NANJING UNIVERSITY

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

Insights into EHM Using Pion and Kaon Targets

Phenomenon of Emergent Mass

- Empirical status:
  - proton is stable compound object formed from three valence light-quarks
  - proton electric and magnetic charge radii $r_{em} \approx 0.85$ fm … see Daniele Binosi's presentation
  - evidently, proton never decays (if it did, wouldn't be many of us here)
- Mass of proton m_p = 939 MeV.
- Mass of valence quarks in proton = 9 MeV
  - ***Missing mass = 930 MeV = 99%***
- Higgs mechanism of mass generation responsible for only 1% of proton mass
- ***Where should science look to find the remaining 99% of visible mass in the Universe?***
- ***Is the answer contained within the SM?***
- ***How will science know when the answer is found?***

  What are the "smoking gun" signals?

Emergence of Hadron Mass

- Proton mass budget

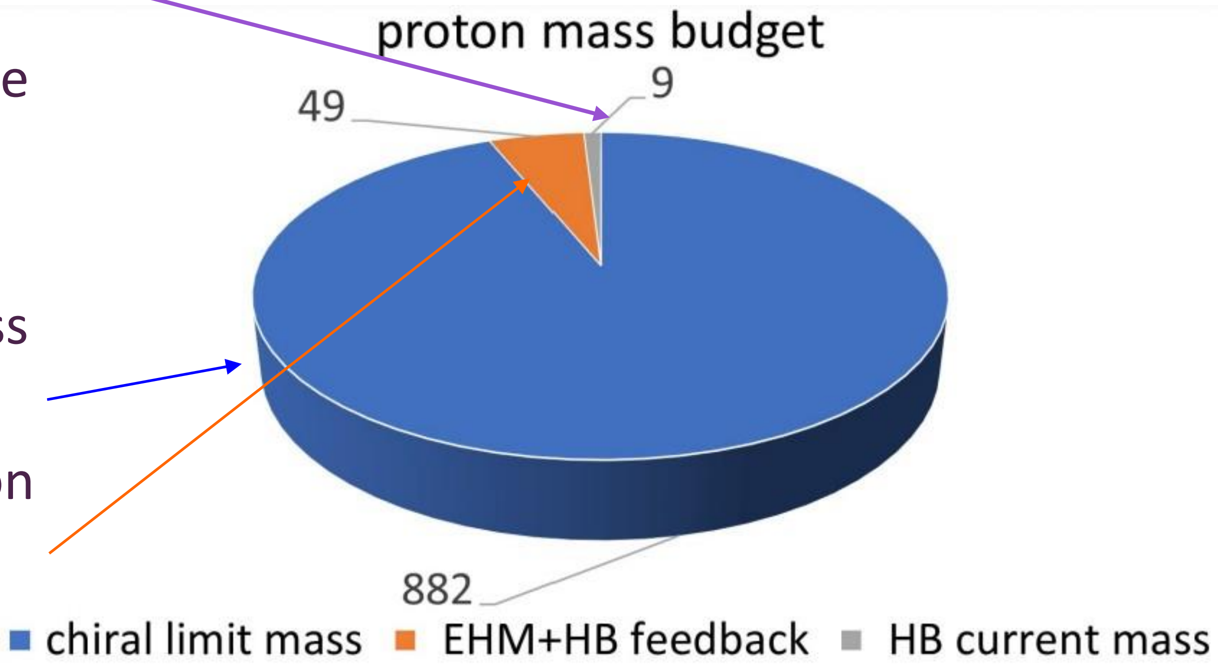
  Only 9 MeV/939 MeV is directly from Higgs

- Plainly, there is another phenomenon in Nature that is extremely effective in producing mass:

  Emergent Hadron Mass (EHM)

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

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



✓ What is EHM?

✓ Does it have a reductionist explanation,

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

✓ If so, what are they?

Emergent Hadron Mass (EHM)

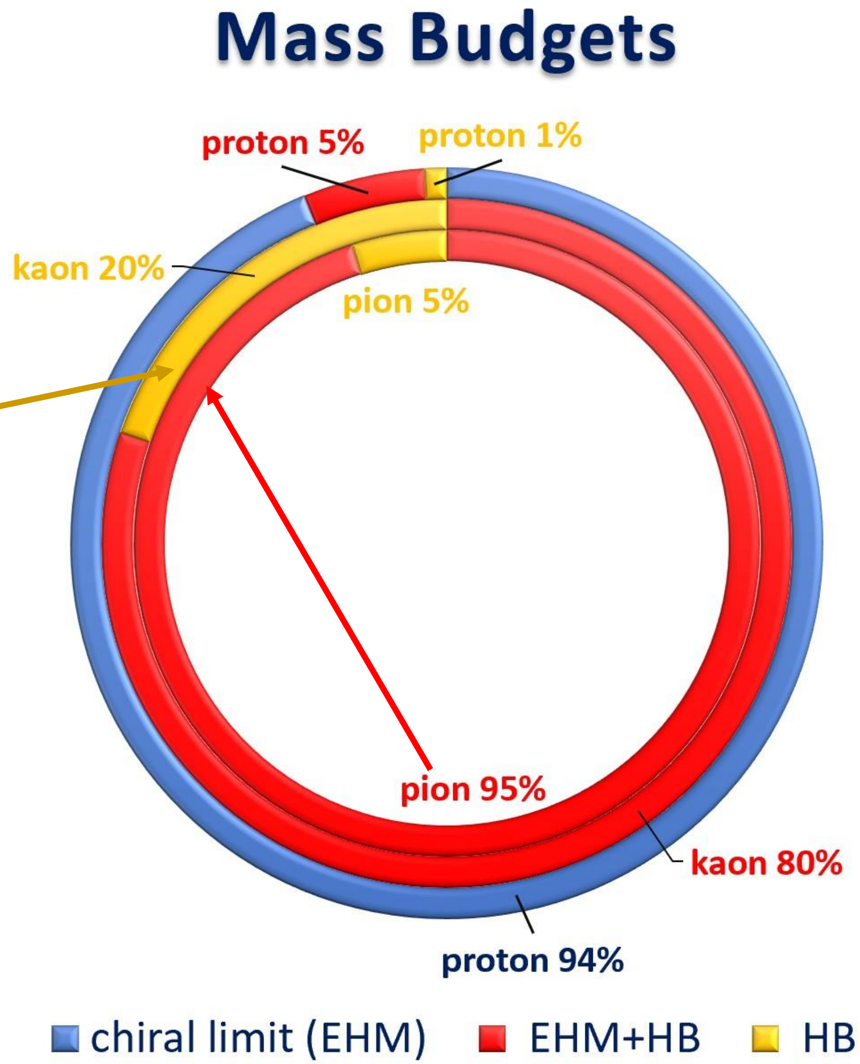
- In quantum field theory, mass and length^{-1} are effectively the same thing
- Thus, asking for the origin of 99% of visible mass in the Universe is possibly/probably the same as asking what is the source of the proton's size
- *Confinement scale!*
- Confinement is far more than the statement that 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* …
  - 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?

Phenomenon of Emergent Mass

- SM paradigm
  - proton is described by QCD … 3 valence quarks
  - pion is also described by QCD … 1 valence quark and 1 valence antiquark
  - ρ-meson is also described by QCD … 1 valence quark and 1 valence antiquark
    - Here $m_p \approx 1.5 \times m_\rho$
  - expect $m_p \approx 1.5 \times m_\pi$ … but, instead $m_p \approx 7 \times m_\pi$
- *Why is ≈ 1 GeV proton mass paired with ≈ $^1/_7$ GeV pion mass in the same theory of Nature?*
  - How is this achieved?
  - Does Nature fine tune?
  - Is there something peculiar about the pion (and by logical extension, the kaon)?
- *Are the answers in QCD?*

Emergence of Hadron Mass - Contrasts

- Compare proton and pion mass budgets
- Pion is a Nambu-Goldstone boson
  - So, massless in chiral-limit
  - No blue annulus
  - EHM+HB is 95% of the total
- Kaon is somewhere in between
  - HB = 20%
  - EHM+HB = 80%
- Critically, without Higgs mechanism of mass generation, π and K would be indistinguishable from each other
- Always distinguishable from proton.
- Yet, all states are supposed to be in QCD!
- What is, wherefrom, whereto mass?



Emergence of Hadron Mass - Basic Questions - How to Answer Them?

- π & K are
  - Nature's most fundamental Nambu-Goldstone (NG) bosons
  - mesons … In many respects = simplest bound-state problems in quantum field theory because only two valence bodies ⇒ modern QCD theory can be rigorous
- A (very) few things are empirically known about π
- But (almost) nothing is known about K – even K radius is no better than an educated guess
- NG modes predicted 80 years ago
  - Yet, today, their structure is still a mystery
  - π is crucial to nuclear binding; yet "no one" has charted its features
  - K is completely unknown. Possibly plays a role in compact astrophysical objects; but "no one" can be certain
- Progress toward understanding needs synergy

  between experiment + phenomenology + theory

EHM & QCD

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

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

- Can a one-line Lagrangian produce almost all visible mass in the Universe …
- If so …

Pure gauge QCD

- QCD doesn't need quarks to be an interacting quantum field theory
  - Gluon self-interactions at tree-level, i.e., in the Lagrangian
- Gluons are massless in perturbation theory
- ***Not preserved non-perturbatively!***

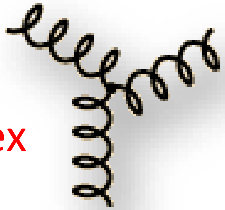
No symmetry in Nature protects four-transverse gluon modes …

$$q_\mu \, \Pi_{\mu\nu}(q) \equiv 0$$

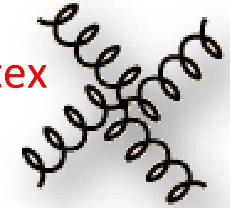
- Gluons acquire a running mass, which is large at infared momenta

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

3-gluon vertex

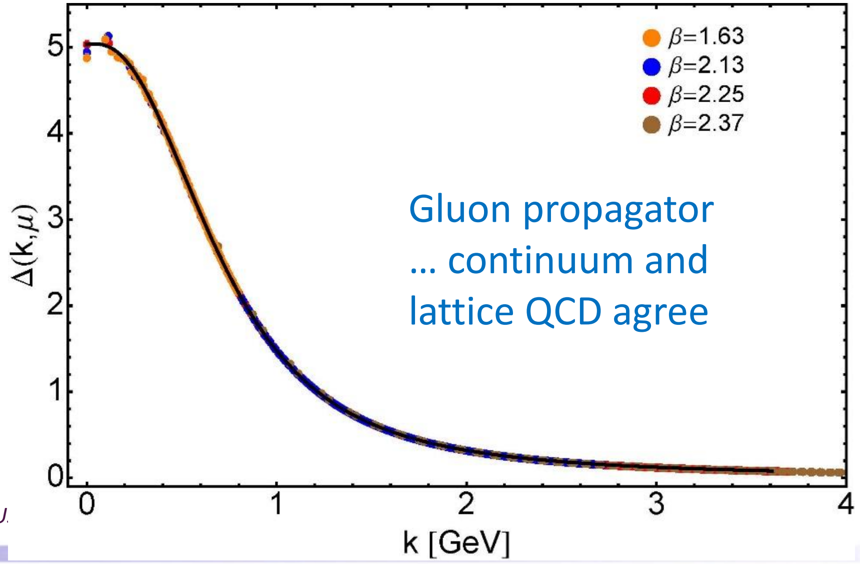


4-gluon vertex



Dynamical mass generation in continuum quantum chromodynamics
J.M. Cornwall, Phys. Rev. D ***26*** *(1981) 1453 … ~ 1000 citations*

The Gluon Mass Generation Mechanism: A Concise Primer
A.C. Aguilar, D. Binosi, J. Papavassiliou, Front. Phys. **11** (2016) 111203

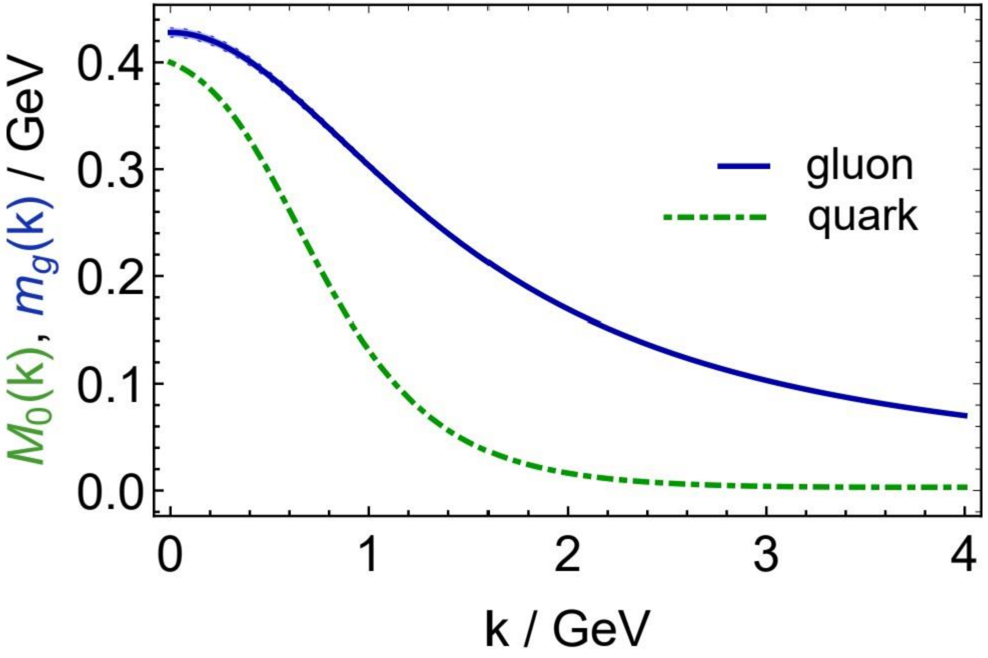


Gluon propagator
… continuum and lattice QCD agree

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

Prediction: Gluon Mass Function

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

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

- The value is a prediction in the sense that it is $\frac{1}{2} m_{\text{proton}}$
- But the value of m_{proton} is taken from experiment
- As written, the SM doesn't "know" any of its mass scales.
- Nature does.
- Once these scales are given, how much predictive power does the SM deliver?
- SM Theory reveals that a gluon mass scale is possible. It can then reveal all its consequences
- Experiment can verify those predictions
- Then the *mechanism* of EHM is exposed

Prediction: Gluon Mass Function

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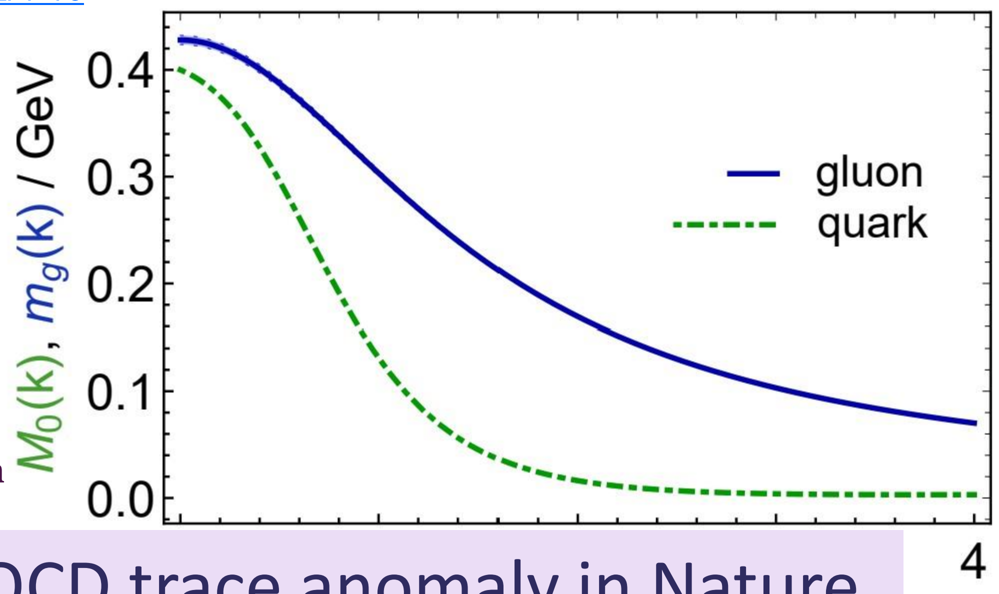

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- B
- A
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- N

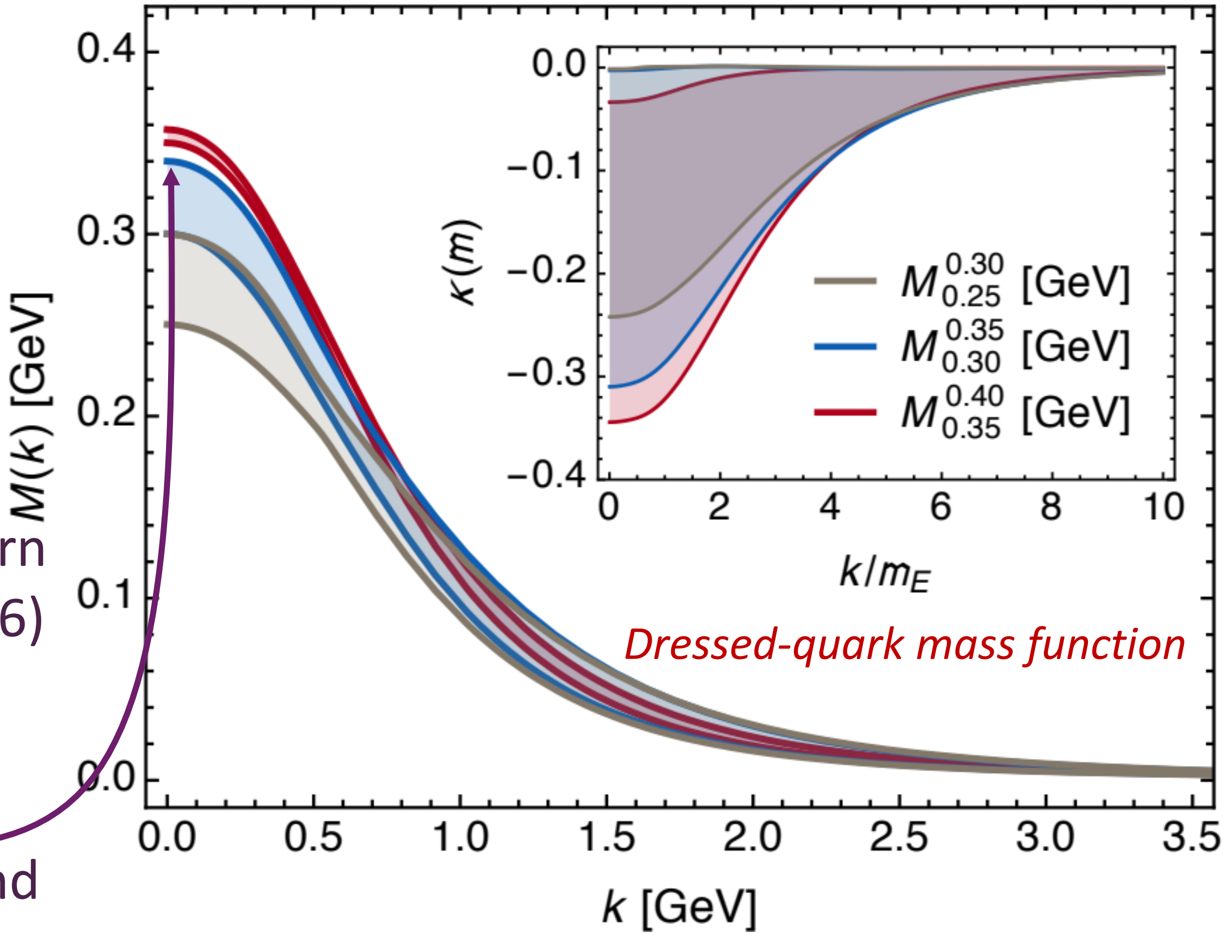
✓ Most fundamental expression of the QCD trace anomaly in Nature
- Massless gauge bosons become massive
- And that mass is of nuclear size.

- Once these scales are given, how much predictive power does the SM deliver?
- SM Theory reveals that a gluon mass scale is possible. It can then reveal all its consequences
- Experiment can verify those predictions
- Then the *mechanism* of EHM is exposed

Prediction: Mass is generated for matter

- $\widehat{\alpha_0}$(s=0) $= 0.97(4)\,\pi$
- Sufficient to drive constructive feedback in dressed-quark gap (Dyson) equation so that 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 of Gell-Mann and Zweig
- Dressed-quark is a bare parton at ultraviolet momenta
  - But that parton carries a cloud of sea and glue with it in the infrared



Dressed-quark mass function

Natural constraints on the gluon-quark vertex, Daniele Binosi, Lei Chang, Joannis Papavassiliou, Si-Xue Qin and Craig D. Roberts, arXiv:1609.02568 [nucl-th], Phys. Rev. D **95** (2017) 031501(R)/1-7

Prediction: Mass is generated for matter

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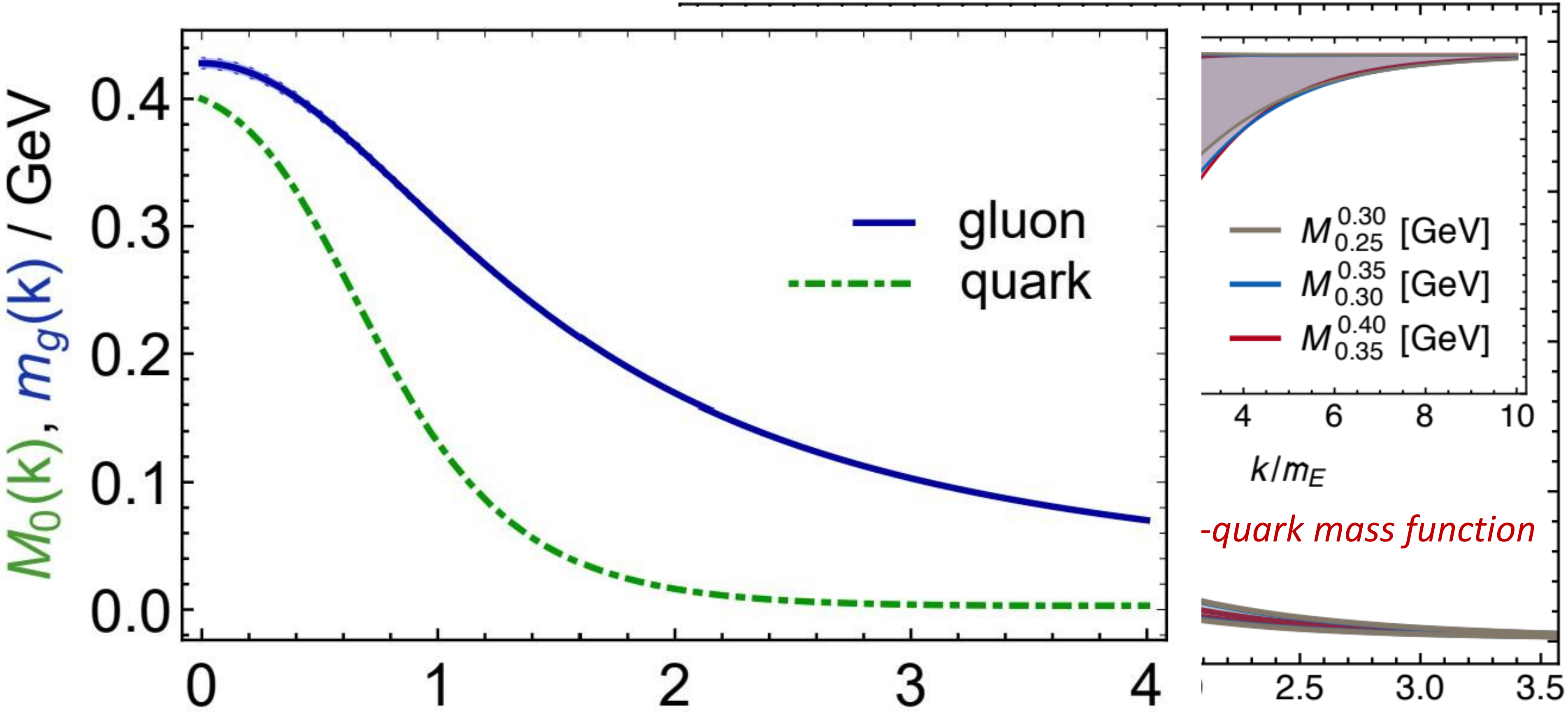


Emergence of mass, with hadron-like scale, in one-body subspace of QCD's gauge and matter sectors

Prediction Pion (Nambu-Goldstone modes) and mass

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

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

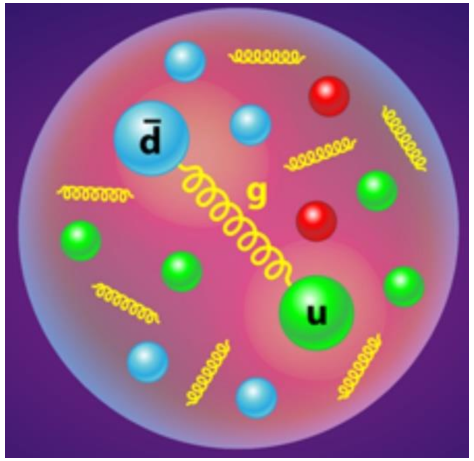
$$f_\pi E_\pi(p^2) = B(p^2)$$

Pion wave function quark mass function

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

Nambu-Goldstone Bosons

- Pions and kaons were discovered 80 years ago
- They're unstable, via weak decays; difficult to use as targets
- Besides masses, lifetimes, (almost) NOTHING has been learnt about their structure
  - Without pions and kaons, there could be no nuclei
  - If they were heavier than they are, there would be no nuclei and no us
  - If they were lighter than they are, there would be no nuclei and no us
- Nambu-Goldstone bosons are somehow different from "ordinary" hadrons.
  - How?
    - Size?
    - Mass distribution?
    - Gluon Distribution?
    - Pressure Distribution?
- Dawn of new era is visible … modern facilities with capability of probing into the heart of Nambu-Goldstone bosons

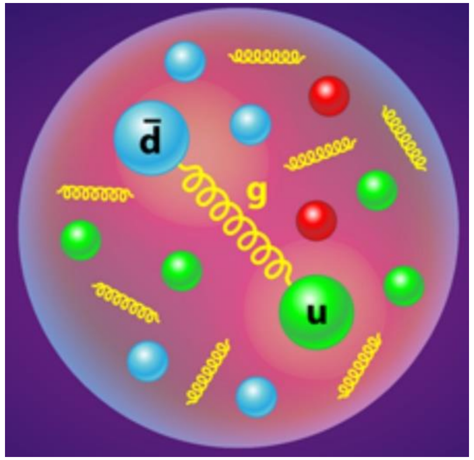


What visible "scars" do these symmetry-demanded cancellations leave on the body of pion observables?

Nambu-Goldstone Bosons

- SM Theory
  - Pions and kaons: bound states of valence-quark & valence-antiquark
    - In being bound states, they are just like all other hadrons
  - Cannot be emphasized too strongly …
    - In the continuum and on the lattice, pions and kaons emerge as poles in the quark+antiquark scattering matrix.
    - Just like the proton appears as a pole in the quark+quark+quark scattering matrix
  - Difference between proton and pion is that in the chiral limit, owing to dynamical chiral symmetry breaking, a basic corollary of EHM:

$$M_Q + M_{\bar{Q}} + U_{Q\bar{Q}} \equiv 0$$



In pion: 2 × one-body-mass + 1 × two-body binding energy ≡ 0

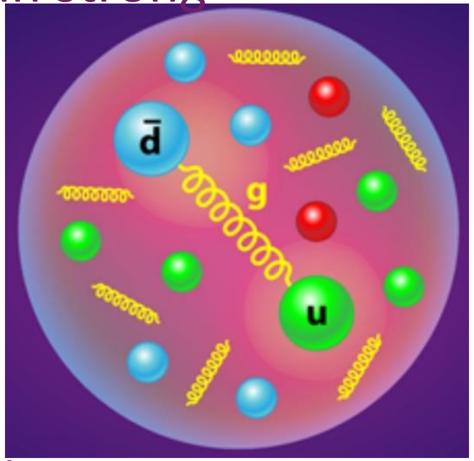
Away from chiral limit, a small part of the 2 × one-body contributions is not cancelled.

Cancellations happen in proton, but no dynamics and symmetry forces them to be exact

What visible "scars" do these symmetry-demanded cancellations leave on the body of pion observables?

Nambu-Goldstone Bosons

- SM Theory
  - Pions and kaons: bound states of valence-quark & valence-antiquark
    - In being bound states, they are just like all other hadrons
- Formulated correctly, the π and K define the simplest bound-state problems in strong interactions
  - Rigorous continuum predictions are available
    - More are being developed
  - Lattice-regularised QCD is beginning to deliver
- Precisions tests of strong QCD and EHM are becoming possible
  - No room for parameters to be varied so theorists can hide from null results



- *Chapters will be closed in textbooks that will be written*

Get off the ground!

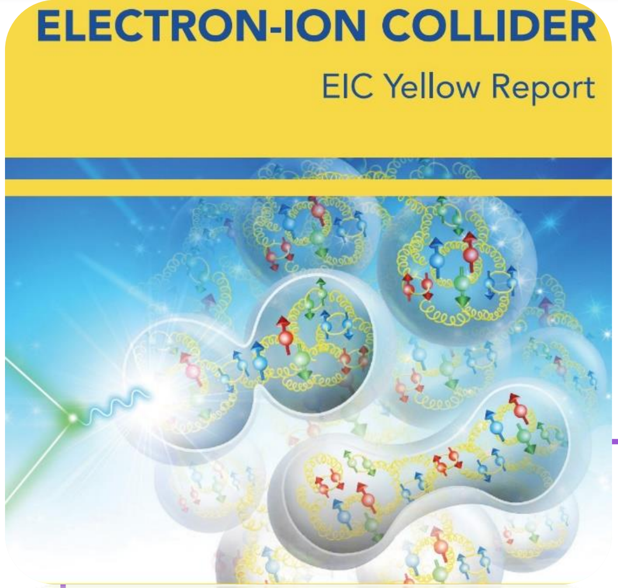
- *Basic message*
  - The ground state proton is not enough
  - Ground state of the hydrogen atom did not give us QED
  - Studies of the proton alone cannot reveal all the wonders of QCD, if QCD is truly the theory of strong interactions in the Standard Model
  - Modern and planned high-luminosity facilities provide unprecedented opportunities to move beyond the 100-year focus on the structure of just one (or two = neutron) hadron(s)
  - How much richer will be our store of knowledge once insights into the full array of Nature’s hadrons is in our hands
  - Numerous presentations during these next few days will demonstrate the truth of these statements

AMBER

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

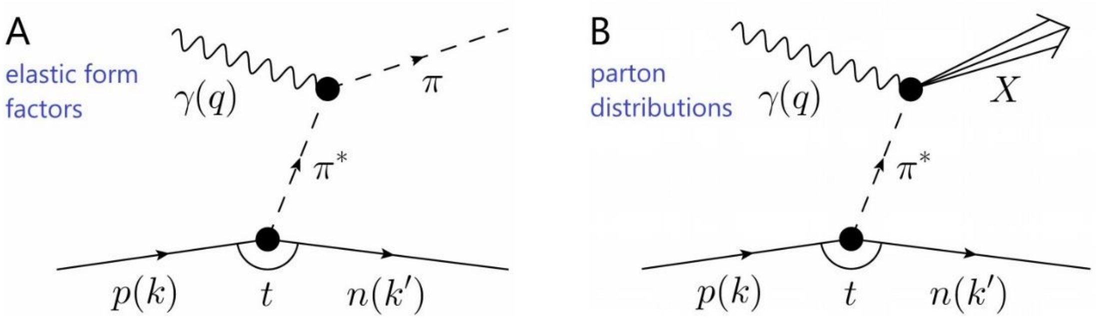
Jefferson Lab

Thomas Jefferson National Accelerator Facility

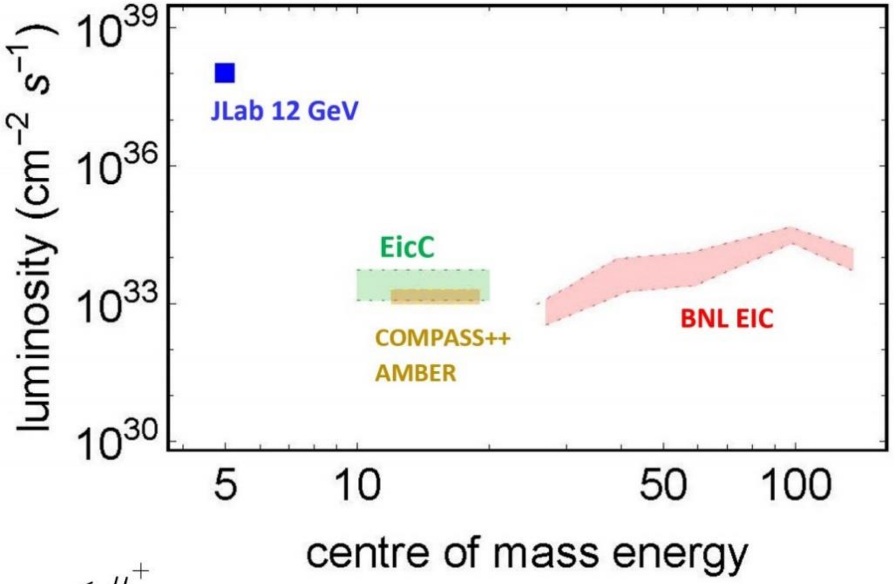


Potential of Existing and Future Facilities

Era of Meson Targets

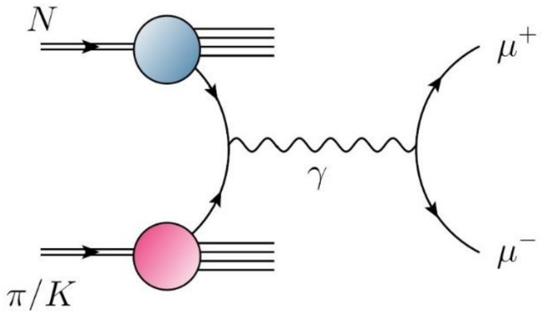


- JLab & EIC & EicC
  - High luminosity electron (+ ion) beams
  - Access to meson targets via the Sullivan Process, i.e., a baryon's "meson cloud"



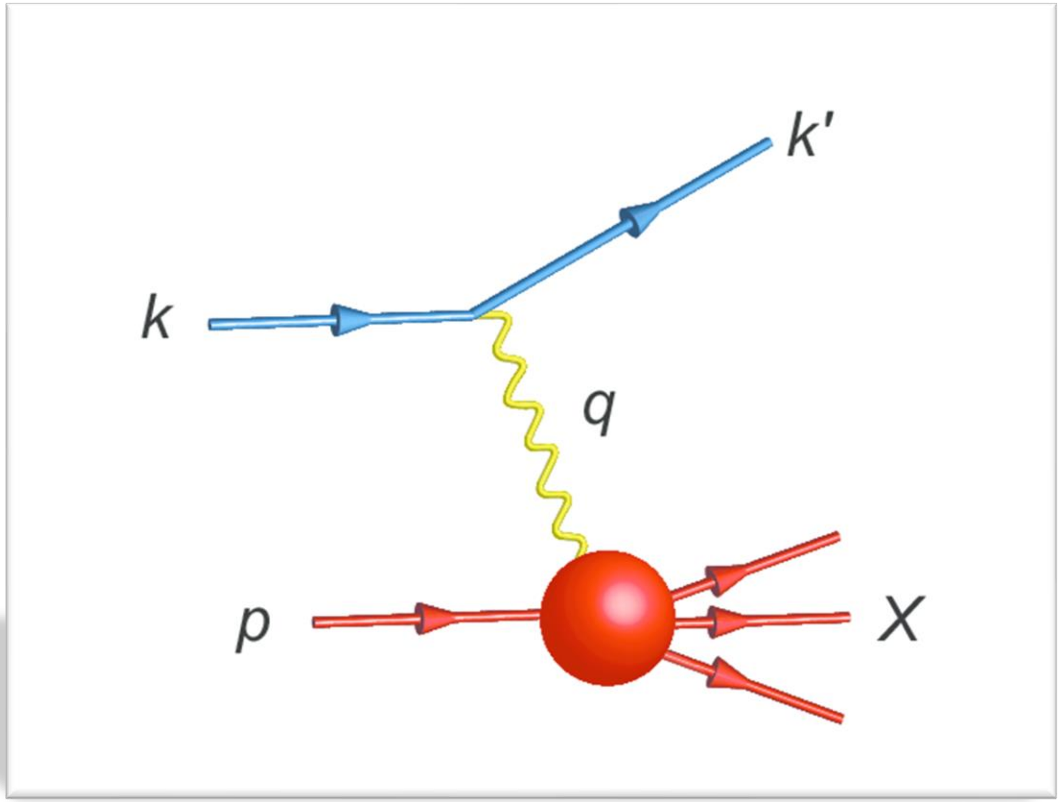
- AMBER @ CERN SPS
  - High-intensity beams of pions ($\gtrsim 10^7$ pions/sec in Phase-1 = approved) and kaons (5×10^6 kaons/sec Phase-2 = proposal being prepared)
  - Drell-Yan, J/ψ production, prompt photon production

    … from proton and nuclear targets



Plans and Goals

- ✓ 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.
- ✓ 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).
- ✓ *Pion and Kaon Structure at the Electron-Ion Collider*, Arlene C. Aguilar *et al*., NJU-INP 001/19, arXiv:1907.08218 [nucl-ex], Eur. Phys. J. A **55** (2019) 190/1-15
- ✓ *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
- ✓ *Selected Science Opportunities for the EicC,* Xurong Chen, Feng-Kun Guo, Craig D. Roberts and Rong Wang, NJU-INP 022/20, 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"
- ✓ 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. (2021) *in press*
- ✓ *Electron-Ion Collider in China,* D. P. Anderle *et al*., NJU-INP 035/21, arXiv:2102.09222 [nucl-ex], Front. Phys. (China) *in press*
- ✓ *Revealing the structure of light pseudoscalar mesons at the Electron-Ion Collider,* John Arrington *et al*., NJU-INP 036/21, arXiv: 2102.11788 [nucl-ex], J. Phys. G (*in press*)



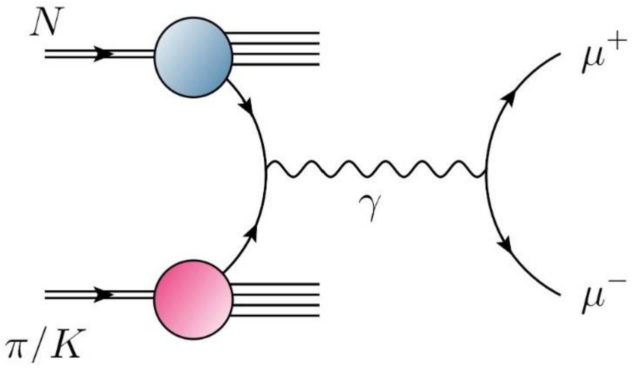
Parton Distribution Functions

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. (2021) *in press*

- 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 verity of QCD
  - Regarding the kaon, worldwide, only 10 points of data exist

NG Boson Distribution Functions



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  - 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 of 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 $\zeta > \zeta_H$ for which experiment can be interpreted through parton distributions, then

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

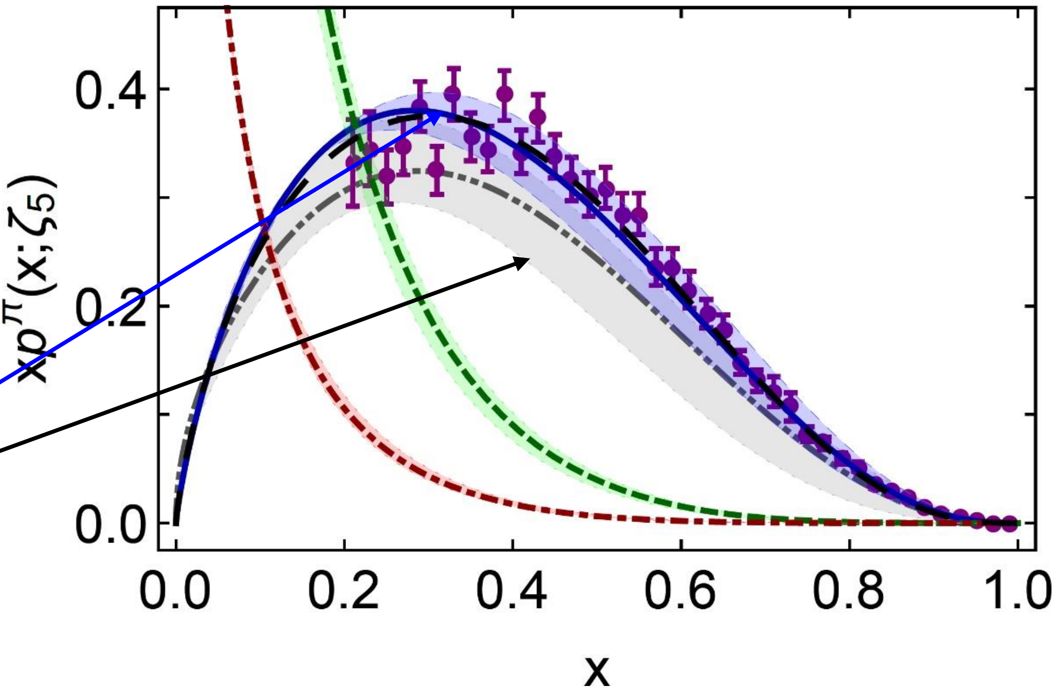
- Consequence
  - Any analysis of DY, DIS, etc. experiment which returns $\beta < 2$ conflicts with QCD.
- Observations
  - All existing internally-consistent calculations preserve connection between large-k^2 behaviour of interaction and large-x behaviour of DF: J=0 … $(1/k^2)^n \Leftrightarrow (1-x)^{2n}$
- No existing calculation with n=1 produces anything other than $(1-x)^2$
- Internally-consistent calculation that preserve RG properties of QCD,

  then $2 \rightarrow 2+\gamma$, $\gamma>0$, at any factorisation-valid scale
- Controversy:
  - Ignore threshold resummation – typical of all contemporary phenomenology, despite Aicher *et al*., then data analysis yields $(1-x)^{\mathbf{1}+\gamma}$
  - Include threshold resummation, then data analysis yields $(1-x)^{\mathbf{2}+\gamma}$

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 pointwise 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 hardened by EHM
- 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: stronger than ever before

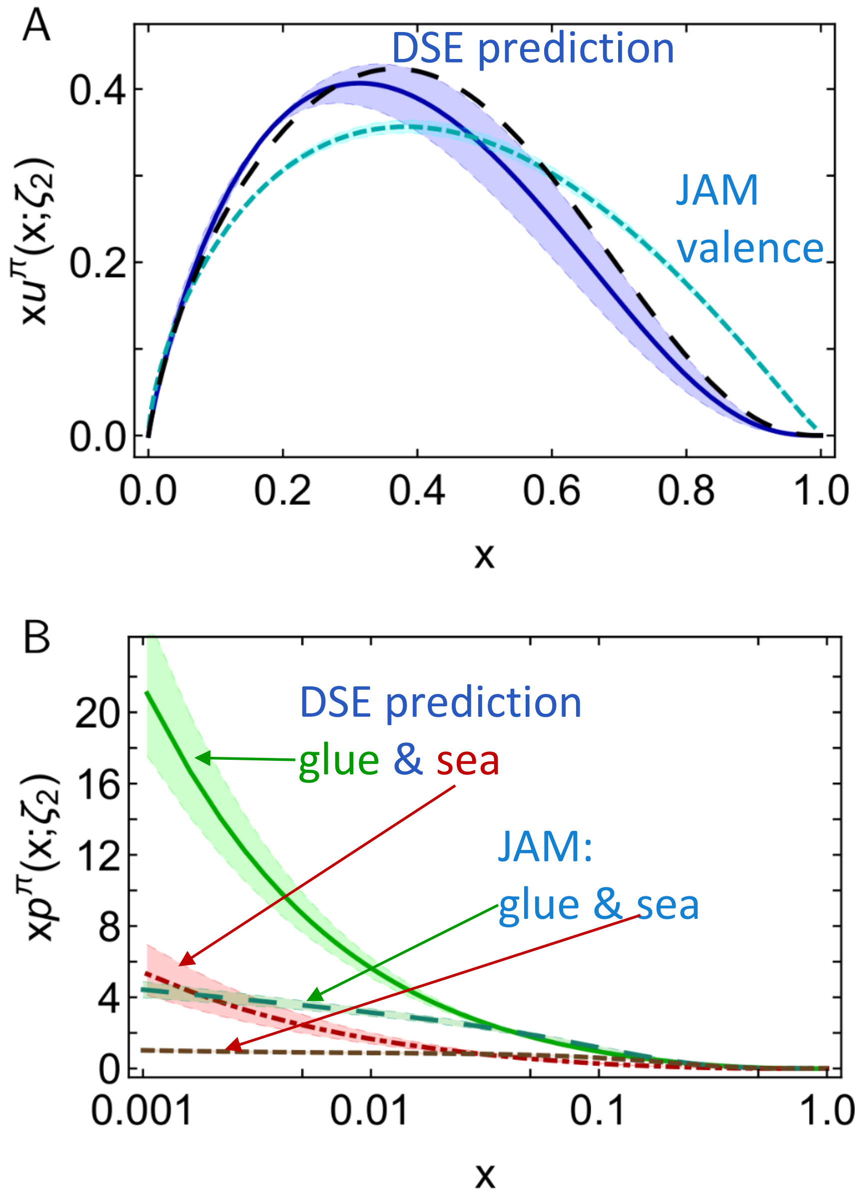


- *After 30 years – new era dawning in which the ultimate experimental checks can be made:*

  JLab12 … M2 beam-line @ CERN … EIC … EicC(?)

π distribution functions … Comparison with JAM fits

- **Valence:**
  - momentum fraction similar
  - JAM … publication ignores NLL resummation … profile much harder & inconsistent with QCD prediction
- **Glue:**
  - Similarities on x ≥ 0.05, but marked disagreement on important 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



π distribution functions … Comparison with JAM fits

- Valence:
  - momentum fraction similar
  - JAM … publication ignores NLL resummation … profile much

Breaking news …

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

important complementary domain

Gluon Parton Distribution of the Pion from Lattice QCD

Zhouyou Fan (Michigan State U.), Huey-Wen Lin (Michigan State U.)

Apr 13, 2021

10 pages

e-Print: 2104.06372 [hep-lat]

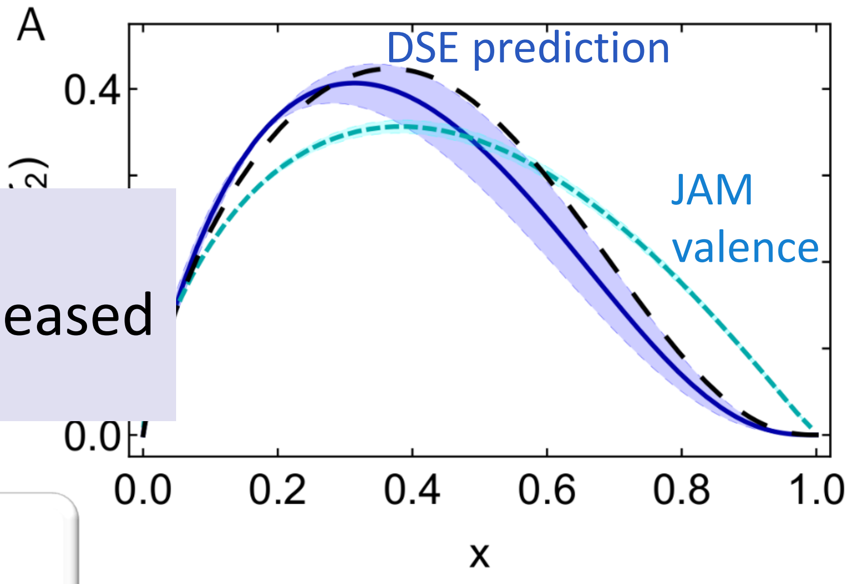
Report number: MSUHEP-21-004

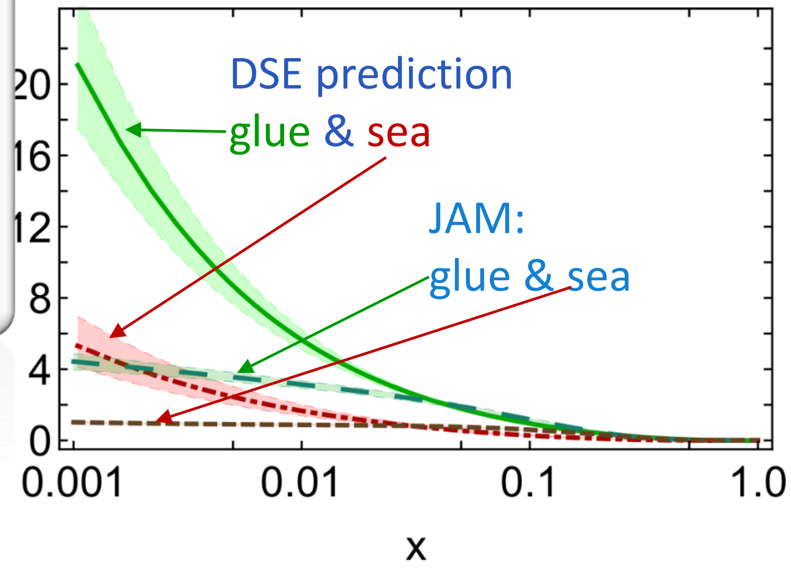
View in: ADS Abstract Service

pdf cite 0 citations

describe sea-quark distribution as empirically unknown

- Motivation for the collection and analysis of DY data with $\pi^{\pm}$ beams on isoscalar targets





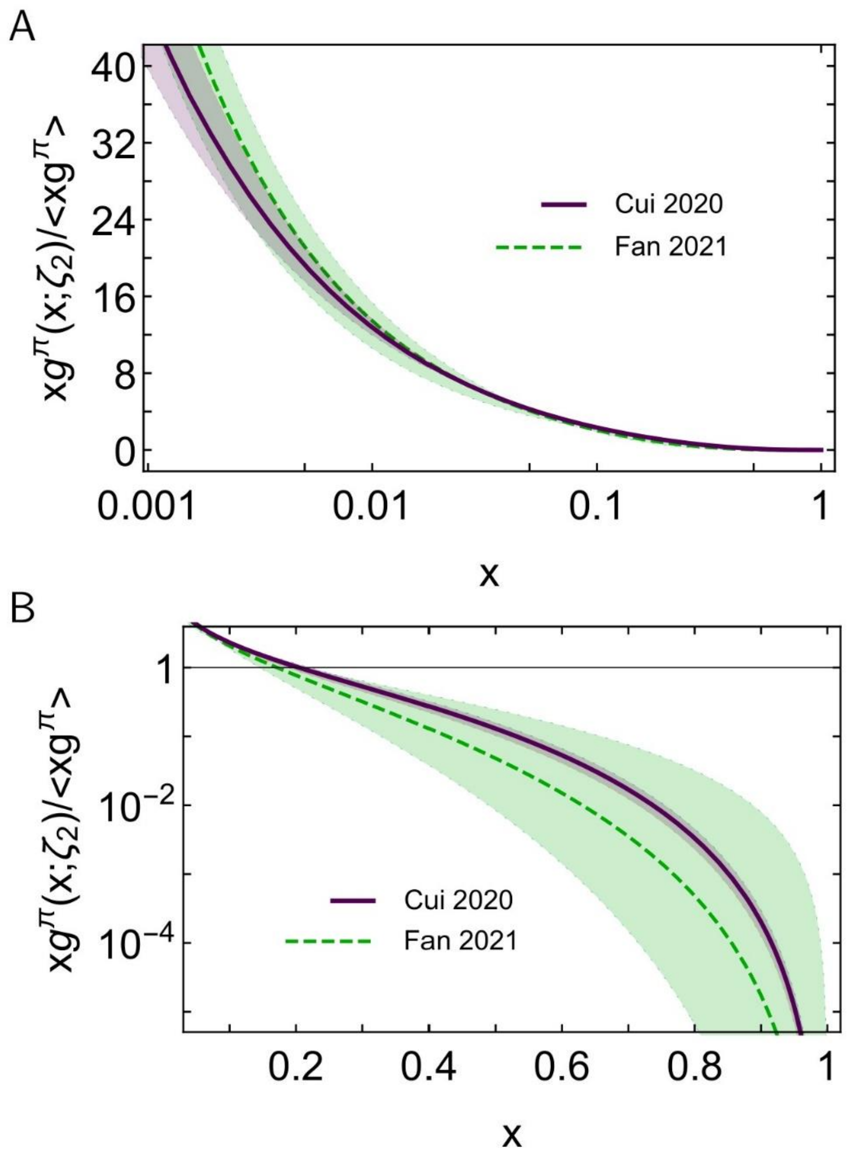
Breaking news for glue in π: Continuum (Eur. Phys. J. C 80 (2020) 1064/1-20) & Lattice Predictions (arXiv:2104.06372)

Two distinct approaches to solving QCD
Agreeing quantitatively on $g^{\pi}(x)$

- JAM and xFitter phenomenological analyses (both ignore NLL corrections to hard scattering kernel)

  exhibit qualitatively different behaviour and are disfavoured by this comparison

- 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 is uniquely placed to provide the necessary precision data.

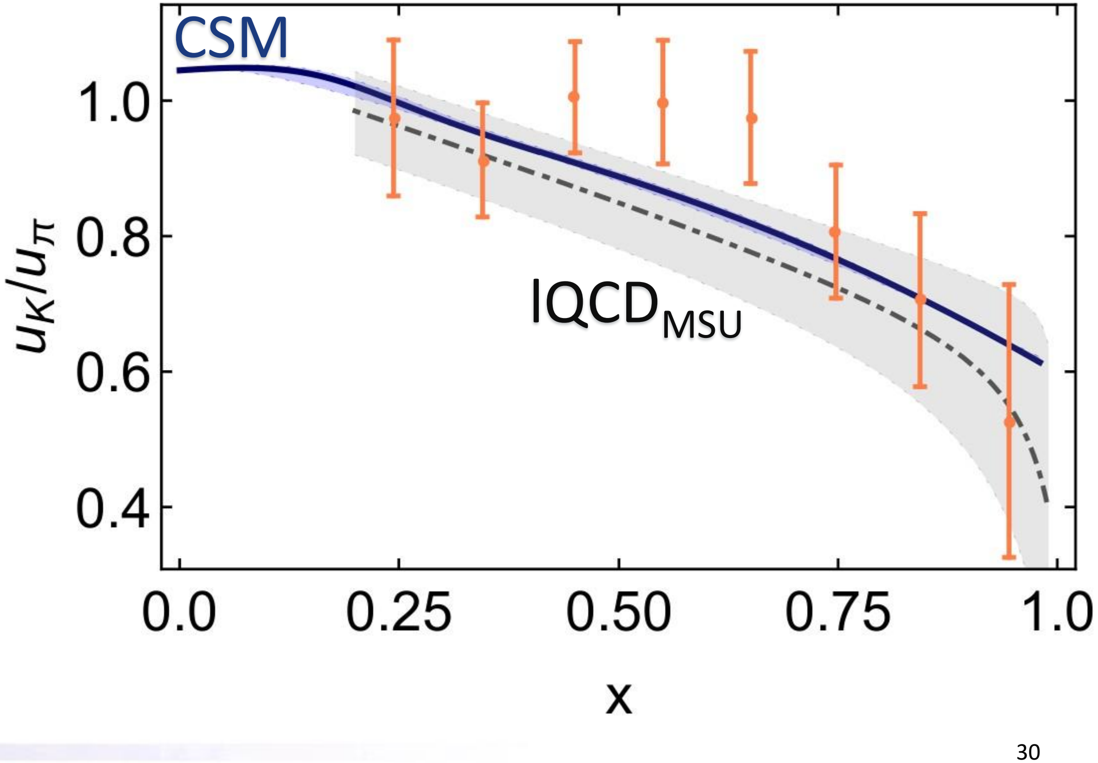


Status: Kaon

- 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: <u>no results</u>
- One piece of available experimental information:

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

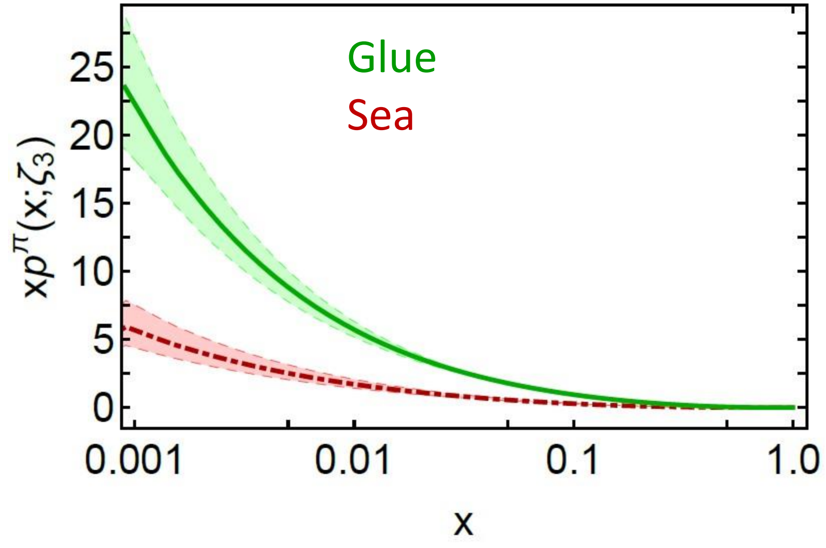
  - Continuum prediction for ratio is consistent with data.
  - But, given large errors, this ratio is very forgiving of even large differences between various calculations of the individual DFs used to produce the ratio.
    - New, precise data critical if this ratio to be used as path to understanding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

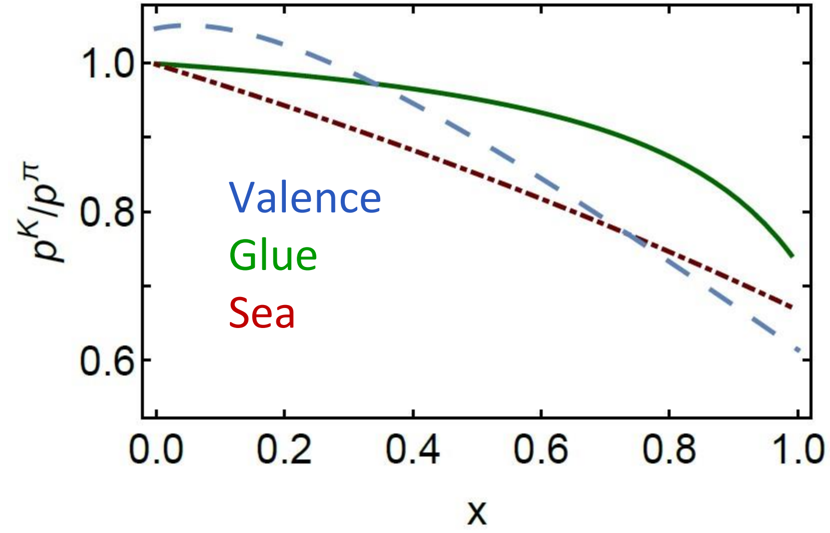


Status: Kaon

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 results until now
- 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 ∼ 5%;
    - ii. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).





$$\Psi(x,t)$$

Hadron Wave Functions

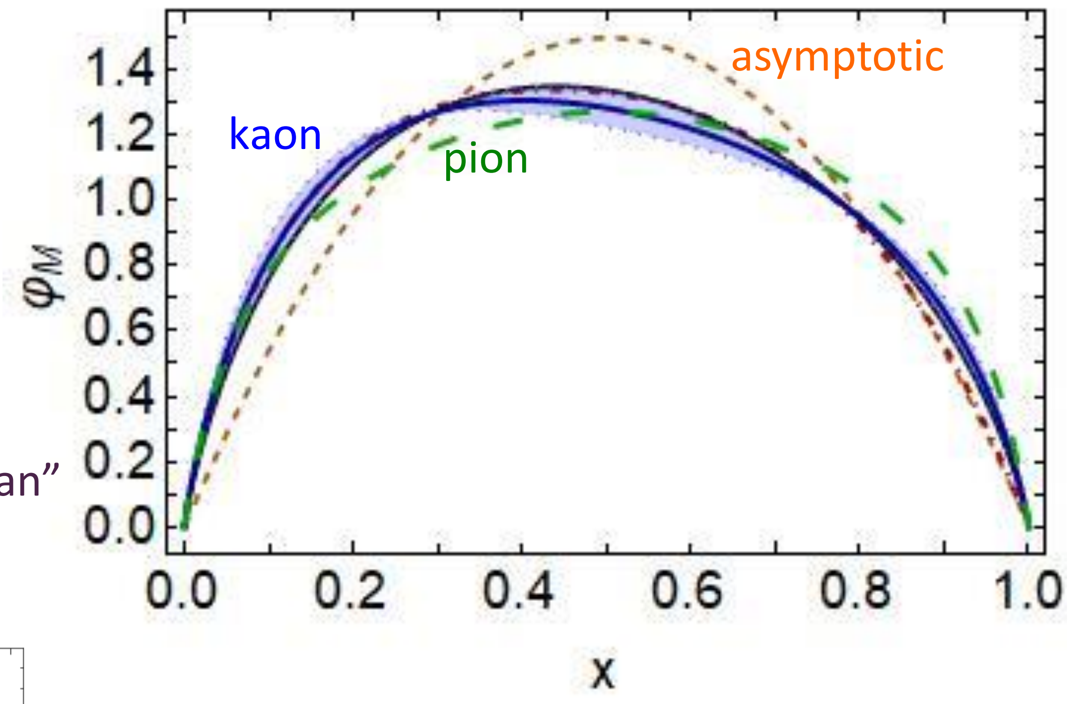
Wave Functions of Nambu Goldstone Bosons

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. (2021) *in press*

- 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 predicts that 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.
  - Moreover, the 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

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”



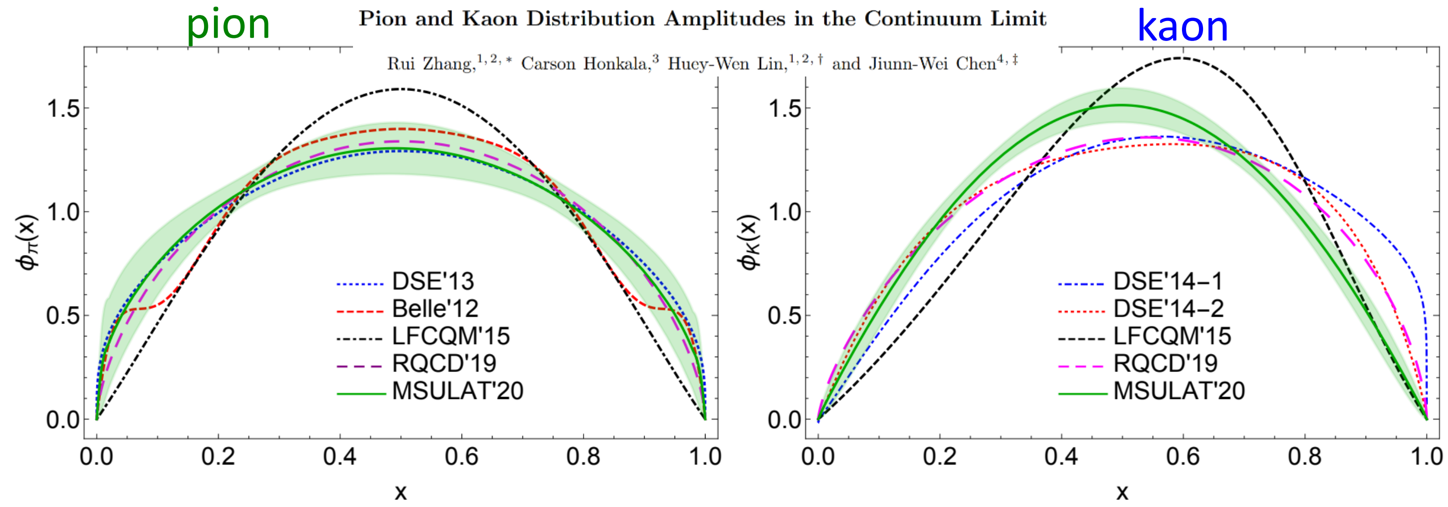


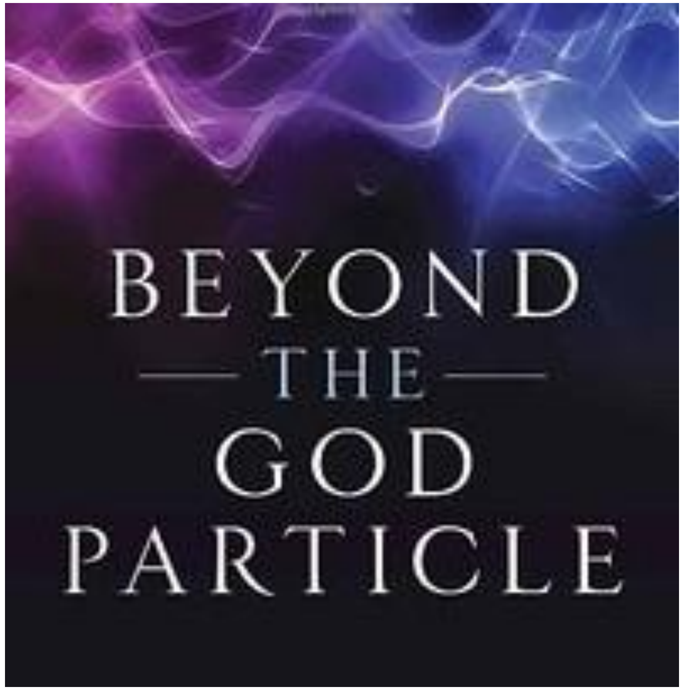
FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around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

Wave Functions of Nambu Goldstone Bosons

- Scientific Context:
  - Today, finally, continuum and lattice theory 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?
- Data: Existing
  - One 20-year-old experiment at Fermilab [E791 – Aitala:2000hb] delivered results on the pion DA that have become controversial.
  - In some ways, the data are internally inconsistent.
- *Data: Future … x-dependence or moments of Nambu-Goldstone boson DAs*
  - *JLab & EIC & EicC ⇒ access to moments via elastic form factors at large Q^2*
  - *AMBER @ CERN with high-intensity π and K beams ⇒ potential access via diffractive production of jets to x-dependence or via two-meson final states to moments*

Epilogue



- Nature has two sources of mass
  - Higgs mass-generating mechanism = understood
  - Phenomenon of Emergent Hadron Mass = much to learn
- EHM (possibly/probably?) lies within the Standard Model,

  i.e., in strong QCD
- Basic predictions:
  - Gluons acquire mass ⇒ running coupling saturates on infrared domain, restoring approximate conformal behaviour
  - Enigmatically, the unusually light Nambu-Goldstone bosons provide the clearest windows onto the Emergence of Mass in Nature
- With modern and on-the-horizon facilities having the capacity to deliver practical pion and kaon “targets”, science can finally move beyond the proton and study an entirely different form of hadron matter = the mesons without which observable Universe could not exist

Get off the Ground!

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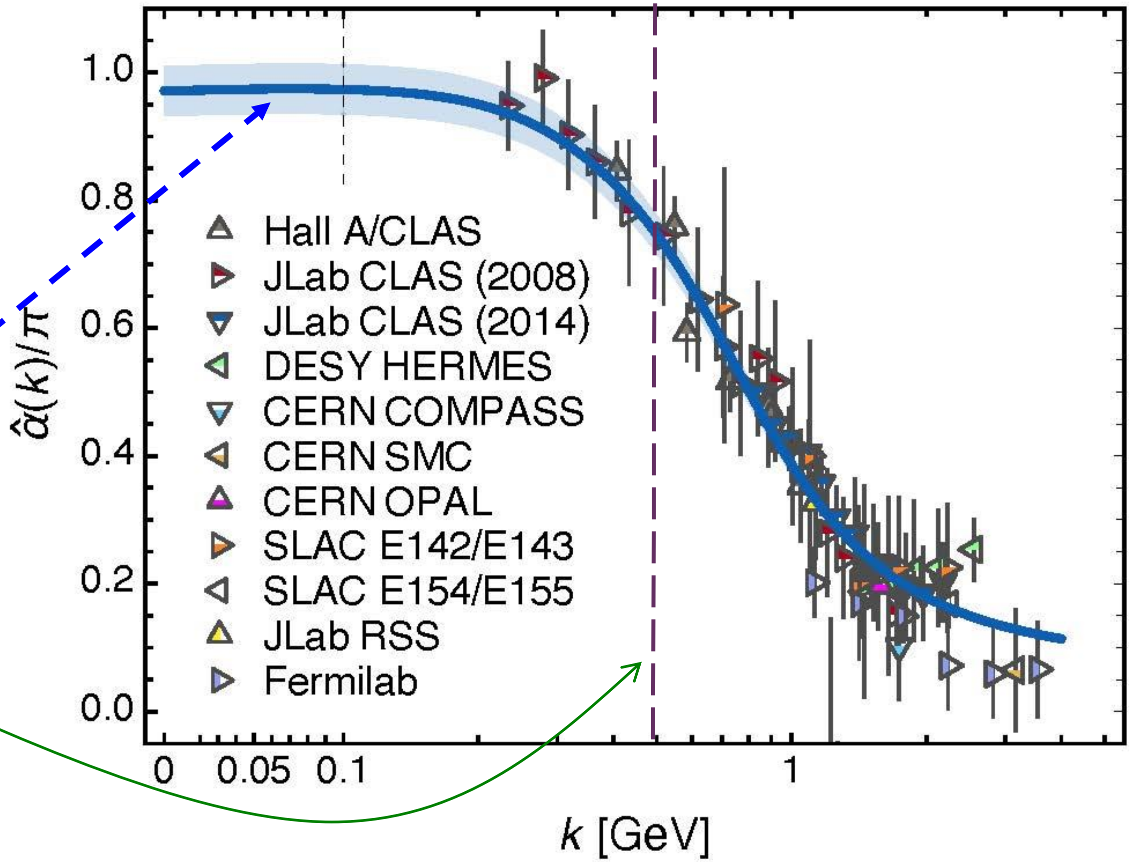
Thankyou
非禮勿言
非禮勿聽

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

Prediction: Process-independent effective-charge in QCD

- Modern continuum & lattice methods for analysing gauge sector enable QCD analogue
  "Gell-Mann – Low"
  running charge to be defined and calculated
- Combined 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 ~ $\hat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



Data = process dependent effective charge [Grunberg:1982fw]:
α_{g1}, defined via Bjorken Sum Rule