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

Explaining the Emergence of Hadron Mass and Structure

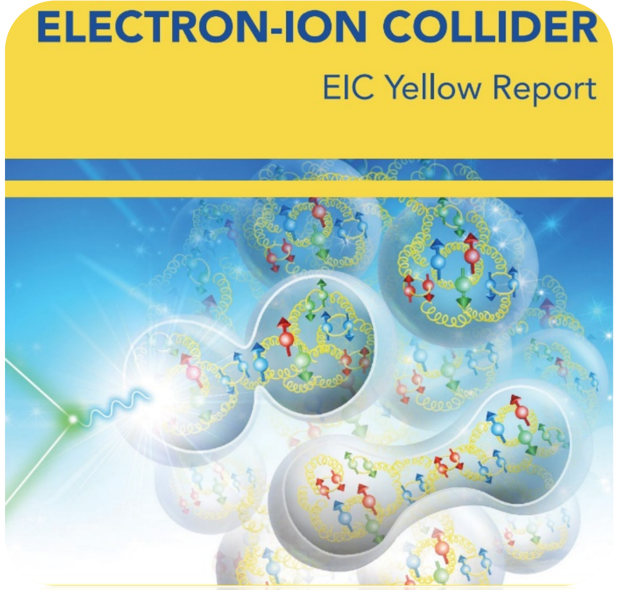
AMBER

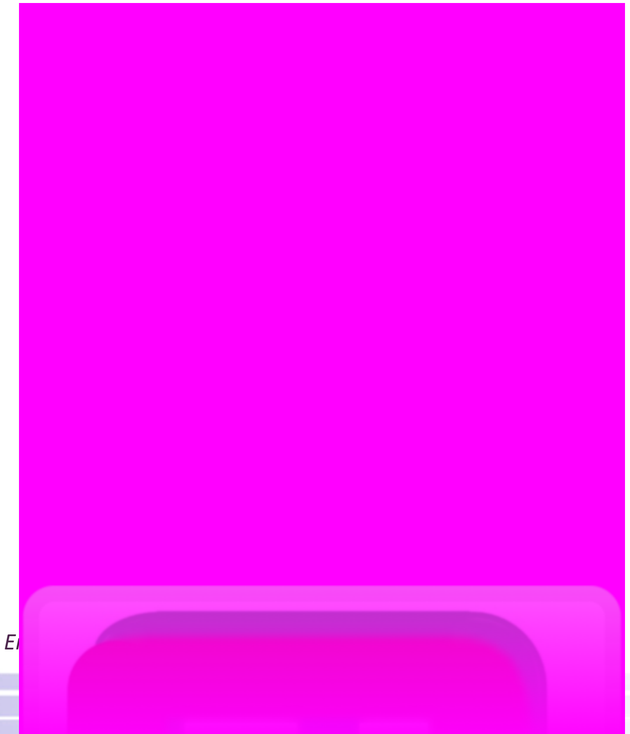
A new QCD facility at the M2 beam line of the CERN SPS

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Existing and Future Facilities





The Higgs boson

Elementary particles gain their mass from a fundamental field associated with the Higgs boson

Or so the story has gone

Mass in Nature

- There are **two** sources of mass in Nature
- This may be surprising to some people
- Because, when considering the origin of mass in the Standard Model (SM), thoughts typically turn to the Higgs boson
- Notion behind Higgs mechanism for mass generation was introduced more than fifty years ago; and it became an essential piece of the SM.
- 2012 – Discovery of something possessing all anticipated properties of the Higgs boson
  - SM became complete
- Nobel Prize in physics awarded to Englert and Higgs

  ". . . for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles . . . "

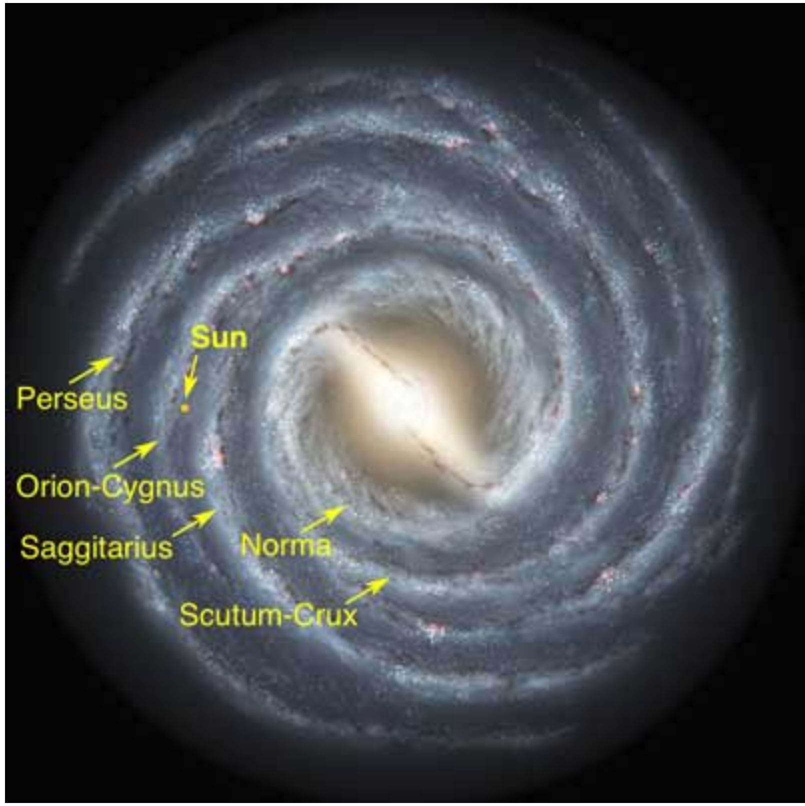
"… a mechanism that contributes …"

NOT the complete story. Far from it …

Emergent Phenomena … in the Standard Model(?)

Existence of our Universe depends critically on, *inter alia*, 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 of Hadron Mass

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

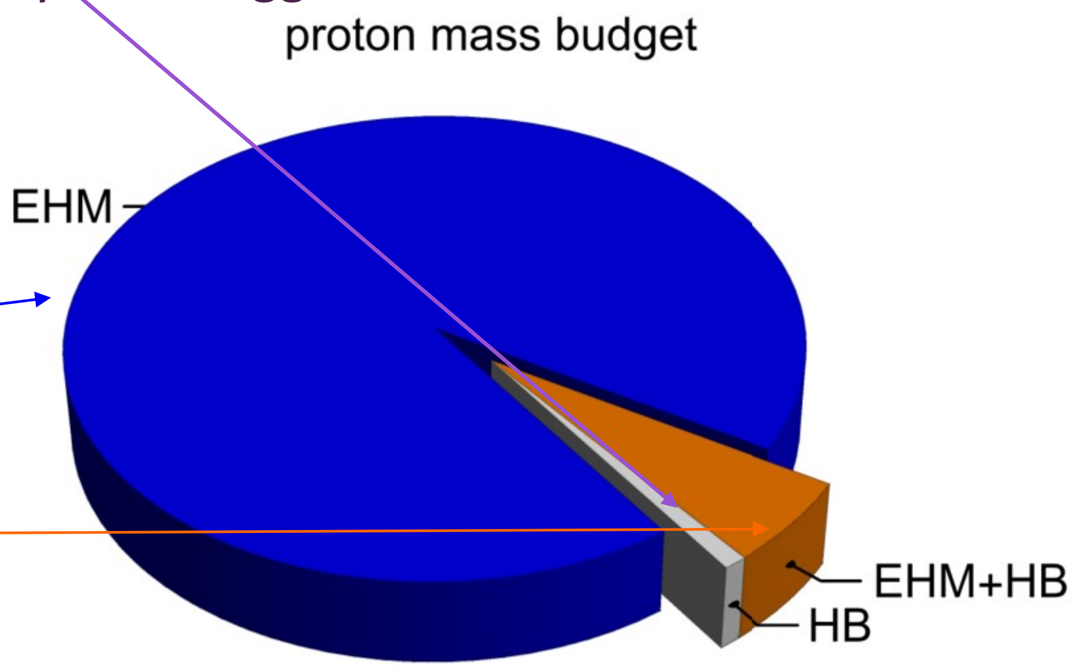
  = Higgs Boson … impacts are critical to evolution of Universe as we know it

  … understood phenomenologically
- However, Higgs boson alone is 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

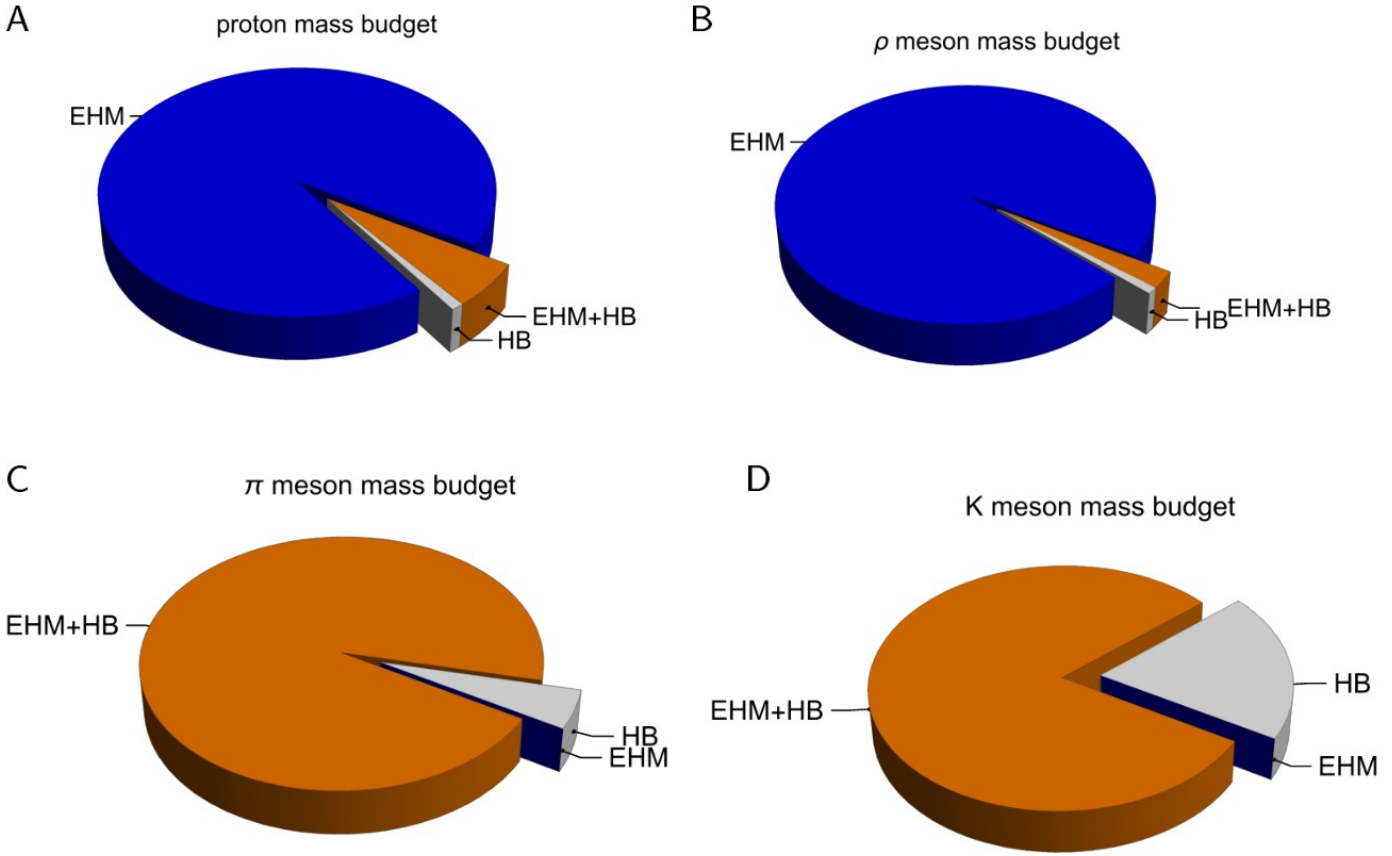
  ✓ Remaining 5% is generated by constructive interference between EHM and Higgs-boson



Emergence of Hadron Mass - Basic Questions

- What is the origin of EHM?
- Does it lie within 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?

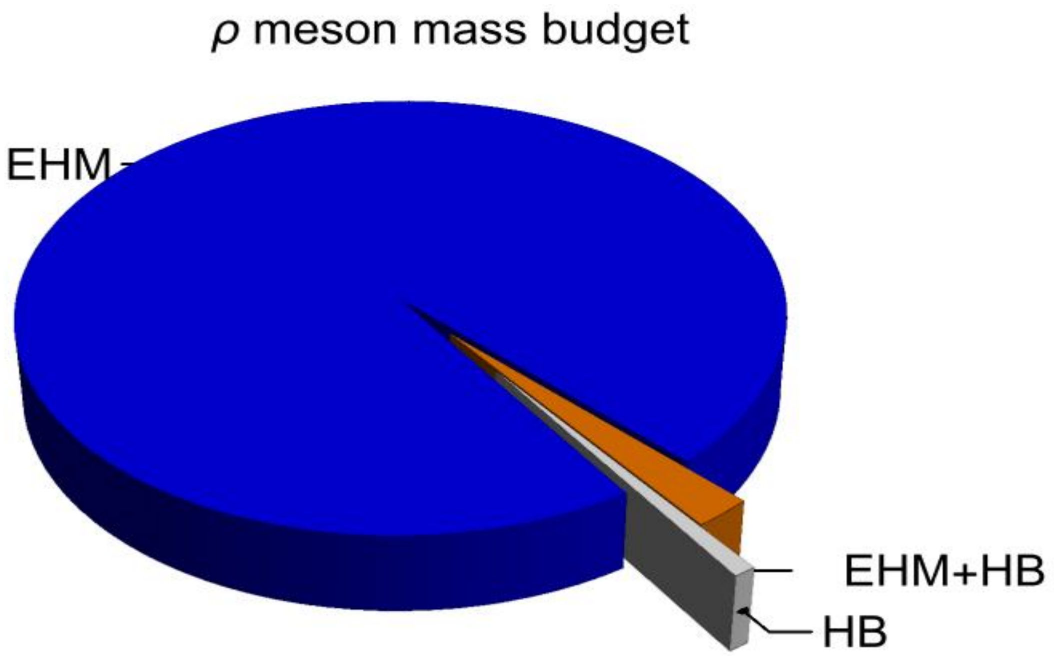
Proton and ρ-meson mass budgets are practically identical

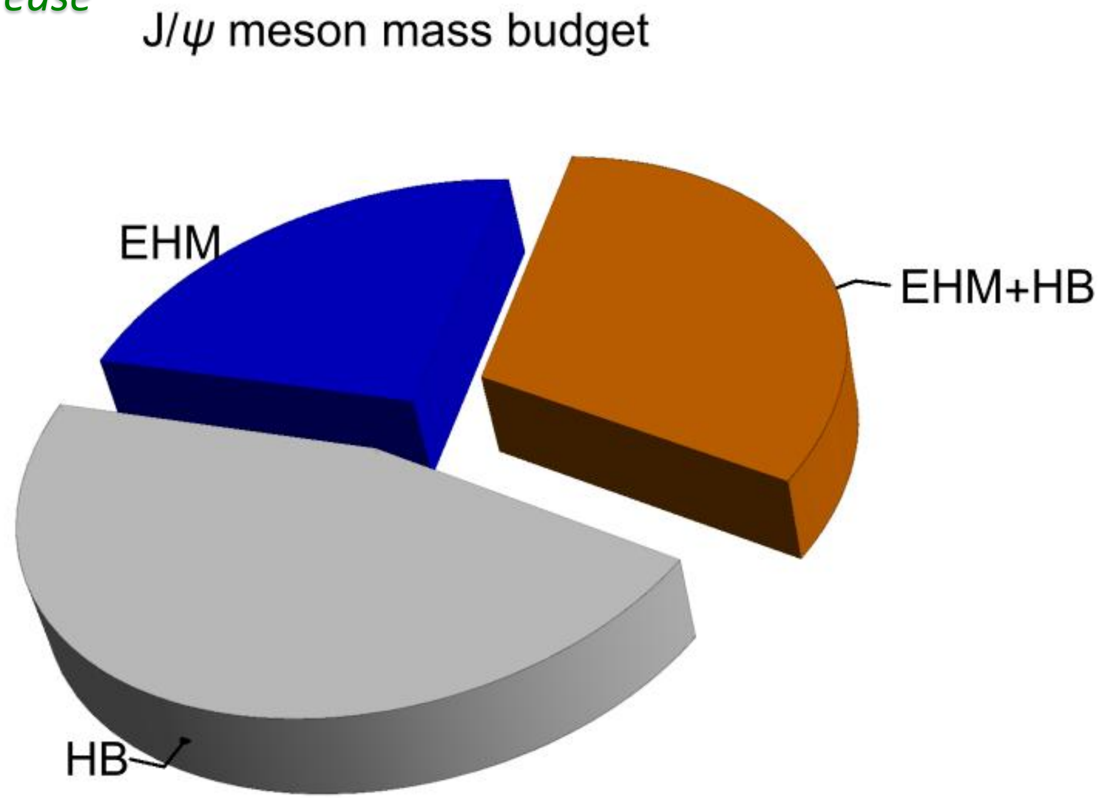


π- and K-meson mass budgets are essentially/completely different from those of proton and ρ

Vector meson mass budgets

With increasing HB couplings, EHM component is unchanged, but EHM fraction of total becomes smaller as HB & HB+EHM fractions increase





G E N E S I S

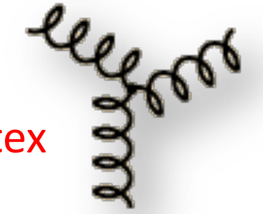
GLUON

Modern Understanding Grew Slowly from *Ancient* Origins

- More than 40 years ago

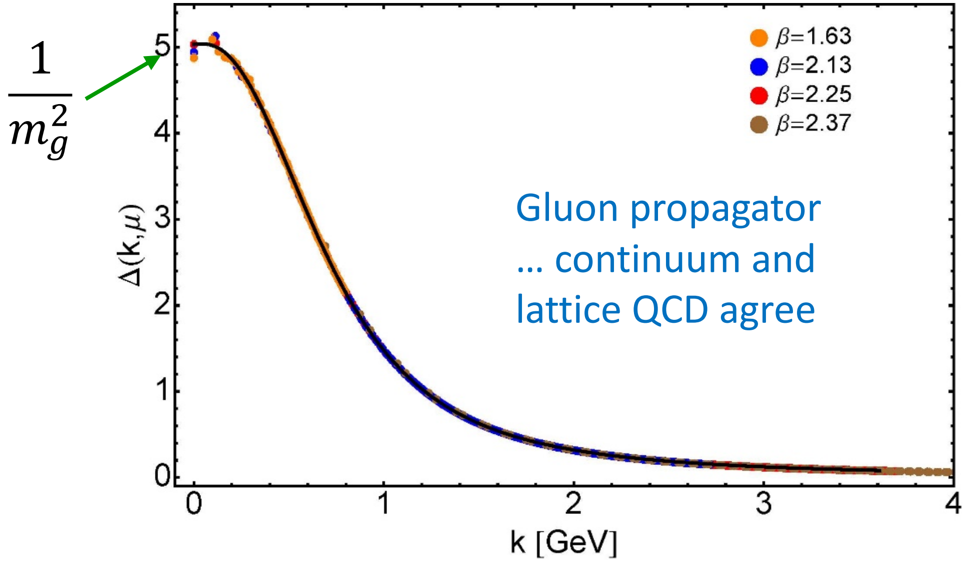
  Dynamical mass generation in continuum quantum chromodynamics,
  J.M. Cornwall, Phys. Rev. D **26** (1981) 1453 … ~ 1100 citations

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



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

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

Modern Understanding Grew Slowly from *Ancient* Origins

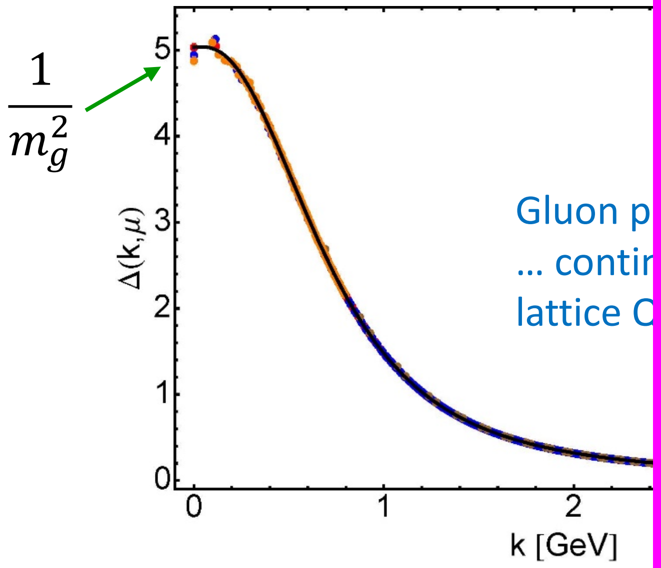
- More than 40 year

  Dynamical mass ger

  J.M. Cornwall, Phys.

- Owing to strong se …icles,

  described by a … a



…CD fact

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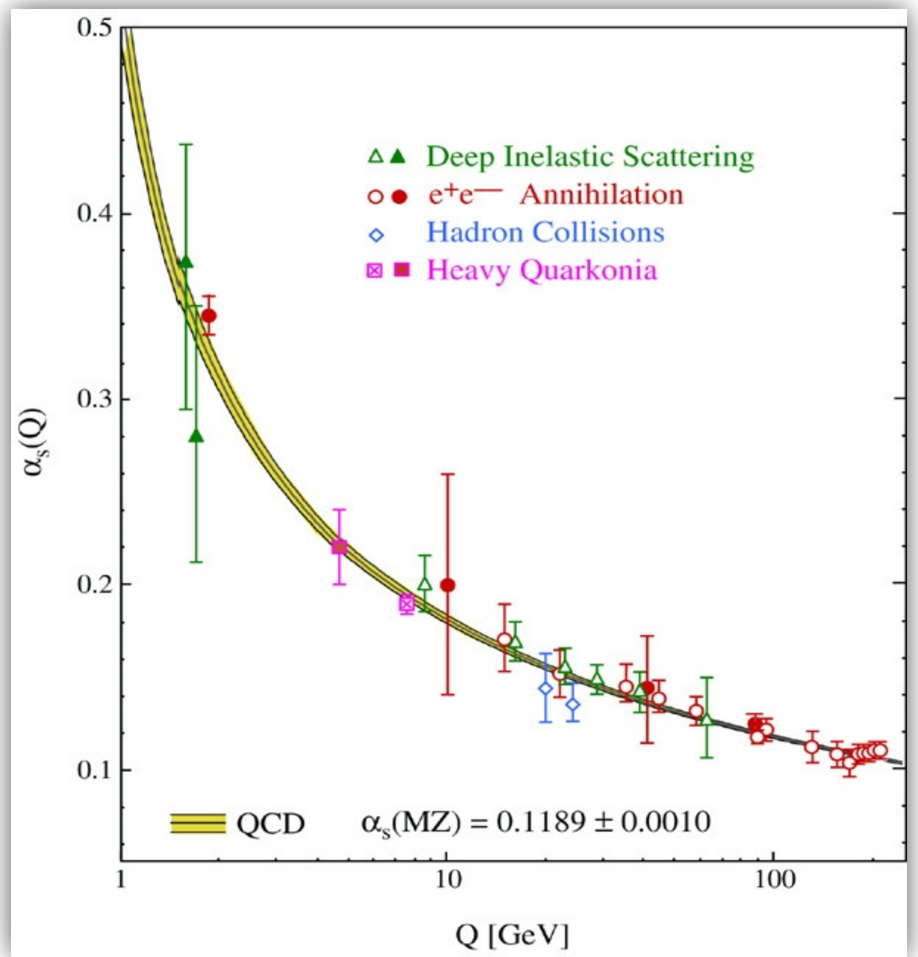
EHM means Gluons are massive

This is where we live

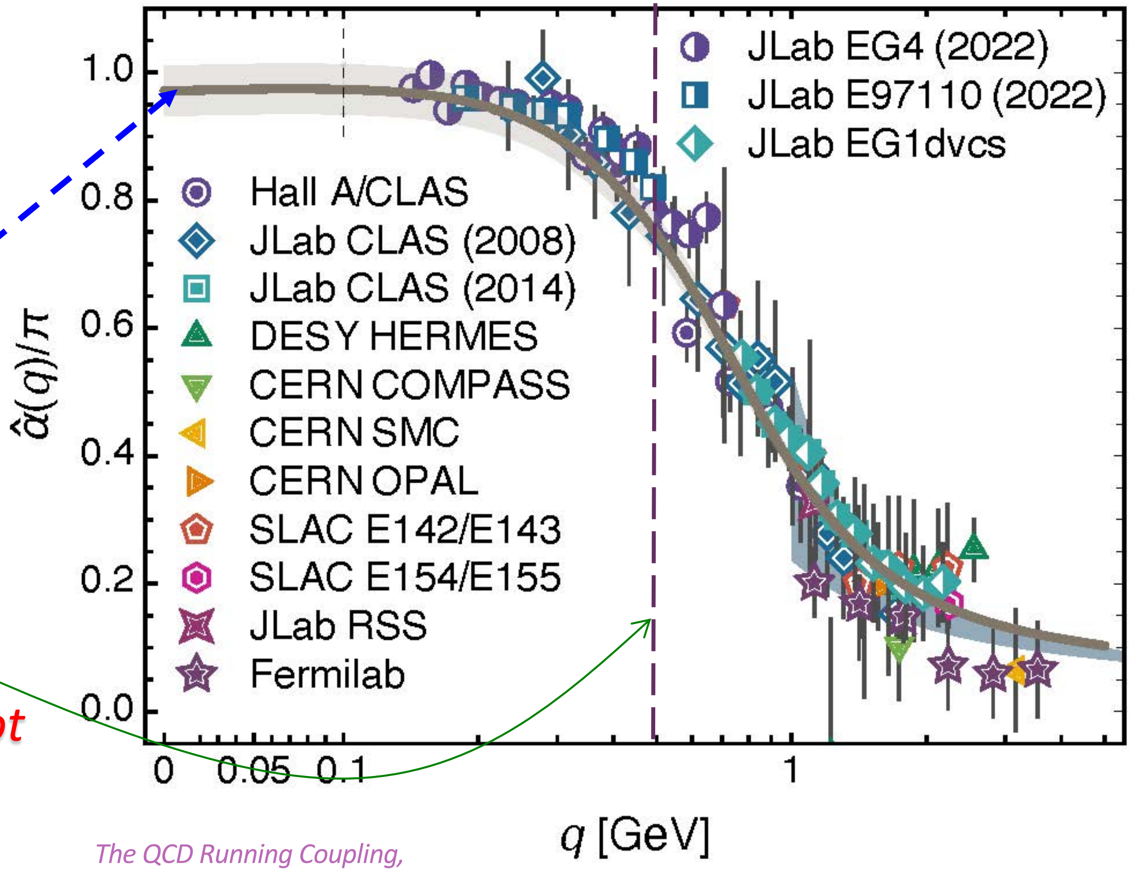
⇐
What's happening out here?!



QCD's Running Coupling

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

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

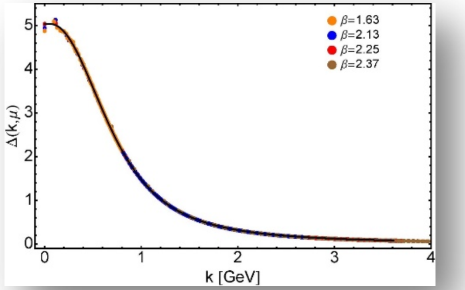
QCD Running Couplings and Effective Charges, A. Deur, S. J. Brodsky, C. D. Roberts – arXiv:2303.00723 [hep-ph]

EHM Basics

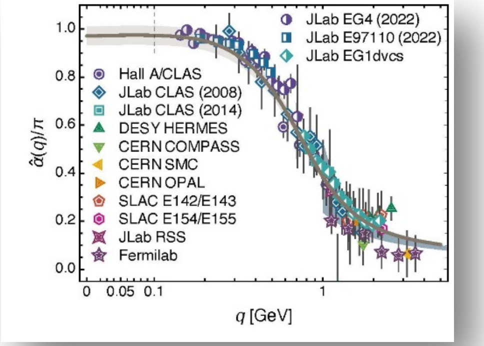
- Absent Higgs boson couplings, the Lagrangian of QCD is scale invariant
- Yet …
  - Massless gluons become massive
  - A momentum-dependent charge is produced
  - Massless quarks become massive
- EHM is expressed in
  EVERY strong interaction observable
- Challenge to Theory =

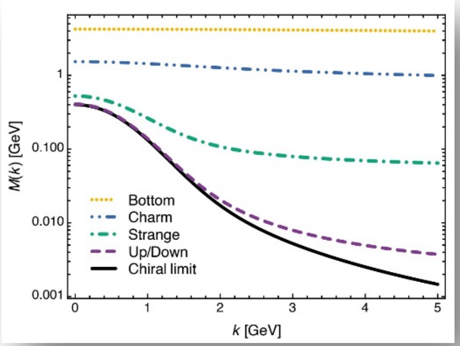
  Elucidate all observable consequences of these phenomena and highlight the paths to measuring them
- Challenge to Experiment =

  Test the theory predictions so that
  the boundaries of the Standard Model can finally be drawn



THREE PILLARS OF EHM





Exposing & Charting EHM

- Proton was discovered 100 years ago

  It is stable; hence, an ideal target in experiments
- But just as studying the hydrogen atom ground state didn't give us QED,

  focusing on the ground state of only one form of hadron matter will not solve QCD
- New Era dawning

  High energy + high luminosity

  ⇒ proton studies can become truly precise

  ⇒ science can move beyond the focus on the proton

AMBER @ CERN
EIC
EicC
JLab12 & JLab20+

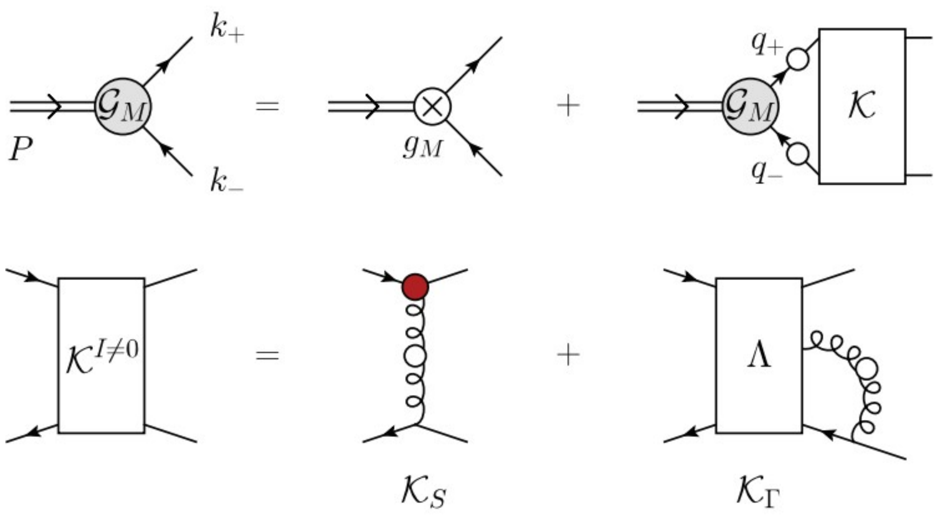
- Enable precision studies of, *e.g.*,
  - Structure of Baryon excited states
    - ✓ Baryons are the most fundamental three-body systems in Nature
    - ✓ If we don't understand how QCD, a Poincaré-invariant quantum field theory, builds each of the baryons in the complete spectrum, then we don't understand Nature.
  - Structure of Nature's most fundamental Nambu-Goldstone bosons (π & K)
  - Spectrum of mesons and their structure

with Strangeness

Quark Models and the Meson Spectrum

- Regarding spectrum of hadrons, results from nonrelativistic or somewhat relativised quark models are still often cited as benchmarks
  - PDG: "*The spectrum of baryons and mesons exhibits a high degree of regularity. The organizational principle which best categorizes this regularity is encoded in the quark model. All descriptions of strongly interacting states use the language of the quark model.*"
- And it was long ago claimed [Godfrey & Isgur] ". . . *all mesons – from the pion to the upsilon – can be described in a unified framework.*"
- Despite following facts:
  a) neither the "quarks" nor the potentials in quark models have been shown to possess any mathematical link with QCD – rigorous or otherwise
  b) Orbital angular momentum and spin used to label quark model states are not Poincaré-invariant (not observable) quantum numbers.
  c) Quark models break all symmetries known to be critical to hadron spectra
  d) No possible means of systematic improvement
- Quark models can be tuned to fit the spectrum, but they can't explain it

EHM and the Meson Spectrum



- Systematic approach to continuum bound-state problems in QCD was introduced almost thirty years ago
- Amongst other things, the scheme
  - ✓ highlighted importance of preserving continuous and discrete symmetries when formulating bound-state problems
  - ✓ enabled proof of Goldberger-Treiman identities & Gell-Mann–Oakes–Renner relation
  - ✓ opened door to symmetry-preserving, Poincaré-invariant predictions of hadron observables
- Leading-order (RL – rainbow-ladder) truncation
  - – good for ground-state hadrons which possess little rest-frame orbital angular momentum between valence constituents
- Limitation: RL inability to realistically express impacts of EHM on hadron observables
  - – weakness not overcome at any finite order of elaboration

EHM and the Meson Spectrum

Bethe-Salpeter kernel and properties of strange-quark mesons,
Zhen-Ni Xu (徐珍妮) et al., *NJU-INP 065/22, e-Print: 2208.13903 [hep-ph]*
Eur. Phys. J. A 59 (Lett.) (2023) 39/1-10

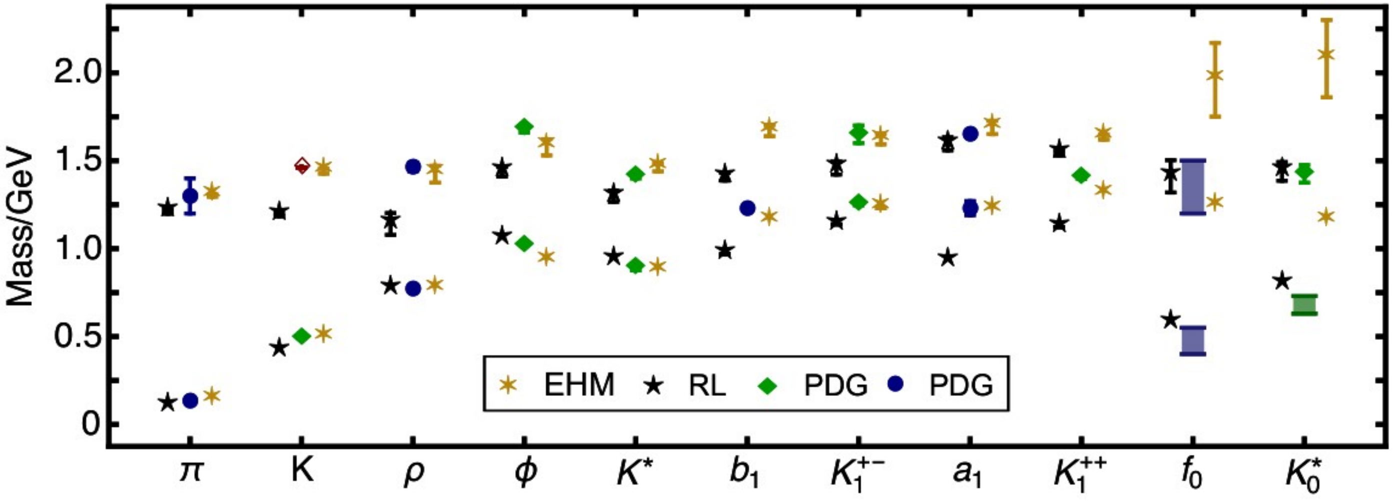
- Improved schemes, expressing EHM in kernels of bound-state equations, have been identified
- Shown promise in applications to ground-state mesons built from u, d valence quarks and/or antiquarks
- But that is a small subset of hadron spectrum; so, recent extension to the spectrum and decay constants of u, d, s meson ground- and first-excited states is important step forward
- EHM entails generation of dressed-quark anomalous chromomagnetic moment (ACM) … means gluon+quark interaction acquires a new, dynamically generated piece:

$$\Gamma_\nu(q,k) = \gamma_\nu + \boxed{\eta\, \kappa\big((q-k)^2\big)\, \sigma_{\nu\rho}(q-k)_\rho}$$

$\eta \sim 1$ is strength; $\kappa(s=0) = 1$ and falls to zero like quark+quark interaction

Dressed-quark anomalous magnetic moments,
Chang, L.; Liu, Y.X.; Roberts, C.D., Phys. Rev. Lett. 2011, 106, 072001.

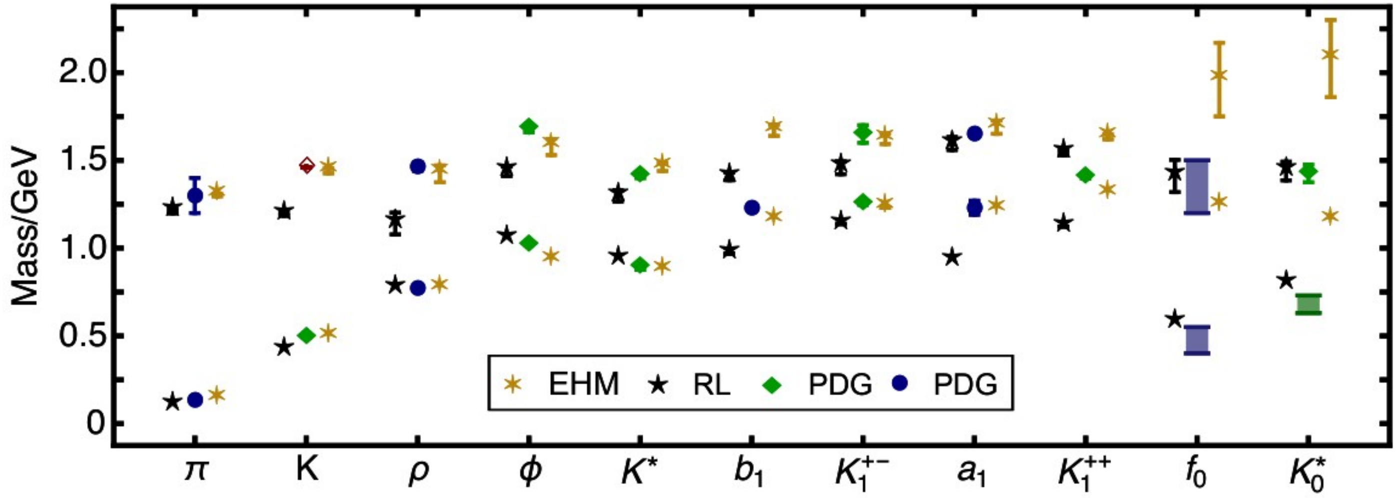
RL and Meson Spectrum



- Features & flaws of RL truncation are evident in figure
- Overall, mean absolute relative difference between RL masses and central experimental = 13(8)%.
- Fair agreement, perhaps …

  but ∃ substantial scatter & many qualitative discrepancies, *e.g.*,
  - $m_K^{excited} < m_\pi^{excited}$ in RL, whereas empirical ordering is opposite
  - Also : $m_\rho^{excited} < m_\pi^{excited}$, $m_\rho^{excited} < m_{K^*}^{excited}$ = wrong ordering
  - $m_{a_1} - m_\rho$ & $m_{b_1} - m_\rho$ are just $\frac{1}{3}$ of empirical values because m_{a_1} & m_{b_1} are far too small
  - $m_\phi^{excited} - m_\phi$ is just $\frac{1}{2}$ experimental value
  - Level ordering of K_1^{+-} and K_1^{++} is incorrect
  - RL truncation produces light quark+antiquark scalar mesons, which are not seen in Nature

EHM and Meson Spectrum



- EHM/ACM improved kernel brings significant improvement
- Mean absolute relative difference between EHM masses and central experimental = 3(3)% = factor 4.6 improvement over RL
- Now, *e.g.*,
  - $m_K^{excited} > m_\pi^{excited}$
  - Also : $m_\rho^{excited} > m_\pi^{excited}, m_\rho^{excited} \approx m_{K^*}^{excited}$ = correct ordering
  - $m_{a_1} - m_\rho$ & $m_{b_1} - m_\rho$ match empirical values
  - $m_\phi^{excited} - m_\phi$ matches experiment
  - Level ordering of K_1^{+-} and K_1^{++} is correct
  - quark+antiquark scalar mesons are pushed to very large masses, leaving room for necessary final-state interaction contributions

Both gross and fine details of spectrum of u, d, s, mesons are very sensitive to expressions of EHM in gluon+quark interaction

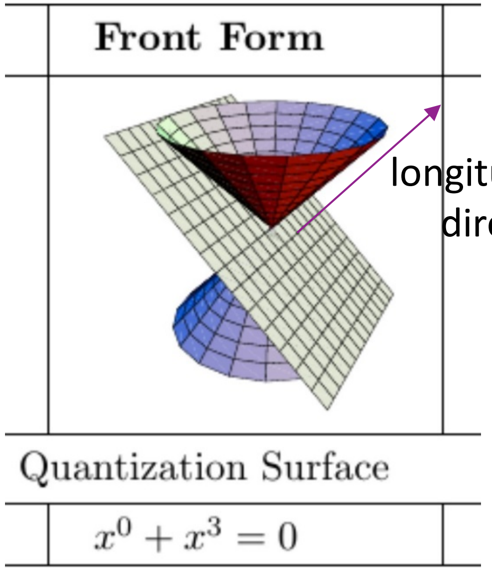
$\Psi(x, t)$

K Wave Functions

Wave Functions of Nambu Goldstone Bosons

- Physics Goals:
  - Pion and kaon distribution amplitudes (DAs – $\varphi_{\pi,K}$)
  - Nearest thing in quantum field theory to Schrödinger wave function
  - Consequently, fundamental to understanding π and K structure.
- Scientific Context:
  - For 40 years, the x-dependence of the pion's dominant distribution amplitude (DA) has been controversial.
  - Modern theory ⇒ EHM expressed in x-dependence of $\varphi_{\pi,K}(x)$
  - $\varphi_{\pi}(x)$ is direct measure of dressed-quark running mass in chiral limit.
  - Kaon DA = asymmetric around midpoint of its domain of support (0<x<1)
    - Degree of asymmetry is signature of constructive interference between EHM and HB mass-generating mechanisms

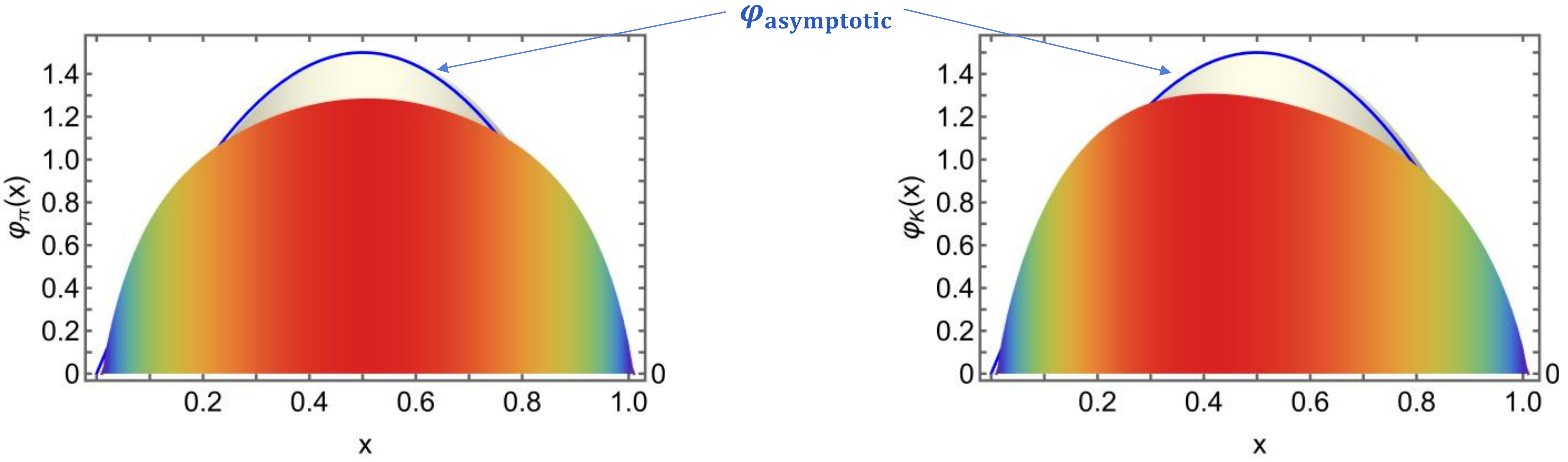
DAs are 1D projection of hadron's light-front wave function, obtained by integration $\sim \int d^2k_\perp \Psi(x,k_\perp)$



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

Exposing strangeness: projections for kaon electromagnetic form factors, Fei Gao *et al.*, arXiv:1703.04875 [nucl-th], Phys. Rev. D **96** (2017) 034024/1-8

π & K DAs cf. asymptotic profile



- EHM generates broadening in both π & K
- EHM + Higgs-boson interference is responsible for skewing in kaon
  - HB-only ⇒ peak shifted to $\frac{m_u^{\text{HB}}}{m_s^{\text{HB}}} \times \frac{1}{2} \approx 0.02$ … *wrong*
  - Instead, EHM*HB for u and s quarks … $\frac{\text{EHM}\ m_u \to M_u}{\text{EHM}\ m_s \to M_s} \times \frac{1}{2} \approx 0.4$

These features have widespread impact in studies of (hard) exclusive processes.

Broadening can be verified, e.g., in measurements of π and K electric charge distributions (elastic form factor measurements at large Q^2) & in $\pi + p$ Drell-Yan measurements

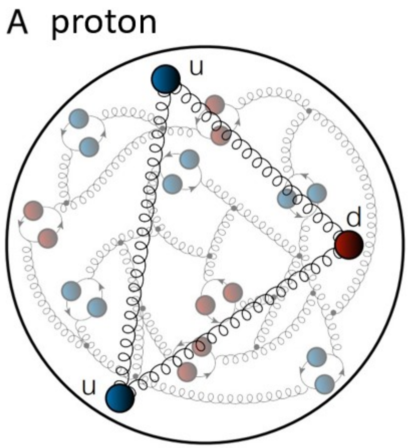
- ✓ *Nucleon mass from a covariant three-quark Faddeev equation*
  G. Eichmann *et al*., Phys. Rev. Lett. 104 (2010) 201601
- ✓ *Poincaré-covariant analysis of heavy-quark baryons*
  Si-Xue Qin (秦思学) *et al*., Phys.Rev. D 97 (2018) 114017/1-13
- ✓ *Weak form factors of octet baryons*
  Zhao-Qian Yao (姚照千), *et al*. – nearing completion

Faddeev Equation for Baryons

Structure of Baryons

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 remains challenging problem – algorithms and numerical analysis

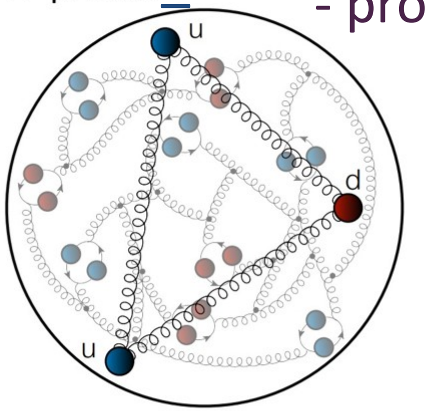


Structure of Baryons

Solution delivers Poincaré-covariant proton wave function

ion sums all possible exchanges and interactions that can take place between three dressed-quarks

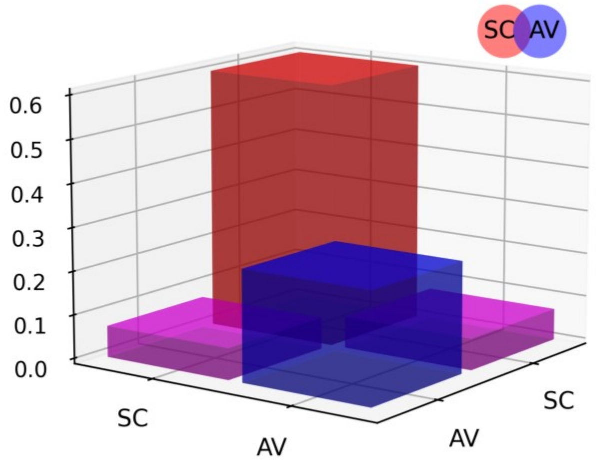
- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but remains challenging problem – algorithms and numerical analysis
- For many/most applications, diquark approximation to quark+quark scattering kernel is used
- ***Prediction***: owing to EHM phenomena*, strong diquark 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

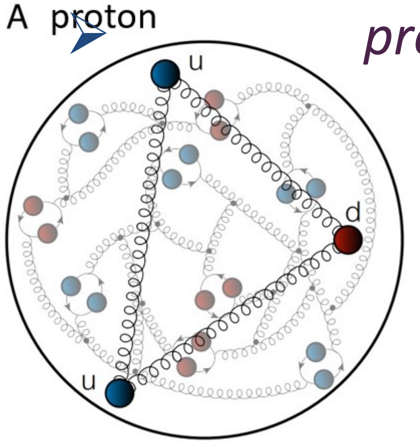


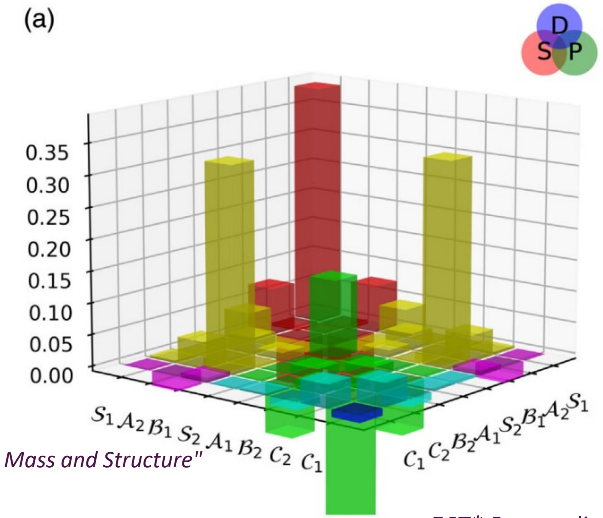
Structure of Baryons

Solution delivers Poincaré-covariant proton wave function

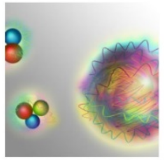
ion sums all possible exchanges and interactions that can take place between three dressed-quarks

- 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*:*
- *proton wave function is not just S-wave, but contains strong P-wave contributions*





- ✓ CSM prediction = canonical normalization dominated by $S \otimes S$, but receives large $S \otimes P$ and $P \otimes P$ contributions
- ✓ Non-$S \otimes S$ make-up 60% of proton charge



23 September 2019 — 27 September 2019

DIQUARK CORRELATIONS IN HADRON PHYSICS: ORIGIN, IMPACT AND EVIDENCE

Modern experimental facilities, new theoretical techniques for the continuum bound-state problem and progress with lattice-regularized QCD have provided strong indications that soft quarkquark (diquark) correlations play a crucial role in hadron physics.

More info

Diquarks - Facts

- Theory predicts experimental observables that would constitute unambiguous measurable signals for the presence of diquark correlations.
- Some connect with spectroscopy of exotics
  - ✓ tetraquarks and pentaquarks
- Numerous observables connected with structure of conventional hadrons, e.g.
  - ✓ existence of zeros in *d*-quark contribution to proton Dirac and Pauli form factors
  - ✓ Q^2-dependence of nucleon-to-resonance transition form factors
  - ✓ x-dependence of proton structure functions
  - ✓ deep inelastic scattering on nuclear targets (nDIS) … proton production described by direct knockout of diquarks, which subsequently form into new protons

ELSEVIER

Progress in Particle and Nuclear Physics

Volume 116, January 2021, 103835

Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6, 7], E. Cisbani [8], M. Ding [9], G. Eichmann [10, 11], R. Ent [12], J. Ferretti [13] ✉, R.W. Gothe [14], T. Horn [15, 12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18, 19] ✉ … B.B. Wojtsekhowski [12] ✉

Eur. Phys. J. A (2022) 58:206
https://doi.org/10.1140/epja/s10050-022-00848-x

THE EUROPEAN PHYSICAL JOURNAL A

Check for updates

Regular Article - Theoretical Physics

Nucleon axial form factor at large momentum transfers

Chen Chen[1,2,a], **Craig D. Roberts**[3,4,b]

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[4] Institute for Nonperturbative Physics, Nanjing University, Nanjing 210093, Jiangsu, China

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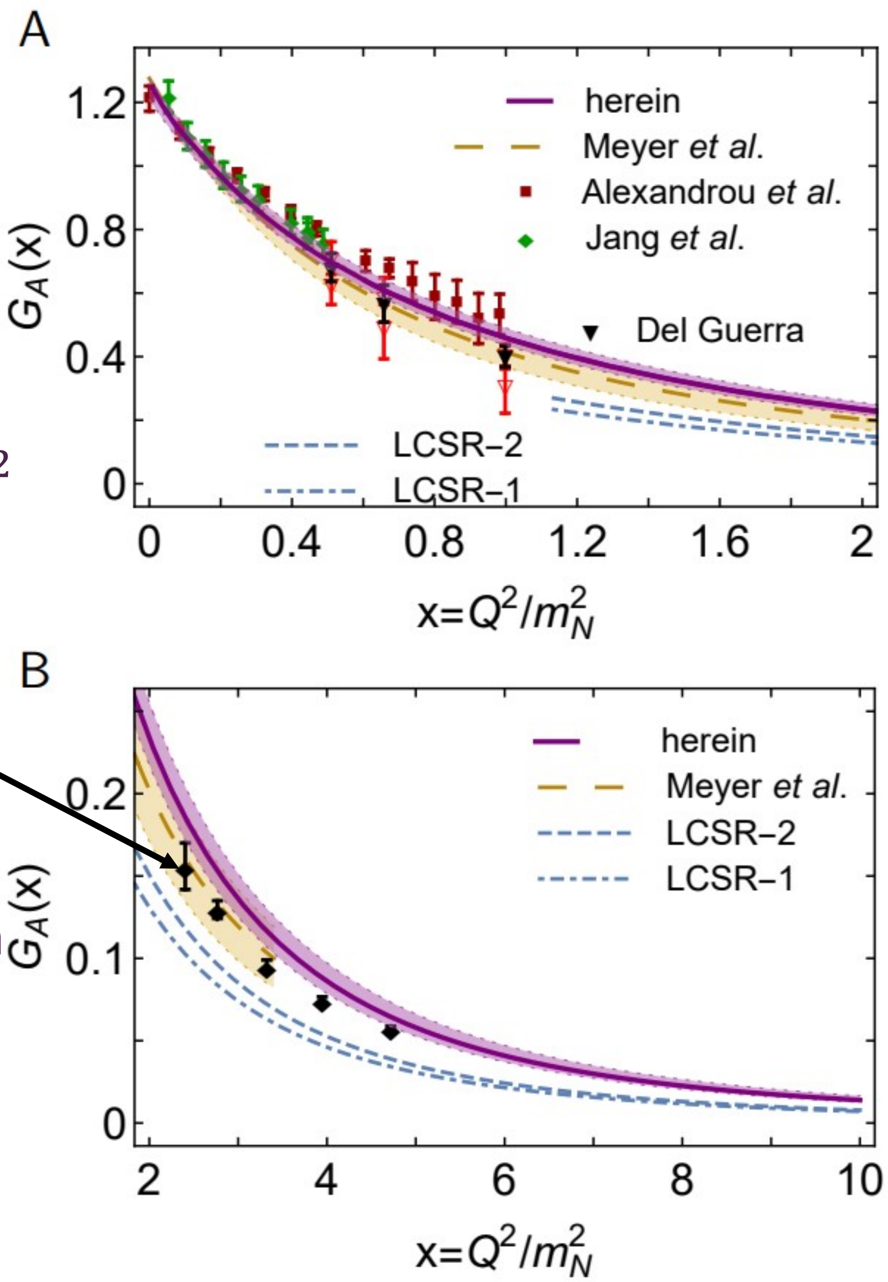
Large Q^2 Nucleon Axial Form Factor

- Parameter-free CSM predictions to $Q^2 = 10\, m_p^2$
- One other calculation, *viz*. LCSRs using different models for proton DA ... Only available on $Q^2 > 1\, m_p^2$
- CSM prediction agrees with available data: small & larger Q^2
- Larger Q^2 data from CLAS [K. Park *et al*., Phys. Rev. C 85 (2012) 035208], threshold pion electroproduction, extends $Q^2 \approx 5\, m_p^2$
  - ✓ This technique could be used to reach higher Q^2
- ✓ Regarding oft-used dipole *Ansatz*,
  - ✓ Fair representation of $G_A(x)$ on $x \in [0, 3]$ = fitting domain
  - ✓ But outside fitted domain, quality of approximation deteriorates quickly
  - ✓ dipole overestimates true result by 56% at x = 10



Large Q^2 Nucleon Axial Form Factor

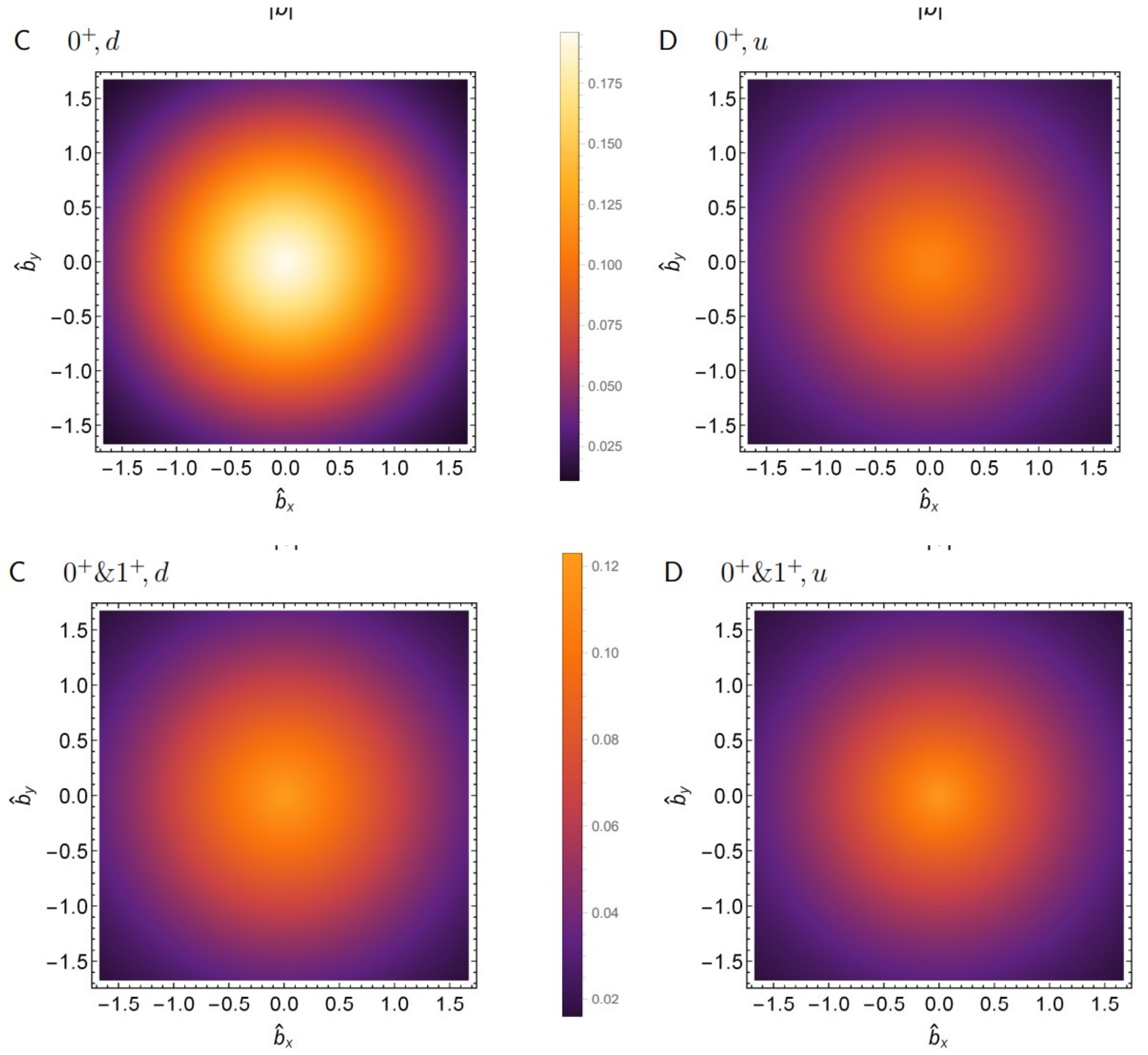
- Light-front transverse density profiles

- Omitting axialvector diquarks
  - ✓ magnitude of the d quark contribution to GA is just 10% of that from the u quark
  - ✓ d quark is also much more localized

$$r_{A_d}^{\perp} \approx 0.5\, r_{A_u}^{\perp}$$

- Working with realistic axialvector diquark fraction
  - ✓ d and u quark transverse profiles are quite similar

$$r_{A_d}^{\perp} \approx 0.9\, r_{A_u}^{\perp}$$



Proton Spin Structure

- Flavour separation of proton axial charge
- d-quark receives large contribution from probe+quark in presence of axialvector diquark
  - $\frac{g_A^d}{g_A^u} =^{0^+\&1^+} -0.32(2)$
  - $\frac{g_A^d}{g_A^u} =^{0^+ \text{ only}} -0.054(13)$

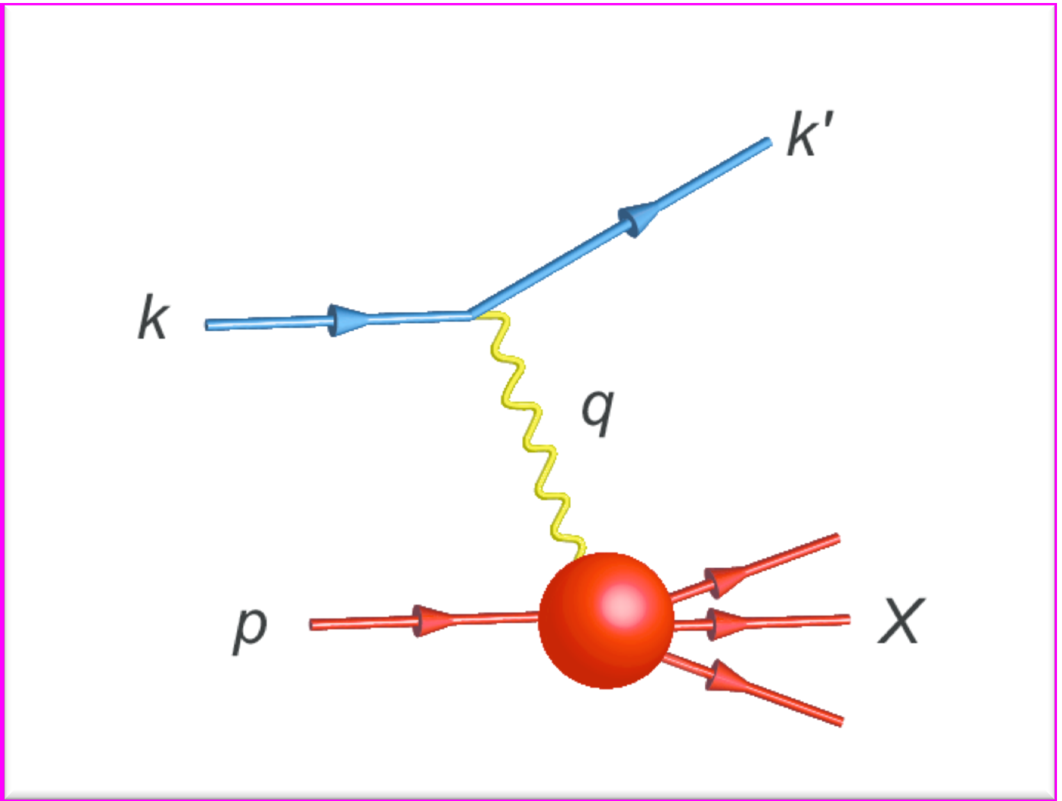
Table 1 Diagram and flavour separation of the proton axial charge: $g_A^u = G_A^u(0)$, $g_A^d = G_A^d(0)$; $g_A^u - g_A^d = 1.25(3)$. The listed uncertainties in the tabulated results reflect the impact of $\pm 5\%$ variations in the diquark masses in Eq. (3), *e.g.* $0.88 6_{\mp} \Rightarrow 0.88 \mp 0.06$.

	$\langle J\rangle_q^S$	$\langle J\rangle_q^A$	$\langle J\rangle_{qq}^{AA}$	$\langle J\rangle_{qq}^{\{SA\}}$	$\langle J\rangle_{ex}^{SS}$	$\langle J\rangle_{ex}^{\{SA\}}$	$\langle J\rangle_{ex}^{AA}$
g_A^u	$0.88 6_{\mp}$	$-0.08 0_{\pm}$	$0.03 0_{\pm}$	$0.08 0_{\mp}$	0	≈ 0	$0.03_{\pm 1}$
$-g_A^d$	0	$0.16 0_{\pm}$	0	$0.08 0_{\mp}$	$0.05 1_{\pm}$	≈ 0	$0.01_{\pm 0}$

Probability that scalar diquark only picture of proton is consistent with data = 1/7,100,000

- Experiment: $\frac{g_A^d}{g_A^u} =^{0^+\&1^+} -0.27(4) \Leftarrow$ strong pointer to importance of AV correlation
- Hadron scale: $g_A^u + g_A^d\ (+g_A^s = 0) = 0.65(2) \Rightarrow$ quarks carry 65% of the proton spin
- Poincaré-covariant proton wave function: remaining 35% lodged with quark+diquark orbital angular momentum
- Extended to entire octet of ground-state baryons: dressed-quarks carry 50(7)% of proton spin at hadron scale

Contact interaction analysis of octet baryon axialvector and pseudoscalar form factors, Peng Cheng (程鹏), Fernando E. Serna, Zhao-Qian Yao (姚照千) et al., NJU-INP 063/22, e-Print: 2207.13811 [hep-ph], Phys. Rev. D **106**,(2022) 054031



Parton Distribution Functions

Proton and pion distribution functions in counterpoint

- Today, 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?

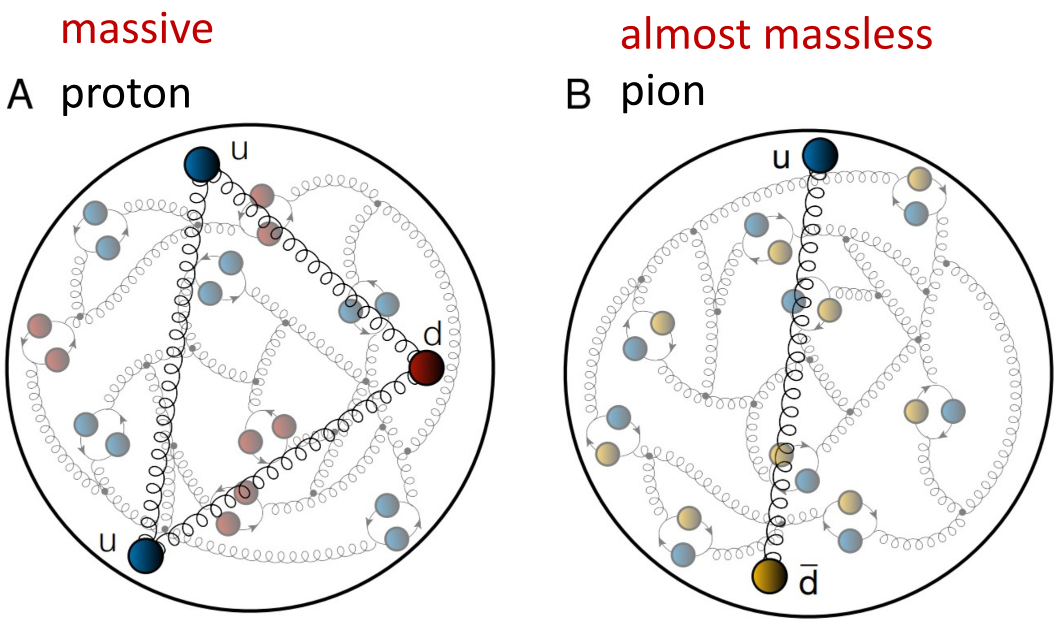
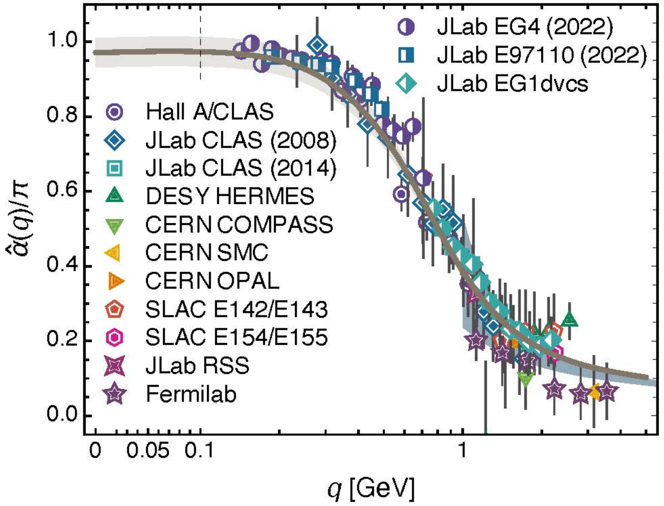


Figure 1: *Left panel* – A. In terms of QCD's Lagrangian quanta, the proton, p, contains two valence up (u) quarks and one valence down (d) quark; and also infinitely many gluons and sea quarks, drawn here as "springs" and closed loops, respectively. The neutron, as the proton's isospin partner, is defined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

All-orders evolution

- **P1** – *In the context of Refs. [73, 74], there exists at least one effective charge, $\alpha_{1\ell}(k^2)$, which, when used to integrate the leading-order perturbative DGLAP equations, defines an evolution scheme for parton DFs that is all-orders exact.*
- CSM Process-Independent charge serves this purpose

- *Hadron scale, ζ_H*
  Scale at which all properties of a given hadron are carried by valence degrees-of-freedom



Physics Letters B
Volume 95, Issue 1, 8 September 1980, Pages 70-74

Renormalization group improved perturbative QCD

G. Grunberg [1]

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Abstract

The results of perturbative QCD calculations are reformulated as renormalization-scheme independent predictions; in so doing, we obtain a renormalization group improvement of perturbation theory. As an application, we show that asymptotic freedom alone does not give the correct quantitative relation between pseudoscalar charmonium decay and the scaling violations in deep inelastic scattering.

[73] G. Grunberg, Renormalization Group Improved Perturbative QCD, Phys. Lett. B 95 (1980) 70, [Erratum: Phys. Lett. B 110, 501 (1982)].

[74] G. Grunberg, Renormalization Scheme Independent QCD and QED: The Method of Effective Charges, Phys. Rev. D 29 (1984) 2315.

[75] A. Deur, S. J. Brodsky, G. F. de Teramond, The QCD Running Coupling, Prog. Part. Nucl. Phys. 90 (2016) 1–74.

[76] A. Deur, V. Burkert, J. P. Chen, W. Korsch, Experimental determination of the QCD effective charge $\alpha_{g_1}(Q)$, Particles 5 (2) (2022) 171–179.

[77] A. Deur, S. J. Brodsky, C. D. Roberts, QCD Running Couplings and Effective Charges – arXiv:2303.00723 [hep-ph] .

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

✓ 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.

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

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

8 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 $\begin{cases} d^p(x;\zeta_H), u^p(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^3 \\ \bar{d}^\pi(x;\zeta_H), u^\pi(x;\zeta_H) \overset{x\simeq 1}{\propto} (1-x)^2 \end{cases}$
- $\zeta > m_p$: 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: $\beta_{p,\pi}^{\text{sea}} \geq \beta_{p,\pi}^{\text{val}} + 2$
- 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.

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,

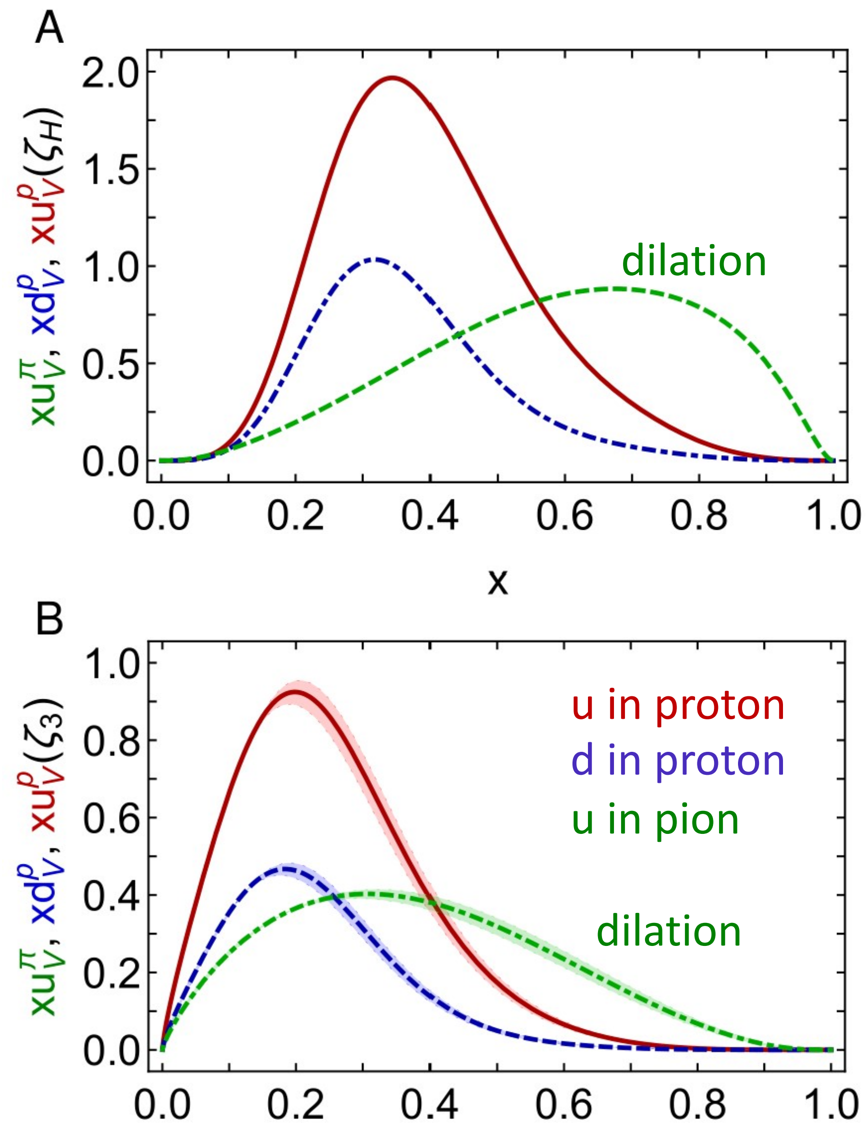
8 *i.e.*, at ζ = $\text{mass}_{\text{charm}}$ valence-quarks are subleading degrees-of-freedom. Instead, gluons dominate on what is typically called the valence-quark domain.

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

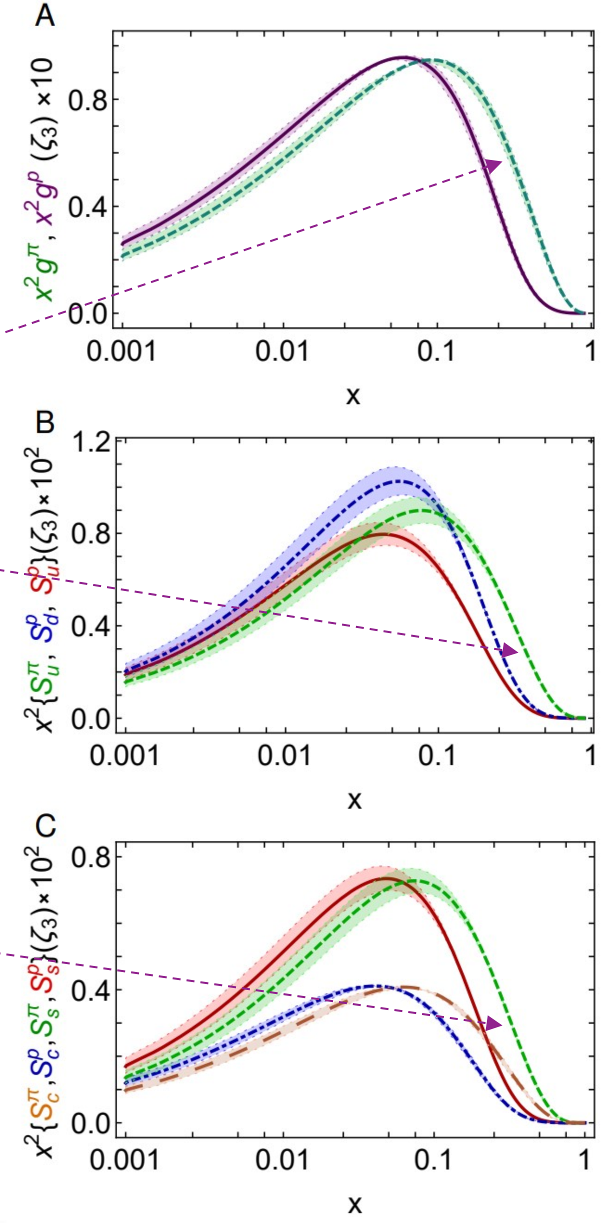


Proton and pion distribution functions in counterpoint - glue and sea

- 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



"Intrinsic" Charm

- CSM $\langle x\rangle_c^{\zeta_2} = 1.32(05)\%, \langle x\rangle_c^{\zeta_3} = 1.86(06)\%$

  cf. Phen. fits $\langle x\rangle_c^{\zeta_2} = 1.7(4)\%$, $\langle x\rangle_c^{\zeta_3} = 2.5(4)\%$
- $\zeta_H =$ scale whereat valence quasiparticle degrees-of-freedom carry all measurable hadron properties
- At ζ_H, Fock space components, which might be interpreted as intrinsic charm, are sublimated into nonperturbatively computed $\zeta = \zeta_H$ Schwinger functions
- Significant c quark momentum fraction obtained under nonperturbative evolution from ζ_H without recourse to "intrinsic charm"
- Outcome largely independent of explicit form of nonperturbative effective charge $= \alpha_{1\ell}(k^2)$
- *Recent claims of "intrinsic charm discovery" might be overstated*
- Notwithstanding size of predicted fractions, CSM $S_c^{\pi,p}(x)$ have sea quark profiles.
- One is thus led to re-evaluate what is meant by intrinsic charm in any hadron

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

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. **128** (2022) 132003

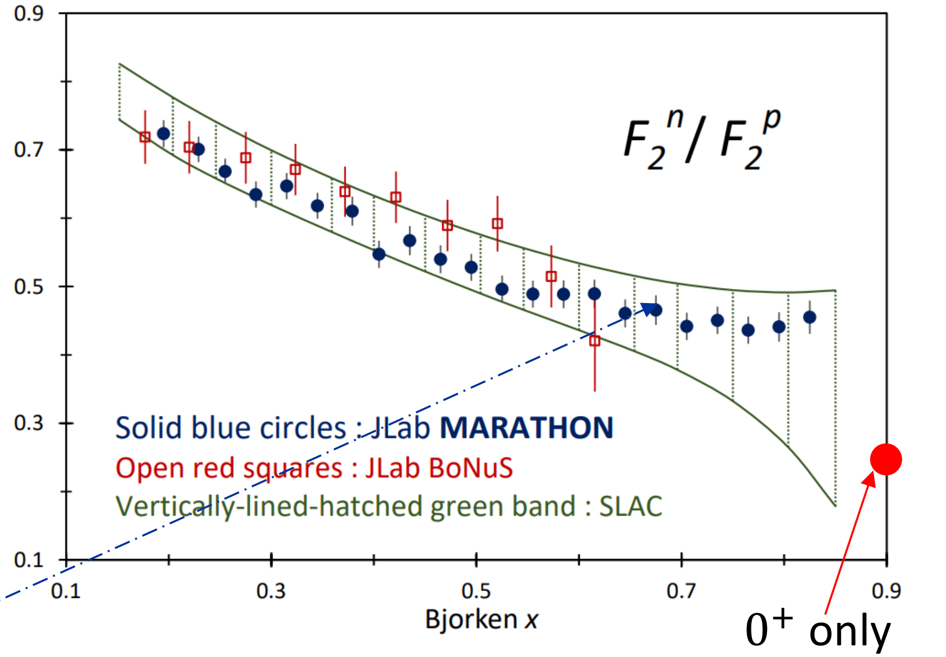


FIG. 2: The F_2^n/F_2^p ratio plotted versus the Bjorken x from the JLab MARATHON experiment. Also shown are JLab Hall B BoNuS data [56], and a band based on the fit of the SLAC data as provided in Ref. [46], for the MARATHON kinematics [$Q^2 = 14 \cdot x$ (GeV/c)^2] (see text). All three experimental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

Neutron/Proton structure function ratio

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

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

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

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

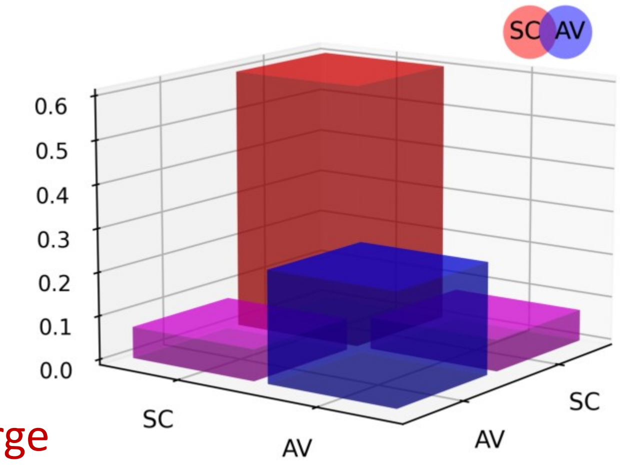
- Comparison with MARATHON data

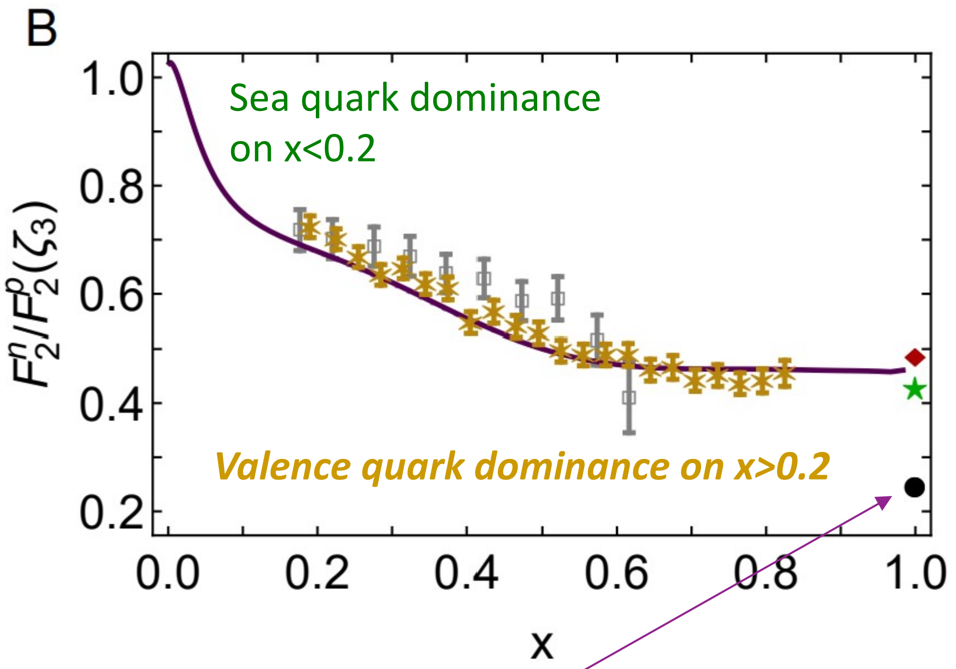
  [D. Abrams, *et al*., Measurement of Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment – arXiv:2104.05850 [hep-ex], Phys. Rev. Lett. (2022) *in press*]

- 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 1/141,000

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

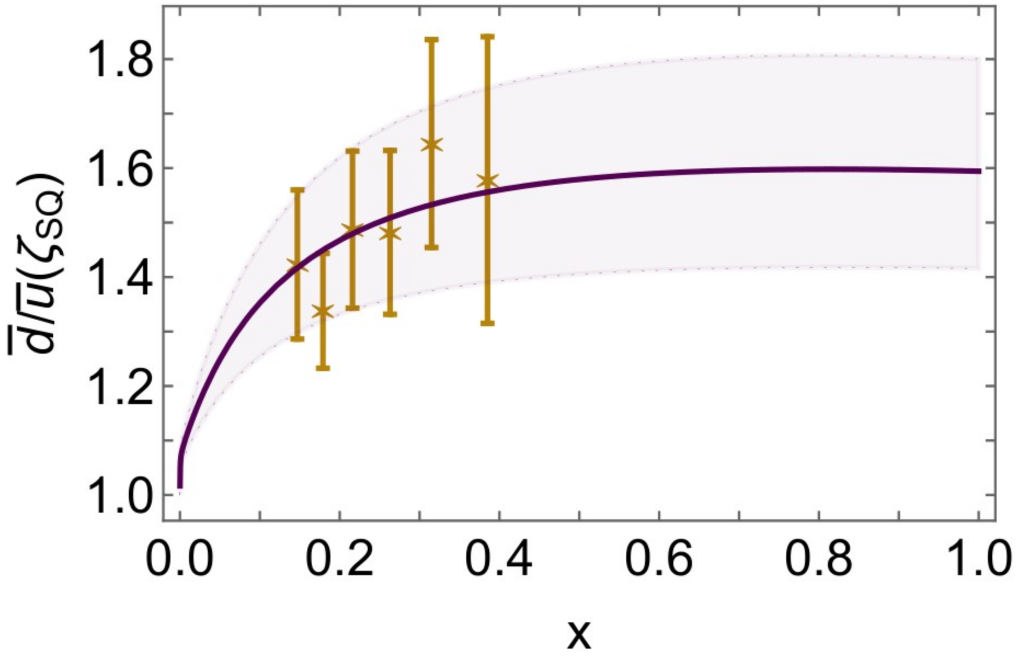
Asymmetry of antimatter in the proton

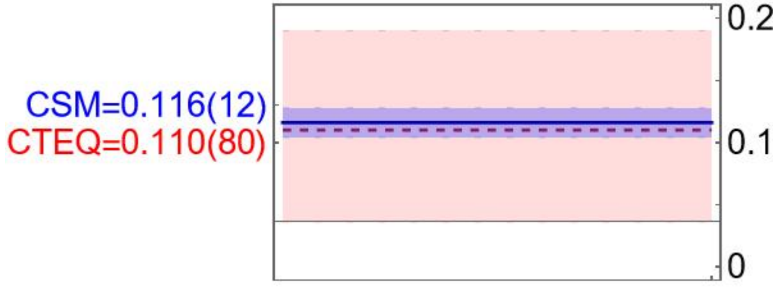
- Proton = u + u + d
  - ⇒ Pauli blocking: gluon splitting produces
    $d+\bar{d}$ in preference to $u+\bar{u}$
- Comparison with SeaQuest data
  [J. Dove, et al., *The asymmetry of antimatter in the proton*, Nature 590 (7847) (2021) 561–565.]
- Gottfried sum rule

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

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

$\zeta = 2$ GeV ... $\langle x\rangle_{\bar{u}} \downarrow 25\%$ & $\langle x\rangle_{\bar{d}} \uparrow 25\%$





Gottfried Sum Rule

✓ *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 Spin Crisis

Proton Spin Crisis

- Long story … 35+ years … $-billions …
- Future … Electron Ion Collider
  … Total project cost is expected to range from $1.7-2.8 billion
  … First beam ~ 2034

USA NAS Report

Hearing from experts on the science that an EIC would be able to carry out, the committee finds that

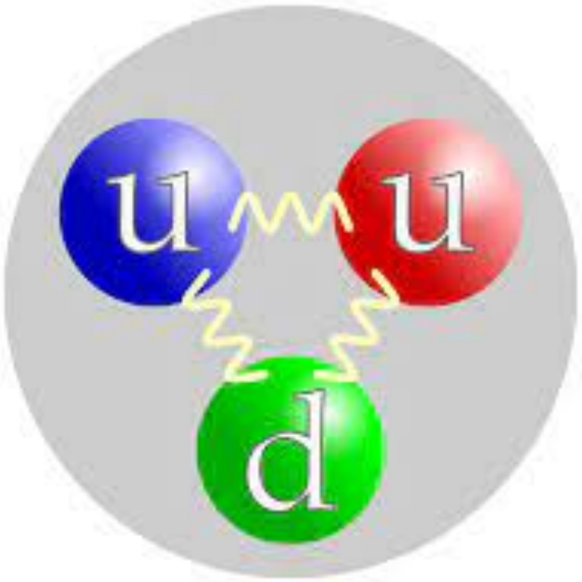
Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

EHM is the keystone for future experiments in hadroparticle physics

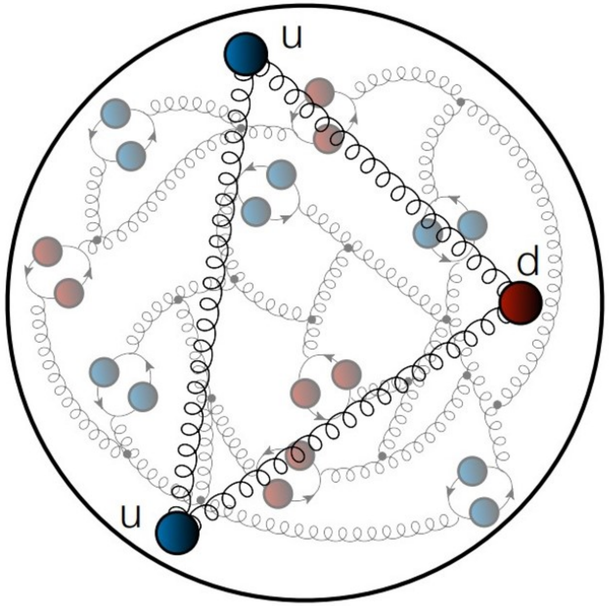
Origin of Proton Spin

- Basic answer
- This is NOT the proton



Infinitely many
spin $(J) = 1$ gluons
Can potentially carry a lot of the proton spin

- In relativistic quantum non-Abelian gauge field theory (QCD), this is the proton



- 2 valence u quarks + 1 valence d quark + sea of infinitely many quarks and antiquarks and gluons

Phys. Lett. B **844** (2023) 138074/1-7

Preprint no. NJU-INP 073/23, USTC-ICTS/PCFT-23-13

Polarised parton distribution functions and proton spin

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Date: 2023 Apr 24

Abstract

Supposing there exists an effective charge which defines an evolution scheme for both unpolarised and polarised parton distribution functions (DFs) that is all-orders exact and using *Ansätze* for hadron-scale proton polarised valence quark DFs, constrained by flavour-separated axial charges and insights from perturbative quantum chromodynamics, predictions are delivered for all proton polarised DFs at the scale $\zeta_C^2 = 3\,\text{GeV}^2$. The pointwise behaviour of the predicted DFs and, consequently, their moments, compare favourably with results inferred from data. Notably, flavour-separated singlet polarised DFs are small. On the other hand, the polarised gluon DF, $\Delta G(x;\zeta_C)$, is large and positive. Using our result, we predict $\int_{0.05}^{1} dx\,\Delta G(x;\zeta_C) = 0.214(4)$ and that experimental measurements of the proton flavour-singlet axial charge should return $a_0^{\rm E}(\zeta_C) = 0.35(2)$.

Keywords: proton structure, high-energy polarised proton-proton collisions, polarised deep inelastic scattering, emergence of mass, continuum Schwinger function methods, Dyson-Schwinger equations

Polarised quark distribution functions at ζ_H

- True in general: at hadron scale, ζ_H … $\Delta q(x;\zeta_H) = f(x) q(x;\zeta_H)$ … what is $f(x)$?
- Constraints from pQCD
  - At low-x: $\exists$ no correlation between helicity of struck quark and that of parent proton

    $\Rightarrow$ polarised:unpolarised ratio of DFs must vanish

    $$\frac{\Delta q(x)}{q(x)} \to 0 \text{ as } x \to 0$$

    Regge phenomenology: $\Delta q(x) \propto \sqrt{x}\, q(x)$
  - At high-x, polarised and unpolarised valence quark distributions possess the same power-law behaviour, *viz*.

    $$\frac{\Delta q(x)}{q(x)} \to \text{constant} \neq 0 \text{ as } x \to 1$$

Polarised quark distribution functions at ζ_H

- Implement constraints ($s_u = 1 = -s_d$):

$$\Delta q(x;\zeta_H) = s_q r_i(x,\gamma_i^q) q(x;\zeta_H)$$

$$r_1(x,\gamma) = \sqrt{x}/[1+\gamma\sqrt{x}]\,, \quad r_2(x,\gamma) = \sqrt{x}/[\gamma+\sqrt{x}]\,,$$
$$r_3(x,\gamma) = \sqrt{x}/[1+\gamma x]\,, \quad r_4(x,\gamma) = \sqrt{x}/[\gamma+x]\,.$$

- In each case, γ chosen to ensure $\int_0^1 dx\, \Delta q(x;\zeta_H) = g_A^q$

i	1	2	3	4
γ_i^u	0.350	0.621	0.575	0.853
γ_i^d	1.47	1.26	2.62	1.60

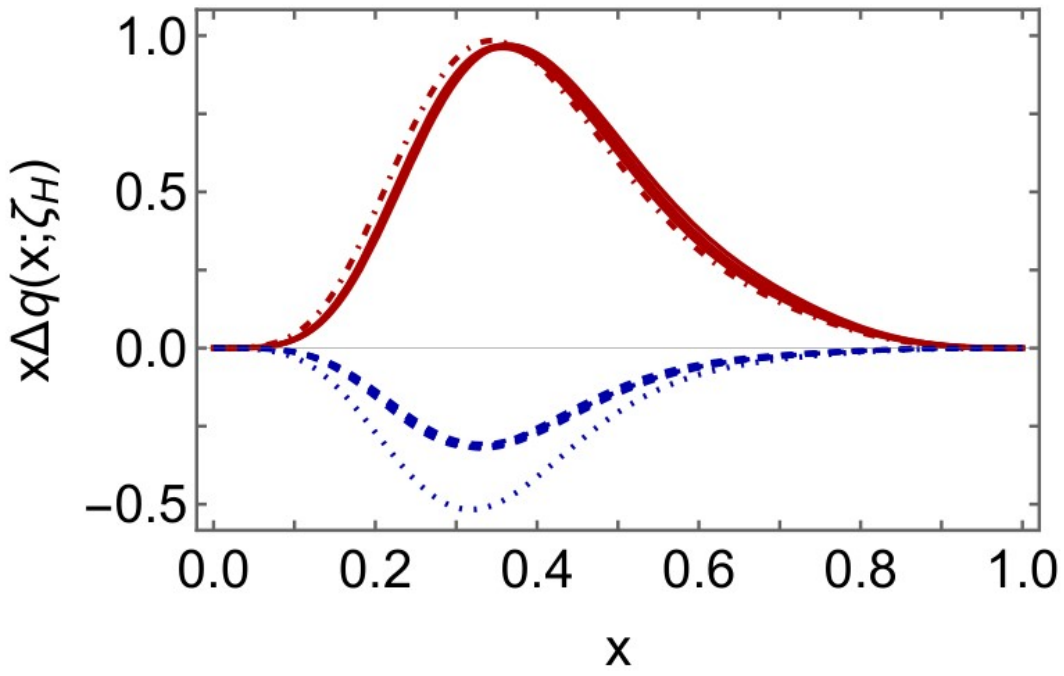


Figure 1: Hadron scale polarised valence quark distributions: solid red curves – u quark; and dashed blue curves – d quark. In each case, there are five curves, *viz*. the four produced by the mapping functions in Eq. (3), with the coefficient values in Table 2, and the average of these curves. Context is provided by the unpolarised valence quark distributions: $xu(x;\zeta_{\mathcal{H}})/2$ – dot-dashed red curve; and $[-xd(x;\zeta_{\mathcal{H}})/2]$ – dotted blue curve.

Polarised quark distribution functions at $\zeta = \sqrt{3}\text{GeV}$

- Predictions deliver quantitative agreement with all available world data
- COMPASS $\Delta u(x)$ lead to underestimate of g_A by 25%
  - Explains why COMPASS data lie below prediction

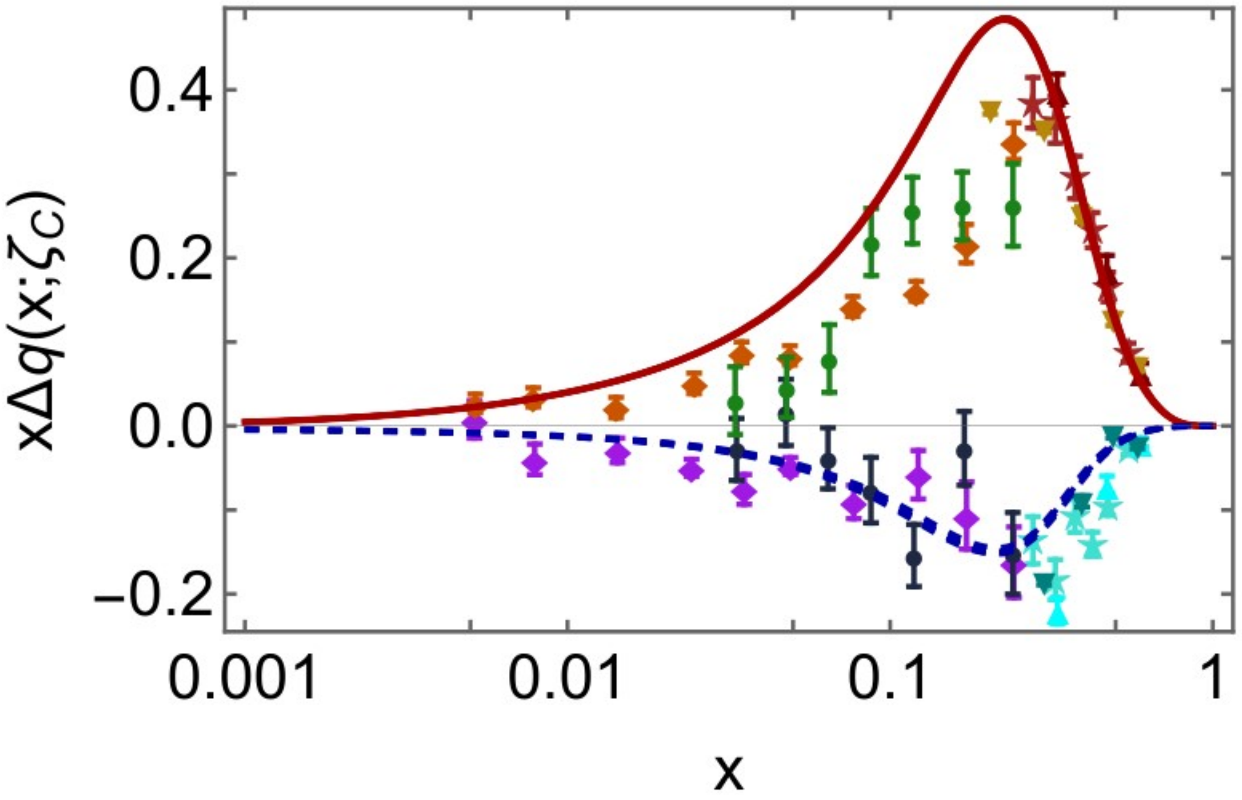
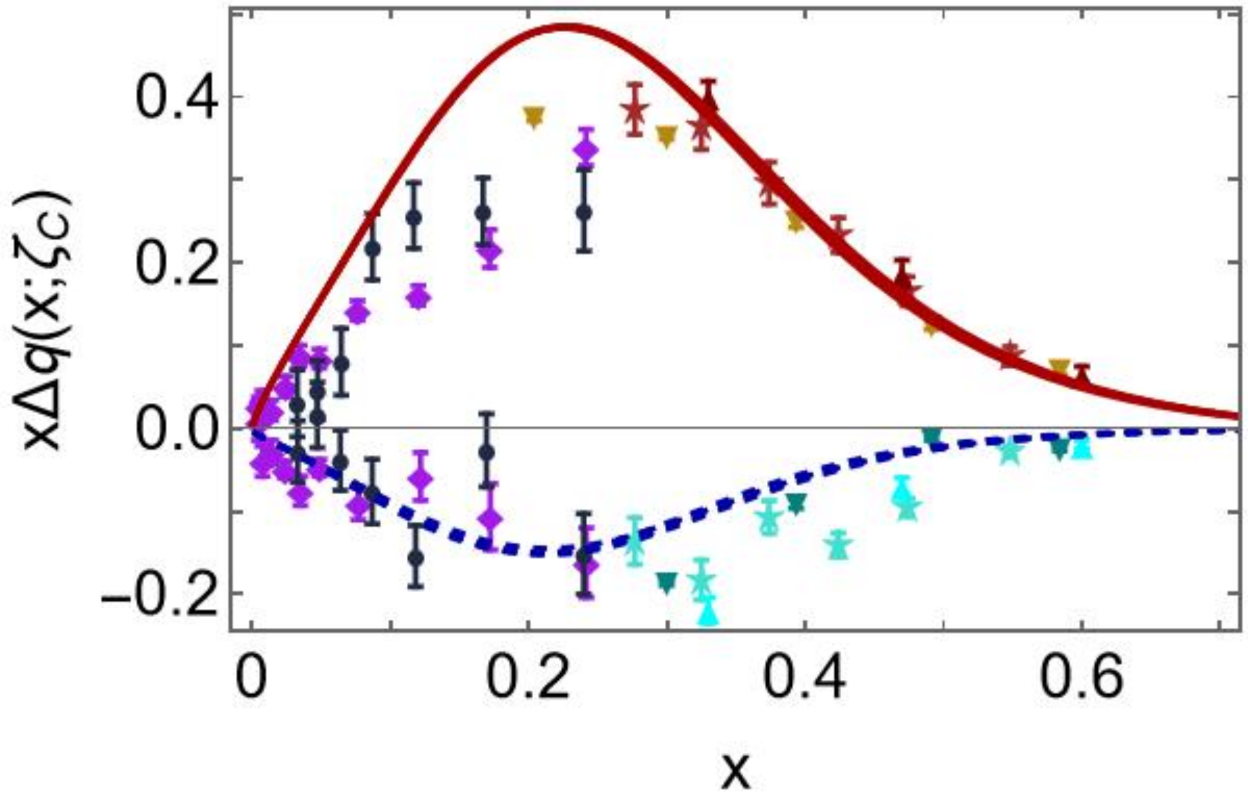


Figure 2: Polarised quark DFs: $\Delta u(x;\zeta_C)$ – solid red curves; and $\Delta d(x;\zeta_C)$ – dashed blue curves. Data: [48, HERMES] – circles; [49, COMPASS] – diamonds; filled down-triangles – [50–53, CLAS EG1]; five-pointed stars – [54, E06-014]; filled up-triangles –[55, 56, E99-117].

Polarised quark distribution functions at $\zeta = \sqrt{3}$GeV

- Predictions deliver quantitative agreement with all available world data
- COMPASS $\Delta u(x)$ lead to underestimate of g_A by 25%
  - Explains why COMPASS data lie below prediction
- Predictions for sea are consistent with available data



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Polarised glue distribution functions at $\zeta = \sqrt{3}\text{GeV}$

- Parameter-free CSM prediction

  compared with COMPASS data

  C. Adolph, *et al.*, *Leading-order determination of the gluon polarization from semi-inclusive deep inelastic scattering data*, Eur. Phys. J. C 77 (4) (2017) 209

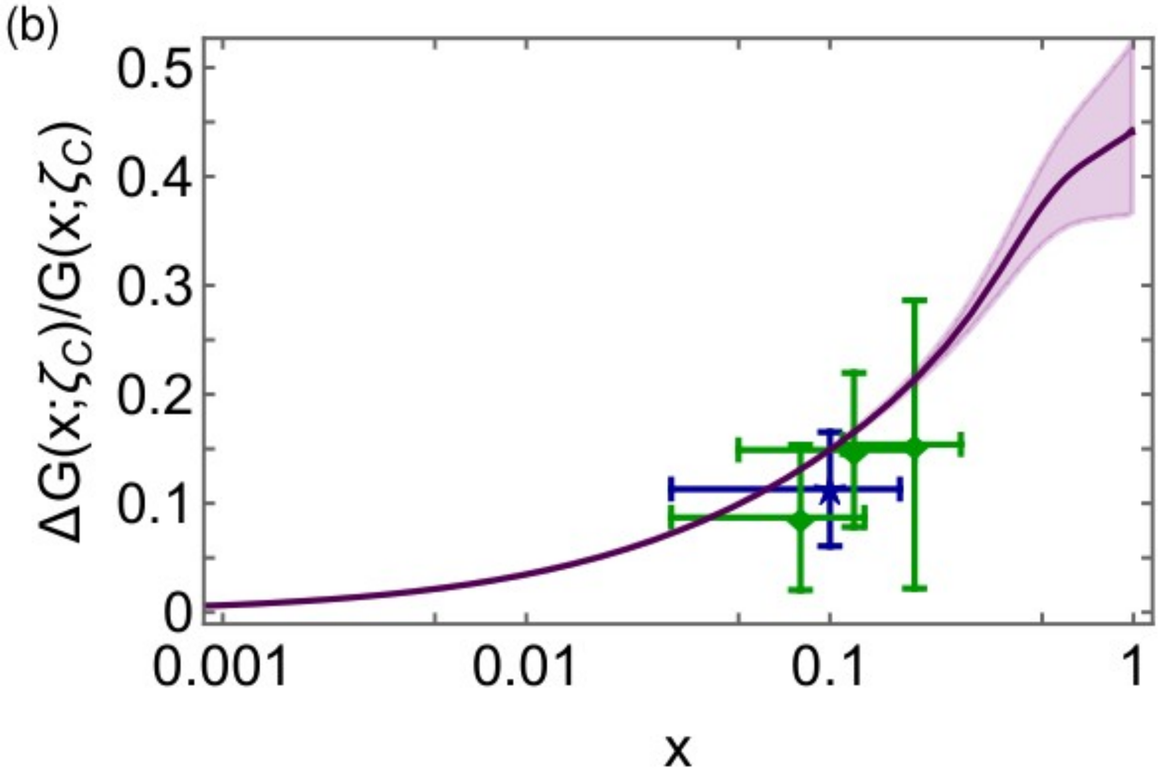
  e.g. average value over data window

  $0.167(3)_{\text{CSM}}$ *cf.* $0.113 \pm 0.038 \pm 0.036_{\text{COMPASS}}$

- Comparison with phenomenological global fits

$$\int_{0.05}^{1} dx\, \Delta G(x; \zeta = 10\text{GeV}) = 0.199(3)_{\text{CSM}}$$

cf. DSSV14: 0.19(6)



Proton Spin

- Recall page 33, which records

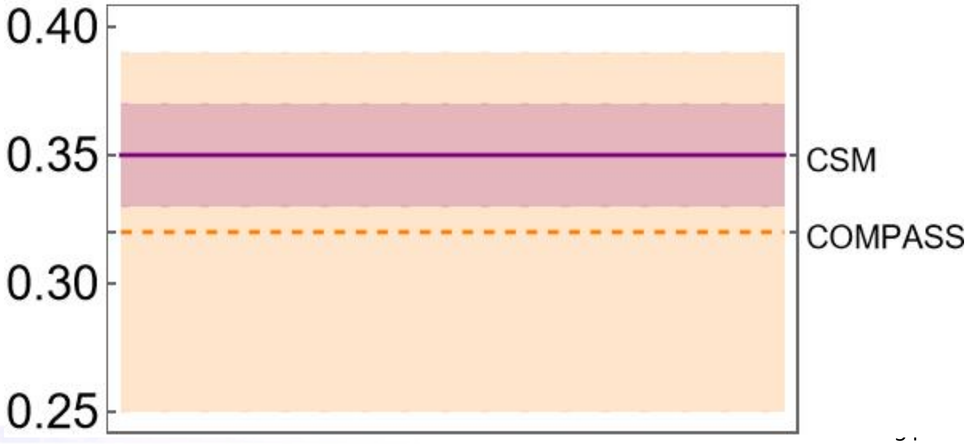
  $a_0 \approx 65\%$ of proton spin
  carried by valence quark
  quasiparticle degrees of freedom at the hadron scale.
- Under **P1** evolution, this value is independent of scale.
- However, measurements of the proton spin are sensitive to

  non-Abelian anomaly corrected combination $(n_f = 4)$

$$a_0^{\mathrm{E}}(\zeta) = a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \int_0^1 dx\, \Delta G(x;\zeta) =: a_0 - n_f \frac{\hat{\alpha}(\zeta)}{2\pi} \Delta G(\zeta)\,,$$

- CSM prediction: $a_0^E(\zeta = \sqrt{3}\mathrm{GeV}) = 0.35(2)$
- COMPASS: $a_0^{\mathrm{COMPASS}}(\zeta = \sqrt{3}\mathrm{GeV}) = 0.32(7)$
- *Parameter-free explanation*

  of proton spin measurement



Proton Spin

All-Orders Evolution of Parton Distributions: Principle, Practice, and Predictions
Pei-Lin Yin (尹佩林) *et al.*, NJU-INP 075/23, e-Print: 2306.03274 [hep-ph], Chin. Phys. Lett. *Express* **40** (2023) 091201/1-8. Express Letter.

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Algebraic formula for Glue contribution to proton spin
✓ ΔG_p necessarily positive
✓ ΔG_p Grows faster than $1/\langle x \rangle^2_{\rm valence}$

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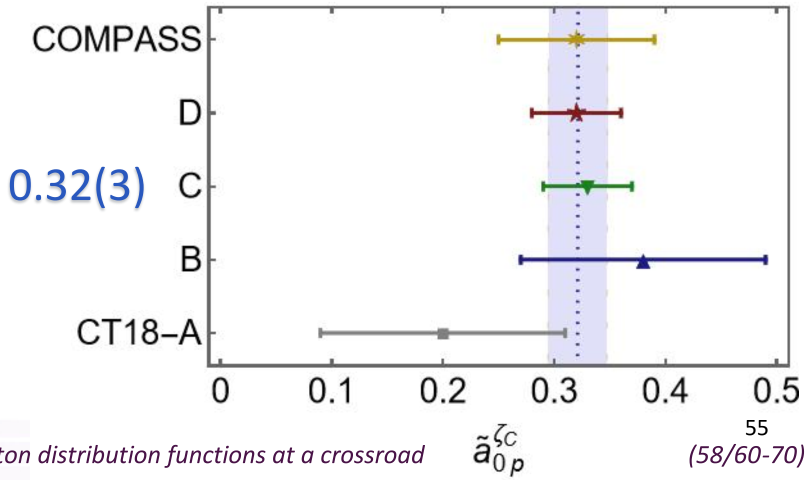
Theory average 0.32(3)



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, unpolarised and polarised
- 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.*

Grant no. 12135007

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

Emergent Hadron Mass

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

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There are theories of many things,
But is there a theory of everything?

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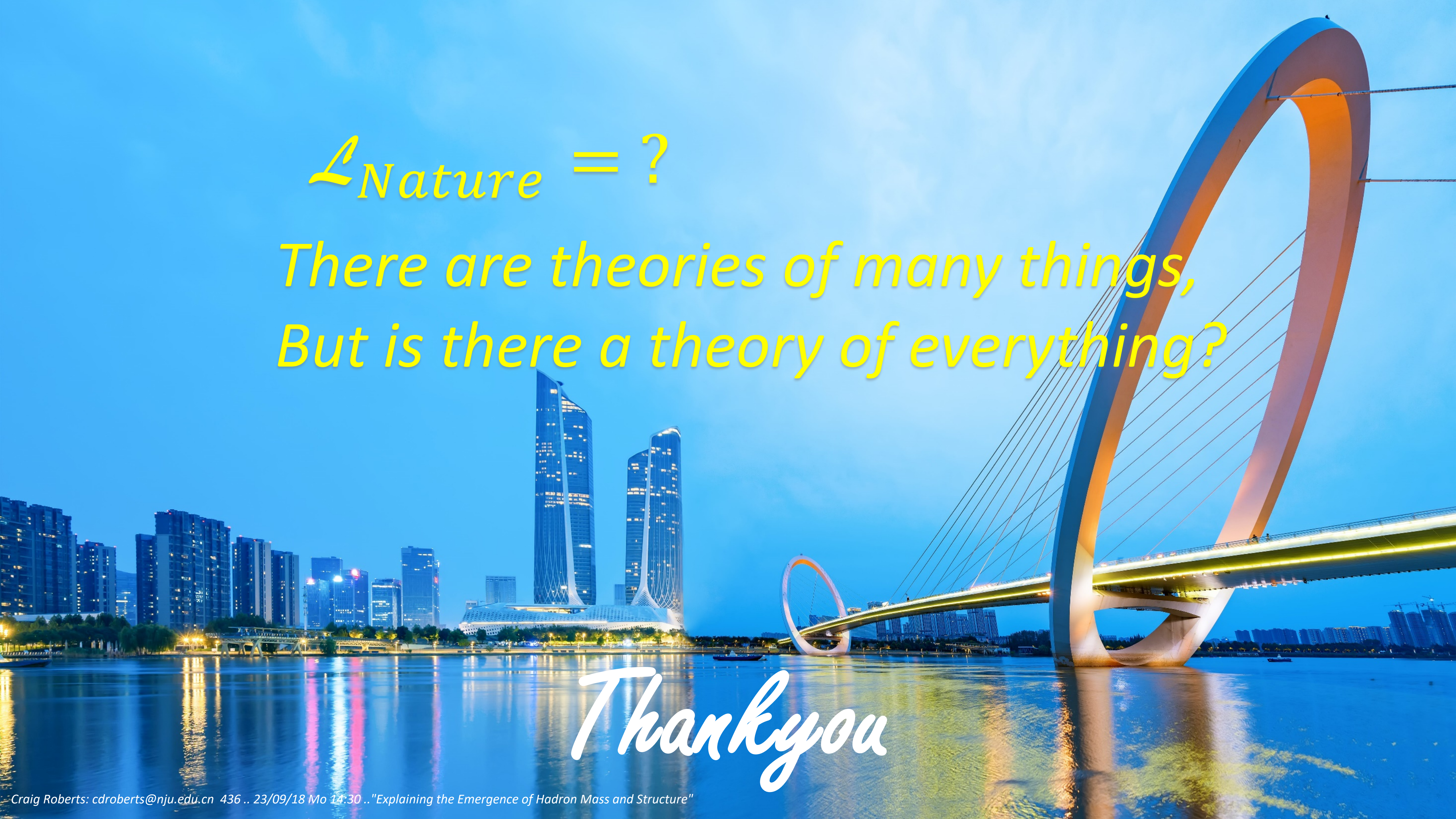

Thankyou

Key to arriving at sound understanding of observable phenomena is preserving Poincaré invariance

- Fundamental scientific principle is that an observer's choice of conventions cannot affect physical phenomena.
- Effects that depend on such choices are artificial rather than objective features of Nature; thus, for example, physics cannot depend on the choice of units.
- Most critically, physical effects cannot depend on the observer's frame: valid phenomena should display Poincaré invariance for relativistic systems.

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Perspective | Published: 09 May 2022

Artificial dynamical effects in quantum field theory

Stanley J. Brodsky, Alexandre Deur & Craig D. Roberts

Nature Reviews Physics **4**, 489–495 (2022) | Cite this article

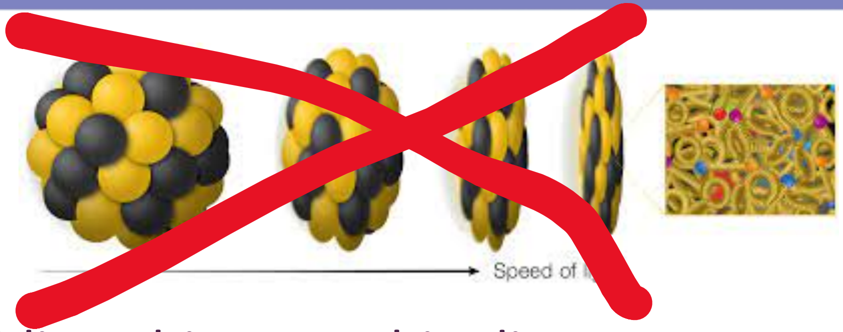
Abstract

In Newtonian mechanics, studying a system in a non-Galilean reference frame can lead to inertial pseudoforces appearing, such as the centrifugal force that seems to arise in dynamics analysed in a rotating frame. Likewise, artificial effects may arise in relativistic quantum field theory (QFT) if a system is studied in a framework that violates Poincaré invariance. In this Perspective, we highlight how such issues complicate the traditional canonical quantization of QFTs and can lead to a subjective description of natural phenomena. By contrast, the treatment of the same problem using light-front quantization is free from spurious pseudoeffects because Poincaré invariance is effectively preserved for all practical intents and purposes. We illustrate these statements using several examples: the Gerasimov–Drell–Hearn (GDH) relation, a fundamental feature of QFT; the absence of any measurable impact of Lorentz contraction in high-energy collisions; and the fictitious character of vacuum fluctuation contributions to the cosmological constant.

Invisibility of the Lorentz Contraction

- Lorentz contraction is a subjective effect because it depends explicitly on the observer's motion relative to the contracted object
- But is it fictitious?
- Lorentz contraction is often invoked when describing relativistic collisions of composite objects
- However, ascribing an objective meaning to Lorentz contraction can lead to erroneous descriptions
- In fact, since Lorentz contraction is not a true observable, it cannot influence any observable properties of any sort of relativistic collision.

Invisibility of the Lorentz Contraction



- In discussions of collisions involving composite objects moving with relativistic velocities, it's common to depict colliding objects as thin discs (pancakes), so as to highlight Lorentz contraction.
- However, if such contractions were fundamental to the dynamical description of the collision, a paradox would ensue because
  - ✓ The internal structure of hadrons is produced by a Poincaré-invariant action
  - ✓ It is therefore observable
  - ✓ It is thus frame-independent
  - ✓ Hence, it can't depend on the motion of the object with respect to the observer
- For instance …
  - ✓ the structure of the proton measured in deep inelastic lepton scattering in the laboratory frame, where the proton is at rest,
  - ✓ is the same as that when measured at a lepton-proton collider, where the proton is, supposedly, Lorentz-contracted.

Invisibility of the Lorentz Contraction

- 1959 First explained by Roger Penrose
  OM FRS HonFInstP
  Nobel Prize in Physics 2022

The apparent shape of a relativistically moving sphere

R. Penrose

Mathematical Proceedings of the Cambridge Philosophical Society / Volume 55 / Issue 01 / January 1959, pp 137 - 139
DOI: 10.1017/S0305004100033776, Published online: 24 October 2008

Link to this article: http://journals.cambridge.org/abstract_S0305004100033776

- 1959 Further expounded by James Terrell,
  who was aware of Penrose' work

PHYSICAL REVIEW VOLUME 116, NUMBER 4 NOVEMBER 15, 1959

Invisibility of the Lorentz Contraction*

JAMES TERRELL
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received June 22, 1959)

- 1960 Terrell's article was popularised by Victor Weisskopf
  Postdocs with Heisenberg,
  Schrödinger, Pauli, Bohr
  Amongst numerous other awards
  ... 1984: Albert Einstein Medal

physics today

The visual appearance of rapidly moving objects

Victor F. Weisskopf

Citation: Phys. Today **13**(9), 24 (1960); doi: 10.1063/1.3057105
View online: http://dx.doi.org/10.1063/1.3057105

Invisibility of the Lorentz Contraction

- First explained by Roger Penrose
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Despite such pedigree, the fact of Lorentz contraction invisibility has largely been forgotten; if not denied.

- Terrell's article was popularised by
  Victor Weisskopf
  Postdocs with Heisenberg,
  Schrödinger, Pauli, Bohr
  Amongst numerous other awards
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Invisibility of the Lorentz Contraction

- First explained by <u>Roger Penrose</u>
  OM FRS HonFInstP
  Nobel Prize in Physics 2022

Fallacy of visible Lorentz contraction has its roots in ignoring the fact that the speed of light is the same finite-number for all observers

Amongst numerous other awards
... 1984: Albert Einstein Medal

annalen der physik

Article | Free Access

Zur Elektrodynamik bewegter Körper

A. Einstein

First published: 1905 | https://doi.org/10.1002/andp.19053221004 | Citations: 2,182

Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität“ genannt werden wird) zur Voraussetzung erheben und ausserdem die mit ihm nur scheinbar unvertragliche Voraussetzung einfuehren, <u>dass sich das Licht im leeren Raume stets mit einer bestimmten, vom Bewegungszustande des emittierenden Koerpers unabhangigen Geschwindigkeit *V* fortpflanze</u>.

Citation: Phys. Today **13**(9), 24 (1960); doi: 10.1063/1.3057105
View online: http://dx.doi.org/10.1063/1.3057105

Invisibility of the Lorentz Contraction - Weisskopf

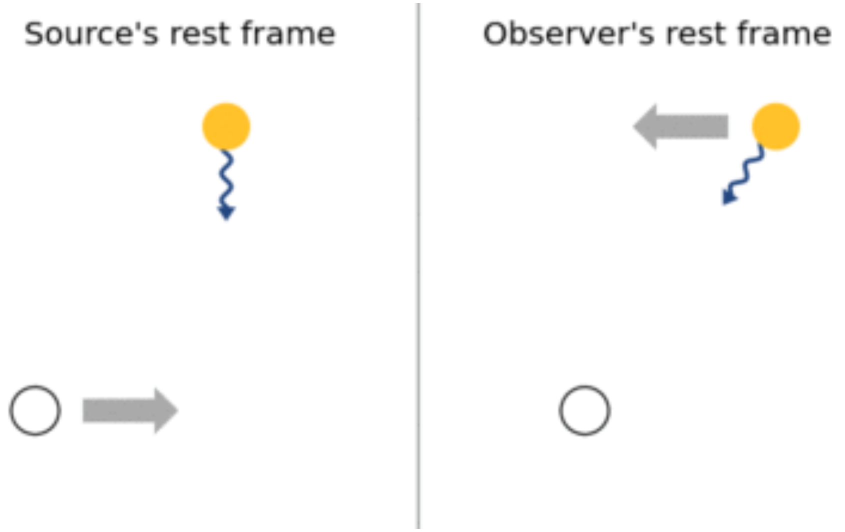
- I WOULD like to draw the attention of physicists to a recent paper by James Terrell in which he does away with an old prejudice held by practically all of us.
- We all believed that, according to special relativity, an object in motion appears to be contracted in the direction of motion by a factor $\left(1-\left(\frac{v}{c}\right)^2\right)^{1/2}$
- A passenger in a fast space ship, looking out of the window, so it seemed to us, would see spherical objects contracted to ellipsoids.
- This is definitely not so according to Terrell's considerations, which for the special case of a sphere were also carried out by R. Penrose.

Invisibility of the Lorentz Contraction – Weisskopf

- The reason is quite simple
- When we see or photograph an object, we record light quanta emitted by the object when they arrive simultaneously at the retina or at the photographic film
- This implies that these light quanta have not been emitted simultaneously by all points of the object
- The points further away from the observer have emitted their part of the picture earlier than the closer points
- Hence, if the object is in motion, the eye or the photograph gets a "distorted" picture of the object, since the object has been at different locations when different parts of it have emitted the light seen in the picture
- In special relativity, this distortion has the remarkable effect of canceling the Lorentz contraction so that objects appear undistorted but only rotated
- This is exactly true only for objects which subtend a small solid angle

Invisibility of the Lorentz Contraction – Penrose

- In order to prove the exact result that the sphere always presents a circular outline, it is convenient to consider the sphere at rest and the observer moving, this being allowable according to the special principle of relativity
- Now it is only necessary to consider what transformation of the field of vision must be employed when passing from a stationary to a moving observer at the same point, and to show that this transformation is one which sends apparent circles into apparent circles
- N.B. I (Penrose) am concerned, here, with a world-picture rather than a world-map, so that the finite velocity of the light coming from the sphere must be taken into account.
- Aberration of light … a phenomenon which produces an apparent motion of celestial objects about their true positions, dependent on the velocity of the observer
  - ✓ Causes (point) objects to appear to be displaced towards the direction of motion of the observer compared to when the observer is stationary



Invisibility of the Lorentz Contraction - Penrose

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- That transformation is the relativistic aberration formula $\sin\theta' = \dfrac{\left(1-\left(\frac{v}{c}\right)^2\right)^{\frac{1}{2}}\sin\theta}{1+\frac{v}{c}\cos\theta}$

  A light beam whose direction includes the angle θ with the x-axis

  is seen including an angle θ' with the x-axis in a system moving at velocity v along the x-axis

- The picture seen from a moving object observed at the angle θ is the same as one would see in the system where the object is at rest but observed at the angle θ'.
- Hence, we see an undistorted picture of a moving object, but a picture in which the object is seemingly rotated by the angle $\theta' - \theta$.
- *A spherical object still appears as a sphere*

Invisibility of the Lorentz Contraction - Weisskopf

- Einstein is correct – these facts never challenged him
- Special relativity entails that, in the appearance of an object, any Lorentz contraction merely compensates for elongation of the image caused by finite signal speed
- The apparent rotation is always negative: $\theta' - \theta < 0$, which means that the object is turned such that it reveals more of its trailing side to the observer.

$$\sin\theta' = \frac{\left(1-\left(\frac{v}{c}\right)^2\right)^{\frac{1}{2}}\sin\theta}{1+\frac{v}{c}\cos\theta}$$

- In the extreme case of $v \approx c$, θ' is tiny for all values of θ,

  except when $180^\circ - \theta \approx \left(1-\left(\frac{v}{c}\right)^2\right)^{1/2}$.

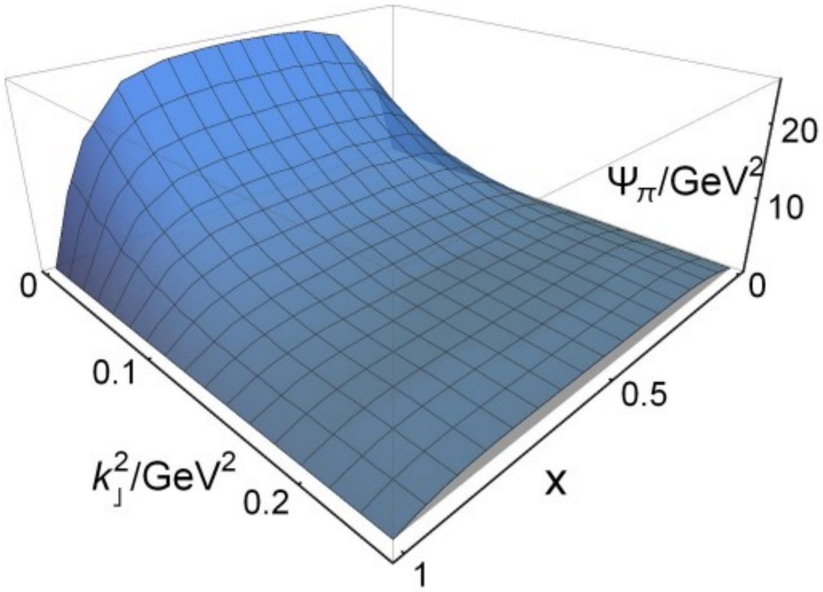
- Since θ goes from 180° to 0° when an object moves by, we find for the case $v \approx c$ that
  - ✓ we see the front side of the object only at the very beginning;
  - ✓ it turns around facing its trailing side at us quite early when we still see it coming at us
  - ✓ and remains doing so until it leaves us and naturally is seen from behind.
- This paradox is not surprising when one recalls that the aberration angle is almost 180° when $v \approx c$. Hence the light we see coming from the object when it is moving towards us, left the object backwards when observed from the object itself.

Contraction Paradox absent in Poincaré-invariant formulations

- Example.
  - ✓ Using a light-front quantisation of QCD, the wave function of every system is independent of the system's total momentum

    ⇒ wave function does not depend on the system's 3-velocity

- Example.
  - ✓ Use continuum Schwinger function methods to calculate the pion's Poincaré-covariant Bethe-Salpeter wave function
  - ✓ Project that wave function onto the light-front – straightforward mathematical operation
  - ✓ Answer is independent of the pion total-momentum




The End