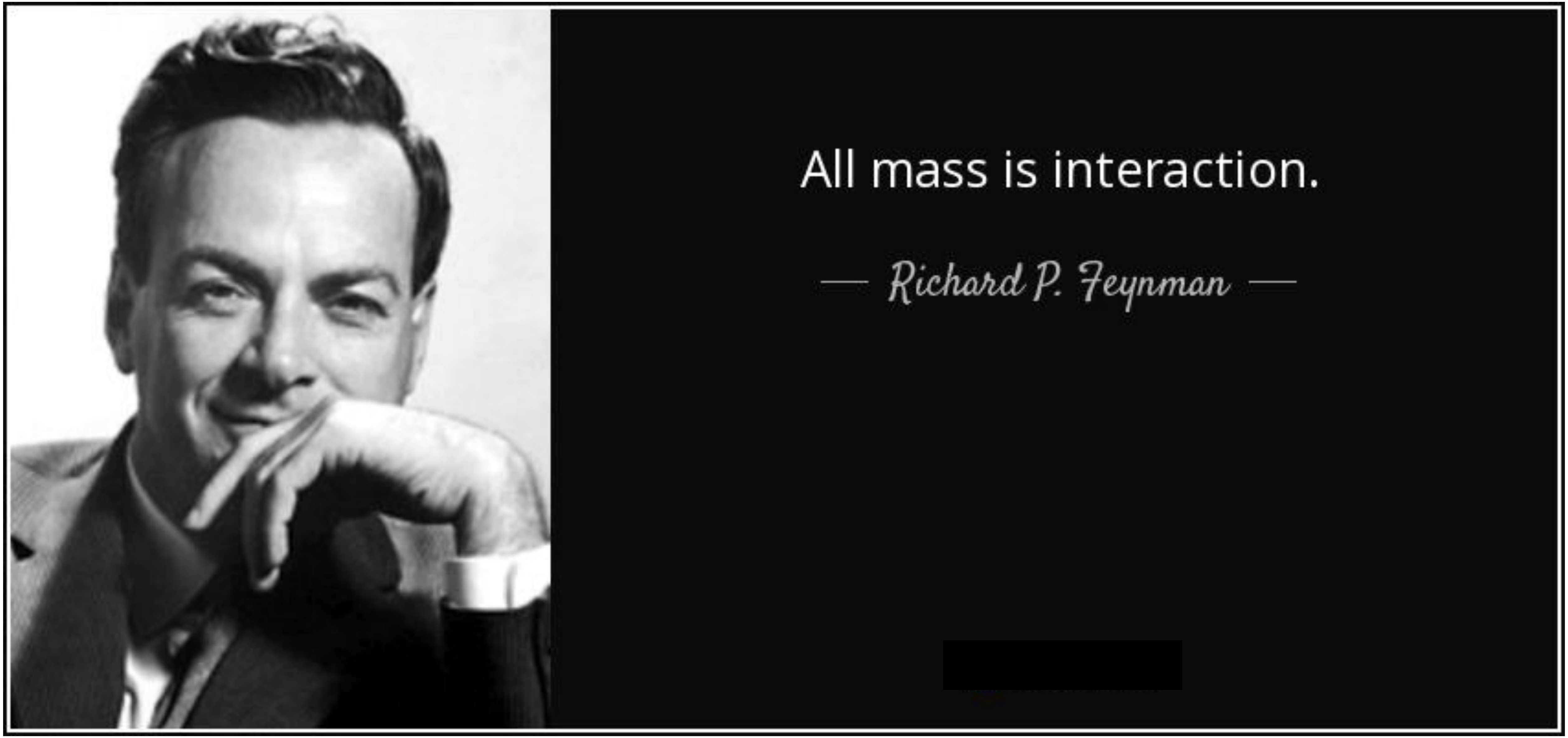
$$G^a_{\mu\nu}(x) = \partial_\mu A^a_\nu(x) - \partial_\nu A^a_\mu(x) - f^{abc} A^b_\mu(x) A^c_\nu(x)$$

- 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


All mass is interaction.
— Richard P. Feynman —
[redacted]

# G E N E S I S

GLUON

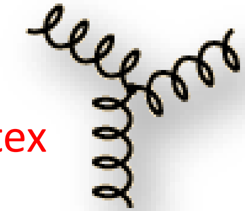
# Modern Understanding Grew Slowly from Ancient Origins

- More than 40 years ago

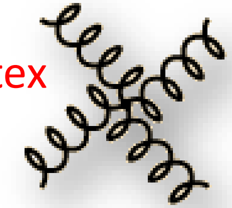
  *Dynamical mass generation in continuum quantum chromodynamics,*
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … > 1100 citations

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

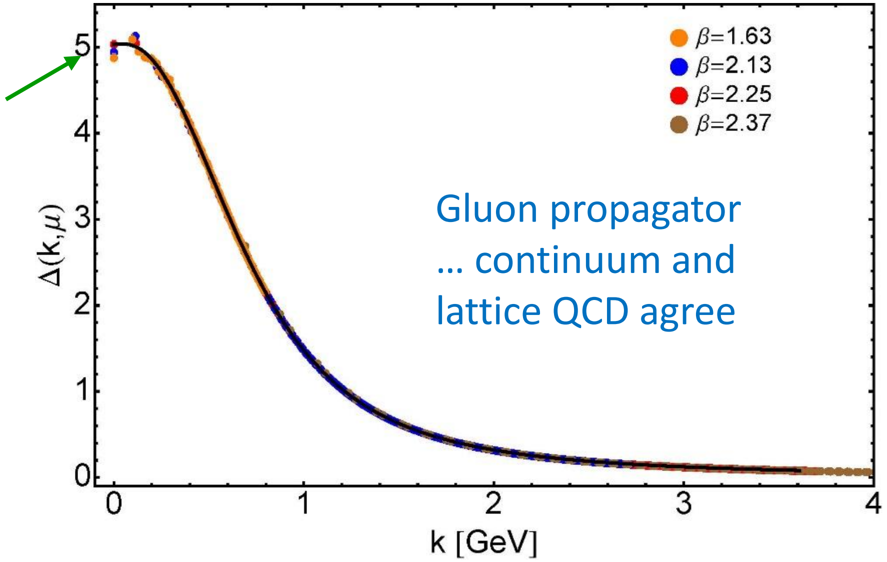
3-gluon vertex



4-gluon vertex



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




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

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

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…

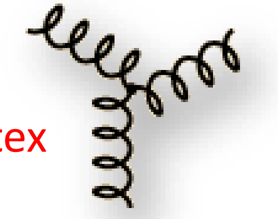
  *Dynamical mass gene…* …*ics,*

  J.M. Cornwall, Phys. R…

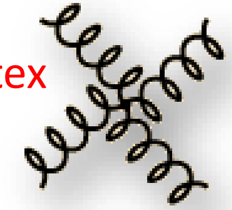
- Owing to strong self-… …siparticles, described by a r… …menta

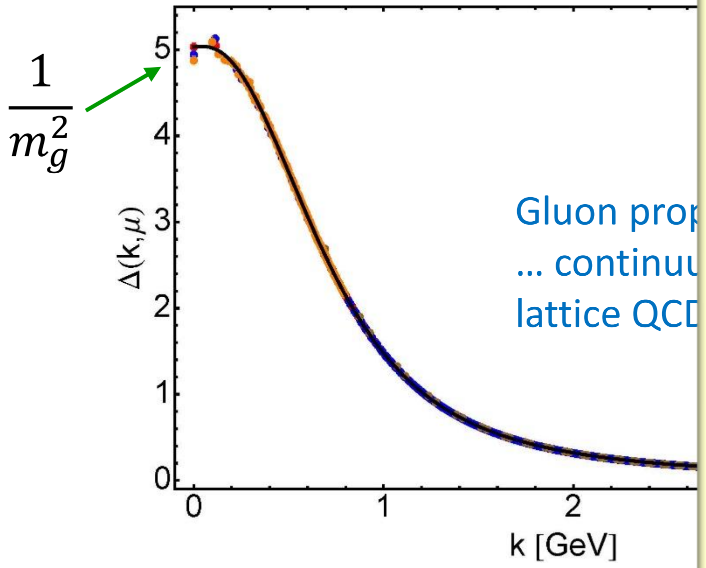
# EHM means Gluons are massive – Schwinger Mechanism

3-gluon vertex



4-gluon vertex



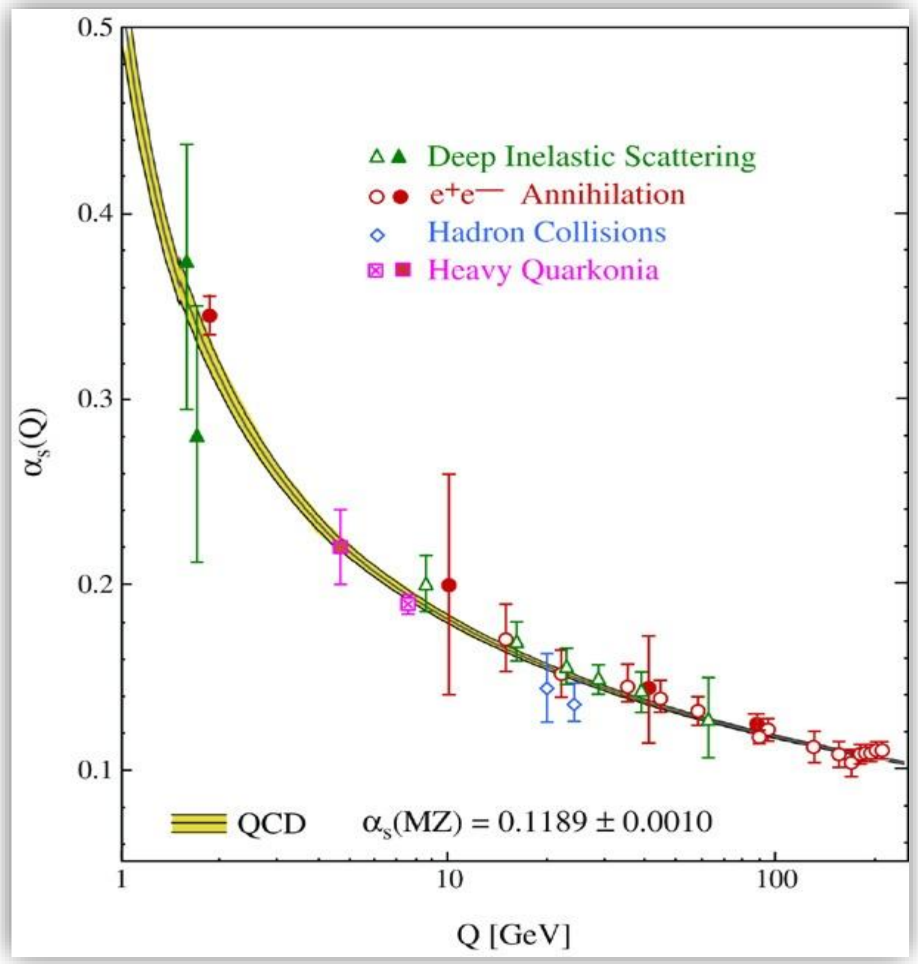



Gluon prop…
… continuu…
lattice QCD…

- ✓ *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.ppnp.2023.104081

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## Abstract

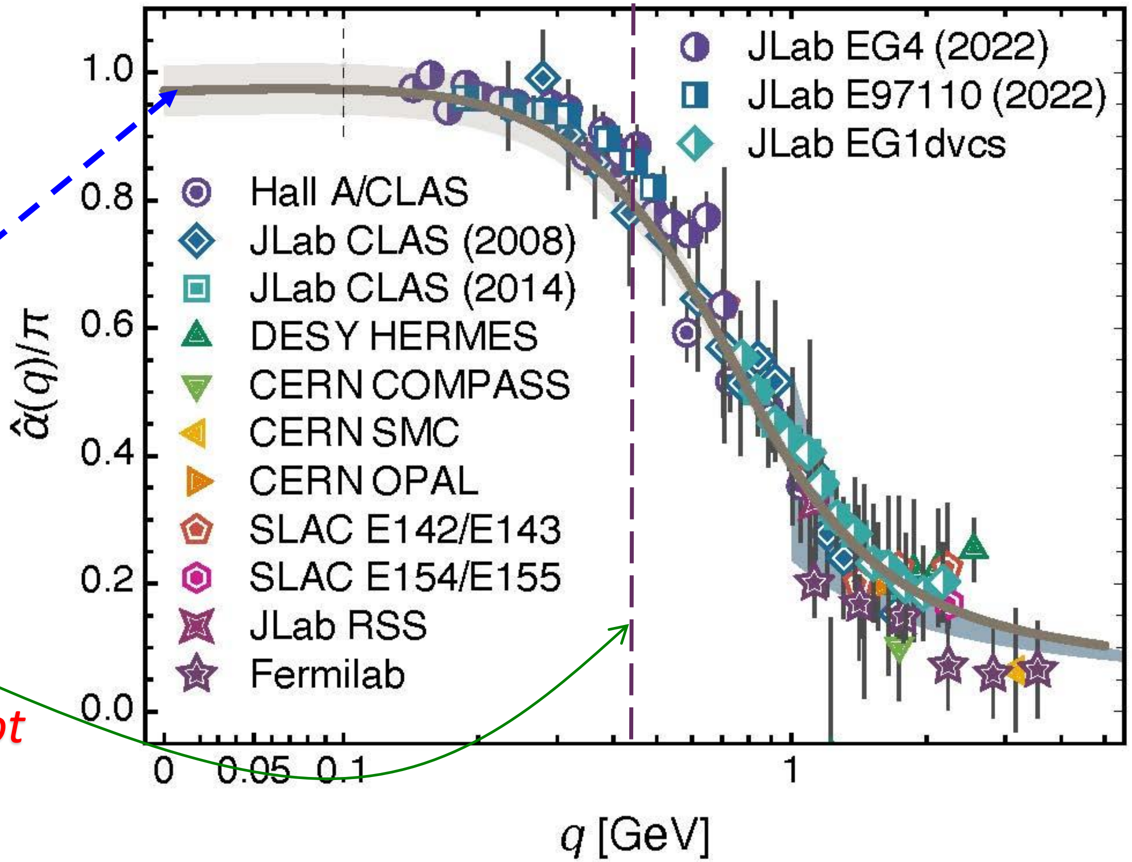
We discuss our present knowledge of $\alpha_s$, the fundamental running coupling or effective charge of Quantum Chromodynamics (QCD). A precise understanding of the running of $\alpha_s(Q^2)$ at high momentum transfer, $Q$, is necessary for any perturbative QCD calculation. Equally important, the behavior of $\alpha_s$ 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 $\alpha_s$. We conclude by highlighting how the nonperturbative knowledge of $\alpha_s$ 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*

**2367 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 $k \sim \hat{m}_0$ , interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again

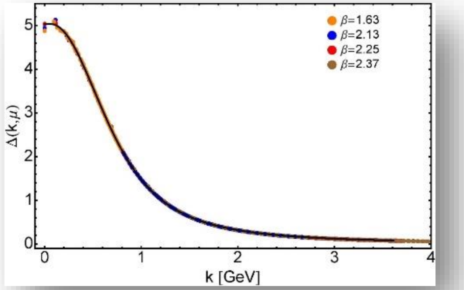


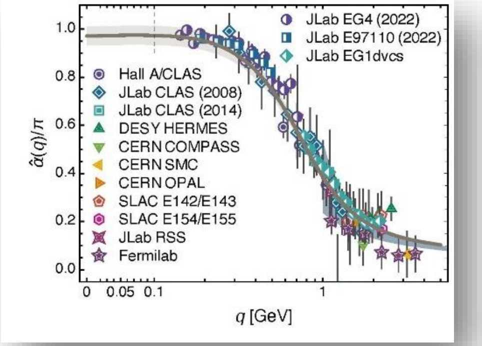

- ✓ *Process independent strong running coupling*
  Daniele Binosi *et al*., arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7
- ✓ *Experimental determination of the QCD effective charge $\alpha_{g1}(Q)$.*
  A. Deur; V. Burkert; J.-P. Chen; W. Korsch, Particles 5 (2022) 171
- ✓ *QCD Running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

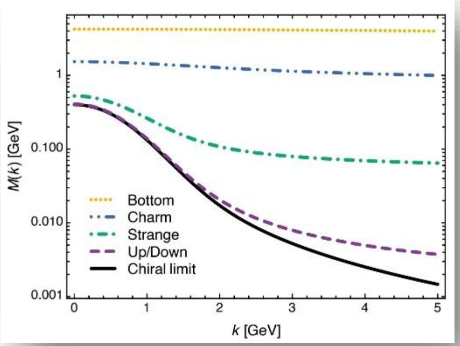
# EHM Basics

- Absent Higgs boson couplings, 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 =
  1. Elucidate all observable consequences of these phenomena
  2. Highlight paths to measuring them
- Challenge to Experiment =
  Test the theory predictions so that
  Boundaries of Standard Model can finally be drawn

THREE PILLARS OF EHM




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

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# Emergence of Hadron Mass and Structure

by Minghui Ding [1,*,†], Craig D. Roberts [2,3,*,†] and Sebastian M. Schmidt [1,4,*,†]

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(This article belongs to the Special Issue **Strong Interactions in the Standard Model: Massless Bosons to Compact Stars**)

# *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
  ⇒ proton studies can become truly precise
  ⇒ science can move beyond the focus on the proton

AMBER @ CERN
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JLab12 & JLab20+

- Enable precision studies of, *e.g.*,
  - Structure of Baryon excited states
    - ✓ Baryons are the most fundamental three-body systems in Nature
    - ✓ We don't understand Nature unless we do understand how QCD, a Poincaré-invariant quantum field theory, builds each of the baryons in the complete spectrum
  - Structure of Nature's most fundamental Nambu-Goldstone bosons ($\pi$ & $K$)
  - Spectrum of mesons and their structure

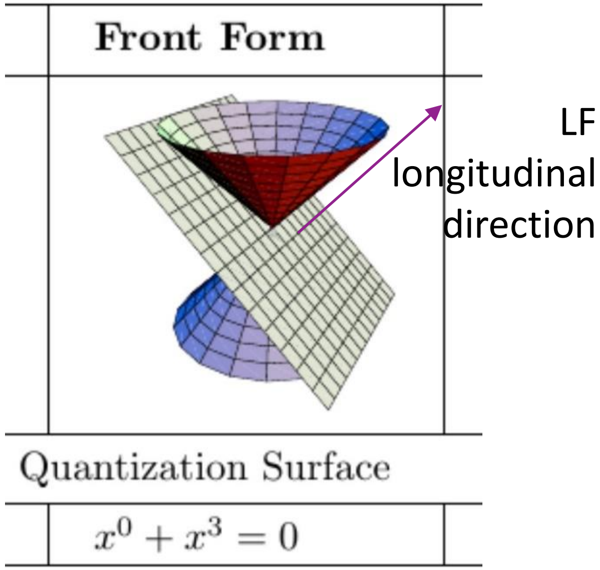
$$\Psi(x,t)$$

# Measuring $\pi$ & $K$ 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 $\pi$ 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* $\sim \int d^2k_\perp \Psi(x,k_\perp)$

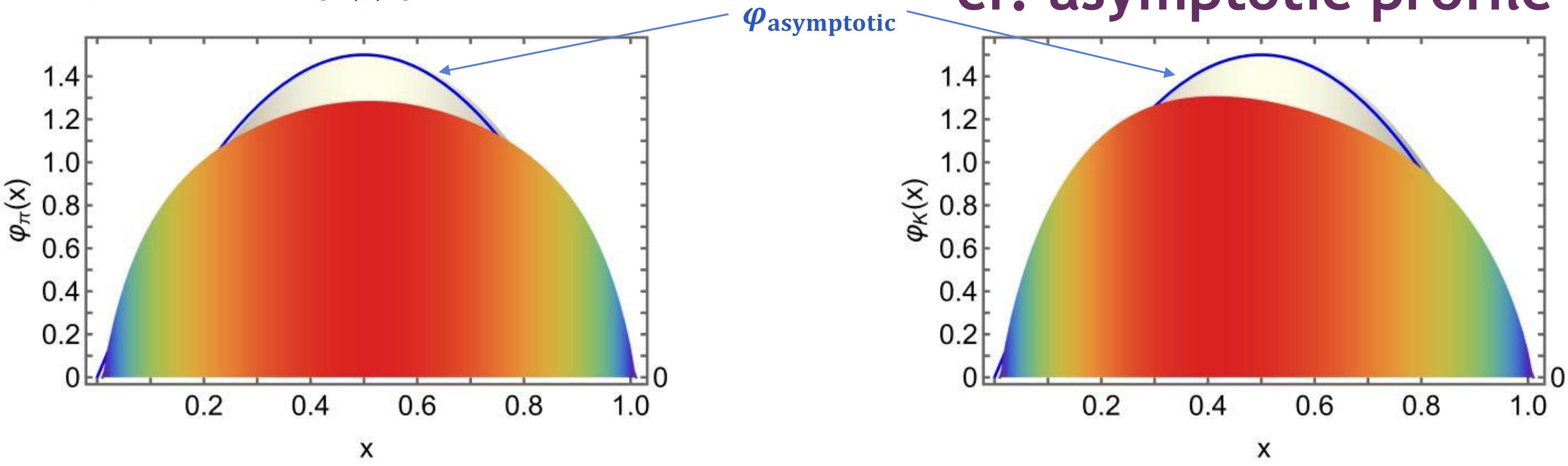



*Insights into the Emergence of Mass from Studies of Pion and Kaon Structure,* Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

*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]

# $\pi$ & K DAs cf. asymptotic profile




- EHM generates broadening in both $\pi$ & 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 $\pi$ and $K$ electric charge distributions (elastic form factor measurements at large $Q^2$) & in $\pi + p$ Drell-Yan measurements*

Chinese Physics Letters **40**, 041201 (2023) **Express Letter**

# Empirical Determination of the Pion Mass Distribution

Y.-Z. Xu(徐胤禛)[1,2], K. Raya[1], Z.-F. Cui(崔著钫)[3,4], C. D. Roberts[3,4*], and J. Rodríguez-Quintero[1]

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(Received 2 March 2023; accepted manuscript online 20 march 2023)

Existing pion+nucleus Drell-Yan and electron+pion scattering data are used to develop ensembles of model-independent representations of the pion generalized parton distribution (GPD). Therewith, one arrives at a data-driven prediction for the pion mass distribution form factor, $\theta_2^\pi$. Compared with the pion elastic electromagnetic form factor, $\theta_2^\pi$ is harder: the ratio of the radii derived from these two form factors is $r_\pi^{\theta_2}/r_\pi = 0.79(3)$. Our data-driven predictions for the pion GPD, related form factors and distributions should serve as valuable constraints on theories of pion structure.

# $\pi$ mass distribution

- Expectation value of the QCD energy-momentum tensor in the pion
  = pion gravitational current

$$\Lambda^{g}_{\mu\nu}(K,Q) = 2K_\mu K_\nu \theta_2^\pi(Q^2) + \tfrac{1}{2}[Q^2\delta_{\mu\nu} - Q_\mu Q_\nu]\theta_1^\pi(Q^2) + 2m_\pi^2\delta_{\mu\nu}\bar{c}^\pi(Q^2)$$

Zero owing to energy+momentum conservation

- Contract with $\delta_{\mu\nu}$: $\Lambda^{g}_{\mu\mu}(K,0) = 2m_\pi^2\theta_2^\pi(Q^2)$
  - $\theta_2^\pi(Q^2=0) = 1$ (canonical mass-normalisation)
  - $\theta_2^\pi(Q^2)$ measures mass distribution in $\pi$

- $\theta_2^\pi$ can be obtained as the first Mellin moment of the pion GPD

Pion GPD

$$\theta_2^\pi(\Delta^2) = \int_{-1}^{1} dx\, 2x\, H_\pi^u(x,0,-\Delta^2;\zeta_{\mathcal{H}})$$

# *Empirical determination of the pion mass distribution*

*Can reconstruct $\pi$ GPD from data on*
- ✓ *$\pi$ em form factor*
- ✓ *$\pi$ valence quark DF*

- GPDs connect DFs with hadron form factors because
  - any elastic form factor can be expressed via a GPD-based sum rule
  - any DF may be recovered as forward limit $(p' = p)$ of relevant GPD
- Working solely with
  - electron+pion scattering data
    - CERN – 1984, 1986
    - JLab 2000, 2006, 2007, 2008
  - existing pion + nucleus Drell-Yan data (CERN and FNAL – 1989)
    - two phenomenological fits to this data [Aicher:2010cb, Barry:2021osv] … use both
- Employed a $\chi^2$-based selection procedure to develop ensembles of model-independent representations of the three-dimensional pointwise behaviour of the pion generalised parton distribution (GPD).
- *These ensembles yield data-driven prediction for pion GPD*

# Pion Generalised Parton Distribution

- Pion GPDs, reconstructed from available analyses of relevant Drell-Yan and electron+pion scattering data
  - Different ensembles only marginally compatible, owing to differences between analyses in

    A = Aicher:2010cb; B = Barry:2021osv
  - Yet, both agree with lQCD based ensembles, within mutual uncertainties, because lQCD-constrained ensemble has large uncertainty – improvement of lQCD results useful
  - CSM prediction favours $u_A^\pi(x;\zeta_5)$ ensemble
- In all cases, support of valence-quark GPD becomes increasingly concentrated in neighbourhood $x \simeq 1$ with increasing $\Delta^2$
  - Namely, greater probe momentum focuses attention on domain whereupon one valence-quark carries a large fraction of pion's light-front momentum

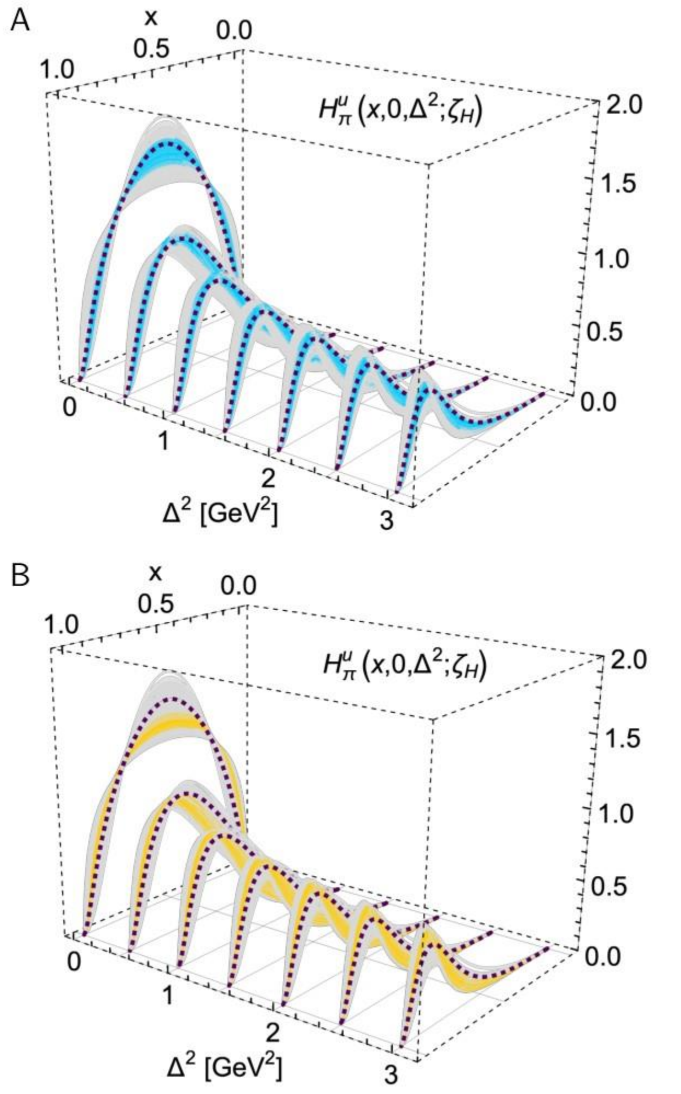



FIG. 3. Pion GPDs. *Panel A*. Working with DFs $u_A^\pi(x;\zeta_\mathcal{H})$ [63] – blue band. *Panel B*. Using DFs $u_B^\pi(x;\zeta_\mathcal{H})$ [54, Sec. 8] – orange band. Comparison curves, both panels: CSM prediction in Refs. [59, 72] – dashed purple curve; GPD ensemble generated from valence-quark DFs developed in Ref. [55], obtained from results computed using lattice Schwinger function methods [65–67] – grey band.

*Revealing pion and kaon structure via generalised parton distributions*, K. Raya, Z. –F. Cui (崔著钫) et al., NJU-INP 051/21, e-Print: 2109.11686 [hep-ph], Chin. Phys. C **46** (01) (2022) 013107/1-22

# Pion charge distribution form factor

- $0^{th}$ Moment of pion GPD

$$F_\pi(\Delta^2) \equiv F_\pi^u(\Delta^2) = \int_{-1}^{1} dx\, H_\pi^u(x,0,-\Delta^2;\zeta_H)$$
$$= \int_0^1 dx\, u^\pi(x;\zeta_H)\, \Phi^\pi(\Delta^2 x^2;\zeta_H)\,,$$

- All ensembles reproduce empirical $F_\pi(\Delta^2)$
  - Blue – based on $u_A^\pi(x;\zeta_5)$ ensembles
  - Orange – based on $u_B^\pi(x;\zeta_5)$ ensembles
- Comparison curves
  - dashed purple – CSM prediction for $F_\pi(\Delta^2)$
  - grey band – Ensemble of $F_\pi(\Delta^2)$ results developed from DFs based on lattice-QCD results
- Again, data-driven results in accord with modern theory predictions.

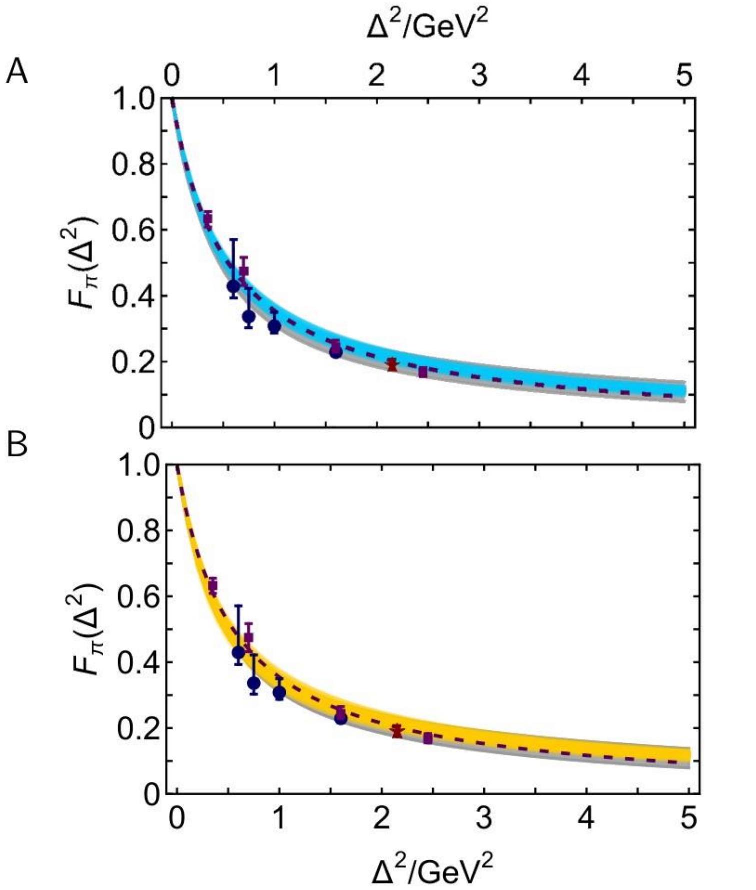



FIG. 2. Pion elastic electromagnetic form factor, $F_\pi(\Delta^2)$, obtained from Eq. (11) using the GPD ensembles generated via S4. *Panel A*. DFs $u_A^\pi(x;\zeta_{\mathcal{H}})$ [63] (blue band). *Panel B*. DFs $u_B^\pi(x;\zeta_{\mathcal{H}})$ [54, Sec. 8] (orange band). Comparison curves: dashed purple – $F_\pi(\Delta^2)$ calculated using CSMs [21, Sec. 4B], [45]; grey band – $F_\pi(\Delta^2)$ ensemble obtained with valence-quark DFs developed in Ref. [55] from results obtained using lattice Schwinger function methods [65–67]. The form factor data are from Refs. [36–40].

See, e.g., Sec. 4B in
📖 *Insights into the Emergence of Mass from Studies of Pion and Kaon Structure,*
C.D. Roberts, D.G. Richards, T. Horn and L. Chang,
NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

# $\pi$ mass distribution

$$\theta_2^\pi(\Delta^2) = \int_{-1}^{1} dx\, 2x\, H_\pi^u(x, 0, -\Delta^2; \zeta_{\mathcal{H}})$$

- Expressed as 1st Mellin-moment of pion GPD
- Principal, dynamical coefficient in expectation value of the QCD energy-momentum tensor in the pion

= pion gravitational current

$$\Lambda^g_{\mu\nu}(K,Q) = 2K_\mu K_\nu \theta_2^\pi(Q^2) + \tfrac{1}{2}[Q^2\delta_{\mu\nu} - Q_\mu Q_\nu]\theta_1^\pi(Q^2) + 2m_\pi^2 \delta_{\mu\nu}\bar{c}^\pi(Q^2)$$

- $\theta_2(\Delta^2)$ is harder than $F_\pi(\Delta^2)$

*i.e.*, the distribution of mass in the pion is more compact than the distribution of electric charge.

- *This is an empirical fact*

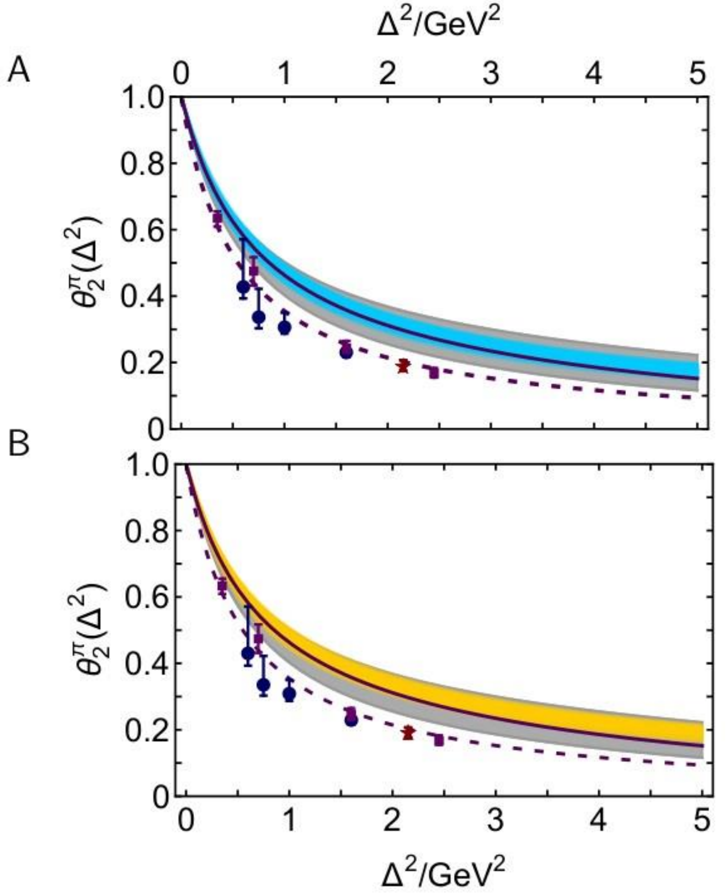



FIG. 4. Pion mass distribution form factor, $\theta_2^\pi(\Delta^2)$. *Panel A.* Developed from the $u_A^\pi(x;\zeta_{\mathcal{H}})$ ensemble [63] – blue band. *Panel B.* Developed from the $u_B^\pi(x;\zeta_{\mathcal{H}})$ ensemble [54, Sec. 8] – orange band. Comparison curves, both panels: CSM prediction for $\theta_2^\pi(\Delta^2)$ in Refs. [59, 72] – solid purple; GPD ensemble generated from valence-quark DFs developed in Ref. [55] using lQCD results [65–67] – grey band. In addition, each panel displays the CSM prediction for $F_\pi(\Delta^2)$ [21, Sec. 4B], [45] – dashed purple curve. The data are those for $F_\pi(\Delta^2)$ from Refs. [36–40], included so as to highlight the precision required to distinguish the mass and electromagnetic form factors.

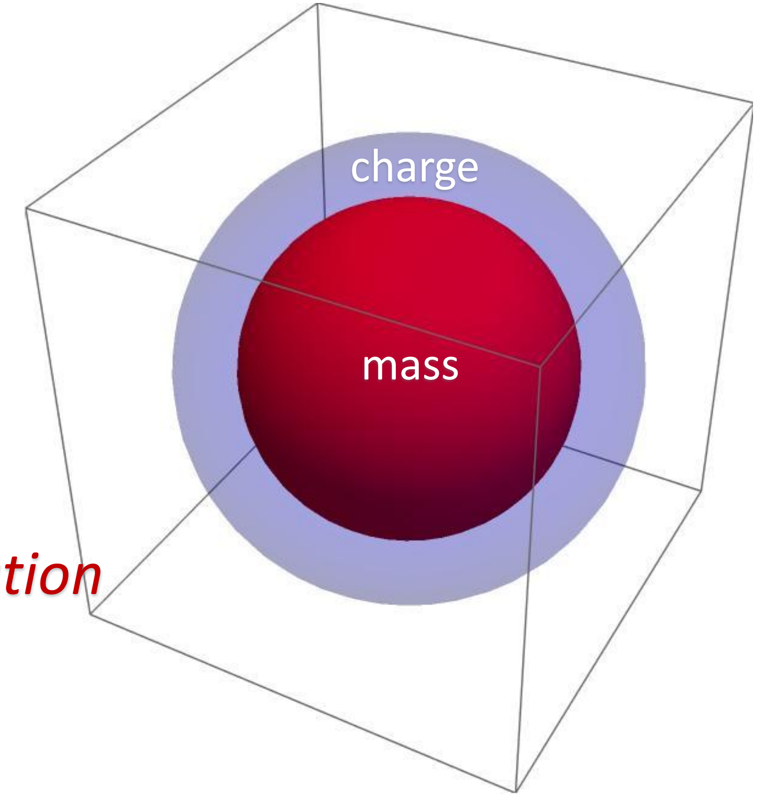
# $\pi$ mass radius

| fm | A | B | lQCD |
|---|---|---|---|
| $r_\pi^{\theta_2}$ | 0.518(16) | 0.498(14) | 0.512(21) |

- Comparison value for charge radius: $r_\pi = 0.64(2)$ fm
- Data-driven prediction: $\frac{r_\pi^{\theta_2}}{r_\pi} = 0.79(3)$
- Translates into spacetime volume ratio = $0.40(6)$

*Pion mass distribution is concentrated within*

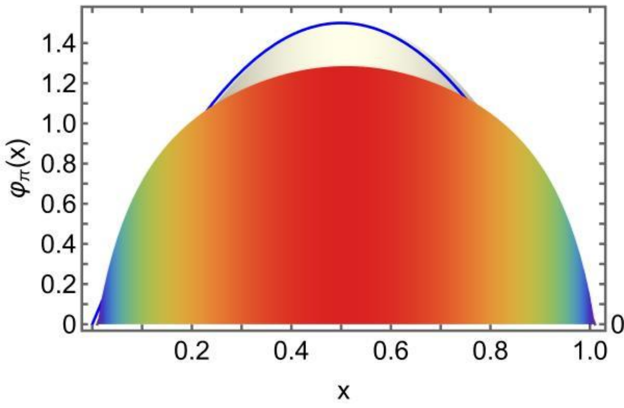
*just 40% of the spacetime volume of the charge distribution*



# $\pi$ mass distribution is harder

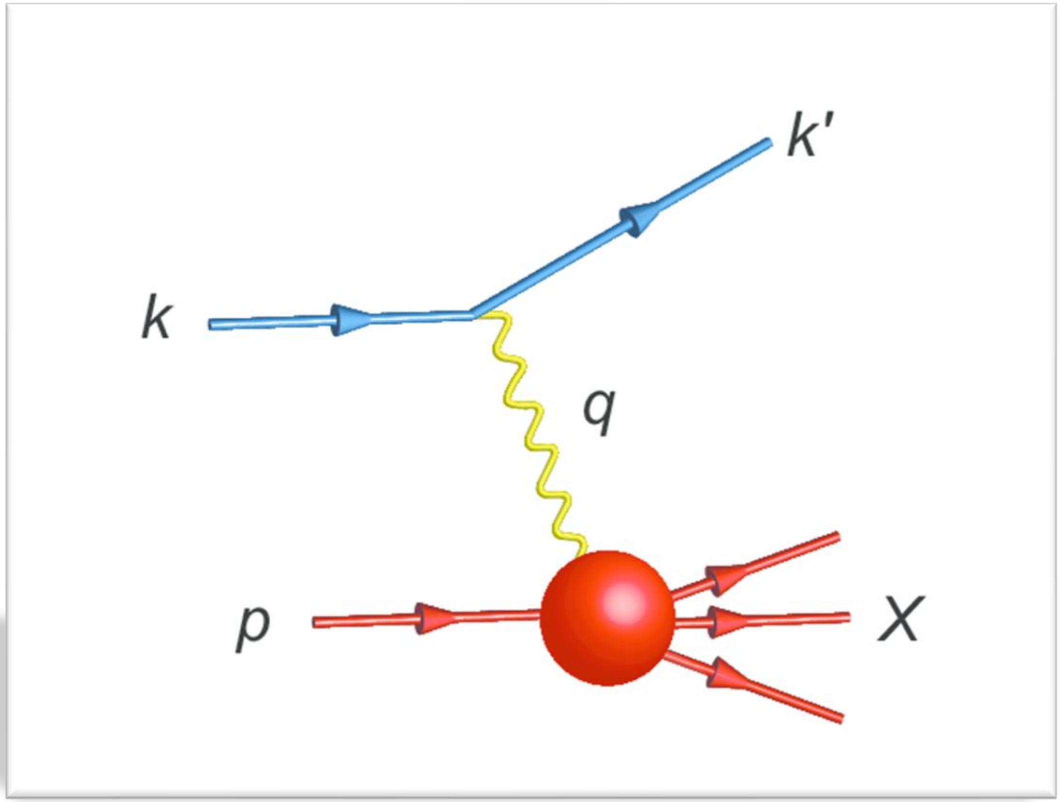
- Empirical fact is readily understood physically
- Pion wave function (hence, pion GPD) is independent of the probe.
  - It's the same whether 1 photon or 2 photons or graviton is the probing object.
- However, probe itself focuses on different features of the target constituents
  - Target quark carries same charge, irrespective of its momentum.
    - So, pion LFWF alone controls distribution of charge.
  - Gravitational interaction of target quark depends on its momentum.

    (The current = the energy momentum tensor)
    - Pion effective mass distribution therefore depends on interference between quark momentum growth and LFWF momentum suppression with increasing $\Delta^2 x^2$.
    - This pushes support to a larger momentum domain in the pion = smaller distance domain.




- "*Is there a specific aspect of the pion GPDs driven by the data which is responsible?*"
- Yes. EHM induced broadening of pion LFWF = GPD.

  Given GPD overlap representation, they're the same thing.




# 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?

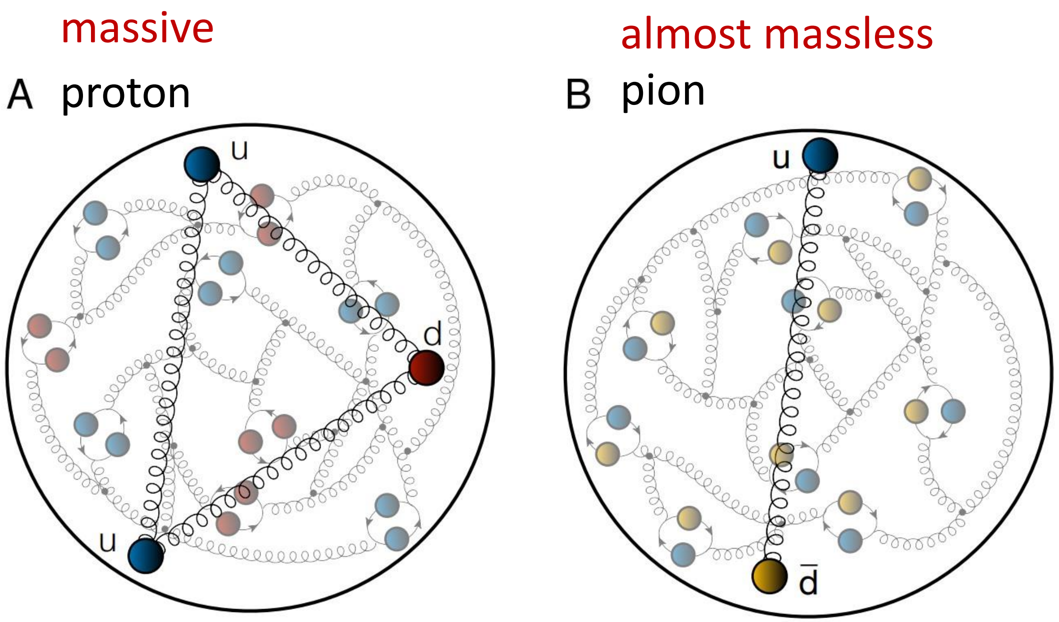



Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, $p$, contains two valence up ($u$) quarks and one valence down ($d$) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined by one $u$ and two $d$ valence quarks. *Right panel* – B. The pion, $\pi^+$, 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 $\begin{cases} d^p(x;\zeta_H), u^p(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_H), u^\pi(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^2 \end{cases}$
- $\zeta > m_p$: 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: $\beta_{p,\pi}^{\rm sea} \geq \beta_{p,\pi}^{\rm val} + 2$
- 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 overlook 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!

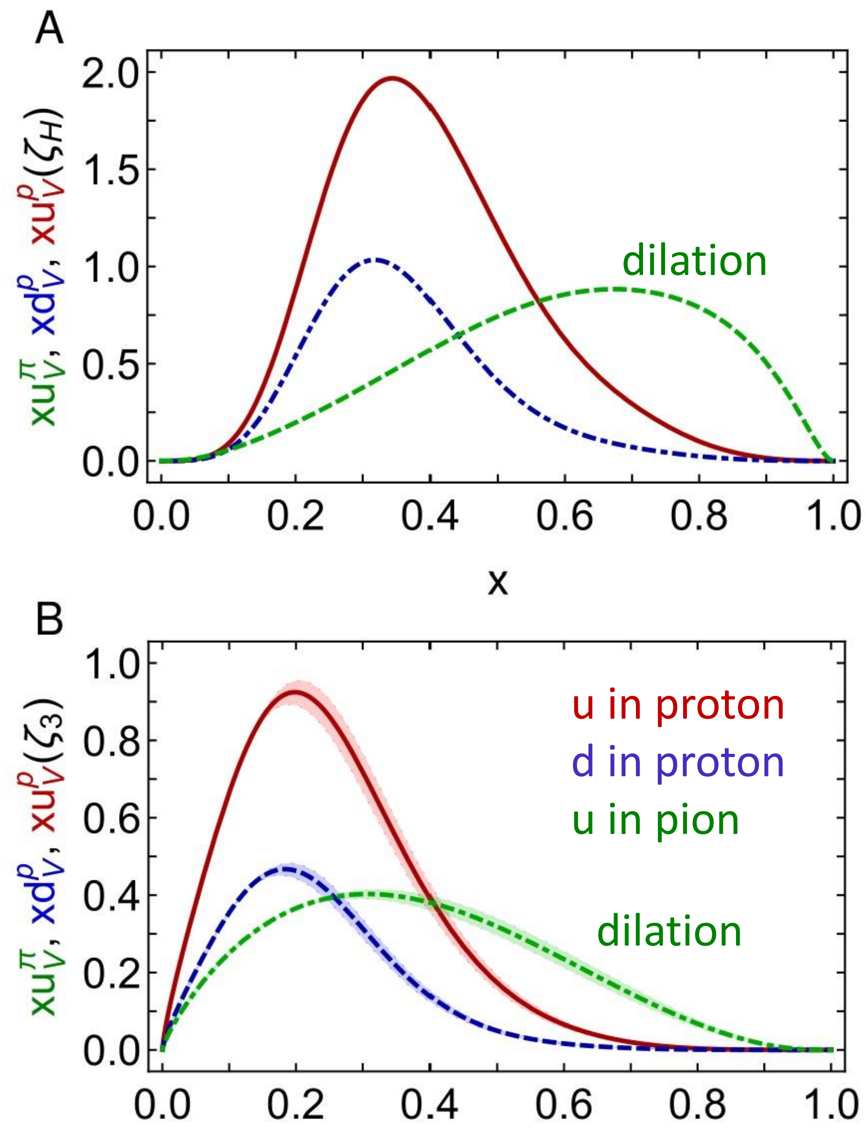
❽ Proton has valence glue but no valence quarks!

# 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

- 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 $\zeta_H$: $\langle x\rangle_{u_p}^{\zeta_H} = 0.687\,,\ \langle x\rangle_{d_p}^{\zeta_H} = 0.313\,,\ \langle x\rangle_{u_\pi}^{\zeta_H} = 0.5$
- 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



# *All-orders 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 DGLAP equations, defines an evolution scheme for parton DFs that is all-orders exact.*
- CSM Process-Independent charge serves this purpose

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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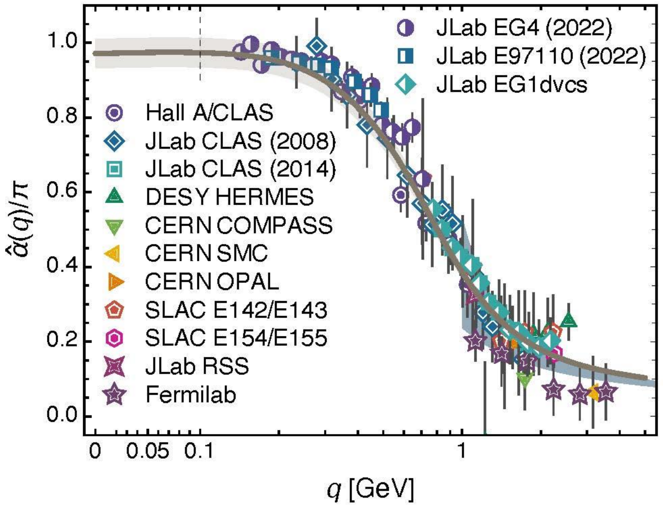
Abstract

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, $\zeta_H$*

  *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)].
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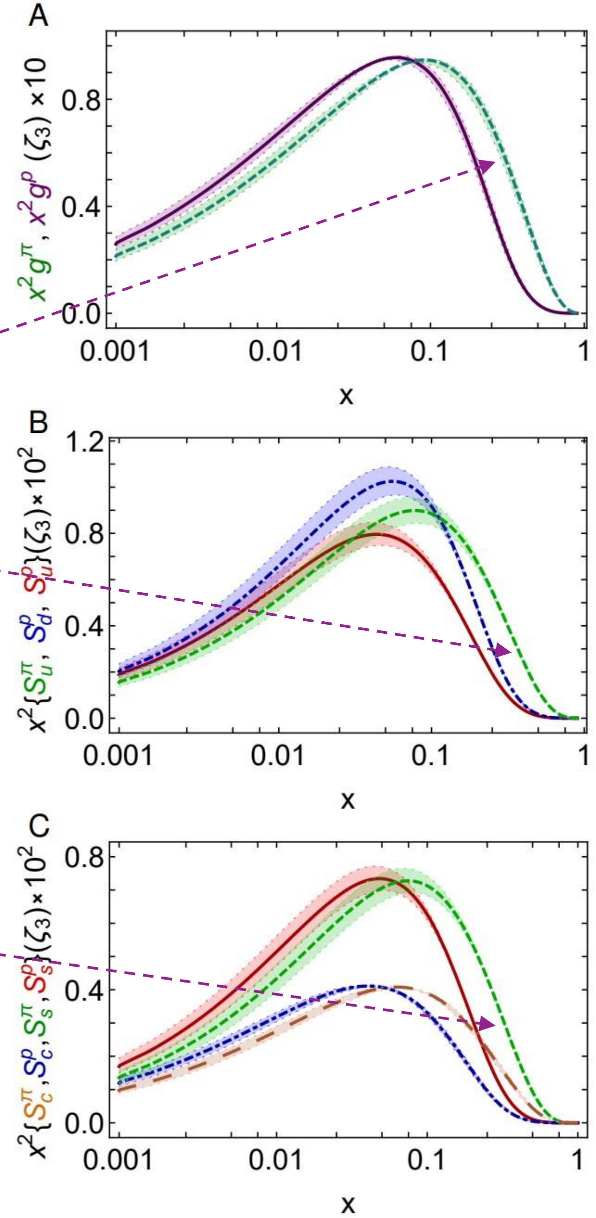
[75] A. Deur, S. J. Brodsky, G. F. de Teramond, The QCD Running Coupling, Prog. Part. Nucl. Phys. 90 (2016) 1–74.
[76] A. Deur, V. Burkert, J. P. Chen, W. Korsch, Experimental determination of the QCD effective charge $\alpha_{g_1}(Q)$, Particles 5 (2) (2022) 171–179.
[77] A. Deur, S. J. Brodsky, C. D. Roberts, QCD Running Couplings and Effective Charges – arXiv:2303.00723 [hep-ph] .

# Proton and pion distribution functions in counterpoint - 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

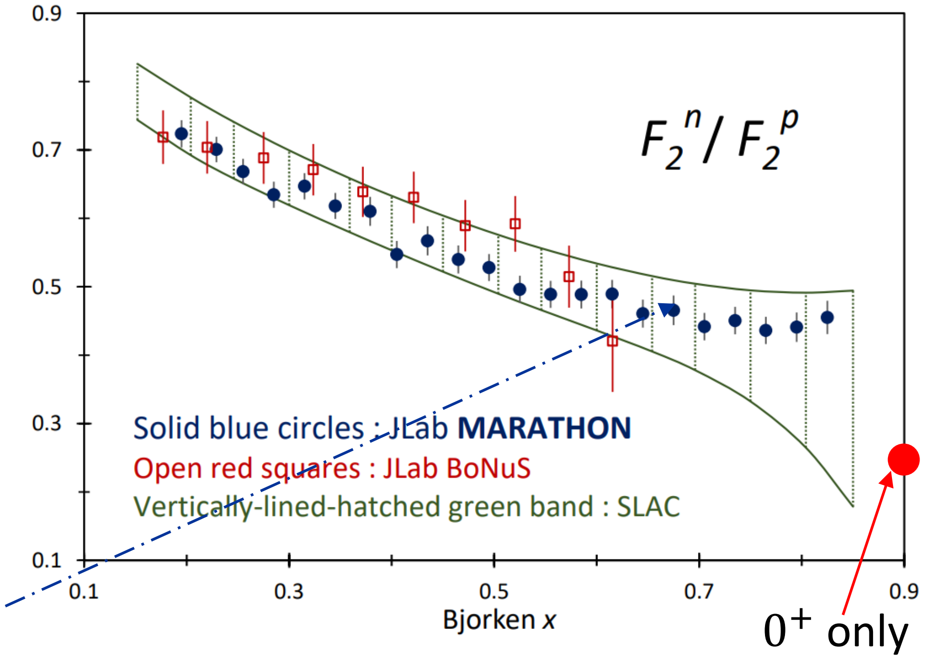



FIG. 2: The $F_2^n/F_2^p$ ratio plotted versus the Bjorken $x$ from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics $[Q^2 = 14 \cdot x\ (\text{GeV}/c)^2]$ (see text). All three 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. **128** (2022) 132003

# Neutron/Proton structure function ratio

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

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

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

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

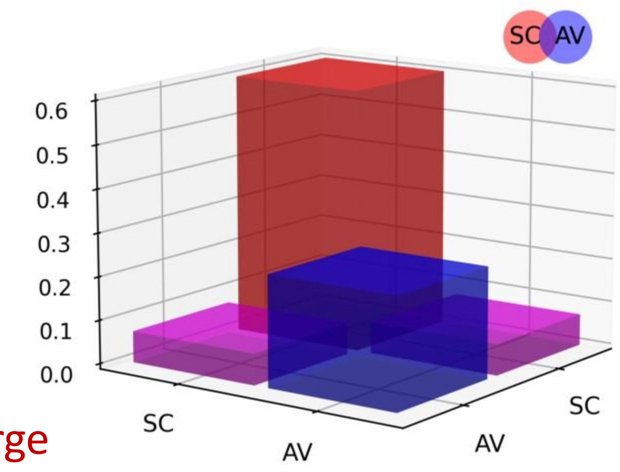
- Comparison with MARATHON data

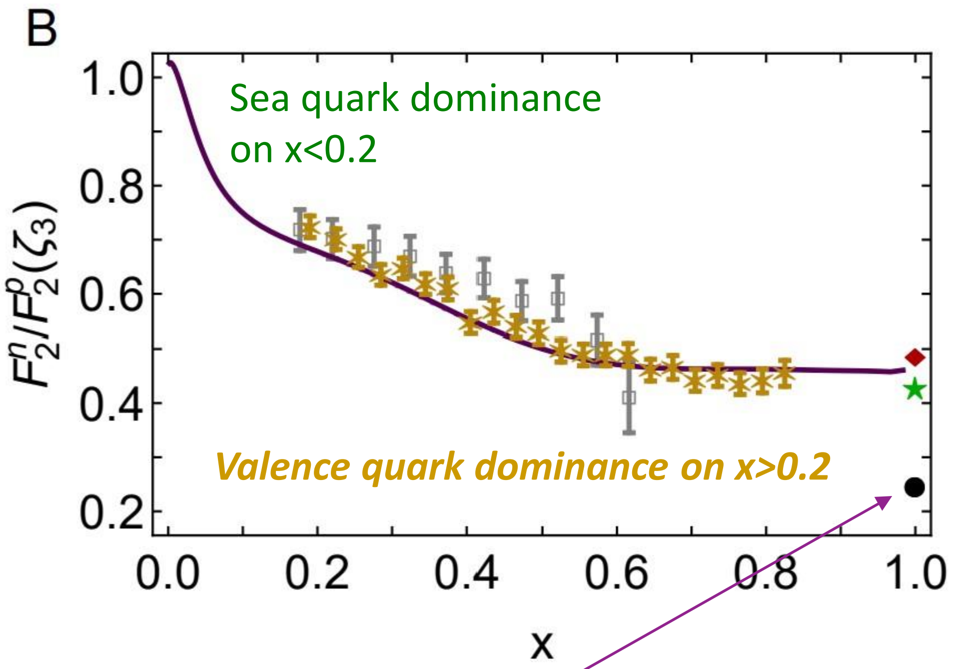
  [D. Abrams, *et al.*, Measurement of Nucleon $F_2^n/F_2^p$ Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- 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

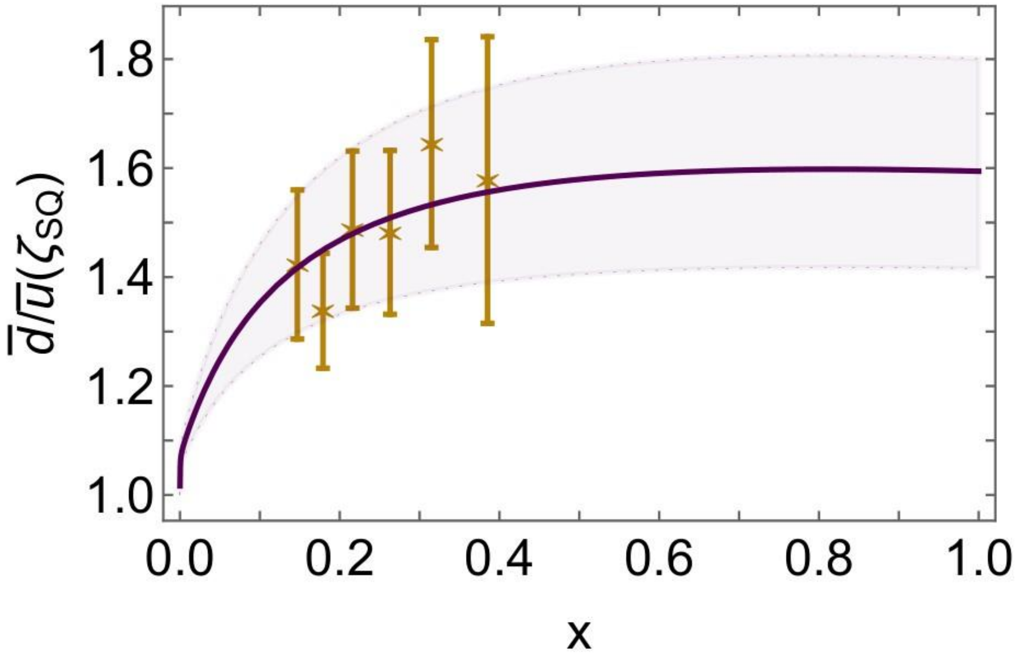
# Asymmetry of antimatter in the proton

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

- Proton = u + u + d

  ⇒ Pauli blocking: gluon splitting produces

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



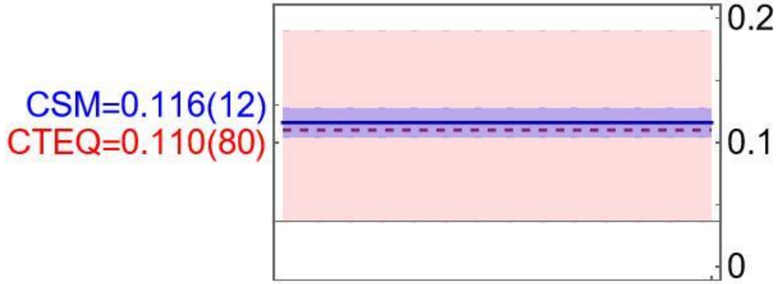

- Comparison with SeaQuest data

  [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)




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

# Proton spin crisis

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From Wikipedia, the free encyclopedia

The **proton spin crisis** (or **proton spin puzzle**) is a theoretical crisis precipitated by a 1987 experiment by the European Muon Collaboration (EMC),[1] which tried to determine the distribution of spin within the proton.[2]

Physicists expected that the quarks carry all a proton's spin. However, not only was the total proton spin carried by quarks far smaller than 100%, these results were consistent with almost zero (4~24%[3]) proton spin being carried by quarks. This surprising and puzzling result was termed the "proton spin crisis".[4] The problem is considered one of the important unsolved problems in physics.[5]

**Unsolved problem in physics**:

? *How do the quarks and gluons carry the spin of protons?*

(more unsolved problems in physics)

# Proton Spin Crisis

# 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

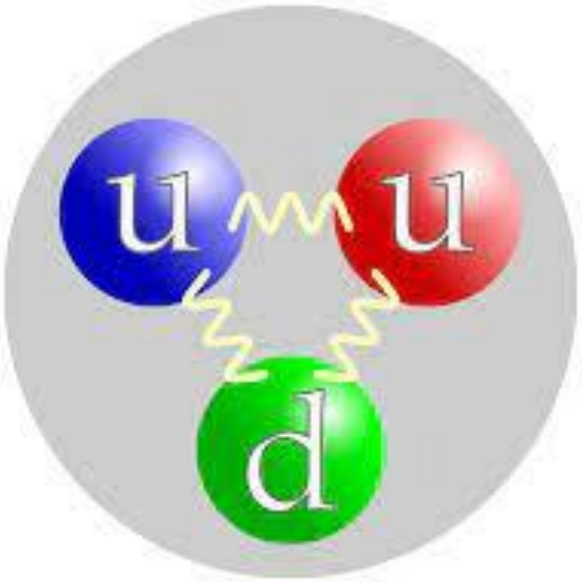
**Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- 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

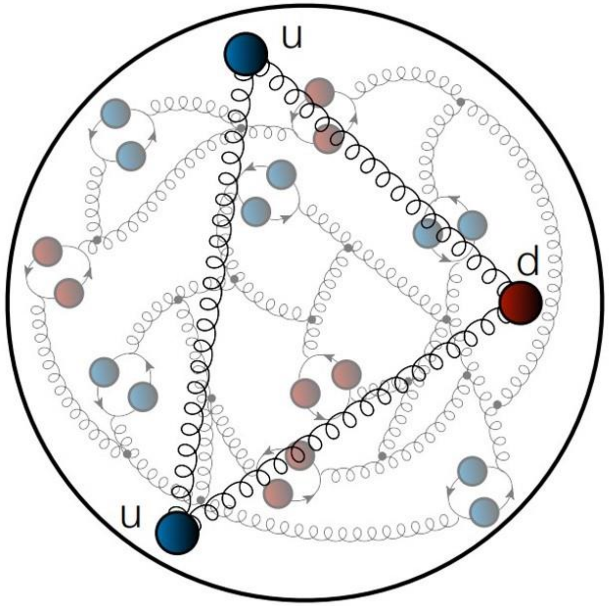



∃orbital angular momentum in every frame

Infinitely many spin $(J) = 1$ gluons

Can potentially carry a lot of the proton spin

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




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

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

- 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

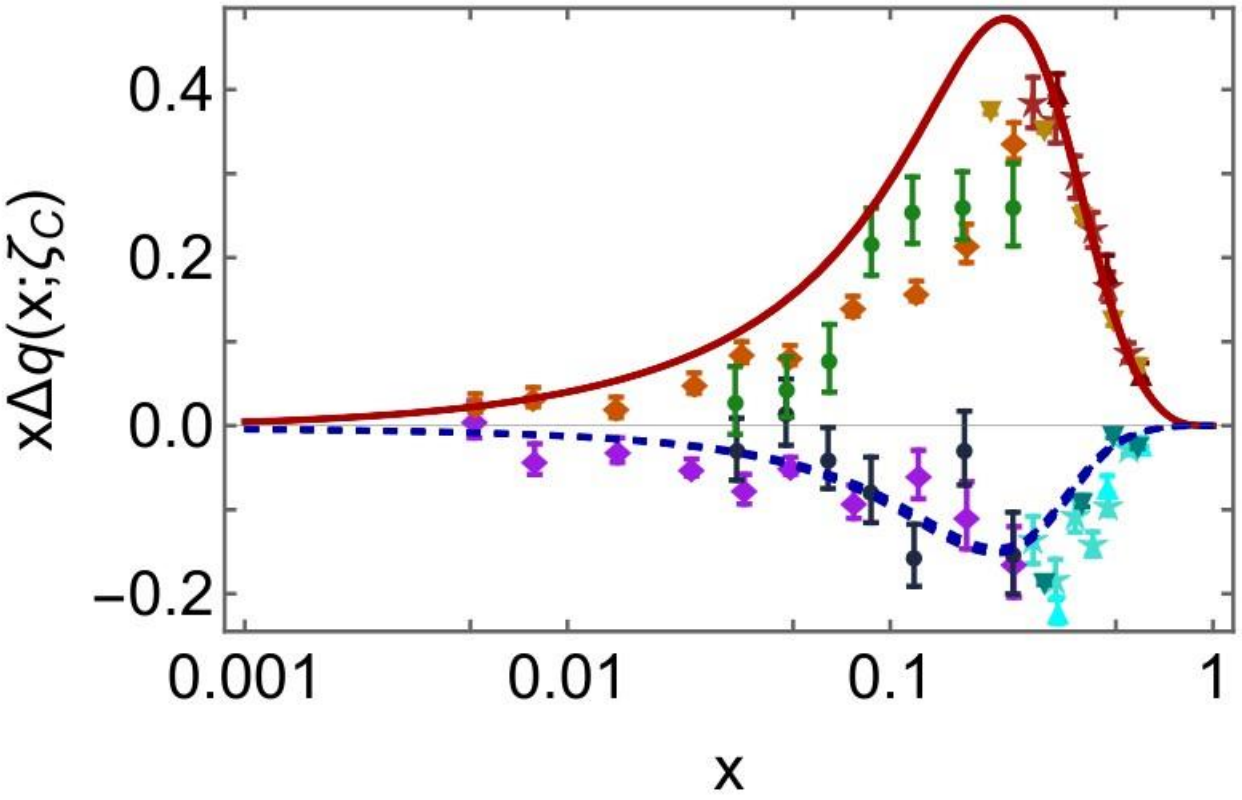
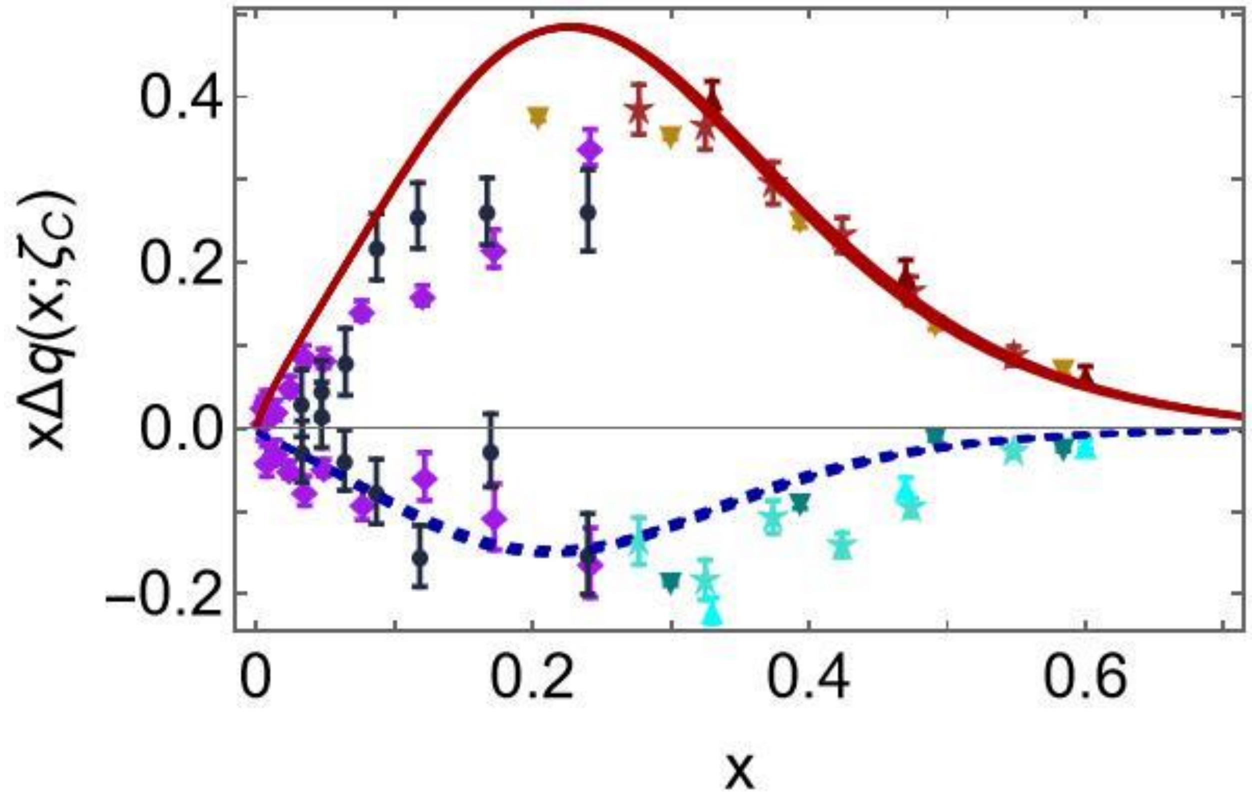



Figure 2: Polarised quark DFs: $\Delta u(x;\zeta_C)$ – solid red curves; and $\Delta d(x;\zeta_C)$ – dashed blue curves. Data: [48, HERMES] – circles; [49, COMPASS] – diamonds; filled down-triangles – [50–53, CLAS EG1]; five-pointed stars – [54, E06-014]; filled up-triangles –[55, 56, E99-117].

*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

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

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

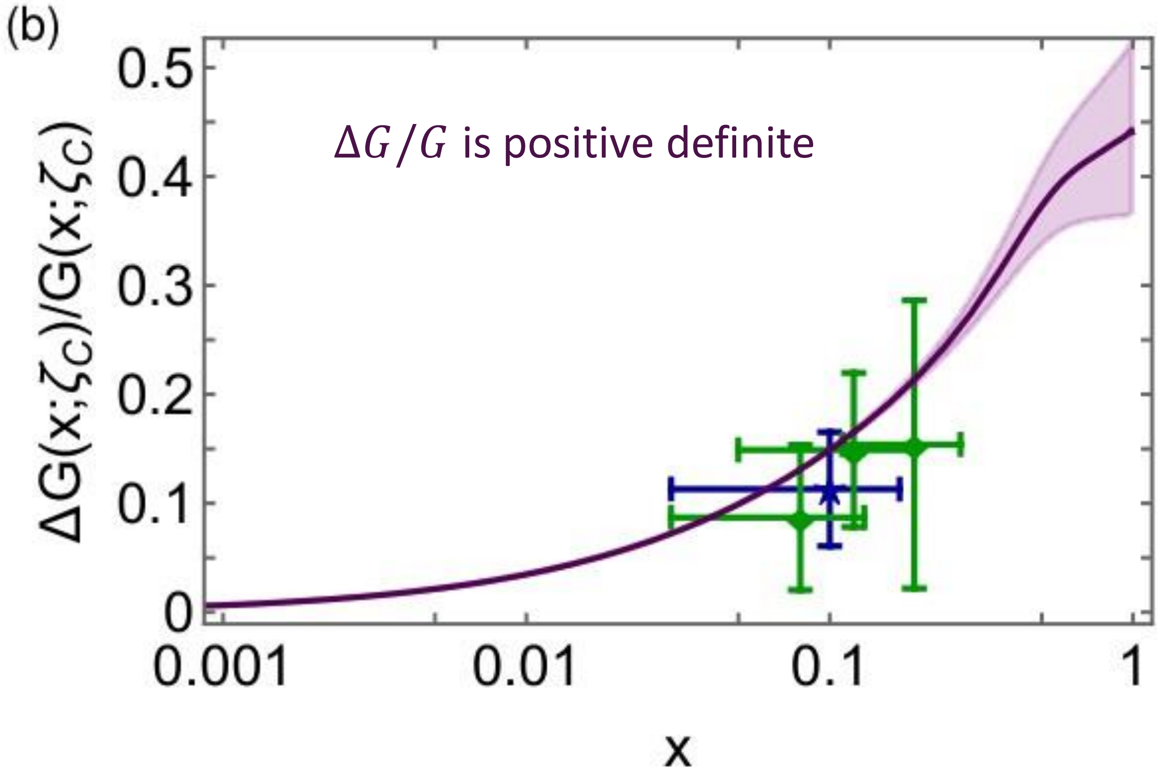
  e.g. average value over data window

  $0.167(3)_{\text{CSM}}$ *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)



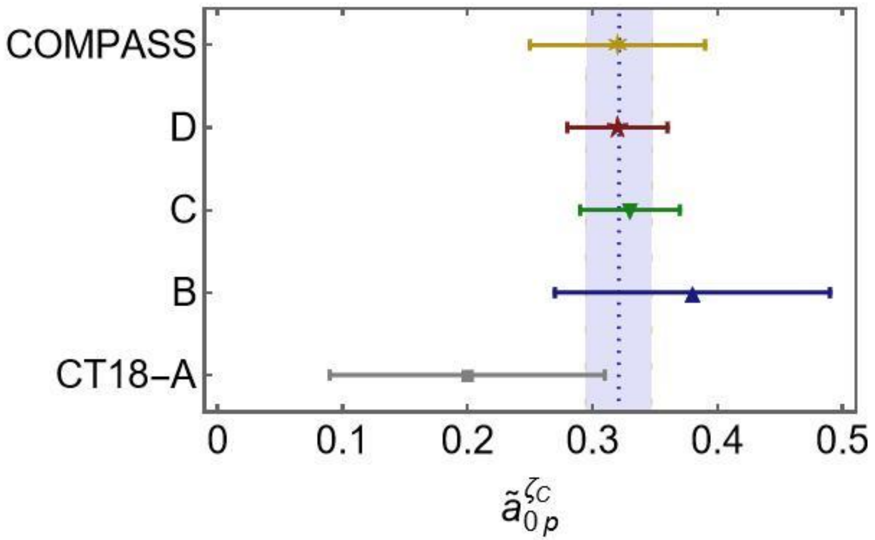
# Theory Predictions

*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.

$$a^{\zeta}_{0H} := \langle x^0\rangle^{\zeta}_{\Delta\Sigma_H} = \langle x^0\rangle^{\zeta_{\mathcal{H}}}_{\Delta\Sigma_H}\,,$$
$$\Delta G^{\zeta}_{H} := \langle x^0\rangle^{\zeta}_{\Delta g_H} = a^{\zeta}_0\,\frac{12}{25}\left[[\langle x\rangle^{\zeta}_{\mathcal{V}_H}]^{-75/32} - 1\right]$$




➢ 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: $a^{E}_0(\zeta = \sqrt{3}\text{GeV}) = 0.32(3)$

➢ COMPASS (CERN) measurement (2016): $a^{\text{COMPASS}}_0(\zeta = \sqrt{3}\text{GeV}) = 0.32(7)$

**Eur. Phys. J. C manuscript No.**
(will be inserted by the editor)

*Preprint no.* NJU-INP 079/23

# Developing predictions for pion fragmentation functions

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[4]Department of Physics, University of Shanghai for Science and Technology, Shanghai 200093, China

Email: phycui@nju.edu.cn (Z.-F. Cui); cdroberts@nju.edu.cn (C. D. Roberts)

# *Fragmentation Functions*

- High energy interactions often produce jets of energetic hadrons
  - nearly parallel longitudinal momenta & relatively small transverse momenta.
- Such jets are normally understood to originate with gluon and quark partons
  - produced in the initial collision
  - escape interaction region
  - driven by "confinement forces", fragment into a shower of colourless hadrons
- Hadronisation processes are described by fragmentation functions (FFs)

  … probability densities:
  - For instance, "$D_u^{\pi^+}(z,\zeta)dz$" is probability that
    - ✓ interaction characterised by energy scale ζ
    - ✓ $u$ quark escaping collision region produces a $\pi^+$
    - ✓ giving up fraction $z$ of its pre-emission light-front momentum
- FFs are independent of parton production process
- *Implicit connection with confinement*

  *⇒ knowledge & understanding of FFs may reveal novel aspects of EHM*

# *Fragmentation Functions*

- Fragmentation functions

  typically extracted in global fits to selections of hadron production data

  *e.g.*, $e^+e^- \to h + X$ ("clean") & SIDIS (convolution with distribution functions – DFs)
- However, existing results have large uncertainties
- Big Issue because precise knowledge of FFs is necessary if best use is to be made of data obtained at forefront and next-generation accelerator facilities
- Magnifies need for and importance of sound theoretical predictions
- Like parton distribution functions (DFs)

  … FFs are nonperturbative objects

  … not calculable in perturbation theory

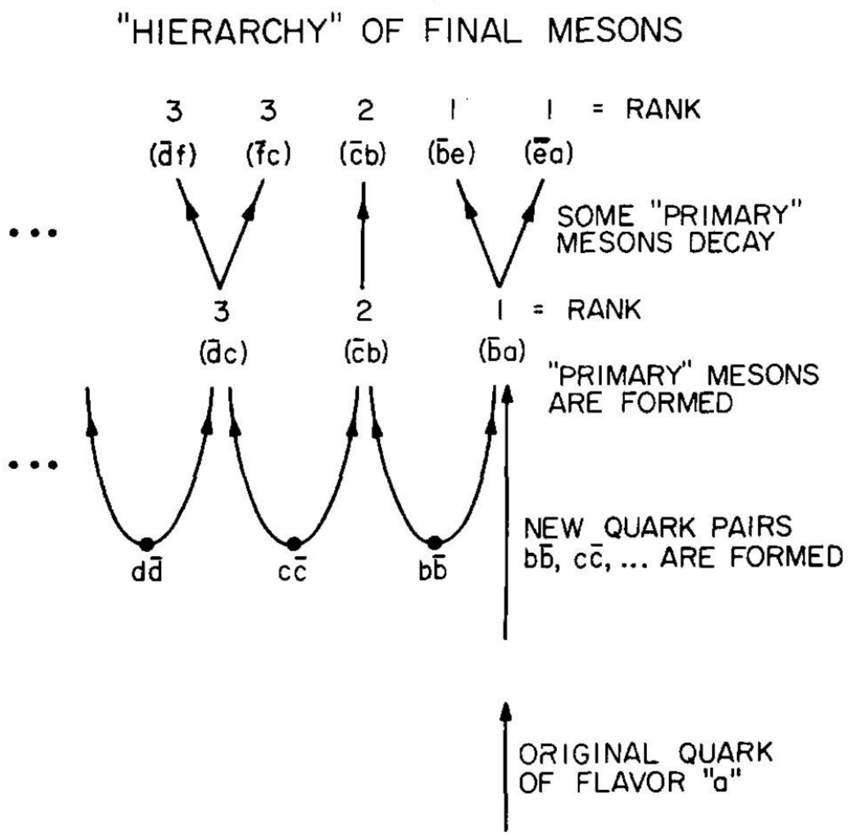
  … not calculable using lattice regularized QCD
- *Hitherto, no realistic results have been available*

# *Fragmentation Functions - Jet Equation*

- Plausible path to calculation of FFs
  … outlined 45 years ago [Field & Feynman]
- Idea straightforward:
  - Begin with knowledge of elementary FF, $d_h^p(z)$:
    - function describes 1st fragmentation event for parton $p$ generating hadron $h$ with momentum fraction $z$
- Then complete FF, $D_h^p(z)$
  – probability density for finding $h$ with mom-fraction $z$ in jet,
  obtained via a recursion (integral) relation that resums entire series of such events:

$$D_p^h(z) = d_p^h(z) + \int_z^1 (dy/y)\, d_p^h(1 - z/y) D_p^h(y)$$

"Jet (cascade) equation"




Unit probability that the parton generates a hadron with some momentum fraction:

$$\int_0^1 dz\, d_h^p(z) = 1$$

If parton gives all momentum to $h$, then none left to contribute to cascade:

$$D_h^p(z) \overset{x\simeq 1}{\approx} d_h^p(z)$$

Entails $\int_0^1 dz\, z\, D_h^p(z) = 1$

# Drell-Levy-Yan & Gribov-Lipatov (crossing symmetry)

- Crossing symmetry in QFT means elementary FFs may be viewed as timelike analogue of parton DFs
- This translates into following correspondence – the DLY relation: $d_p^{\pi}(z;\zeta) \propto z p^{\pi}(1/z;\zeta)$

  where $p^h(x;\zeta)$ is $p$-parton DF in $h$ at resolving scale ζ
- DLY relation entails that all manifestations of EHM in $p^h$ are also expressed in source function which drives fragmentation $p \to h$
- This information flows into full FF via jet equation
- Thus, not unexpectedly, seeds of confinement, expressed in hadronisation, are already present in wave functions of the hadrons involved because, recall GPD

  … $p^h(x;\zeta) \sim \int d^2k_\perp \left|\Psi_p^h(x,k_\perp^2)\right|^2$

Confinement & EHM = analytic structure of dressed-parton propagators is very different from that of perturbative partons – spectral functions are not positive definite

*Spectral functions of confined particles*, Binosi, Tripolt
Phys. Lett. B 801 (2020) 135171 • e-Print: 1904.08172 [hep-ph] … citations = 97

Expressed in LFWFs, which have propagator legs attached

# *Fragmentation Functions*

- Owing to scaling violations in QCD, one must identify scale at which DLY relation is valid
- Natural value: $\zeta = \zeta_H$, whereat dressed valence degrees-of-freedom carry all pion properties
  - in-pion sea and glue DFs vanish at $\zeta_H$ (true for all hadrons)
- Choice is logical for, *inter alia*, following reasons
  - Any realistic pion valence quark DF, $q^\pi(x;\zeta_H)$, is symmetric under $x \leftrightarrow (1-x)$
  - vanishes at the endpoints, $x = 0, 1$
  - can be written in form that ensures DLY relation produces elementary FF which vanishes at $z = 0, 1$ … *e.g.*, $u^\pi(x;\zeta_{\mathcal{H}}) = n_\pi \ln[1 + x^2(1-x)^2/\rho^2]$
  - QCD scaling violations mean that such cannot be guaranteed for $\zeta > \zeta_H$
- Hence, on $z \simeq 1$ behaviour of $\zeta = \zeta_H$ FF matches that of related valence quark DF on $x \simeq 1$
- In QCD, on $x \simeq 1$: $q^\pi(x;\zeta_H) \propto (1-x)^2 \Rightarrow d_h^p(z;\zeta_H) \propto (1-z)^2 \Rightarrow D_h^p(z;\zeta_H)$
- Evolution … any QCD-consistent FF satisfies, $\gamma(\zeta) > \gamma(\zeta_H) = 0$:

$$D^\pi_{S_q,N_q}(z;\zeta) \overset{z\simeq 1}{\propto} (1-z)^{2+\gamma(\zeta)}$$

# Fragmentation Functions - Hadron Scale DF

1. DF prediction obtained using continuum Schwinger function methods

$$u^{\pi}(x;\zeta_H) = \ln(1+\frac{x^2(1-x)^2}{\rho^2})/1.89$$

$$\rho = 0.0660$$

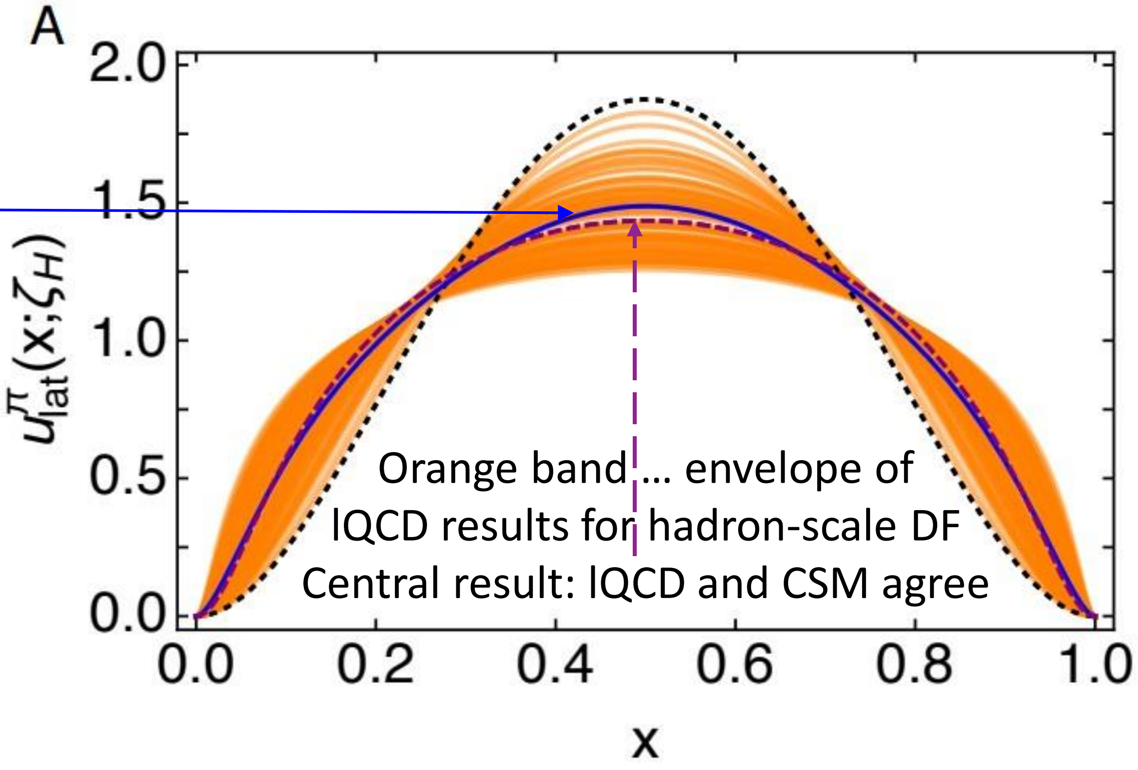
2. DLY relation gives elementary FF

$$d_{\pi}(z;\zeta_{\mathcal{H}}) = 0.420\, z \ln[1+(1-z)^2/(z^4\rho^2)]$$

3. Solve cascade equation to obtain complete FF

$$D_p^h(z) = d_p^h(z) + \int_z^1 (dy/y)\, d_p^h(1-z/y) D_p^h(y)$$

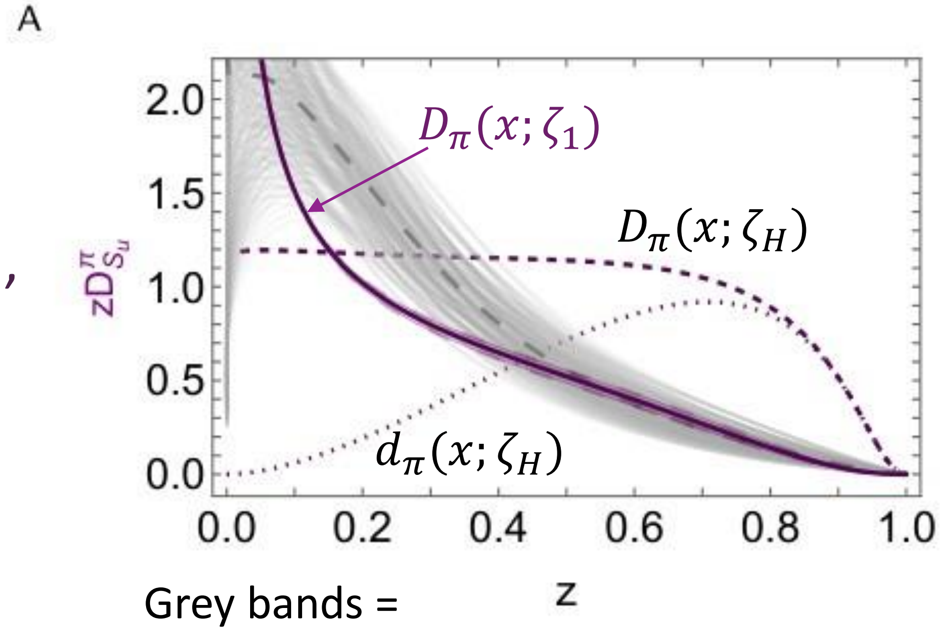
4. Evolve to obtain all pion FFs at phenomenology scale $\zeta = 1\text{GeV}$



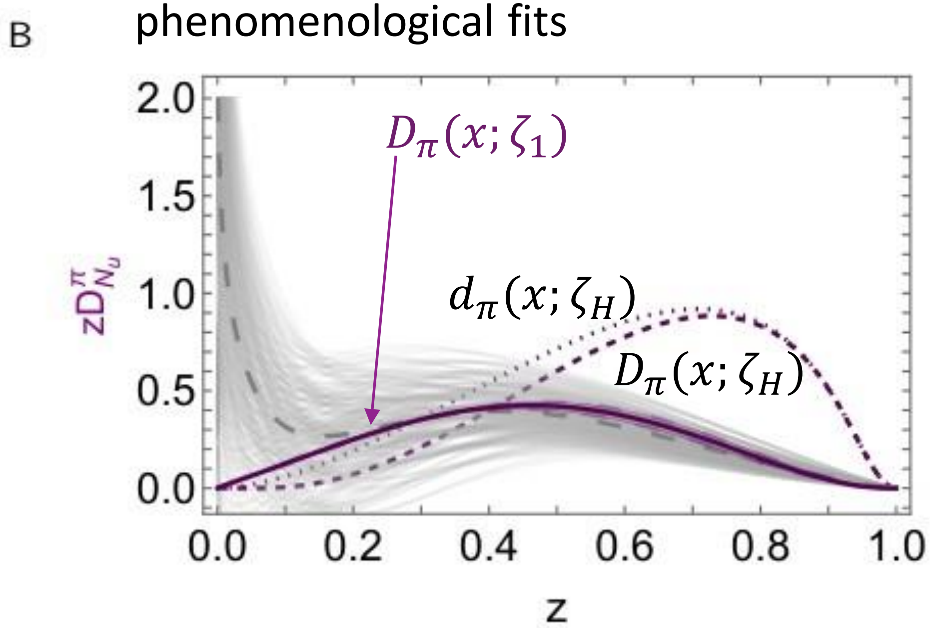

*Pion distribution functions from low-order Mellin moments*, Ya Lu (陆亚), Yin-Zhen Xu (徐胤禛), Khépani Raya, Craig D. Roberts and José Rodríguez-Quintero, NJU-INP 080/23, e-Print: 2311.01613 [hep-ph]

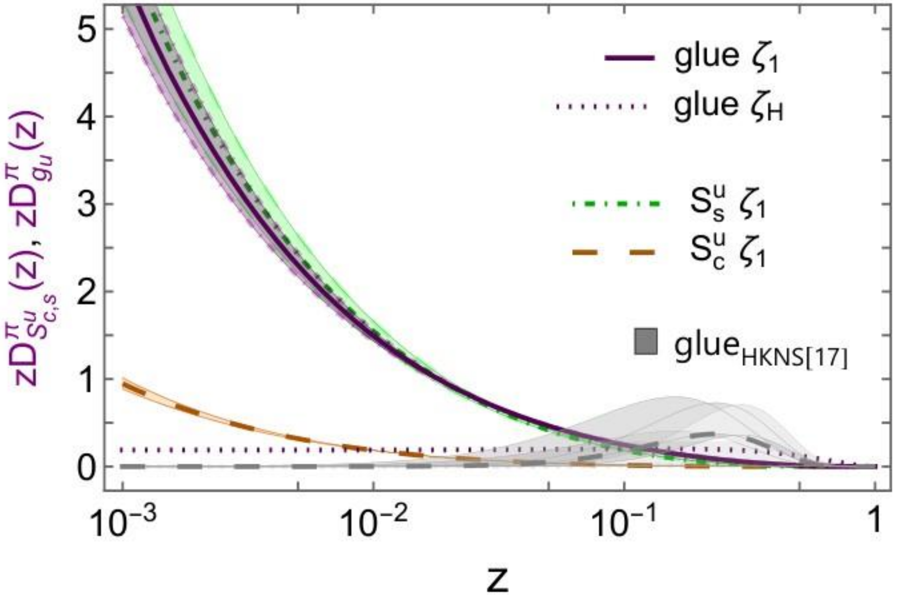
# *Fragmentation Functions - Predictions*

- Light quark FFs:
  - qualitative similarity on a large part of entire domain, especially once low-z fitting uncertainties are taken into account
  - fair quantitative agreement on z ≳ 0.4.




Grey bands = phenomenological fits




- Glue … is poorly constrained by data
- $z$-dependence of CSM prediction is markedly different from that of phenomenological fit

# Fragmentation Functions - Summary

- Unified treatment of pion DFs and FFs:
  - Direct from QCD:
    - Continuum and lattice Schwinger function methods ⇒ DF
    - DF ⇒ FF via DLY relation
- First such predictions
- Given large uncertainty in FFs determined via fits to data

  … qualitative features of parameter-free predictions

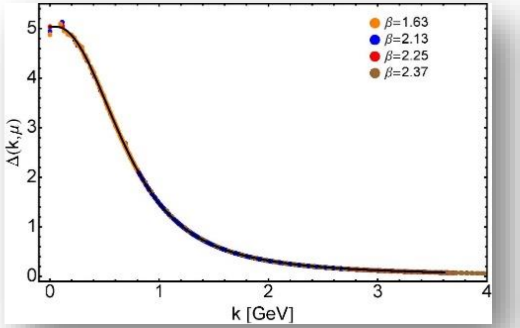
  should provide valuable guidance on future FF fits
  - Including constraints on large-$z$ behaviour
- Critical because improved knowledge of FFs is needed

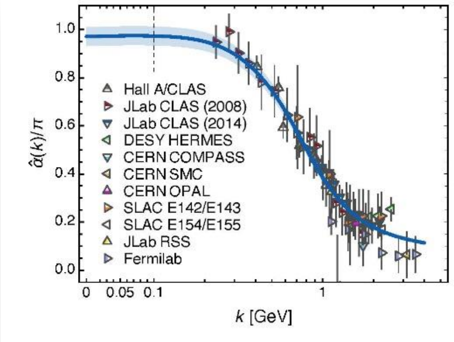
  … if best use to be made of data expected from forefront and anticipated facilities.

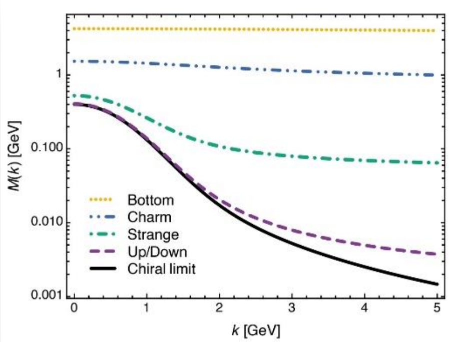
# Synergy of Experiment, Phenomenology, Theory

- *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, 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*



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

- Emergent fe
- They can als

  EHM ir

*There are theories of many things,*

*But is there a theory of everything?*

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*There are theories of many things,*
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*Thankyou*