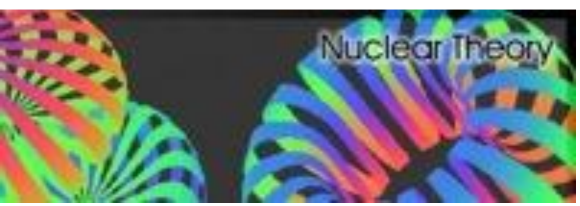
Partons to Reality: A Matter of Substance

Craig Roberts



Physics Division

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

National Science Foundation
WHERE DISCOVERIES BEGIN

Published collaborations: 2010-present

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Early-career scientists

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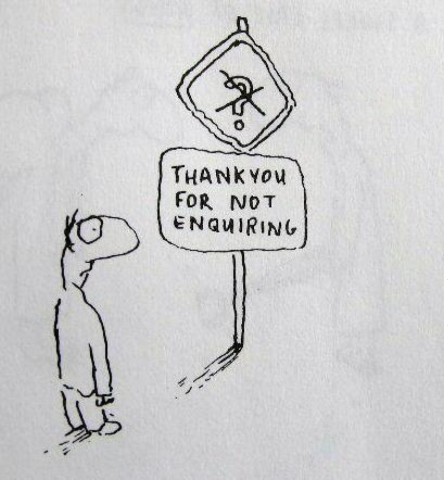
U.S. DEPARTMENT OF ENERGY



Excited Baryons
V. Mokeev: Tues. 13:30
D. Wilson: Tues. 15:10
R. Gothe: Wed. 14:10
T.-S.H. Lee: Wed. 16:00

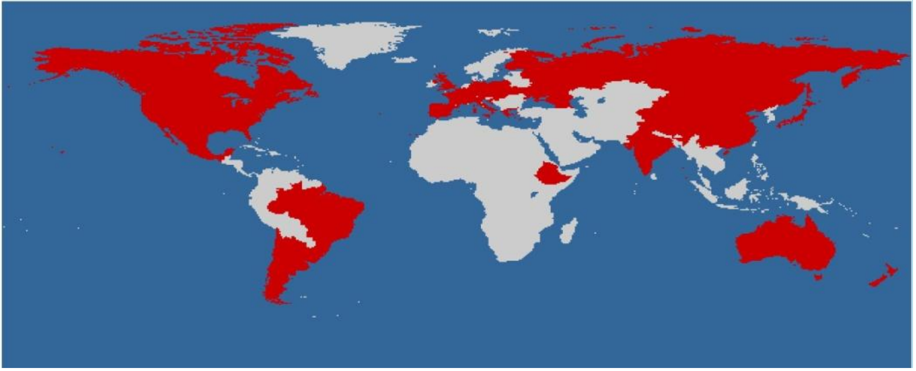
QCD's Challenges

Understand emergent phenomena

- *Quark and Gluon Confinement*
  No matter how hard one strikes the proton,
  one cannot liberate an individual gluon or quark
- *Dynamical Chiral Symmetry Breaking*
  Very unnatural pattern of bound state masses;
  e.g., Lagrangian (pQCD) quark mass is small but
  . . . no degeneracy between $J^P=+$ and $J^P=-$ *(parity partners)*

J^P	$\frac{1}{2}^+$ (p)	$\frac{1}{2}^-$
Mass	940 MeV	1535 MeV

- *Neither of these phenomena is apparent in QCD's Lagrangian*
  Yet they are the dominant determining characteristics of real-world QCD.
- QCD
  – Complex behaviour from apparently simple rules.



Dyson-Schwinger Equations

- Well suited to Relativistic Quantum Field Theory
- Simplest level: Generating Tool for Perturbation Theory . . . Materially Reduces Model-Dependence … Statement about long-range behaviour of quark-quark interaction
- NonPerturbative, Continuum approach to QCD
- Hadrons as Composites of Quarks and Gluons
- Qualitative and Quantitative Importance of:
  - Dynamical Chiral Symmetry Breaking
    - Generation of fermion mass from *nothing*
  - Quark & Gluon Confinement
    - Coloured objects not detected, *Not detectable?*

- Approach yields Schwinger functions; i.e., propagators and vertices
- Cross-Sections built from Schwinger Functions
- Hence, method connects observables with long-range behaviour of the running coupling
- Experiment ↔ Theory comparison leads to an understanding of long-range behaviour of strong running-coupling

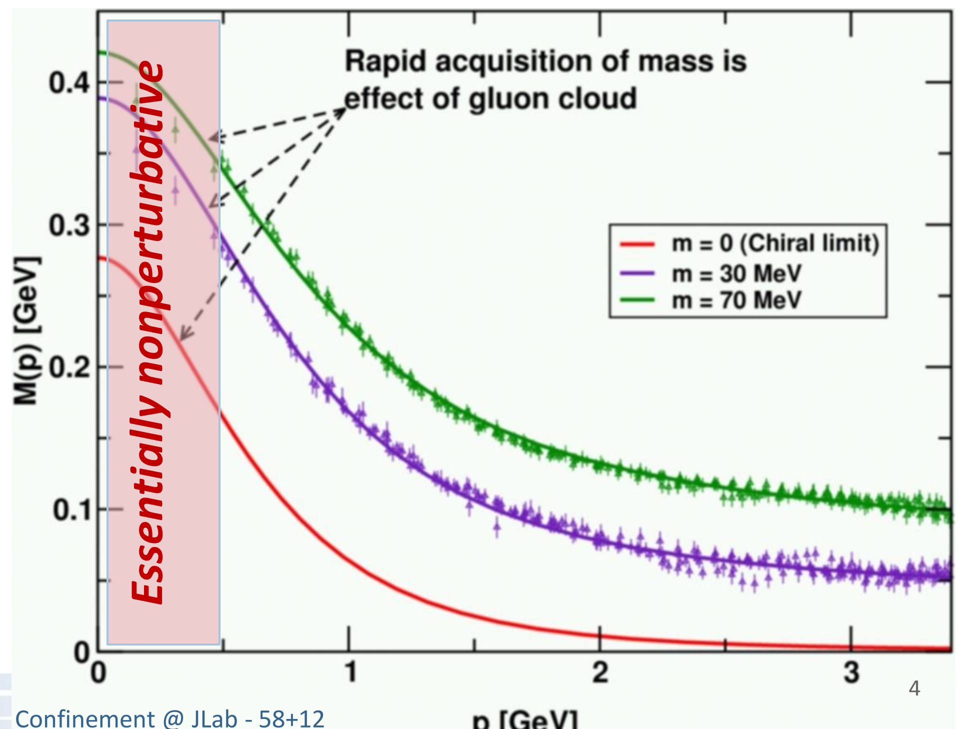
Necessary Precondition

- Experiment ↔ Theory comparison leads to an understanding of long-range behaviour of strong running-coupling
- However, if one wants to draw reliable conclusions about Q^2-dependence of QCD's running coupling,
- Then, approach must veraciously express Q^2-dependence of QCD's running masses
- True for ALL observables
  - ✓ From spectrum …
  - ✓ through elastic & transition form factors …
  - ✓ to PDFs and GPDs … etc.

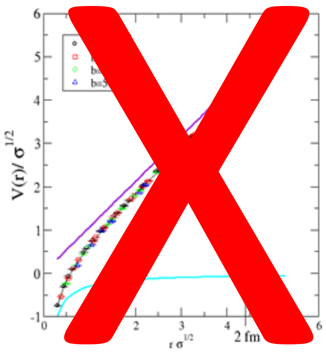
- Mass function exhibits inflexion point at Q_{IR}≈0.5GeV
- So … pQCD is *definitely invalid* for momenta $Q<Q_{IR}$
- E.g., use of DGLAP equations cannot be justified in QCD at $Q<Q_{IR}=0.5$GeV, irrespective of order.

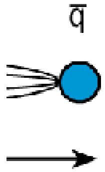
Distribution Functions of the Nucleon and Pion in the Valence Region, Roy J. Holt and Craig D. Roberts
arXiv:1002.4666 [nucl-th],
Rev. Mod. Phys. **82** (2010) pp. 2991-3044

& *presentations by Adnan Bashir and Peter Tandy on Thursday*



Confinement



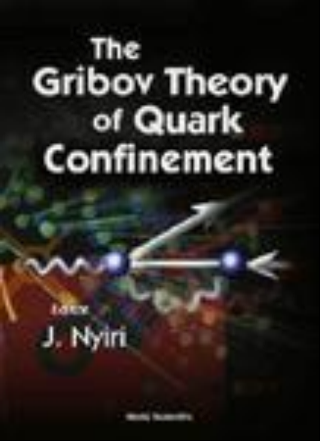


Confinement

$$\mathcal{H}_{\rm QCD} = \sum_n E_n |H_n^{1_c}\rangle\langle H_n^{1_c}|$$

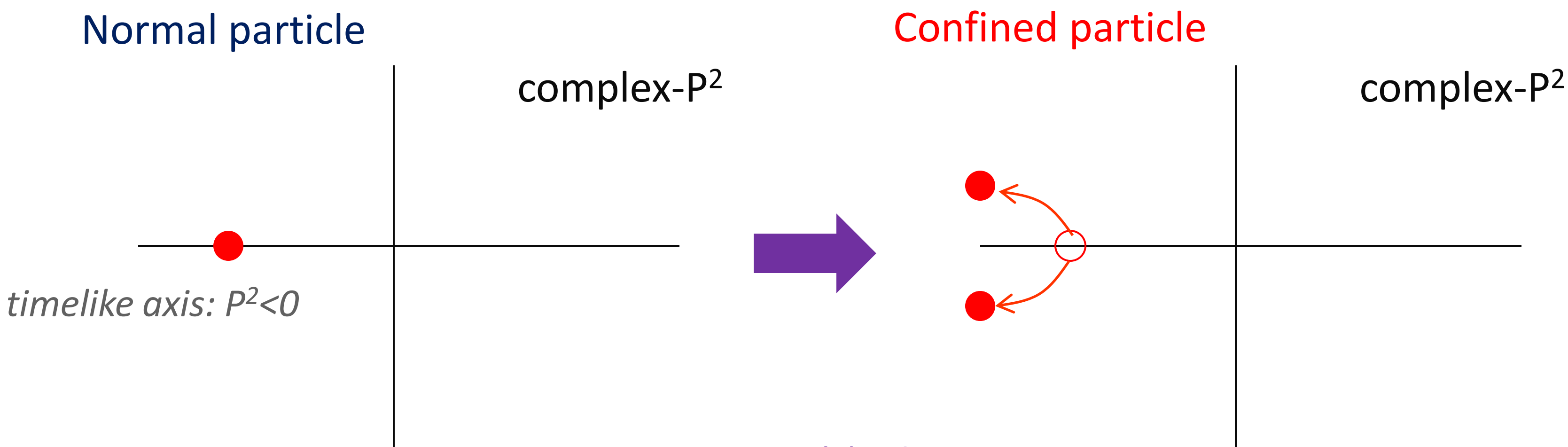
Colour singlets

- Gluon and Quark Confinement
  - No coloured states have yet been observed to reach a detector
- Empirical fact. However
  - There is no agreed, theoretical definition of light-quark confinement
  - Static-quark confinement is irrelevant to real-world QCD
    - *There are no long-lived, very-massive quarks*
    - *But light-quarks are ubiquitous*
- Confinement entails *quark-hadron duality*; i.e., that *all observable consequences of QCD can, in principle, be computed using an hadronic basis.*



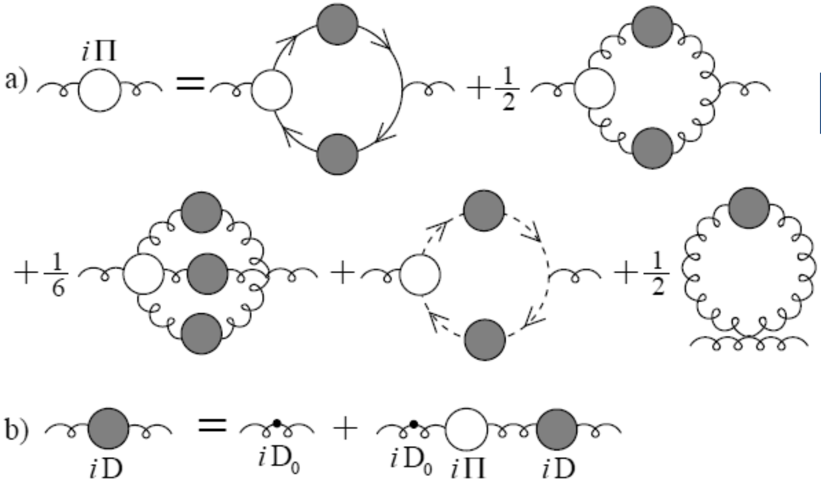
Confinement

- Confinement is expressed through a *dramatic* change in the analytic structure of propagators for coloured particles & can almost be read from a plot of a states' dressed-propagator
  - Gribov (1978); Munczek (1983); Stingl (1984); Cahill (1989); Roberts, Williams & Krein (1992); Tandy (1994); …



○ *Real-axis mass-pole splits, moving into pair(s) of complex conjugate poles or branch points, or more complicated nonanalyticities …*

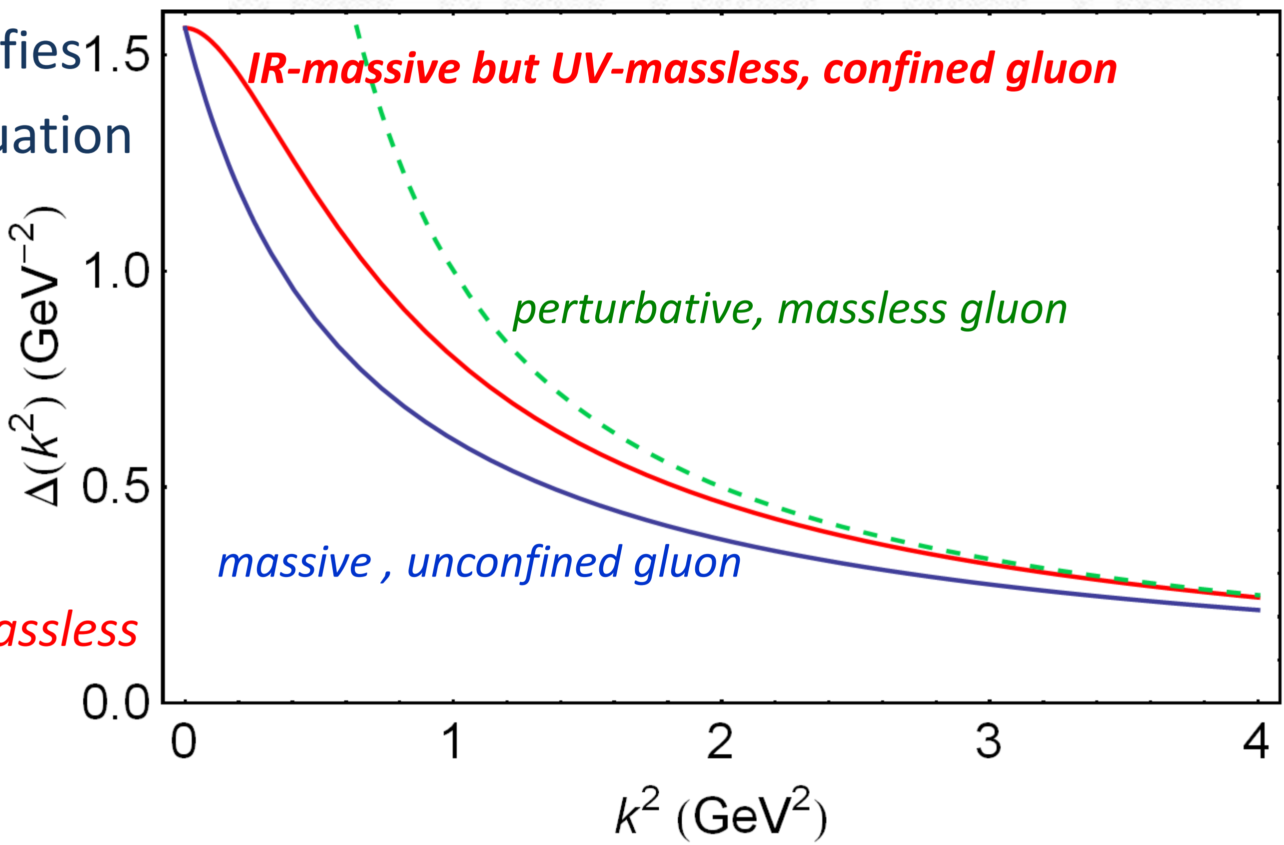
○ *Spectral density no longer positive semidefinite & hence state cannot exist in observable spectrum*



Dressed-gluon propagator

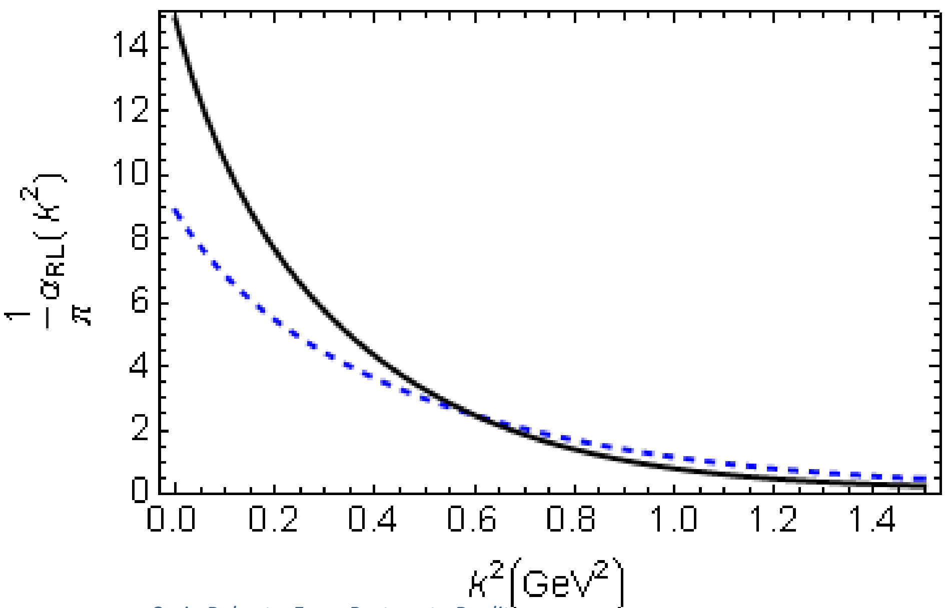
A.C. Aguilar et al., Phys.Rev. D80 (2009) 085018

- Gluon propagator satisfies a Dyson-Schwinger Equation
- Plausible possibilities for the solution
- DSE and lattice-QCD agree on the result
  - *Confined gluon*
  - *IR-massive but UV-massless*
  - $m_G \approx$ 2-4 Λ_{QCD}

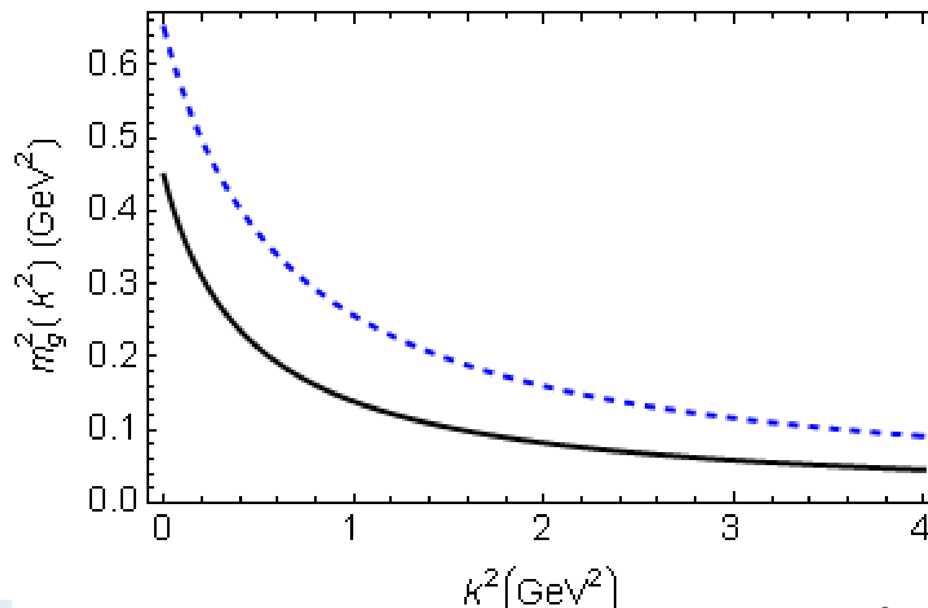


DSE Studies
- Phenomenology of gluon

- Wide-ranging study of π & ρ properties
- Effective coupling
  - Agrees with pQCD in ultraviolet
  - Saturates in infrared
    - $\alpha(0)/\pi$ = 8-15
    - $\alpha(m_G^2)/\pi$ = 2-4



- Running gluon mass
  - Gluon is massless in ultraviolet in agreement with pQCD
  - Massive in infrared
    - $m_G(0)$ = 0.67-0.81 GeV
    - $m_G(m_G^2)$ = 0.53-0.64 GeV

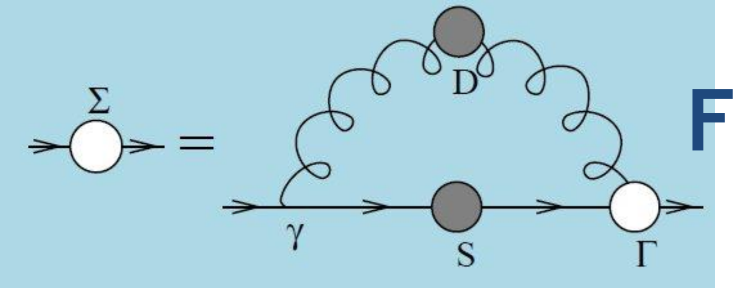


Dynamical Chiral Symmetry Breaking

Dynamical Chiral Symmetry Breaking

- Strong-interaction: QCD
- Confinement
  - Empirical feature
  - Modern theory and lattice-QCD support conjecture
    - that light-quark confinement is a fact
    - associated with violation of reflection positivity;
      i.e., novel analytic structure for propagators and vertices
  - Still circumstantial, no proof yet of confinement
- On the other hand, *DCSB is a fact in QCD*
  - It is the most important mass generating mechanism for visible matter in the Universe.

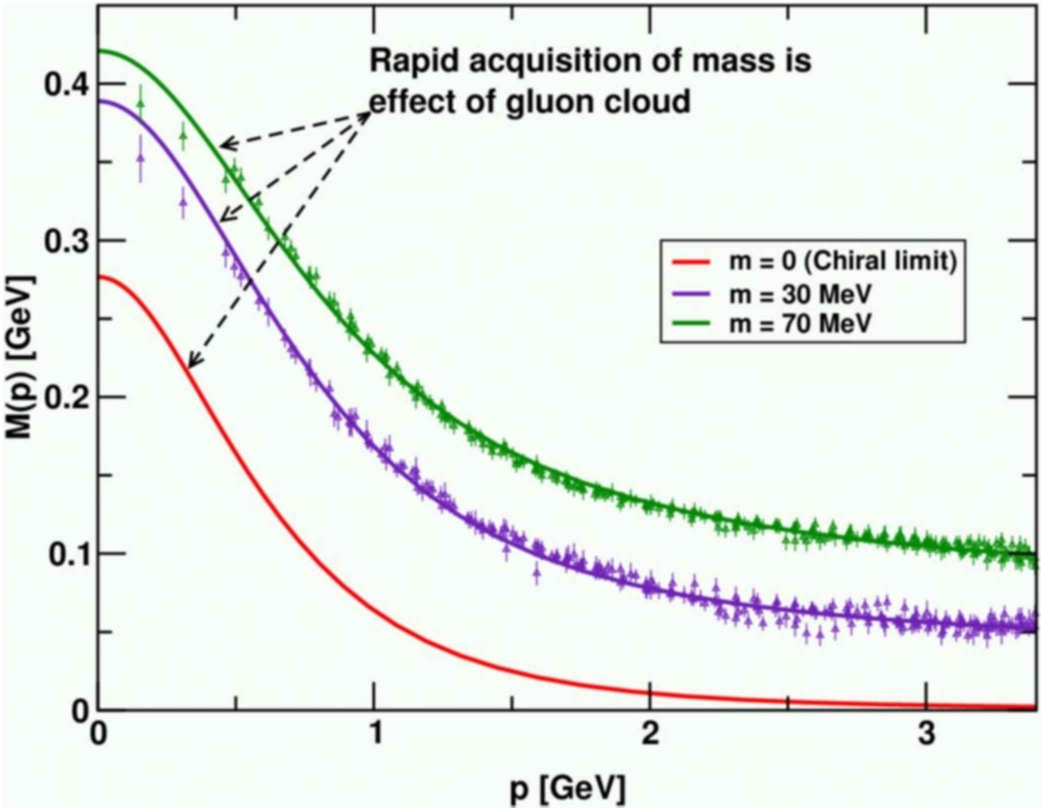
    Responsible for approximately 98% of the proton's mass.
    Higgs mechanism is (*almost*) irrelevant to light-quarks.



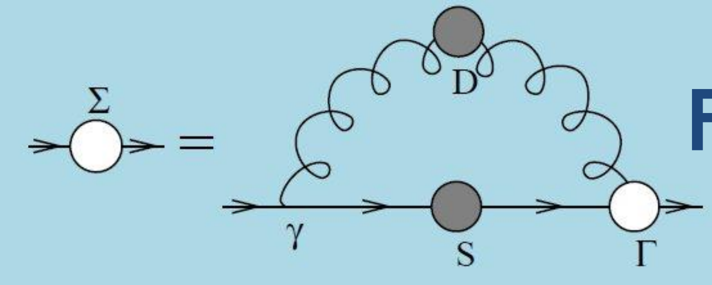
Frontiers of Nuclear Science: Theoretical Advances

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

In QCD a quark's effective mass depends on its momentum. The function describing this can be calculated and is depicted here. **Numerical simulations of lattice QCD** (data, at two different bare masses) **have confirmed model predictions** (solid curves) **that the vast bulk of the constituent mass of a light quark comes from a cloud of gluons that are dragged along by the quark as it propagates**. In this way, a quark that appears to be absolutely massless at high energies (m =0, **red curve**) acquires a large constituent mass at low energies.



C.D. Roberts, Prog. Part. Nucl. Phys. 61 (2008) 50
M. Bhagwat & P.C. Tandy, AIP Conf.Proc. 842 (2006) 225-227



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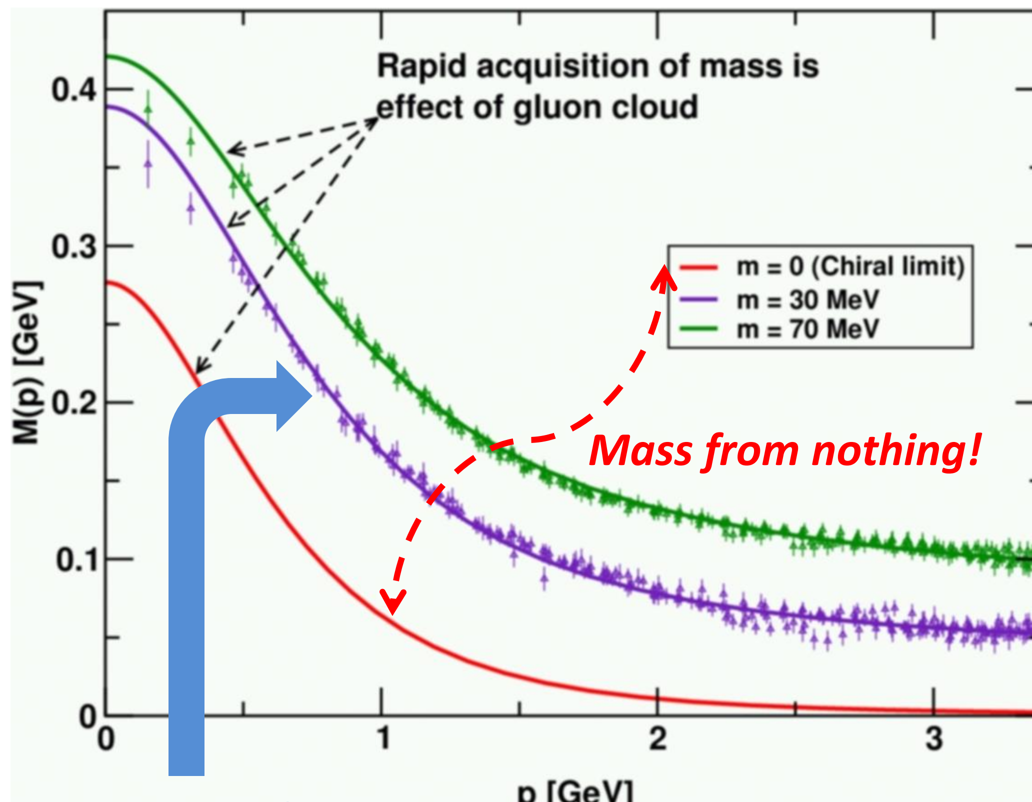
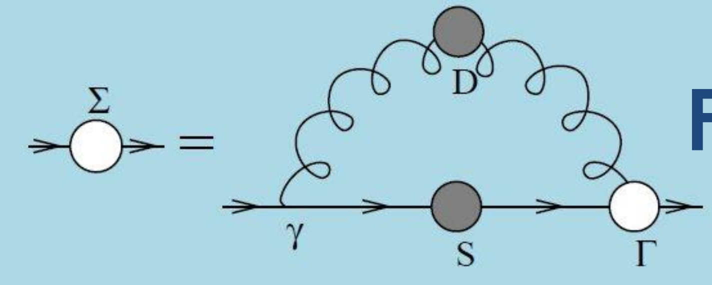


DSE prediction of DCSB confirmed



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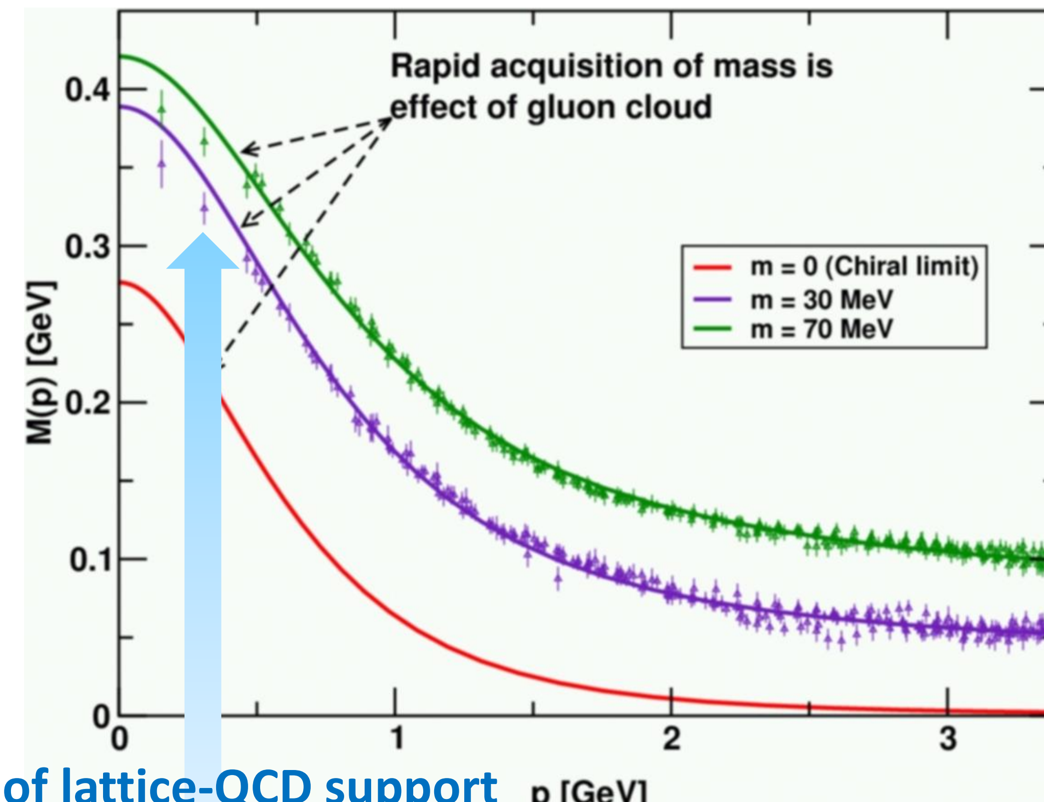

Hint of lattice-QCD support for DSE prediction of violation of reflection positivity

12GeV
The Future of JLab

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

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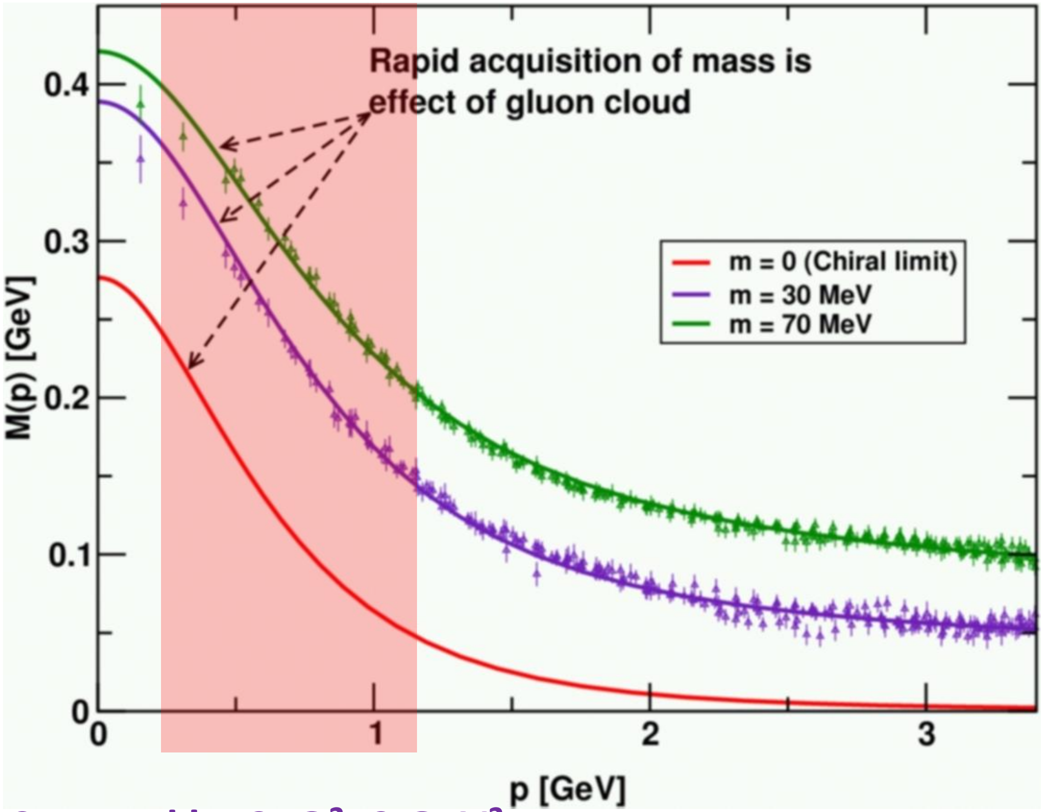
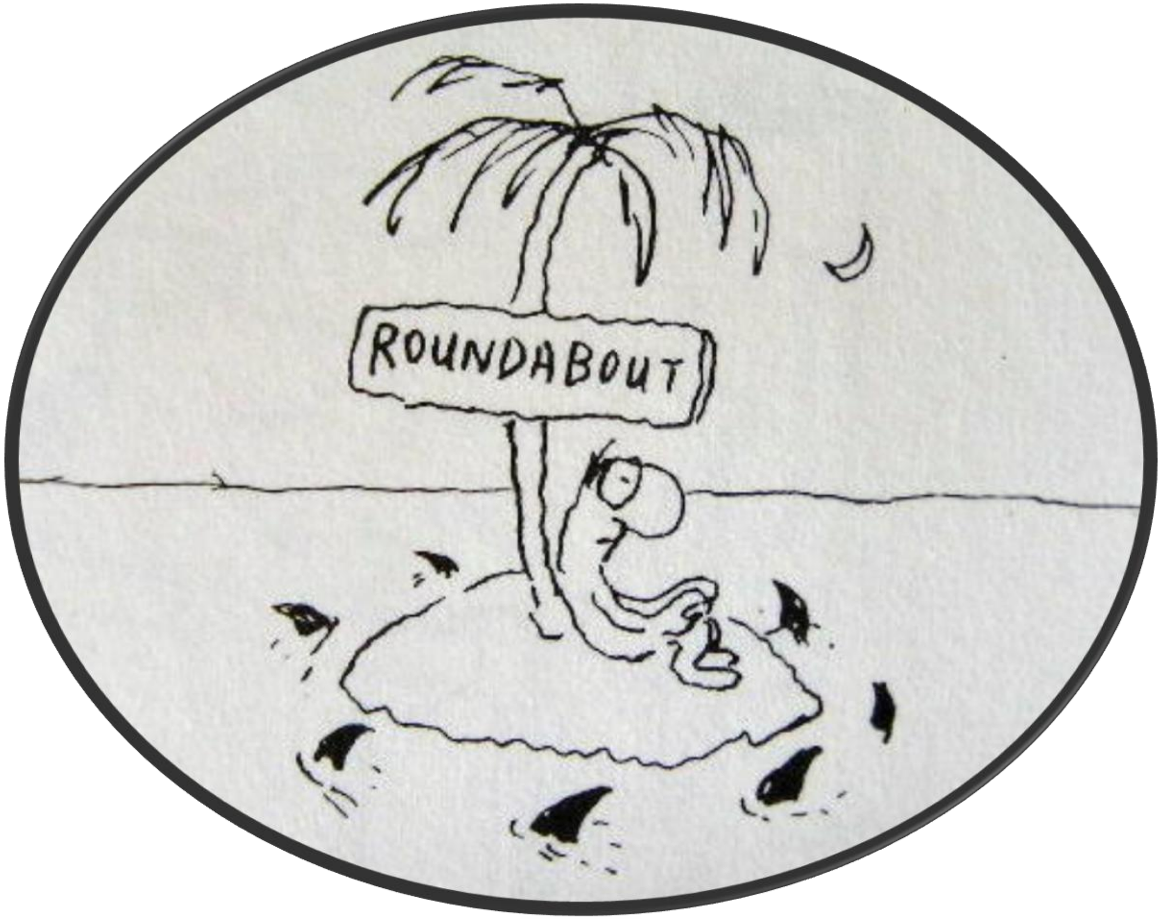


Jlab 12GeV: Scanned by $2<Q^2<9$ GeV^2 elastic & transition form factors.



Persistent Challenge

Truncation

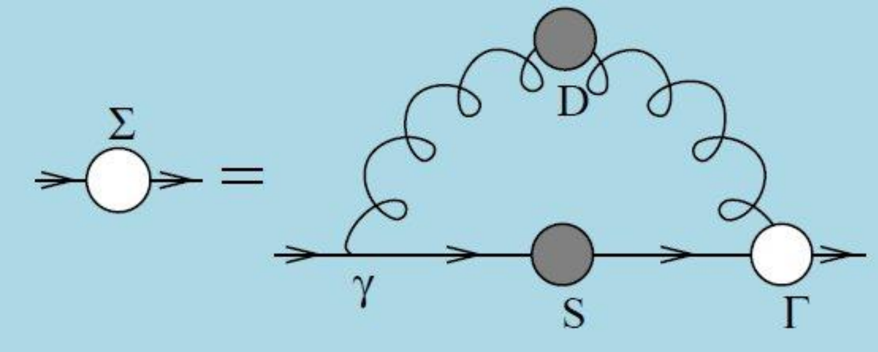
Dichotomy of the pion
Goldstone mode and bound-state

- The *correct understanding* of pion observables; e.g. mass, decay constant and form factors, requires an approach to contain a
  - well-defined and valid chiral limit;
  - and an accurate realisation of dynamical chiral symmetry breaking.

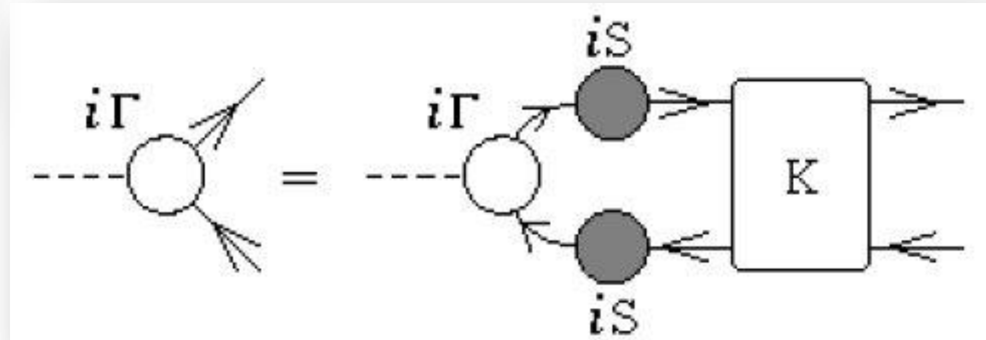
HIGHLY NONTRIVIAL

Impossible in quantum mechanics

Only possible in asymptotically-free gauge theories

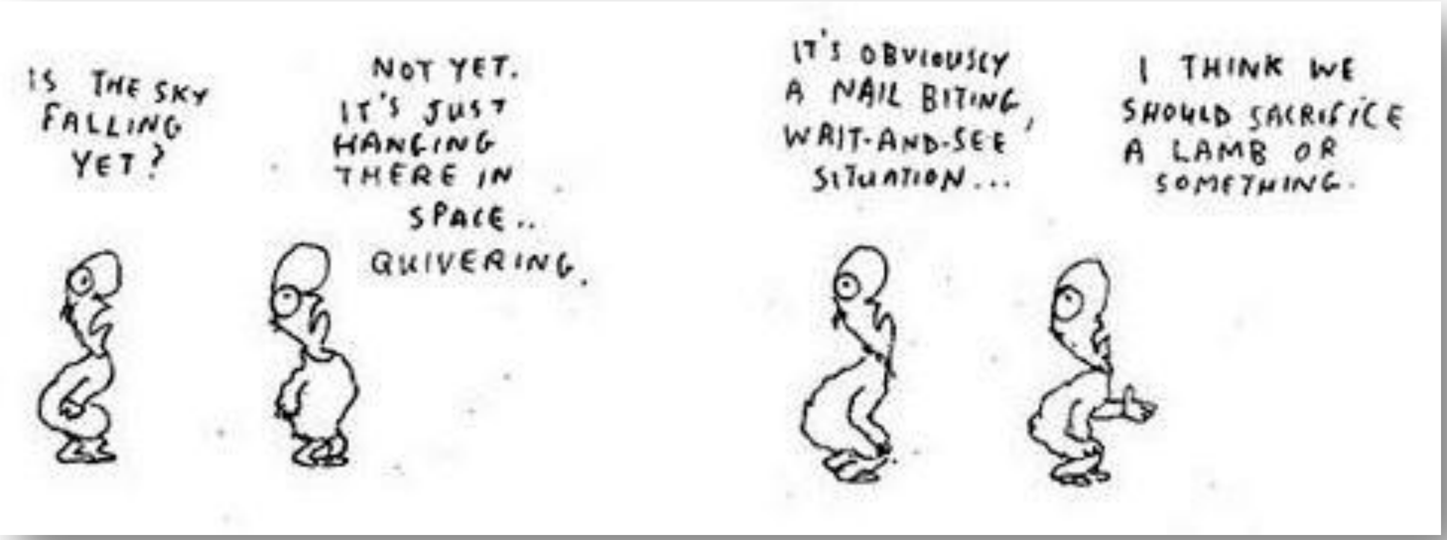


Persistent challenge - truncation scheme



- There are now two ***nonperturbative*** & ***symmetry preserving*** truncation schemes
  1. ***1995*** – H.J. Munczek, Phys. Rev. D **52** (1995) 4736, *Dynamical chiral symmetry breaking, Goldstone's theorem and the consistency of the Schwinger-Dyson and Bethe-Salpeter Equations*

     1996 – A. Bender, C.D. Roberts and L. von Smekal, Phys.Lett. B **380** (1996) 7, *Goldstone Theorem and Diquark Confinement Beyond Rainbow Ladder Approximation*
  2. ***2009*** – Lei Chang and C.D. Roberts, Phys. Rev. Lett. 103 (2009) 081601, 0903.5461 [nucl-th], *Sketching the Bethe-Salpeter kernel*
- Enables proof of numerous exact results



Some of many Exact Results

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

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

Pseudovector components necessarily nonzero. Cannot be ignored!

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

- Axial-vector Ward-Takahashi identity entails

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

Exact in Chiral QCD

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

Dichotomy of the pion
Goldstone mode and bound-state

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

- Goldstone's theorem
  has a pointwise expression in QCD;

  Namely, in the chiral limit the wave-function for the two-body bound-state Goldstone mode is intimately connected with, and almost completely specified by, the fully-dressed one-body propagator of its characteristic constituent

  - The one-body momentum is equated with the relative momentum of the two-body system

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

Dichotomy of the pion
Mass Formula for 0⁻ Mesons

$$f_{H_5} m^2_{H_5} = \rho^{\zeta}_{H_5} \mathcal{M}^{\zeta}_{H_5}$$

- Mass-squared of the pseudscalar hadron
- Sum of the current-quark masses of the constituents;

  e.g., pion = $m_u^\varsigma + m_d^\varsigma$, where "ς" is the renormalisation point

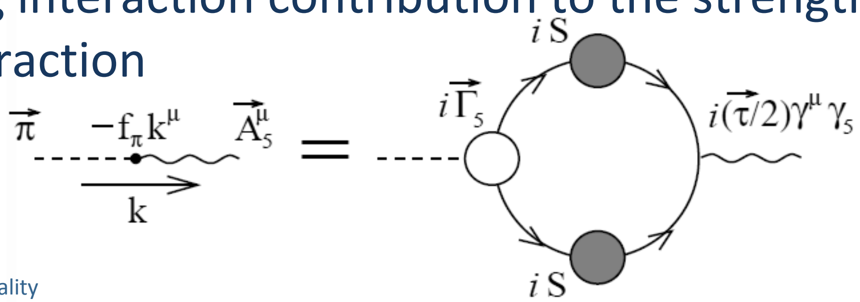
Maris, Roberts and Tandy
nucl-th/9707003, Phys.Lett. B**420** (1998) 267-273

Dichotomy of the pion Mass Formula for 0⁻ Mesons

$$f_{H_5}\, m^2_{H_5} = \rho^\zeta_{H_5} \mathcal{M}^\zeta_{H_5}$$

$$f_{H_5} P_\mu = Z_2 \mathrm{tr} \int \frac{d^4q}{(2\pi)^4} \frac{1}{2} (T^{H_5})^{\mathrm{t}} \gamma_5 \gamma_\mu S(q+\frac{1}{2}P) \Gamma_{H_5}(q;P) S(q-\frac{1}{2}P)$$

- Pseudovector projection of the Bethe-Salpeter wave function onto the origin in configuration space
  - Namely, the pseudoscalar meson's leptonic decay constant, which is the strong interaction contribution to the strength of the meson's weak interaction

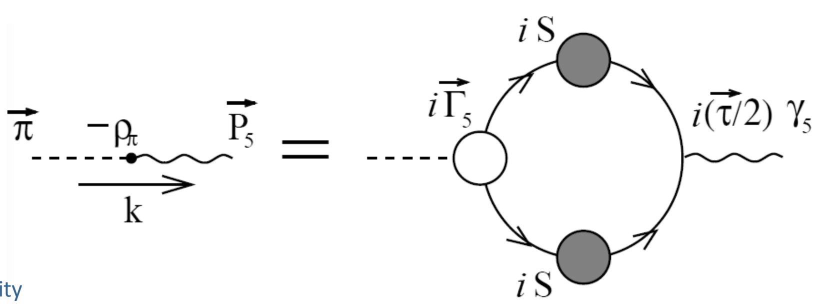


Dichotomy of the pion
Mass Formula for 0⁻ Mesons

$$f_{H_5}\, m^2_{H_5} = \rho^{\zeta}_{H_5} \mathcal{M}^{\zeta}_{H_5}$$

$$i\rho_{H_5} = Z_4 \mathrm{tr} \int \frac{d^4q}{(2\pi)^4} \frac{1}{2} (T^{H_5})^{\rm t} \gamma_5 S(q+\frac{1}{2}P)\Gamma_{H_5}(q;P)S(q-\frac{1}{2}P)$$

- Pseudoscalar projection of the Bethe-Salpeter wave function onto the origin in configuration space
  - Namely, a pseudoscalar analogue of the meson's leptonic decay constant



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

Dichotomy of the pion
Mass Formula for 0^- Mesons

$$f_{H_5}\, m^2_{H_5} = \rho^\zeta_{H_5} \mathcal{M}^\zeta_{H_5}$$

- Consider the case of light quarks; namely, $m_q \approx 0$
  - If chiral symmetry is dynamically broken, then
    - $f_{H5} \to f_{H5}^0 \neq 0$
    - $\rho_{H5} \to -<q\text{-bar}\, q> / f_{H5}^0 \neq 0$

    both of which are independent of m_q
- Hence, one arrives at the corollary

The so-called "vacuum quark condensate." More later about this.

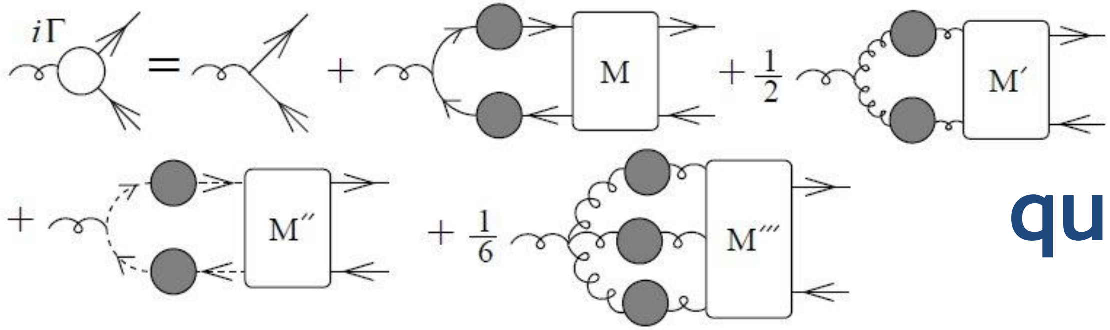
Gell-Mann, Oakes, Renner relation 1968

$$m^2_{H_5} = 2 m_q \frac{-\langle \bar{q} q \rangle}{f^0_{H_5}}$$

$$m_\pi^2 \propto m$$

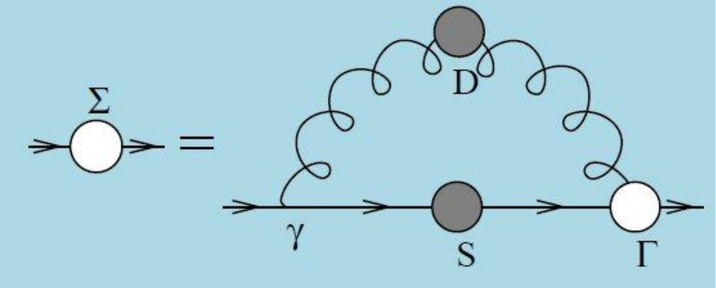
Dynamical Chiral Symmetry Breaking

Importance of being well-dressed for quarks & mesons



Dressed-quark-gluon vertex

- Single most important feature
  - Perturbative vertex is helicity-conserving:
    - Cannot cause spin-flip transitions
  - *However,* DCSB introduces nonperturbatively generated structures that very strongly break helicity conservation
  - These contributions
    - Are large when the dressed-quark mass-function is large
      - Therefore vanish in the ultraviolet; i.e., on the perturbative domain
  - Exact form of the contributions is still the subject of debate *but* their *existence* is model-independent - *a fact*.



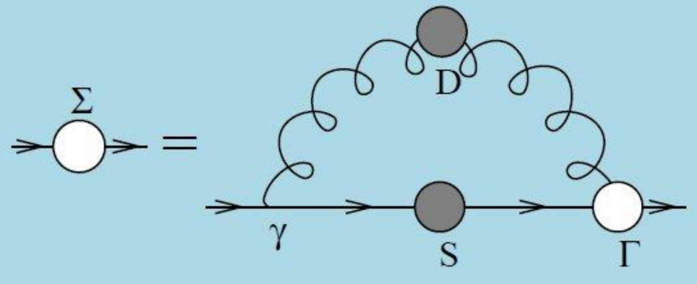
Gap Equation General Form

$$S_f(p)^{-1} = Z_2\,(i\gamma\cdot p + m_f^{\rm bm}) + \Sigma_f(p)\,,$$

$$\Sigma_f(p) = Z_1 \int_q^\Lambda g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S_f(q)\frac{\lambda^a}{2}\Gamma^f_\nu(q,p)$$

- ***$D_{\mu\nu}(k)$ – dressed-gluon propagator***
- ***$\Gamma_\nu(q,p)$ – dressed-quark-gluon vertex***
- Until 2009, all studies of other hadron phenomena used the leading-order term (or LO+NLO) in a symmetry-preserving truncation scheme; viz.,
  – ***$D_{\mu\nu}(k)$ =*** fully-dressed
  – ***$\Gamma_\nu(q,p) = \gamma_\mu$***
    • **…** plainly, key nonperturbative effects are missed and cannot be recovered through any step-by-step improvement procedure

Bender, Roberts & von Smekal
Phys.Lett. B380 (1996) 7-12



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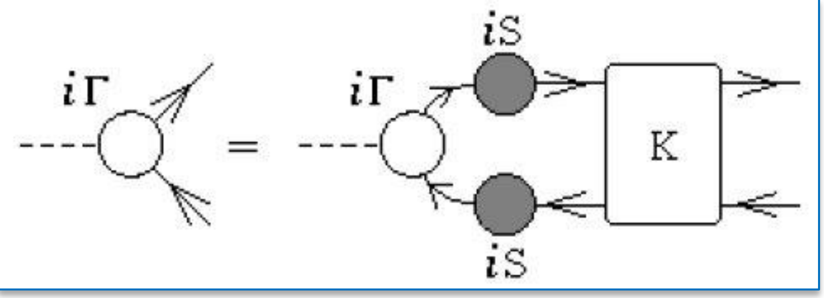
- ***$D_{\mu\nu}(k)$ – dressed-gluon propagator***
  - ***good deal of information available***
- ***$\Gamma_\nu(q,p)$ – dressed-quark-gluon vertex***
  - ***Information accumulating***
- **Suppose one has in hand – from anywhere – the exact form of the dressed-quark-gluon vertex**

If kernels of Bethe-Salpeter and gap equations don't match, one won't even get right charge for the pion.

What is the associated symmetry-preserving Bethe-Salpeter kernel?!



Bethe-Salpeter Equation
Bound-State DSE

$$[\Gamma_\pi^j(k;P)]_{tu} = \int_q^\Lambda [S(q+P/2)\Gamma_\pi^j(q;P)S(q-P/2)]_{sr} K_{tu}^{rs}(q,k;P)$$

- ***K(q,k;P) – fully amputated, two-particle irreducible, quark-antiquark scattering kernel***
- **Textbook material.**
- **Compact. Visually appealing. Correct**

Blocked progress for more than 60 years.

Bethe-Salpeter Equation General Form

Lei Chang and C.D. Roberts
0903.5461 [nucl-th]
Phys. Rev. Lett. 103 (2009) 081601

$$\Gamma^{fg}_{5\mu}(k;P) = Z_2\gamma_5\gamma_\mu$$
$$- \boxed{\int_q g^2 D_{\alpha\beta}(k-q)\,\frac{\lambda^a}{2}\,\gamma_\alpha S_f(q_+)\Gamma^{fg}_{5\mu}(q;P)S_g(q_-)\frac{\lambda^a}{2}\,\Gamma^g_\beta(q_-,k_-)}$$
$$+ \int_q g^2 D_{\alpha\beta}(k-q)\,\frac{\lambda^a}{2}\,\gamma_\alpha S_f(q_+)\frac{\lambda^a}{2}\Lambda^{fg}_{5\mu\beta}(k,q;P),$$

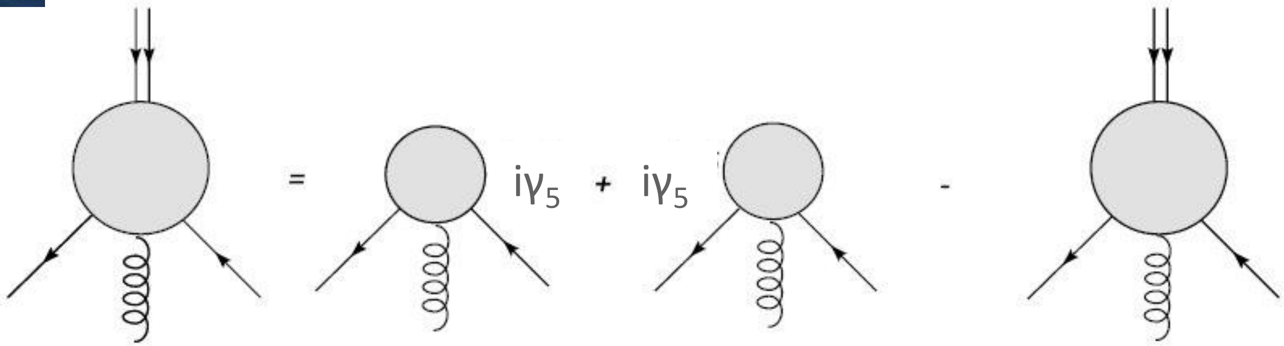
- **Equivalent exact bound-state equation *but* in this form**

  K(q,k;P) → Λ(q,k;P)

  which is *completely determined by dressed-quark self-energy*
- **Enables derivation of a Ward-Takahashi identity for Λ(q,k;P)**

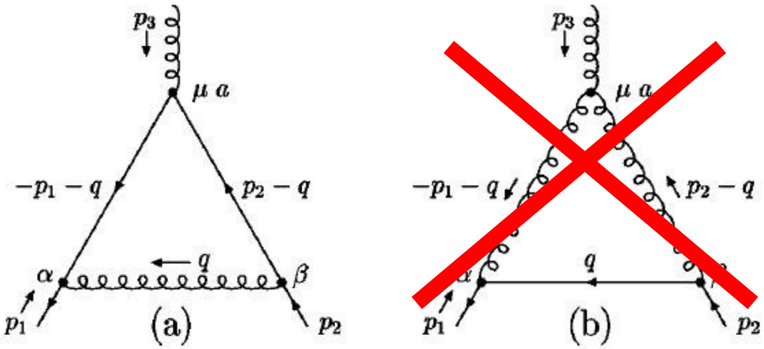
Ward-Takahashi Identity Bethe-Salpeter Kernel

Lei Chang and C.D. Roberts
0903.5461 [nucl-th]
Phys. Rev. Lett. 103 (2009) 081601



$$P_\mu \Lambda^{fg}_{5\mu\beta}(k,q;P) = \Gamma^f_\beta(q_+,k_+)\, i\gamma_5 + i\gamma_5\, \Gamma^g_\beta(q_-,k_-) - i[m_f(\zeta)+m_g(\zeta)]\Lambda^{fg}_{5\beta}(k,q;P),$$

- Now, for first time, it's possible to formulate an *Ansatz* for Bethe-Salpeter kernel given *any form* for the dressed-quark-gluon vertex by using this identity
- This enables the identification and elucidation of a wide range of novel consequences of DCSB



QCD and dressed-quark anomalous magnetic moments

- Schwinger's result for QED: $$\frac{q}{2m} \to \left(1+\frac{\alpha}{2\pi}\right)\frac{q}{2m}$$
- pQCD: two diagrams
  - (a) is QED-like
  - (b) is only possible in QCD – involves 3-gluon vertex
- Analyse (a) and (b)
  - (b) vanishes identically: the 3-gluon vertex does *not* contribute to a quark's anomalous chromomag. moment at leading-order
  - (a) Produces a finite result: " – ⅙ $\alpha_s/2\pi$ "
    ~ (– ⅙) QED-result
- But, in QED and QCD, the *anomalous chromo- and electro-magnetic moments vanish identically in the chiral limit*!
- In QCD, chiral symmetry is dynamically broken, strongly
  - What then?

L. Chang, Y. –X. Liu and C.D. Roberts
arXiv:1009.3458 [nucl-th]
Phys. Rev. Lett. **106** (2011) 072001

Dressed-quark anomalous magnetic moments

- DCSB → **Three strongly-dressed and essentially-nonperturbative contributions to dressed-quark-gluon vertex:**

Ball-Chiu term
•Vanishes if no DCSB
•Appearance driven by STI

$$\lambda^3_\mu(p,q) = 2(p+q)_\mu \Delta_B(p,q)$$

$$\Delta_F(p,q) = \frac{F(p^2)-F(q^2)}{p^2-q^2}$$

Anom. chrom. mag. mom. contribution to vertex
•Similar properties to BC term
•Strength commensurate with lattice-QCD
Skullerud, Bowman, Kizilersu *et al.* hep-ph/0303176

$$\Gamma^{\rm acm_5}_\mu = \sigma_{\mu\nu} k_\nu \tau_5(p_1,p_2)\,,$$

$$\Gamma^{\rm acm_4}_\mu = [\ell^{\rm T}_\mu \gamma\cdot k + i\gamma^{\rm T}_\mu \sigma_{\nu\rho}\ell_\nu k_\rho]\tau_4(p_1,p_2)\,,$$

$$\tau_4 = \frac{2\,\tau_5(p_1,p_2)}{\mathcal{M}(p_1^2,p_2^2)}\,,$$

$$\tau_5 = \eta\,\Delta_B(p_1^2,p_2^2) \text{ and } \mathcal{M}(x,y) = [x+M(x)^2+y+M(y)^2]/(2[M(x)+M(y)]).$$

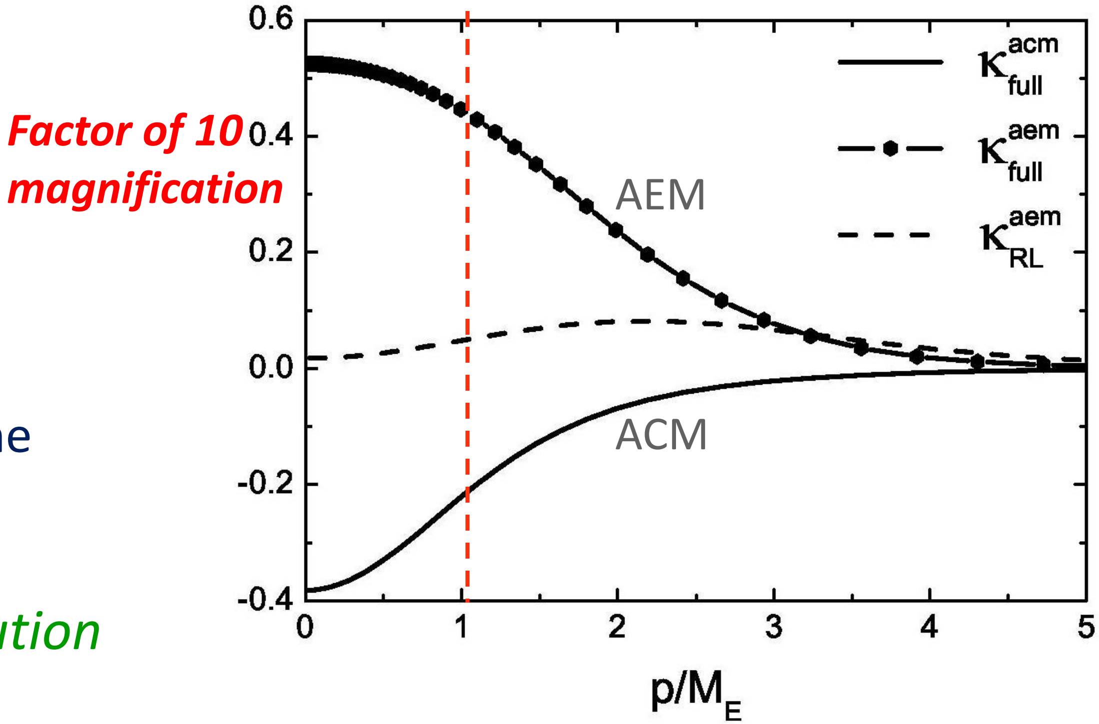
Role and importance is novel discovery
•Essential to recover pQCD
•Constructive interference with Γ^5

$M_E = \{s|s>0, s=M^2(s)\}$ is the Euclidean constituent-quark mass

L. Chang, Y. –X. Liu and C.D. Roberts
arXiv:1009.3458 [nucl-th]
Phys. Rev. Lett. **106** (2011) 072001

Dressed-quark anomalous magnetic moments

- Formulated and solved general Bethe-Salpeter equation
- Obtained dressed electromagnetic vertex
- Confined quarks don't have a mass-shell
  - Can't unambiguously define magnetic moments
  - But can define *magnetic moment distribution*



- AEM is opposite in sign but of roughly equal magnitude as ACM

	M^E	κ^{ACM}	κ^{AEM}
Full vertex	0.44	-0.22	0.45
Rainbow-ladder	0.35	0	0.048

L. Chang, Y. –X. Liu and C.D. Roberts
[arXiv:1009.3458 [nucl-th]]
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- Obtained dressed electromagnetic vertex
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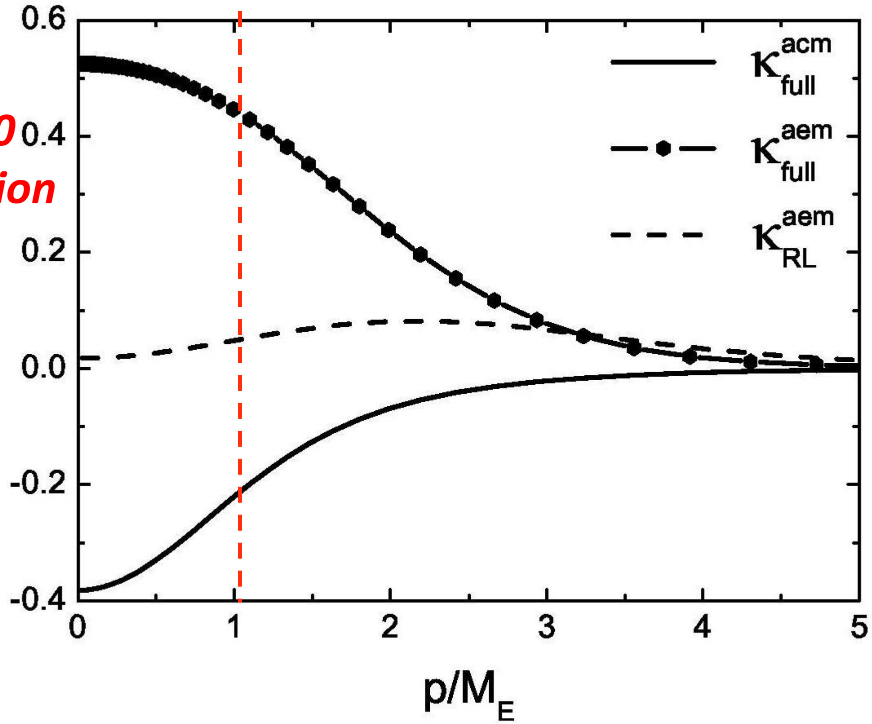
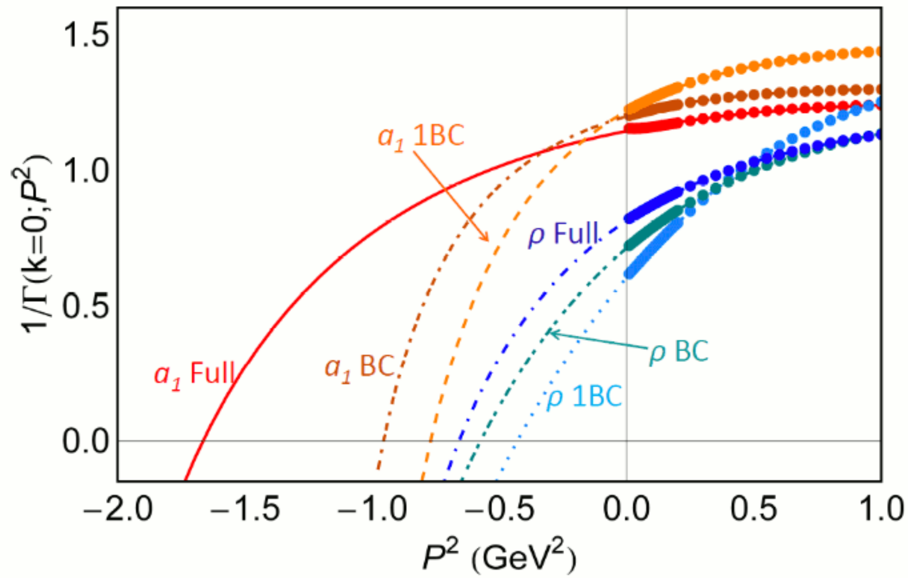
Factor of 10 magnification



- Potentially important for elastic and transition form factors, etc.
- Indeed, for any process involving photons coupling to a dressed-quark



Solves problem of a_1 - ρ mass splitting

Lei Chang & C.D. Roberts,
arXiv:1104.4821 [nucl-th]
Tracing massess of ground-state light-quark mesons

M(p^2) magnifies spin orbit splitting here, precisely as in σ-π comparison

- Fully nonperturbative BSE kernel that incorporates and expresses DCSB: establishes unambiguously that a_1 & ρ are parity-partner bound-states of dressed light valence-quarks.

	Experiment	Rainbow-ladder	One-loop corrected	Ball-Chiu	Full vertex
a1	1230	759	885	1020	1280
ρ	770	644	764	800	840
Mass splitting	455	115	121	220	440

Dynamical Chiral Symmetry Breaking

Vacuum Condensates?

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

Dichotomy of the pion
Mass Formula for 0⁻ Mesons

$$f_{H_5}\, m_{H_5}^2 = \rho_{H_5}^\zeta \mathcal{M}_{H_5}^\zeta$$

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We now have sufficient information to address the question of just what is this so-called "vacuum quark condensate."

- H

elation
1968

$$m_{H_5}^2 = 2 m_q \frac{-\langle \bar{q} q \rangle}{f_{H_5}^0}$$

$$m_\pi^2 \propto m$$

Spontaneous(Dynamical) Chiral Symmetry Breaking

The 2008 Nobel Prize in Physics was divided, one half awarded to Yoichiro Nambu

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Nambu - Jona-Lasinio Model

Dynamical Model of Elementary Particles
Based on an Analogy with Superconductivity. I
Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122 (1961) 345–358
Dynamical Model Of Elementary Particles
Based On An Analogy With Superconductivity. II
Y. Nambu, G. Jona-Lasinio, Phys.Rev. 124 (1961) 246-254

- Treats a chirally-invariant four-fermion Lagrangian & solves the gap equation in Hartree-Fock approximation (analogous to rainbow truncation)
- Poss … ed
- *Esse…* … nd Nam… & de… ther… dege… Nambu vacua, related by a chiral rotation
- ***Nontrivial Vacuum is "Born"***

The following Lagrangian density will be assumed ($\hbar = c = 1$):

$$L = -\bar{\psi}\gamma_\mu\partial_\mu\psi + g_0[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2]. \qquad (2.6)$$

The coupling parameter g_0 is positive, and has dimensions $[\text{mass}]^{-2}$. The γ_5 invariance property of the interaction is evident from Eq. (2.5). According to the

…rlds described …3.22) are then … (3.31)

which form another orthogonal set. Since the original total H commutes with X, it will have no matrix elements connecting different "worlds." Moreover, as

Gell-Mann - Oakes - Renner Relation

Behavior of current divergences under SU(3) x SU(3).
Murray Gell-Mann, R.J. Oakes , B. Renner
Phys.Rev. 175 (1968) 2195-2199

- This paper derives a relation between

  m_π^2 and the expectation-value $< \pi | u_0 | \pi >$,

  where u_o is an operator that is linear in the putative Hamiltonian's explicit chiral-symmetry breaking term
  - NB. QCD's current-quarks were not yet invented, so u_0 was not expressed in terms of current-quark fields
- PCAC-hypothesis (partial conservation of axial current) is used in the derivation
- Subsequently, the concepts of soft-pion theory
  - Operator expectation values do not change as $t=m_\pi^2 \to t=0$

  to take $< \pi | u_0 | \pi > \to < 0 | u_0 | 0 >$ ... *in-pion → in-vacuum*

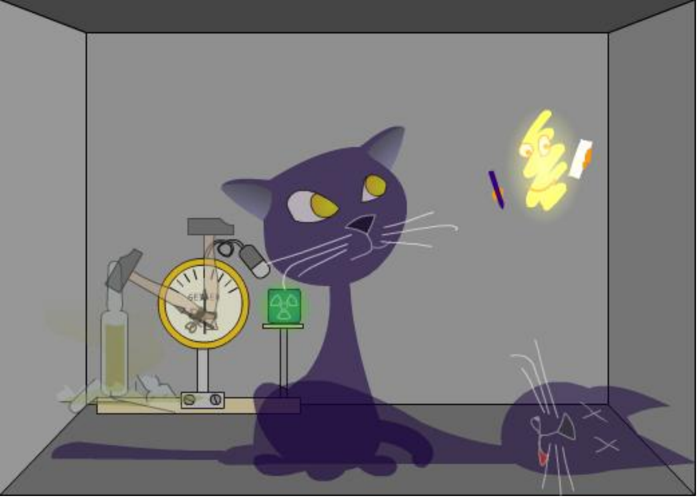
Gell-Mann - Oakes - Renner Relation

$$m_\pi^2 \propto m\langle 0|\bar{q}q|0\rangle$$

$- (0.25\text{GeV})^3$

- Theoretical physics at its best.
- But no one is thinking about how properly to consider or define what will come to be called the *vacuum quark condensate*
- So long as the condensate is just a mass-dimensioned constant, which approximates value of another well-defined matrix element, there is no problem.
- Problem arises if one over-interprets this number, which textbooks have been doing for a *VERY LONG TIME*.

Note of Warning

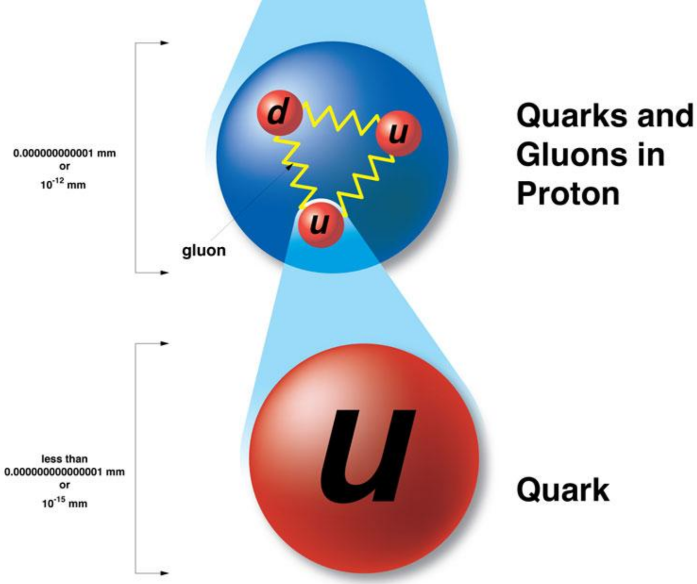


Chiral Magnetism (or Magnetohadrochironics)
A. Casher and L. Susskind, Phys. Rev. D9 (1974) 436

The spontaneous breakdown of chiral symmetry in hadron dynamics is generally studied as a vacuum phenomenon.[1] Because of an instability of the chirally invariant vacuum, the real vacuum is "aligned" into a chirally asymmetric configuration. On the other hand an approach to quantum field theory exists in which the properties of the vacuum state are not relevant. This is the parton or constituent approach formulated in the infinite-momentum frame.[2] A number of investigations

- *These authors argue that dynamical chiral-symmetry breaking can be realised as a property of hadrons, instead of via a nontrivial vacuum exterior to the measurable degrees of freedom*

The essential ingredient required for a spontaneous symmetry breakdown in a composite system is the existence of a divergent number of constituents
– DIS provided evidence for divergent sea of low-momentum partons – parton model.



QCD

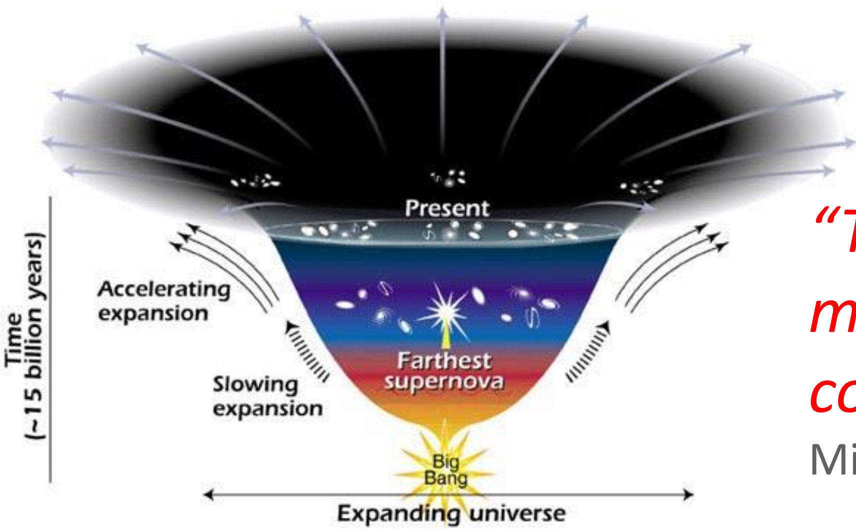
973-1974

$$\langle 0|\bar{q}q|0\rangle$$

Why does it matter?

- How should one approach thi… …erstand it, within Quantum Chrom…

1) Are the quark an… …sates" theoretically well-defined?
2) Is there… …ning to this quantity or is it merely jus… …sioned parameter in a theoretical …procedure?



"Dark Energy"

"The advent of quantum field theory made consideration of the cosmological constant obligatory not optional."

Michael Turner, "Dark Energy and the New Cosmology"

- The only possible covariant form for the energy of the (quantum) vacuum; viz.,

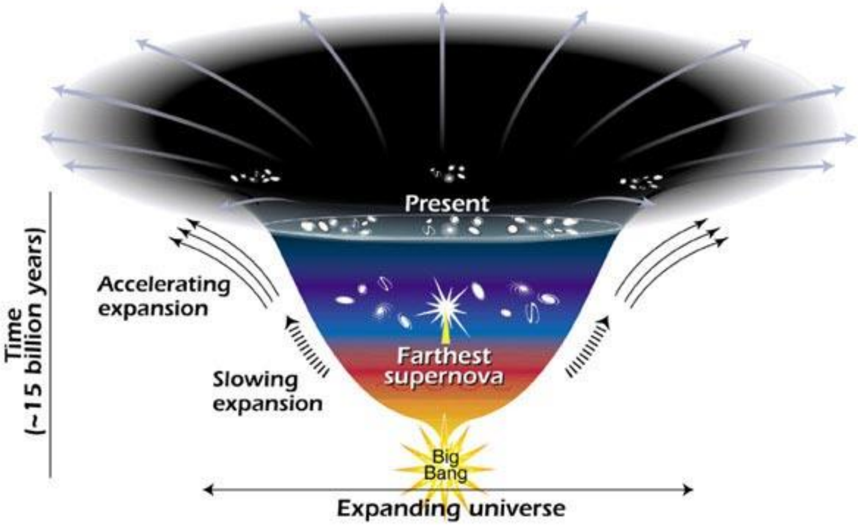
$$T^{\mu\nu}_{\rm VAC} = \rho_{\rm VAC}\, g^{\mu\nu}$$

is mathematically equivalent to the cosmological constant.

"It is a perfect fluid and precisely spatially uniform"

"Vacuum energy is almost the perfect candidate for dark energy."

"Dark Energy"



$$T^{\mu\nu}_{\rm VAC} = \rho_{\rm VAC} g^{\mu\nu}$$

Enormous and even greater contribution from Higgs VEV!

- *QCD vacuum contribution*
  - If chiral symmetry breaking is expressed in a nonzero expectation value of the quark bilinear, then the energy difference between the symmetric and broken phases is of order

$M_{QCD} \approx 0.3$ GeV

Mass-scale generated by spacetime-independent condensate

  - One obtains therefrom:

$$\rho_\Lambda^{QCD} = 10^{46} \rho_\Lambda^{obs}$$

"The biggest embarrassment in theoretical physics."


AT LAST!
NOW I CAN
RELATE TO THE
SYSTEM ...
IT'S OFFICIAL
THE SYSTEM
IS
COLLAPSING
INTO
CHAOS
Leunig

Resolution?

Relevant References

- **arXiv:1202.2376**
  Confinement contains condensates
  Stanley J. Brodsky, Craig D. Roberts, Robert Shrock, Peter C. Tandy
- arXiv:1109.2903 [nucl-th], Phys. Rev. C**85** (2012) 012201(RapCom),
  Expanding the concept of in-hadron condensates
  Lei Chang, Craig D. Roberts and Peter C. Tandy
- arXiv:1005.4610 [nucl-th], Phys. Rev. C**82** (2010) 022201(RapCom.)
  New perspectives on the quark condensate,
  Brodsky, Roberts, Shrock, Tandy
- arXiv:0905.1151 [hep-th], PNAS **108**, 45 (2011)
  Condensates in Quantum Chromodynamics and the Cosmological Constant , Brodsky and Shrock,
- hep-th/0012253
  The Quantum vacuum and the cosmological constant problem,
  Svend Erik Rugh and Henrik Zinkernagel.

$$\langle 0 | \bar{q}q | 0 \rangle$$

QCD

1973-1974

Are the condensates real?

Or … just mass-dimensioned parameters in a theoretical computation procedure?

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

Dichotomy of the pion
Mass Formula for 0⁻ Mesons

$$f_{H_5}\, m_{H_5}^2 = \rho_{H_5}^{\zeta} \mathcal{M}_{H_5}^{\zeta}$$

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We now have sufficient information to address the question of just what is this so-called "vacuum quark condensate."

$$m_{H_5}^2 = 2 m_q \frac{-\langle \bar{q} q \rangle}{f_{H_5}^0}$$

$$m_\pi^2 \propto m$$

$$f_\pi m_\pi^2 = 2\, m(\zeta)\rho_\pi^\zeta$$

In-meson condensate

Maris & Roberts
nucl-th/9708029

- Pseudoscalar projection of pion's Bethe-Salpeter wave-function onto the origin in configuration space: ***|Ψ$_\pi$^{PS}(0)|***

  – or the pseudoscalar pion-to-vacuum matrix element

$$i\rho_\pi = -\langle 0|\bar{q} i\gamma_5 q|\pi\rangle$$
$$= Z_4(\zeta,\Lambda)\, \mathrm{tr}_{\mathrm{CD}} \int^\Lambda \frac{d^4q}{(2\pi)^4} \gamma_5 S(q_+)\Gamma_\pi(q;P)S(q_-)$$

- Rigorously defined in QCD – gauge-independent, cutoff-independent, etc.
  - For arbitrary current-quark masses
  - For any pseudoscalar meson

$$f_\pi m_\pi^2 = 2\, m(\zeta) \rho_\pi^\zeta$$

In-meson condensate

Maris & Roberts
nucl-th/9708029

- Pseudovector projection of pion's Bethe-Salpeter wave-function onto the origin in configuration space: $|\Psi_\pi^{AV}(0)|$
  – or the pseudoscalar pion-to-vacuum matrix element
  – or the pion's leptonic decay constant

$$
\begin{aligned}
i f_\pi P_\mu &= \langle 0|\bar{q}\gamma_5\gamma_\mu q|\pi\rangle \\
&= Z_2(\zeta,\Lambda)\, \mathrm{tr}_{\rm CD} \int^\Lambda \frac{d^4 q}{(2\pi)^4} i\gamma_5\gamma_\mu S(q_+)\Gamma_\pi(q;P)S(q_-)
\end{aligned}
$$

- Rigorously defined in QCD – gauge-independent, cutoff-independent, etc.
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  - For any pseudoscalar meson

$$f_\pi m_\pi^2 = 2\, m(\zeta) \rho_\pi^\zeta$$

In-meson condensate

Maris & Roberts
nucl-th/9708029

- Define $-\langle \bar{q} q \rangle_\zeta^\pi \equiv -f_\pi \langle 0 | \bar{q} \gamma_5 q | \pi \rangle = f_\pi \rho_\pi(\zeta) =: \kappa_\pi(\hat{m}; \zeta).$
- Then, using the pion Goldberger-Treiman relations (equivalence of 1- and 2-body problems), one derives, in the chiral limit

Chiral limit

$$\kappa_\pi(0;\zeta) = -<\bar{q}q>_\zeta^0$$

$|\Psi_\pi^{PS}(0)| * |\Psi_\pi^{AV}(0)|$

- Namely, the so-called *vacuum quark condensate* is the *chiral-limit value* of the *in-pion condensate*
- The *in-pion condensate* is the *only well-defined function of current-quark mass* in QCD that is *smoothly connected to the vacuum quark condensate*.

$$f_\pi m_\pi^2 = 2\, m(\zeta) \rho_\pi^\zeta$$

There is *only one* condensate

Langeld, Roberts *et al*.
nucl-th/0301024,
Phys.Rev. C67 (2003) 065206

I. Casher Banks formula:

Density of eigenvalues of Dirac operator

$$-\langle 0|\bar{q}q|0\rangle = 2m \int_0^\infty d\lambda \, \frac{\rho(\lambda)}{\lambda^2 + m^2}$$

II. Constant in the Operator Product Expansion:

$$M(p^2) \overset{\text{large}-p^2}{=} \frac{2\pi^2 \gamma_m}{3} \frac{\left(-\langle \bar{q}q \rangle^0\right)}{p^2 \left(\frac{1}{2} \ln\left[\frac{p^2}{\Lambda_{QCD}^2}\right]\right)^{1-\gamma_m}}$$

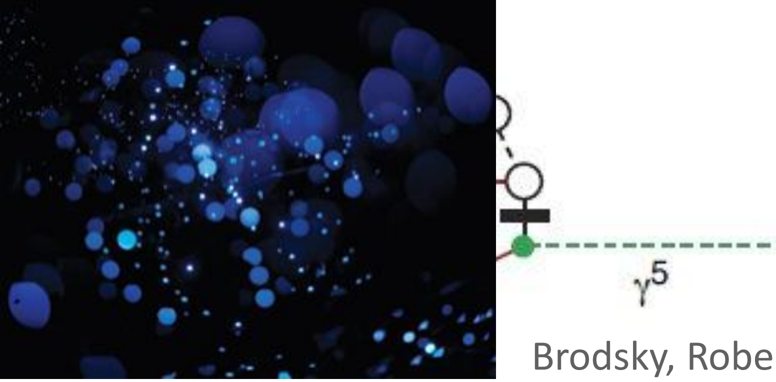
III. Trace of the dressed-quark propagator:

$$\tilde{\sigma}(m) := N_c \, \mathrm{tr}_D \int_p^\Lambda \tilde{S}_m(p)$$

$m \rightarrow 0$

Algebraic proof that these are all the same. So, no matter how one chooses to calculate it, one is always calculating the same thing; viz.,

$|\Psi_\pi^{PS}(0)| * |\Psi_\pi^{AV}(0)|$



Paradigm shift: In-Hadron Condensates

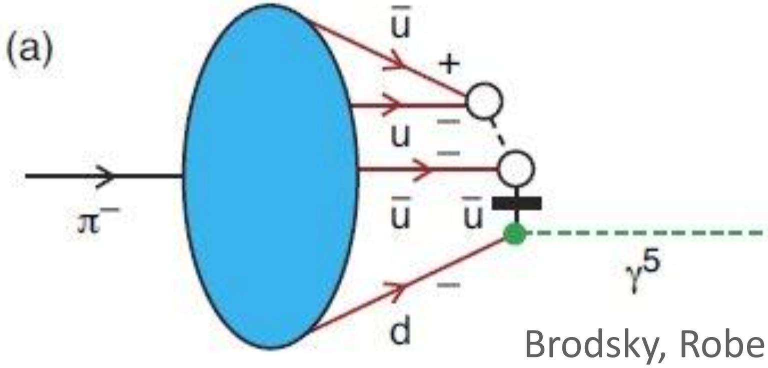
Brodsky, Roberts, Shrock, Tandy, Phys. Rev. C**82** (Rapid Comm.) (2010) 022201
Brodsky and Shrock, PNAS **108**, 45 (2011)

- **Resolution**
  - **Whereas it might sometimes be convenient in computational truncation schemes to imagine otherwise, "condensates" do not exist as spacetime-independent mass-scales that fill all spacetime.**
  - ***So-called* vacuum condensates can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wavefunctions.**
  - **GMOR**
    cf.

$$f_\pi^2 m_\pi^2 = -2\, m(\zeta) \langle \bar{q} q \rangle_0^\zeta$$

QCD

$$f_\pi m_\pi^2 = 2\, m(\zeta) \rho_\pi^\zeta$$



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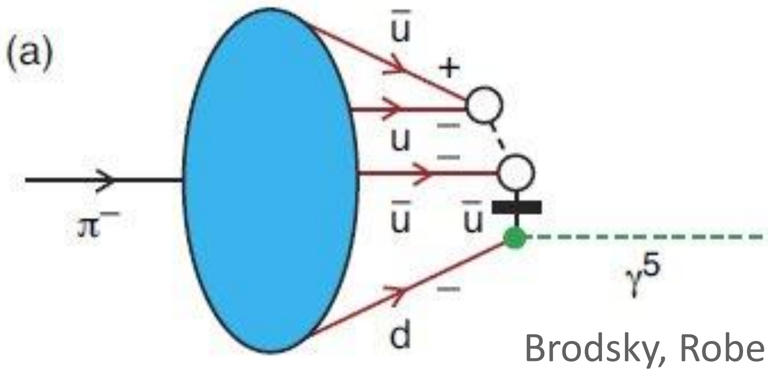
  - ***So-called*** **vacuum condensates can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wavefunctions.**
  - **No qualitative difference between f_π and ρ_π**

$$i f_\pi P_\mu = \langle 0|\bar{q}\gamma_5\gamma_\mu q|\pi\rangle$$
$$= Z_2(\zeta,\Lambda)\,\mathrm{tr}_{CD}\int^\Lambda \frac{d^4q}{(2\pi)^4} i\gamma_5\gamma_\mu S(q_+)\Gamma_\pi(q;P)S(q_-), \quad (5)$$

$$i\rho_\pi = -\langle 0|\bar{q} i\gamma_5 q|\pi\rangle$$
$$= Z_4(\zeta,\Lambda)\,\mathrm{tr}_{CD}\int^\Lambda \frac{d^4q}{(2\pi)^4}\gamma_5 S(q_+)\Gamma_\pi(q;P)S(q_-). \quad (6)$$



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  - **No qualitative difference between f_π and ρ_π**
  - **And**

Chiral limit

$$\kappa_\pi(0;\zeta) = -<\bar{q}q>_\zeta^0$$

$$-\langle \bar{q}q \rangle_\zeta^\pi \equiv -f_\pi \langle 0|\bar{q}\gamma_5 q|\pi\rangle = f_\pi \rho_\pi(\zeta) =: \kappa_\pi(\hat{m};\zeta).$$

PHYSICAL REVIEW VOLUME 175, NUMBER 5 25 NOVEMBER 1968

Behavior of Current Divergences under $SU_3 \times SU_3$*†

Murray Gell-Mann
California Institute of Technology, Pasadena, California 91109

AND

R. J. Oakes
Northwestern University, Evanston, Illinois 60201

AND

B. Renner‡
California Institute of Technology, Pasadena, California 91109

(Received 22 July 1968)

GMOR Relation

Expanding the concept of in-hadron condensates
Lei Chang, Craig D. Roberts and Peter C. Tandy
arXiv:1109.2903 [nucl-th], Phys. Rev. C**85** (2012) 012201(R)

GMOR Relation

- Valuable to highlight the precise form of the Gell-Mann–Oakes–Renner (GMOR) relation: Eq. (3.4) in Phys.Rev. 175 (1968) 2195

$$m_\pi^2 = \lim_{P' \to P \to 0} \langle \pi(P') | \mathcal{H}_{\chi \mathrm{sb}} | \pi(P) \rangle$$

  - *m_π is the pion's mass*
  - *$H_{\chi sb}$ is that part of the* hadronic Hamiltonian density which explicitly breaks chiral symmetry.
- Crucial to observe that the operator expectation value in this equation is evaluated between pion states.
- Moreover, the virtual low-energy limit expressed in the equation is purely formal. It does not describe an achievable empirical situation.

GMOR Relation

- In terms of QCD quantities, GMOR relation entails

$$\forall m_{ud} \sim 0\,,\; m_{\pi^\pm}^2 = m_{ud}^\zeta\, \mathcal{S}_\pi^\zeta(0)\,,$$
$$\mathcal{S}_\pi^\zeta(0) \;=\; -\langle \pi(P)|\tfrac{1}{2}(\bar{u}u + \bar{d}d)|\pi(P)\rangle$$

  - $m_{ud}^\zeta = m_u^\zeta + m_d^\zeta$ … the current-quark masses
  - $S_\pi^\zeta(0)$ is the pion's scalar form factor at zero momentum transfer, $Q^2=0$

- RHS is proportional to the pion σ-term
- Consequently, using the connection between the σ-term and the Feynman-Hellmann theorem, GMOR relation is actually the statement

$$\forall m_{ud} \sim 0\,,\; m_\pi^2 = m_{ud}^\zeta \frac{\partial}{\partial m_{ud}^\zeta} m_\pi^2$$

Expanding the concept of in-hadron condensates
Lei Chang, Craig D. Roberts and Peter C. Tandy
arXiv:1109.2903 [nucl-th], Phys. Rev. C**85** (2012) 012201(R)

GMOR Relation

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

- Using

$$f_{H_5}\, m_{H_5}^2 = \rho_{H_5}^{\zeta} \mathcal{M}_{H_5}^{\zeta}$$

it follows that

$$\mathcal{S}_{\pi}^{\zeta}(0) = \frac{\partial}{\partial m_{ud}^{\zeta}} m_{\pi}^2 = \frac{\partial}{\partial m_{ud}^{\zeta}} \left[m_{ud}^{\zeta} \frac{\rho_{\pi}^{\zeta}}{f_{\pi}} \right]$$

- This equation is valid for any values of $m_{u,d}$, including the neighbourhood of the chiral limit, wherein

$$\frac{\partial}{\partial m_{ud}^{\zeta}} \left[m_{ud}^{\zeta} \frac{\rho_{\pi}^{\zeta}}{f_{\pi}} \right]_{m_{ud}=0} = \frac{\rho_{\pi}^{\zeta 0}}{f_{\pi}^{0}}$$

Expanding the concept of in-hadron condensates
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arXiv:1109.2903 [nucl-th], Phys. Rev. C**85** (2012) 012201(R)

GMOR Relation

- Consequently, in the neighbourhood of the chiral limit

$$m_{\pi^\pm}^2 = -m_{ud}^\zeta \frac{\langle \bar{q}q \rangle^{\zeta 0}}{(f_\pi^0)^2} + \mathrm{O}(m_{ud}^2)$$

- This is a QCD derivation of the commonly recognised form of the GMOR relation.
- Neither PCAC nor soft-pion theorems were employed in the analysis.
- Nature of each factor in the expression is abundantly clear; viz., chiral limit values of matrix elements that explicitly involve the hadron.

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Expanding the concept of in-hadron condensates

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The in-pseudoscalar-meson condensate can be represented through the pseudoscalar meson's scalar form factor at zero-momentum transfer. With the aid of a mass formula for scalar mesons, revealed herein, the analog is shown to be true for in-scalar-meson condensates. The concept is readily extended to all hadrons so that, via the zero-momentum-transfer value of any hadron's scalar form factor, one can readily extract the value for a quark condensate in that hadron which is a measure of dynamical chiral symmetry breaking.

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Expanding the Concept ...

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In-Hadron Condensates

- Plainly, the in-pseudoscalar-meson condensate can be represented through the pseudoscalar meson's scalar form factor at zero momentum transfer *Q*² = *0*.
- Using an *exact mass formula for scalar mesons*, one proves the in-scalar-meson condensate can be represented in precisely the same way.

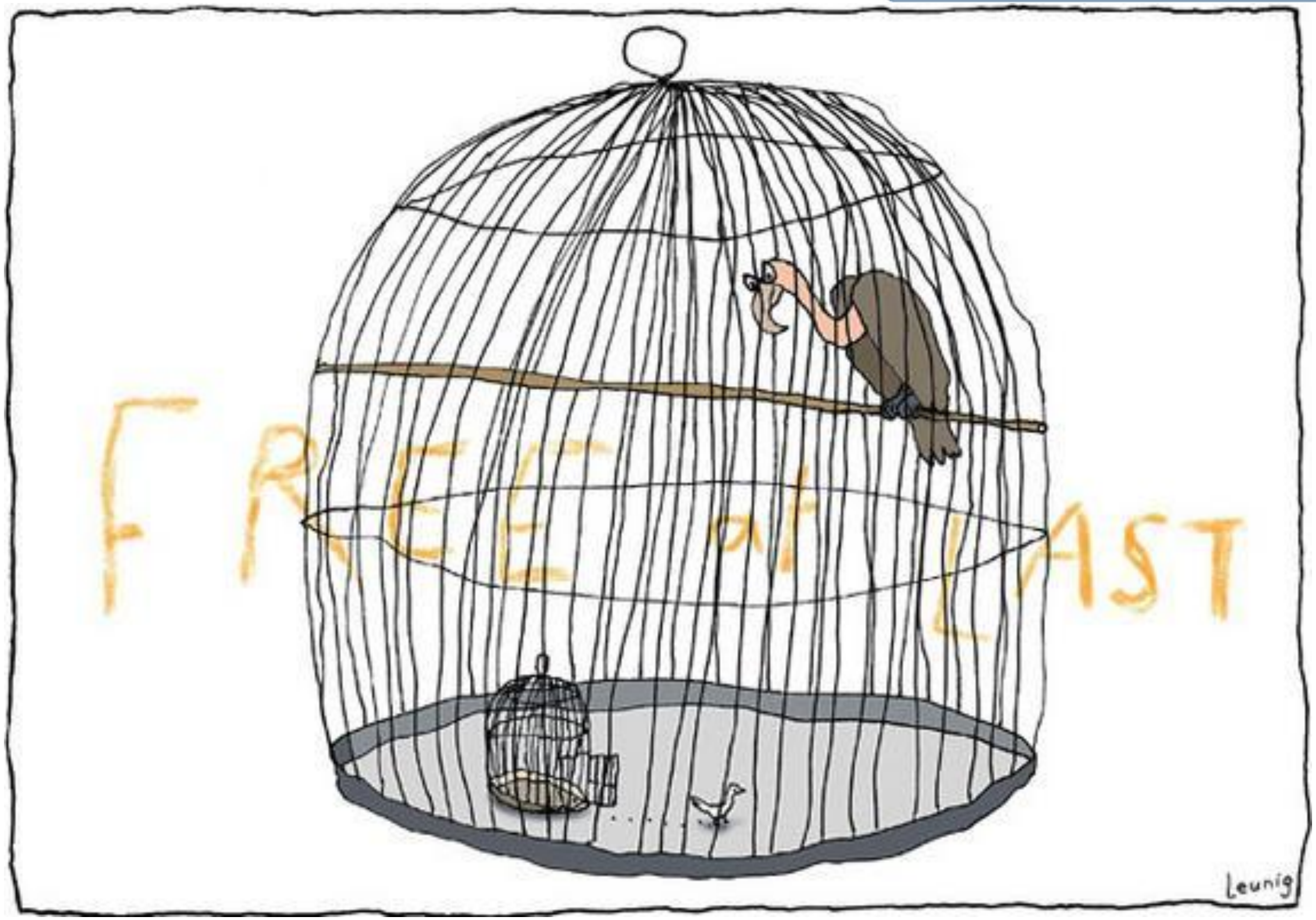
$$f_{S_{qQ}} m^2_{S_{qQ}} = -\check{m}_{qQ} \rho^{\zeta}_{S_{qQ}}$$

- By analogy, and with appeal to demonstrable results of heavy-quark symmetry, the $Q^2 = 0$ values of vector- and pseudovector-meson scalar form factors also determine the in-hadron condensates in these cases.
- This expression for the concept of in-hadron quark condensates is readily extended to the case of baryons.
- Via the $Q^2 = 0$ value of any hadron's scalar form factor, one can extract the value for a quark condensate in that hadron which is a reasonable and realistic measure of dynamical chiral symmetry breaking.

$$\langle H(p')|\bar{q}\mathcal{O}q|H(p)\rangle$$

Hadron Charges

- Hadron Form factor matrix elements
- *Scalar charge of a hadron is an intrinsic property of that hadron … no more a property of the vacuum than the hadron's electric charge, axial charge, tensor charge, etc. …*



Confinement

Confinement Contains Condensates
S.J. Brodsky, C.D. Roberts, R. Shrock and P.C. Tandy
arXiv:1202.2376 [nucl-th]

Confinement

- Confinement is essential to the validity of the notion of in-hadron condensates.
- Confinement makes it impossible to construct gluon or quark quasiparticle operators that are nonperturbatively valid.
- So, although one can define a perturbative (bare) vacuum for QCD, it is impossible to rigorously define a ground state for QCD upon a foundation of gluon and quark quasiparticle operators.
- Likewise, it is impossible to construct an interacting vacuum – a BCS-like trial state – and hence DCSB in QCD cannot rigorously be expressed via a spacetime-independent coherent state built upon the ground state of perturbative QCD.
- Whilst this does not prevent one from following this path to build practical models for use in hadron physics phenomenology, it does invalidate any claim that theoretical artifices in such models are empirical.

Paradigm shift: In-Hadron Condensates

"Void that is truly empty
solves dark energy puzzle"
Rachel Courtland, New Scientist 4th Sept. 2010

~~*"EMPTY space may really be empty. Though quantum theory suggests that a vacuum should be fizzing with particle activity, it turns out that this paradoxical picture of nothingness may not be needed. A calmer view of the vacuum would also help resolve a nagging inconsistency with [dark energy], the elusive force thought to be speeding up the expansion of the universe."*~~

$$\Omega_{QCD-condensate} = 8\pi G_N \frac{\Lambda_{QCD}^4}{3H_0^2} \cong 10^{46}$$

Cosmological Constant:

- ✓***Putting QCD condensates back into hadrons reduces the mismatch between experiment and theory by a factor of 10^{46}***
- ✓***Possibly by far more, if technicolour-like theories are the correct paradigm for extending the Standard Model***

This is not the end