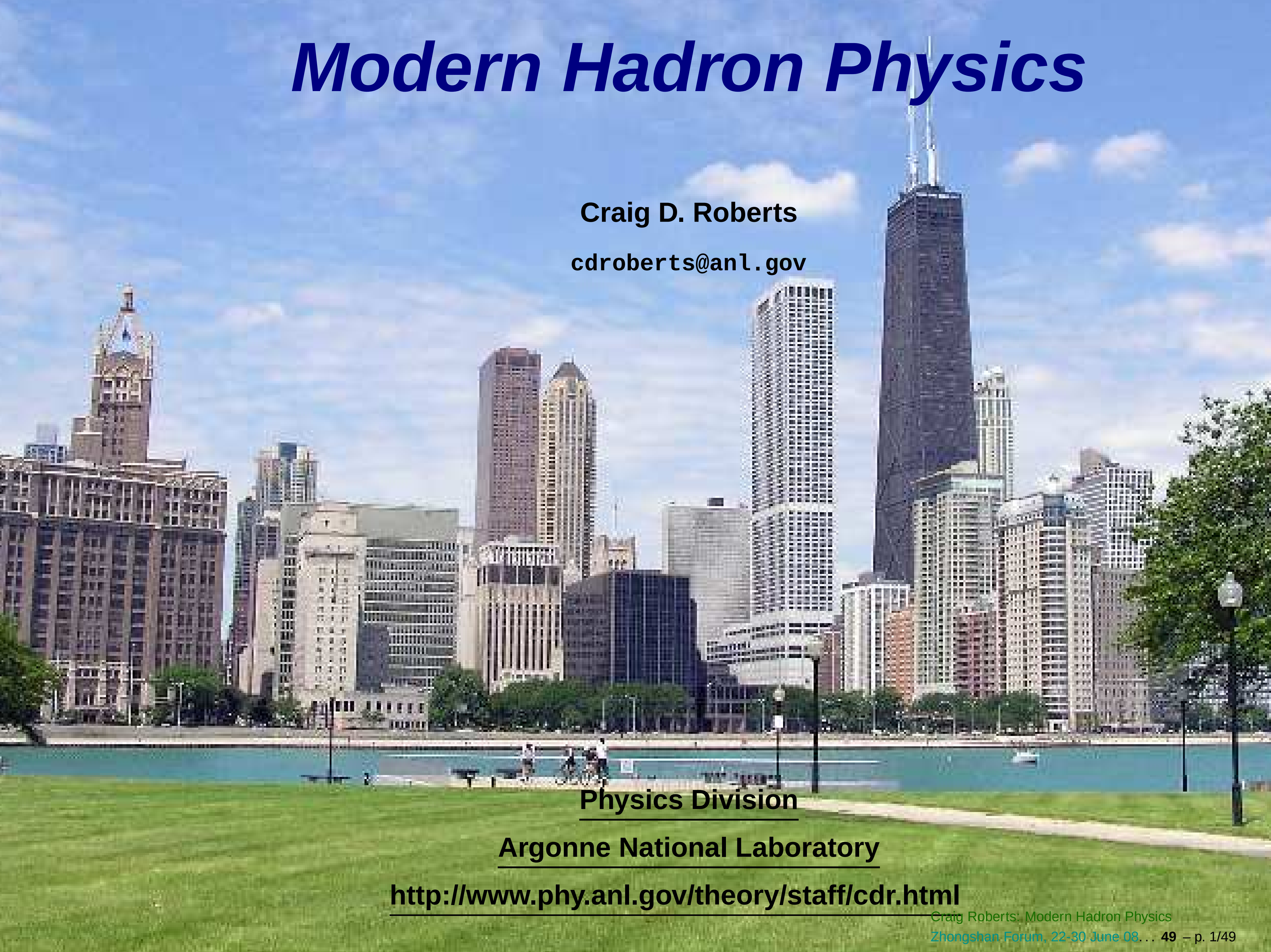
Modern Hadron Physics



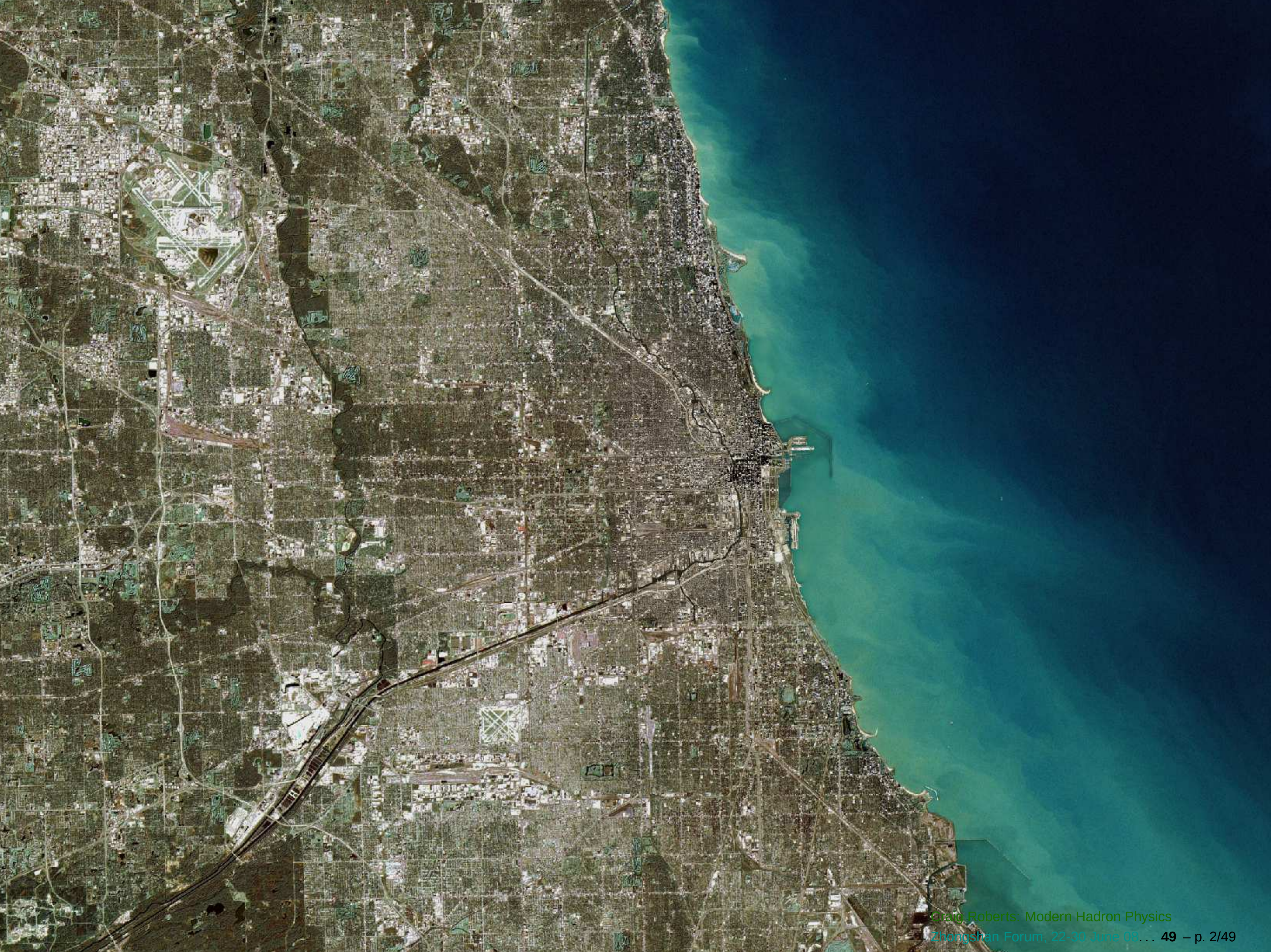
Craig D. Roberts

`cdroberts@anl.gov`

Physics Division

Argonne National Laboratory

http://www.phy.anl.gov/theory/staff/cdr.html



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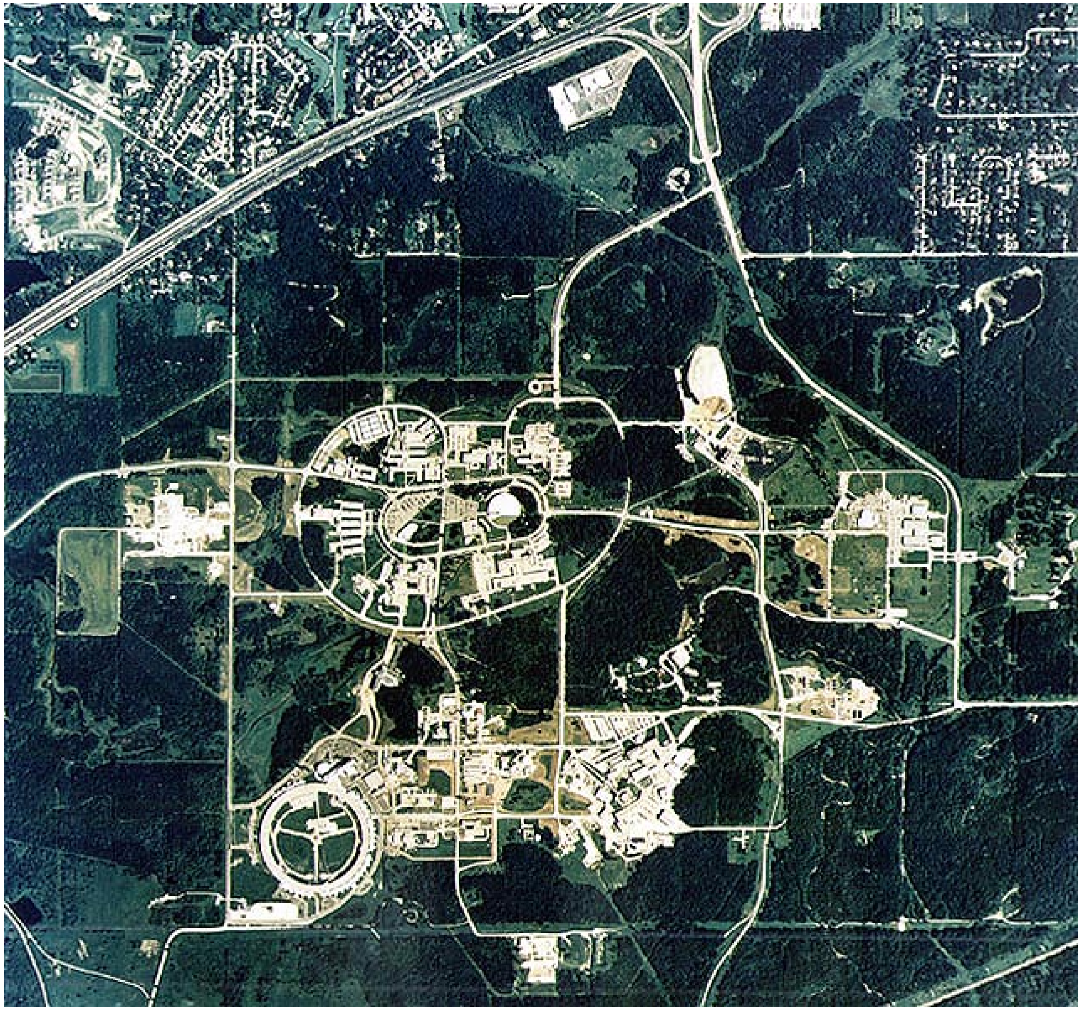

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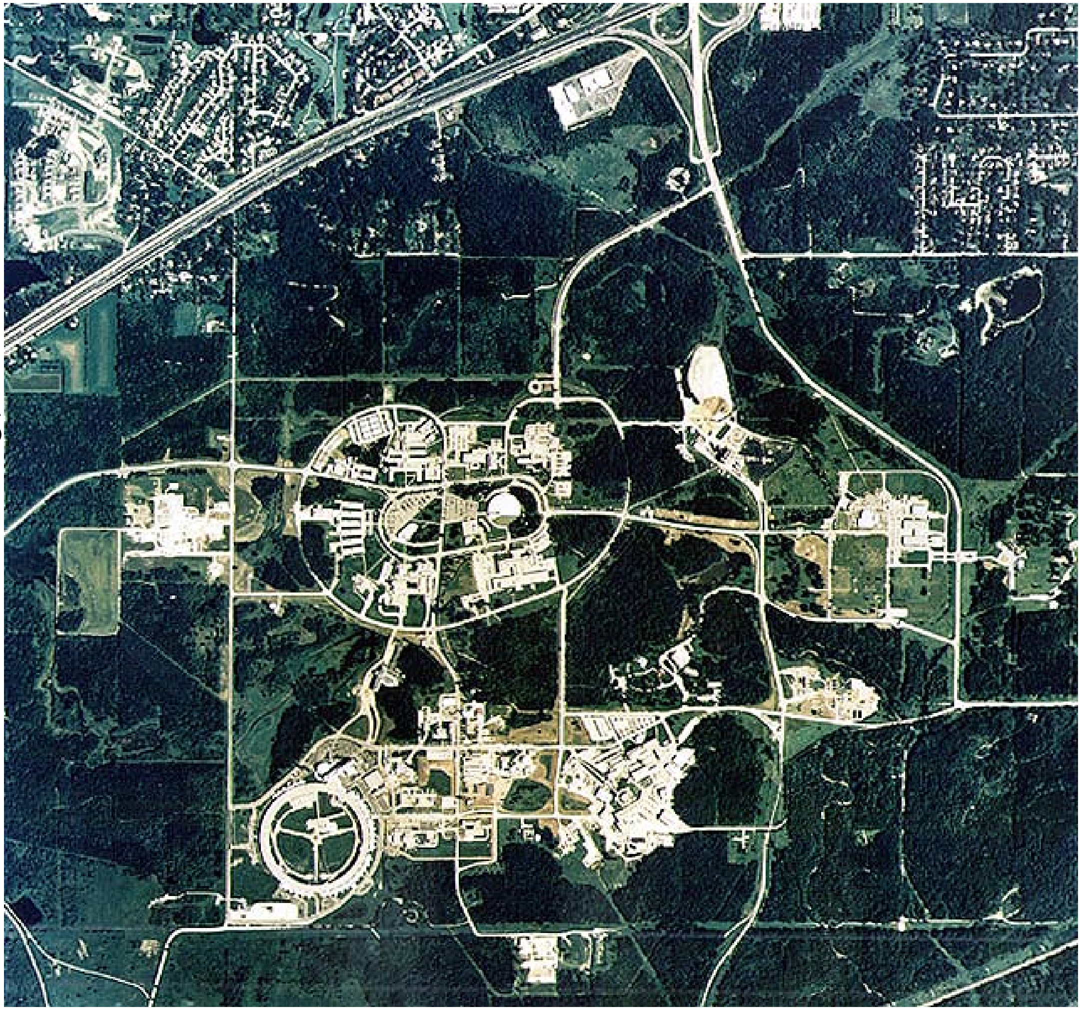
Argonne National Laboratory

Physics Division

- ATLAS Tandem Linac Low Energy Nuclear Physics
- 35 PhD Scientific Staff
- Annual Budget: $22 million



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Our research addresses the five key questions that comprise the USA's nuclear physics agenda. We place heavy emphasis on the prediction of phenomena accessible at Argonne's ATLAS facility, at JLab, and at other laboratories around the world; and on anticipating and planning for FRIB.

Theory Group

- 7 Staff
- 5 Postdocs
- 7 Special Term Appointees

Our research explores problems in: theoretical and computational nuclear astrophysics; quantum chromodynamics and hadron physics; light-hadron reaction theory; ab-initio many-body calculations based on realistic two- and three-nucleon potentials; and coupled-channels calculations of heavy-ion reactions. Our programs provide much of the scientific basis for the drive to physics with rare isotopes. Additional research in the Group focuses on: atomic and neutron physics; fundamental quantum mechanics; quantum computing; and tests of fundamental symmetries and theories unifying all the forces of nature, and the search for a spatial or temporal variation in Nature's basic parameters. The pioneering development and use of massively parallel numerical simulations using hardware at Argonne and elsewhere is a major component of the Group's research.

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U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

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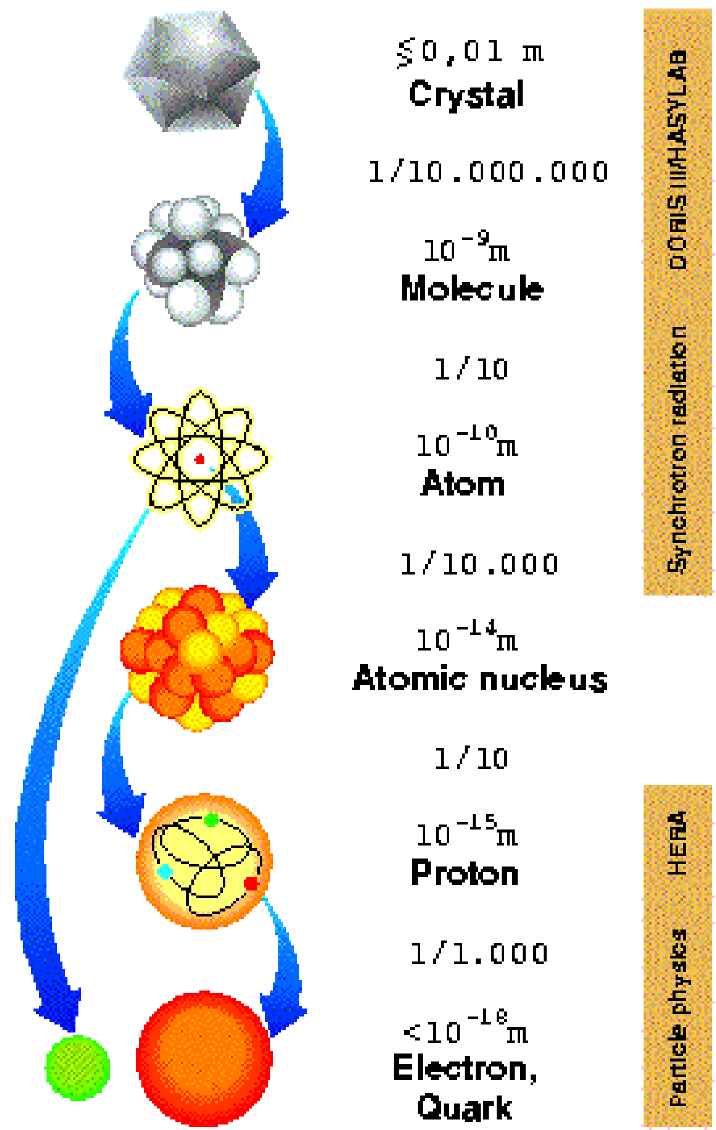
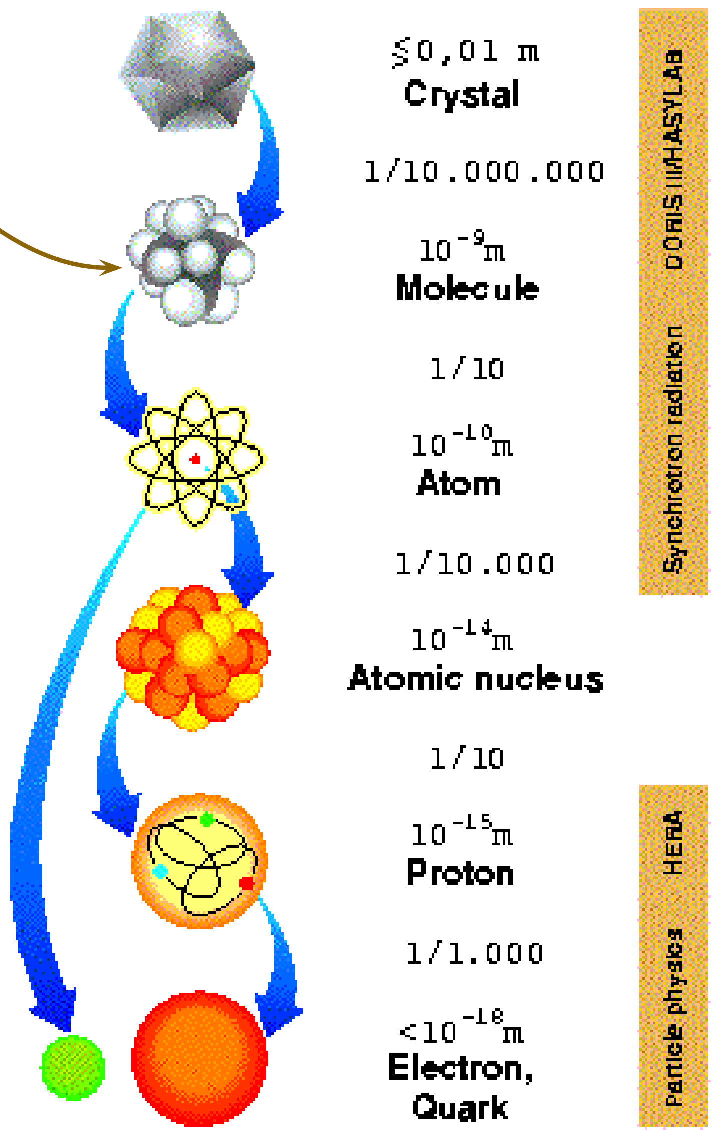
Hadron Physics



Hadron Physics

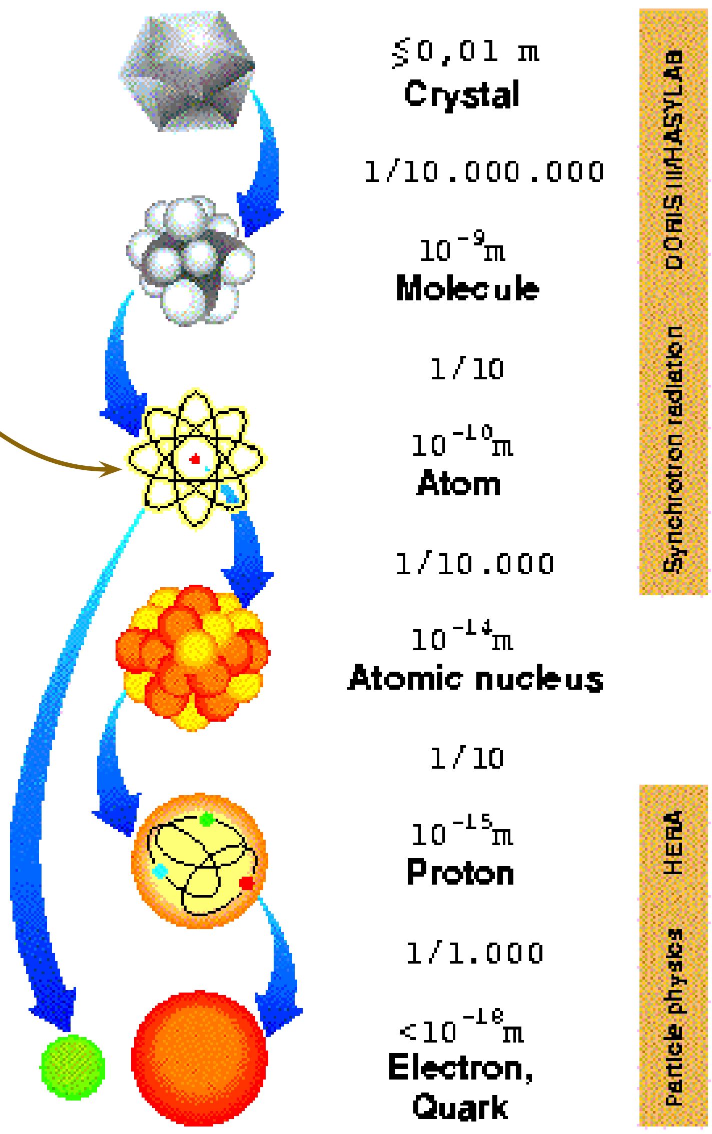
Molecular Physics
Scale = nm



Hadron Physics

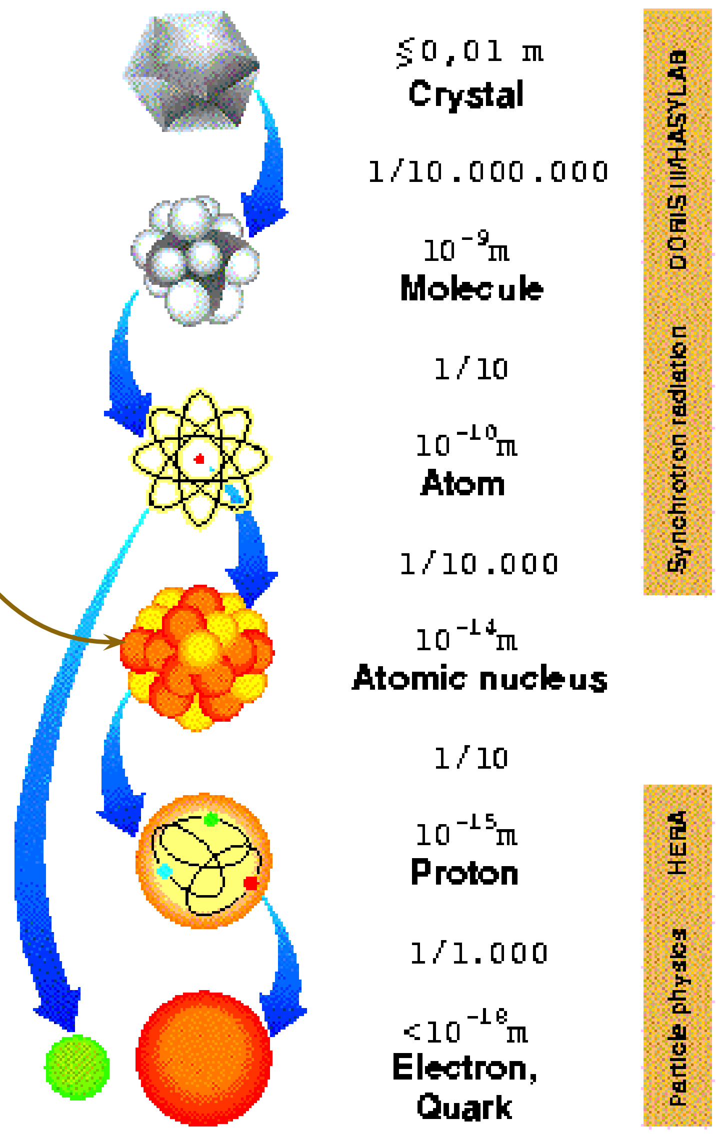
Atomic Physics

Scale = Å



Hadron Physics

Nuclear Physics
Scale = 10 fm



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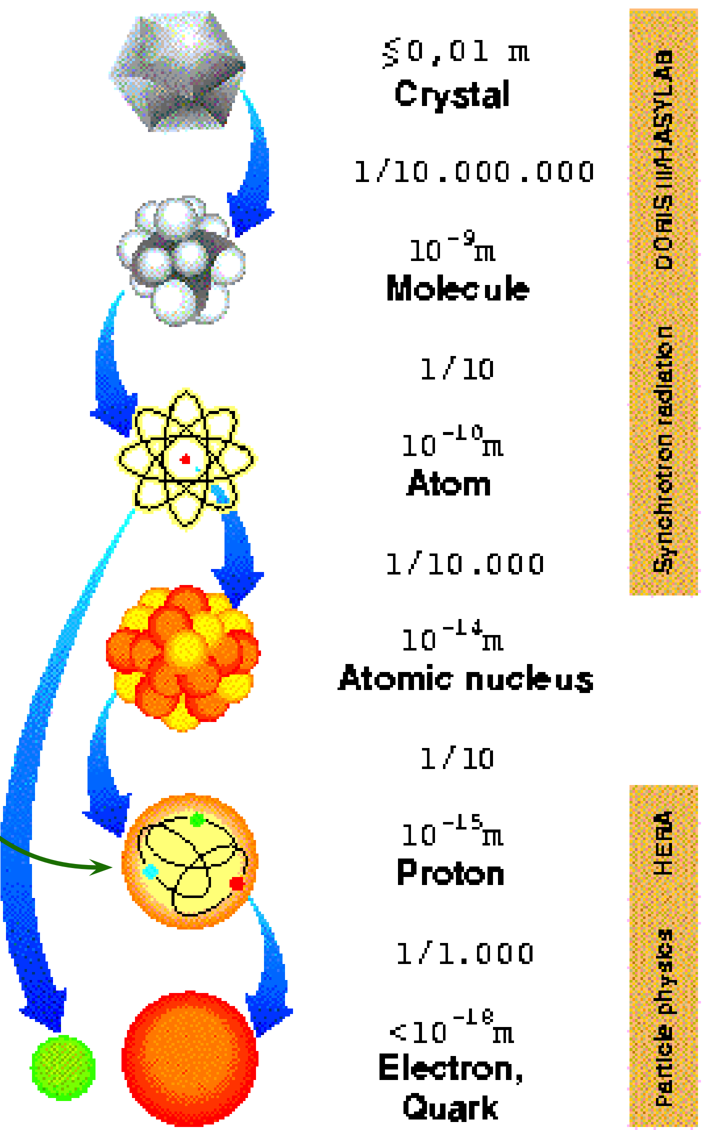
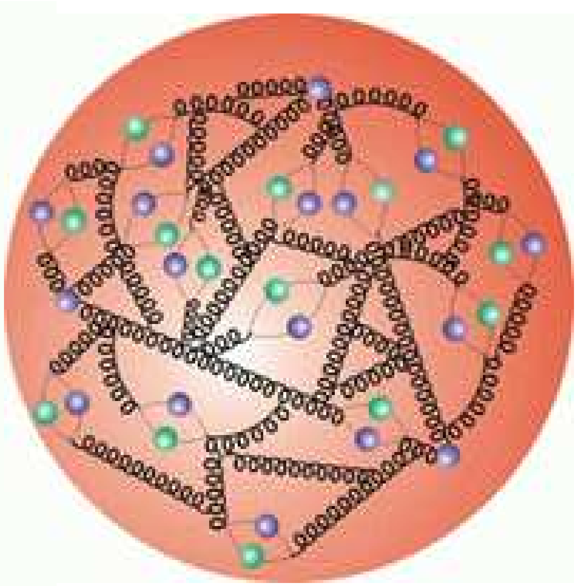
Hadron Physics

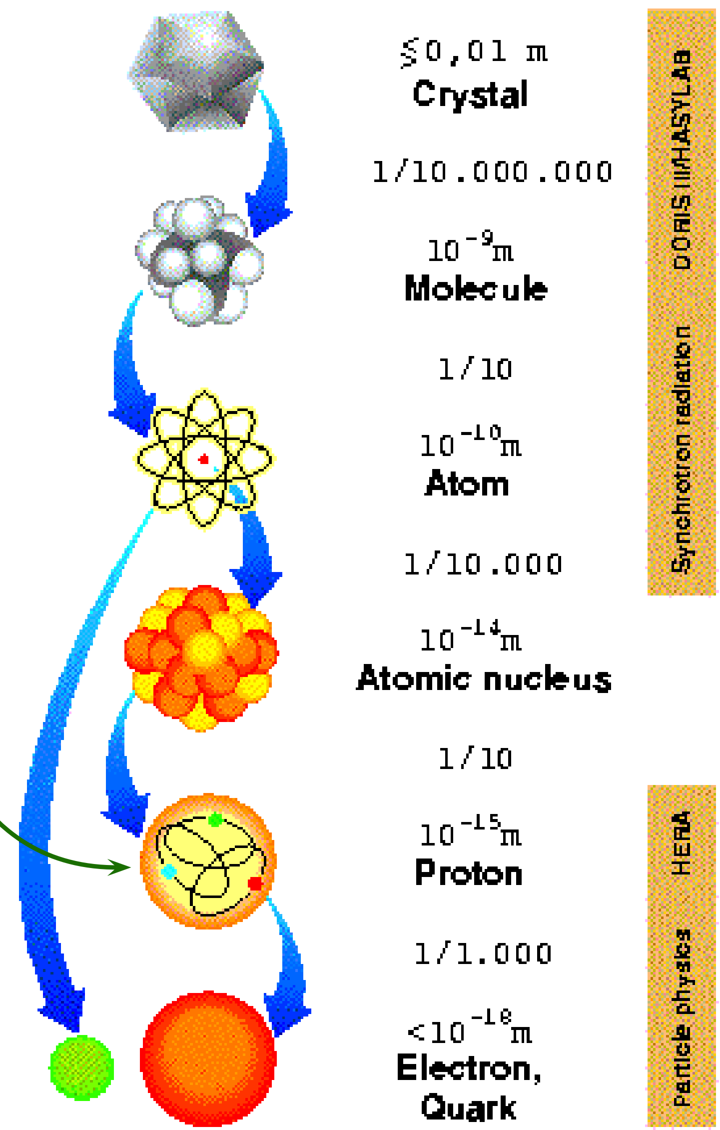
Hadron Physics
Scale = 1 fm



Hadron Physics

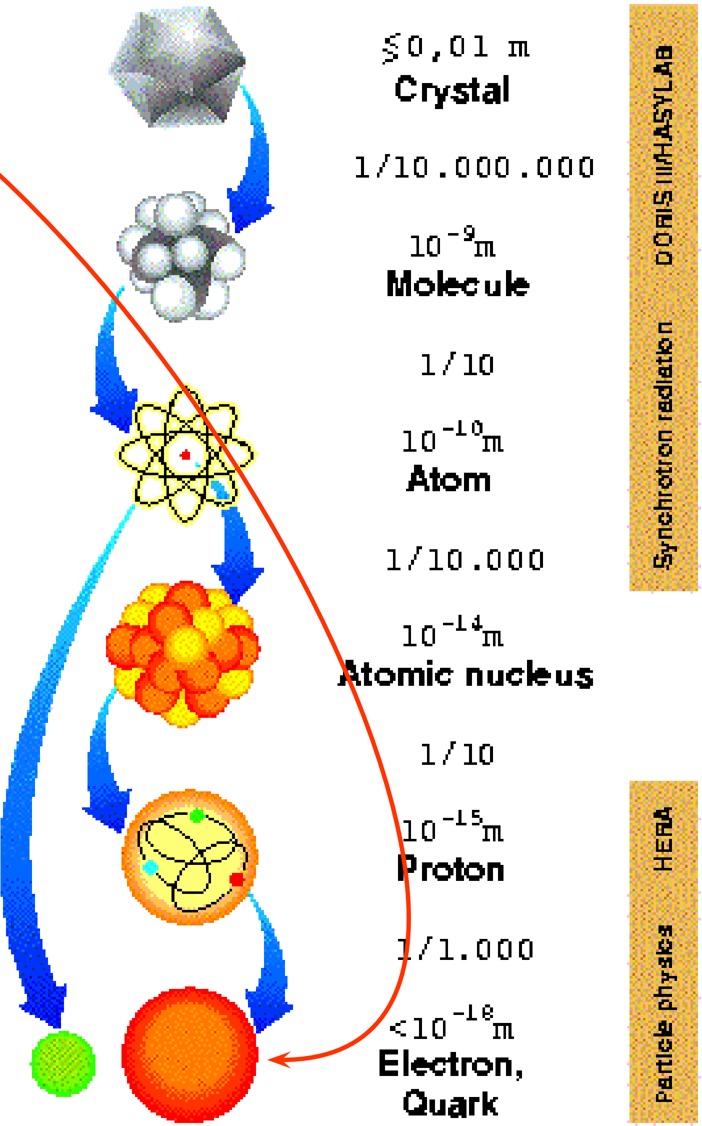
Hadron Physics
Scale = 1 fm





Hadron Physics

Meta-Physics
Scale = Limited only
by Theorists
Imagination



Nucleon . . . 2 Key Hadrons
= Proton and Neutron

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- Fermions – two static properties:
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- Fermions – two static properties:
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- Magnetic Moment discovered by Otto Stern and collaborators in 1933; Awarded Nobel Prize in 1943
  - Dirac (1928) – pointlike fermion: $\mu_p = \dfrac{e\hbar}{2M}$

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  - Dirac (1928) – pointlike fermion: $\mu_p = \dfrac{e\hbar}{2M}$
- Stern (1933) – $\mu_p = (1 + 1.79)\dfrac{e\hbar}{2M}$
  - Big Hint that Proton is not a point particle
  - Proton has constituents
  - These are Quarks and Gluons
    Quark discovery via $e^- p$-scattering at SLAC in 1968
    – the elementary quanta of Quantum Chromo-dynamics

Thomas Jefferson National Accelerator Facility

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- World’s Premier Hadron Physics Facility

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- Design goal (4 GeV) experiments began in 1995

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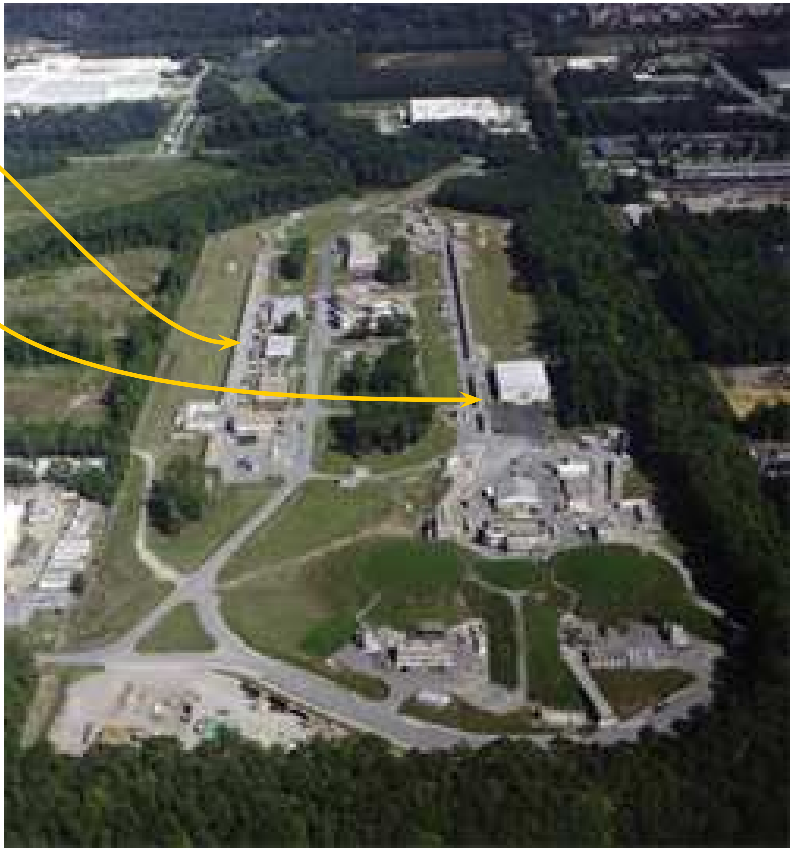
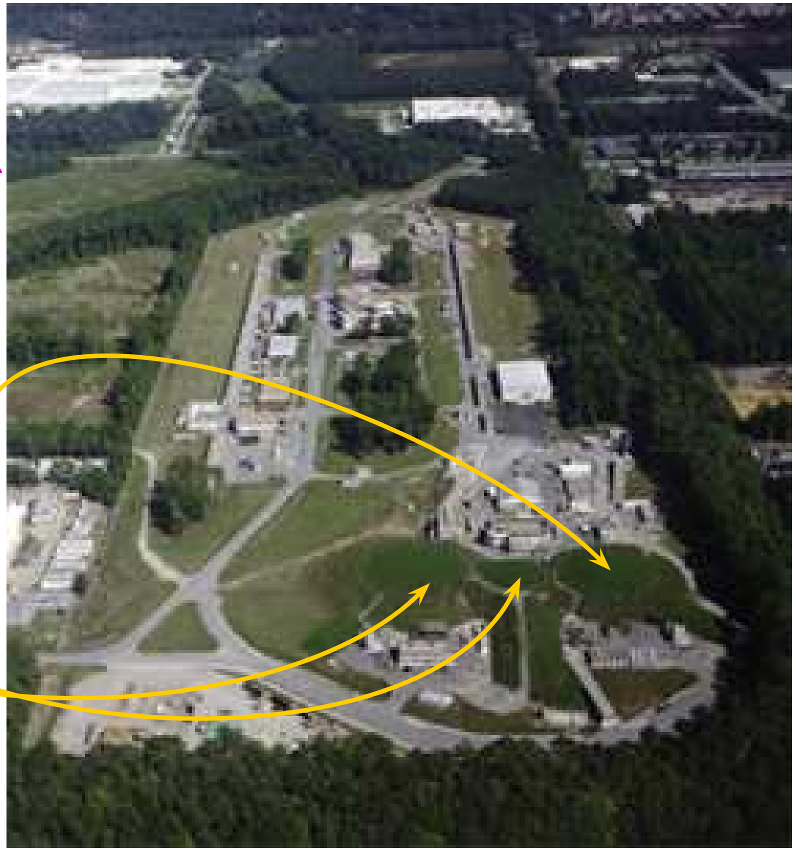


Thomas Jefferson National Accelerator Facility

- World's Premier Hadron Physics Facility
- Design goal (4 GeV) experiments began in 1995
- Electrons accelerated by repeated journeys along *linacs*
- Once desired energy is reached, Beam is directed into Experimental Halls A, B and C



JLab

Thomas Jefferson National Accelerator Facility

- World's Premier Hadron Physics Facility
- Design goal (4 GeV) experiments began in 1995
- Electrons accelerated by repeated journeys along *linacs*
- Once desired energy is reached, Beam is directed into Experimental Halls A, B and C
- Current Peak
  Electron Beam Energy
  Nearly 6 GeV

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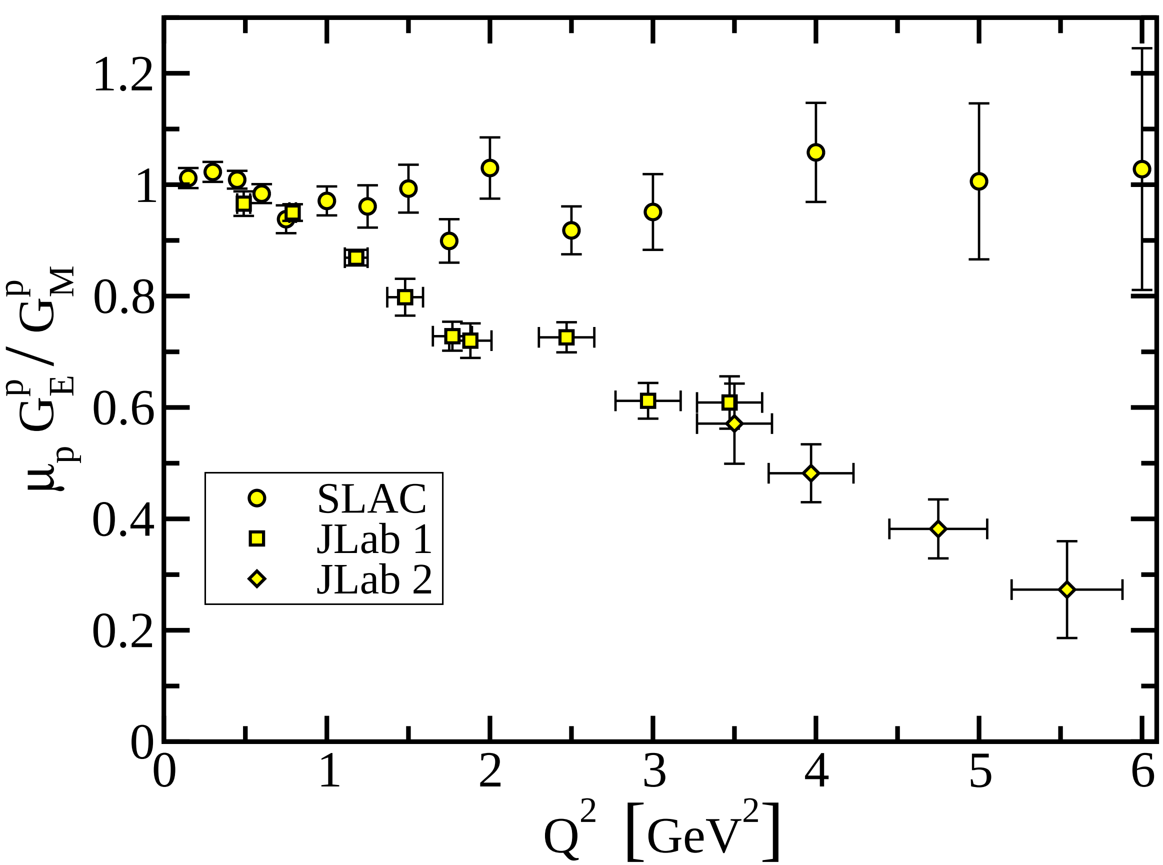
JLab Hall-A

- Measured Ratio of
  Proton’s Electric and Magnetic Form Factors

JLab Hall-A



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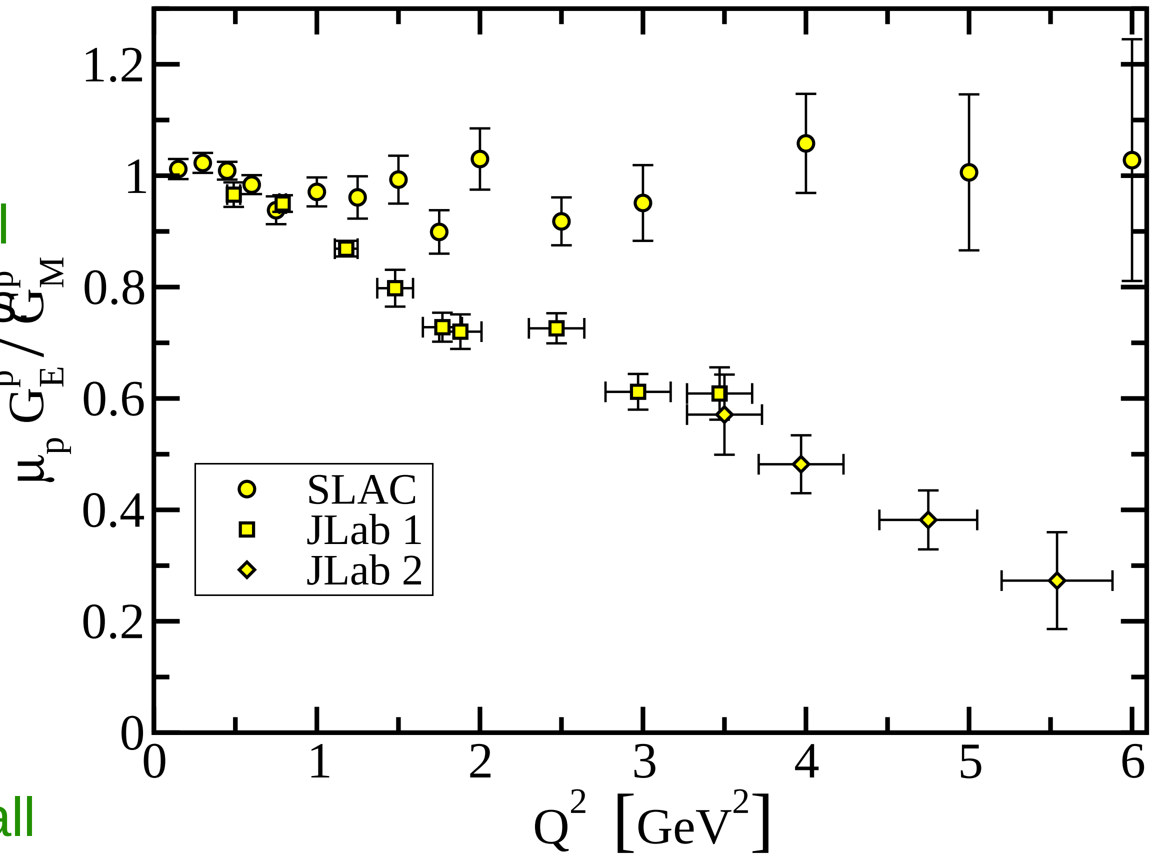
JLab Hall-A

- Walker *et al.*, Phys. Rev. **D 49**, 5671 (1994). (SLAC)
- Jones *et al.*, JLab Hall A Collaboration, Phys. Rev. Lett. **84**, 1398 (2000)
- Gayou, *et al.*, Phys. Rev. **C 64**, 038202 (2001)
- Gayou, *et al.*, JLab Hall A Collaboration, Phys. Rev. Lett. **88** 092301 (2002)



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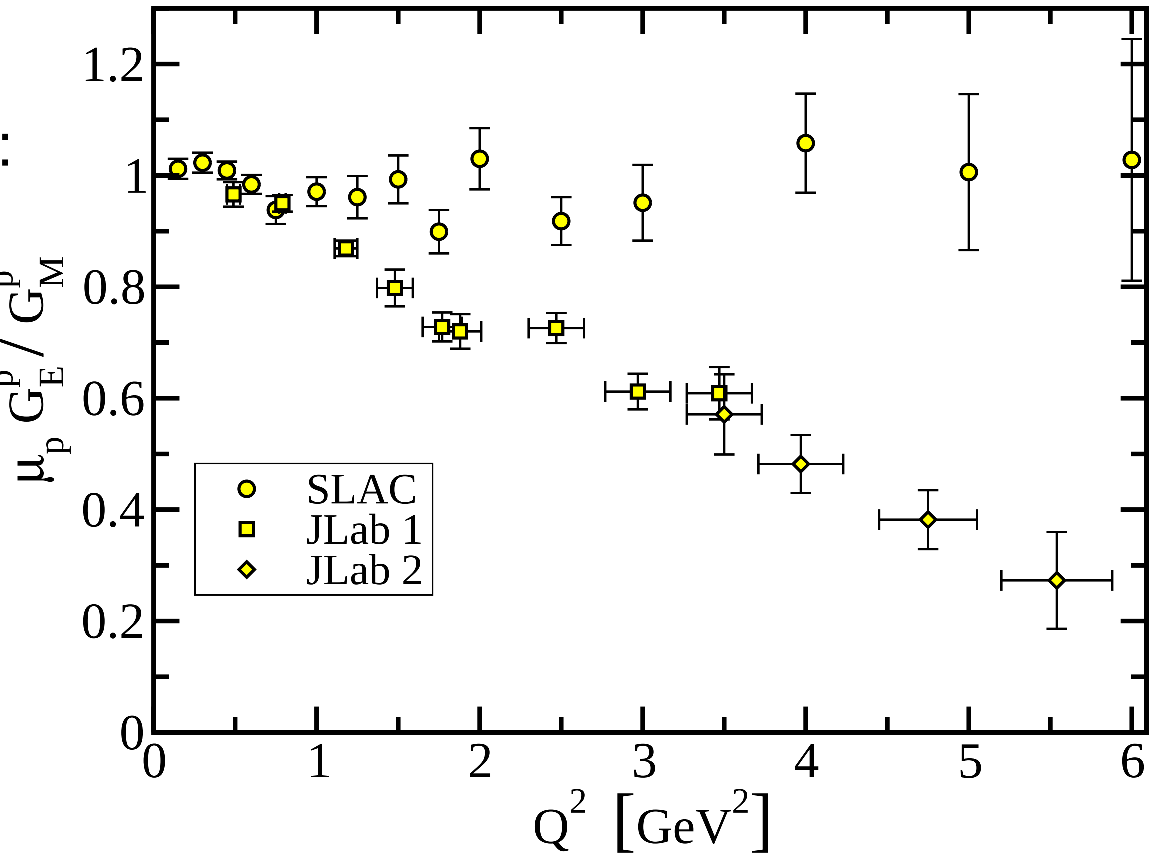
JLab Hall-A

- If JLab Correct, then
  Completely
  Unexpected Result:
  In the Proton
  – On Relativistic
  Domain
  – Distribution of
  Quark-Charge
  Not Equal
  Distribution of
  Quark-Current!



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Frontiers of Nuclear Science: A Long Range Plan (2007)

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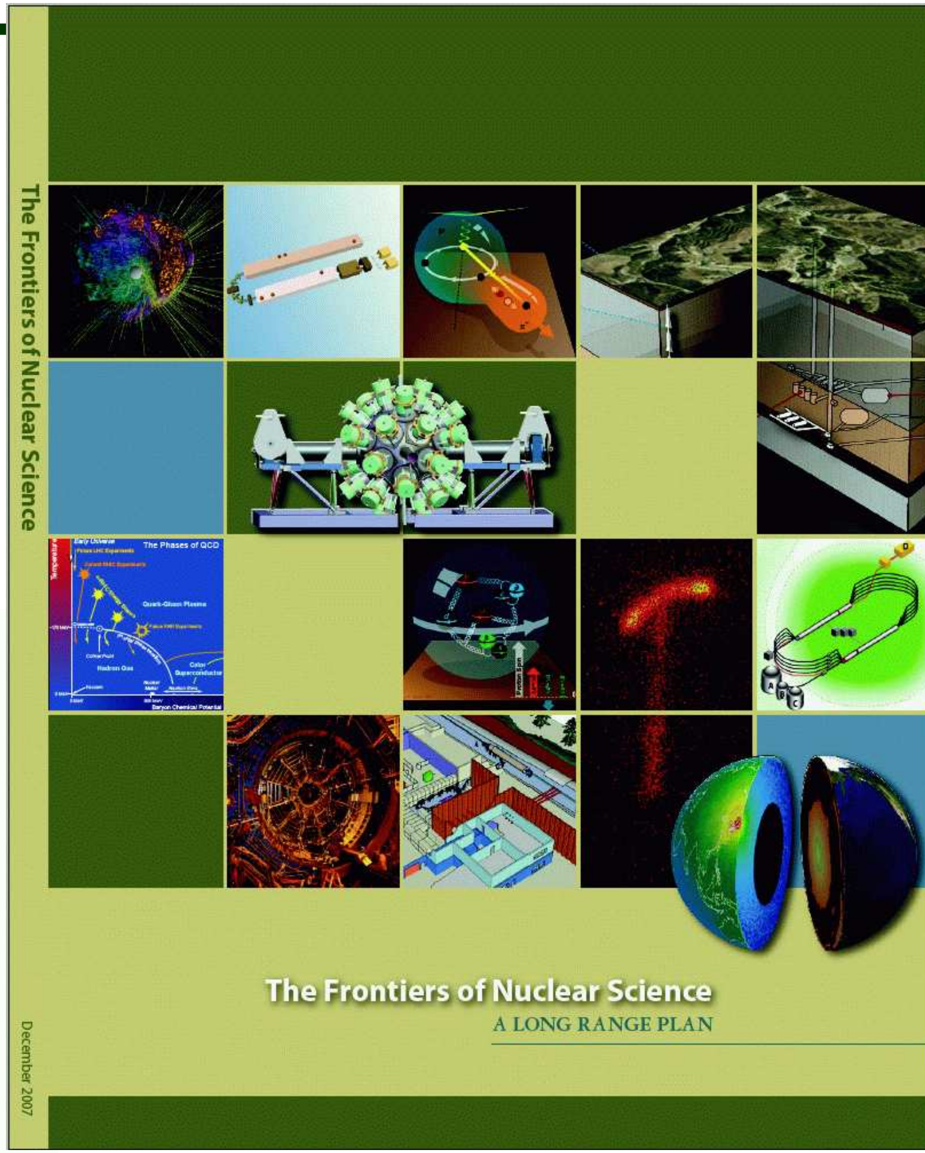

In a letter dated ***17 July, 2006***, the Department of Energy's (DOE) Office of Science for Nuclear Physics and the National Science Foundation's (NSF) Mathematical and Physical Sciences Directorate charged the Nuclear Science Advisory Committee (NSAC) to "conduct a study of the opportunities and priorities for U.S. nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the nation's nuclear science research programs over the next decade."

Frontiers of Nuclear Science: A Long Range Plan (2007)

Primary Recommendations

1. Completion of the 12 GeV CEBAF Upgrade at Jefferson Lab.

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1. Completion of the 12 GeV CEBAF Upgrade at Jefferson Lab.
2. Construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics. NB. On 20 May, 2008, the Department of Energy released a Funding Opportunity Announcement regarding the submission of applications for the conceptual design and establishment of a Facility for Rare Isotope Beams (FRIB). Proposals are due by 21 July, 2008.

Frontiers of Nuclear Science: A Long Range Plan (2007)

Primary Recommendations

1. Completion of the 12 GeV CEBAF Upgrade at Jefferson Lab.

3. A targeted program of experiments to investigate neutrino properties and fundamental symmetries.

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Frontiers of Nuclear Science: A Long Range Plan (2007)

Primary Recommendations

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4. Implementation of the RHIC II luminosity upgrade, together with detector improvements.

Frontiers of Nuclear Science:
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These recommendations were followed by *Initiatives*. Leading the list was a statement on Theory: “We recommend the funding of finite-duration, multi-institutional topical collaborations initiated through a competitive, peer-review process. [. . .] These initiatives are intended to bring together the best in the field, leverage resources of smaller research groups, and provide expanded opportunities for the next generation of nuclear theorists.”

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It was followed by a statement on accelerator R&D, which urged: "targeted support of proposal-driven accelerator Research and development supported by DOE and NSF nuclear physics."

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Complete report: http://www.sc.doe.gov/np/nsac/nsac.html

What is QCD?

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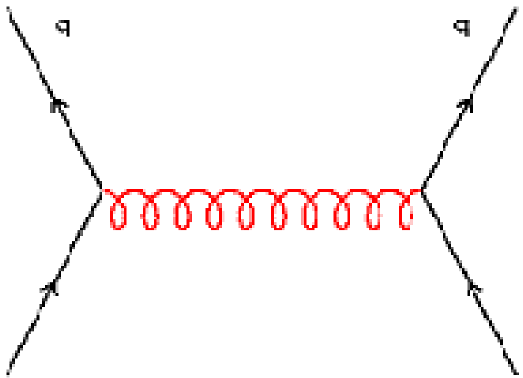
- Gauge Theory:

  Interactions Mediated by massless vector bosons

Feynman Diagram of Quark—Quark Scattering



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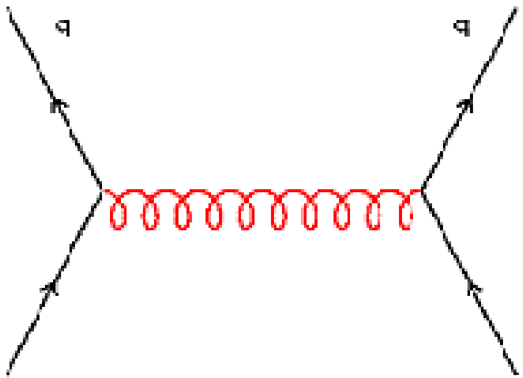

- Similar interaction in QED

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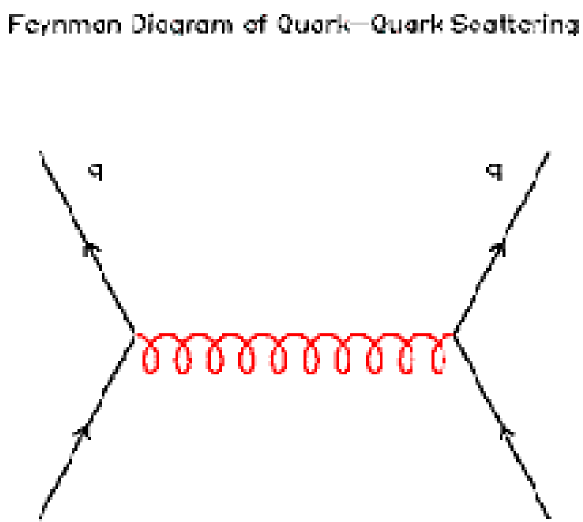
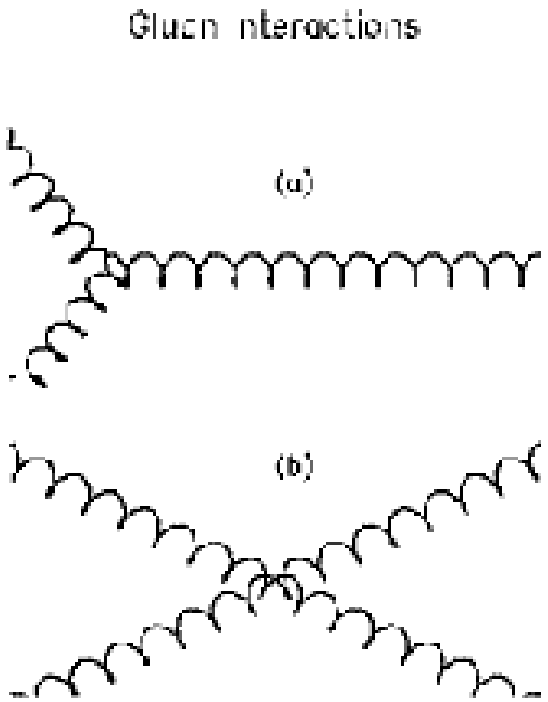




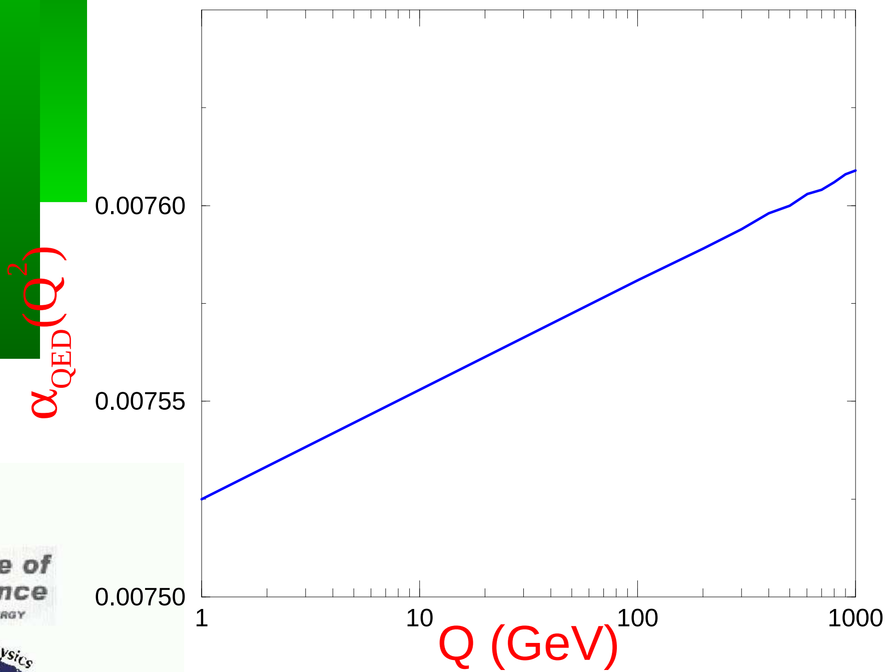
- Similar interaction in QED

- Special Feature of QCD – gluon self-interactions

  Completely Change the Character of the Theory

QED cf. QCD

QED cf. QCD



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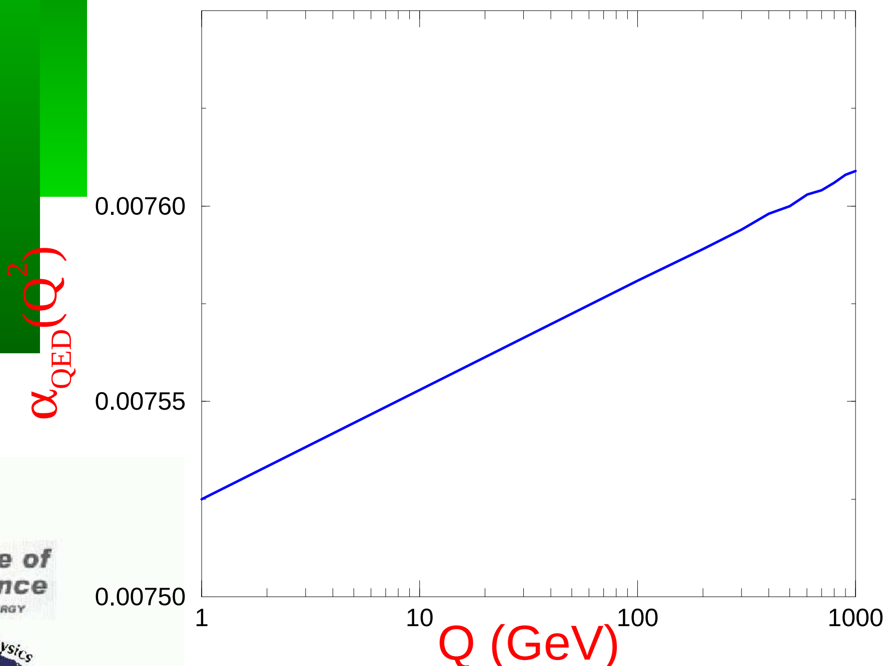
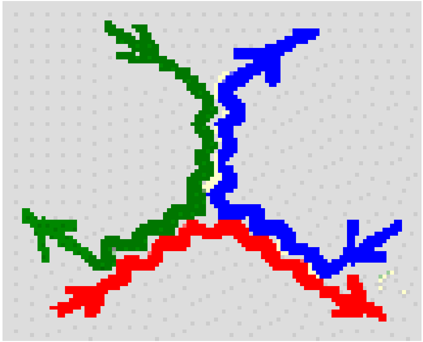
Add three-gluon interaction





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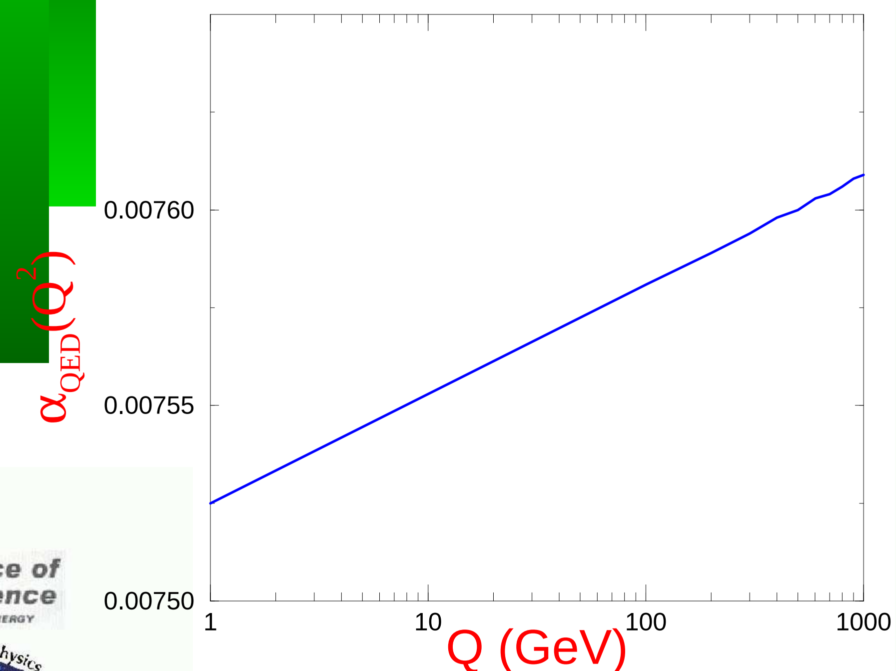
QED cf. QCD



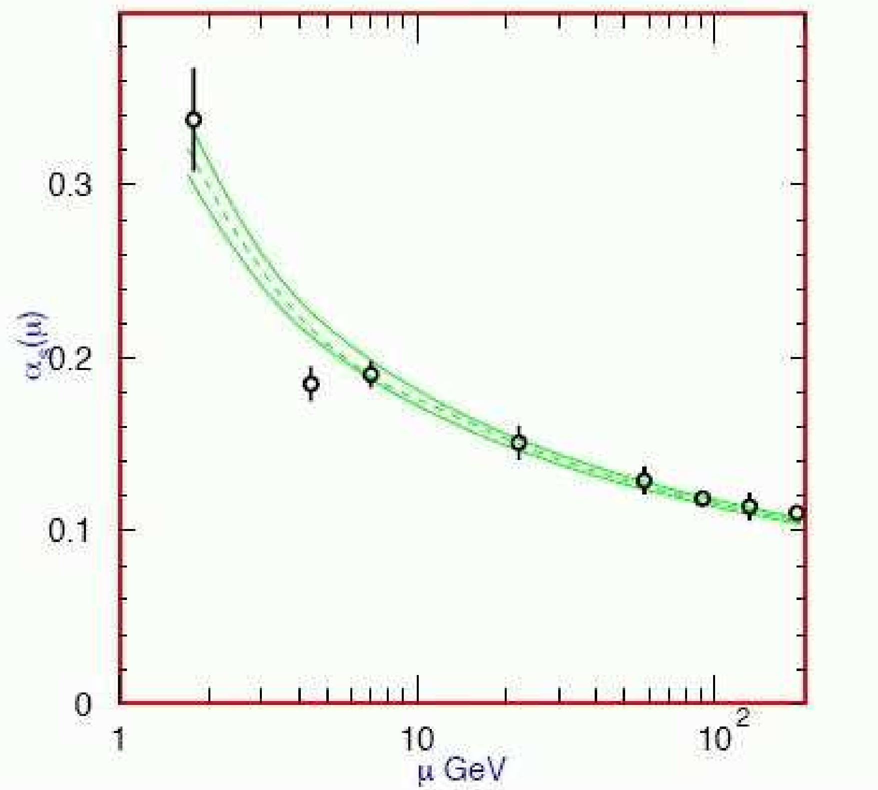


Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ. The data are, in increasing order of μ, τ width, Υ decays, deep inelastic scattering, e^+e^- event shapes at 22 GeV from the JADE data, shapes at TRISTAN at 58 GeV, Z width, and e^+e^- event shapes at 135 and 189 GeV.

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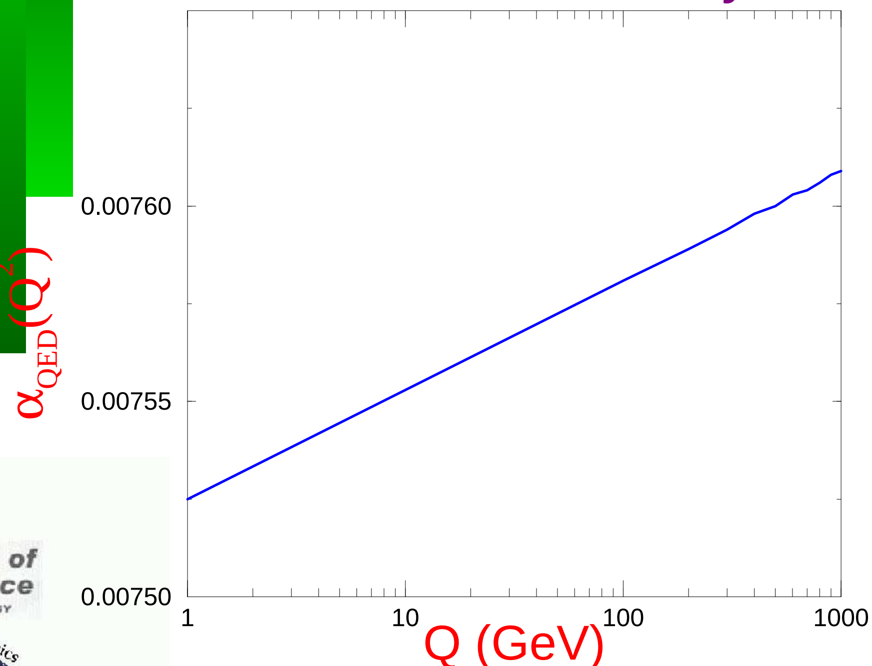
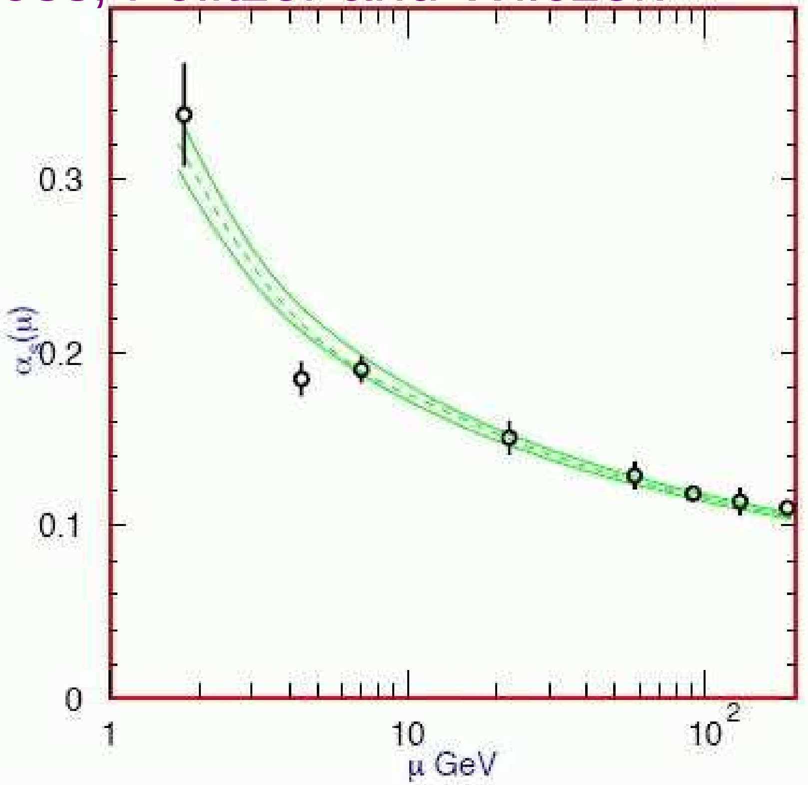
QED cf. QCD

2004 Nobel Prize in Physics: Gross, Politzer and Wilczek





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Quarks and Nuclear Physics

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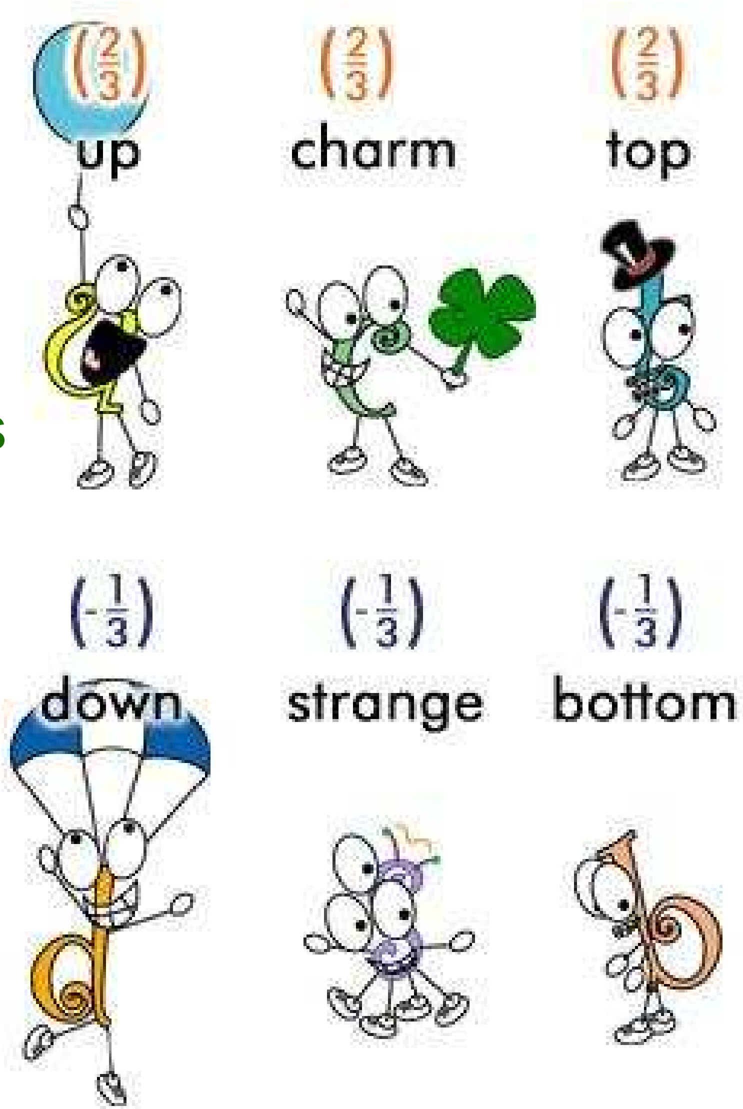
Quarks and Nuclear Physics

Standard Model

of Particle Physics

Six Flavours



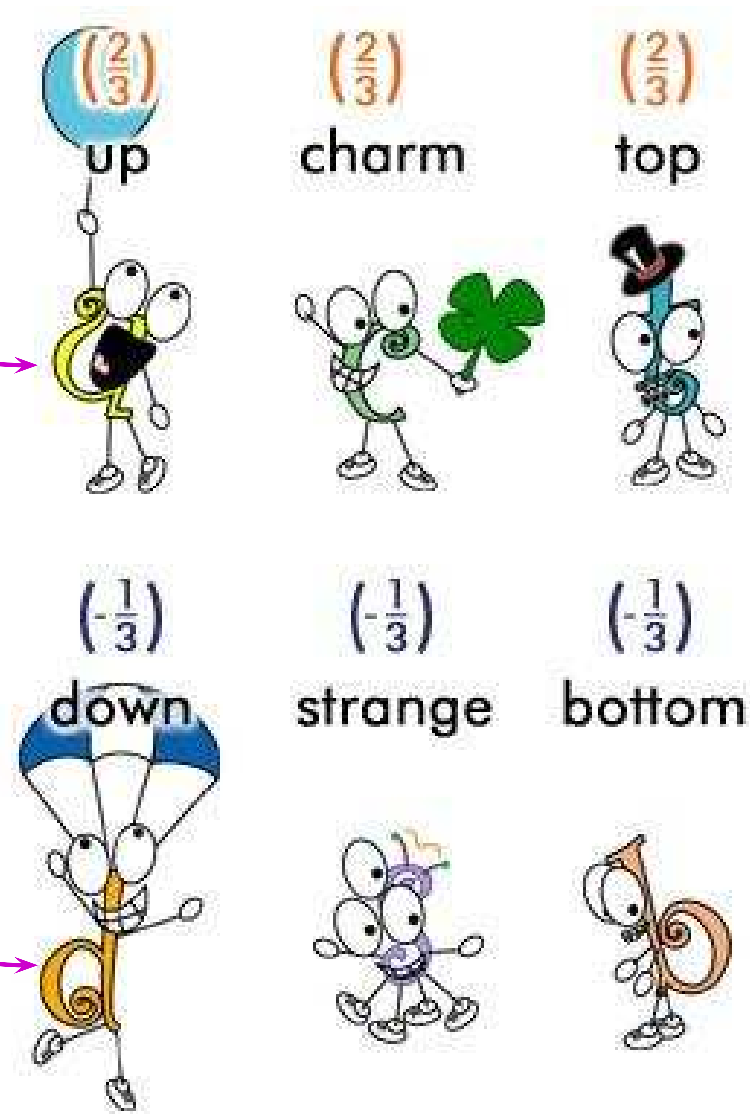
Quarks and Nuclear Physics

Real World

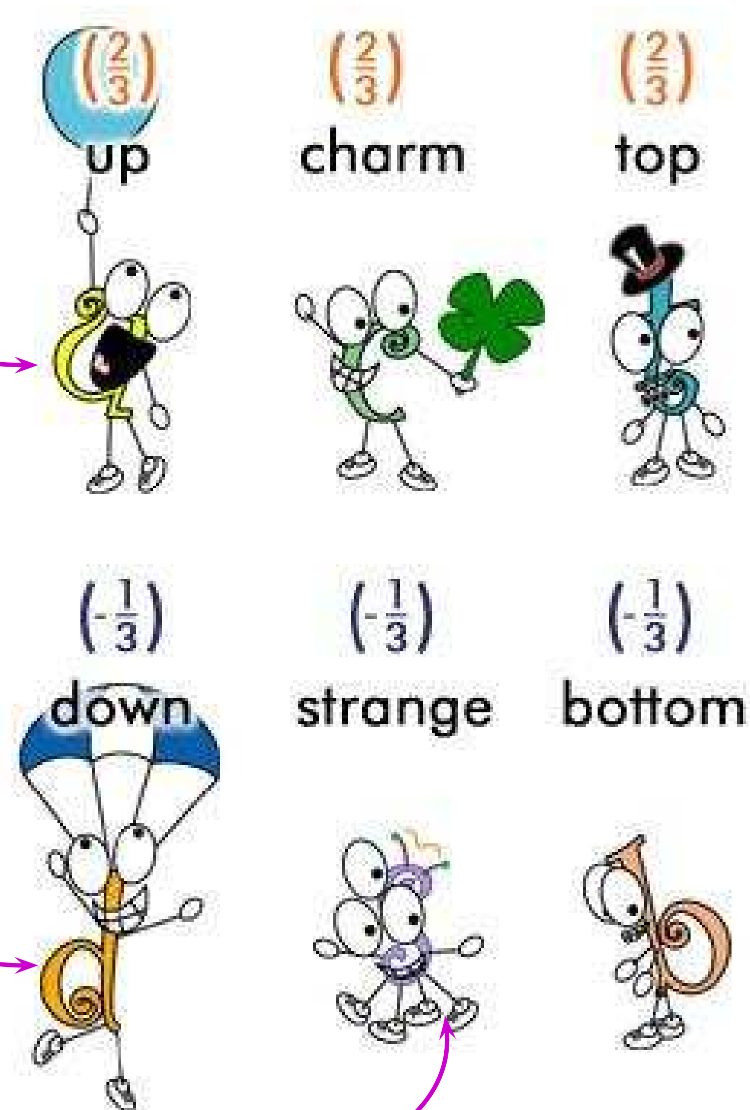
Normal Matter . . .

Only Two Light

Flavours Active



Quarks and Nuclear Physics



Real World

Normal Matter . . .

Only Two Light

Flavours Active

or, perhaps, three

Quarks and Nuclear Physics

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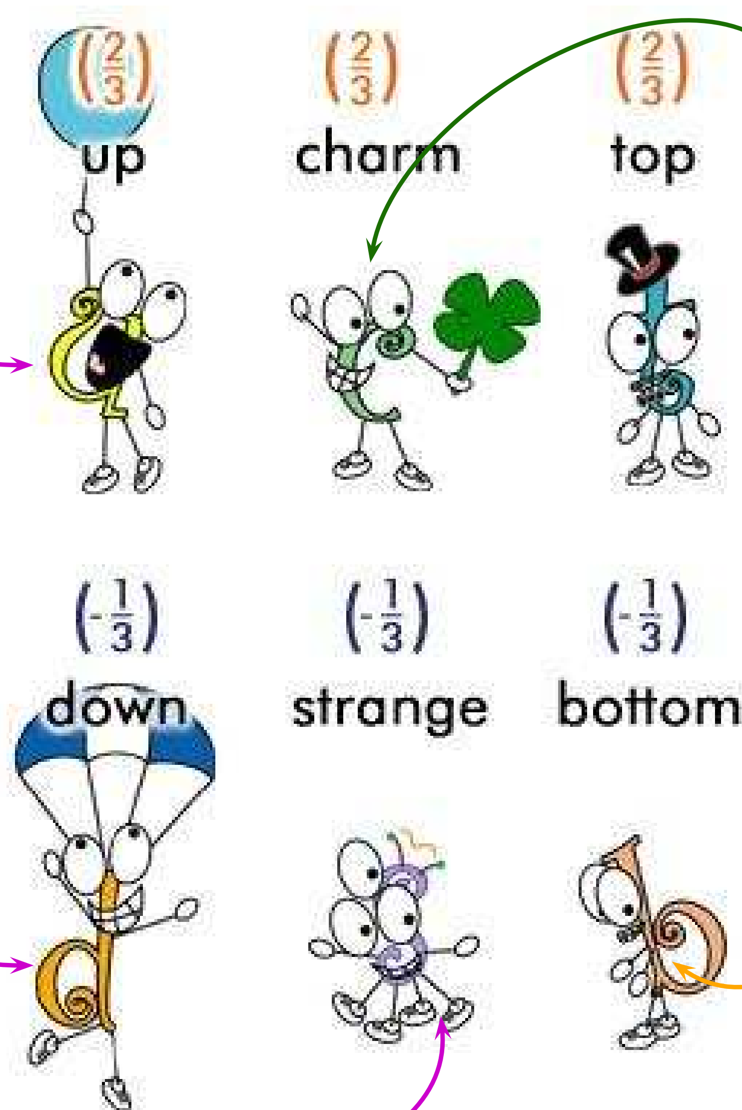
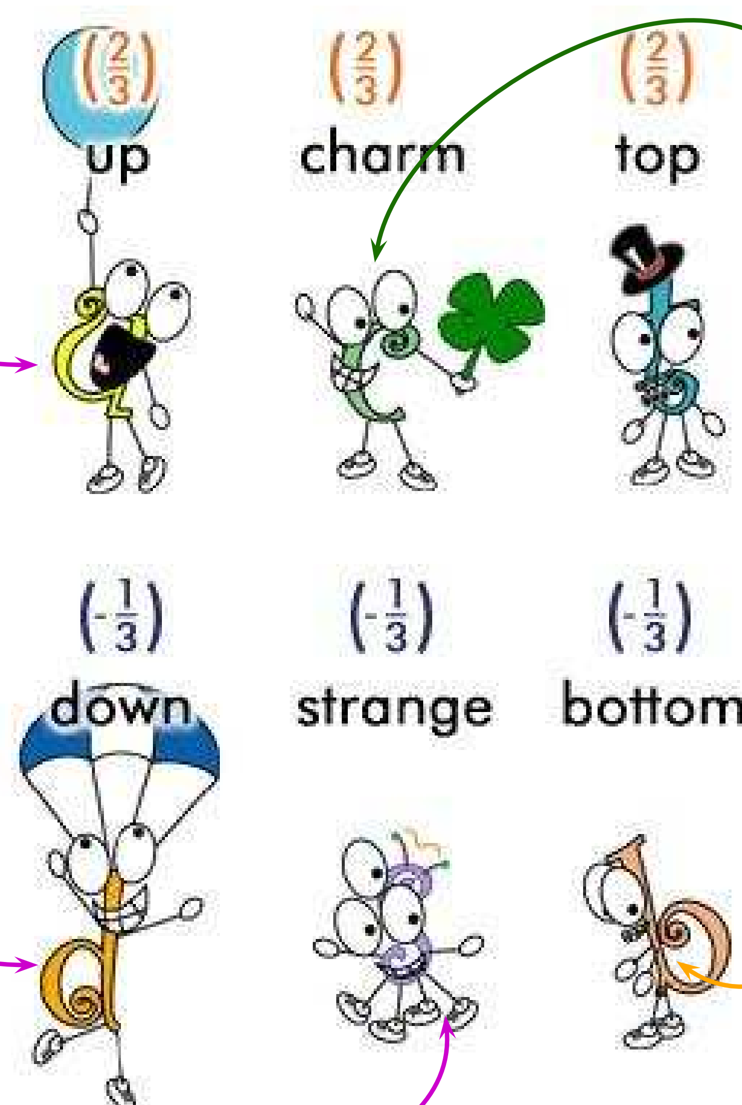


For numerous good reasons, much research also focuses on accessible heavy-quarks

or, perhaps, three

Quarks and Nuclear Physics

Nevertheless, I will focus primarily on the light-quarks.



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Simple Picture

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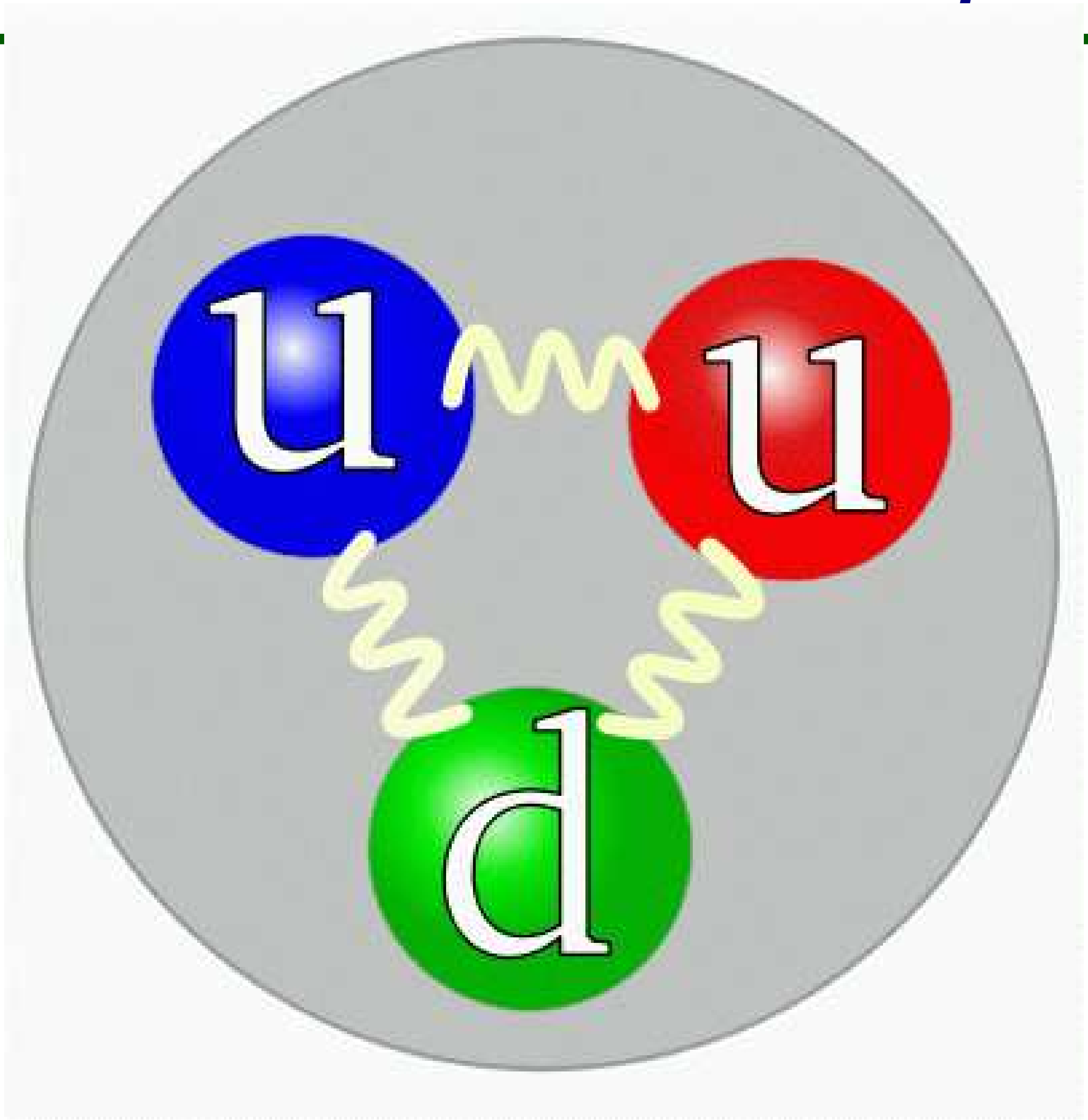
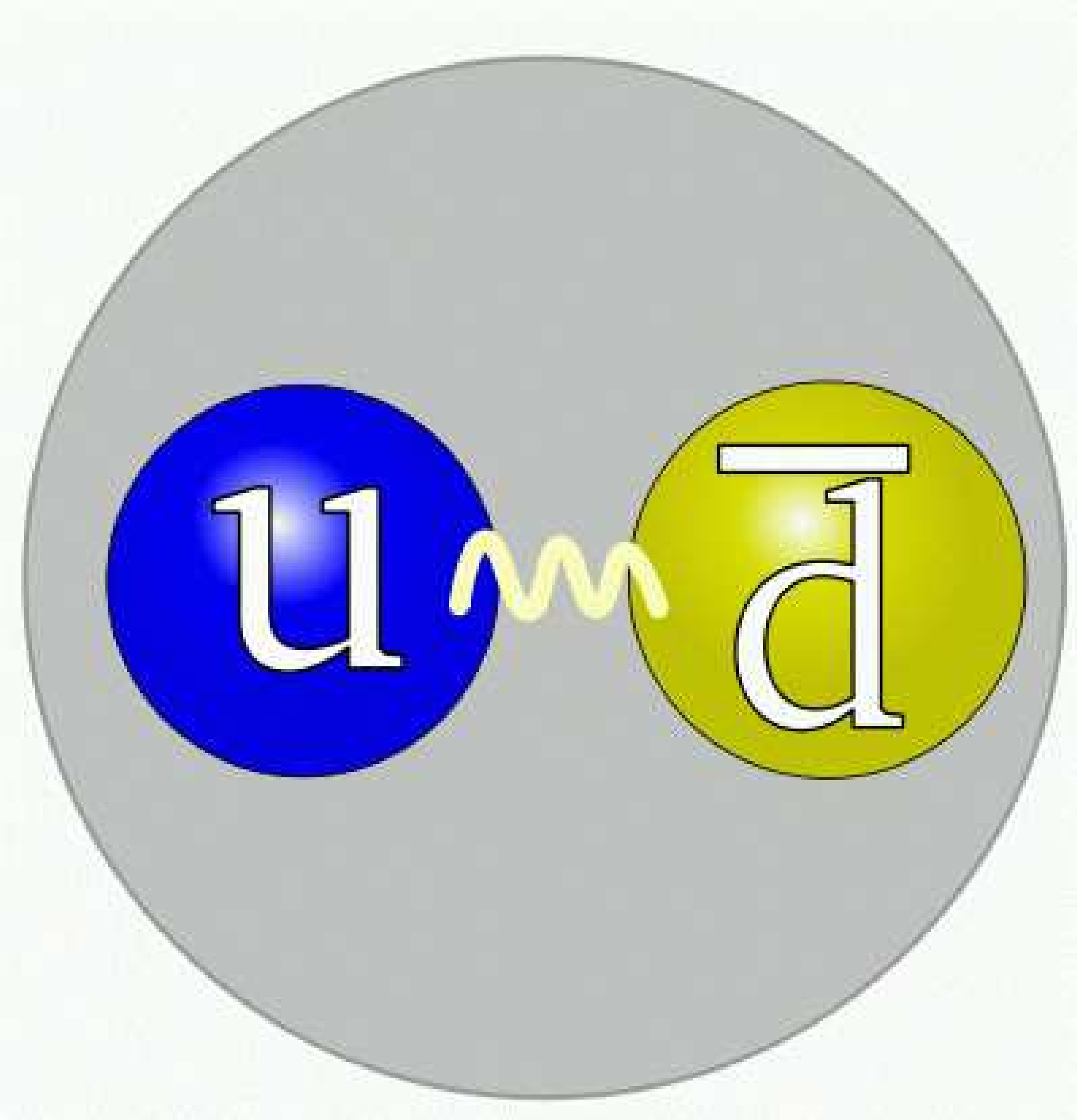


PROTON

Simple Picture



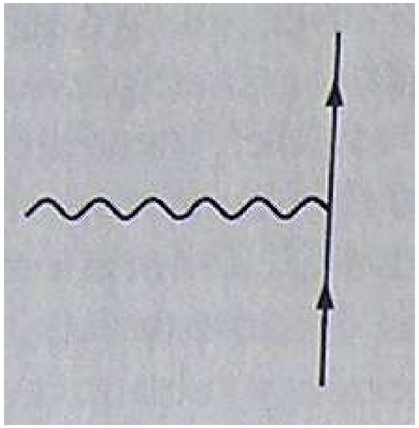
PION

Study Structure via
Nucleon Form Factors

Study Structure via Nucleon Form Factors

- Electron's relativistic electromagnetic current:

$$\begin{aligned} j_\mu(P',P) &= ie\,\bar{u}_e(P')\,\Lambda_\mu(Q,P)\,u_e(P)\,,\;\; Q=P'-P \\ &= ie\,\bar{u}_e(P')\,\gamma_\mu(-1)\,u_e(P) \end{aligned}$$



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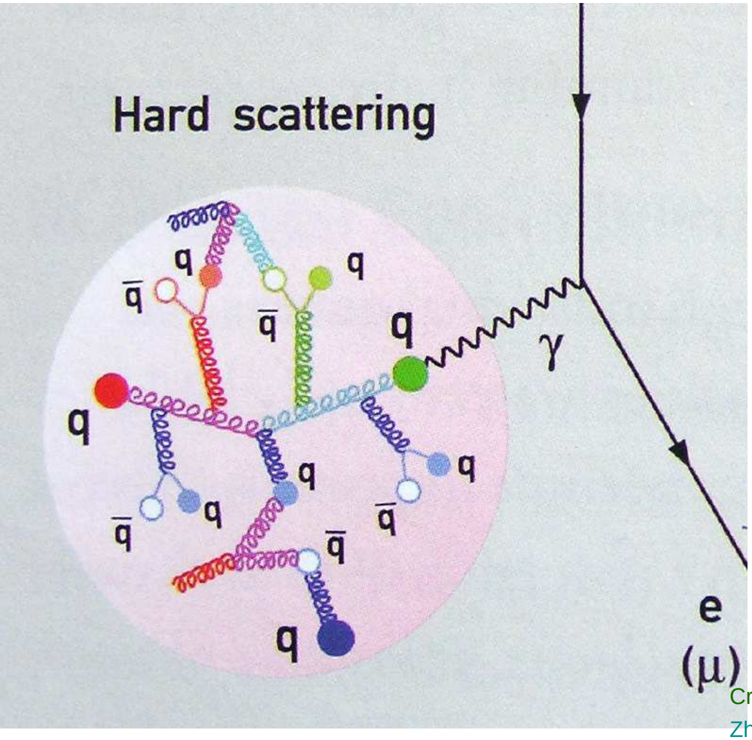

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$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2}F_2(Q^2)\,,\; G_M(Q^2) = F_1(Q^2) + F_2(Q^2)\,.$$

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Point-particle: $\boldsymbol{F_2 \equiv 0} \Rightarrow \boldsymbol{G_E \equiv G_M}$

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Why?

Why?

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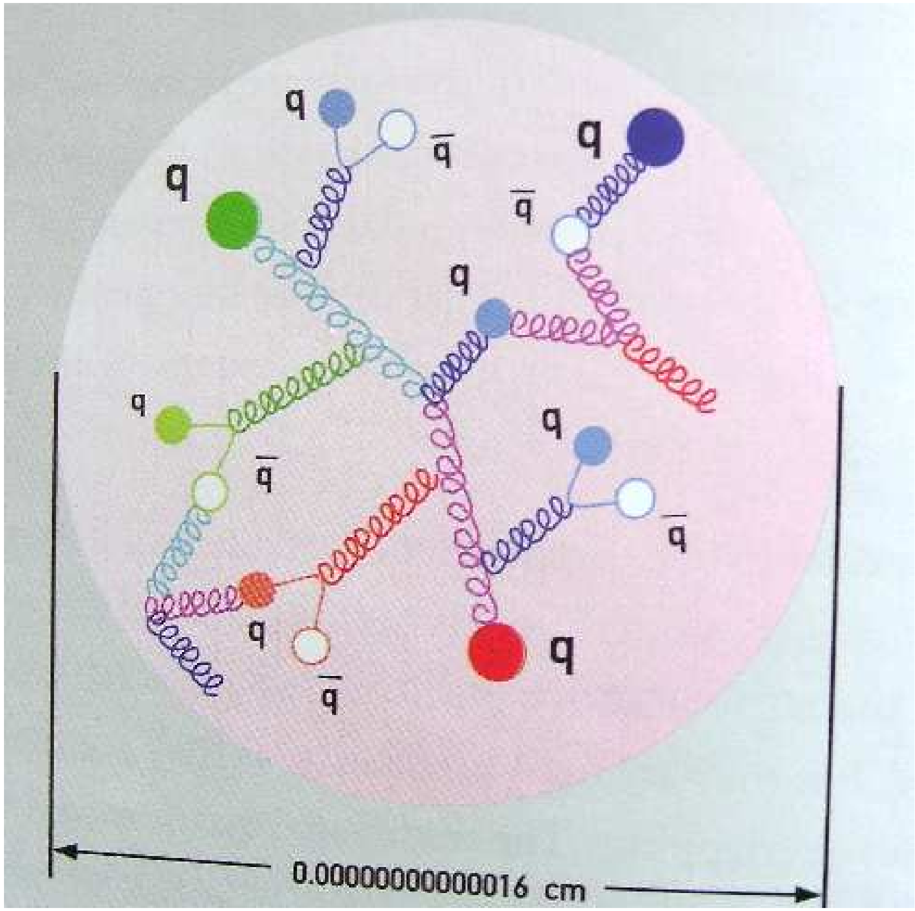
- Despite this, many urgent questions remain unanswered.

NSAC Long Range Plan

A central goal of nuclear physics is to understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD



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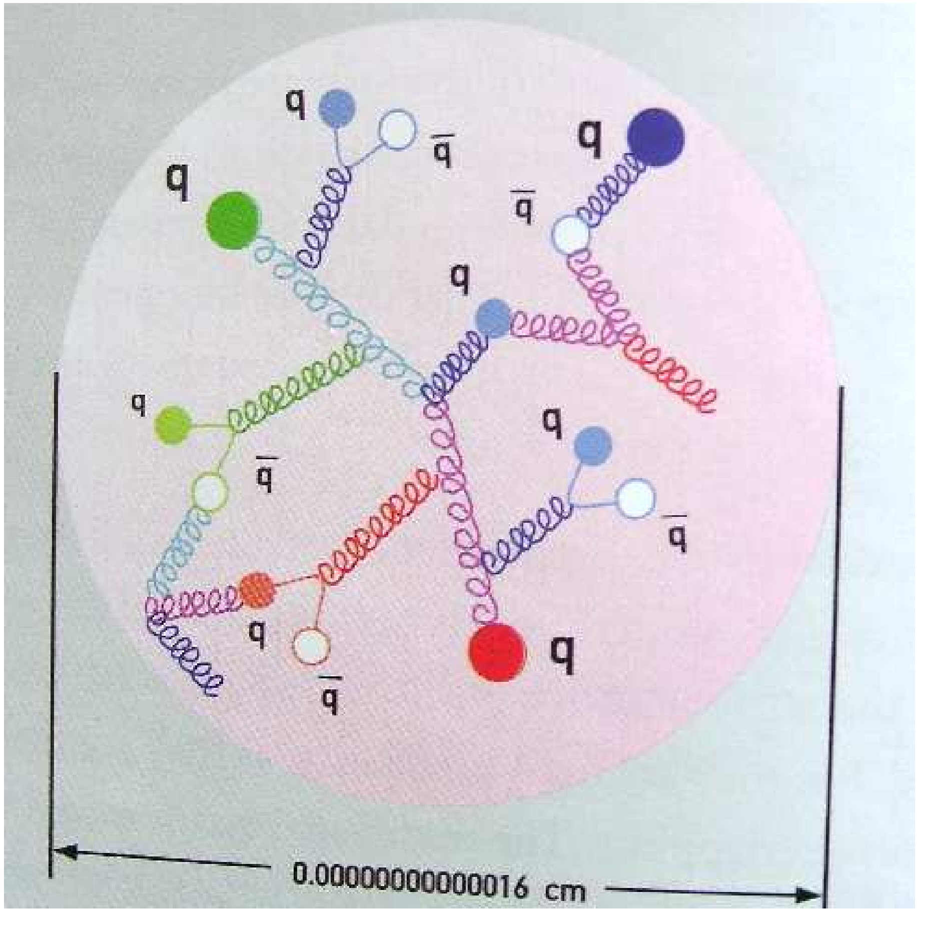

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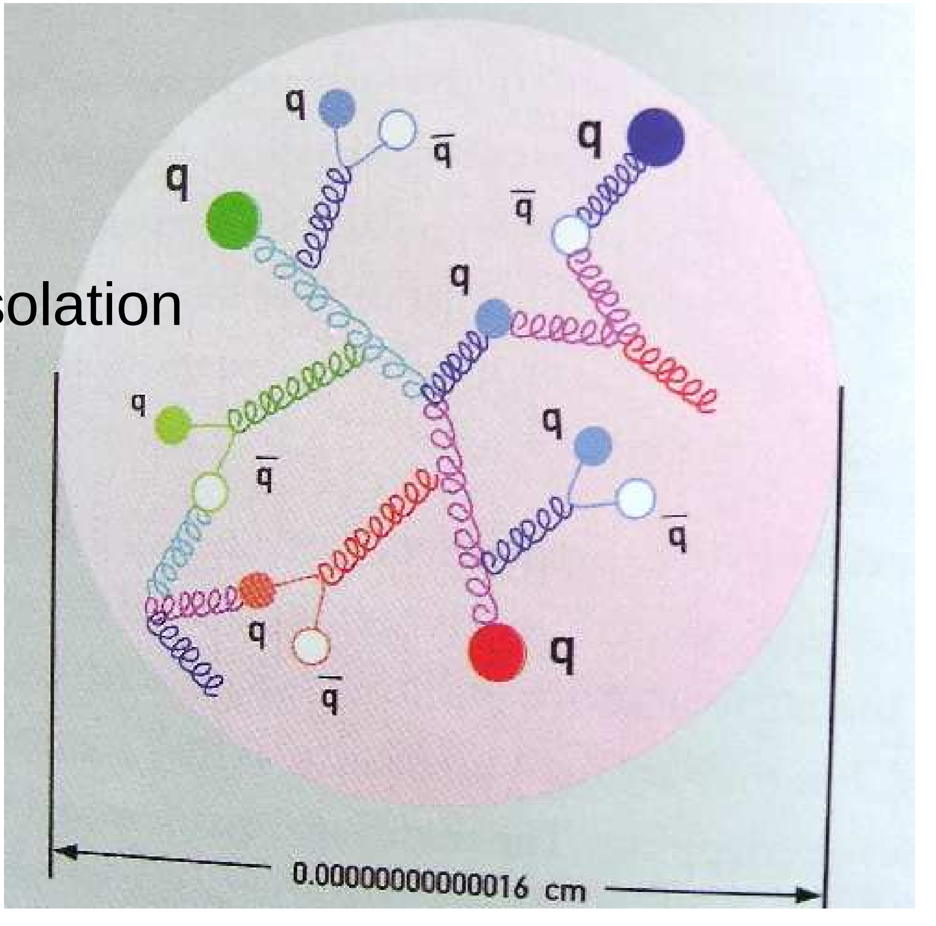

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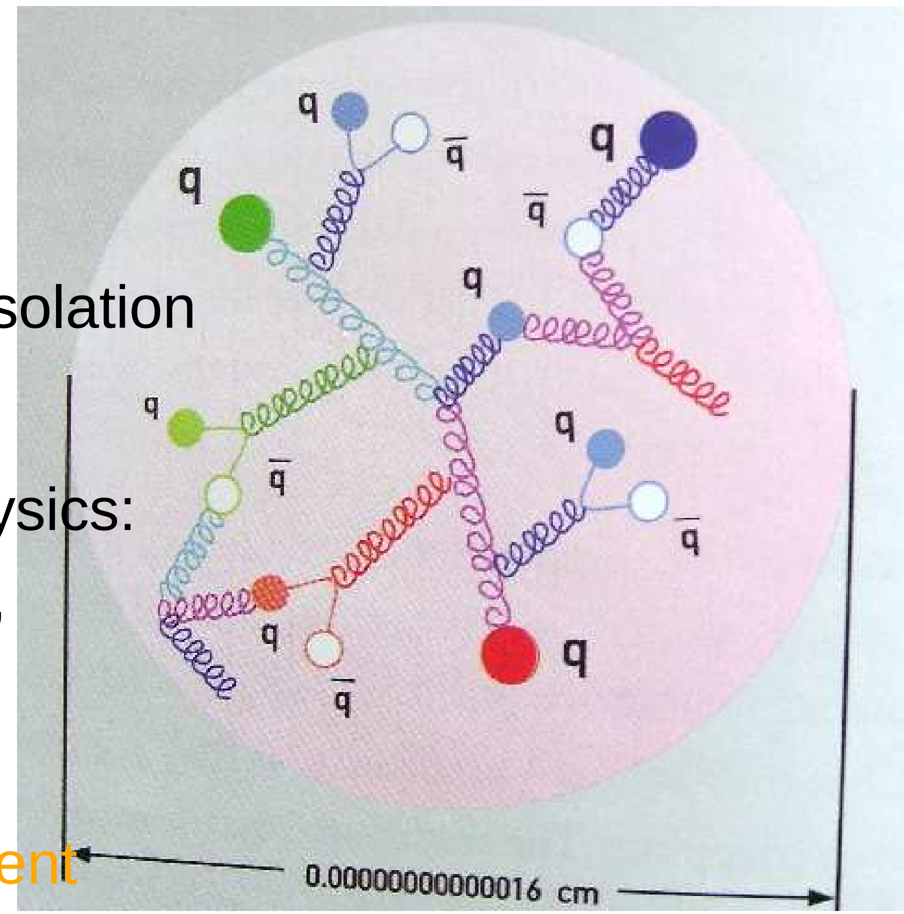
A central goal of nuclear physics is to understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD

So, what's the problem?

- Confinement
  – No quark ever seen in isolation
- Weightlessness
  – 2004 Nobel Prize in Physics:
  Mass of $u-$ & $d-$quarks,
  each just 5 MeV;
  Proton Mass is 940 MeV
  $\Rightarrow$ No Explanation Apparent
  for 98.4 % of Mass



Meson Spectrum

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$	STRANGE ($S = \pm 1$, $C = B = 0$)	$I(J^P)$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$	• $K^\pm$	$1/2(0^-)$
• π^0 140 MeV	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$	• K^0	$1/2(0^-)$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$	• K^0_S	$1/2(0^-)$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$	• K^0_L	$1/2(0^-)$
• $\rho(770)$ 770	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$	$K_0^*(800)$	$1/2(0^+)$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$	• $K^*(892)$	$1/2(1^-)$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$	• $K_1(1270)$	$1/2(1^+)$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$	• $K_1(1400)$	$1/2(1^+)$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$	• $K^*(1410)$	$1/2(1^-)$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$	• $K_0^*(1430)$	$1/2(0^+)$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$	• $K_2^*(1430)$	$1/2(2^+)$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$	$K(1460)$	$1/2(0^-)$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$	$K_2(1580)$	$1/2(2^-)$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$	$K(1630)$	$1/2(?^?)$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$	$K_1(1650)$	$1/2(1^+)$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$	• $K^*(1680)$	$1/2(1^-)$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$	• $K_2(1770)$	$1/2(2^-)$

Gauge Theories with Massless Fermions have

$\boxed{\text{CHIRAL SYMMETRY}}$

- Helicity $\lambda \propto J \cdot p$
  - Projection of Spin onto Direction of Motion
  - For massless particles, helicity is a Lorentz invariant *Spin Observable*.
  - $\lambda = \pm$ ($\|$ or anti-$\|$ to p_μ)

Chiral Symmetry

- Chirality Operator: γ_5
  - Chiral Transformation $q(x) \to \mathrm{e}^{i\gamma_5\theta}\, q(x)$

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  - Chiral Rotation $\theta = \dfrac{\pi}{2}$
    - $q_{\lambda=+} \to q_{\lambda=+},\; q_{\lambda=-} \to -\, q_{\lambda=-}$
    - Hence, a theory invariant under chiral transformations can only contain interactions that are insensitive to a particle's helicity.

Chiral Symmetry

- Chirality Operator: γ_5
  - Chiral Transformation $q(x) \to \mathrm{e}^{i\gamma_5\theta}\, q(x)$
  - Chiral Rotation $\theta = \dfrac{\pi}{4}$
    - Composite Particles: $J^{P=+} \leftrightarrow J^{P=-}$
    - Equivalent to "Parity Conjugation" Operation

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Chiral Symmetry

- A Prediction of Chiral Symmetry
  - Degeneracy between Parity Partners

$$N(\tfrac{1}{2}^+,938) = N(\tfrac{1}{2}^-,1535),$$
$$\pi(0^-,140) = \sigma(0^+,600),$$
$$\rho(1^-,770) = a_1(1^+,1260)$$

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  Predictions *not* Valid – Violations *too* Large.

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How can pion mass be so small

If quarks are so heavy?!

Explicit Chiral Symmetry Breaking

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  Can be discussed in terms of Quark Propagator

  - Free Quark Propagator $S_0(p) = \dfrac{-i\gamma\cdot p + m}{p^2 + m^2}$

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- Chiral Transformation

$$\begin{aligned}\mathbf{S}_0(p) &\to \mathrm{e}^{i\gamma_5\theta} S_0(p) \mathrm{e}^{i\gamma_5\theta} \\ &= \frac{-i\gamma\cdot p}{p^2+m^2} + \mathrm{e}^{2i\gamma_5\theta}\frac{m}{p^2+m^2}\end{aligned}$$

  - Symmetry Violation $\propto m$
  - $\mathbf{m} = 0$: $S_0(p) \to S_0(p)$

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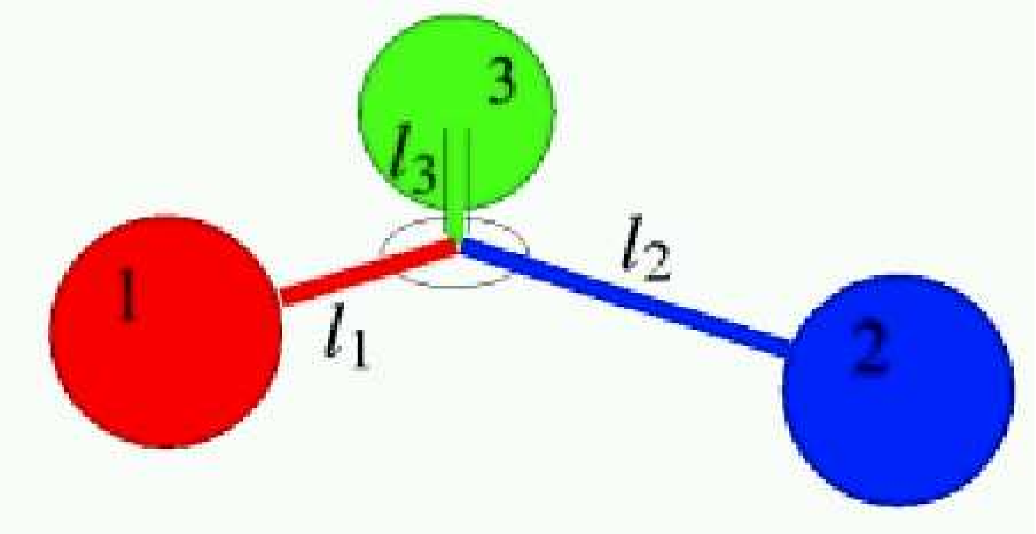
  - A Measure of the Chiral Symmetry Violating Term
  - Perturbative QCD: Vanishes if $m=0$

- proton = three constituent quarks



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Modern Miracles in Hadron Physics

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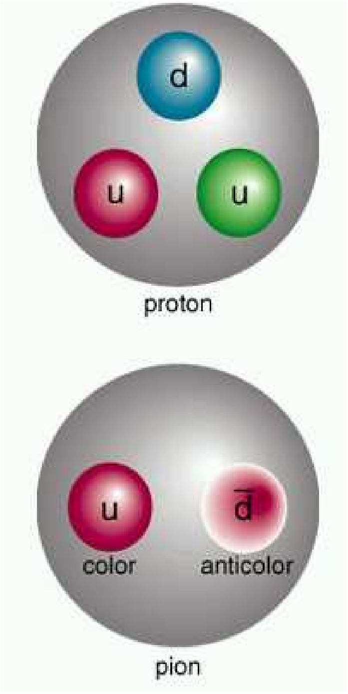

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- Another meson:

  .... $M_\rho = 770\,$MeV .... No Surprises Here

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- What is "wrong" with the pion?

Dichotomy of Pion
– Goldstone Mode and *Bound state*

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Current Algebra . . . 1968

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Highly Nontrivial

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  - detailed understanding of connection between Current-quark and Constituent-quark masses;
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  - Interaction between quarks – the Interquark “Potential” – unknown throughout $> 98\%$ of a hadron's volume

Intranucleon Interaction

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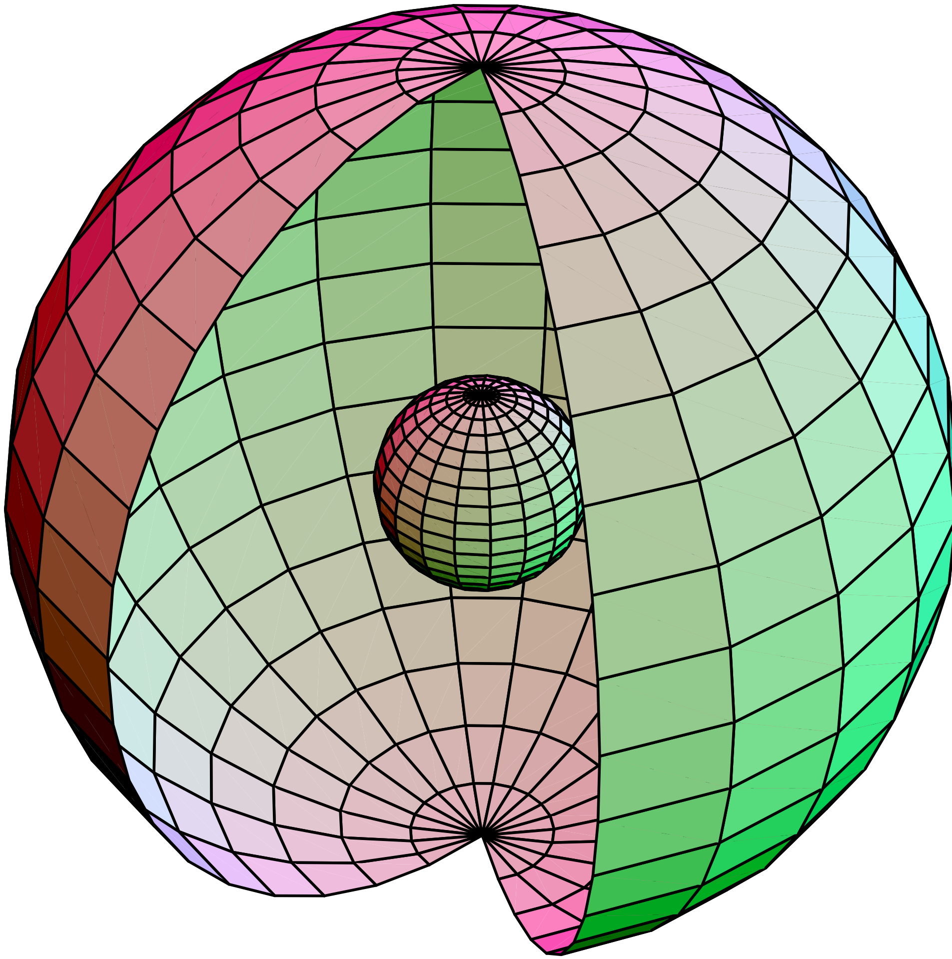
Intranucleon Interaction



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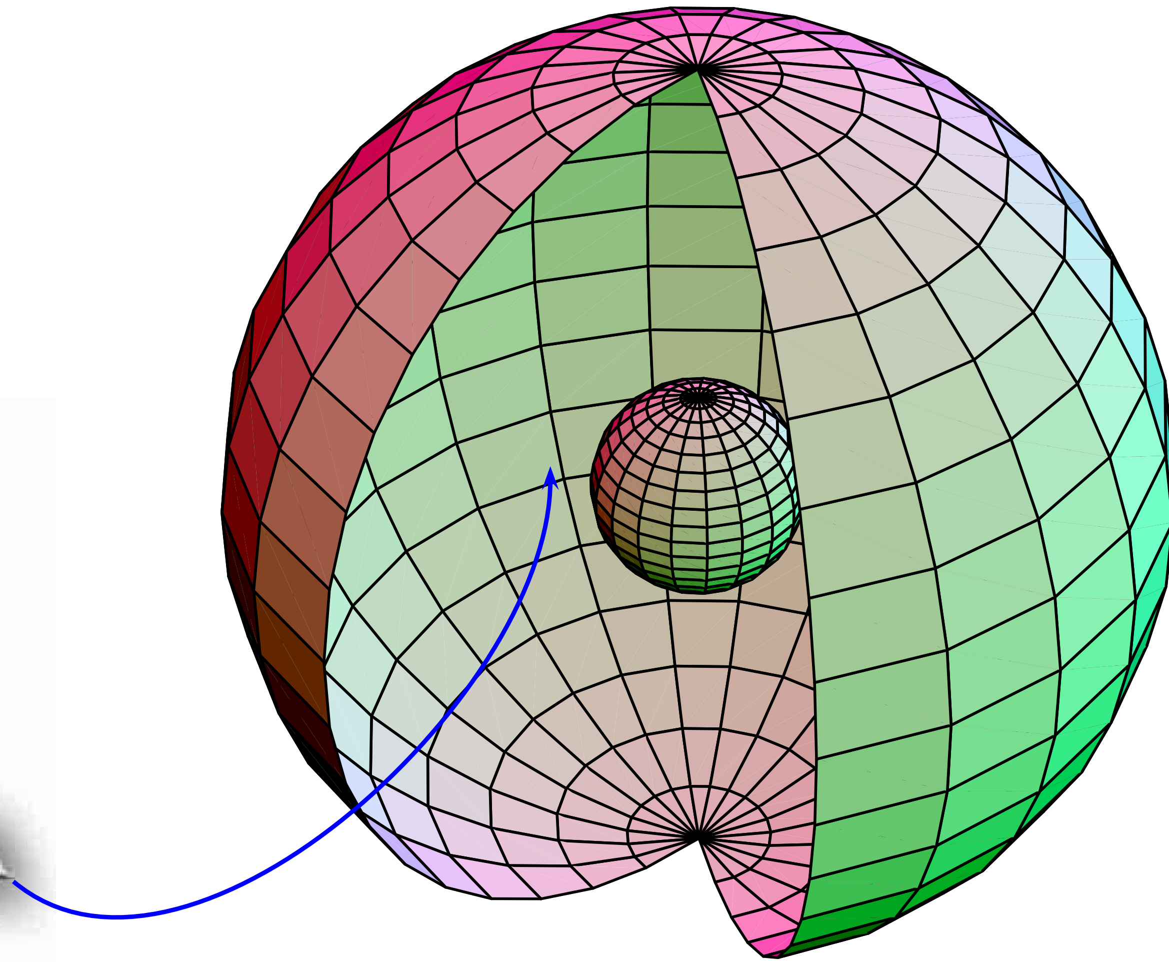
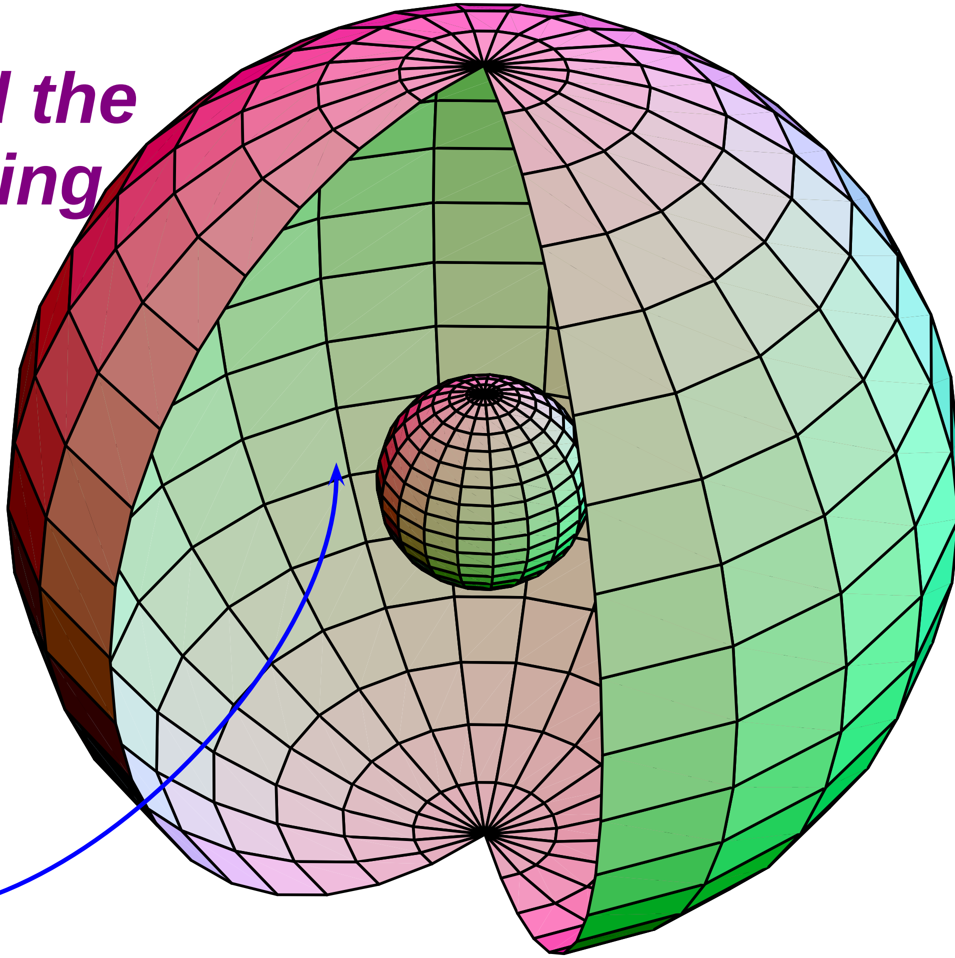
Intranucleon Interaction



98% of the volume

What is the Intranucleon Interaction?

The question must be rigorously defined, and the answer mapped out using experiment and theory.



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QCD’s Challenges

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- Neither of these phenomena is apparent in QCD's Lagrangian ***yet*** they are the dominant determining characteristics of real-world QCD.

QCD's Challenges

Understand Emergent Phenomena

- Quark and Gluon Confinement
  - No matter how hard one strikes the proton, one cannot liberate an individual quark or gluon
- Dynamical Chiral Symmetry Breaking
  - Very unnatural pattern of bound state masses
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- QCD – Complex behaviour

  arises from apparently simple rules

Why should You care?

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Office of Science
U.S. DEPARTMENT OF ENERGY
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars
Argonne NATIONAL LABORATORY

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Is a unique long-range interaction between light-quarks responsible for all this or are there an uncountable infinity of qualitatively equivalent interactions?

Hamiltonian?

- Plainly, nonperturbative method is necessary.

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NB. Hadron Physics Milestone, 2012: Measure the electromagnetic excitations of low-lying hadrons and their transition form factors.

Model QCD

Traditional approach to strong force problem

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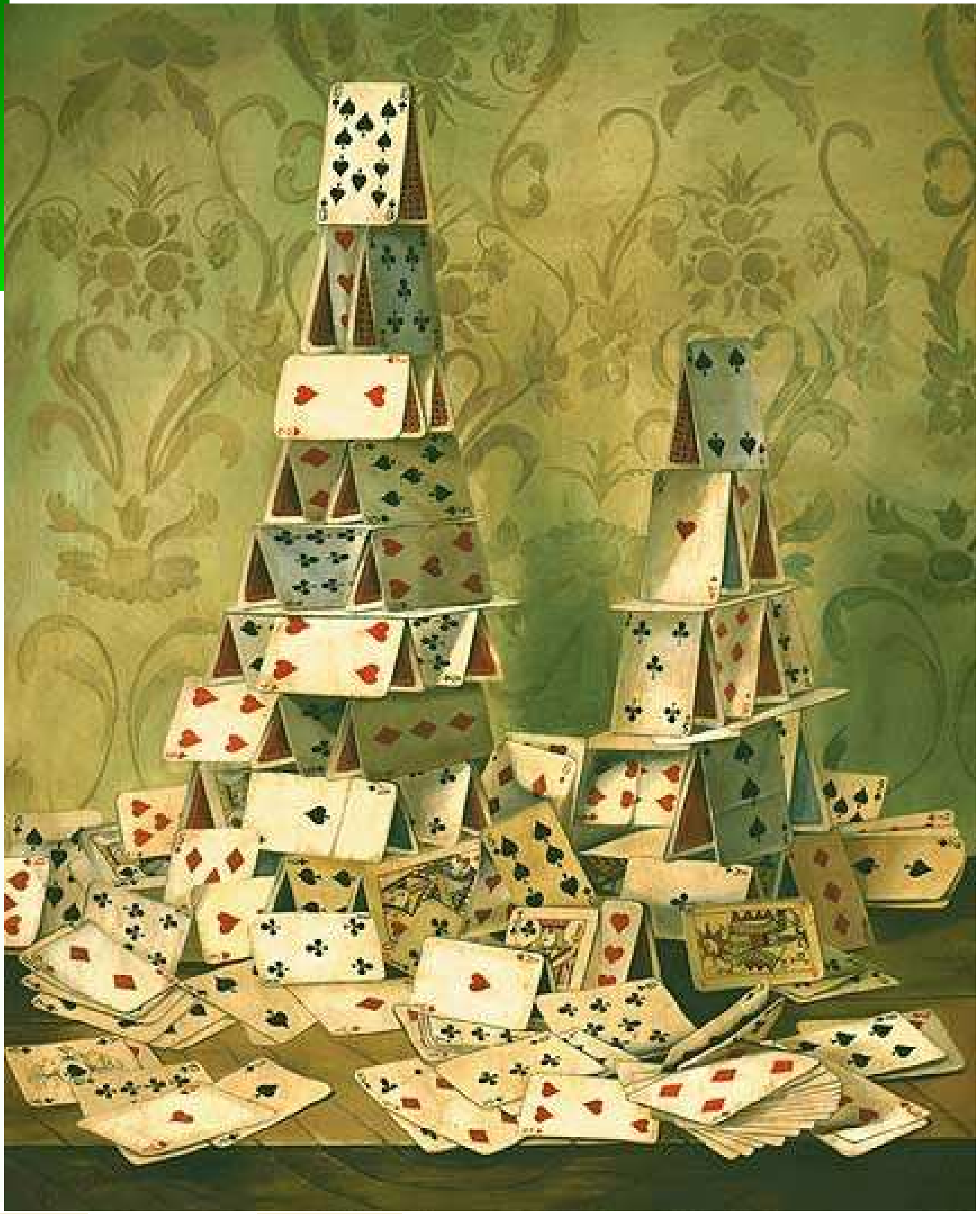
Model QCD



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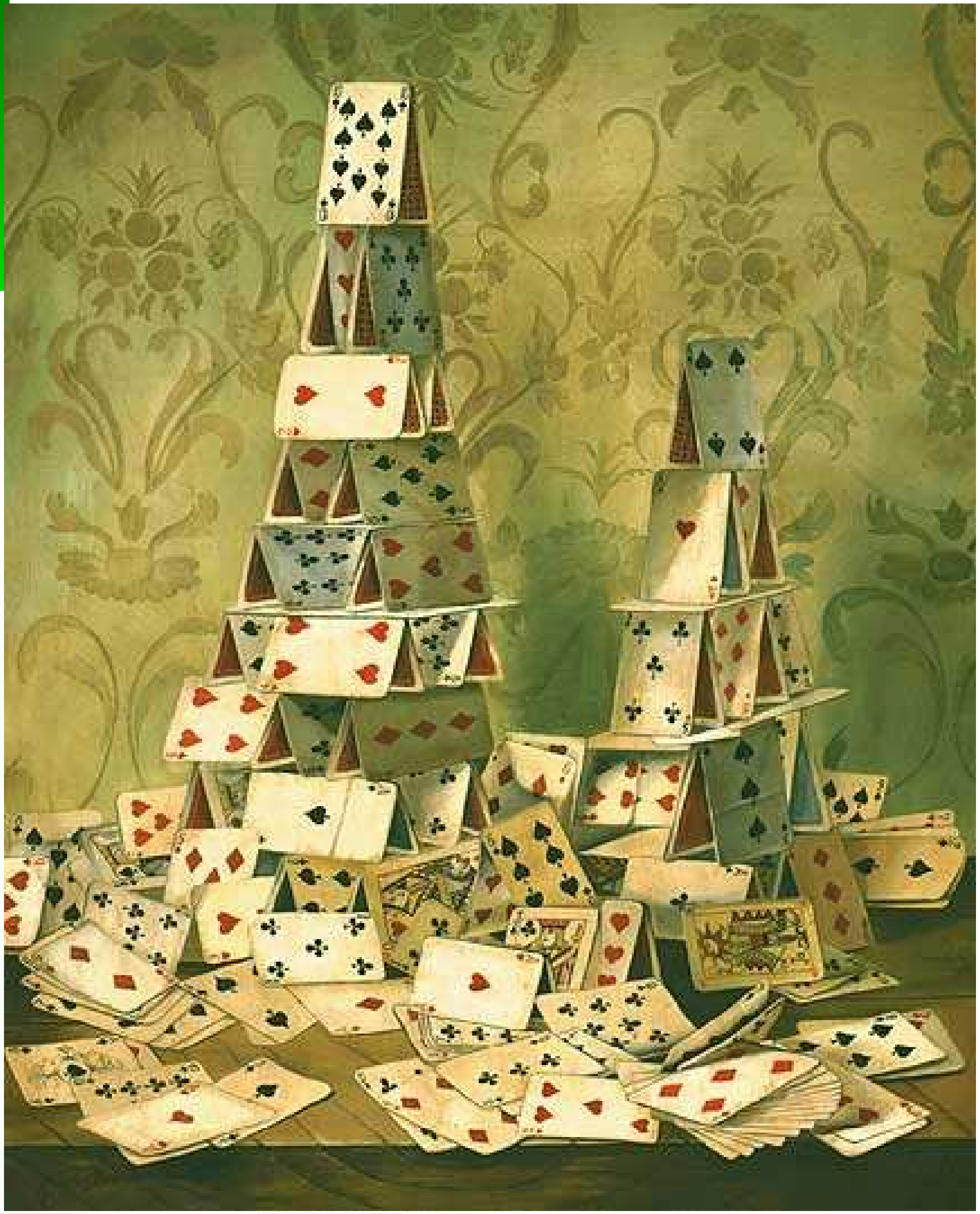

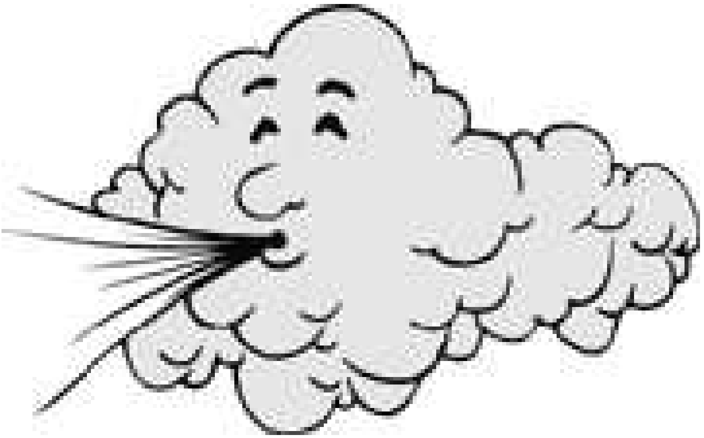

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Lattice QCD

One modern nonperturbative approach *Lattice QCD*

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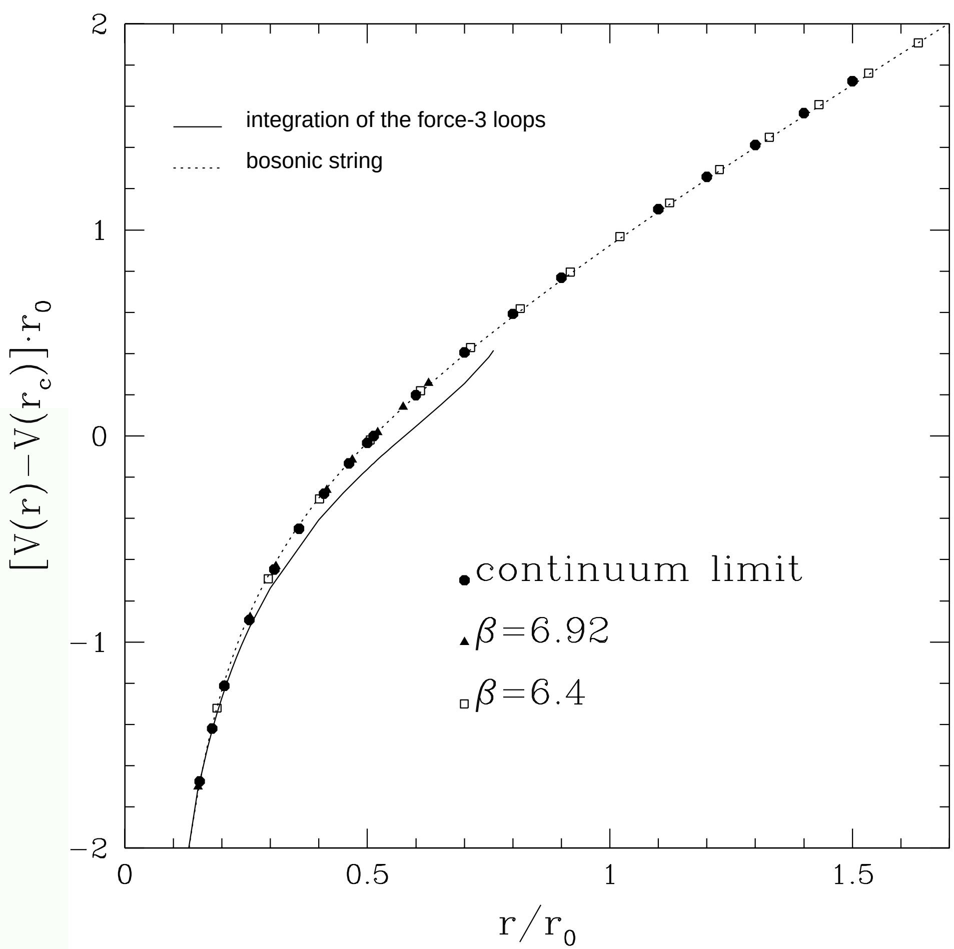
Confinement

Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



$$V(r) = \sigma\, r - \frac{\pi}{12}\,\frac{1}{r}$$

$\sigma \sim 470\,$MeV

Necco & Sommer
he-la/0108008

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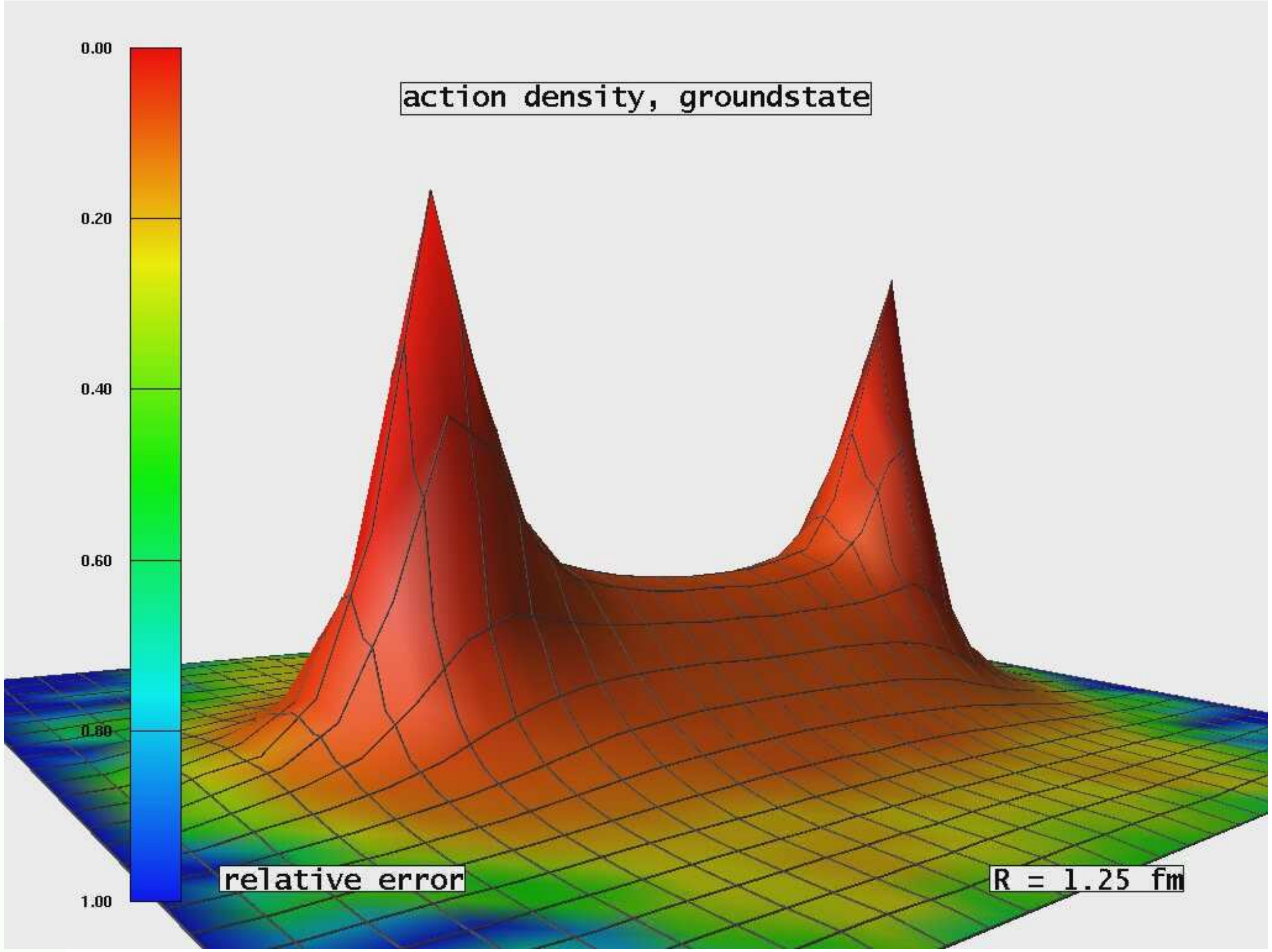
Confinement

- Illustrate this in terms of the action density ... analogous to plotting the Force $= F_{\bar{Q}Q}(r) = \sigma + \dfrac{\pi}{12}\dfrac{1}{r^2}$



Bali, *et al*.
he-la/0512018

Confinement

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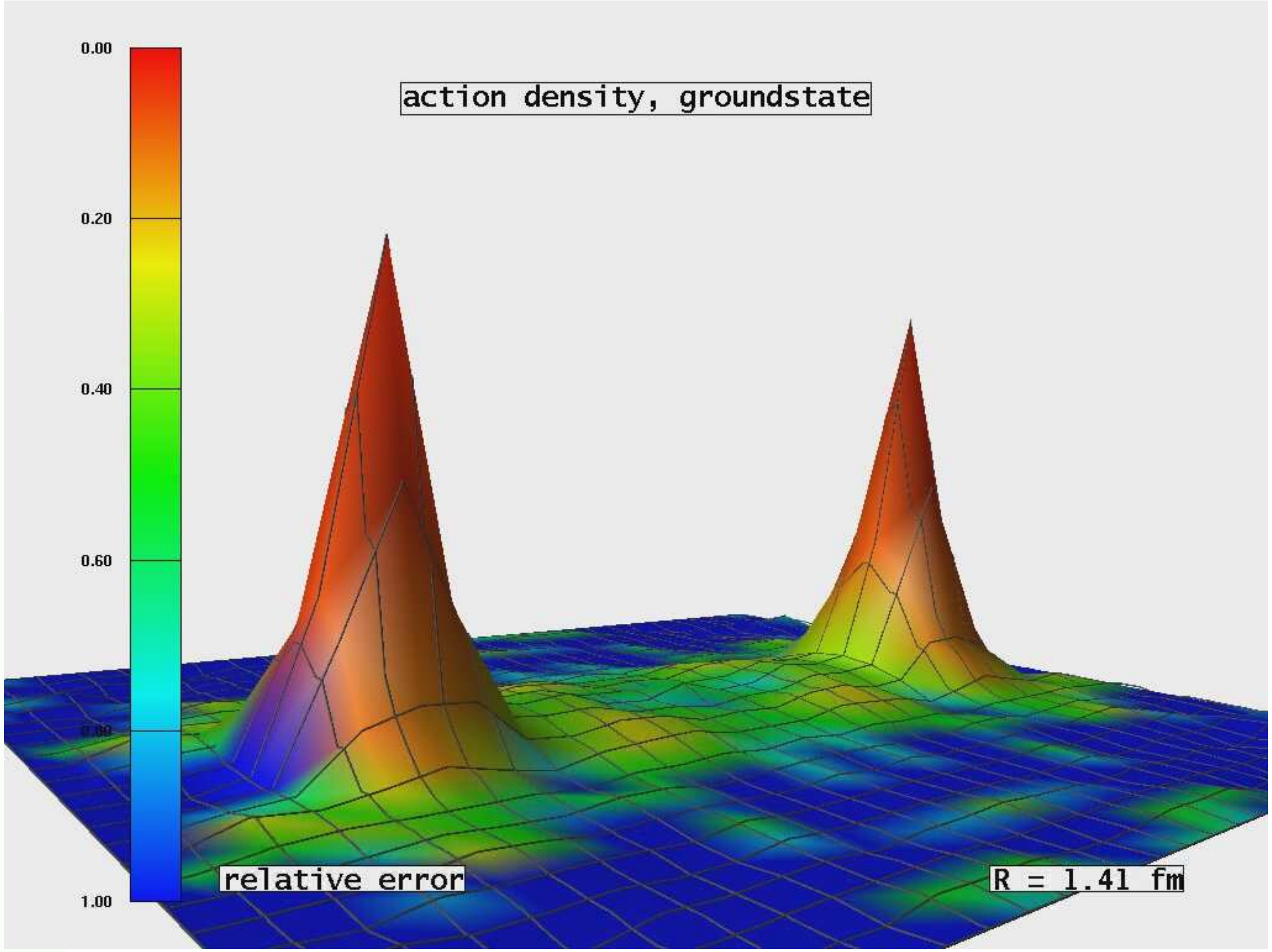

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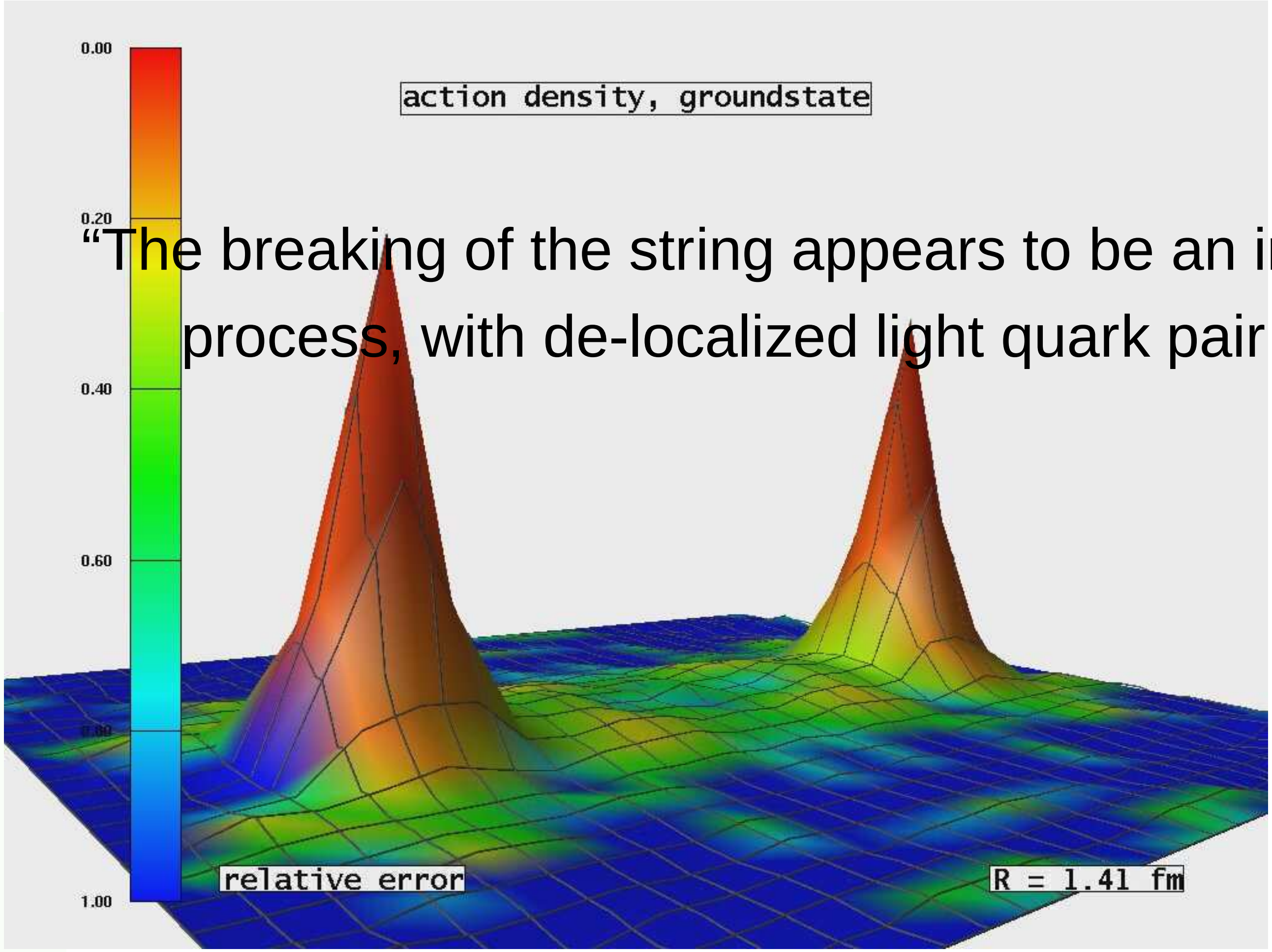

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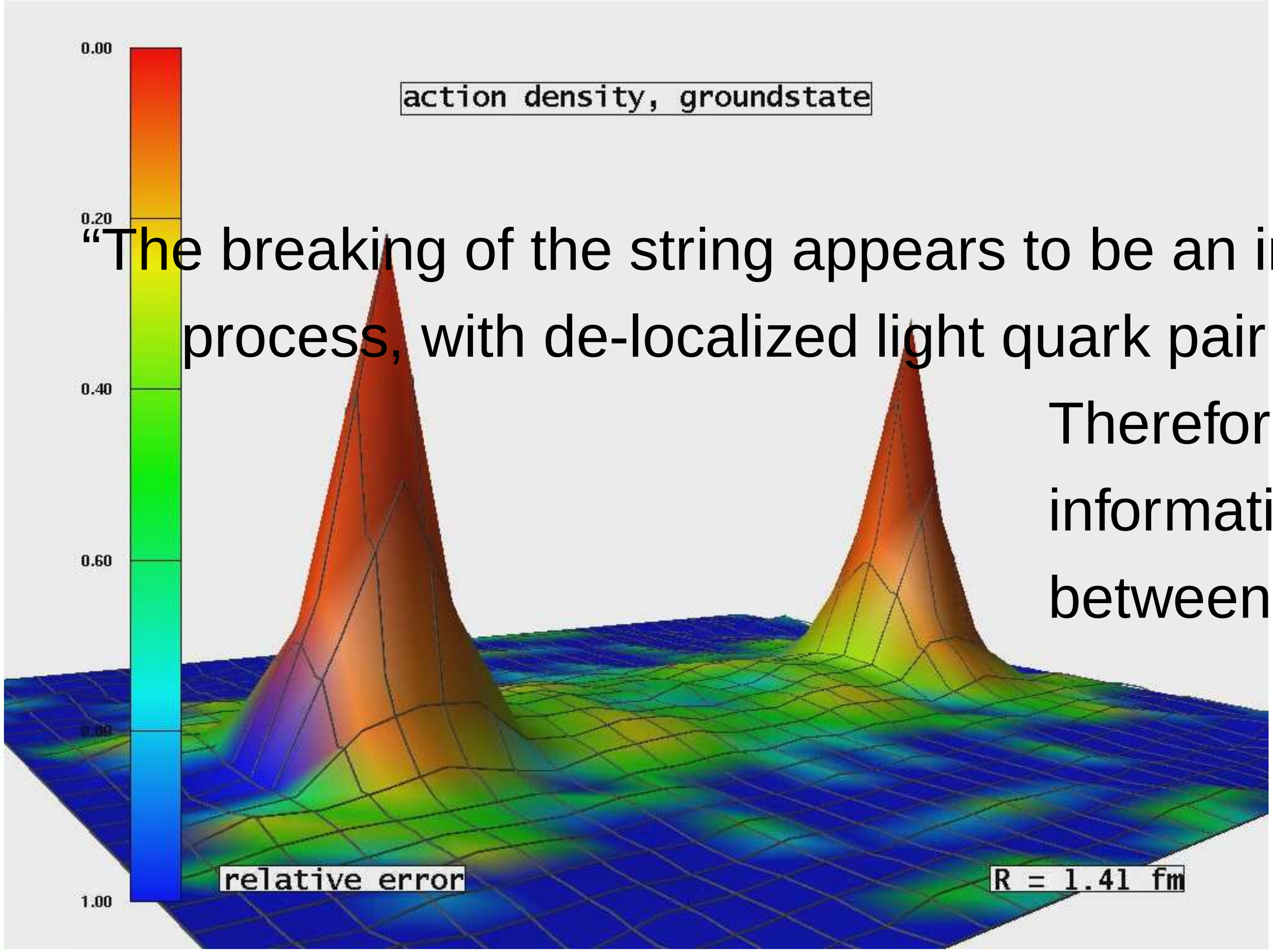

"The breaking of the string appears to be an instantaneous process, with de-localized light quark pair creation."

Therefore . . . No information on *potential* between light-quarks.

A Compromise?

Dyson-Schwinger Equations

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A Compromise?
Dyson-Schwinger Equations

- 1994 . . . “*As computer technology continues to improve, lattice gauge theory [LGT] will become an increasingly useful means of studying hadronic physics through investigations of discretised quantum chromodynamics [QCD]. . . . .*”

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A Compromise?
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- 1994 . . . "*However, it is equally important to develop other complementary nonperturbative methods based on continuum descriptions. In particular, with the advent of new accelerators such as CEBAF and RHIC, there is a need for the development of approximation techniques and models which bridge the gap between short-distance, perturbative QCD and the extensive amount of low- and intermediate-energy phenomenology in a single covariant framework. . . .*"

Dyson-Schwinger Equations

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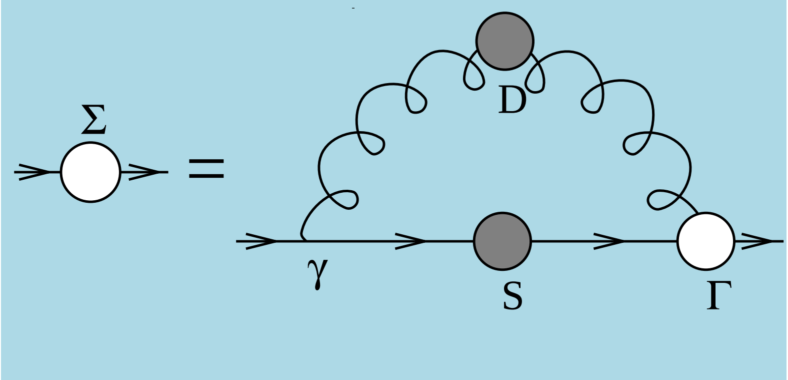

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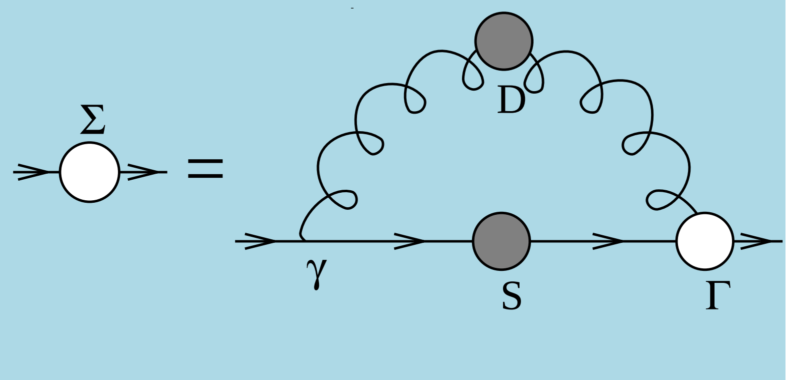

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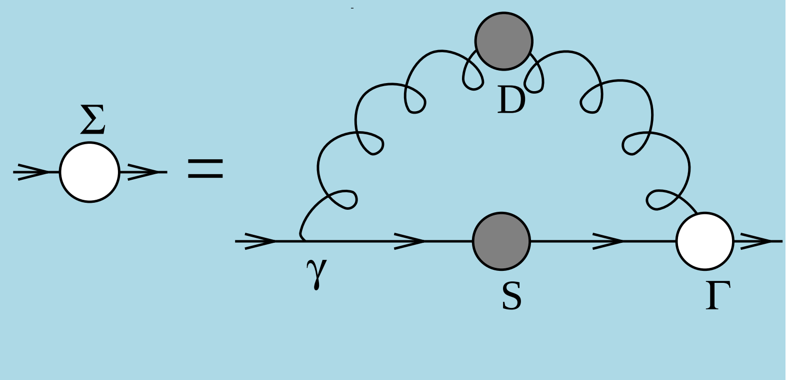

- These are nonperturbative equivalents in quantum field theory to the Lagrange equations of motion.
- Essential in simplifying the general proof of renormalisability of gauge field theories.

Dyson-Schwinger Equations

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- Well suited to Relativistic Quantum Field Theory

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Cross-Sections built from Schwinger Functions

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World . . .

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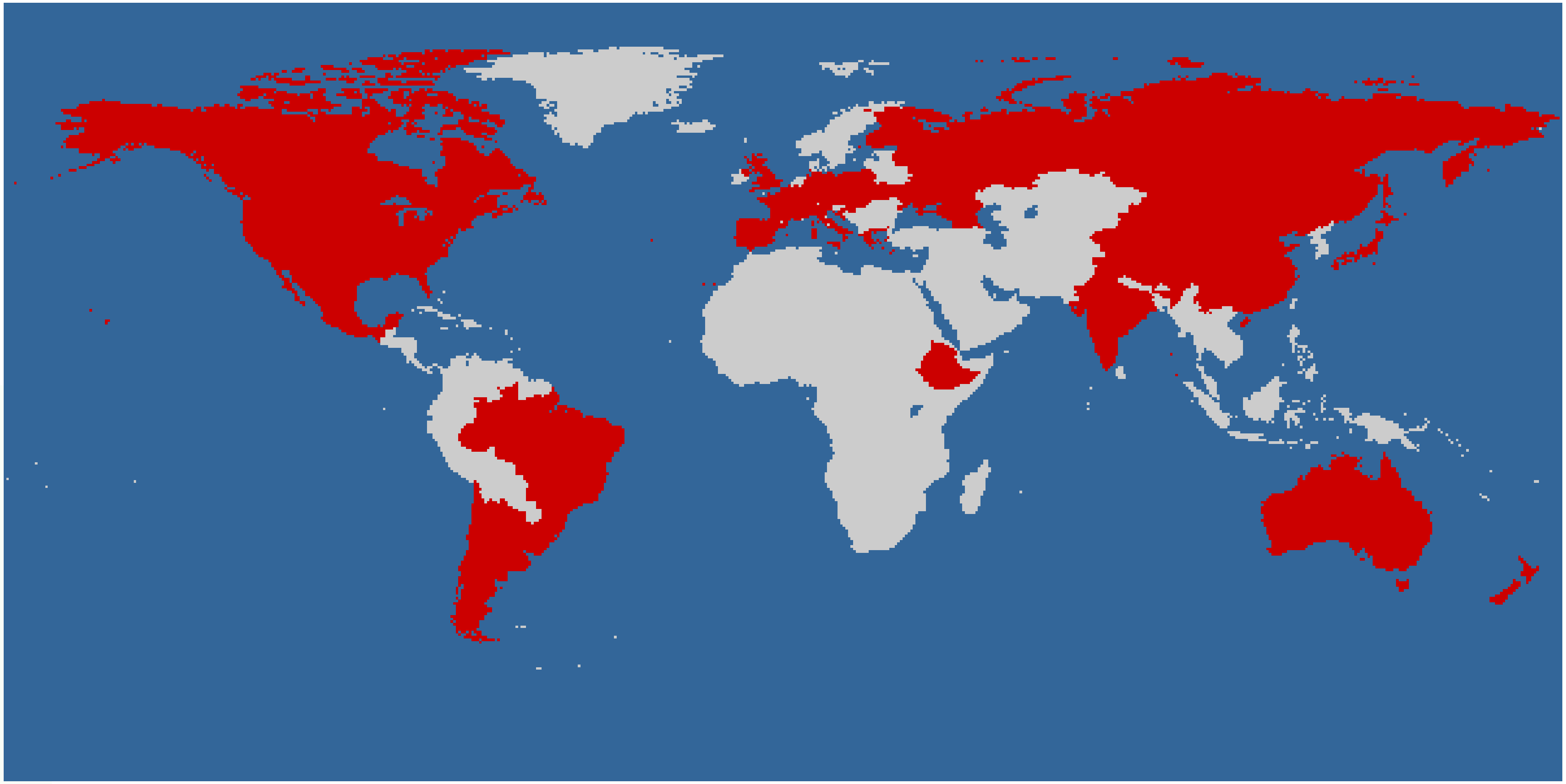
World . . .
DSE Perspective



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Persistent Challenge

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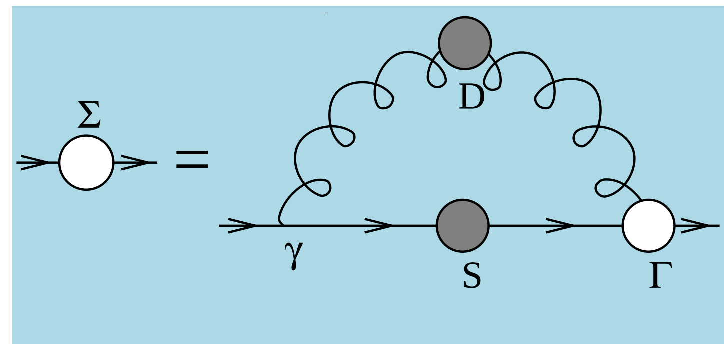
- Infinitely Many Coupled Equations



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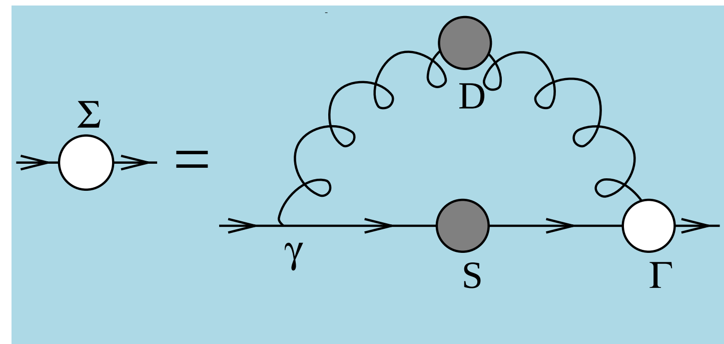

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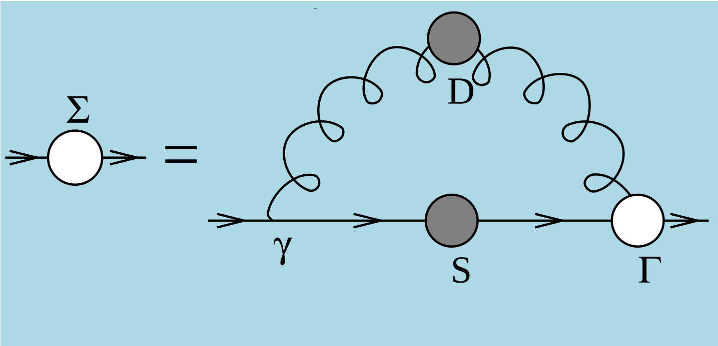

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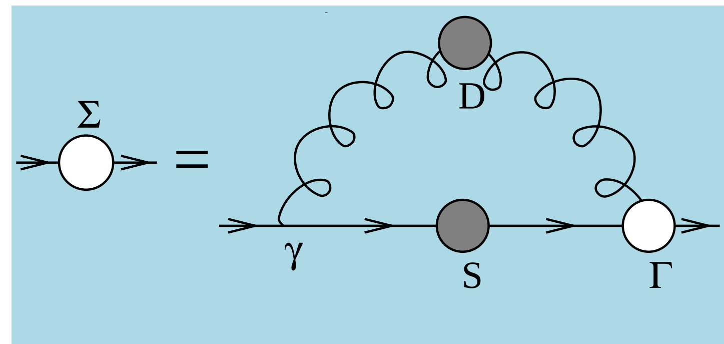

- Coupling between equations necessitates truncation
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    Not useful for the nonperturbative problems
    in which we're interested

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Persistent Challenge

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  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
  A. Bender, C. D. Roberts and L. von Smekal, Phys. Lett. B **380** (1996) 7
  Goldstone Theorem and Diquark Confinement Beyond Rainbow Ladder Approximation

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Perturbative Dressed-quark Propagator

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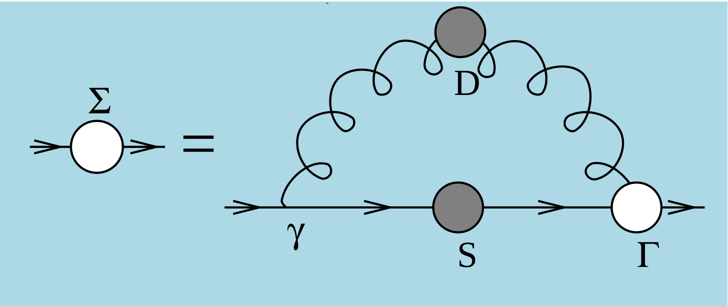
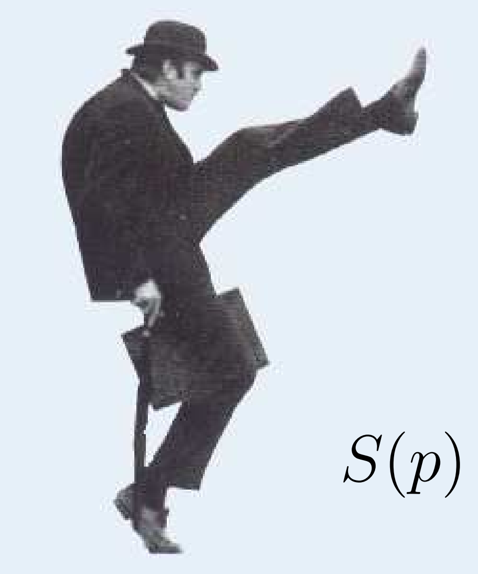
$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



Gap Equation



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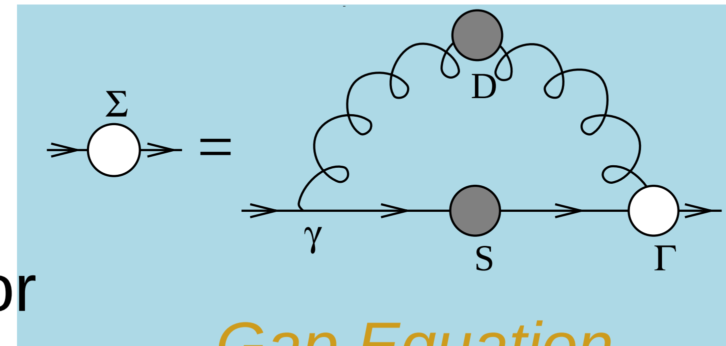

- dressed-quark propagator

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

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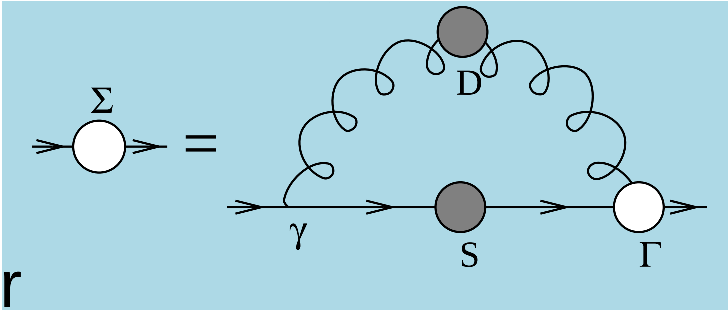

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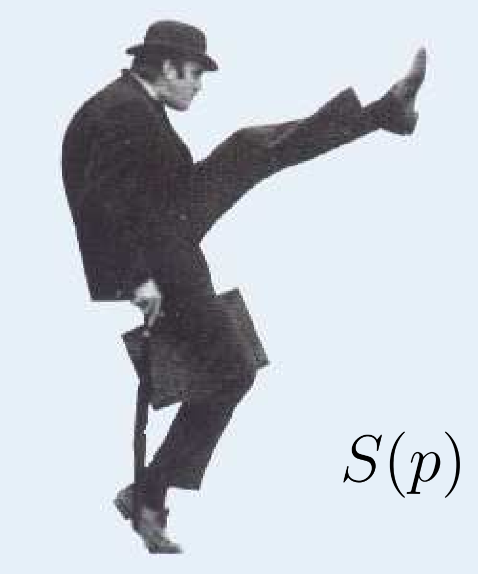

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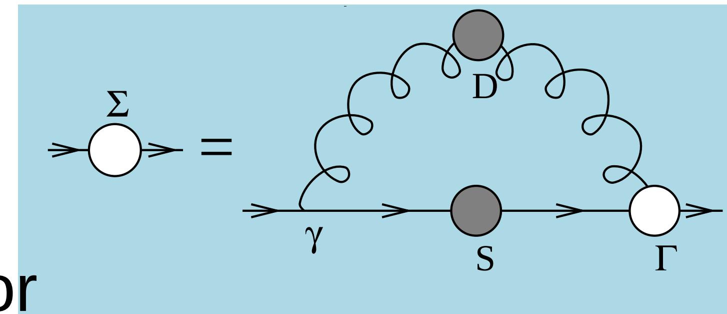

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- But in Perturbation Theory

$$B(p^2) = m\left(1 - \frac{\alpha}{\pi}\ln\left[\frac{p^2}{m^2}\right] + \ldots\right) \stackrel{m\to 0}{\to} 0$$

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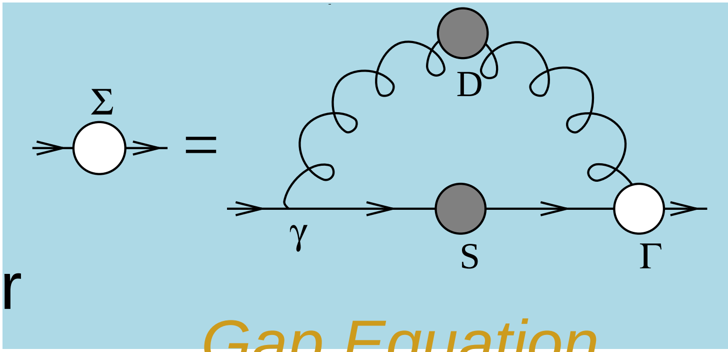
Perturbative Dressed-quark Propagator

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

- dressed-quark propagator



Gap Equation

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No DCSB Here!

- Weak Coupling Expansion
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- But in Perturbation Theory

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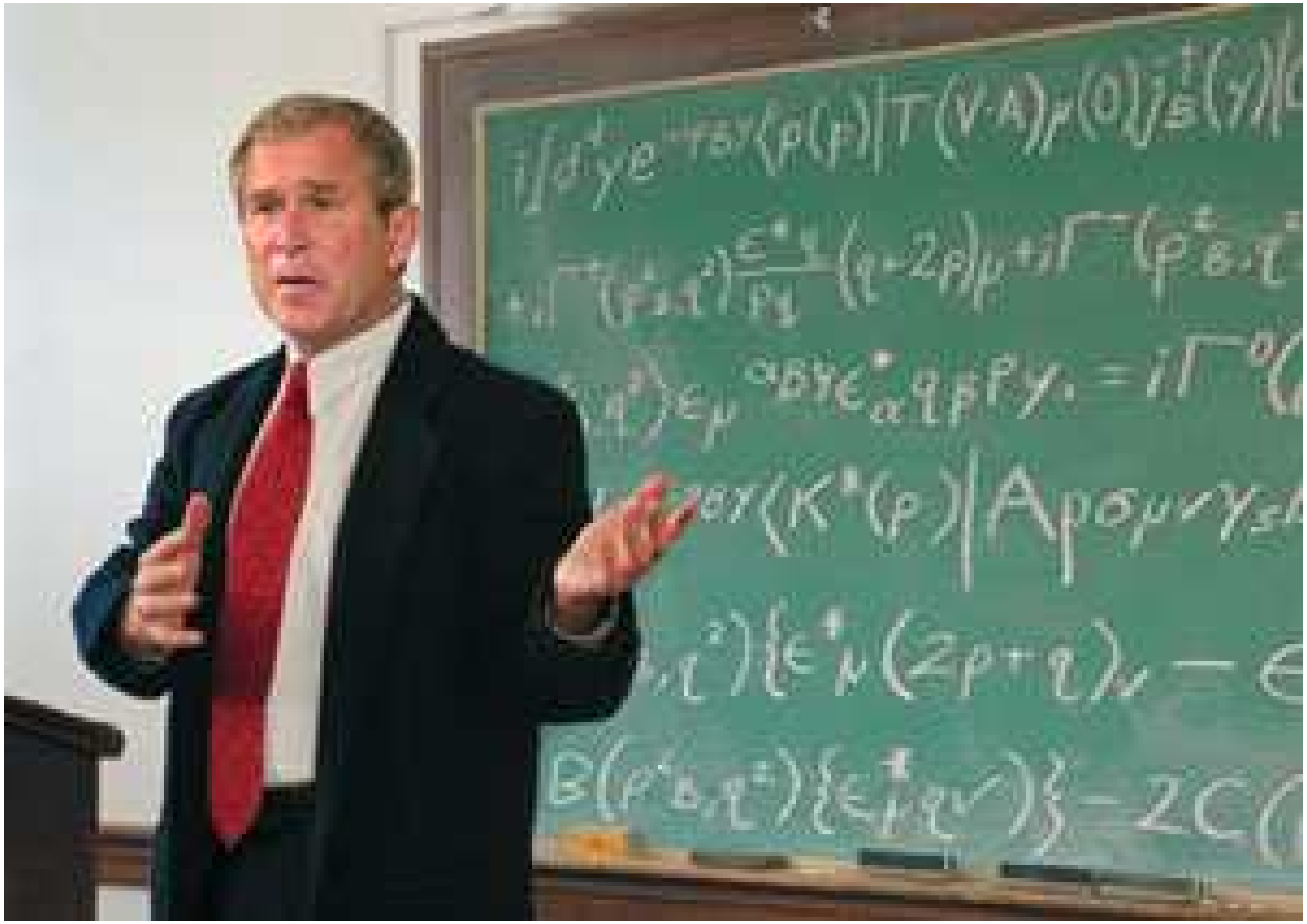
Explanation?



Dressed-Quark Propagator

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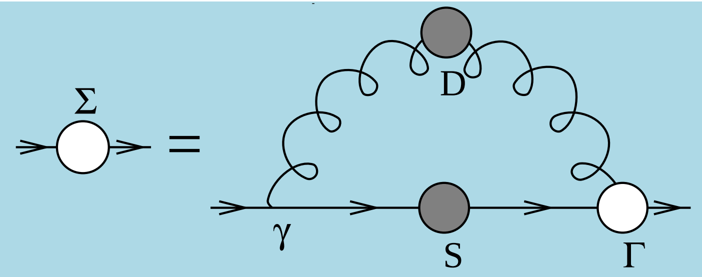

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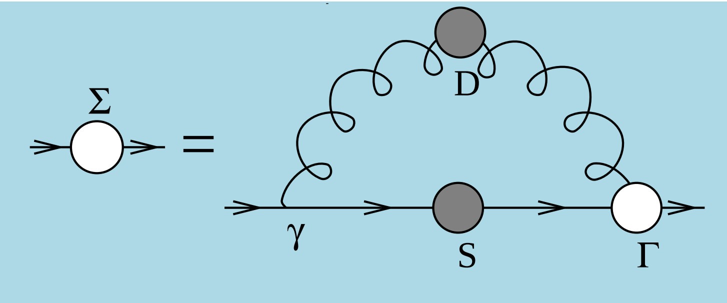
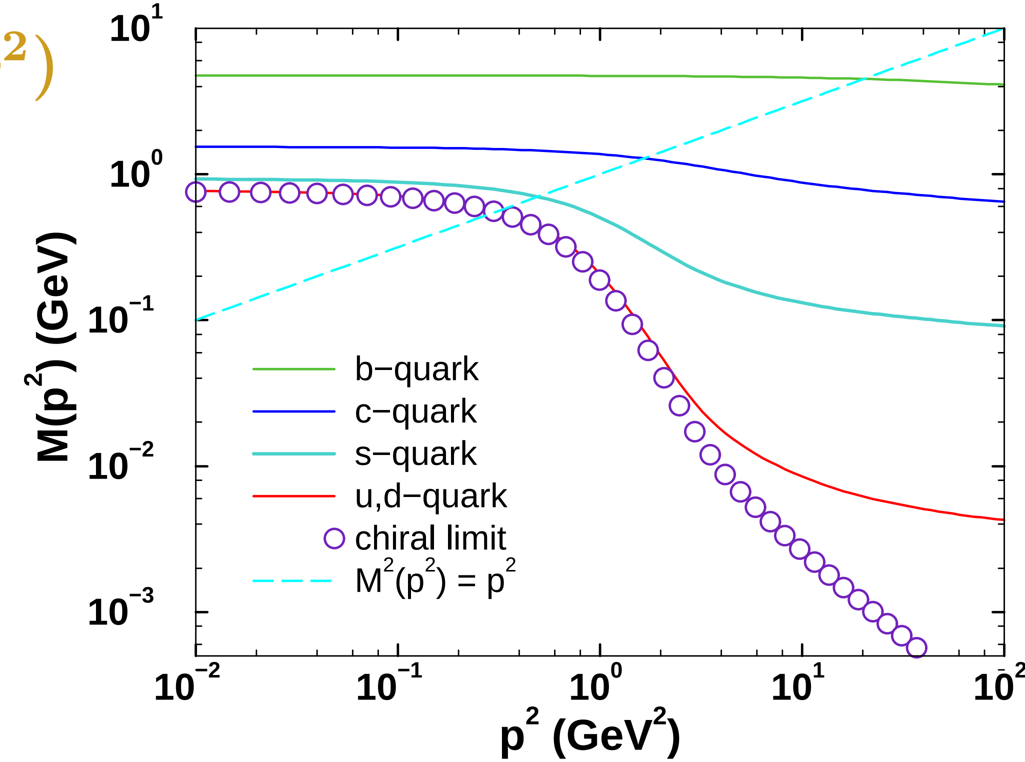


Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

$\Rightarrow$ IR Enhancement of $M(p^2)$



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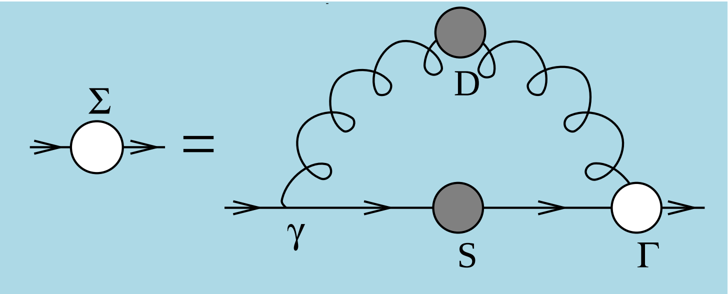


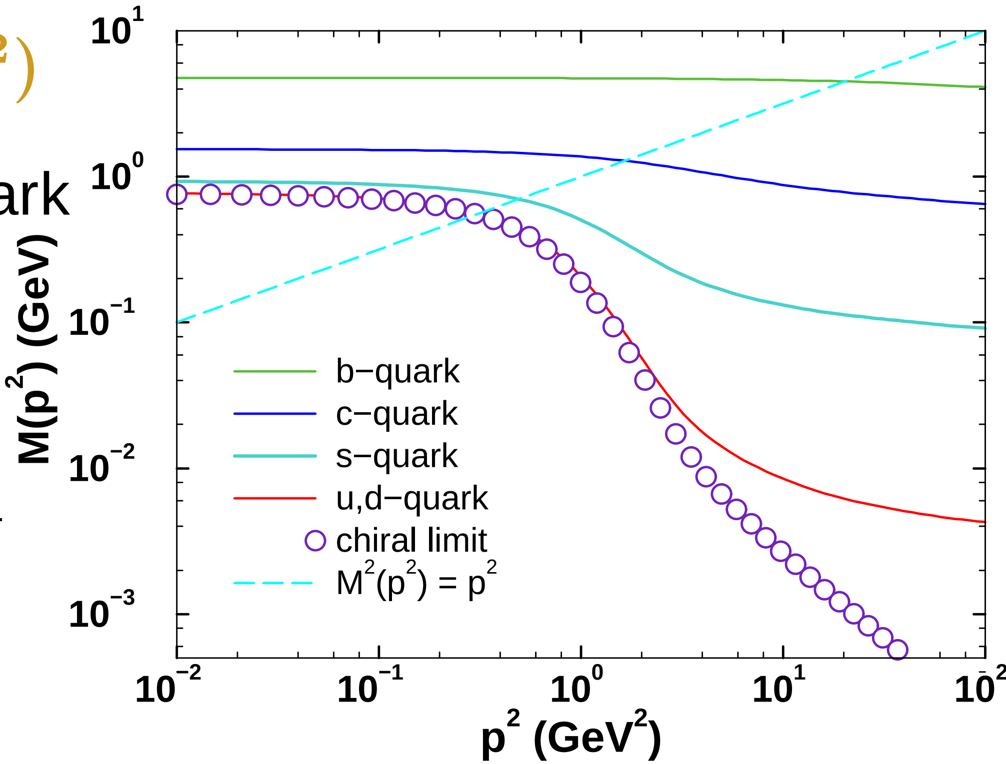
Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

$\Rightarrow$ IR Enhancement of $M(p^2)$

- Euclidean Constituent–Quark Mass: M_f^E: $p^2 = M(p^2)^2$

flavour	u/d	s	c	b
$\frac{M^E}{m_\zeta}$	$\sim 10^2$	~ 10	~ 1.5	~ 1.1



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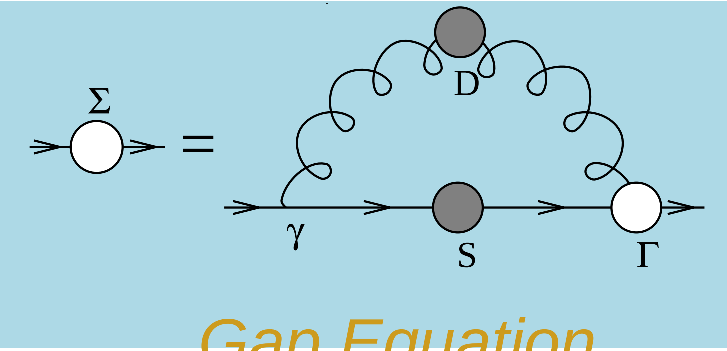

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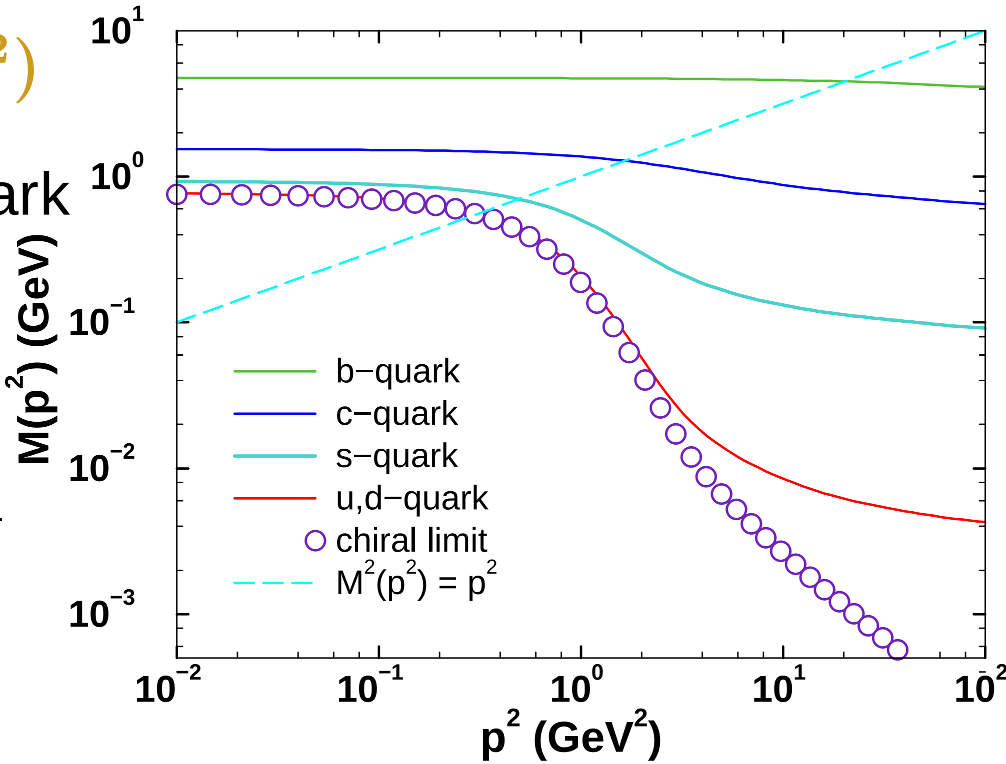

Predictions confirmed in numerical simulations of lattice-QCD

Dressed-Quark Propagator

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- Longstanding Prediction of Dyson-Schwinger Equation Studies

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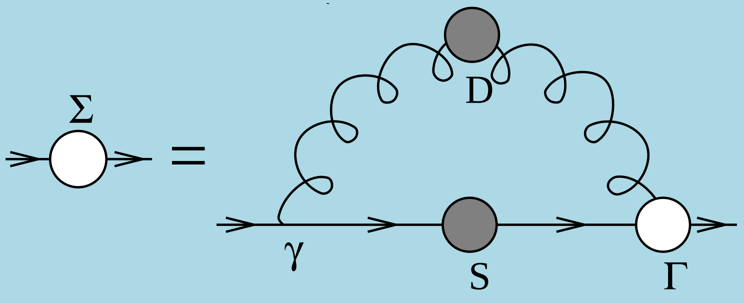
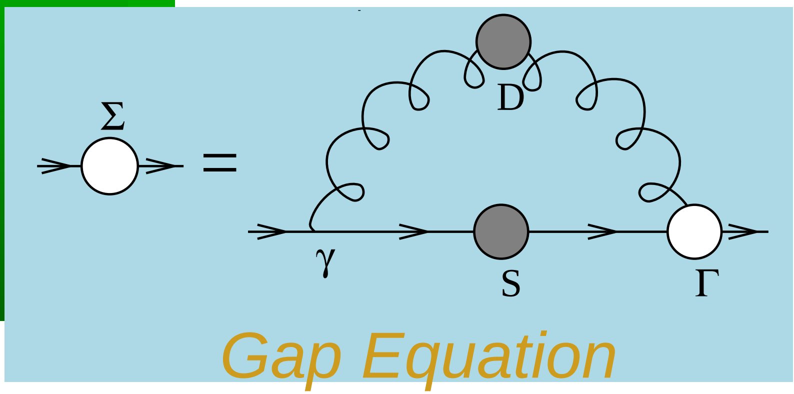
Office of Nuclear Physics
Argonne NATIONAL LABORATORY

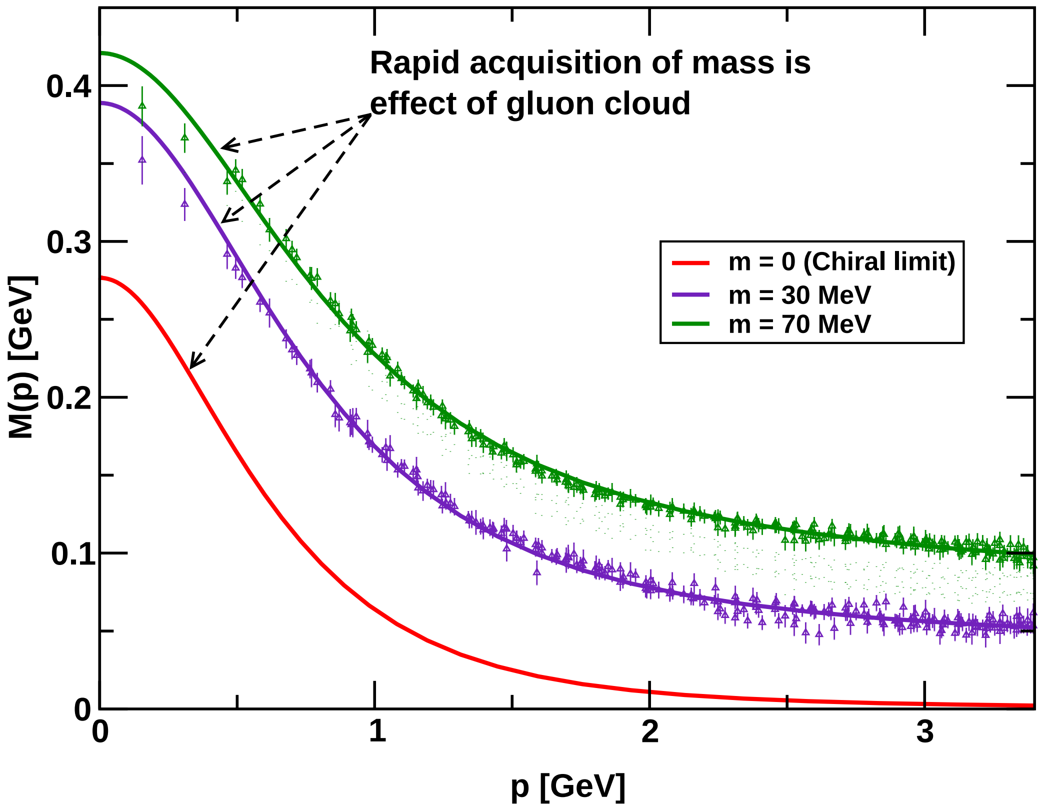
Frontiers of Nuclear Science: A Long Range Plan (2007)



Gap Equation

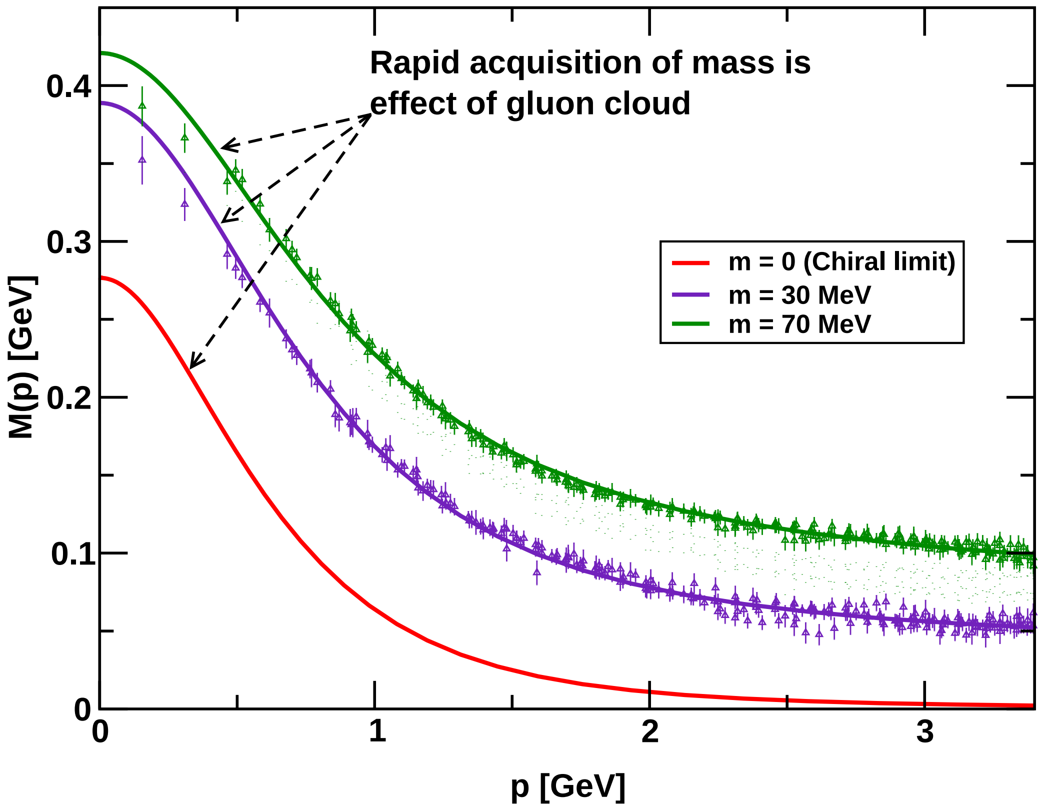
Frontiers of Nuclear Science: Theoretical Advances





Mass from nothing.

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.



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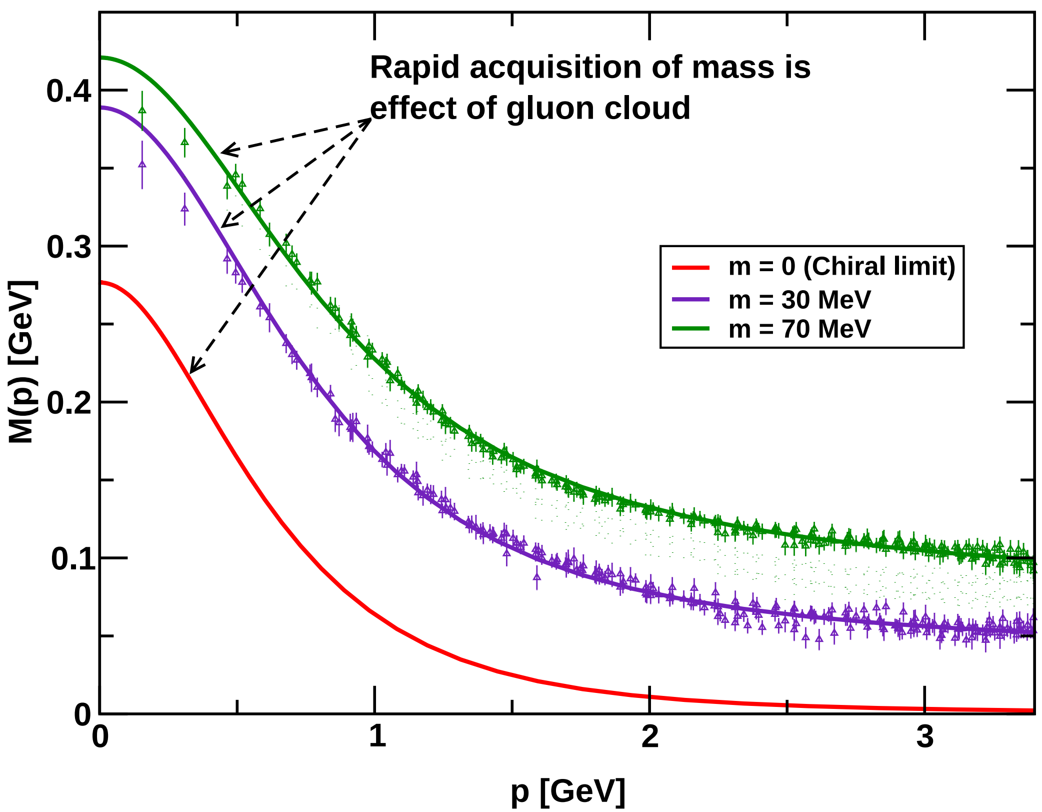

Consituent-quark σ-term

- Impact of Dynamical chiral symmetry breaking ... exhibited via constituent-quark σ-term

$$\sigma_f := m_f(\zeta)\,\frac{\partial M_f^E}{\partial m_f(\zeta)}\,,\;(M^E)^2 := s\,|\,s = M(s)^2\,.$$

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- Renormalisation-group-invariant and determined from solutions of the gap equation

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- Unambiguous probe of impact of explicit chiral symmetry breaking on the mass function

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- Ratio $\boxed{\dfrac{\sigma_f}{M_f^E} = \dfrac{\text{EXPLICIT}}{\text{EXPLICIT} + \text{DYNAMICAL}}}$

measures effect of *EXPLICIT* chiral symmetry breaking on dressed-quark mass-function

cf. *SUM* of effects of *EXPLICIT* AND *DYNAMICAL CHIRAL SYMMETRY BREAKING*

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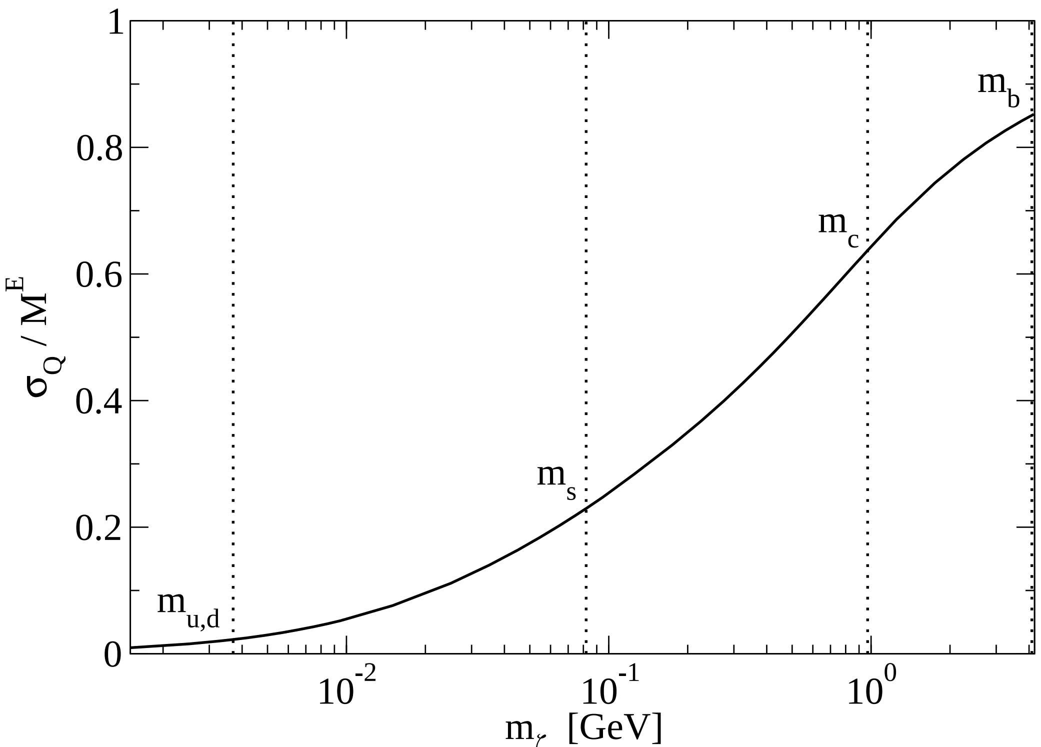

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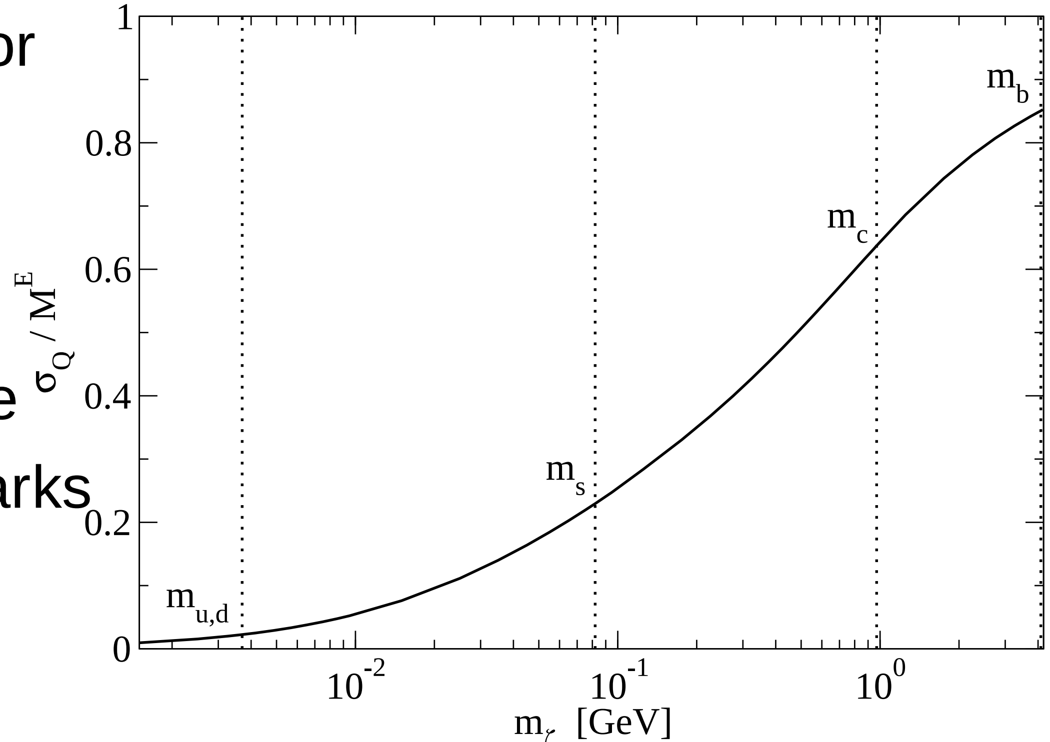
Obvious: ratio vanishes for light-quarks because magnitude of their constituent-mass owes primarily to DCSB. On the other hand, for heavy-quarks it approaches one.



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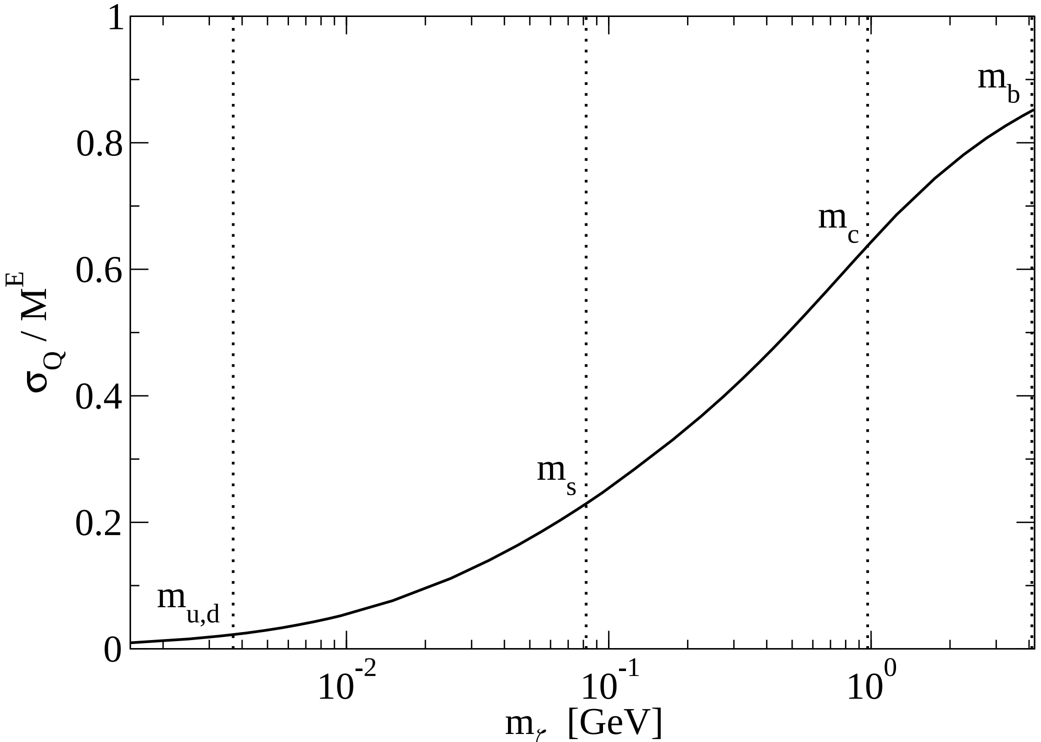
Essentially dynamical component of chiral symmetry breaking, and manifestation in all its order parameters, vanishes with increasing current-quark mass



Hadrons

- Established understanding of two- and three-point functions

Hadrons

- Established understanding of two- and three-point functions
- What about bound states?

Hadrons

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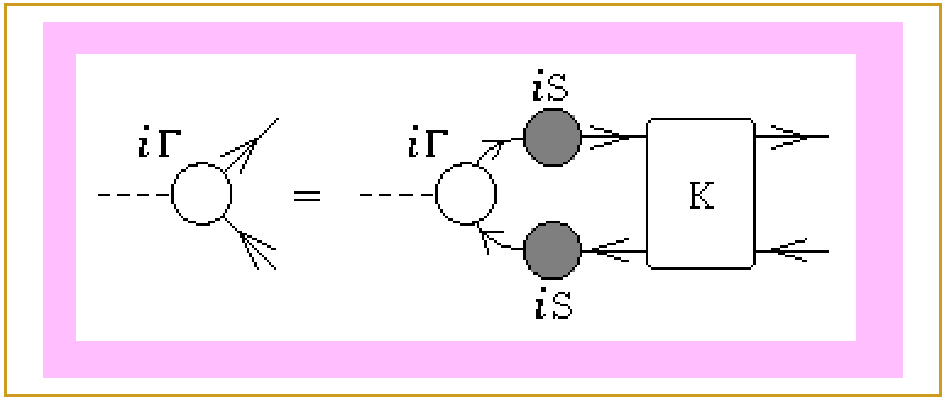
- They appear as pole contributions to $n \geq 3$-point colour-singlet Schwinger functions

- Without bound states, Comparison with experiment is impossible
- Bethe-Salpeter Equation



QFT Generalisation of Lippmann-Schwinger Equation.

- Without bound states, Comparison with experiment is impossible
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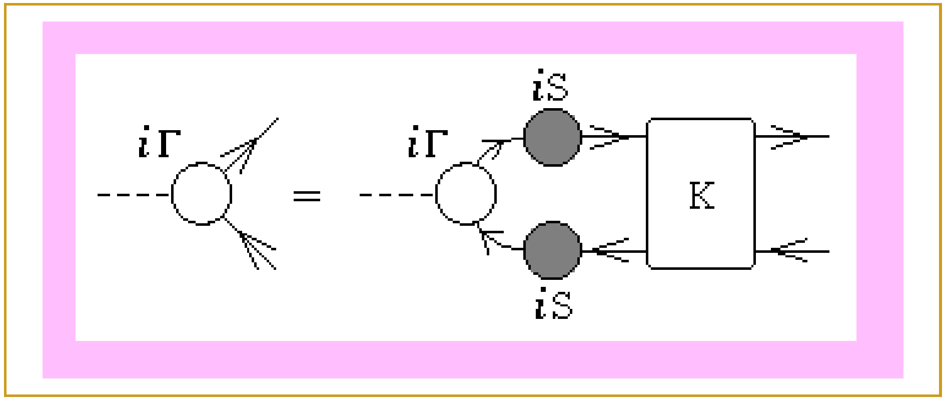

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

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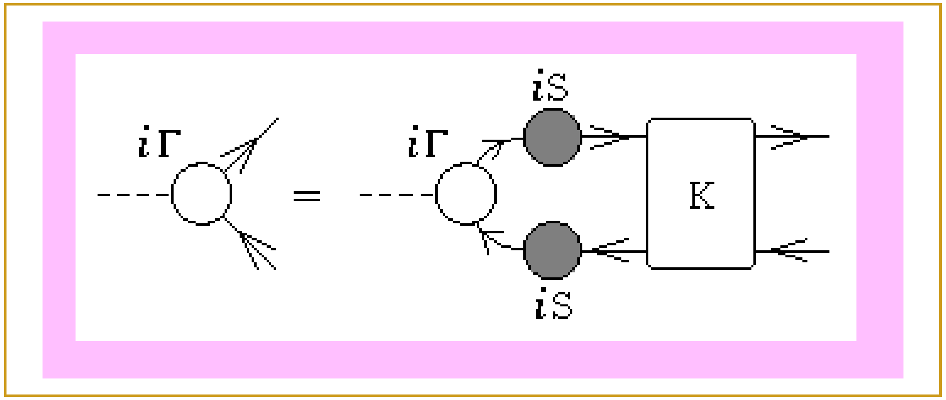

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

or

What is the light-quark Long-Range Potential?

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Exploring Nuclear Matter - Quarks to Stars
Argonne NATIONAL LABORATORY

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What is the light-quark Long-Range Potential?

Potential between static (infinitely heavy) quarks measured in simulations of lattice-QCD ***is not related*** in any simple way to the light-quark interaction.

Bethe-Salpeter Kernel

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- Axial-vector Ward-Takahashi identity

$$P_\mu \; \Gamma^l_{5\mu}(k;P) \;=\; \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5 \; \mathcal{S}^{-1}(k_-)$$

$$- M_\zeta \, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\, M_\zeta$$

QFT Statement of Chiral Symmetry

Bethe-Salpeter Kernel

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but must be intimately related

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- **Nontrivial** constraint

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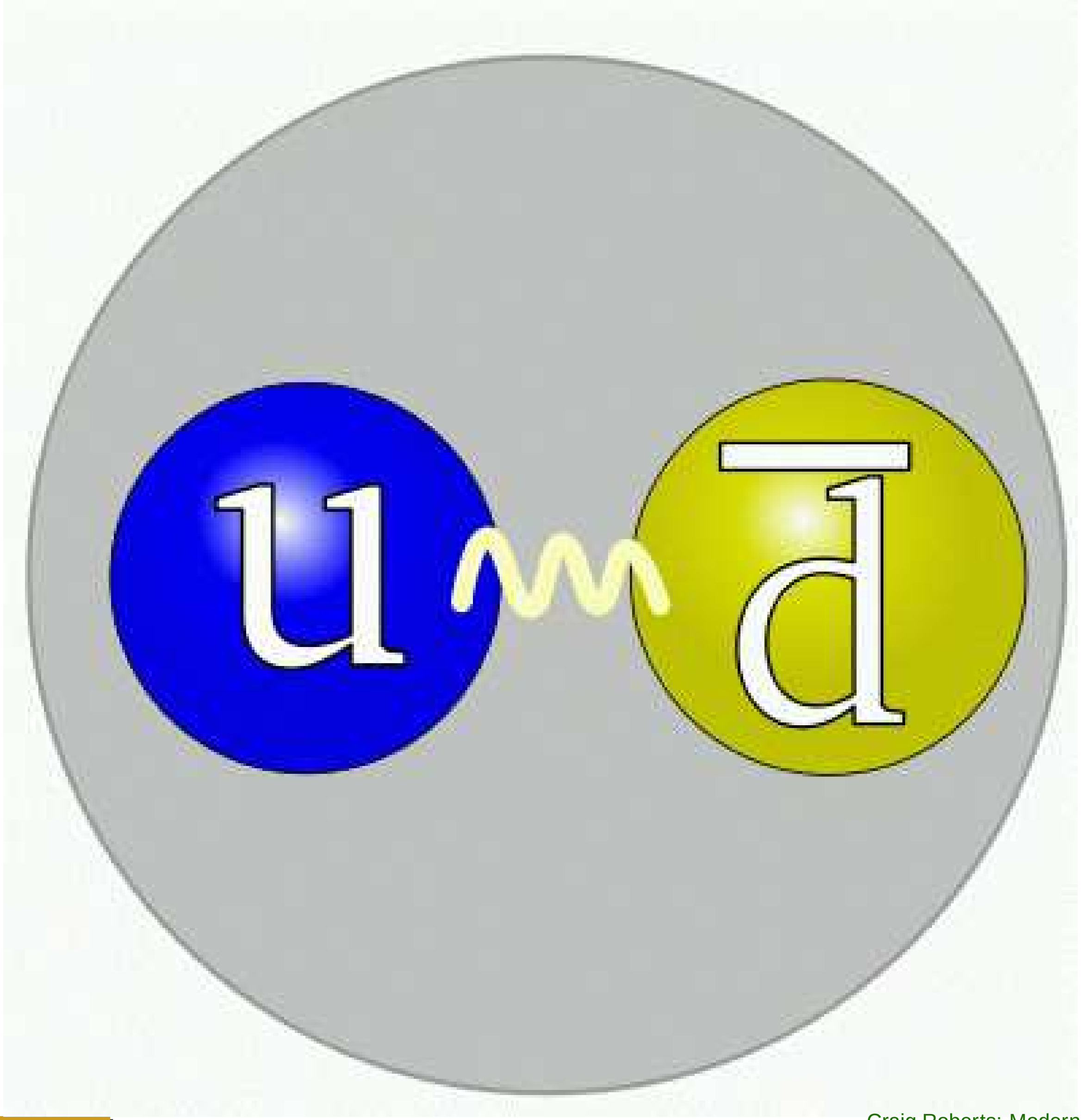
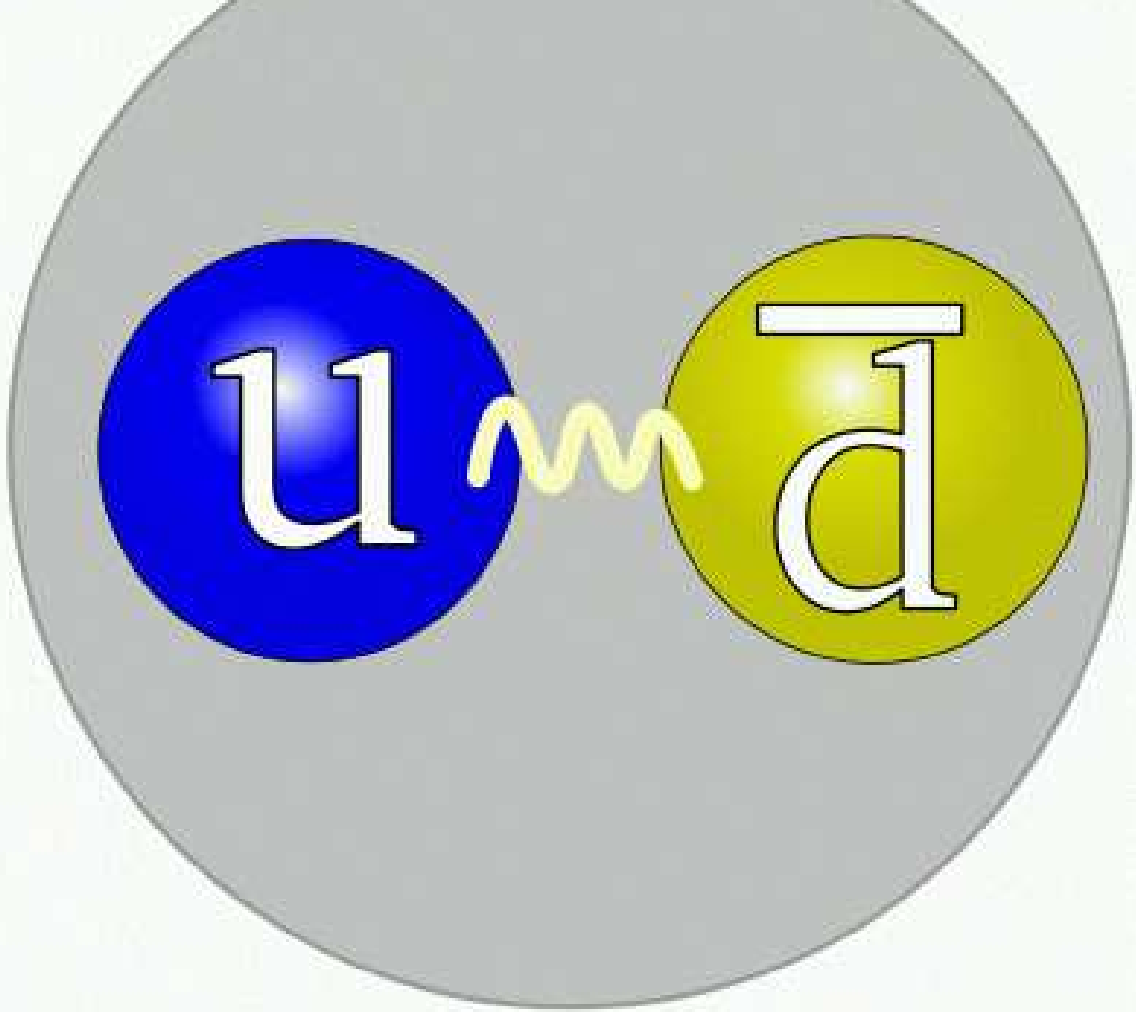
- Relation must be preserved by truncation
- Failure $\Rightarrow$ Explicit Violation of QCD's Chiral Symmetry

Pseudoscalar Mesons?



Pseudoscalar Mesons?

Can a bound-state of massive constituents truly be massless . . . without fine-tuning?



Radial Excitations & Chiral Symmetry

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(Maris, Roberts, Tandy nu-th/9707003)

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Radial Excitations & Chiral Symmetry

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- Mass^2 of pseudoscalar hadron

Radial Excitations & Chiral Symmetry

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$$\mathcal{M}_H := \mathrm{tr}_{\mathrm{flavour}}\left[M_{(\mu)}\left\{T^H, \left(T^H\right)^{\mathrm{t}}\right\}\right] = m_{q_1} + m_{q_2}$$

- Sum of constituents' current-quark masses
- e.g., $T^{K^+} = \frac{1}{2}\left(\lambda^4 + i\lambda^5\right)$

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Radial Excitations & Chiral Symmetry

(Maris, Roberts, Tandy nu-th/9707003)

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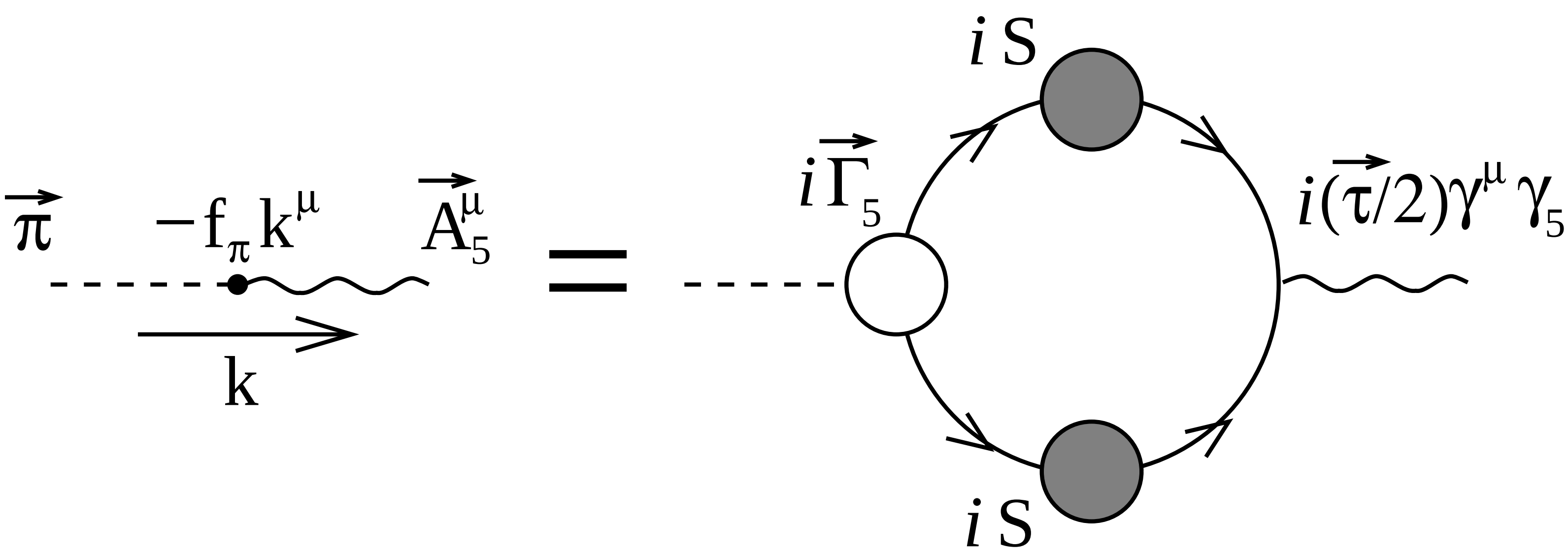
- Pseudovector projection of BS wave function at $x = 0$
- Pseudoscalar meson's leptonic decay constant



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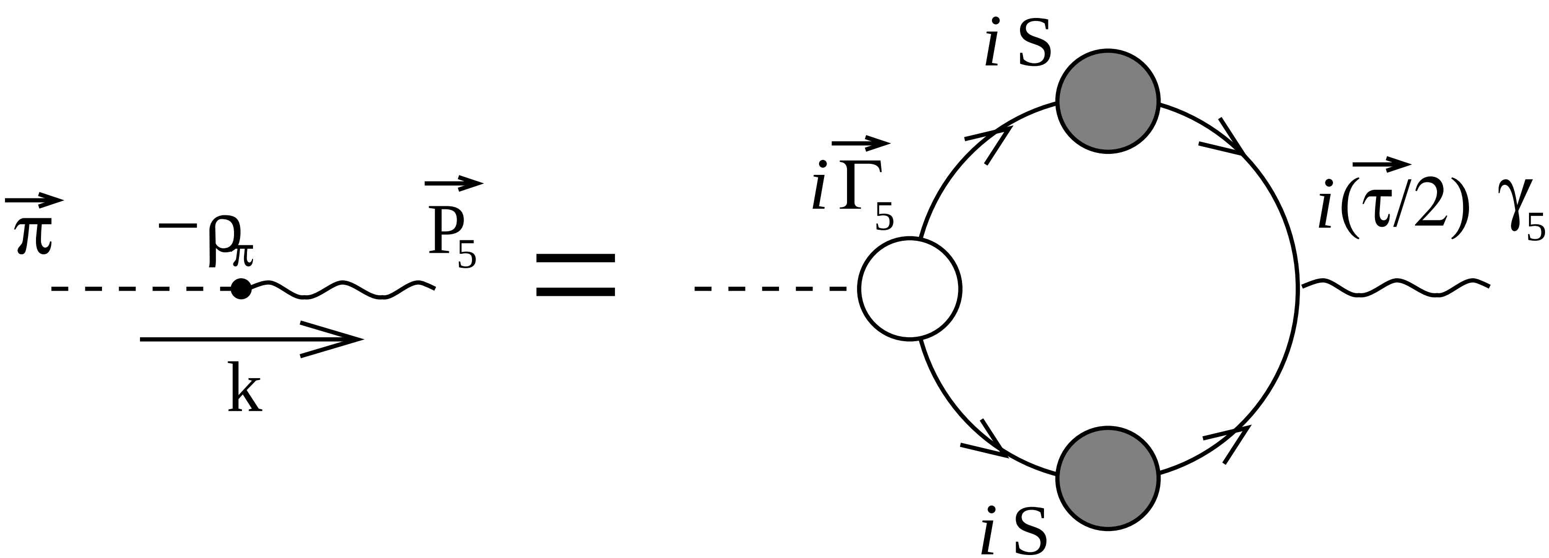

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- Light-quarks; i.e., $m_q \sim 0$
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- Heavy-quark + light-quark

$\Rightarrow f_H \propto \dfrac{1}{\sqrt{m_H}}$ and $\rho_\zeta^H \propto \sqrt{m_H}$

Hence, $\boxed{m_H \propto m_q}$

. . . QCD Proof of Potential Model result

Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
nu-th/0406030

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  ALL pseudoscalar mesons except $\boldsymbol{\pi(140)}$ in chiral limit
- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

  impacts upon *every* pseudoscalar meson

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McNeile and Michael
he-la/0607032

Radial Excitations & Lattice-QCD

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  $\Rightarrow f_{\pi_1} < 8.4$ MeV
  Diehl & Hiller
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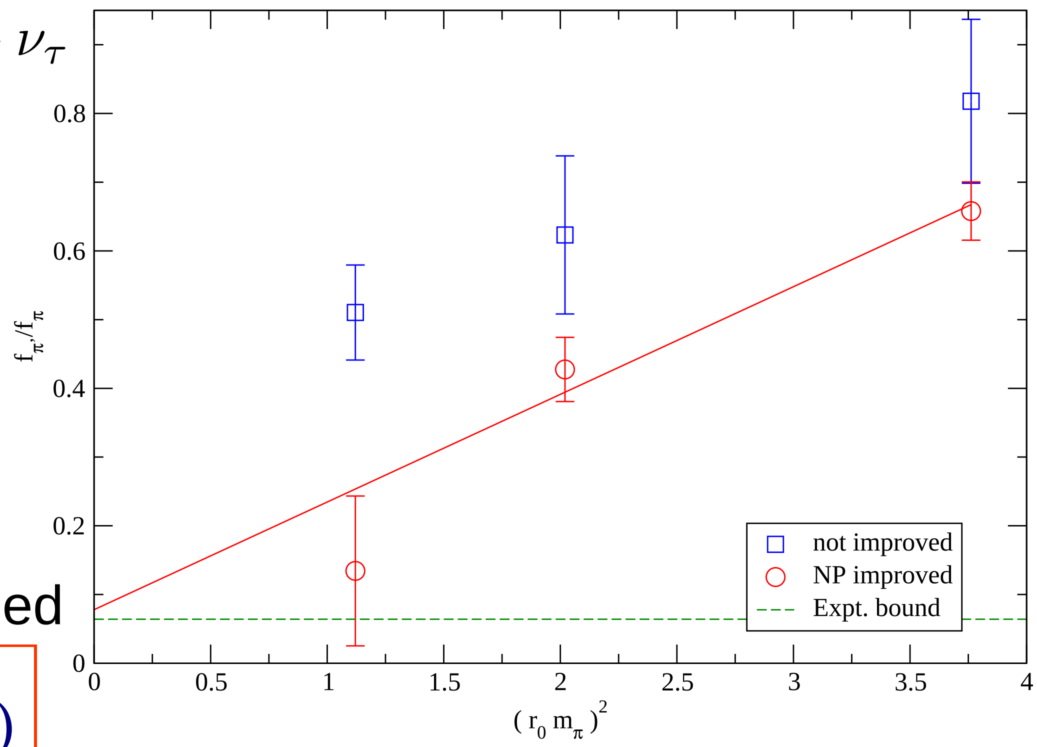
$$\Rightarrow \frac{f_{\pi_1}}{f_\pi} = \mathbf{0.078\,(93)}$$



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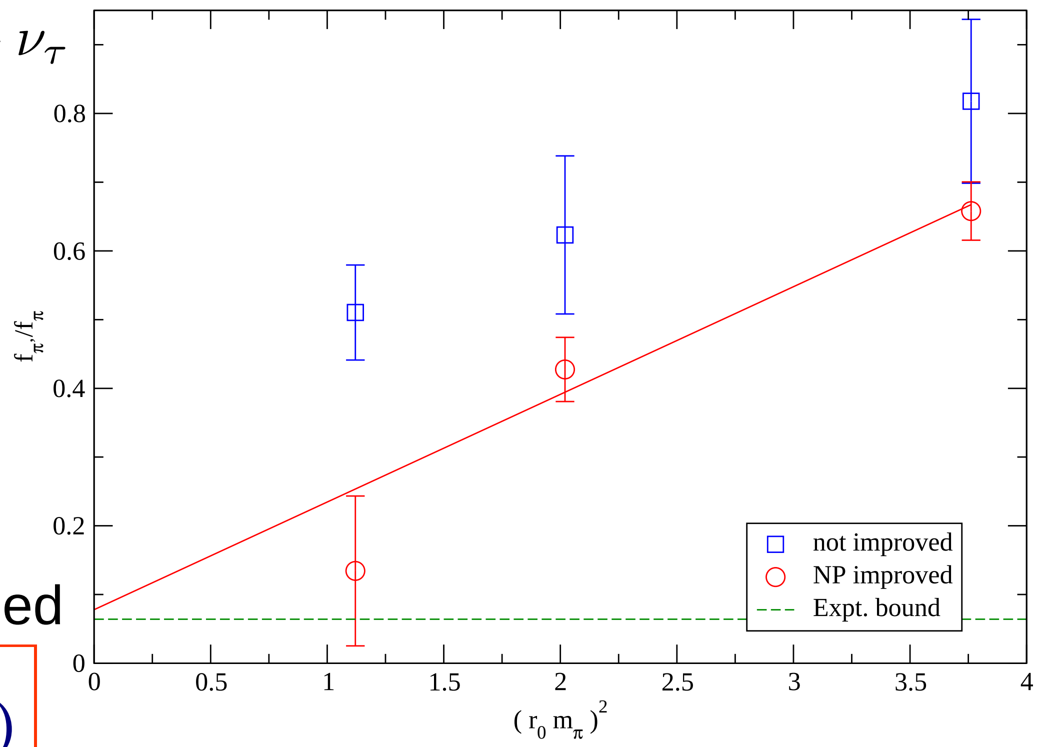

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

Radial Excitations & Lattice-QCD

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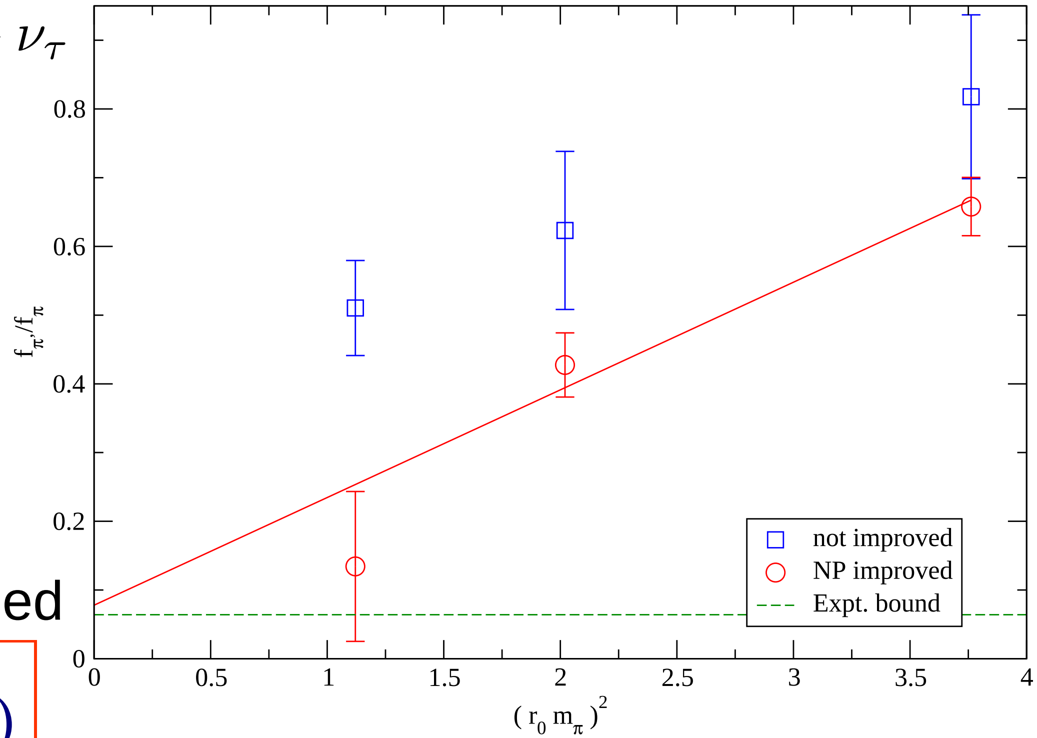
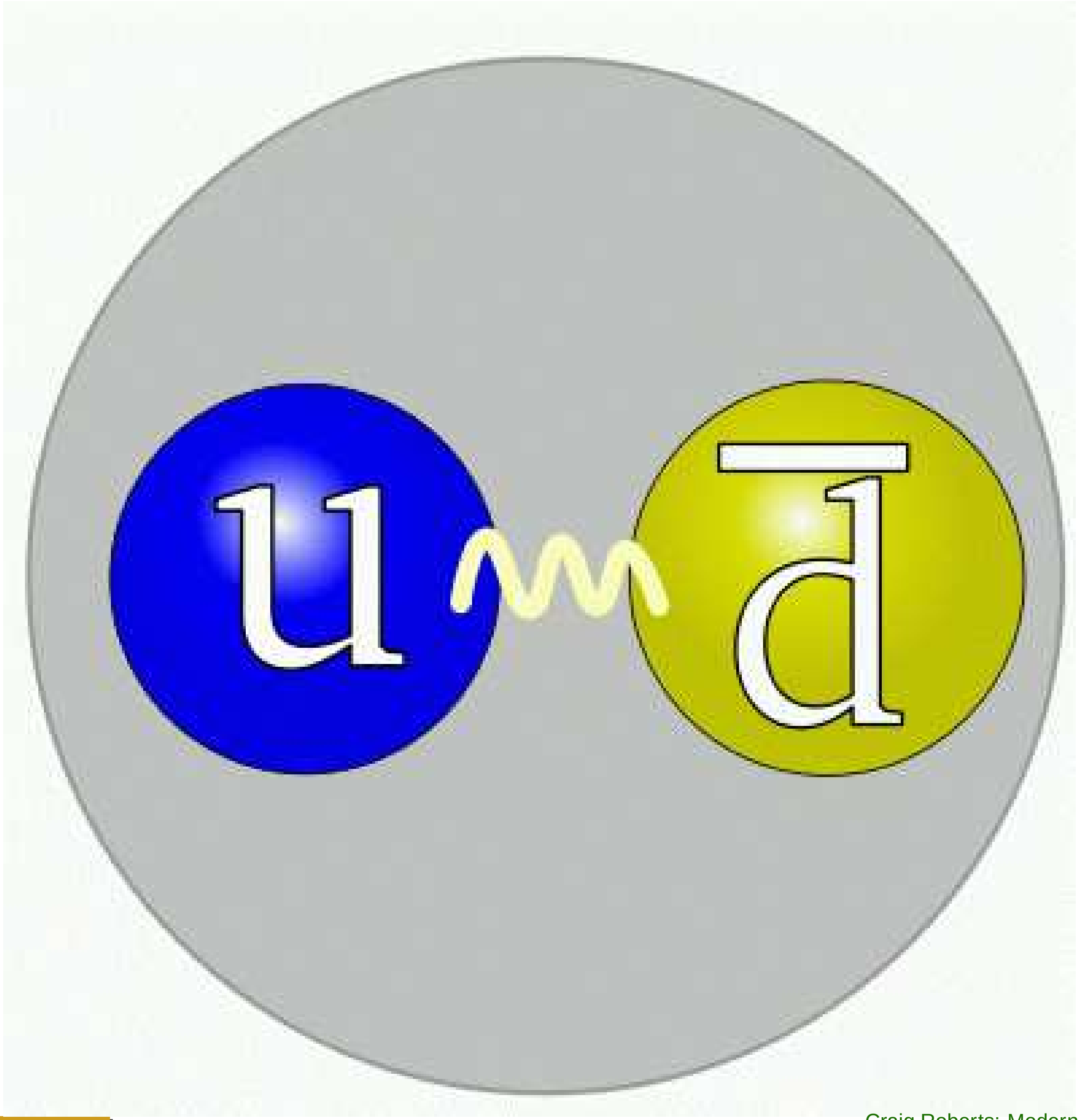


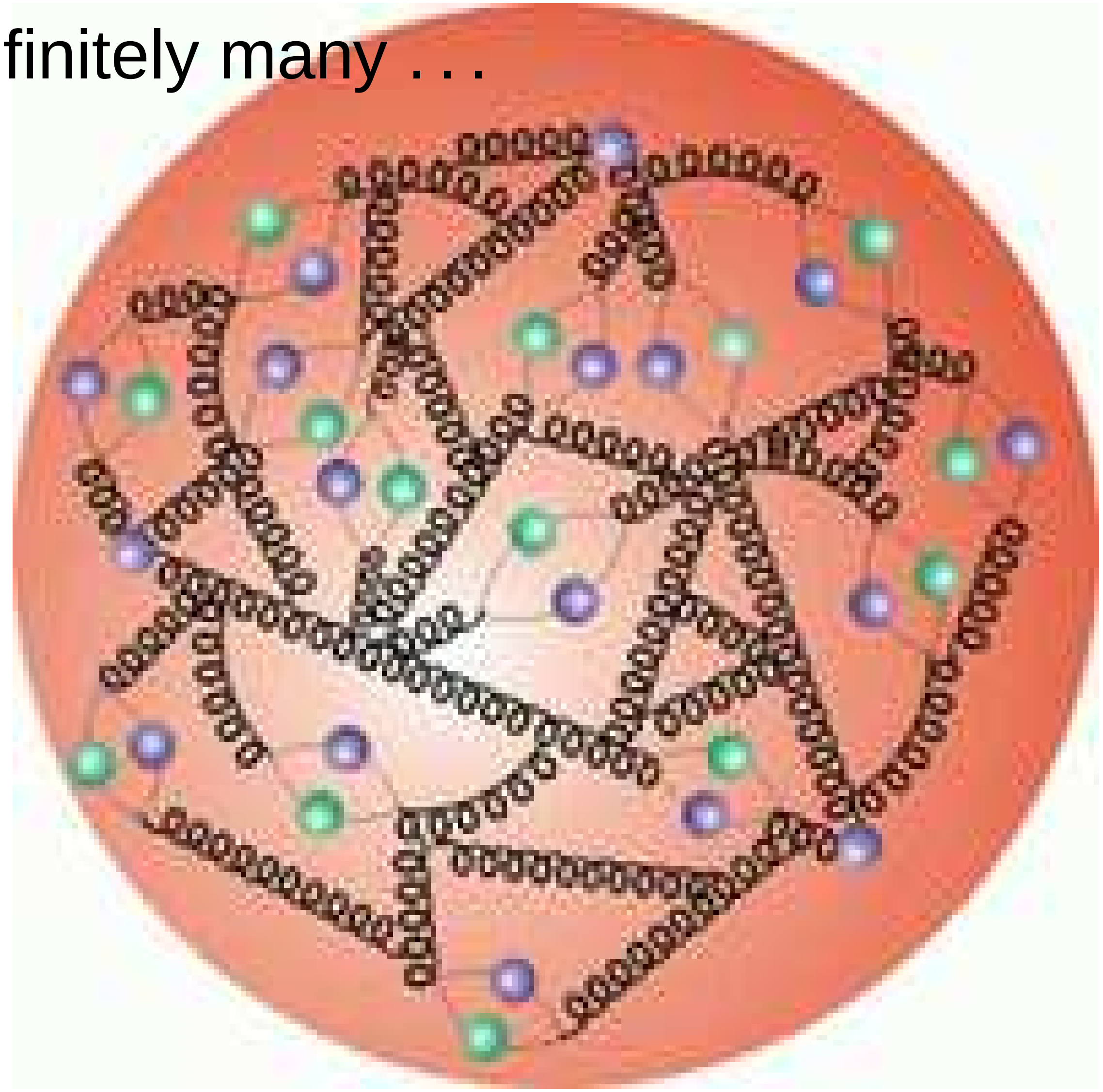
- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

Answer for the pion



Answer for the pion

Two → Infinitely many . . .



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Handle that
properly in
quantum
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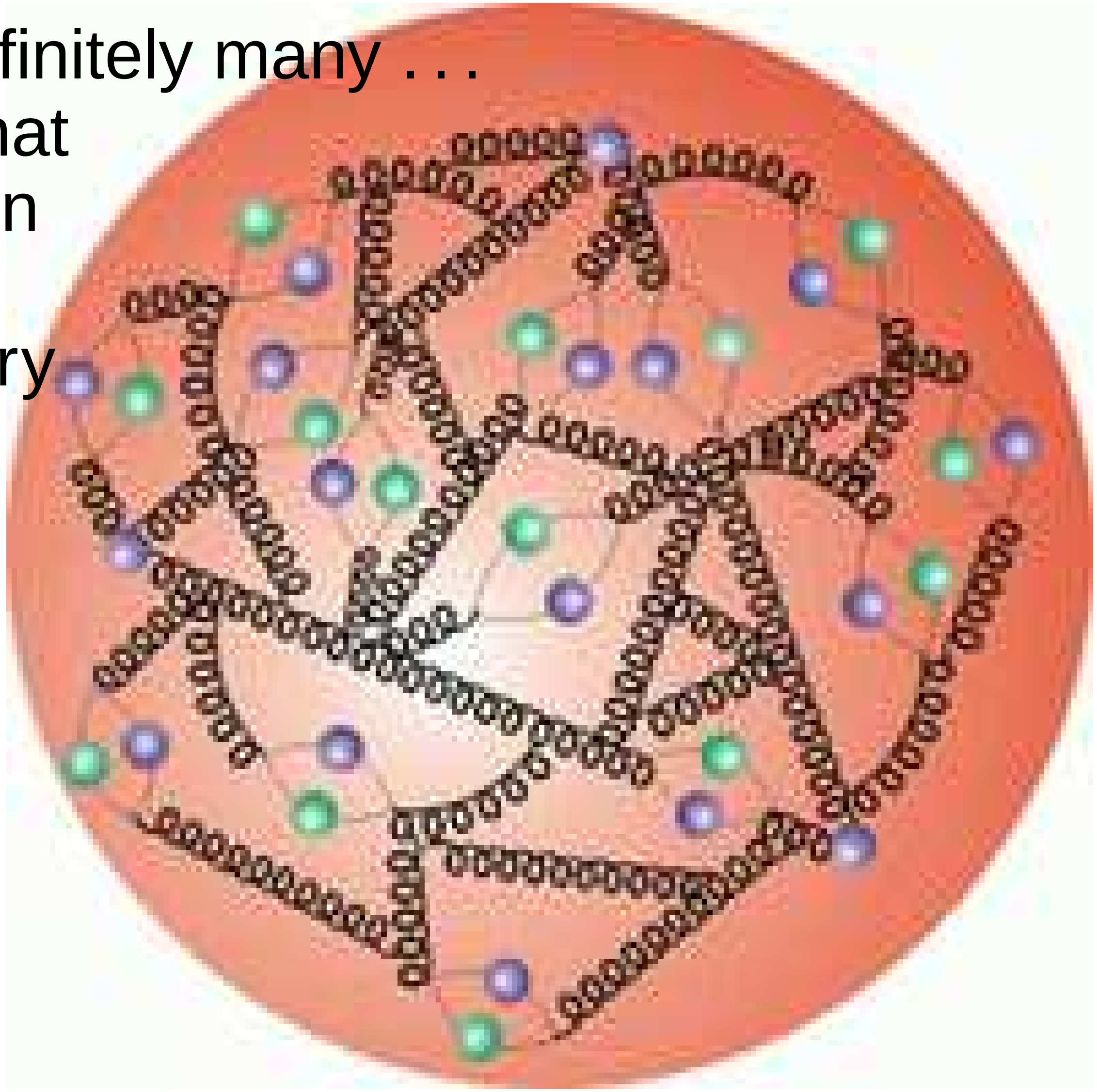

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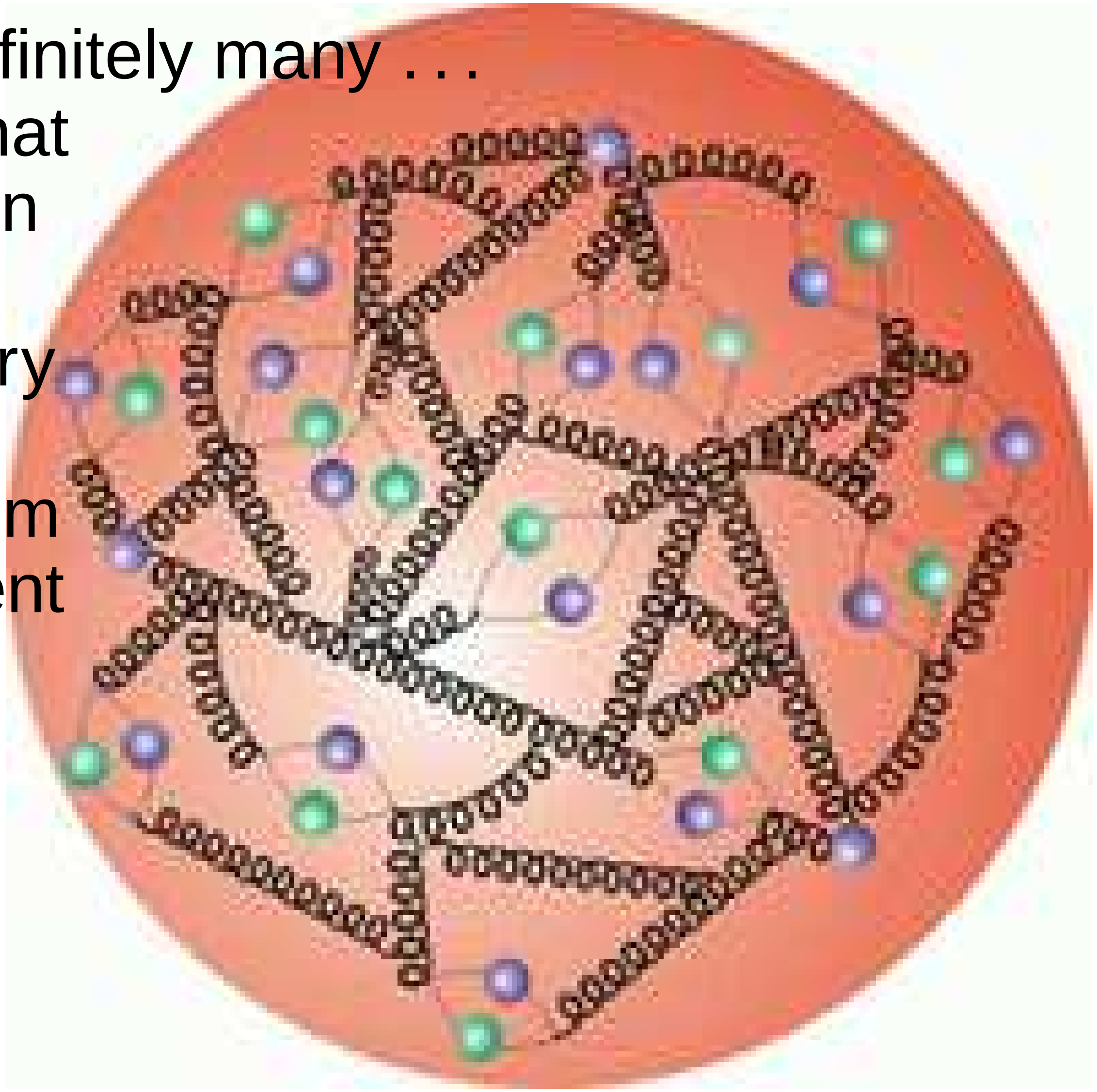
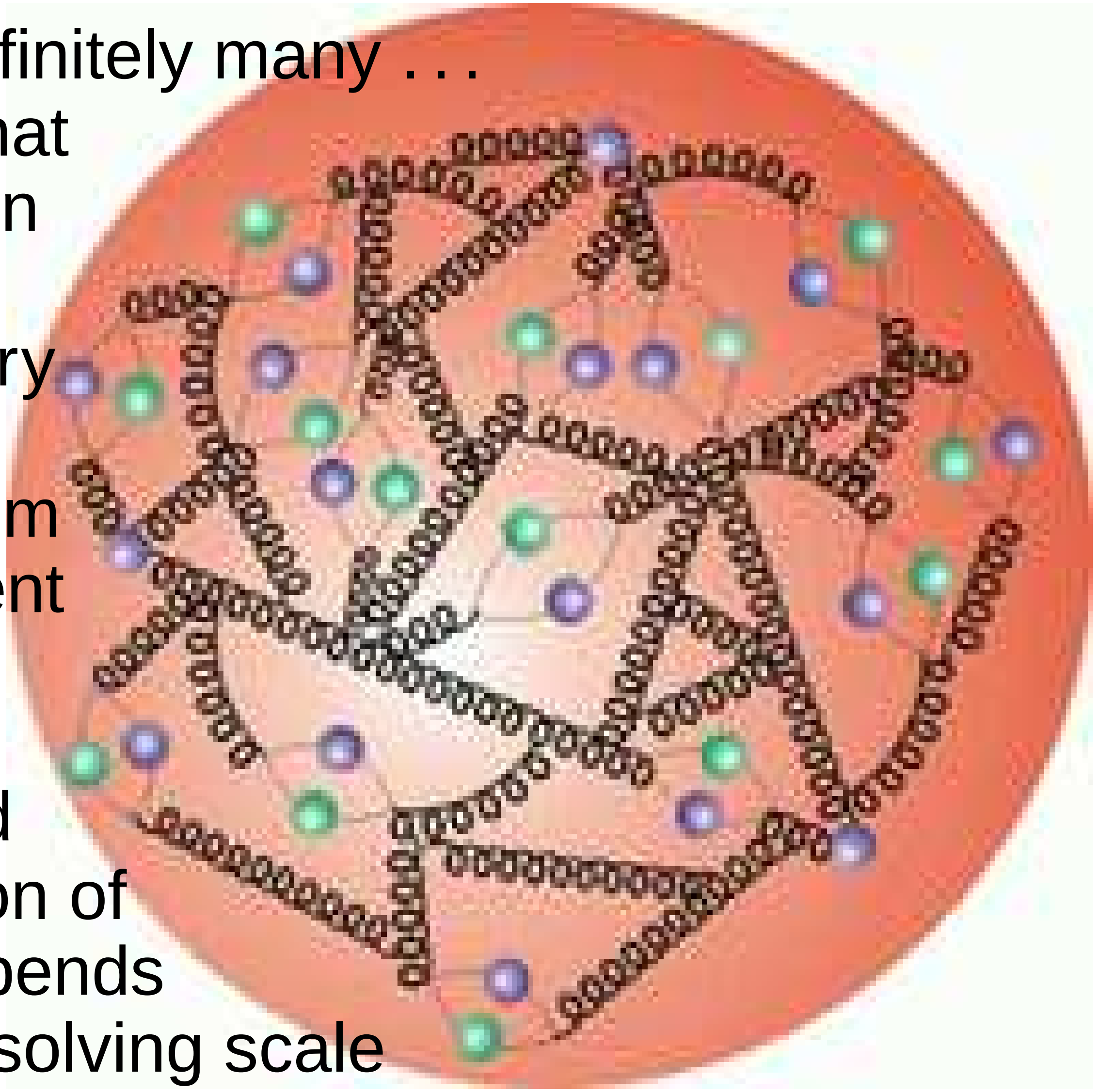
momentum-dependent dressing



Answer for the pion



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. . .
momentum-dependent dressing

. . .
perceived distribution of mass depends on the resolving scale

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    – quarks and gluons never alone reach a detector
  - Dynamical Chiral Symmetry Breaking
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- Next lecture:
  - Elastic electromagnetic pion form factor
  - Deep Inelastic Scattering – discovery of quarks
  - Nature of Baryons
  - Hadron Physics just after the Big Bang
    – nonzero temperature and chemical potential