The Mass at the Heart of Matter

Craig Roberts

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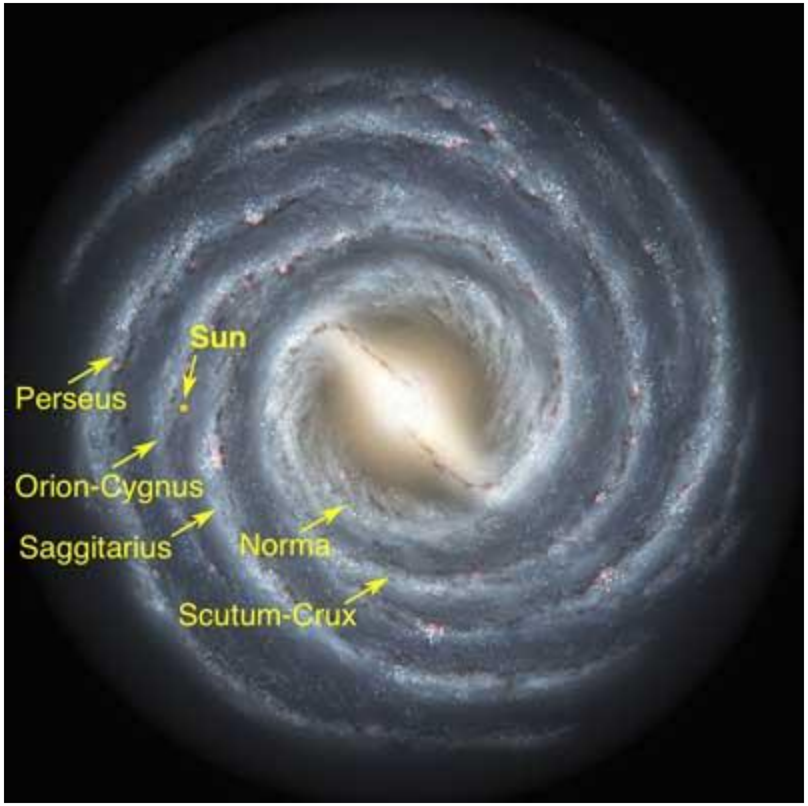
Emergent Phenomena in the Standard Model

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

Strong Interactions in the Standard Model

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

- 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 1/250th 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_{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_{QED}

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

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, L(m=0)

  QCD β function

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

  $L \to \sigma\, \alpha\beta(\alpha)\, dL/d\alpha$

  Trace anomaly

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

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

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

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

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.*

Where is the mass?

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

Trace Anomaly

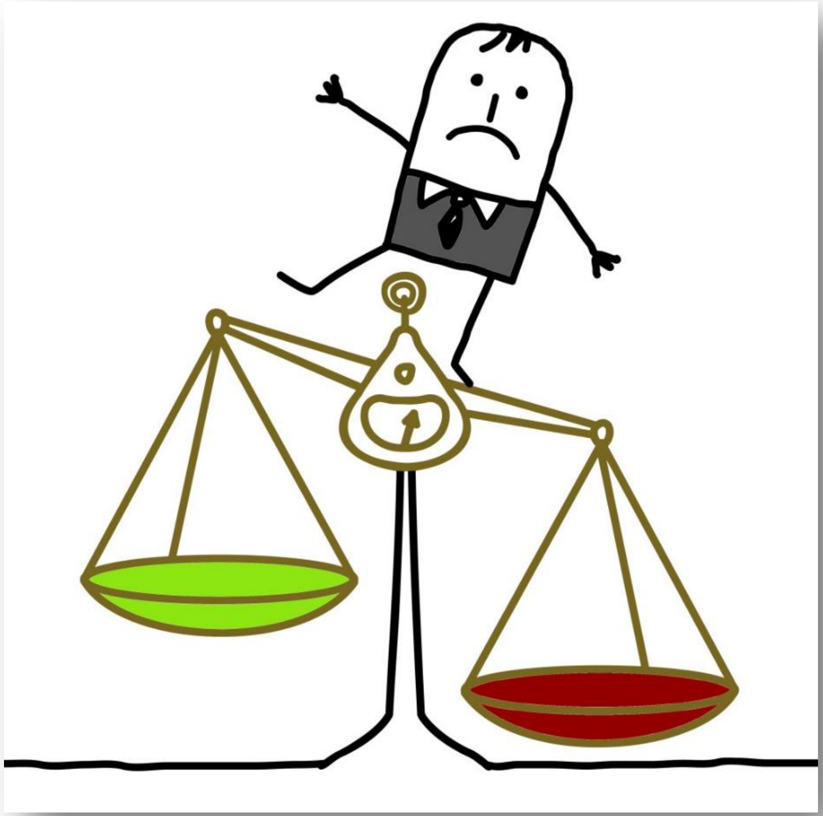
- Knowing that a trace anomaly exists does not deliver a great deal
  … Indicates only that a mass-scale must exist
- Can one compute and/or understand the magnitude of that scale?
- One can certainly *measure* the magnitude … consider proton:

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

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

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

- 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 …

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

Trace Anomaly

- 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

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.

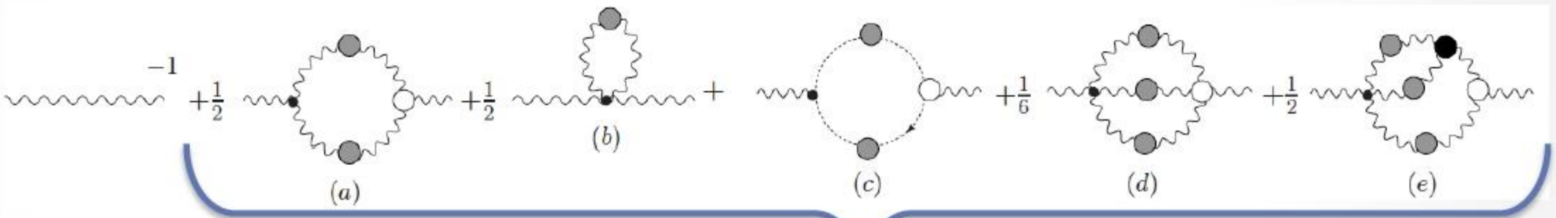
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

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.)

Pinch Technique: Theory and Applications
Daniele Binosi & Joannis Papavassiliou
Phys. Rept. 479 (2009) 1-152

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



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

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

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

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

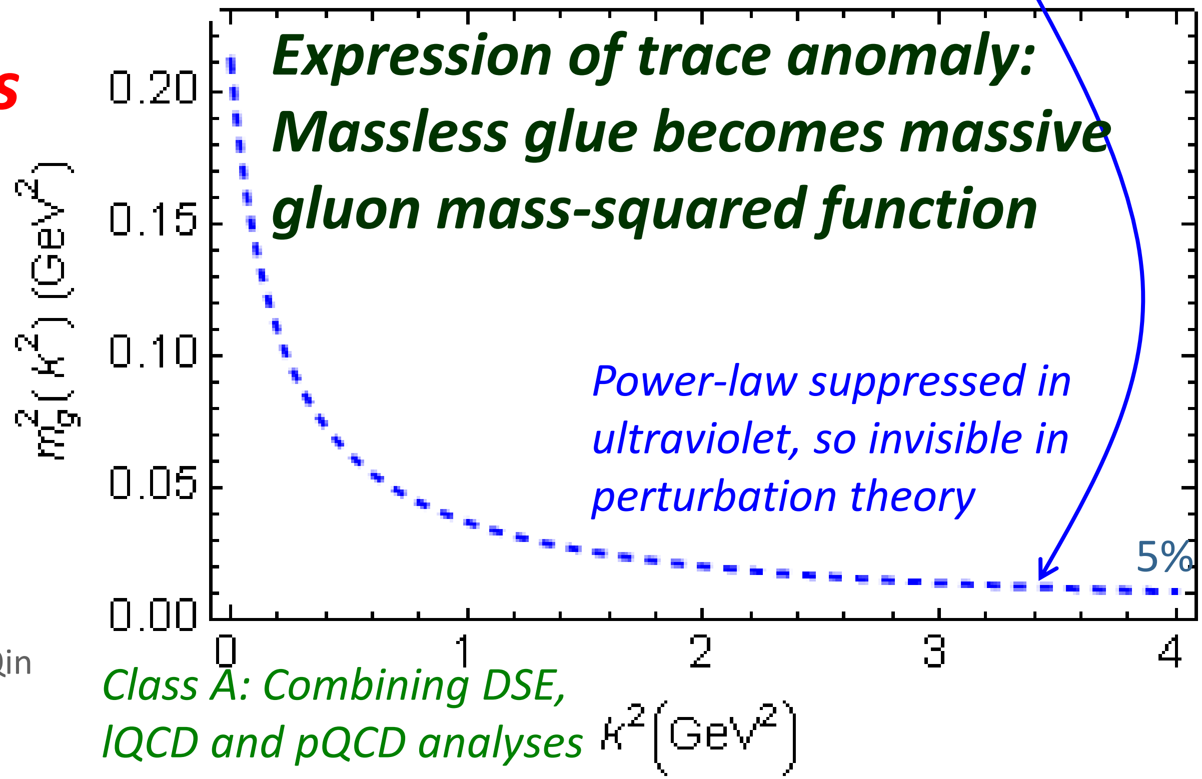
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

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

- 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]

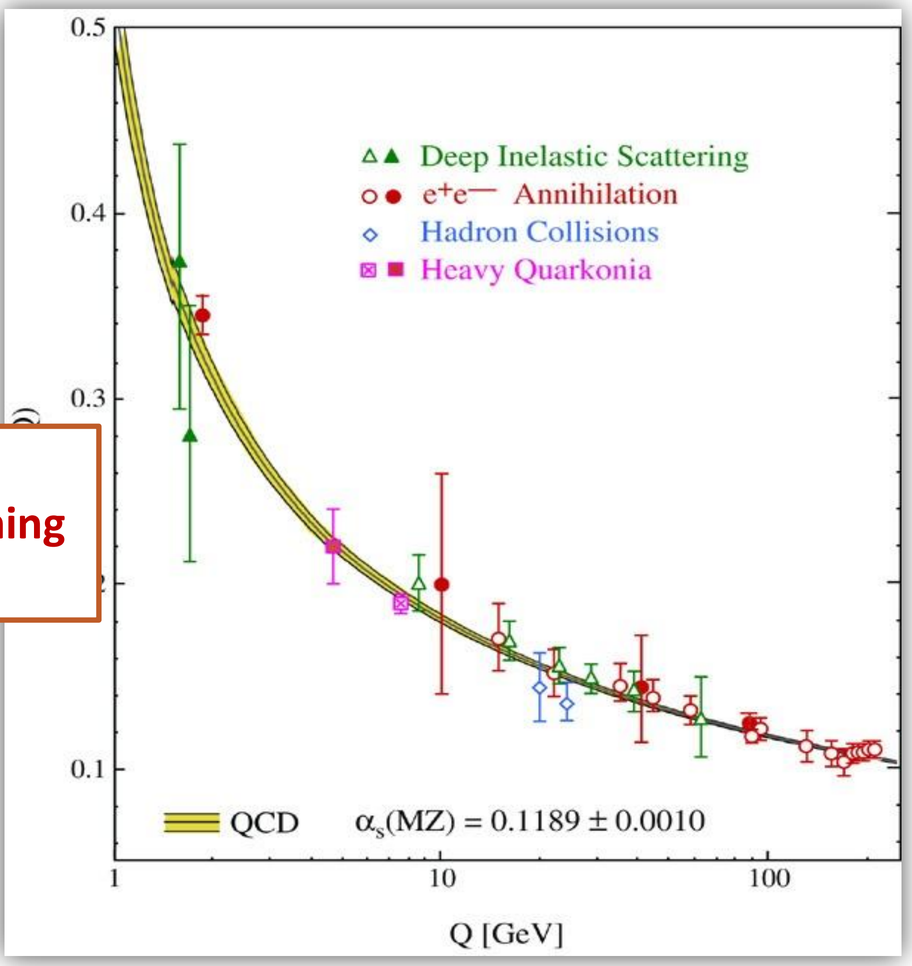
Massive Gauge Bosons!

- 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

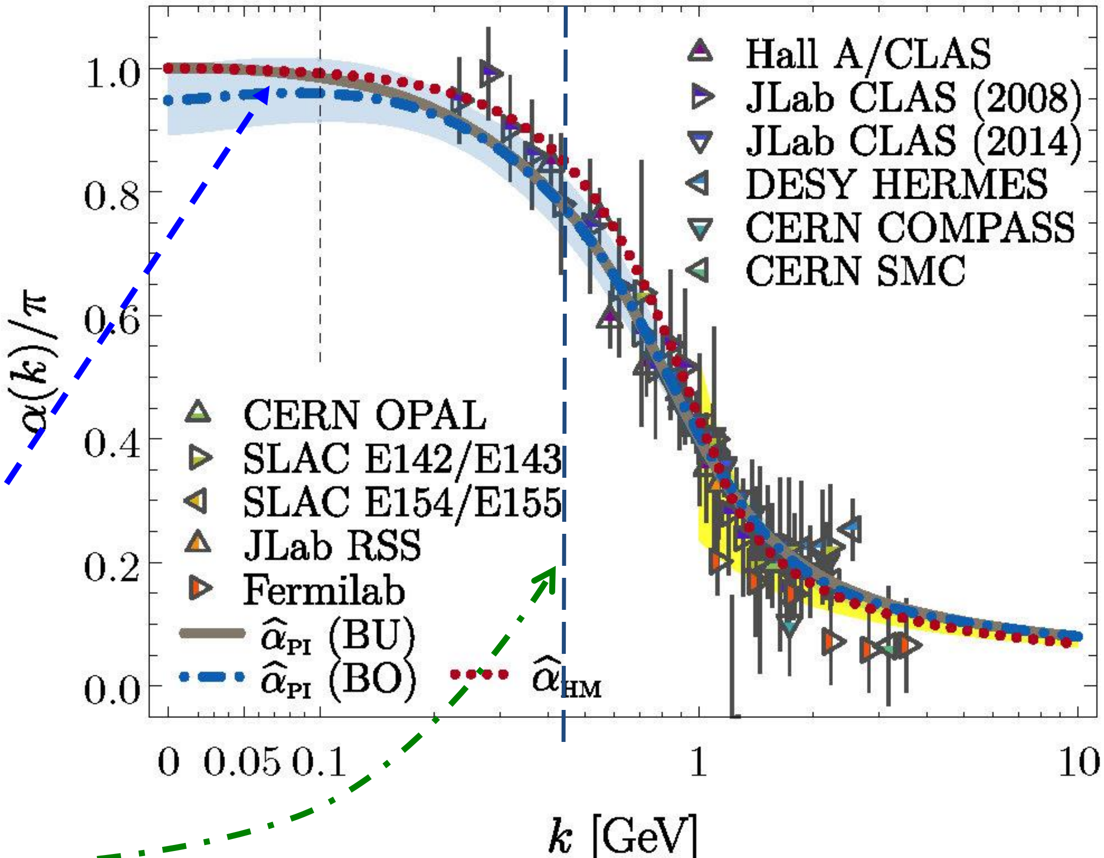


⇐
What's happening out here?!

QCD's Running Coupling

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

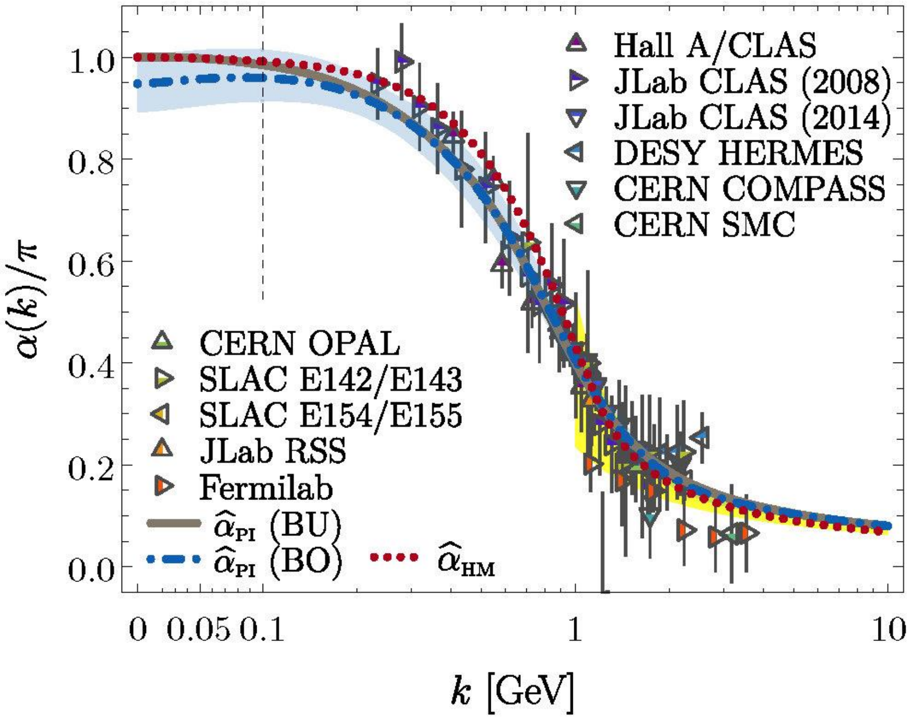
  $\hat{\alpha}_{PI}$ and α_{g1}
  & $\hat{\alpha}_{PI} \approx \alpha_{HM}$

- Perturbative domain:

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

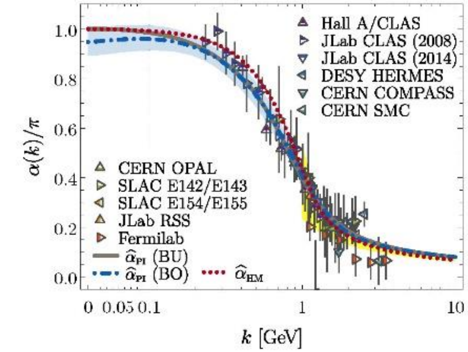
difference = (1/20) $\alpha_{\overline{MS}}^2$

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



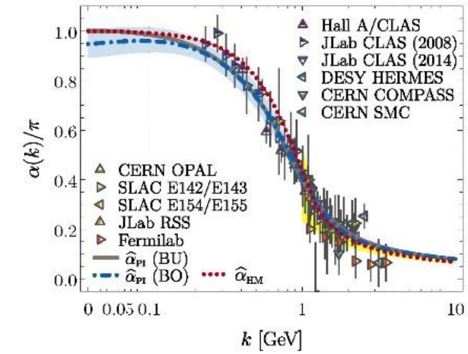
Data = process dependent effective charge [Grunberg:1982fw]:
α_{g1}, defined via Bjorken Sum Rule

QCD Effective Charge



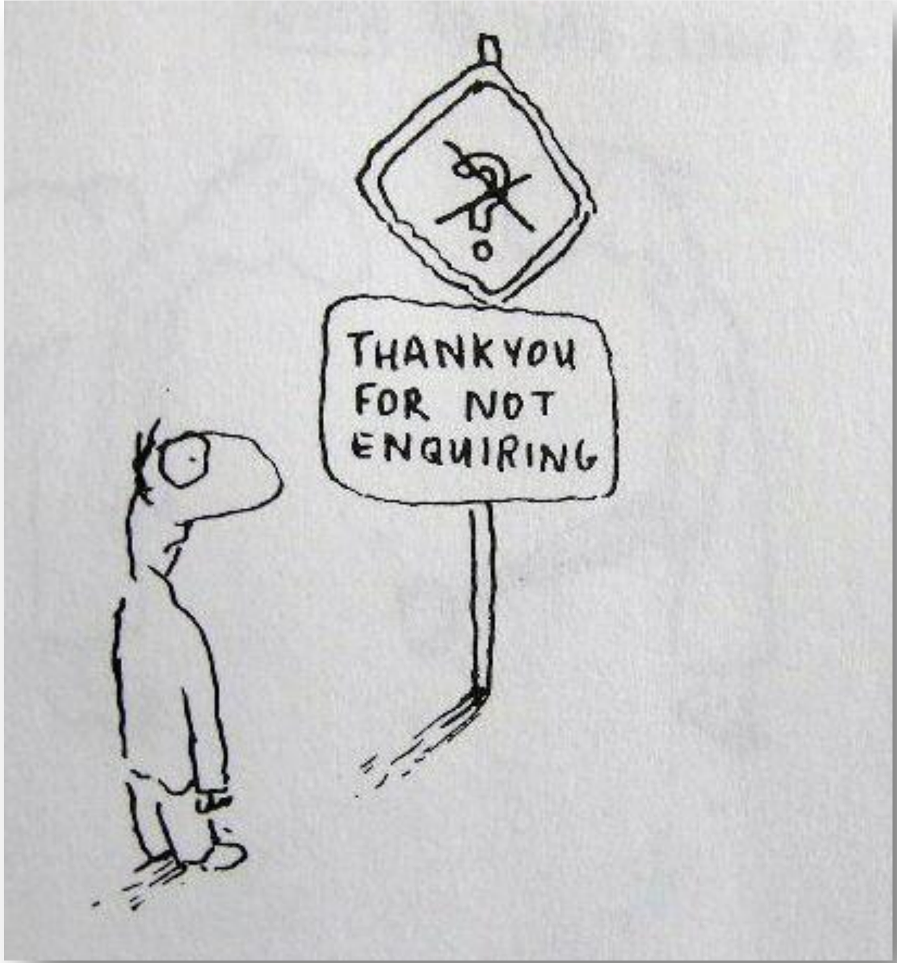
- $\hat{\alpha}_{PI}$ is a new type of effective charge
  - direct analogue of the Gell-Mann–Low effective coupling in QED, *i.e*. completely determined by the gauge-boson two-point function.
- $\hat{\alpha}_{PI}$ is
  - process-independent
  - appears in every one of QCD's dynamical equations of motion
  - 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 … tion.
- $\hat{\alpha}_{PI}$ is
  - pro…
  - app…
  - know…
- $\hat{\alpha}_{PI}$ posse…
  - Nonp… n QCD
- QCD is IR … of gluon mass-scale, which als… …inate 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



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 $S(p) = \dfrac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$

- 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.

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

Whence "0" ?

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

Whence "0" ?

The answer is algebraic

*Munczek, H. J., Phys. Rev. D **52** (1995) pp. 4736-4740*
*Bender, A., Roberts, C.D. and von Smekal, L., Phys. Lett. B **380** (1996) pp. 7-12*
*Maris, P. , Roberts, C.D. and Tandy, P.C., Phys. Lett. B **420** (1998) pp. 267-273*
*Binosi, Chang, Papavassiliou, Qin, Roberts, Phys. Rev. D **93** (2016) 096010/1-7*

Pion masslessness

- Obtain a coupled set of gap- and Bethe-Salpeter equations

Quantum field theory statement:
In the pseudsocalar channel, the dynamically generated mass of the two fermions is precisely cancelled by the attractive interactions between them – iff –

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

- Cancellation guarantees that

$$\Rightarrow 2 M_q + U_g \equiv 0$$

...at $P^2=0$ ...

- Interacting, bound system remains massless

Observing *Mass*

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

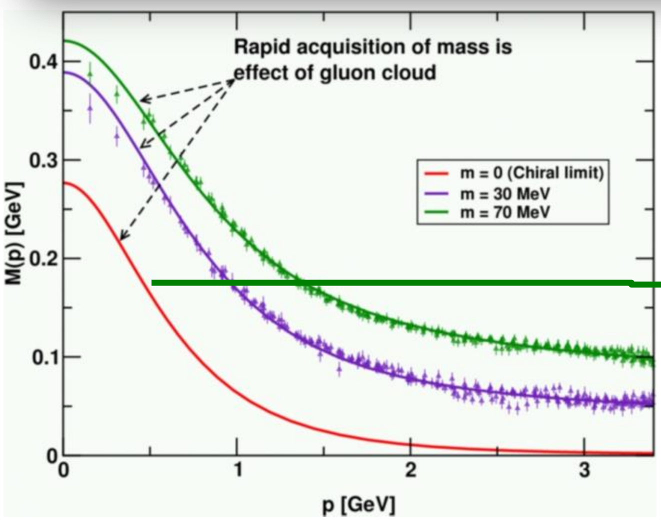
$$\varphi_\pi(x) \propto x^\alpha (1-x)^\alpha, \text{ with } \alpha \approx 0.5$$

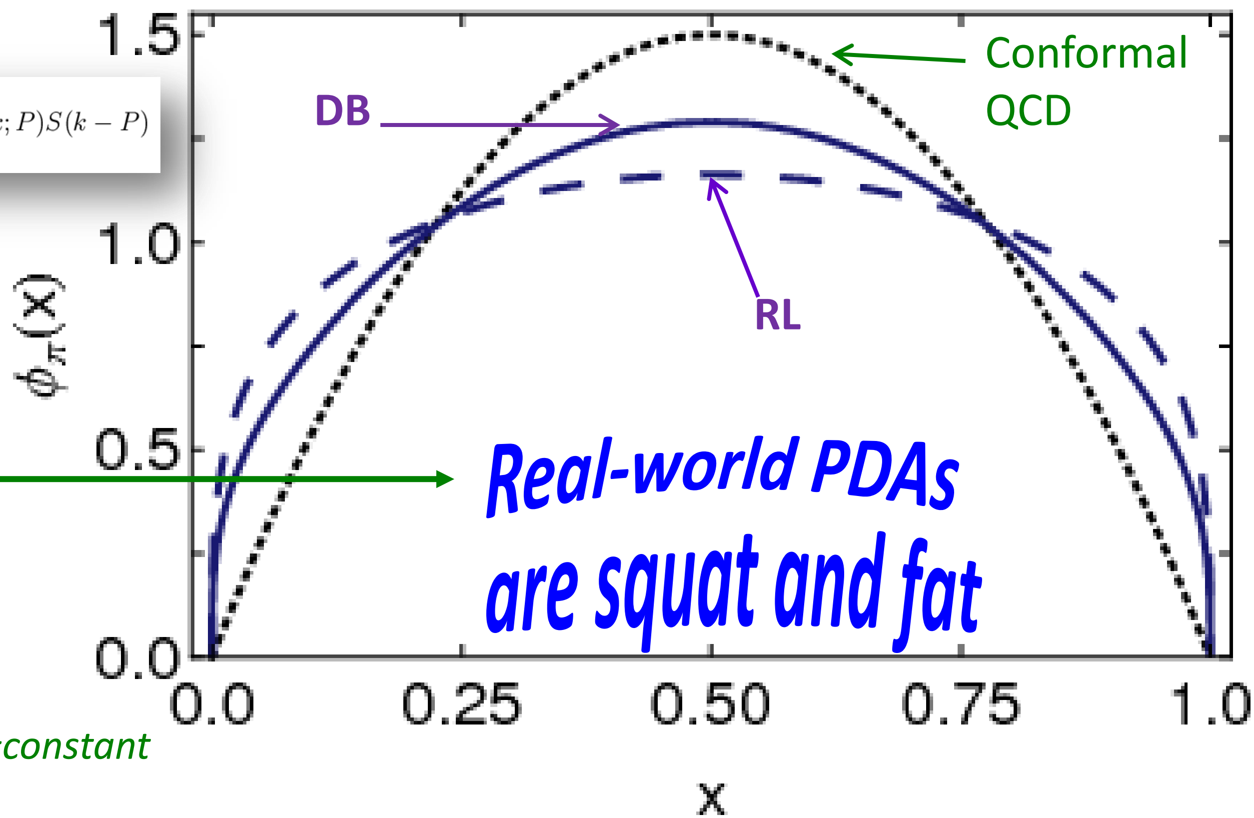
Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, *et al.*, arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

- Continuum 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

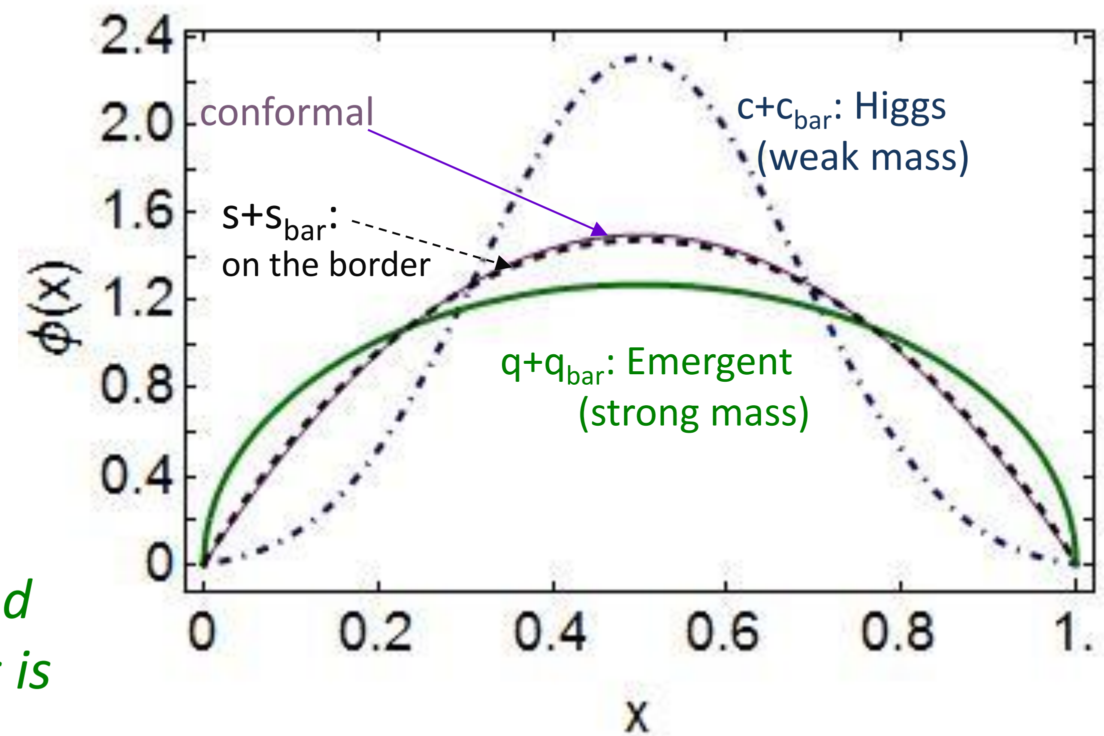
Leading-twist PDAs of *S*-wave light-quark mesons

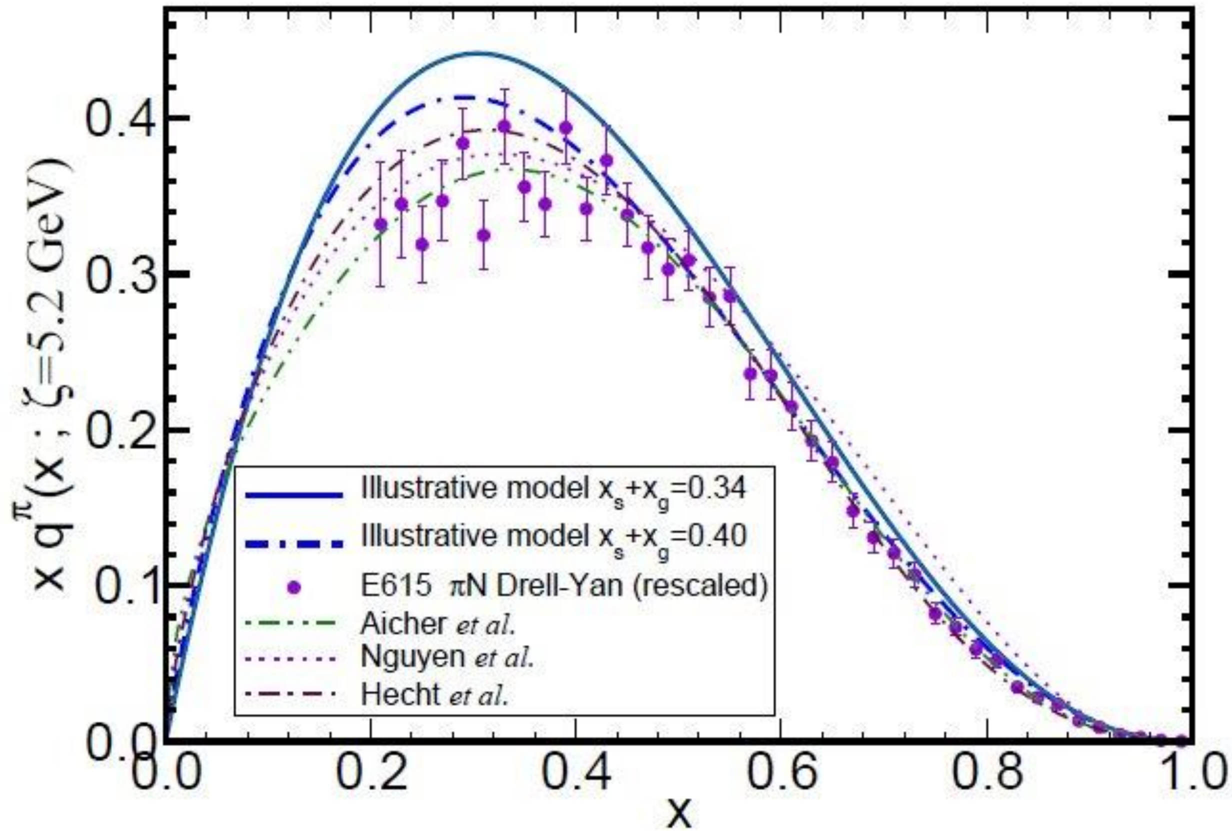
- End of a <u>*long*</u> story (longer than 30 years war)
- Continuum predictions that pion and kaon PDAs are broad, concave functions confirmed by simulations of lattice-regularised QCD
  - *Pion Distribution Amplitude from Lattice QCD*, Jian-Hui Zhang *et al.*, Phys.Rev. D95 (2017) 094514; 1702.00008
  - *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.* Phys. Rev. D**97** (2018) 094014; 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
- ***Many empirically verifiable predictions***

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*





π & K Valence-quark Distribution Functions

π & K PDFs

- Extant data on π & K PDFs (mesonic Drell-Yan) is old: 1980-1989
- New 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
  - Similar technique *should* also serve for the kaon.
- Future:
  - new mesonic Drell-Yan measurements at modern facilities could yield valuable information on π and K PDFs (COMPASS),
  - 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

Basic features of the pion valence-quark distribution function,
Lei Chang, Cédric Mezrag, et al.,
arXiv:1406:5450 [nucl-th], Phys. Lett. B **737** (2014) pp. 23–29

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

Valence-quark PDFs within mesons

- Compute PDFs from imaginary part of virtual-photon – pion forward Compton scattering amplitude:

  $\gamma\, \pi \rightarrow \gamma\, \pi$

- Handbag diagram is insufficient. Doesn't even preserve global symmetries. Exists a class of leading-twist corrections that remedies this defect ⇒

Projection onto light-front

$$u_V^\pi(x) = N_c \mathrm{tr} \int_{dk} \delta_n^x(k_\eta^\pi)$$

Partial derivative wrt relative momentum

$$\times\, \partial_{k_\eta^\pi} \left[\Gamma_\pi(k_\eta^\pi, -P_\pi) S(k_\eta^\pi)\right] \Gamma_\pi(k_{\bar\eta}^\pi, P_\pi)\, S(k_{\bar\eta}^\pi)\,,$$

Similar expressions for $u_V^K(x)$, $s_V^K(x)$

Measurable quantities
Directly related to
dynamically generated quark masses
& bound-state wave functions

Basic features of the pion valence-quark distribution function,
Lei Chang, Cédric Mezrag, et al.,
arXiv:1406:5450 [nucl-th], Phys. Lett. B **737** (2014) pp. 23–29

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

Valence-quark PDFs within mesons

- Formulae guarantee that valence-quark PDFs satisfy, independent of any and all structural details:

$$\langle x \rangle_u^0 = \int_0^1 dx\, x\, u_V^0(x) = \frac{1}{2}$$

$$\int_0^1 dx\, x [u_V^K(x) + \bar{s}_V^K(x)] = 1$$

- Algebraic proof that at an hadronic scale $\zeta \approx 0.5$ GeV

  $q_V^M(x \simeq 1) \propto (1-x)^{2n}$

  in any theory with $(1/k^2)^n$ vector-boson exchange interaction

Pion PDF

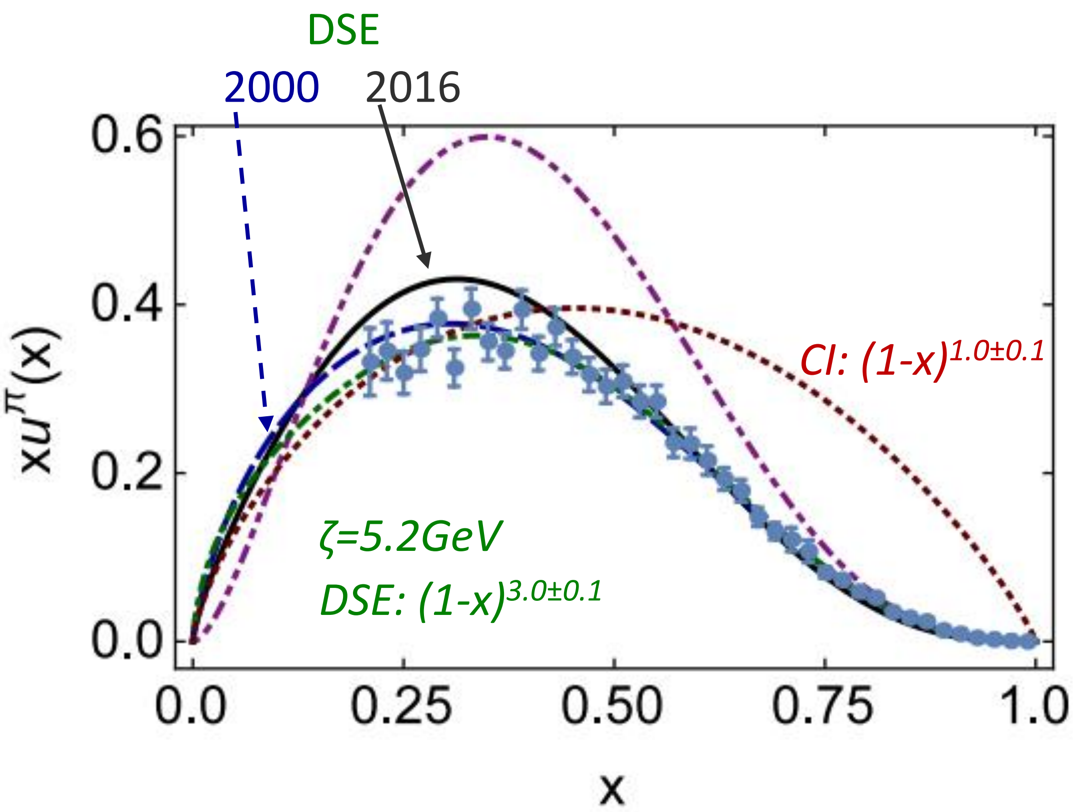


FIG. 3. $xu^{\pi}(x;\zeta_{5.2})$. Solid (black) curve, our prediction, expressed in Eqs. (32), (33); dot-dot-dashed (purple) curve, result obtained when sea-quark and gluon contributions are neglected at ζ_H, *i.e.* using $u_V^{\pi}(x)$ from Eqs. (14), (17); dashed (blue) curve first DSE prediction [38]; and data, Ref. [4], rescaled according to the reanalysis described in Ref. [40], from which the dot-dashed (green) curve is drawn. The dotted (red) curve is the result obtained using a Poincaré-covariant regularisation of a contact interaction, Eq. (36).

- Purple dot-dot-dash = prediction at ζ_H
- Data = modern reappraisal of E615: NLO analysis plus soft-gluon resummation (ASV)
- Solid black curve, prediction evolved to ζ=5.2GeV, the scale associated with the experiments
- Blue dashed curve = first DSE prediction, in 2000 (ζ=5.2GeV)
- Dotted red curve = result obtained with momentum-independent gluon exchange (contact interaction, ζ=5.2GeV)

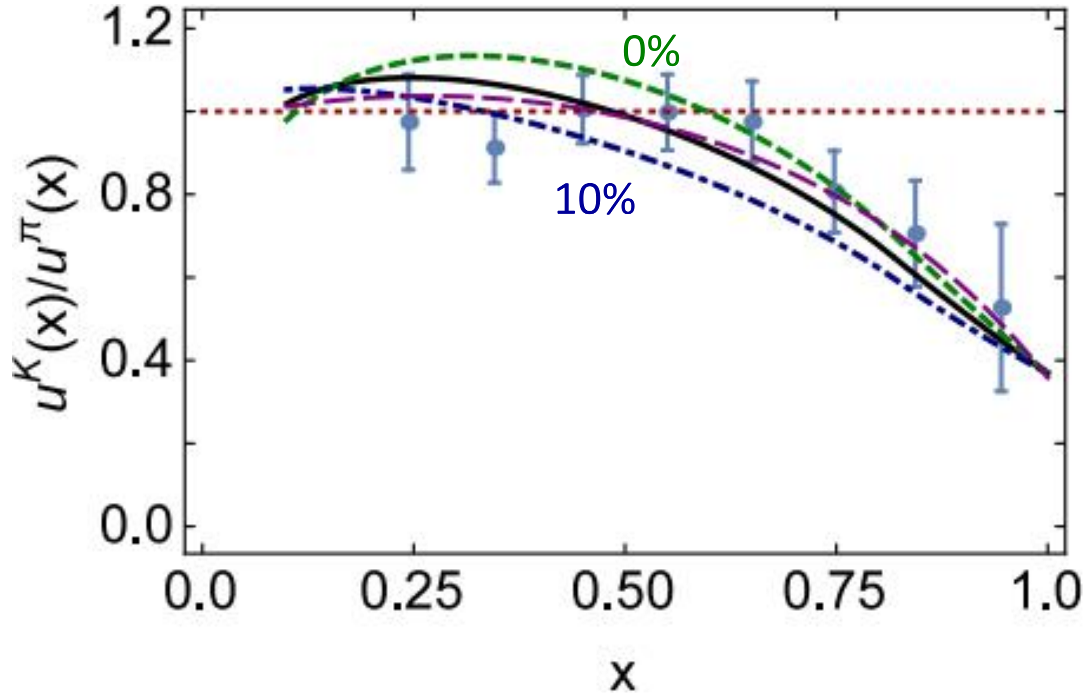
Kaon's gluon content

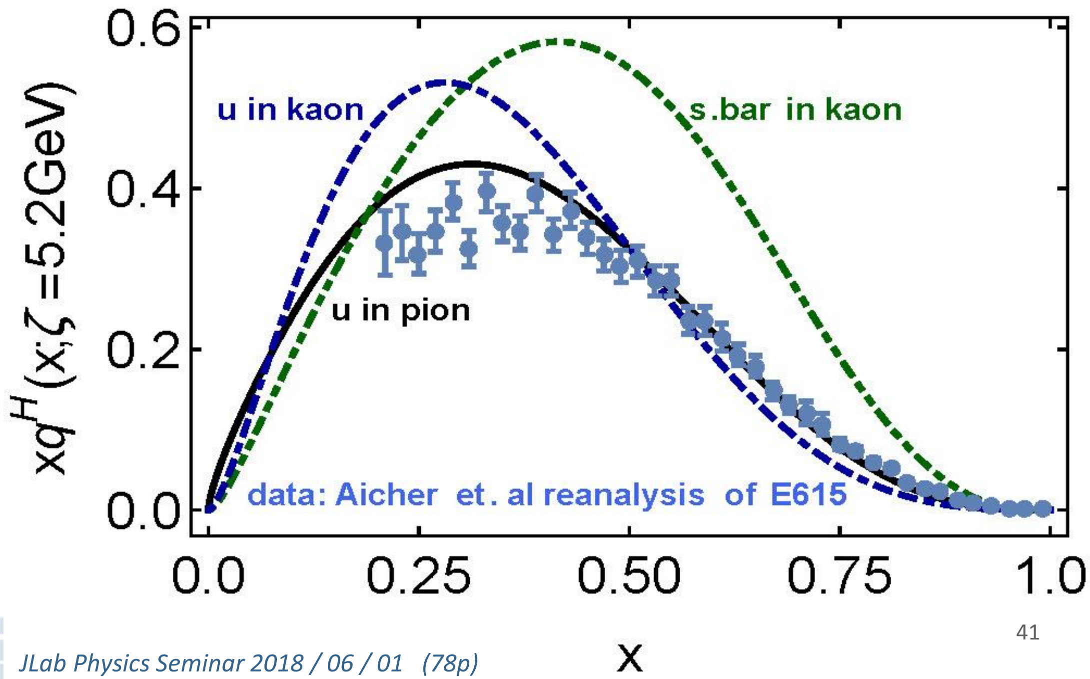
- $\langle x\rangle_g^K(\zeta_H) = 0.05 \pm 0.05$
  $\Rightarrow$ Valence quarks carry 95% of kaon's momentum at ζ_H
- DGLAP-evolved to ζ_2

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 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

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

K/π valence-quark quasidistributions

- $u_V^K(x)/u_V^\pi(x)$ serves as sensitive probe of difference between gluon distributions in π & K
- This difference can reveal much about emergence of mass in Standard Model
- Experimental data [Badier:1980jq]
  - One measurement is insufficient for complete confidence
- Can PqDFs contribute?
  - On $P_z \geq 1.75$ GeV
    Ratio of PqDFs is quantitatively a good approximation to the objective ratio on $0.4 < x < 0.8$
- This domain ~covers that upon which empirical data is available.

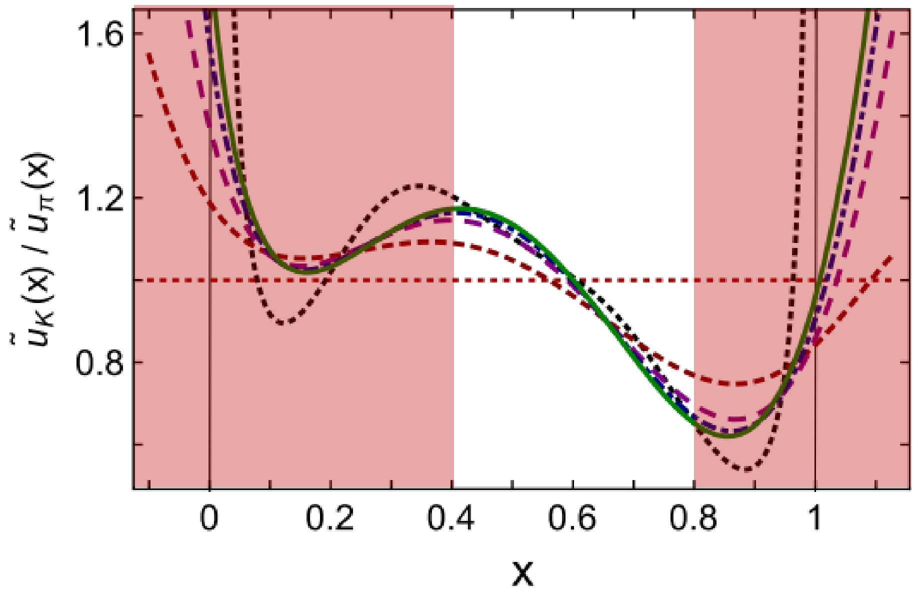


FIG. 8. x-dependence of the PqDF ratio $\tilde{u}_K/\tilde{u}_\pi$ at the hadronic scale, ζ_H, computed with $P_z/\text{GeV} = 1$ (short-dashed, red), 1.75 (dashed, purple), 2.4 (dot-dashed, blue), and 3.0 (solid, green). The dotted (black) curve is the associated objective ratio, u_K/u_π, obtained using the dotted (black) curves in Fig. 6. [The dotted (red) line is drawn at unity, and the thin vertical lines at $x = 0, 1$ highlight the boundaries of support for a physical valence-quark PDF.]

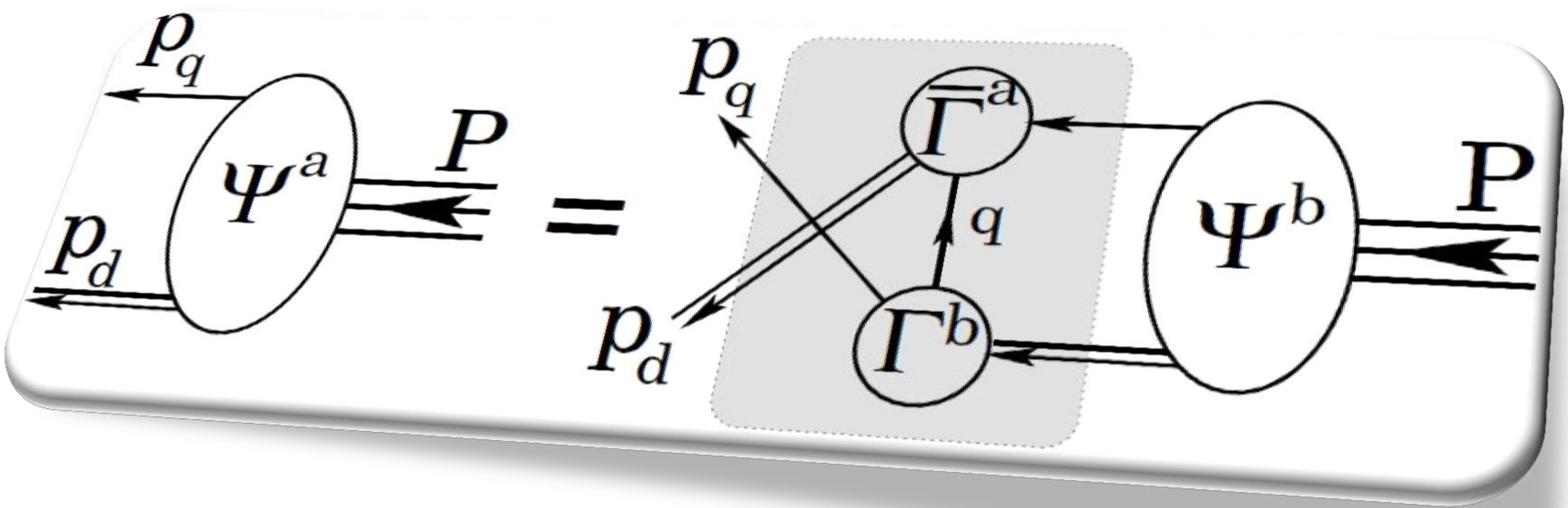
lQCD simulations could potentially provide sound prediction for this ratio before next generation experiments are completed

π & *K* PDFs

- The character of Nambu-Goldstone modes in the Standard Model is far more interesting than usually thought
  - 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



Structure of Baryons

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

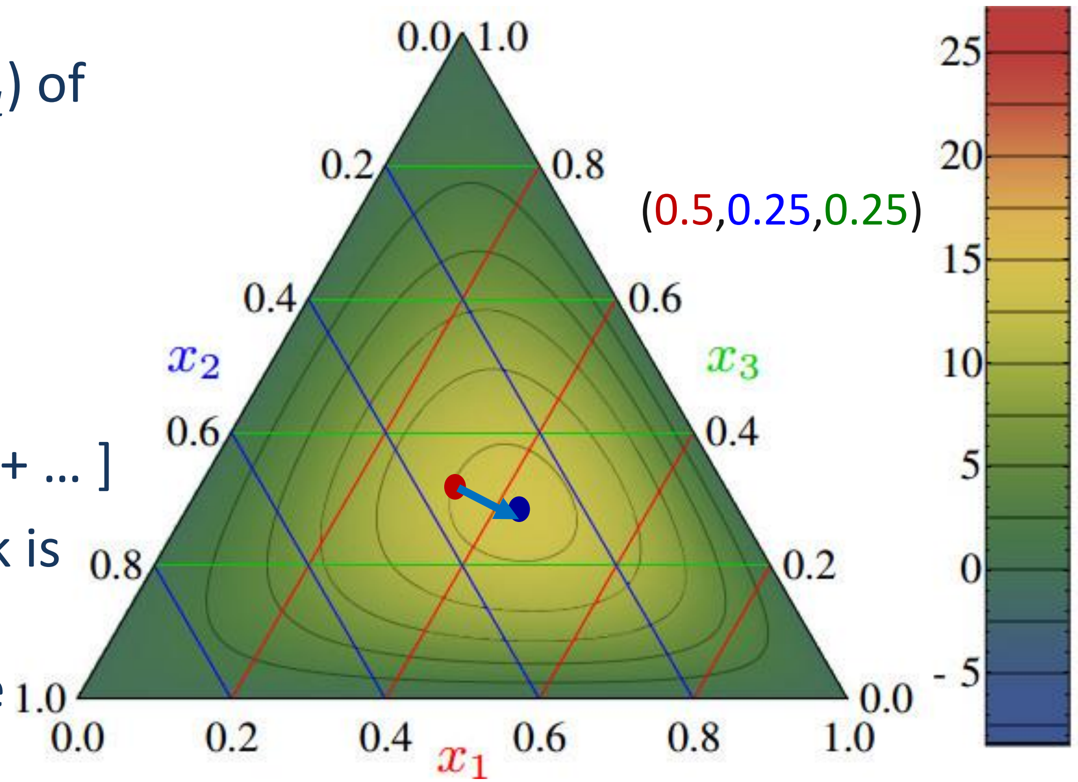
Nucleon PDAs & lQCD

- 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:

$\Phi(x_1,x_2,x_3)$

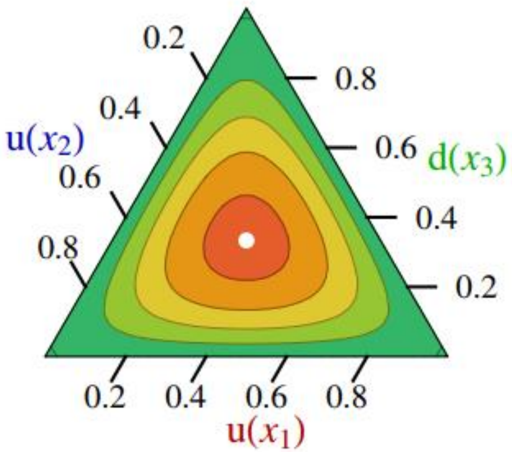
$= 120\, x_1\, x_2\, x_3\, [\, 1 + a_{11}\, P_{11}(x_1,x_2,x_3) + \dots\,]$

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

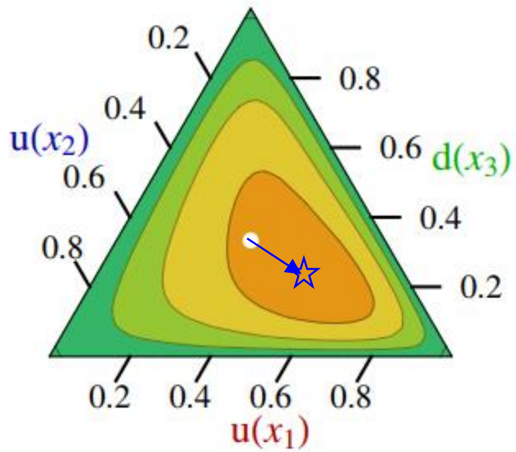


PDAs of Nucleon & its 1st Radial Excitation

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



conformal



nucleon

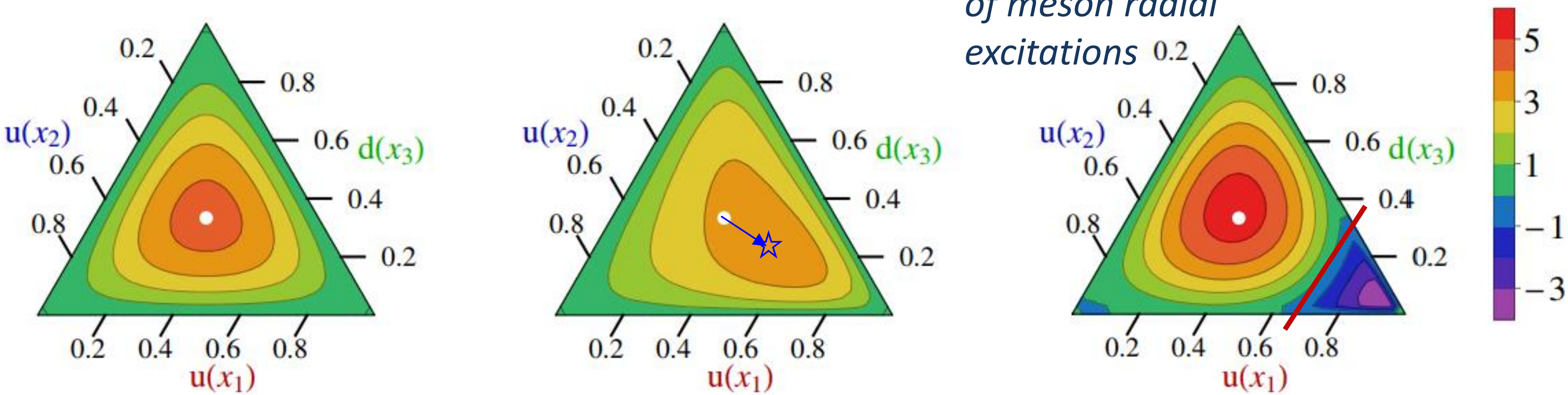
Diquark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton's light-front momentum

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

Just like QM & PDAs of meson radial excitations



conformal

nucleon

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

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 "$\not{D}$ 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 $\not{D}$ 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 $\not{D}$ 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

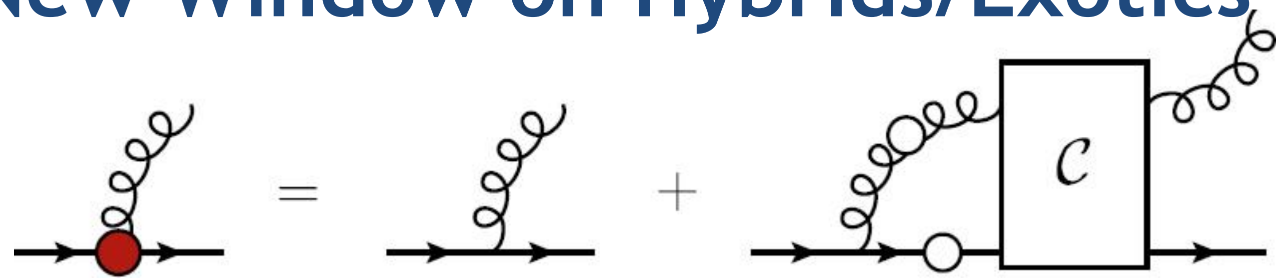
    both scalar & axial-vector diquark correlations in the nucleon
    - scalar generates around 60% of the proton's normalisation.
- The radial-excitation (Roper) is constituted similarly
  - Pointwise form of its PDA
    - Negative on a material domain
  - Is result of marked interferences between the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

Hybrids & Exotics

New Perspective on Hybrid Mesons
Shu-Sheng Xu, *et al.*
arXiv:1805.06430 [nucl-th]

New Window on Hybrids/Exotics



C = 1PI gluon-quark scattering amplitude

- Question:

  Does QCD support bound-states with valence gluons?

  Exotic/Hybrid meson = g q $\bar{q}$

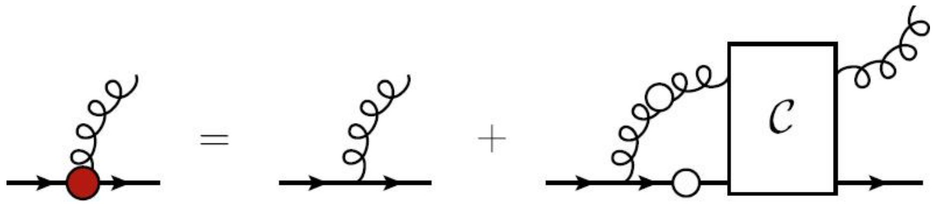
  If so, then distinction is lost between force and matter fields

- Three valence-body problem in quantum field theory:

  Novel formulation based on observation gluon-quark vertex can be represented 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

New Perspective on Hybrid Mesons



- Recall two things …
  - Textbook derivations of the two-body Bethe-Salpeter equation in analyses of two-particle scattering and relationship between the scattering matrix and kernel
  - Role that coloured quark-quark (diquark) correlations play in simplifying the baryon three-body problem
- Then, reinterpretation of gluon-quark vertex suggests that

  gluon-quark [q_g=gq] & degenerate gluon-antiquark [$\bar{q}_g$=g$\bar{q}$]

  correlations play important role in solving 3-body problem for hybrids
- Conjecture: Hybrids = highly-correlated $q_g\bar{q} \leftrightarrow q\bar{q}_g$ bound-states

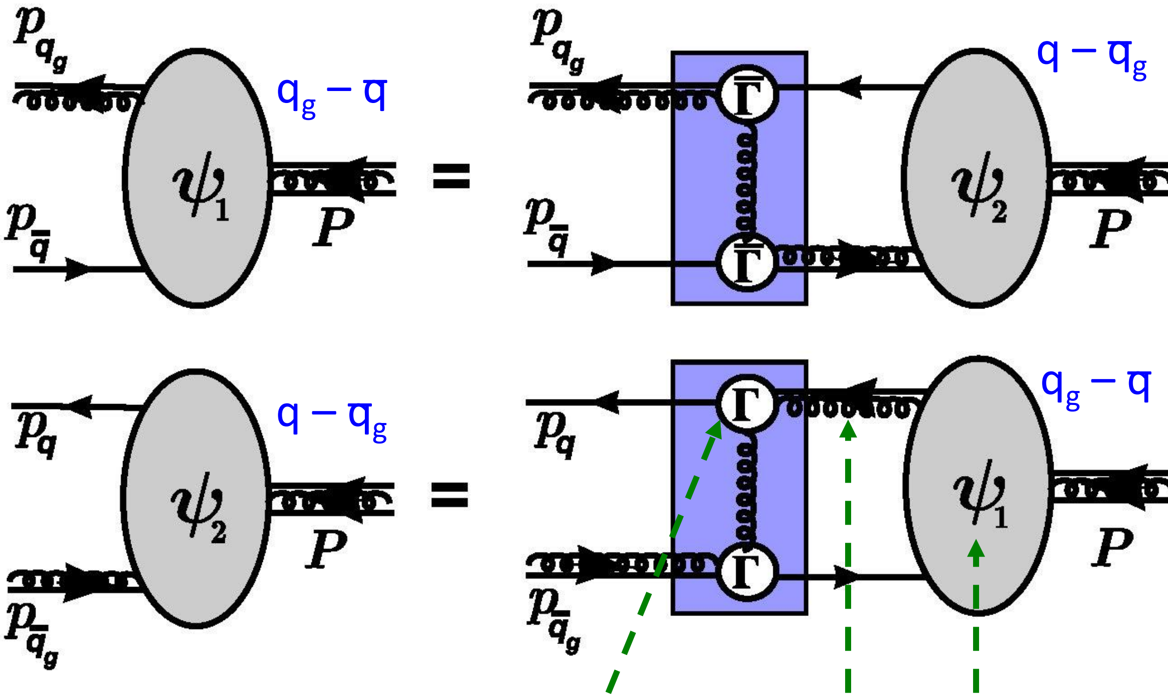
New Perspective on Hybrids

- ***Suppose*** strong q_g and $\bar{q}_g$ correlations exist, then …

  Hybrids mesons explained by:
  - ✓ Coupled-channels Faddeev-like bound-state equation

  $\Psi = \Psi_1 + \Psi_2$,

  $\Psi_1 = q_g\bar{q}$ & $\Psi_2 = q\bar{q}_g$
- Challenges:
  - ✓ Confirm existence of tight gluon-quark correlations
  - ✓ Determine their properties



$\Psi_1 = \Gamma^a_\mu(l;p_{qg})\, S_{gq}(p_{qg})\, \psi_1(p;P)$

gq correlation amplitude

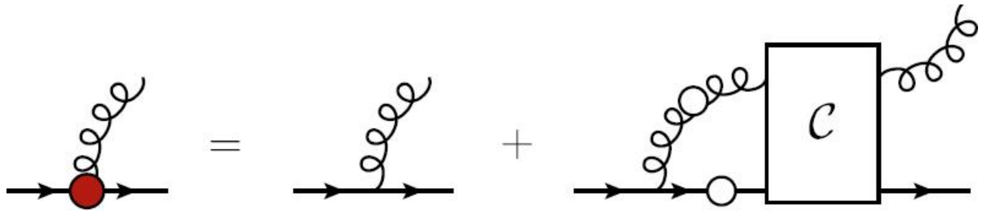
gq correlation propagator

bystander+correlation Faddeev amplitude

Gluon-Quark Correlations

- Adapt logic used to establish existence and properties of diquark correlations:

  Search for a pole solution to a leading-order (rainbow-ladder) truncation of vertex equation



- i.e. for a solution of the following homogeneous Bethe-Salpeter equation, $\Gamma^a_\mu = t^a\Gamma_\mu$, $k=p-\ell$:

$$t^a\Gamma_\mu(p;Q)\Lambda_+ = -\int_{d\ell} \mathcal{G}(k^2)t^b\gamma_\rho S(\ell_+) \times t^c\Gamma_\lambda(\ell;Q)D_{\lambda\tau}(\bar{\ell}_-) f_{3g}(k^2)\, {}_0V^{bca}_{\rho\tau\mu}(k,\bar{\ell}_-,\bar{p}_-)\Lambda_+$$

valence quark

bare 3-gluon vertex

valence gluon

3g vertex dressing factor

continuum & lattice: 3g vertex greatly suppressed on $k^2<1$ GeV^2

Gluon-Quark Correlations

- Any kernel that provides good description of π- and ρ-meson properties (masses, decay constants, etc.):
  - Generates quark+quark correlations in all possible J^{PC} channels
    - Diquarks play crucial role in determining structure and interactions of baryons
  - Generates gluon+quark correlations
    - Dressed valence gluon and valence quark both have running masses, large in infrared
      - $M_g^{IR} \approx \frac{1}{2}\, m_{proton}$
      - $M_q^{IR} \approx \frac{1}{3}\, m_{proton}$
    - $Mass_{(g+q)} \approx m_{proton} \approx 1$ GeV

Hybrid Meson Spectrum

	0^{-+}	1^{-+}	1^{--}	0^{+-}	0^{--}
RL direct	1.28(9)	1.80(4)	1.64(10)	1.73(13)	1.74(3)
ACM improved	1.62(6)	1.75(8)	1.86(10)	1.87(14)	1.90(3)
lQCD_R - 16^3	1.72(2)	1.73(2)	1.84(2)	2.03(1)	
lQCD_R - 20^3	1.69(2)	1.72(2)	1.77(6)	1.99(2)	
lQCD - 16^3	2.14(1)	2.15(2)	2.26(2)	2.45(1)	
lQCD - 20^3	2.12(2)	2.16(2)	2.21(6)	2.43(2)	

lQCD. Rows 5, 6: $m_\pi > 0.4$ GeV … Dudek *et al.*: arXiv:1004.4930 [hep-ph]

These simulations overestimate mass of pion's first radial excitation by $\delta_{\pi 1} = 0.43$ GeV

lQCD. Rows 3, 4: = Rows 5, 6 – $\delta_{\pi 1}$

Hybrid Meson Spectrum

	0^{-+}	1^{-+}	1^{--}	0^{+-}	0^{--}
RL direct	1.28(9)	1.80(4)	1.64(10)	1.73(13)	1.74(3)
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lQCD - 20^3	2.12(2)	2.16(2)	2.21(6)	2.43(2)	

Faddeev Equation with [gq] correlations

- ✓ Bound-states exist in all channels
- ✓ Notably: 0^{-+} & 1^{--} hybrids are structurally distinct from those accessible using the 2-body Bethe-Salpeter equation in these channels, as in all such previous studies

However, in comparison with lQCD predictions:

- ❖ All states too light, especially 0^{-+}, and 1^{-+}-1^{--} ordering is reversed.
- ❖ Wide variations of model parameters do not alter this outcome.

Hitherto, such problems typical of continuum studies

Hybrid Meson Spectrum

- Mismatch between RL-direct (Row 1) and lQCD results
  - Reconsider each element in our formulation of hybrid meson problem
- Analyses of improvements to RL truncation indicate origin:
  - [gq] correlation amplitude was computed in RL truncation
  - RL truncation underestimates DCSB in bound-state amplitudes
- Consequently, anomalous chromomagnetic moment (ACM) associated with this correlation is underestimated
  - ACM enhancement essential to explain, *e.g*. $a_1 - \rho$ splitting
- Introduce correction factor
  - Multiplication of ACM term in [gq] correlation by constant, κ_{gq}
- *Ask question: Can any value of κ_{gq} yield match with lQCD?*

Hybrid Meson Spectrum

	0^{-+}	1^{-+}	1^{--}	0^{+-}	0^{--}
RL direct	1.28(9)	1.80(4)	1.64(10)	1.73(13)	1.74(3)
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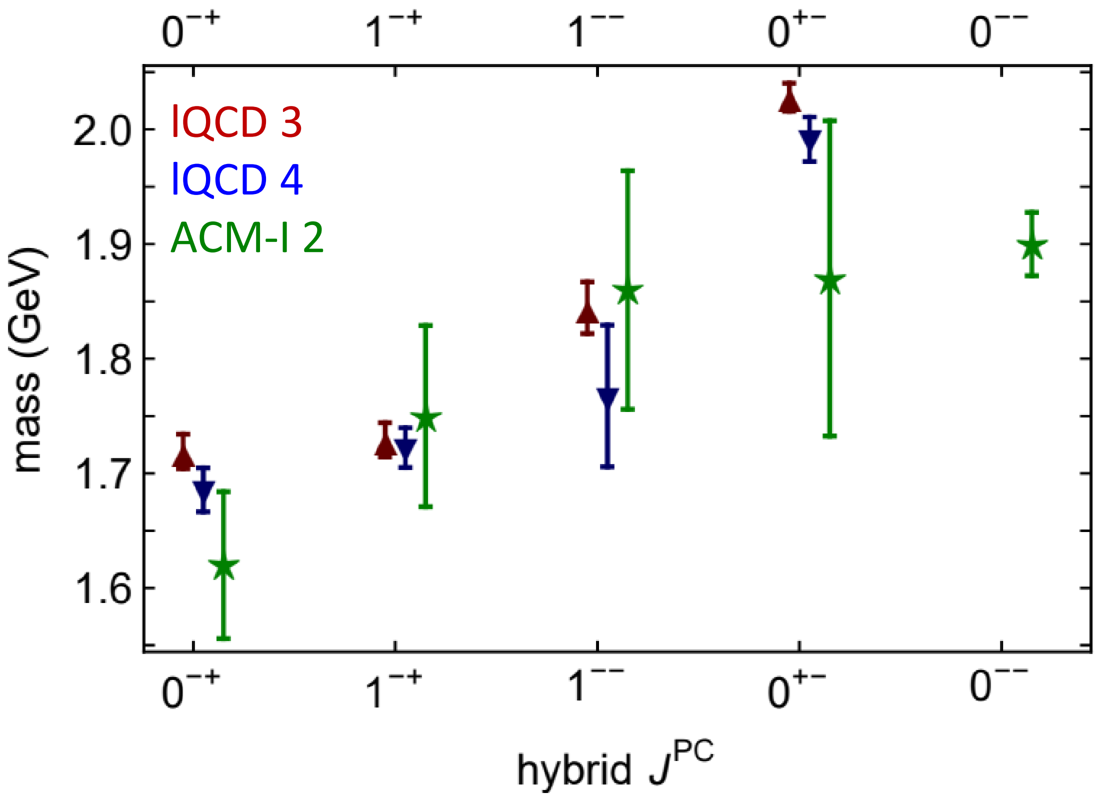
lQCD - 20^3	2.12(2)	2.16(2)	2.21(6)	2.43(2)	

- ***YES***: κ_{gq} … RL = 1 → 2.4 = ACM
  - Magnification typical of result obtained with DCSB-improved kernels
- ACM-improved calculations in Row 2:
  - Level ordering identical to lQCD (3, 4)
  - Absolute values of the masses are commensurate.

Hybrid Spectrum

New Perspective on Hybrid Mesons
Shu-Sheng Xu, *et al*.
arXiv:1805.06430 [nucl-th]

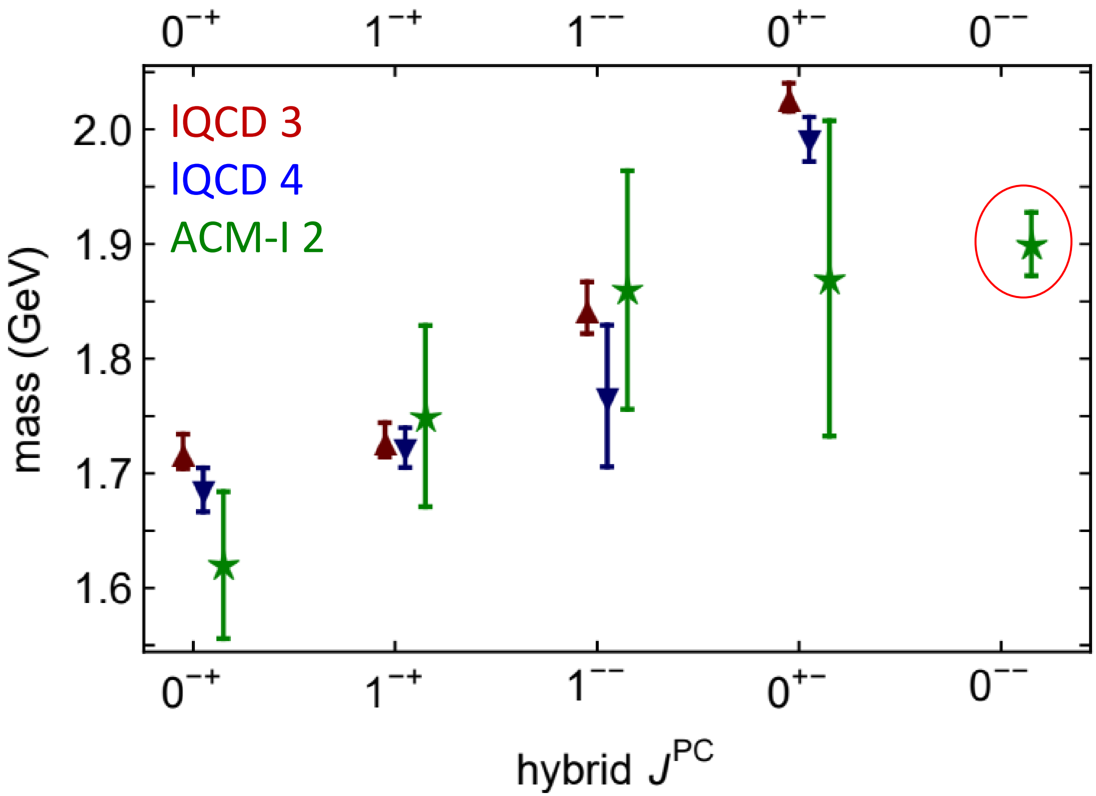
- Beyond-RL essential to agreement with lQCD
- Agreement is non-trivial
  - lQCD masses are rescaled by subtraction of $\delta_{\pi 1}$, a number which is completely unrelated to our calculations.
- No single lQCD mass was used as a constraint when fitting κ_{gq}
- Magnitude of our results set by
  - infrared values of the running gluon and quark masses
  - determined by π- and ρ-meson properties
  - unrelated to hybrid channels.



Hybrid Spectrum

New Perspective on Hybrid Mesons
Shu-Sheng Xu, *et al*.
arXiv:1805.06430 [nucl-th]

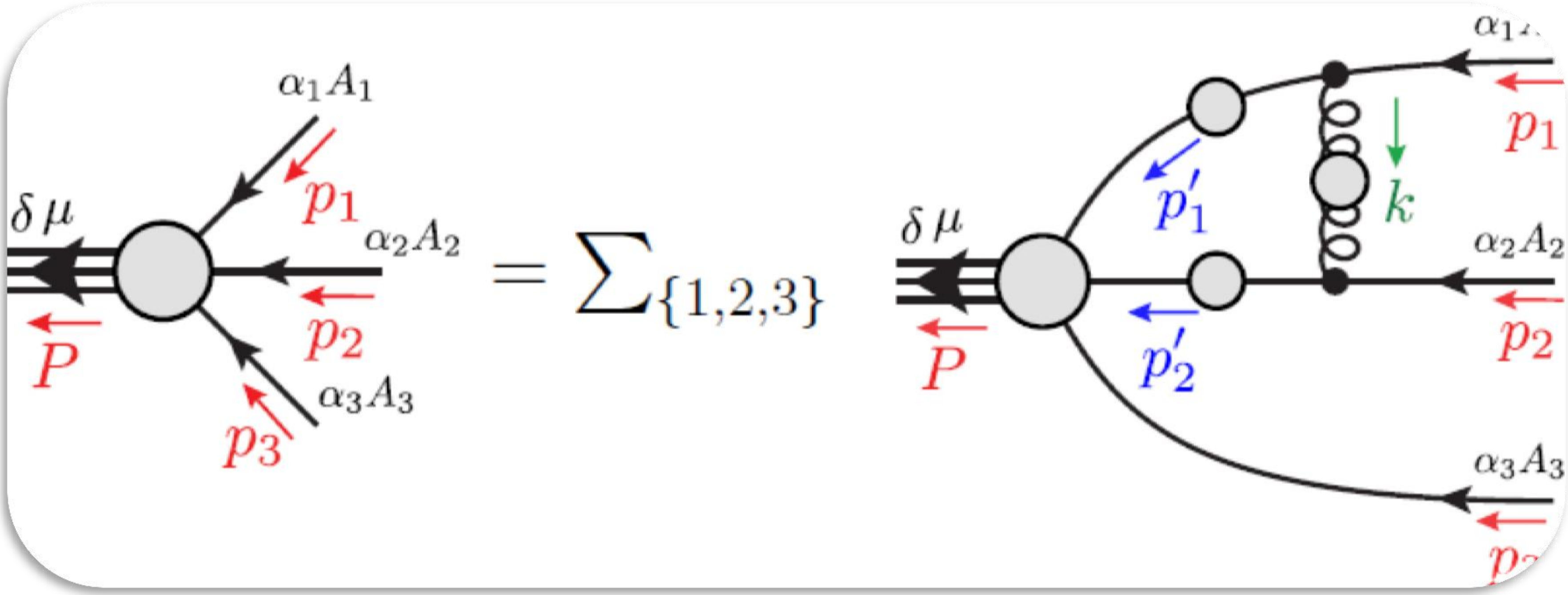
- 0^{--} … deserves special attention
- lQCD predicts lightest state in this channel above m_ρ+2GeV
- [gq] Faddeev equation confirms 0^{--} is ground-state heaviest hybrid
  - Corrects defect of RL-truncation analyses of exotics using the two-body Bethe-Salpeter equation
- Computed 0^{--} mass nevertheless probably too light
  - Such a system is likely to possess large amount of angular momentum
  - Leads to significant DCSB-enhanced repulsion within the bound-state
  - Simple expedient for correcting associated defects of RL truncation may not be completely adequate.
  - Approach we have described will always produce a heavy 0^{-} state, but precise location must await future, more sophisticated analyses.



New Perspective on Hybrid Mesons
Shu-Sheng Xu, *et al.*
arXiv:1805.06430 [nucl-th]

New Perspective on Hybrids

- Faddeev equation approach to the valence-gluon+quark+antiquark bound-state problem in relativistic quantum field theory.
  - Strong correlations exist in the [q_g=gq] & [$\bar{q}_g$ = g$\bar{q}$] channels
  - Hybrid mesons appear as highly-correlated $q_g\bar{q} \leftrightarrow q\bar{q}_g$
  - Given role that diquark correlations play in determining baryon properties, existence and importance of kindred correlations within hybrids appears credible
- Described a first analysis of hybrids from this new perspective
  - Established plausibility
  - More sophisticated treatments necessary before the validity of the formulation can be firmly established
- Meanwhile:
  - Serve as a guide for subsequent continuum treatments of hybrid-meson three-body problem
  - Computed, highly-correlated wave functions can be used to predict a range of hybrid decays and other processes
    - Elucidate empirical signatures for the presence and role of q_g & $\bar{q}_g$



Baryons as a 3-valence-body problem

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

Only two people in the world can do this.
Neither of them is in the USA
Si-Xue Qin, was at Argonne
Now a Professor at Chongqing U.

- No diquark approximation to the quark-quark scattering kernel
  - Reverse engineering … searching for dynamical emergence of diquark correlations and their effects
- 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

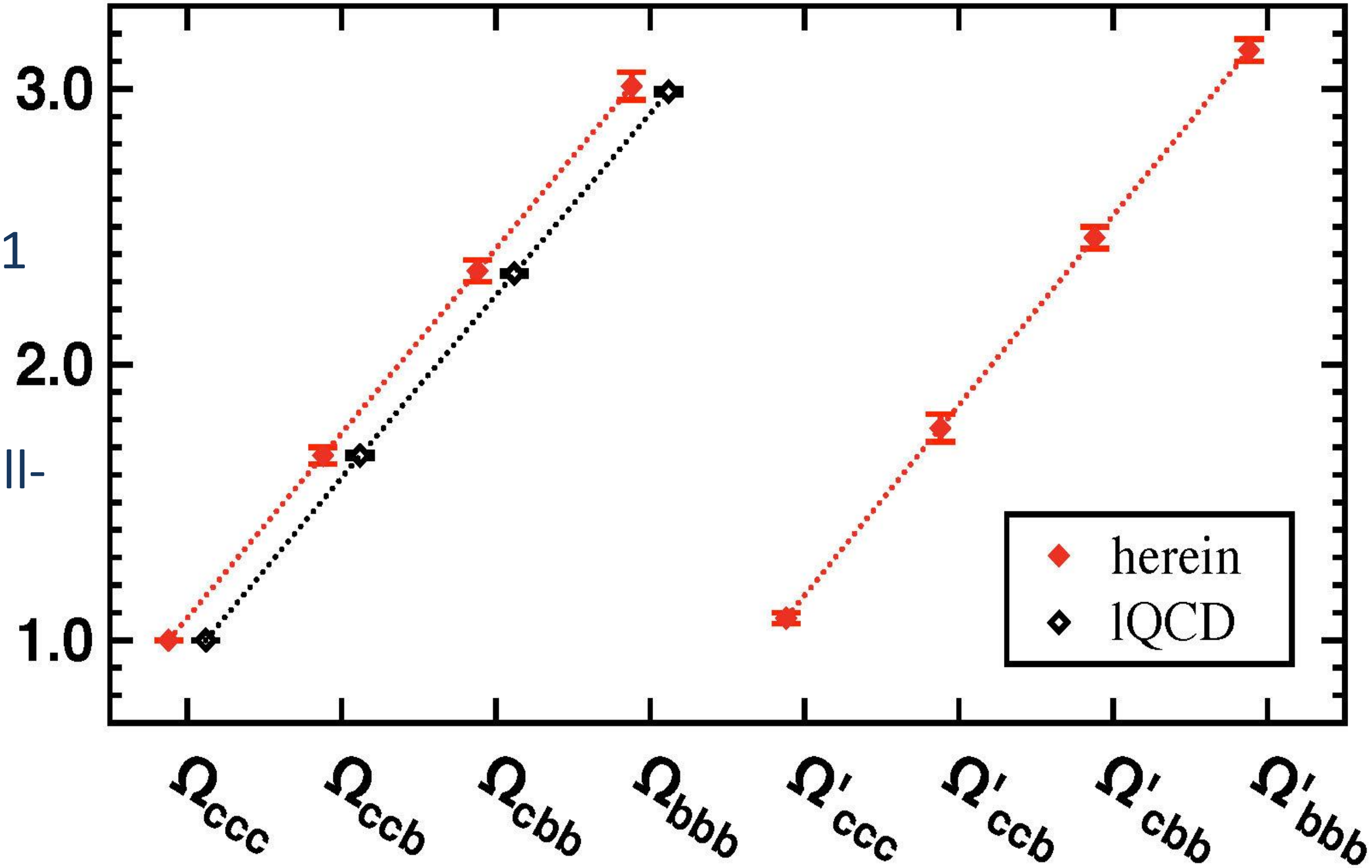
& masses of $J^P=3/2^+$ qqq, QQQ ground state baryons and their first positive-parity excitations.

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

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

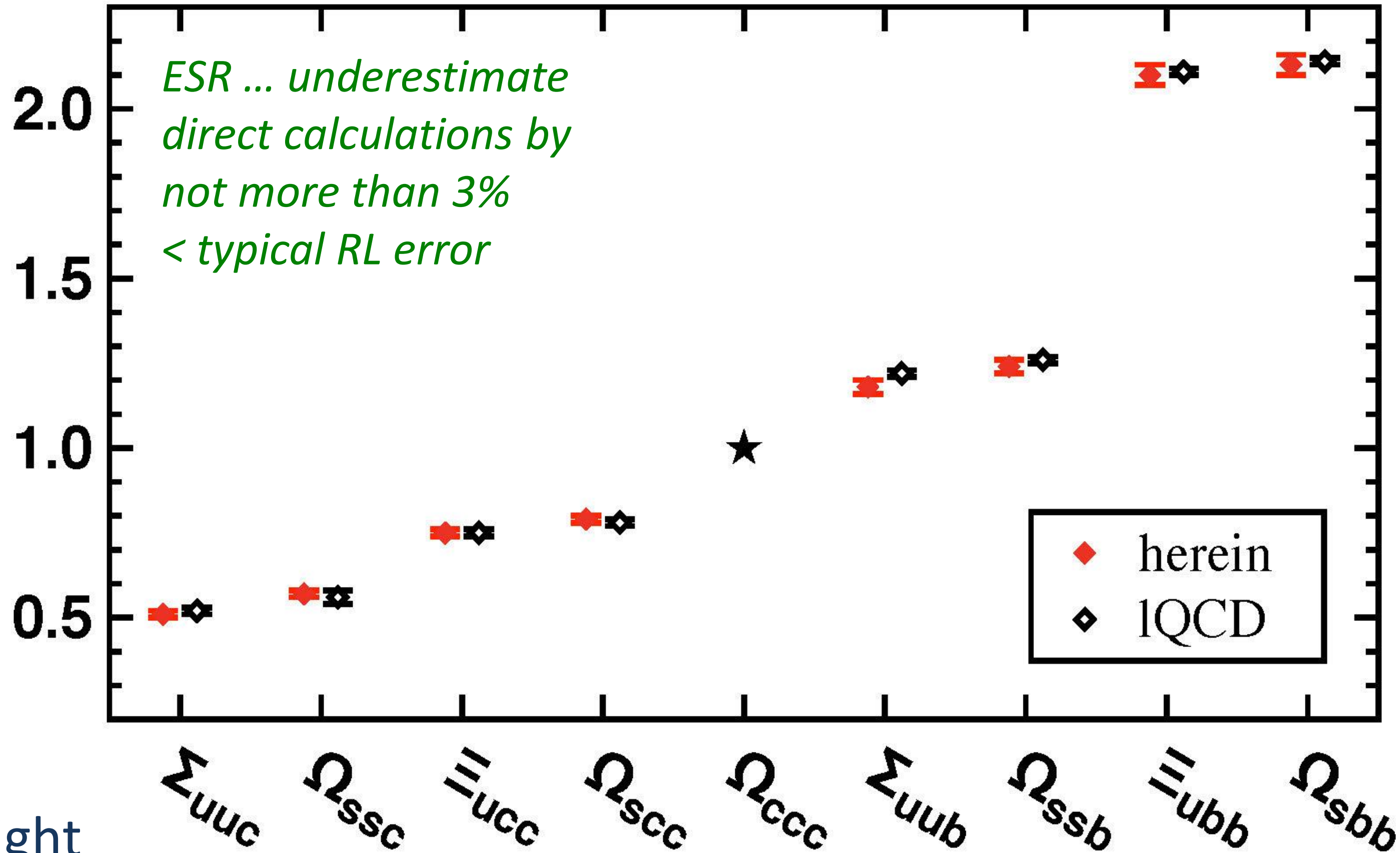


lQCD = Z. S. Brown, W. Detmold, S. Meinel and K. Orginos, Phys. Rev. D 90, 094507 (2014).

Heavy Baryons

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

  of all systems considered



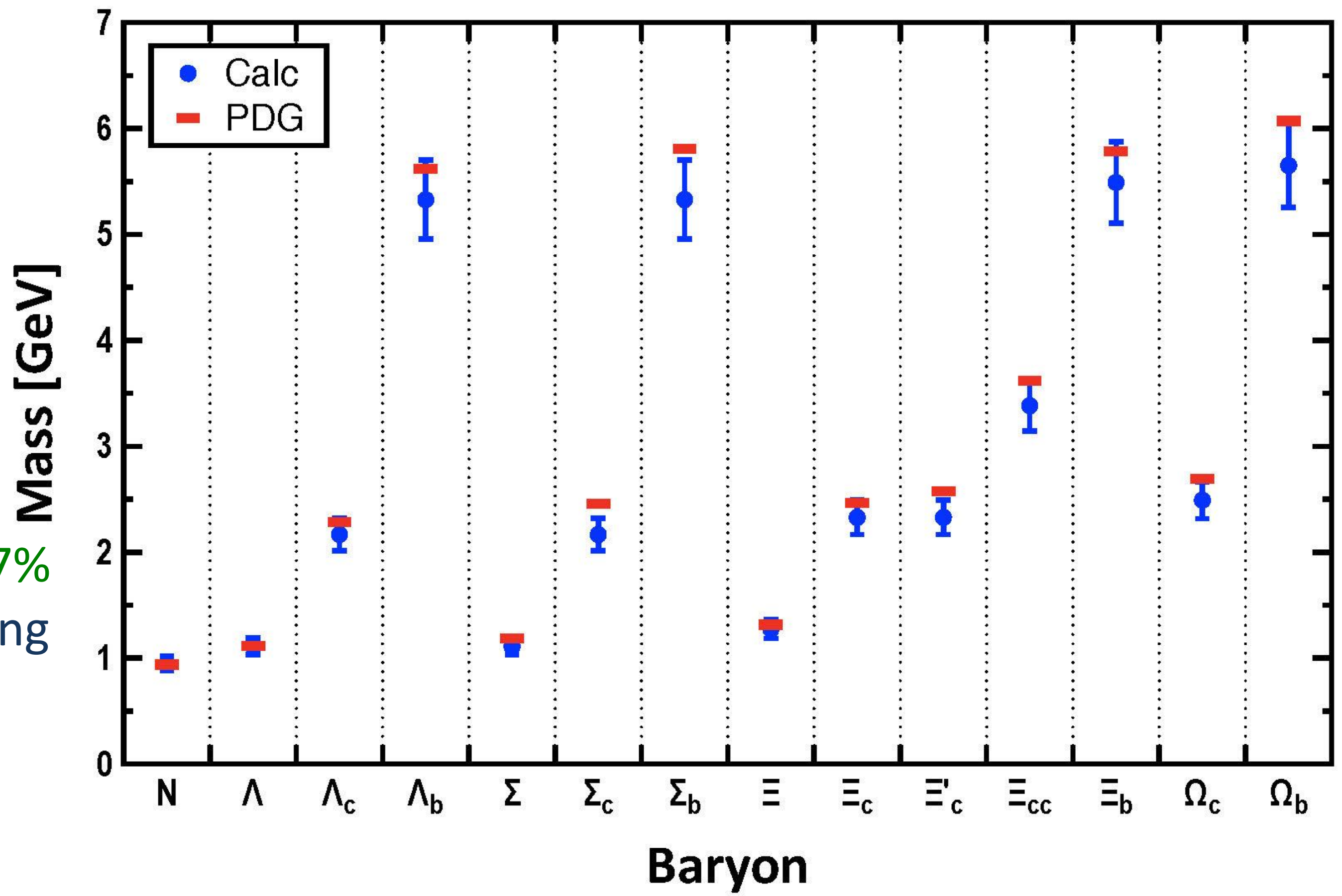
- Obvious in hindsight

  … QCD's interaction is flavour-independent

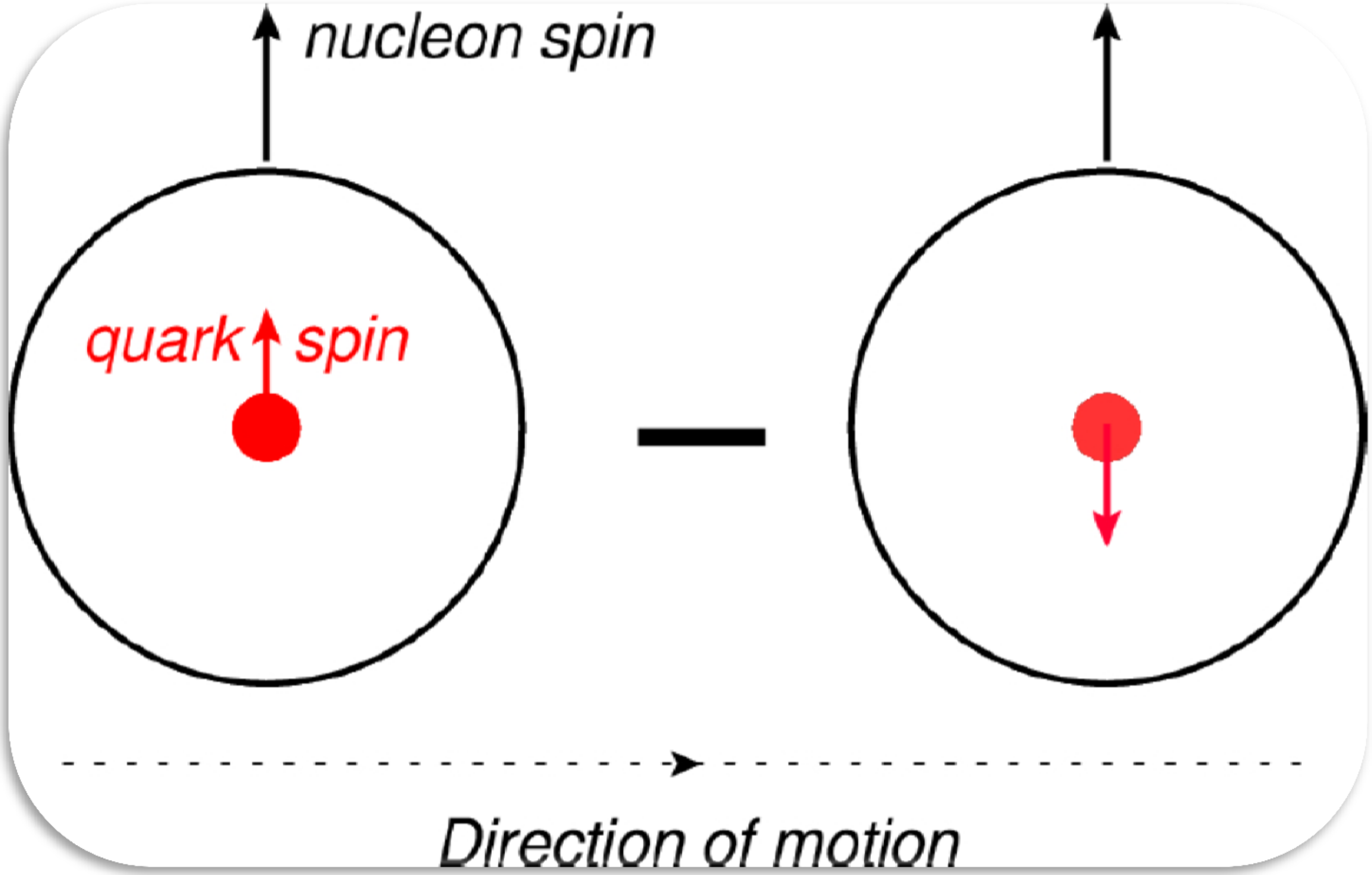
  … need only survey DSE studies of these observables in kindred systems

J=½ Baryons

- Extending analysis to J=½ baryons
- Leading-order (RL truncation) computation of J=½ baryon spectrum, including states with one heavy quark:
  rms-relative error = 7%
  size of isospin breaking
- General features of ground-state baryon spectrum are reproduced by three dressed-quarks interacting via dressed-gluon exchange



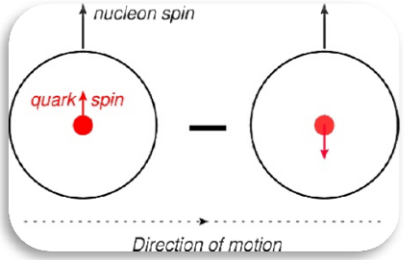
- MB FSIs are important for lighter systems
  Expressed in renormalisation of interaction mass-scale



Proton's Tensor Charge

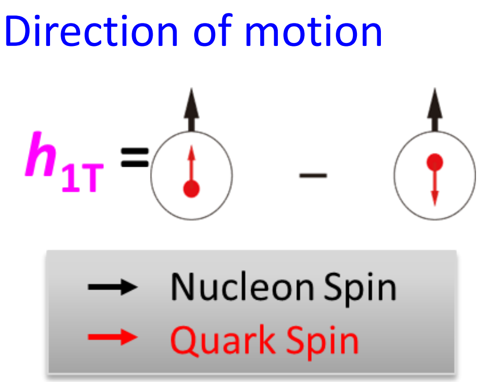
Tensor Charge and TMDs

- New generation experiments aim to obtain data that can be used to determine the proton's transverse momentum dependent parton distribution functions (TMDs)
- At leading-twist, three distinct TMDs are nonzero in the collinear limit, i.e. in the absence of parton transverse momentum within the target, $k_\perp = 0$:
  - unpolarized = f_1 ,
  - helicity = g_{1L} ,
  - transversity = h_{1T} .



- Proton's tensor charges: $\delta_T q = \int_{-1}^{1} dx\, h_{1T}^q(x) = \int_0^1 dx\, \left[h_{1T}^q(x) - h_{1T}^{\bar{q}}(x)\right]$

  measure any bias in quark transverse polarisation induced by a polarisation of the parent proton
- Phenomenological extraction/inference from extant data on h_{1T}



TMDs … Transversity … Tensor Charge

$$\delta q = \int_0^1 dx\, \left(h_1^q(x) - h_1^{\bar{q}}(x)\right)$$

- Intrinsic, defining property of the nucleon
  - … just as significant as axial-charge
  - … in non-relativistic limit it is axial charge
- No gluon transversity distribution
- Value of tensor charge places constraints on some extensions of the Standard Model <PRD85 (2012) 054512>
- Current knowledge of transversity:
  - SIDIS @HERMES, COMPASS, JLab
- Future SIDIS at JLab (SoLID), EIC, …

Electron Ion Collider: The Next QCD Frontier

Proton Tensor Charges

- Theoretical predictions:

  Compute directly from matrix element

$$\langle P(k,\sigma)|\bar{q}\sigma_{\mu\nu}q|P(k,\sigma)\rangle = \boxed{\delta_T q}\,\bar{u}(k,\sigma)\sigma_{\mu\nu}u(k,\sigma)$$

- Used widely for Lattice-QCD analyses:

  [Bhattacharya:2015esa, Bhattacharya:2016zcn, Alexandrou:2017qyt, Bali:2014nma]

- Continuum studies, too:
  - Quark model [He:1994gz, Yamanaka:2013zoa]
  - Diquark approximations to Faddeev equation [Hecht:2001ry, Pitschmann:2014jxa, Xu:2015kta]

Proton Faddeev Amplitude

- Using precisely same interaction as for mesons, solved for the nucleon, using symmetry-preserving RL-truncation of all relevant equations:
  - Gap equations
  - Bethe-Salpeter equations
  - and Faddeev-equations
- No diquark approximation to the quark-quark scattering kernel
- Must solve for dressed-quark tensor charges, via tensor vertex
  - Only Q=0 required
  - Renormalise at ζ_2 = 2 GeV

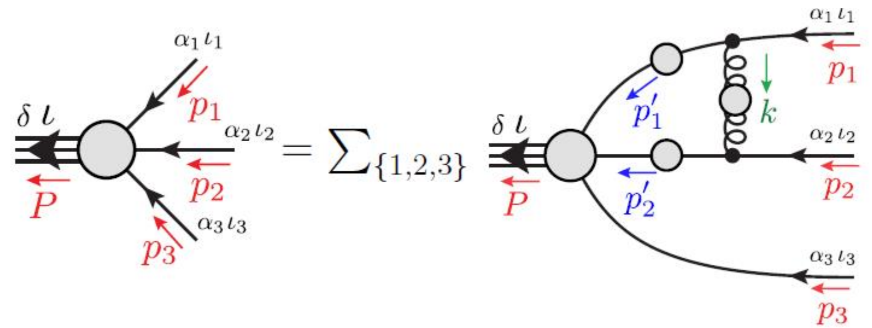


FIG. 2. Three-body equation in Eq. (19), solved herein for the ... de: vert ... rk- qua ... led circl ... by solving a gap equation with the same interaction (Sec. IV B).

$$m_N\ (\mathrm{GeV}) = 0.932^{(5)}_{(11)}$$

$$\Gamma_{\mu\nu}(k;Q=0) = T_1(k^2;\zeta)\sigma_{\mu\nu} + T_2(k^2;\zeta)\{\gamma\cdot\hat{k},\sigma_{\mu\nu}\} + T_3(k^2;\zeta)(\sigma_{\mu\rho}\hat{k}_\rho\hat{k}_\nu - \sigma_{\nu\rho}\hat{k}_\rho\hat{k}_\mu)\,,$$

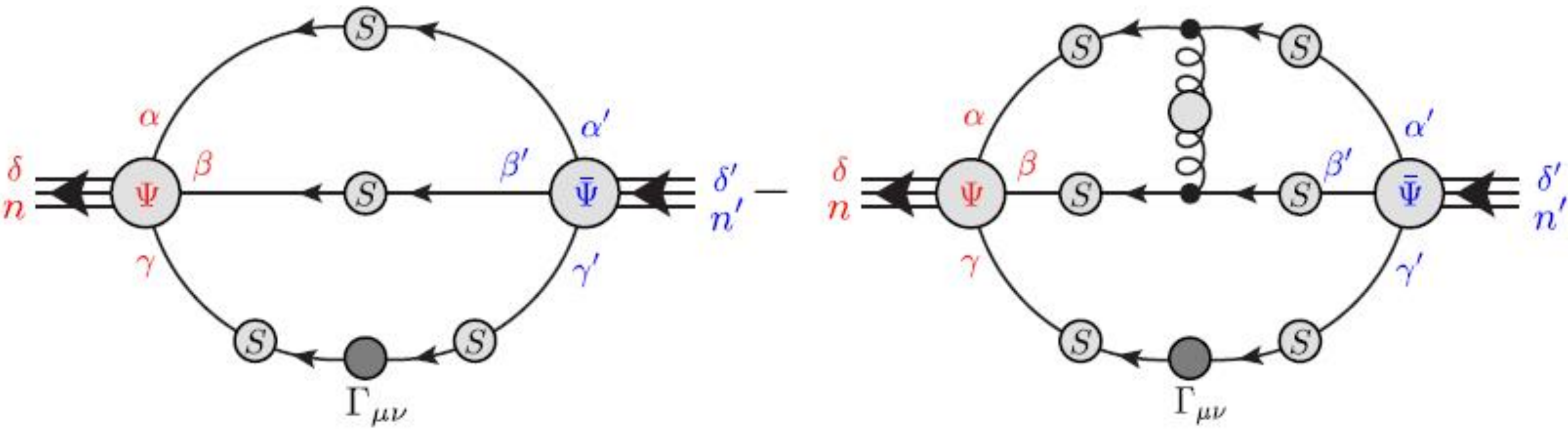
$$T_1(k^2=0;\zeta_2) = 0.67(5) =: \tilde{\delta}_T q$$

Natural size is now evident

Proton tensor charges from a Poincaré-covariant Faddeev Equation
Q.-W. Wang, S.-X. Qin, C. D. Roberts & S. M. Schmidt

Proton's Tensor Charges

$$[J^{(3)}_{nn'}(Q)]^{\delta\delta'}_{\mu\nu} =$$



- Charges computed from the proton's tensor current
  - Symmetry-preserving form, consistent with Faddeev amplitude
- Two isospin channels in Faddeev equation and in current
  - 00 = kernel for isoscalar-scalar diquark
  - 11 = isovector-axial-vector diquark

$$\delta_T u = 3\delta_T^3 u = 3\mathrm{J}_{00}^{(3)} + \mathrm{J}_{11}^{(3)}\,,$$

$$\delta_T d = 3\delta_T^3 d = 2\mathrm{J}_{11}^{(3)}\,.$$

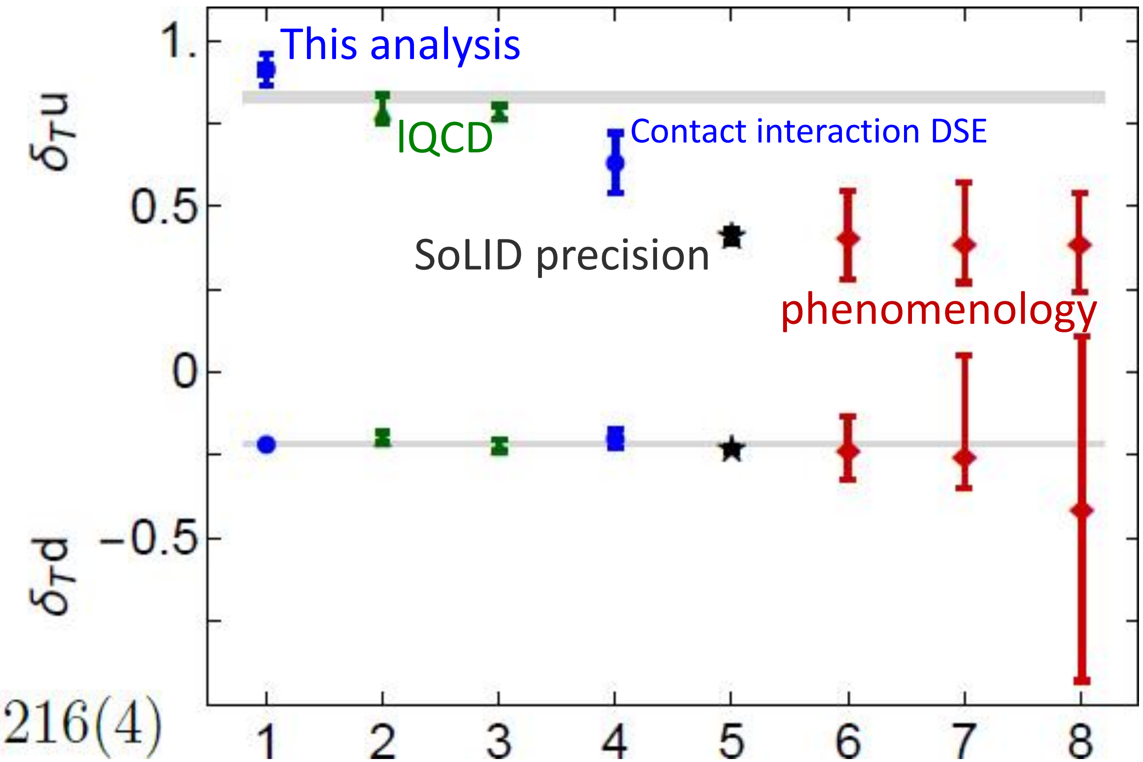
Signal that
$\delta_T d \approx 0$ in models that
suppress axial-vector diquarks

Proton's Tensor Charges

- Interaction kernel has one parameter, ω
  - Fixed by requiring a good description of π and ρ properties
  - Variation shows sensitivity to ± 10% changes in ω around the favoured value
- $\delta_T u$: Increasing tension between theory and phenomenology
- $\delta_T d$: Theory and Phenomenology agree
- Theory average

$$\delta_T u = 0.912^{(42)}_{(47)}\,, \qquad \delta_T d = -0.218^{(4)}_{(5)}\,,$$

$$g_T^{(1)} = 1.130^{(42)}_{(47)}\,, \qquad g_T^{(0)} = 0.694^{(42)}_{(47)}$$



$$\overline{\delta_T u} = 0.803(17)\,,\ \overline{\delta_T d} = -0.216(4)$$

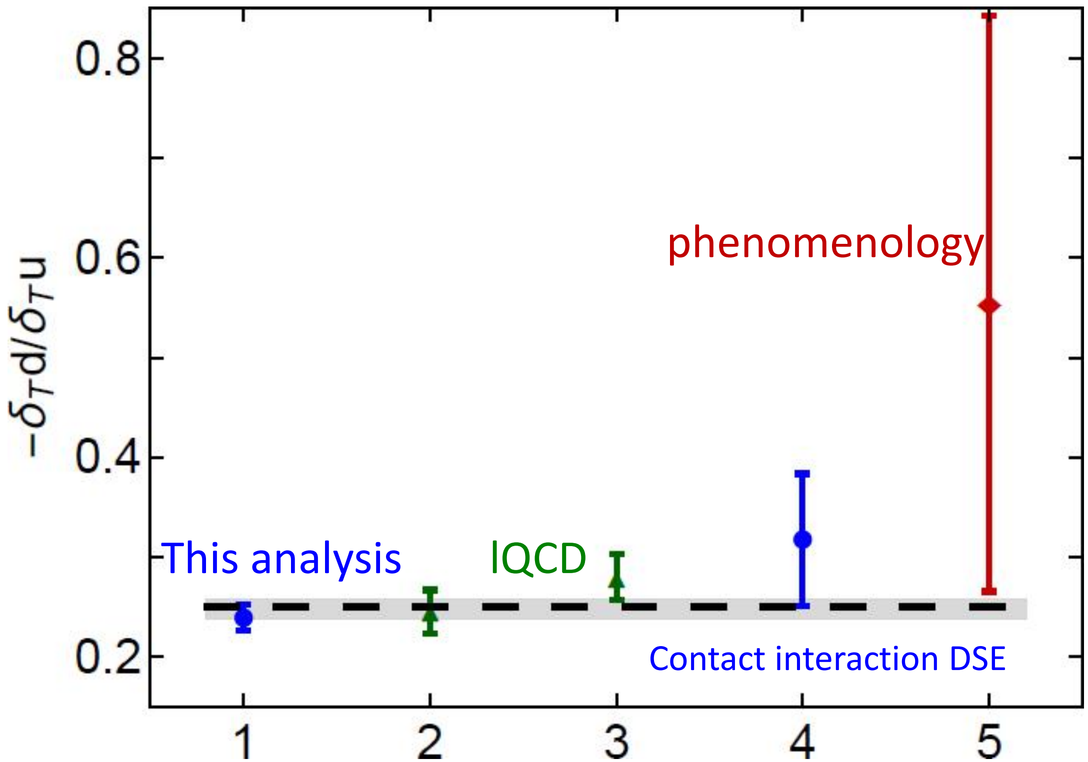
Proton's Tensor Charges

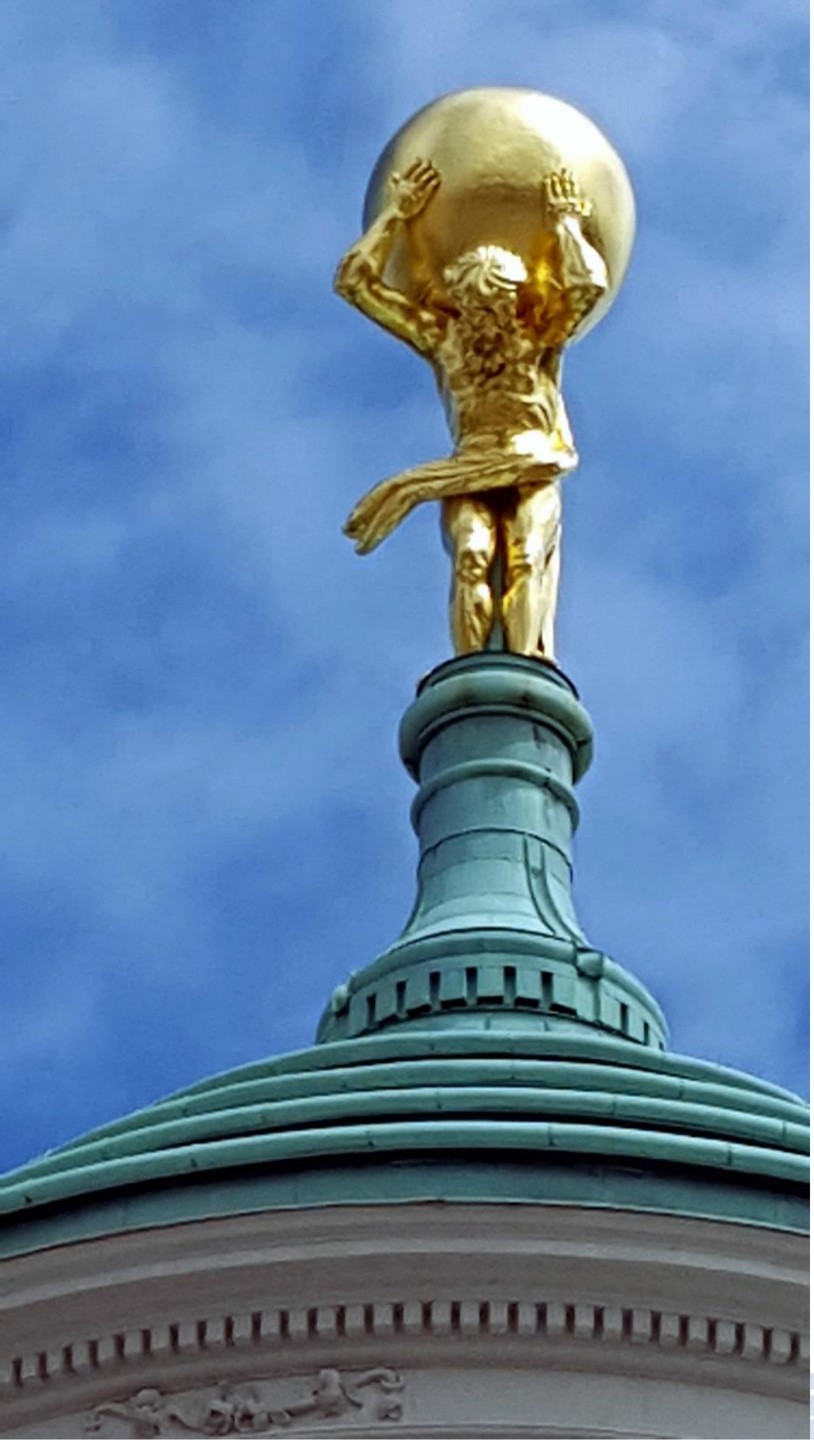
- Scale-invariant ratio
  $-\delta_T d/\delta_T u$
- Phenomenology [Ye:2016prn] produces ratio that is roughly twice as large
- Using simple nonrelativistic quark model spin-flavour wave function this ratio is
  $-\delta_T d/\delta_T u = ¼$

Practically the same in MIT bag model

- But, in both cases, the individual tensor charges are measurably larger in magnitude
- Agreement accidental, like μ_p/μ_n

$$-\frac{\delta_T d}{\delta_T u} = 0.248(10)$$

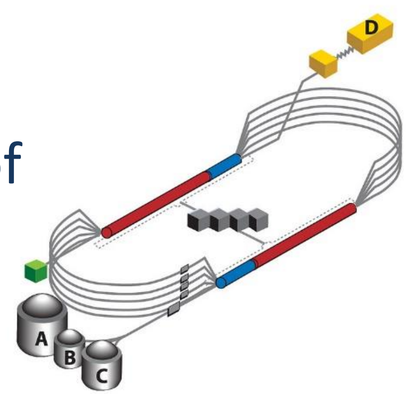




Epilogue

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
- **Tough Problem**
- *Progress* and *Insights* being delivered by amalgam of
  - Experiment
  - Phenomenology
  - Theory
- Must continue into eras of



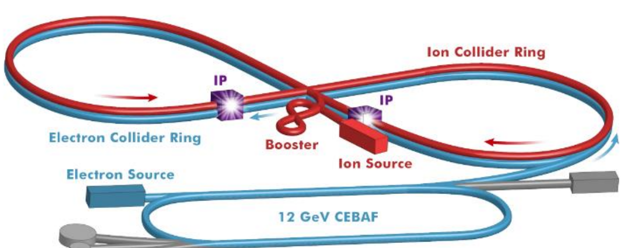


Figure 1. Schematics of the JLEIC facility.

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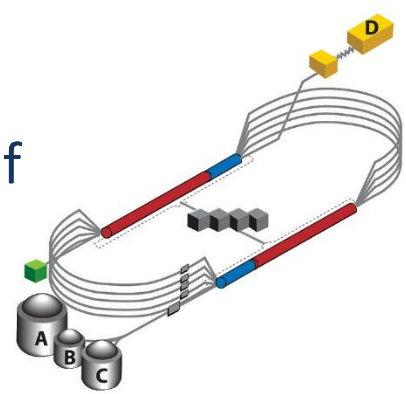
Thankyou



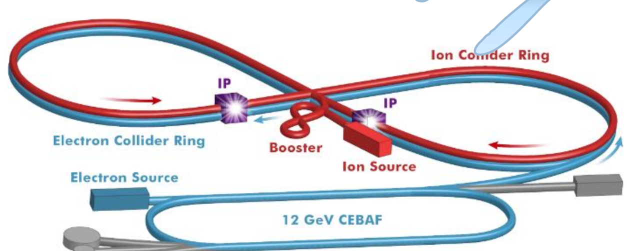


Figure 1. Schematics of the JLEIC facility.

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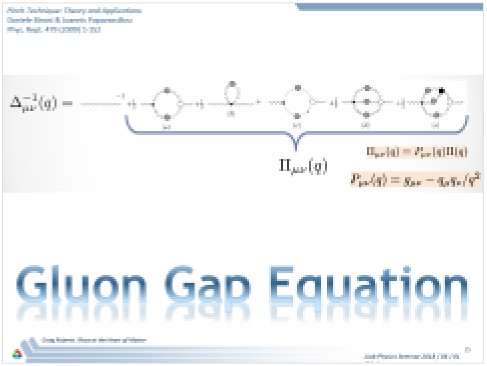
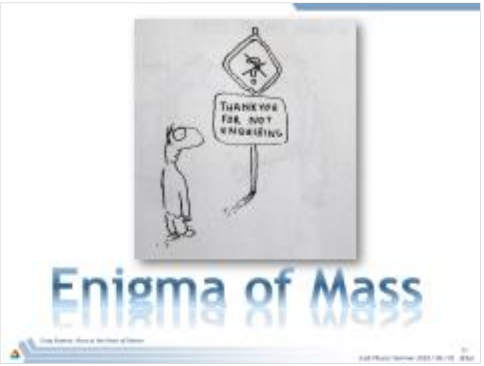
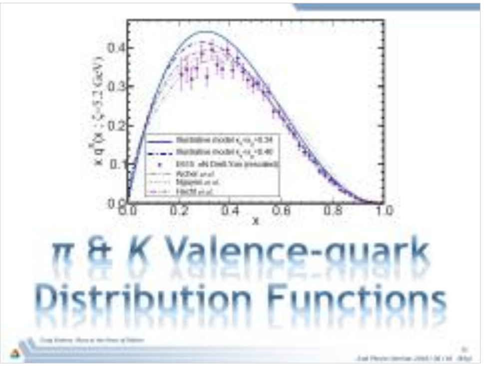
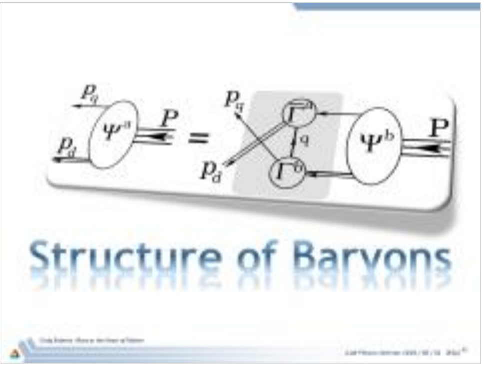

Gluon Gap Equation


What's happening out here?!
QCD's Running Coupling

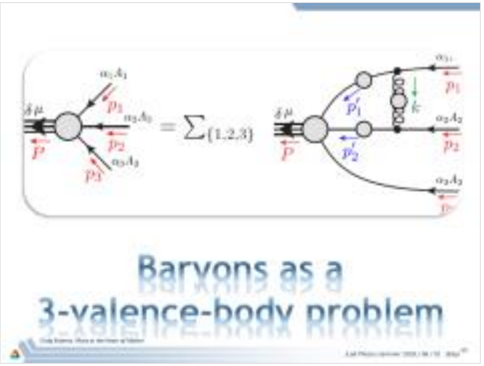

Enigma of Mass

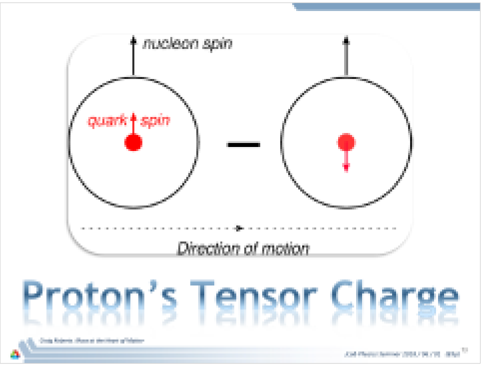

Observing Mass


π & K Valence-quark Distribution Functions


Structure of Baryons


GLUEX citations periment
Hybrids & Exotics


Baryons as a 3-valence-body problem


nucleon spin
quark spin
Direction of motion
Proton's Tensor Charge