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

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1902 – 2022

On Mass and Matter

The Nature of Things

- In looking at the known Universe, one could be awed by the many complex things it contains.
- Even the Earth itself is complicated enough to generate questions in the minds of we observers
- Basic amongst them are those which focus on our own very existence and composition.
- Here, too, there are many levels to be explored, running right down to the nuclei at the core of every atom and molecule
- Even deeper, to the neutrons and protons (nucleons) that constitute those nuclei.
- Faced with all this, physicists (scientists) nevertheless assume that a few simple mathematical rules should be sufficient to provide a complete explanation of everything we can now perceive, and which might become perceptible in future.
- This may be correct
- Or it might be hubris

L’ANIMAL-MACHINE

L'**animal-machine** est une hypothèse éthologique selon laquelle les animaux sont des machines. Comme les machines, les animaux seraient des assemblages de pièces et rouages, dénués de conscience ou de pensée. D'un point de vue religieux, l'application du mécanisme à la vie revient à nier l'âme des bêtes qui périssent donc entièrement au moment de leur mort. Poussée à l'extrême, notamment par Nicolas Malebranche, cette conception implique que leurs cris et gémissements ne peuvent être que le reflet de dysfonctionnements dans les « rouages » plutôt que l'expression d'une souffrance. Même si cette vision du problème est complètement décalée par rapport à la vision moderne, elle peine à être délogée par des conceptions plus en adéquation avec les avancées scientifiques récentes.

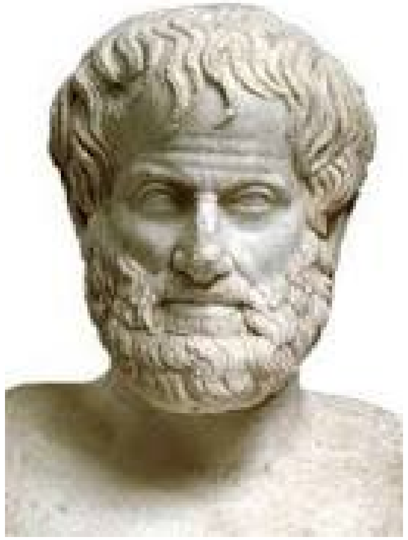
In the nineteenth century, Descartes was revered for his mechanistic physiology and theory that animal bodies are machines (that is, are constituted by material mechanisms, governed by the laws of matter alone).

Reductionist Perspective

Holism = Emergentism

- One might define emergent phenomena as those features of Nature which don't readily admit explanation solely in terms of known or conjectured rules.
- The concept is at least as old as Aristotle (384-322 BC), who argued that a compound item can have (emergent) properties in the whole which are not explicable merely through the independent actions of the item's constituent parts
- His view is often represented by the statement:

  "The whole is more than the sum of its parts".

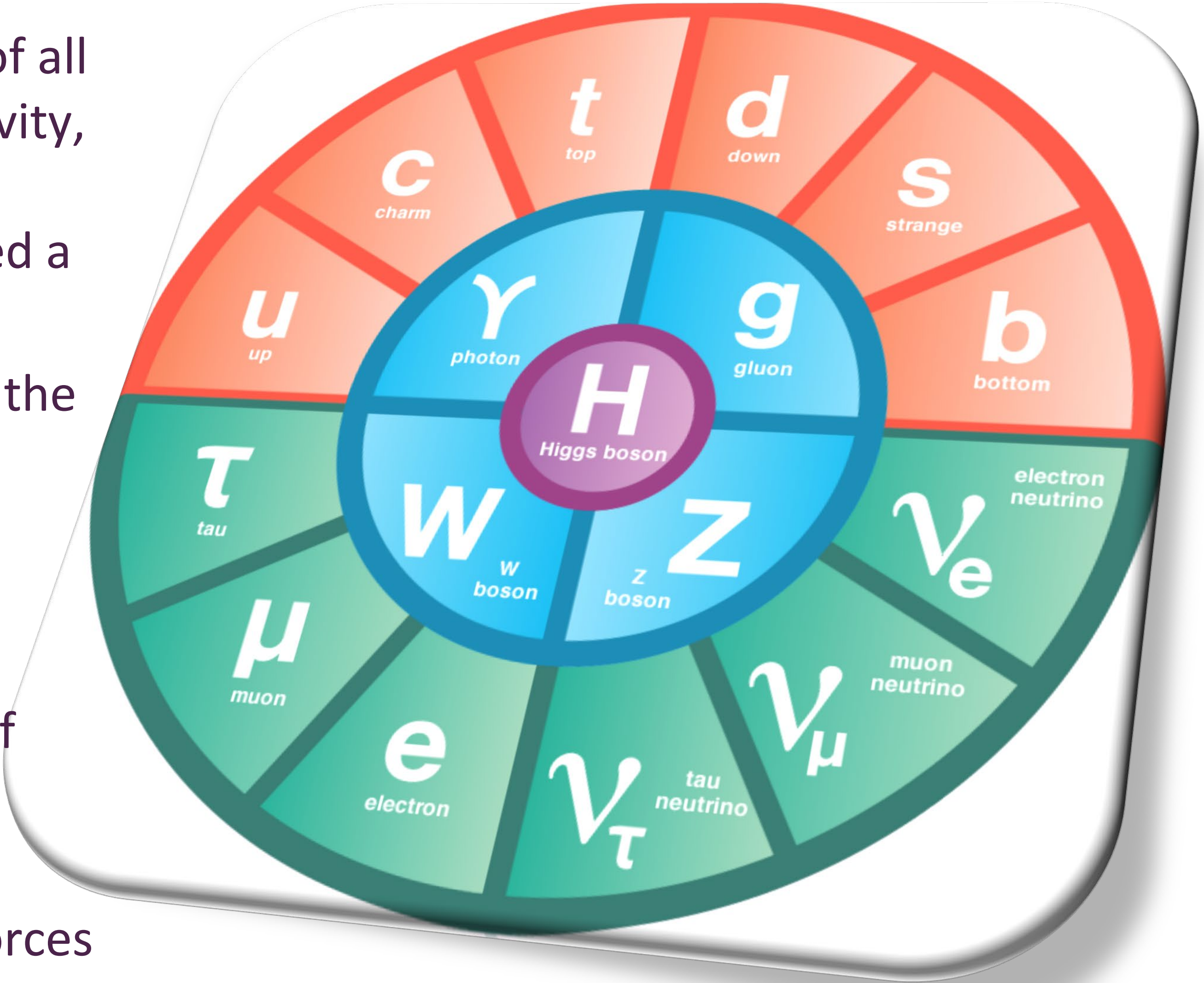


- In this sense, ***emergence*** has its origins in the Greek "sunergos": "together" plus "working" = origin of our concept of synergy, *viz*. things working together more effectively than could be anticipated from their independent actions in isolation.
- This perspective is typically contrasted with that described as reductionism; namely, the view that everything in Nature can ultimately be viewed as no more complex, in principle, than,

  e.g. a (very good) watch, which is clearly a complex object; but, equally clearly, not more than the sum of its parts.

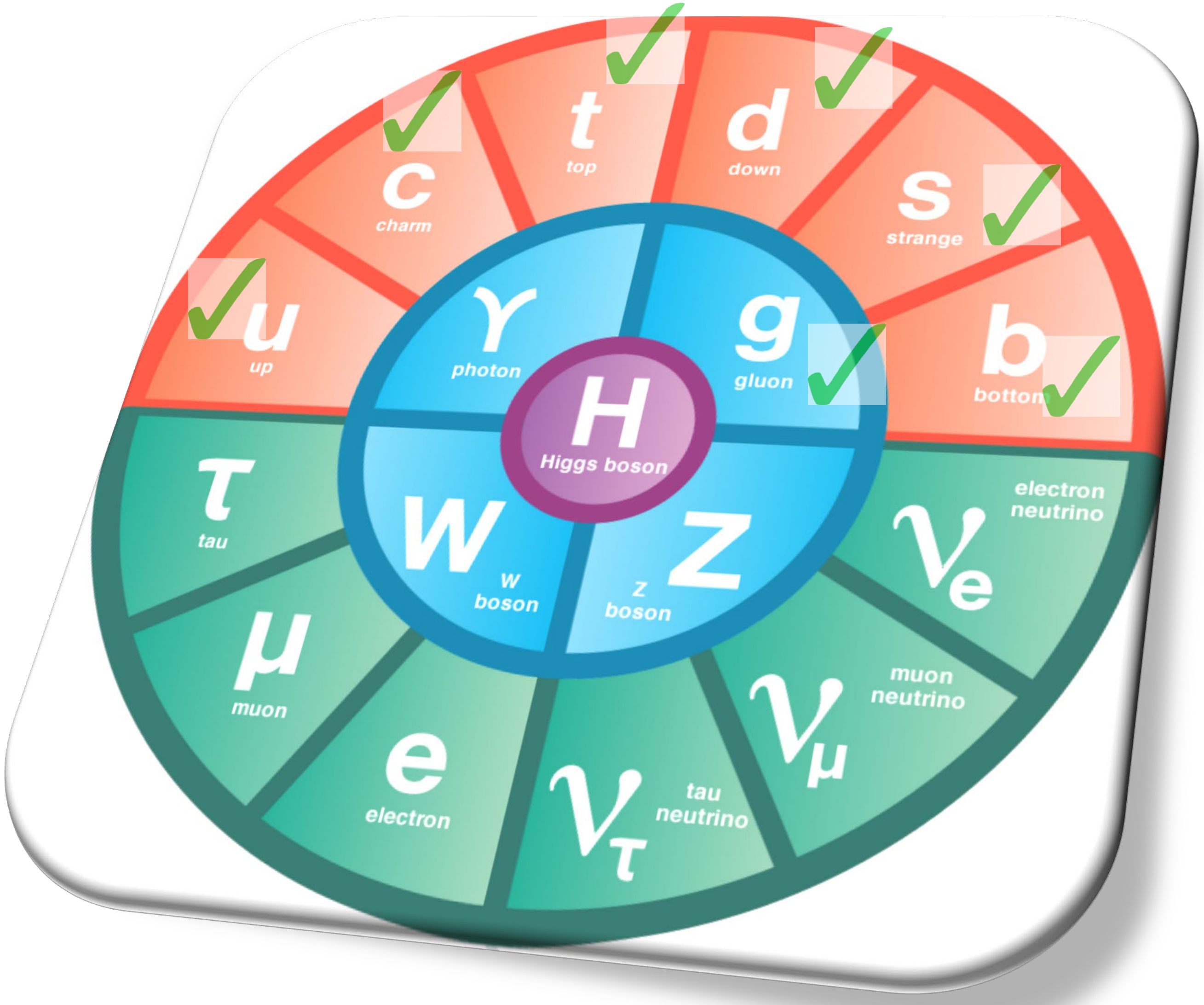
Standard Model of Particle Physics

- Standard Model (SM) 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.
- 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



Standard Model of Particle Physics

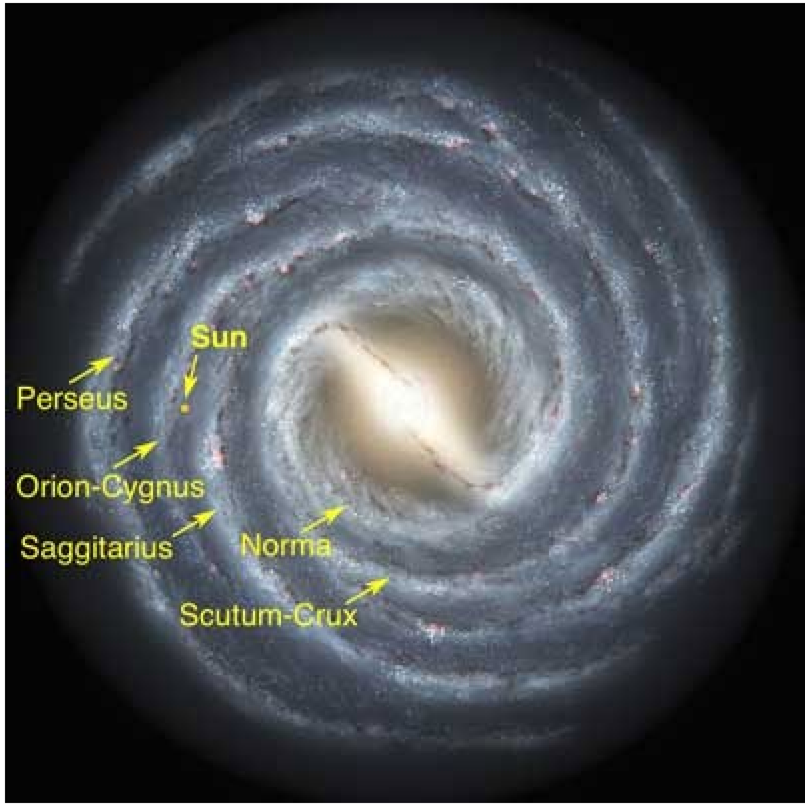
- Strong Interactions in the Standard Model are supposed to be described by quantum chromodynamics (QCD)
- Only two of the parameters are intrinsic to QCD
  - Higgs enters through current-quark masses
- One of them – θ_{QCD} – appears to be zero (exactly or almost) … know this because nucleon EDM is unmeasurably small
- Just one parameter remains to be fixed
- Perhaps science has a chance of <u>*understanding*</u> QCD ∈ SM?



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

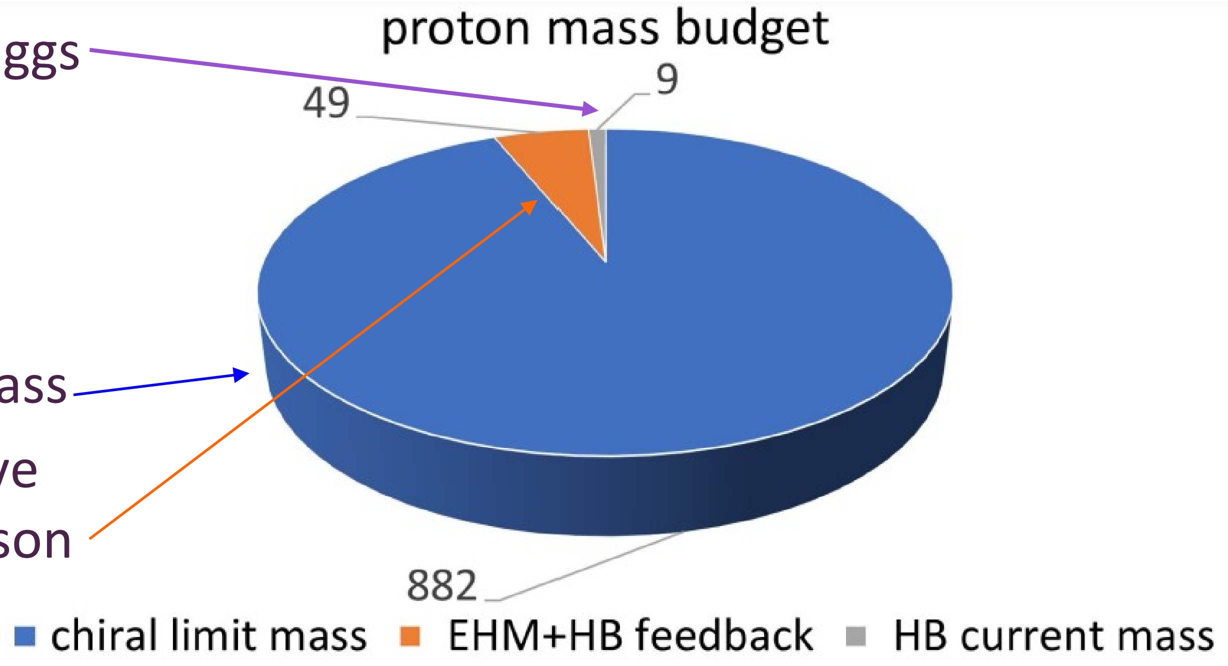
  = Higgs Boson … impacts are critical to evolution of Universe as we know it
- However, Higgs boson is alone responsible for just ~ 1% of the visible mass in the Universe
- Proton mass budget

  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



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
- What is and wherefrom mass?

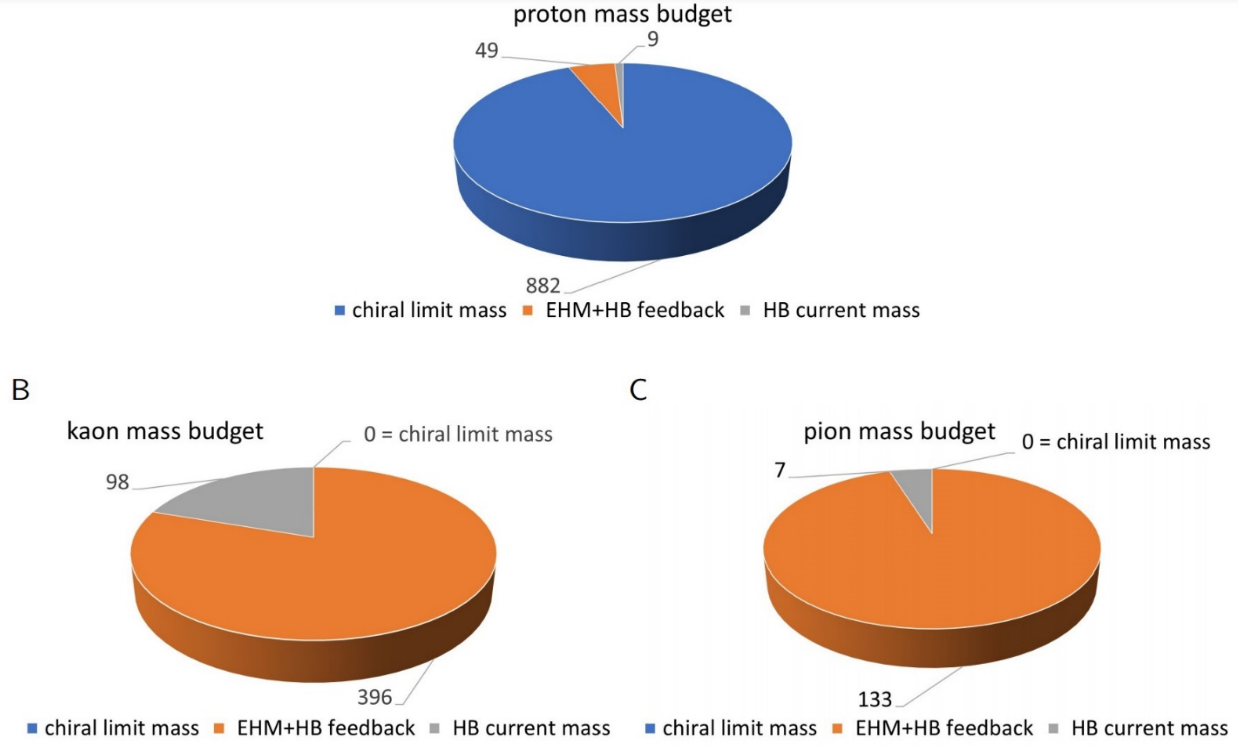


FIG. 1.1. Mass budgets for A – proton, B – kaon and C – pion, drawn using a Poincaré invariant decomposition. There are crucial differences. The proton's mass is large in the chiral limit, *i.e.* even in the absence of Higgs couplings into QCD. This nonzero chiral-limit component is an expression of 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].)

All mass is interaction.

— *Richard P. Feynman* —

In QCD, so is the absence of mass

[redacted]

It’s not just about MASS

Emergent Hadron Mass (EHM)

- In Nature, mass and length^{-1} are effectively the same thing
- Thus, asking for the origin of 99% of visible mass in the Universe is possibly/probably the same as asking what is the source of the proton's size

Confinement scale!

- Confinement is far more than the statement that Nature contains only colour-singlet combinations of gluons and quarks
  - Those combinations have fm-scale sizes – this is crucial
  - It wouldn't be confinement if the scales were Å size

Confinement … only guarantee of proton stability

  - If one can't measure them, what are the gluons and quarks in the QCD Lagrangian?
  - Are they anything more than a theoretical artifice; useful things for calculations in perturbation theory, but practically irrelevant when resolving detectable hadrons?
  - What degrees-of-freedom should be used to compute and *understand* hadron properties?

Quantum Chromodynamics

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

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

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

Questions

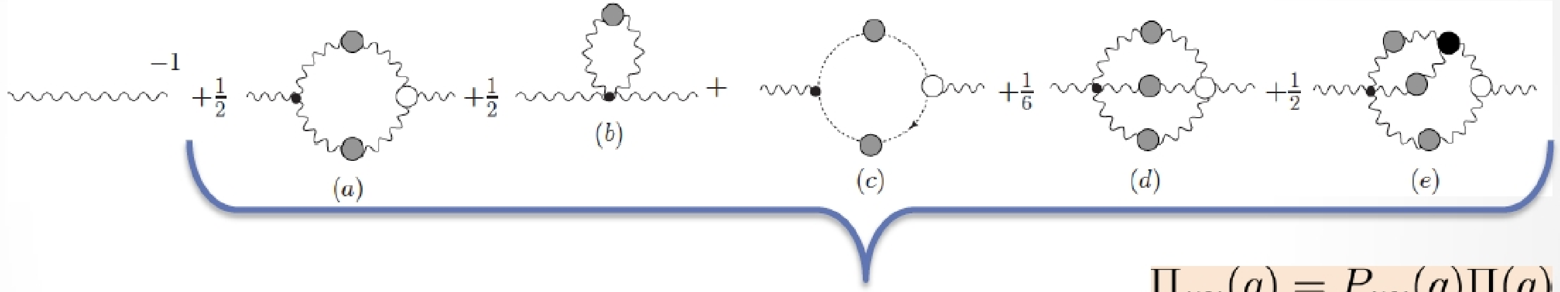
- What are the asymptotic detectable degrees-of-freedom?
- How are they built from the Lagrangian degrees-of-freedom?
- Is QCD really the theory of strong interactions?
- Is QCD really a theory? ⇒ Implications far beyond Standard Model


G E N E S I S

GLUON

Pinch Technique: Theory and Applications
Daniele Binosi & Joannis Papavassiliou
Phys. Rept. 479 (2009) 1-152

$$\Delta^{-1}_{\mu\nu}(q) =$$



$$\Pi_{\mu\nu}(q)$$

$$\Pi_{\mu\nu}(q) = P_{\mu\nu}(q)\Pi(q)$$

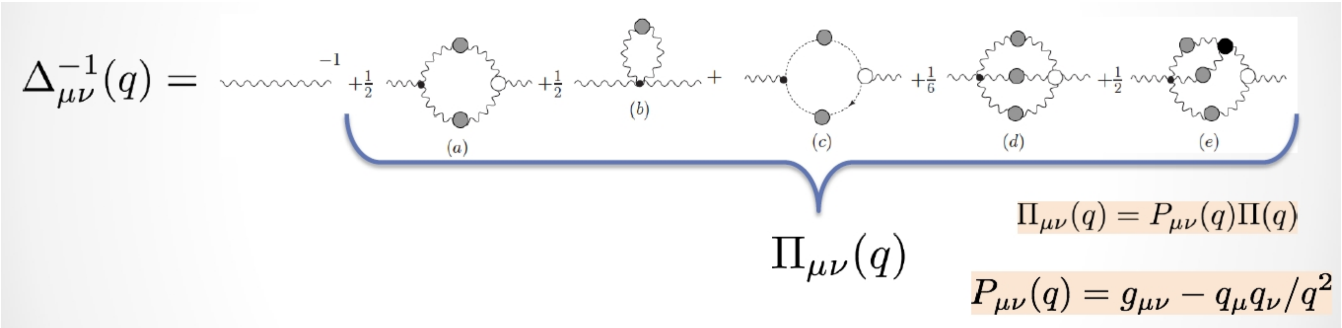
$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

Gluon self interactions modify the propagation characteristics of the gluon partons that define QCD.

They produce dressed gluons, with a mathematical connection to the gluon partons but with markedly different properties.

Gluon Dyson/Gap Equation

IR Behaviour of QCD



- Running gluon mass

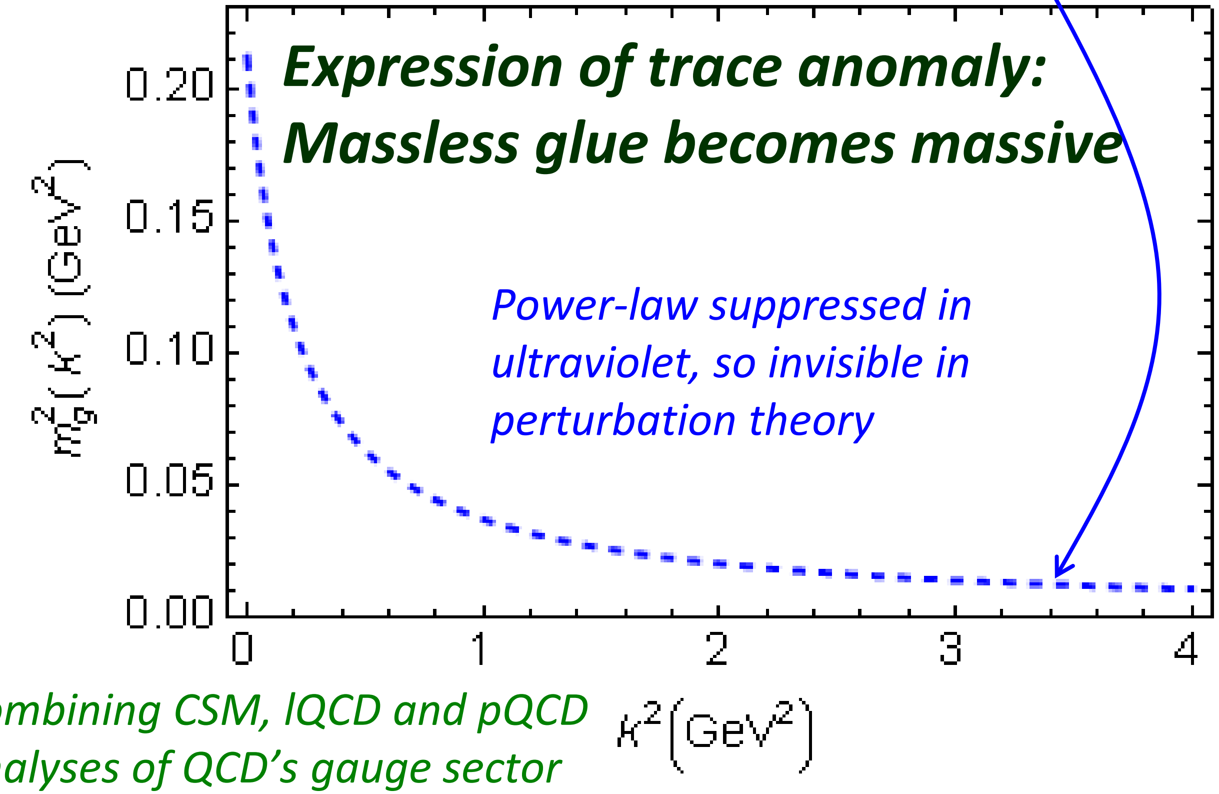
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

$$\alpha_s(0) = 2.77 \approx 0.9\pi\,,\ m_g^2(0) = (0.46\,\text{GeV})^2$$

- Gluons are ***cannibals*** – a particle class whose members become massive by eating each other!

$\mu_g \approx ½\, m_p$

$$m_g^2(k^2) \approx \frac{\mu_g^4}{\mu_g^2 + k^2}$$



Combining CSM, lQCD and pQCD analyses of QCD's gauge sector

Recent reviews …

Emergent Hadron Mass in Strong Dynamics
Daniele Binosi, e-Print: 2203.00942 [hep-ph]
Few Body Syst. 63 (2022) 2, 42

Emergence of mass in the gauge sector of QCD
Joannis Papavassiliou, arXiv:2207.04977 [hep-ph]
To appear in Chin. Phys. C.

Gluon mass scale

- QCD permits a gluon mass scale to emerge – the character of QCD is sufficient
  - However, the emergence of a gluon mass scale is not necessary
- The magnitude of the gluon mass-scale is not contained within the SM
  - On the other hand, we exist; hence, it can be measured
- QCD is a renormalizable quantum field theory
  - Perturbation theory is a valid tool for high-energy phenomena
  - Can fix the scale by something perturbative, *e.g*. the value of QCD's running coupling at the mass of the τ lepton
  - Once that number is fixed, then nonperturbative tools can predict the value of the gluon mass function on the entire domain of spacelike momenta

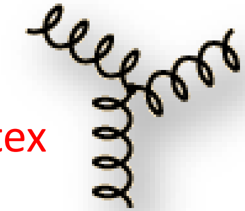
Modern Understanding Grew Slowly from Ancient Origins

- More than 40 years ago

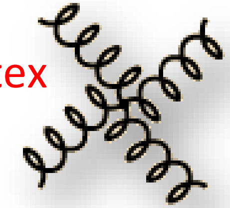
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1050 citations

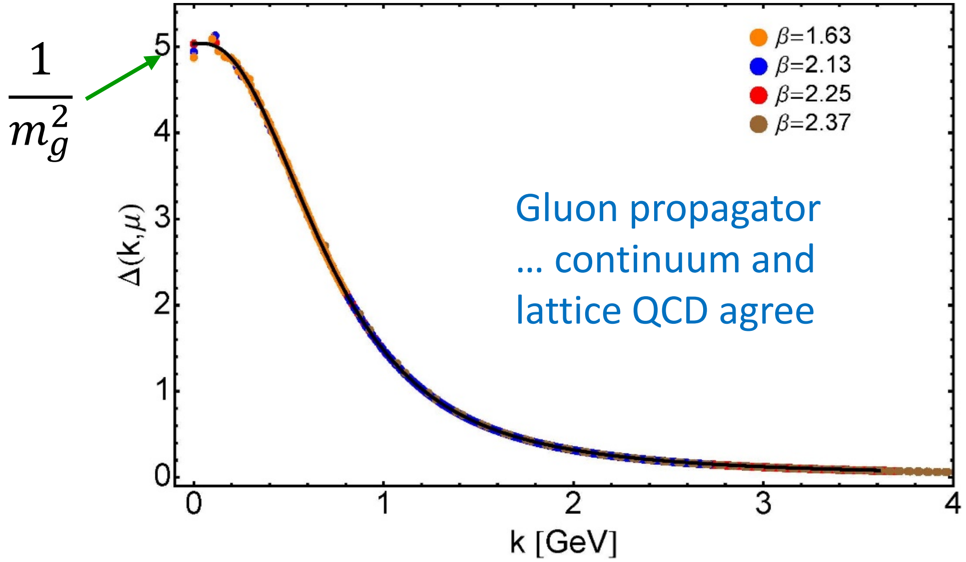
- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

3-gluon vertex



4-gluon vertex





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

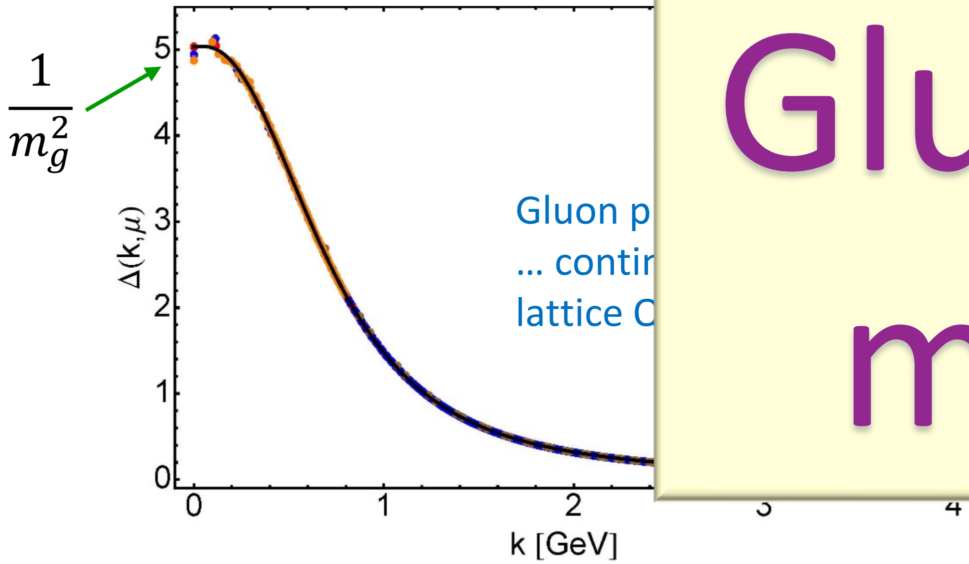
- ✓ *QCD fact*
- ✓ *Continuum theory and lattice simulations agree*
- ✓ *Empirical verification?*

Modern Understanding Grew Slowly from ... Origins

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

> Owing to strong se ... uasiparticles,
described by a ... omenta

EHM means Gluons are massive

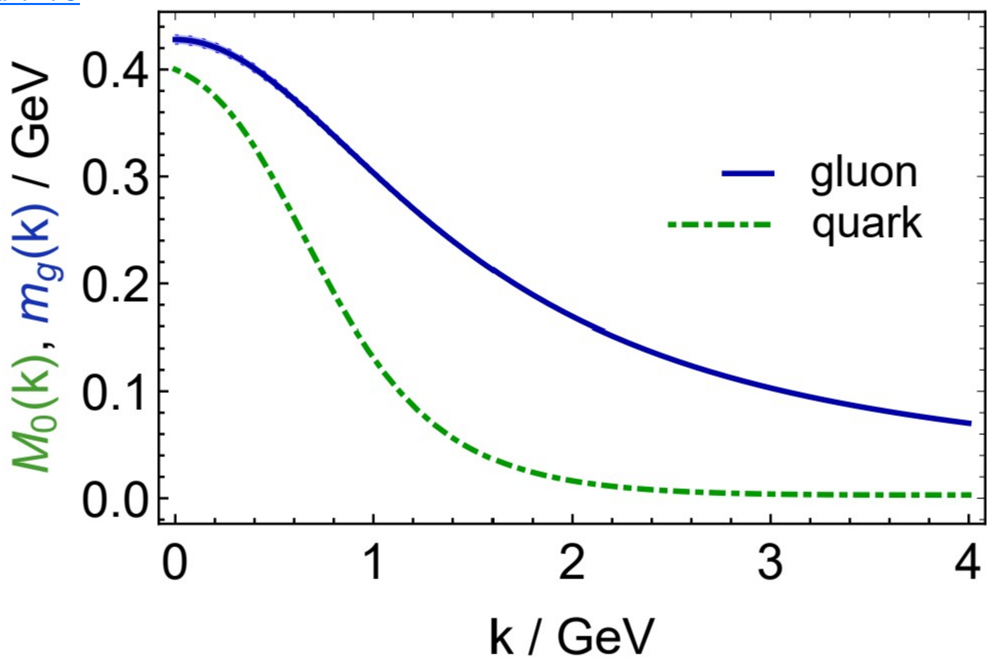


- ✓ *QCD fact*
- ✓ *Continuum theory and lattice simulations agree*
- ✓ *Empirical verification?*

Today:
Gluon Mass Function

2014 total downloads

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



- Gluon mass function characterised by renormalisation group invariant IR mass

$$\hat{m}_0 = 0.43(1)\ \mathrm{GeV} \approx \tfrac{1}{2} m_{\rm proton}$$

- The value is a prediction in the sense that it is $\frac{1}{2} m_{\rm proton}$
- Follows that long-wavelength gluons are screened from interactions
- Such screening eliminates the Landau pole
- Solves the Gribov ambiguity

Locating the Gribov horizon

Fei Gao (Peking U. and Peking U., SKLNPT), Si-Xue Qin (Chongqing U.), Craig D. Roberts (Argonne, PHY), Jose Rodriguez-Quintero (Huelva U.) (Jun 14, 2017)

Published in: *Phys.Rev.D* 97 (2018) 3, 034010 • e-Print: 1706.04681 [hep-ph]

pdf DOI cite 53 citati

Seminar 24 March 2022 | 17:00 VIRTUAL

EMERGENCE OF SCALE IN THE GAUGE SECTOR OF QCD

One of the greatest challenges in contemporary physics is presented by the emergence of a nuclear-size mass-scale in Nature

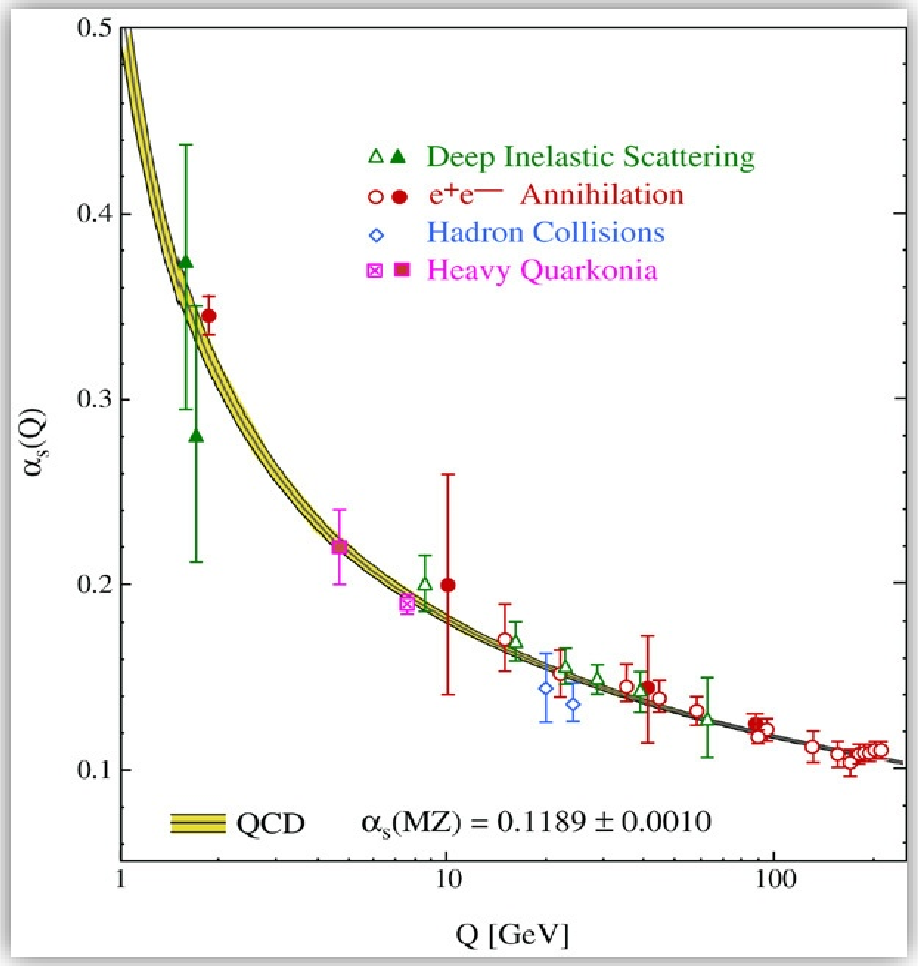
More info

J. Papavassiliou

https://www.youtube.com/watch?v=xlkvz2V8ZRw

This is where we live

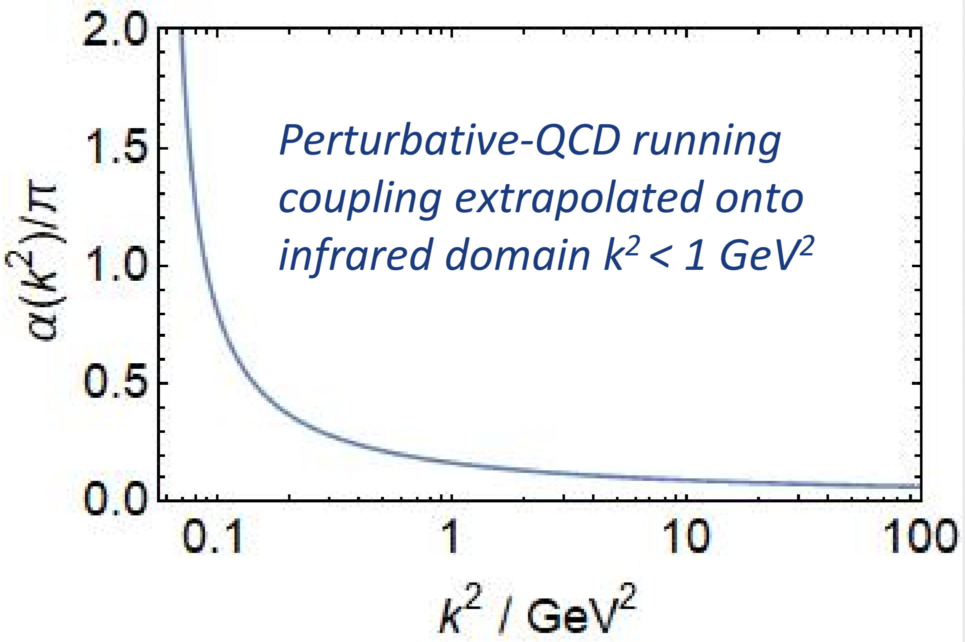
⇐
What's happening out here?!



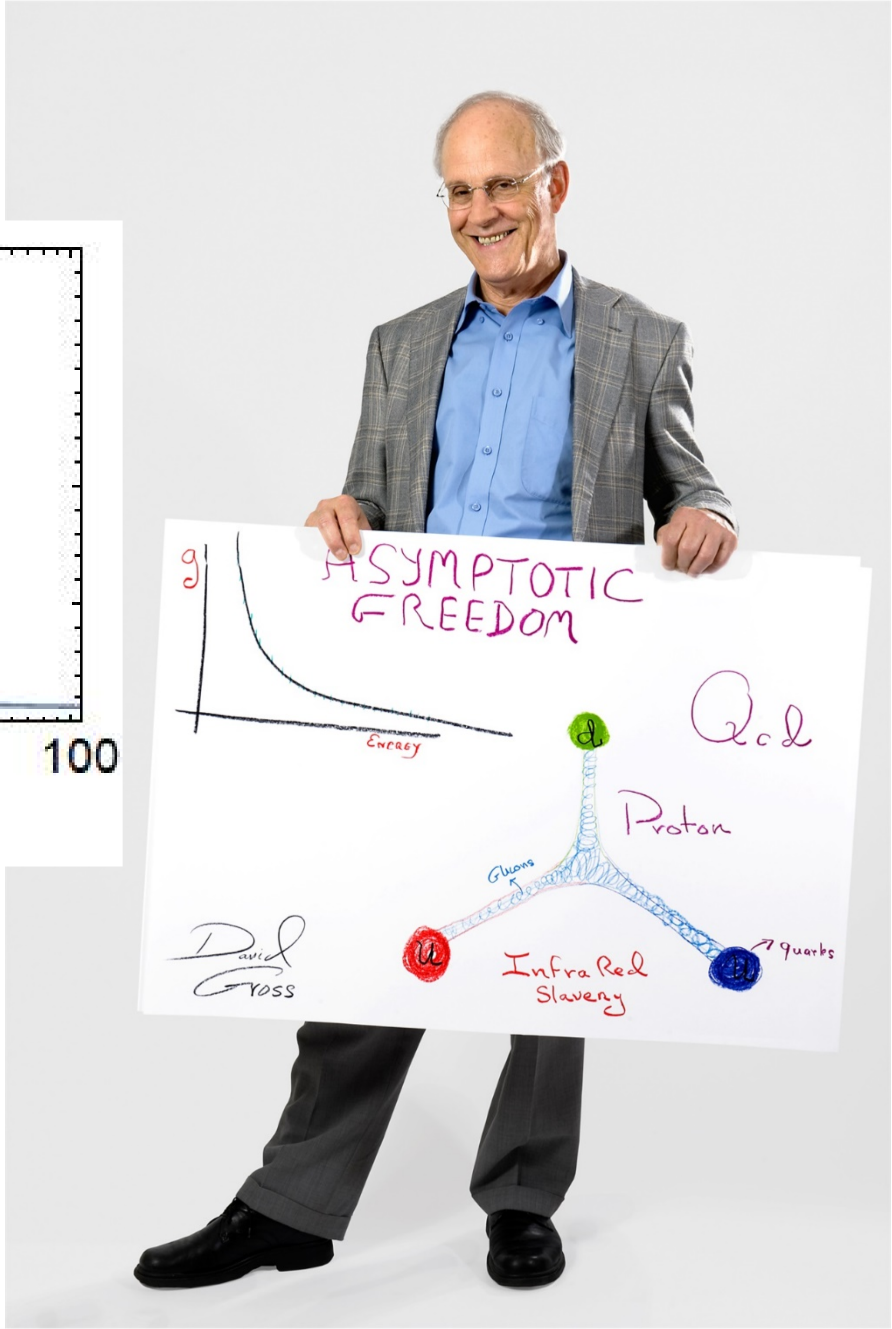
QCD's Running Coupling

"Asymptotic freedom comes with a flip side"

- "Imaginatively called infrared slavery"
- Based on perturbative analyses, appearance of a Landau pole at infrared momenta, became common to assume coupling runs to infinity as k^2 runs to zero

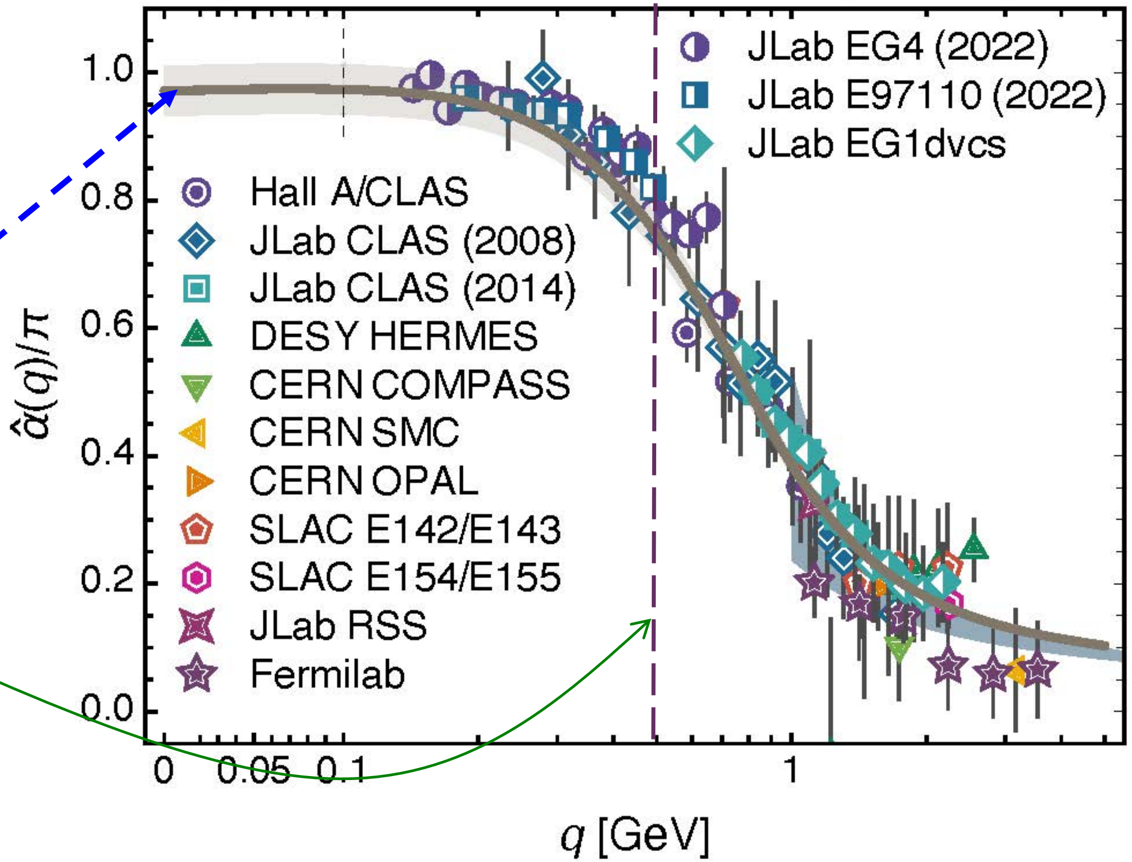


- Many people interpreted/still interpret this as being synonymous with confinement
- *Is the notion correct?*



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 is not correct*
- Below $k \sim \widehat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



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

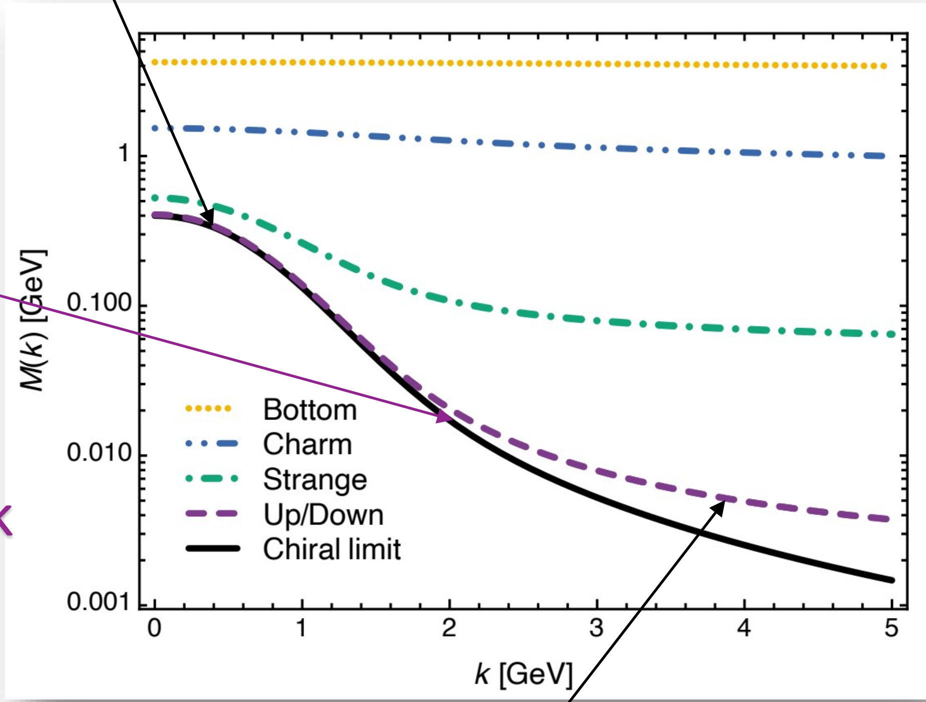
Perturbation Theory and the Onset of Nonperturbative Physics

- The domains of applicability for all the tools of perturbative QCD are set by the scale of EHM
  - $\Lambda_{\text{QCD}} \sim 0.25$ GeV is the theorist's QCD scale
  - m_p – the proton mass – is the empirical QCD scale
- perturbative QCD is applicable on $k^2 \gtrsim 4m_p^2$
- Dressed *u*-quark mass-function is a primary expression of EHM+HB effects

Chiral limit = essentially nonperturbative

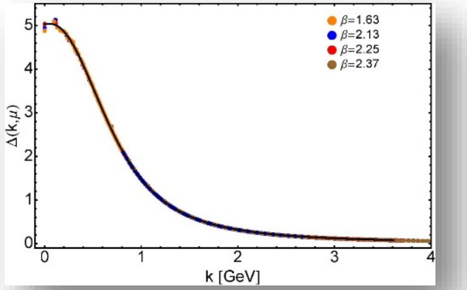
Perturbative domain becomes evident when $M_0(k^2)$ splits from $M_u(k^2)$

Dressed-quark mass function

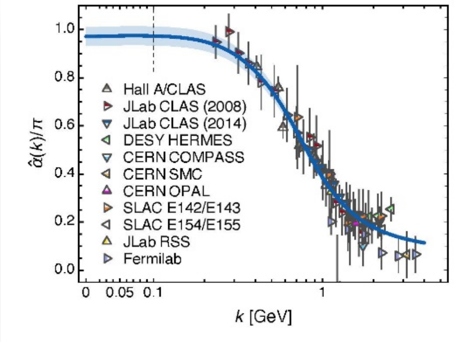


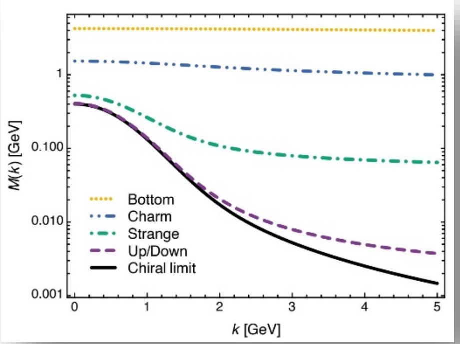
u-quark mass function
Becomes perturbative on $k^2 \gtrsim 4m_p^2$

EHM Basics



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





- EHM is expressed in EVERY strong interaction observable
- Challenge to Theory =

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

  Test the theory predictions so that the boundaries of the Standard Model can finally be drawn

QCD Fact Pion (Nambu-Goldstone modes) and mass

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

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

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

Pion wave function quark mass function

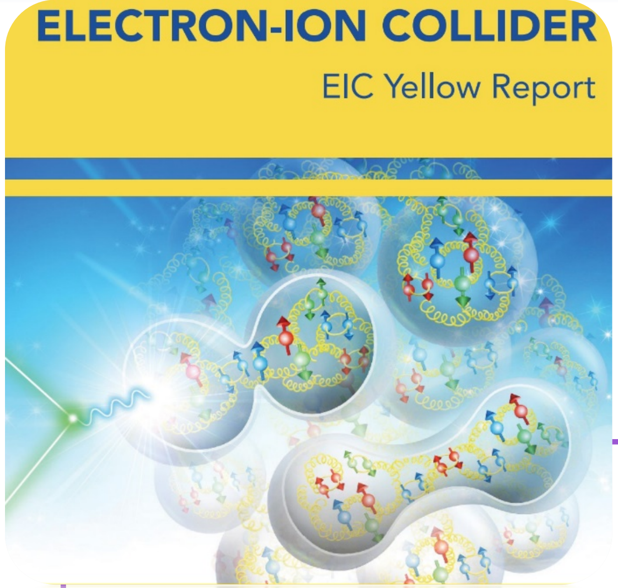
- **Thus, enigmatically, properties of the nearly massless pion are the cleanest expression of EHM in the Standard Model !**

AMBER

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

Jefferson Lab

Thomas Jefferson National Accelerator Facility



Potential of Existing and Future Facilities

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

$$\langle p_0(P)|T_{\mu\mu}|p_0(P)\rangle = -P^2 = m_{p_0}^2 = \langle p_0(P)|\Theta_0|p_0(P)\rangle$$

Prima Facie, the QCD Lagrangian
CANNOT support a nonzero value of this expectation value.

QCD's scale anomaly

Femtoscopy of the Origin of the Nucleon Mass

G. Krein (Sao Paulo, IFT), T.C. Peixoto (Sao Paulo, IFT and Unlisted, BR) (Nov 23, 2020)

Published in: *Few Body Syst.* 61 (2020) 4, 49 • e-Print: 2011.11615 [hep-ph]

EHM Measurements
How does the mass of the nucleon arise?

- One suggestion = QCD scale anomaly
- Measurement = femtoscopic low-momentum correlation measurements
- QCD multipole expansion … J/ψ and/or Υ chromopolarisability relates forward scattering amplitude to a key matrix element in the origin of the nucleon mass problem

  viz. the average chromoelectric gluon distribution in the nucleon:

$$\langle N|\left[(g\boldsymbol{E}^a)^2-(g\boldsymbol{B}^a)^2\right]|N\rangle=-\frac{1}{2}\langle N|g^2G^a_{\mu\nu}G^{a\mu\nu}|N\rangle=\frac{16\pi^2}{9}m_N\leq\langle(g\boldsymbol{E})^2\rangle$$

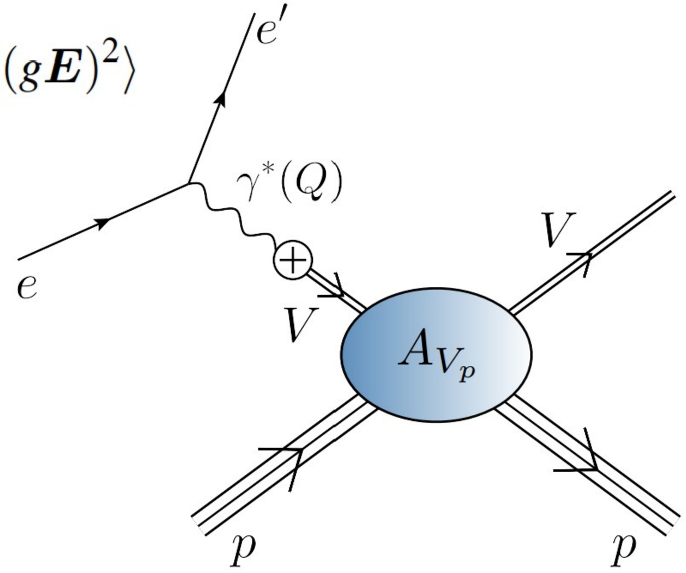
- Once considered viable …

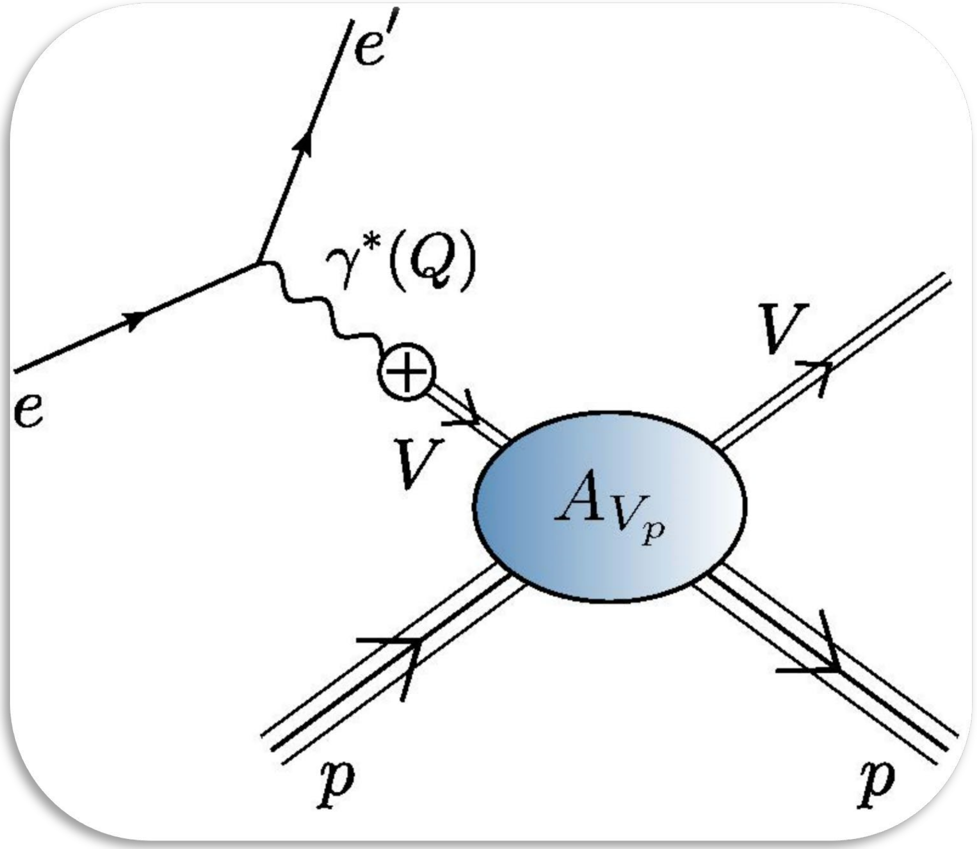
  electromagnetic vector-meson production reaction ($V=J/\psi,\Upsilon$)

$$e+p\to e'+V+p$$

  to access purely hadronic process

$$V+p\to V+p$$





Vector-meson production & Vector meson dominance

Vector-meson production and vector meson dominance, Yin-Zhen Xu (徐胤禛), Si-Yang Chen (陈斯阳), Zhao-Qian Yao (姚照千), D. Binosi, Z.-F. Cui (崔著钫) and C. D. Roberts, NJU-INP 044/21, arXiv:2107.03488 [hep-ph], Eur. Phys. J. C 81 (2021) 895/1-11

Trace Anomaly via Heavy-meson photo-production?

- Is there a relation between the electromagnetic vector-meson production reaction

  e + p → e′ + V + p   and the purely hadronic process   V + p → V + p ?
- Answer depends on the fidelity of single-pole VMD assumption
- If this VMD assumption is false …

  Then all existing cross-section estimates and conclusions based on VMD must be reviewed
- For EIC this means … will need to rethink access to and understanding of
  - hidden-charm pentaquark production
  - origin of the proton mass via trace anomaly

Photon Vacuum Polarisation

- Consider the photon vacuum polarisation. Statement of simple fact:

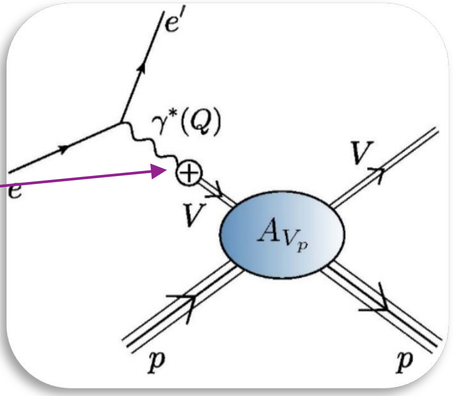
$$Q^2\,\Pi(Q^2) \overset{Q^2+m_V^2\simeq 0}{=} \bar{e}_V^2 \, \frac{2 f_V^2 m_V^2}{Q^2+m_V^2}$$

V-meson e+ e- decay constant

- Thus, on $Q^2 + m_V^2 \simeq 0$ the timelike photon is indistinguishable from the vector-meson.
- This is merely the statement that e+ e− collisions with a tuned centre-of-mass energy can be used to produce vector-mesons.
- However: VMD assumption asserts that the photon is also indistinguishable from the vector-meson on $Q^2 \simeq 0$: $Q^2\Pi(Q^2) = \frac{2\bar{e}_V^2 f_V^2}{m_V^2}$
  - Very different statement
- Plainly false because photon is massless & associated Ward-Green-Takahashi identity demands:

$$Q^2\,\Pi(Q^2)\big|_{Q^2\simeq 0} \equiv 0 \quad \neq \frac{2\bar{e}_V^2 f_V^2}{m_V^2}$$

Photon-quark vertex



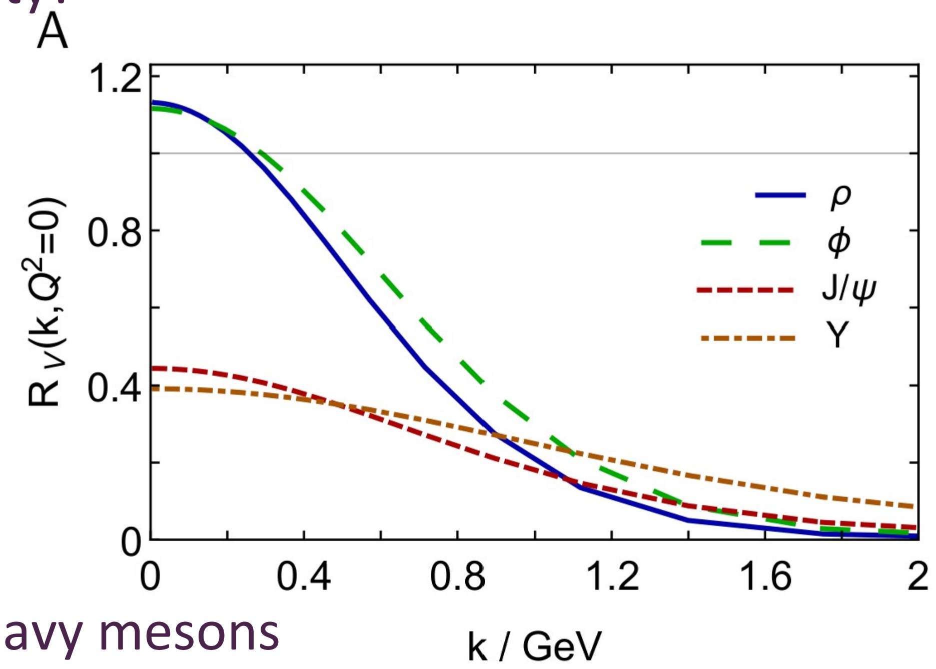
- Can one save VMD by looking at photon-quark vertex ?
- This statement is always true: $$\epsilon^\lambda \cdot \Gamma^\gamma(k;Q) \overset{Q^2+m_V^2\simeq 0}{=} \frac{2 f_V m_V}{Q^2+m_V^2} \Gamma_V^\lambda(k;Q)$$
- Are there any conditions under which $\Gamma_\nu^\gamma(k;Q)|_{Q^2\simeq 0}$ has a link to an on-shell vector-meson that may be approximated by the VMD current-field identity?
- No.
- Example. VMD validity would require

  this ratio to be unity:

  Leading term in vector meson bound-state amplitude

$$R_V(k^2;Q^2=0) := \frac{2 f_V}{m_V} \frac{F_1^0(k^2;-m_V^2)}{G_1^0(k^2;Q^2=0)}$$

Leading term in photon-quark vertex



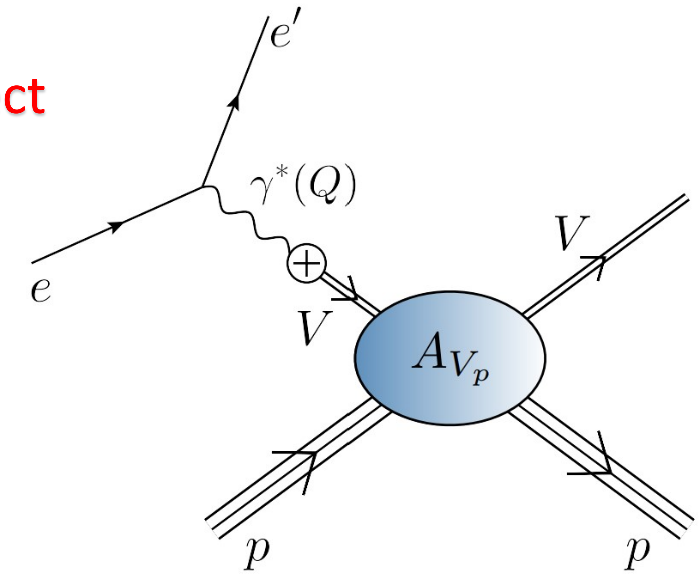
- Might be workable for light mesons but plainly false for heavy mesons

Vector-meson production and vector meson dominance, Yin-Zhen Xu (徐胤禛), Si-Yang Chen (陈斯阳), Zhao-Qian Yao (姚照千), D. Binosi, Z.-F. Cui (崔著钫) and C. D. Roberts, NJU-INP 044/21, arXiv:2107.03488 [hep-ph], Eur. Phys. J. C 81 (2021) 895/1-11

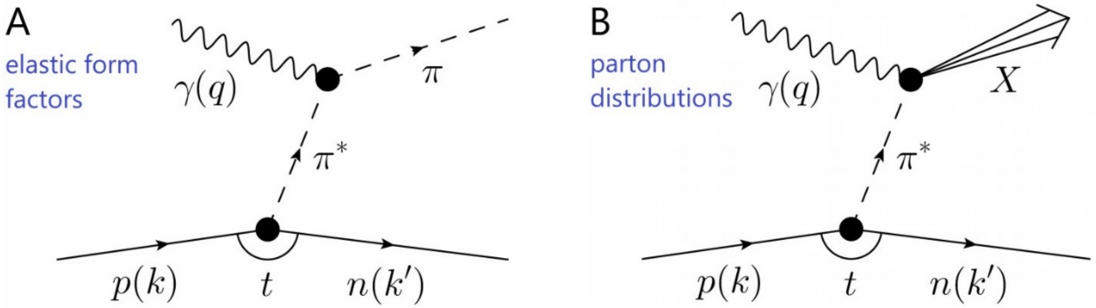
EHM Measurements

How does the mass of the nucleon arise?

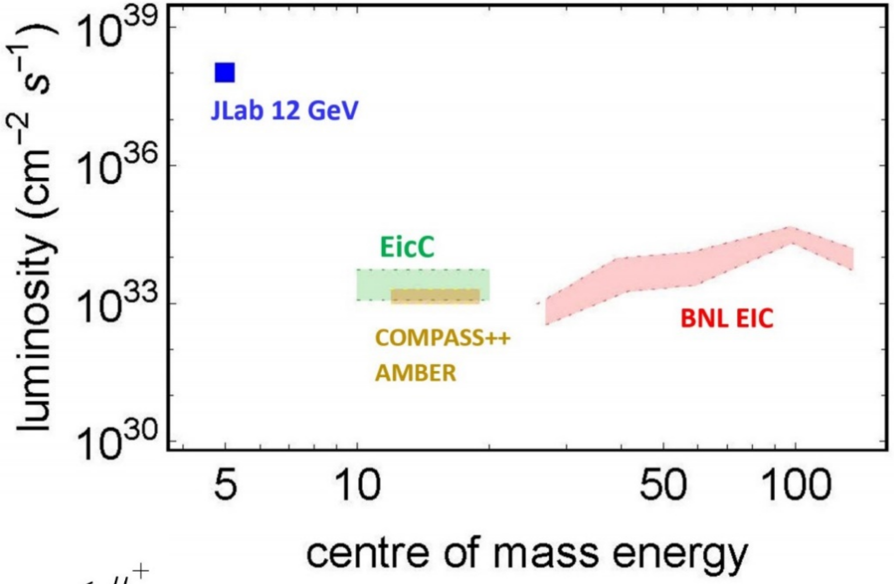
- Many other tests failed by VMD assumption for heavy vector-mesons:
- See also …
  - *Deciphering the mechanism of near-threshold J/ψ photoproduction*, M.-L. Du, V. Baru, F.-K. Guo et al., Eur. Phys. J. C **80**, 1053 (2020)
  - *Perturbative QCD analysis of near threshold heavy quarkonium photoproduction at large momentum transfer,* Peng Sun, Xuan-Bo Tong, Feng Yuan, Phys. Lett. B 822 (2021) 136655
- There is no objective, model-independent means by which to connect $e+p \to e'+V+p$ with $V+p \to V+p$
- Hence, vector meson photoproduction does not provide a path to the QCD trace anomaly
- Is there a viable alternative?



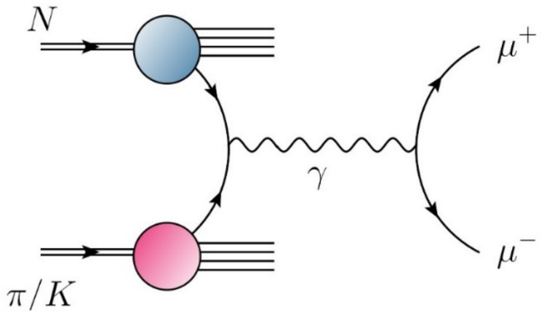
Era of Meson Targets



- JLab & EIC & EicC
  - High luminosity electron (+ ion) beams
  - Access to meson targets via the Sullivan Process,
    i.e., a baryon's "meson cloud"



- AMBER @ CERN SPS
  - High-intensity beams of pions
    ($\gtrsim 10^7$ pions/sec in Phase-1 = approved)
    and kaons (5×10^6 kaons/sec Phase-2 = proposal being prepared)
  - Drell-Yan, J/ψ production, prompt photon production
    … from proton and nuclear targets



$$\Psi(x,t)$$

π & K DAs & Form Factors

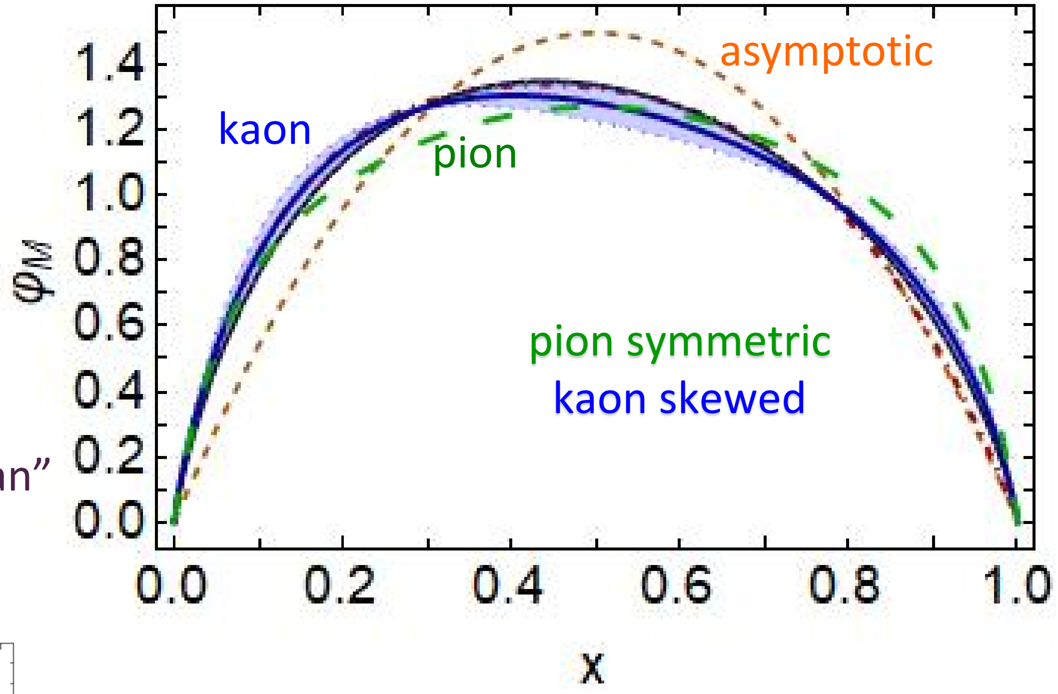
Wave Functions of Nambu Goldstone Bosons

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

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

Meson leading-twist DAs

- Continuum results exist & lQCD results arriving
  - Common feature = broadening
  - Origin = EHM
- NO differences between π & K if EHM is all there is
  - Differences arise from Higgs-modulation of EHM mechanism
  - "Contrasting π & K properties reveals Higgs wave on EHM ocean"



pion
Pion and Kaon Distribution Amplitudes in the Continuum Limit
kaon

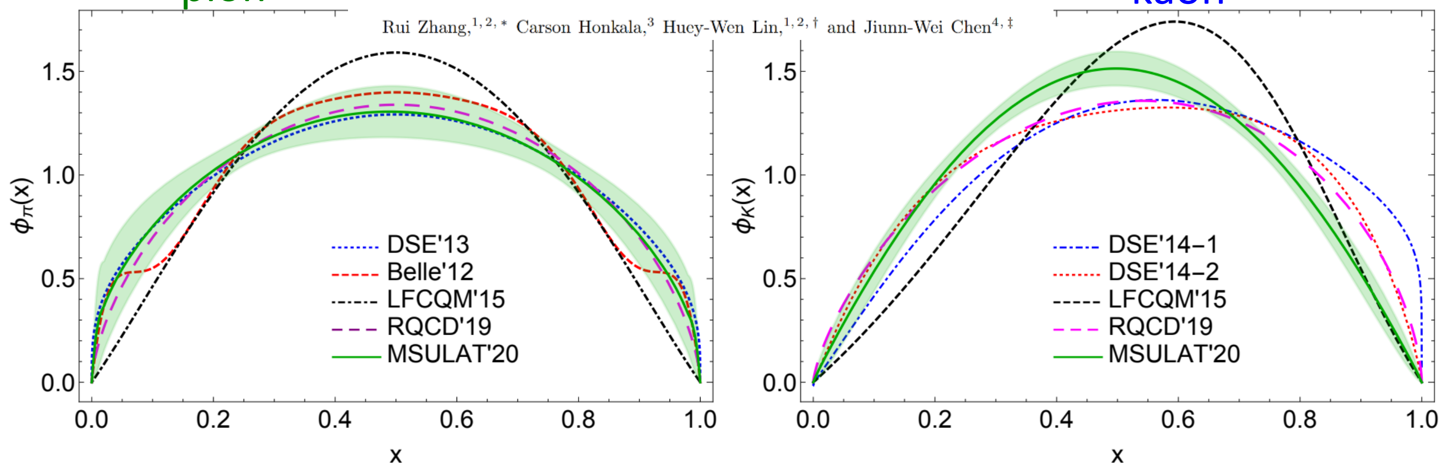


FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around $x = 1/2$ within error.

- Kaon DA vs pion DA
  - almost as broad
  - peak shifted to x=0.4(5)
  - $\langle\xi^2\rangle = 0.24(1)$, $\langle\xi\rangle = 0.035(5)$
- ERBL evolution logarithmic
- Broadening & skewing persist to *very* large resolving scales – beyond LHC

Hard Exclusive Processes
e.g, meson form factors

Normalisation of large Q^2 behaviour of meson form factors is largely determined by EHM, expressed in

- ✓ f_M = order parameter for DCSB (EHM)
- ✓ $\varphi_M(x)$ = meson wave function

Parton distribution functions (PDFs) and parton distribution amplitudes (PDAs) are connected through the hadron's light-front wave function

$$\varphi(x) \sim \int d^2k_\perp \psi(x, k_\perp^2)\,,$$

$$q(x) \sim \int d^2k_\perp |\psi(x, k_\perp^2)|^2$$

Hadron's LFWF is the key.

- ✓ EHM is expressed in every hadron LFWF
- ✓ LFWF correlates all observables

The impetus for measuring $F_M(Q^2)$ at large momentum transfers is a need to understand and validate a strict prediction of QCD [32–34], *viz.* $\exists Q_0 \gg \Lambda_{\rm QCD}$ such that

$$Q^2 F_M(Q^2) \stackrel{Q^2>Q_0^2}{\approx} 16\pi\alpha_s(Q^2) f_M^2 w_M^2(Q^2)\,, \qquad (1)$$

where α_s is the one-loop strong running coupling, $\Lambda_{\rm QCD} \approx 0.3\,{\rm GeV}$, $f_\pi = 0.092\,{\rm GeV}$, $f_K = 0.110\,{\rm GeV}$ [1]; and $w_M^2 = e_{\bar q} w_{\bar q}^2(Q^2) + e_u w_u^2(Q^2)$,

$$w_f = \frac{1}{3}\int_0^1 dx\, g_f(x)\, \varphi_M(x;Q^2)\,, \qquad (2)$$

$$g_u = \frac{1}{x},\; g_{\bar q} = \frac{1}{1-x}$$

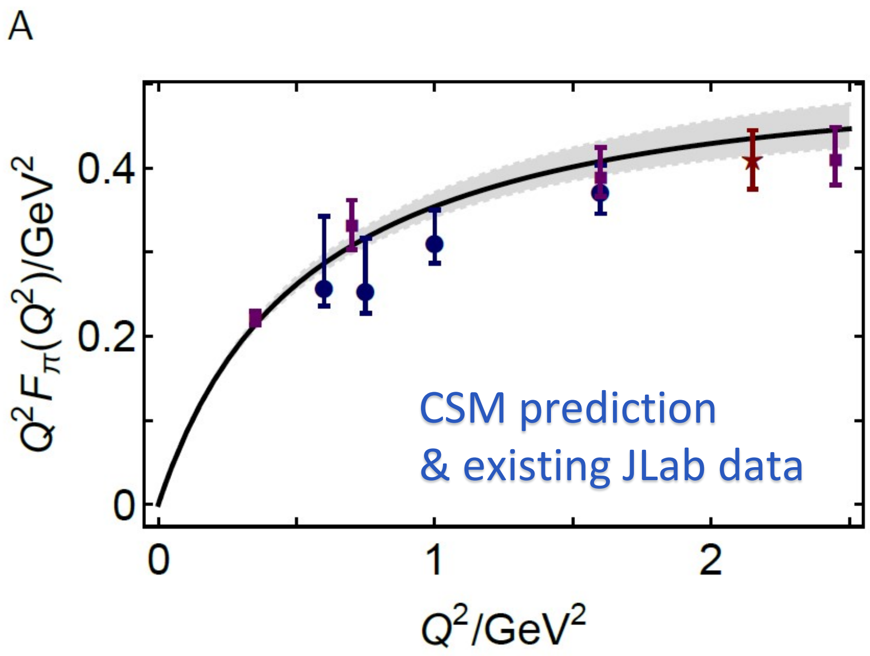
- ➢ High-energy nuclear and particle physics have long focused on finding evidence for power-law scaling in experimental data.
- ➢ Certainly, an important first step; BUT it should be remembered that QCD is not found in scaling laws.
- ➢ Instead, since quantum field theory requires deviations from strict scaling, then QCD is found in the existence and character of scaling violations.

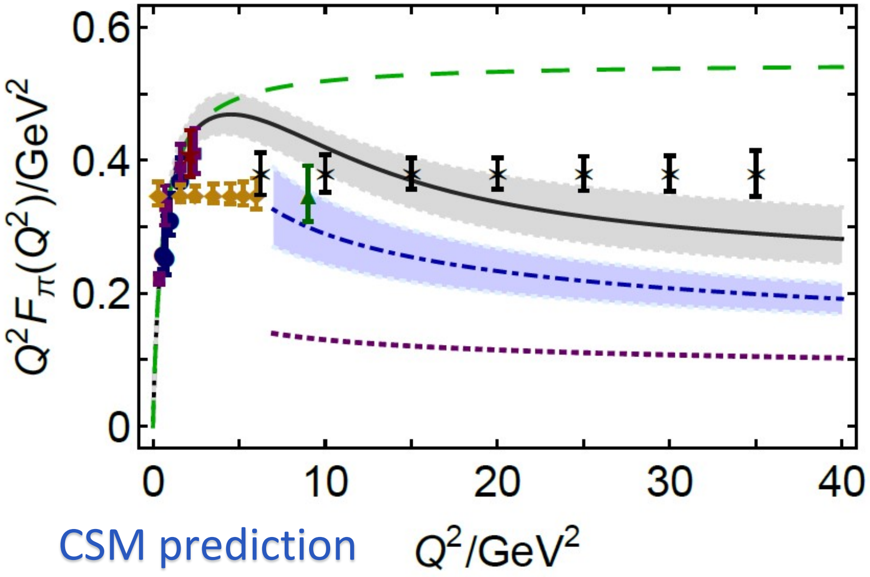
Wave Functions of Nambu Goldstone Bosons

- Scientific Context:
  - Today, continuum and lattice are delivering consistent predictions for $\varphi_{\pi,K}(x)$
  - Can signature features of interference between EHM and HB, which are manifest in low-order Mellin moments of the DAs, be probed experimentally?
- Measurement

Elastic electromagnetic form factors

Breakaway from scaling at $Q^2 \approx 6\ GeV^2$
Thereafter, Q^2 dependence
is largely described by hard-scattering formula with realistic DA
Reveal QCD scaling violations for 1st time in hard elastic scattering





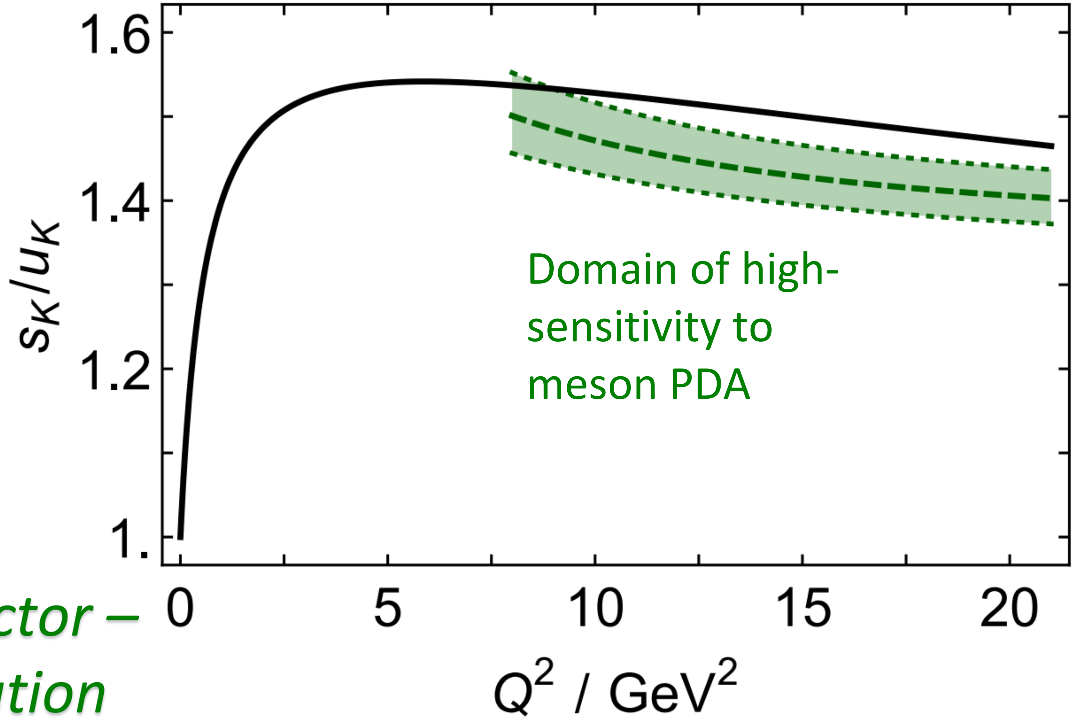
CSM prediction
& JLab + EIC projections

Hard Exclusive Processes

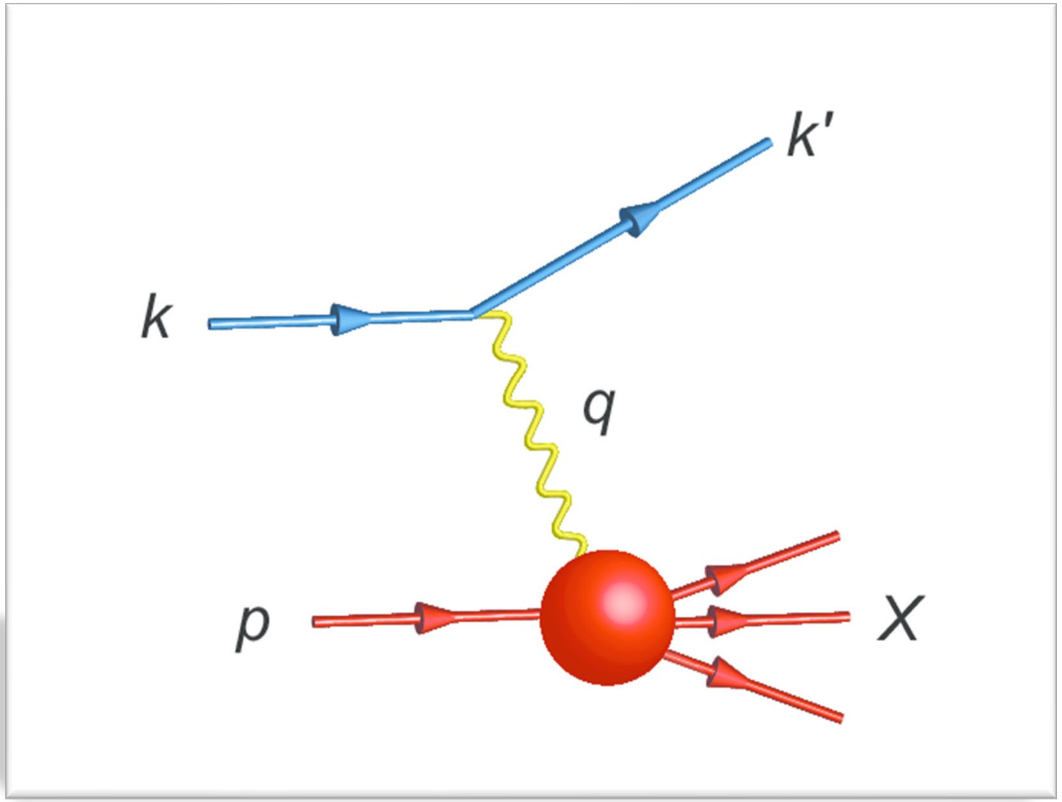
- Considering hard exclusive processes & focusing on meson electromagnetic form factors, modern theory predicts that
  - scaling violations become apparent to experiment on $Q^2 > 10\ \text{GeV}^2$
  - magnitude of any given form factor on a sizeable domain above $Q^2 = 10\ \text{GeV}^2$ determined by the physics of emergent hadronic mass (EHM).
- Experiments focused in this area are of the greatest importance.

✓ Location of maximum points to beginning of pQCD evolution = scaling violations

✓ Height of ratio measures relative strength of emergent- and Higgs-generated mass for *s*- and *u*-quarks



Kaon Form Factor – flavour separation



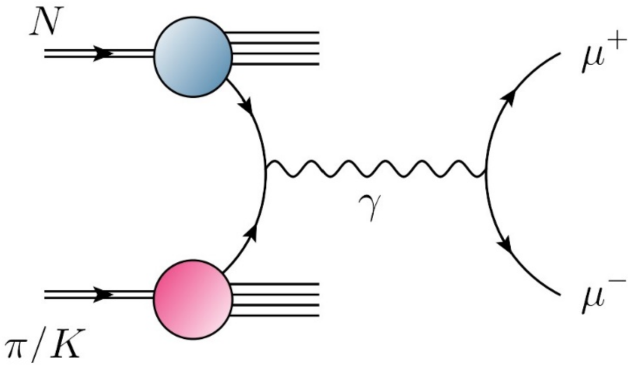
Parton Distribution Functions

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.

Controversy over pion valence DF

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

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

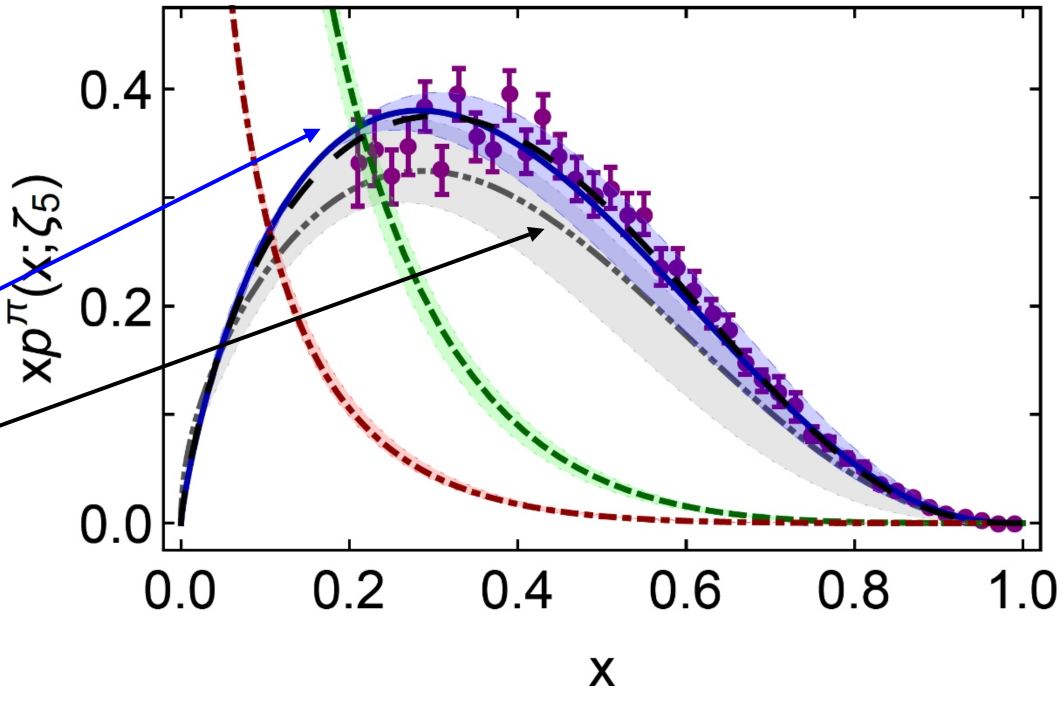
- Consequence
  - Any analysis of DY, DIS, etc. experiment which returns β <2 conflicts with QCD.
- Observations
  - All existing internally-consistent calculations preserve connection between large-k^2 behaviour of interaction and large-x behaviour of DF: J=0 … $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$
- 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:
  - Contemporary data fits yield $(1-x)^{1+\gamma}$

  - 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
23 Years of Theory Evolution → 2022

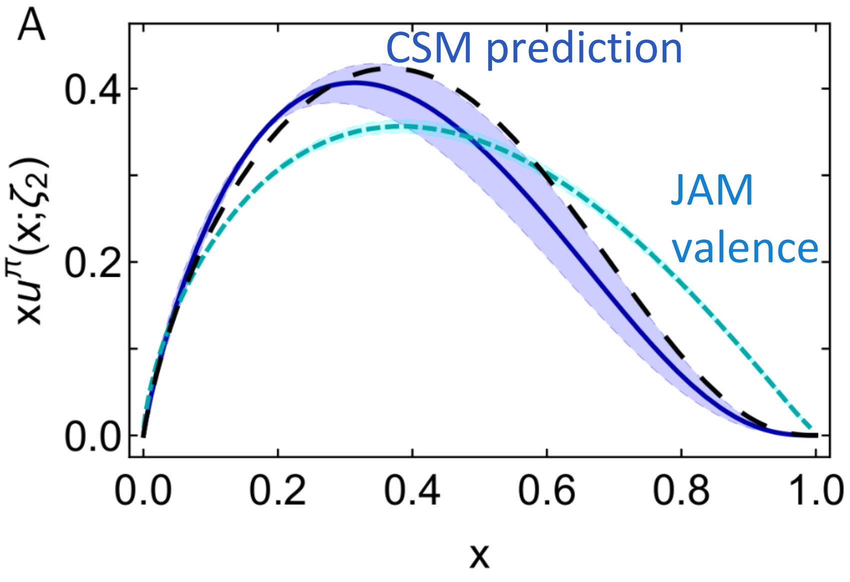
$\beta^{contm}(\zeta_5) = 2.66(12)$
$\beta^{lattice}(\zeta_5) = 2.45(58)$

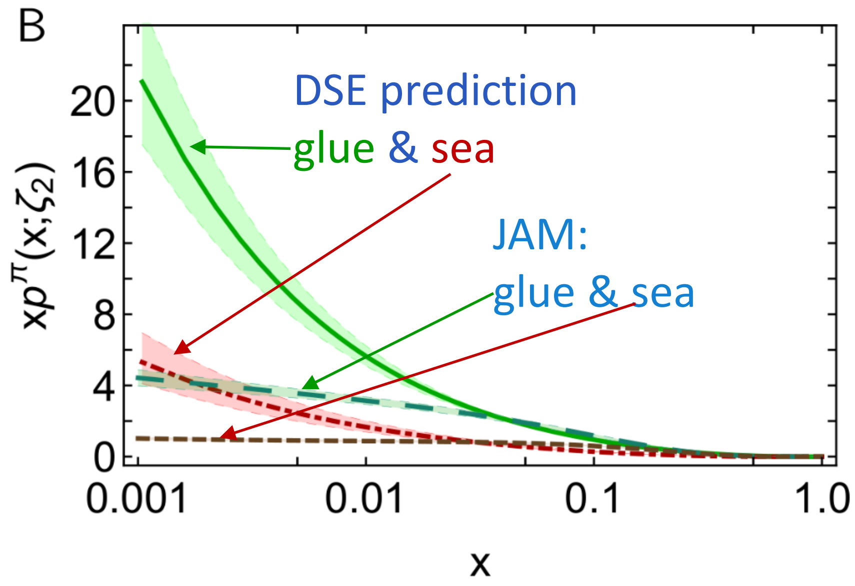
- Developments in continuum-QCD enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^\pi(x;\zeta)$ is hardened by EHM
- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^\pi(x;\zeta)$
- Agreement between new continuum prediction for $u^\pi(x;\zeta)$ [Ding:2019lwe] and recent 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 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 $x \geq 0.05$, 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

Breaking news …

1st exploratory lQCD results for pion's glue DF have been released

important complementary domain

- Both conti

Physics Letters B

Volume 823, 10 December 2021, 136778

ELSEVIER

PHYSICS LETTERS B

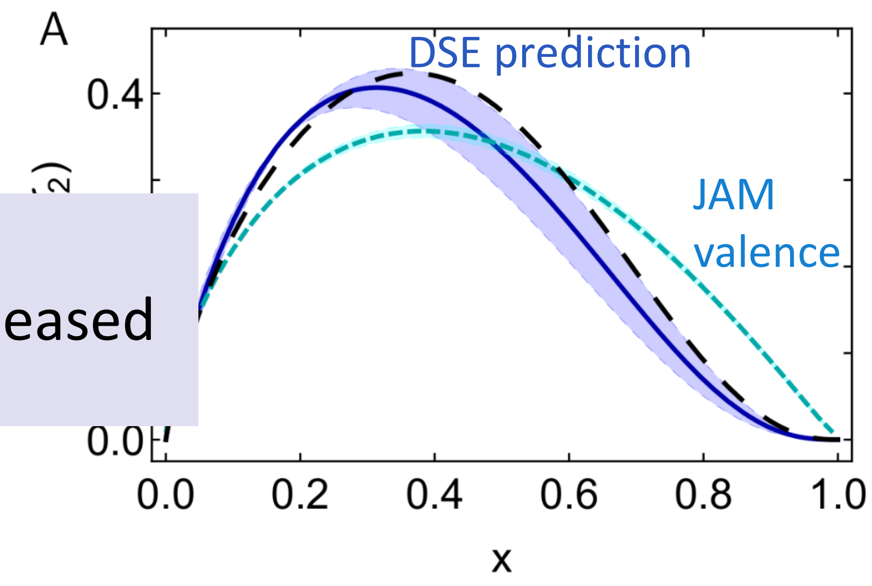
Gluon parton distribution of the pion from lattice QCD

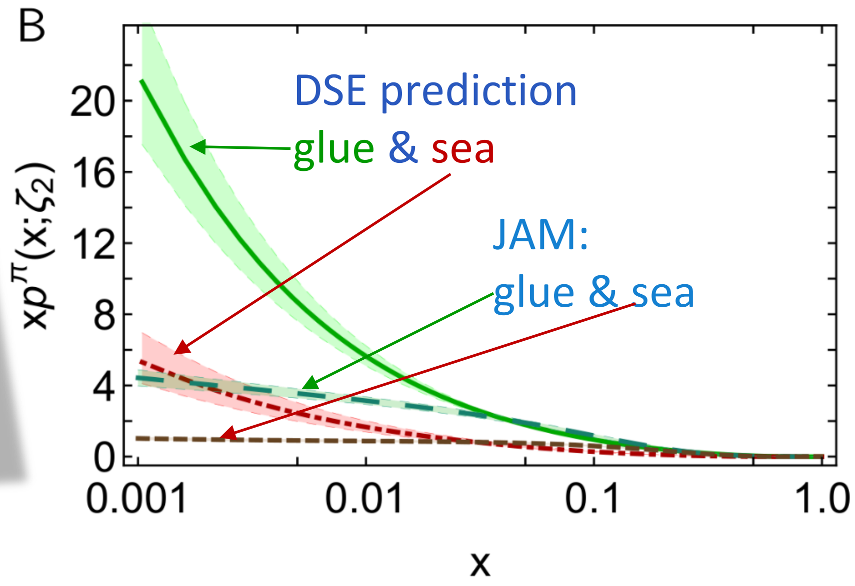
Zhouyou Fan a, Huey-Wen Lin a, b

- S

- … DY data with π±

… targets

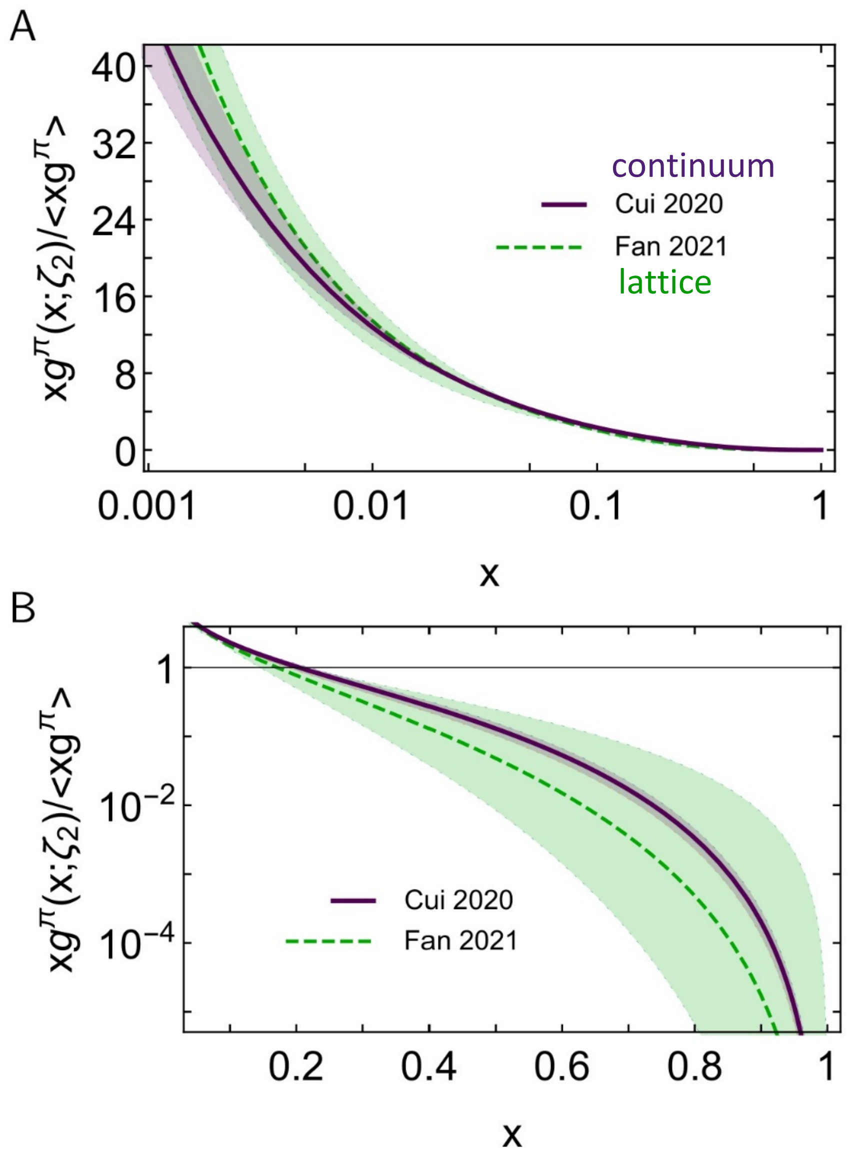




Breaking news for glue in π: Continuum (Eur. Phys. J. C 80 (2020) 1064/1-20) & Lattice Predictions (arXiv:**2104.06372**)

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

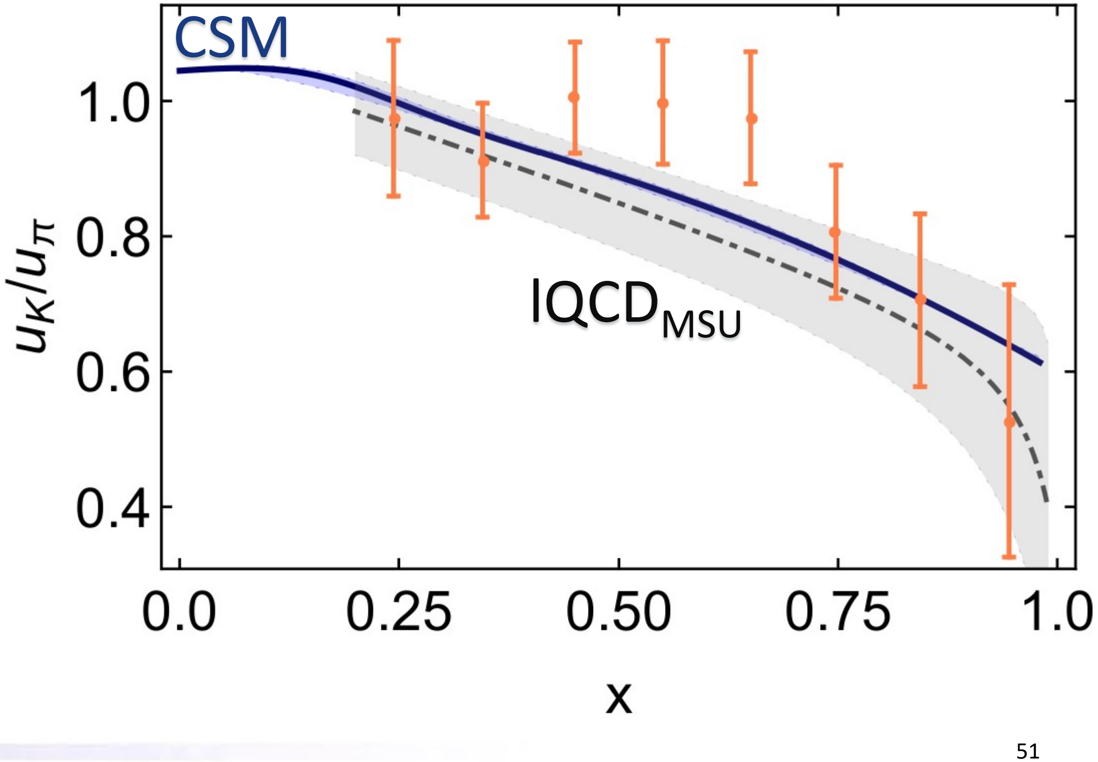
- Little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no results
- One piece of available experimental information:

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

  - 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

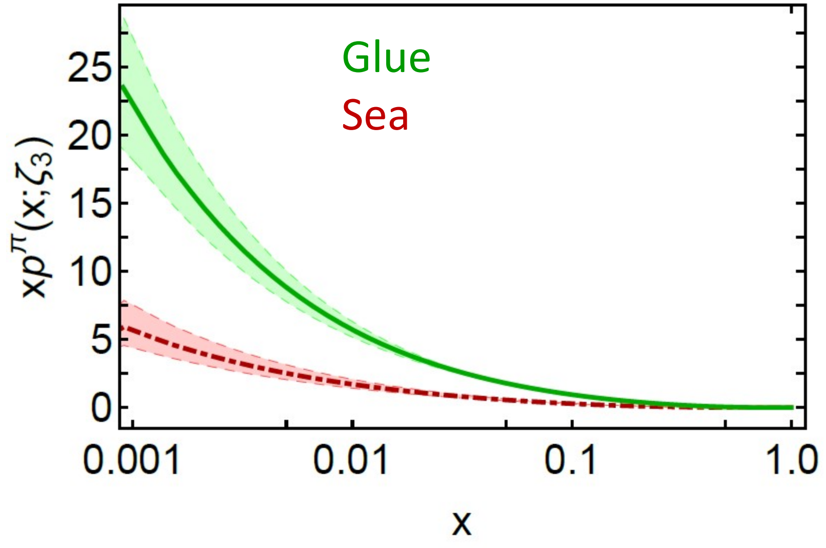
Entirety of Human history
– only 8 kaon data in existence
CERN … *Phys. Lett. B* 93 (1980) 354-356

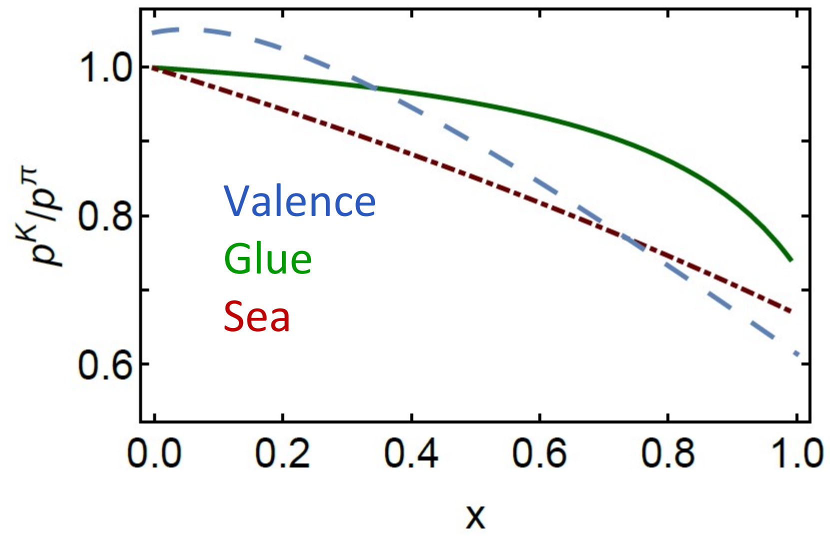


Status: Kaon

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.
  - Development underway … Preliminary 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 & Deep Inelastic Scattering

- The ratio of neutron and proton structure functions at large x is keen discriminator between competing pictures of proton structure
- Example:
  - Only scalar diquark in the proton (no axial-vector):
    $$\lim_{x\to 1}\frac{F_2^n(x)}{F_2^p(x)} = \frac{1}{4}$$
  - No correlations in the proton wave function
    (SU(4) spin-flavour) $\lim_{x\to 1}\frac{F_2^n(x)}{F_2^p(x)} = \frac{2}{3}$
- Experiments have been trying to deliver reliable data on this ratio for fifty years!
- MARATHON – a more-than ten-year effort, using a tritium target at JLab, has delivered precise results

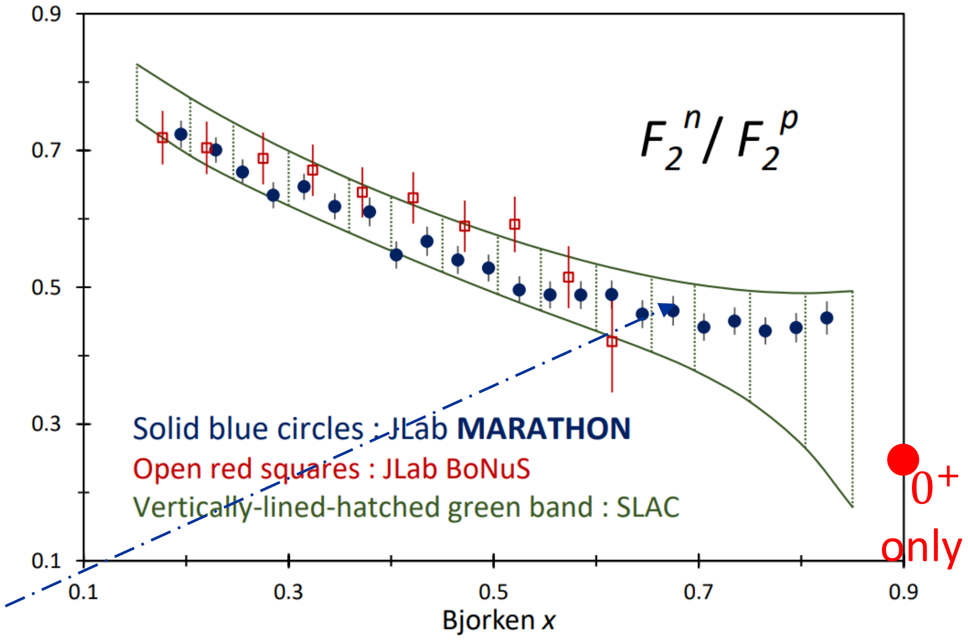
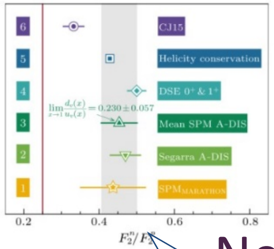


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14\cdot x$ (GeV/c)^2] (see text). All three experimental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

D. Abrams, *et al., Measurement of the Nucleon Fn2/Fp2 Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment* – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. **128** (2022) 132003



Valence Quark Ratio in the Proton

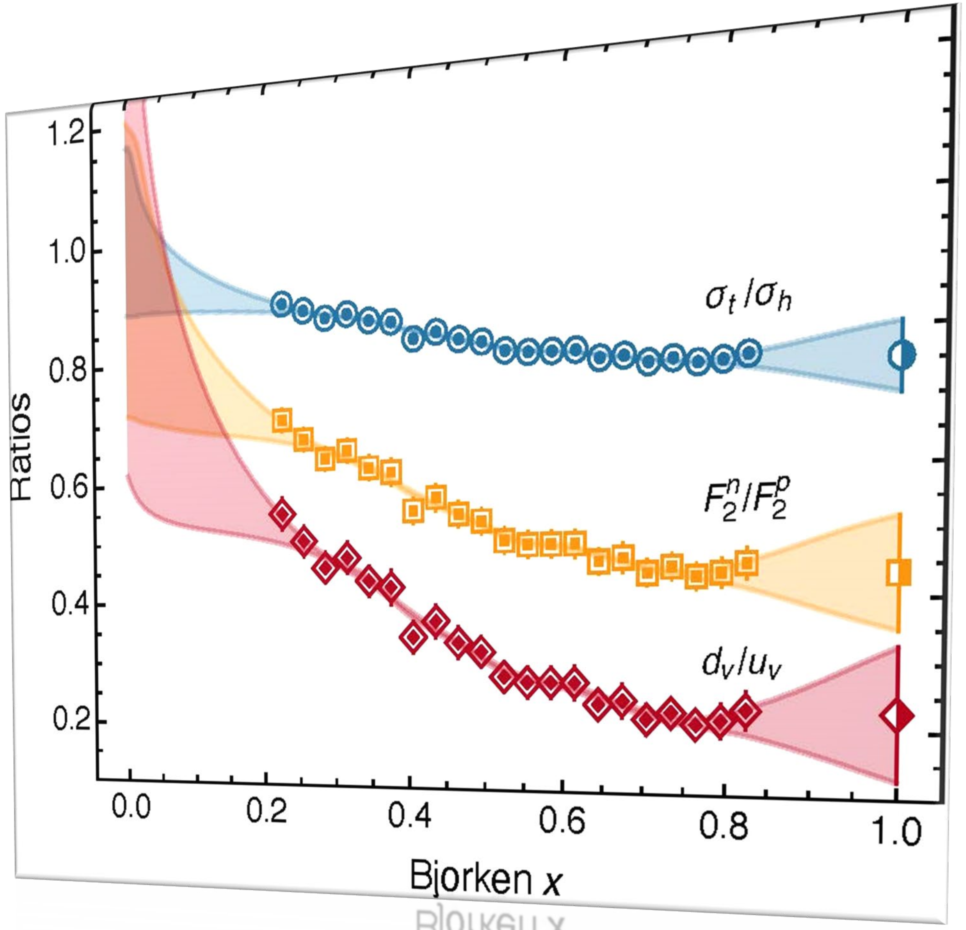
Zhu-Fang Cui, Fei Gao, Daniele Binosi, Lei Chang, Craig D. Roberts, and Sebastian M. Schmidt

Chin. Phys. Lett. 2022, 39 (**4**): 041401 . DOI: 10.1088/0256-307X/39/4/041401

Abstract HTML PDF (571KB)

MARATHON EXPERIMENT - Schlessinger point method

- New mathematical method for interpolation and extrapolation of data
  - based on continued-fraction representation of functions, augmented by statistical sampling
- Delivers model-independent prediction for all ratios
  - No reference to models or physics theories
- Provides benchmark against which all pictures of nucleon structure can be measured
- *Probability that scalar diquark only models of nucleon might be consistent with available data is 1/7,000,000*



Valence quark ratio in the proton, Zhu-Fang Cui (崔著钫), Fei Gao (高飞), Daniele Binosi, Lei Chang (常雷), C. D. Roberts and S. M. Schmidt, NJU-INP 049/21, e-print: 2108.11493 [hep-ph], Chin. Phys. Lett. *Express* **39** (04) (2022) 041401/1-5: Express Letter

MARATHON EXPERIMENT - Schlessinger point method

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  - based on continued-fraction representation of functions, augmented by statistical sampling
- Delivers model-independent prediction for all ratios
  - No reference to models or physics theories
- Provides benchmark against which all pictures of nucleon structure can be measured in future.
- *Probability that scalar diquark only models of nucleon might be consistent with available data is 1/7,000,000*

0^+ only

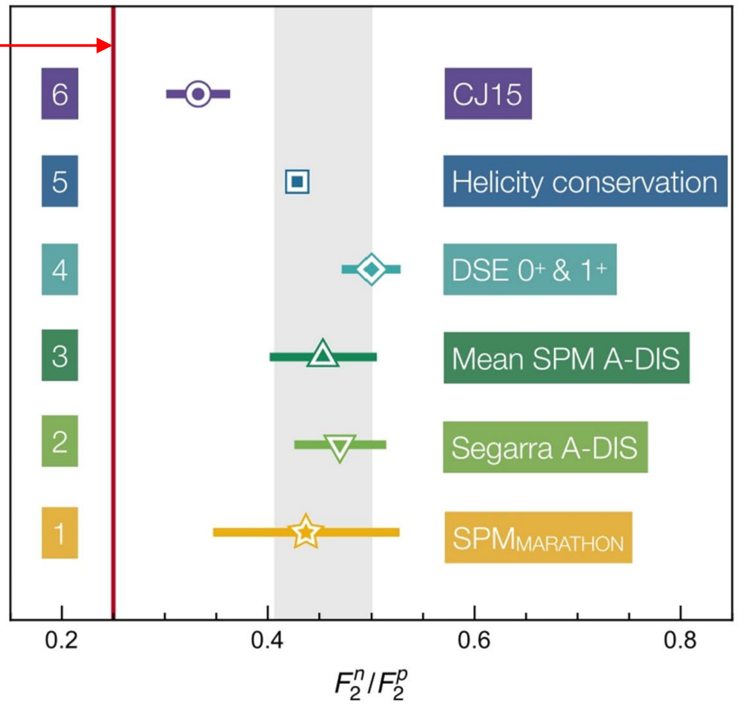


FIG. 3. $\lim_{x\to 1} F_2^n(x)/F_2^p(x)$. MARATHON-based SPM prediction compared with results inferred from: nuclear DIS [35]; Dyson-Schwinger equation analyses (DSE) [57, 58]; quark counting (helicity conservation) [59]; and a phenomenological fit (CJ15) [53]. The vertical red line marks the Nachtmann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

Proton and pion distribution functions in counterpoint

- Today, notwithstanding the enormous expense of time and effort, much must still be learnt before proton and pion structure may be considered understood in terms of DFs
- Most simply, what are the differences, if any, between the distributions of partons within the proton and the pion?
- The question of similarity/difference between proton and pion DFs has particular resonance today as science seeks to explain EHM
- How are obvious macroscopic differences between protons and pions expressed in the structural features of these two bound-states?

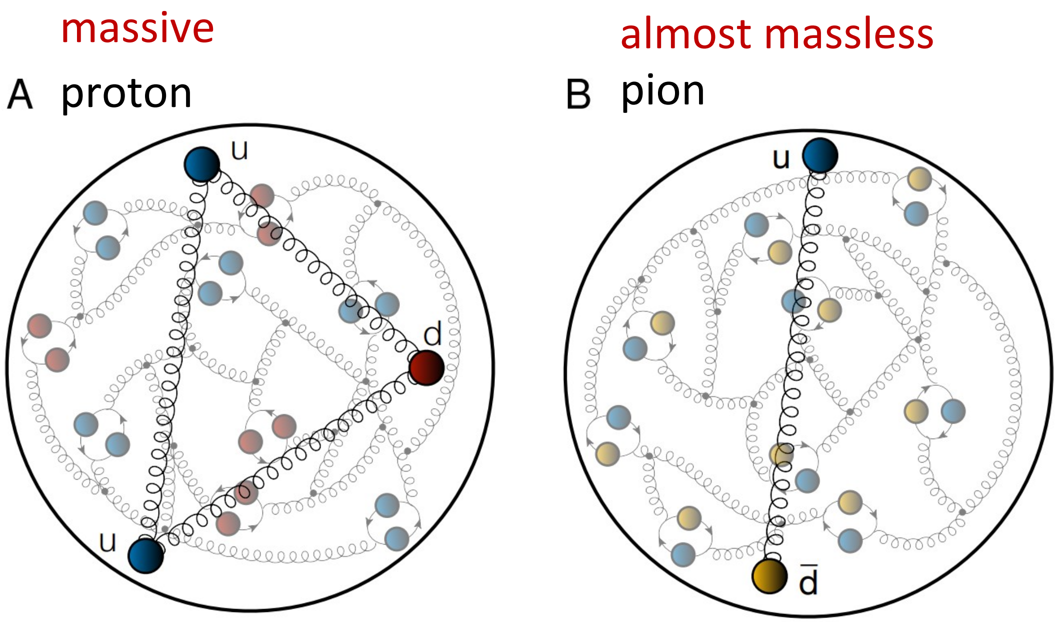


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

Proton and pion DFs - QCD predictions

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

✓ These are simple consequence of DGLAP equations.

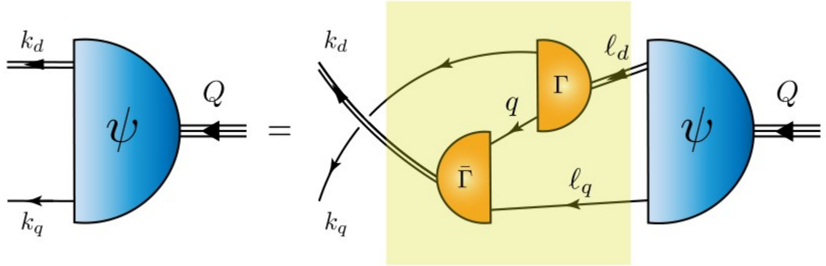
✓ Notably, argument can be reversed:

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.

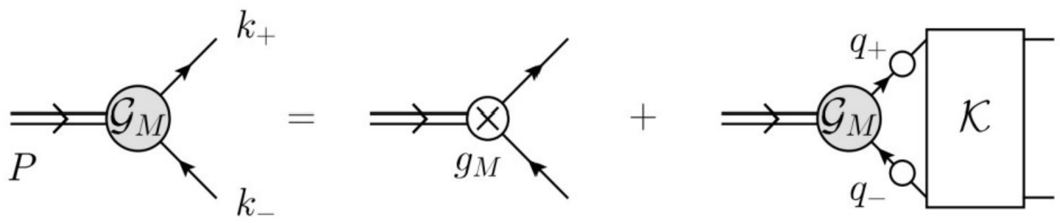
✓ DF with lowest exponent defines the valence degree-of-freedom.

Proton and pion distribution functions in counterpoint Continuum Schwinger function methods

- Proton via Faddeev equation

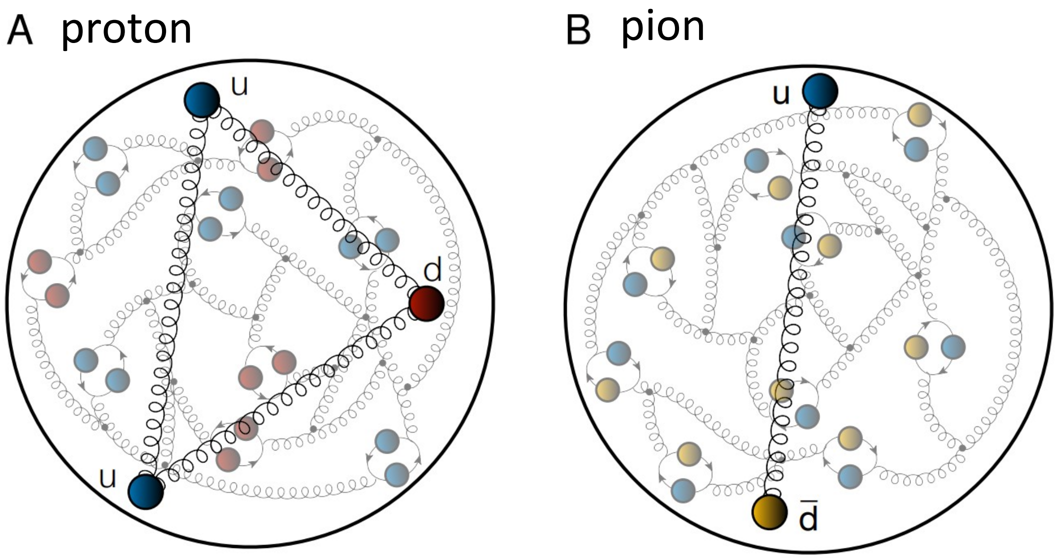


- Pion via Bethe-Salpeter equation



massive

almost massless



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Resolving the Bethe-Salpeter kernel, Si-Xue Qin and Craig D Roberts, NJU-INP 026/20, arXiv:2009.13637 [hep-ph], Express Letter in Chin. Phys. Lett. **38** (7) (2021) 071201/1-6 - Editors' Suggestion

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

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

- $\zeta > m_p$: 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 consequence of DGLAP equations.
- ✓ Notably, 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.
- ✓ Modern global analyses of proton DIS and related data encompass fits with role of glue and valence-quarks reversed!
- ✓ Proton has valence glue but no valence quarks!

Proton and pion distribution functions in counterpoint

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

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- 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.

✓ CT18: large-x power of glue distribution at the scale ζ = mass$_{\text{charm}}$ is (almost) identical to that of valence-quarks. With this behavior, the proton has valence-gluon degrees of freedom at all scales. That would make the proton a hybrid baryon, which it is not.

✓ CT18Z: large-x power of glue distribution is a_2=1.87, whereas that on the valence quarks is a_2=3.15, *i.e.*, at ζ = mass$_{\text{charm}}$ valence-quarks are subleading degrees-of-freedom. Instead, gluons dominate on what is typically called the valence-quark domain.

Proton and pion distribution functions in counterpoint

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

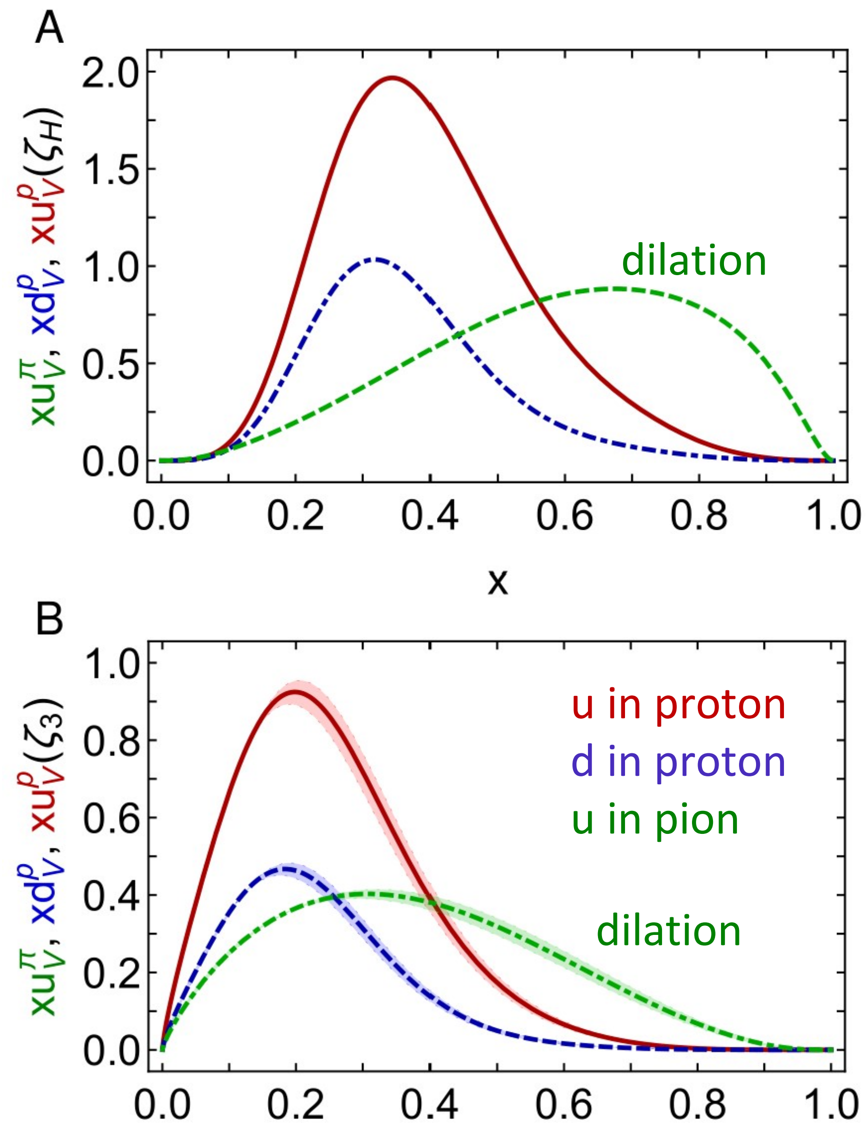
- Symmetry-preserving analyses using continuum Schwinger function methods (CSMs) deliver hadron scale DFs that agree with QCD constraints

$$\langle x \rangle_{u_p}^{\zeta_{\mathcal{H}}} = 0.687\,,\ \langle x \rangle_{d_p}^{\zeta_{\mathcal{H}}} = 0.313\,,\ \langle x \rangle_{u_\pi}^{\zeta_{\mathcal{H}}} = 0.5$$

- Valence-quark degrees-of-freedom carry all hadron's momentum at ζ_H
- 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
  - "Obvious" because of $(1-x)^2$ vs. $(1-x)^3$ behaviour and preservation of this unit difference under evolution
  - Also "hidden" = strong EHM-induced broadening

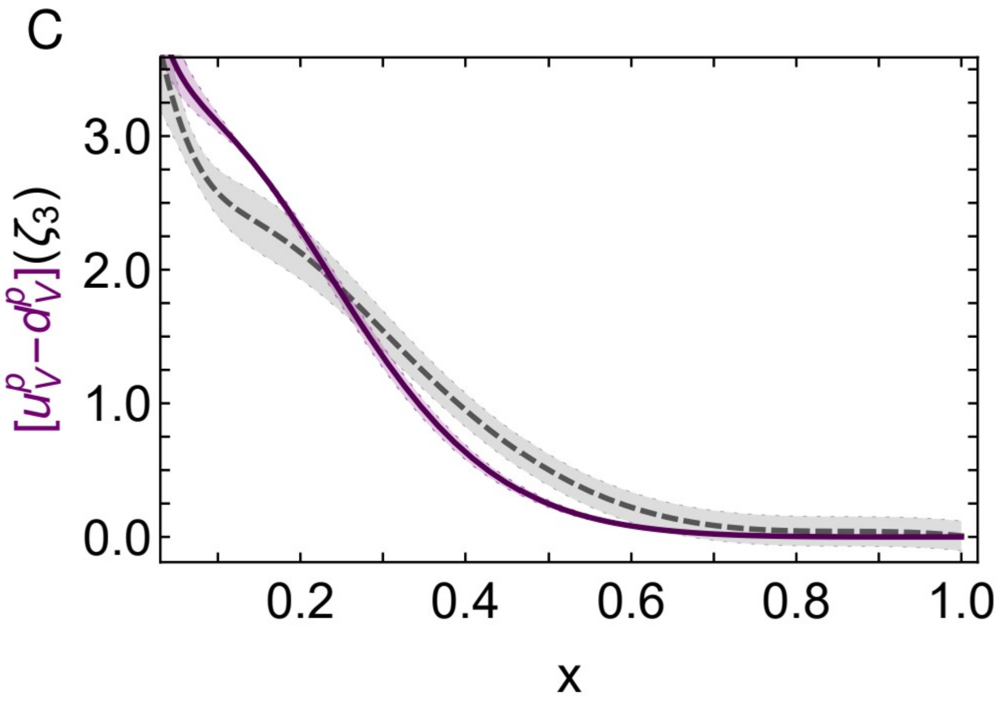


Proton valence-quark DFs: Continuum cf. Lattice

- Owing to difficulties in handling so-called disconnected contributions, the calculation of individual valence DFs using lattice-regularised QCD (lQCD) is problematic
- lQCD results are typically only available for isovector distributions, from which disconnected contributions vanish in the continuum limit.
- Comparison of isovector distributions

$$u^p(x;\zeta_3) - d^p(x;\zeta_3)$$

- Completely different approaches; yet good agreement, especially since refinements of both calculations may be anticipated.

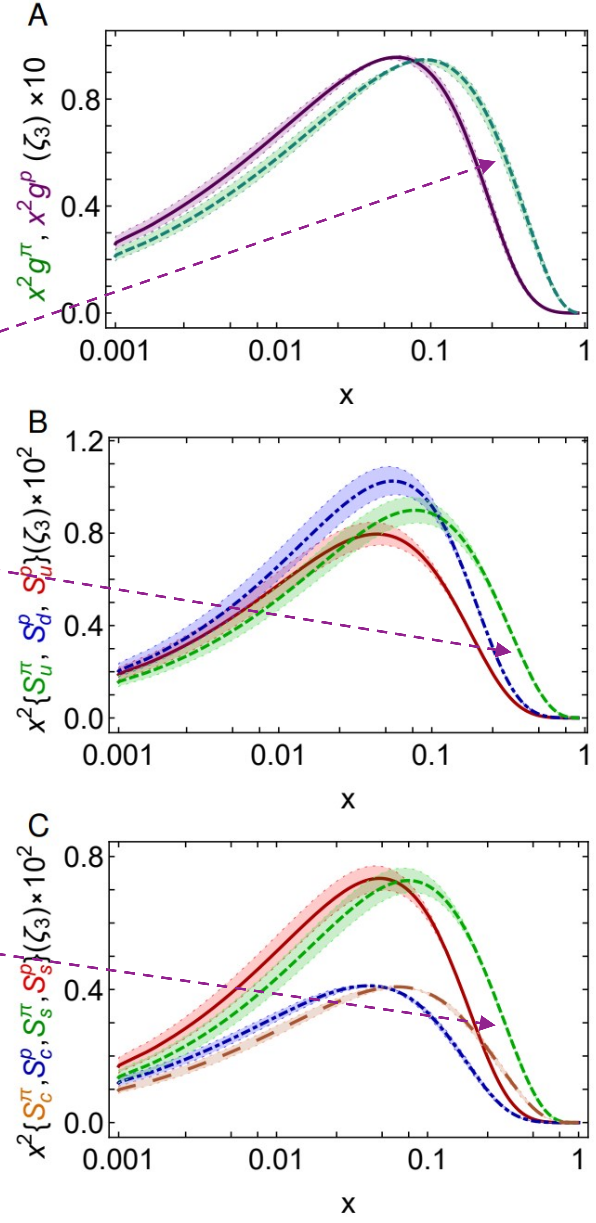


- ✓ Continuum: *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚) *et al.*, NJU-INP 056/22, e-Print: 2203.00753 [hep-ph]
- ✓ Lattice: *Nucleon Isovector Unpolarized Parton Distribution in the Physical-Continuum Limit*, H.-W. Lin *et al.*, arXiv:2011.14971 [hep-lat]

Proton and pion distribution functions in counterpoint - glue and sea

- Predicted CSM glue-in-pion DF is confirmed by recent lQCD calculation

  [*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 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



Asymmetry of antimatter in the proton

- Pauli blocking: gluon splitting produces

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

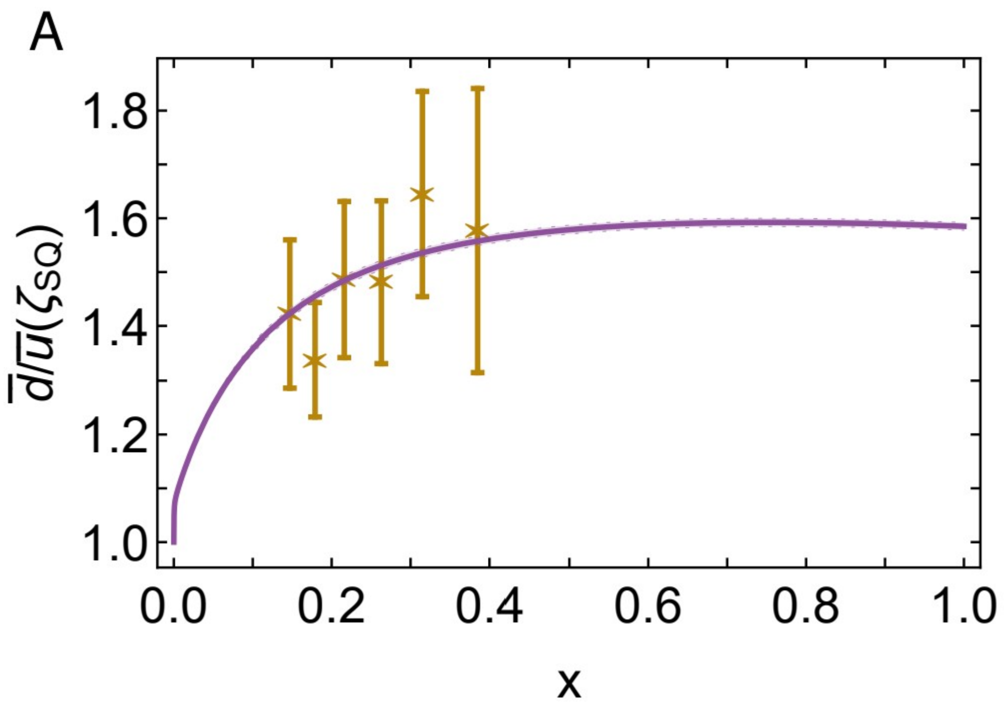
- Comparison with SeaQuest data

  [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)



Neutron/Proton structure function ratio

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

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

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

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

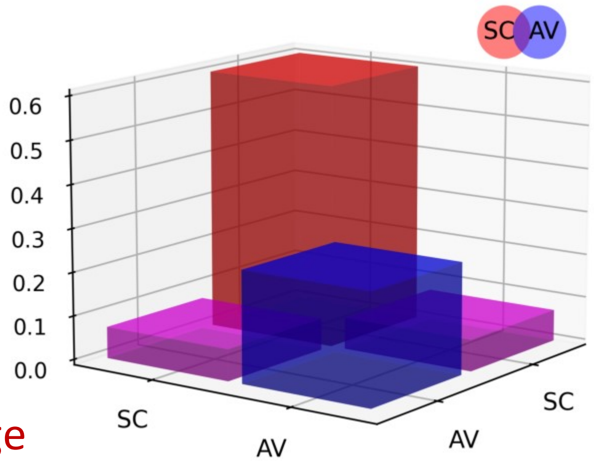
- Comparison with MARATHON data

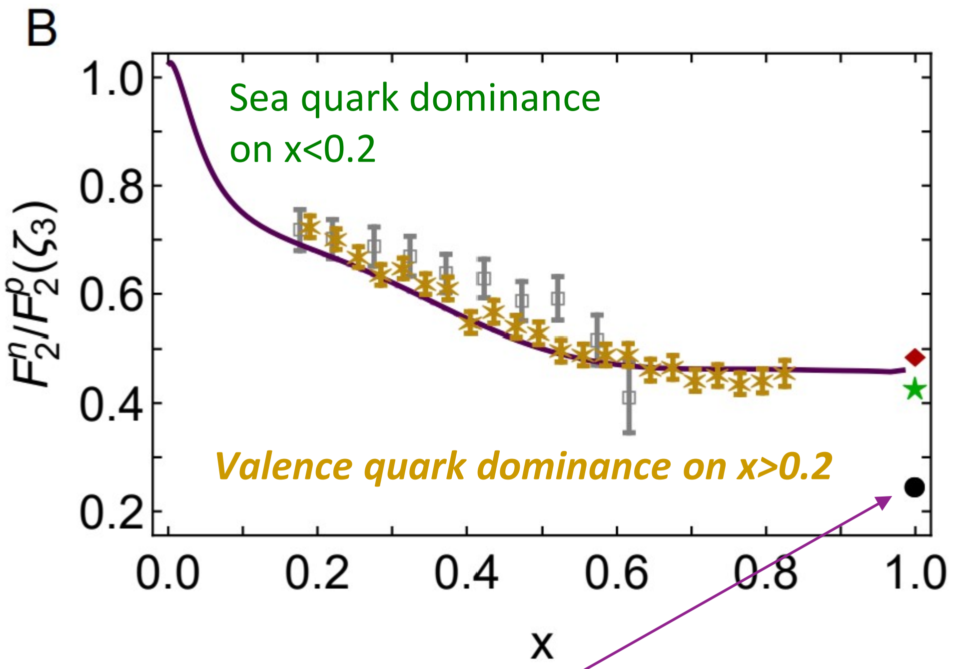
  [D. Abrams, *et al.*, Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- 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 1/7,000,000

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

Proton and pion distribution functions in counterpoint

- CSMs have delivered 1st 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.

Table 2: Low-order Mellin moments, $\langle x^m\rangle_{pH}^{\zeta_3}$, of the DFs drawn in Figs. 2B – 3, measured in %. As an illustration of the numerical accuracy of our evolution procedure, we note that $\langle x\rangle_{c_\pi}^{\zeta_3}$ and $\langle x\rangle_{c_p}^{\zeta_3}$ differ by only 0.3%. Uncertainties associated with $\zeta_{\mathcal{H}} \to \zeta_{\mathcal{H}}(1 \pm 0.05)$ are shown. To simplify comparisons with phenomenological fits to relevant data, results for $\langle x^m\rangle_{pH}^{\zeta_2}$, $\zeta_2 = 2$ GeV, are also listed. The $m = 1, 2, 3$ moments of the proton isovector distribution, $[u - d]$, are: ζ_2 – 17.9(8)%, 5.1(3)%, 1.8(2)%; and ζ_3 – 16.6(7)%, 4.5(3)%, 1.6(1)%

pion	u^π	$\bar{d}^\pi$	g^π	S_π^u	$S_\pi^{\bar{d}}$	S_π^s	S_π^c
$\langle x\rangle^{\zeta_2}$	24.0(1.1)	24.0(1.1)	41.0(1.2)	3.3(3)	3.3(3)	2.65(22)	1.33(5)
$\langle x^2\rangle^{\zeta_2}$	9.5(7)	9.5(7)	3.7(1)	0.27(1)	0.27(1)	0.21(1)	0.092(2)
$\langle x^3\rangle^{\zeta_2}$	4.7(4)	4.7(4)	0.92(6)	0.057(1)	0.057(1)	0.044(0)	0.018(1)
$\langle x\rangle^{\zeta_3}$	22.1(1.0)	22.1(1.0)	42.9(1.0)	3.7(3)	3.7(3)	3.0(2)	1.83(6)
$\langle x^2\rangle^{\zeta_3}$	8.4(6)	8.4(6)	3.5(1)	0.27(1)	0.27(1)	0.22(1)	0.120(3)
$\langle x^3\rangle^{\zeta_3}$	4.0(3)	4.0(3)	0.82(5)	0.056(0)	0.056(0)	0.044(0)	0.022(1)

proton	u^p	d^p	g^p	S_p^u	S_p^d	S_p^s	S_p^c
$\langle x\rangle^{\zeta_2}$	32.9(1.4)	15.0(0.7)	40.9(1.1)	2.9(2)	3.7(3)	2.64(22)	1.32(5)
$\langle x^2\rangle^{\zeta_2}$	8.7(6)	3.6(2)	2.4(1)	0.14(1)	0.21(1)	0.13(0)	0.059(2)
$\langle x^3\rangle^{\zeta_2}$	2.9(3)	1.1(1)	0.39(2)	0.019(0)	0.030(1)	0.019(0)	0.008(0)
$\langle x\rangle^{\zeta_3}$	30.4(1.3)	13.8(0.6)	42.8(1.0)	3.3(3)	4.1(3)	3.0(2)	1.82(6)
$\langle x^2\rangle^{\zeta_3}$	7.7(5)	3.2(2)	2.2(1)	0.15(1)	0.21(1)	0.14(0)	0.075(2)
$\langle x^3\rangle^{\zeta_3}$	2.5(2)	0.9(1)	0.35(2)	0.019(0)	0.028(0)	0.019(0)	0.010(1)

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

Many, Many Other Expressions of EHM

- EHM ⇒ formation of strong nonpointlike quark+quark (diquark) correlations within baryons
  - All baryons, including those with one or more heavy quarks
- Nucleons possess 0^+ isoscalar & 1^+ isovector correlations
  - Marathon data

    ⇒ Probability that scalar diquark only models might be consistent is $\frac{1}{7{,}000{,}000}$
- Nucleon resonances contain more correlations … 0^- isoscalar, 1^- isoscalar & 1^- isovector
- Δ-baryon resonances … 1^- isoscalar & 1^- isovector
- Nucleon-elastic & nucleon-to-resonance transition form factors can test these and other structural predictions
- On to … GPDs, TMDs, TDAs … gluon+quark correlations within baryons, etc.
- Progress demands Synergy between Experiment + Phenomenology + Theory

EHM Measurements
Meson Structure

i. Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS. This document covers all ideas for future experiments as of January 2019.

ii. Proposal for Phase-1: COMPASS++/AMBER: Proposal for Measurements at the M2 beam line of the CERN SPS Phase-1: 2022-2024. This document covers the three phase-1 experiments (start in 2022).

iii. *Pion and Kaon Structure at the Electron-Ion Collider*, Arlene C. Aguilar *et al*., arXiv:1907.08218 [nucl-ex], Eur. Phys. J. A 55 (2019) 190/1-15

iv. *Strong QCD from Hadron Structure Experiments*, S. J. Brodsky *et al*., arXiv:2006.06802 [hep-ph], Int. J. Mod. Phys. E 29 (2020) 08, 2030006/1-122

v. *Selected Science Opportunities for the EicC,* Xurong Chen, Feng-Kun Guo, Craig D. Roberts and Rong Wang, arXiv:2008.00102 [hep-ph], Few Body Syst. 61 (2020) 4, 43/1-37. Invited contribution to the Special Issue: "New Trends in Hadron Physics: a Few-Body Perspective"

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

vii. *Electron-Ion Collider in China,* D. P. Anderle *et al*., arXiv:2102.09222 [nucl-ex], Front. Phys. (Beijing) 16 (2021) 6, 64701

viii. *Revealing the structure of light pseudoscalar mesons at the Electron-Ion Collider,* John Arrington *et al*., arXiv: 2102.11788 [nucl-ex], J. Phys. G 48 (2021) 7, 075106

AMBER @ CERN SPS: *Excerpts* from the Science Roadmap

Desired Quantities	Scientific Grounds	Experiments
Pion and kaon distribution amplitudes (DAs) – $\varphi(x)$ {Nearest thing in quantum field theory to a Schrödinger wave function}	Theory predicts EHM is expressed in the shape of DAs 40-year controversy over x-dependence of φ Higgs-boson modulation of EHM measured by *skewing* of K DA cf. π DA Today, finally, continuum and lattice theory delivering consistent predictions for x-dependence Signature features of EHM and HB-interference manifest in low-order DA moments	One 20-year-old FNAL experiment on π DA yielded controversial results – in some ways, internally inconsistent Low-order moments of DAs are accessible via π & K beam–induced production of 3-meson final states AMBER@CERN with high-intensity π & K beams stands tall in the world with the capacity to place novel constraints on NG-mode DAs
Pion and kaon distribution functions (DFs) {provide detailed structural information}	How does NG-mode structure differ from that of proton? After all, mass profiles are completely different 30-year controversy: x-dependence of π valence-quark DF & Only 10 data points in existence for kaon ZERO empirical information on sea and glue in π & K Gluon content? Controversial yet prominent theory predictions that π contains no glue. What are NG modes?	Existing experiments are more than 40-years-old. Data only on valence-quark domain. AMBER@CERN anticipates high-luminosity, high-energy π & K beams for DY & J/ψ-production & prompt-γ production ⇒ especially capable of providing precision data to answer ALL these questions

AMBER @ CERN SPS: *Excerpts* from the Science Roadmap

Desired Quantities	Scientific Grounds	Experiments
Pion and kaon distribution amplitudes (DAs) – $\varphi(x)$ {Nearest thing in quantum field theory to a Schrödinger wave function} ☑ ***Sullivan process ⇒ Meson form factors at large Q^2***	Theory predicts EHM is expressed in the shape of DAs 40-year controversy over x-dependence of φ Higgs-boson modulation of EHM measured by *skewing* of K DA cf. π DA Today, finally, continuum and lattice theory delivering consistent predictions for x-dependence Signature features of EHM and HB-interference manifest in low-order DA moments	One 20-year-old FNAL experiment on π DA yielded controversial results – in some ways, internally inconsistent Low-order moments of DAs are accessible via π & K beam–induced production of 3-meson final states AMBER@CERN with high-intensity π & K beams stands tall in the world with the capacity to place novel constraints on NG-mode DAs
Pion and kaon distribution functions (DFs) {provide detailed structural information} ☑ ***Sullivan process ⇒ Meson structure functions***	How does NG-mode structure differ from that of proton? After all, mass profiles are completely different 30-year controversy: x-dependence of π valence-quark DF & Only 10 data points in existence for kaon ZERO empirical information on sea and glue in π & K Gluon content? Controversial yet prominent theory predictions that π contains no glue. What are NG modes?	Existing experiments are more than 40-years-old. Data only on valence-quark domain. AMBER@CERN anticipates high-luminosity, high-energy π & K beams for DY & J/ψ-production & prompt-γ production ⇒ especially capable of providing precision data to answer ALL these questions

Revealing the structure of light pseudoscalar mesons at the Electron-Ion Collider,
John Arrington *et al*., arXiv: 2102.11788 [nucl-ex], J. Phys. G **48** (2021) 7, 075106

Selected Science Questions for EIC

Science Question	Key Measurement[1]	Key Requirements[2]
What are the quark and gluon energy contributions to the pion mass?	Pion structure function data over a range of x and Q^2.	• Need to uniquely determine $e + p \to e' + X + n$ (low -t) • CM energy range ~10-100 GeV • Charged- and neutral currents desirable
Is the pion full or empty of gluons as viewed at large Q^2?	Pion structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
What are the quark and gluon energy contributions to the kaon mass?	Kaon structure function data over a range of x and Q^2.	• Need to uniquely determine Λ, Σ^0: $e + p \to e' + X + \Lambda/\Sigma^0$ (low -t) • CM energy range ~10-100 GeV
Are there more or less gluons in kaons than in pions as viewed at large Q^2?	Kaon structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
Can we get quantitative guidance on the emergent pion mass mechanism?	Pion form factor data for $Q^2 = 10\text{-}40\ (\text{GeV/c})^2$.	• Need to uniquely determine exclusive process $e + p \to e' + \pi^+ + n$ (low -t) • e-p and e-d at similar energies • CM energy ~10-75 GeV
What is the size and range of interference between emergent-mass and the Higgs-mass mechanism?	Kaon form factor data for $Q^2 = 10\text{-}20\ (\text{GeV/c})^2$.	• Need to uniquely determine exclusive process $e + p \to e' + K^+ + \Lambda$ (low -t) • L/T separation at CM energy ~10-20 GeV • e-p Λ/Σ^0 ratios at CM energy ~10-50 GeV
What is the difference between the impacts of emergent- and Higgs-mass mechanisms on light-quark behaviour?	Behaviour of (valence) up quarks in pion and kaon at large x	• CM energy ~20 GeV (lowest CM energy to access large-x region) • Higher CM energy for range in Q^2 desirable
What is the relationship between dynamically chiral symmetry breaking and confinement?	Transverse-momentum dependent Fragmentation Functions of quarks into pions and kaons	• Collider kinematics desirable (as compared to fixed-target kinematics) • CM energy range ~20-140 GeV

Meson structure functions

Meson form factors

Meson fragmentation functions

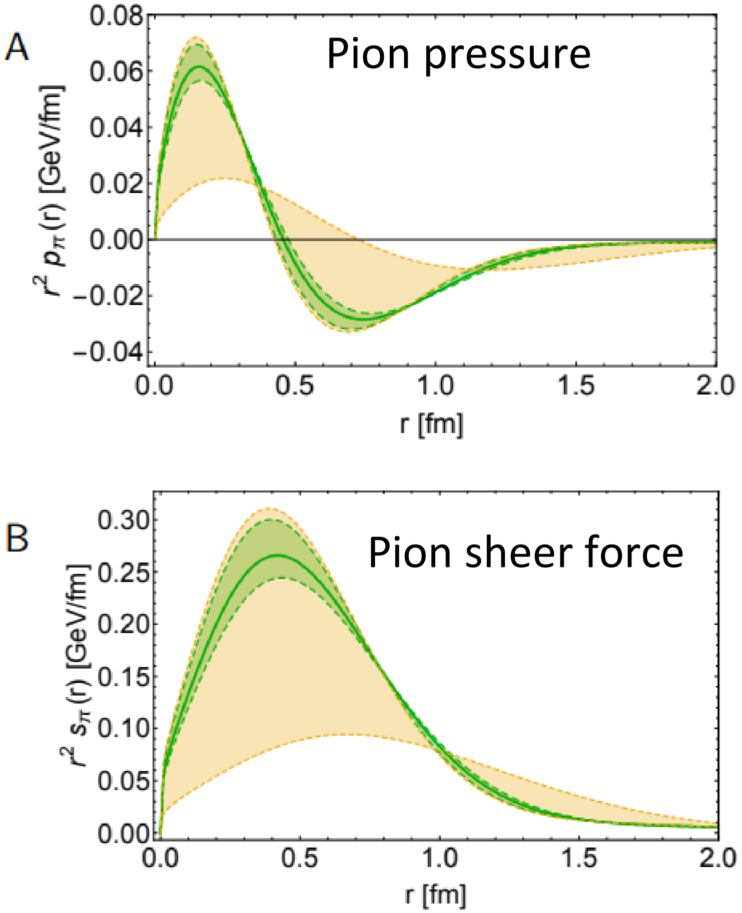
Revealing the structure of light pseudoscalar mesons at the Electron-Ion Collider,
John Arrington *et al*., arXiv: 2102.11788 [nucl-ex], J. Phys. G **48** (2021) 7, 075106

Selected Science Questions for EIC

More speculative observables		
What is the trace anomaly contribution to the pion mass?	Elastic J/ψ production at low W off the pion.	• Need to uniquely determine exclusive process $e + p \to e' + \pi^+ + J/\Psi + n$ (low -t) • High luminosity (10^{34+}) • CM energy ∼70 GeV
Can we obtain tomographic snapshots of the pion in the transverse plane? What is the pressure distribution in a pion?	Measurement of DVCS off pion target as defined with Sullivan process	• Need to uniquely determine exclusive process $e + p \to e' + \pi^+ + \gamma + n$ (low -t) • High luminosity (10^{34+}) • CM energy ∼10-100 GeV
Are transverse momentum distributions universal in pions and protons?	Hadron multiplicities in SIDIS off a pion target as defined with Sullivan process	• Need to uniquely determine scattered off pion: $e + p \to e + h + X + n$ (low -t) • High luminosity (10^{34+}) • e-p and e-d at similar energies desirable • CM energy ∼10-100 GeV

Selected Science Questions for EIC

More speculative observables
What is the trace anomaly contribution to the pion mass?
Can we obtain tomographic snapshots of the pion in the transverse plane? What is the pressure distribution in a pion?
Are transverse momentum distributions universal in pions and protons?



Revealing pion and kaon structure via generalised parton distributions, Khépani Raya *et al*. e-Print: 2109.11686 [hep-ph], Chin. Phys. C **46** (01) (2022) 013107/1-22

- ✓ The analyses predict that mass-squared gravitational form factors are stiffer than electromagnetic form factors
- ✓ Reveal that K pressure profiles are tighter than profiles
- ✓ Both π and K mesons sustain near-core pressures at magnitudes similar to that expected at the core of neutron stars

Grant no. 12135007

国家自然科学基金委员会
NSFC
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*

This is the Fascination and Urgency of Physics

The Nature of Things

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

- Is there a Lagrangian for Nature?
- If so, then the natural mass/length scales for all things are contained within
- Much more than that …
- If there is $\mathcal{L}_{Nature}$, then Logic, as expressed in Mathematics, is innate to Nature
- Then, Mathematics is not something we invented to describe Nature
  - It is a secret of Nature that we discovered
- So that Nature is Mathematics and Mathematics describes everything
  - Including us.
- This may be true
  - If so, then there *are* answers to the questions we have long asked
  - And answers to questions we have not yet thought to ask

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

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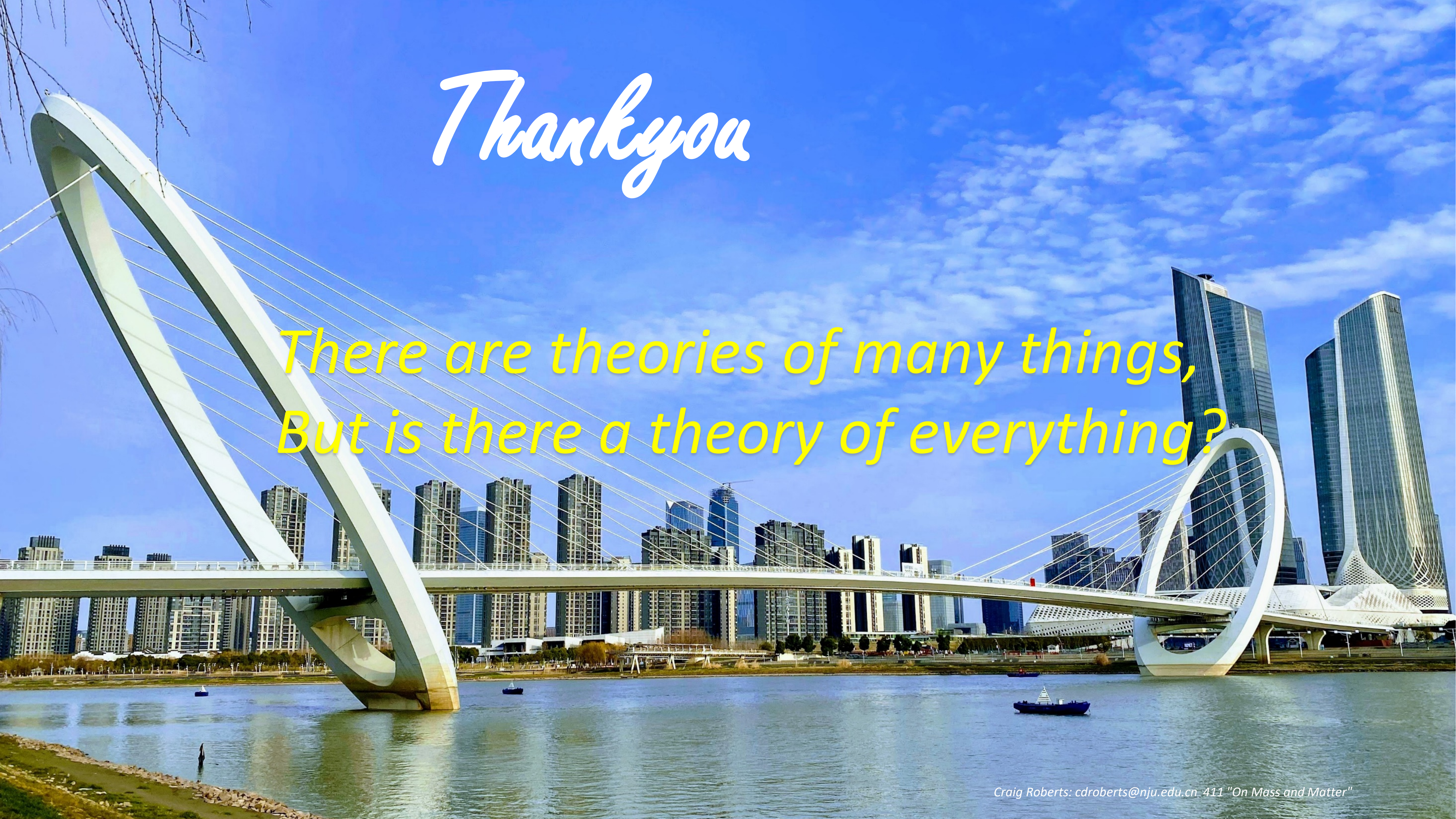


Thankyou

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

Quantum Chromodynamics

- Definition: "Well-defined" quantum field theory
  - finite number of renormalization constants, $\{Z_i, i = 1, \ldots, N\}$
  - $\{Z_i, i = 1, \ldots, N\}$ can all be computed and remain bounded real numbers as any regularization scale is removed
    - Quantum electrodynamics fails this test owing to Landau pole in ultraviolet
    - Weak interactions are essentially perturbative because addition of Higgs scalar introduces enormous infrared scale that suppresses all nonperturbative effects

      But Higgs boson mass itself is quadratically divergent $\Rightarrow$ not renormalizable
- Nonperturbative QCD has come a long way in the last few years.
- Beginning to look increasingly likely that QCD is humanity's first well-defined four-dimensional quantum field theory
- Stands alone as an internally consistent theory

  – a predictive tool – as written, with nothing needing to be added

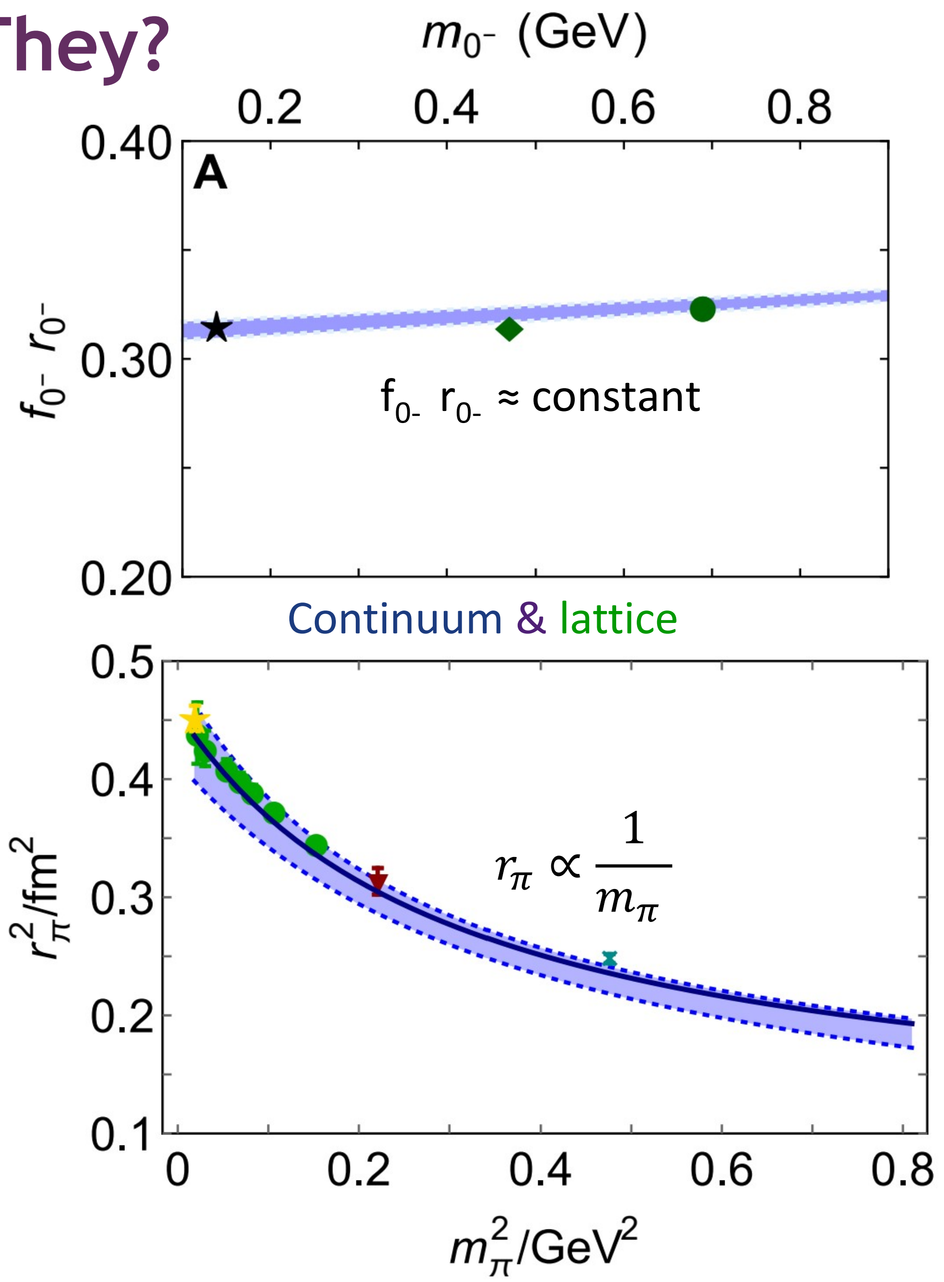
Hadron Radii

Nambu Goldstone Bosons: How Big are They?

- **Physics Measurements**:
  - Pion and kaon charge radii
- **Scientific Context**:
  - Hadron masses and radii are a direct expression of the links between EHM and confinement
  - Example: within Nambu-Goldstone boson domain of pseudoscalar-meson mass trajectory

    $f_{0-}\ r_{0-} \approx$ constant

    product of meson leptonic decay constant (f_{0-}) and charge radius (r_{0-}) is practically constant
  - f_{0-} is an order parameter EHM.
    Equally, so is r_π
  - Precise measurements of π & K radii will reveal compositeness (confinement) scale for Nambu-Goldstone bosons

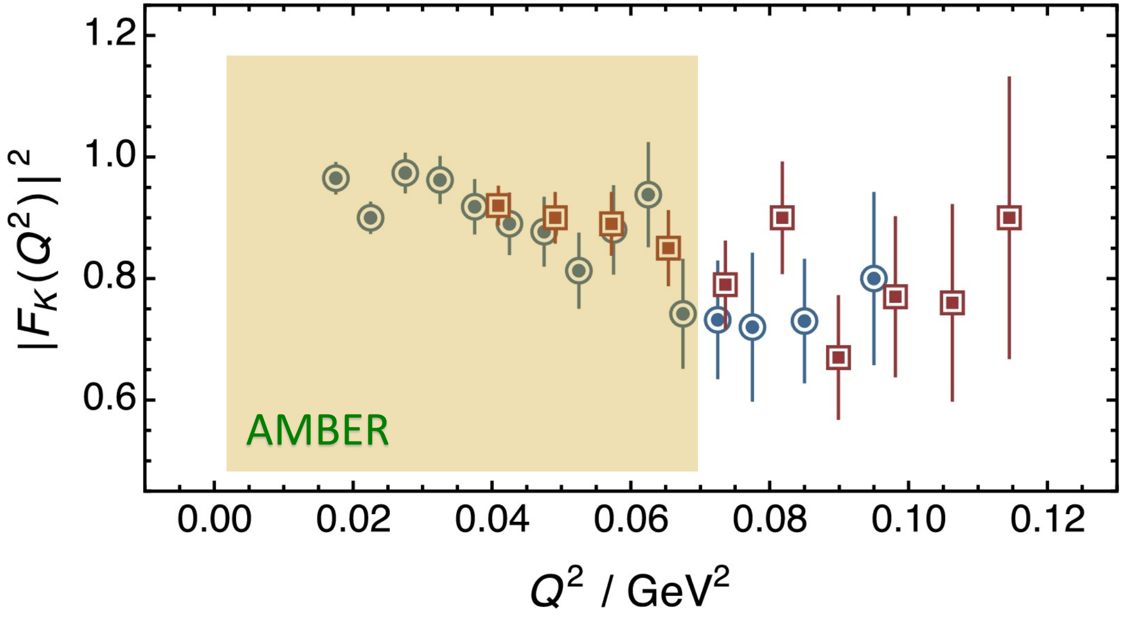


Size of Nambu Goldstone Bosons

- Data – Existing:
  - 70+ years after their discovery, knowledge of pion and kaon radii is very limited.
  - Pion charge radius is poorly known.
    - m_π measured to one-part in a million;
    - r_π only constrained to 1% & even this is debatable
    - The most precise data (charged-pion scattering at CERN) are more than 30-years-old and do not reach to very low momentum transfers
    - The most recent data (Selex) yield a result with errors more than 10-times larger than CERN
  - New theory methods enable model-independent extraction of radii from precise low-Q^2 data
  - New method ⇒ r_π : 2.4σ tension with PDG 2021
  - No information beyond least-squares fit in K data
  - E.g. AMBER, with high-intensity π & K beams, capable of delivering precise data that are required

Pion charge radius from pion+electron elastic scattering data, Zhu-Fang Cui (崔著钫), Daniele Binosi, C.D. Roberts, S.M. Schmidt, NJU-INP 047/21, arXiv:2108.04948 [hep-ph], Phys. Lett. B **822** (2021) 136631/1-5

This data is all we have … It cannot reasonably be used to claim a result for the kaon charge radius



- Kaon radius is practically unknown
  - 15 imprecise scattering points, on $Q^2 > 0.015$ GeV^2, analysed using a simple monopole fit, which is today known to be a poor approach
  - Recall that > 60-years of *ep* scattering measurements, analysed this way, led to proton radius extractions that are likely wrong by an amount in excess of 7σ.

Enable 1st objective extraction of kaon size