Why $m_p \approx 2000 \times m_e$

Craig

2013: Higgs and Englert

- The 2013 Nobel Prize in Physics was awarded to Peter Higgs and Francois Englert following discovery of the Higgs boson at the Large Hadron Collider.
- With this discovery the Standard Model of Particle Physics became complete.

Where to now?

- Its formulation and verification are a remarkable story.

News › Science › Particle physics **theguardian**

One year on from the Higgs boson find, has physics hit the buffers?

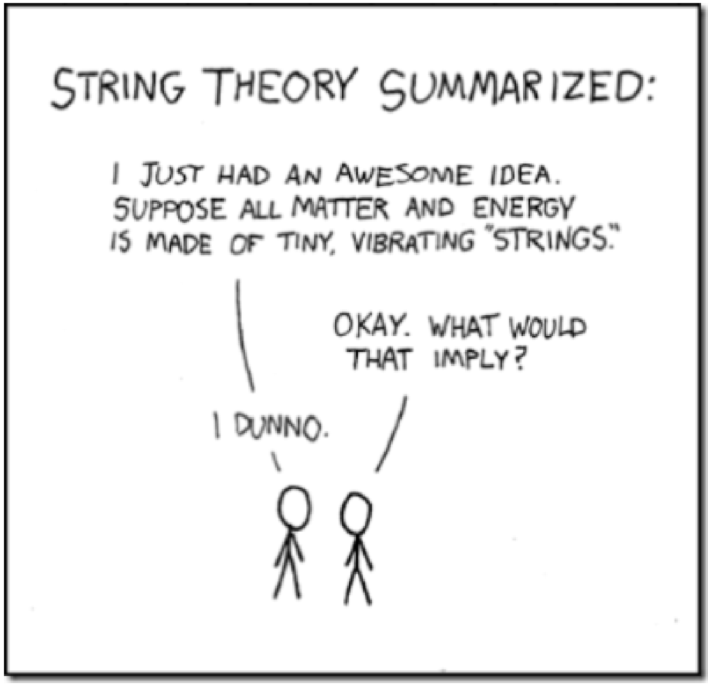
Despite the success of the Large Hadron Collider, evidence for the follow-up theory – supersymmetry – has proved elusive

A little over a year ago, physicists put the finishing touches to the most successful scientific theory of all time: the Standard Model of particle physics. When the Higgs boson was found at the Large Hadron Collider in July 2012, it was the final piece in our picture of the universe at the smallest, subatomic scales.

Champagne corks flew in physics labs around the world at this vindication of quantum field theory, which had been more than 80 years and dozens of Nobel prizes in the making.

Inevitably, a hangover followed. The leading idea for how to push physics beyond the Standard Model – and explain the many remaining mysteries of the universe – is looking shaky. Thousands of physicists have spent their career carefully constructing the theory, called supersymmetry. It has taken almost four decades. But, so far, the most powerful particle accelerator ever built – the Large Hadron Collider (LHC) at Cern, near Geneva – has not found any hard evidence to back up the theory.

This conspicuous lack of proof has led a growing number of physicists, particularly those who are less invested in supersymmetry, to publicly call time on the idea. Perhaps, despite all the work, the theory is just plain wrong.



Problems in Theory

www.nature.com/news/scientific-method-defend-the-integrity-of-physics-1.16535

- Faced with difficulties in applying fundamental theories to the observed Universe, some researchers have called for a change in how theoretical physics is done.
- They begin to argue — explicitly — that if a theory is sufficiently elegant and explanatory, it need not be tested experimentally …
- Chief among the "elegance will suffice" advocates are some string theorists and cosmologists …
- Is this science?

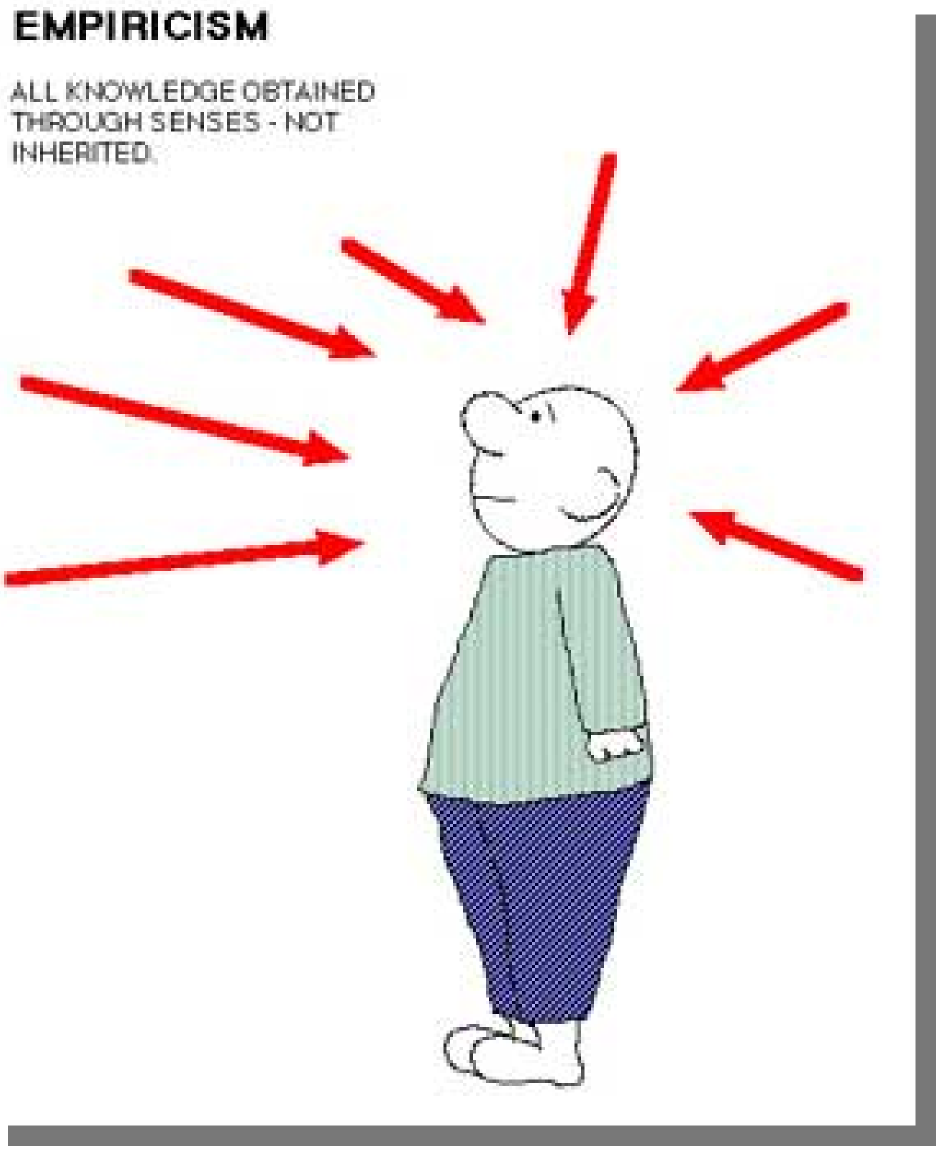
Scandal in Academia

- "I have no data yet.

  It is a capital mistake to theorize before one has data.

  Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

Sherlock Holmes



Physics is an empirical science

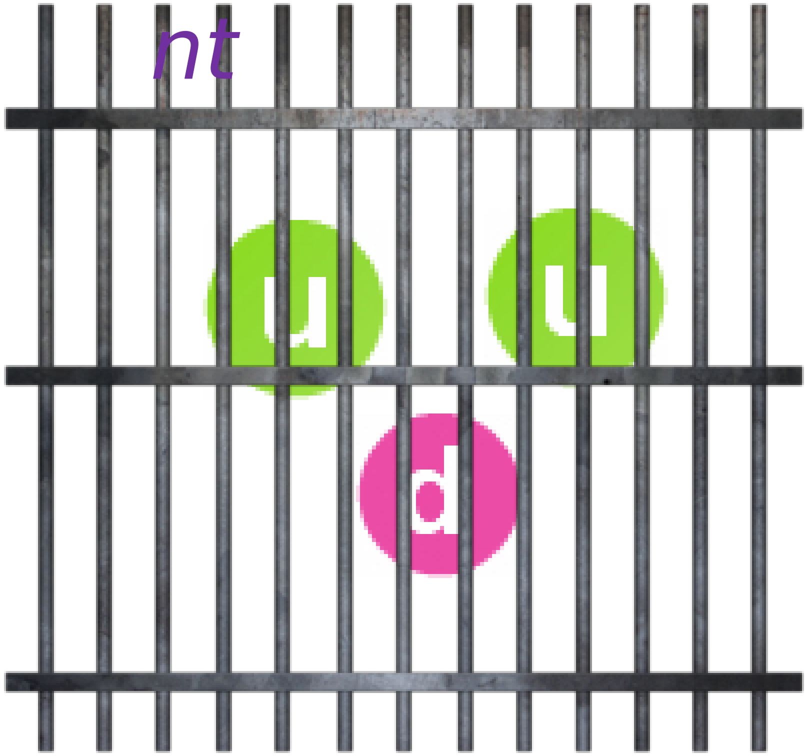
2013: Higgs and Englert

- The most important chapter of the Standard Model is the least understood.
- Quantum Chromodynamics (QCD) is that part of the Standard Model which is supposed to describe all of nuclear physics
  - Matter = quarks
  - Gauge bosons = gluons
- Yet, fifty years after the discovery of quarks, we are only just beginning to understand how QCD builds the basic bricks for nuclei: pions, neutrons, protons, etc.

2013: Higgs and Englert

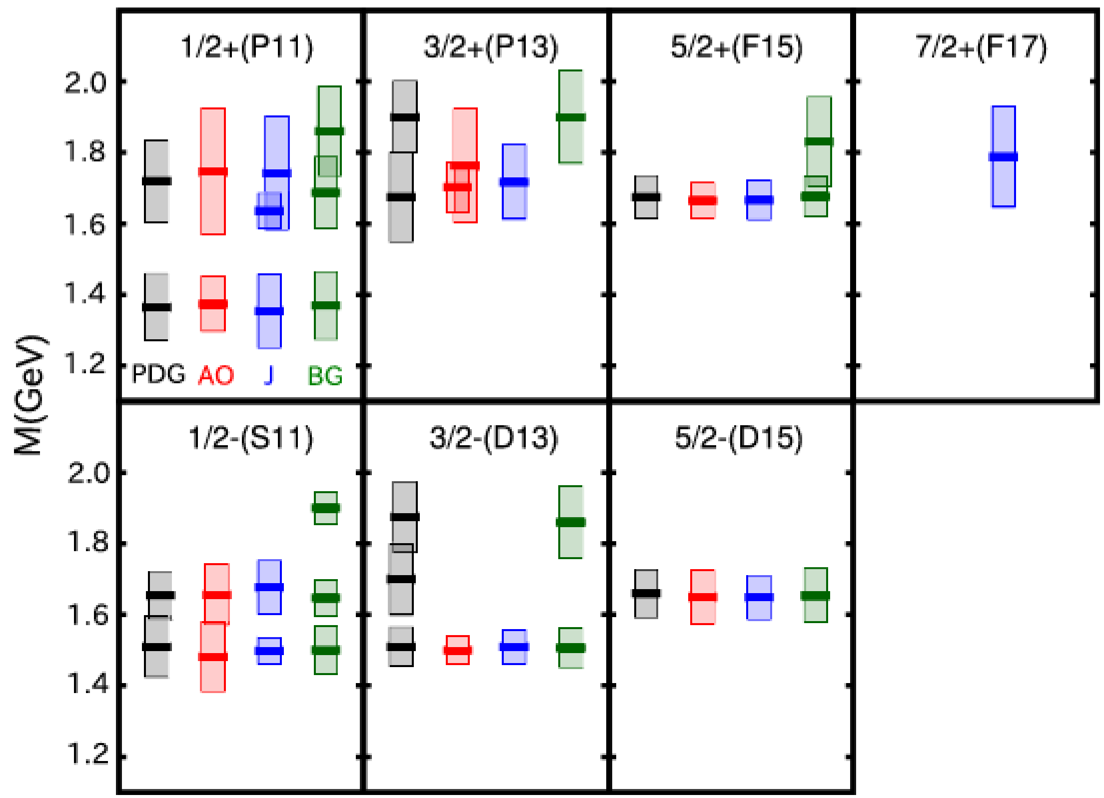
- “The Higgs boson is often said to give mass to everything. However, that is wrong. It only gives mass to some very simple particles, accounting for only one or two percent of the mass of more complex things like atoms, molecules and everyday objects, from your mobile phone to your pet llama.”
- *“The vast majority of mass comes from the energy needed to hold quarks together inside nuclei.”*

confinement



Strong Interactions in the Standard Model of Particle Physics

- Extract from spectrum of nucleon states (resonances) with
  mass less-than 2GeV
- Experiment (PDG) compared with theory (AO, J, BG)
- Theory results are outcome of massive computational effort, analysing *22,348 independent data points*, representing



Nature's scale for visible, strongly-interacting matter = 1 GeV = 1.783×10^{-27} kg ≈ 2000 × m_e

Strong Interactions in the Standard Model of Particle Physics

- Extr
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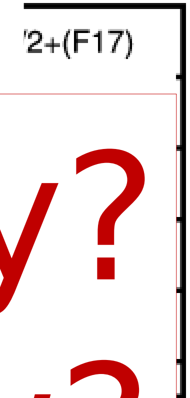
2GeV



Why?
How?

- Expe
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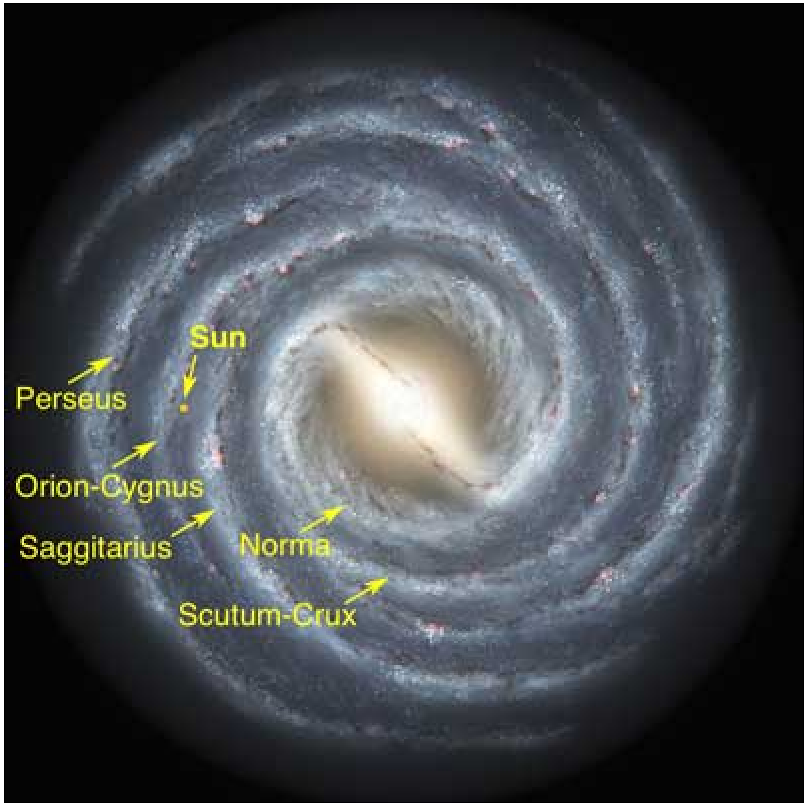
  effort, analysing *22,348 independent data points*, representing

Nature's scale for visible, strongly-interacting matter = 1 GeV = 1.783×10^{-27} kg ≈ 2000 × m_e

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 (but not massless), despite being a strongly interacting composite object built from a valence-quark and valence antiquark



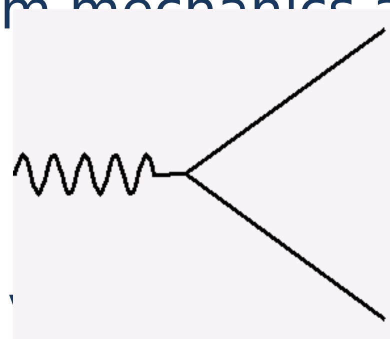
Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

What is QCD?

What is QCD?

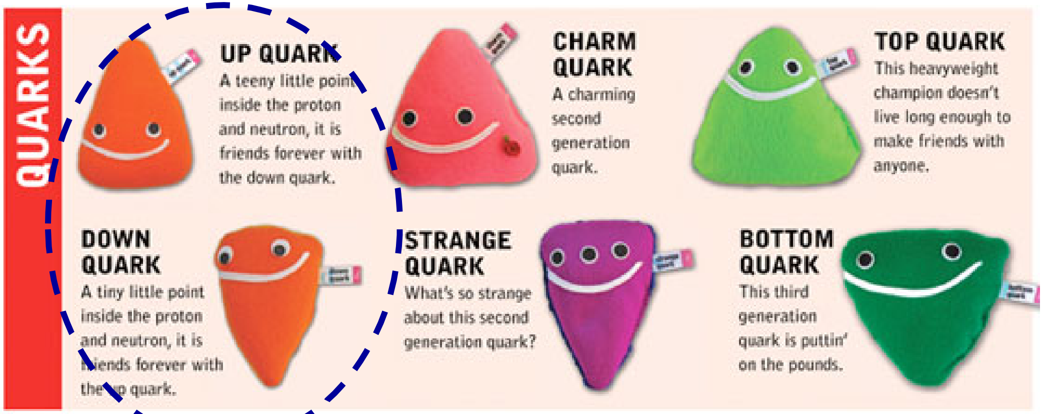
- Supposed to describe all known strongly-interacting matter, *viz*. the properties of protons, neutrons, pions, …, nuclei
- Quantum Field Theory
  - Only known way to unify quantum mechanics and special relativity
- Local
  - No action at a distance

    … simple, pointlike interaction



- Relativistic
- Non-Abelian gauge symmetry
  - Invariant under local SU(3) transformations, *i.e*. transformations generated by a set of eight non-commuting matrices, with spacetime-dependent coefficients
- Renormalisable
  - 2004 Nobel Prize: Politzer, Gross and Wilzcek
  - Proof that theory is "well-behaved" at high-energy, in

What is QCD?



Light quarks = constituents of all ordinary matter

- Lagrangian of QCD $\mathcal{L}_{\text{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$
  $= \bar{\psi}_i (i\gamma^\mu \partial_\mu - m)\psi_i - g G^a_\mu \bar{\psi}_i \gamma^\mu T^a_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$
  - Ψ = quark fields
  - G = gluon fields
- The key to complexity in QCD … gluon field

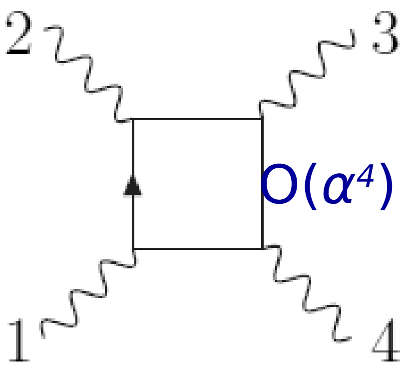
$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f^{abc} G^a_\mu G^b_\nu$$

- Generates gluon self-interactions, whose consequences are extraordinary

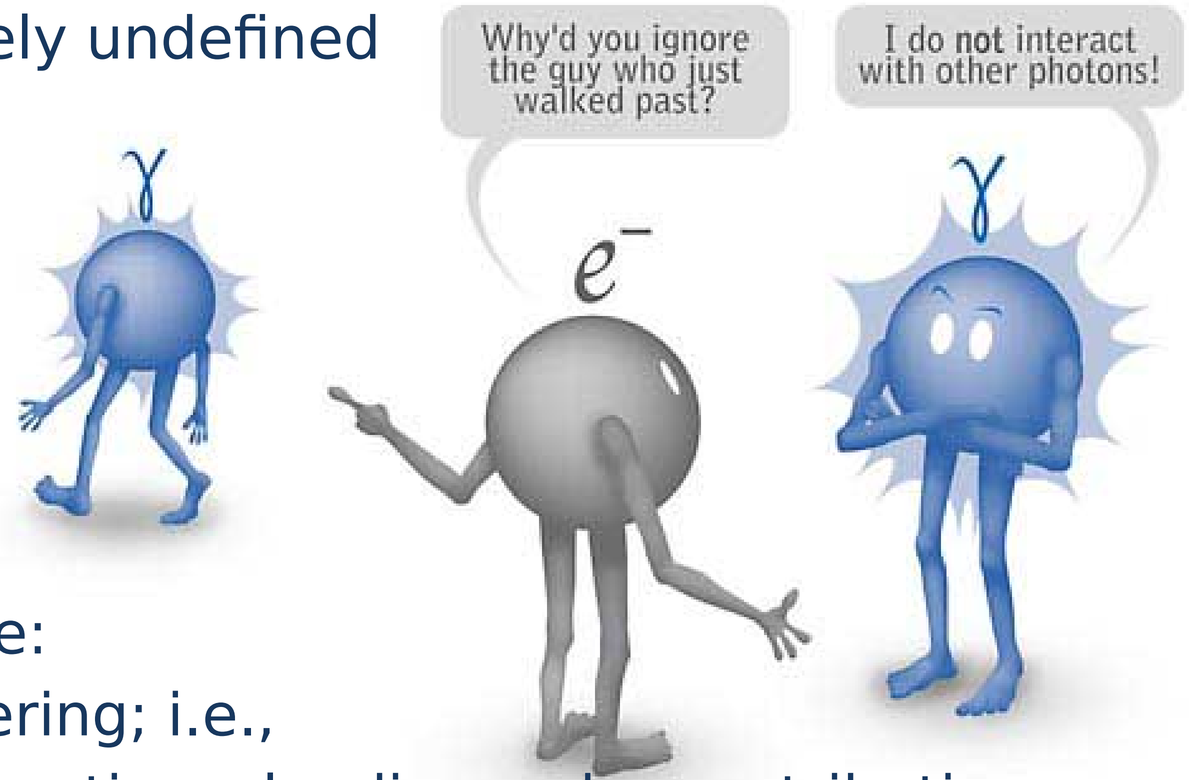
The "glue" of the strong nuclear force, the **GLUON** is the boson that communicates the strong force, which holds quarks together. It has no electric charge.

*cf.*Quantum Electrodynamics

- QED is the archetypal gauge field theory
- Perturbatively simple
  but nonperturbatively undefined



$O(\alpha^4) \approx 10^{-9}$

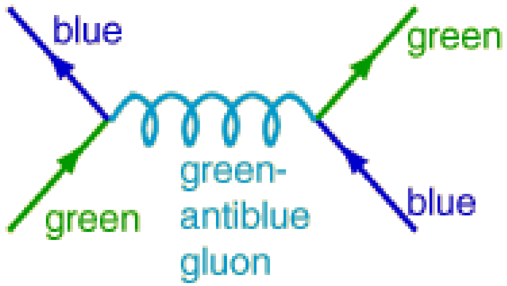


- Chracteristic feature:
  Light-by-light scattering; i.e.,
  photon-photon interaction – leading-order contribution takes
  place at order α^4. Extremely small probability because $\alpha^4 \approx 10^{-9}$!

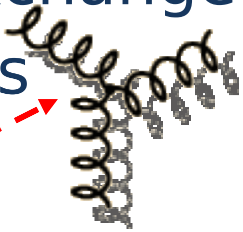
What is QCD?

Relativistic Quantum Gauge Field Theory:

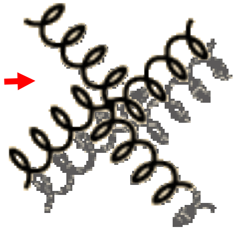
- Interactions mediated by vector boson exchange
- Vector bosons are *perturbatively*-massless



Feynman diagram for an interaction between quarks generated by a gluon.



3-gluon vertex



4-gluon vertex

- Similar interaction in QED
- Special feature of QCD – gluon self-interactions

Strong Interactions in the Standard Model of Particle Physics

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

- Only apparent scale in chromodynamics is mass of the quark field
- 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
- Quark mass is said to be generated by Higgs boson.
- Plainly, however, that 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,

What & where is mass?

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

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

Whence Mass?

- Lorentz-invariance is *not* enough … must add the effect of space-time translations, invariance under which guarantees energy and momentum conservation ⇐ *Poincaré invariance*
- Poincaré invariance entails that the Energy-Momentum Tensor is di $\partial_\mu T_{\mu\nu} = 0$, *i.e.* it defines a conserved current:

$T_{\mu\nu}$ can always be made symmetric

- Noether current associated with a global scale transformation:

$$x \to e^{-\sigma} x$$

is the c $\partial_\mu \mathcal{D}_\mu = 0 = [\partial_\mu T_{\mu\nu}] x_\nu + T_{\mu\nu}\delta_{\mu\nu}$

- In a sca $= T_{\mu\mu}\,,$ ent is conserved

Trace Anomaly

- 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
- *α → α(ζ)* in QCD's (massless) Lagrangian density, L(m=0)
  Under a scale transformation $\zeta \to e^{\sigma}\zeta$, then $\alpha \to \sigma\, \alpha\beta(\alpha)$
  $L \to \sigma\, \alpha\beta(\alpha)\, dL/d\alpha$
  $\Rightarrow \partial_\mu D_\mu = \delta L/\delta\sigma = \alpha\beta(\alpha)\, dL/d\alpha = \beta(\alpha)\, \tfrac{1}{4} G_{\mu\nu} G_{\mu\nu} = T_{\rho\rho} =: \Theta_0$

QCD β function

Trace anomaly

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

quantisation of renormalisable four-dimensional

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

Trace Anomaly

- The trace anomaly is not peculiar to QCD
- Quantum electrodynamics (QED) … the first real quantum field theory … also exhibits a trace anomaly
  - Form is the same
  - But, empirically, the scale is vastly different

- Can we understand Why?
  - Is there a theoretical explanation?
  - Can it be verified empirically?

Where’s the mass?

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

Trace Anomaly

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

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

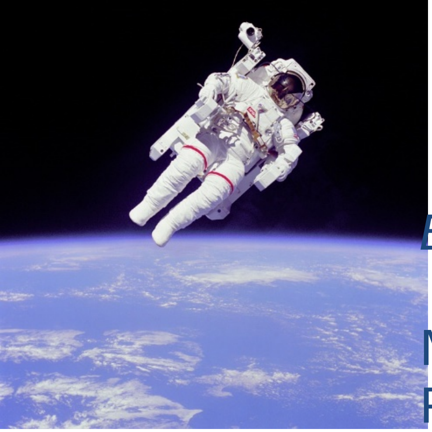
$$\langle p(P)|T_{\mu\mu}|p(P)\rangle = -P^2 = m_p^2$$

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

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

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

On the other hand …



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 supposes the Standard Model Hamiltonian possesses an operator that produces a light-quark mass: u_0
- Assumes a set of empirically-validated symmetries, then provides an algebraic proof that

  $$m_\pi^2 \propto < \pi|u_0|\pi>$$
- Corollary:

  $$m_\pi^2 = 0 \quad \text{for} \quad u_0=0$$

  the pion is massless in the chiral limit,

  i.e. if there is no Higgs-generated mass for the light quarks

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

Trace Anomaly

- In the chiral limit

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

- Does this mean that the scale anomaly vanishes trivially in the pion state, *i.e*. gluons contribute nothing to the pion mass?
- That is a difficult way to obtain "zero"
- Easier, perhaps, to imagine that "zero" owes to cancellations between different operator-component 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

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

Trace Anomaly

- In the chiral limit

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

- *No statement of the question*

"Whence the proton's mass?"

is complete without the additional clause

"Whence the of a pion mass?"

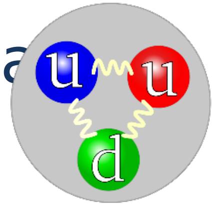
- Natural nuclear-physics mass-scale must emerge simultaneously with apparent preservation of scale invariance in related systems

– Expectation value of Θ_0 in pion is always zero,

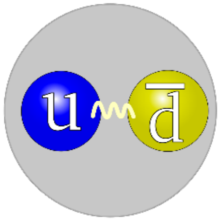
Whence "1" and yet "0"

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

- Both statements are Poincaré invaria



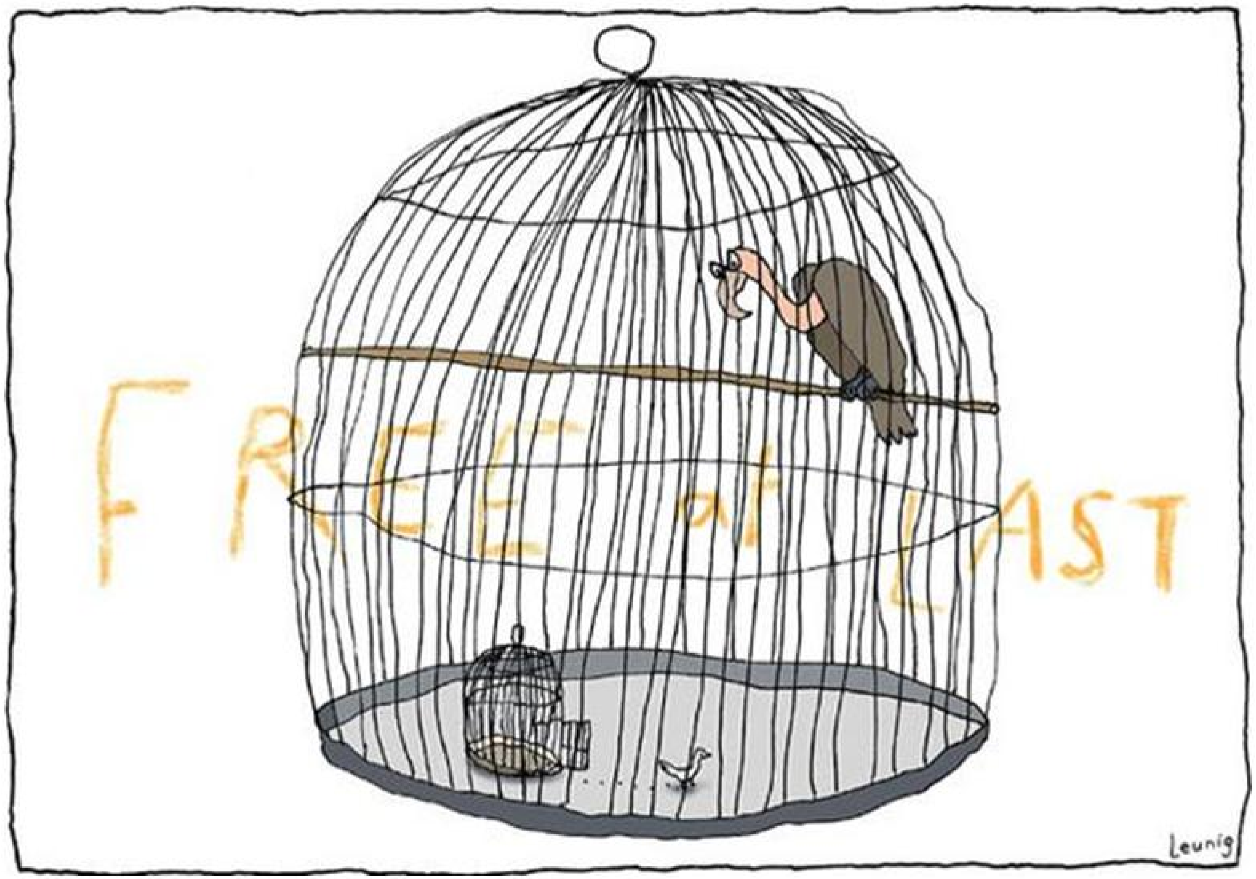
  - Proton is massive
  - But the pion is massless (unnaturally light)



    - In fact, all the pion's mass is generated by the Higgs mechanism

      $m_\pi^2 \propto m_{\text{light-quark}}$

    - Empirically, u & d quarks are light ($m_{u,d} \sim 10\ m_e$), hence pion remains light after Higgs-coupling is introduced
- Two of the Standard Model's Emergent features we started with
- *Are they connected with the stability of the proton?*



Confinement

The New York Times

Excerpt from the top-10

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

10 Physics Questions to Ponder for a Millennium or Two

By George Johnson
Published: August 15, 2000

- ***Can we quantitatively understand quark and gluon confinement in quantum chromodynamics and the existence of a mass gap?***

  Quantum chromodynamics is the theory describing the strong nuclear force. Carried by gluons, it binds quarks into particles like protons and neutrons. Apparently, the tiny subparticles are permanently confined: one can't pull a quark or a gluon from a proton because the strong force gets stronger with distance and snaps them right back inside.

Millennium prize of $1,000,000 for proving that $SU_c(3)$ gauge theory is mathematically well-defined, which will necessarily prove or disprove a confinement conjecture

Yang–Mills Existence and Mass Gap. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

5. Comments

An important consequence of the existence of a mass gap is clustering: Let $\vec{x} \in \mathbb{R}^3$ denote a point in space. We let H and $\vec{P}$ denote the energy and momentum, generators of time and space translation. For any positive constant $C < \Delta$ and for any local quantum field operator $\mathcal{O}(\vec{x}) = e^{-i\vec{P}\cdot\vec{x}}\mathcal{O}e^{i\vec{P}\cdot\vec{x}}$ such that $\langle\Omega, \mathcal{O}\Omega\rangle = 0$, one has

$$|\langle\Omega, \mathcal{O}(\vec{x})\mathcal{O}(\vec{y})\Omega\rangle| \leq \exp(-C|\vec{x}-\vec{y}|), \quad (2)$$

as long as $|\vec{x}-\vec{y}|$ is sufficiently large. Clustering is a locality property that, roughly speaking, may make it possible to apply mathematical results established on $\mathbb{R}^4$ to any 4-manifold, as argued at a heuristic level (for a supersymmetric extension of four-dimensional gauge theory) in [**49**]. Thus the mass gap not only has a physical significance (as explained in the introduction), but it may also be important in mathematical applications of four-dimensional quantum gauge theories to geometry. In addition the existence of a uniform gap for finite-volume approximations may play a fundamental role in the proof of existence of the infinite-volume limit.

There are many natural extensions of the Millennium problem. Among other things, one would like to prove the existence of an isolated one-particle state (an upper gap, in addition to the mass gap), to prove confinement, to

Confinement?

Millennium prize of $1,000,000 for proving that $SU_c(3)$ gauge

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Confinement?

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

Whence?

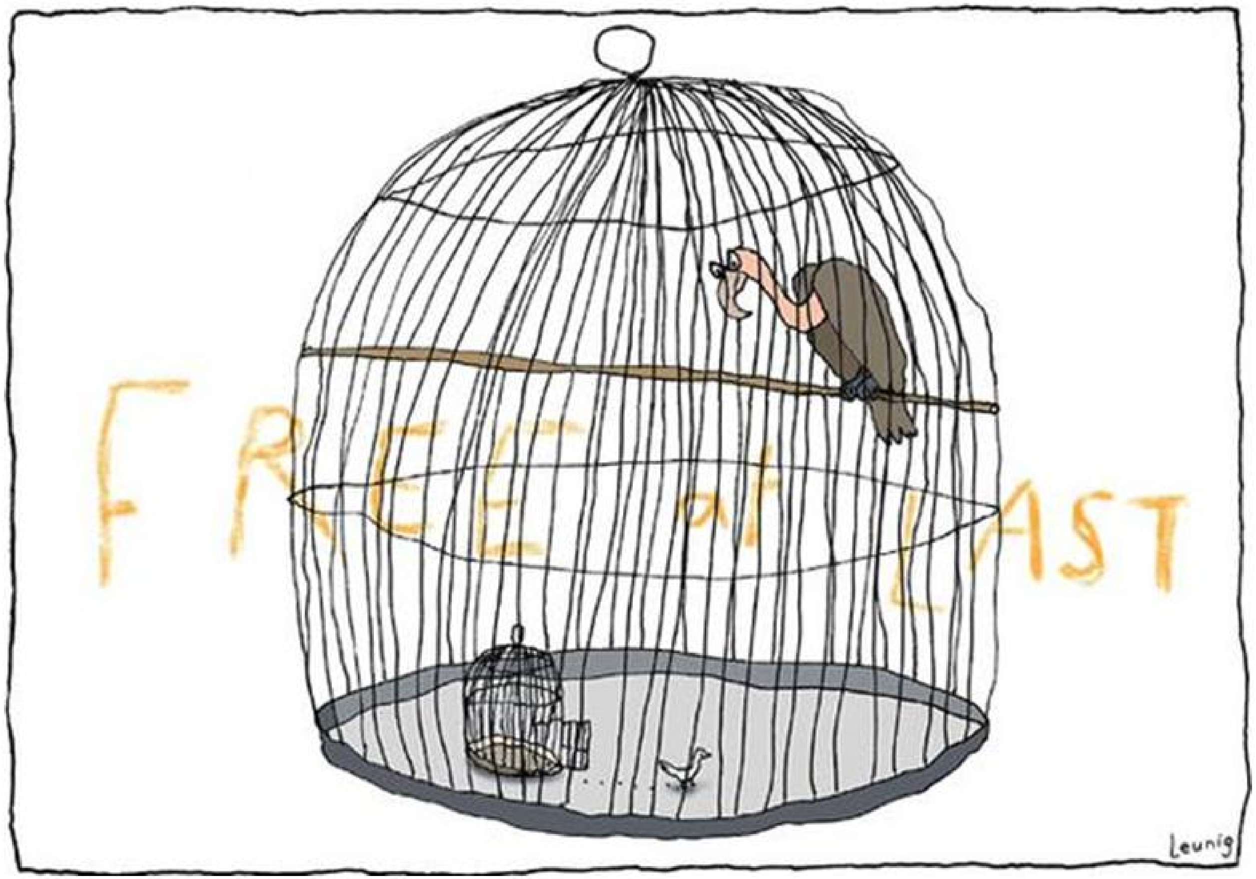
- Classical chromodynamics … non-Abelian local gauge theory
- Local gauge invariance; but there is no confinement without a mass-scale
  - Three quarks can still be colour-singlet
  - Colour rotations will keep them colour singlets
  - But they need have no proximity to one another
    … proximity is meaningless in a scale-invariant theory
- Whence mass … equivalent to whence a mass-scale
  … equivalent to whence a confinement scale
- *Understanding the origin and absence of mass in QCD is quite likely inseparable from the task of understanding confinement. Existence alone of a scale anomaly answers neither question*

Overarching Science Challenges for the coming decade

- What is origin of mass in our Universe?
- What is the nature of confinement in real (dynamical-quarks) QCD?
- How are they connected?
- How can any
  - answers,
  - conjectures
  - and/or conclusions

  be empirically verifie

Physics is an Empirical Science



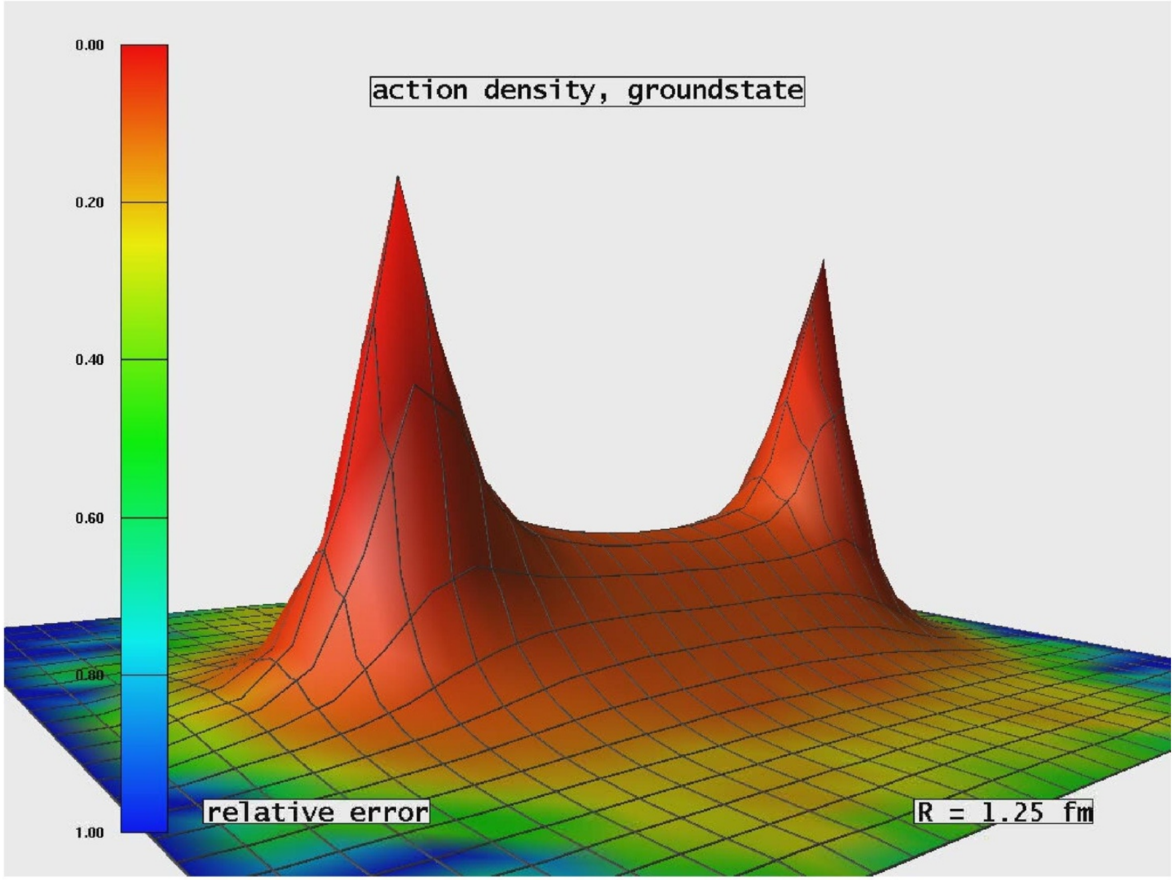
What is Confinement?

Light quarks & Confinement

- Folklore … ***Hall-D Conceptual Design Report(5)***

“The color field lines between a quark and an anti-quark form flux tubes.

A unit area placed midway between the quarks and perpendicular to the line connecting them intercepts a constant number of field lines, independent of the distance between the quarks.



This leads to a constant force between the quarks – and a large force at that, equal to about

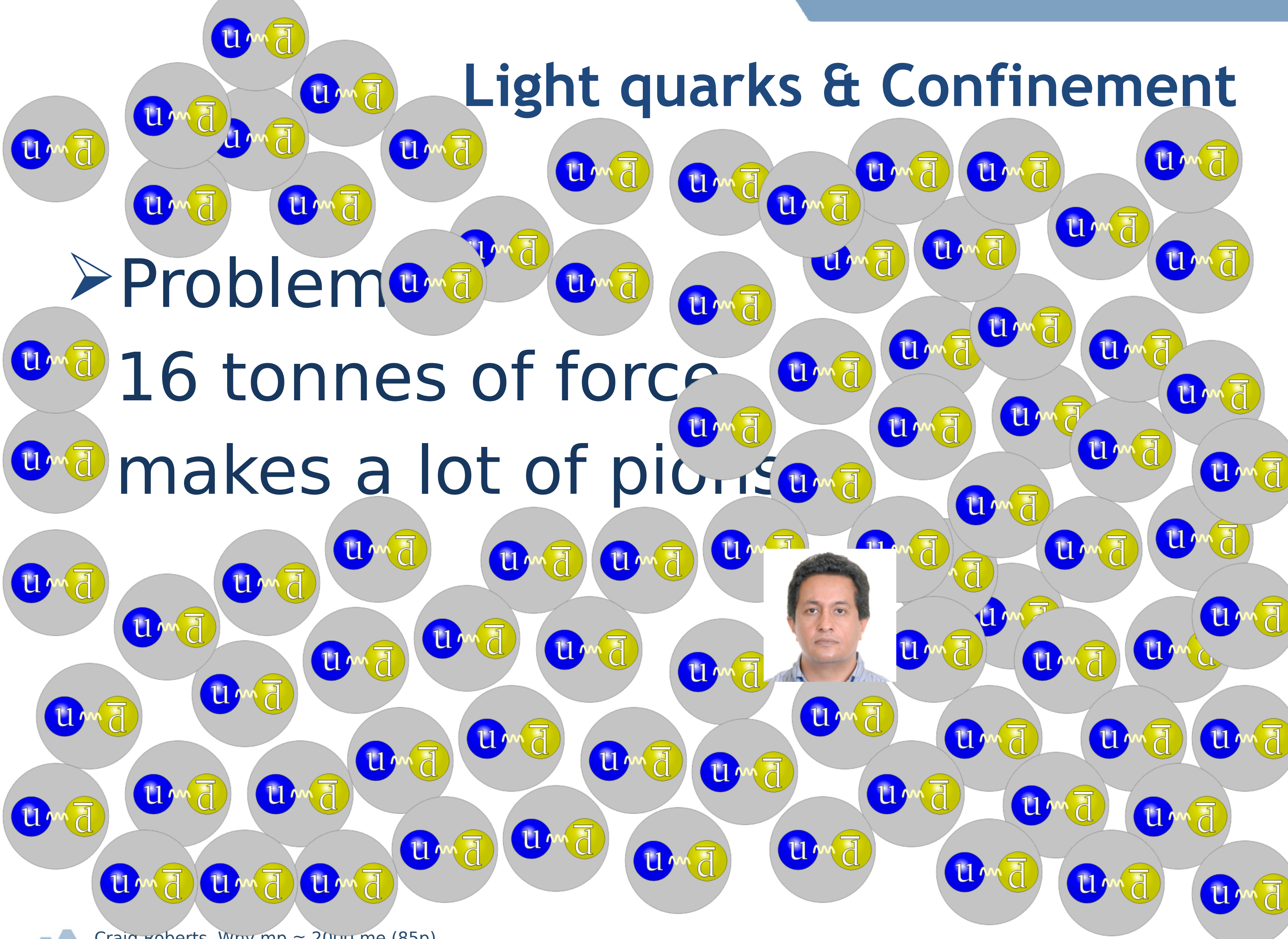
Light quarks & Confinement

- *Static* picture of confinement

Light quarks & Confinement

- Problem:
  16 tonnes of force
  makes a lot of pions.

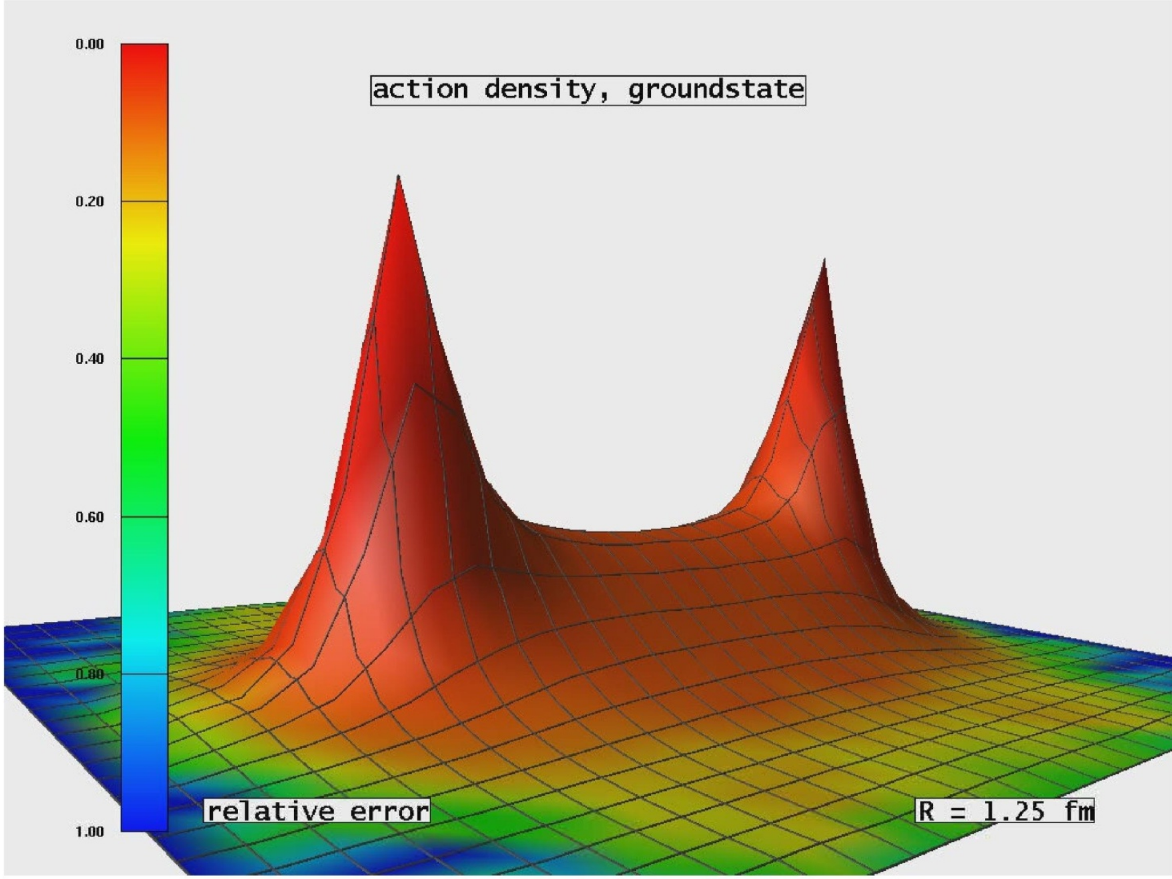
Light quarks & Confinement



- Problem
16 tonnes of force
makes a lot of pions

Light quarks & Confinement

- In the presence of light quarks, *pair creation seems to occur non-localized and instantaneously*
- No flux tube in a theory with light-quarks.
- ***Flux-tube is not the correct paradigm for confinement in***



Light quarks & Confinement

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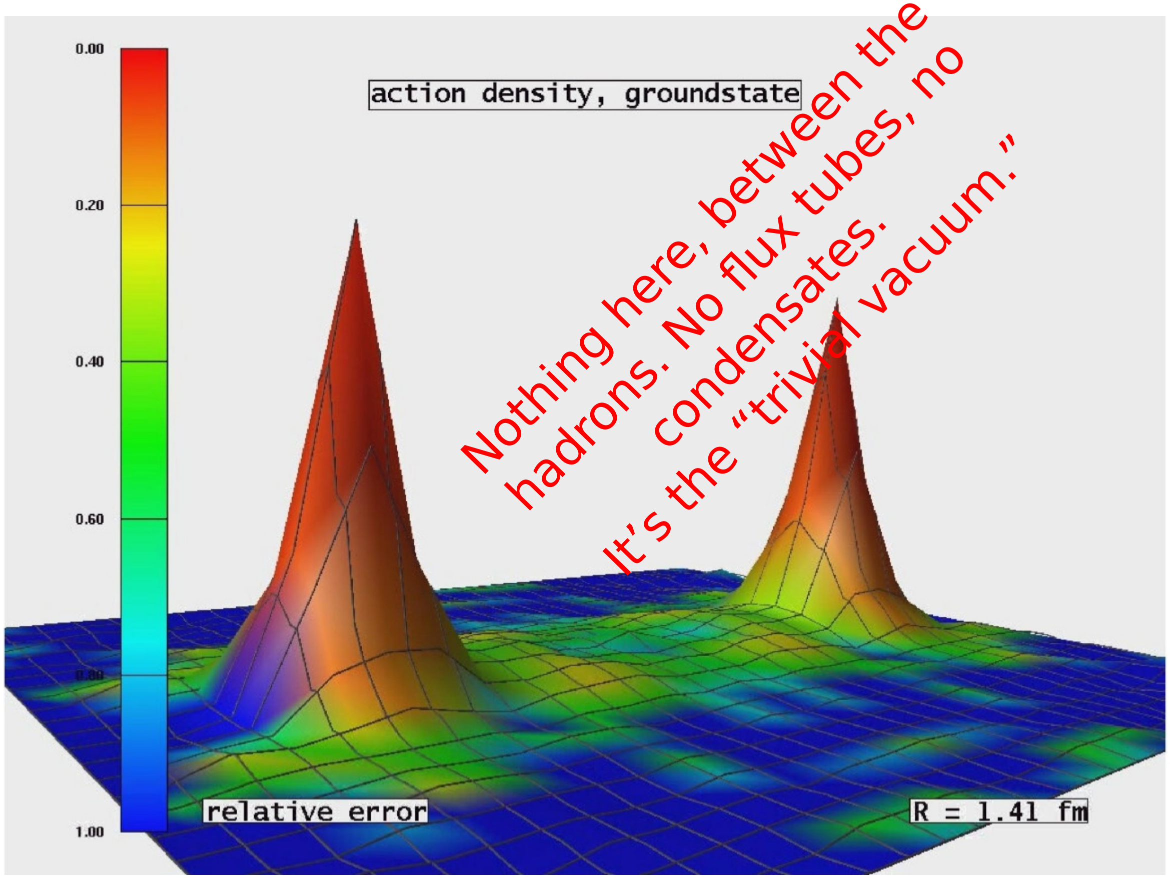
Confinement contains condensates
Brodsky, Roberts, Shrock,Tandy
arXiv:1202.2376 [nucl-th], Phys. Rev. C**85** (2012) 065202



conjecture: lQCD predicts $\Delta \sim 1.5$ GeV

- But $\Delta^2/m_\pi^2 > 100$,

  So, can mass-gap in pure Yang-Mills play any role in understanding confinement when dynamical chiral symmetry breaking (DCSB) ensures existence of an almost-massless strongly-interacting excitation in our Universe?

- Conjecture: If *answer is* not *simply* ***no***, then it is probable that one cannot claim to provide an understanding of confinement without simultaneously explaining its connection with DCSB.

- Conjecture: *Pion must play critical role in any explanation of real-world confinement. Any discussion that omits reference to the pion's role is possibly irrelevant.*

Yang–Mills Existence and Mass Gap. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

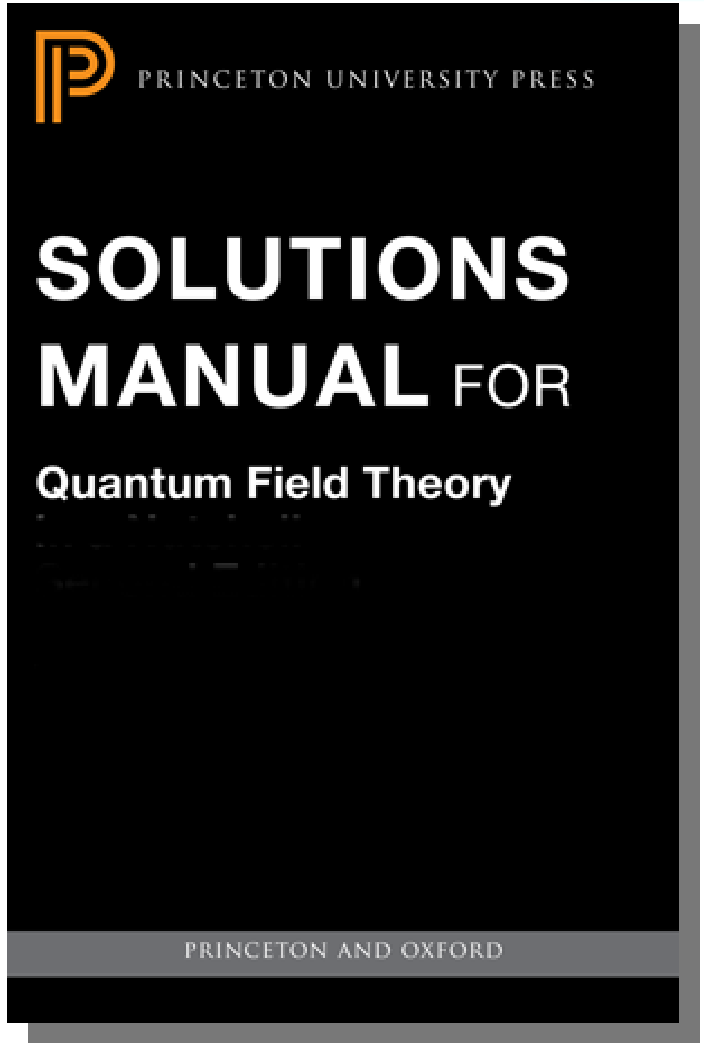
5. Comments

An important consequence of the existence of a mass gap is clustering: Let $\vec{x} \in \mathbb{R}^3$ denote a point in space. We let H and $\vec{P}$ denote the energy and momentum, generators of time and space translation. For any positive constant $C < \Delta$ and for any local quantum field operator $\mathcal{O}(\vec{x}) = e^{-i\vec{P}\cdot\vec{x}}\mathcal{O}e^{i\vec{P}\cdot\vec{x}}$ such that $\langle \Omega, \mathcal{O}\Omega \rangle = 0$, one has

$$(2) \qquad |\langle \Omega, \mathcal{O}(\vec{x})\mathcal{O}(\vec{y})\Omega \rangle| \leq \exp(-C|\vec{x} - \vec{y}|),$$

as long as $|\vec{x} - \vec{y}|$ is sufficiently large. Clustering is a locality property that, roughly speaking, may make it possible to apply mathematical results established on $\mathbb{R}^4$ to any 4-manifold, as argued at a heuristic level (for a supersymmetric extension of four-dimensional gauge theory) in [**49**]. Thus the mass gap not only has a physical significance (as explained in the introduction), but it may also be important in mathematical applications of four-dimensional quantum gauge theories to geometry. In addition the existence of a uniform gap for finite-volume approximations may play a fundamental role in the proof of existence of the infinite-volume limit.

There are many natural extensions of the Millennium problem. Among other things, one would like to prove the existence of an isolated one-particle state (an upper gap, in addition to the mass gap), to prove confinement, to



Theoretical Answers?

Textbook definition: Gauge Boson

- A gauge boson is a force carrier, mediating one of Nature's fundamental interactions
- All known gauge bosons have spin "1", *i.e*. all are vector bosons.
- Owing to gauge invariance, no term of the form

  $$m^2 B_\mu B_\mu$$

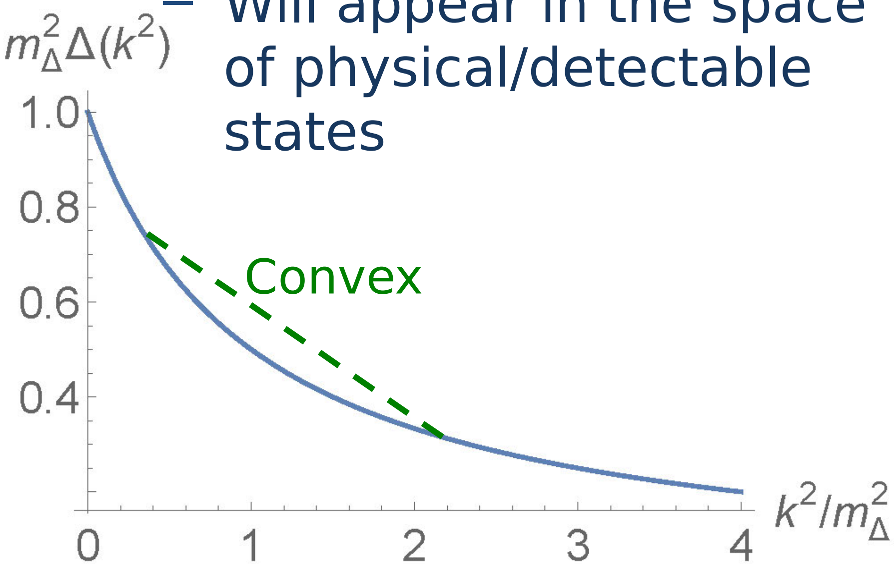
  can appear in the gauge theory Lagrangian.
- Thus, all gauge bosons are massless in the absence of a Higgs mechanism:
  - Photon … known to be massless
  - W and Z bosons … begin life massless, but known to become massive, owing to Higgs mechanism, which is abundantly clear in the Lagrangian
  - Gluon … there is no Higgs coupling and textbooks describe them as massless

Normal Particle

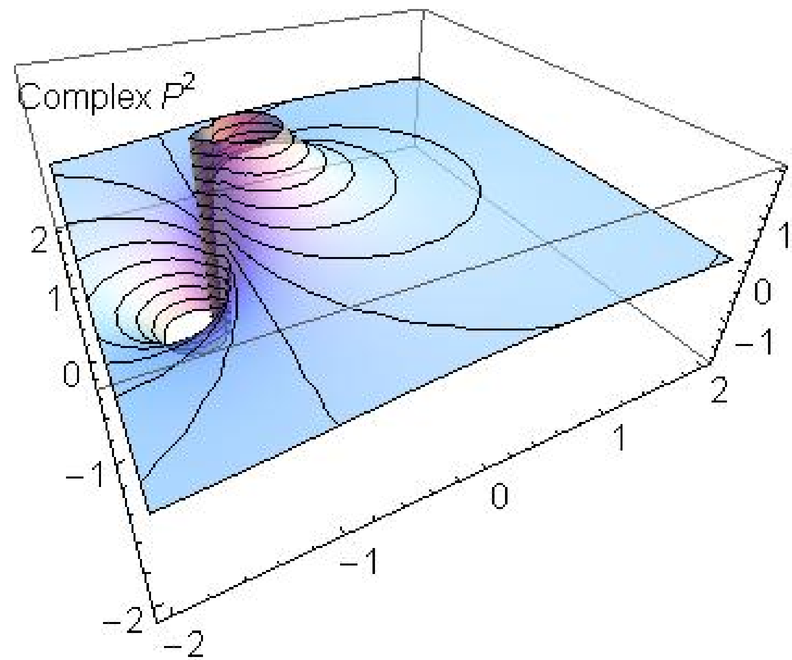
- Free-particle propagator
  - Convex function
- Spectral function is po

$$\Delta(k^2) = \int_0^\infty ds \, \frac{\rho(s)}{s + k^2}$$

  - *ρ(s)*>0
- Corresponds to a state with positive norm
  - Will appear in the space of physical/detectable states

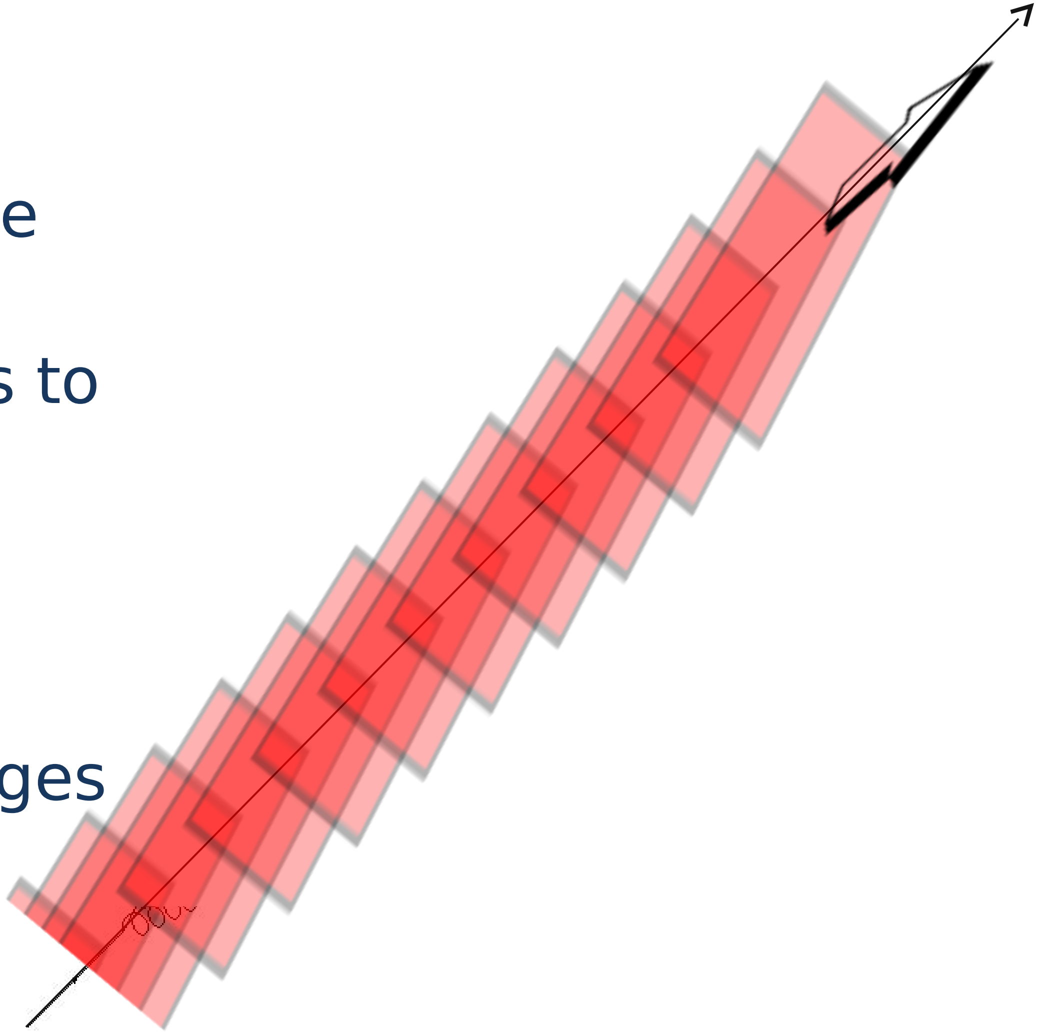


- Exhibits a simple pole on the timelike axis

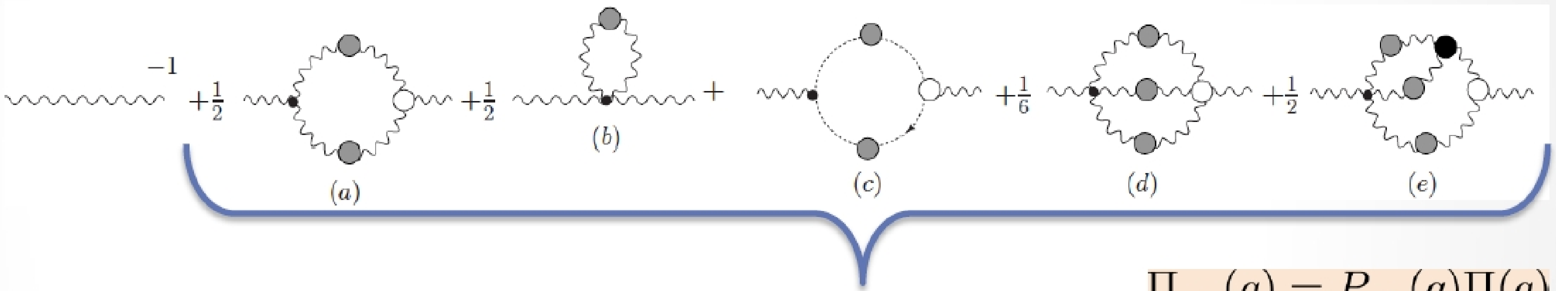


Plane wave propagation

- Feynman propagator for a free particle describes a Plane Wave
- A particle begins to propagate
- It can proceed a long way before undergoing any qualitative changes



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



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

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

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

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!

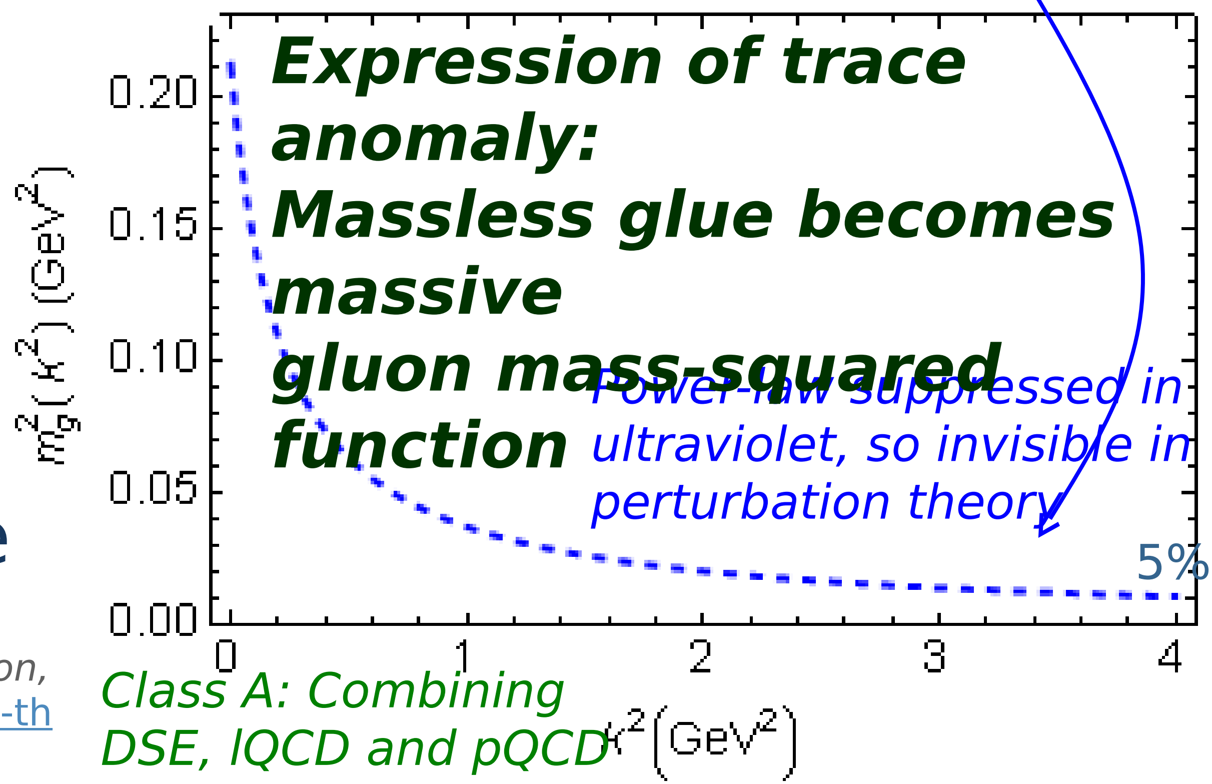
- Running gluon mass

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

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

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

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



Expression of trace anomaly: Massless glue becomes massive gluon mass-squared function

Power-law suppressed in ultraviolet, so invisible in perturbation theory

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]

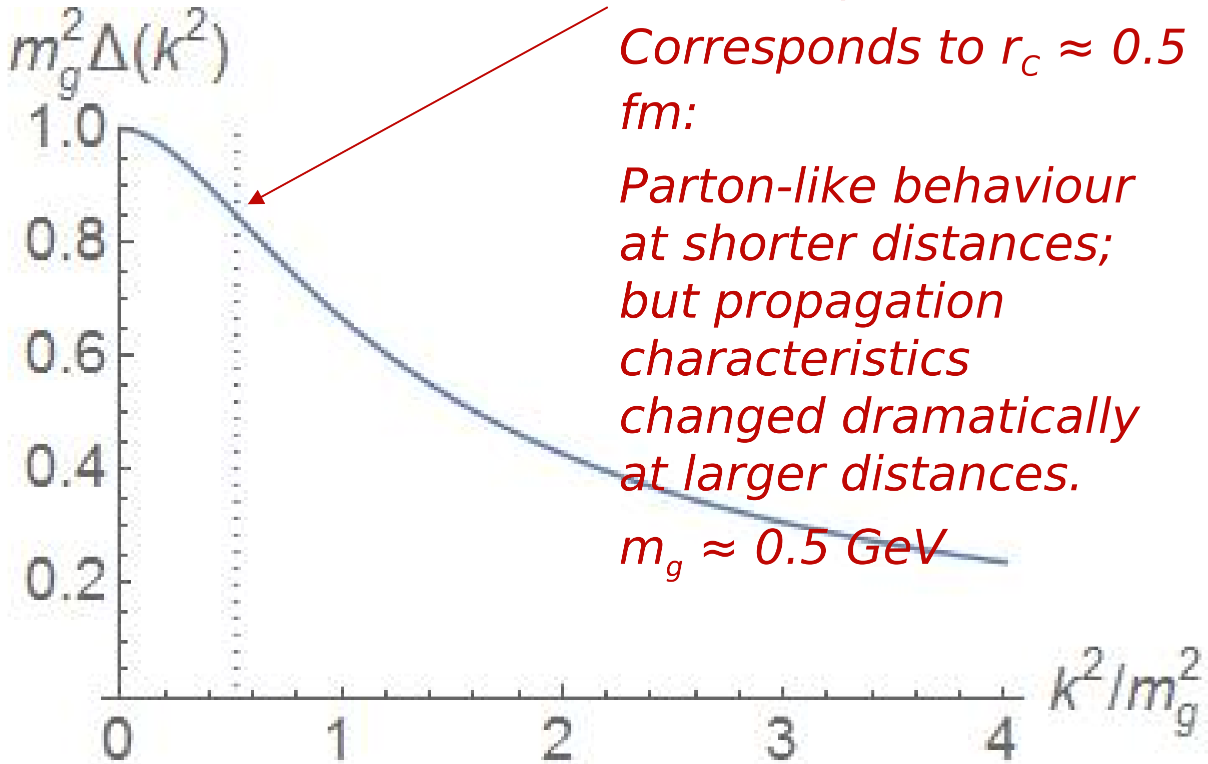
Confined particle

- All QCD solutions for Landau-gauge gluon & quark propagators exhibit an inflection point in k^2 … consequence of the running-mass function

⇒ Spectral function is NOT positive

⇒ Such states have negative norm (negative probability)

⇒ Negative norm states are not observable



Inflexion point

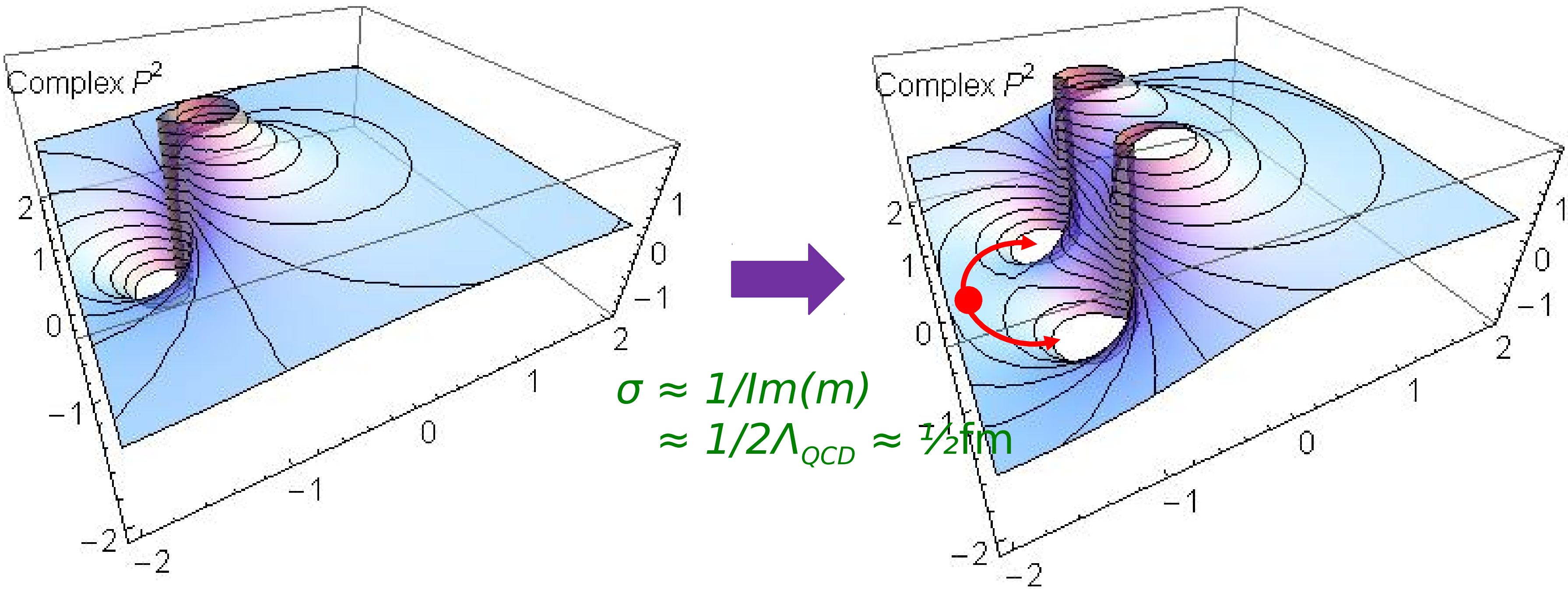
Corresponds to $r_C \approx 0.5$ fm:

Parton-like behaviour at shorter distances; but propagation characteristics changed dramatically at larger distances.

$m_g \approx 0.5$ GeV

Confinement

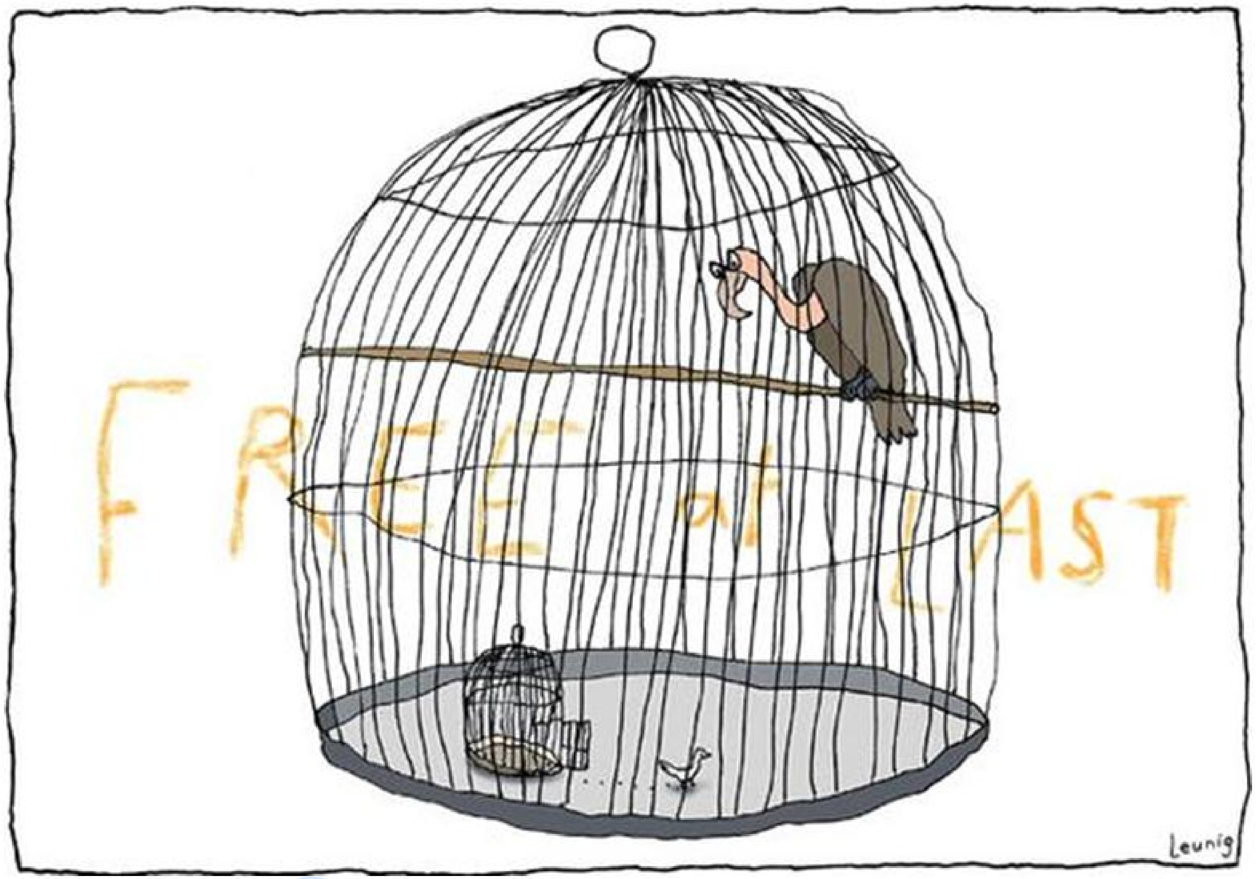
- Meaning …



$\sigma \approx 1/Im(m)$
$\approx 1/2\Lambda_{QCD} \approx$ ½fm

Real-particle mass-pole splits, moving into pair(s) of complex conjugate singularities, (or qualitatively analogous structures chracterised by a dynamically generated mass-scale)

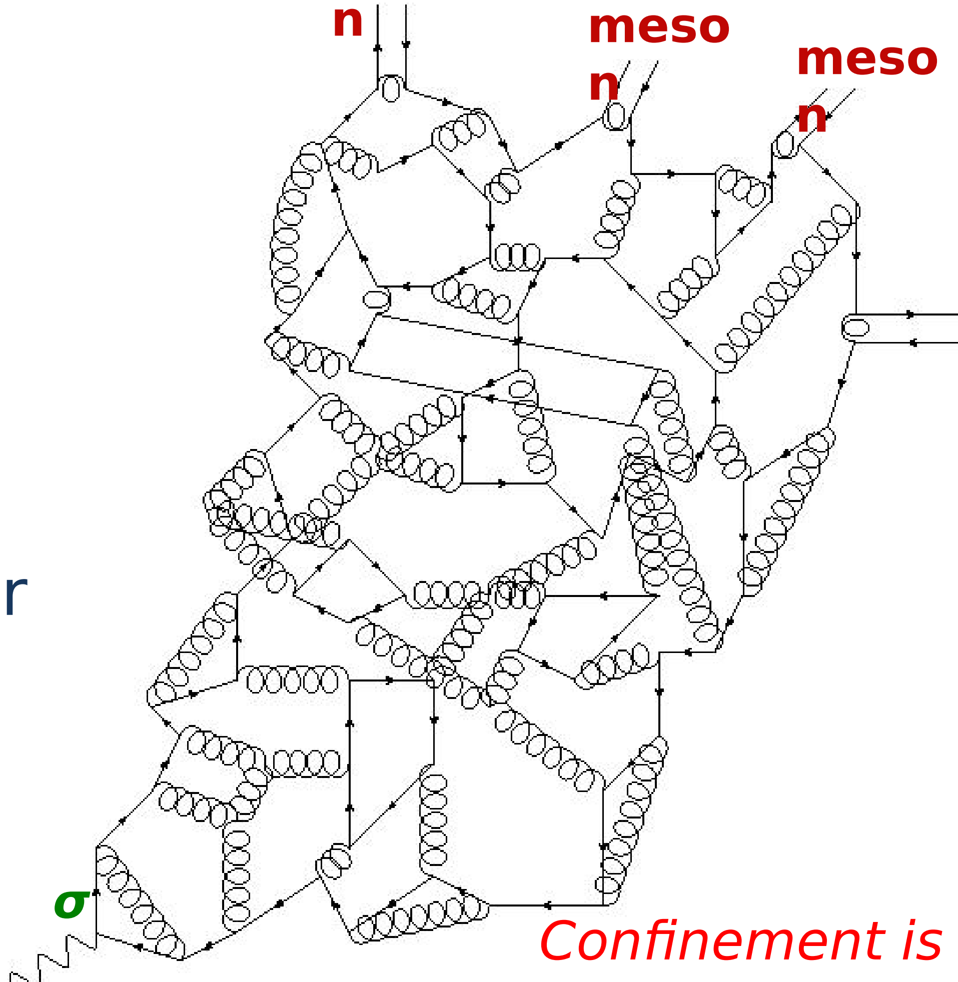
Propagation described by rapidly damped wave & hence state cannot exist in observable spectrum



Confinement is dynamical

Quark Fragmentation

- A quark begins to propagate
- But after each “step” of length ***σ***, on average, an interaction occurs, so that the quark *loses* its identity, sharing it with other partons
- Finally, a cloud of partons is produced, which coalesces into colour-singlet final states



Confinement is a dynamical phenomenon!

Spontaneous(Dynamical) Chiral Symmetry Breaking = Mass Generation

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

"*for the discovery of the mechanism of spontane*
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

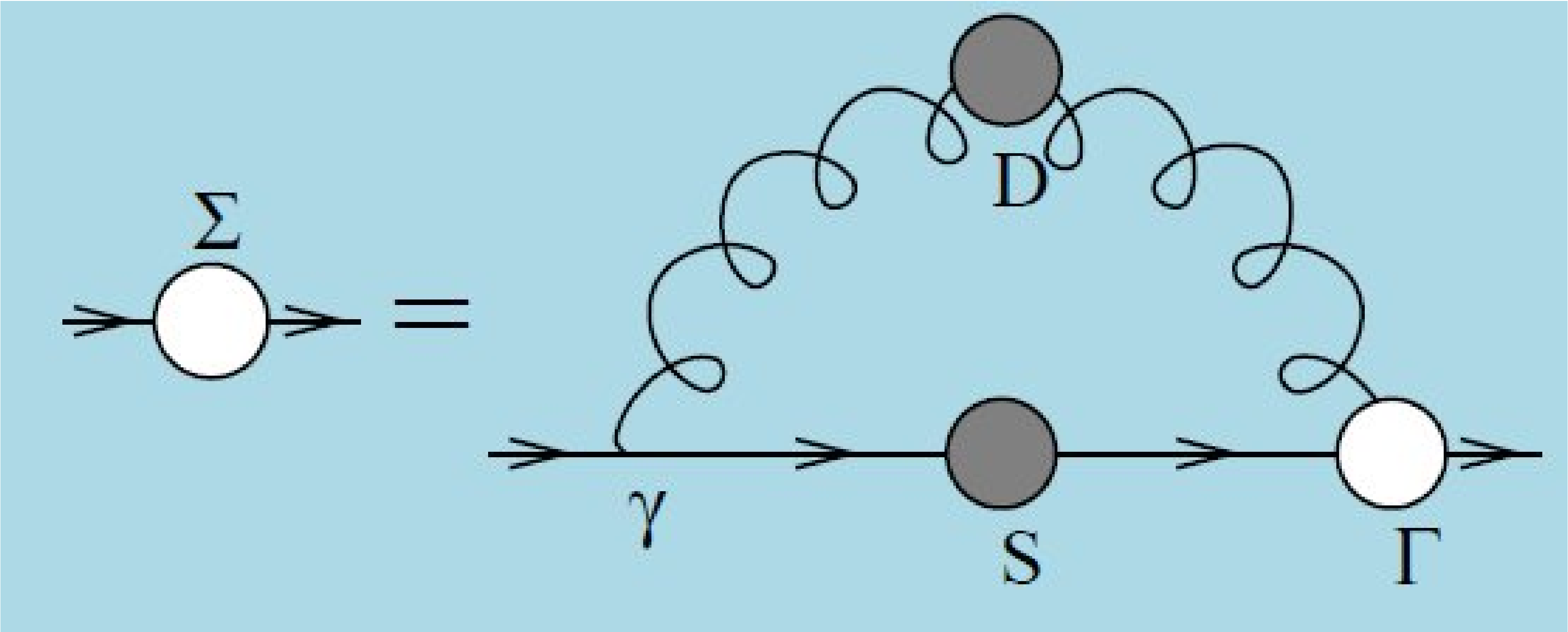
- Treats a massless (chirally-invariant) four-fermion Lagrangian & solves the gap equation in Hartree-Fock approximation (analogous to rainbow truncation)

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

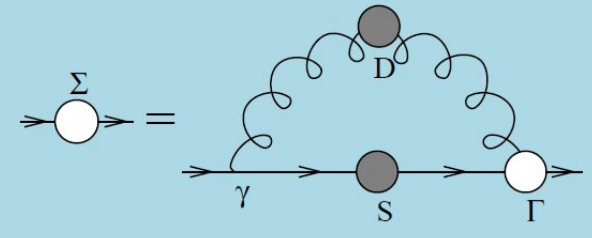
$$L = -\bar{\psi}\gamma_\mu \partial_\mu \psi + g_0[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5\psi)^2]. \qquad (2.6)$$

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

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

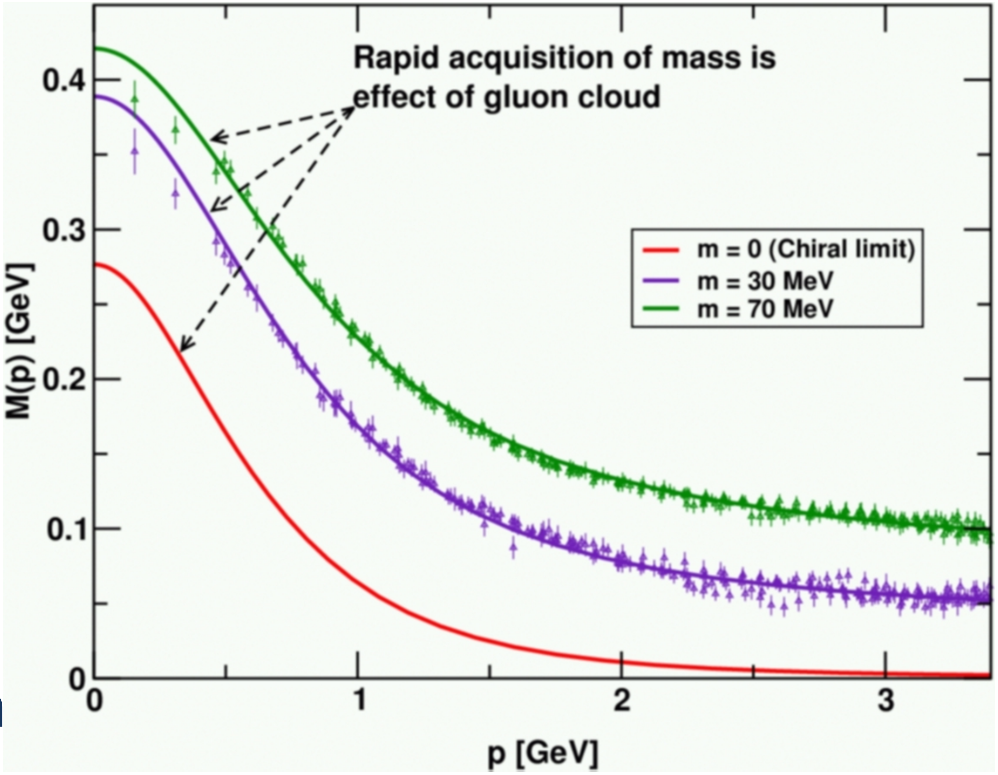


Quark Gap Equation



Quark running mass

- Nonperturbative analyses of the propagation characteristics of quarks in QCD yield a dressed-quark mass function, *M(p)*
- Textbook behaviour on *p*>1GeV
  - can be computed using perturbation theory
- Momentum-dependence on *p*<1GeV is essentially nonpeturbative
- Red curve
  - Quark begins massless
  - Owing to interaction with its own (massive) gluon field, the quark becomes

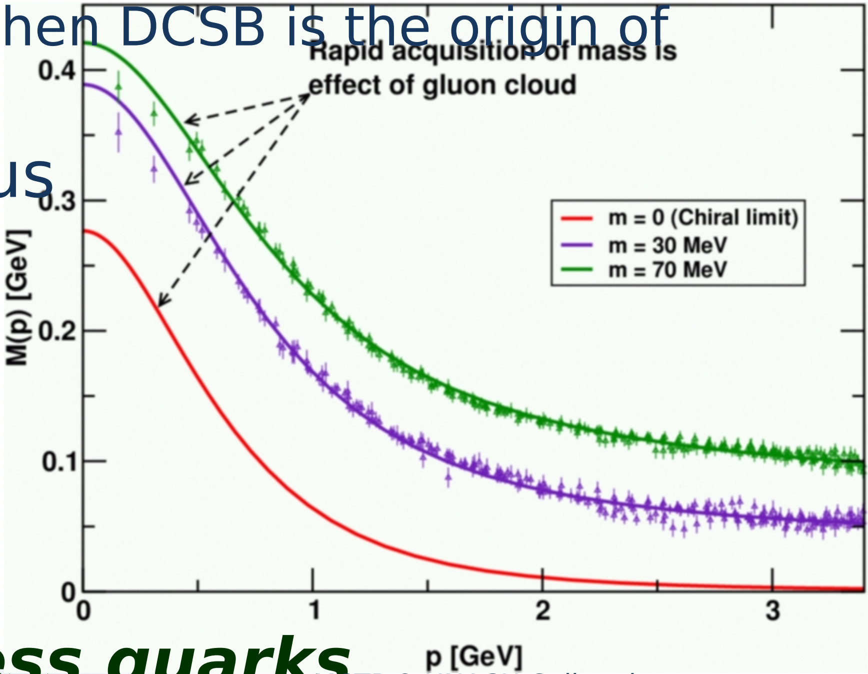


Dynamical chiral symmetry breaking
"Mass from nothing"

DCSB

- Dynamical chiral symmetry breaking (DCSB) is a critical emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Dynamical generation/enhancement of the quark mass can be understood as the origin of more than 98% of the visible mass in the Universe
  - Namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of *mass from nothing*.
- ***Dynamical***, not spontaneous
  - Add nothing to *QCD* ,

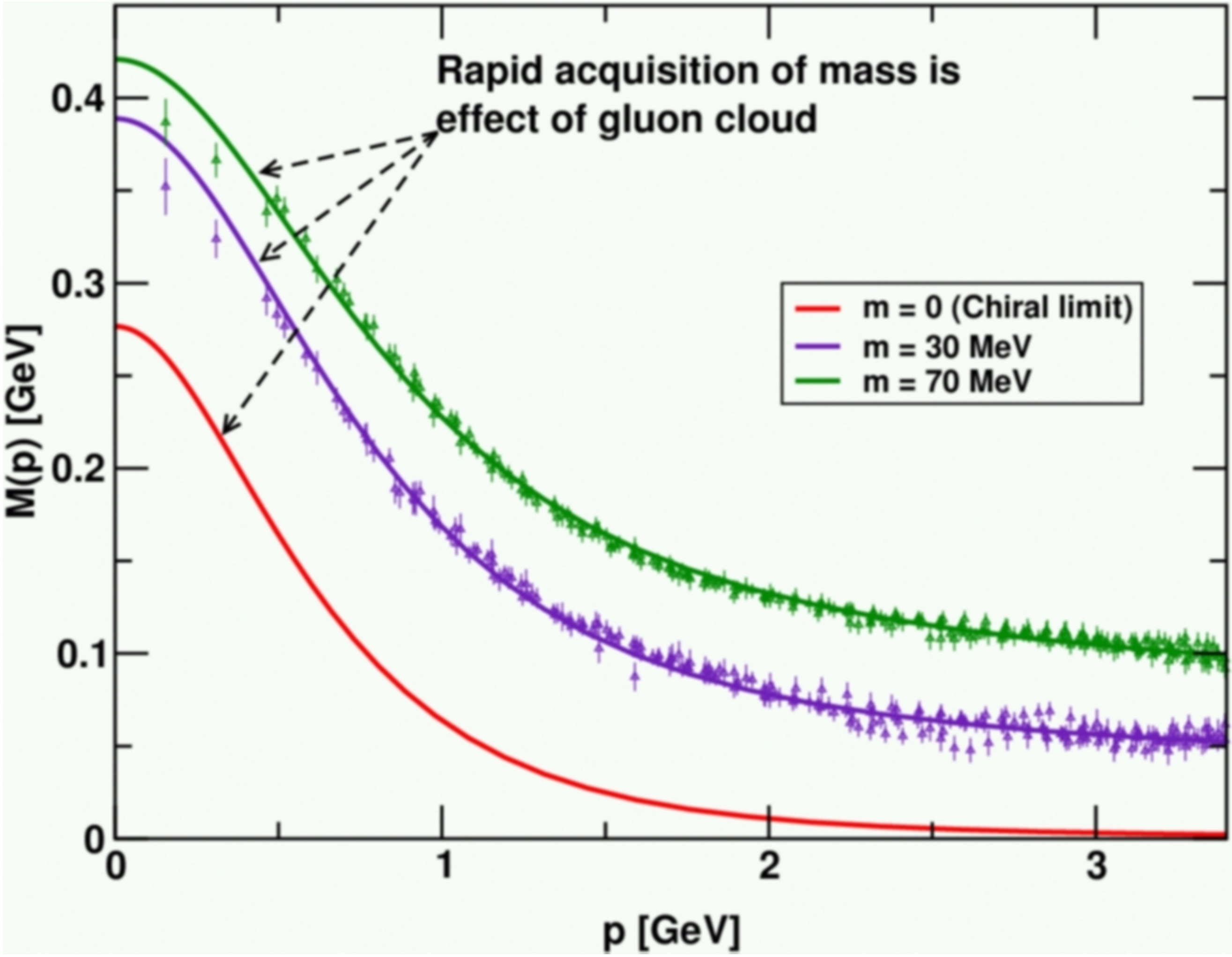
    No Higgs field, nothing! Effect achieved purely through quark+gluon dynamics.

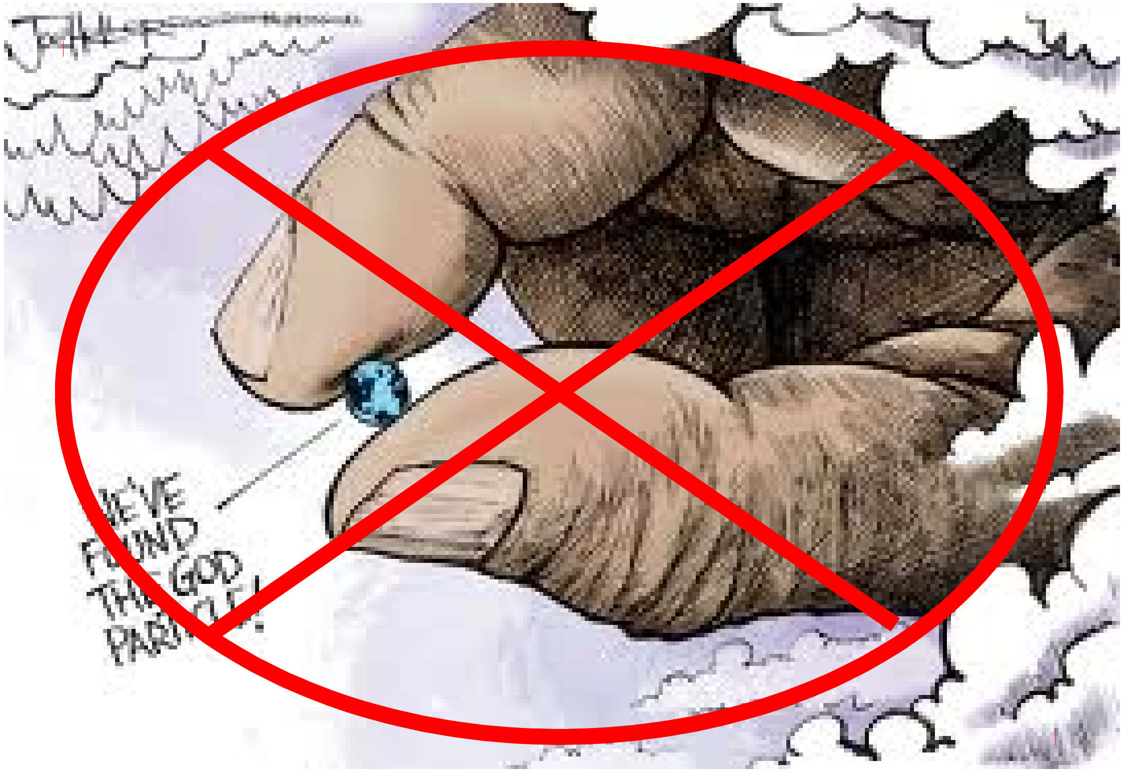


✓ ***Trace anomaly: massless quarks become massive***

Calories for quarks

- One of the most important figures in the Standard Model of Particle Physics
- 98% of the mass in this room owes to the phenomeno





DCSB: Mass from Nothing

Ward-Green-Takahashi identities

- Quantum mechanics is typically formulated using a Hamiltonian
  - There are conservation laws, associated with operators that commute with the Hamiltonian
- But quantum mechanics can only treat a finite number of bodies
  - The particles retain their identity despite interacting with a "potential"
- Quantum field theory is the only known way to reconcile quantum mechanics and special relativity
  - Particles are replaced by fields
  - Conservation laws are expressed via
    - Noether currents
    - Ward-Green-Takahasi identities
- Simplest Ward identity
  - QED $Z_1=Z_2$
  - → interaction induced divergences in 2-point photon

Express relationships between correlations that involve a different number of "particles"

General structure: WGTIs relate (n+1)-body to n-body pro

Ward Identity

studies and the latter in studying atmospheric ionization at ground level. These increases in ionization are considered to be due to radioactive matter brought down with the rain. Between 0935 and 1900 hr. GMT on November 29 at Ottawa precipitation was falling. The precipitation started as snow and changed to rain about 1400 hr. Compared with the results of Doan and Wait and McNish the 35 percent increase in the soft component registered at Ottawa by counters seems too high to be explained in the same way, unless there was an exceptionally high density of radioactive matter in the atmosphere at the time. An alternative, but not very likely explanation, might be that there was a burst of hard gamma-rays or some other radiation which would increase the number of soft shower particles without any appreciable effect on the hard component.

An interesting feature of the November 19 increase is the difference between the measurements at the various stations, particularly between Resolute and Godhaven (geomagnetic latitude 80°). These two stations are about 900 miles apart and the differences confirm previous indications that sudden increments in cosmic-ray intensity occur over a limited area. The lack of a sudden decrease after the increment is unusual, since a decrease has been reported on previous occasions.

The cooperation of the Department of Transport of the Government of Canada is appreciated for supplying facilities at Resolute and for weather information.

[1] A. Dauvillier, Comptes Rendus 229, 1096 (1949).
[2] Forbush, Stinchcomb, and Schein, Bull. Am. Phys. Soc. 25, No. 1, 15 (1950).
[3] I. L. Chakraborty and S. D. Chatterjee, Ind. J. Phys. 23, 525 (1949).
[4] Forbush, Gill, and Vallarta, Rev. Mod. Phys. 21, 44 (1949).
[5] R. L. Doan, Phys. Rev. 49, 107 (1936).
[6] G. R. Wait and A. G. McNish, Monthly Weather Rev. 62, 1 (1934).

An Identity in Quantum Electrodynamics

J. C. Ward
The Clarendon Laboratory, Oxford, England
February 27, 1950

IT has been recently proved by Dyson[1] that all divergencies in the S-matrix of electrodynamics may be removed by a renormalization of mass and charge. Dyson defines certain fundamental divergent operators Γ_μ, S_F', D_F' and gives a procedure for the calculation of their finite parts $\Gamma_{\mu 1}$, S_{F1}', D_{F1}' by a process of successive approximation. It is then shown that

$$\Gamma_\mu = Z_1^{-1}\Gamma_{\mu 1}(e_1), \quad S_F' = Z_2 S_{F1}(e_1), \quad D_F' = Z_3 D_{F1}(e_1),$$
$$e_1 = Z_1^{-1} Z_2 Z_3^{\frac{1}{2}} e,$$

where Z_1, Z_2, and Z_3 are certain infinite constants and e_1 is the renormalized electronic charge. Dyson conjectured that $Z_1 = Z_2$, and it is proposed here to give a formal proof of this relation.

In the first place, with any proper electron self-energy part W, may be associated a set of proper vertex parts V^i obtained by inserting a photon line in one of the electron lines of W. Now consider the operators $\Lambda_\mu(V^i, p, p)$ in which the two external electron momentum variables p have been set equal, and the external photon variable made to vanish. Then $\Lambda_\mu(V^i, p, p)$ may be obtained from $\Sigma(W, p)$ by replacing S_F by $S_F \gamma_\mu S_F$ at one electron line of W. Because of the identity

$$-(1/2\pi)\partial S_F/\partial p_\mu = S_F \gamma_\mu S_F,$$

on summing $\Lambda_\mu(V^i, p, p)$ over all vertex parts V^i associated with W, one finds

$$\Sigma_{V^i}\Lambda_\mu(V^i, p, p) = -(1/2\pi)(\partial\Sigma(W, p)/\partial p_\mu).$$

(One can verify that any closed loop in W gives zero total effect.) Finally summing over all proper electron self-energy parts W, one finds

$$\Lambda_\mu(p, p) = -(1/2\pi)(\partial\Sigma^*(p)/\partial p_\mu).$$

Now substitute this identity into Eqs. (91) and (95) of reference 1. One finds

$$\Lambda_\mu = Z_1^{-1}[(1-Z_1)\gamma_\mu + \Lambda_{\mu C}], \quad \Sigma^* = Z_2^{-1}[(Z_2-1)S_F^{-1} + S_F^{-1}S_C/2\pi].$$

We have

$$-(1/2\pi)Z_2^{-1}\{(Z_2-1)2\pi\gamma_\mu + \gamma_\mu S_C + (\gamma_\lambda p_\lambda - iK_0)(\partial S_C/\partial p_\mu)\}$$
$$= Z_1^{-1}\{(1-Z_1)\gamma_\mu + \Lambda_{\mu C}(p, p)\}.$$

Now put

$$\gamma_\lambda p_\lambda = iK_0, \quad (p_\lambda)^2 = -K_0^2.$$

The convergent parts of these equations then vanish and there is left the relation

$$-(1/2\pi)Z_2^{-1}(Z_2-1)2\pi\gamma_\mu = Z_1^{-1}(1-Z_1)\gamma_\mu$$

which reduces immediately to $Z_1 = Z_2$.

[1] F. J. Dyson, Phys. Rev. 75, 1736 (1949).

The Partial Molal Entropy of Superfluid in Pure He[4] below the λ-Point

O. K. Rice
Department of Chemistry, University of North Carolina, Chapel Hill, North Carolina
March 3, 1950

IN a recent article[1] (the notation of which is retained here, except that subscripts $4n$ and $4s$ refer to normal fluid and superfluid, respectively, in place of 1 and 2), I have considered the thermodynamics of liquid helium on the two-fluid theory, taking account of the fact that if two "phases" or "components," the normal fluid and the superfluid, exist together they must be in equilibrium with each other. On this basis, using the assumed relation[2] which states that the total molal entropy S at any temperature is the mole fraction x_{4n} of normal fluid times the molal entropy S_λ at the λ-point

$$S = x_{4n}S_\lambda = (1-x_{4s})S_\lambda, \tag{1}$$

using the empirical relation for S as a function of temperature

$$S = S_\lambda(T/T_\lambda)^r \tag{2}$$

(with $r \sim 5.6$), and assuming that the partial molal enthalpy of superfluid, $\bar{H}_{4s}$, is independent of temperature (at essentially constant pressure), and independent of x_{4s} (i.e., there is no heat of mixing), I derived the equation for the partial molal entropy of superfluid

$$\bar{S}_{4s} = S_\lambda x_{4n}/(r+1). \tag{3}$$

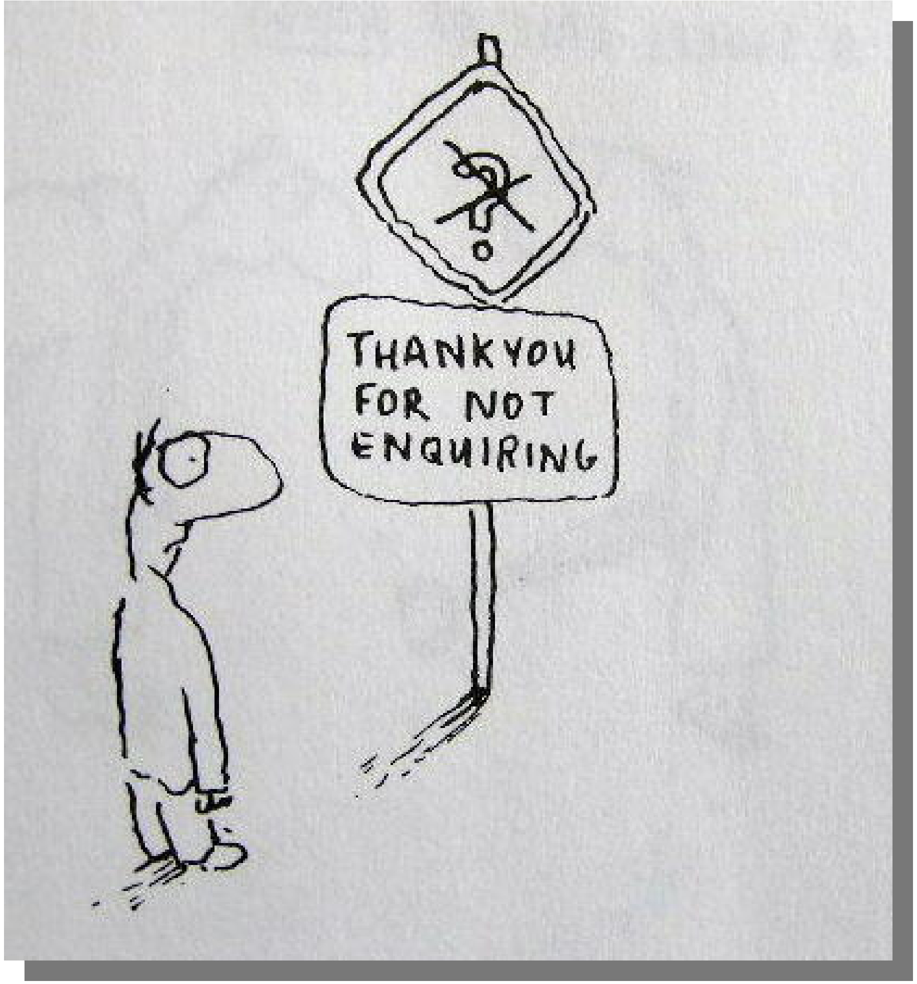
However, as I remarked in reference 1, there are some approximations involved in this procedure. Equation (1) is based on the assumption that below T_λ the entropy is contributed solely by the normal fluid, whose molal entropy is always set equal to the constant S_λ, thus neglecting any temperature dependence. Furthermore, there is an implied inconsistency, since Eq. (1) assumes no entropy of mixing while Eq. (3) implies that there is a mixing entropy. In fact, in the following letter we shall show that we may derive a somewhat different expression for S from Eq. (3). We shall, therefore, discard Eq. (1) and turn to a consideration of the enthalpies.

If $\bar{H}_{4s}$ is independent of x_{4n}, then $\bar{H}_{4n}$ must be also, and we have $\bar{H}_{4n} = H_{4n}$, where H_{4n} is the enthalpy of pure normal helium. We can write for the total molal enthalpy[3]

$$H = x_{4n}H_{4n}. \tag{4}$$

We will now proceed to derive an expression for $\bar{S}_{4s}$, in a somewhat more direct way than in reference 1, using Eq. (4) in place of Eq. (1). Since $F = H - TS$ and $\mu_{4s} = \bar{H}_{4s} - T\bar{S}_{4s} = -T\bar{S}_{4s}$ the condition for internal equilibrium, $F = \mu_{4s}$, gives

$$\bar{S}_{4s} = S - H/T. \tag{5}$$



Enigma of Mass

is, Roberts and Tandy
-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 propag $S(p)=\frac{1}{i\gamma\cdot p\,A(p^2)+B(p^2)}$

- Axial-vector Ward-Takahashi identity entails

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

Owing to DCSB & Exact in Chiral QCD

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

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

Model independent
Gauge independent
Scheme independent

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

The most fundamental expression of Goldstone's Theorem and DCSB

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

Model independent
Gauge independent
Scheme independent

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

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

Enigma of mass

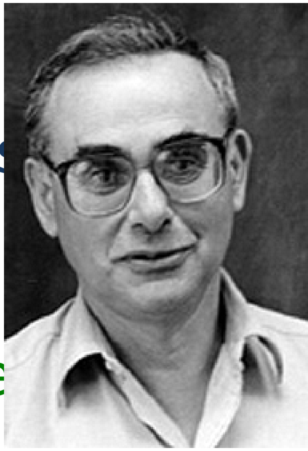
$$f_\pi E_\pi(p^2) = B(p^2)$$

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 meas of
  the dressed-quark mass function.
- Thus, enigmatically, the properties of the *massle* pion
  are the cleanest expression of the mechanism that is



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

Massless Pion

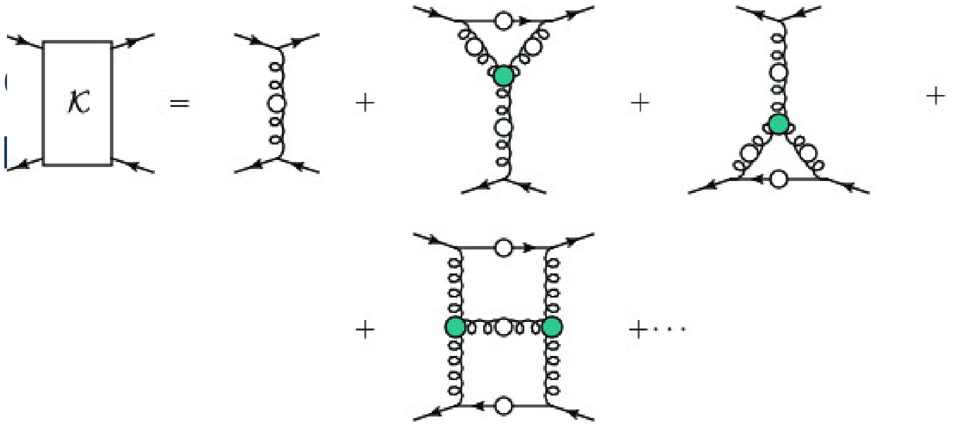
- Recall that in the chiral limit

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

- We now have enough information in hand to explain this result

Pion masslessness

- Pion's Poincaré-invariant mass and Poincaré-covariant wave function are obtained by solving a Bethe-Salpeter equation.
- This is a scattering problem
- In chiral limit
  - two massless fermions interact via exchange of massless gluons … initial system is massless;
   … and it remains massless at every order in perturbation theory
- But, complete the cal
infinity of dressings a



- Then …

*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
  - Bethe-Salpeter Kernel:
    - valence-quarks with a momentum-dependent running mass produced by self-interacting gluons, which have given themselves a running mass
    - Interactions of arbitrary but enumerable complexity involving these “basis vectors”
  - Chiral limit:
    - Algebraic proof
      - at any & each finite order in symmetry-preserving construction of kernels for
        - » the gap (quark dressing)
        - » and Bethe-Salpeter (bound-state) equations,
      - there is a precise cancellation between
        - » mass-generating effect of dressing the valence-quarks
        - » and attraction introduced by the scattering events
    - Cancellation guarantees that
      - simple system, which began massless,
      - becomes a complex system, with
        - » a nontrivial bound-state wave function
        - » attached to a pole in the scattering matrix, which remains at $P^2=0$

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**

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 inte ***iff –***

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

quarks

nts

•

– becomes a complex system, with
  - » a nontrivial bound-state wave function
  - » attached to a pole in the scattering matrix, which remains at $P^2=0$

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

Massless Pion

- Recall that in the chiral limit

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

- We now have enough information in hand to explain this result
- "Zero" owes to cancellations between different operator-component contributions to the expectation value of Θ_0.
- The cancellations are precise

  Arising naturally because chiral symmetry – the apparent masslessness of the QCD action – is broken by strong dynamics in a very particular manner.

- In the chiral limit, the pion is massless irrespective

Observing *Mass*

Observing Mass

- Goldberger-Treiman relations entail that on $m \simeq 0$, dressed-quark mass function (almost) completely determines χ_π (wave function)
- χ_π can be projected onto the light-front
  - Object thus obtained is strictly a probability amplitude and moments of a probability measure are truly observable.
  - Consequently, there is a mathematically strict sense in which moments of the dressed-quark mass function are observable.
  - Additionally, *e.g*. generalised parton distributions can rigorously be defined as an overlap of light-front wave functions
- Practically, the mass function can be "measured" because it influences and determines a vast array of experimental observables
- *In this sense, $M(p^2)$, microscopic expression of trace anomaly, is observable at modern facilities, in measurements of*

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

- 2012 … methods were 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

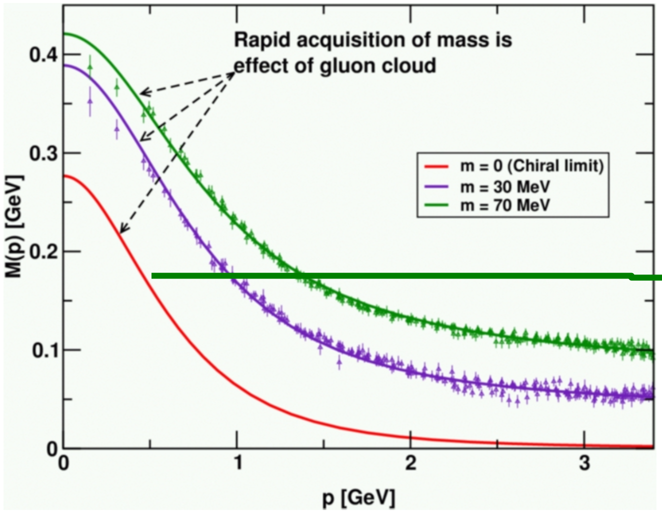
$$\phi_\pi(x) \;\propto\; x^\alpha\,(1-x)^\alpha, \text{ with } \alpha \approx 0.5$$

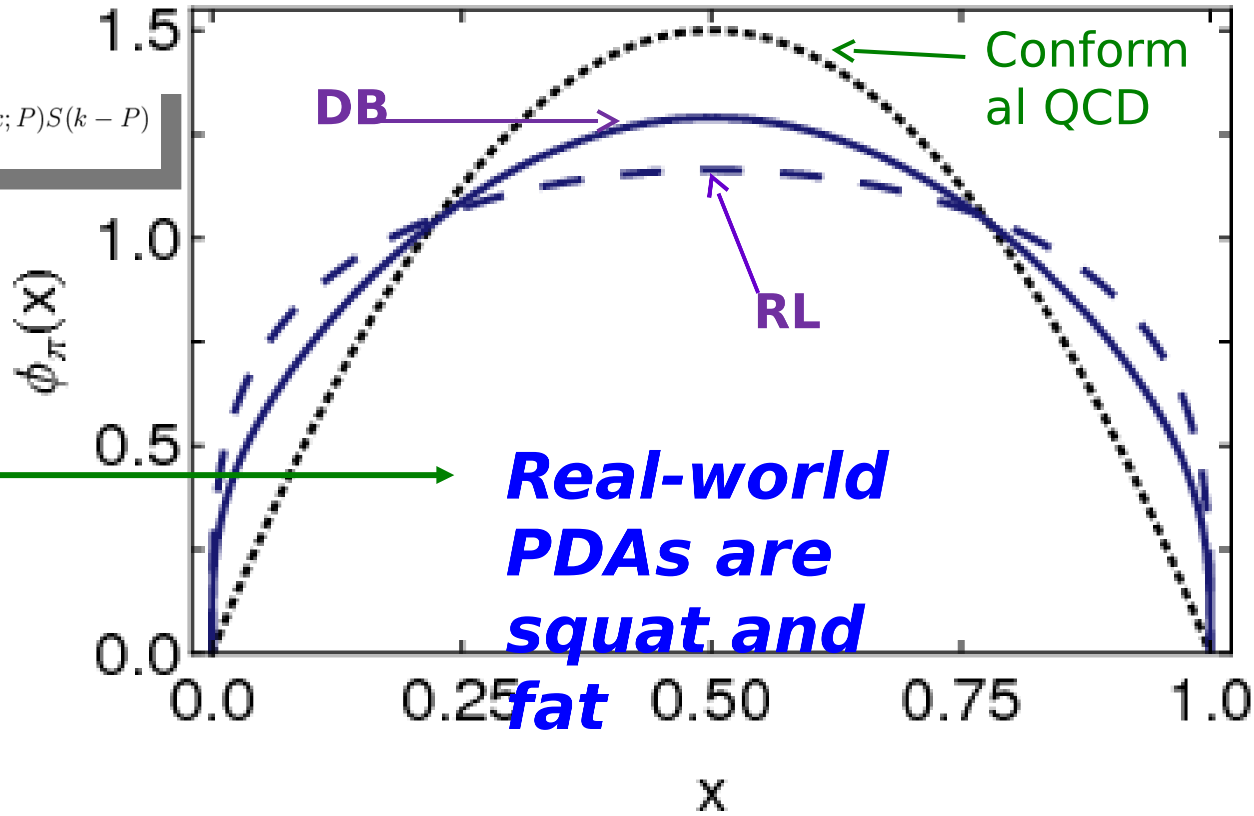
Imaging dynamical chiral symmetry breaking: pion wave function on the light front, Lei Chang, *et al.*, arXiv:1301.0324 [nucl-th], Phys. Rev. Lett. **110** (2013) 132001 (2013) [5 pages].

Pion's valence-quark Distribution Amplitude

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

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





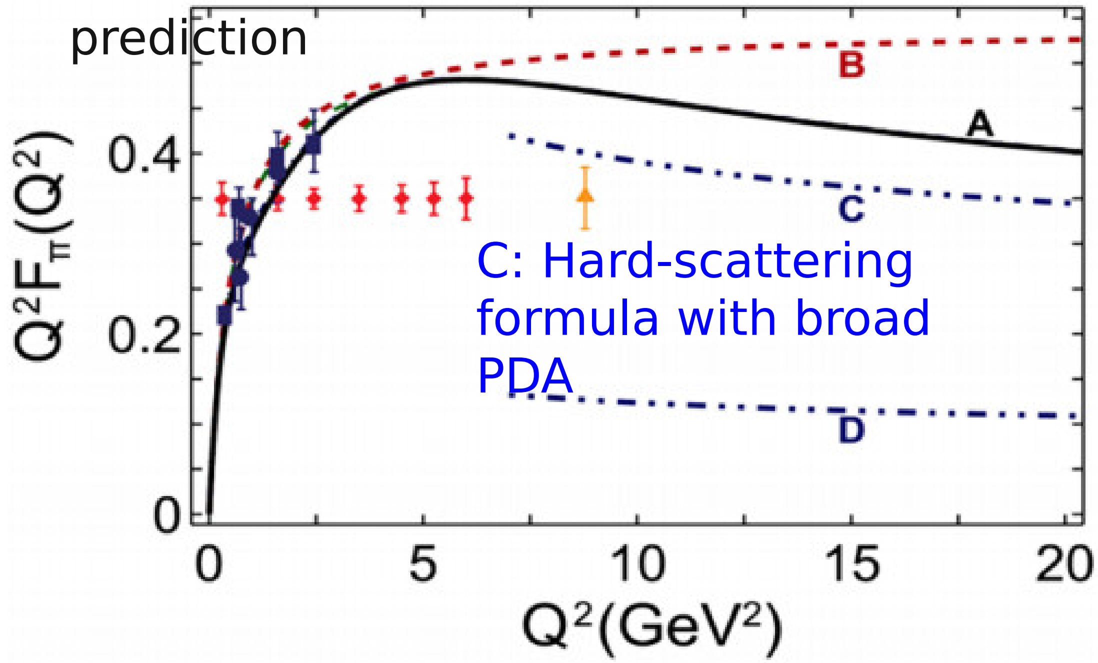
Real-world PDAs are squat and fat

Pion electromagnetic form factor at spacelike momenta
L. Chang *et al., arXiv:1307.0026 [nucl-th], Phys. Rev. Lett.* ***111****, 141802 (2013)*

Pion's electromagnetic form factor

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

A: Internally-consistent DSE prediction



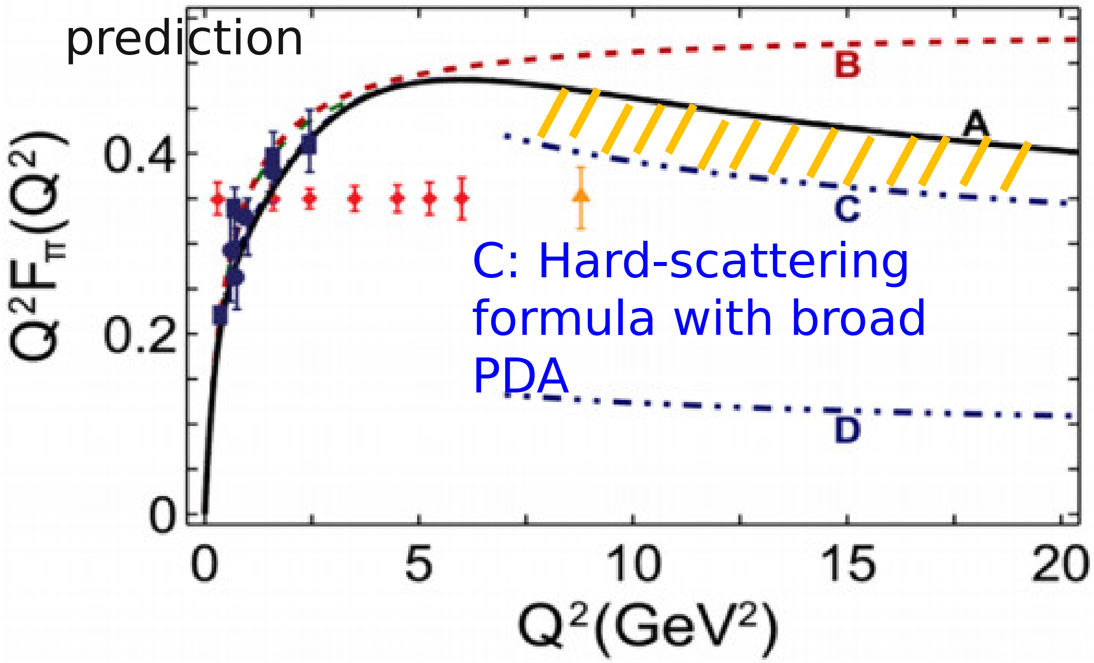
C: Hard-scattering formula with broad PDA

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

Pion's electromagnetic form factor

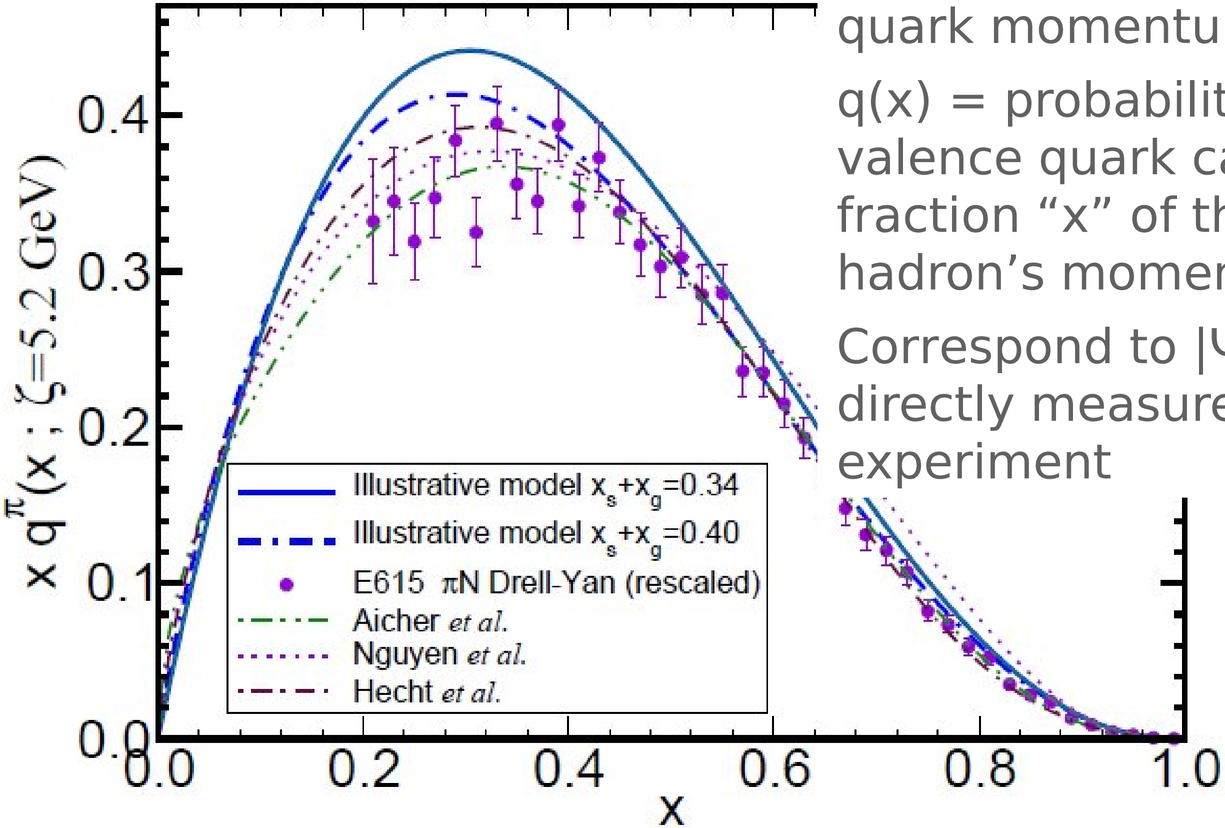
- Broadening has enormous impact on understanding $F_\pi(Q^2)$
- Appears that JLab12 is within reach of first verification of a QCD hard-scattering formula

A: Internally-consistent DSE prediction



C: Hard-scattering formula with broad PDA

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



Probability densities for quark momentum …

q(x) = probability that this valence quark carries a fraction "x" of the hadron's momentum

Correspond to $|\Psi|^2$, so directly measureable in experiment

π & *K* Valence-quark Distribution Functions

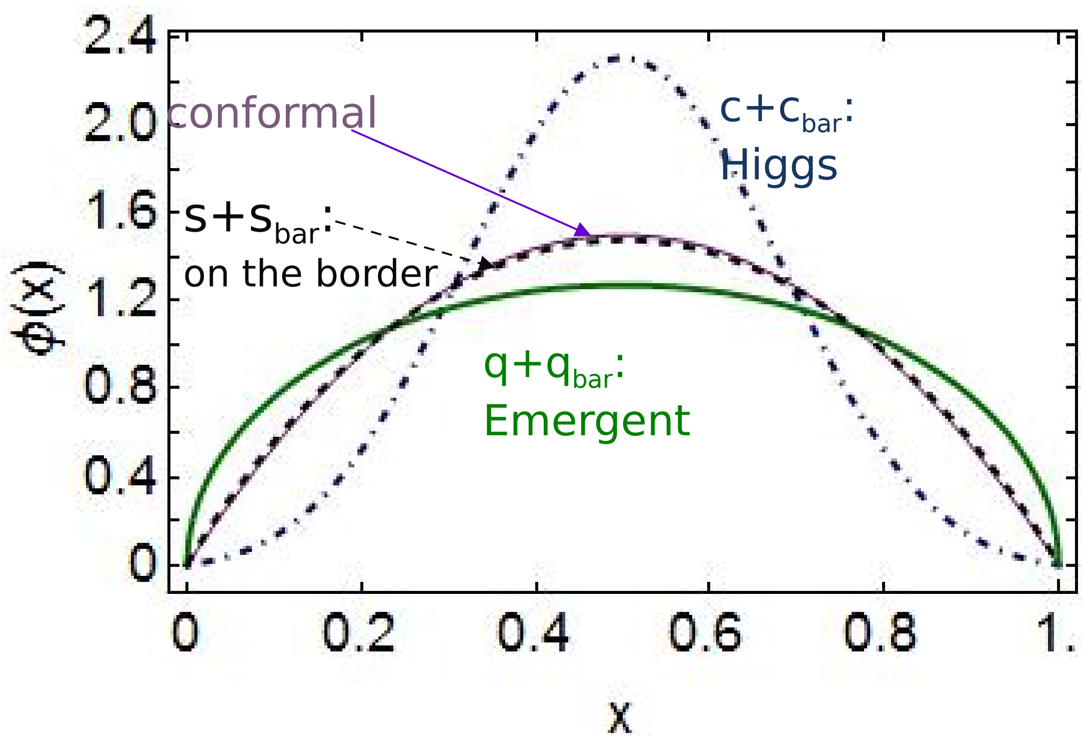
Parton distribution amplitudes of S-wave heavy-quarkonia
Minghui Ding, Fei Gao, Lei Chang, Yu-Xin Liu and Craig D. Roberts
arXiv:1511.04943 [nucl-th], Phys. Lett. B **753** (2016) pp. 330-335

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 obvious place to find signals for strong-mass generation



Basic features of the pion valence-quark distribution function, Lei Chang, Cédric Mezrag, Hervé Moutarde, Craig D. Roberts, Jose Rodríguez-Quintero and Peter C. Tandy, 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, Craig D. Roberts, Shaolong Wan and Hong-Shi Zong, arXiv:1602.01502 [nucl-th], Phys. Rev. D**93** (2016) 074021/1-11

π & *K* PDFs

- Continuum QCD analysis reveals marked differences between the gluon content of the *π* & *K*
  - ζ_H:
    - One-third of pion's light-front momentum carried by glue
    - One-twentieth of the kaon's light-front momentum lies with glue
  - $\zeta_2^{\,2}$ = 4 GeV²
    - Glue carries half of pion's momentum and two-thirds of kaon's momentum
  - Evident in differences between large-x behaviour of valence-quark distributions in these mesons
- Signal of Nambu-Goldstone boson chara
  - Nearly complete cancellation betwee one-particle dressing and binding attraction

π & K PDFs

- Existing textbook description of Goldstone's theorem via pointlike modes is old-fashioned, outdated and simplistic
- The appearance of Nambu-Goldstone modes in the Standard Model is far more interesting
  - Nambu-Goldstone modes are nonpointlike!
  - Intimately connected with origin of mass!
  - Quite probably inseparable from expression of confinement!
- Difference between gluon content is measurable … using well-designed EIC
- Write a definitive new ch on the Standard Model

Electron Ion Collider: The Next QCD Frontier

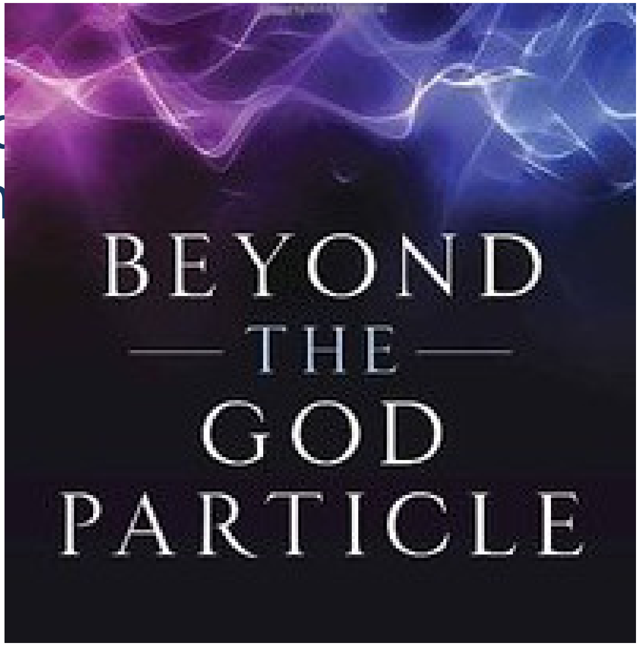
Experiment: π & *K* PDFs

- The main goal of this (ECT*) Workshop is to discuss in depth the physics opportunities and experimental feasibilities to investigate hadron structures using the Drell-Yan (D-Y) process with high-intensity meson and antiproton beams.
  - There are new initiatives to perform high-statistics kaon and antiproton induced D-Y experiments at *CERN*, using RF-separated beam with a factor of 20-50 increase in intensity over previous experiments.
- Many important topics on the structures of mesons, nucleons, and nuclei can be explored.
- New initiatives to measure exclusive D-Y reactions for the first time at the *J-PARC* and *FAIR* facilities will also be discussed.

Epilogue

Epilogue

- LHC has NOT found the "God Particle" because the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated mass-scales explain neither the proton's mass nor the pion's (*near*-)masslessness
  - Hence LHC has, as yet, taught us very little about the origin, structure and nature of the nuclei whose existence support the Cosmos



- Strong interaction sector of the Standard *i.e.* QCD, is the key to understanding th origin, existence and properties of (almost) all known matter
- Answers are in sight
  - Theoretical tools are reaching the point where sound QCD predictions can be made
  - New experimental facilities are in operation or being planned that can validate those predictions