NANJING UNIVERSITY

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

Grant no. 12135007

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

Challenges and Opportunities in Hadron Physics

- https://indico.cern.ch/event/938795/
- 231 Registered Participants
  - Often > 60 participants on−line each day and more on−site
- $5\frac{1}{2}$ days of presentations – 133 in total
  - 53 plenary
  - 80 parallel
- Very “Broad Church”
  - Coverage of questions and progress in formulation, phenomenology and theory of light-front approach to hadron physics
  - Also, presentations and discussions of phenomenology and theory in many other areas
  - Canvassing of potential for existing and future hadron physics facilities

International Advisory Committee

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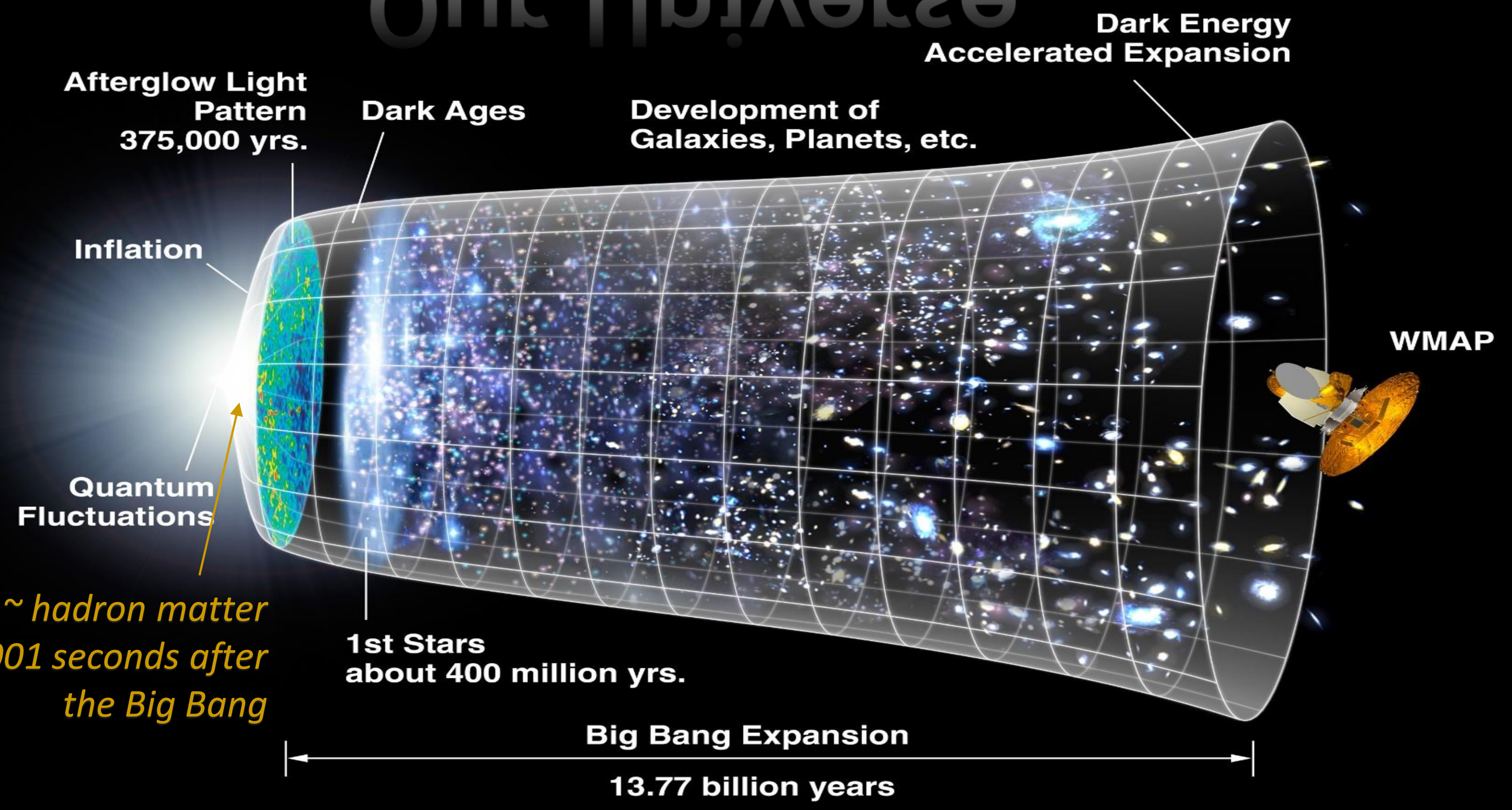
Our Universe

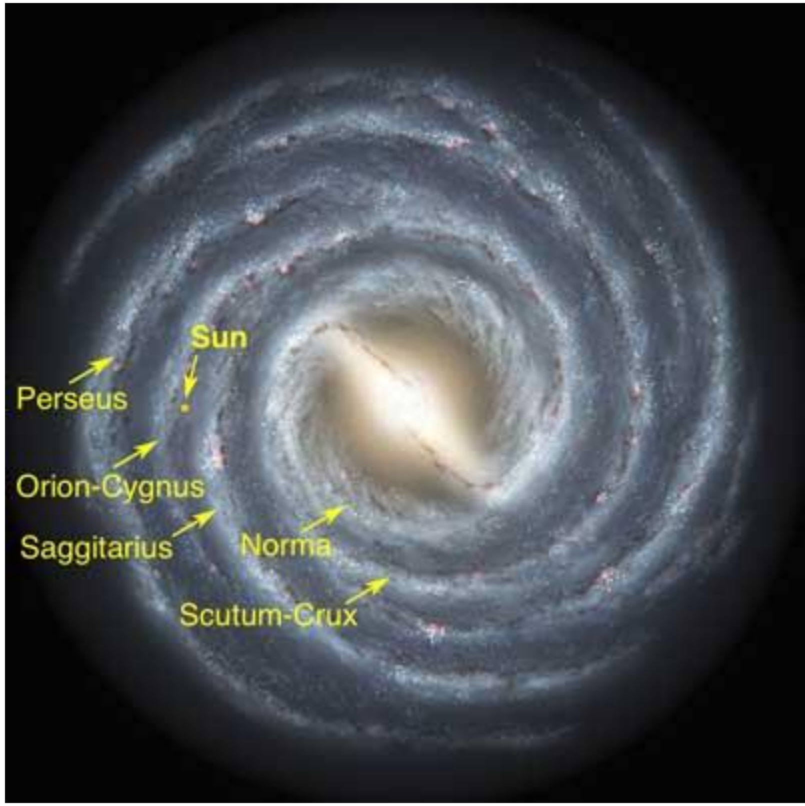


Emergence of Mass ~ hadron matter originated 0.000001 seconds after the Big Bang

Emergent Phenomena … in the Standard Model(?)

Existence of our Universe depends critically, *inter alia*, on 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 ⇔ Reductionism

- (Many/Most) Physicists like to imagine that all things can be explained by a single equation

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

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

- Our equation is QCD
- We suppose that this single line Lagrangian
  contains answers to these three questions
  and many more

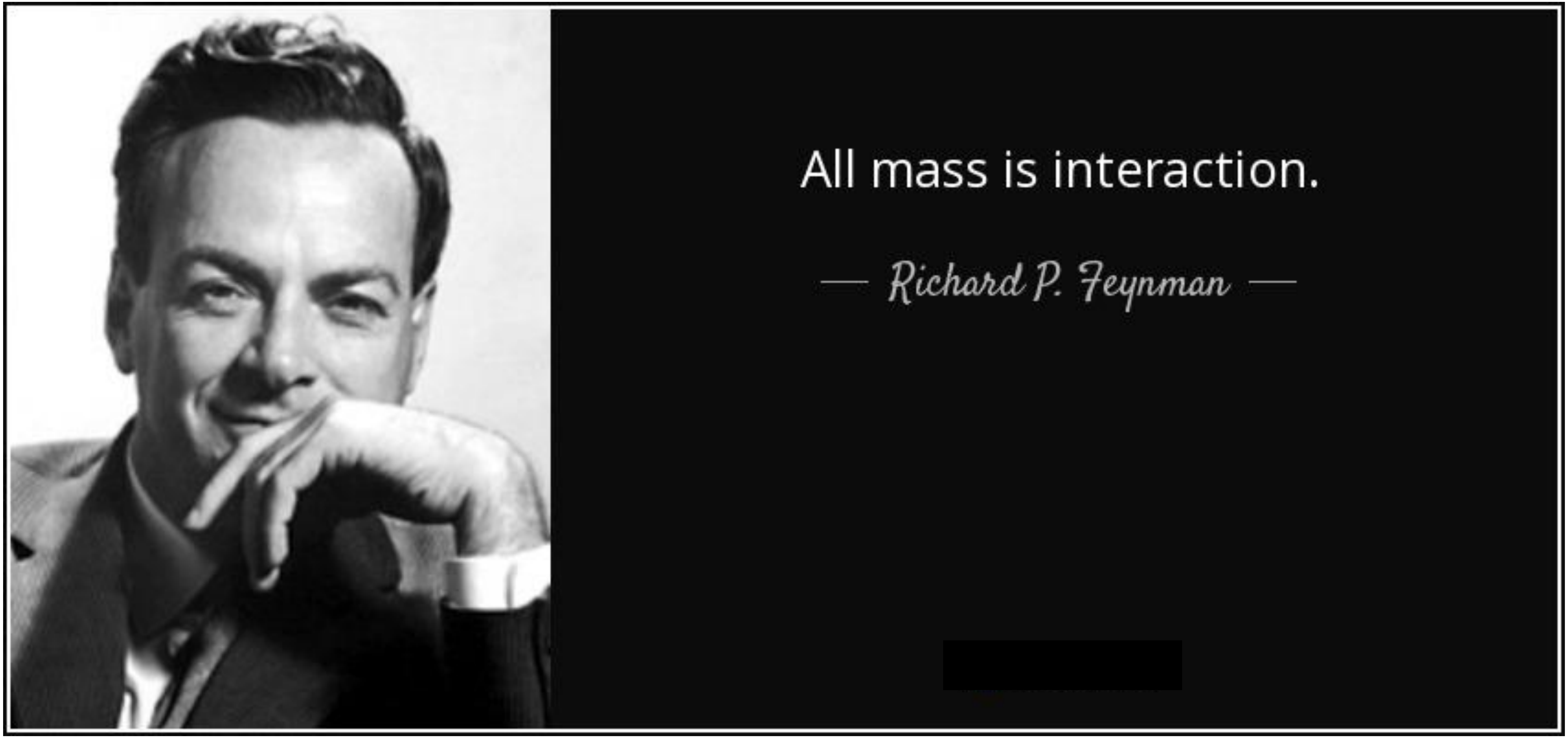
Emergence of Hadron Mass

ANSWERING FUNDAMENTAL QUESTIONS

An EIC—with its exceptionally powerful probing capability—would uniquely address profound, fundamental questions about nucleons (neutrons and protons) and their assembly into nuclei of atoms, such as:

(1) How does the mass of the nucleon arise?
(2) How does the spin of the nucleon arise?
(3) What are the emergent properties of dense systems of gluons?

- One can defend the view that (1) is primary
- That understanding how a nucleus-size mass-scale (1 GeV) can emerge from a theory that, *a priori* – absent Higgs couplings – contains no masses, will supply the key for answering all the other questions


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

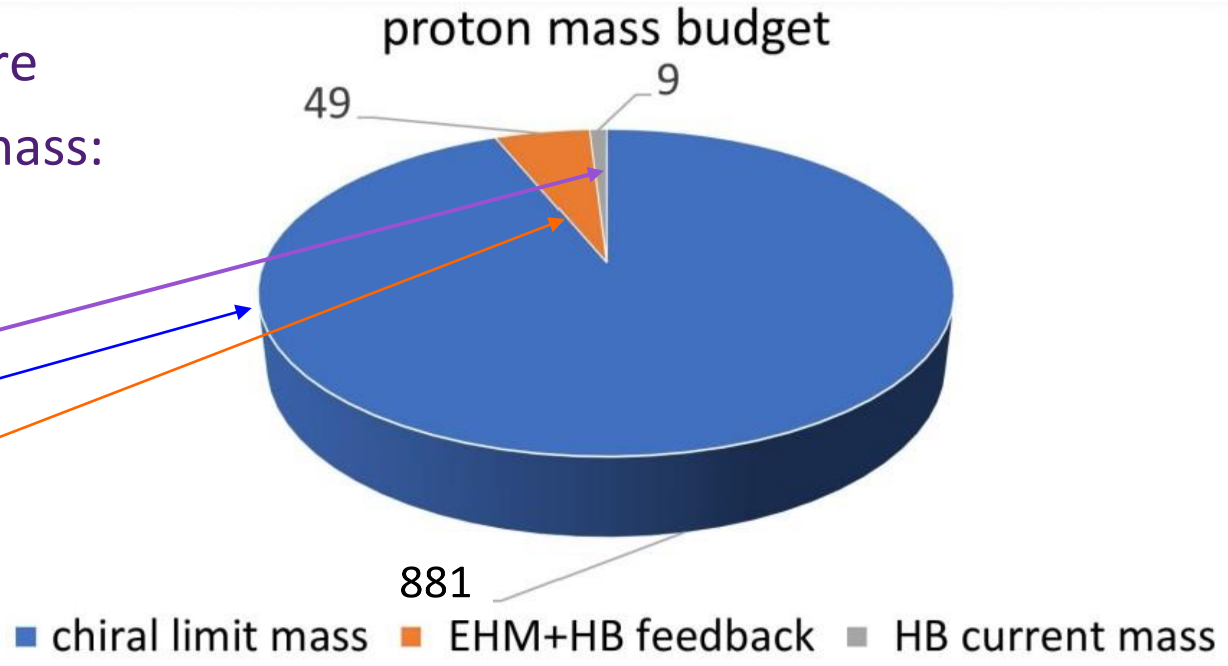
Origin of Visible Mass (?)

- In our Universe, all visible material is characterised by a nuclear-sized mass-scale: *1 GeV*
- Within the Standard Model, this material is built from light quarks: *u*, *d* … and perhaps *s*
- Higgs boson gives electron-size masses to *u*- and *d*-quarks … $m_{u,d}$ are just a few MeV
- Proton mass is $\sim 100 \times (m_u + m_u + m_d)$
- What is the source for this nuclear-size mass-scale?
- Plainly, there is another phenomenon in Nature

  that is extremely effective in producing mass:

  Emergent Hadron Mass (EHM)

✓ Higgs Boson (HB): 1%
✓ Emergent hadron mass (EHM): 94%
✓ EHM+HB interference: 5%



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?

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

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

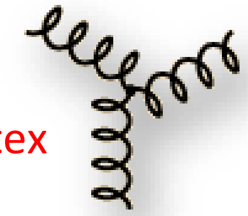
Prima Facie, the QCD Lagrangian
CANNOT support a nonzero value of this expectation value.

QCD's scale anomaly

Primary Expression of EHM in SM - Emergence of Gluon Mass Scale

- QCD doesn't need quarks to be an interacting quantum field theory
  - Gluon self-interactions at tree-level, *i.e.*, in the Lagrangian

3-gluon vertex

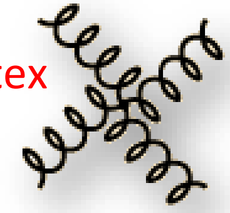


- Gluons are massless in perturbation theory
- ***Not preserved non-perturbatively!***

  Nature's symmetries (only) require $q_\mu \, \Pi_{\mu\nu}(q) \equiv 0$

  3 gluon polarisations are permitted to be massive

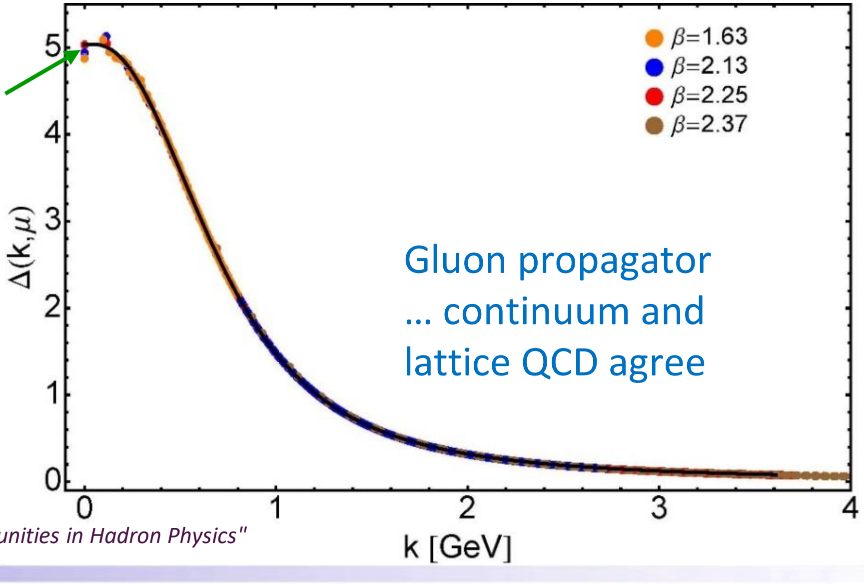
4-gluon vertex



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

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

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



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

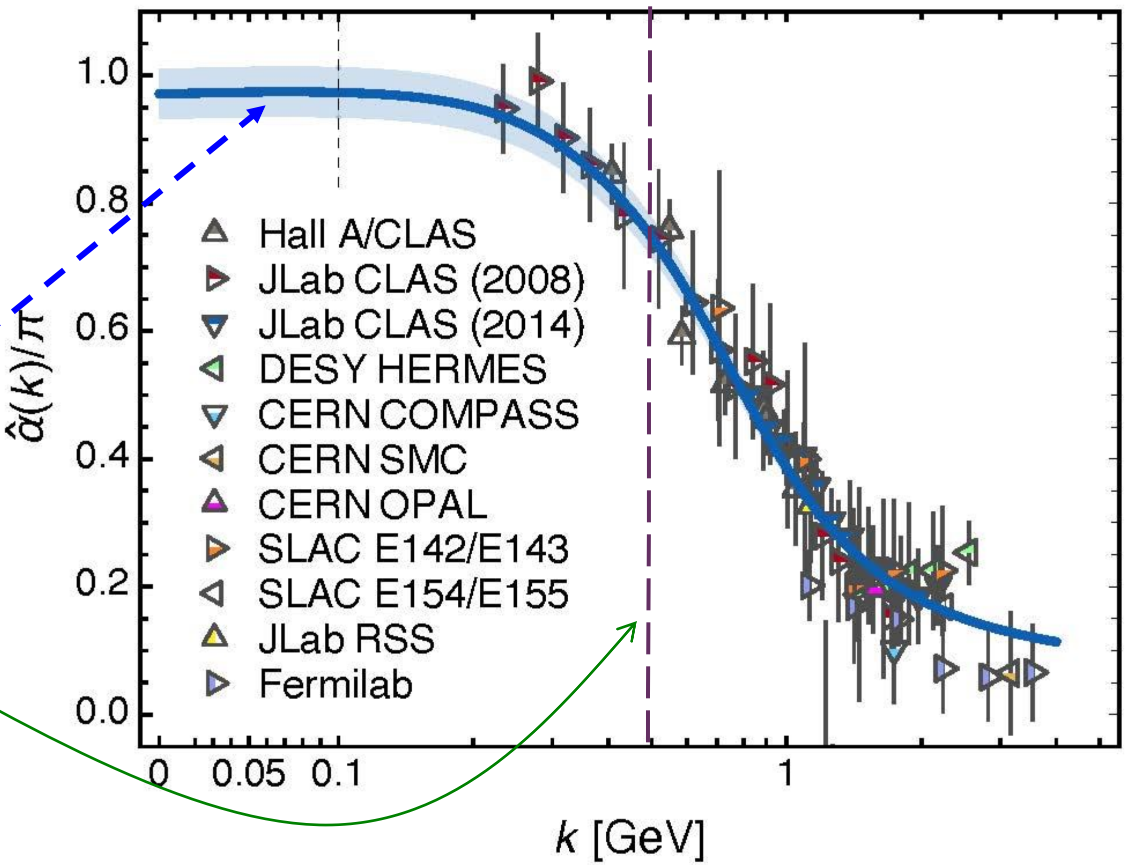
The Gluon Mass Generation Mechanism: A Concise Primer
A.C. Aguilar, D. Binosi, J. Papavassiliou, Front. Phys. **11** (2016) 111203

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

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" confinement scenario is incorrect
- Below $k \sim \hat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



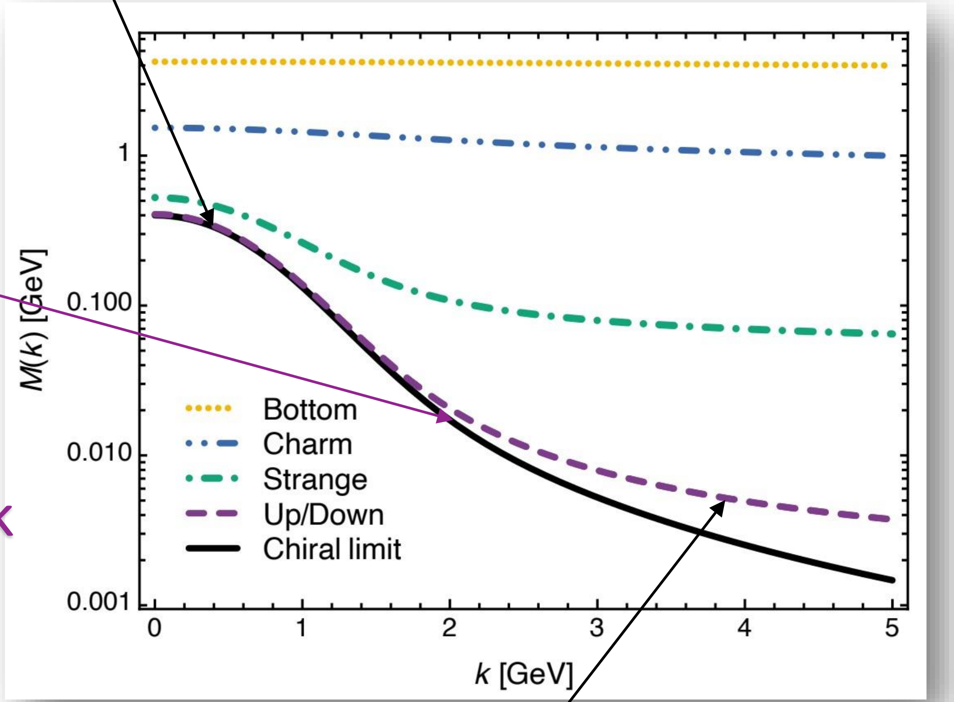
Data = process dependent effective charge [Grunberg:1982fw]: α_{g1}, defined via Bjorken Sum Rule

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
  - $\Lambda_{\rm QCD} \sim 0.25$ 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 $M_u(k^2)$

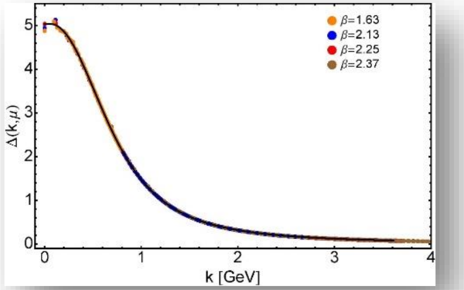
Dressed-quark mass function

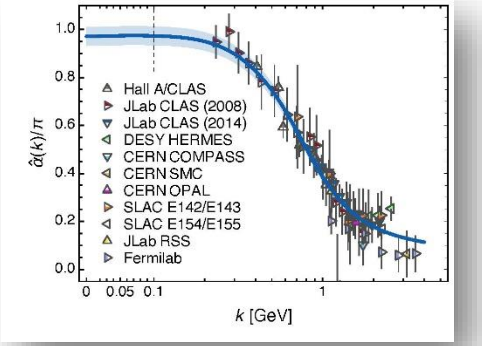


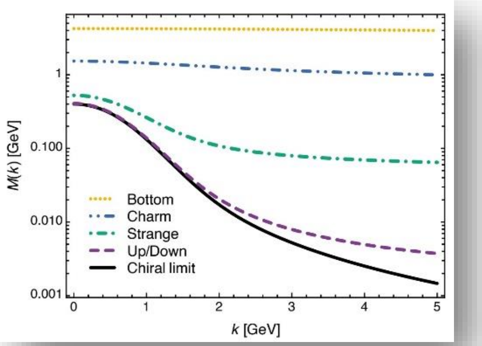
u-quark mass function
Becomes perturbative on $k^2 \gtrsim 4m_p^2$

EHM Basics

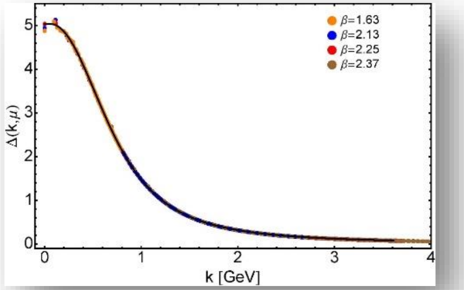
- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =
  Elucidate all observable 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



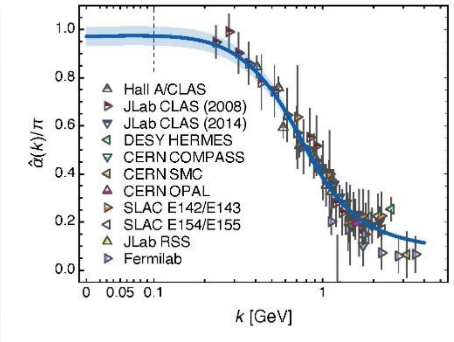


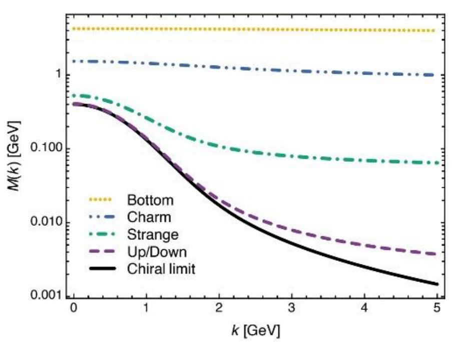


EHM Basics



- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- Can these basic QCD functions be computed using the light-front formulation of QCD?
- Example





existence of a nonzero dressed-quark mass function in the absence of Higgs couplings, dramatically changing the character of the quark propagator, is equivalent to the emergence of a nonzero in-hadron chiral condensate

$$\lim_{\hat{m}\to 0} \kappa^{\zeta}_{P_{fg}} = -\lim_{\hat{m}\to 0} f_\pi \langle 0|\bar{q} i\gamma_5 q|\pi\rangle = Z_4\, \mathrm{tr}_{\mathrm{CD}} \int_{dq}^{\Lambda} S^0(q;\zeta) = -\langle \bar{q}q\rangle^0_\zeta$$

Perhaps this relates to the problems posed by zero modes in LF QCD?

EHM Basics

- Absent Higgs boson couplings, the Lagrangian
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produce
  - Massless quarks become massive
- Can these basic QCD functions be computed
  using the light-front formulation of QCD?
- Example

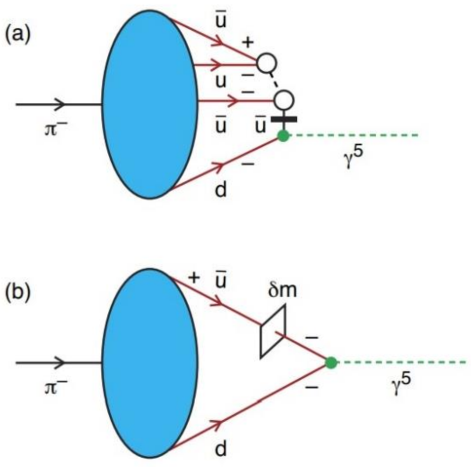
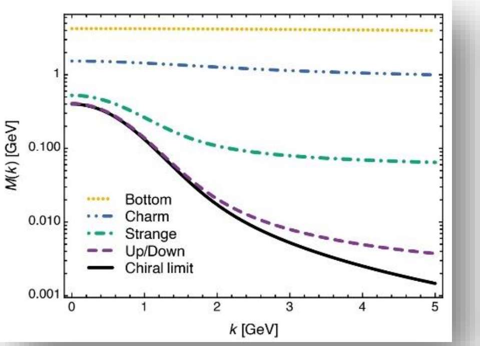


FIG. 2. Light-front contributions to $\rho_\pi = -\langle 0|\bar{q}\gamma_5 q|\pi\rangle$, $f_\pi \rho_\pi$ is the in-pion condensate. *Upper panel* – A non-valence piece of the meson's light-front wave-function, whose contribution to ρ_π is mediated by the light-front instantaneous quark propagator (vertical crossed-line). The "±" denote parton helicity. *Lower panel* – There are infinitely many such diagrams, which can introduce chiral symmetry breaking in the light-front wave-function in the absence of a current-quark mass. (The case of f_π, which is also an order parameter for DCSB, is analogous.)

Perhaps derives from resummation of infinitely many diagrams involving exchange of light-front-instantaneous quark propagator?



existence of a nonzero dressed-quark mass function in the absence of Higgs couplings, dramatically changing the character of the quark propagator, is equivalent to the emergence of a nonzero in-hadron chiral condensate

$$\lim_{\hat{m}\to 0} \kappa_{P_{fg}}^{\zeta} = -\lim_{\hat{m}\to 0} f_\pi \langle 0|\bar{q} i\gamma_5 q|\pi\rangle = Z_4 \,\mathrm{tr}_{\mathrm{CD}} \int_{dq}^{\Lambda} S^0(q;\zeta) = -\langle \bar{q}q\rangle_\zeta^0$$

Critical and Crucial

- Must learn where the in-pion condensate is hidden on the light front
  - Because there is no real understanding of the pion without it
- To explain the pion, one must have access to the current-quark mass, m
  - some constituent-quark mass parameter is inadequate
- Explaining the pion is NOT only getting $m_\pi^2 \to 0$ as $m \to 0$
  - That's a very small part of the story
- There is a far more fundamental statement
  - From which $m_\pi^2 \to 0$ as $m \to 0$
  - and many other features of Nambu-Goldstone bosons will follow …
- Need the pion Bethe-Salpeter wave function & dressed-quark propagator

$$S(k;\zeta) = \frac{1}{i\gamma\cdot k A(k^2;\zeta) + B(k^2;\zeta)} = \frac{Z(k^2;\zeta)}{i\gamma\cdot k + M(p^2)}$$

$$\chi_{PS}^{f\bar{g}}(k,P) = S_f(p_1)\Gamma_{PS}^{f\bar{g}}(k,P)S_g(p_2)\,,$$

$$\Gamma_{PS}^{f\bar{g}}(k,P) = i\gamma_5\left[E_{PS}^{f\bar{g}}(k,P) + \gamma\cdot P F_{PS}^{f\bar{g}}(k,P) + \gamma\cdot k G_{PS}^{f\bar{g}}(k,P) + \sigma_{\mu\nu}k_\mu P_\nu H_{PS}^{f\bar{g}}(k,P)\right]$$

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

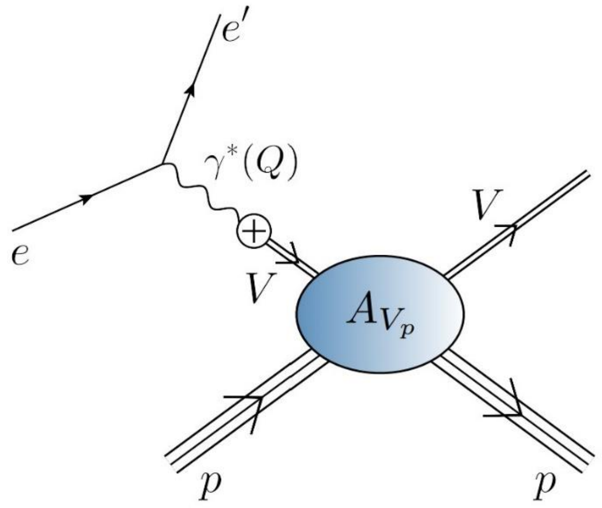
$$f_\pi E_\pi(p^2) = B(p^2)$$

Pion wave function — quark mass function

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

EHM Measurements
How does the mass of the nucleon arise?

- "Measure" trace anomaly in proton $\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2 = \langle p(P)|\Theta_0|p(P)\rangle$
- Once considered viable … use electromagnetic vector-meson production reaction
  $(V = J/\psi, \Upsilon)$ $e + p \to e' + V + p$ to access purely hadronic process $V + p \to V + p$
- But …
  - *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)
  - *Vector-meson production and vector meson dominance*, Y.-Z. Xu (徐胤禛), S. –Y. Chen (陈斯阳), Z.-Q. Yao (姚照千) et al., Eur. Phys. J. C **81** (2021) 895/1-11
  - *Near Threshold Heavy Quarkonium Photoproduction at Large Momentum Transfer,* Peng Sun, Xuan-Bo Tong, Feng Yuan, e-print 2111.07034



- Show … There is no objective 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

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

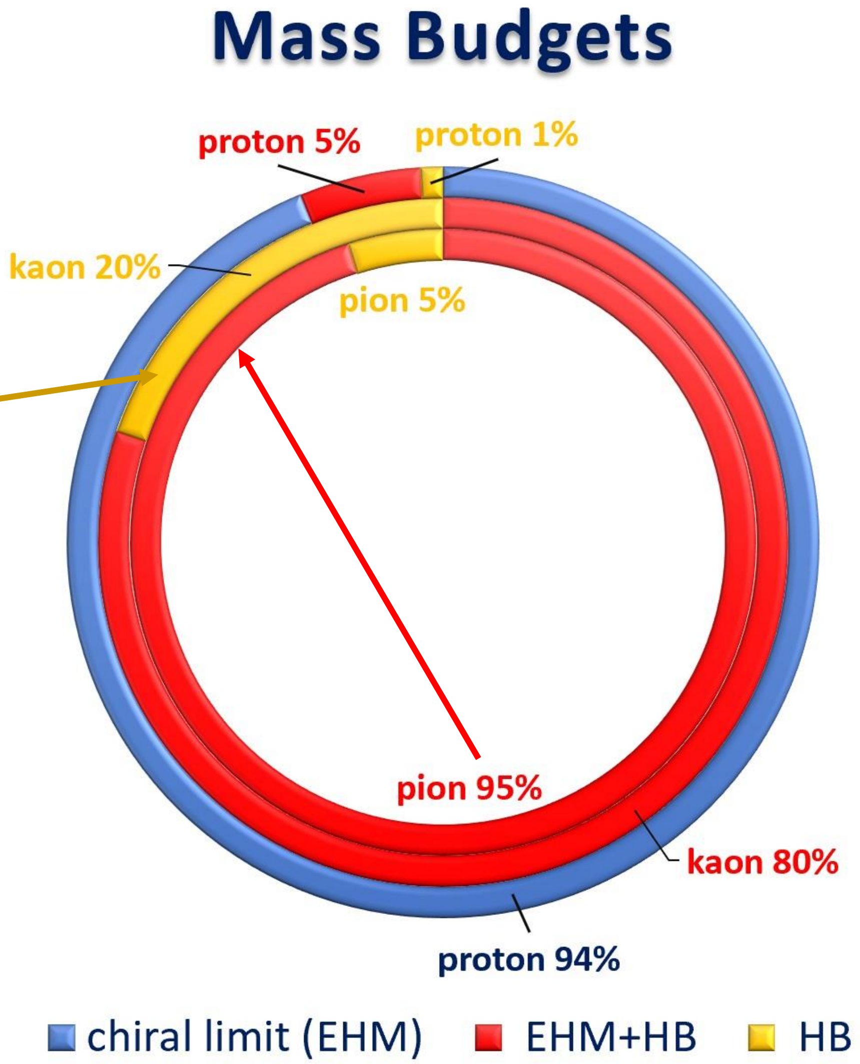
vii. *Electron-Ion Collider in China,* D. P. Anderle *et al*., arXiv:2102.09222 [nucl-ex], Front. Phys. (Beijing) 16 (2021) 6, 64701

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

Emergence of Hadron Mass - Contrasts

- ✓ Pion definitive connection to EHM
- ✓ Kaon exposes Higgs-boson modulation of EHM = constructive interference between Nature's two known sources of mass

- Compare proton and pion mass budgets
- Pion is a Nambu-Goldstone boson
  - No blue annulus because massless in chiral-limit
  - EHM+HB is 95% of the total
- Kaon is somewhere in between π & p
  - 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!
- Proof Wanted

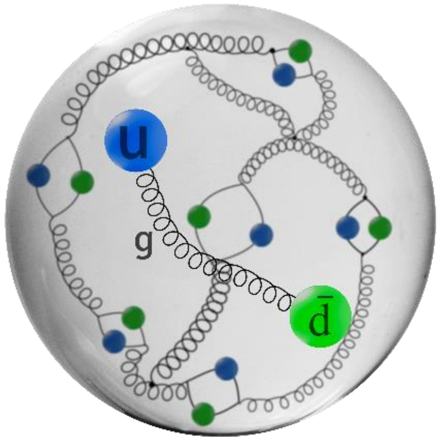


QCD Structure of Nature's Most Fundamental Nambu Goldstone Bosons

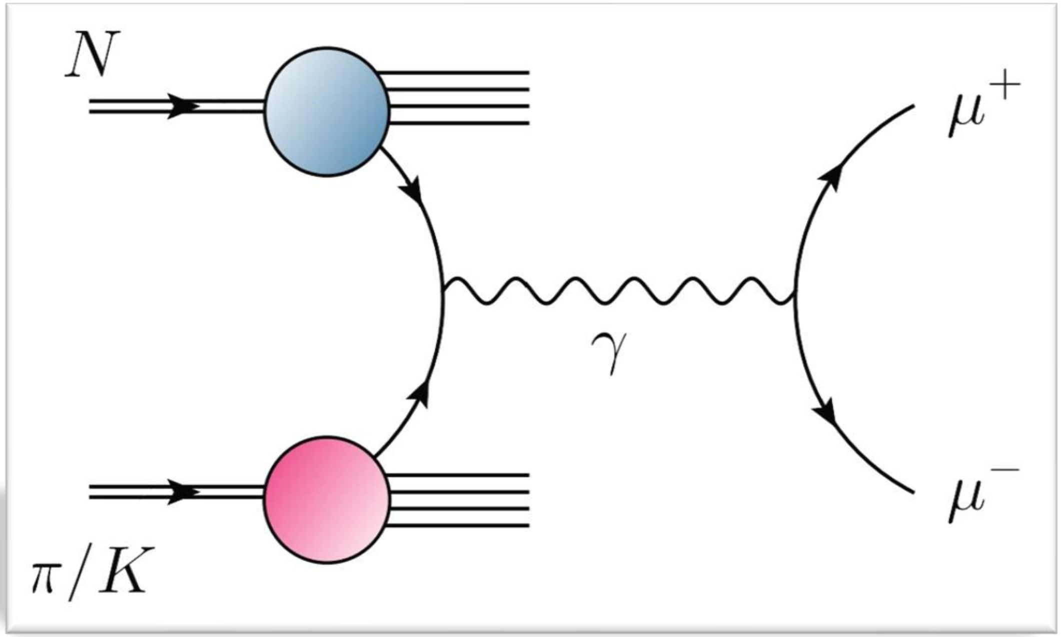
- SM Theory
  - Pions and kaons: bound states of valence-quark & valence-antiquark
    - In being bound states, they are just like all other hadrons
- Formulated correctly, π and K define

  the simplest bound-state problems in strong interactions
  - Rigorous continuum predictions are available
    - More are being developed
  - Lattice-regularised QCD is beginning to deliver
- Enabling precision tests of strong QCD
  - No room for parameters to be varied

    ⇒ theorists can't hide from null results or disagreements with data



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



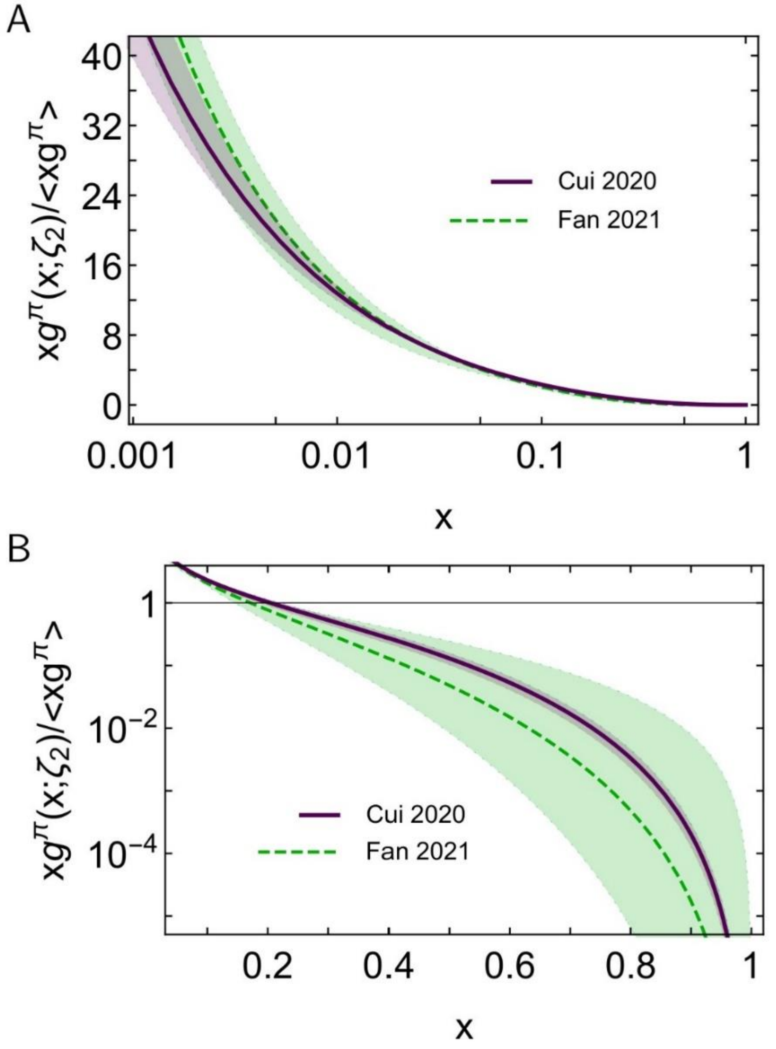
Parton Distribution Functions

NG Boson Distribution Functions

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

📖 *Regarding the distribution of glue in the pion*, L. Chang (常雷) and C.D. Roberts, NJU-INP 042/21, e-Print: 2106.08451 [hep-ph], Chin. Phys. Lett. **38 (8) (2021) 081101/1-6** - Editors' Suggestion

- 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
- Future:
  - Reveal and explain the mechanisms behind the phenomena can make a meson massless whilst simultaneously producing a massless baryon
  - And much more that goes along with it …



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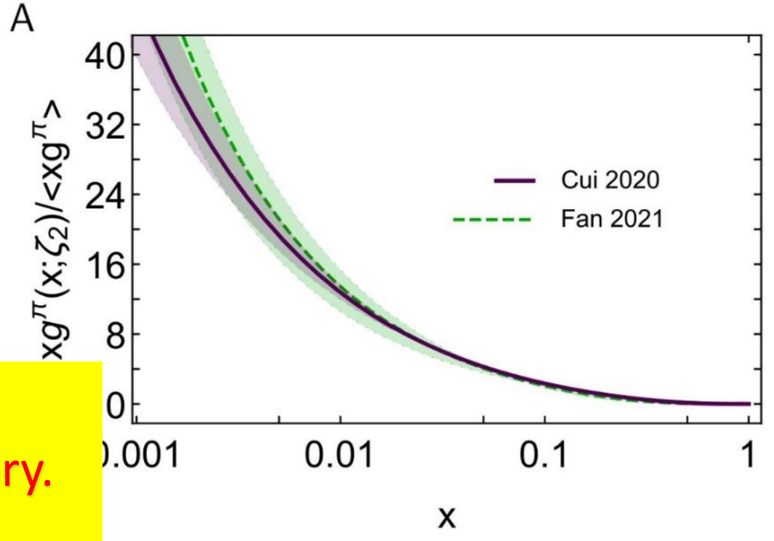
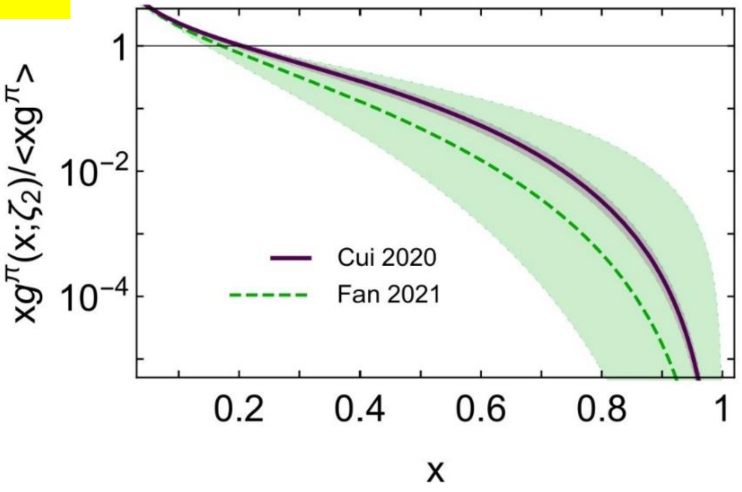
  -
  -

❖ Continuum and lattice agree on gluon DFs.
❖ Global fits, using contemporary methods, disagree with theory.
❖ So, empirically, we understand nothing.

QCD

  - Regarding the kaon, worldwide, only 8 points of data exist
- Future:
  - Reveal and explain the mechanisms behind the phenomena can make a meson massless whilst simultaneously producing a massless baryon
  - And much more that goes along with it …





Controversy over pion valence DF

- QCD understanding of pion wave function 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 … $(1/k^2)^n \Leftrightarrow (1\text{-}x)^{2n}$
- No existing calculation with n=1 produces anything other than $(1\text{-}x)^2$
- Internally-consistent calculation that preserve RG properties of QCD,

  then 2 → 2+γ, γ>0, at any factorisation-valid scale
- Controversy:
  - Some contemporary data fits yield $(1\text{-}x)^{1+\gamma}$
  - While others produce $(1\text{-}x)^{2+\gamma}$

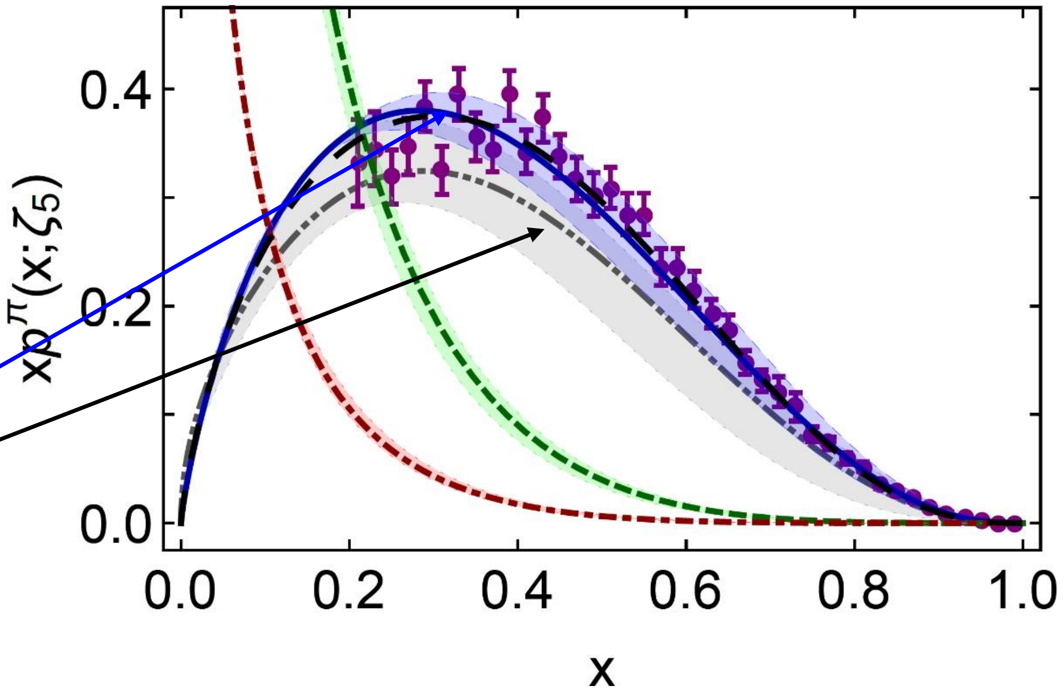
- Is QCD wrong?
- Is existing large-x data a true measure of $q^{\pi}(x;\zeta)$?
- Are fitter-favoured analysis methods correct/complete?

π valence-quark distributions
22 Years of Theory Evolution → 2021

- Developments in continuum-QCD enabled
  1st and only
  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:*
  JLab12 … M2 beam-line @ CERN … EIC … EicC

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

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



M. Ding, K. Raya, D. Binosi, L. Chang, C. D. Roberts, S. M. Schmidt, *Symmetry, symmetry breaking, and pion parton distributions*, Phys. Rev. D 101 (5) (2020) 054014.

R. S. Sufian, J. Karpie, C. Egerer, K. Orginos, J.-W. Qiu, D. G. Richards, *Pion Valence Quark Distribution from Matrix Element Calculated in Lattice QCD*, Phys. Rev. D 99 (2019) 074507.

$$\Psi(x,t)$$

π & K DAs & Form Factors

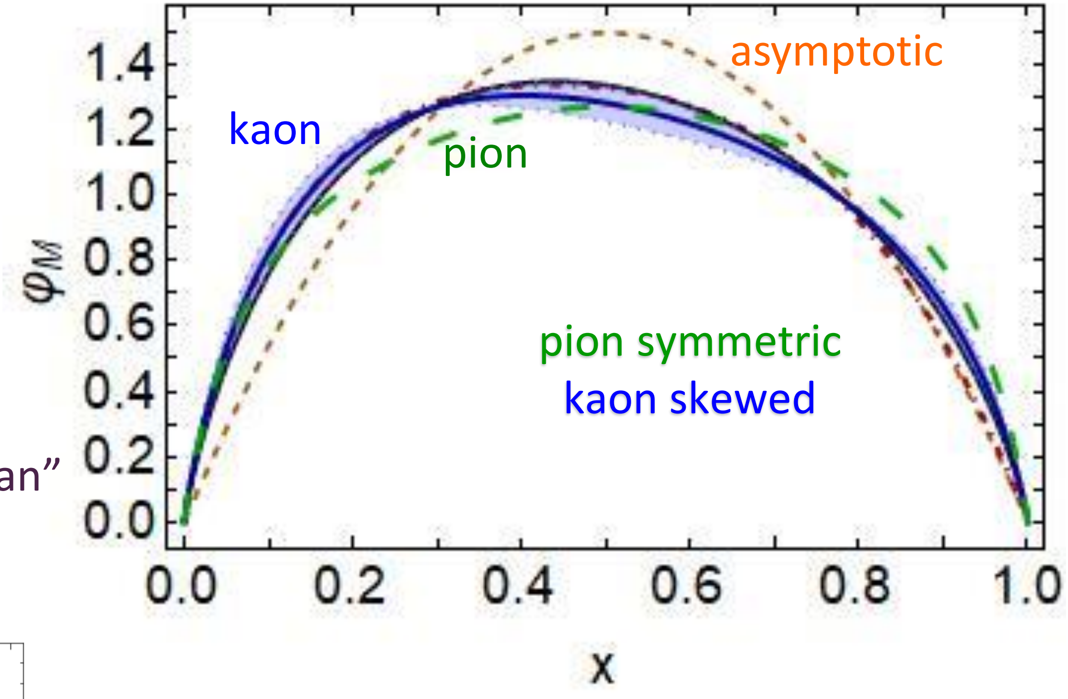
Wave Functions of Nambu Goldstone Bosons

- 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 and Kaon Distribution Amplitudes in the Continuum Limit

Rui Zhang,[1,2,*] Carson Honkala,[3] Huey-Wen Lin,[1,2,†] and Jiunn-Wei Chen[4,‡]

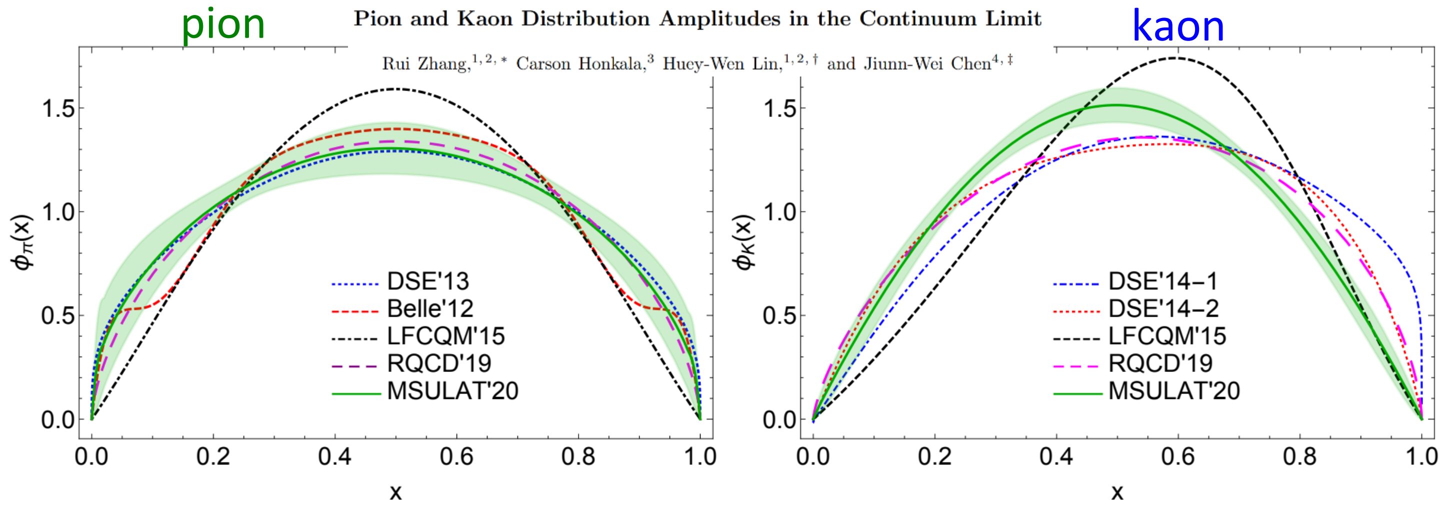


FIG. 10. Fit of the $P_z = 4\frac{2\pi}{L}$ pion (left) and kaon (right) data to the analytical form in Bjorken-x space, compared with previous calculations (with only central values shown). Although we do not impose the symmetric condition $m = n$, both results for the pion and kaon are symmetric around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

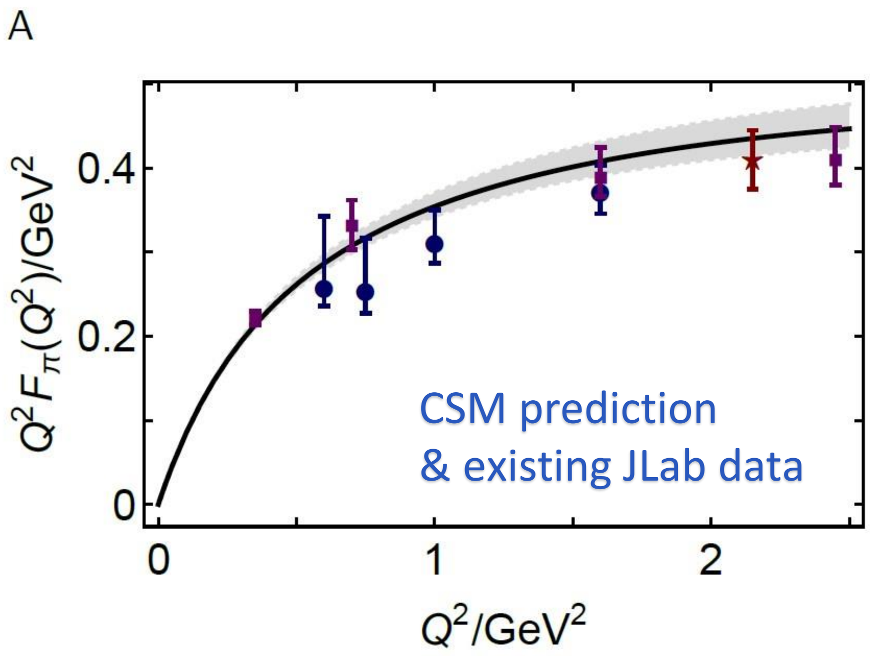
- ➢ Kaon DA vs pion DA
  - – almost as broad
  - – peak shifted to x=0.4(5)
  - – $\langle\xi^2\rangle = 0.24(1)$, $\langle\xi\rangle = 0.035(5)$
- ➢ ERBL evolution logarithmic
- ➢ Broadening & skewing persist to ***very*** large resolving scales – beyond LHC

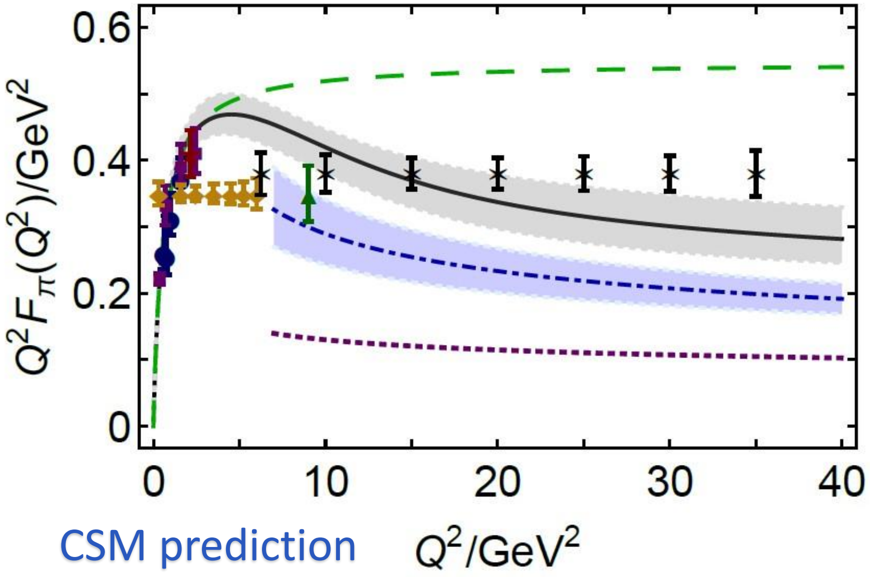
Wave Functions of Nambu Goldstone Bosons

- Scientific Context:
  - Today, 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

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 $\frac{1}{14{,}000{,}000}$
- 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

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*


Thankyou