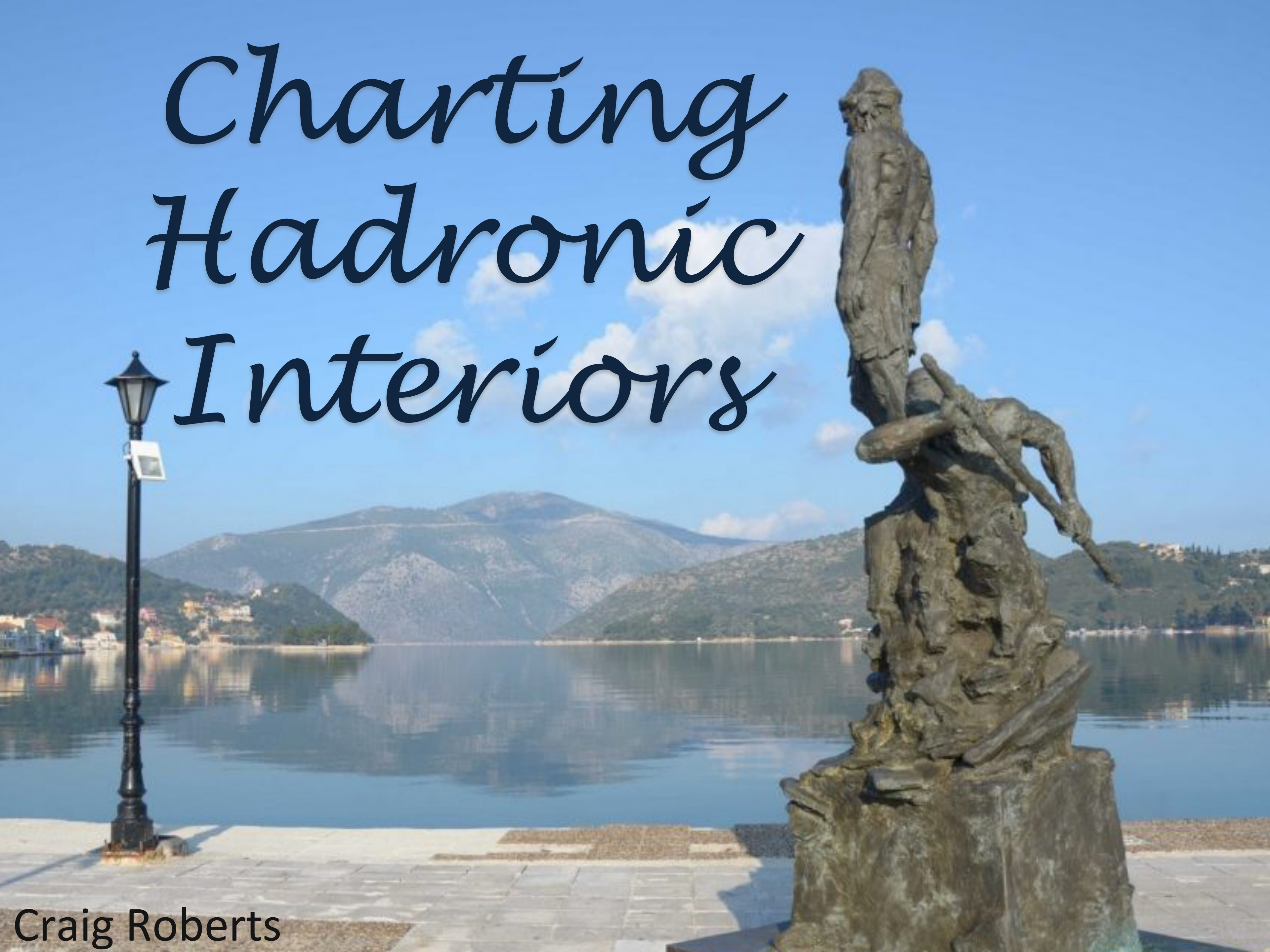
Charting Hadronic Interiors



Craig Roberts

Collaborators: 2015-Present

Students, Postdocs, Profs.

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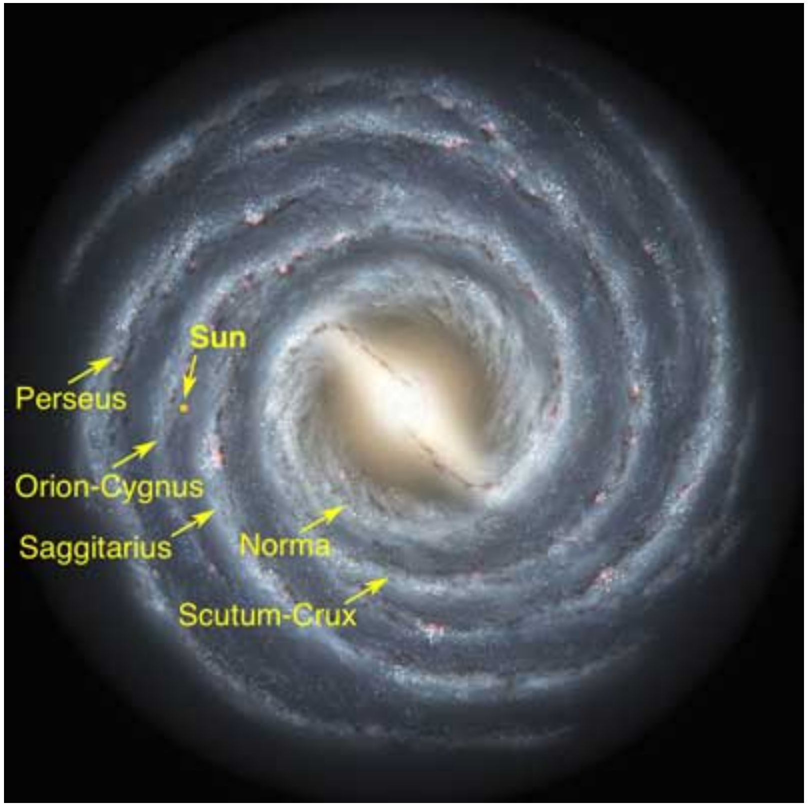
Emergent Phenomena in the Standard Model

Existence of the Universe as we know it depends critically on the following empirical facts:

- Proton is massive, *i.e*. the mass-scale for strong interactions is vastly different to that of electromagnetism
- Proton is absolutely stable, despite being a composite object constituted from three valence quarks
- Pion is unnaturally light (not massless, but lepton-like mass), despite being a strongly interacting composite object built from a valence-quark and valence antiquark



Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

A New Era

- Strong-QCD is the first place we fully experience the collisions and collusions between relativity and quantum mechanics.
- In attempting to match QCD with Nature, we confront the diverse complexities of nonperturbative, nonlinear dynamics in relativistic quantum field theory, *e.g*.
  - loss of particle number conservation,
  - frame and scale dependence of the explanations and interpretations of observable processes,
  - and evolving character of the relevant degrees-of-freedom.

Model independent statement:
There is quark orbital angular momentum in the pion
Probable corollary: What is true in the pion, is true in the proton

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  - loss of particle number conservation,
  - frame and scale dependence of the explanations and interpretations of observable processes,
  - and evolving character of the relevant degrees-of-freedom.
- Origin and distribution of *mass*, *momentum*, *spin*, *etc.* within hadrons? *e.g*. where is the proton's spin and how is the pion spinless?
  - Don't forget the latter!
  - How do all the spin-1/2 quarks and spin-1 gluons combine to make a massless, J=0 composite mode?

Model independent statement:
There is quark orbital angular momentum in the pion
Probable corollary: What is true in the pion, is true in the proton

A New Era

- Strong-QCD is the first place we fully experience the collisions and collusions between relativity and quantum mechanics.
- In attempting
  complexities
  quantum fiel
  - loss of par
  - frame and
    observable
  - and evolvi

Answer depends on the the observer's frame and scale at which observations are made!

So-called** spin crisis **is largely the consequence of ignoring these facts

- Origin and distribution of *mass*, *momentum*, *spin*, *etc.* within hadrons? *e.g*. where is the proton's spin and how is the pion spinless?
  - Don't forget the latter!
  - How do all the spin-1/2 quarks and spin-1 gluons combine to make a massless, J=0 composite mode?

Ideas: Old & New

Particle Data Group

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

g **or gluon**

$I(J^P) = 0(1^-)$

SU(3) color octet

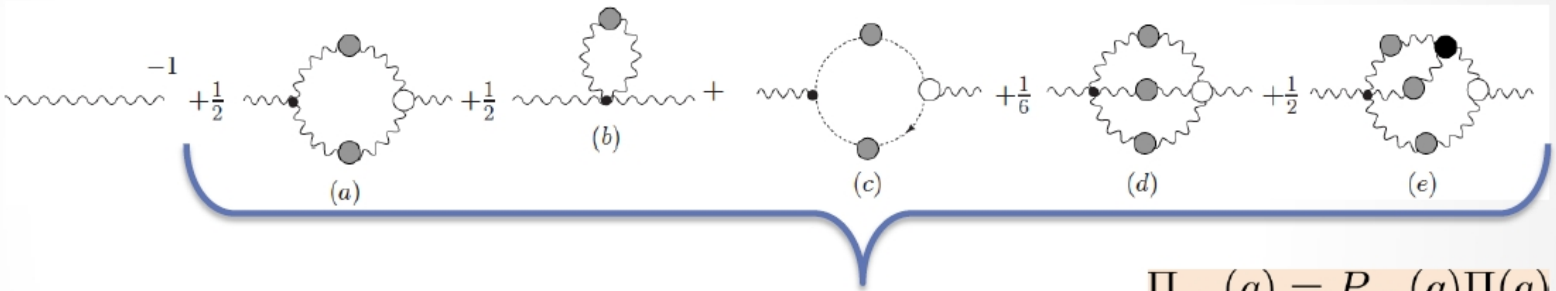
Mass $m = 0$. Theoretical value. A mass as large as a few MeV may not be precluded, see YNDURAIN 95.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

gluon REFERENCES

YNDURAIN	95	PL B345 524	F.J. Yndurain	(MADU)
ABREU	92E	PL B274 498	P. Abreu *et al.*	(DELPHI Collab.)
ALEXANDER	91H	ZPHY C52 543	G. Alexander *et al.*	(OPAL Collab.)
BEHREND	82D	PL B110 329	H.J. Behrend *et al.*	(CELLO Collab.)
BERGER	80D	PL B97 459	C. Berger *et al.*	(PLUTO Collab.)
BRANDELIK	80C	PL B97 453	R. Brandelik *et al.*	(TASSO Collab.)

$$\Delta^{-1}_{\mu\nu}(q) =$$



$$\Pi_{\mu\nu}(q)$$

$$\Pi_{\mu\nu}(q) = P_{\mu\nu}(q)\Pi(q)$$

$$P_{\mu\nu}(q) = g_{\mu\nu} - q_\mu q_\nu / q^2$$

Gluon Gap Equation

Bridging a gap between continuum-QCD and ab initio predictions of hadron observables, D. Binosi *et al.*, arXiv:1412.4782 [nucl-th], Phys. Lett. B742 (2015) 183-188

In QCD: Gluons become massive!

- Running gluon mass

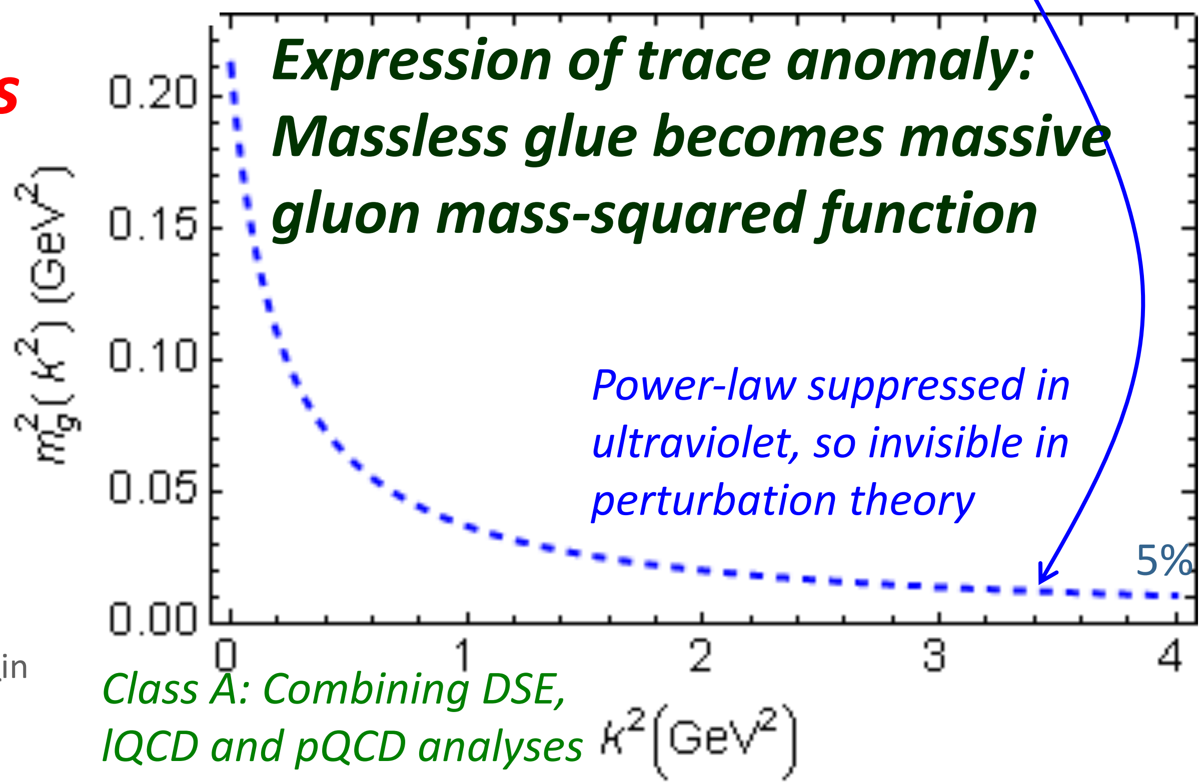
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

$$\alpha_s(0) = 2.77 \approx 0.9\pi\,,\ m_g^2(0) = (0.46\,\text{GeV})^2$$

- Gluons are ***cannibals*** – a particle species whose members become massive by eating each other!

$\mu_g \approx ½\, m_p$

$$m_g^2(k^2) \approx \frac{\mu_g^4}{\mu_g^2 + k^2}$$



Class A: Combining DSE, lQCD and pQCD analyses of QCD's gauge sector

Interaction model for the gap equation, S.-x.Qin *et al.*, arXiv:1108.0603 [nucl-th], Phys. Rev. C **84** (2011) 042202(R) [5 pages]

Massive Gauge Bosons!

- Gauge boson cannibalism

  … a new physics frontier … within the Standard Model
- Asymptotic freedom means

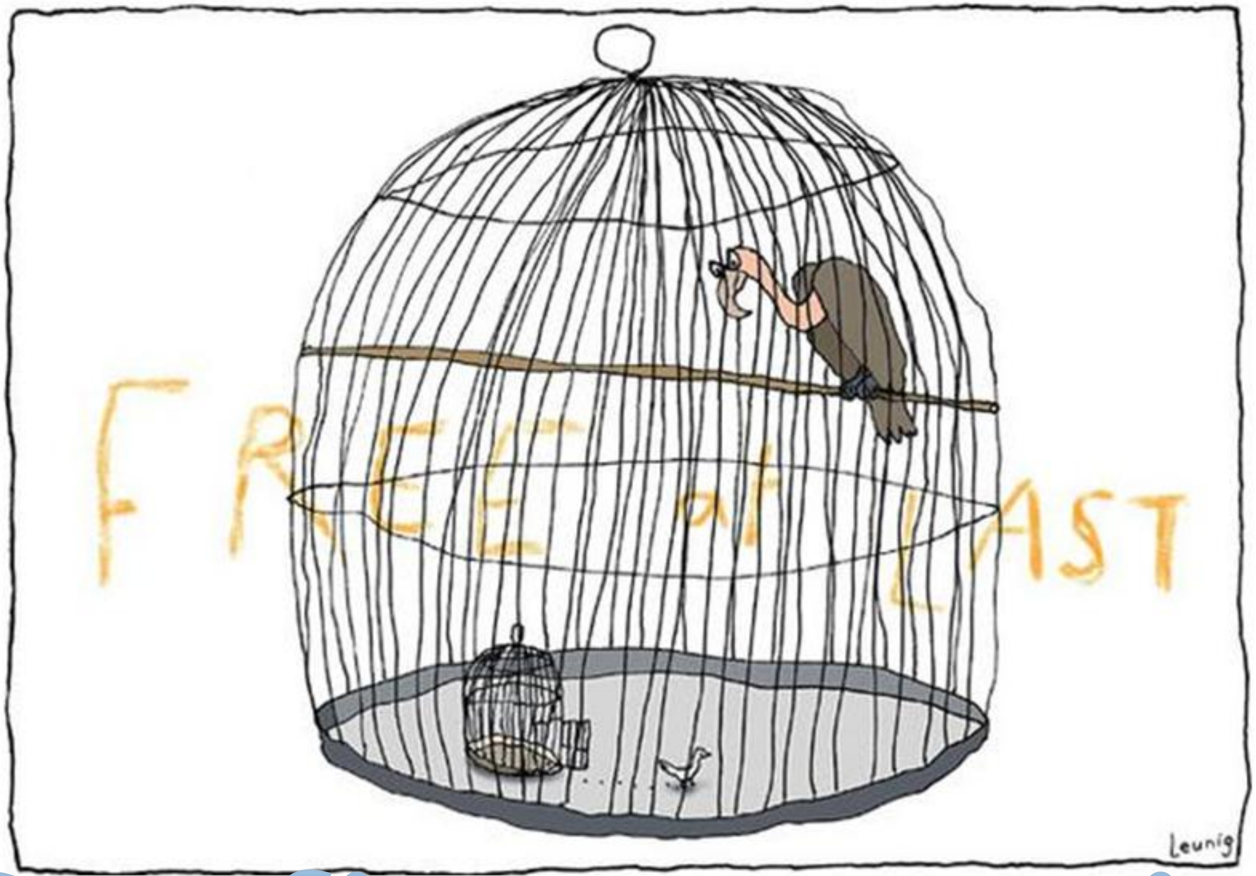
  … ultraviolet behaviour of QCD is controllable
- Dynamically generated masses for gluons and quarks means that QCD dynamically generates its own infrared cutoffs
  - Gluons and quarks with

    wavelength $\lambda > 1/\text{mass} \approx 0.5$ fm

    decouple from the dynamics … ***Confinement?!***
- How does that affect observables?
  - It will have an impact in any continuum study
  - Possibly (probably?) plays a role in gluon saturation ...

    In fact, could be a harbinger of gluon saturation?

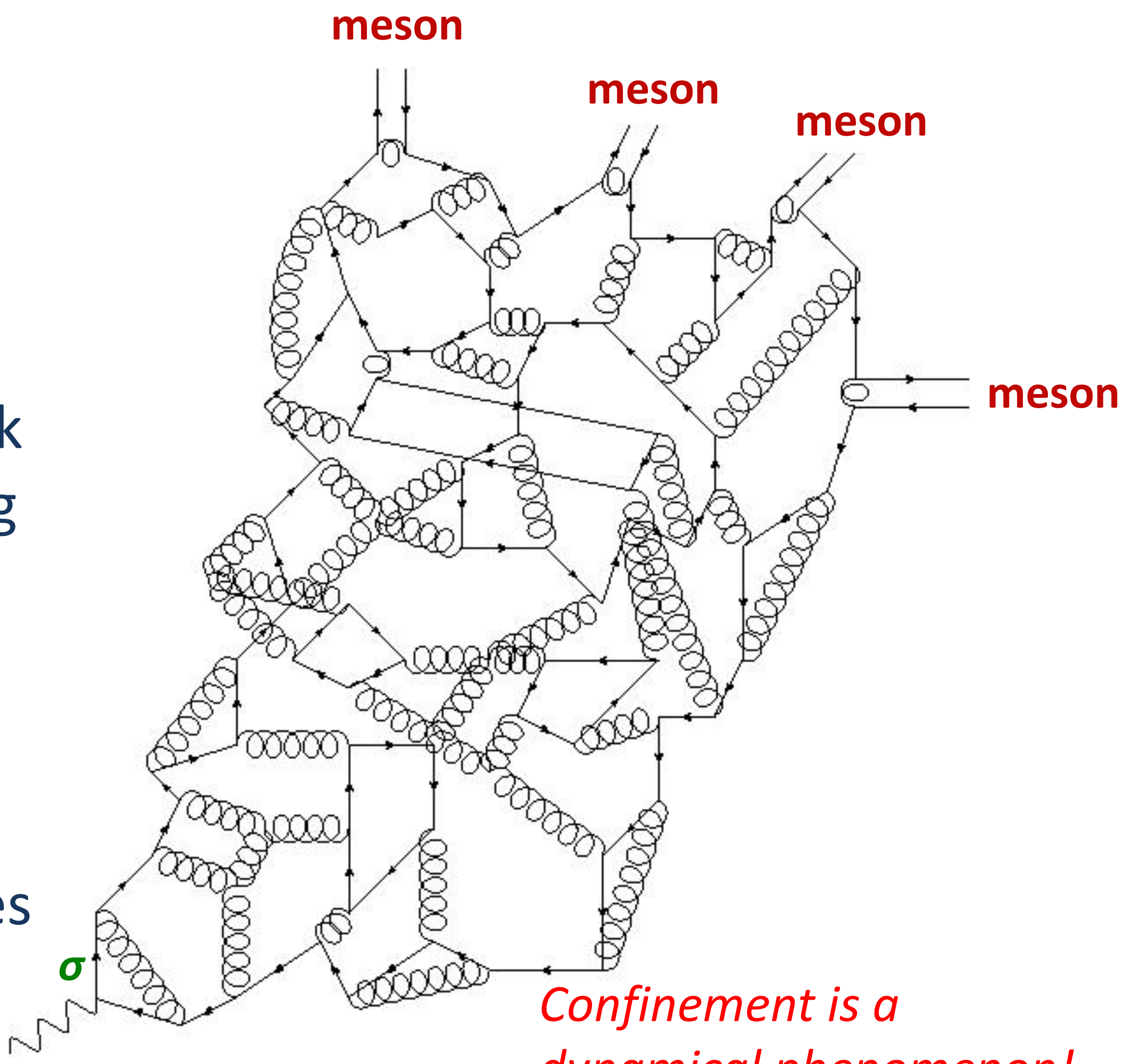
Electron Ion Collider: The Next QCD Frontier



Confinement is dynamical

Quark Fragmentation

- A quark begins to propagate
- But after each "step" of length $\sigma \approx 1/m_g$, on average, an interaction occurs, so that the quark *loses* its identity, sharing it with other partons
- Finally, a cloud of partons is produced, which coalesces into colour-singlet final states



Confinement is a dynamical phenomenon!

Quark Fragmentation

- A quark begins to propagate
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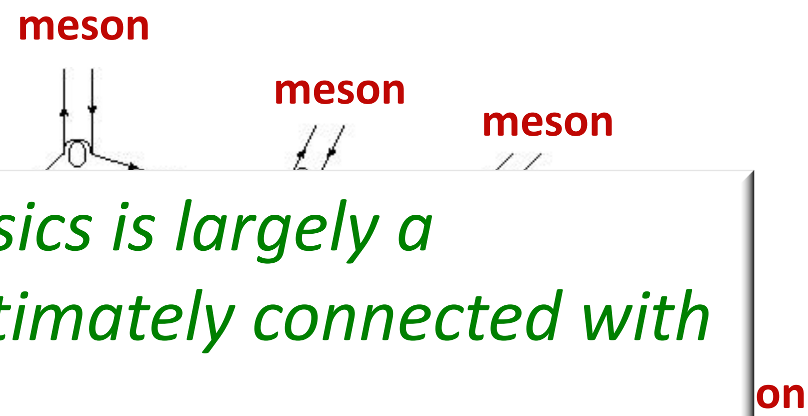
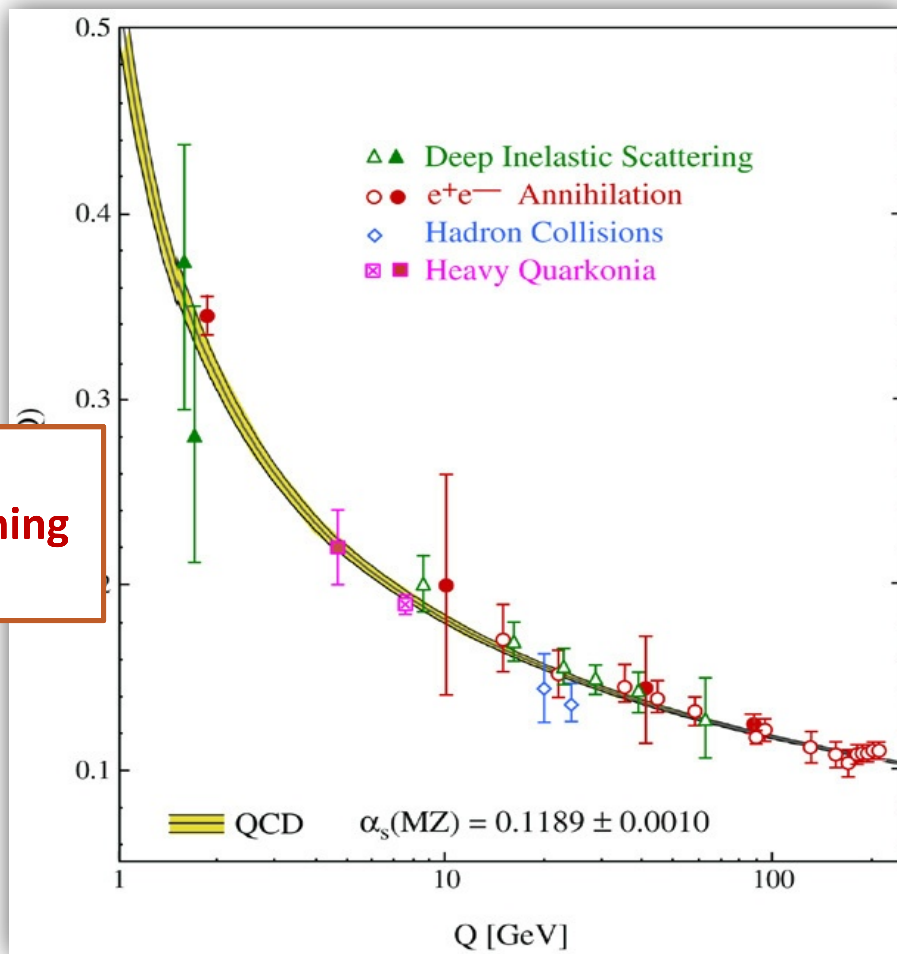


Confinement in hadron physics is largely a dynamical phenomenon, intimately connected with the fragmentation effect.

It is unlikely to be comprehended without simultaneously understanding dynamical chiral symmetry breaking, which is the origin of a nearly-massless hadron (pion).

Confinement is a dynamical phenomenon!



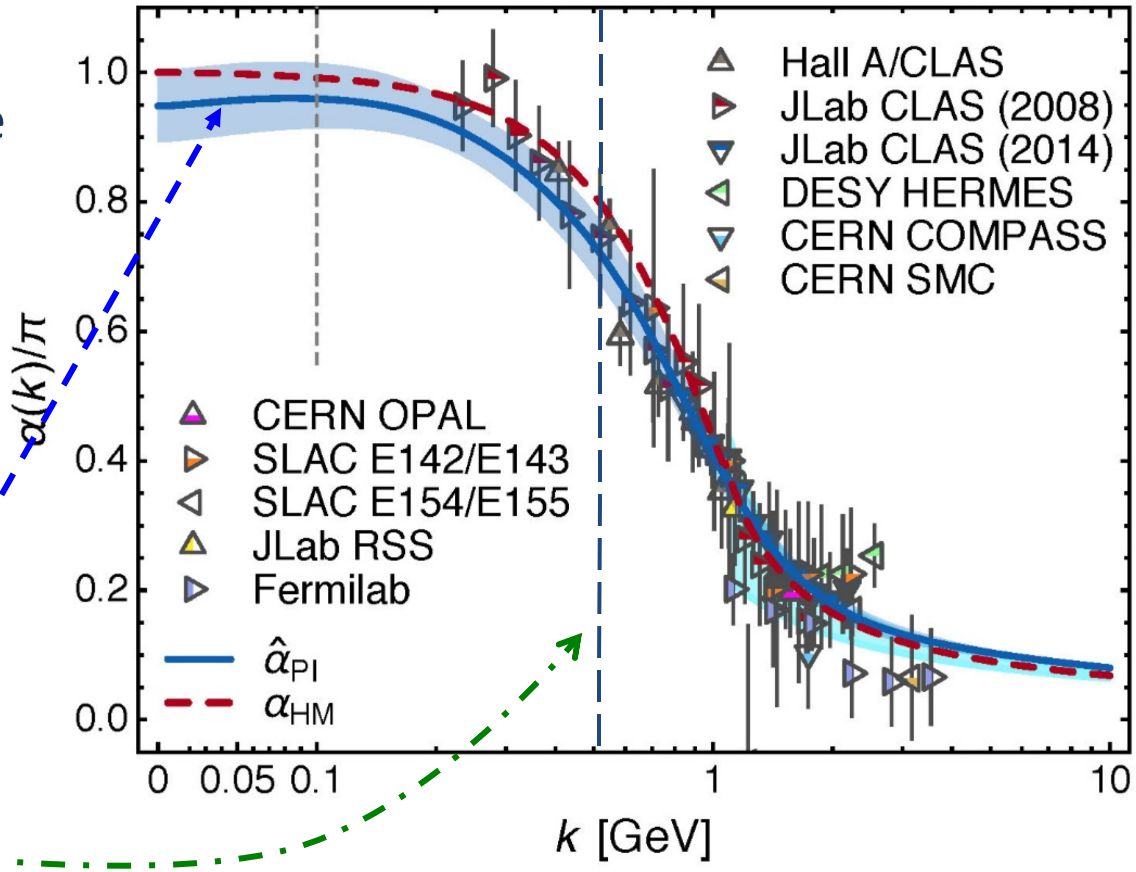
⇐
What's happening out here?!

QCD's Running Coupling

Process independent strong running coupling
Binosi, Mezrag, Papavassiliou, Roberts, Rodriguez-Quintero
arXiv:1612.04835 [nucl-th], Phys. Rev. D 96 (2017) 054026/1-7

Process-independent effective-charge in QCD

- Modern continuum & lattice methods for analysing gauge sector enable "Gell-Mann – Low" running charge to be defined in QCD
- Combined continuum and lattice analysis of QCD's gauge sector yields a parameter-free prediction
- N.B. Qualitative change in $\hat{\alpha}_{PI}(k)$ at $k \approx ½\, m_p$



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

QCD Effective Charge

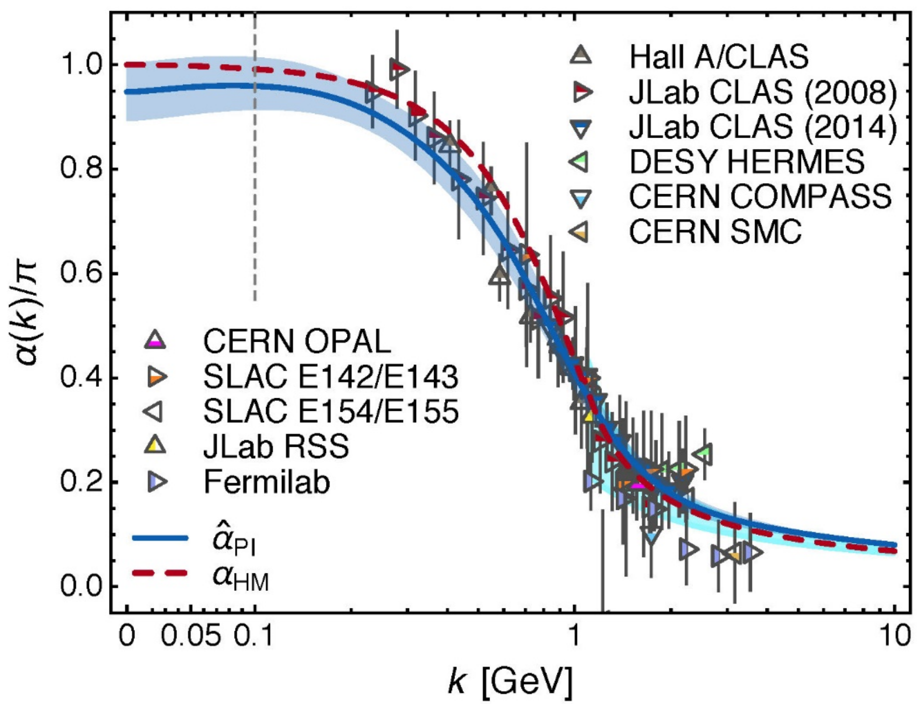
- Near precise agreement between process-independent $\hat{\alpha}_{PI}$ and α_{g1}
  and $\hat{\alpha}_{PI} \approx \alpha_{HM}$

- Perturbative domain:

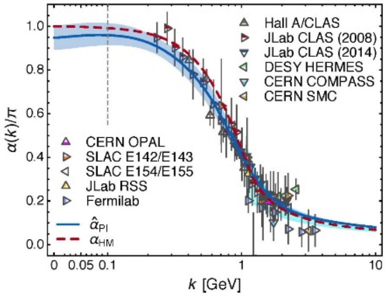
$$\alpha_{g_1}(k^2) = \alpha_{\overline{\rm MS}}(k^2)(1 + 1.14\,\alpha_{\overline{\rm MS}}(k^2) + \ldots)\,,$$
$$\widehat{\alpha}_{\rm PI}(k^2) = \alpha_{\overline{\rm MS}}(k^2)(1 + 1.09\,\alpha_{\overline{\rm MS}}(k^2) + \ldots)\,,$$

  difference = (1/20) $\alpha_{\overline{MS}}^2$

- Parameter-free prediction:
  - curve completely determined by results obtained for gluon & ghost two-point functions using continuum and lattice-regularised QCD.

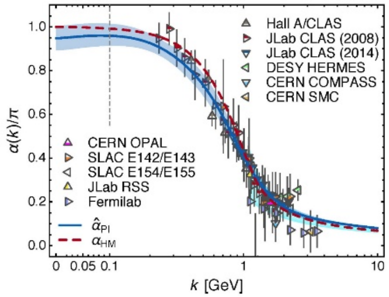


Data = process dependent effective charge: α_{g1}, defined via Bjorken Sum Rule



QCD Effective Charge

- $\hat{\alpha}_{PI}$ is a new type of effective charge
  - direct analogue of the Gell-Mann–Low effective coupling in QED, *i.e*. completely determined by the gauge-boson two-point function.
- $\hat{\alpha}_{PI}$ is
  - process-independent
  - appears in every one of QCD's dynamical equations of motion
  - known to unify a vast array of observables
- $\hat{\alpha}_{PI}$ possesses an infrared-stable fixed-point
  - Nonperturbative analysis demonstrating absence of a Landau pole in QCD
- QCD is IR finite, owing to dynamical generation of gluon mass-scale, which also serves to eliminate the Gribov ambiguity
- Asymptotic freedom ⇒ QCD is well-defined at UV momenta
- ***QCD is therefore unique amongst known 4D quantum field theories***
  - ***Potentially, defined & internally consistent at all momenta***

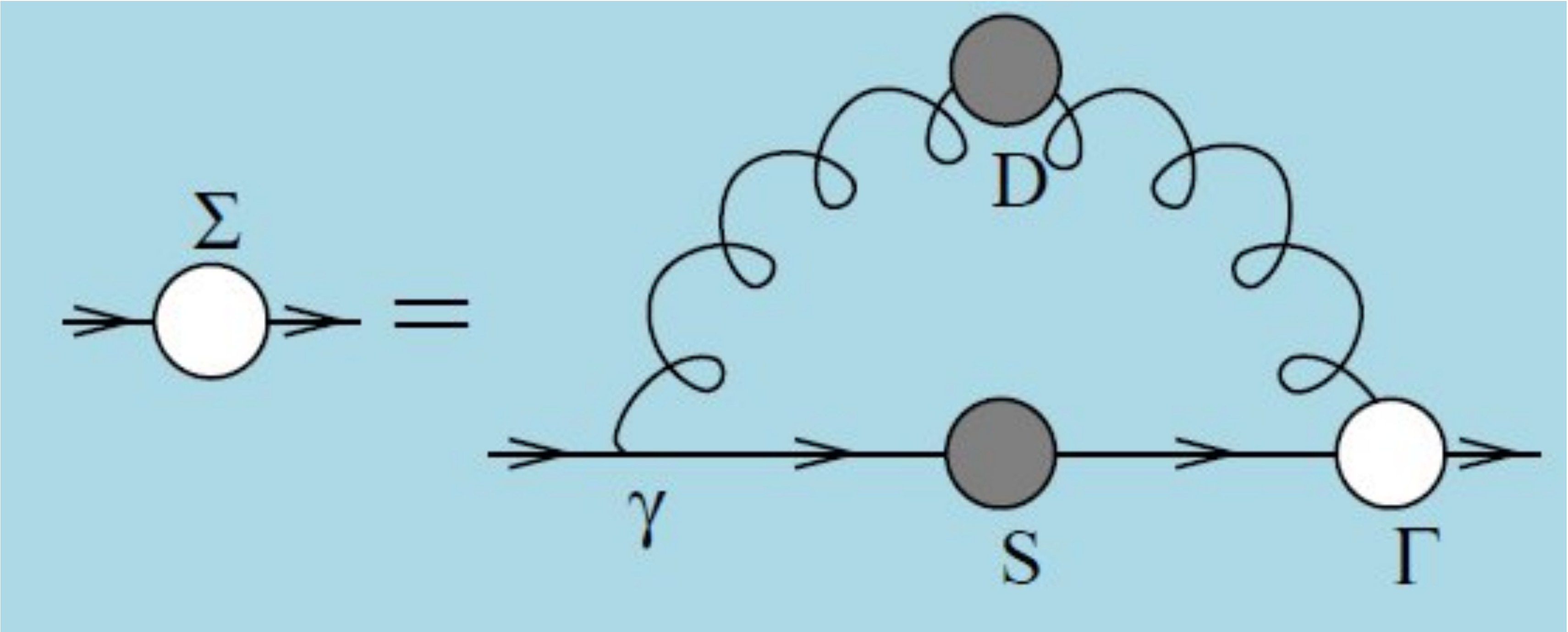


QCD Effective Charge

- $\hat{\alpha}_{PI}$ is a new type of effective charge
  - direct analogue of the Gell-Mann–Low effective coupling in QED, *i.e*. completely determined by the gauge b… …tion.
- $\hat{\alpha}_{PI}$ is
  - pro…
  - app…
  - know…
- $\hat{\alpha}_{PI}$ posse…
  - Nonp… …n QCD
- QCD is IR… …ation of gluon mass-scale, which als… …minate the Gribov ambiguity
- Asymptotic freedom ⇒ QCD is well-defined at UV momenta
- ***QCD is therefore unique amongst known 4D quantum field theories***
  - ***Potentially, defined & internally consistent at all momenta***

Conceivably, therefore, QCD can serve as a basis for theories that take physics beyond the Standard Model

$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$

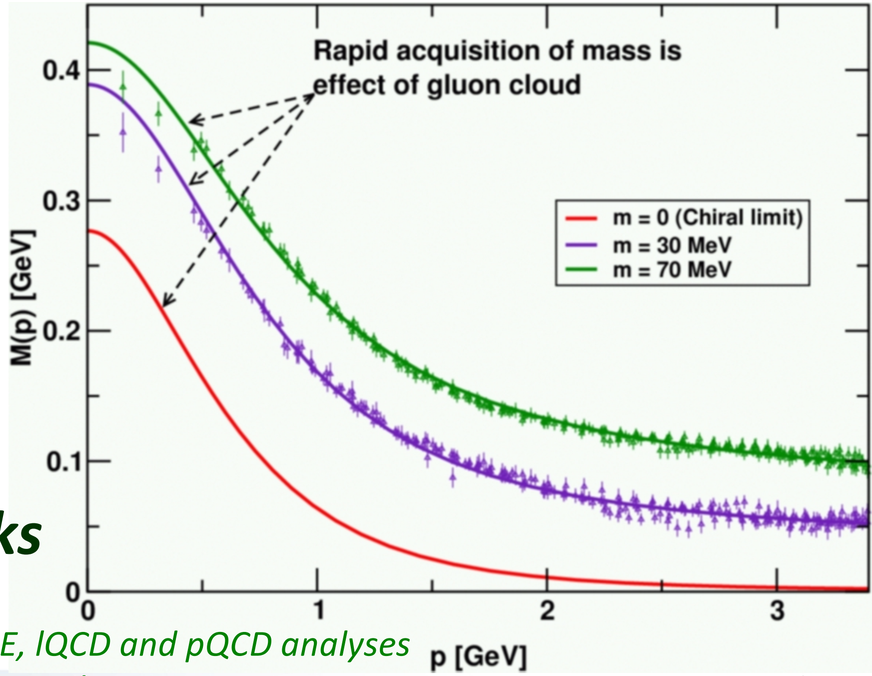


Quark Gap Equation

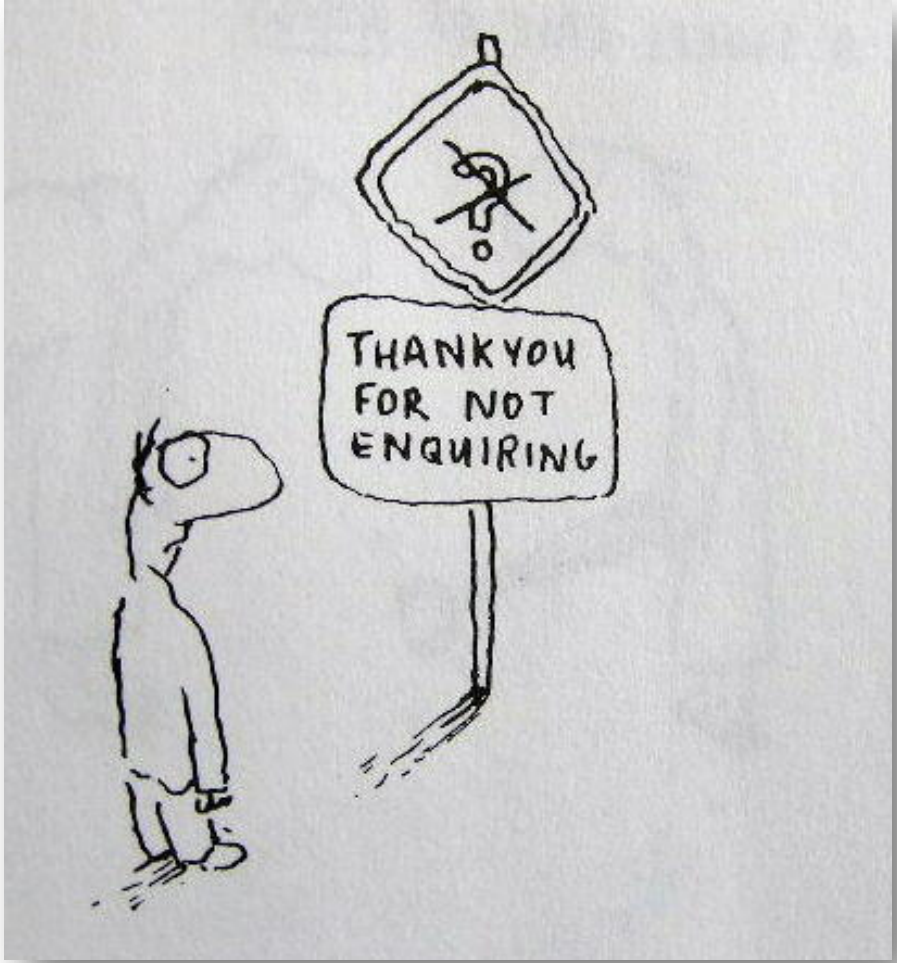
DCSB

- Dynamical chiral symmetry breaking (DCSB) is a key emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory indicates that DCSB is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of *mass from nothing*.
- ***Dynamical***, not spontaneous
  - Add nothing to *QCD* ,

    No Higgs field, nothing!
    Effect achieved purely through quark+gluon dynamics.
  - ✓ ***Trace anomaly: massless quarks become massive***



Combining DSE, lQCD and pQCD analyses of QCD's gauge and matter sectors



Enigma of Mass

Maris, Roberts and Tandy
nucl-th/9707003, Phys.Lett. B**420** (1998) 267-273

Pion's Goldberger -Treiman relation

- Pion's Bethe-Salpeter amplitude

Solution of the Bethe-Salpeter equation

$$\Gamma_{\pi^j}(k;P) = \tau^{\pi^j}\gamma_5\left[iE_\pi(k;P) + \gamma\cdot P F_\pi(k;P) + \gamma\cdot k\, k\cdot P\, G_\pi(k;P) + \sigma_{\mu\nu}\, k_\mu P_\nu\, H_\pi(k;P)\right]$$

- Dressed-quark propagator $S(p) = \frac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$

- Axial-vector Ward-Takahashi identity entails

$$f_\pi E_\pi(k;P=0) = B(k^2)$$

Owing to DCSB & Exact in Chiral QCD

***Miracle*: two body problem solved, almost completely, once solution of one body problem is known**

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

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

The most fundamental expression of Goldstone's Theorem and DCSB

Rudimentary version of this relation is apparent in Nambu's Nobel Prize work

Model independent
Gauge independent
Scheme independent

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

Pion exists if, and only if, mass is dynamically generated

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

Enigma of mass

This algebraic identity is why QCD's pion is massless in the chiral limit

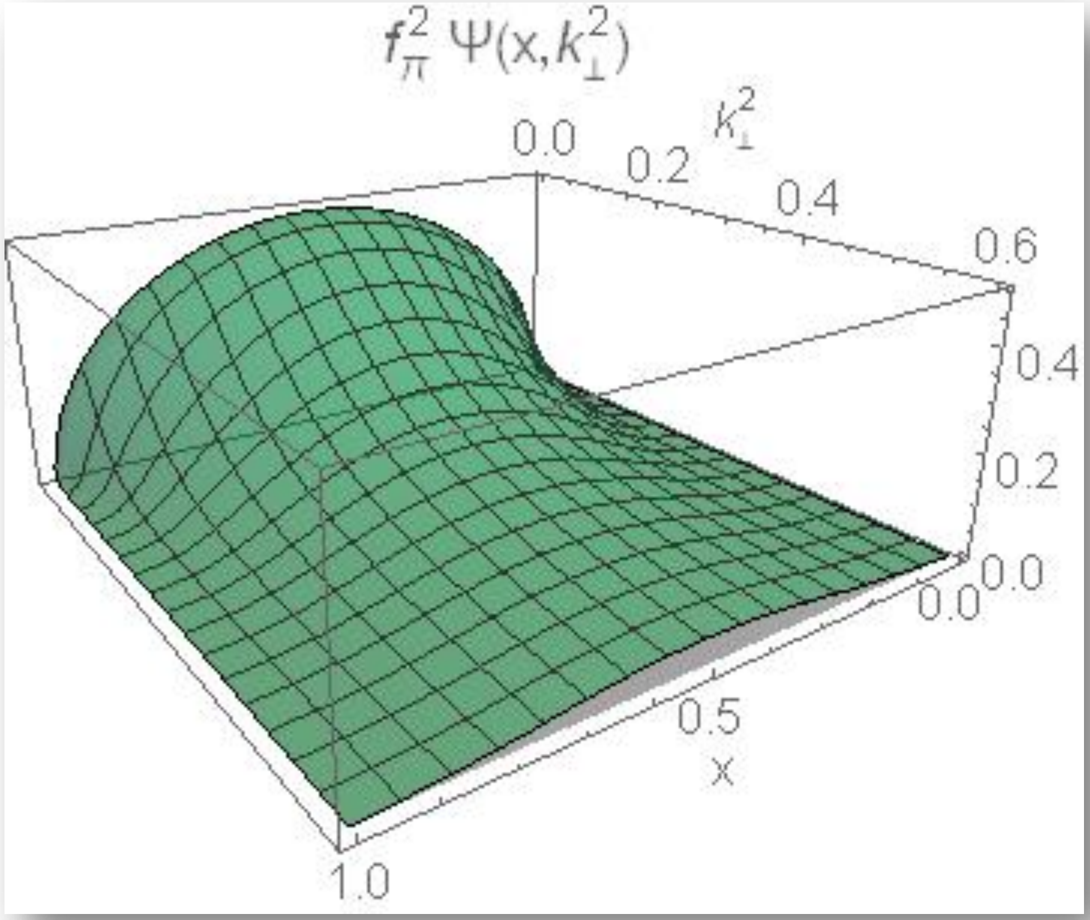
- The quark level Goldberger-Treiman relation shows that DCSB has a very deep and far reaching impact on physics within the strong interaction sector of the Standard Model; viz.,

  Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

- This emphasises that Goldstone's theorem has a pointwise expression in QCD
- Hence, pion properties are an almost direct measure of the dressed-quark mass function.
- Thus, enigmatically, the properties of the *massless* pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.

Craig Roberts. Charting Hadronic Interiors (64p)

Observing *Mass*



Pion's Wave Function

Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, et al., arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Methods have been developed that enable direct computation of the pion's light-front wave function
- $\varphi_\pi(x)$ = twist-two parton distribution amplitude = projection of the pion's Poincaré-covariant wave-function onto the light-front

$$\varphi_\pi(x) = Z_2 \mathrm{tr}_{CD} \int \frac{d^4k}{(2\pi)^4} \delta(n\cdot k - x n\cdot P)\, \gamma_5 \gamma\cdot n\, S(k)\Gamma_\pi(k;P)S(k-P)$$

- Results have been obtained with the DCSB-improved DSE kernel, which unifies matter & gauge sectors

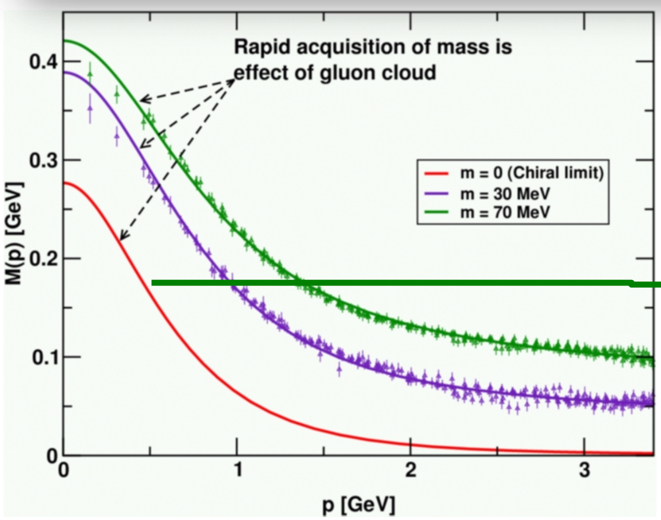
$$\varphi_\pi(x) \propto x^\alpha (1-x)^\alpha, \text{ with } \alpha \approx 0.5$$

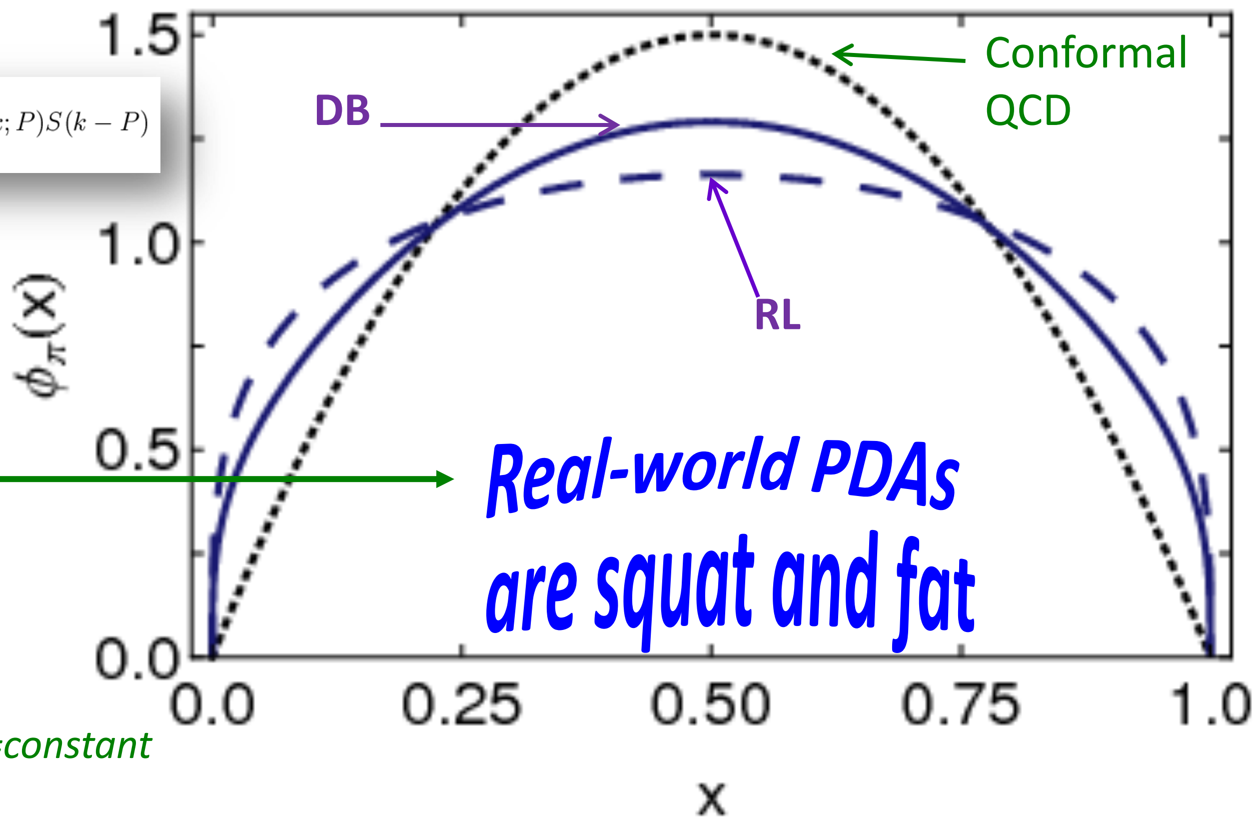
Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, *et al.*, arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Continuum-QCD prediction: marked broadening of $\varphi_\pi(x)$, which owes to DCSB

$$\varphi_\pi(x) = Z_2 \mathrm{tr}_{CD} \int \frac{d^4k}{(2\pi)^4} \delta(n\cdot k - x n\cdot P)\, \gamma_5 \gamma\cdot n\, S(k)\Gamma_\pi(k;P)S(k-P)$$





A theory that produces M(p)=constant also produces φ(x)=constant

Leading-twist PDAs of *S*-wave light-quark mesons

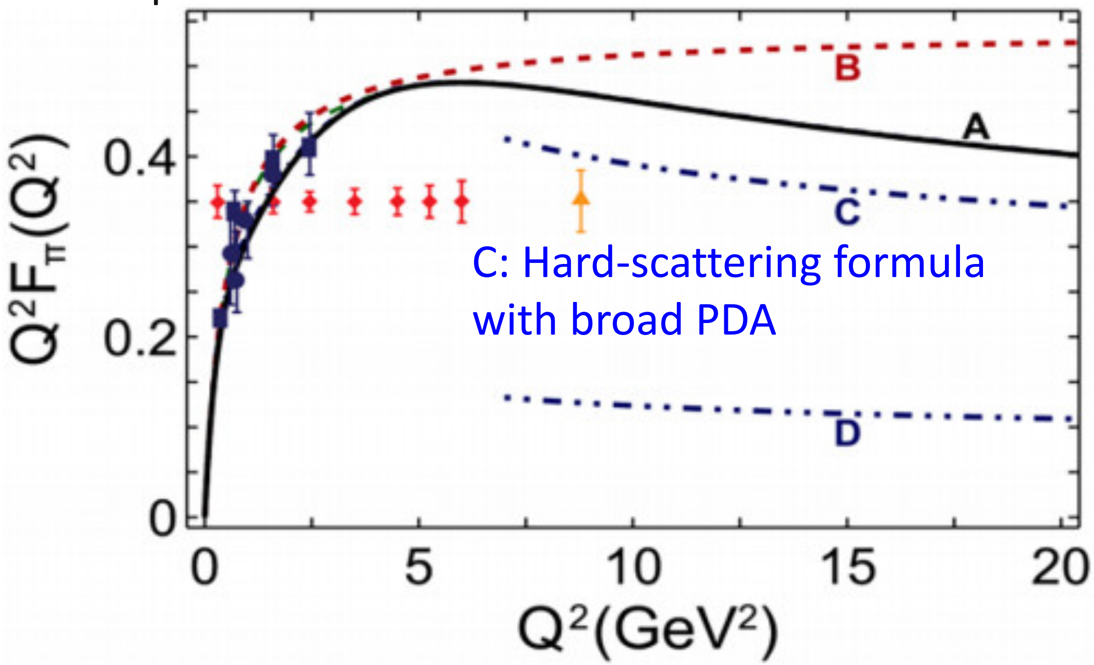
- End of a <u>*long*</u> story (longer than 30 years war)
- Continuum predictions that pion and kaon PDAs are broad, concave functions confirmed by simulations of lattice-regularised QCD
  - *Pion Distribution Amplitude from Lattice QCD*, Jian-Hui Zhang *et al.*, Phys.Rev. D95 (2017) 094514; 1702.00008
  - *Kaon Distribution Amplitude from Lattice QCD and the Flavor SU(3) Symmetry*, Jiunn-Wei Chen *et al*., arXiv:1712.10025 [hep-ph]
  - *Pion and kaon valence-quark parton quasidistributions*, S.-S. Xu, L. Chang *et al.* arXiv:1802.09552 [nucl-th]
- Continuum analyses predict that these properties <u>characterise</u> the leading-twist PDAs of ***all*** *S*-wave light-quark mesons
- ***Numerous empirically verifiable predictions***

Pion's electromagnetic form factor

- Example:

  PDA Broadening has enormous impact on understanding $F_\pi(Q^2)$

A: Internally-consistent DSE prediction



C: Hard-scattering formula with broad PDA

Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

Pion's electromagnetic form factor

- Example:

  PDA Broadening has enormous impact on understanding $F_\pi(Q^2)$

- Appears that JLab12 is within reach of first verification of a QCD hard-scattering formula

Unified with kaon … *Exposing strangeness: projections for kaon electromagnetic form factors*, Fei Gao, L. Chang *et al*. Phys. Rev. D **96** (2017) 034024

A: Internally-consistent DSE prediction

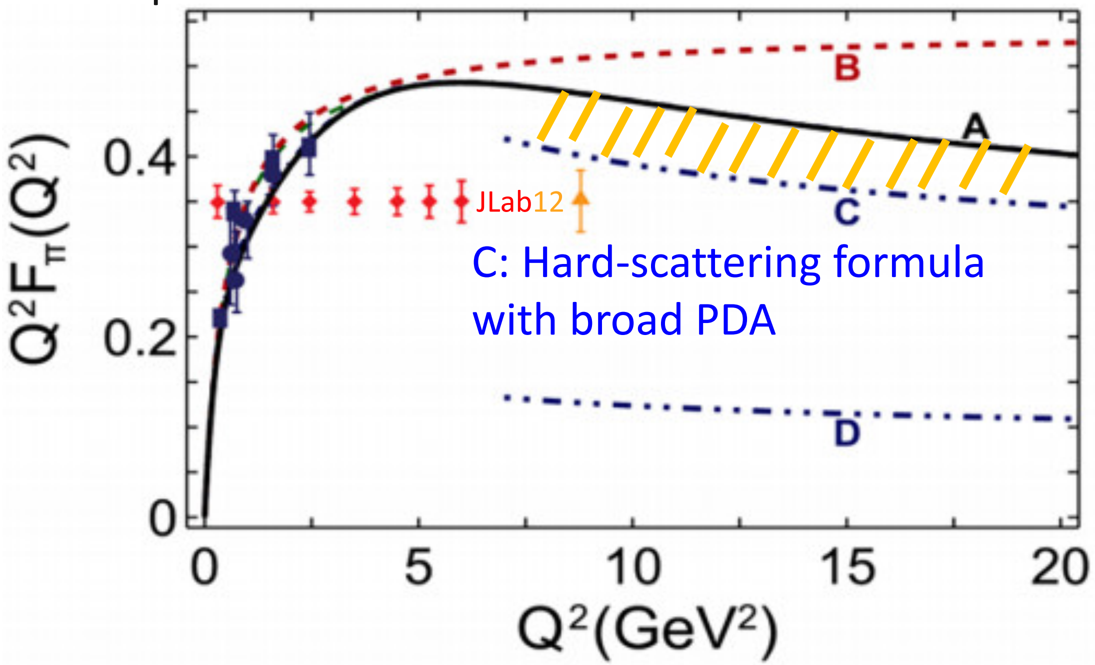
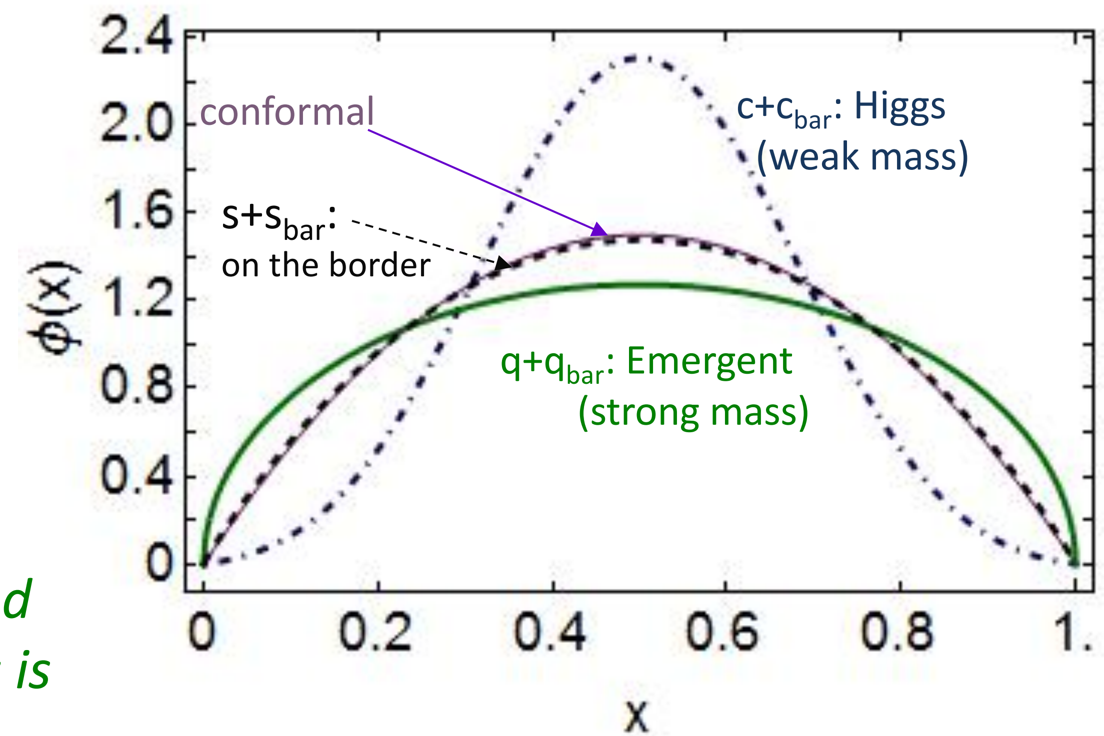


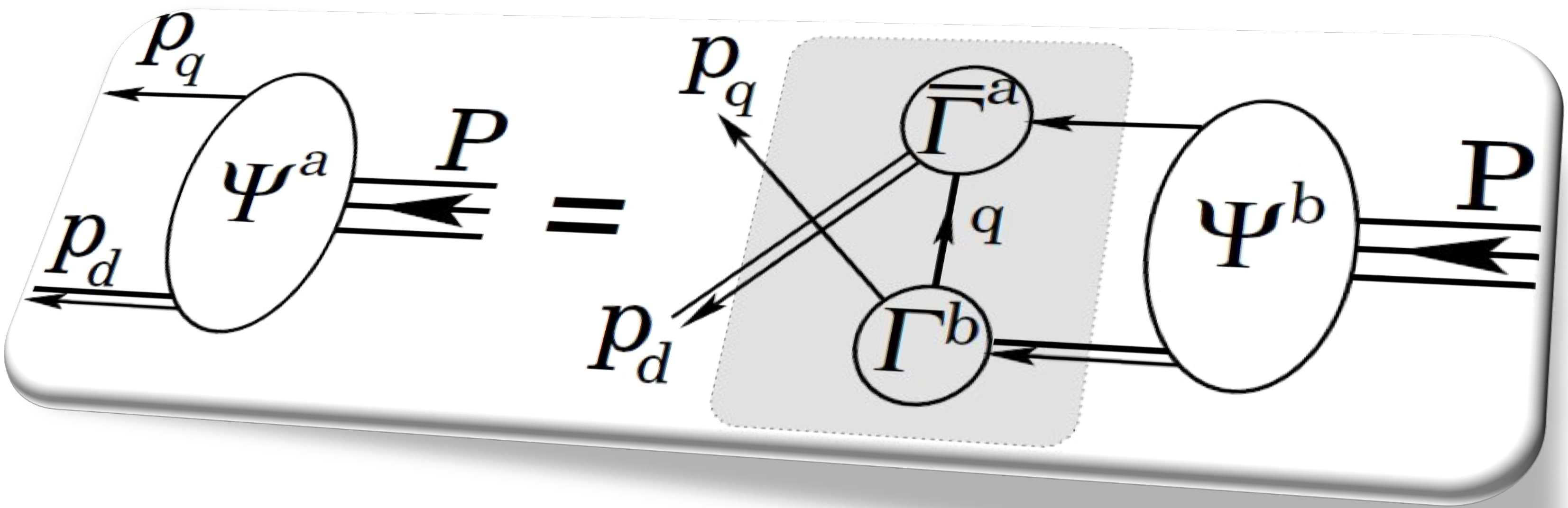
Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, Fei Gao, Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1511.04943 [nucl-th], Phys. Lett. B **753** (2016) pp. 330-335

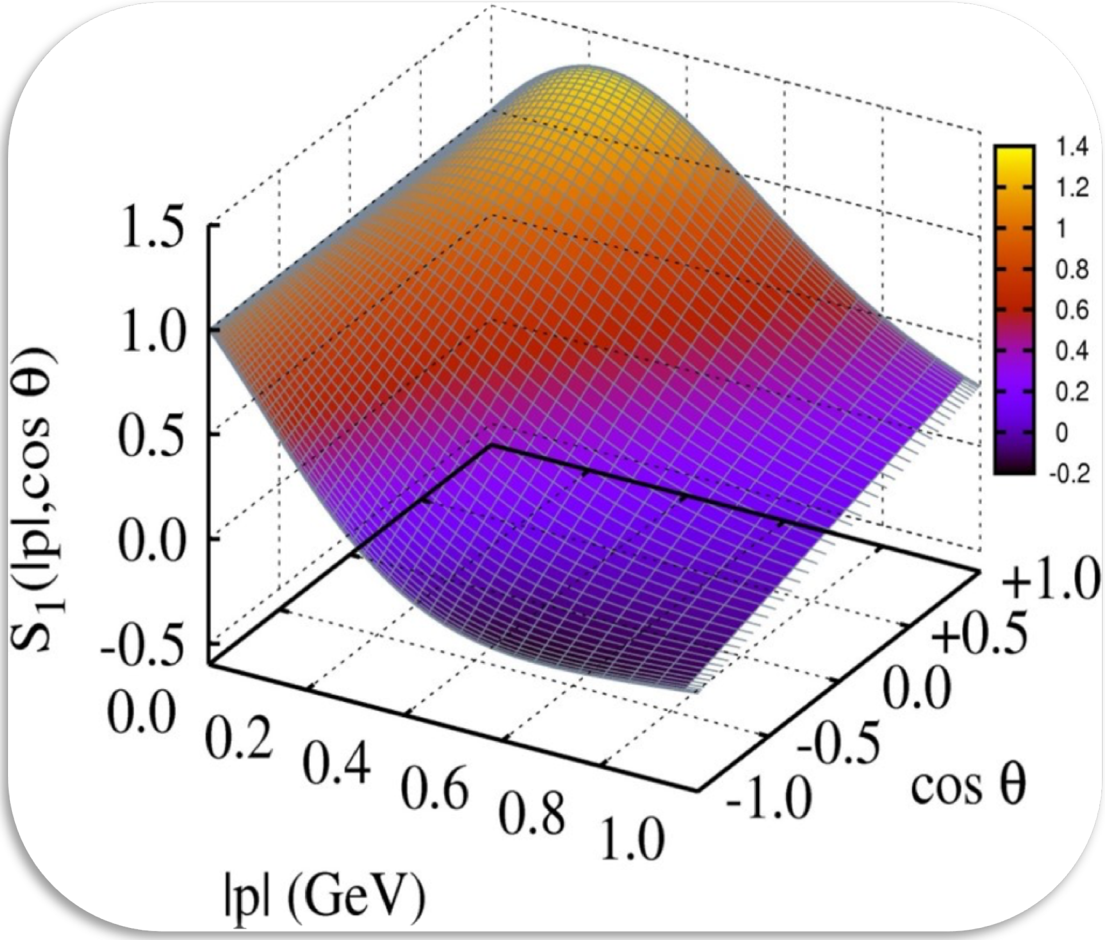
Emergent Mass *vs.* Higgs Mechanism

- When does Higgs mechanism begin to influence mass generation?
- limit $m_{quark} \to \infty$
  $\varphi(x) \to \delta(x-½)$
- limit $m_{quark} \to 0$
  $\varphi(x) \sim (8/\pi)\,[x(1-x)]^{½}$
- Transition boundary lies just above $m_{strange}$
- *Comparison between distributions of light-quarks and those involving strange-quarks is good place to seek signals for strong-mass generation*





Structure of Baryons



Baryon Wave Functions

Light-cone distribution amplitudes of the nucleon and negative parity nucleon resonances from lattice QCD
V. M. Braun *et al*., Phys. Rev. D 89 (2014) 094511

Light-cone distribution amplitudes of the baryon octet
G. S. Bali *et al*. JHEP 1602 (2016) 070

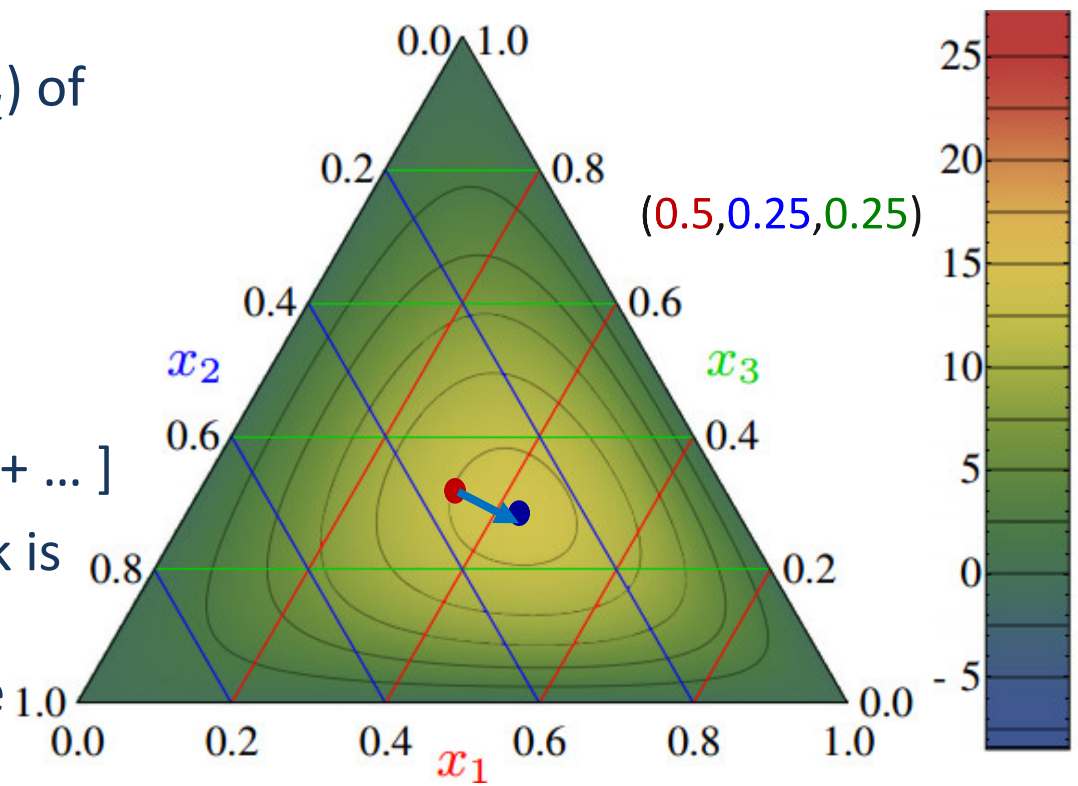
Nucleon PDAs & lQCD

- First lQCD results for n=0, 1 moments of the leading twist PDA of the nucleon are available
- Used to constrain strength (a_{11}) of the leading-order term in a conformal expansion of the nucleon's PDA:

$\Phi(x_1,x_2,x_3)$

$= 120\, x_1\, x_2\, x_3\, [\, 1 + a_{11}\, P_{11}(x_1,x_2,x_3) + \ldots\,]$

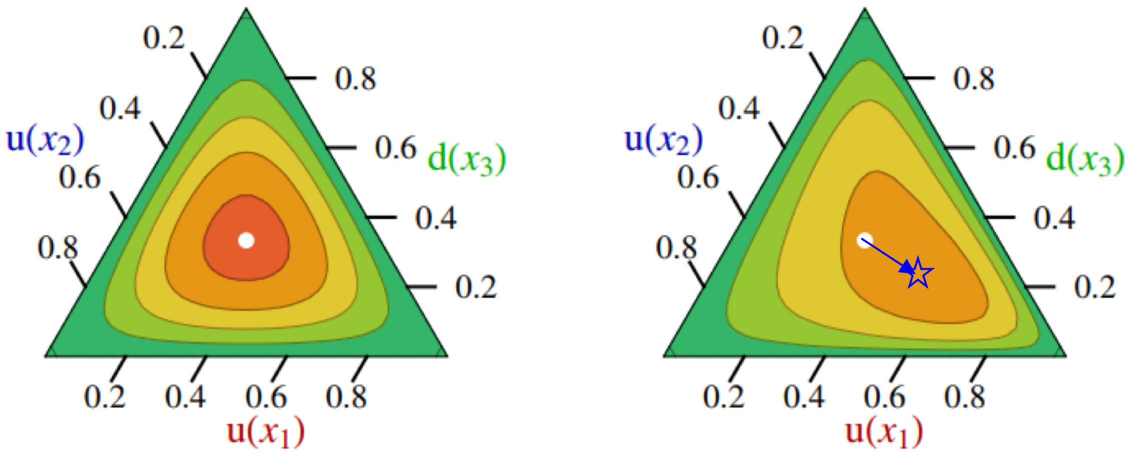
- Shift in location of central peak is consistent with existence of diquark correlations within the nucleon



Parton distribution amplitudes: revealing diquarks in the proton and Roper resonance, Cédric Mezrag, Jorge Segovia, Lei Chang and Craig D. Roberts
arXiv:1711.09101 [nucl-th]

PDAs of Nucleon & its 1st Radial Excitation

- Methods used for mesons can be extended to compute pointwise behaviour of baryon PDAs



conformal

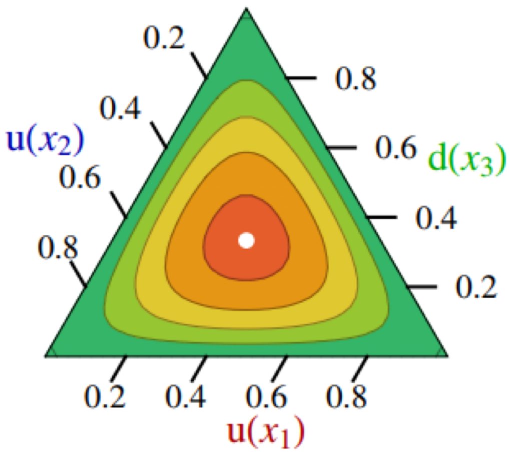
nucleon

Diquark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton's light-front momentum

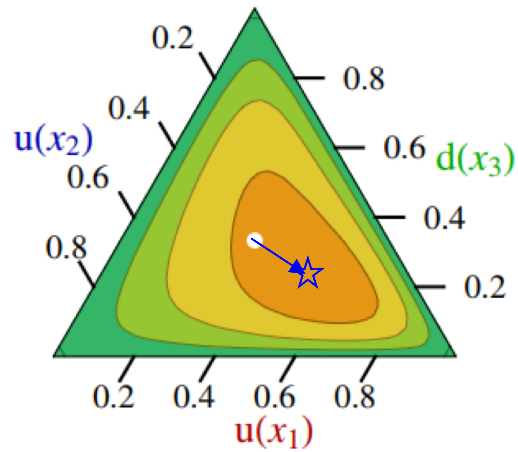
PDAs of Nucleon & its 1st Radial Excitation

➤ Methods used for mesons can be extended to compute pointwise behaviour of baryon PDAs

Just like QM & PDAs of meson radial excitations



conformal



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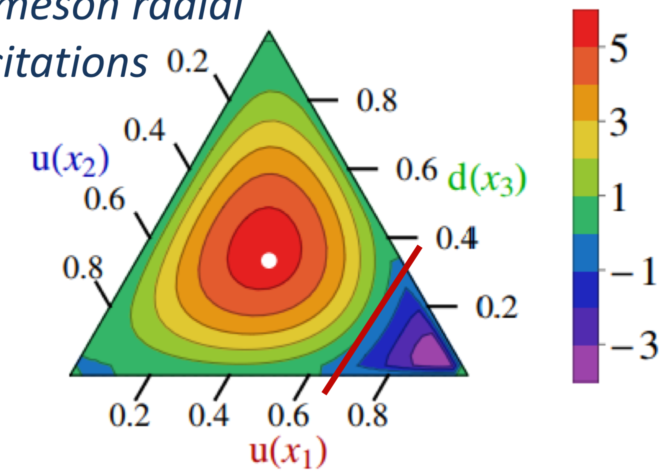


Roper's quark core

Excitation's PDA is not positive definite … there is a prominent locus of zeros in the lower-right corner of the barycentric plot

Diquark correlations in the nucleon

- Agreement between continuum and lattice results

  ONLY when nucleon contains scalar & axial-vector diquark correlations

- Nucleon with only a scalar-diquark, omitting the axial-vector diquark, ruled-out by this confluence between continuum and lattice results

TABLE I. A – Eq. (13) interpolation parameters for the proton and Roper PDAs in Fig. 2. B – Computed values of the first four moments of the PDAs. Our error on f_N reflects a scalar diquark content of $65 \pm 5\%$; and values in rows marked with "$\not\supset$ av" were obtained assuming the baryon is constituted solely from a scalar diquark. (All results listed at $\zeta = 2\,\text{GeV}$.)

A	$n_{\hat\varphi}$	α	β	w_{01}	w_{11}	w_{02}	w_{12}	w_{22}
p	65.8	1.47	1.28	0.096	0.094	0.15	−0.053	0.11
R	14.4	1.42	0.78	−0.93	0.22	−0.21	−0.057	−1.24

B	$10^3 f_N/\text{GeV}^2$	$\langle x_1\rangle_u$	$\langle x_2\rangle_u$	$\langle x_3\rangle_d$
conformal PDA		0.333	0.333	0.333
lQCD [17]	2.84(33)	0.372(7)	0.314(3)	0.314(7)
lQCD [18]	3.60(6)	0.358(6)	0.319(4)	0.323(6)
herein proton	3.78(14)	0.379(4)	0.302(1)	0.319(3)
herein proton $\not\supset$ av	2.97	0.412	0.295	0.293
herein Roper	5.17(32)	0.245(13)	0.363(6)	0.392(6)
herein Roper $\not\supset$ av	2.63	0.010	0.490	0.500

Parton distribution amplitudes: revealing diquarks in the proton and Roper resonance, Cédric Mezrag, Jorge Segovia, Lei Chang and Craig D. Roberts
arXiv:1711.09101 [nucl-th]

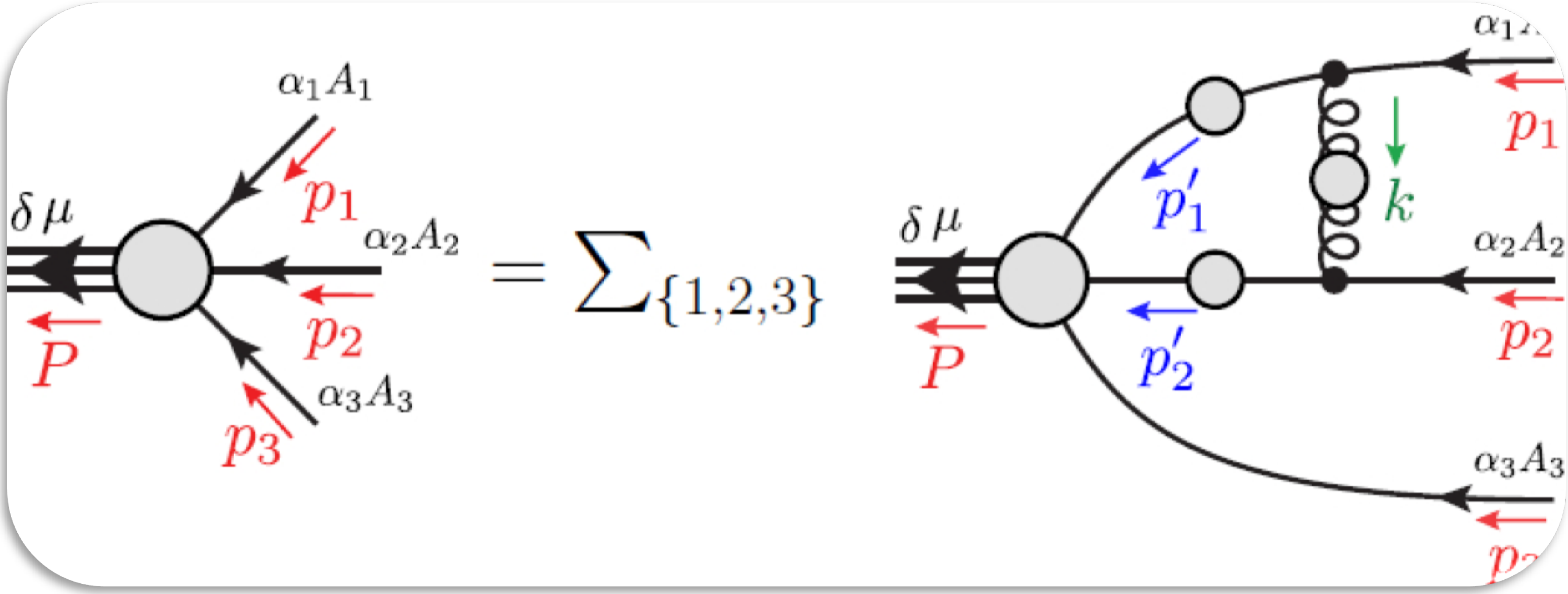
Nucleon and Roper PDAs

No humps or bumps in leading-twist PDAs of ground-state S-wave baryons

- The proton's PDA is a broad, concave function
  - maximum shifted relative to peak in QCD's conformal limit expression
  - Magnitude of shift signals presence of

    both scalar & axial-vector diquark correlations in the nucleon
    - scalar generates around 60% of the proton's normalisation.
- The radial-excitation (Roper) is constituted similarly
  - Pointwise form of its PDA
    - Negative on a material domain
  - Is result of marked interferences between the contributions from both scalar and axial-vector diquarks
    - particularly, the locus of zeros, which

      highlights its character as a radial excitation.
- These features originate with the emergent phenomenon of dynamical chiral symmetry breaking in the Standard Model.



Heavy Baryons

Heavy Baryons

- Unified study of an array of mesons and baryons constituted from light- and heavy-quarks
  - Symmetry-preserving rainbow-ladder truncation of all relevant bound-state equations:
    - Gap equations
    - Bethe-Salpeter equations
    - and Faddeev-equations ⇐ *pioneered by Gernot Eichmann*
- Produced spectrum and decay constants of ground-state pseudoscalar- and vector-mesons:
  - $q' \bar{q}$ & and $Q' \bar{Q}$, with q′,q=u,d,s, Q′,Q = c,b

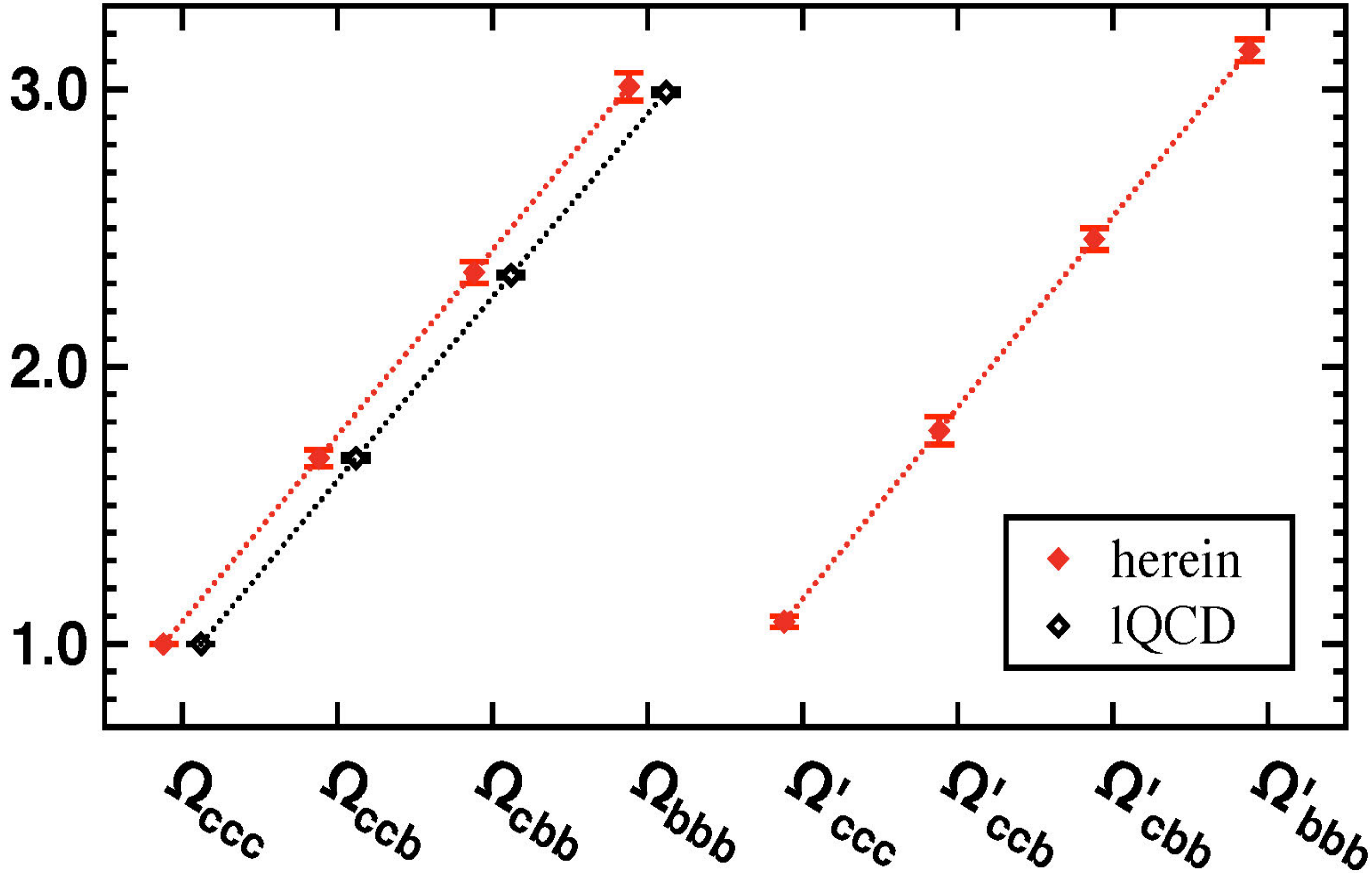
& masses of $J^P=3/2^+$ qqq, QQQ ground state baryons and their first positive-parity excitations.

Poincaré-covariant analysis of heavy-quark baryons
S.-X. Qin, C. D. Roberts & S. M. Schmidt,
arXiv:1801.09697 [nucl-th]

Triply Heavy Baryons

Ω_{ccc}= 4.76(7) GeV (RL DSE)
Ω_{ccc}= 4.80(2) GeV (lQCD)

- Solved Faddeev equation in RL-truncation directly for n=0,1 ccc & bbb
- Used equal spacing rule (Gell-Mann+Okubo) for other states



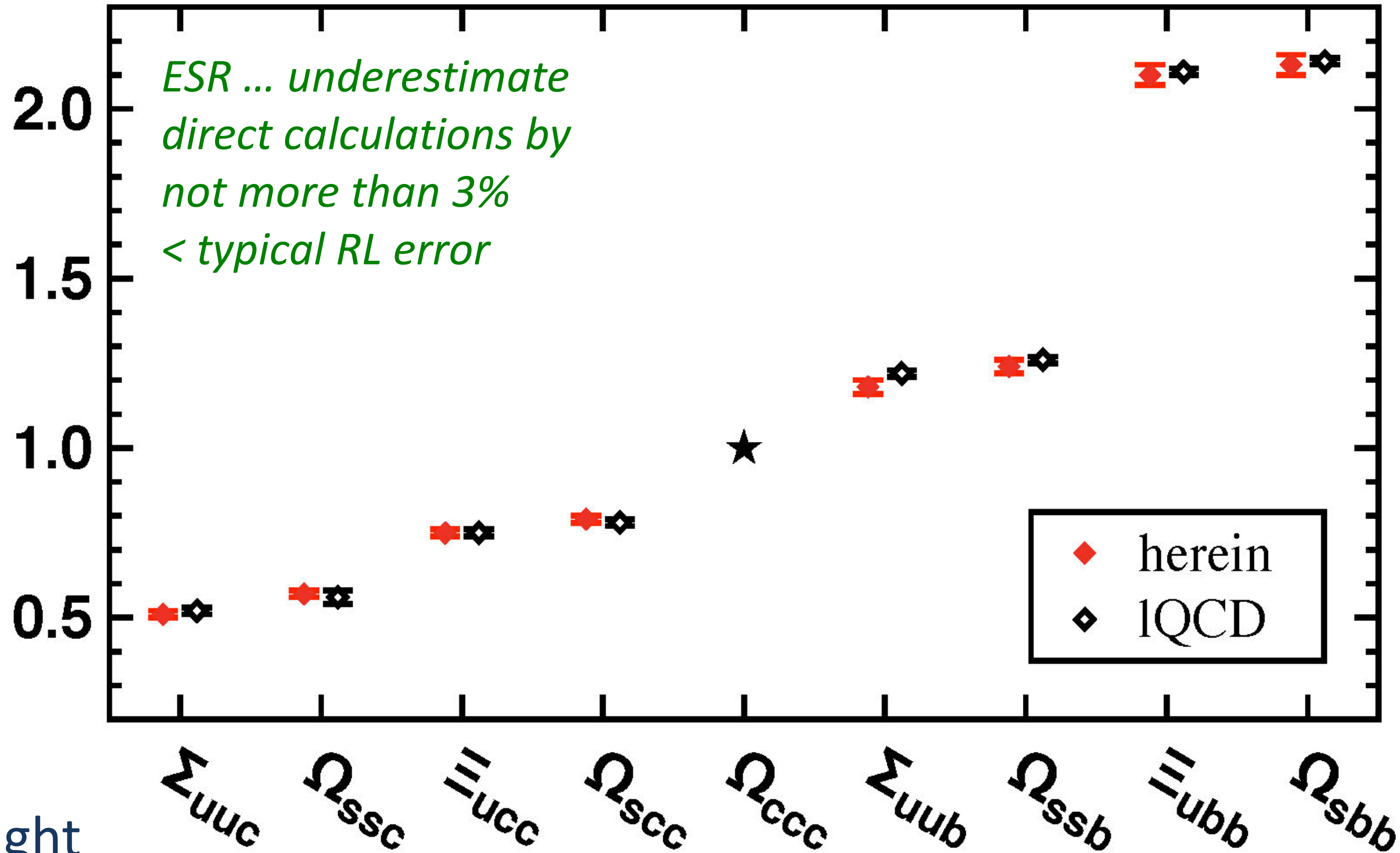
lQCD = Z. S. Brown, W. Detmold, S. Meinel and K. Orginos, Phys. Rev. D 90, 094507 (2014).

Poincaré-covariant analysis of heavy-quark baryons
S.-X. Qin, C. D. Roberts & S. M. Schmidt,
arXiv:1801.09697 [nucl-th]

Heavy Baryons

- Equal spacing rule provides sound estimates for
  - masses
  - decay constants

  of all systems considered



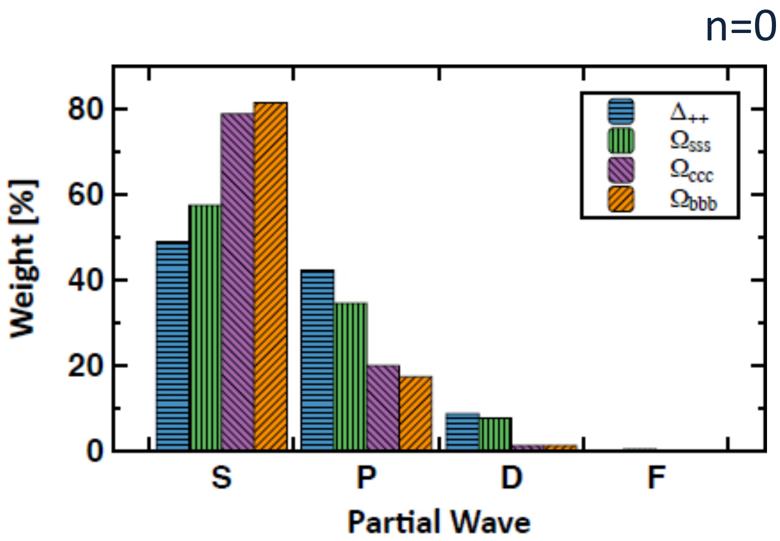
- Obvious in hindsight

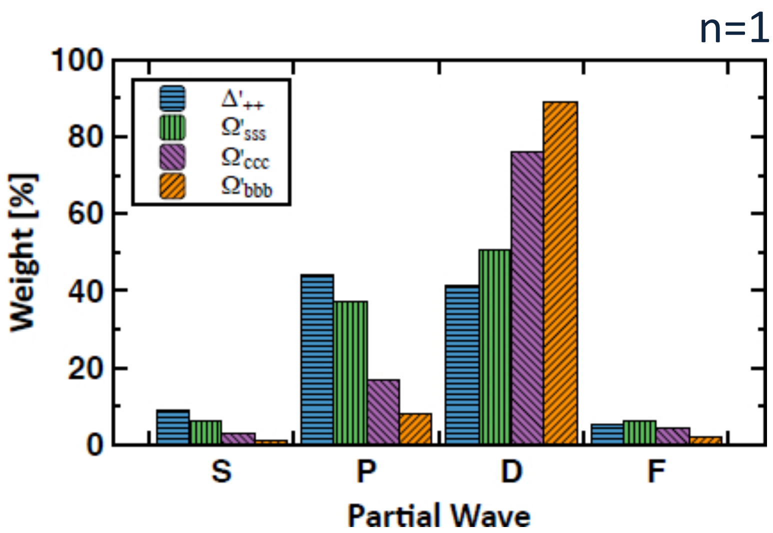
  … QCD's interaction is flavour-independent

  … need only survey DSE studies of these observables in kindred systems

Heavy Baryons

- Analysed internal structure of the ground and first positive-parity excited states of qqq, QQQ
  - Each system has a complicated angular momentum structure, e.g.
    - Ground states
      - primarily S-wave
      - but each possesses P-, D- and F-wave components
      - P-wave fraction is large in the *u* and *s*-quark states;
    - First positive-parity excitation
      - large D-wave component,
      - grows with increasing current-quark mass
      - but state also exhibits features consistent with a radial excitation.

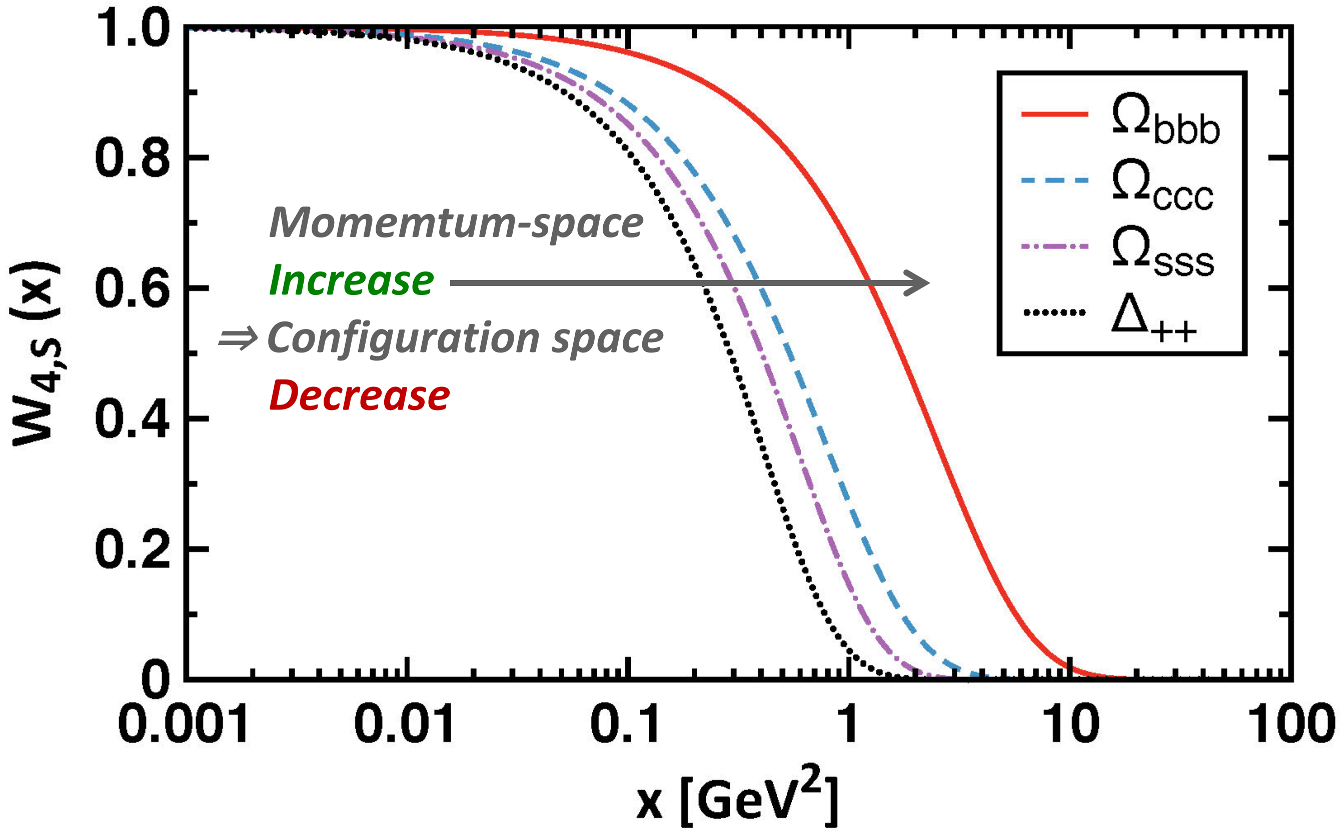




Heavy Baryons

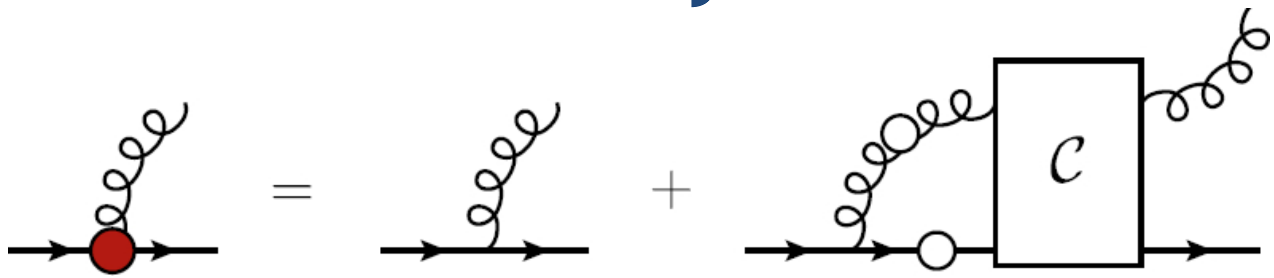
- Pointwise behaviour of Faddeev wave functions

⇒ configuration space extent of such bound states *decreases* as the mass of the valence-quark constituents *increases*.



Hybrids & Exotics

New Window on Hybrids/Exotics



C = 1PI gluon-quark scattering amplitude

- Foundation:

  Observation that one can represent the gluon-quark vertex in terms of a gluon-quark scattering amplitude

  - Described in *Symmetry preserving truncations of the gap and Bethe-Salpeter equations,* Binosi, Chang, Papavassiliou, Qin, Roberts, arXiv:1601.05441 [nucl-th], Phys. Rev. D **93** (2016) 096010/1-7

- Exploiting this, one arrives at Faddeev equation for colour-singlet gluon+quark+antiquark bound-states

Hybrids/Exotics - Preliminary Results

Calc^n/GeV	0^{-+}	1^{-+}	1^{--}	0^{+-}	0^{--}
S.-S Xu et al. Rainbow Ladder	1.23	1.78	1.61	1.69	1.73
S.-S Xu *et al.* Faddeev	1.67	1.72	1.86	1.87	1.93
[1]	2.13	2.17	2.25	2.43	
[2]	2.1	1.9	2.3	2.3	

1. lQCD, $m_\pi > 0.4$ GeV … Dudek *et al*. e-Print: arXiv:1004.4930 [hep-ph]
2. Meyer and Swanson, e-Print: arXiv:1502.07276 [hep-ph]

Remarks:

- ✓ Xu *et al*. is a beyond-rainbow-ladder (BRL) Faddeev equation calculation
  - ✓ BRL structure is essential to reproducing lQCD ordering of states
- ✓ Xu *et al*. masses are lower than lQCD.

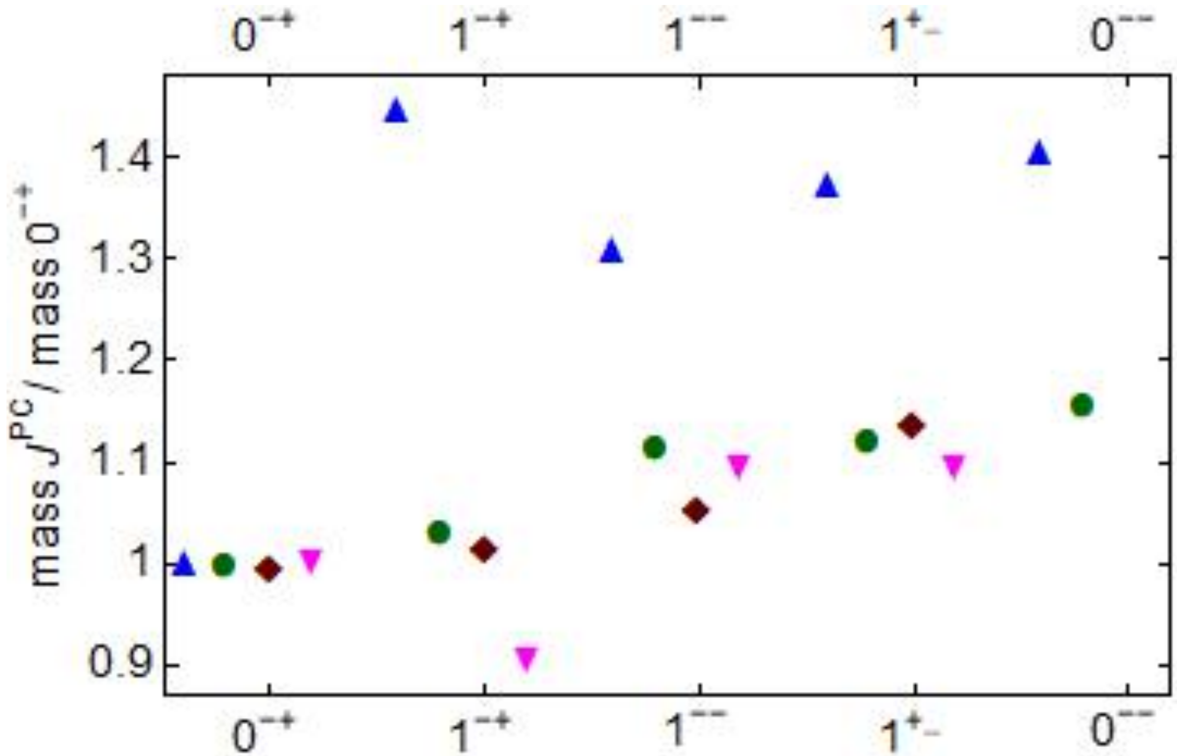
  Perhaps lQCD results too high because use inflated pion masses?

  This is being studied.

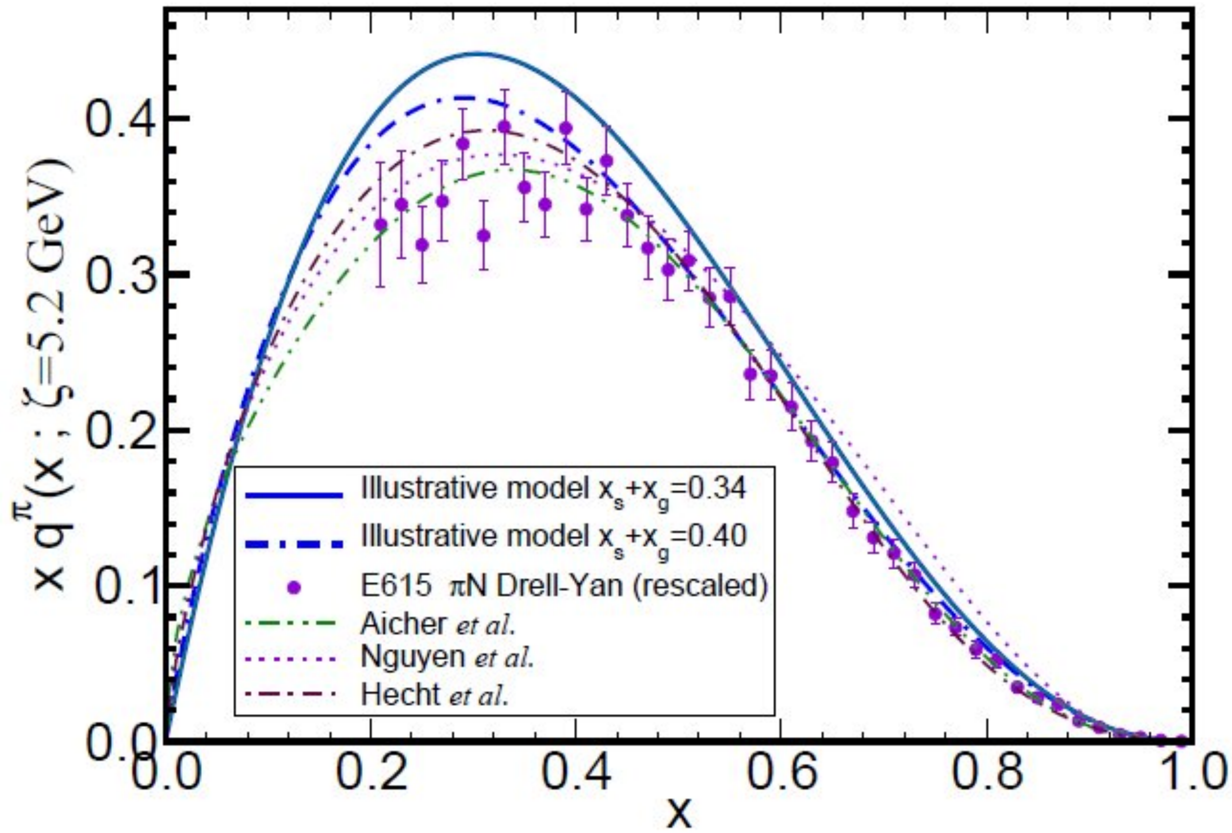
Hybrids/Exotics
Preliminary Results

S.-S. Xu, L. Chang, J. Papavassiliou, C. D. Roberts, H.-S Zong

- ● Xu *et al.*, Faddeev
- ◆ Dudek, *et al.*, lQCD



✓ Only Faddeev (Xu *et al.*) produces spectrum with same ordering as lQCD



π & *K* Valence-quark Distribution Functions

π & K PDFs

- Experimental data on π & K PDFs obtained in mesonic Drell-Yan scattering from nucleons in heavy nuclei; but it's old: 1980-1989
- Newer data would be welcome:
  - persistent doubts about the Bjorken-$x \simeq 1$ behaviour of the pion's valence-quark PDF
  - single modest-quality measurement of $u^K(x)/u^\pi(x)$ cannot be considered definitive.
- Approved experiment, using tagged DIS at JLab 12, should contribute to a resolution of pion question; and a similar technique might also serve for the kaon.
- Future:
  - new mesonic Drell-Yan measurements at modern facilities could yield valuable information on π and K PDFs,
  - as could two-jet experiments at the large hadron collider;
  - EIC would be capable of providing access to π and K PDFs through measurements of forward nucleon structure functions.
- Gribov-Lipatov reciprocity (crossing symmetry) entails connection between PDFs and fragmentation functions on $z \simeq 1$ ($z \geq 0.75$)

$$D_{H/q}(z) \approx z\, q^H(z)$$

Reliable information on meson fragmentation functions is critical if the worldwide programme aimed at determining TMDs is to be successful

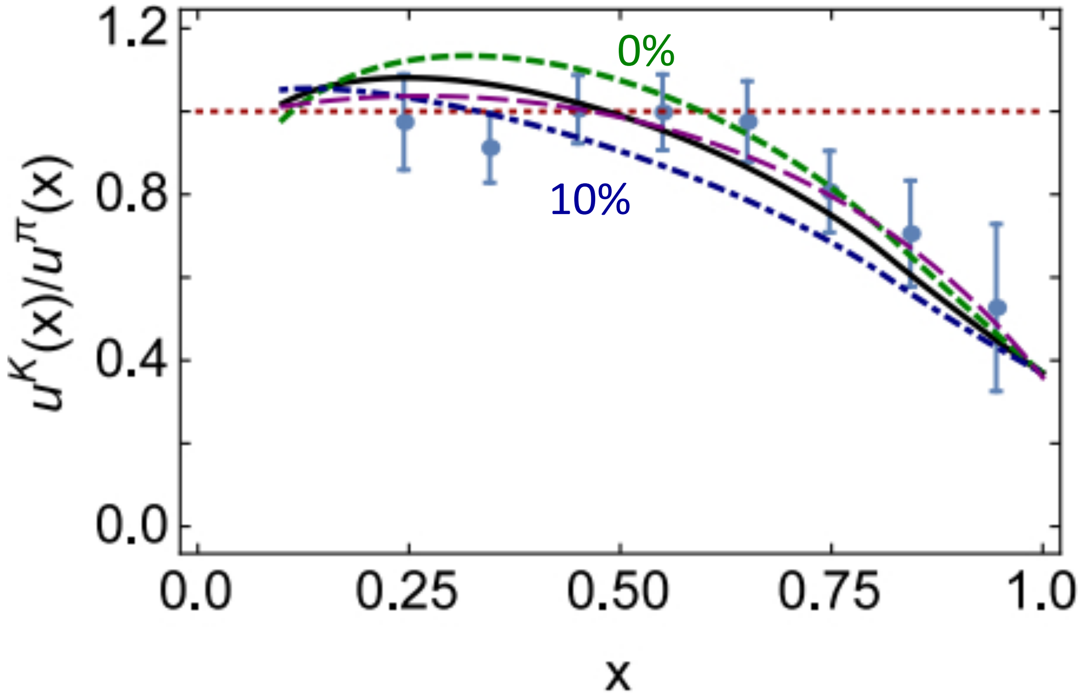
Kaon's gluon content

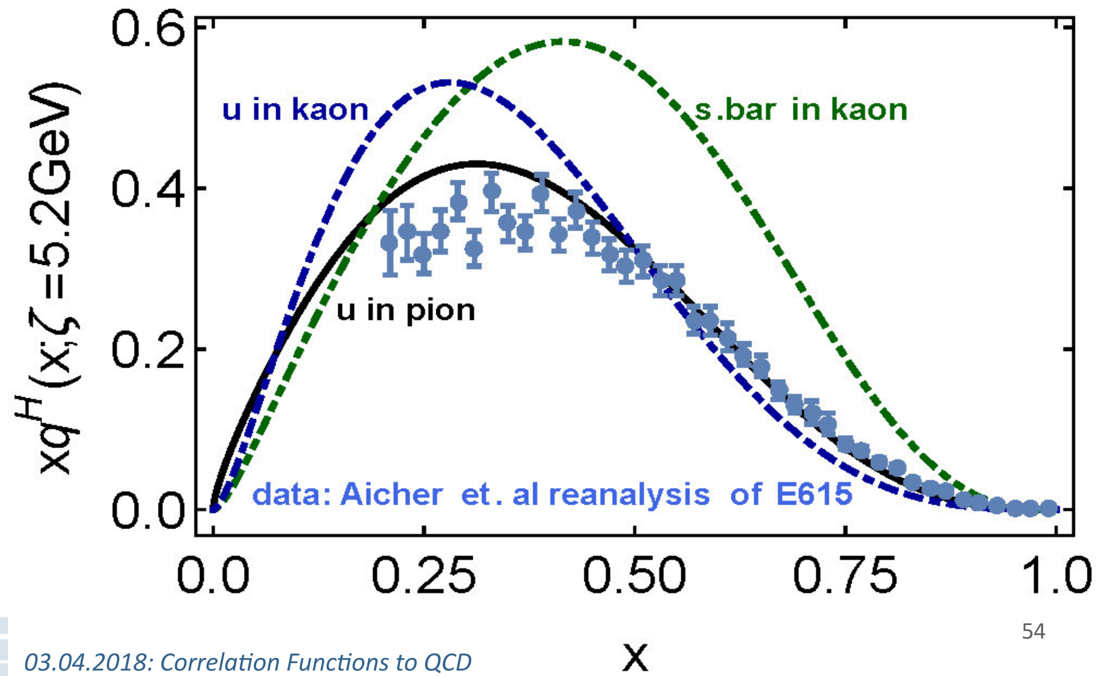
- $\langle x\rangle_g^K(\zeta_H) = 0.05 \pm 0.05$
  $\Rightarrow$ Valence quarks carry 95% of kaon's momentum at ζ_H
- DGLAP-evolved to ζ_2

q	$\langle x\rangle_q^K$	$\langle x^2\rangle_q^K$	$\langle x^3\rangle_q^K$
u	0.28	0.11	0.048
$\bar{s}$	0.36	0.17	0.092

Valence-quarks carry ⅔ of kaon's light-front momentum

Cf. Only ½ for the pion





Valence-quark distribution functions in the kaon and pion,
Chen Chen, Lei Chang *et al.*
arXiv:1602.01502 [nucl-th], Phys. Rev. D**93** (2016) 074021/1-11

π & *K* PDFs

- Marked differences between *π* & *K* gluon content
  - ζ_H:
    - Whilst $\frac{1}{3}$ of pion's light-front momentum carried by glue
    - $Only$ $\frac{1}{20}$ of the kaon's light-front momentum lies with glue
  - $\zeta_2^{\,2} = 4\ \mathrm{GeV}^2$
    - Glue carries $\frac{1}{2}$ of pion's momentum and $\frac{1}{3}$ of kaon's momentum
  - Evident in differences between large-*x* behaviour of valence-quark distributions in these two mesons
- Signal of Nambu-Goldstone boson character of *π*
  - Nearly complete cancellation between one-particle dressing and binding attraction in this almost massless pseudoscalar system

$$2\ \mathrm{Mass}_Q + U_g \approx 0$$

Valence-quark distribution functions in the kaon and pion,
Chen Chen, Lei Chang *et al*.
arXiv:1602.01502 [nucl-th], Phys. Rev. D**93** (2016) 074021/1-11

π & *K* PDFs

- Existing textbook description of Goldstone's theorem via pointlike modes is *outdated* and *simplistic*

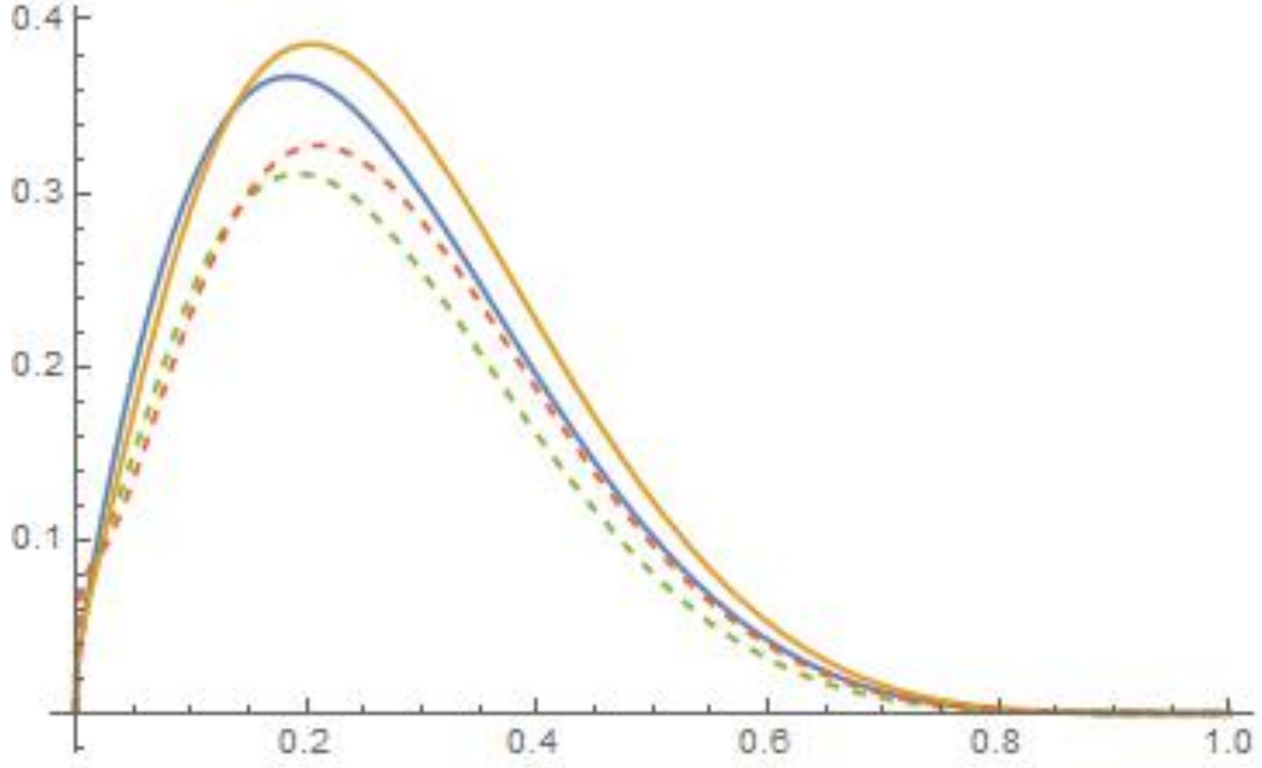
Valence-quark distribution functions in the kaon and pion,
Chen Chen, Lei Chang *et al*.
arXiv:1602.01502 [nucl-th], Phys. Rev. D**93** (2016) 074021/1-11

π & K PDFs

- The appearance of Nambu-Goldstone modes in the Standard Model is far more interesting
  - Nambu-Goldstone modes are nonpointlike!
  - Intimately connected with origin of mass!
  - Possibly/Probably(?) inseparable from expression of confinement!

- Difference between gluon content of π & K is measurable … using well-designed EIC
- Write a definitive new chapter in future textbooks on the Standard Model

Electron Ion Collider: The Next QCD Frontier

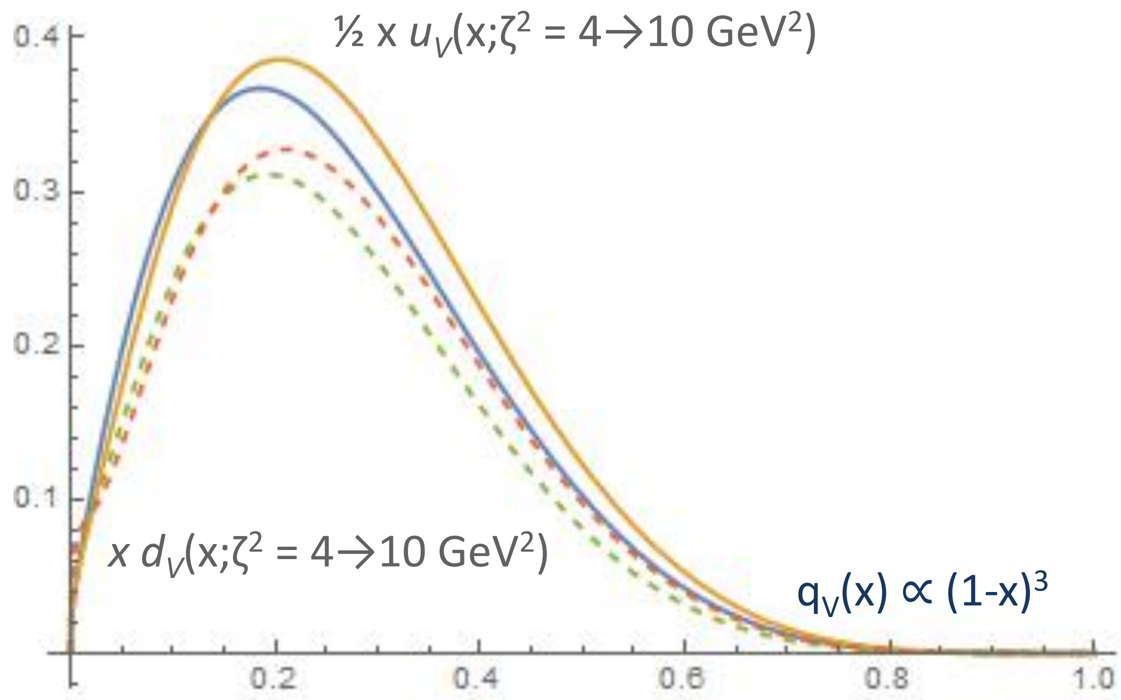


Proton Valence-quark Distribution Functions

Proton valence-quark PDFs

F. Gao, L. Chang, Y.-X. Liu, J. Papavasssiliou C. D. Roberts, *in progress*

- ✓ Methods used for mesons can be generalised to baryons
- ✓ Yield pointwise form for u(x) & d(x) in proton
  - ✓ $x \simeq 1$: $q_V(x) \propto (1-x)^3$
- ✓ Relative strength 0^+:1^+ determines
  - ✓ shift in location and size of peaks: $d_V(x)$ compared with $u_V(x)$
  - ✓ $d_V(x)/u_V(x)$ on $x \simeq 1$



$\langle\, x\, u_V(x;\zeta_4^2)\, \rangle = 0.32$
$\langle\, x\, d_V(x;\zeta_4^2)\, \rangle = 0.13$
$\langle\, x\, u_V(x;\zeta_4^2) + x\, d_V(x;\zeta_4^2)\, \rangle = 0.45$

Ratio of proton valence-quark PDFs

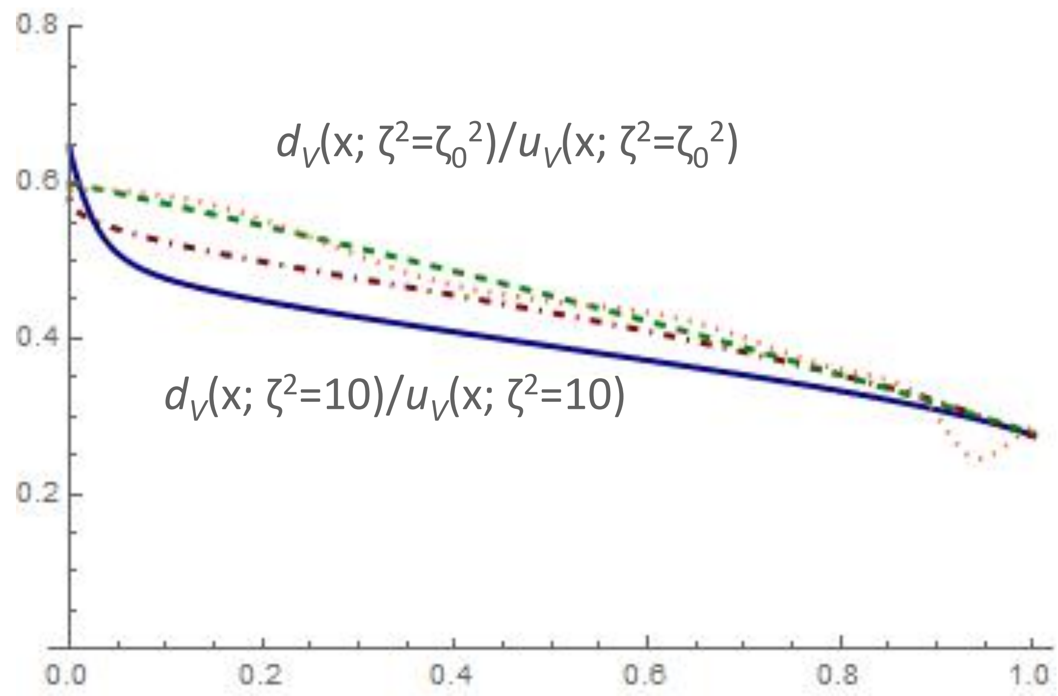
F. Gao, L. Chang, Y.-X. Liu, J. Papavasssiliou C. D. Roberts, *in progress*

- ✓ Value of

  $d_V(x)/u_V(x)|_{x=1}$

  is fixed under DGLAP evolution
- ✓ Without axial-vector diquarks,

  $d_V(x)/u_V(x)|_{x=1} \approx 0$
- ✓ Prediction derived from Faddeev amplitude that produces nucleon PDA
  - ✓ $d_V(x)/u_V(x)|_{x=1} = 0.28$



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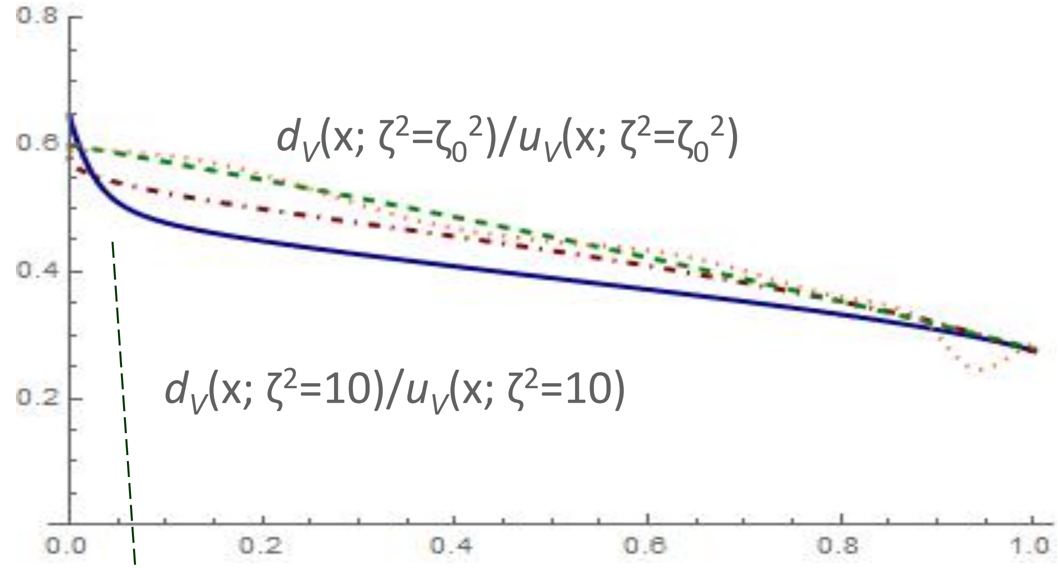
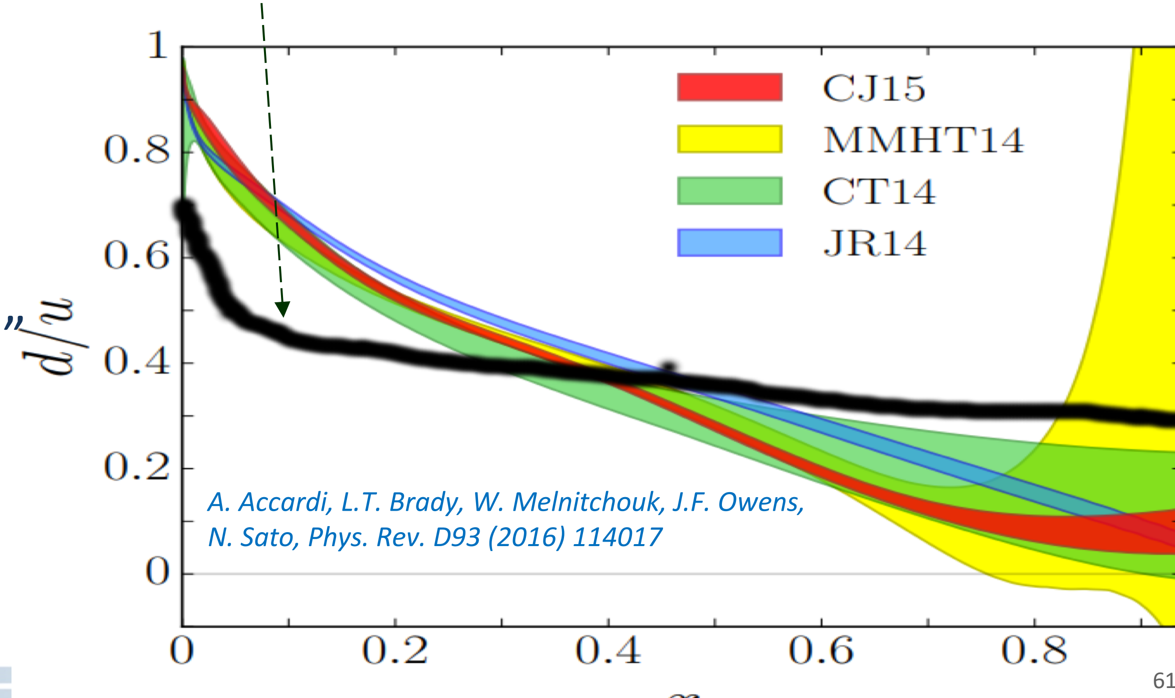
- ✓ Prediction derived from Faddeev amplitude that produces nucleon PDA
  - ✓ $d_V(x)/u_V(x)|_{x=1} = 0.28$
- ✓ Comparison with "modern" PDF parametrisations
- ✓ As learnt from pion PDF, parametrisations can be misleading

F. Gao, L. Chang, Y.-X. Liu, J. Papavasssiliou C. D. Roberts, *in progress*





Epilogue

Epilogue

- Challenge: Explain and Understand
  the Origin and Distribution of the Vast Bulk of Visible Mass
- Current Paradigm: Quantum Chromodynamics
- QCD is plausibly a mathematically well-defined quantum field theory,
  The only one we've ever produced
  - Consequently, it is a worthwhile paradigm for developing Beyond-SM theories
- Challenge is to reveal the content of strong-QCD
- Continuum strong-QCD
  - Past 20 years have seen vast improvement in understanding and spread in diversity of applications
  - Exist now an array of predictions; ripe for validation
  - Raft of existing and future applications includes
    parton distributions of all types
    spectrum of hadrons, including hybrids/exotics
    elastic and transition form factors of mesons and baryons

Epilogue

- Challenge: Explain and Understand
  the Origin and Distribution of the Vast Bulk of Visible Mass
- Current Paradigm: Quantum Chromodynamics

Electron Ion Collider:
The Next QCD Frontier

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  - Raft of existing and future applications includes
    parton distributions of all types
    spectrum of hadrons, including hybrids/exotics
    elastic and transition form factors of mesons and baryons

Strong Interactions in the Standard Model

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i\,(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij})\,\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

- Only apparent scale in chromodynamics is mass of the quark field
- Quark mass is said to be generated by Higgs boson.
- In connection with everyday matter, that mass is $1/250^{th}$ of the natural (empirical) scale for strong interactions,
  viz. more-than two orders-of-magnitude smaller
- Plainly, the Higgs-generated mass is very far removed from the natural scale for strongly-interacting matter
- *Nuclear physics mass-scale* – 1 GeV – is an *emergent feature of the Standard Model*
  - No amount of staring at $L_{\rm QCD}$ can reveal that scale
- Contrast with quantum electrodynamics, *e.g*. spectrum of hydrogen levels measured in units of m_e, which appears in $L_{\rm QED}$

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} \qquad\qquad \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Whence Mass?

- Classical chromodynamics … non-Abelian local gauge theory
- Remove the current mass … there's no energy scale left
- *No dynamics in a scale-invariant theory*; only kinematics … the theory looks the same at all length-scales … there can be no clumps of anything … *hence bound-states are impossible*.
- *Our Universe can't exist*
- *Higgs boson doesn't solve this problem* …
  - normal matter is constituted from light-quarks &
  - the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce
- *Where did it all begin?*

  … becomes … Where did it all come from?

Trace Anomaly

- Classically, in a scale invariant theory

  the *energy-momentum tensor must be traceless:* $T_{\mu\mu} \equiv 0$

- Classical chromodynamics is meaningless … must be quantised
- Regularisation and renormalisation of (ultraviolet) divergences introduces a mass-scale

  … *dimensional transmutation*: mass-dimensionless quantities become dependent on a mass-scale, ζ

- $\alpha \to \alpha(\zeta)$ in QCD's (massless) Lagrangian density, $\mathcal{L}(m=0)$

  QCD β function

  Under a scale transformation $\zeta \to e^{\sigma}\zeta$, then $\alpha \to \sigma\, \alpha\beta(\alpha)$

  $\mathcal{L} \to \sigma\, \alpha\beta(\alpha)\, d\mathcal{L}/d\alpha$

  $\Rightarrow \partial_\mu \mathcal{D}_\mu = \delta\mathcal{L}/\delta\sigma = \alpha\beta(\alpha)\, d\mathcal{L}/d\alpha = \beta(\alpha)\, \tfrac{1}{4} G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho} =: \Theta_0$

  Trace anomaly

- Straightforward, nonperturbative derivation, without need for diagrammatic analysis …

  Quantisation of renormalisable four-dimensional theory forces nonzero value for trace of energy-momentum tensor

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} \qquad \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Whence?

- Classical chromodynamics … non-Abelian local gauge theory
- Local gauge invariance; but there is no confinement without a mass-scale
  - Three quarks can still be colour-singlet
  - Colour rotations will keep them colour singlets
  - But they need have no proximity to one another
    … proximity is meaningless in a scale-invariant theory
- Whence mass … equivalent to whence a mass-scale … equivalent to whence a confinement scale
- *Understanding the origin of mass in QCD is quite likely inseparable from the task of understanding confinement.*

Existence alone of a scale anomaly answers neither question

Where is the mass?

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

Trace Anomaly

- Knowing that a trace anomaly exists does not deliver a great deal … indicates only that a mass-scale exists
- Can one compute and/or understand the magnitude of that scale?
- One can certainly *measure* the magnitude … consider proton:

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

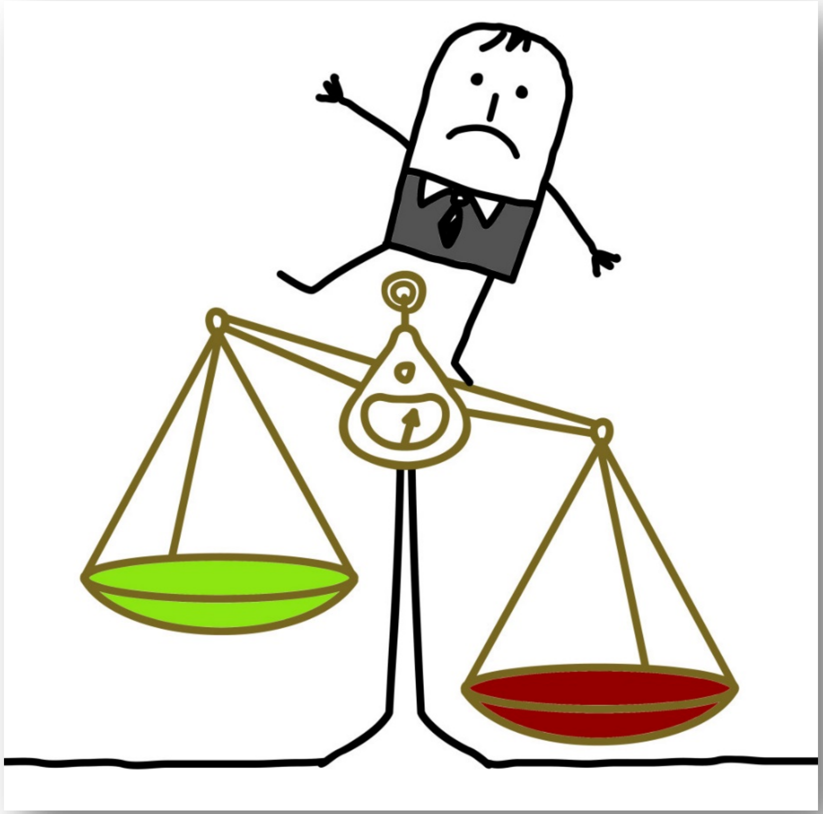
$$\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2$$

$$= \langle p(P)|\Theta_0|p(P)\rangle$$

- In the chiral limit the entirety of the proton's mass is produced by the trace anomaly, Θ_0

  … In QCD, Θ_0 measures the strength of gluon self-interactions

  … so, from one perspective, m_p is completely generated by glue.



On the other hand …

Trace Anomaly

$$T_{\mu\mu} = \frac{1}{4}\beta(\alpha(\zeta))G^a_{\mu\nu}G^a_{\mu\nu}$$

- In the chiral limit

$$\langle\pi(q)|T_{\mu\nu}|\pi(q)\rangle = -q_\mu q_\nu \;\Rightarrow\; \langle\pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- Does this mean that the scale anomaly vanishes trivially in the pion state, *i.e*. gluons contribute nothing to the pion mass?
- Difficult way to obtain "zero"!
- Easier to imagine that "zero" owes to cancellations between different operator contributions to the expectation value of Θ_0.
- Of course, such precise cancellation should not be an accident.

  It could only arise naturally because of some symmetry and/or symmetry-breaking pattern.

Whence "1" and yet "0" ?

$$\langle p(P)|\Theta_0|p(P)\rangle = m_p^2\,, \quad \langle \pi(q)|\Theta_0|\pi(q)\rangle = 0$$

- *No statement of the question*

  "Whence the proton's mass?"

  is complete without the additional clause

  "Whence the **absence** *of a pion mass?"*

- Natural visible-matter mass-scale must emerge simultaneously with apparent preservation of scale invariance in related systems
  - Expectation value of Θ_0 in pion is always zero, irrespective of the size of the natural mass-scale for strong interactions = m_p