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

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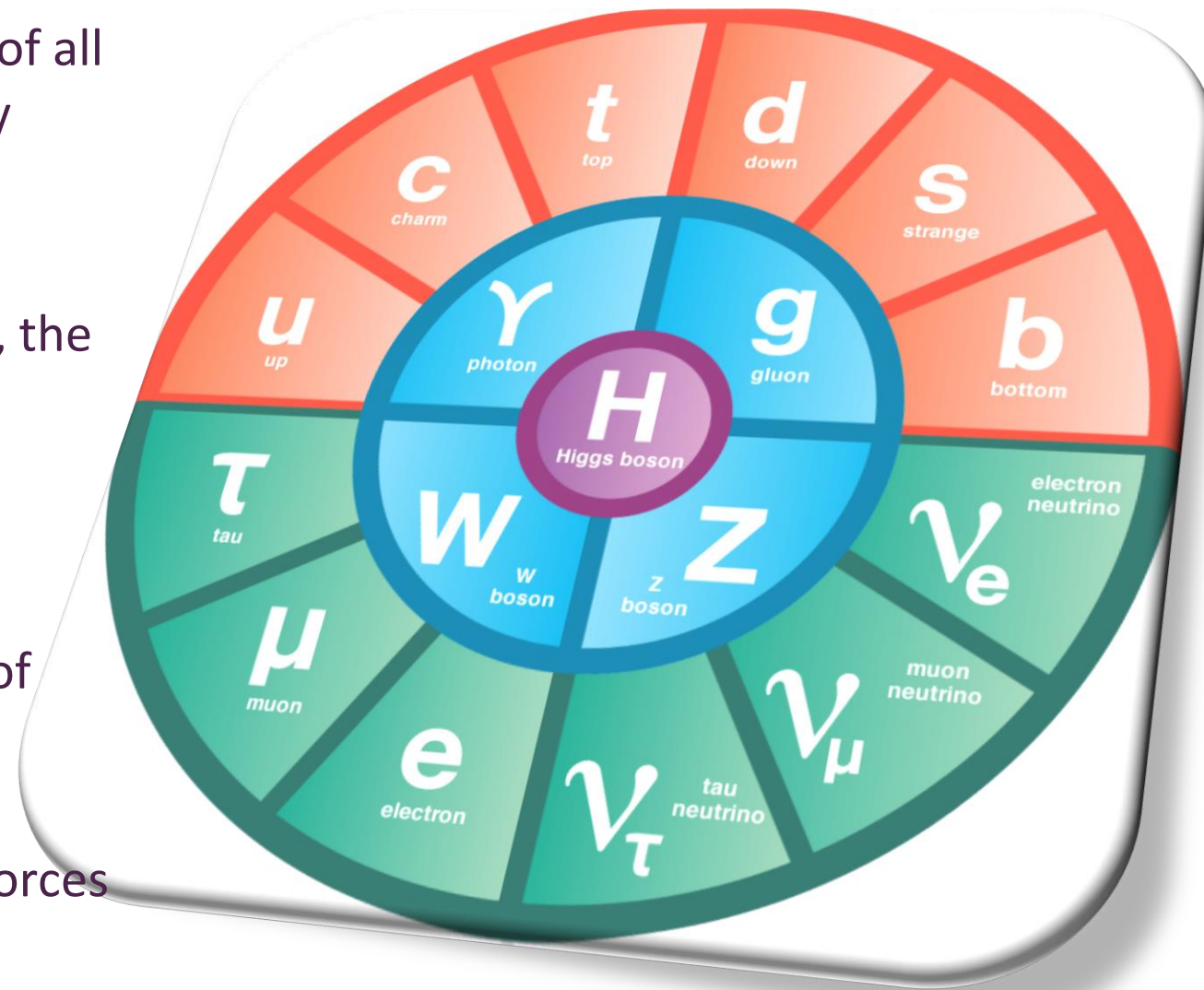NSFC

Origin of the proton mass

2013: Englert & Higgs

➢ The 2013 Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert following discovery of the Higgs boson at the Large Hadron Collider.

➢ With this discovery the Standard Model of Particle Physics became complete.

Where to now?

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2

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Standard Model of Particle Physics

- Standard Model (SM) offers a description of all known fundamental physics except gravity

- Gravity has no discernible effect when particles are studied a few at a time.

- Since LHC's discovery of the Higgs in 2012, the Higgs Boson has been promoted to the *Centre of Things*

- Standard Model has
  17 particles and 19 parameters,
  most of which relate to the Higgs and all of which must be determined through comparison with experiment

- SM supposedly describes most powerful forces in Nature

- Yet, somewhat unsatisfactory

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3

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2013: Englert & Higgs

> ➤ "The Higgs boson is often said to give mass to everything."

> ➤ "However, that is wrong. It only gives mass to some very simple particles, accounting for only one or two percent of the mass of more complex things …"

> ➤ *The vast majority of mass comes from the energy needed to hold quarks together inside hadrons*

confinement

What does this mean?!

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4

Standard Model of Particle Physics

- Strong Interactions in the Standard Model are supposed to be described by quantum chromodynamics (QCD)

- Only two parameters are intrinsic to QCD
  - Higgs enters through current-quark masses

- One of them – θ_{QCD} – appears to be zero (exactly or almost) ... know this because nucleon EDM is (as yet) unmeasurably small

- Just one parameter remains to be fixed

- Perhaps science has a chance of *understanding* QCD ∈ SM?

5

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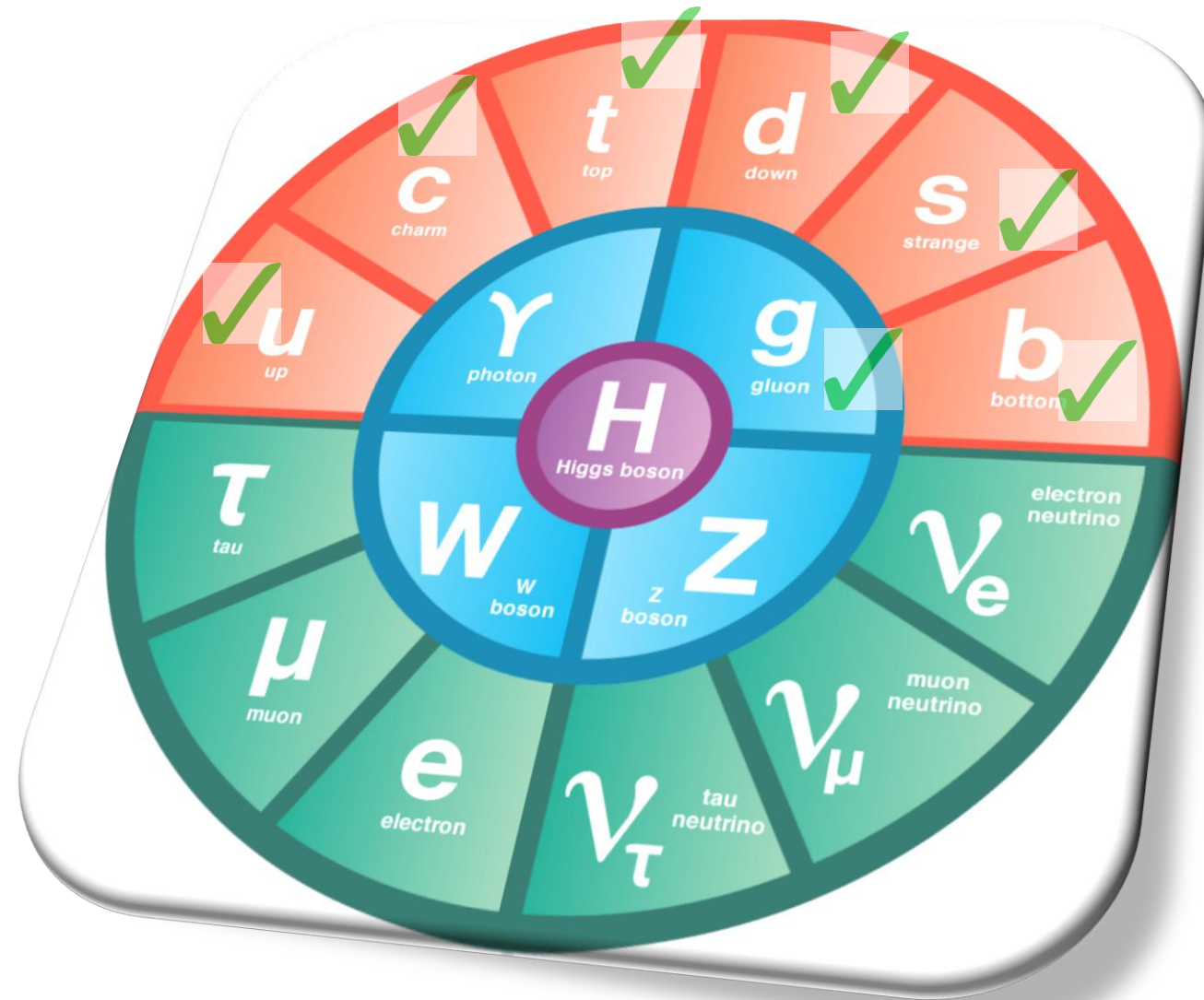
2013: Englert & Higgs

- The most important chapter of the Standard Model is the least understood.
- Quantum Chromodynamics (QCD) is supposed to describe all nuclear physics
  - Matter = quarks
  - Gauge bosons = gluons
- Yet, fifty years after discovery of quarks, we are only just beginning to understand how QCD moulds the basic elements of nuclei:
  pions, neutrons, protons, etc.
- And there are controversies – as theory begins to predict quantities that hitherto were only inferred from measurements via phenomenological fits

6

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Why are we here?

➤ *Suppose* quantum field theories are the correct paradigm for understanding Nature

➤ We find ourselves in a Universe where time and space give us Four Dimensions (D = 4)

➤ D = 4 is a critical point
  – Quantum Field Theories with D ≠ 4 possess an explicit mass-dimension
  – Couplings are mass-dimensioned, setting scale for all quantities
    • D > 4 … uncontrollable ultraviolet divergences
    • D < 4 … super-convergent, but hierarchy problem with dynamical effects being < 10% of explicit scale

➤ Standard Model is built from scale-invariant classical field theories (Ignoring Higgs couplings)
  – Such theories are renormalizable & Procedure introduces a mass scale
  – The size of the mass-scale is not determined by the theory

➤ What determines the natural mass-scale for visible matter?

➤ We know it is $m_{\mathrm{Nature}} \approx m_{\mathrm{proton}} \approx 1\,\mathrm{GeV}$
  – How much tolerance exists? … We can exist so long as $m_{\mathrm{Nature}} = 1\pm?\,\mathrm{GeV}$

7

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Emergent Phenomena ... in the Standard Model(?)

Existence of our Universe depends critically on, *inter alia*, the following empirical facts:

➤ Proton is massive

  – *i.e.*, the mass-scale for strong interactions is vastly different to that of electromagnetism

➤ Proton is absolutely stable

  – Despite being a composite object constituted from three valence quarks

➤ Pion is unnaturally light (not massless, but lepton-like mass)

  – Despite being a strongly interacting composite object built from a valence-quark and valence antiquark
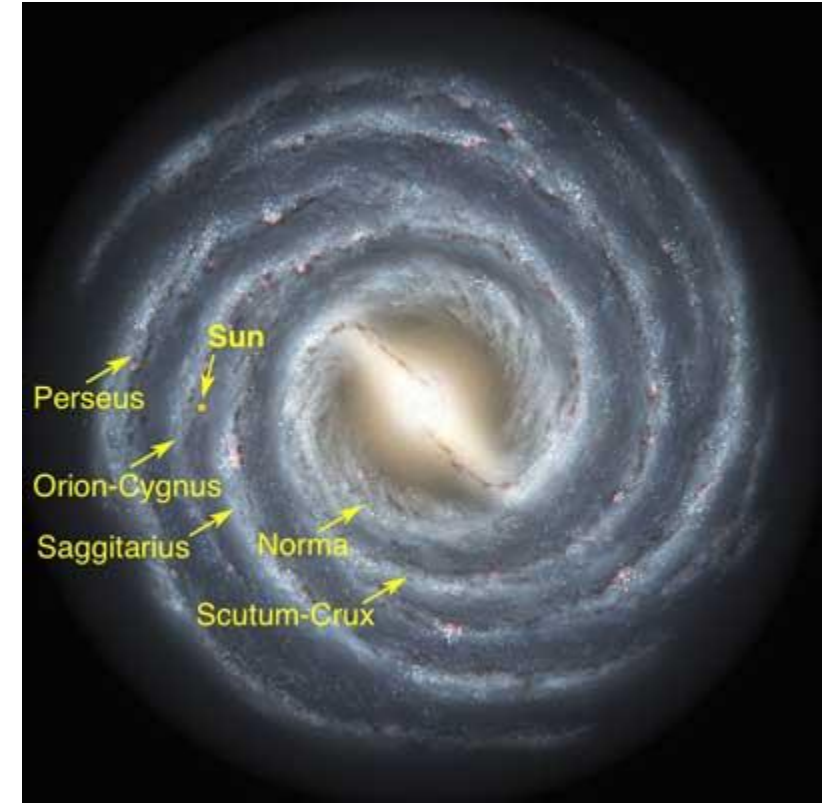
Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

Emergence of Hadron Mass

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

= Higgs Boson ... impacts are critical to evolution of Universe as we know it

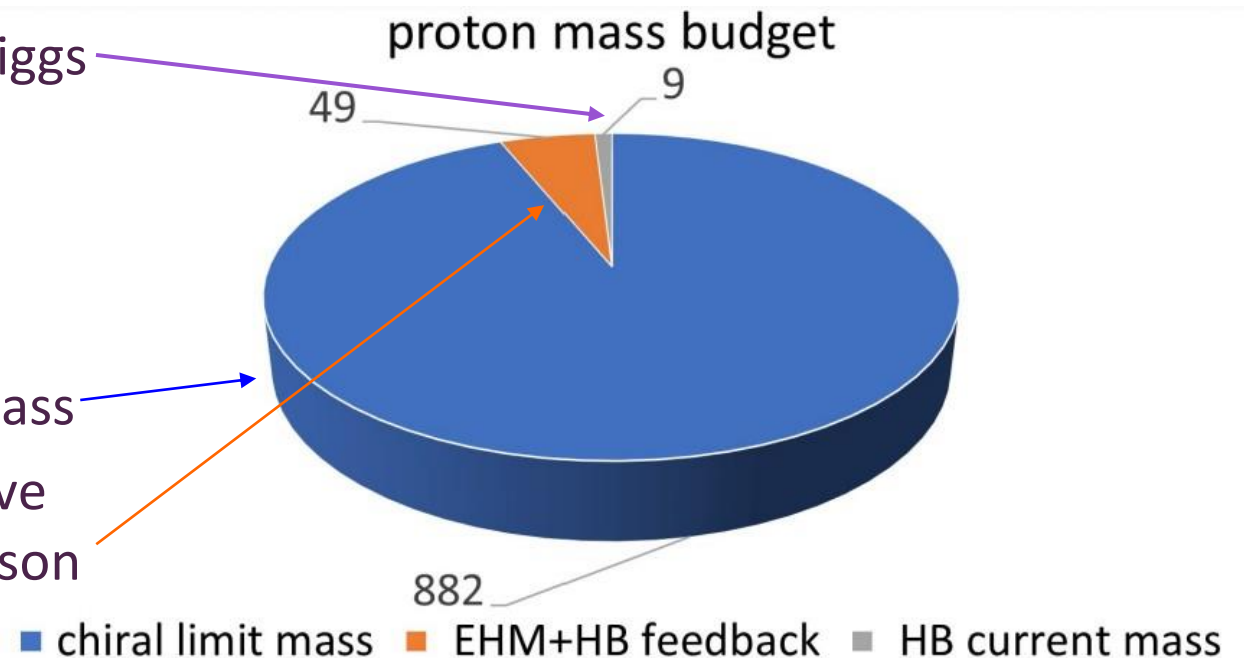➢ However, Higgs boson is alone responsible for just ~ 1% of the visible mass in the Universe

➢ Proton mass budget

Only 9 MeV/939 MeV is directly from Higgs

➢ Evidently, Nature has another, *very effective* mechanism for producing mass:

Emergent Hadron Mass (EHM)

✓ Alone, it produces 94% of the proton's mass

✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson

proton mass budget

49   9

882

■ chiral limit mass   ■ EHM+HB feedback   ■ HB current mass

9

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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?

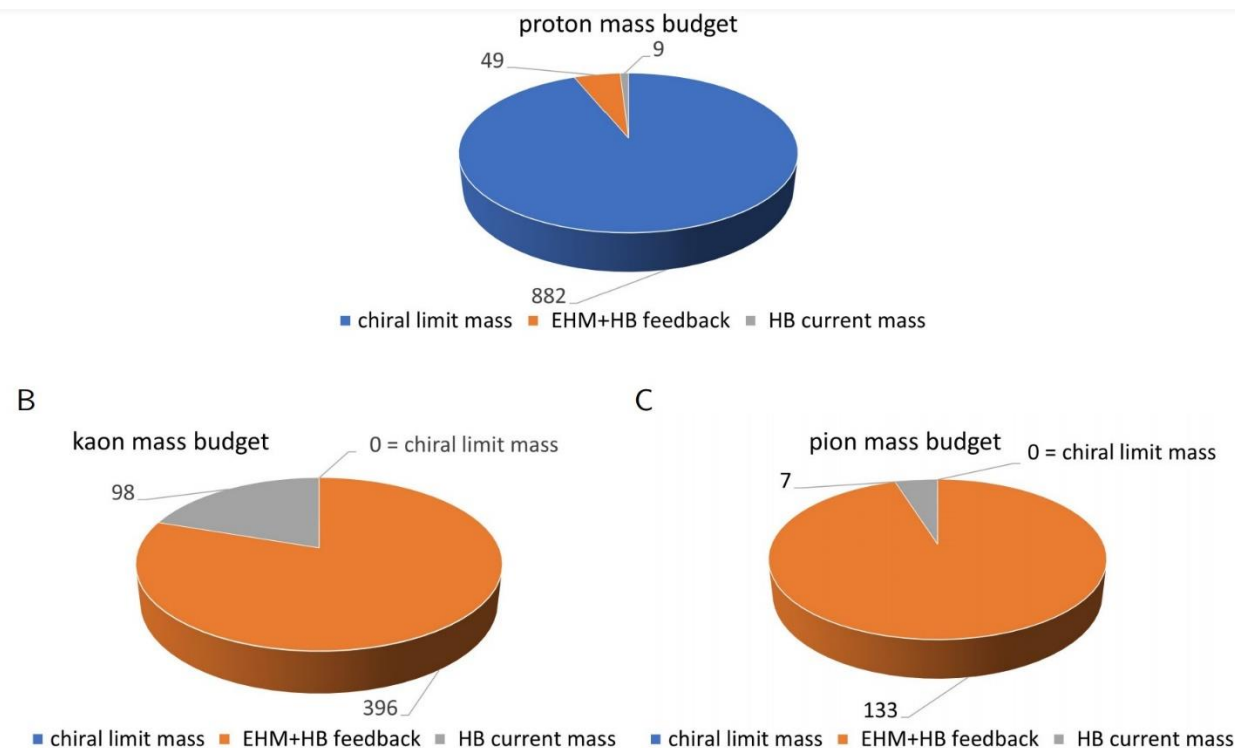*Craig Roberts: cdroberts@nju.edu.cn 413 "Origin of the proton mass"*

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].)

10

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All mass is interaction.

— *Richard P. Feynman* —

Quantum Chromodynamics

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

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

➤ One-line Lagrangian – expressed in terms of gluon and quark partons

➤ Which are NOT the degrees-of-freedom measured in detectors

Questions

➤ What are the asymptotic detectable degrees-of-freedom?

➤ How are they built from the Lagrangian degrees-of-freedom?

➤ Is QCD really the theory of strong interactions?

➤ Is QCD really a theory? ⇒ Implications far beyond Standard Model

12

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Strong Interactions in the Standard Model

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_i \left(i (\gamma^\mu D_\mu)_{ij} - m\, \delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

➢ Only apparent scale in chromodynamics is mass of the quark field

➢ Quark mass is said to be generated by Higgs boson.

➢ In connection with everyday matter, that mass is 1/250th of the natural (empirical) scale for strong interactions,
   viz. more-than two orders-of-magnitude smaller

➢ Plainly, the Higgs-generated mass is very far removed from the natural scale for strongly-interacting matter

➢ *Nuclear physics mass-scale* – 1 GeV – is an *emergent feature of the Standard Model*
   – No amount of staring at L_{QCD} can reveal that scale

➢ Contrast with quantum electrodynamics, *e.g.* spectrum of hydrogen levels measured in units of m_e, which appears in L_{QED}

13

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$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i (\gamma^\mu D_\mu)_{ij} - \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Whence Mass?

➢ Classical chromodynamics … non-Abelian local gauge theory

➢ Remove the current mass … there's no energy scale left

➢ *No dynamics in a scale-invariant theory*; only kinematics … the theory looks the same at all length-scales … there can be no clumps of anything … *hence bound-states are impossible*.

➢ *Our Universe can't exist*

➢ *Higgs boson doesn't solve this problem* …

  – normal matter is constituted from light-quarks

  – the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce

➢ *Where did it all begin? … becomes … Where did it all come from?*

14

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$$T_{\mu\mu} = \tfrac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

➤ In a scale invariant theory

the *energy-momentum tensor must be traceless:* $T_{\mu\mu} \equiv 0$

➤ Regularisation and renormalisation of (ultraviolet) divergences in <u>Quantum</u>
Chromodynamics introduces a mass-scale
... *dimensional transmutation*:

Lagrangian's *constants* (couplings and masses) become dependent on a mass-scale, ζ

➤ $\alpha \rightarrow \alpha(\zeta)$ in QCD's (massless) Lagrangian density, $\mathcal{L}(m=0)$

$\Rightarrow \partial_\mu \mathcal{D}_\mu = \delta\mathcal{L}/\delta\sigma = \alpha\beta(\alpha)\, d\mathcal{L}/d\alpha = \boxed{\beta(\alpha)\, \tfrac{1}{4}G_{\mu\nu}\, G_{\mu\nu} = T_{\rho\rho} =: \Theta_0}$ *Trace anomaly*

QCD β function ... specifies how the coupling "runs"

Quantisation of renormalisable four-dimensional theory forces nonzero value for trace of energy-momentum tensor

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15

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$$T_{\mu\mu} = \tfrac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

➢ Knowing that a trace anomaly exists does not deliver a great deal
      … Indicates only that a mass-scale must exist

➢ Key Question: Can one compute and/or understand the magnitude of that scale?

➢ One can certainly *measure* the magnitude … consider proton:

$$\langle p(P)|T_{\mu\nu}|p(P)\rangle = -P_\mu P_\nu$$

$$\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2$$

$$= \langle p(P)|\Theta_0|p(P)\rangle$$

➢ In the chiral limit the entirety of the proton's mass is produced by the trace anomaly, Θ_0

      … In QCD, Θ_0 measures the strength of gluon self-interactions

      … so, from one perspective,
          m_p is (somehow) completely generated by glue.

16

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On the other hand ...

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$$T_{\mu\mu} = \tfrac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

Trace Anomaly

- In the chiral limit, pion is massless Nambu-Goldstone boson:

$$\langle\pi(q)|T_{\mu\nu}|\pi(q)\rangle = -q_\mu q_\nu \quad \Rightarrow \quad \langle\pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- Does this mean that the scale anomaly vanishes trivially in the pion state, *i.e.* gluons contribute nothing to the pion mass?

- Difficult way to obtain "zero"!

- Easier to imagine that "zero" owes to cancellations between different operator contributions to the expectation value of Θ_0.

- Of course, such precise cancellation should not be an accident.

    It could only arise naturally because

    of some symmetry and/or symmetry-breaking pattern.

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18

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Whence "1" and yet "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

➤ *No statement of the question*

   "How does the mass of the proton arise?"

   is complete without the additional clause

   "How does the pion remain **massless***?"*

➤ Natural visible-matter mass-scale must emerge simultaneously with apparent preservation of scale invariance in related systems

– Expectation value of Θ_0 in pion is always zero, irrespective of the size of the natural mass-scale for strong interactions = m_p

19

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Whence "1" and yet "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2, \qquad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

➤ *No statement of the question*

    "How does the mass of the proton arise?"

    is complete without the additional clause

    "How does the pion remain **massless***?"*

➤   Modern Physics must

Elucidate the entire array of Empirical Consequences
of the Mechanism responsible
so that the Standard Model can be Validated

20

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All mass is interaction.

— Richard P. Feynman —

In QCD, so is the absence of mass

Modern Understanding Grew Slowly from *Ancient* Origins

➢ More than 40 years ago

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

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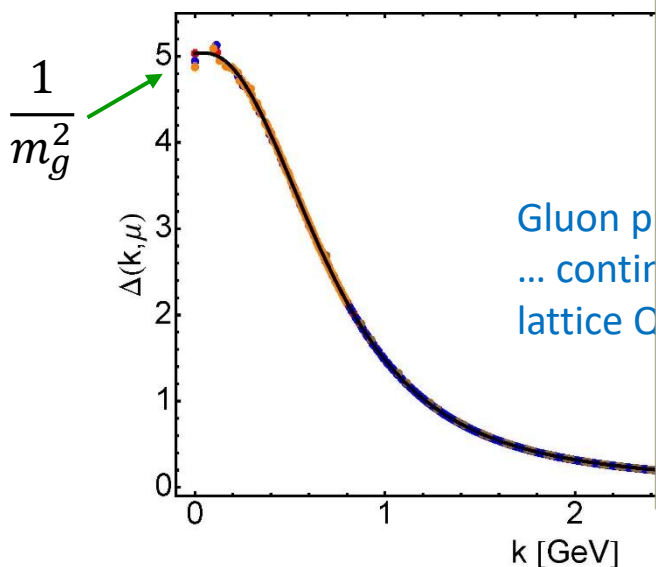 described by a mass function that is large at infrared momenta

3-gluon vertex

4-gluon vertex

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

Gluon propagator
… continuum and
lattice QCD agree

Legend: $\beta=1.63$, $\beta=2.13$, $\beta=2.25$, $\beta=2.37$

Truly <u>mass from nothing</u>
*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*
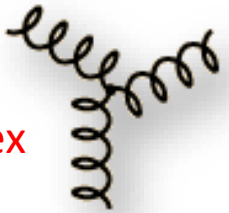✓ *Empirical verification?*

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➤ More than 40 year
Dynamical mass ger ... *mics,*
J.M. Cornwall, Phys.

➤ Owing to strong se ... *uasiparticles,*
described by a ... *omenta*

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

3-gluon vertex

4-gluon vertex

Gluon p
... contin
lattice Q

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

EHM means Gluons are massive

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This is where we live

$\Leftarrow$

**What's happening
out here?!**

QCD's Running Coupling

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25

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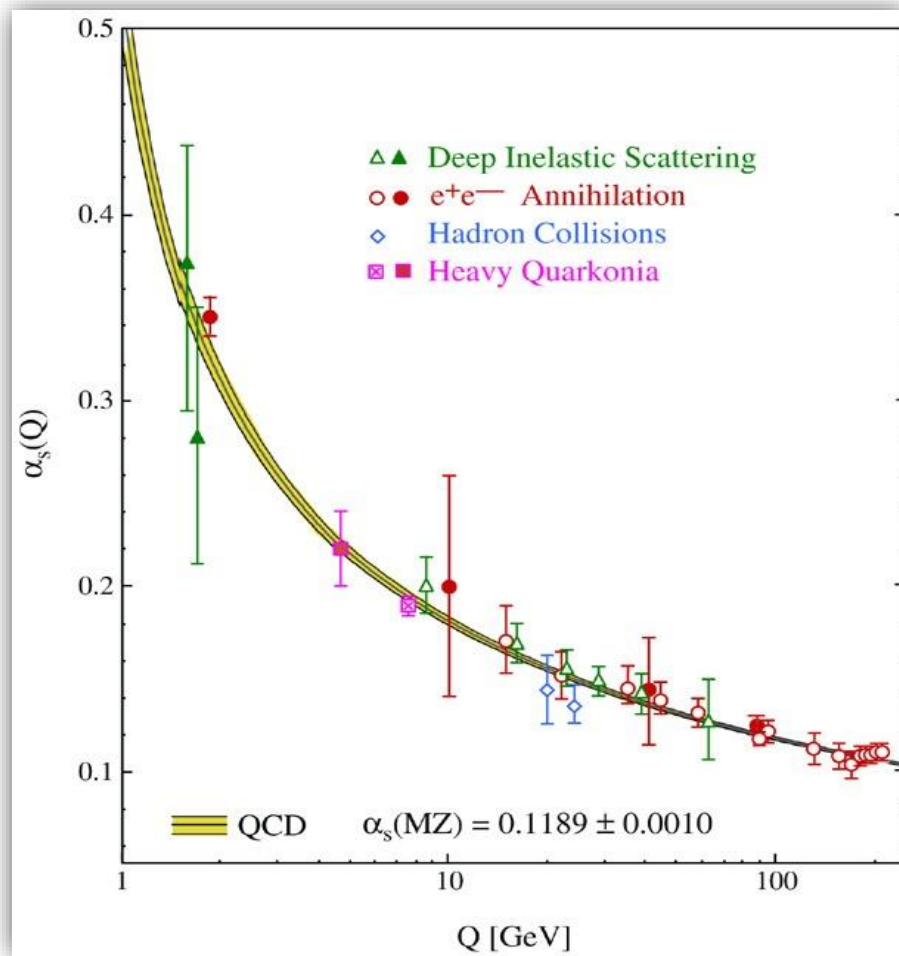
# *Process independent effective charge = running coupling*

- Modern theory enables unique QCD analogue of "Gell-Mann – Low" running charge to be rigorously defined and calculated

- Analysis of QCD's gauge sector

   yields a *parameter-free prediction*

- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx \frac{1}{2}\, m_p$

- No Landau Pole

   – *"Infrared Slavery" picture – linear potential – is not correct explanation of confinement*

- Below $k \sim \hat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again
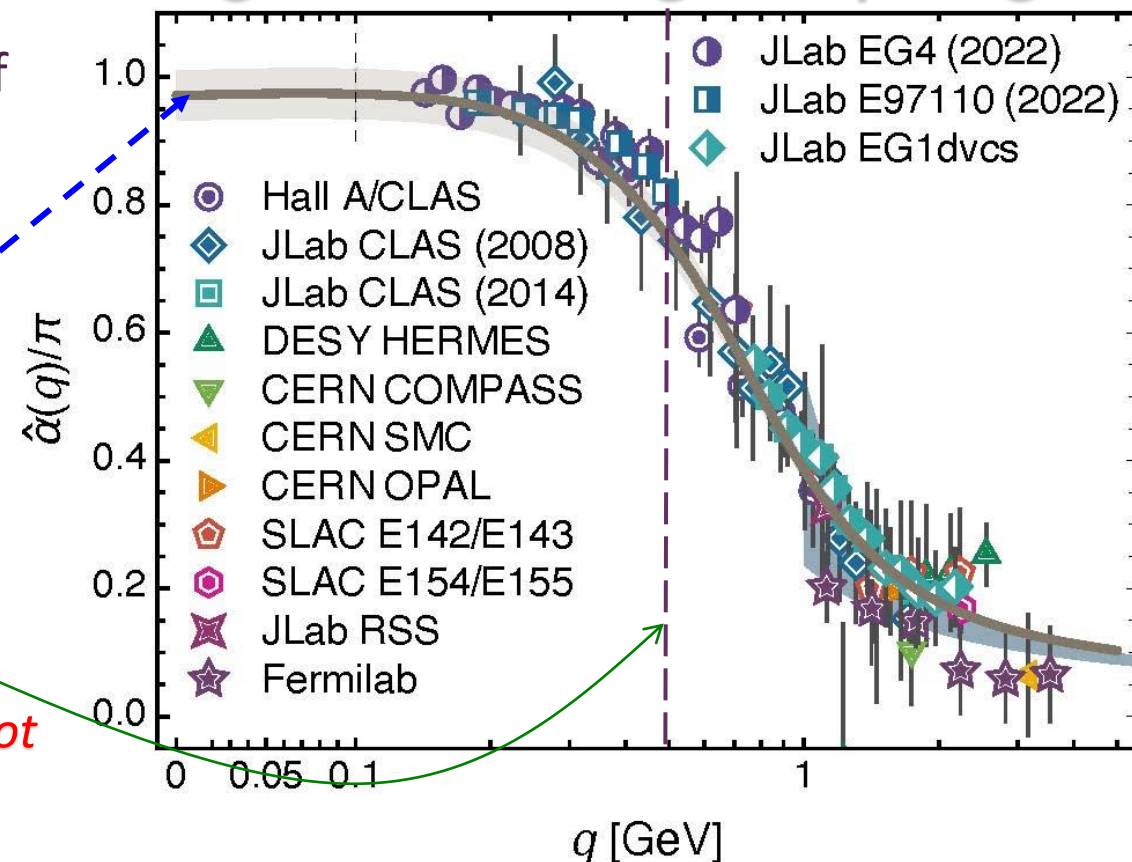
- JLab EG4 (2022)
- JLab E97110 (2022)
- JLab EG1dvcs
- Hall A/CLAS
- JLab CLAS (2008)
- JLab CLAS (2014)
- DESY HERMES
- CERN COMPASS
- CERN SMC
- CERN OPAL
- SLAC E142/E143
- SLAC E154/E155
- JLab RSS
- Fermilab

$\hat{\alpha}(q)/\pi$ vs q [GeV]

EHM Basics

➢ Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant

➢ Yet …

  – Massless gluons become massive

  – A momentum-dependent scale-expressing
        charge is produced

  – Massless quarks become massive

➢ EHM is expressed in
        EVERY strong interaction observable

➢ Challenge to Theory =
        Elucidate all observable consequences of these phenomena
        and highlight the paths to measuring them

➢ Challenge to Experiment =
        Test the theory predictions so that
        the boundaries of the Standard Model can finally be drawn
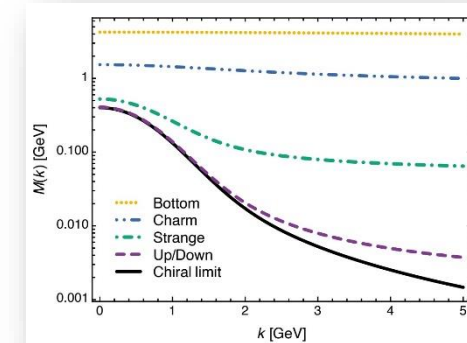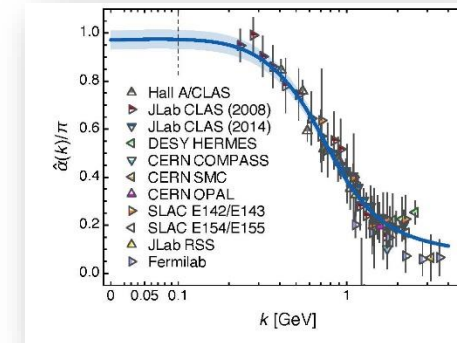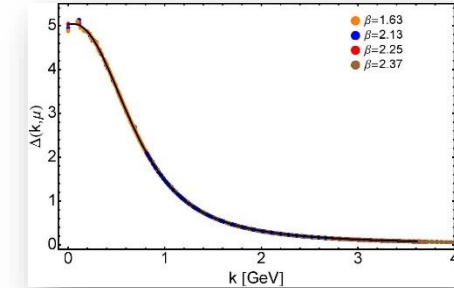
27

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QCD Fact   Pion (Nambu-Goldstone modes) and mass

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

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

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

Pion wave function   quark mass function

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

28

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QCD Fact   Pion (Nambu-Goldstone modes) and mass

- Higgs boson couplings → 0
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- Pion Bethe-Salpeter amplitude

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

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

Pion wave function   quark mass function

- Entails, enigmatically, properties of the nearly massless pion are the cleanest expression of EHM in the Standard Model !
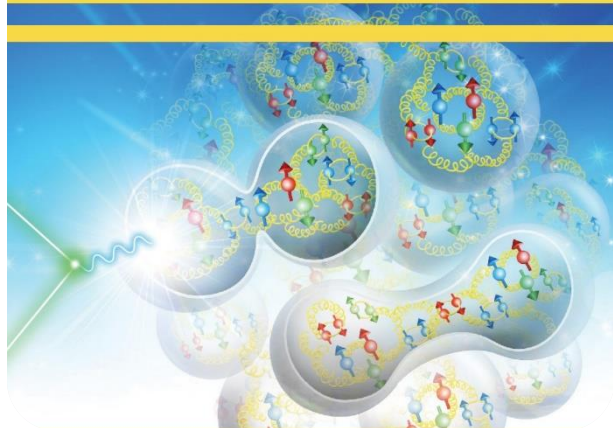
29

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EHM at
Existing and Future Facilities

AMBER

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

Jefferson Lab
Thomas Jefferson National Accelerator Facility

ELECTRON-ION COLLIDER

EIC Yellow Report

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Parton Distribution Functions

31

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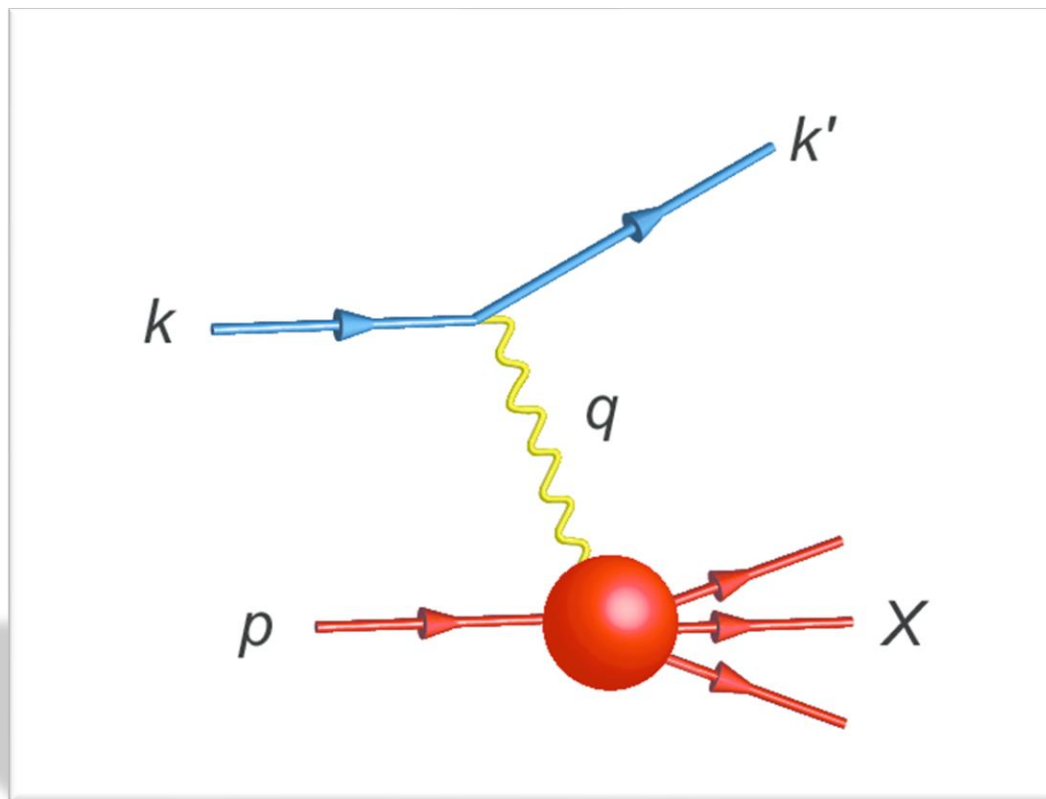
Proton and pion distribution functions in counterpoint

- 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?
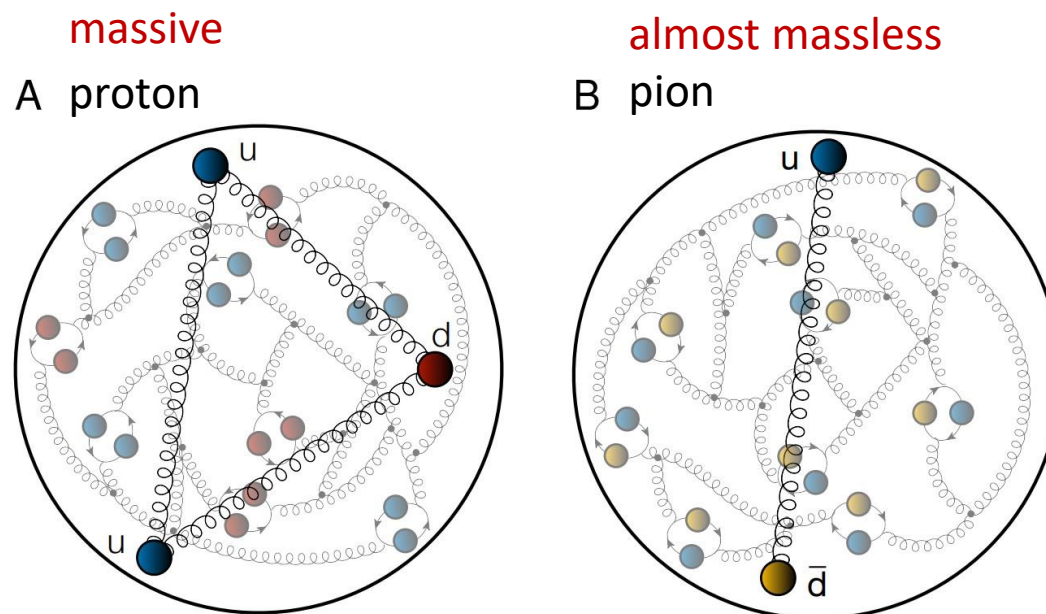
massive   almost massless

A   proton   B   pion

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 $\pi^0 \sim u\bar{u} - d\bar{d}$.)

32

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Proton and pion distribution functions in counterpoint

➢ Valence-quark domain: there is a scale $\zeta_H < m_p$ at which

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

➢ $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p$, $\beta_\pi = 2 + \gamma_\pi$

- Gluon DFs: $\beta_{p,\pi}^{\text{glue}} \geq \beta_{p,\pi}^{\text{val}} + 1$
- Sea DFs: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$

➢ Further, no simultaneous global fits to proton and pion data have ever been performed
- Largely because pion data are scarce

➢ Existing approaches are unlikely to yield definitive answers because practitioners typically ignore QCD constraints

✓ These are simple consequences of DGLAP equations.

✓ Argument can be reversed:

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

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

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

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

❽ Proton has valence glue but no valence quarks!

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33

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➤ Valence-quark domain: there is a scale $\zeta_H < m_p$ at which

$$\begin{cases} d^p(x;\zeta_{\mathcal{H}}), u^p(x;\zeta_{\mathcal{H}}) \overset{x\simeq1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_{\mathcal{H}}), u^\pi(x;\zeta_{\mathcal{H}}) \overset{x\simeq1}{\propto} (1-x)^2 \end{cases}$$

➤ $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p, \beta_\pi = 2 + \gamma_\pi$

- – Gluon DFs: $\beta_{p,\pi}^{\text{glue}} \geq \beta_{p,\pi}^{\text{val}} + 1$
- – Sea DFs: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$

➤ Further, no simultaneous global fits to proton and pion data have ever been performed
- – Largely because pion data are scarce

➤ Existing approaches are unlikely to yield definitive answers because practitioners typically ignore QCD constraints

✓ These are simple consequence of DGLAP equations.

❽ CT18: large-x power of glue distribution at the scale ζ = mass_charm is (almost) identical to that of valence-quarks.

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

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

  ❽ *i.e.*, at ζ = mass_charm valence-quarks are subleading degrees-of-freedom. Instead, gluons dominate on what is typically called the valence-quark domain.

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34

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Proton and pion distribution functions in counterpoint

➢ 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: $\langle x \rangle^{\zeta_{\mathcal{H}}}_{u_p} = 0.687$, $\langle x \rangle^{\zeta_{\mathcal{H}}}_{d_p} = 0.313$, $\langle x \rangle^{\zeta_{\mathcal{H}}}_{u_\pi} = 0.5$

➢ 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

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35

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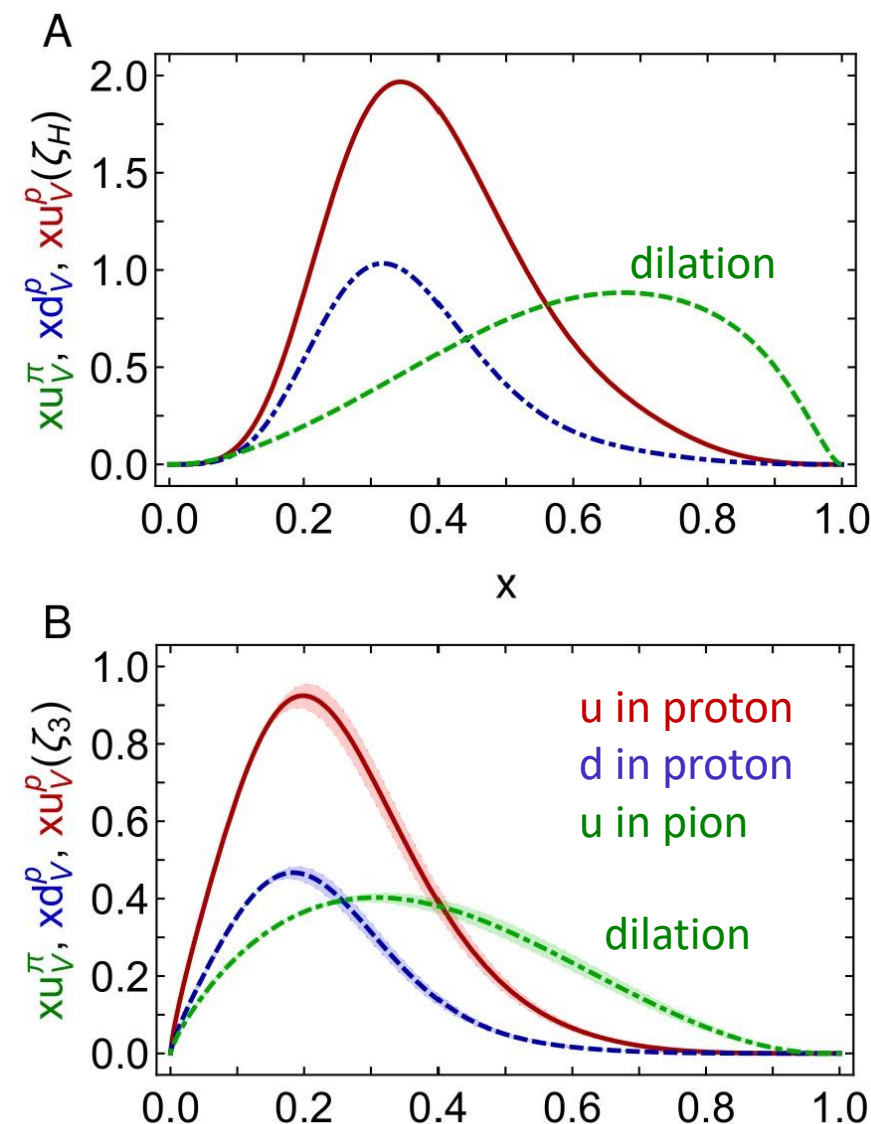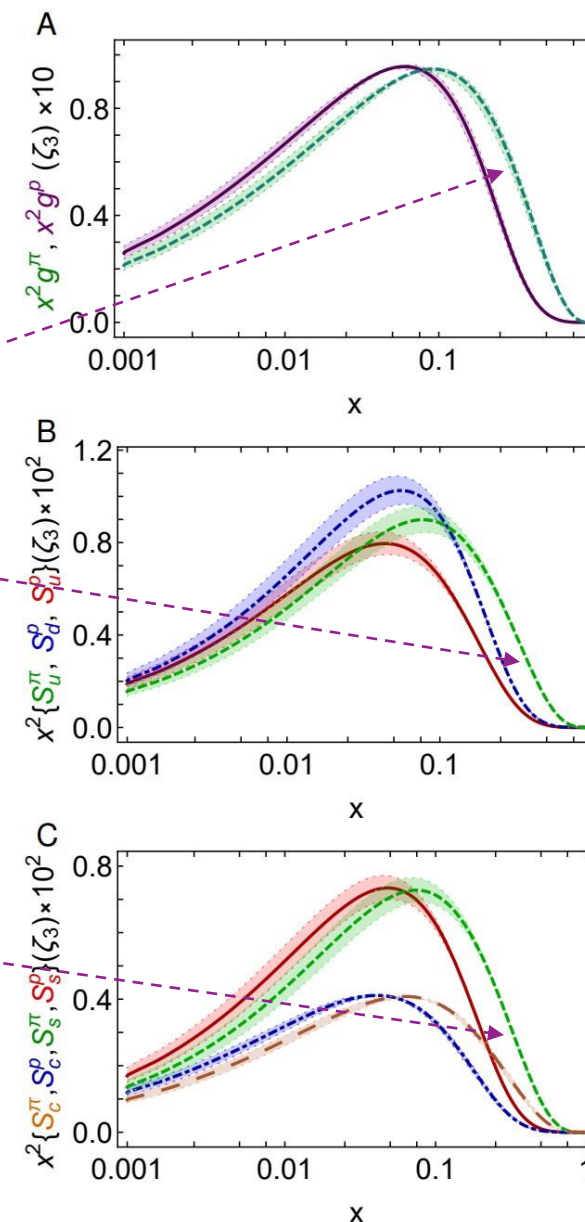
Proton and pion distribution functions in counterpoint – glue and sea

- 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

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Proton and pion distribution functions in counterpoint

➢ CSMs have delivered 1st ever unified body of predictions for all proton and pion DFs
  – valence, glue, and four-flavour-separated sea.

➢ Within mesons & baryons that share familial flavour structure, light-front momentum fractions carried by identifiable, distinct parton classes are identical at any scale.

➢ On the other hand, *x*-dependence of DFs is strongly hadron dependent
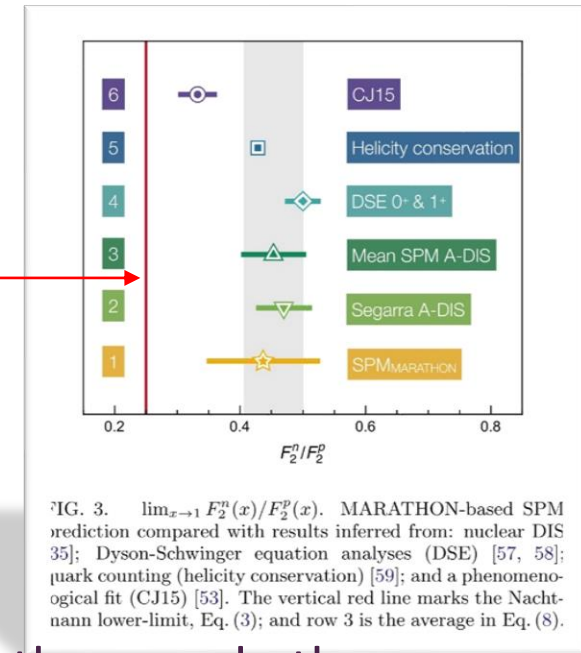
  Smoking gun for EHM

  – At any resolving scale, ζ, those in the pion are the hardest (most dilated).

➢ All CSM DFs comply with QCD constraints on endpoint (low- and high-x) scaling behaviour.

➢ However, existing global fits ignore QCD constraints, so:

  – Fail to deliver realistic DFs, even from abundant proton data

  – Meson data almost nonexistent and controversial results from fits

➢ *Only after imposing QCD constraints on future phenomenological data fits will it be possible to draw reliable pictures of hadron structure.*

➢ *Especially important for attempts to expose and understand differences between Nambu-Goldstone bosons and seemingly less complex hadrons.*

37

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Many, Many Other Expressions of EHM

➤ EHM ⇒ formation of nonpointlike diquark correlations within baryons

  – All baryons, including those with one or more heavy quarks

➤ Proton possess 0^+ isoscalar & 1^+ isovector correlations

  – Marathon data ⇒ Probability that proton contains

    scalar-diquark-only = $\dfrac{1}{7{,}000{,}000}$

0^+ only

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

➤ Nucleon resonances
   contain more correlations ... 0^- isoscalar, 1^- isoscalar & 1^- isovector

➤ Nucleon-elastic & nucleon-to-resonance transition form factors can test these and other structural predictions

➤ Electroweak transitions: heavy+light systems (Higgs boson dominant mass mechanism) to light (lighter) final states (in which EHM dominates) – interference between Nature's two mass-generating mechanisms

➤ Progress demands Synergy between Experiment + Phenomenology + Theory

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38

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Emergent Hadron Mass

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

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

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

Emergent Hadron Mass

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

NSFC

- ➤ QCD is unique amongst known fundamental theories of natural phenomena

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

  - The degrees-of-freedom ~~used to express the Lagrangian~~ are not directly observable
  - Massless gauge bosons b~~ecome massive through self-i~~nterference
  - Gluon mass ensures a stable, infrared completion of the theory through the appearance of a running ~~coupling~~

  - Massles~~s~~

    - Mas~~s~~

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

- ➤ These eme~~rgent features of QCD are observa~~ble

- ➤ 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*

40

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Thankyou

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

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