
QCD:
Carrying our Weight
Craig Roberts

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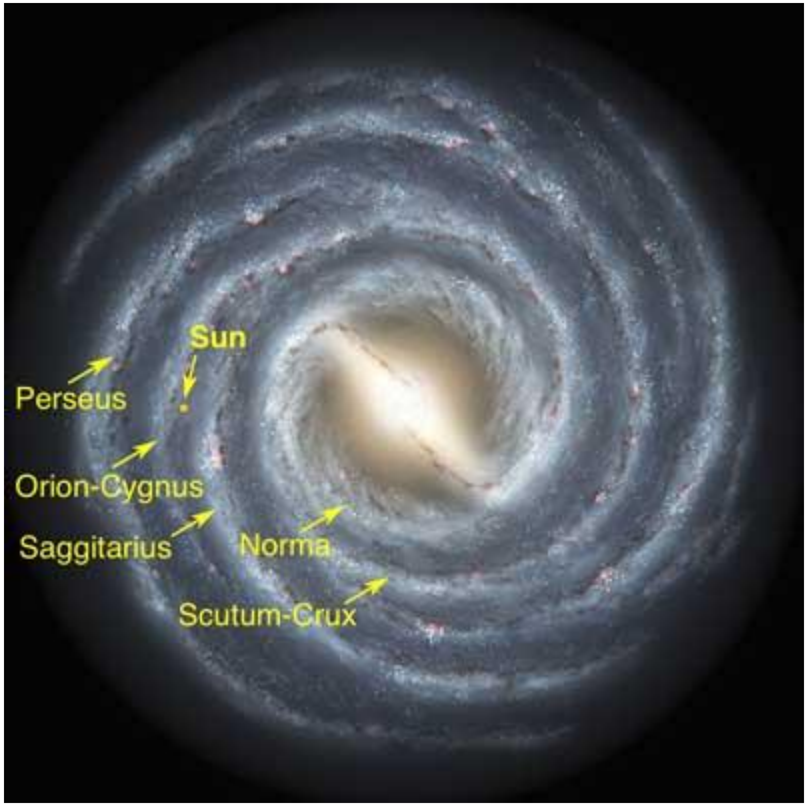
Emergent Phenomena in the Standard Model

Existence of our Universe 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

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

- 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 $1/250^{th}$ 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 $L_{\rm QED}$

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

Whence 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?

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

Whence?

- Classical chromodynamics
  - non-Abelian local gauge theory
  - local gauge invariance
- But 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 appearance of mass in QCD is quite likely inseparable from the task of understanding confinement.*

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

Trace Anomaly

- Classically, in a scale invariant theory

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

- Regularisation and renormalisation of (ultraviolet) divergences in Quantum Chromodynamics 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)

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

Trace anomaly

QCD β function

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

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:

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

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

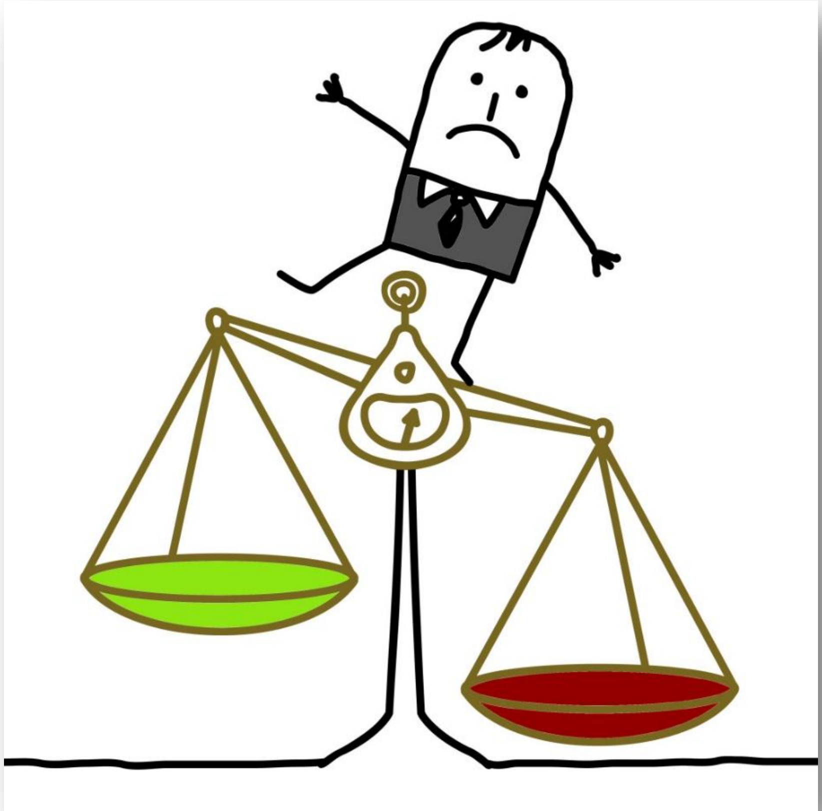
$$= \langle p(P)|\Theta_0|p(P)\rangle$$

- 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 (somehow) 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

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

- 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*

  "How does the mass of the proton arise?"

  is complete without the additional clause

  "How does the pion remain **massless***?"*

- 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

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*

  "How does the mass of the proton arise?"

  is complete without the additional clause

  *"How does the pion remain **massless**?"*

- Natu ... usly with ... stems
  - Ex ... e of th ... $= m_p$

Elucidate the entire array of empirical consequences of the mechanism responsible so that the theory can be validated

Ideas: Old & New

Observations … 1

- Quantum field theories provide only known realisation of the Poincaré algebra with a particle interpretation

  $\Longrightarrow$ Observable 1-particle states are characterised by just two invariants

  ✓ eigenvalues of M^2 – mass-squared operator

  ✓ eigenvalues of W^2 – W_μ is Pauli-Lubanski four-vector

  - W_μ contains no information about angular momentum

- Consequences:

  The only ***unambiguous*** labels attached to a hadron state are its

  – Total Mass (conserved)

  – Total Spin (J^2 – conserved & quantised = boson or fermion)

- Any separation of either quantity

  into contributions from various constituent species

  (or other subcomponents)

  is frame and scale dependent

Observations … 2

- Only light-front wave functions possess a probability interpretation
- Computations using bare-parton Fock-space expansion are useful in the neighbourhood $\Lambda^2_{QCD}/Q^2 \simeq 0$:
  - Operators simple
  - But wave functions complicated and very difficult (impossible?) to compute
- At accessible energies, better to use dressed-parton Fock-space
  - Operators complicated; but sound approximations calculable
    - (countable infinity of parton contributions)
  - And wave functions simple
- Interpretation of given observable depends on the basis employed
- K. G. Wilson, Walhout, Harindranath, Zhang, Perry, Glazek: Phys. Rev. D **49** (1994) pp. 6720-6766 … Arguing for the use of quasiparticle operators:

  As is always the case, the division of the Hamiltonian into a free part and an interaction part is arbitrary; however, it is also true that the convergence of a perturbative expansion depends crucially on how this choice is made.
- **Clearest/simplest picture will likely change with the resolution scale**

Observations … 3

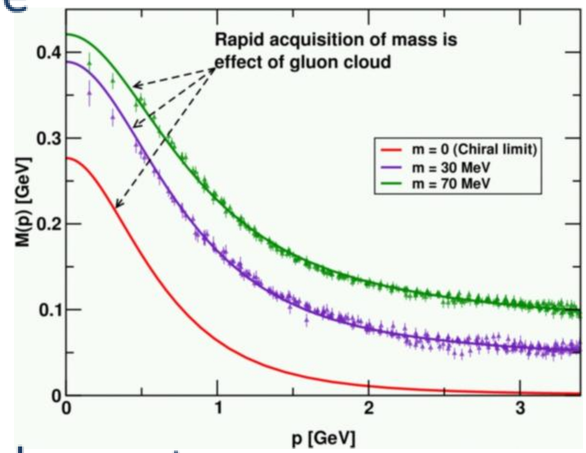
- Simultaneous elucidation of the content and consequences of

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

cannot be achieved by focusing on a particular reference frame

- Example: massless pion doesn't have a rest frame
- Poincaré-invariant result:

$$m_\pi^2 = 2\, m_\zeta \frac{-\langle \bar{q} q\rangle_\zeta}{f_\pi^2}$$



- In the neighbourhood of the chiral limit:
  - ALL the pion's mass-squared originates with QCD Lagrangian's Higgs-generated current-quark mass term
  - **But** there is a *huge* *emergent* magnification factor ~ 250 m_ζ

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.

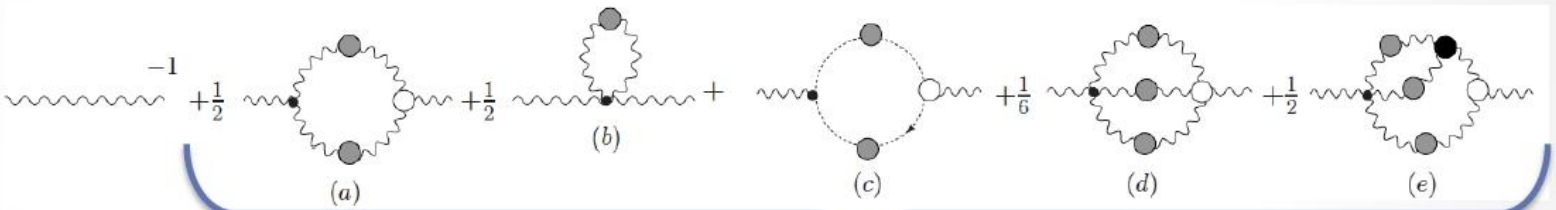
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	ABREU	92E	DLPH	Spin 1, not 0
	ALEXANDER	91H	OPAL	Spin 1, not 0
	BEHREND	82D	CELL	Spin 1, not 0
	BERGER	80D	PLUT	Spin 1, not 0
	BRANDELIK	80C	TASS	Spin 1, not 0

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

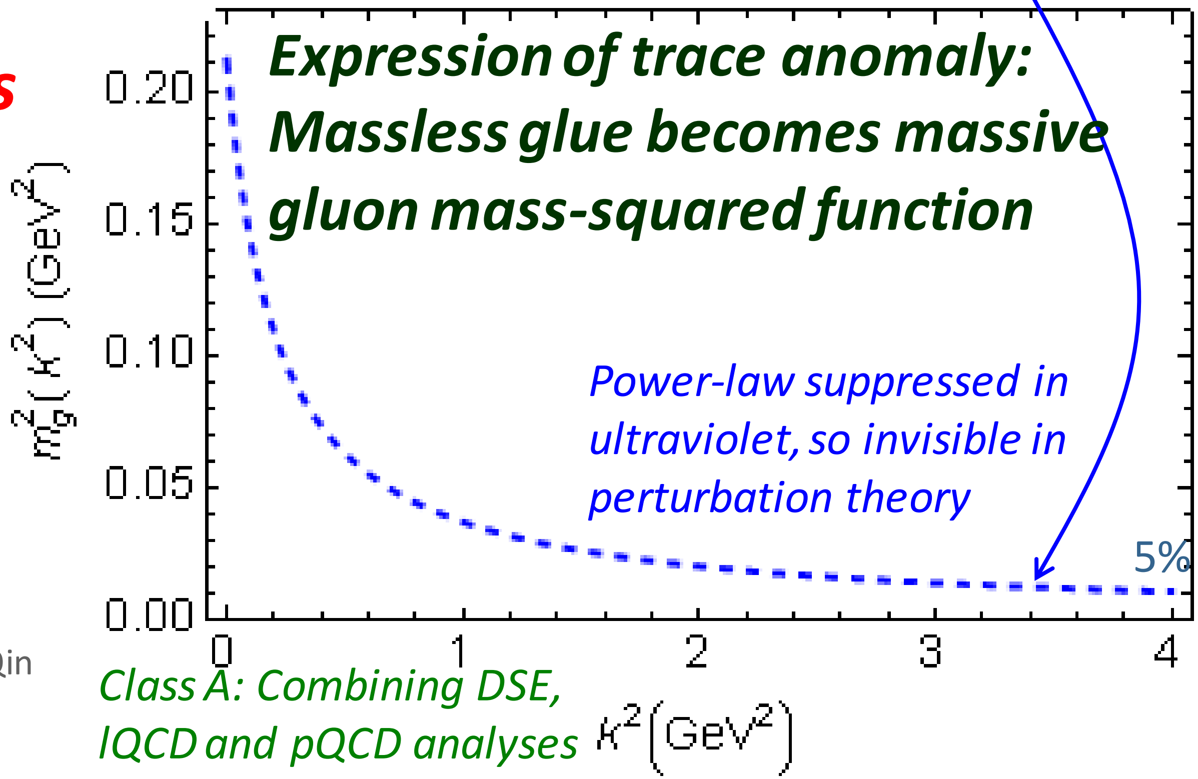
$$d(k^2) = \frac{\alpha(\zeta)}{k^2 + m_g^2(k^2;\zeta)}$$

$$\alpha_S(0) \approx \pi \qquad m_g^2(0) = (0.46\,\text{GeV})^2$$

$\mu_g \approx ½\, m_p$

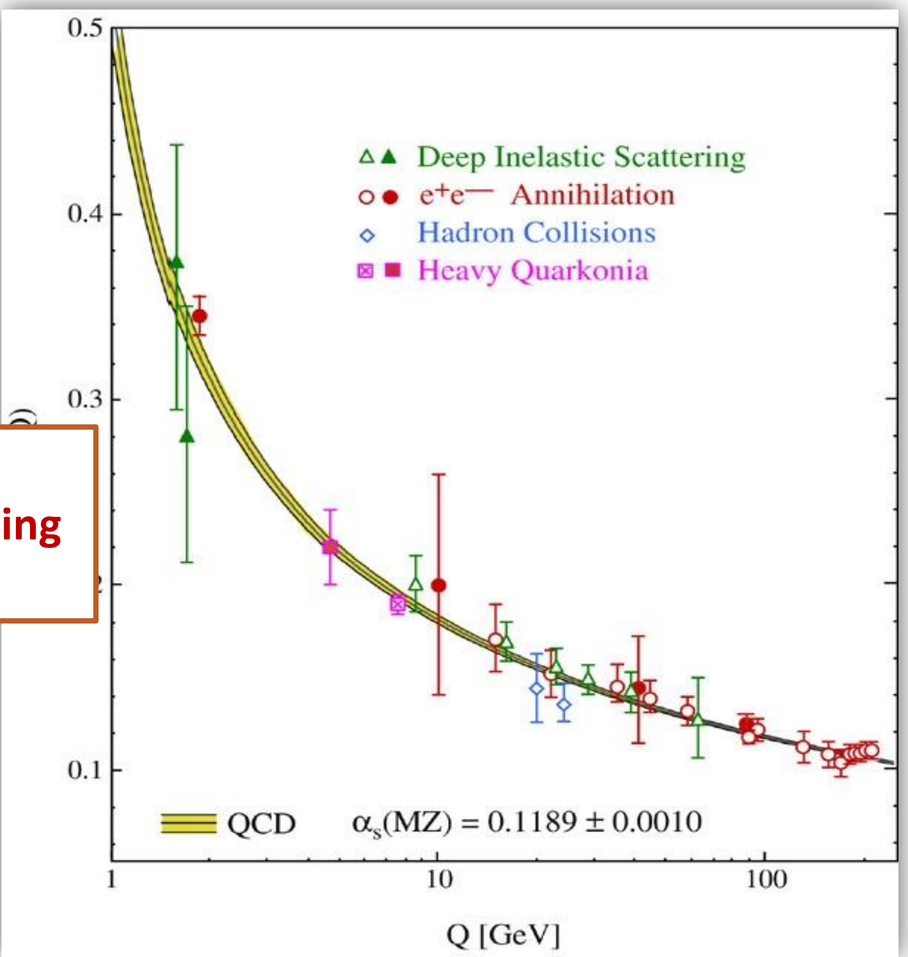
$$m_g^2(k^2) \approx \frac{\mu_g^4}{\mu_g^2 + k^2}$$

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



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]



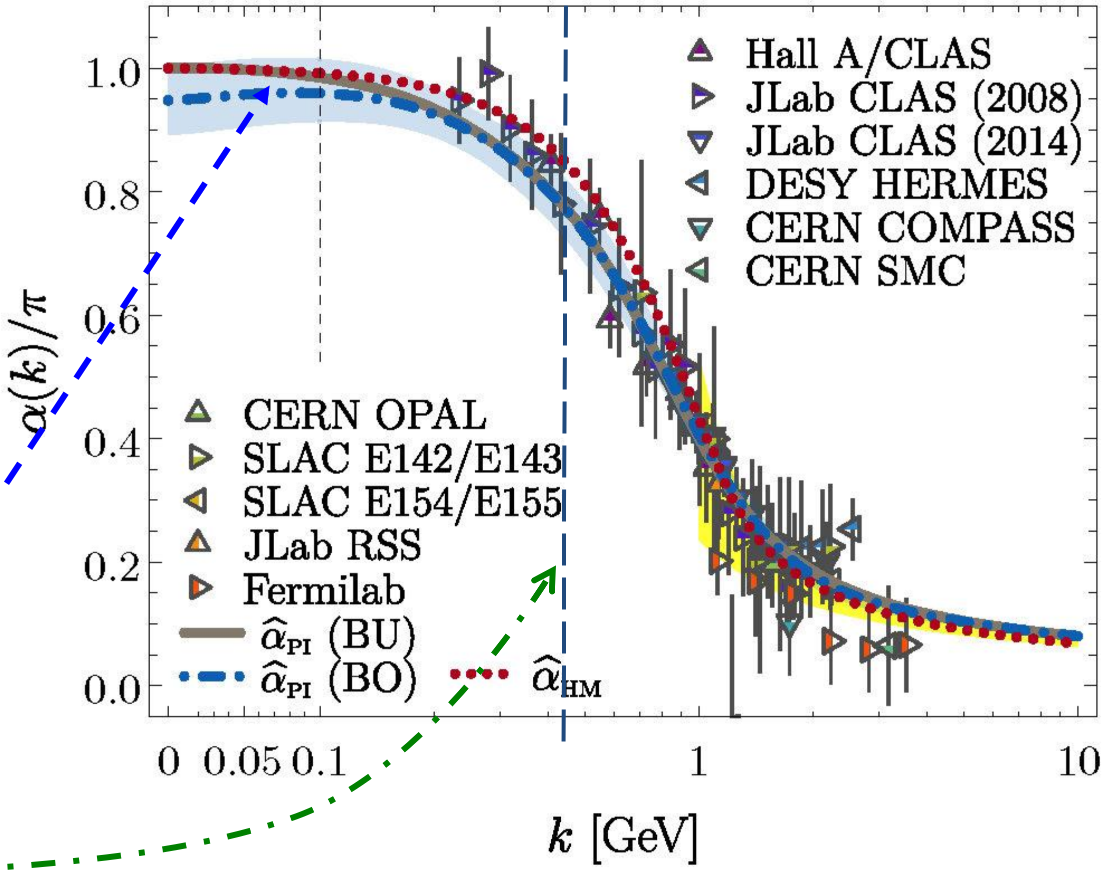
⇐ What's happening out here?!

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

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 $k \approx ½\, m_p$



QCD Effective Charge

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

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

  $\hat{\alpha}_{PI}$ and α_{g1}

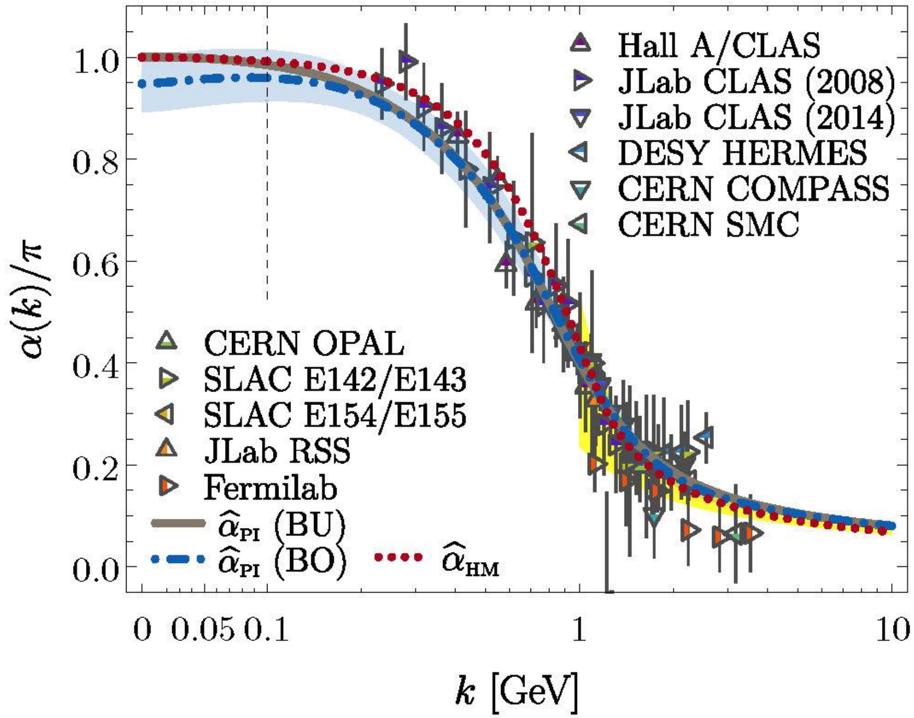
  & $\hat{\alpha}_{PI} \approx \alpha_{HM}$

- Perturbative domain:

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

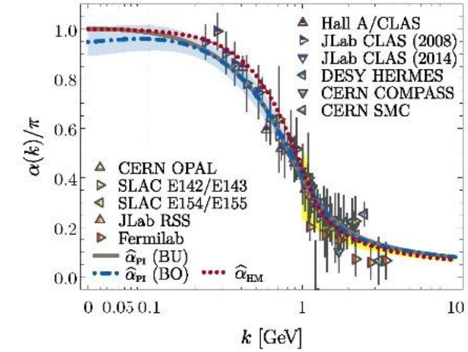
$$\widehat{\alpha}_{\rm PI}(k^2) = \alpha_{\overline{\rm MS}}(k^2)(1 + 1.09\,\alpha_{\overline{\rm MS}}(k^2) + \ldots)\,,$$

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

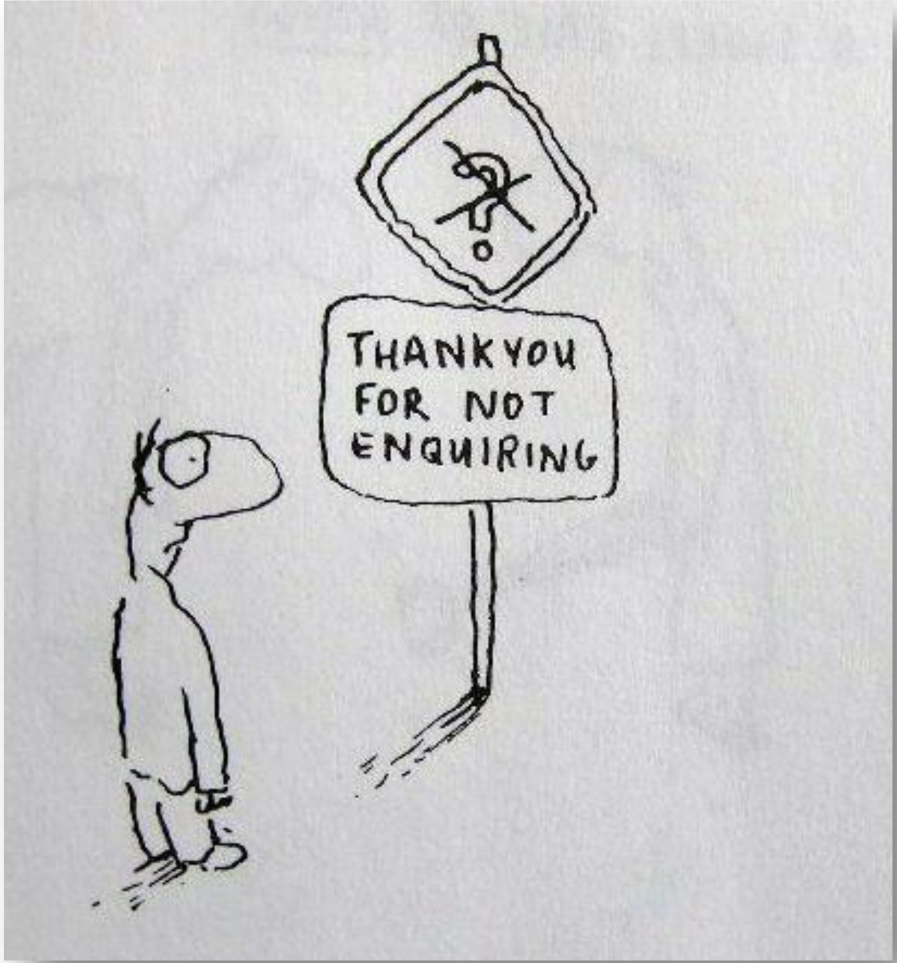


Data = process dependent effective charge [Grunberg:1982fw]:
α_{g1}, defined via Bjorken Sum Rule

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
  - 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***



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

This means that π necessarily has dressed-quark L=0 & L=1 components in any frame
Twist-3 on light-front

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

- 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

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

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.

Revealing Mass

Consequences … 1

- Mass is dynamically generated in QCD: Scale ~ Λ_{QCD}
  - Empirically $\Lambda_{QCD} \approx 0.2$ GeV … Standard Model can't predict this value.
- Gluon self-interactions make $\Lambda_{QCD} \approx 0.2$ GeV possible.
  They do not guarantee it.
- *Understanding* of observables (almost always) depends on frame of reference and scale of probe
  - gluons and quarks → dressed quasiparticles:
    - massless in perturbation theory
    - possess mass functions which are large at infrared momenta ≤ $m_g \approx 2\,\Lambda_{QCD}$
  - at hadronic scale: wave functions, cross-sections, *etc*. are most readily understood using evolving quasiparticle operators for dressed-g, -q
    - Each contains a (distinct) countable infinity of partons

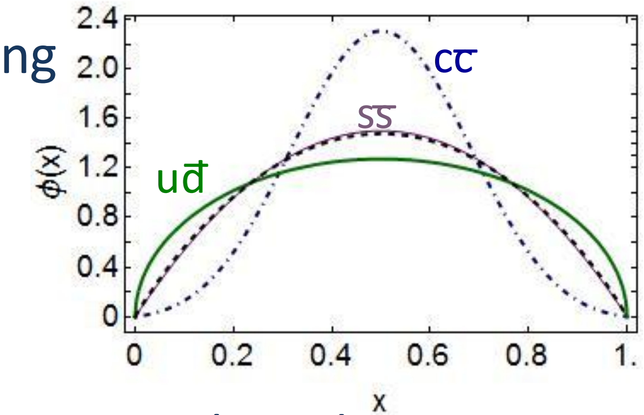
⇒ All bound-states have GeV-scale masses

⇒ Except Nambu-Goldstone modes

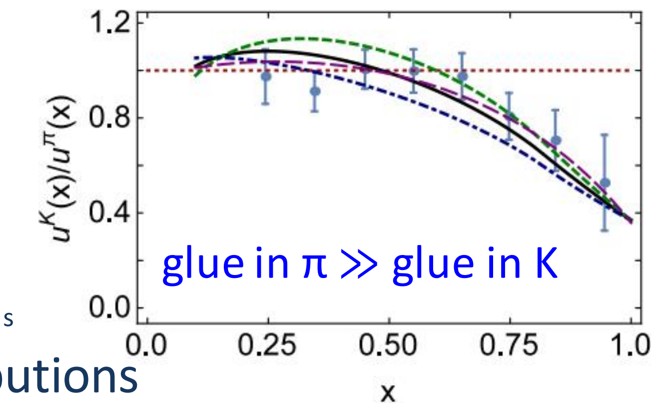
✓ DCSB: whilst constituents are massive, NG-modes are (nearly) massless

Consequences … 2

- QCD's unique Gell-Mann–Low effective coupling
  - ✓ Infrared finite … α(~ 0) ≈ π
  - ✓ Landau pole of perturbation theory is eliminated by emergence of gluon mass
  - ✓ Cross-sections are free of infrared divergences



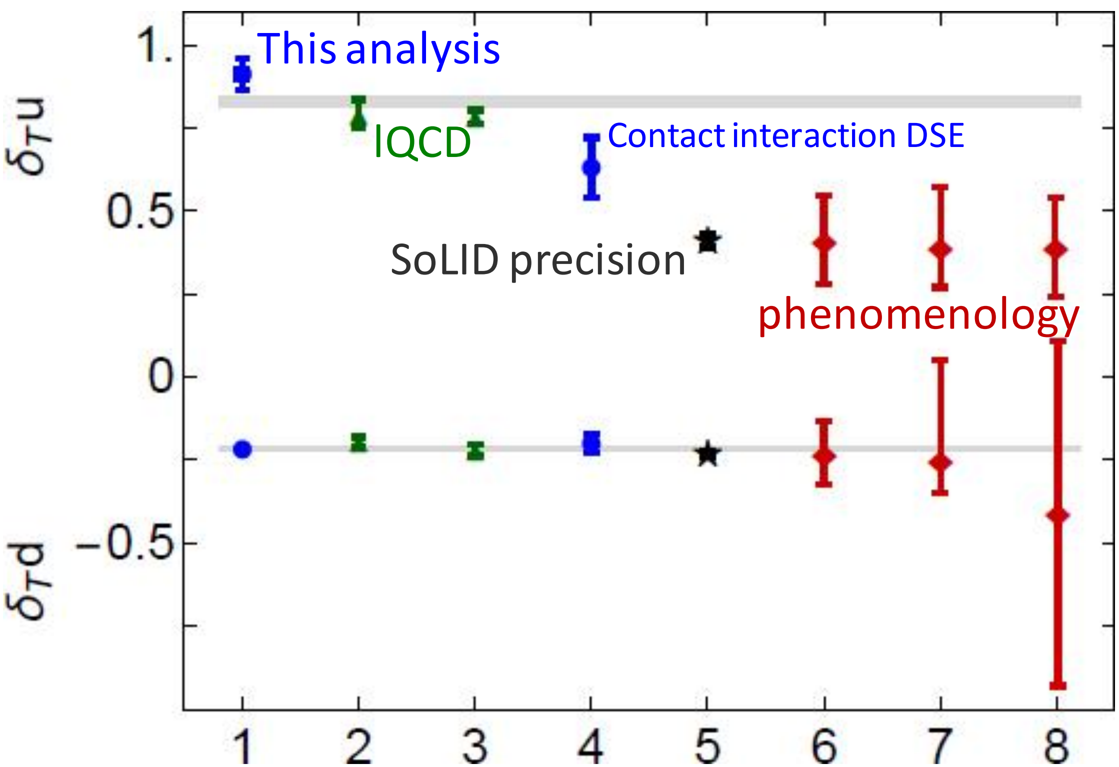
- PDAs of ground-state *S*-wave mesons and baryons are broad, concave functions
  - – Numerous empirical consequences ⇒ empirically verifiable
    - Hadron elastic and transition form factors
- Emergent vs Explicit (Higgs) mass generation
  - – s-quark defines a boundary:
    - emergent mass generation dominates for $m < m_s$
    - but explicit (Higgs) mass is most important for $m > m_s$
  - – s-quark/u-quark comparisons in parton distributions are a sensitive probe of emergent mass and its distribution



Consequences … 3

- Existence of strong nonpointlike scalar and axial-vector diquark correlations in the nucleon.
  - Scalar-diquark-only picture of nucleon structure is ruled-out.
  - Axial-vector correlations are essential
- Empirically verifiable consequences
  - Example … proton's tensor charges:
    - $\delta_T d \neq 0 \Rightarrow$ rules-out scalar-diquark-only nucleon
    - $\delta_T u \approx 4\,|\,\delta_T d\,|$

    can be understood as result of highly-correlated proton wave function



Hybrids & Exotics

Spectrum of light hadrons

- Known spectrum of light hadrons is simple
  - Qualitatively matches the pattern established by the constituent-quark models of Gell-Mann and Zweig (1964)
    - Mesons built from a constituent-quark-antiquark ($Q\bar{Q}$) pair
    - Baryons constituted from three constituent quarks (QQQ)

  where *Q* is associated with any one of the light *u*-, *d*-, *s*-quarks.

- Gell-Mann and Zweig also raised possibility that more complicated bound-states are possible, *e.g*.
  - $QQ\bar{Q}\bar{Q}$ & $Q\bar{Q}QQQ$ (they didn't know about glue)

  No candidates were then known

  But after ~ 50 years, in systems involving the heavier *c*- and *b*-quarks, that has now changed

  X, Y, Z … pentaquarks

Spectrum of light hadrons

- Early ‘70s … “discovery” of quantum chromodynamics (QCD)
  - Non-Abelian, relativistic quantum gauge field theory
  - 8 self-interacting gauge bosons (gluons) mediate the interactions between current quarks
- New possibilities arose, *viz*. systems with valence glue,
  - hybrid (& exotic) mesons – $GQ\bar{Q}$
  - hybrid baryons – QQQG,
  - even *glueballs* – GG.

Distinction is lost between force and matter fields

“G” is a “constituent gluon” degree of freedom

- Unknown quantity
- Character will only become known once such systems are detected

- Today's tabulations of hadron masses identify at least three plausible hybrid-meson candidates below 2 GeV
  - Dedicated searches for such states are underway at modern facilities (*e.g*. COMPASS @ CERN, GlueX @ JLab)

Models & Hybrids

- Over time, numerous models have been employed to calculate spectrum of light hybrid mesons
- Approaches are distinguished by, *inter alia*:
  - Disparate treatments/definitions of G
- Resulting spectra disagree
- Nevertheless
  - Development of a reliable continuum method for calculating hybrid meson properties would be very valuable
    - For interpretation of empirical observations
    - Provide insights into results obtained via the numerical simulation of lattice regularised QCD (lQCD)

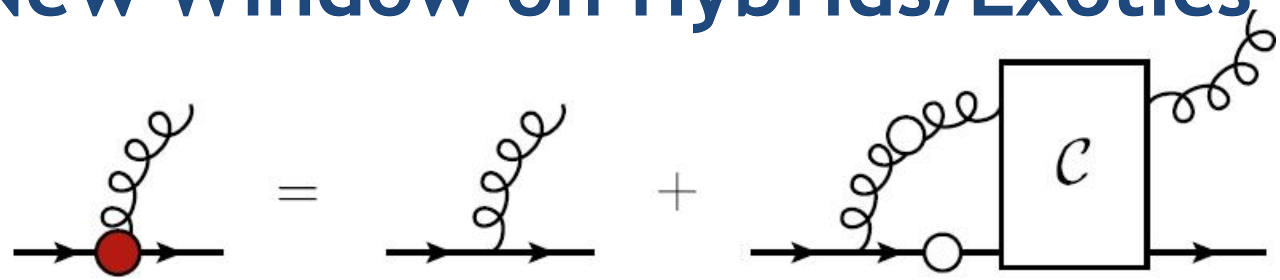
Basic Hypothesis

- *A hybrid meson is not qualitatively different from any other strong interaction bound-state, viz. it can be described by a Poincaré-covariant bound-state equation built with the dressed-parton degrees of freedom that are generated by solutions of gap equations in the matter and gauge sectors.*
- Within quantum field theory, there is no alternative to this position. Stated simply, we search for a bound-state solution in the gluon-quark-antiquark scattering problem.
- Lattice-QCD analyses of hybrids and glueballs formulate the problem in the same way.
- The only difference between the lattice starting point and ours is that we work in momentum space, whereas lattice studies are in configuration space.

Continuum Bound-State Problem

- $Q\bar{Q}$ mesons in quantum mechanics can't possess following (exotic) quantum numbers: $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}$, etc.
- Not so in Poincaré-covariant treatments of two-valence-body bound states owing to existence of additional degree of freedom
  - relative time between the valence-quark and –antiquark => $k{\cdot}P \neq 0$
- However, extant studies of exotic mesons using simple *Ansätze* or truncations for Bethe-Salpeter kernel produce unrealistic spectra
  - exotic mesons with masses so light that they should already have been seen empirically when, in fact, signals for such states are currently weak and lie at significantly higher masses.
- Furthermore, 2-body Bethe-Salpeter equation does not readily distinguish between regular mesons and hybrids with same J^{PC}.
- Weaknesses: not remedied by using more sophisticated kernels
- Strong signal that hybrid mesons must contain explicit valence-gluon degree-of-freedom

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 $\bar{q}$

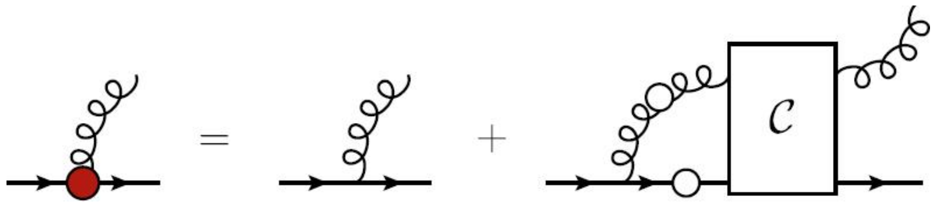
  If so, then distinction is lost between force and matter fields

- 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

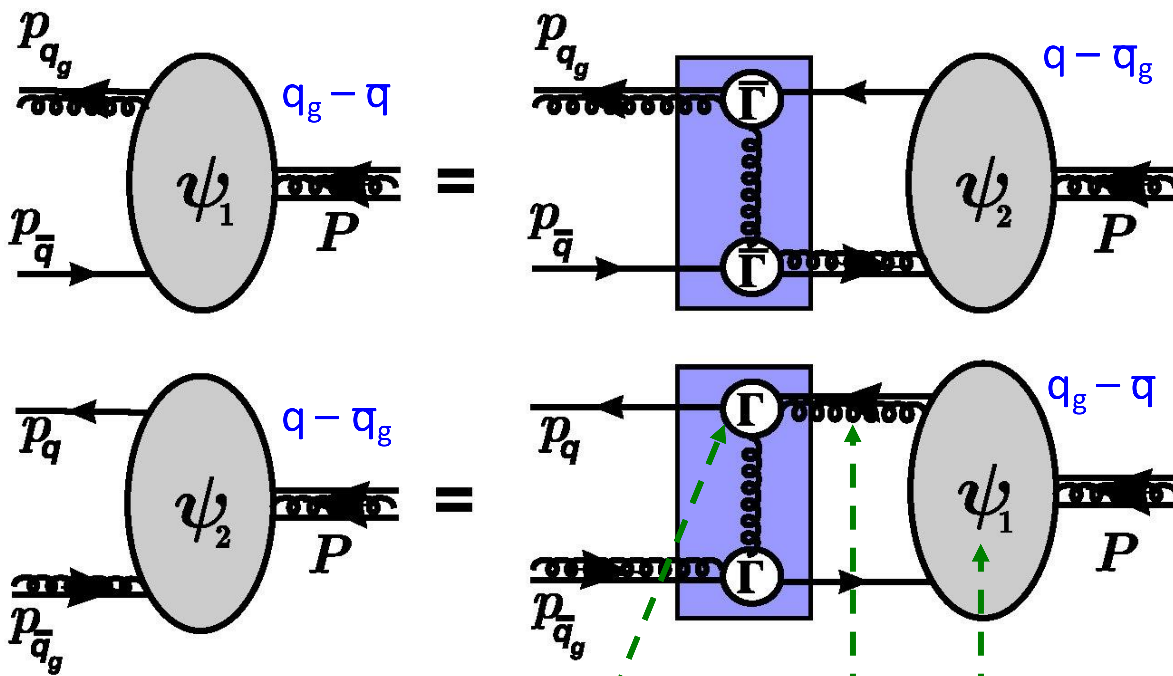
  $\Psi = \Psi_1 + \Psi_2$,

  $\Psi_1 = q_g\bar{q}$ & $\Psi_2 = q\bar{q}_g$

- 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

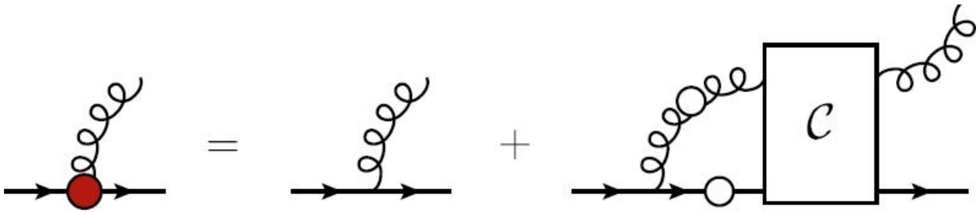
gq correlation propagator

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

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

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
      - $M_g^{IR} \approx ½\ m_{proton}$
      - $M_q^{IR} \approx ⅓\ m_{proton}$
    - $Mass_{(g+q)} \approx m_{proton} \approx 1$ 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 – $\delta_{\pi 1}$

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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?*

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

Hybrid Meson Spectrum

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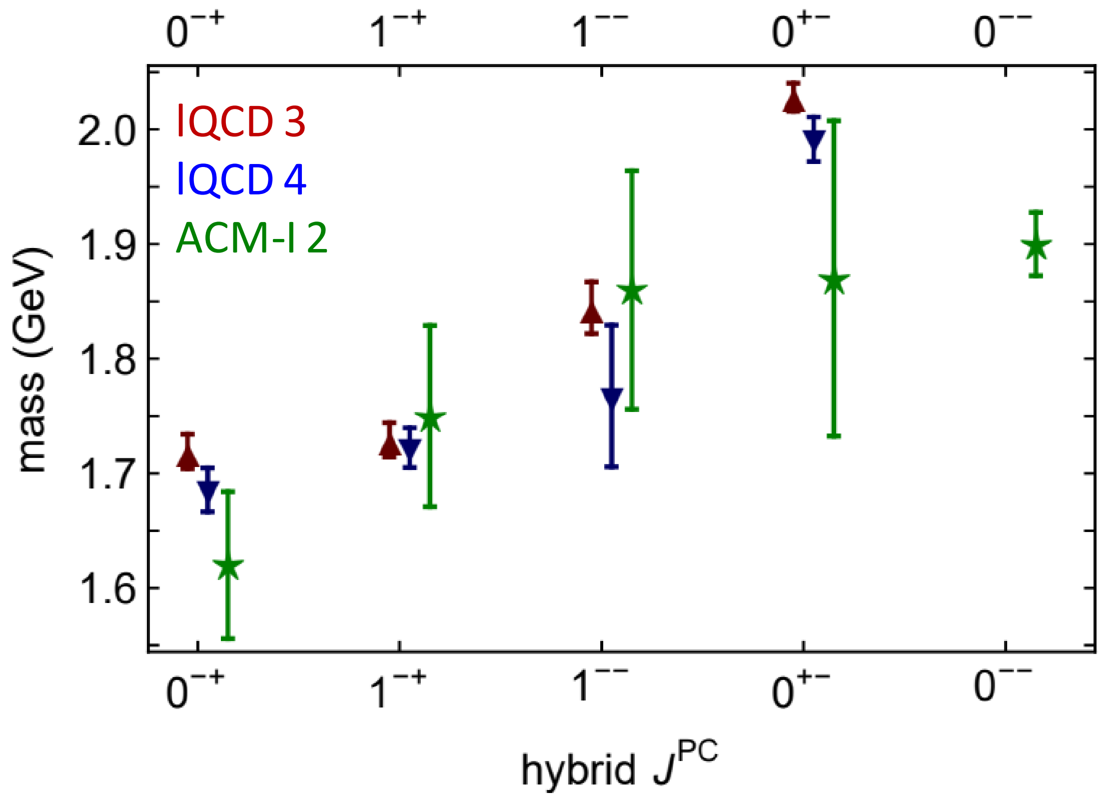
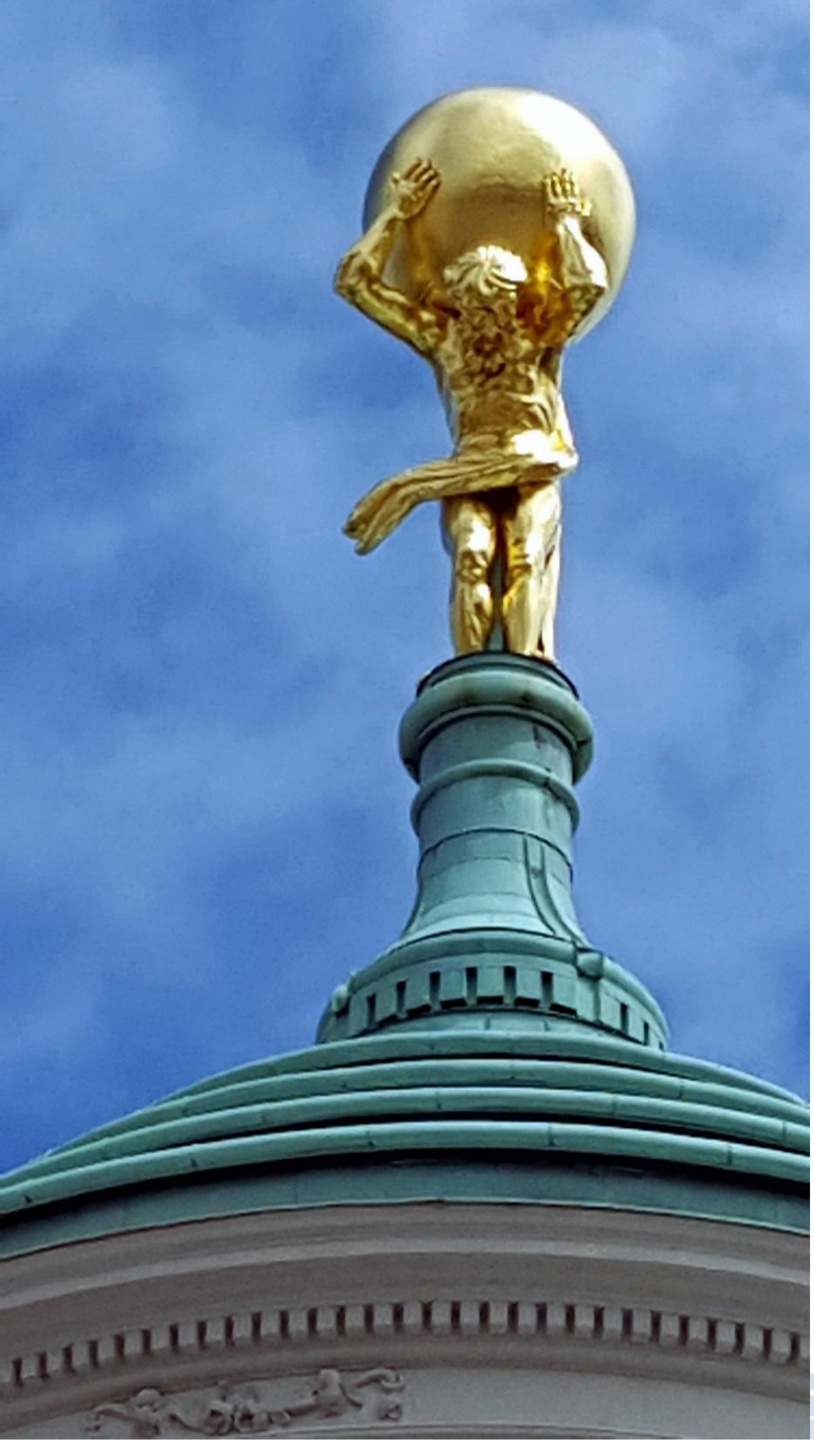
- Beyond-RL essential to agreement with lQCD
- Agreement is non-trivial
  - lQCD masses are rescaled by subtraction of $\delta_{\pi 1}$, a number which is completely unrelated to our calculations.
- No single lQCD mass was used as a constraint when fitting κ_{gq}
- Magnitude of our results set by
  -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



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 $q_g\bar{q} \leftrightarrow q\bar{q}_g$
  - Since diquark correlations basic to determining baryon properties, existence & importance of kindred correlations in 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 & $\bar{q}_g$

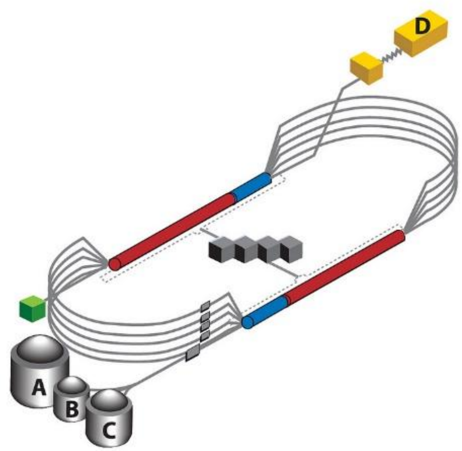


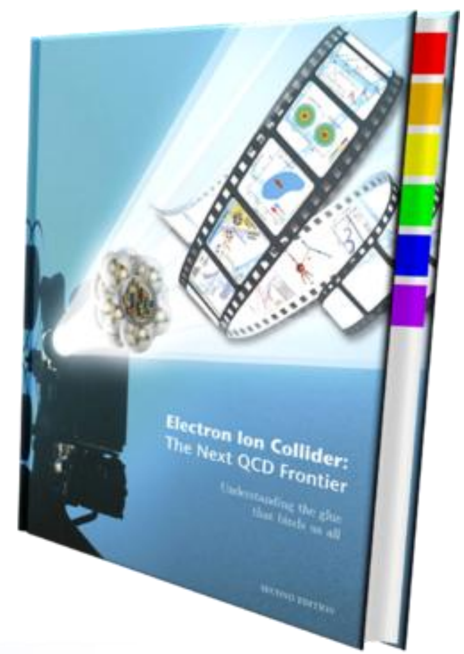
Epilogue

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 amalga
  - Experiment
  - Phenomenology
  - Theory
- Must continue into eras of



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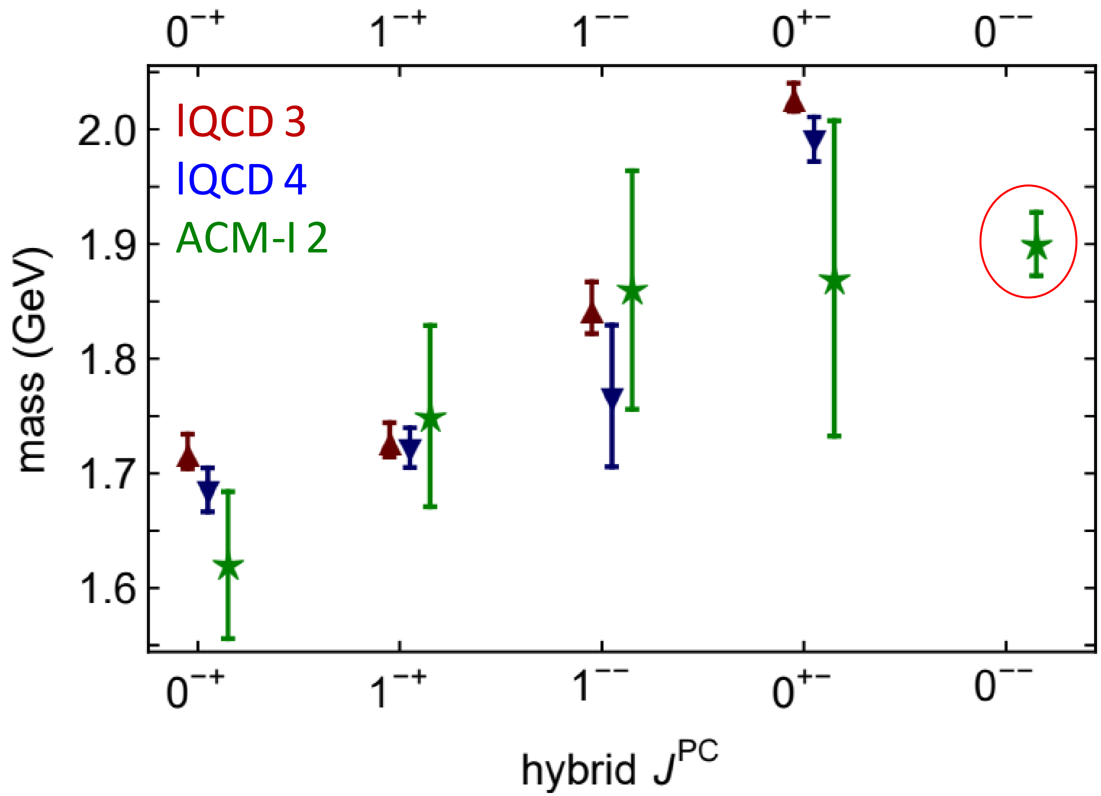
Thankyou

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.

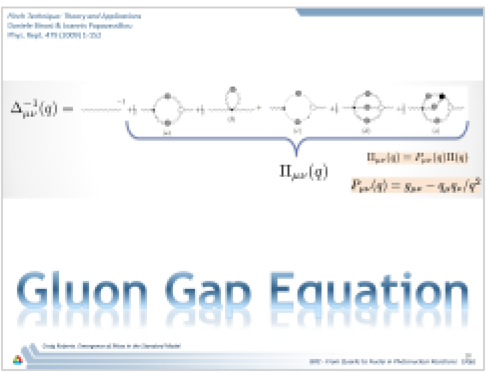


Contents

Emergent Phenomena in the Standard Model
Existence of our Universe 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

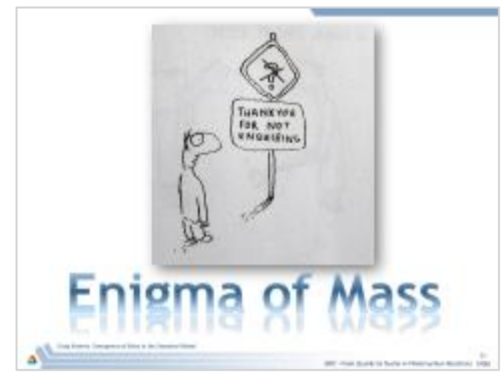
Where is the mass?

Ideas: Old & New



Gluon Gap Equation

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



THANK YOU FOR NOT ENQUIRING
Enigma of Mass

Revealing Mass

GLUEX
citations
periment
Hybrids & Exotics