NANJING UNIVERSITY

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Pion & Kaon Structure – Window onto EHM

Character of Mass

- Key questions posed to modern science:
  - What is the origin of mass?
  - What are the consequences of the appearance of mass?
- When considering the source of mass, many people think of explicit mass, generated via the Higgs-mechanism
  - especially because the Higgs boson was discovered relatively recently at CERN (2012)
  - importance acknowledged by the Nobel Prize awarded to Englert and Higgs:
    - *for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles …*

Character of Mass

- Discovery of the Higgs was a watershed.
- However, it should be placed in context.
- Therefore, consider the mass-energy budget of the Universe
  - Dark energy = 71%
  - Dark Matter = 24%
  - Visible material = 5%
    - Higgs effect is just 0.1% of the visible matter
- Little is known about the first two

  Science can say almost nothing about 95% of the mass-energy in the Universe.
- The explanation lies outside the Standard Model.

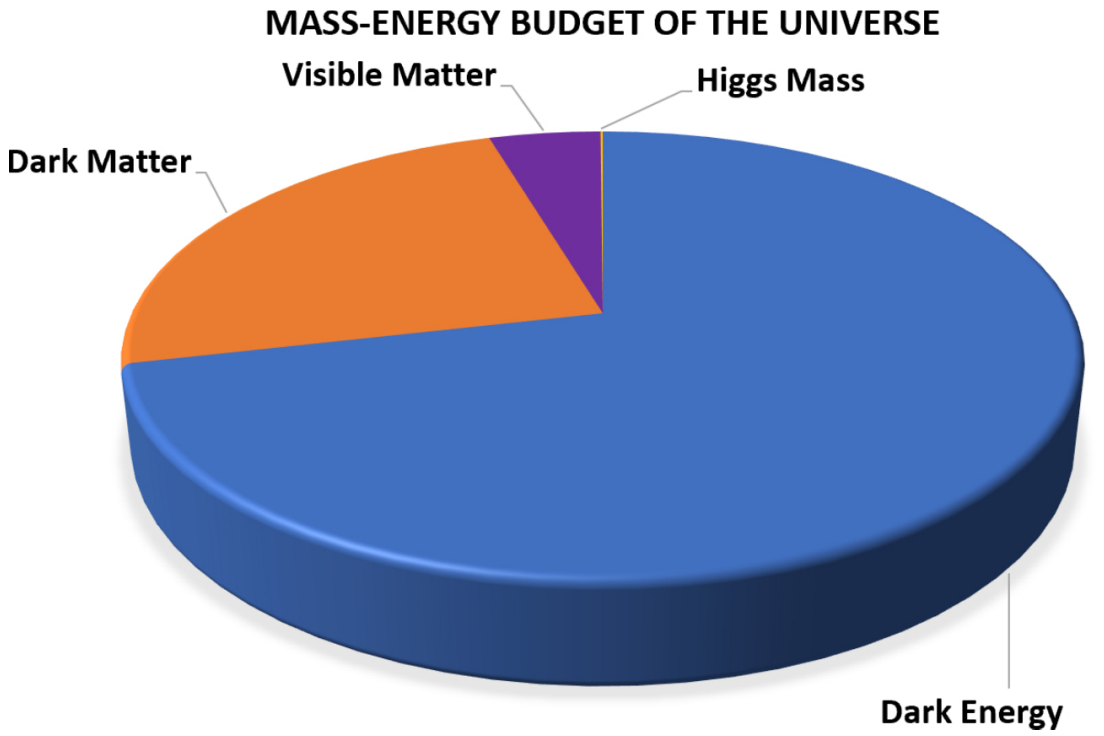
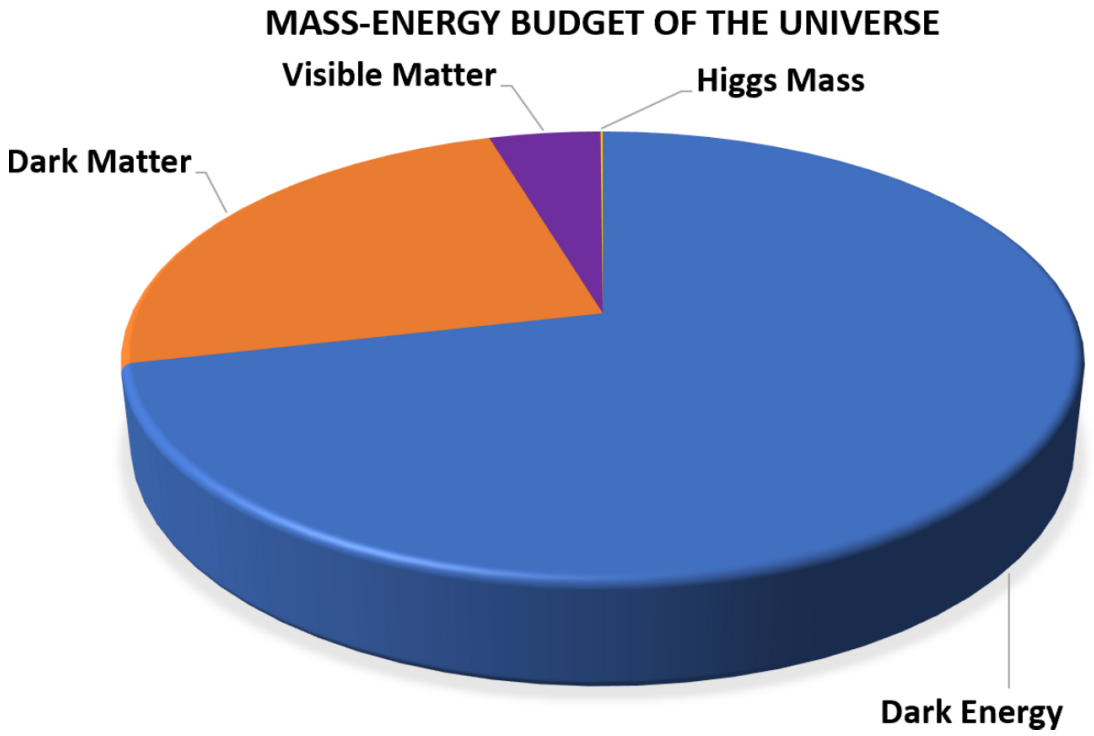


FIG. 1. The Wilkinson Microwave Anisotropy Probe (WMAP) [5] determined that the universe is flat, from which it follows that the mean energy density in the Universe is equal to the critical density, *viz.* only 5.9 protons/m^3. Of this total density [6]: dark energy is 71%; dark matter is another 24%; and the remaining 5% is visible material. Of this 5%, less than 0.1% is tied simply to the Higgs boson, as indicated by the yellow sliver at the top of the disk.

Character of Mass

- Little is known about Dark Energy and Dark Matter …

  Science can say almost nothing about 95% of the mass-energy in the Universe.
- On the other hand, the remaining 5% has forever been the source of everything tangible.
- Yet, amongst this 5%, less-than 0.1% is tied directly to the Higgs boson
- Hence, even concerning visible material, too much remains unknown.



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Visible Mass

- More than 98% of visible mass is contained within nuclei.
- First approximation:
  - atomic weights = sum of the masses of all the nucleons they contain.
- Each nucleon has a mass $m_N \sim 1$ GeV $\approx 2000\ m_e$
- Higgs boson produces m_e the latter, but what produces m_N ?
- This question is the crux of modern physics
  - How can science explain the emergence of hadronic mass (EHM)?

Standard Model

- Strong interactions are described by quantum chromodynamics (QCD).
- QCD: hadrons are composites,
  - built from quarks and/or antiquarks (matter fields)
  - held together by forces produced by the exchange of gluons (gauge fields).
- These forces are unlike any previously encountered.
  - become very weak when two quarks are brought close together within a nucleon
  - but all experimental attempts to remove a single quark from within a nucleon and isolate it in a detector have failed.
- Seemingly, then, the forces become enormously strong as the separation between quarks is increased
- Modern science is encumbered with The Confinement Problem

confinement

Google Scholar:
25,000 mentions of quark confinement since 2000

Confinement Problem

- Modern science is encumbered with The Confinement Problem
- Confinement is crucial because it ensures absolute stability of the proton.
- In the absence of confinement:
  - protons in isolation could decay;
  - the hydrogen atom would be unstable;
  - nucleosynthesis would be a chance event, having no lasting consequences;
  - and without nuclei, there would be no stars and no living Universe.
- Without confinement, our Universe could not exist.

confinement

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Confinement Problem

- Modern science is encumbered with The Confinement Problem
- As the 21st Century began, the Clay Mathematics Institute established seven Millennium Prize Problems
  - Each represents one of the toughest challenges in mathematics.
  - The set contains the problem of confinement; and presenting a sound solution will win its discoverer $1,000,000
- Even with such motivation, today, almost 50 years after the discovery of quarks, no rigorous solution has been found
- Confinement and EHM are inextricably linked
- Consequently, as science plans for the next thirty years, solving the problem of EHM has become a Grand Challenge

confinement

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QCD is full of surprises

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

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

- In appearance, QCD is simple.
- QCD is also unique.
- Fundamental theory with the capacity to sustain massless elementary degrees-of-freedom, *viz*. gluons and quarks;
  - Yet gluons and quarks are predicted to acquire mass dynamically
  - And nucleons and almost all other hadrons likewise
- Only massless systems in QCD = composite Nambu-Goldstone (NG) bosons,
  e.g. pions and kaons.
- Pions responsible for binding systems as diverse as atomic nuclei and neutron stars
- Energy associated with the gluons and quarks within the NG modes is not readily apparent.
- Stark contrast with all other "everyday" hadrons:
  - systems constituted from *u*, *d*, *s* quarks possess nuclear-size masses
  - masses far in excess of anything that can directly be tied to the Higgs boson

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- In trying to match QCD with Nature, one confronts the many complexities of strong, nonlinear dynamics in relativistic quantum field theory, *e.g.*:
  - loss of particle number conservation
  - frame and scale dependence of the explanations and interpretations of observable processes
  - evolving character of the relevant degrees-of-freedom
- Electroweak theory and phenomena are essentially perturbative; hence, possess little of this complexity.
- Science has never before encountered an interaction such as that at work in QCD.
- Understanding this interaction, explaining everything of which it is capable, can potentially change the way we look at the Universe.

QCD is full of surprises

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- Comparison with QED
  - One essential difference = circled term, describing gluon self-interactions.

- If QCD is correct, then this term must hold the answers to an enormous number of Nature's basic questions, e.g.:
  - what is the origin of visible mass?
  - how is mass distributed within atomic nuclei?
  - what carries the proton's spin?
  - how can the same degrees-of-freedom combine to ensure the pion is spinless?
- Nowhere are there more basic expressions of *emergence* in Nature

QCD is full of surprises

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- Treated as a classical theory, chromodynamics is a non-Abelian local gauge field theory.
- Formulated in four spacetime dimensions, such theories do not possess any mass-scale in the absence of Lagrangian masses for the quarks.
  - There is no dynamics in a scale-invariant theory, only kinematics.
  - Bound states are therefore impossible
  - Accordingly, our Universe cannot exist.
- A Spontaneous breaking of symmetry - Higgs mechanism - does not solve this problem
  - $m_N \approx$ 100-times larger than Higgs-generated current-masses of the light *u*- and *d*-quarks, the valence constituents of nucleons

QCD is full of surprises

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- On the other hand … NG bosons are (nearly) massless
- In these systems, the strong interaction's $m_N \approx 1$ GeV mass-scale is <u>hidden</u>.
- Chiral limit, when Higgs-generated masses are omitted, NG modes are massless
  - Exactly massless … no fine tuning … no danger of tachyons
- In this case, perturbative QCD predicts that strong interactions cannot distinguish between quarks with negative or positive helicity – <u>chiral symmetry</u>
- Such a chiral symmetry would have numerous corollaries, *e.g*.
  - pion would be partnered with a scalar meson of equal mass.
- However, no such state is observed
- No consequences of this chiral symmetry found in Nature – symmetry broken by interactions.
- Dynamical chiral symmetry breaking (DCSB) ensures both
  - massless quarks in QCD's Lagrangian acquire large effective masses
  - interaction energy between those quarks cancels their masses exactly so that $m_\pi = 0$

QCD is full of surprises

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- Restore the Higgs mechanism = add realistic current-quark masses
- DCSB is responsible for, *inter alia*:
  - physical size of the pion mass
    - $m_\pi \approx 0.15\ m_N$
  - large mass-splitting between pion and its valence-quark spin-flip partner, ρ-meson
    - $m_\rho > 5\ m_\pi$
  - neutron and proton possessing masses
    - $m_N \approx 1$ GeV
  - Interesting things also happen to the kaon
    - Like a pion, but with one light quark replaced by *s*-quark, K possesses a mass $m_K \approx 0.5$ GeV
    - Here a competition is taking place, between dynamical and Higgs-driven mass-generation.

Fundamental Mysteries

- These phenomena and features, their origins and corollaries, entail that the question
  - how did the Universe evolve?

  is inseparable from the questions
  - how does the $m_N \approx 1$ GeV mass-scale that characterises atomic nuclei appear?
  - why does it have the observed value?
  - and, enigmatically, why does the dynamical generation of m_N have seemingly no effect on the composite NG bosons in QCD?
    - *i.e*. whence the near-absence of the pion mass?

Confinement

- Confinement is one of the most fascinating aspects of QCD
- At issue is the definition.
- When communicating about confinement, a typical practitioner has a notion in mind; yet the perspectives of any two different practitioners are often distinct
  - e.g., [Wilson:1974sk, Gribov:1998kb, Cornwall:1981zr].
- The proof of one expression of confinement will be contained within demonstration that quantum $SU_c(3)$ gauge field theory is mathematically well-defined,
  - *i.e*. a solution to the "Millennium Problem" [Clay Mathematics Institute $1,000,000]
- However, that may be of limited utility because
  - Nature has provided light-quark degrees-of-freedom
  - They seemingly play a crucial role in the empirical realisation of confinement,
  - Perhaps because they enable screening of colour at low couplings [Gribov:1998kb].

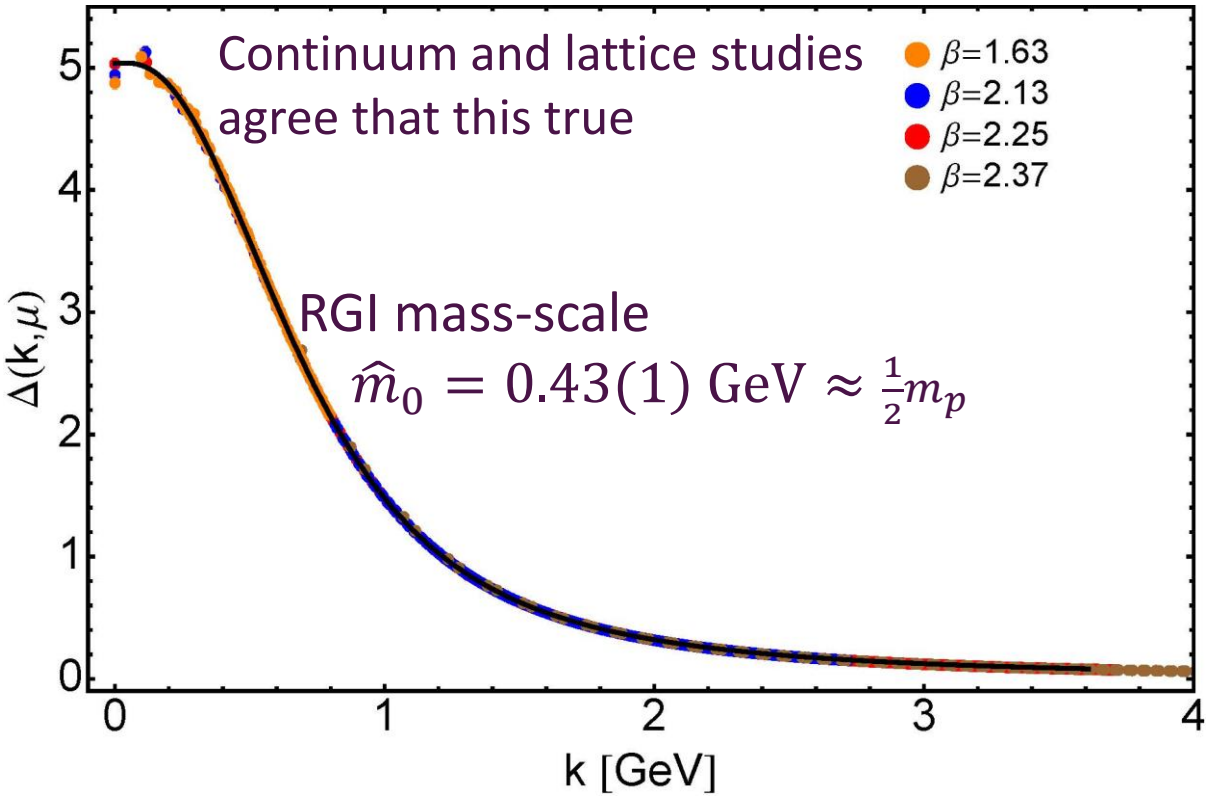
IR Behaviour of QCD

- Gluons are *supposed* to be massless … This is true in perturbation theory
- ***Not preserved non-perturbatively!***

  No symmetry in Nature protects four-transverse gluon modes …

  $q_\mu \, \Pi_{\mu\nu}(q) \equiv 0$
- Gluons acquire a running mass, which is large at infared momenta

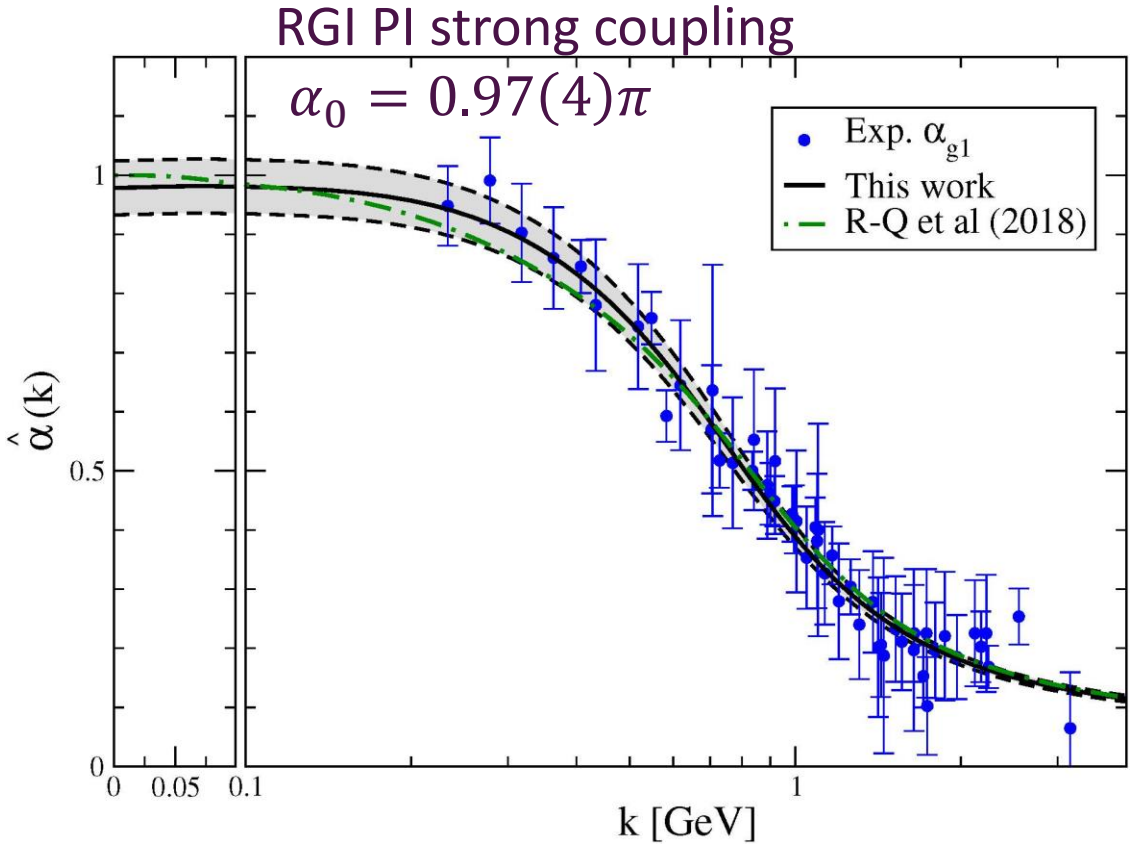
  ⇒ Prediction: Gluon two-point function is nonzero and finite at $q^2 = 0$



Dynamical mass generation in continuum quantum chromodynamics
*J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1000 citations … approach modernized and sketched results are confirmed*

RGI PI Effective Charge

- Gluon vacuum polarization can be translated into a RGI process independent effective charge for QCD
  - Use pinch technique and background field method
- Unique analogue of Gell-Mann – Low running coupling in QED
- Parameter-free prediction



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

Process-independent effective coupling. From QCD Green functions to phenomenology,
Jose Rodríguez-Quintero *et al.*, arXiv:1801.10164 [nucl-th]. Few Body Syst. **59** (2018) 121/1-9

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

RGI PI Effective Charge

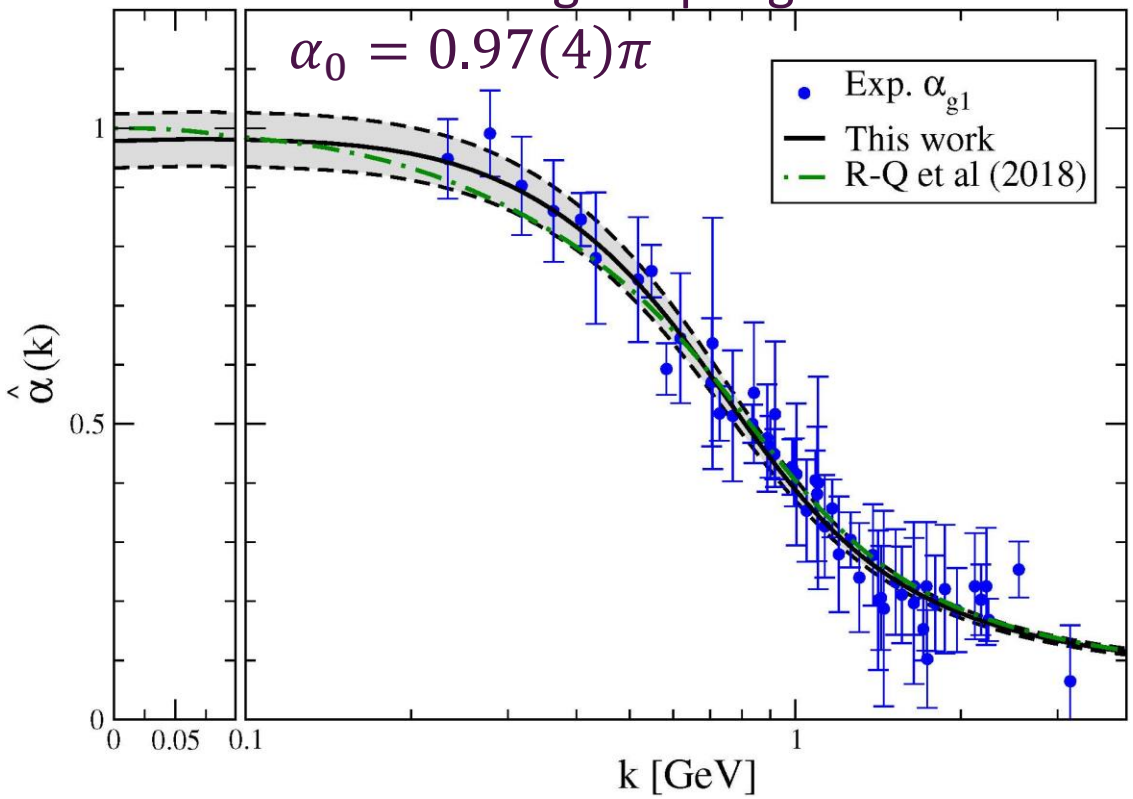
- Also, $\hat{\alpha}(k^2)$is:

i. pointwise (almost) identical to the process-dependent (PD) effective charge,α_{g_1}, defined via the Bjorken sum rule;

ii. capable of marking the boundary between soft and hard physics;

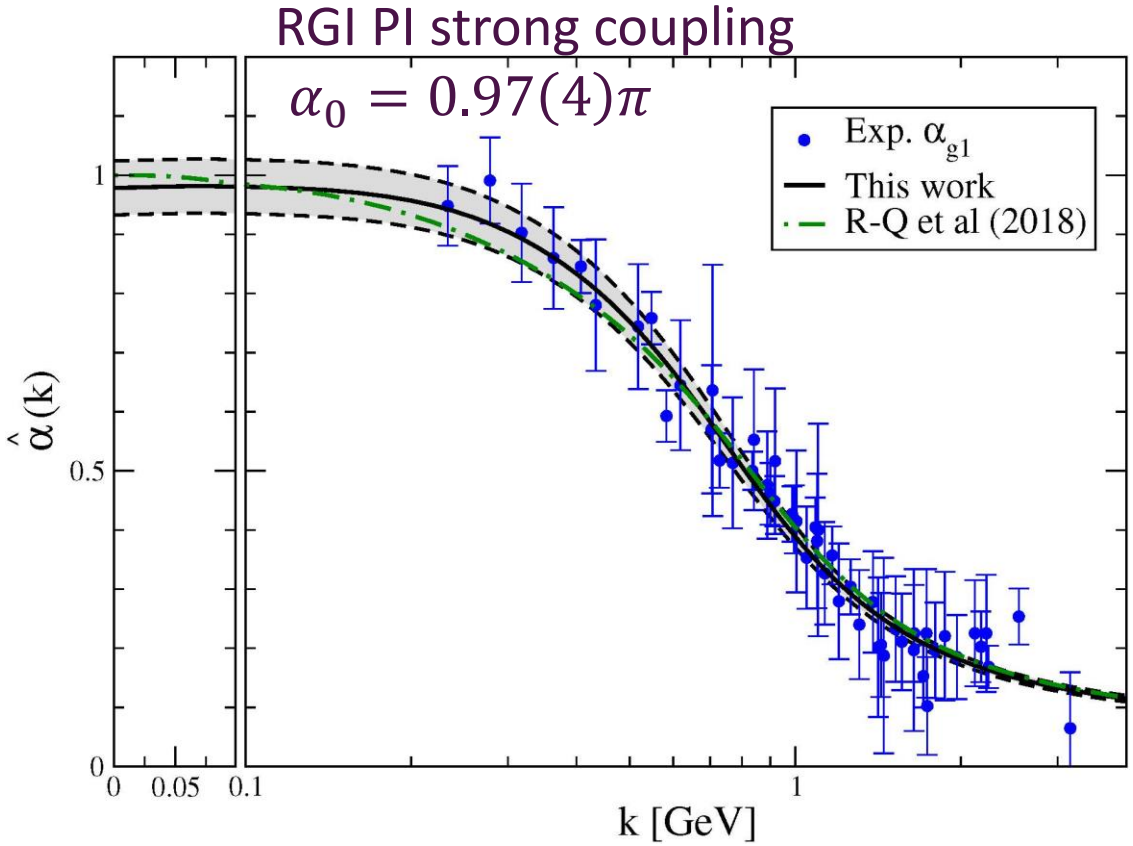
iii. that PD charge which, used at one-loop in the QCD evolution equations, delivers agreement between pion parton distribution functions calculated at the hadronic scale and experiment.

RGI PI strong coupling



RGI PI Effective Charge

- In playing so many diverse roles, $\hat{\alpha}(k^2)$ is a strong candidate for that object which properly represents the interaction strength in QCD at any given momentum scale.
- Landau pole, a prominent feature of perturbation theory, is screened (eliminated) in QCD by the dynamical generation of a gluon mass-scale
- Theory possesses an infrared stable fixed point.



- Accordingly, with standard renormalisation theory ensuring that QCD's ultraviolet behaviour is under control, ***QCD emerges as a mathematically well-defined quantum field theory in four dimensions.***

Matter Sector

- Dynamical violation of scale invariance in QCD enables emergence of gluon mass
- What about the matter sector?
- Inspired by BCS theory, Nambu developed simple model … won him Nobel Prize
  - fermion & antifermion form a "Cooper pair" so long as coupling is strong enough
- Studied via Dyson's Gap Equation – describes emergence of quasiparticle in many body systems & quantum field theories are systems with infinitely many bodies

$$S^{-1}(p) = Z_2\,(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p)\,,$$

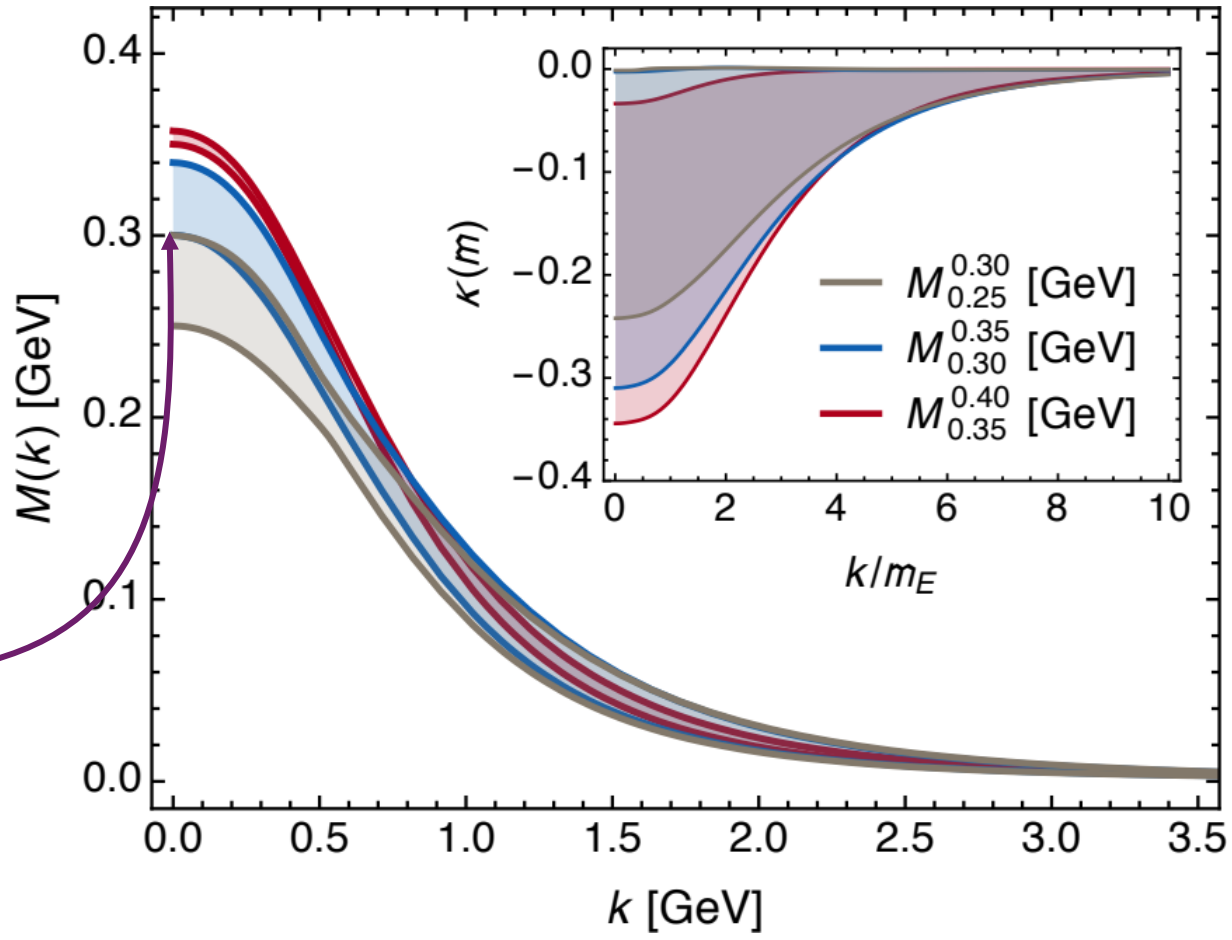
$$\Sigma(p) = Z_2 \int_{dq}^{\Lambda} 4\pi\hat{\alpha}(k^2)\mathcal{D}_{\mu\nu}(k)\gamma_\mu S(q)\hat{\Gamma}^a_\nu(q,p)\,,$$

- If and only if $\alpha_0 \geq 0.3\pi$, then this gap equation produces a nonzero fermion mass even in the absence of a Higgs coupling
- Dynamical chiral symmetry breaking – emergence of a fermion mass *from nothing*

Matter Sector

$\alpha_0 = 0.97\,\pi$

- Dressed-quark quasiparticles emerge
- Characterised by a running mass M(k)
  - Vanishes in ultraviolet, following the pattern predicted by Lane (1974) and Politzer (1976)
  - Large at infrared momenta, *i.e.* $M(0) \approx \frac{1}{3} m_p$
  - Just like constituent quark
- Dressed-quark is a bare parton at ultraviolet momenta
- But that parton carries a cloud of sea and glue with it in the infrared



Craig Roberts. pi & K structure - window onto EHM

Empirical Consequences of EHM

- QCD's interactions are universal … same in all hadrons
- However, expression need not be the same in all hadrons
- DCSB in chiral limit ensures <u>SUM</u> of different trace-anomaly operator-contributions cancel amongst each other to yield $m_\pi = 0$
  - Individual terms do not vanish separately
- In proton, no symmetry requires cancellations to be complete

  Thus, value of proton's mass is typical of the magnitude of scale breaking in one body sectors = dressed-gluon and -quark mass scales
- This "DCSB paradigm" provides basis for understanding why:
  - mass-scale for strong interactions is vastly different to that of electromagnetism
  - proton mass expresses that scale
  - pion is nevertheless unnaturally light

Pion mass - a decomposition?

- Rest frame decomposition of the trace anomaly has been used [Yang:2014qna] to separate the pion's mass into contributions from pieces defined as the
  - m_q-term,
  - H_A = trace-anomaly,
  - H_{KU} = quark E_K+E_U,
  - H_g = gluon energy
- Conclusion:

  "For the light PS mesons, the m_q-term is about 50% of the total mass. This implies that H_A contributes ~ 12% of the mass.

  The remaining contributions from H_g and H_{KU} are ~ 30% and ~ 8% respectively.

  It is interesting to observe that all these contributions are positive which suggests that they all approach zero at the chiral limit when the pion mass approaches zero."
- Unfortunately … none of this makes sense.

Pion mass - problems

- Rest frame decomposition in this form leads to a precarious position because
  i. Any conclusions are frame- and scale-dependent
  ii. the gluons in the trace anomaly and in the kinetic and potential energy are seemingly being treated as separate entities, which, of course, they're not
  iii. chiral limit – massless particle does not have a rest frame – no simple-minded limit of separate terms is meaningful
- No quantum mechanics picture of a bound-state's mass has all terms positive:
  – kinetic energy and mass terms are positive
  – binding energy is negative
- Gell-Mann – Oakes – Renner [GellMann:1968rz] … known for > 50 years:

$$m_\pi^2 \propto m \times DCSB\ enhancement\ factor \quad \ldots \quad \text{explicitly, } m_\pi^2 = (m_u + m_d)\frac{-\langle \bar{q}q \rangle}{f_\pi^2}$$

Huge EHM enhancement factor $\approx 200\ (m_u + m_d)$

If ALL of m_π^2 owes to the current-quark mass term in a Poincaré-invariance statement

Then what possible meaning can one associate with "rest frame" statement that only half m_π comes from the quark mass term, *i.e.* m_q-term produces 0.25 m_π^2 ?!

Decompositions of mass – Solution

- Avoid a Mass Crisis
- Stay away from decompositions whose definitions and interpretations are muddled by frame- and scale- dependence
- Cleanest statement of the origin of mass
  - There is a trace anomaly: $\Theta_0 = \beta(\alpha)\ \frac{1}{4} G_{\mu\nu}\, G_{\mu\nu} = T_{\rho\rho}$
  - In the chiral limit

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

- Understand, explain and explicate how this dichotomy is resolved.

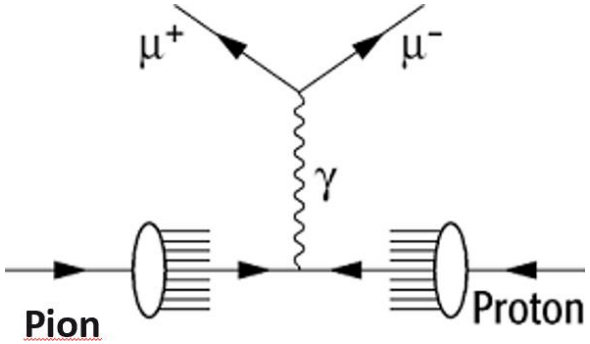
Empirical Consequences of EHM

- No significant mass-scale is possible unless one of similar size is expressed in the dressed-propagators of gluons and quarks.
- Follows that the mechanism(s) responsible for emergence of mass can be exposed by measurements sensitive to such dressing
- This potential is offered by many observables:
  - Spectra and static properties
  - Form factors, elastic and transition
  - All types of parton distributions
- Describe some examples … π & K structure

QCD prediction of *meson* valence-quark distributions

- Owing to absence of stable pion targets, the pion's valence-quark distribution functions have hitherto been measured via the Drell-Yan process:

$$\pi\, p \rightarrow \mu^+ \mu^- X$$



- Consider a theory in which quarks scatter via a vector-boson exchange interaction whose $k^2 >> m_G^2$ behaviour is $(1/k^2)^\beta$
- Then at a resolving scale ζ_H … $u_\pi(x;\zeta_H) \sim (1-x)^{2\beta}$

  Namely, the large-x behaviour of the quark distribution function is a direct measure of the momentum-dependence of the underlying interaction.
- In QCD, β=1 and hence

$$QCD: Q > \zeta_H \Rightarrow 2 \rightarrow 2+\gamma,\ \gamma > 0$$

$$^{QCD}\, u_\pi(x;\zeta_H) \sim (1-x)^2$$

QCD prediction of *meson* valence-quark distributions

- **Fact 1**: After 40 years, no flaw has been found in the proof
- **Fact 2**: Power law fixed by asymptotic behaviour of bound-state wave function
- **Fact 3**: Gluon corrections do NOT change power laws.

  They only modify anomalous dimensions.

  Again, proof is 40 years old and no flaw has been found. Rather, it has been confirmed in numerous continuum calculations.
- Exact statement – in textbooks, but often overlooked:
  - *β(ζ) increases logarithmically with inverse of valence-quark momentum fraction*
  - Coefficient decreases also, but at a different rate

The Introduction reiterated one of the earliest predictions of the QCD-improved parton model [44–47]:

$$q^M(x;\zeta_H) \overset{x\simeq 1}{=} c(\zeta_H)\,(1-x)^{\beta(\zeta_H)}\,,\ \beta(\zeta_H)=2\,, \tag{20}$$

where $c(\zeta_H)$ is a constant, *i.e.* independent of x, and the exponent increases logarithmically with ζ: $\beta(\zeta) > \beta(\zeta_H)$ for $\zeta > \zeta_H$. In fact, as shown in Appendix A, an analysis of the large-n behaviour of Eqs. (18) yields

$$\beta(\zeta) = \beta(\zeta_H) + \frac{3}{2}\ln \varkappa_M^1(\zeta,\zeta_H)\,, \tag{21a}$$

$$c(\zeta) = c(\zeta_H)\frac{\Gamma(1+\beta(\zeta_H))}{\Gamma(1+\beta(\zeta))}\left[\varkappa_M^1(\zeta,\zeta_H)\right]^{\frac{3}{2}[\frac{3}{4}-\gamma_E]}\,, \tag{21b}$$

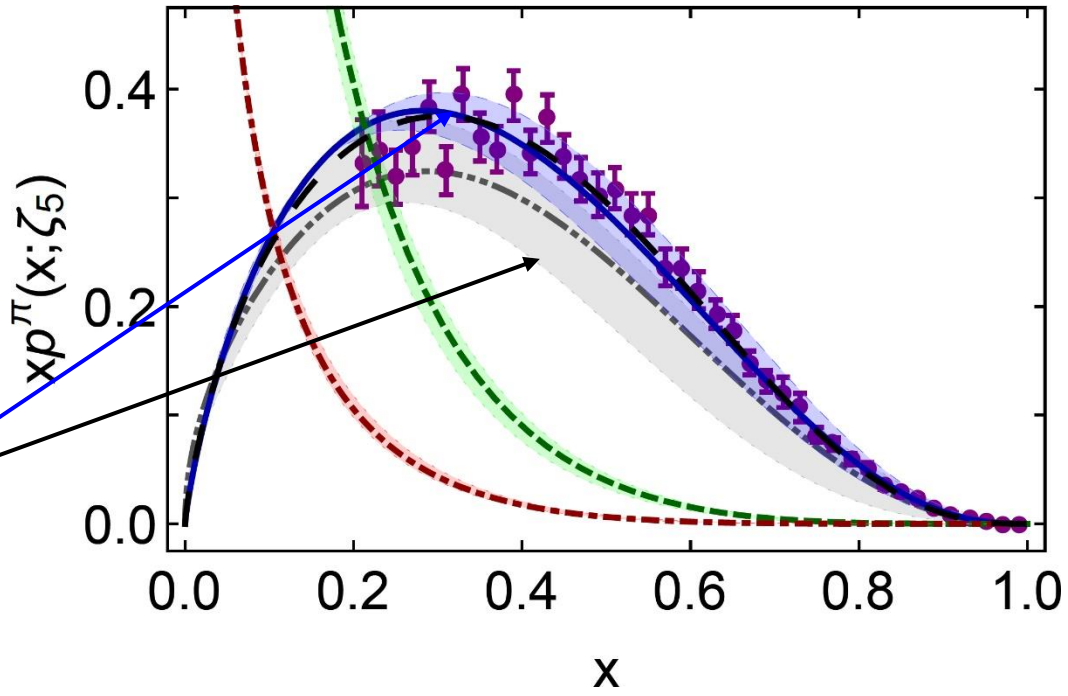
where $\gamma_E = 0.5772\ldots$ is Euler's constant.

$$\varkappa_M^n(\zeta_H,\zeta) := \frac{\langle x^n q^M\rangle_\zeta}{\langle x^n q^M\rangle_{\zeta_H}}$$

π valence-quark distributions
20 Years of Evolution → 2019

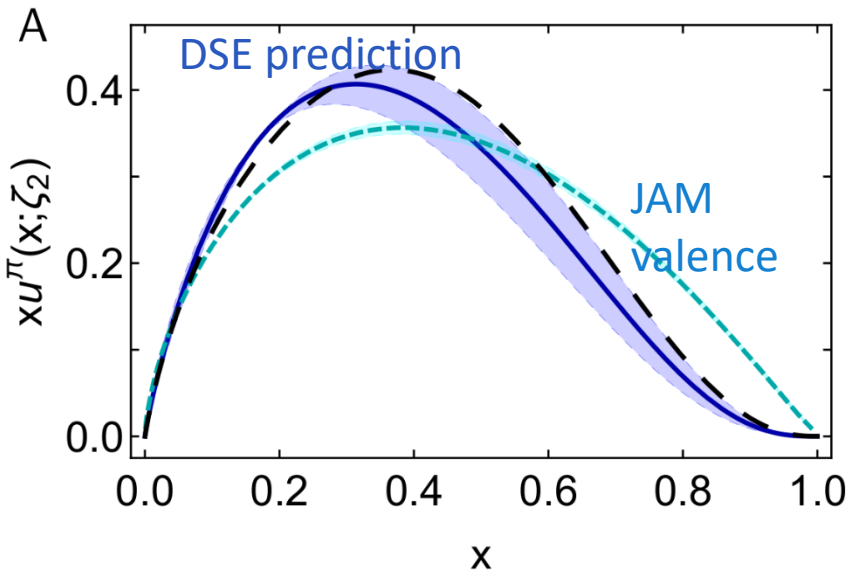
$\beta^{contm}(\zeta_5) = 2.66(12)$
$\beta^{lattice}(\zeta_5) = 2.45(58)$

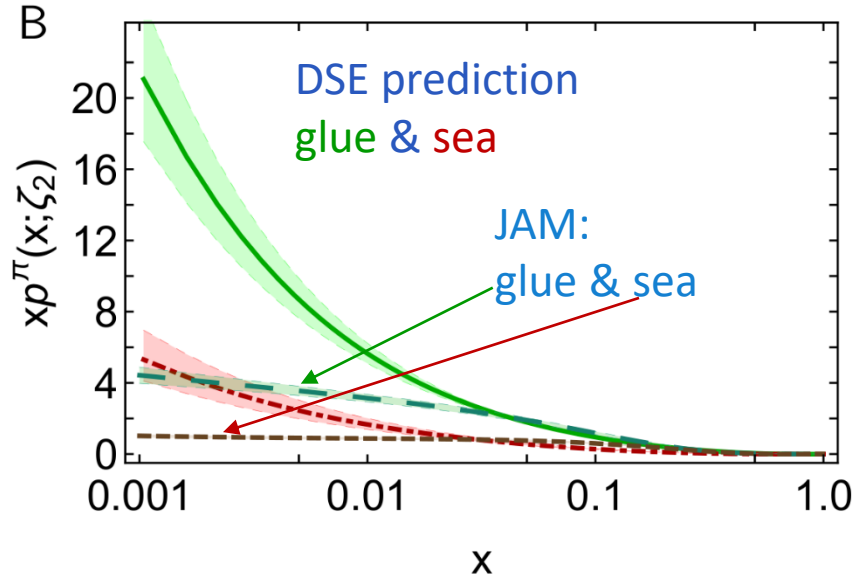
- Novel lattice-QCD algorithms beginning to yield results for <u>pointwise</u> behaviour of $u^\pi(x;\zeta)$
- Developments in continuum-QCD have enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^\pi(x;\zeta)$is <u>hardened</u> by emergent mass
- Agreement between new continuum prediction for $u^\pi(x;\zeta)$ [Ding:2019lwe] and recent lattice-QCD result [Sufian:2019bol]
- Real strides being made toward understanding pion structure.
- Standard Model prediction is stronger than ever before
- *Now – after 30 years – new era dawning in which the ultimate experimental checks can be made*



π valence-quark distributions Comparison with JAM fits

- Valence:
  - momentum fraction similar
  - JAM profile much harder & inconsistent with QCD prediction
- Glue:
  - Pointwise agreement on x ≥ 0.05, but marked disagreement on <u>important</u> complementary domain
  - Both continuum prediction and JAM fit are very different from early phenomenology
  - Should be tested in new experiments that are directly sensitive to the pion's gluon content.
  - Perhaps, 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





Kaon Distribution Functions

- ✓ Improved & extended approach used for pion DFs
- ✓ Unified distribution amplitudes and functions for pion and kaon – connect with pion and kaon form factors
- ✓ Introduced mass-dependence into splitting functions

$q\backslash\zeta_5$	$\langle x q^K\rangle$	$\langle x^2 q^K\rangle$	$\langle x^3 q^K\rangle$
u	0.18(2)	0.062(1)	0.027(4)
$\bar{s}$	0.20(2)	0.074(1)	0.034(6)

- ✓ valence momentum fraction at ζ_5 = 0.39(3)

- One lQCD calculation (2003.14128 [hep-lat]):
  - Fractions systematically larger than continuum predictions, especially for $\bar{s}$:
    - u – 5.6(5)%, 30(6)%, 55(4)%
    - $\bar{s}$ – 31(7)%, 67(12)%, 106(16)%
  - lQCD *vs*. with DSE predictions, lQCD DFs = *much* harder.
  - lQCD DFs inconsistent with QCD prediction

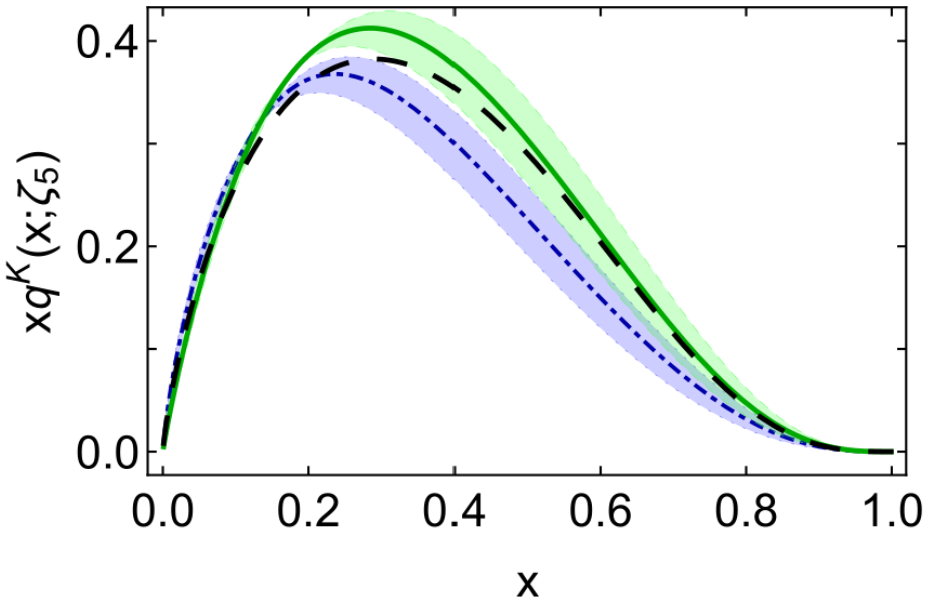


FIG. 13. Solid green curve – kaon's valence $\bar{s}$-quark distribution defined at ζ_H by Eq. (45) and Table III–middle, evolved $\zeta_H \to \zeta_5$ using the procedure explained in Sec. IV A, including the splitting function modification in Eq. (58a) with $\sigma_{ss} = 1$. Dot-dashed blue curve – kaon's valence u-quark distribution, unchanged from Fig. 11. Dashed black curve – central $\bar{s}$-quark distribution from Fig. 11, *i.e.* obtained with mass-independent evolution. (The bands bracketing the central DFs reflect the uncertainty in the $k^2 = 0$ value of the PI charge, Fig. 1.)

Kaon Distribution Functions: $u_K(x)/u_\pi(x)$

- Uncertainty in continuum predictions for DFs cancels in ratio
- First lQCD results for ratio also drawn
- Relative difference between the central lQCD result and DSE prediction is ≈ 5% … despite fact that individual lQCD DFs are very different from continuum results
- Long known fact, *i.e.* $u_K(x)/u_\pi(x)$ is very forgiving of even large differences between the individual DFs used to produce the ratio
- More precise data crucial if ratio is to be used effectively to inform and test the modern understanding of SM NG modes
- Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately have greater discriminating power.

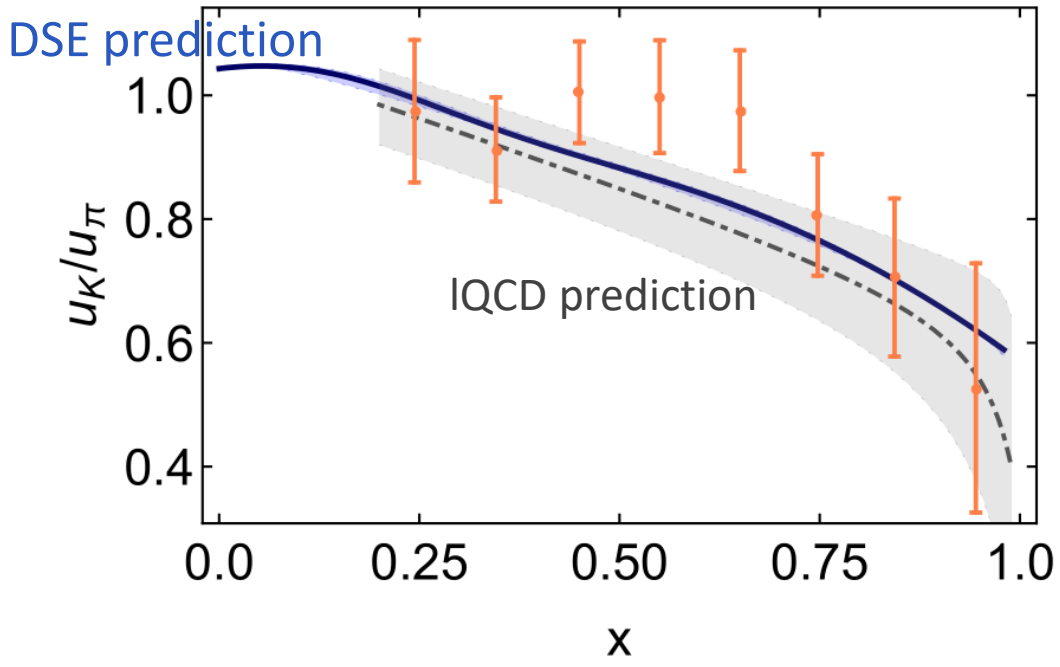


FIG. 12. $u^K(x;\zeta_5)/u^\pi(x;\zeta_5)$. Solid blue curve – result obtained for the ratio after $\zeta_H \to \zeta_5$ evolution of Eq. (28) [π] and Eq. (45), Table III–middle [K]. The lighter-blue band bracketing this curve reveals the effect of $\zeta_H \to \zeta_H(1.0 \pm 0.1)$: it is negligible. Dot-dashed grey curve within grey band – lQCD result [116]. Data (orange) from Ref. [115].

Glue and Sea in Kaon

- Glue and sea distributions in the kaon differ from those of the pion only on the valence region x > 0.25.
- Not surprising
  - Mass-dependent splitting functions act primarily to modify valence DF of heavier quark
  - Valence DFs are negligible at low-x, where glue and sea distributions are large, and vice versa
  - Hence biggest impact of a change in the valence DFs must lie at large-x.

	valence quark	valence antiquark	glue	sea
Kaon	0.18(2)	0.22(2)	0.45(1)	0.15(2)
Pion	0.19(2)	0.19(2)	0.46(1)	0.15(2)

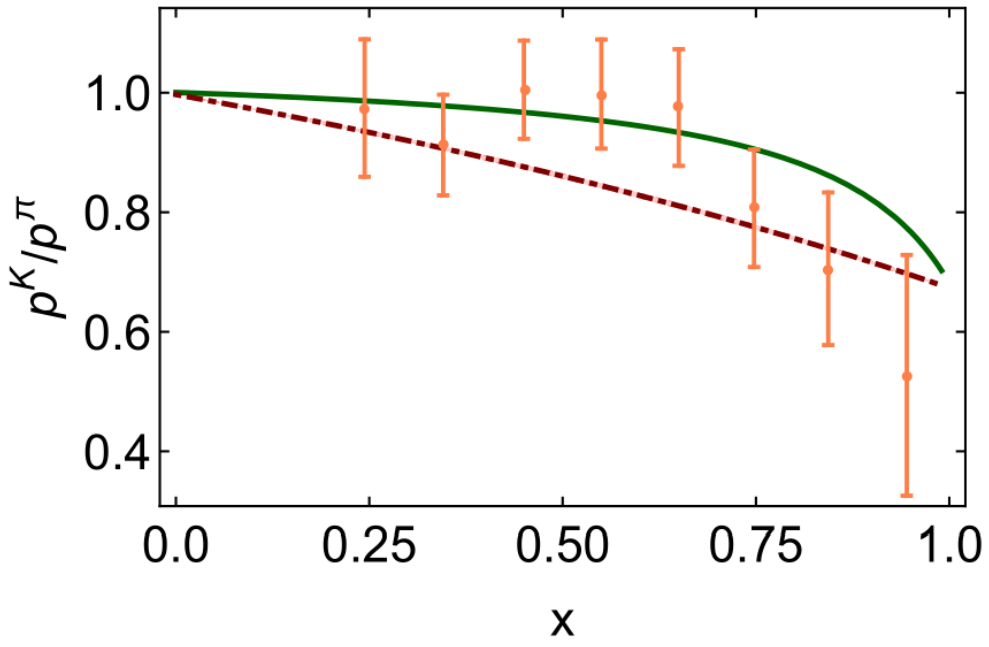


FIG. 14. Prediction for $g^K(x;\zeta_5)/g^\pi(x;\zeta_5)$ – solid green curve within green shading; and for $\mathcal{S}^K(x;\zeta_5)/\mathcal{S}^\pi(x;\zeta_5)$ – dot-dashed red curve within red shading. (The uncertainty introduced by that in the $k^2 = 0$ value of the PI charge, Fig. 1, is indicated by the shaded band bracketing each curve. In both cases here, that band is no thicker than the width of the central line.) Data on $u^K(x;\zeta_5)/u^\pi(x;\zeta_5)$ (orange) from Ref. [115] are included to guide comparisons.

Status: pion and kaon structure functions

Pion

- Pointwise behaviour of pion's valence-quark distribution function: agreement between predictions from lQCD and symmetry-preserving QCD-consistent continuum analyses
- Amongst existing phenomenological studies of pion structure functions, only one employs a next-to-leading-order analysis that includes threshold resummation. This study is unique in producing a valence-quark DF that is consistent with large-*x* QCD and matches continuum and lattice prediction
- General disagreement between phenomenological results and theory predictions for the pion's valence-quark DF feeds into uncertainty about pion's glue and sea distributions
- Resolution of these conflicts must await
  - Improved phenomenological analyses that include threshold resummation
  - New data that constrains the pion's glue and sea distributions.

Status: pion and kaon structure functions

Kaon

- Very 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: <u>no results</u>
- Hence, symmetry-preserving continuum QCD predictions sketched here for entire array of kaon DFs currently stand alone.
- One piece of available experimental information: $u_K(x) / u_\pi(x)$
  - Continuum prediction for ratio is consistent with the data.
  - But, given the large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - Modern, precise data is critical if this ratio is to be used as a path to understanding the Standard Model's Nambu-Goldstone modes;
    - Results for $u_\pi(x;\zeta_5)$, $u_K(x;\zeta_5)$ separately would be better.

Status: pion and kaon structure functions

Kaon

- Glue and Sea – Predictions:
  - DFs very similar to those in the pion
  - Detailed comparison requires the use of mass-dependent splitting functions.
  - Development underway … Preliminary conclusions:
    i. Light-front momentum fraction carried by s-quarks in the kaon increases by ~ 10%;
    ii. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).

NEEDS: pion and kaon structure functions

- Standard Model's (pseudo-) Nambu-Goldstone modes – pions and kaons – are basic to the formation of everything from nucleons, to nuclei, and on to neutron stars.
- Hence, new-era experiments capable of discriminating between the results from models, phenomenology and QCD-connected predictions should have high priority.
- Phenomenological methods needed to proceed from data to DFs must match modern experiments in precision.
- Theory: continuum and lattice analyses of the pion's valence-quark DF are converging on the same form, confirming the longstanding QCD expectation
  - But, lattice results for the pion's glue and sea distributions would be very valuable.
- Even more true for the kaon.
  - Only one extant lattice study of kaon DFs
  - Addressing solely valence distributions
  - Disagreeing in many respects with continuum predictions
  - Conflict with large-x QCD

  ⇒ Many opportunities are available.

Future

Center for Frontiers in Nuclear Science
Workshop series

Workshop on Pion and Kaon Structure Functions at the EIC

- Challenge: Explain the Origin & Distribution of the Bulk of Visible Mass
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Continued exploitation of synergies essential
  to capitalise on new opportunities provided by existing & planned facilities
- This Discussion … join theorists from high-energy nuclear & particle physics in dialogue with the experimentalists … address the Emergence of Hadron Mass
- Consolidate & expand collaboration between experimentalists proposing new measurements, phenomenologists doing global data analyses, & hadron-structure theorists.

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Workshop on Pion and Kaon Structure Functions at the EIC

- Challenge: Explain the Origin & Distribution of the Bulk of Visible Mass
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment … Phenomenology …Theory
- Next Steps …
  - Ongoing efforts/meetings toward
    - Entering a significant new element into the EIC User Group Physics and Detector Handbook
    - Developing contributions as part of Yellow Report Initiative.
  - Discussions to explore EicC reach into pion and kaon structure
  - ~ 20th July … Tele-conversation: EHM through AMBER @ CERN
  - Oct. 2020 … 1-week workshop *Exploring QCD with Tagged Processes* – Université Paris-Saclay
  - Autumn 2020 … Hopefully, a face-to-face meeting at CERN in Autumn.
  - April 2021 … ECT* Trento

Thank you