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

Predicting Parton DFs

Parton Distribution Functions

- Parton distribution functions (DFs) = preeminent source of hadron structure information
- Experiments interpretable in terms of DFs have long been a priority ~ 50 years
- For most of this time, DFs were inferred from global fits to data & viewed as benchmarks
  - Such fitting remains crucial, providing input for conduct of many experiments worldwide
- However, past decade has seen dawn of a new theory era
  - Continuum and lattice QCD studies beginning to yield robust predictions for DF(x)
- These developments are exposing conflicts with fitting results
- Such disagreements invite one of the following conclusions:
  a) the global fit outcomes are misconstrued/misrepresented
  b) not all considered data are a true expression of intrinsic hadron qualities
  c) or QCD, as currently understood, is not the theory of strong interactions

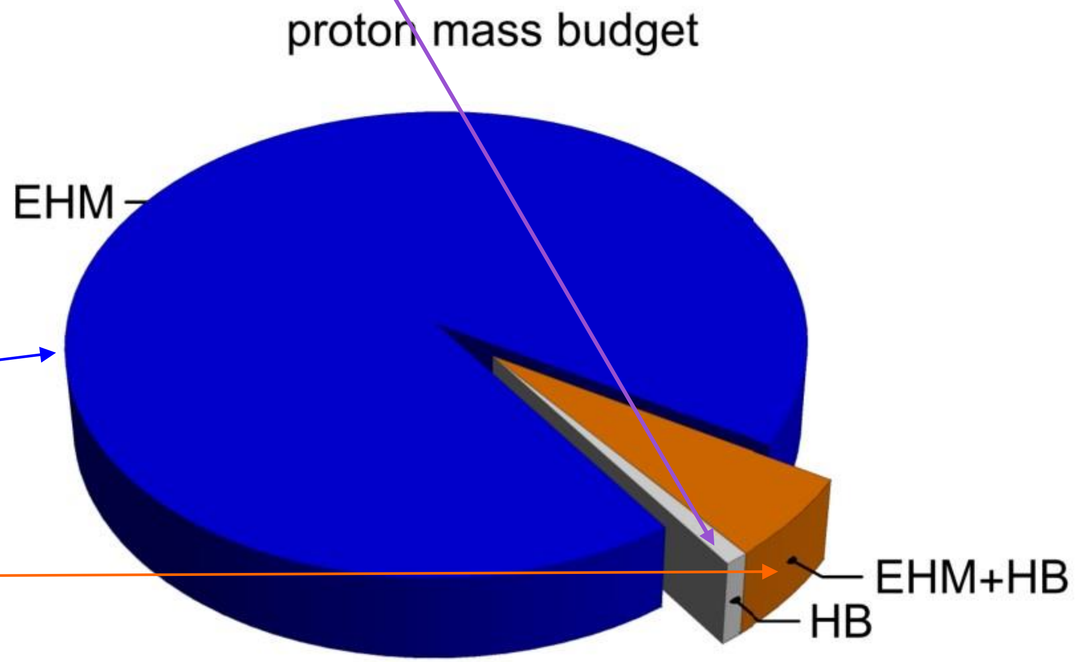
Emergence of Hadron Mass

- Standard Model of Particle Physics has one obvious mass-generating mechanism

  = Higgs Boson … impacts are critical to evolution of Universe as we know it
- However, Higgs boson is alone responsible for just ~ 1% of the visible mass in the Universe
- Proton mass budget … only 9 MeV/939 MeV is directly from Higgs

- Evidently, Nature has another very effective mechanism for producing mass:

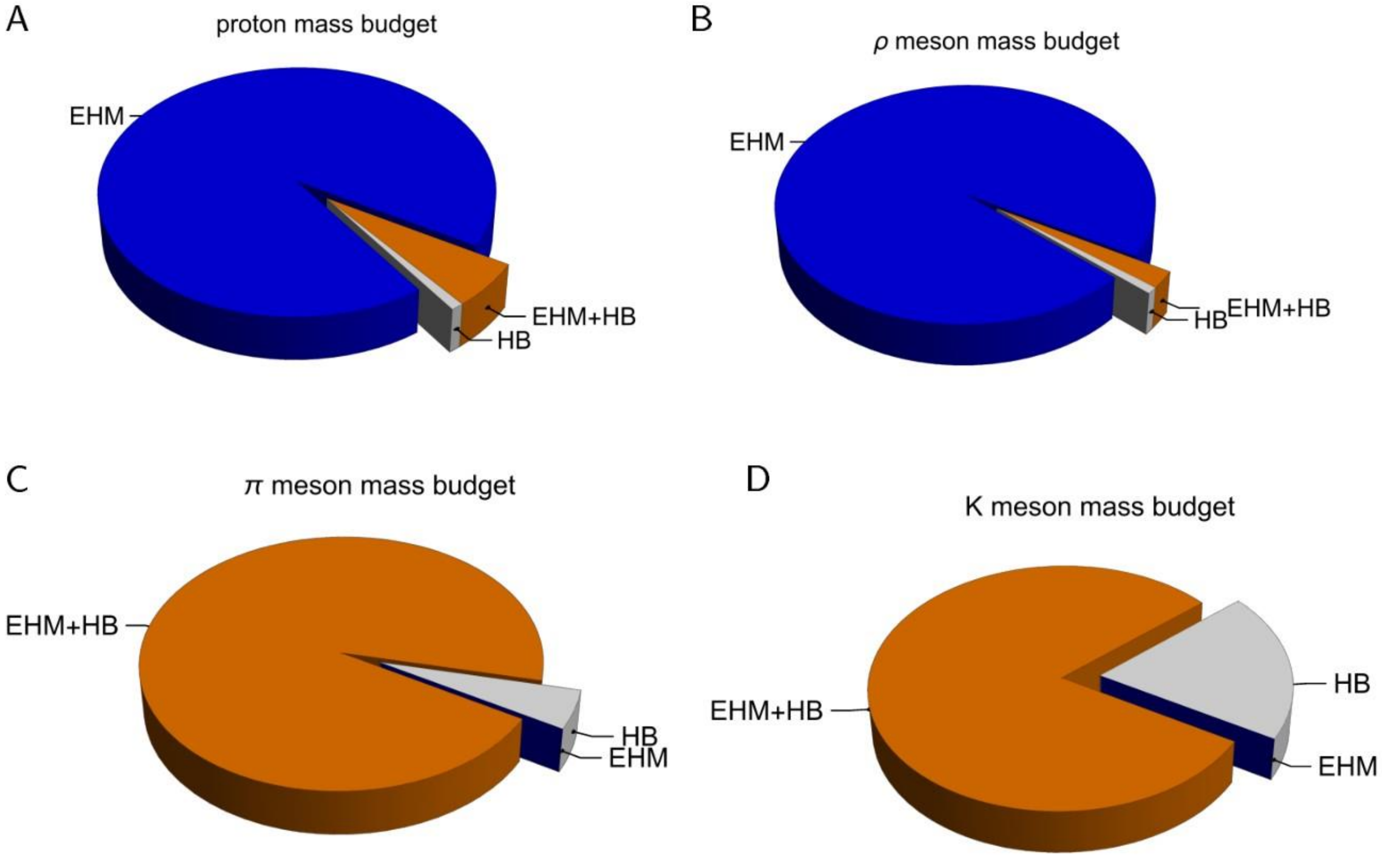
  Emergent Hadron Mass (EHM)
  - ✓ Alone, it produces 94% of the proton's mass
  - ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



Emergence of Hadron Mass - Basic Questions

- What is the origin of EHM?
- Does it lie within the Standard Model, i.e., within QCD
- What are the connections with …
  - Gluon and quark confinement?
  - Dynamical chiral symmetry breaking (DCSB)?
  - Nambu-Goldstone modes = π & K?
- What is the role of Higgs in modulating observable properties of hadrons?
  - Without Higgs mechanism of mass generation, π and K would be indistinguishable
- What is and wherefrom mass?

Proton and ρ-meson mass budgets are practically identical



π- and K-meson mass budgets are essentially/completely different from those of proton and ρ

G E N E S I S

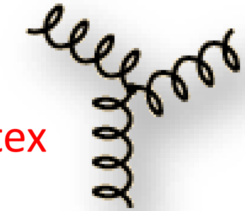
GLUON

Modern Understanding Grew Slowly from Ancient Origins

- More than 40 years ago

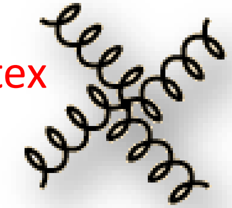
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1070 citations

3-gluon vertex

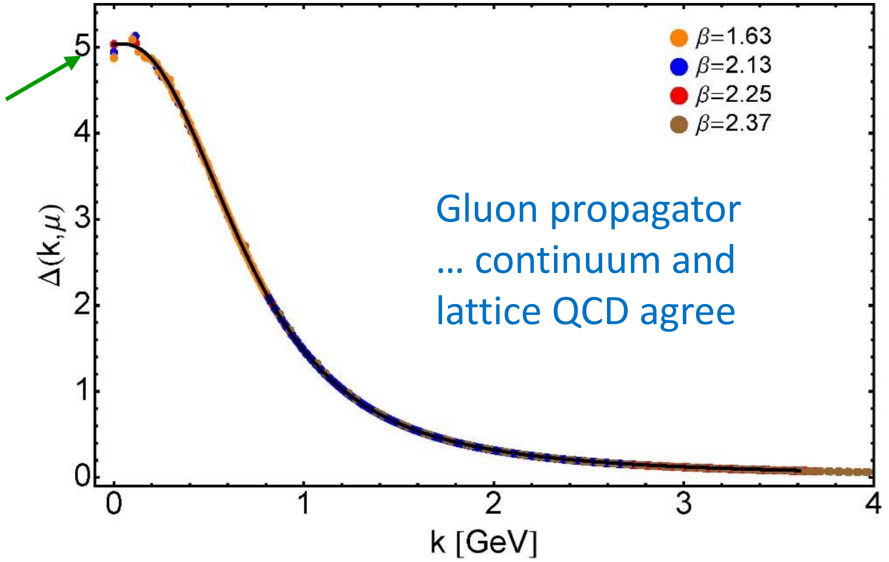


- Owing to strong self-interactions, gluon partons ⇒ gluon quasiparticles, described by a mass function that is large at infrared momenta

4-gluon vertex



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



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

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

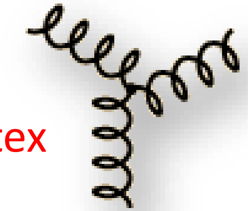
Presentation by … Papavassiliou

Modern Understanding
Grew Slowly from … Origins

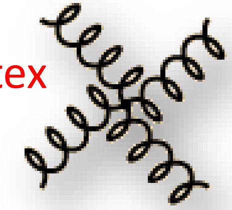
EHM means Gluons are massive

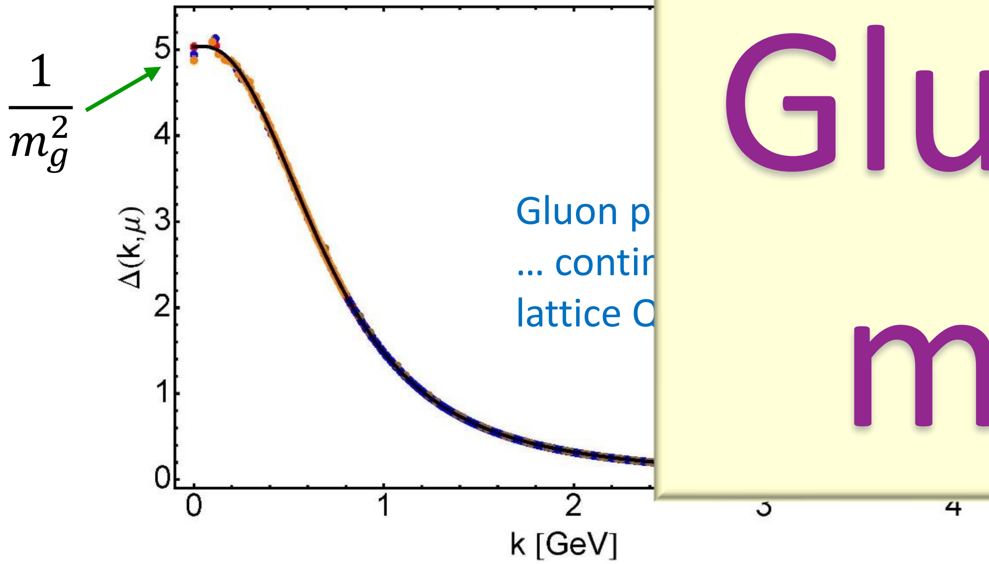
- More than 40 year
  Dynamical mass ger … *mics,*
  J.M. Cornwall, Phys.
- Owing to strong se … uasiparticles,
  described by a … omenta

3-gluon vertex



4-gluon vertex



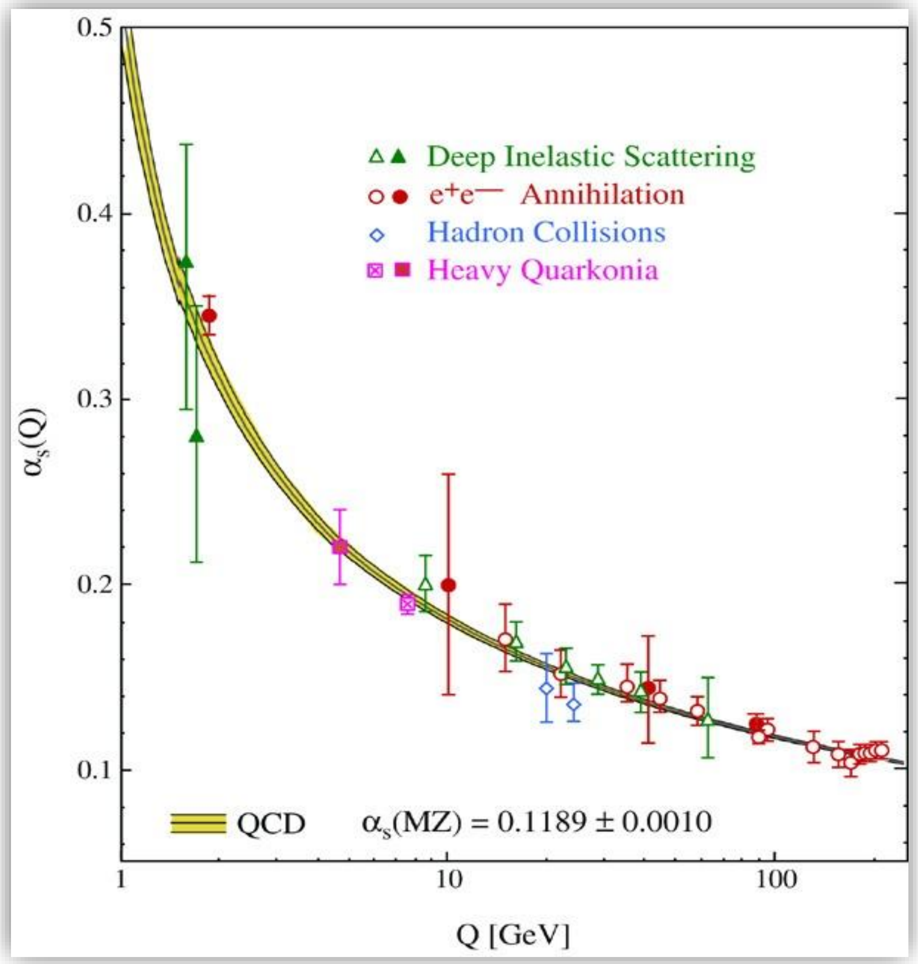


t
tion

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

This is where we live

⇐ **What's happening out here?!**



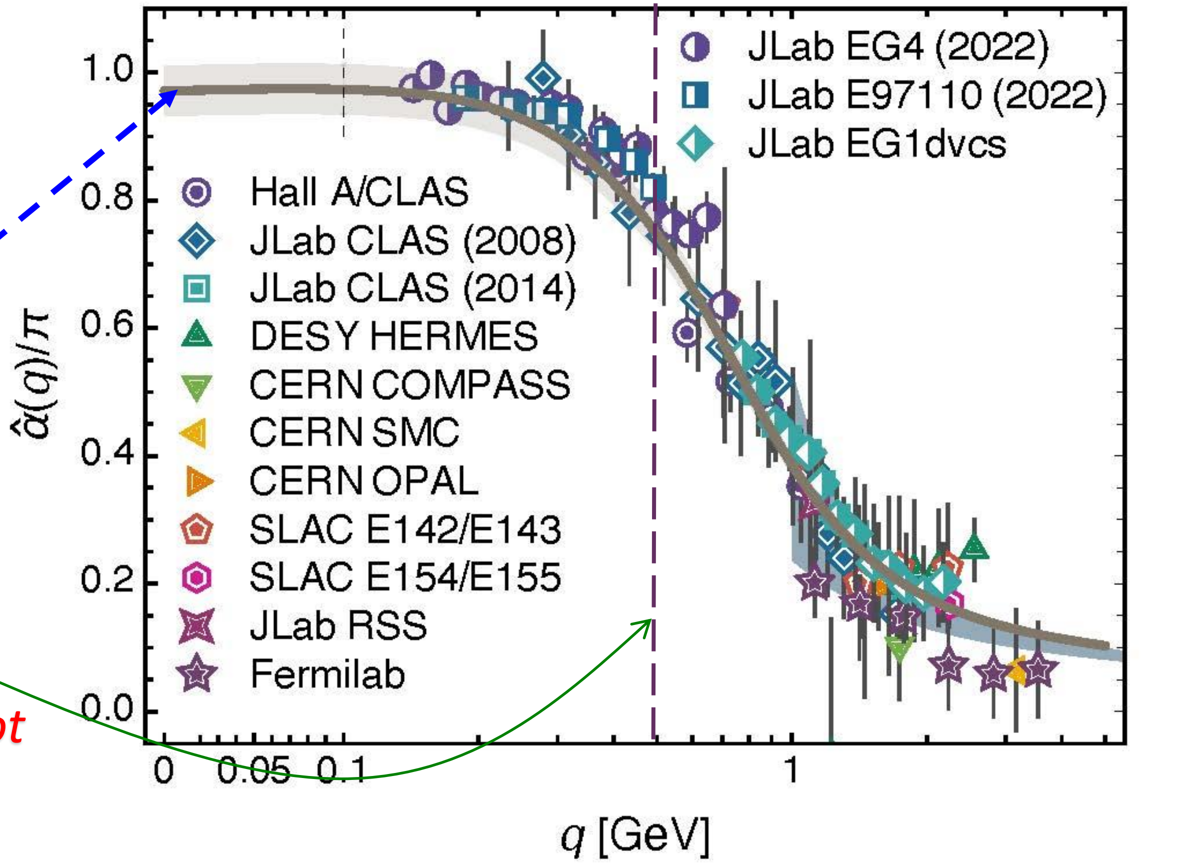
QCD's Running Coupling

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*

2064 total downloads

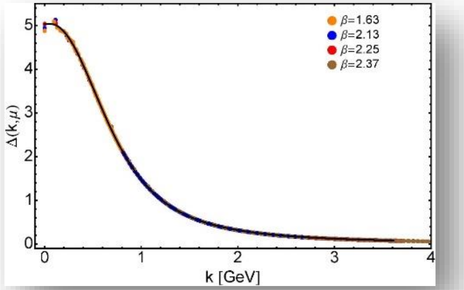
Process independent effective charge = running coupling

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

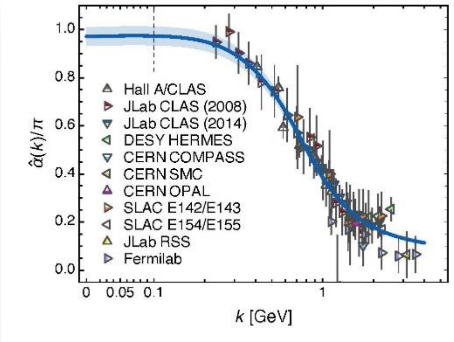


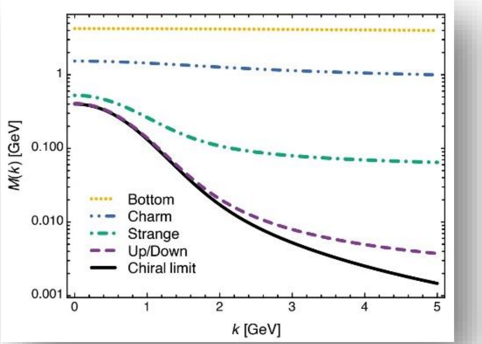
The QCD Running Coupling,
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. **90** (2016) 1-74
Process independent strong running coupling
Daniele Binosi *et al.*, arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

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

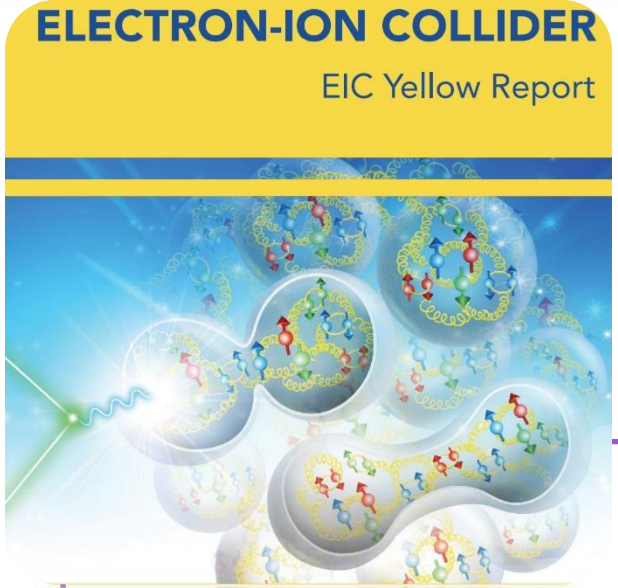
CERN

AMBER

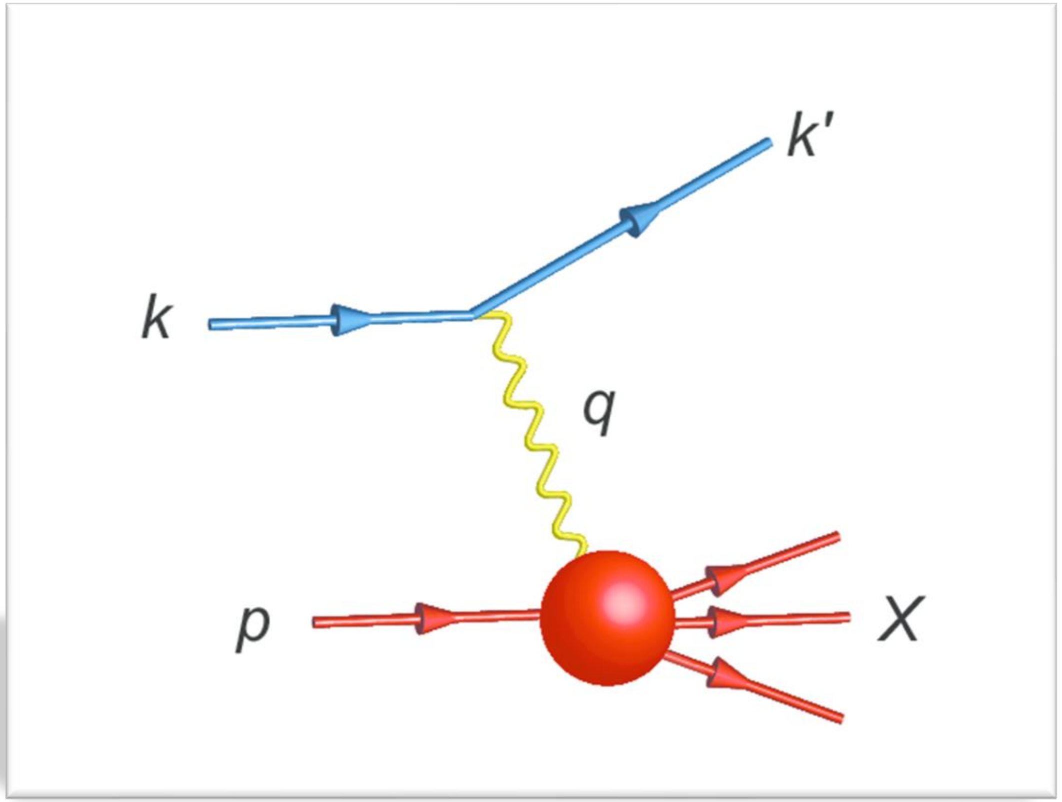
A new QCD facility at the M2 beam line of the CERN SPS

Jefferson Lab

Thomas Jefferson National Accelerator Facility



EHM at Existing and Future Facilities



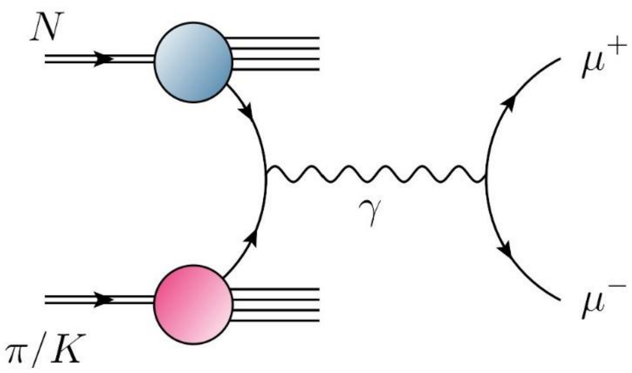
Parton Distribution Functions

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:

Presentations by … Ent & Horn

  - JLab, EIC, EicC
    ⇒ pion and kaon elastic electromagnetic form factors … reveal and quantify scaling violations in hard exclusive processes … hard prediction of QCD, never seen
    ⇒ pion and kaon valence quark distribution functions at large x_B
  - AMBER
    → precision data to chart π and K structure: DFs of valence, sea and glue.
    → Glue is particularly important … because controversial, yet prominent theory predicts that pions contain (almost) zero glue.

Proton and pion DFs - QCD predictions

- Valence-quark domain: there is a scale $\zeta_H < m_p$ at which $\begin{cases} d^p(x;\zeta_{\mathcal{H}}), u^p(x;\zeta_{\mathcal{H}}) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_{\mathcal{H}}), u^\pi(x;\zeta_{\mathcal{H}}) \overset{x\simeq 1}{\propto} (1-x)^2 \end{cases}$

- $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p$, $\beta_\pi = 2 + \gamma_\pi$
  - Gluon DFs: $\beta_{p,\pi}^{\text{glue}} \geq \beta_{p,\pi}^{\text{val}} + 1$
  - Sea DFs: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$

✓ *Simple, direct consequences of DGLAP equations.*

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

✓ *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.

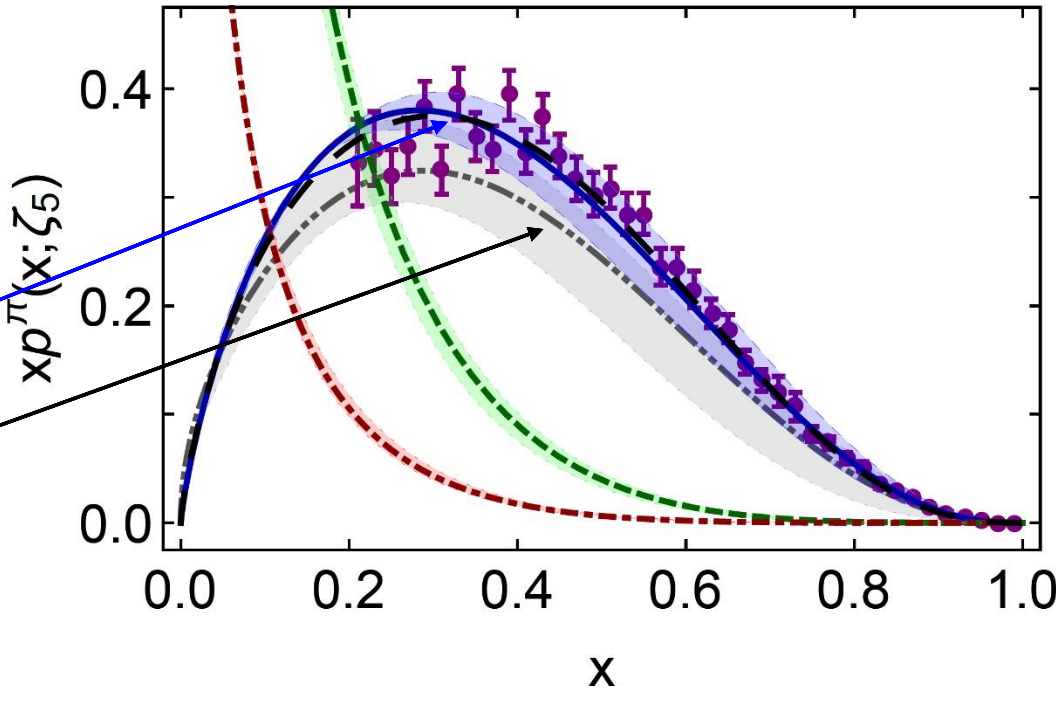
π valence-quark distributions
23 Years of Theory Evolution → 2022

- ✓ *Symmetry, symmetry breaking, and pion parton distributions*, Minghui Ding, Khépani Raya et al., NJU-INP 003/19, arXiv:1905.05208 [nucl-th], Phys. Rev. D **101** (2020) 054014/1-14
- ✓ *Pion Valence Quark Distribution from Matrix Element Calculated in Lattice QCD*, R. Sufian, et al. Phys. Rev. D 99 (2019) 074507

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

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

- 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 "meson target" era dawning … dense, precise data will be obtained: M2 beam-line @ CERN … JLab12 … EIC … EicC*



Strict Constraints on Pion Valence-quark DFs

- Proposition I:

  There exists at least one effective charge, $\alpha_{1\ell}(k^2)$, such that, when used to integrate the one-loop DGLAP equations, an evolution scheme for parton DFs is defined that is all-orders exact

- Charges of this type are discussed in

  G. Grunberg, *Renormalization scheme independent QCD and QED: The method of effective charges*, Phys. Rev. D 29, 2315 (1984) … 617 citations

- They need not be process-independent (PI); hence, not unique.
  - Nevertheless, a suitable PI charge is not excluded
- Each such $\alpha_{1\ell}(k^2)$ is:
  - consistent with the renormalization group;
  - renormalization scheme independent;
  - everywhere analytic and finite;
  - and supplies an infrared completion of any standard running coupling

Strict Constraints on Pion Valence-quark DFs

- Proposition II:

  There exists a scale, ζ_H, at which all pion properties are carried by its valence degrees-of-freedom

- Nature's G-parity symmetry $\Rightarrow u_V(x;\zeta_H) = u_V(1-x;\zeta_H)$

  $g(x;\zeta_H) \equiv 0 \equiv S(x;\zeta_H)$

- Working solely with Propositions I and II, the following can be proved (γ_0^n are anomalous dimensions):

$$\frac{1}{2^n} \leq \langle x^n\rangle^{\zeta}_{\mathrm{u}_\pi} (\langle 2x\rangle^{\zeta}_{\mathrm{u}_\pi})^{-\gamma_0^n/\gamma_0^1} \leq \frac{1}{1+n}$$

Bounds on all Mellin moments of valence-quark DF

$$\langle x^{2n+1}\rangle^{\zeta}_{\mathrm{u}_\pi} = \frac{(\langle 2x\rangle^{\zeta}_{\mathrm{u}_\pi})^{\gamma_0^{2n+1}/\gamma_0^1}}{2(n+1)} \times \sum_{j=0,1,\ldots}^{2n} (-)^j \binom{2(n+1)}{j} \langle x^j\rangle^{\zeta}_{\mathrm{u}_\pi} (\langle 2x\rangle^{\zeta}_{\mathrm{u}_\pi})^{-\gamma_0^j/\gamma_0^1}.$$

Recursion relation for Mellin moments of valence-quark DF

… any odd moment is completely determined by the lower-order even moments

Pion Valence-quark DF from lattice-QCD moments

- Lattice-QCD input
  - ✓ [66] B. Joó et al., *Pion valence structure from Ioffe-time parton pseudodistribution functions*, Phys. Rev. D 100, 114512 (2019).
  - ✓ [67] R. S. Sufian et al., *Pion valence quark distribution from matrix element calculated in lattice QCD*, Phys. Rev. D 99, 074507 (2019).
  - ✓ [68] C. Alexandrou et al., Pion and kaon $\langle x^3 \rangle$ from lattice QCD and PDF reconstruction from Mellin moments, Phys. Rev. D 104, 054504 (2021).

TABLE I. Lattice-QCD results for Mellin moments of the pion valence-quark DF at $\zeta = \zeta_2 = 2$ GeV [66] and $\zeta_5 = 5.2$ GeV [67,68].

n	[66]	[67]	[68]
1	0.254(03)	0.18(3)	0.23(3)(7)
2	0.094(12)	0.064(10)	0.087(05)(08)
3	0.057(04)	0.030(05)	0.041(05)(09)
4			0.023(05)(06)
5			0.014(04)(05)
6			0.009(03)(03)

Pion Valence-quark DF from lattice-QCD moments

TABLE I. Lattice-QCD results for Mellin moments of the pion valence-quark DF at $\zeta = \zeta_2 = 2$ GeV [66] and $\zeta_5 = 5.2$ GeV [67,68].

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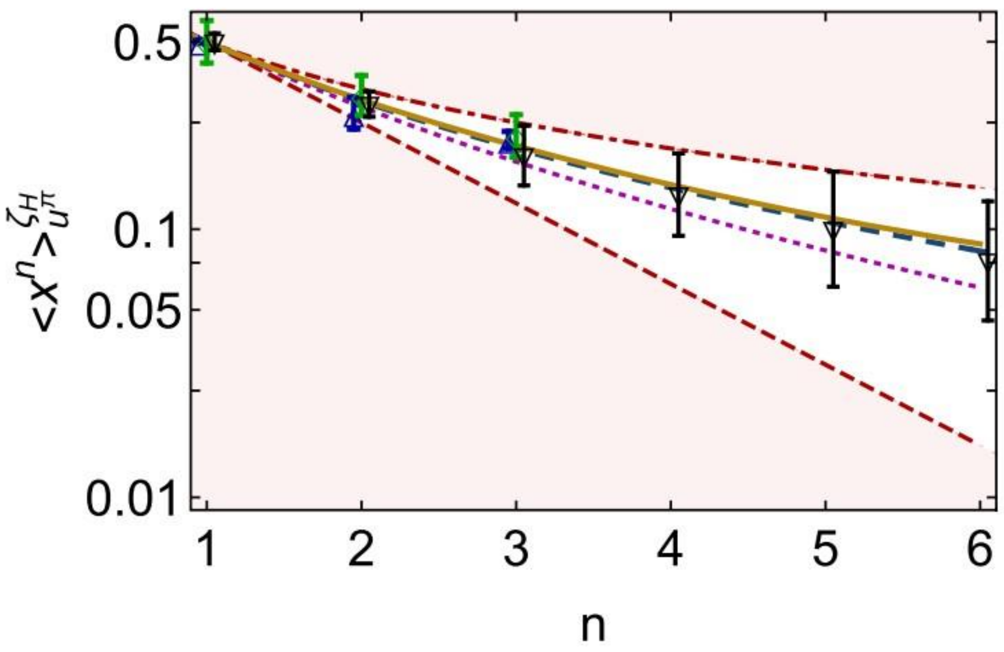


FIG. 2. Mellin moments from Table I, referred to $\zeta_{\mathcal{H}}$ via Eq. (8). blue up-triangles [66]; green diamonds [67]; and black down-triangles [68]. Results consistent with the bounds in Eq. (9) fall within the open band. The excluded regions are lightly shaded in red. Gold curve: trajectory of moments that minimizes Eq. (12). Long-dashed dark-blue curve: moments of CSM distribution [54]. Dotted magenta curve: moments of the scale-free distribution: $q^{sf}(x) = 30x^2(1-x)^2$.

- Lattice-QCD moments [66-68] are all consistent with the bounds … means all are consistent with Proposition II = pion DF is symmetric at ζ_H
  - ✓ Gold curve: best-fit trajectory of moments
  - ✓ Long-dashed dark-blue curve: moments of CSM distribution
  - ✓ *Curves are indistinguishable*

Emergence of pion parton distributions, Z.-F. Cui (崔著钫), M. Ding (丁明慧) *et al.*,
NJU-INP 054/22, e-Print: 2201.00884 [hep-ph], Phys. Rev. D 105 (2022) L091502/1-8

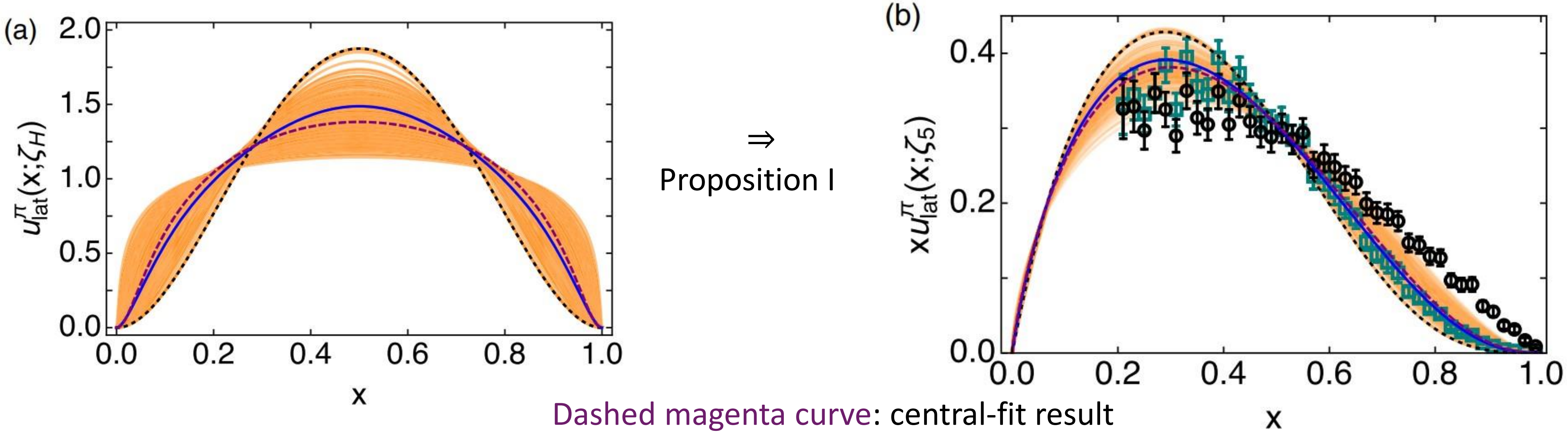
Pion Valence-quark DF from lattice-QCD moments

- One-parameter (ρ) reconstruction function

$$\mathbf{u}^{\pi}(x;\zeta_{\mathcal{H}}) = \mathfrak{n}_0 \ln(1 + x^2(1-x)^2/\rho^2)$$

Flexible enough to both reproduce scale-free distribution and express EHM-induced dilation, which is known feature of QCD

- Using best-fit moment curve, generate ensemble of pion DFs with Gaussian-distributed uncertainty



Dashed magenta curve: central-fit result
Solid blue curve: CSM prediction

Pion Valence-quark DF from lattice-QCD moments

- One-parameter (ρ) reconstruction function

$$\mathbf{u}^{\pi}(x;\zeta_{\mathcal{H}}) = \mathfrak{n}_0 \ln(1 + x^2(1-x)^2/\rho^2)$$

Flexible enough to both reproduce scale-free distribution and express EHM-induced dilation, which is known feature of QCD

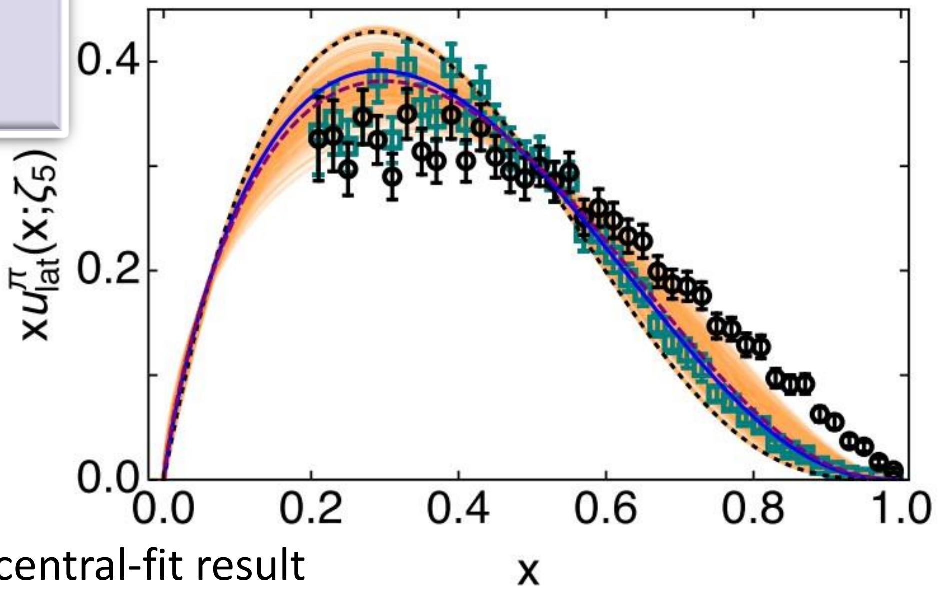
- Using best-fit moment curve, generate ensemble of fits with Gaussian-distributed uncertainty

Lattice QCD & CSM in agreement
pQCD power law confirmed in nonperturbative predictions

Lattice QCD: $\langle x \rangle_{\pi}^{\zeta_5} = 0.218(6)$
CSM: $\langle x \rangle_{\pi}^{\zeta_5} = 0.20(1)$

Large-x power,
Lattice QCD = 2.45(38)
CSM = 2.81(08)

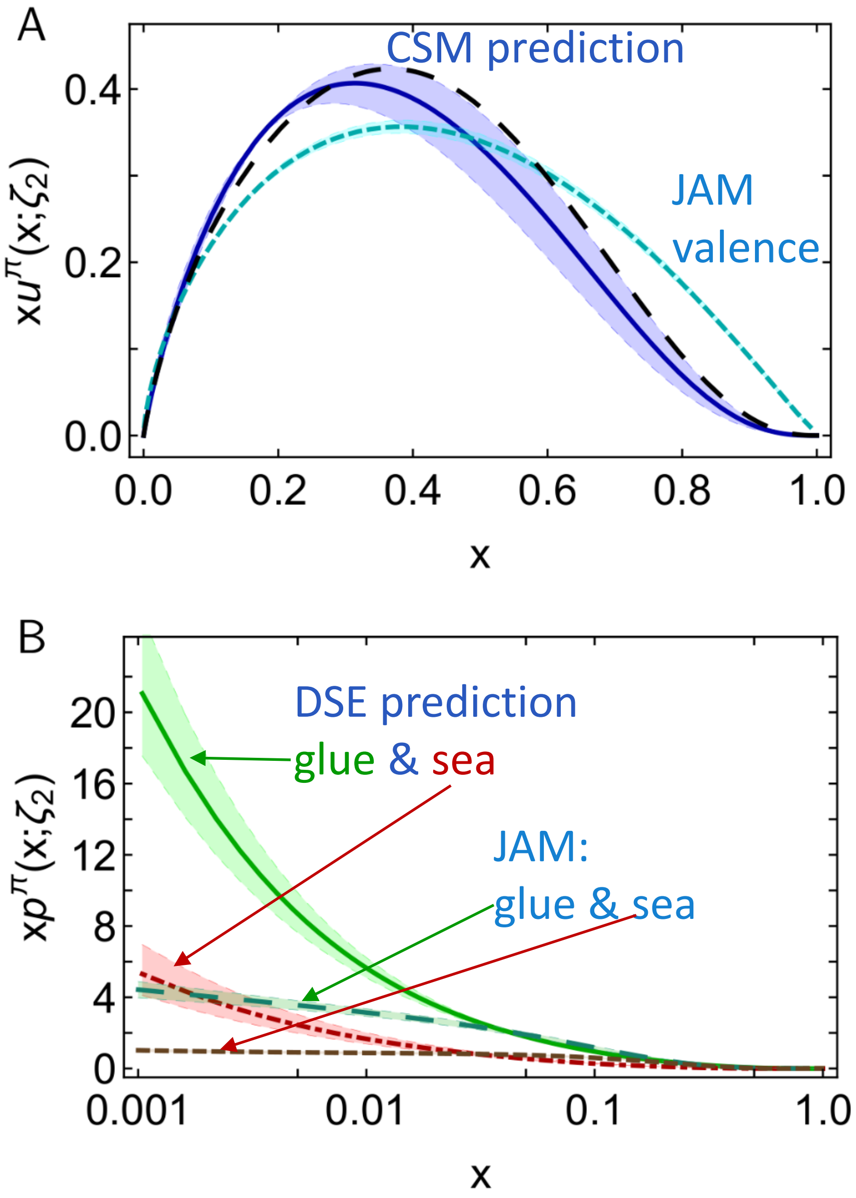
$\Rightarrow$ Proposition I



Dashed magenta curve: central-fit result
Solid blue curve: CSM prediction

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

- **Valence:**
  - momentum fraction similar
  - Phenomenological Fits … profile much harder & inconsistent with QCD prediction
- **Glue:**
  - Qualitative similarities on $x \geq 0.05$, but marked quantitative disagreement, especially on complementary domain
  - Both continuum prediction and fit are very different from early phenomenology
  - Should be tested in new experiments that are directly sensitive to the pion's gluon content.
  - Possibly: 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 …

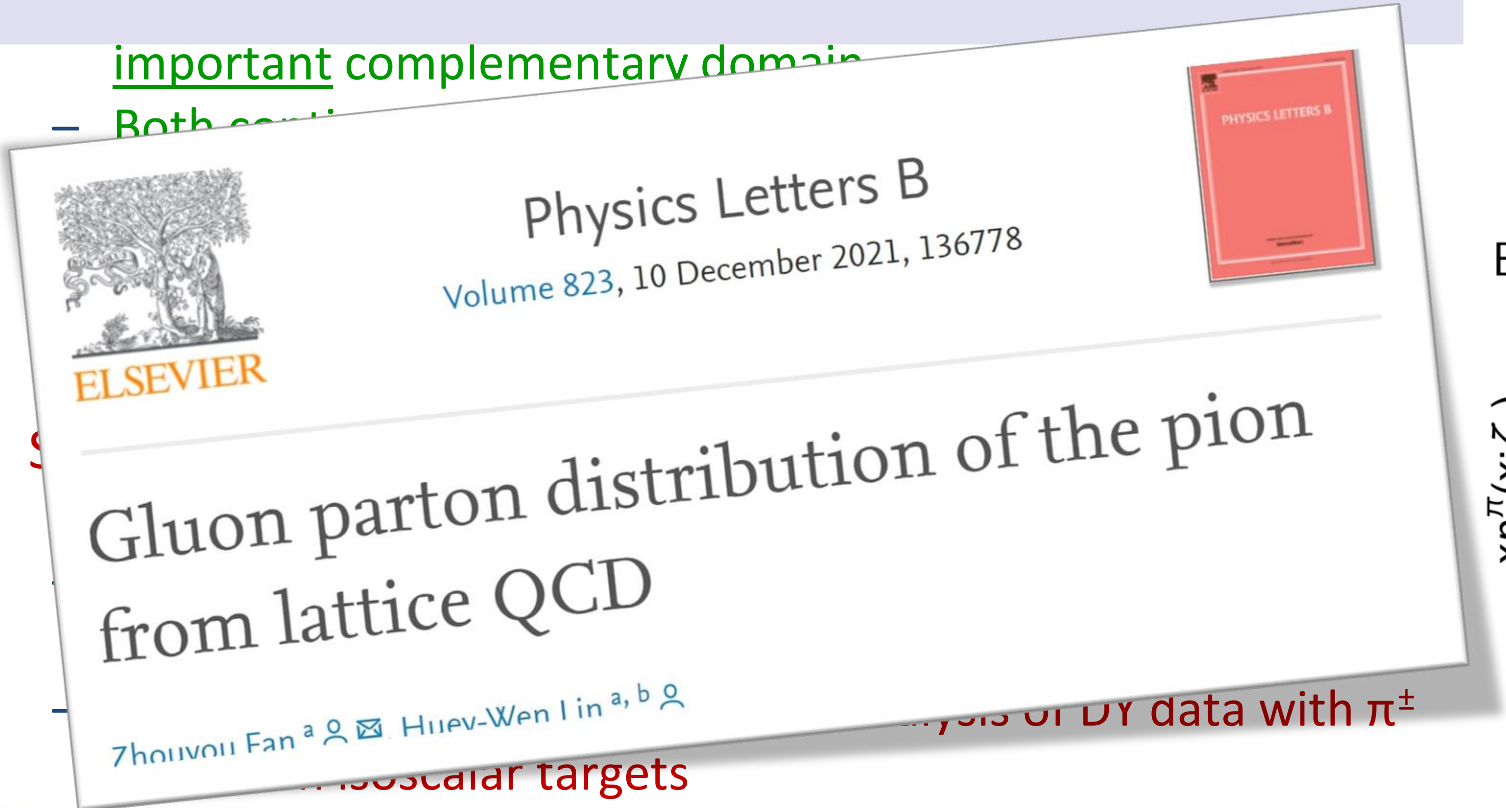
1st lQCD results for pion's glue DF have been released

important complementary domain

- Both conti

- S

  - …alysis of DY data with π±
  - …isoscalar targets


Physics Letters B
Volume 823, 10 December 2021, 136778
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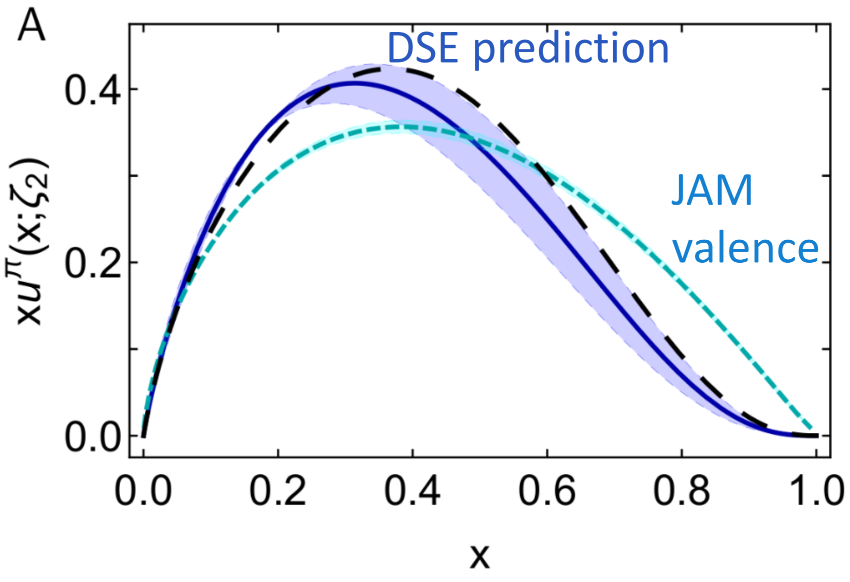
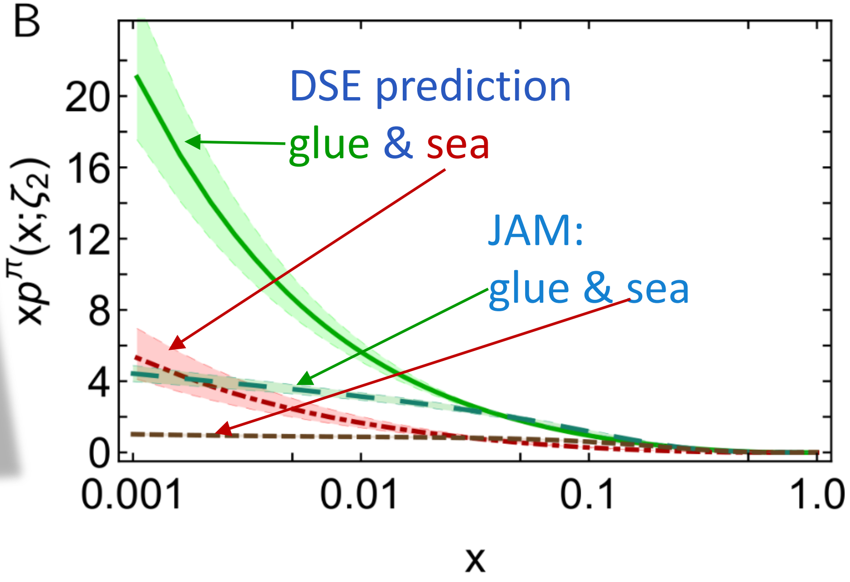
PHYSICS LETTERS B

Gluon parton distribution of the pion from lattice QCD

Zhouyou Fan a, Huey-Wen Lin a, b

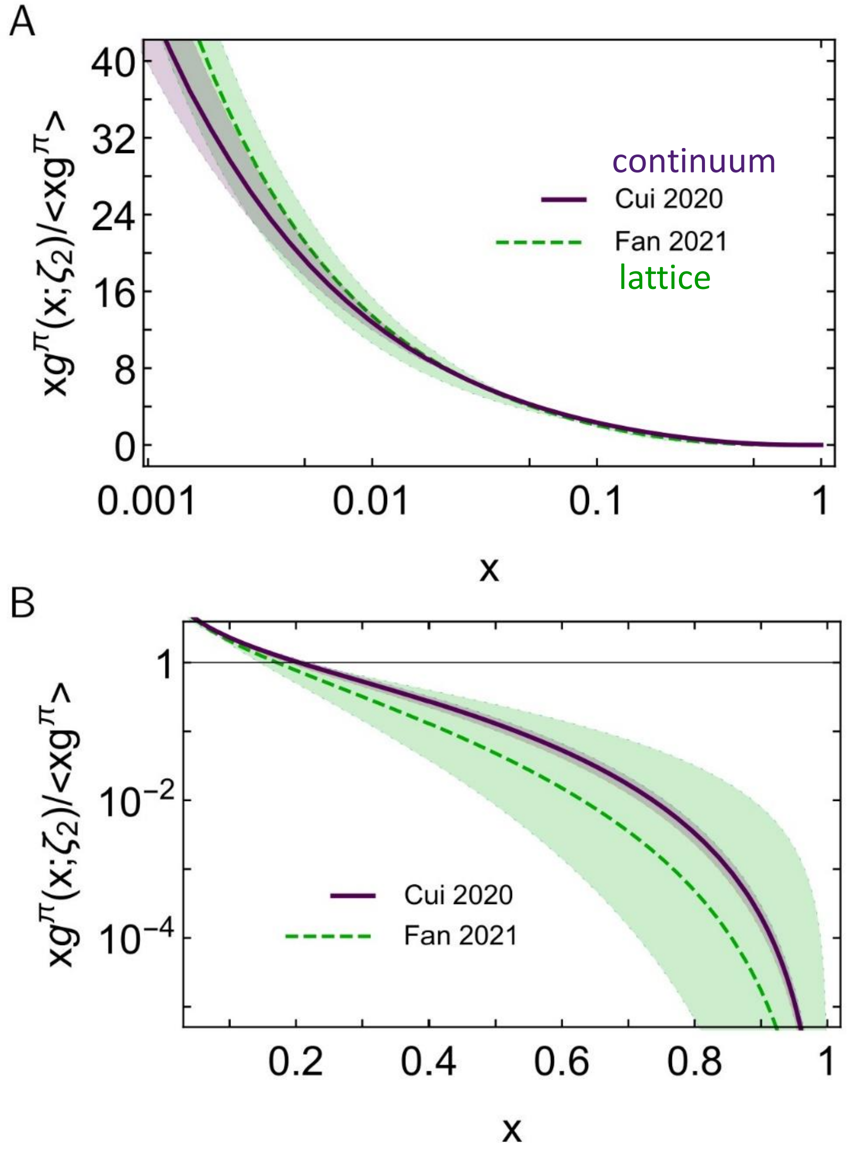




Breaking news for glue in π: Continuum (Eur. Phys. J. C 80 (2020) 1064/1-20) & Lattice Predictions (arXiv:2104.06372)

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.



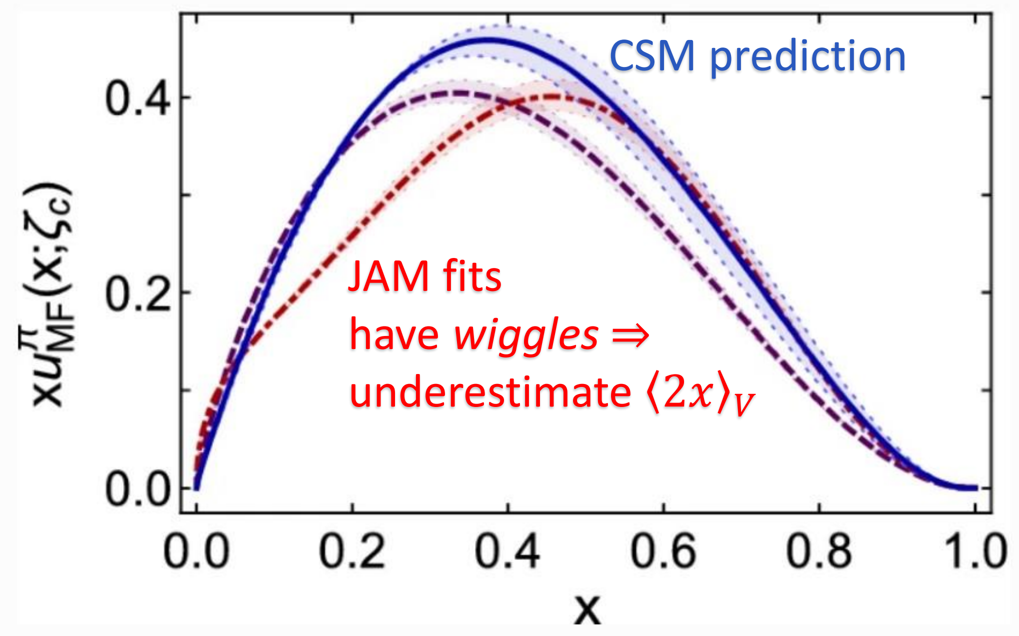
Regarding the distribution of glue in the pion, Lei Chang (常雷) and Craig D Roberts,
e-Print: 2106.08451 [hep-ph], Chin. Phys. Lett. **38** (8) (2021) 081101/1-6 - Editors' Suggestion

Issues with Recent JAM Fits

✓ *Concerning pion parton distributions*, Z.-F. Cui (崔著钫), M. Ding (丁明慧) et al., NJU-INP 053/21, e-Print: 2112.09210 [hep-ph], Eur. Phys. J. A 58 (2022) 10/1-14

- New fits place much less of pion's light-front momentum with the valence quarks
  - 12% smaller than previous fits and existing predictions
- Momentum is shifted to sea DF, leaving gluon fraction largely unchanged
  - Inconsistent with QCD
  - Internally consistent evolution says valence *produces* glue *produces* sea
  - Can't have valence ↔ sea with passive glue
- Wiggly valence-quark DFs … possibly owing to
  - limitations introduced by the simple DF fitting Ansatz employed
  - and/or choosing to treat valence, glue, and sea DFs as uncorrelated at input scale

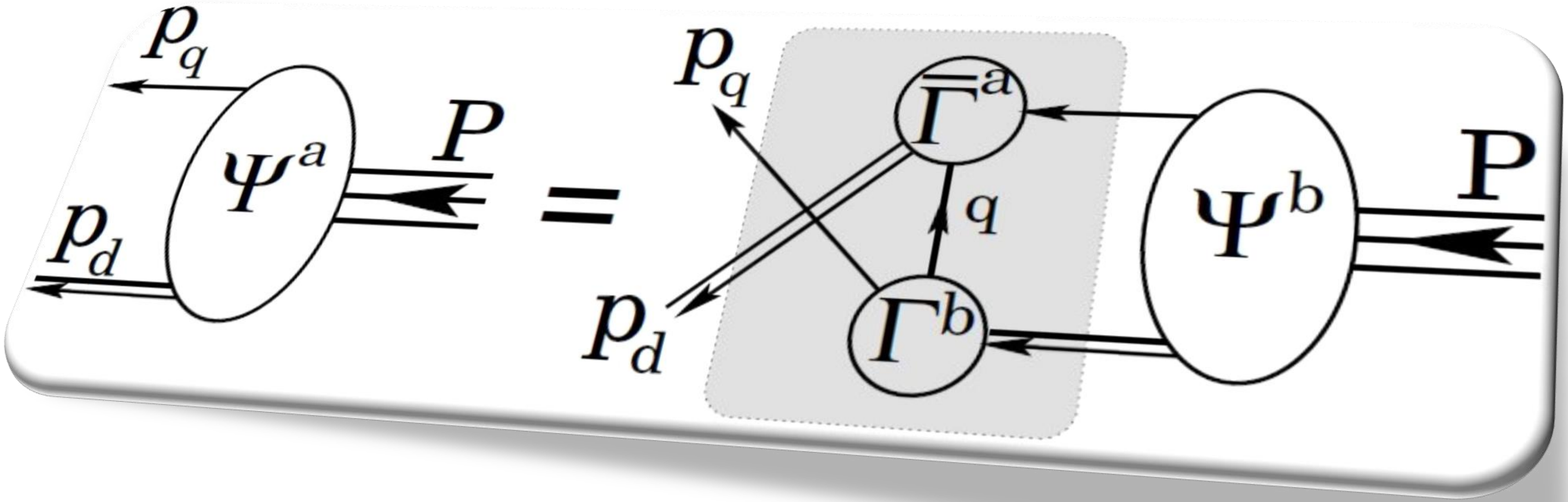
Fig. 6



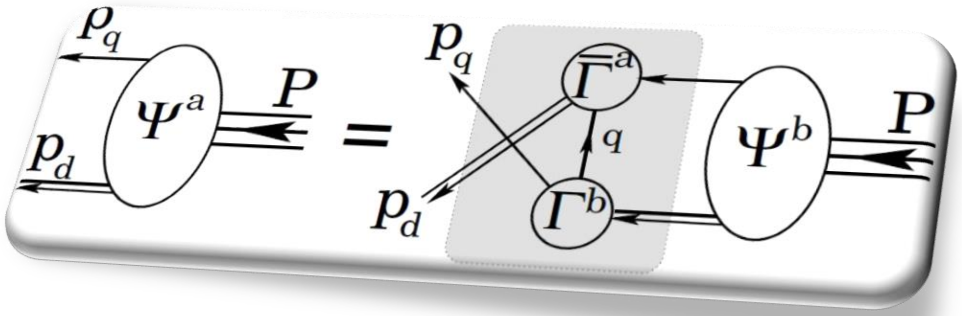
Valence-quark DF at $\zeta = \zeta_c = 1.27$ GeV. Dot-dashed red curve within like-coloured band – Eq. (23), derived from Ref. [36], with $\beta_{\rm eff}(\zeta_c) = 2.45(11)$; solid blue curve and band – prediction from Refs. [69,70,71], which express $\beta_{\rm eff}(\zeta_c) = 2.52(5)$; and dashed purple curve and band – Eq. (26), $\beta_{\rm eff}(\zeta_c) = 2.06(2)$

- QCD – valence & glue & sea DFs are intimately connected at ALL scales.
- Unsound to treat them as uncorrelated/independent

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

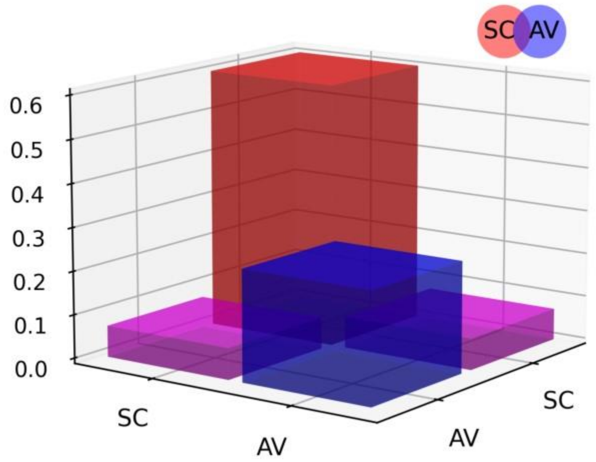


Structure of Baryons - diquark correlations



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
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena, *strong diquark correlations exist within baryons*
  - proton and neutron … both scalar and axial-vector diquarks are present
    - ✓ CSM prediction = presence of axialvector (AV) diquark correlation in the proton
    - ✓ AV Responsible for ≈ 40% of proton charge



Craig Roberts: cdroberts@nju.edu.cn 415 "Predicting Parton DFs"

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

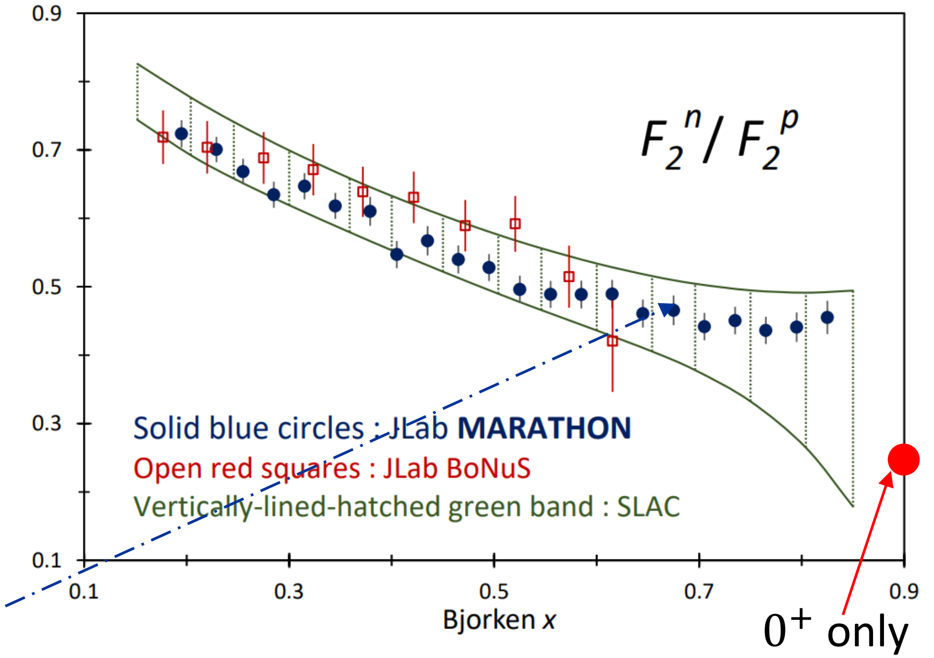
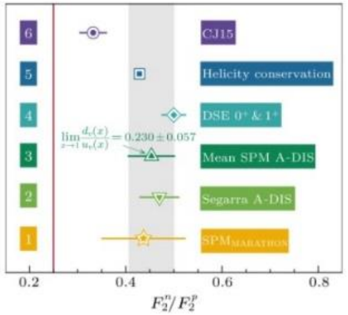


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics $[Q^2 = 14 \cdot x\ (\mathrm{GeV}/c)^2]$ (see text). All three experimental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

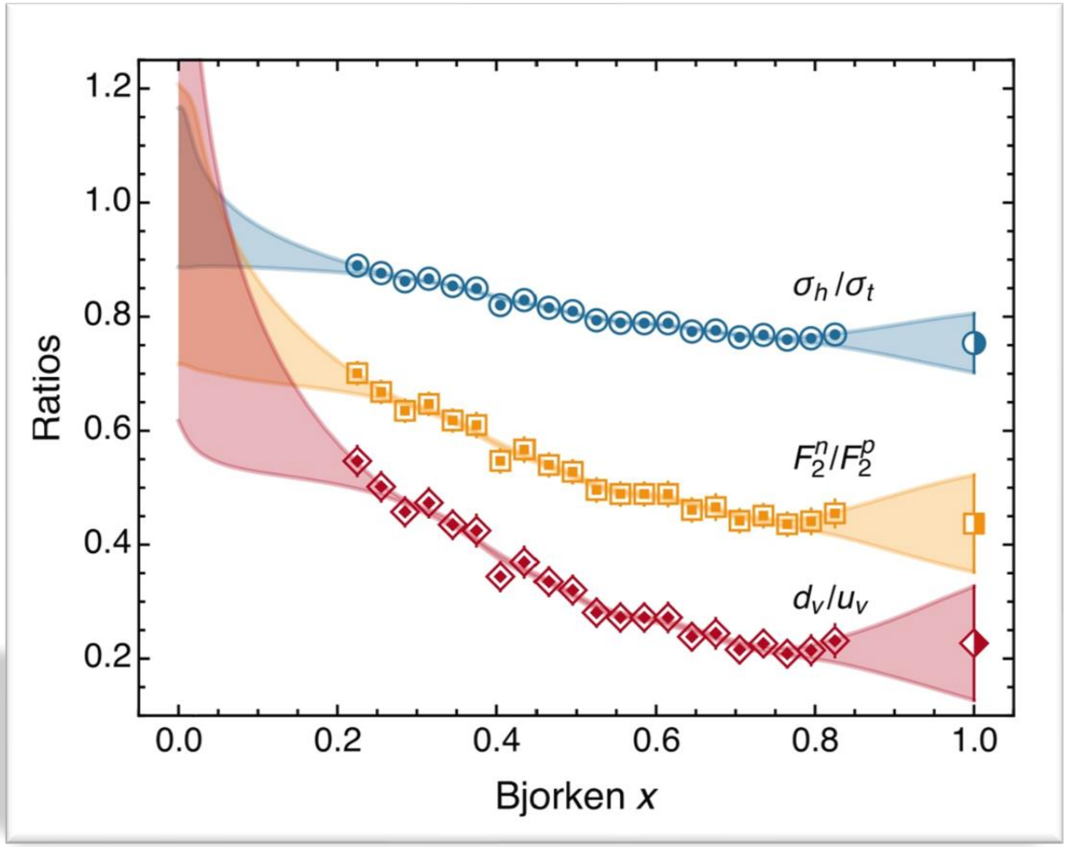
Zhu-Fang Cui, Fei Gao, Daniele Binosi, Lei Chang, Craig D. Roberts, and Sebastian M. Schmidt

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



Proton and pion distribution functions in counterpoint

- Despite 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?

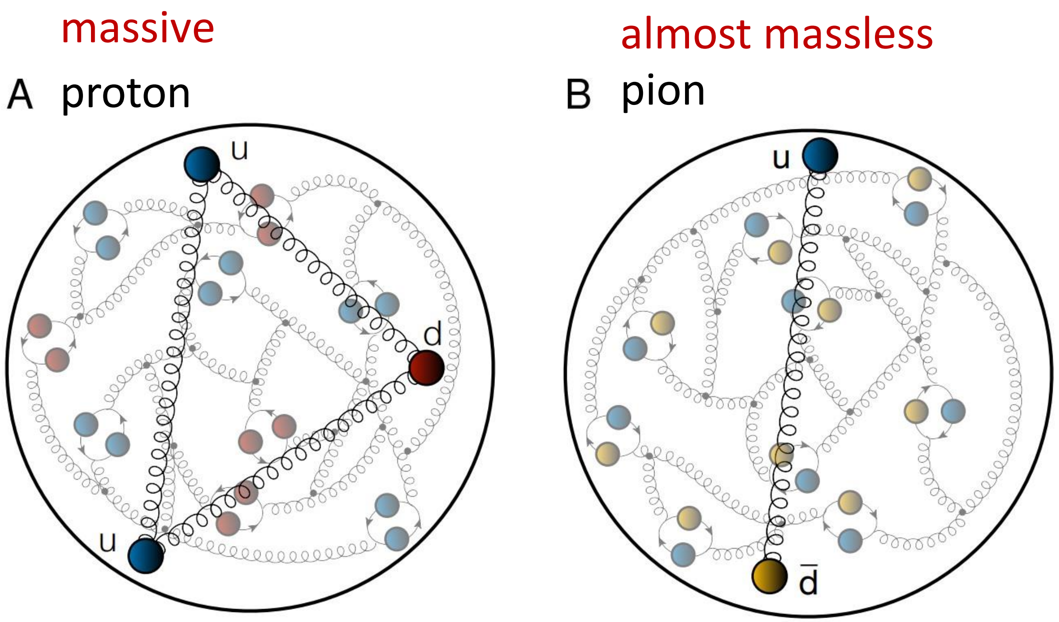


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined 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

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

- $\zeta > m_p$: val. $\propto (1-x)^{\beta_{p,\pi}}$, $\beta_p = 3 + \gamma_p$, $\beta_\pi = 2 + \gamma_\pi$
  - Gluon DFs: $\beta_{p,\pi}^{\text{glue}} \geq \beta_{p,\pi}^{\text{val}} + 1$
  - Sea DFs: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$

✓ These are simple consequences of DGLAP equations.

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

✓ 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.

✓ Proton is supposed to be a stable bound-state of three valence-quarks

❽ Yet, modern global analyses of proton DIS and related data encompass fits with role of glue and valence-quarks reversed!

❽ Proton has valence glue but no valence quarks!

- 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

Proton and pion distribution functions in counterpoint

Proton and pion distribution functions in counterpoint, Ya Lu (陆亚) *et al.*,
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8 CT18: large-x power of glue distribution at the scale ζ = $\text{mass}_{\text{charm}}$ is (almost) identical to that of valence-quarks.

- 8 With this behavior, proton has valence-gluon degrees of freedom at all scales. That would make the proton a hybrid baryon, which it is not.

8 CT18Z: large-x power of glue distribution is a_2=1.87, whereas that on the valence quarks is a_2=3.15,

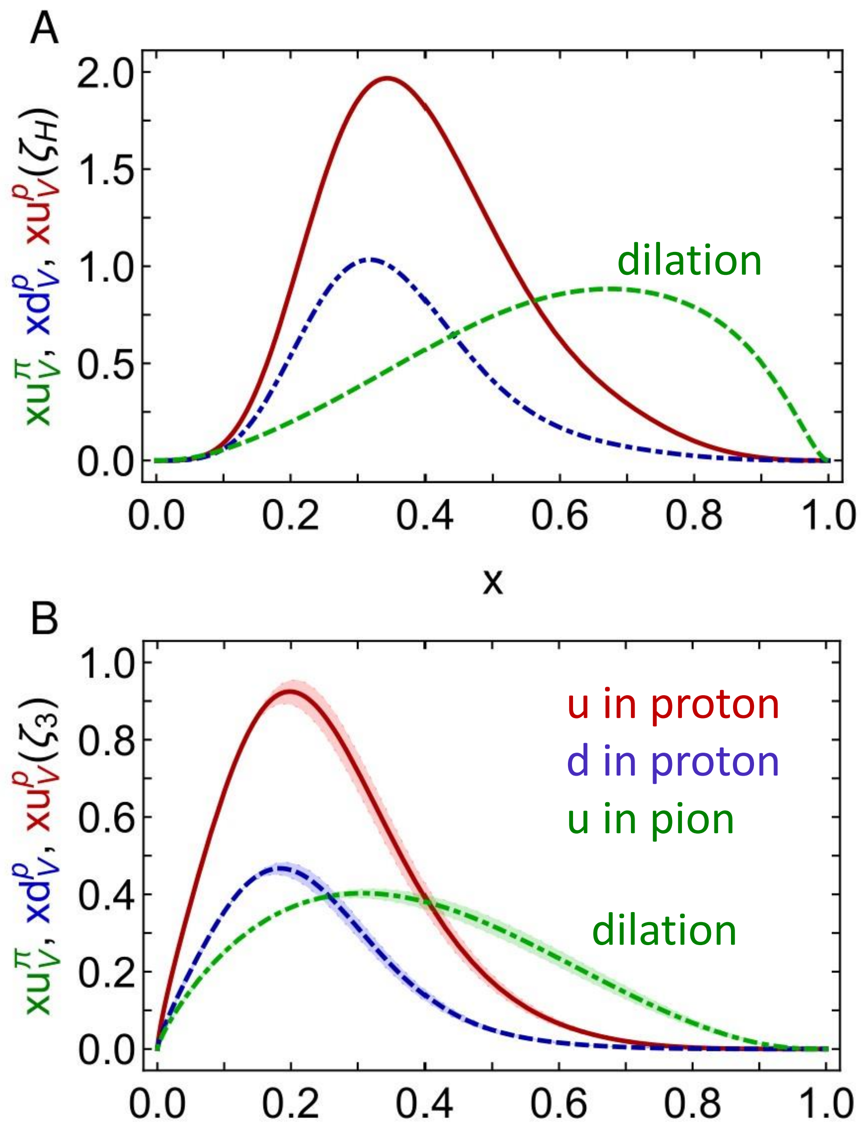
- 8 *i.e.*, at ζ = $\text{mass}_{\text{charm}}$ valence-quarks are subleading degrees-of-freedom. Instead, gluons dominate on what is typically called the valence-quark domain.

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
- Valence-quark degrees-of-freedom carry all hadron's momentum at ζ_H: $\langle x\rangle_{u_p}^{\zeta_{\mathcal{H}}} = 0.687\,,\ \langle x\rangle_{d_p}^{\zeta_{\mathcal{H}}} = 0.313\,,\ \langle x\rangle_{u_\pi}^{\zeta_{\mathcal{H}}} = 0.5$
- 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
  - i. "Obvious" because $(1-x)^2$ vs. $(1-x)^3$ behaviour & preservation of this unit difference under evolution
  - ii. Also "hidden" = strong EHM-induced broadening

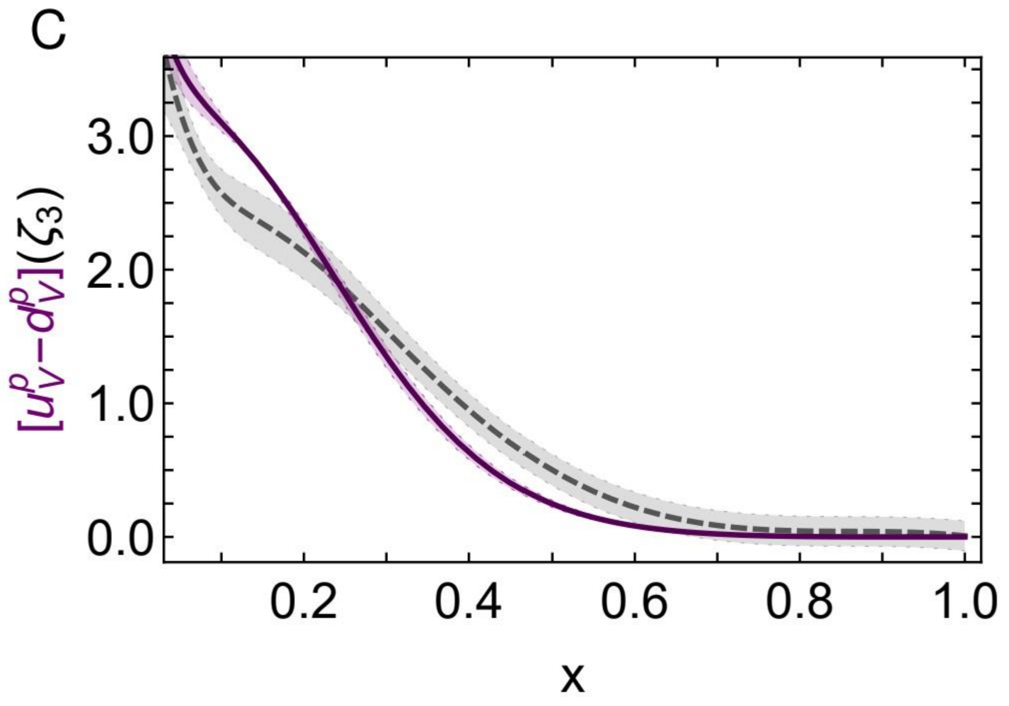


Proton valence-quark DFs: Continuum cf. Lattice

- Owing to difficulties in handling so-called disconnected contributions, the calculation of individual proton 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]

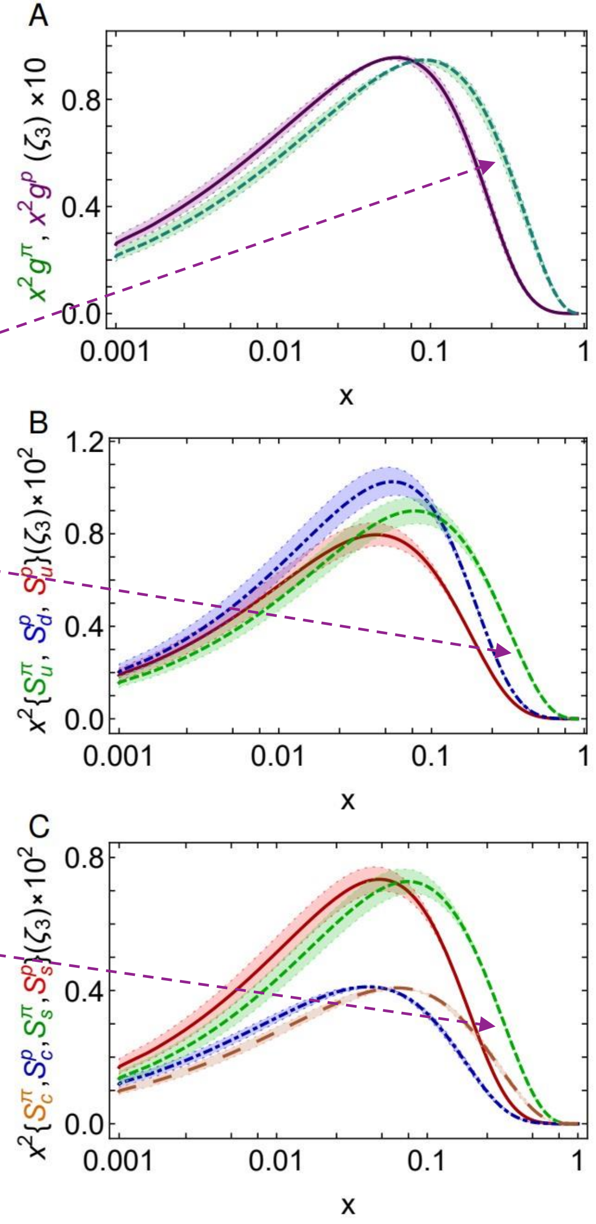
✓ Lattice: *Nucleon Isovector Unpolarized Parton Distribution in the Physical-Continuum Limit*, H.-W. Lin *et al.*, arXiv:2011.14971 [hep-lat]

Proton and pion distribution functions in counterpoint - glue and sea

- CSM prediction for glue-in-pion DF confirmed by recent lQCD simulation

  [*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 $(x \geq 0.2)$ 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



Neutron/Proton structure function ratio

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

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

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

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

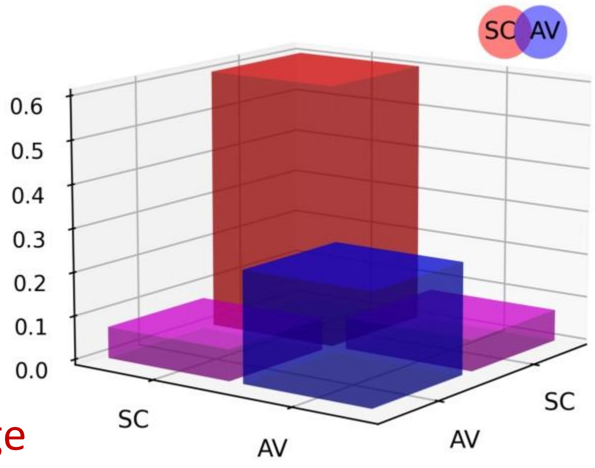
- Comparison with MARATHON data

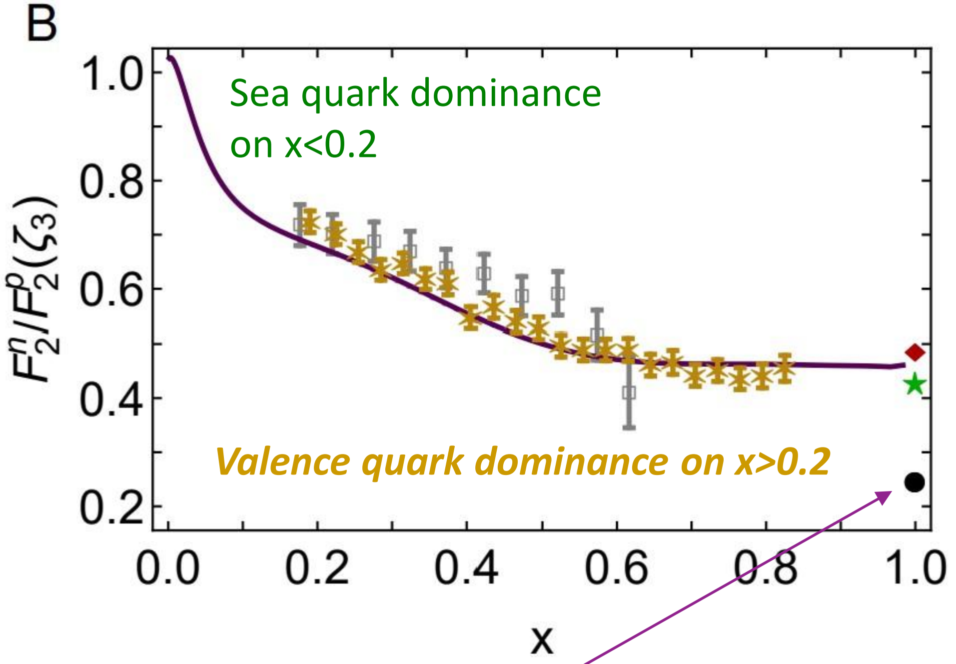
  [D. Abrams, *et al.*, Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- Agreement with modern data on entire x-domain – parameter-free prediction

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

✓ Responsible for ≈ 40% of proton charge





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

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

Asymmetry of antimatter in the proton

- Pauli blocking: gluon splitting produces

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

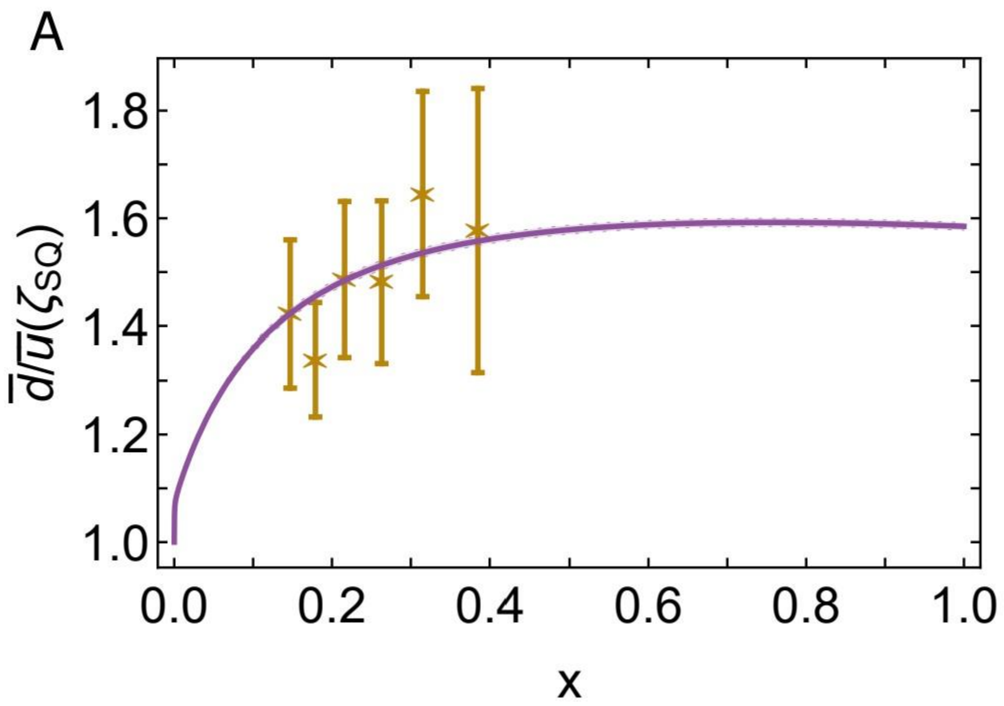
- Comparison with SeaQuest data

  [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)



✓ *Proton and pion distribution functions in counterpoint,* Ya Lu (陆亚), Lei Chang (常雷), Khépani Raya, Craig D. Roberts and José Rodríguez-Quintero, NJU-INP 056/22, e-Print: 2203.00753 [hep-ph], Phys. Lett. B 830 (2022) 137130/1-7

✓ *Parton distributions of light quarks and antiquarks in the proton*, Lei Chang (常雷), Fei Gao (高飞) and Craig D. Roberts, NJU-INP 055/22, e-Print: 2201.07870 [hep-ph], Phys. Lett. B 829 (2022) 137078/1-7

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, *x*-dependence of DFs is strongly hadron dependent

  Smoking gun for EHM

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

Many Other Expressions of EHM

- EHM ⇒ formation of nonpointlike diquark correlations within baryons
  - All baryons, including those with one or more heavy quarks
- Proton possess 0^+ isoscalar & 1^+ isovector correlations
  - Marathon data ⇒ Probability that proton contains scalar-diquark-only = $\frac{1}{7{,}000{,}000}$
- *Ground state proton is not enough*
- Nucleon resonances contain more correlations … 0^- isoscalar, 1^- isoscalar & 1^- isovector
- Nucleon-elastic & resonance transition form factors can test structural predictions
- Electroweak transitions: heavy+light systems (Higgs boson dominant mass mechanism) to light (lighter) final states (in which EHM dominates) – interference between Nature's two mass-generating mechanisms
- **Progress demands Synergy between Experiment + Phenomenology + Theory**

Presentations by … d'Angelo, Segovia, Gothe, Kumano, Wilson

0^+ only

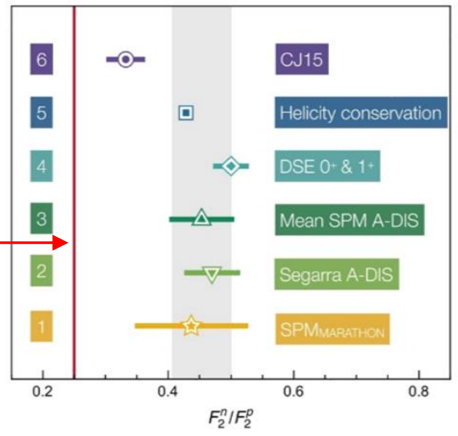


FIG. 3. $\lim_{x\to 1} F_2^n(x)/F_2^p(x)$. MARATHON-based SPM prediction compared with results inferred from: nuclear DIS [35]; Dyson-Schwinger equation analyses (DSE) [57, 58]; quark counting (helicity conservation) [59]; and a phenomenological fit (CJ15) [53]. The vertical red line marks the Nachtmann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

Grant no. 12135007

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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*

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

There are theories of many things,

But is there a theory of everything?


Thankyou