NANJING UNIVERSITY

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

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

Emergence of Mass in the Standard Model

Quantum Chromodynamics

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

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

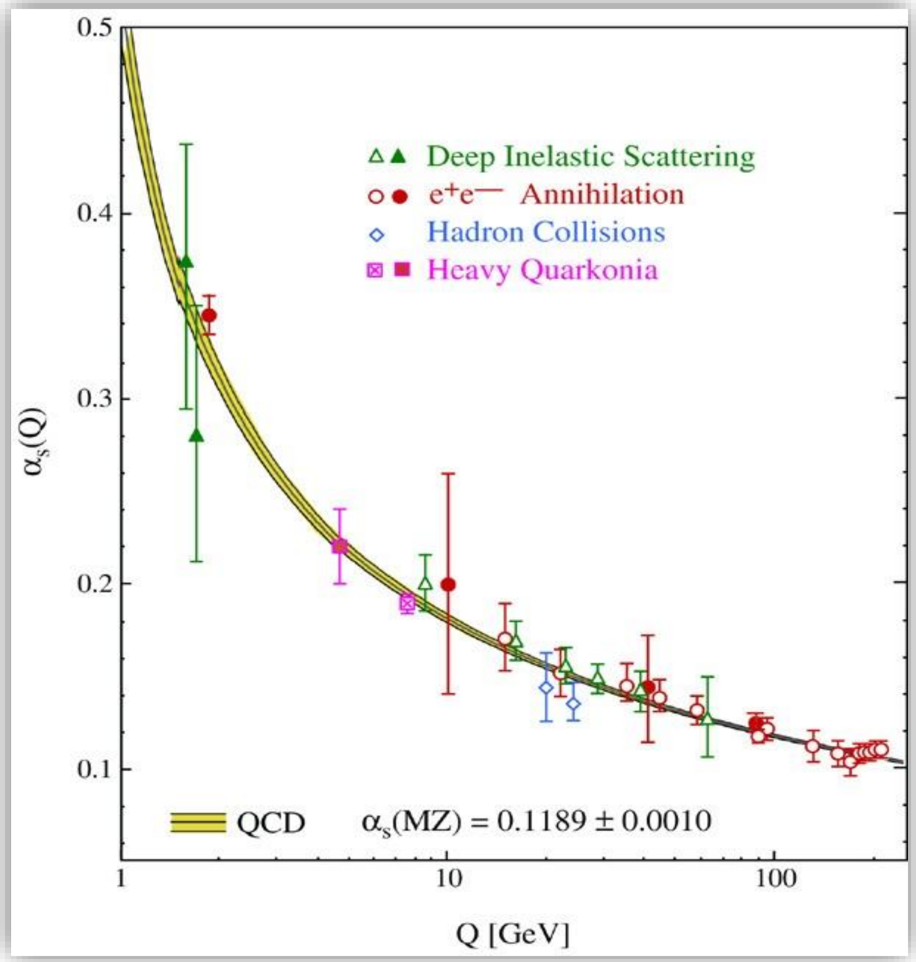
- One-line Lagrangian – expressed in terms of gluon and quark partons
- Which are NOT the degrees-of-freedom measured in detectors

Questions

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

This is where we live

⇐
What's happening out here?!



QCD's Running Coupling

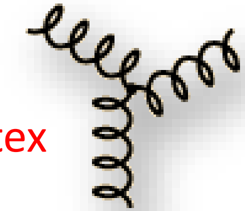
Modern Understanding Grew Slowly from *Ancient* Origins

- More than 40 years ago

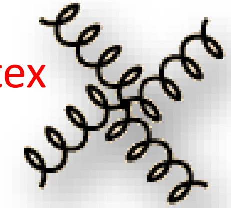
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1050 citations

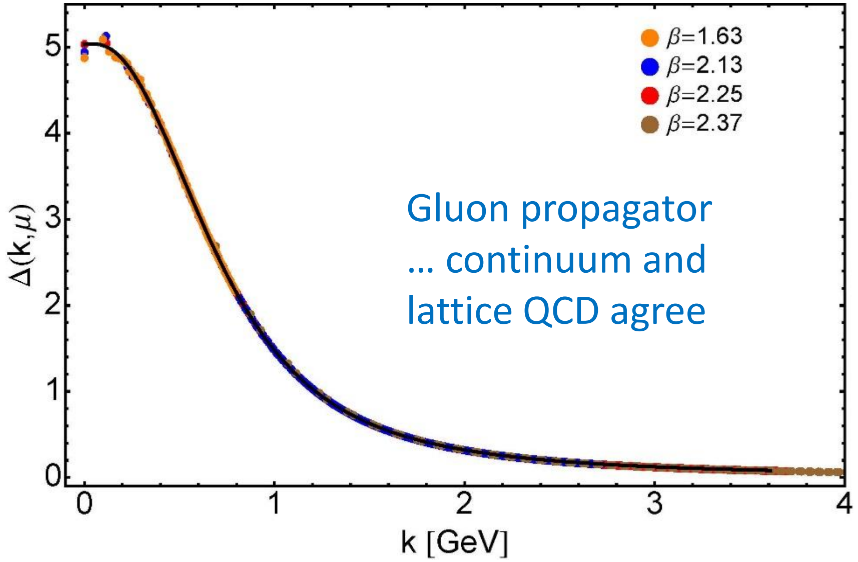
- Owing to strong self-interactions, gluon partons become gluon quasiparticles, described by a mass function that is large at infrared momenta

3-gluon vertex



4-gluon vertex





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

This is a QCD fact
Continuum theory and lattice simulations agree

Empirical verification?

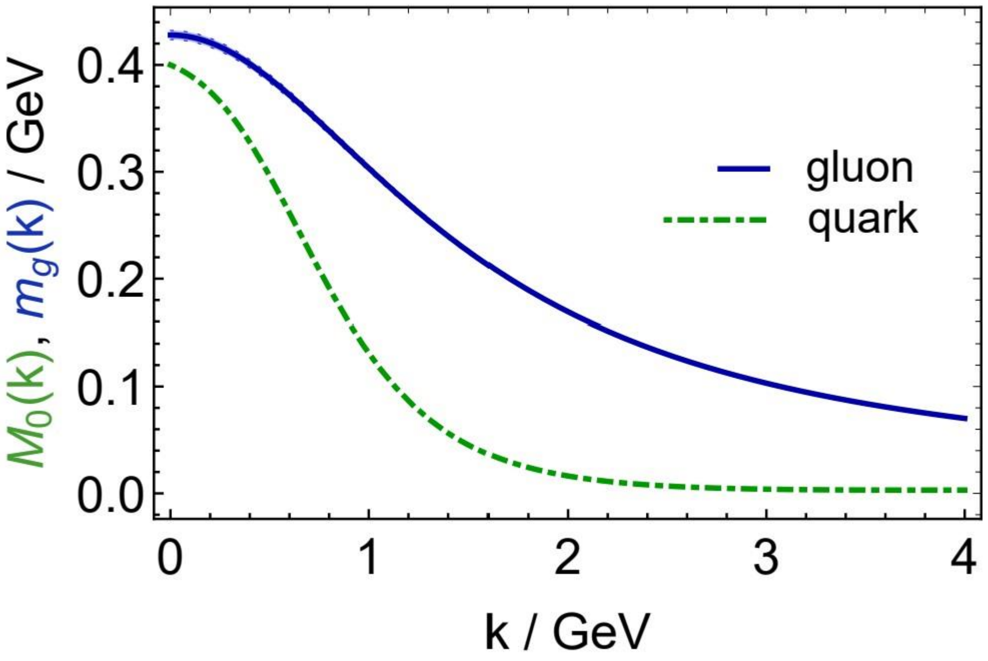
Today: Gluon Mass Function

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

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

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

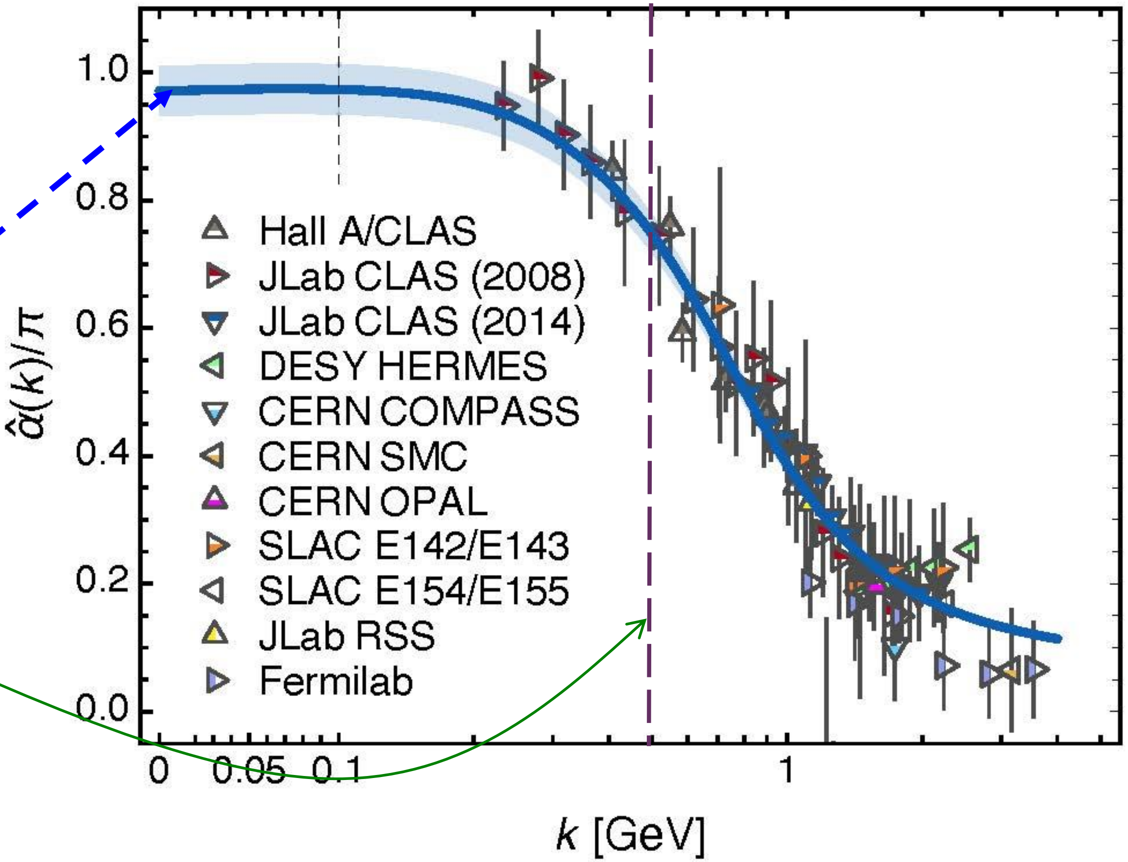


J. Papavassiliou

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

Process independent effective charge = running coupling

- Modern theory enables QCD analogue of "Gell-Mann – Low" running charge to be rigorously defined and calculated
- Analysis of QCD's gauge sector yields a *parameter-free prediction*
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$
- No Landau Pole
  - "Infrared Slavery" picture is not correct
- Below $k \sim \widehat{m}_0$, interactions become scale independent, just as they were in the Lagrangian; so, QCD becomes practically conformal again



The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74

Process independent strong running coupling
Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

Effective charge from lattice QCD, Zhu-Fang Cui et al., NJU-INP 014/19, arXiv:1912.08232 [hep-ph], Chin. Phys. C **44** (2020) 083102/1-10

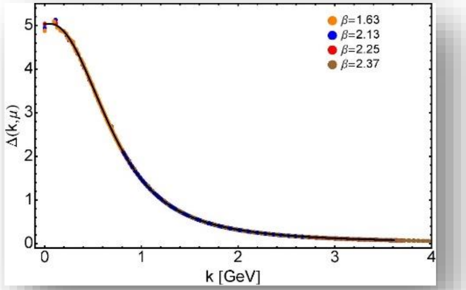
All mass is interaction.

— Richard P. Feynman —

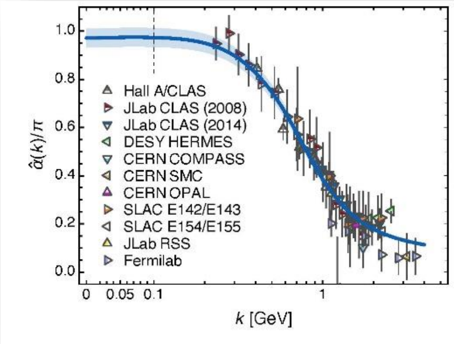
And, in QCD, the absence of mass, too

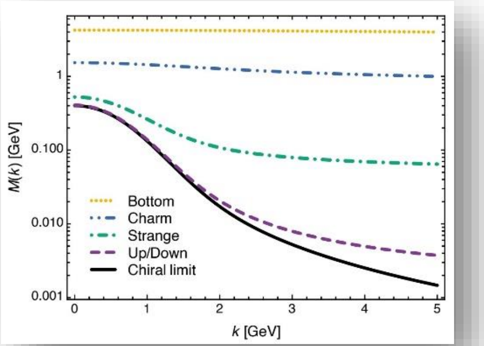
[redacted]

EHM Basics

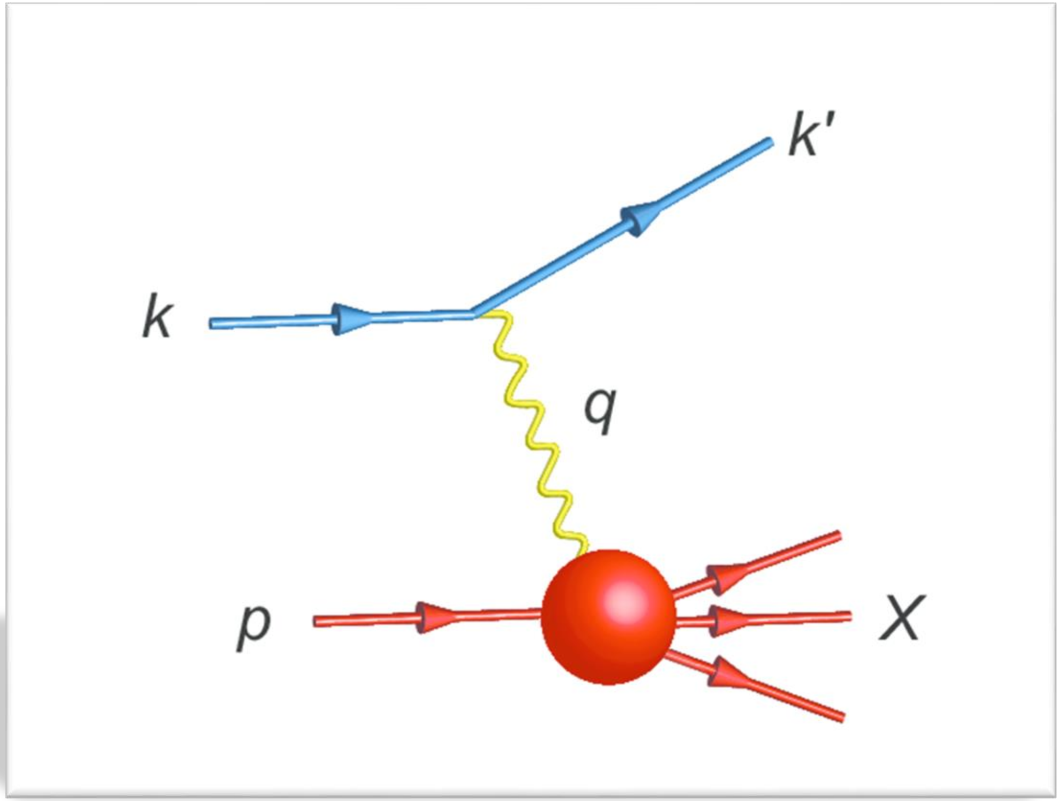


- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent scale-expressing charge is produced
  - Massless quarks become massive





- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- Challenge to Experiment =
  Test the theory predictions so that
  the boundaries of the Standard Model can finally be drawn



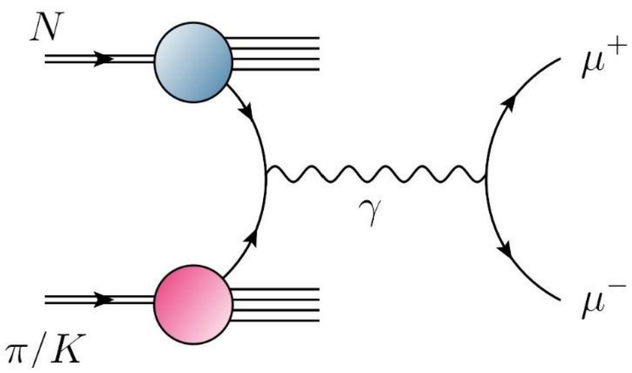
Parton Distribution Functions

NG Boson Distribution Functions

Insights into the Emergence of Mass from Studies of Pion and Kaon Structure, Craig D. Roberts, David G. Richards, Tanja Horn and Lei Chang, NJU-INP 034/21, arXiv: 2102.01765 [hep-ph], Prog. Part. Nucl. Phys. **120** (2021) 103883/1-65

- Physics Goals:
  - Precise data that can be used to determine
    Pion and Kaon Distribution Functions – valence, sea and glue
  - Provide the first complete charts of the internal structure of Nature's most fundamental Nambu-Goldstone bosons.
- Today:
  - Existing pion data are more than 40-years-old
  - That data only covers the valence-quark domain
  - A forty-year controversy, with doubts persisting over whether the data agree with QCD predictions or challenge the truth of QCD
  - Regarding the kaon, worldwide, only 8 points of data exist

NG Boson Distribution Functions

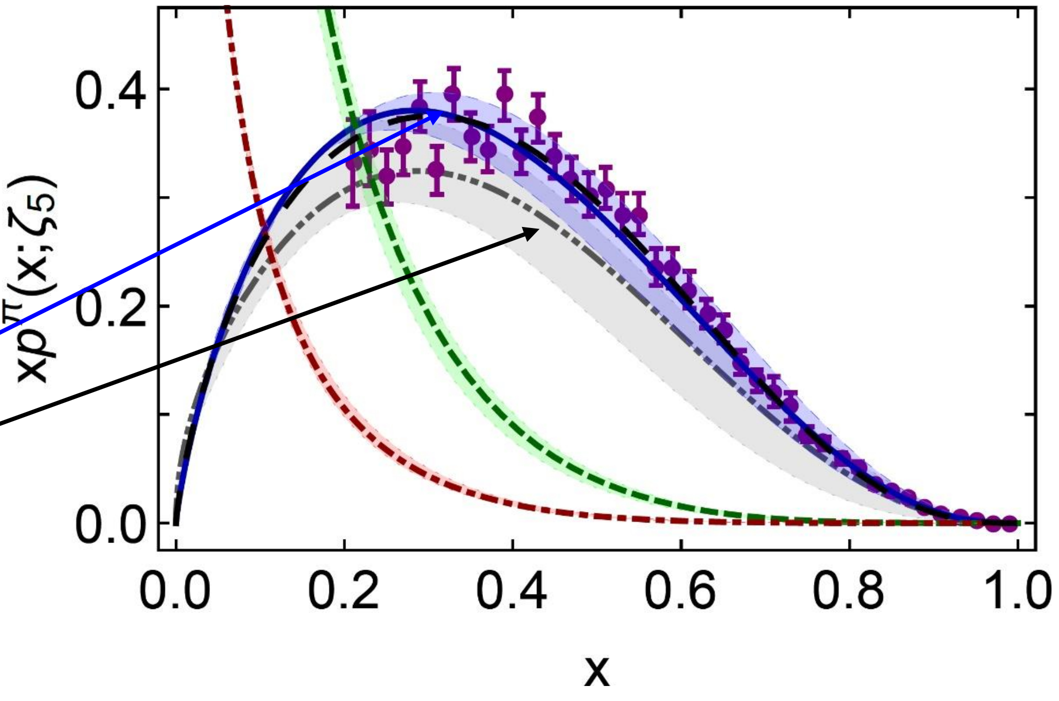


- **Physics Goals**:
  - Precise data that can be used to determine
    Pion and Kaon Distribution Functions – valence, sea and glue
  - Provide the first complete charts of the internal structure of Nature's most fundamental Nambu-Goldstone bosons.
- **Future**:
  - JLab, EIC, EicC
    - ⇒ pion and kaon elastic electromagnetic form factors … reveal and quantify scaling violations in hard exclusive processes … hard prediction of QCD, never seen
    - ⇒ pion and kaon valence quark distribution functions at large x_B
  - AMBER
    - → precision data to chart 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.

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

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

- Developments in continuum-QCD enabled 1st parameter-free predictions of valence, glue and sea distributions within the pion
  - Reveal that $u^\pi(x;\zeta)$ is hardened by EHM
- Novel lattice-QCD algorithms beginning to yield results for pointwise behaviour of $u^\pi(x;\zeta)$
- Agreement between new continuum prediction for $u^\pi(x;\zeta)$ [Ding:2019lwe] and recent lattice-QCD result [Sufian:2019bol]
- Real strides toward understanding pion structure.
- Standard Model prediction: stronger than ever before

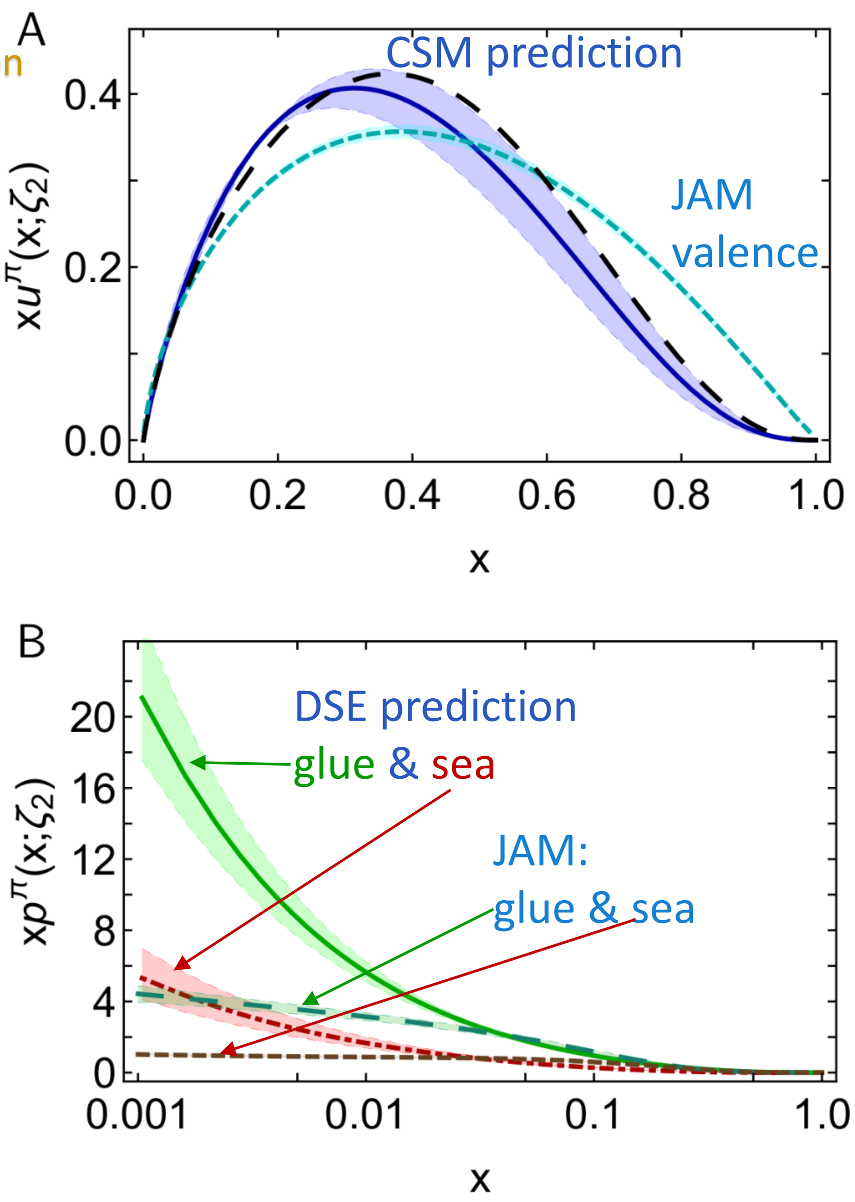


- *After 30 years – new era dawning in which the ultimate experimental checks can be made: M2 beam-line @ CERN … JLab12 … EIC … EicC*

π DFs … Modern Theory Predictions vs Traditional Phenomenological Fits to Data

See also Huey-Wen & Pepe this afternoon … Friday's presentation by Wayne de Paula

- **Valence:**
  - momentum fraction similar
  - Phenomenological Fits … profile much harder & inconsistent with QCD prediction
- **Glue:**
  - Qualitative similarities on $x \geq 0.05$, but marked quantitative disagreement, especially on complementary domain
  - Both continuum prediction and fit are very different from early phenomenology
  - Should be tested in new experiments that are directly sensitive to the pion's gluon content.
  - E.g., prompt photon & J/Ψ production
- **Sea:**
  - Prediction and fit disagree on entire x-domain
  - If pion's gluon content is considered uncertain, then fair to describe sea-quark distribution as empirically unknown
  - Motivation for the collection and analysis of DY data with $\pi^{\pm}$ beams on isoscalar targets



π DFs … Modern Theory Predictions vs Traditional Phenomenological Fits to Data

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

Breaking news …

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

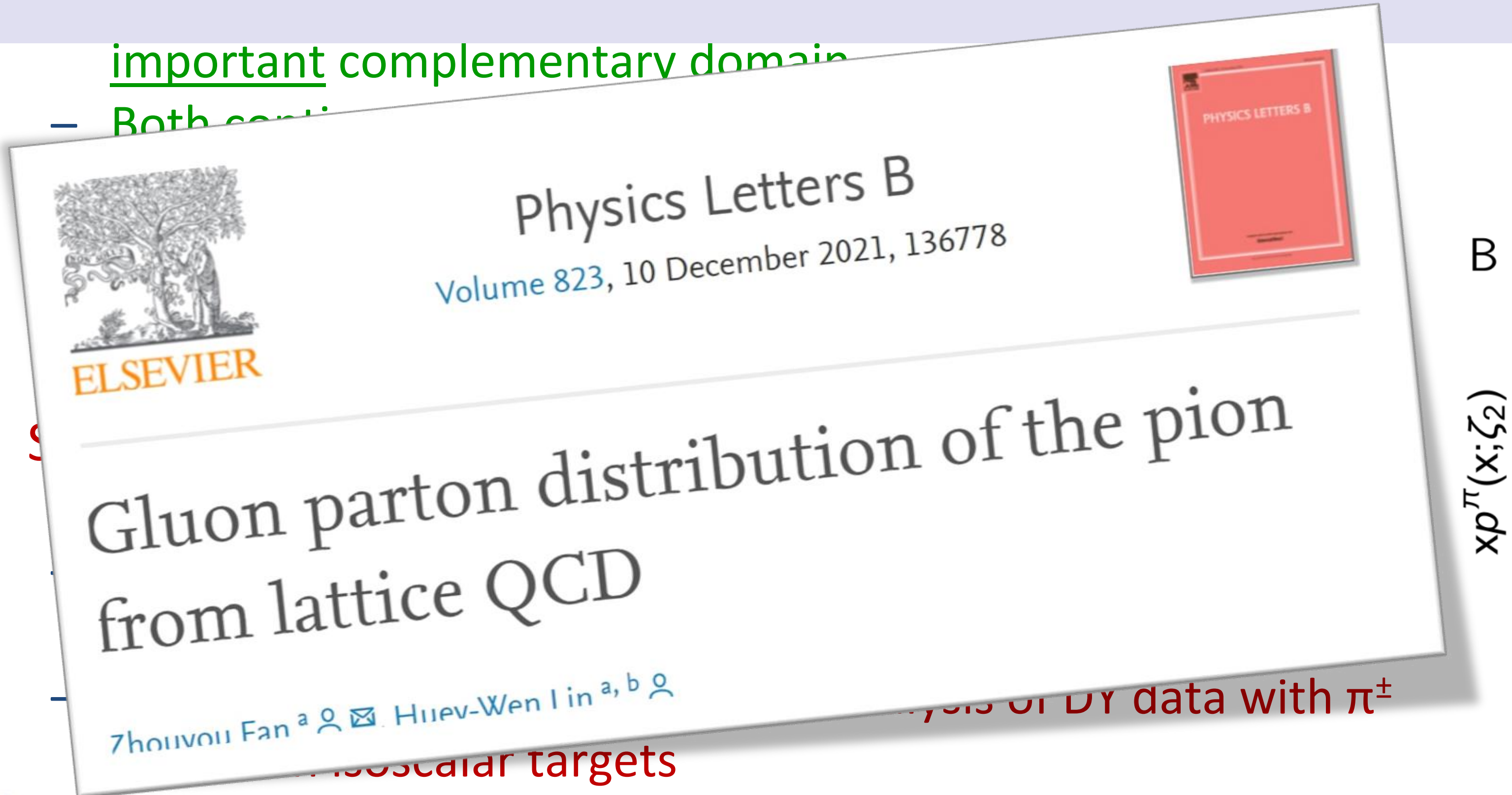
important complementary domain

- Both conti…

- S…

…ysis of DY data with $\pi^{\pm}$

…isoscalar targets


Physics Letters B

Volume 823, 10 December 2021, 136778

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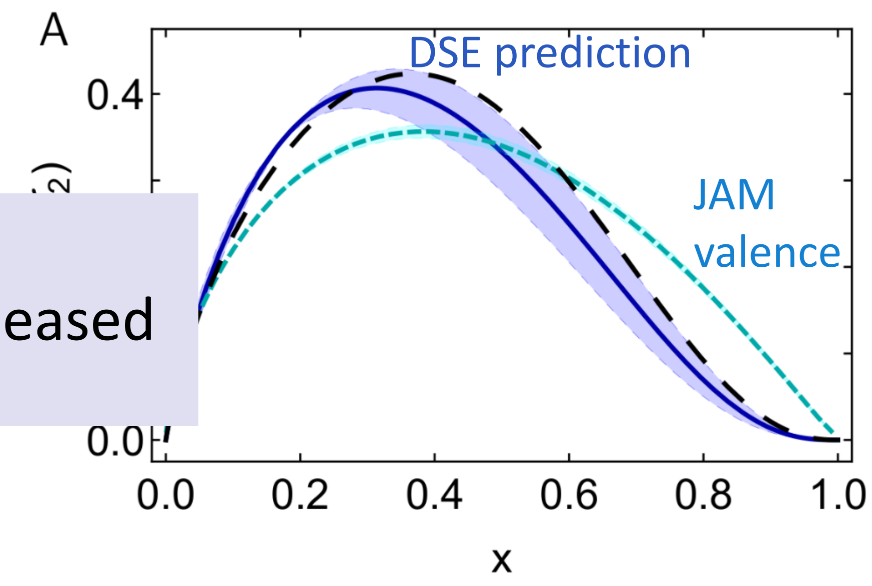
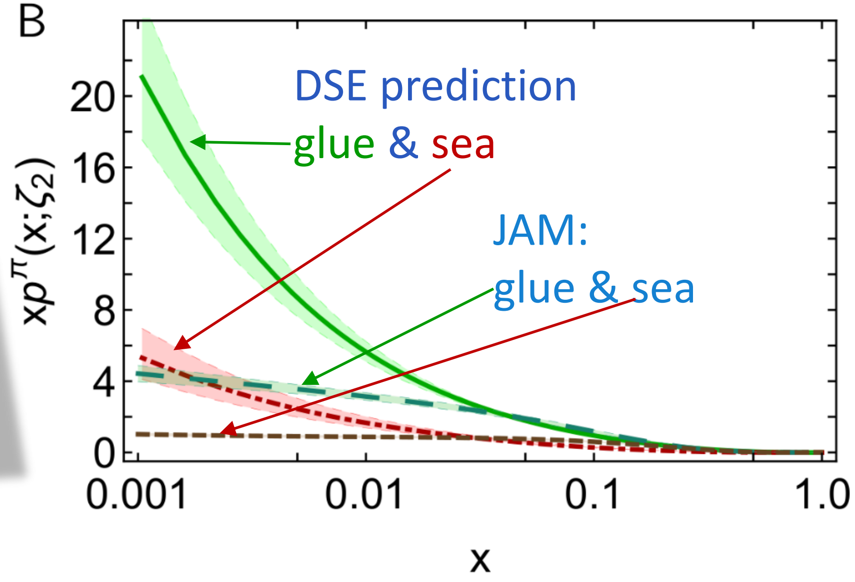
PHYSICS LETTERS B

Gluon parton distribution of the pion from lattice QCD

Zhouyou Fan [a], Huey-Wen Lin [a, b]





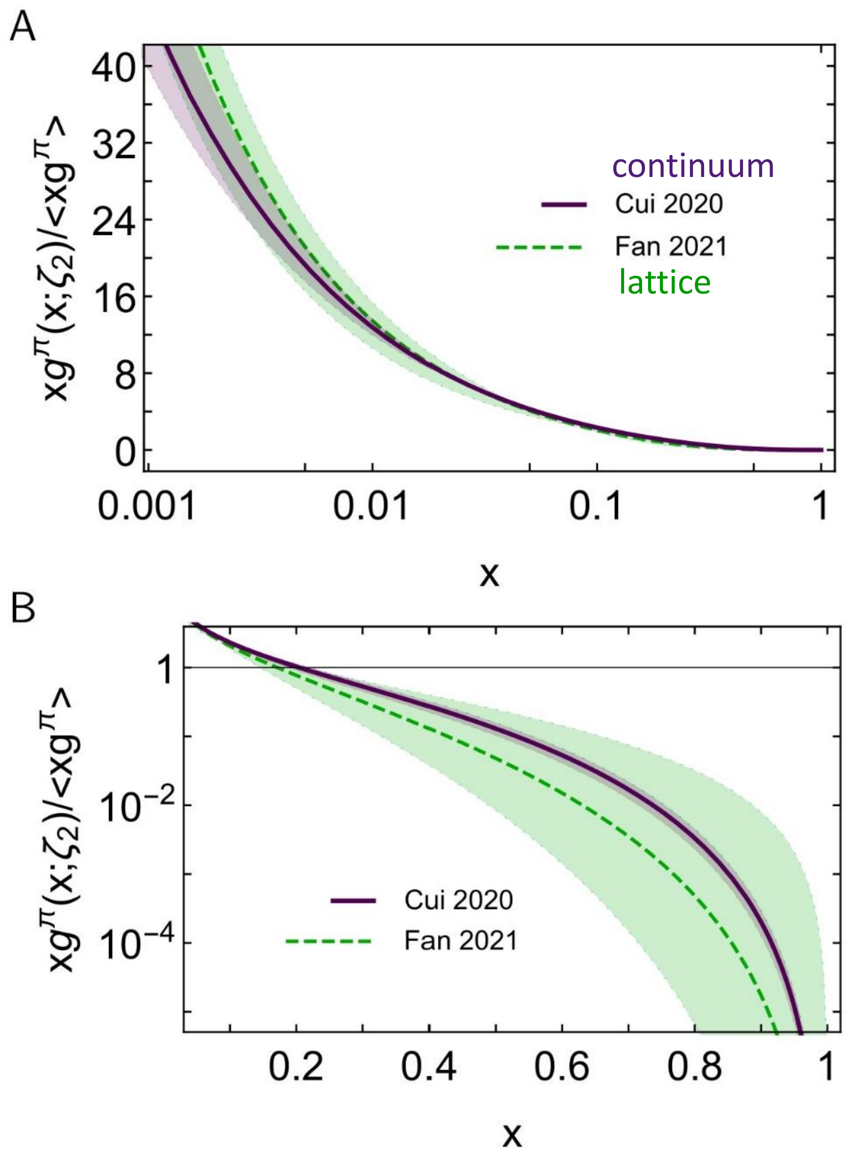
Breaking news for glue in π: Continuum (Eur. Phys. J. C 80 (2020) 1064/1-20) & Lattice Predictions (arXiv:2104.06372)

Two distinct methods for tackling QCD
Agree quantitatively on $g^{\pi}(x)$

- Phenomenological analyses
  exhibit qualitatively different behaviour

- Highlights need for new data and improved phenomenology in order to turn that data into a real test of QCD and our understanding of Nambu-Goldstone modes.

- AMBER @ CERN can provide the necessary precise data.



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

Status: Kaon

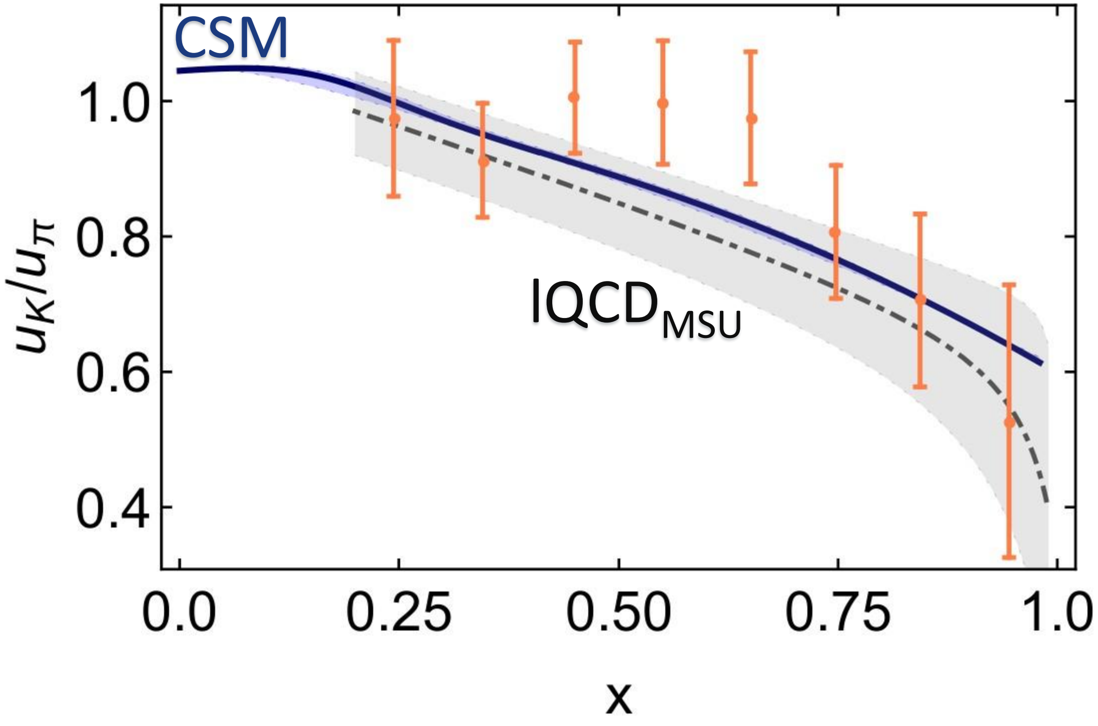
- Little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no results
- One piece of available experimental information:

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

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

Programmes at JLab, AMBER
Proposals at EIC and EicC
Tackling the kaon structure function at EicC
Gang Xie *et al.* e-Print: 2109.08483 [hep-ph]

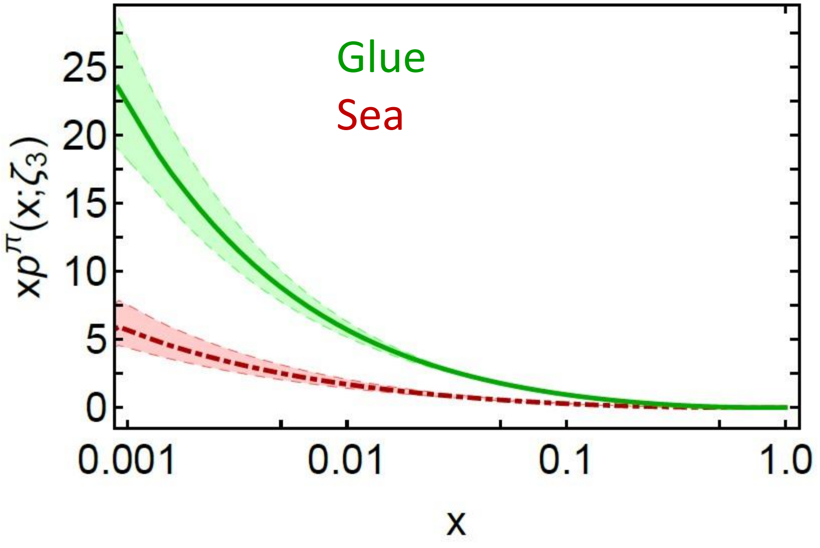
Entirety of Human history
– only 8 kaon data in existence
CERN … *Phys. Lett. B* 93 (1980) 354-356

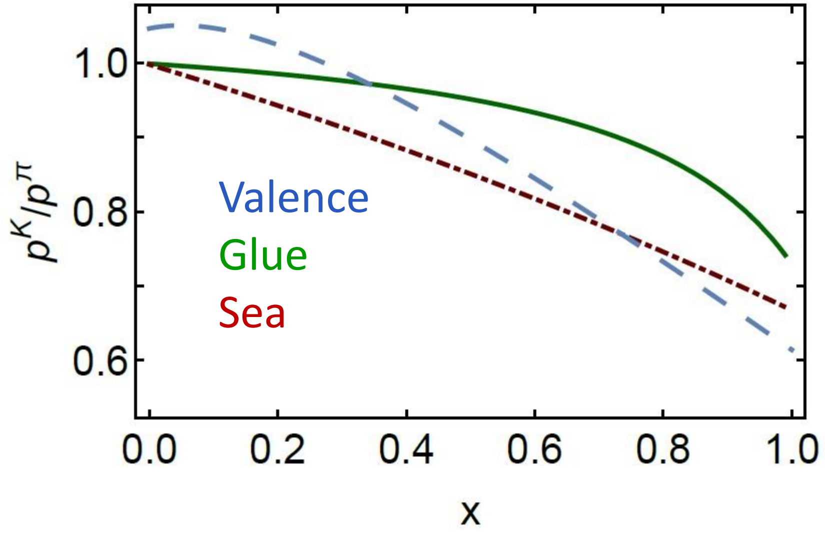


Status: Kaon

Kaon parton distributions, Z.-F. Cui et al., arXiv:2006.14075 [hep-ph], Eur. Phys. J. C 80 (2020) 1064/1-20

- Little empirical information available on K DFs ⇒ no recent phenom. inferences.
  - Valence-quark distributions: results from models and a single, recent lQCD study
  - Kaon's glue and sea distributions: no predictions … until now
- Glue and Sea – Predictions:
  - DFs similar to those in the pion
  - Detailed comparison requires use of mass-dependent splitting functions.
  - Development underway … Preliminary conclusions:
    1. Light-front momentum fraction carried by s-quarks in the kaon increases by ~ 5%;
    2. Compensated by a commensurate decrease in fractions carried by glue (−1%) and sea (−2%).





Proton and pion distribution functions in counterpoint

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

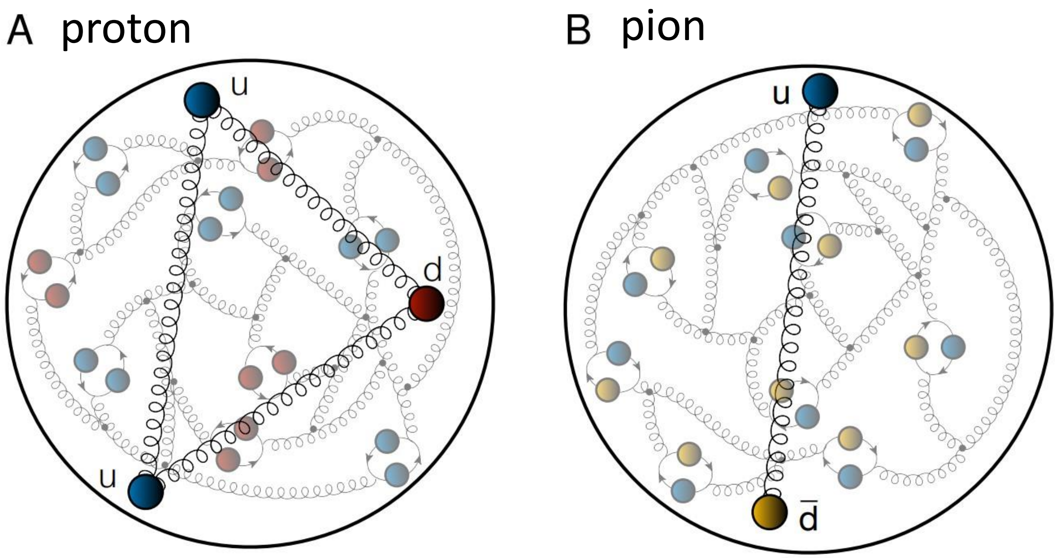


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

Proton and pion distribution functions in counterpoint

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

- Valence-quark domain: there is a scale $\zeta_H < m_p$ at which
$$\begin{cases} d^p(x;\zeta_H),\, u^p(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_H),\, u^\pi(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^2 \end{cases}$$
- Gluon DFs have power at least one unit larger
- Sea DFs have power at least two units larger

- Further, no simultaneous global fits to proton and pion data have ever been performed
- Largely because pion data are scarce
- Existing approaches are unlikely to yield definitive answers because practitioners typically ignore QCD constraints

✓ These are simple consequence of DGLAP equations.

✓ Notably, argument can be reversed:

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

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

✓ Modern global analyses of proton DIS and related data encompass fits with role of glue and valence-quarks reversed!

✓ Proton has valence glue but no valence quarks!

Proton and pion distribution functions in counterpoint

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

- Valence-quark domain: there is a scale $\zeta_H < m_p$ at which $\left\{ \begin{array}{l} d^p(x;\zeta_H), u^p(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_H), u^\pi(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^2 \end{array} \right.$
- Gluon DFs have power at least one unit larger
- Sea DFs have power at least two units larger

- Further, no simultaneous global fits to proton and pion data have ever been performed
- Largely because pion data are scarce
- Existing approaches are unlikely to yield definitive answers because practitioners typically ignore QCD constraints

✓ These are simple consequence of DGLAP equations.

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

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

T.-J. Hou, *et al.*, *New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC*, Phys. Rev. D 103 (1) (2021) 014013

Proton and pion distribution functions in counterpoint

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

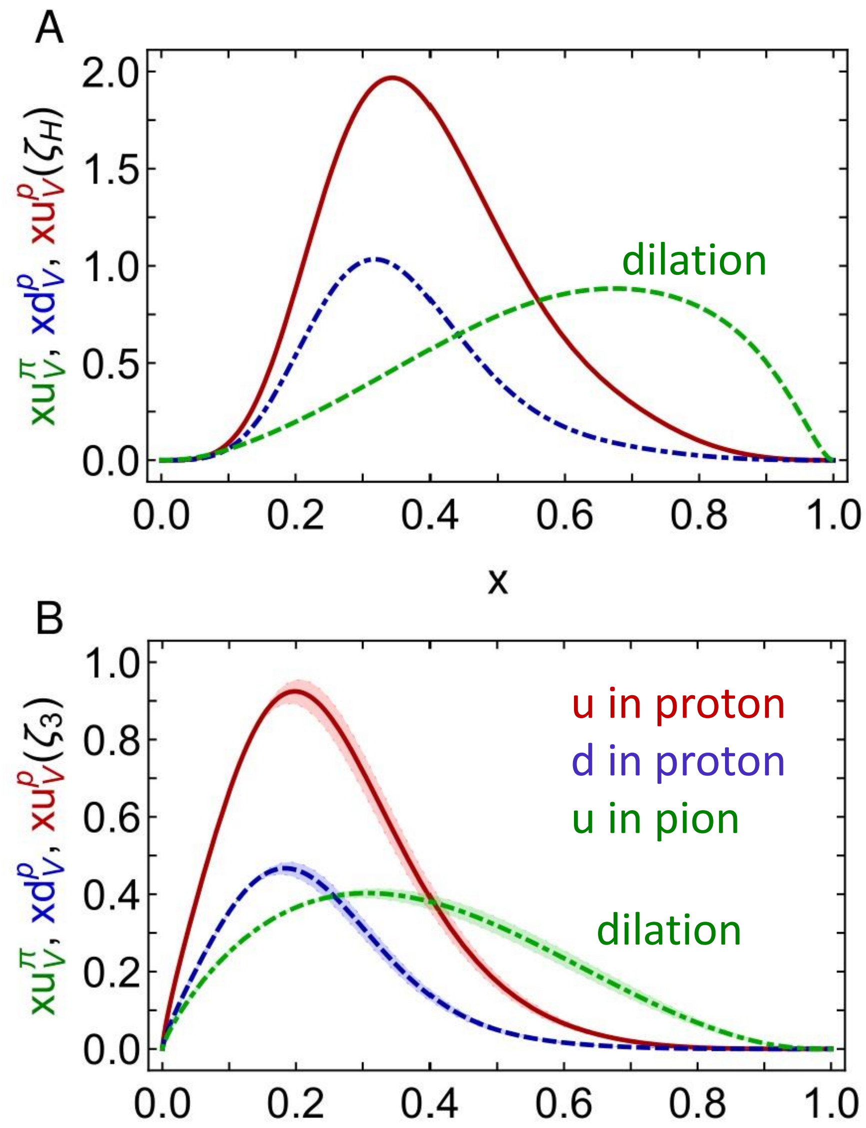
- Symmetry-preserving analyses using continuum Schwinger function methods (CSMs) deliver hadron scale DFs that agree with QCD constraints

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

- Valence-quark degrees-of-freedom carry all hadron's momentum at ζ_H
- Diquark correlations in proton, induced by EHM

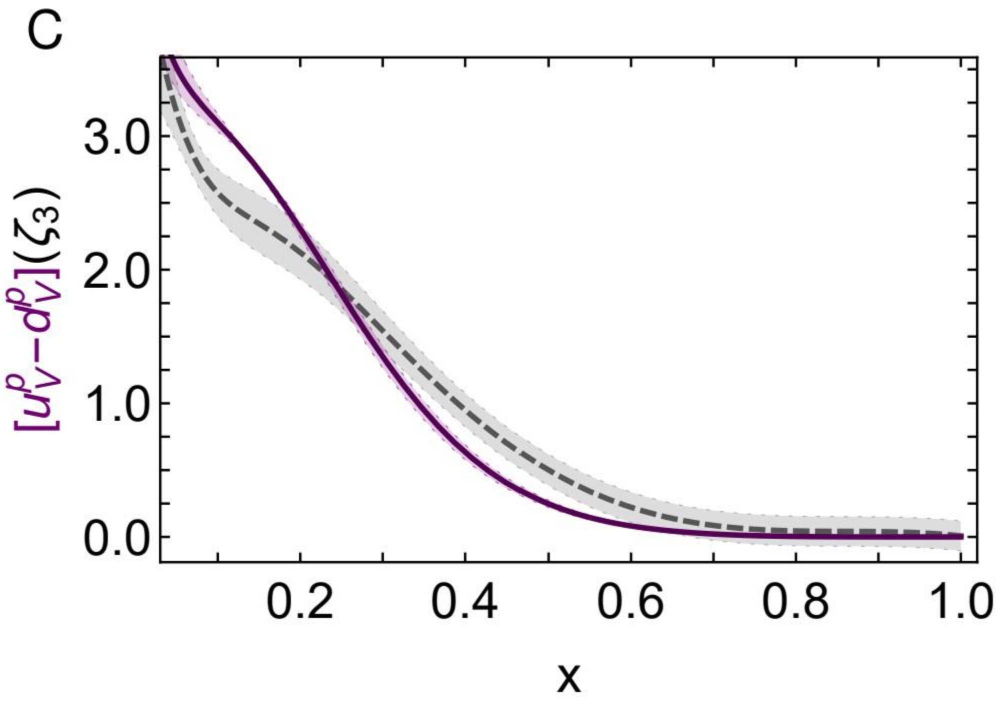
$$\Rightarrow u_V\ (x) \neq 2d_V(x)$$

- Proton and pion valence-quark DFs have markedly different behaviour
  - $u^\pi(x;\zeta_H)$ is Nature's most dilated DF
  - "Obvious" because of $(1-x)^2$ vs. $(1-x)^3$ behaviour and preservation of this unit difference under evolution
  - Also "hidden" = strong EHM-induced broadening



Proton valence-quark DFs: Continuum cf. Lattice

- Owing to difficulties in handling so-called disconnected contributions, the calculation of individual valence DFs using lattice-regularised QCD (lQCD) is problematic
- lQCD results are typically only available for isovector distributions, from which disconnected contributions vanish in the continuum limit.
- Comparison of isovector distributions
  $$u^p(x;\zeta_3) - d^p(x;\zeta_3)$$
- Completely different approaches; yet good agreement, especially since refinements of both calculations may be anticipated.



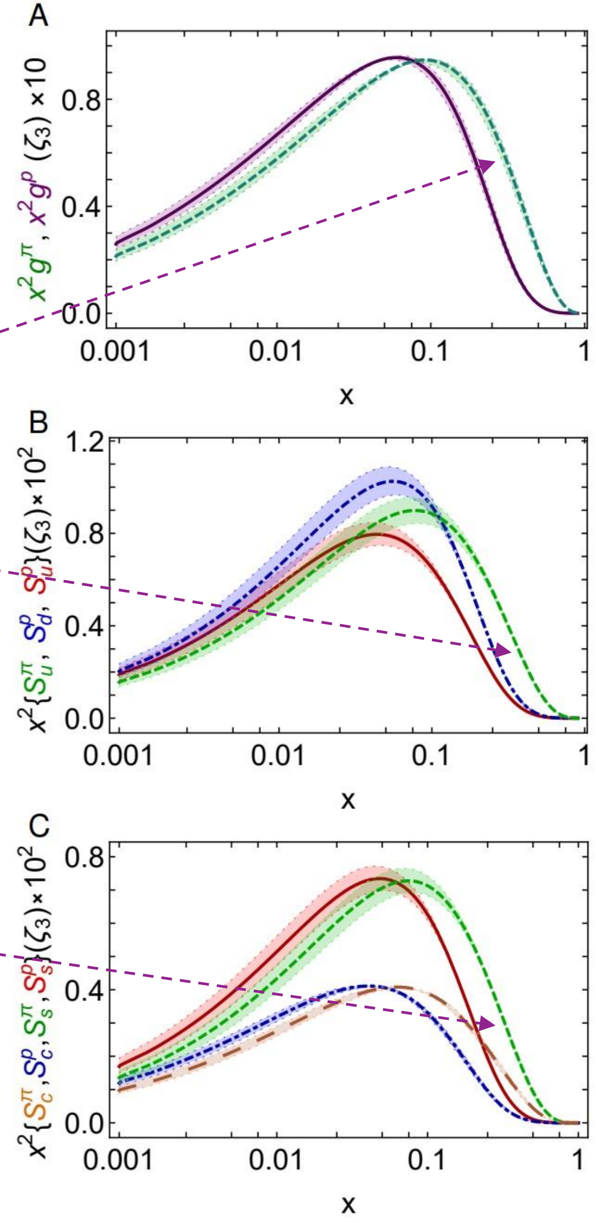
✓ Continuum: *Proton and pion distribution functions in counterpoint*, Ya Lu (陆亚) *et al.*, NJU-INP 056/22, e-Print: 2203.00753 [hep-ph]

✓ Lattice: *Nucleon Isovector Unpolarized Parton Distribution in the Physical-Continuum Limit*, H.-W. Lin *et al.*, arXiv:2011.14971 [hep-lat]

Proton and pion distribution functions in counterpoint - glue and sea

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

  [*Regarding the distribution of glue in the pion*, Lei Chang (常雷) and Craig D Roberts, e-Print: 2106.08451 [hep-ph], Chin. Phys. Lett. 38 (8) (2021) 081101/1-6]
- Glue-in-π DF possess significantly more support on the valence domain than the glue-in-p DF
- Sea-in-π DF possess significantly more support on the valence domain than sea-in-p DFs.
- *s* and *c* sea DFs are commensurate in size with those of the light-quark sea DFs
- For s-and c-quarks, too, the pion DFs possess significantly greater support on the valence domain than the kindred proton DFs.
- These outcomes are measurable expressions of EHM



Asymmetry of antimatter in the proton

- Pauli blocking: gluon splitting produces

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

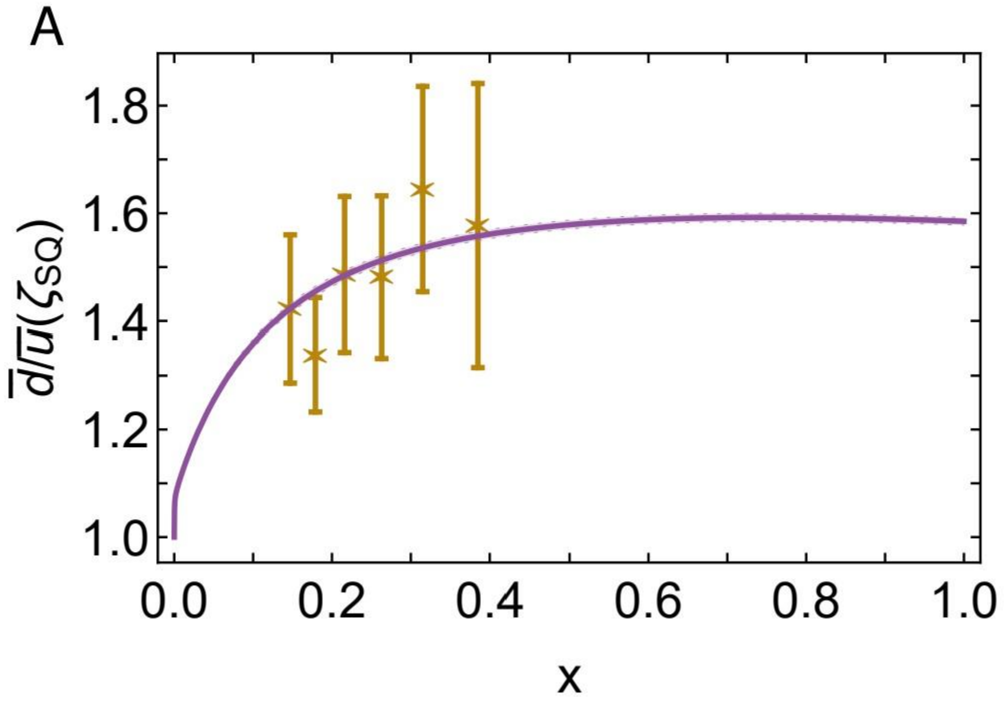
- Comparison with SeaQuest data

  [J. Dove, et al., *The asymmetry of antimatter in the proton*, Nature 590 (7847) (2021) 561–565.]

- Gottfried sum rule

$$\int_{0.004}^{0.8} dx\,[\bar{d}(x;\zeta_3) - \bar{u}(x;\zeta_3)] = 0.116(12)$$

  ✓ Most recent result from global fits [CT18]: 0.110(80)



Neutron/Proton structure function ratio

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

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

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

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

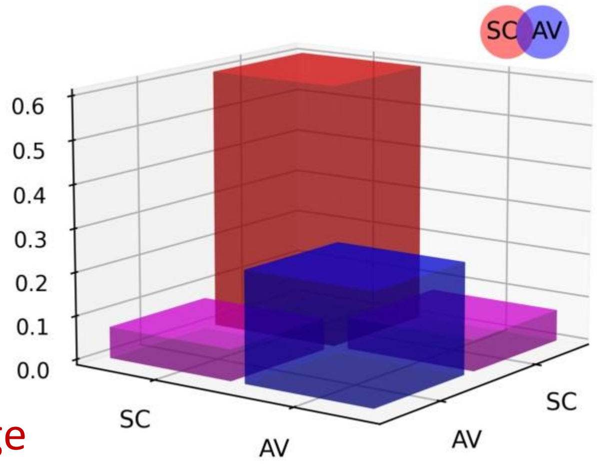
- Comparison with MARATHON data

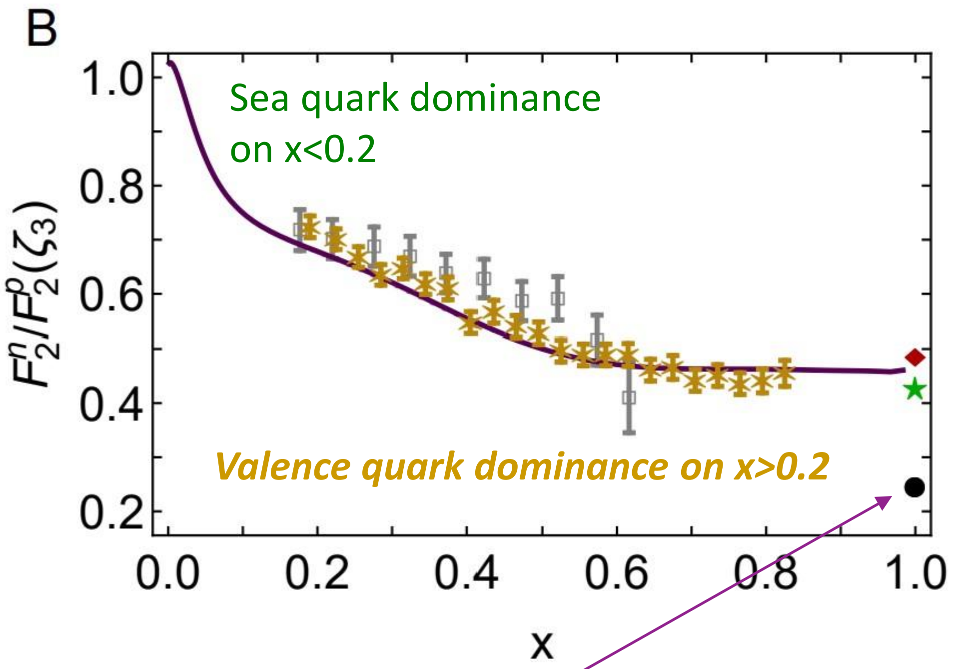
  [D. Abrams, *et al*., Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- Agreement with modern data on entire x-domain

✓ CSM prediction = presence of axial-vector diquark correlation in the proton

✓ Responsible for ≈ 40% of proton charge





Probability that scalar diquark only models of nucleon might be consistent with available data is 1/7,000,000

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

Proton and pion distribution functions in counterpoint

- CSMs have delivered 1st ever unified body of predictions for all proton and pion DFs – valence, glue, and four-flavour-separated sea.
- Within mesons & baryons that share familial flavour structure, light-front momentum fractions carried by identifiable, distinct parton classes are identical at any scale.

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

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

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

Craig Roberts: cdroberts@nju.edu.cn 408 "Proton & Pion DFs in Counterpoint"

Proton and pion distribution functions in counterpoint

- CSMs have delivered 1st ever unified body of predictions for all proton and pion DFs – valence, glue, and four-flavour-separated sea.
- Within mesons & baryons that share familial flavour structure, light-front momentum fractions carried by identifiable, distinct parton classes are identical at any scale.
- On the other hand, ***smoking gun for EHM***, x-dependence of DFs is strongly hadron dependent
  - At any resolving scale, ζ, those in the pion are the hardest (most dilated).
- All CSM DFs comply with QCD constraints on endpoint (low- and high-x) scaling behaviour.
- However, existing global fits ignore QCD constraints, so:
  - Fail to deliver realistic DFs, even from abundant proton data
  - Meson data almost nonexistent and controversial results from fits
- Only after imposing QCD constraints on future phenomenological data fits will it be possible to draw reliable pictures of hadron structure.
- Especially important for attempts to expose and understand differences between Nambu-Goldstone bosons and seemingly less complex hadrons.

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National Natural Science Foundation of China
NSFC

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

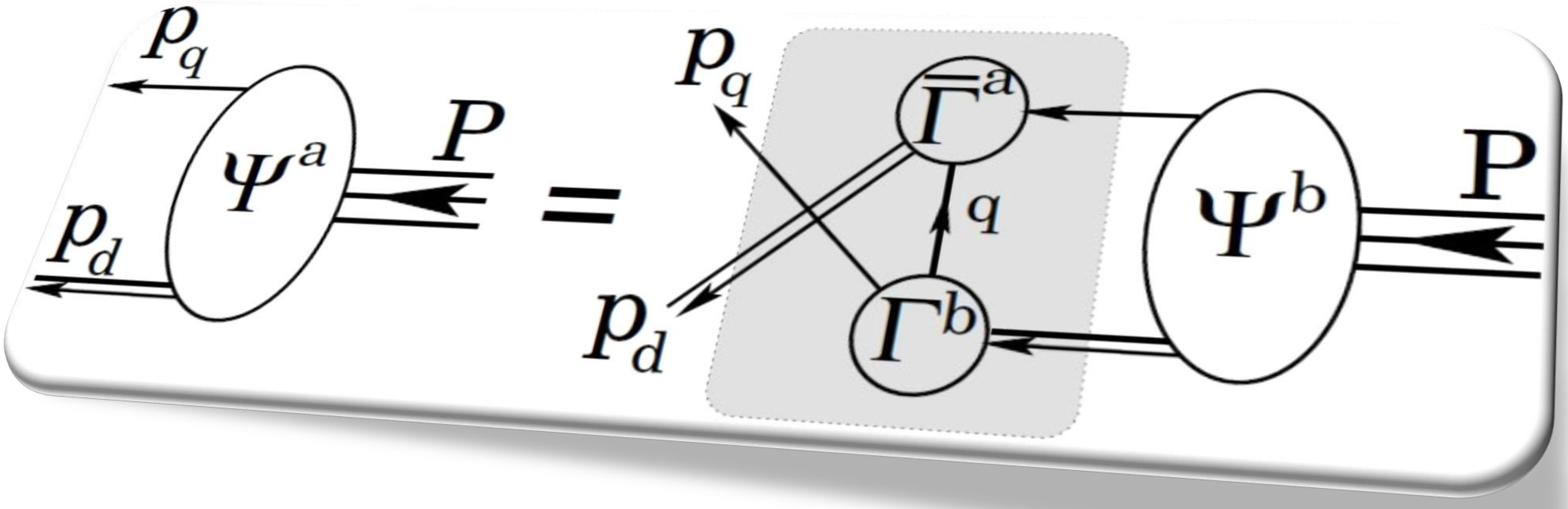
Quantum Chromodynamics

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

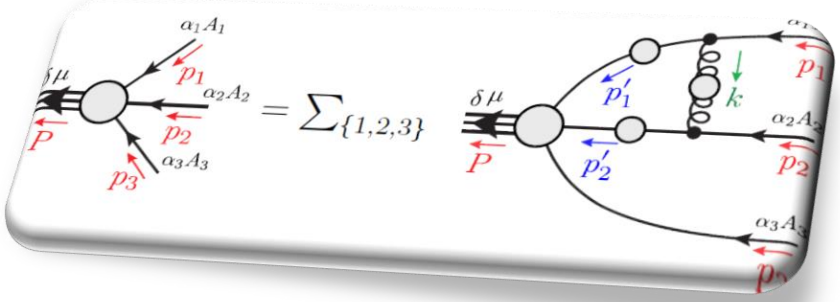
      But Higgs boson mass itself is quadratically divergent $\Rightarrow$ not renormalizable
- Nonperturbative QCD has come a long way in the last few years.
- Beginning to look increasingly likely that QCD is humanity's first well-defined four-dimensional quantum field theory
- Stands alone as an internally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

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

Baryon Structure and QCD
R.T. Cahill, C. D. Roberts, J. Praschifka
Austral. J. Phys. **42** (1989) 129-145

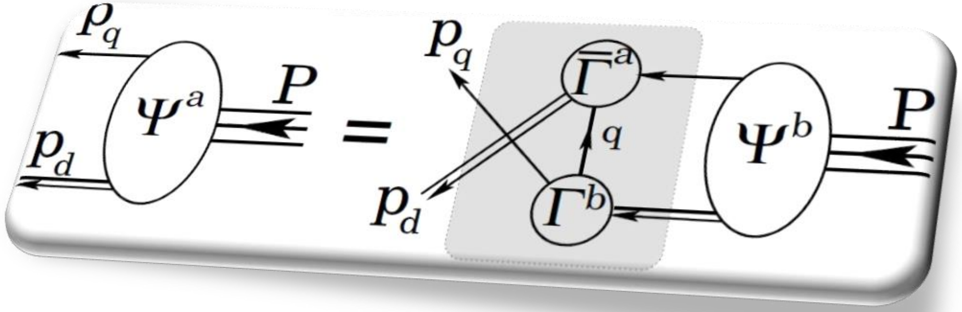


Structure of Baryons - diquark correlations



Structure of Baryons

- Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but numerical challenges remain
- ***Prediction***: owing to EHM phenomena, *strong diquark correlations exist within baryons*
  - proton and neutron … both scalar and axial-vector diquarks are present
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- Confinement and DCSB are readily expressed
- Diquark correlations are not pointlike
  - Typically, $r_{0+} \sim r_\pi$ & $r_{1+} \sim r_\rho$ (actually 10% larger)
  - They have soft form factors



Composition of low-lying $\mathbf{J} = \frac{3}{2}^{\pm}$ $\mathbf{\Delta}$-baryons

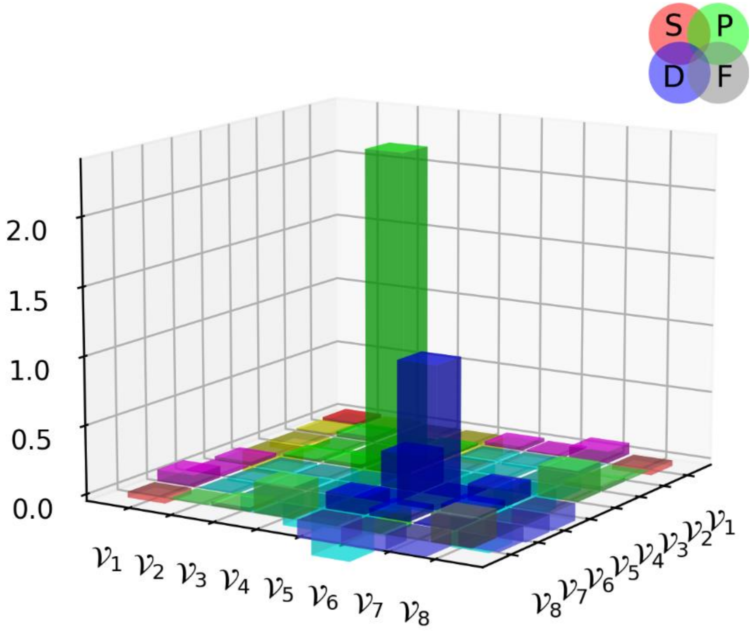
Langtian Liu (Nanjing U.), Chen Chen (Hefei, CUST and PCFT, Hefei), Ya Lu (Nanjing U.), Craig D. Roberts (Nanjing U.), Jorge Segovia (Nanjing U. and Pablo de Olavide U., Seville)

Mar 22, 2022

13 pages

e-Print: 2203.12083 [hep-ph]

Report number: NJU-INP 057/22, USTC-ICTS/PCFT-22-11



Exposing orbital angular momentum structure of, e.g., $\Delta(1700)\,\frac{3}{2}^{-}$ … providing motivation and support for extensive baryon resonance programme at JLab

Electroexcitation of baryon resonances

- *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!
- Poincaré-covariant Faddeev equation is shedding new light on the structure of ALL baryons

Diquarks & Deep Inelastic Scattering

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

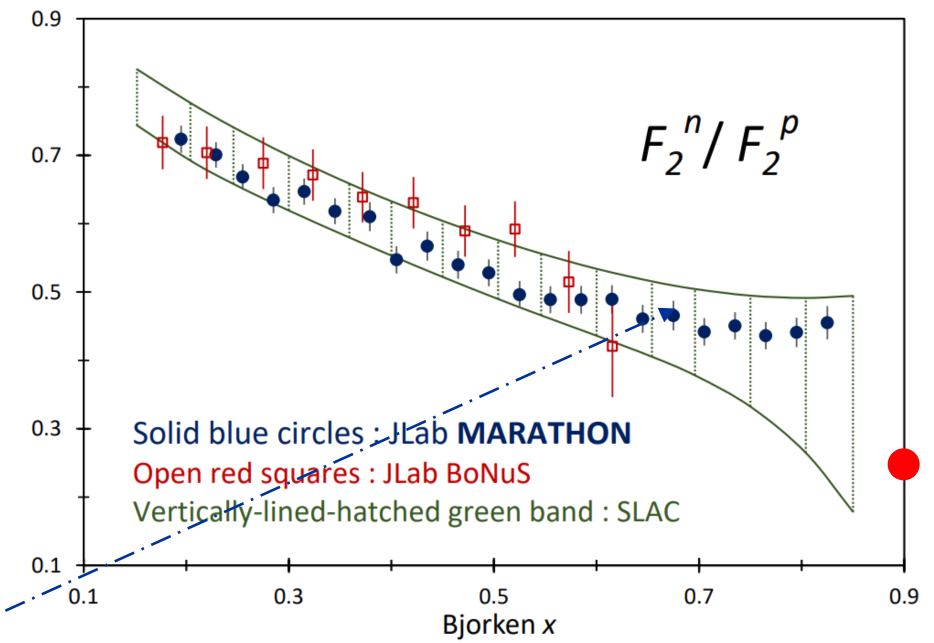
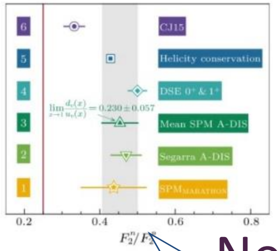


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14\cdot x$ (GeV/c)^2] (see text). All three experimental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

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



Valence Quark Ratio in the Proton

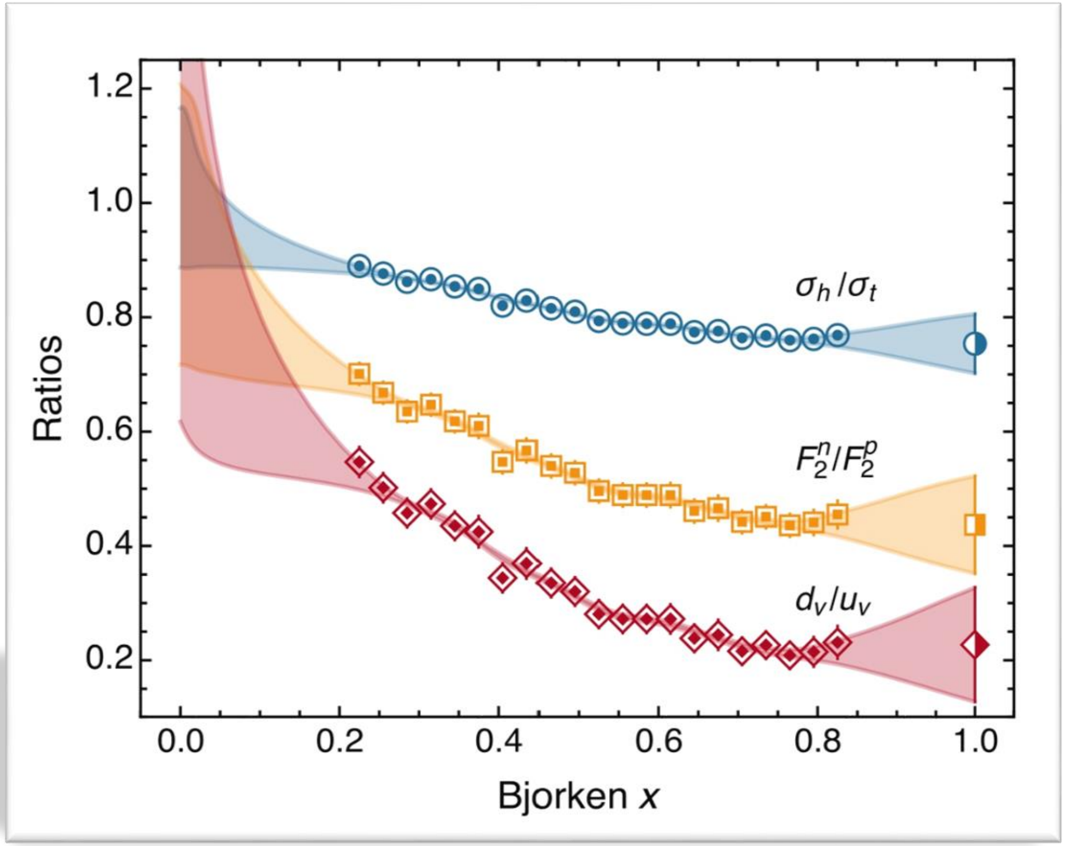
Zhu-Fang Cui, Fei Gao, Daniele Binosi, Lei Chang, Craig D. Roberts, and Sebastian M. Schmidt

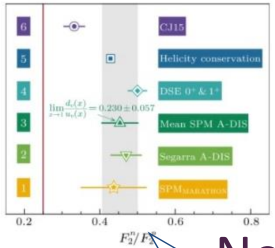
Chin. Phys. Lett. 2022, 39 (**4**): 041401 . DOI: 10.1088/0256-307X/39/4/041401

Abstract HTML PDF (571KB)

MARATHON EXPERIMENT - Schlessinger point method

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





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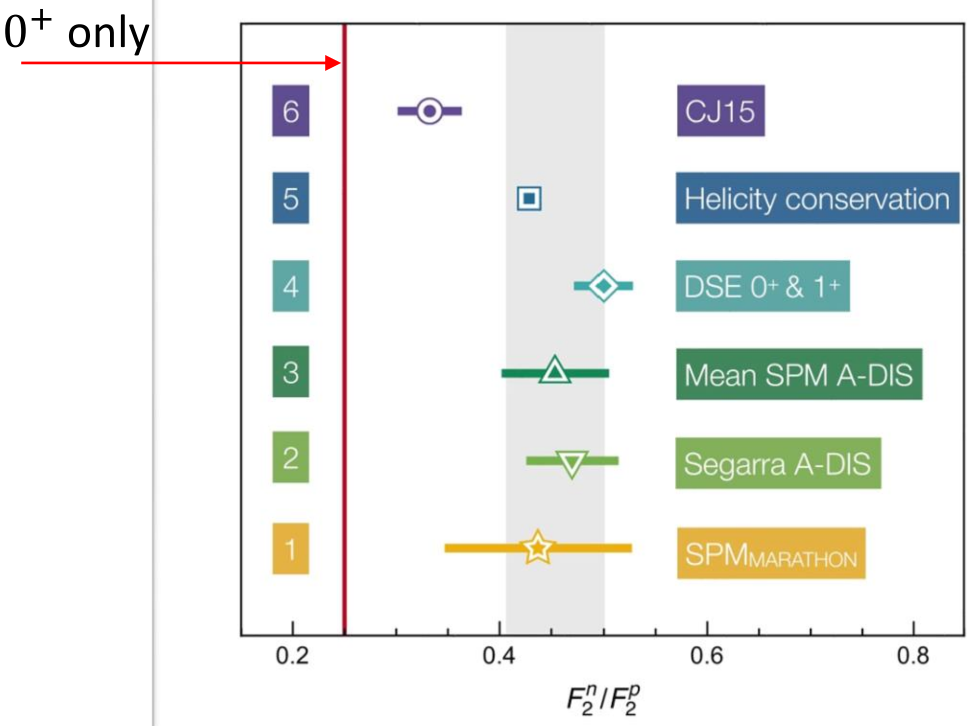

FIG. 3. $\lim_{x\to 1} F_2^n(x)/F_2^p(x)$. MARATHON-based SPM prediction compared with results inferred from: nuclear DIS [35]; Dyson-Schwinger equation analyses (DSE) [57, 58]; quark counting (helicity conservation) [59]; and a phenomenological fit (CJ15) [53]. The vertical red line marks the Nachtmann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