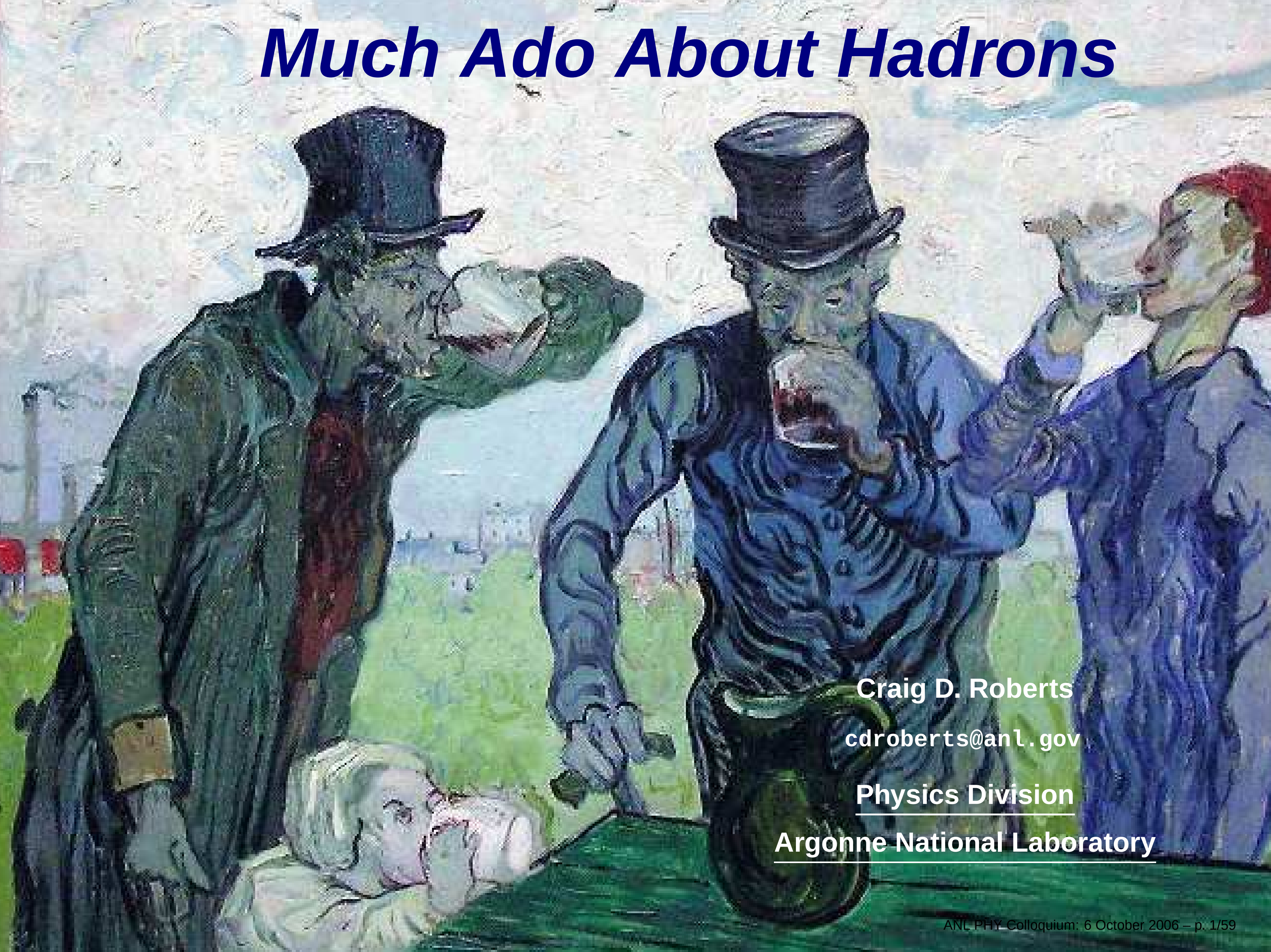
Much Ado About Hadrons



Craig D. Roberts

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Physics Division

Argonne National Laboratory

It that hath a cloud is more than a parton,

And it that hath no cloud is less than an hadron.

Anon.

First Contents Back Conclusion

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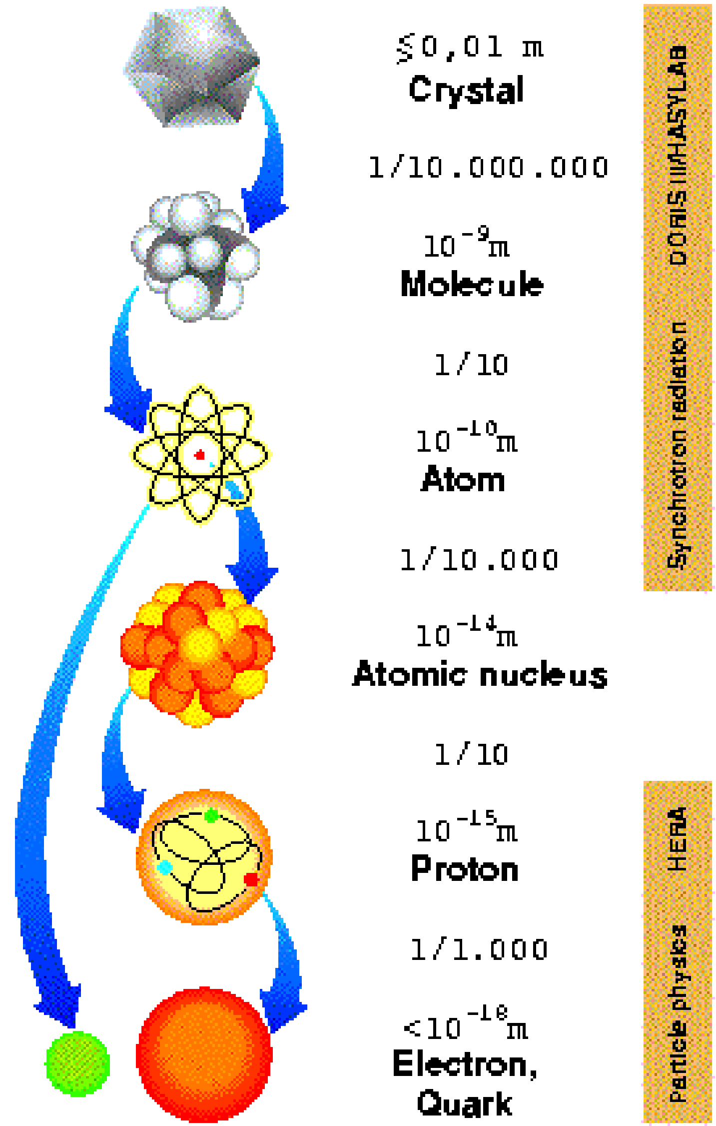
First Contents Back Conclusion

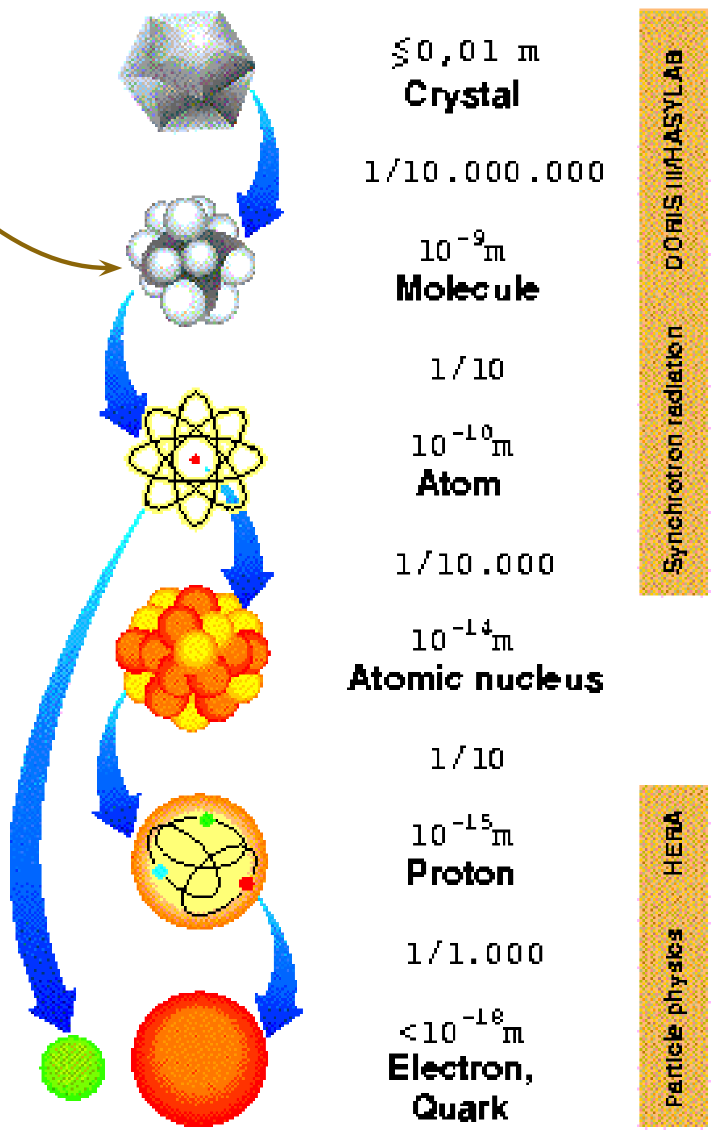
Hadron Physics



First Contents Back Conclusion

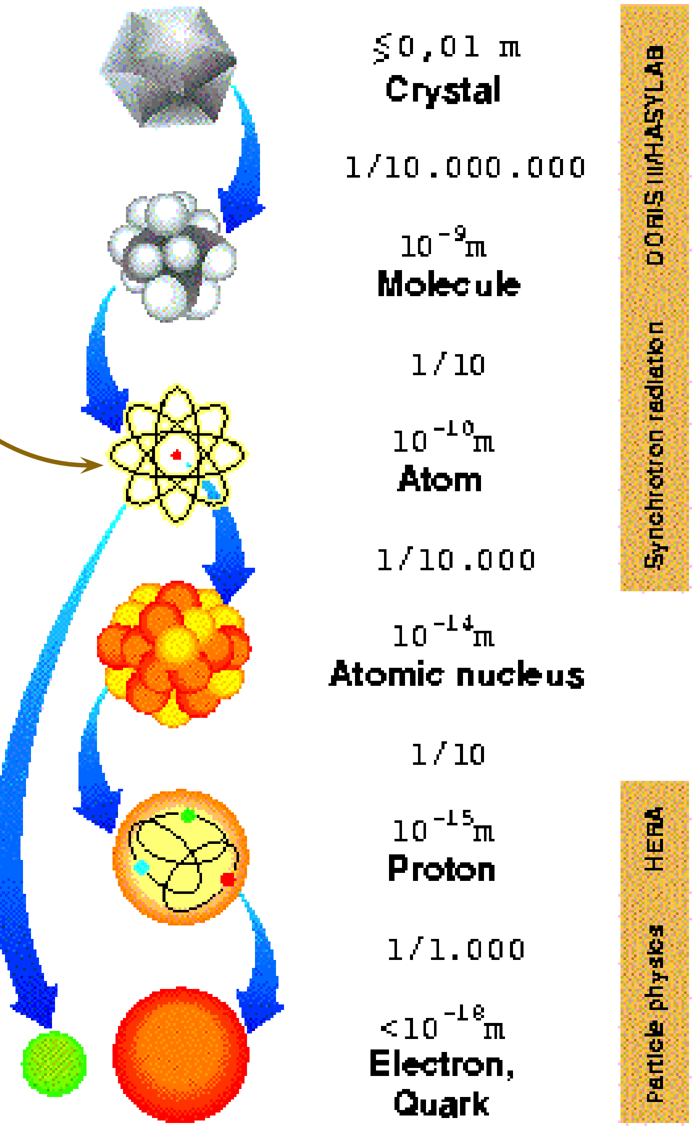
Hadron Physics

Molecular Physics
Scale = nm



Hadron Physics

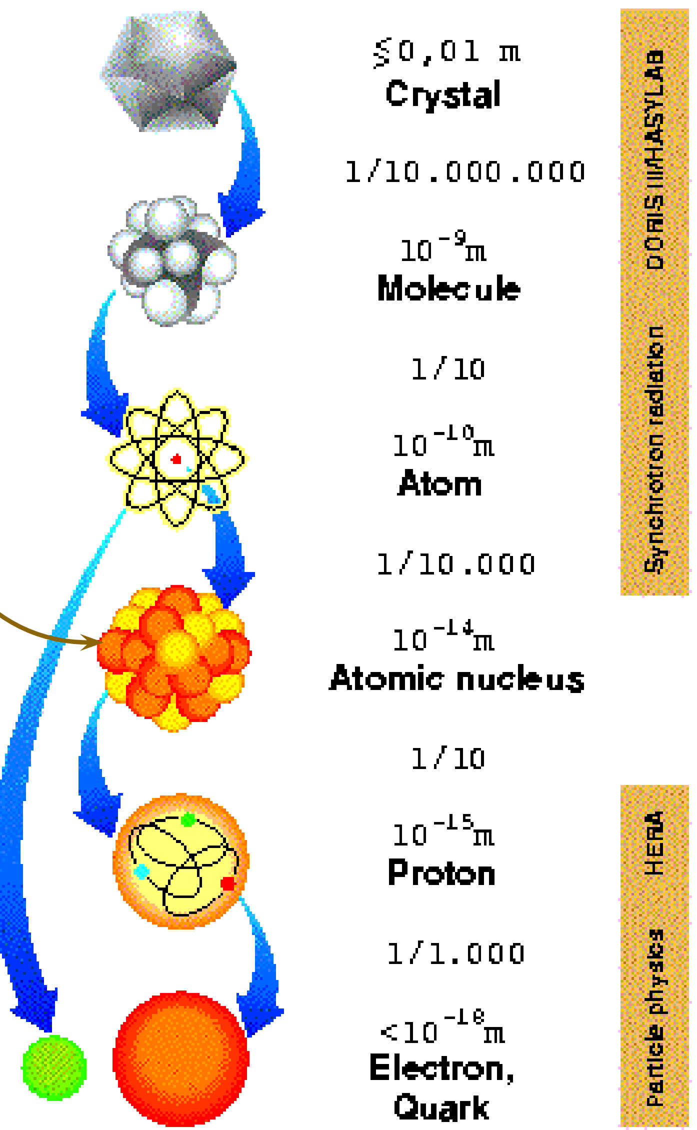
Atomic Physics
Scale = Å



First Contents Back Conclusion

Hadron Physics

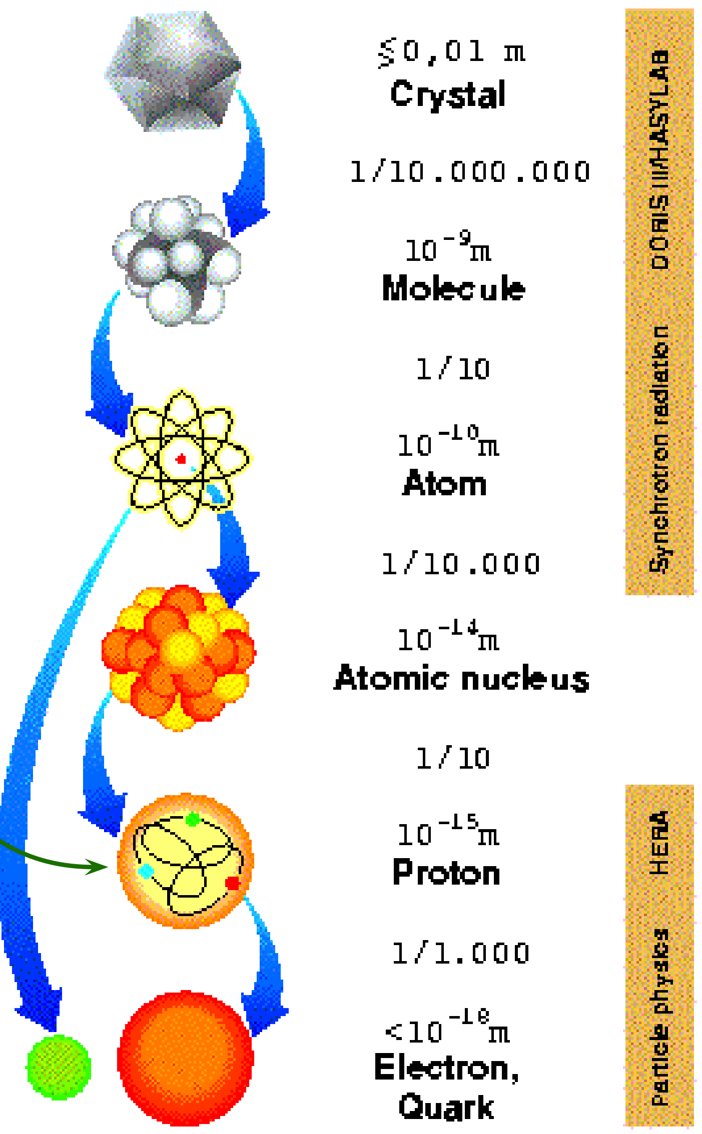
Nuclear Physics
Scale = 10 fm



First Contents Back Conclusion

Hadron Physics

Hadron Physics
Scale = 1 fm



Hadron Physics

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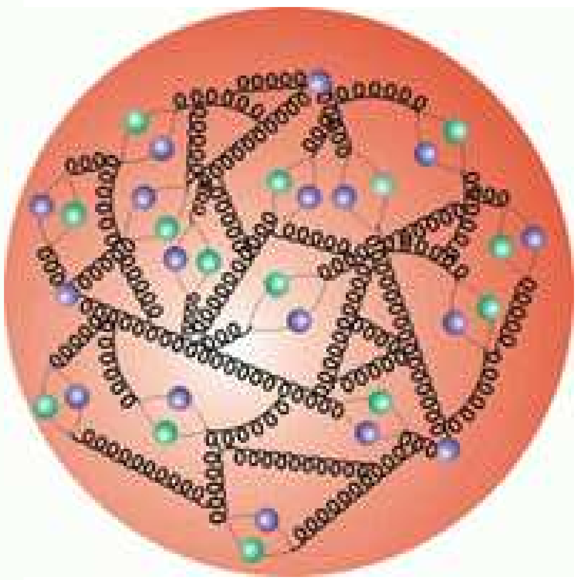
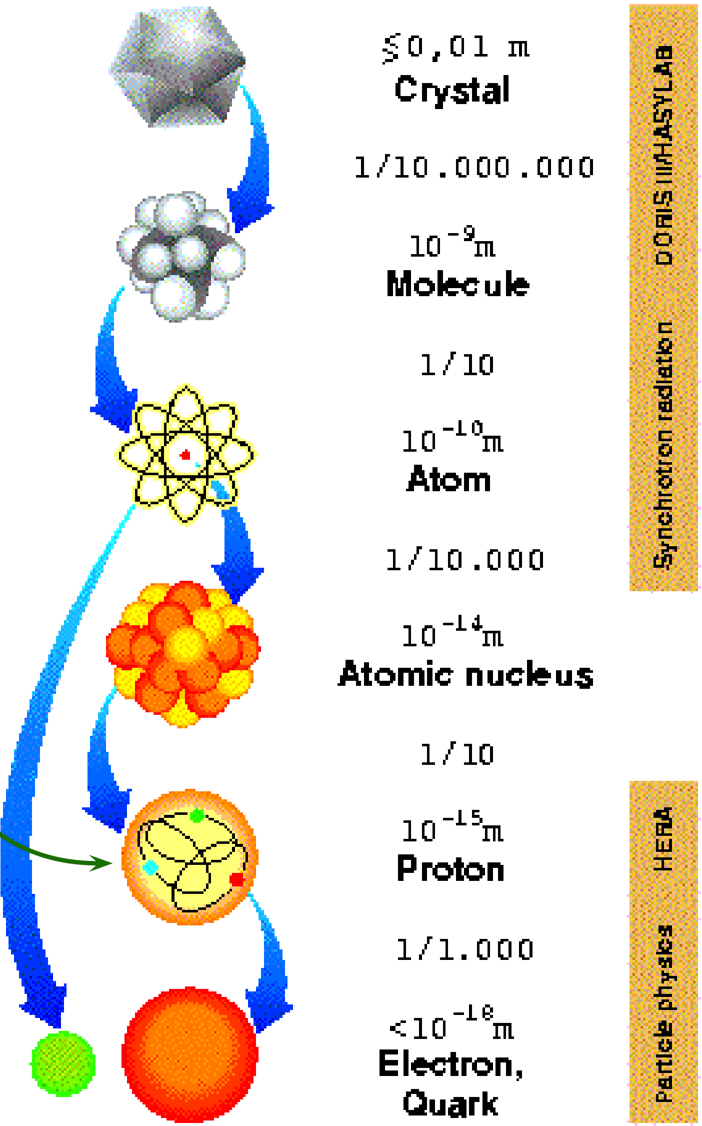
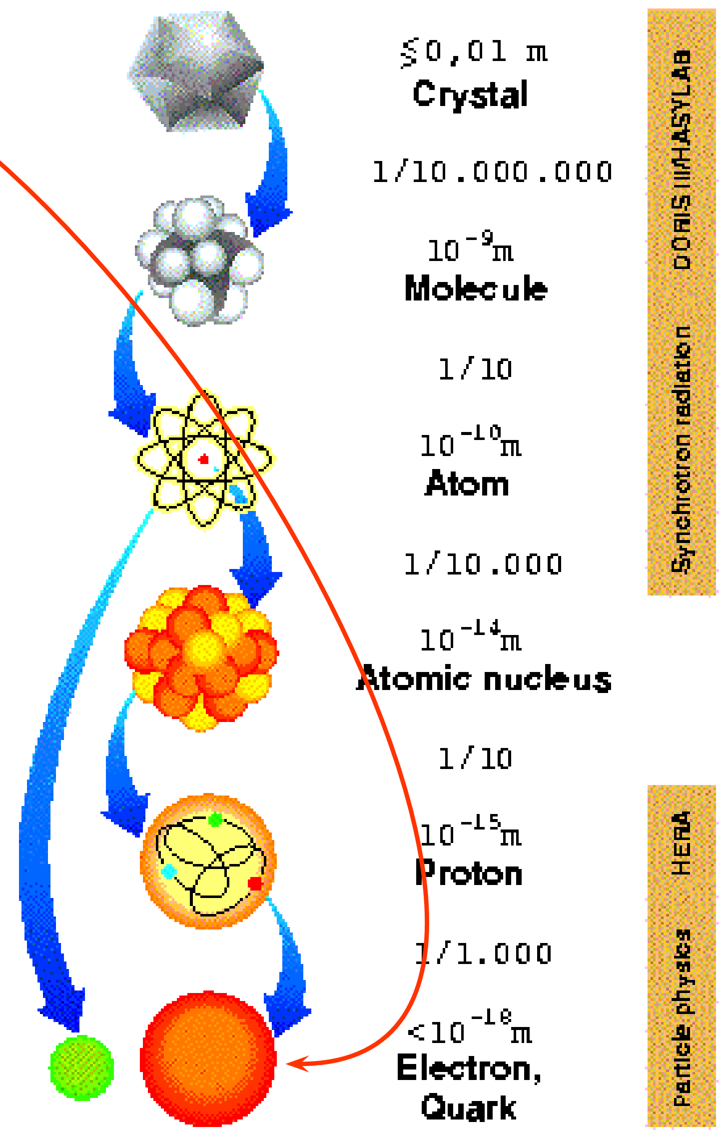




Hadron Physics

Meta-Physics
Scale = Limited only
by Theorists
Imagination



Nucleon . . . 2 Key Hadrons
= Proton and Neutron

First Contents Back Conclusion

Nucleon . . . 2 Key Hadrons
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- Fermions – two static properties:
  proton electric charge $= +1$; and magnetic moment, μ_p

Nucleon . . . 2 Key Hadrons
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  - Dirac (1928) – pointlike fermion: $\mu_p = \dfrac{e\hbar}{2M}$

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First | Contents | Back | Conclusion

Nucleon . . . 2 Key Hadrons $=$ Proton and Neutron

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First Contents Back Conclusion

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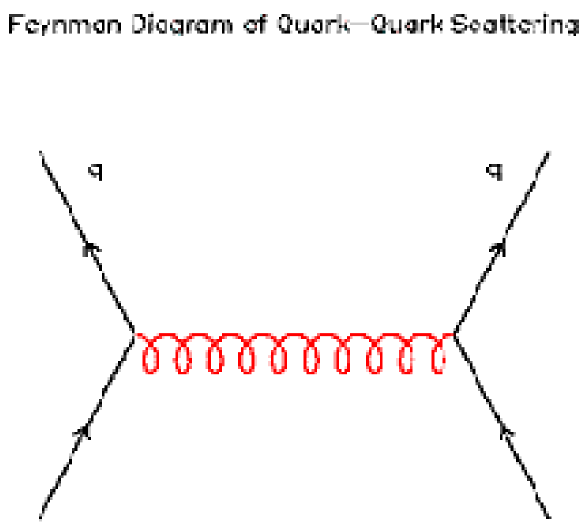
  - Dirac (1928) – pointlike fermion: $\mu_p = \frac{e\hbar}{2M}$
- Stern (1933) – $\mu_p = (1 + 1.79)\frac{e\hbar}{2M}$
  - Big Hint that Proton is not a point particle
  - Proton has constituents
  - These are Quarks and Gluons
    Quark discovery via $e^- p$-scattering at SLAC in 1968
    – the elementary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

What is QCD?

What is QCD?

- Gauge Theory:

  Interactions Mediated by massless vector bosons



First | Contents | Back | Conclusion

What is QCD?

- Gauge Theory:

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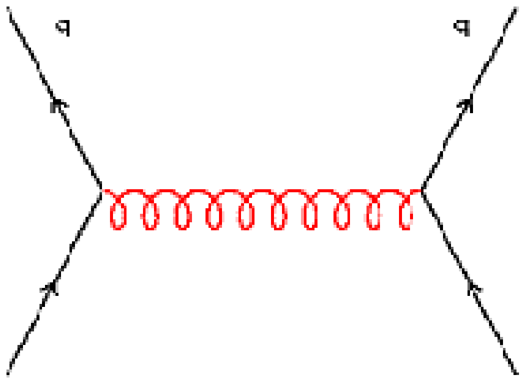
Feynman Diagram of Quark—Quark Scattering



- Similar interaction in QED

First Contents Back Conclusion

What is QCD?

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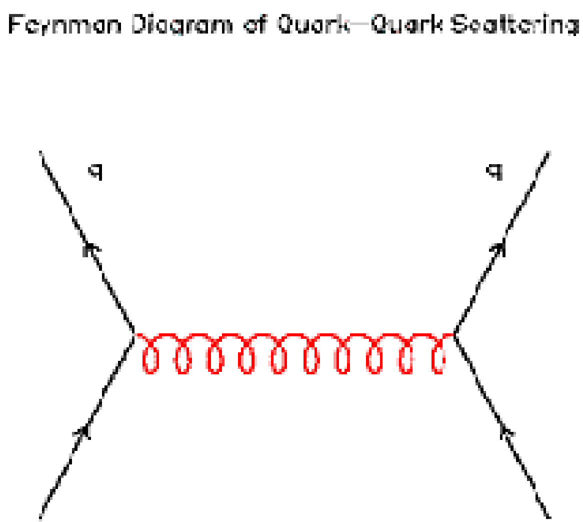
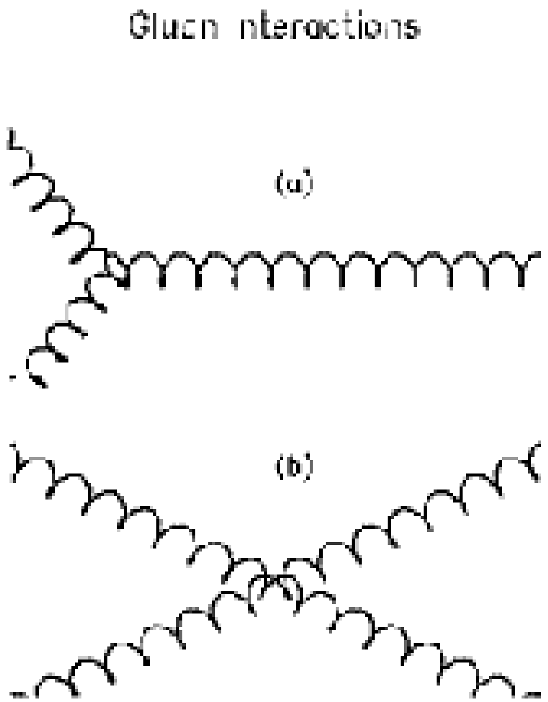




- Similar interaction in QED

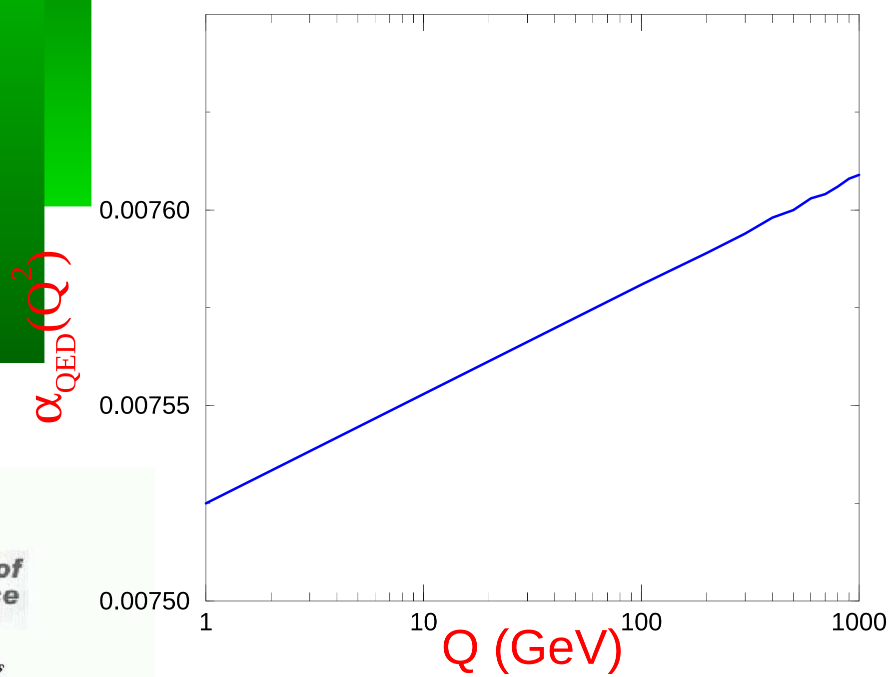
- Special Feature of QCD – gluon self-interactions

  Completely Change the Character of the Theory

QED cf. QCD

First Contents Back Conclusion

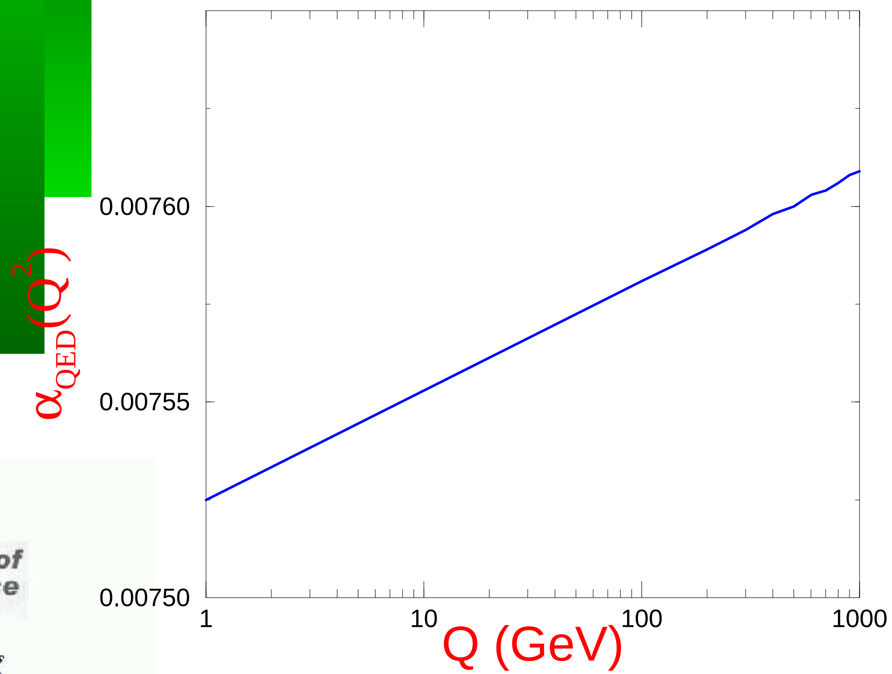
QED cf. QCD



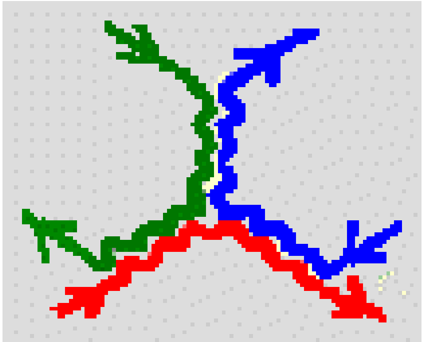
$$\alpha_{\rm QED} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

First Contents Back Conclusion

QED cf. QCD



Add three-gluon interaction



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First Contents Back Conclusion

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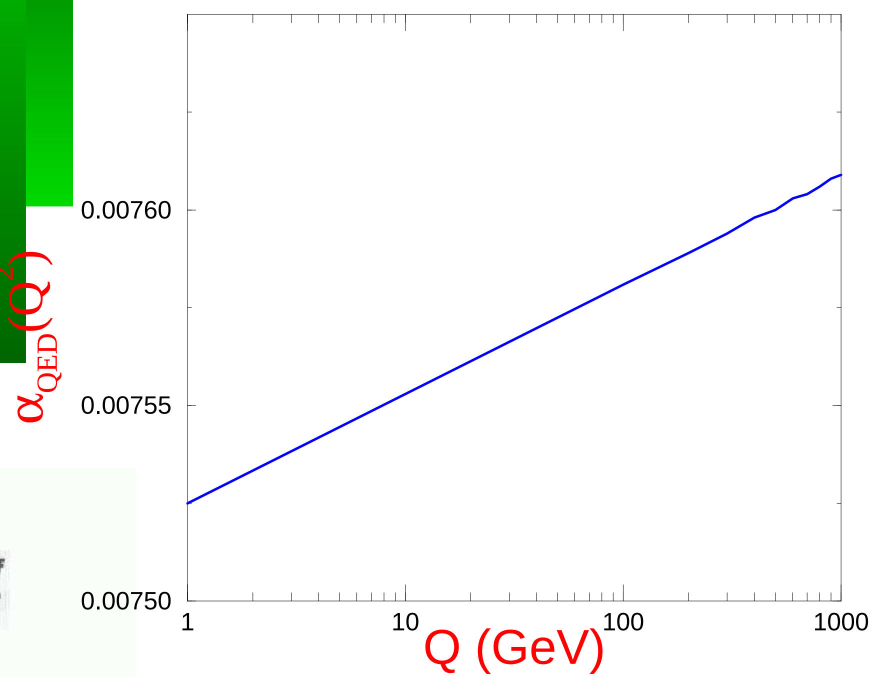


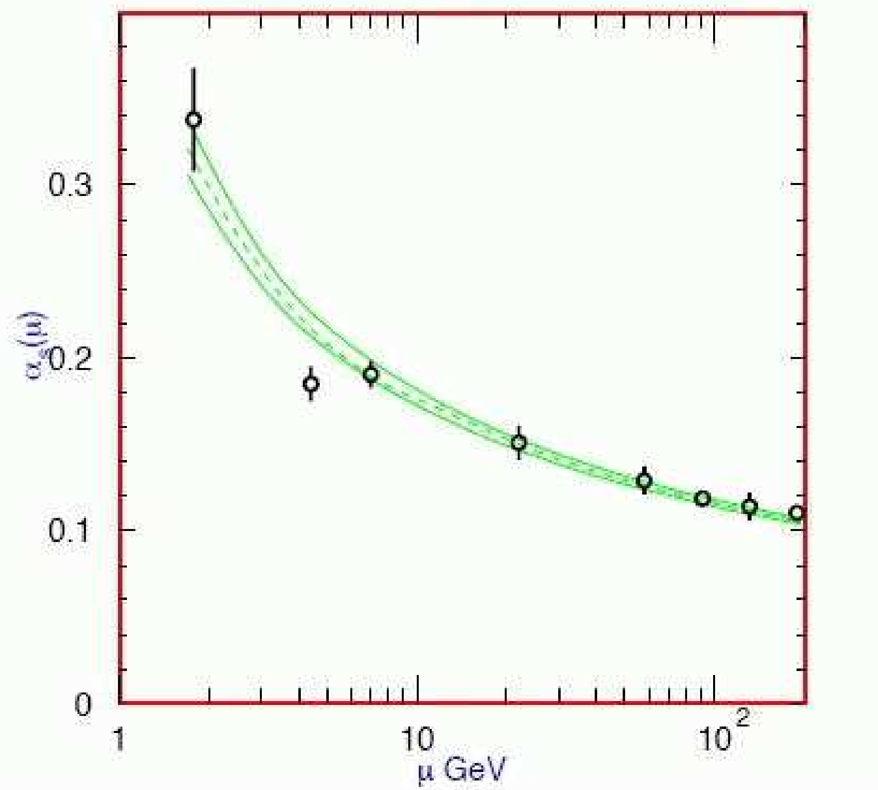


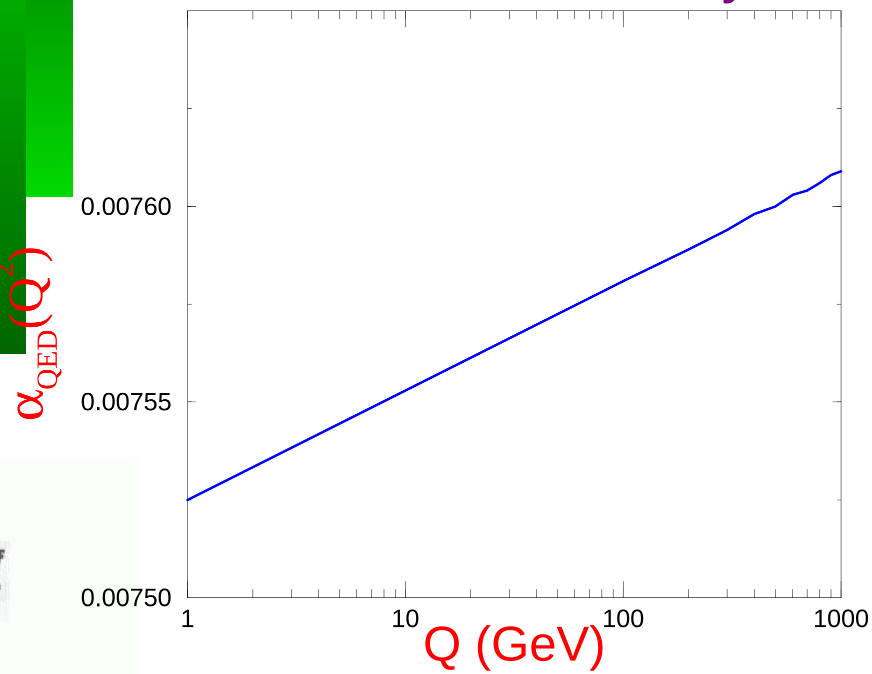
Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ. The data are, in increasing order of μ, τ width, 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.

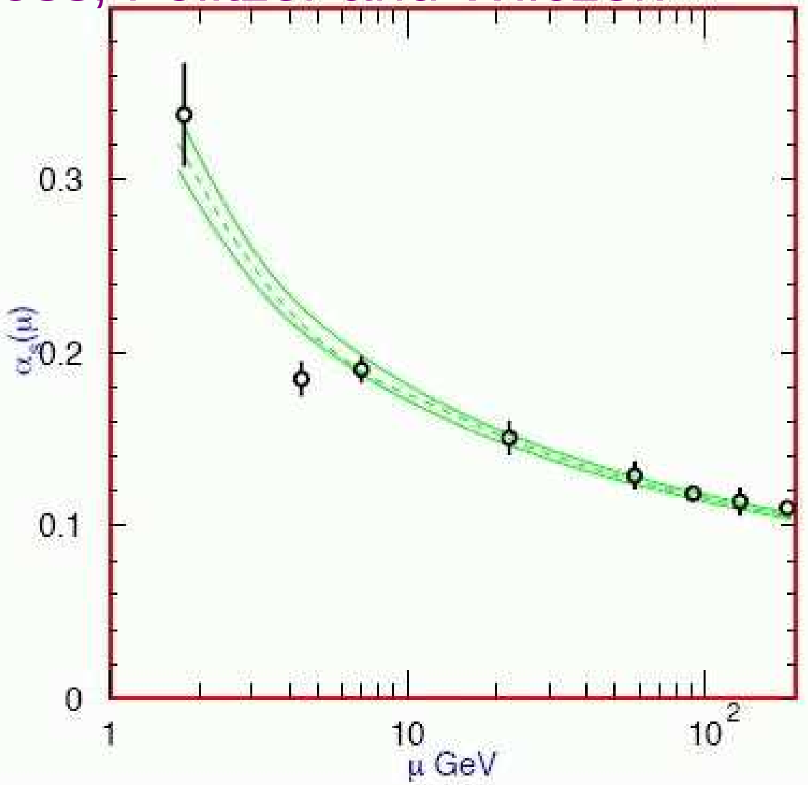
$$\alpha_{\rm QED} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

$$\alpha_{\rm QCD} = \frac{12\pi}{(33 - 2N_f)\ln\left(Q^2/\Lambda^2\right)}$$

QED cf. QCD

2004 Nobel Prize in Physics: Gross, Politzer and Wilczek





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First Contents Back Conclusion

Quarks and Nuclear Physics

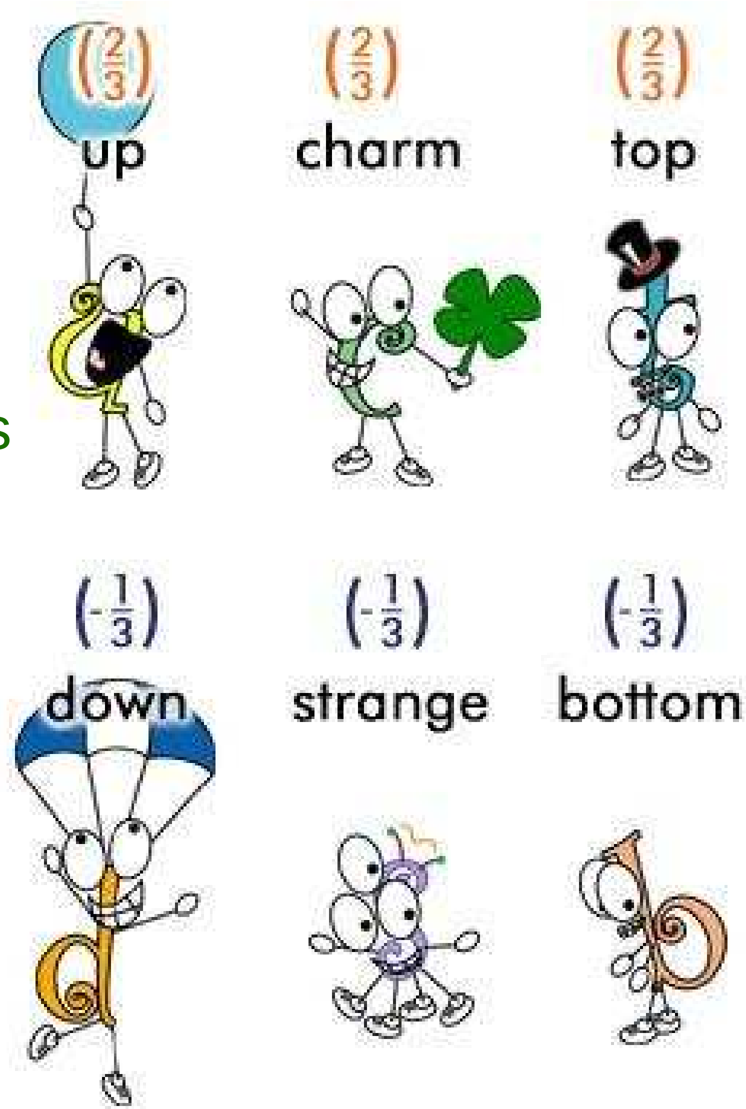
First Contents Back Conclusion

Quarks and Nuclear Physics

Standard Model

of Particle Physics

Six Flavours



First Contents Back Conclusion

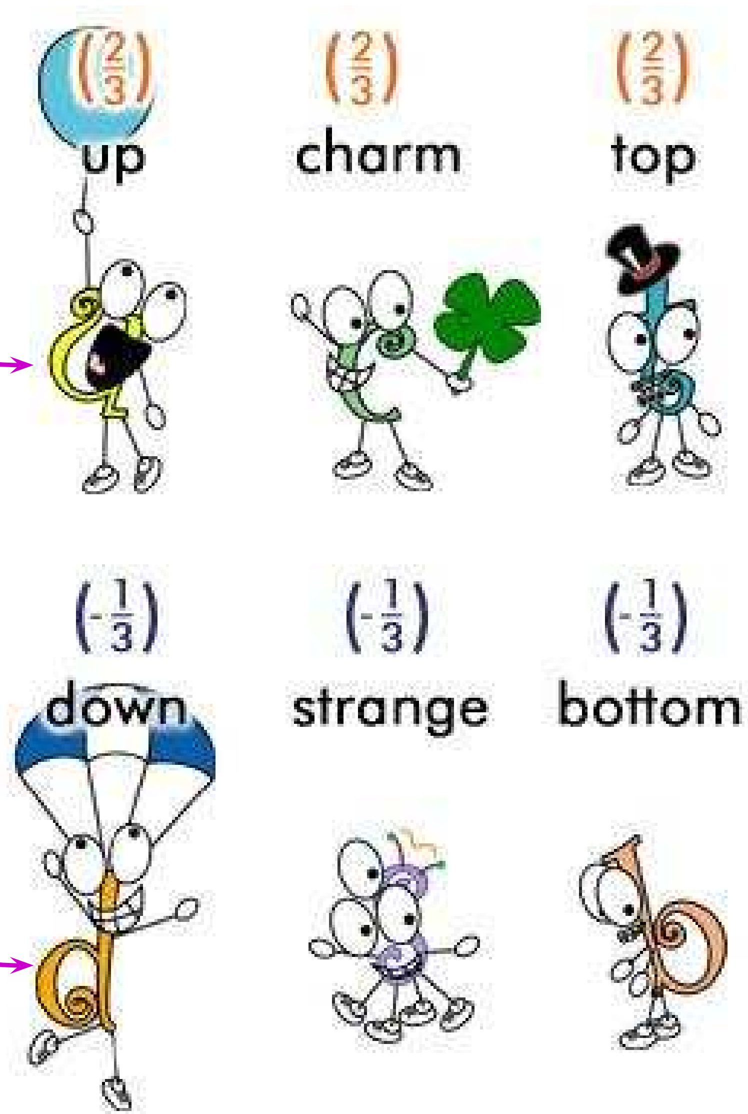
Quarks and Nuclear Physics

Real World

Normal Matter . . .

Only Two Light

Flavours Active



Quarks and Nuclear Physics

Real World

Normal Matter . . .

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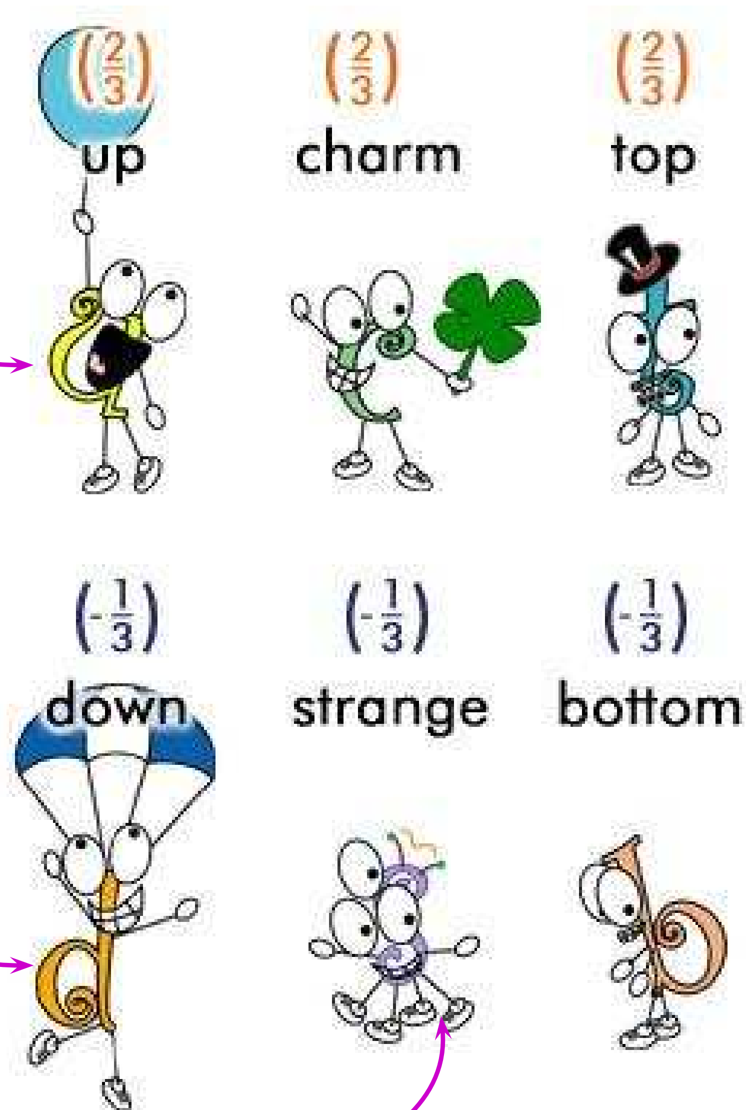
Flavours Active

or, perhaps, three



Quarks and Nuclear Physics

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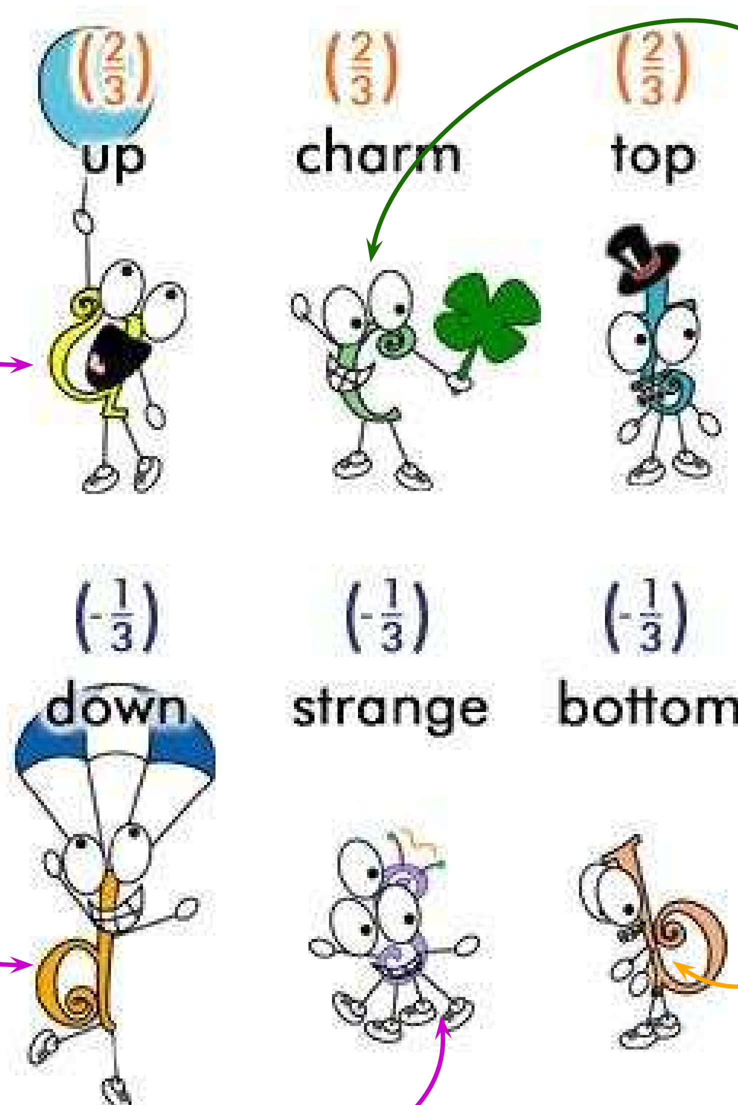
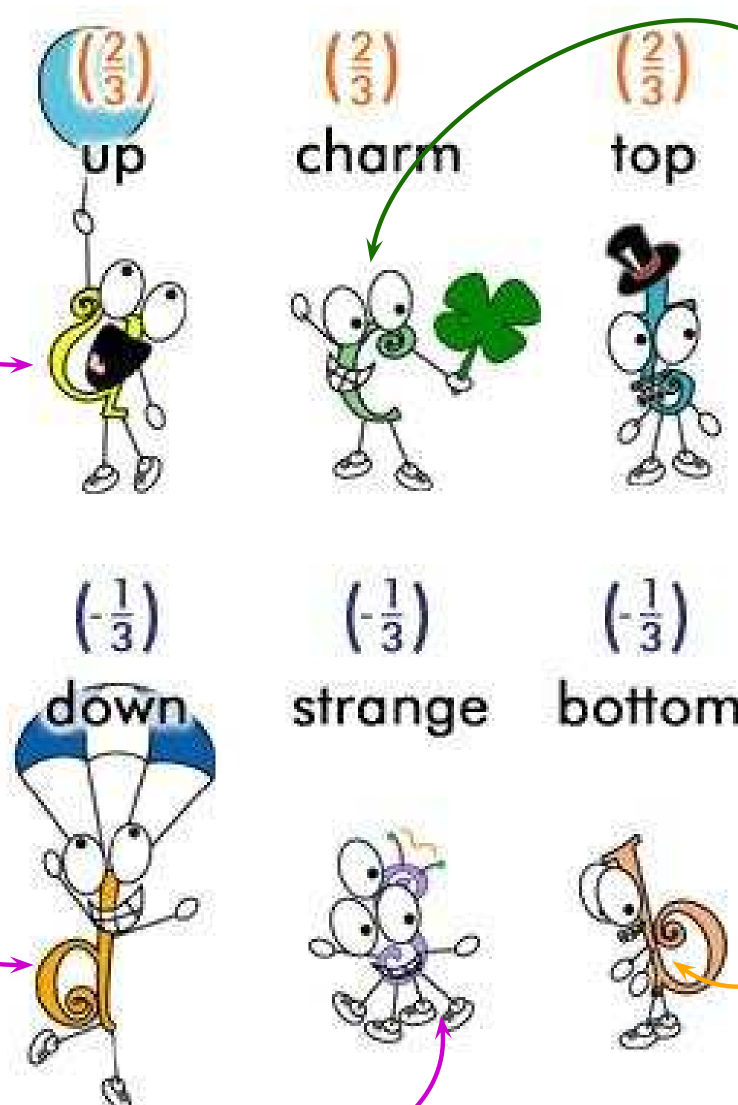


For numerous good reasons, much research also focuses on accessible heavy-quarks

or, perhaps, three

Quarks and Nuclear Physics

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



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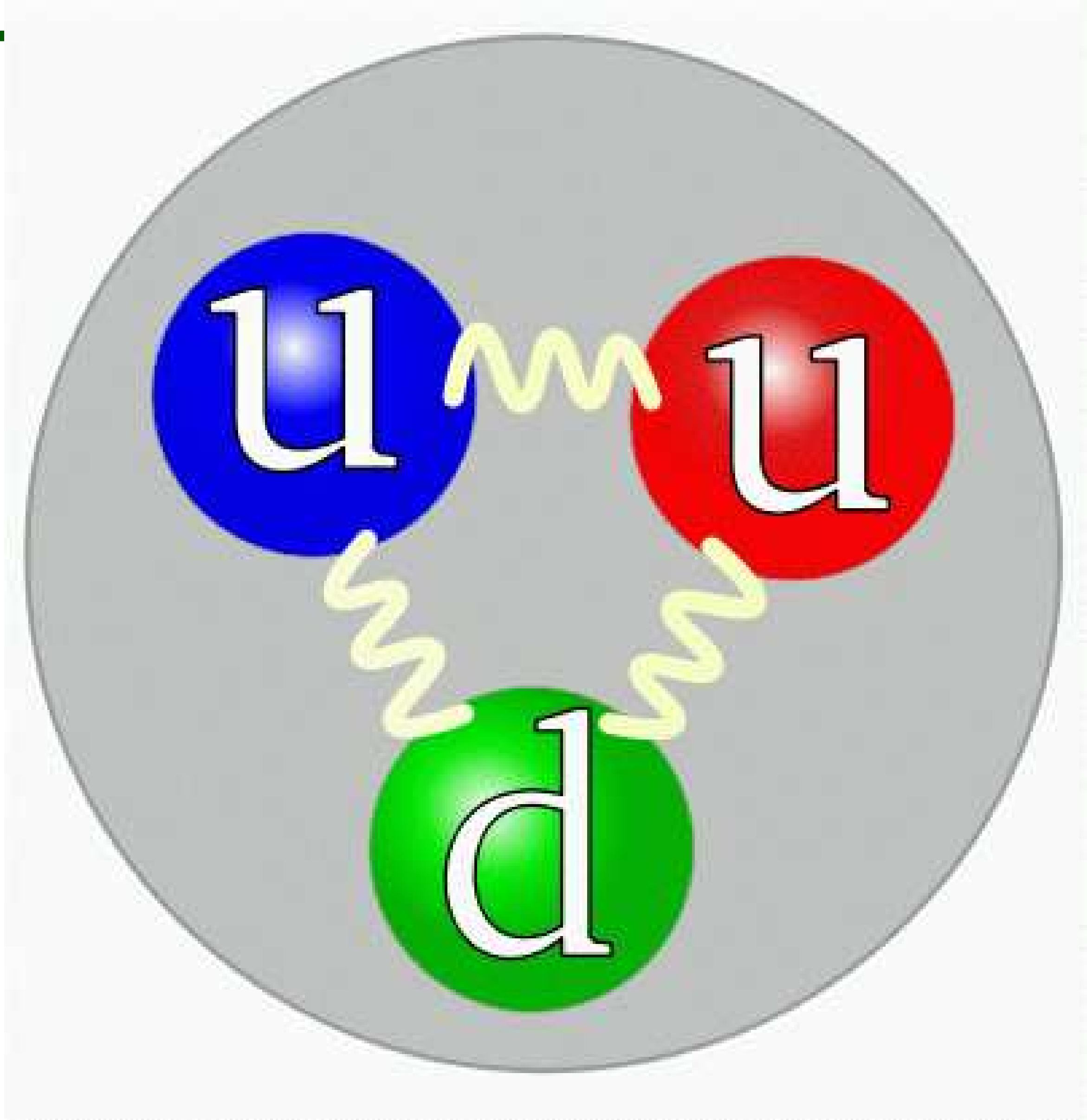
Simple Picture

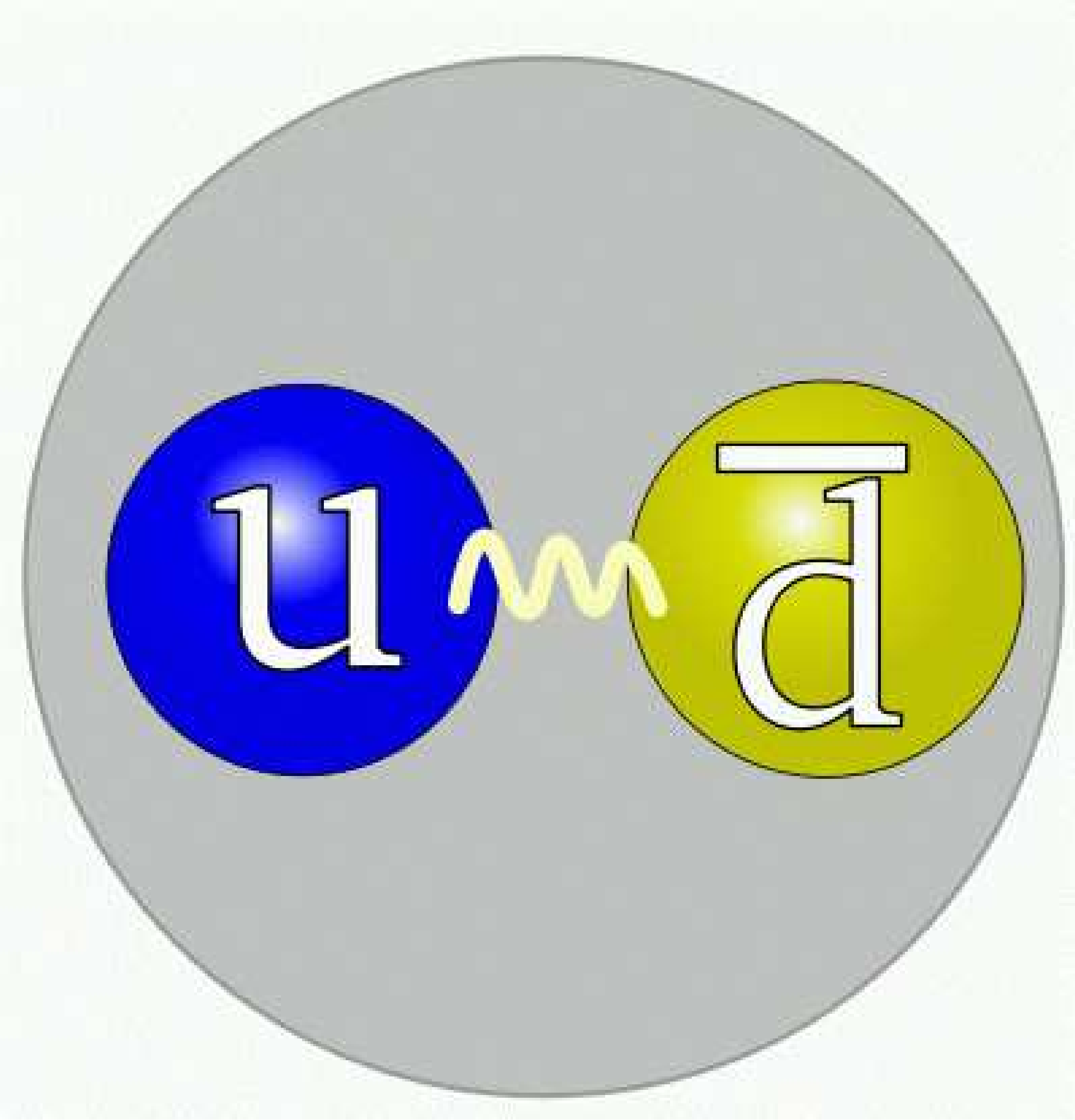
First Contents Back Conclusion

Simple Picture



PROTON

Simple Picture



PION

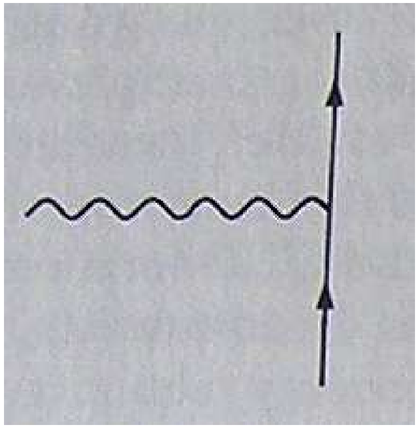
Study Structure via Nucleon Form Factors

First Contents Back Conclusion

Study Structure via Nucleon Form Factors

- Electron's relativistic electromagnetic current:

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



First | Contents | Back | Conclusion

Study Structure via Nucleon Form Factors

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$$

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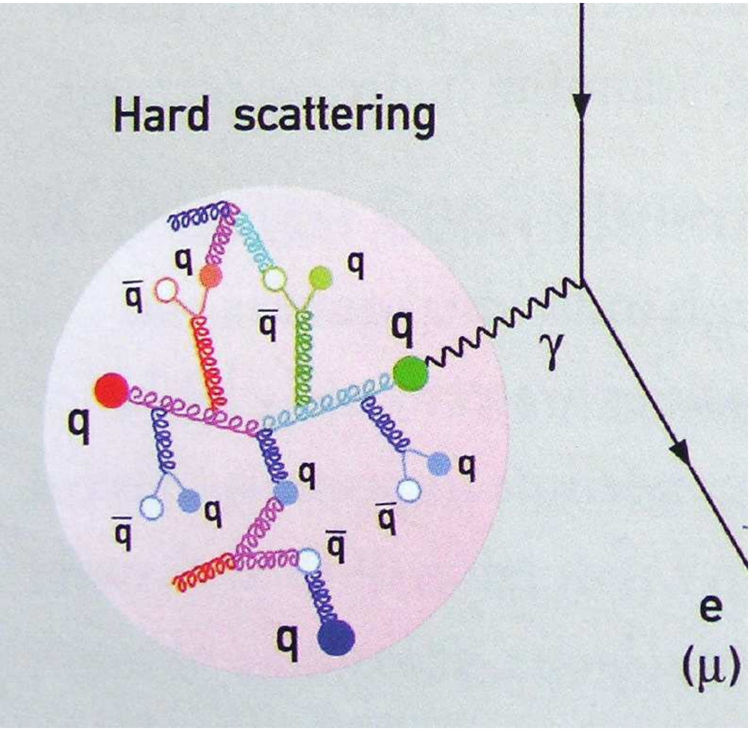

First Contents Back Conclusion

Study Structure via Nucleon Form Factors

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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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First Contents Back Conclusion

Study Structure via Nucleon Form Factors

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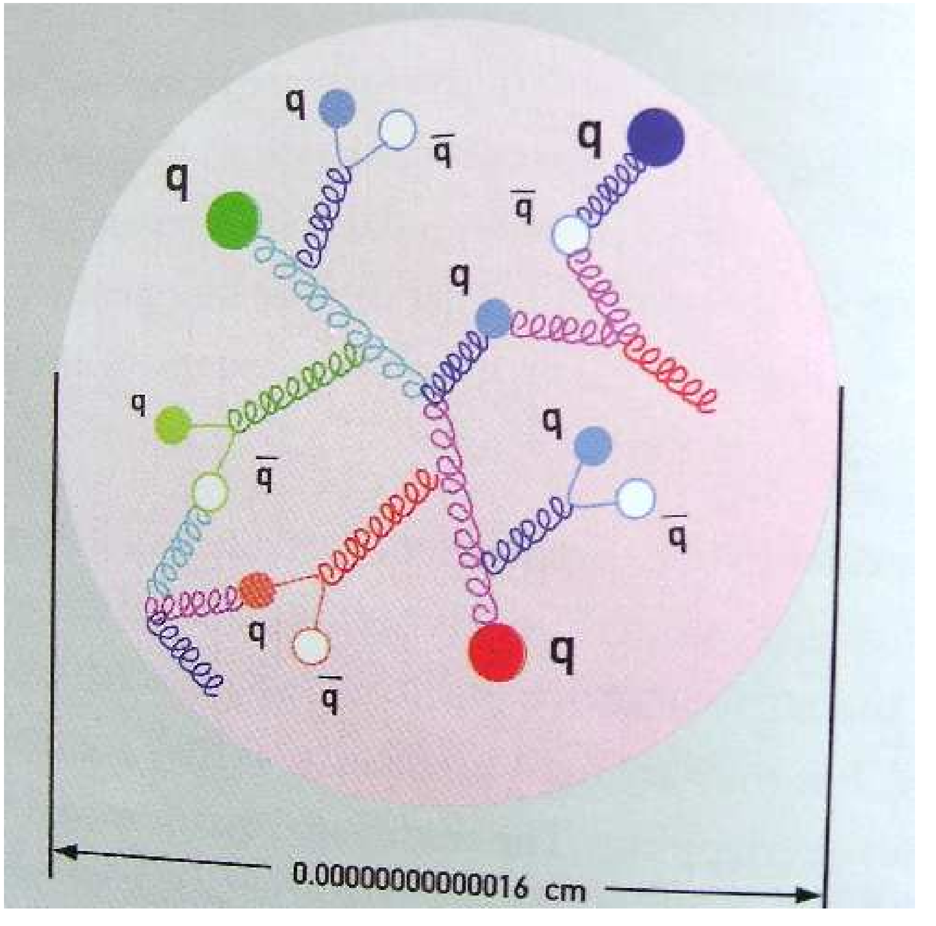
Point-particle: $\boldsymbol{F_2 \equiv 0} \Rightarrow \boldsymbol{G_E \equiv G_M}$

First Contents Back Conclusion

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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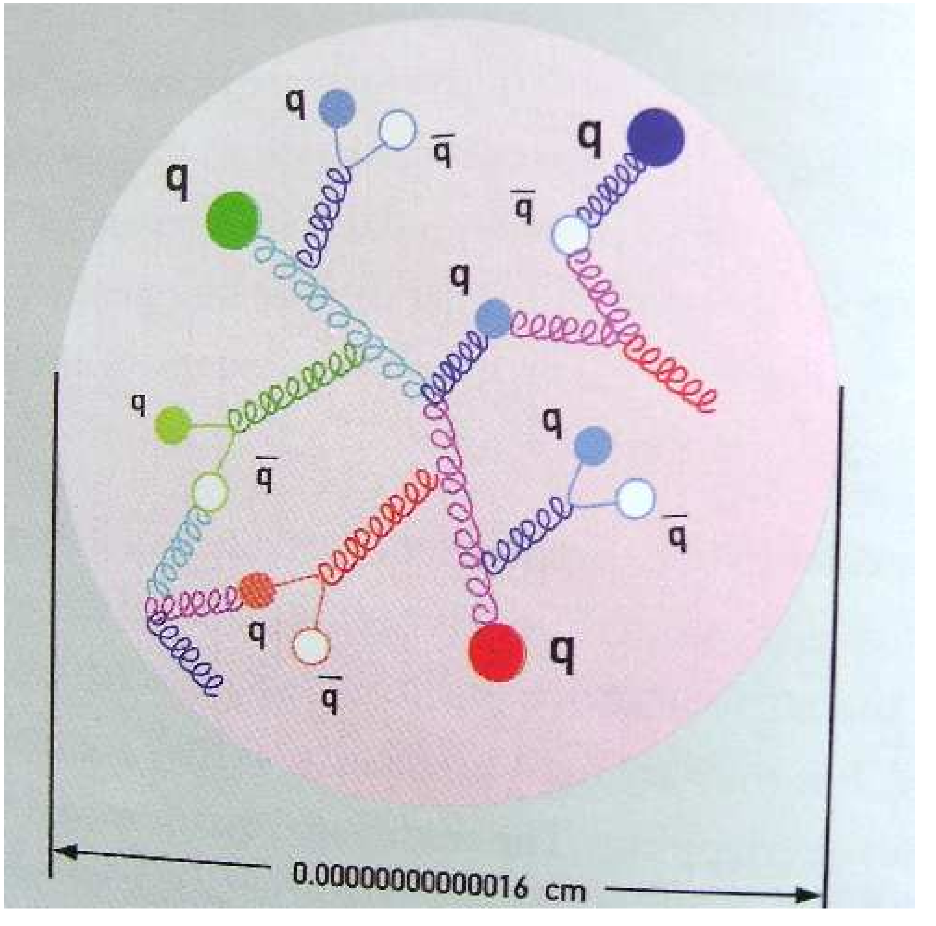

First Contents Back Conclusion

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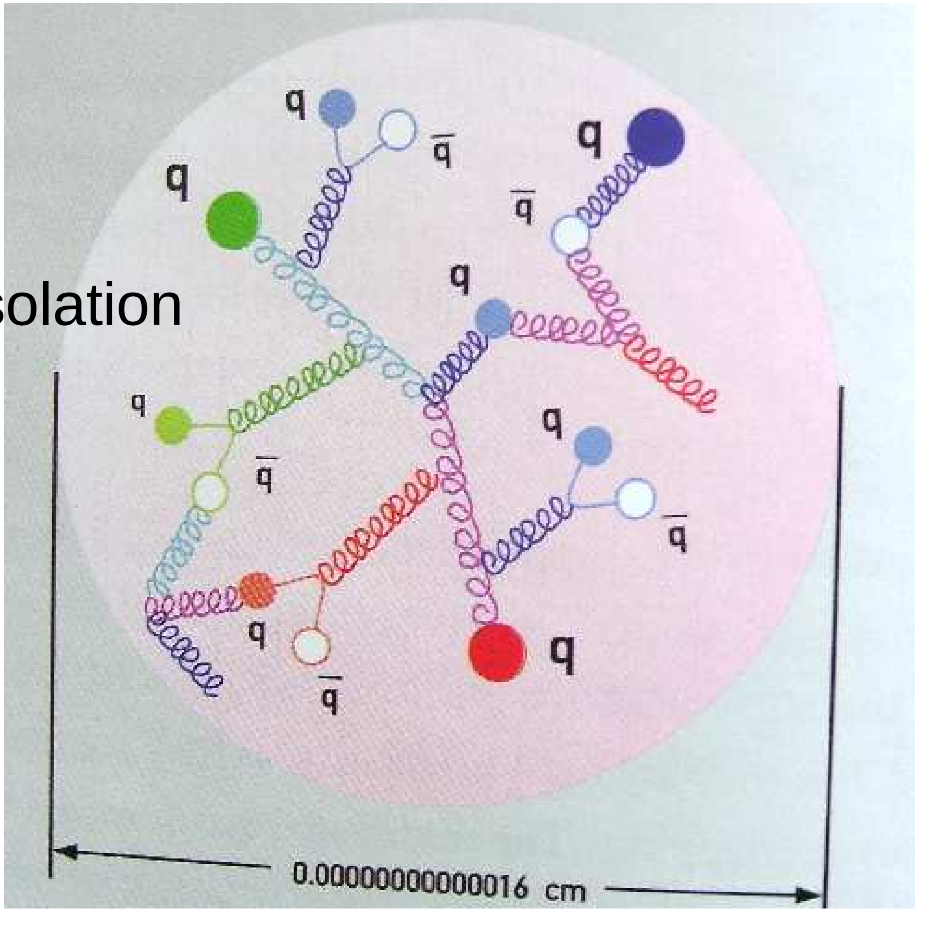
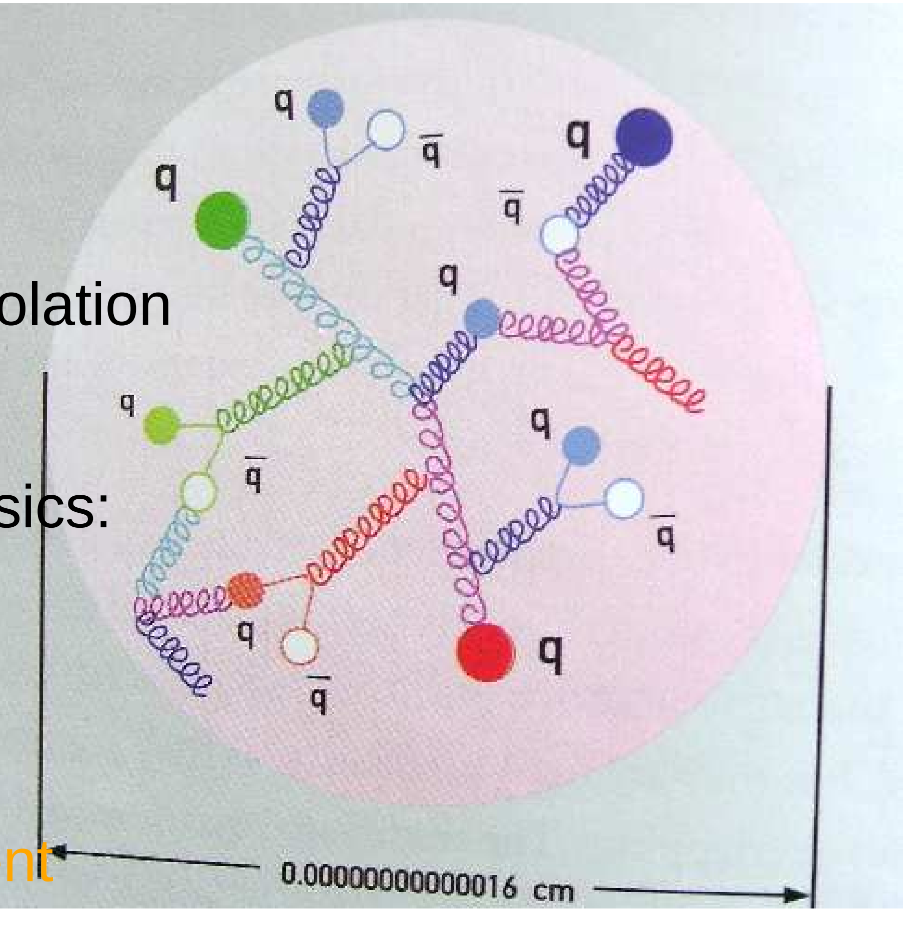


NSAC Long Range Plan

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

So, what's the problem?

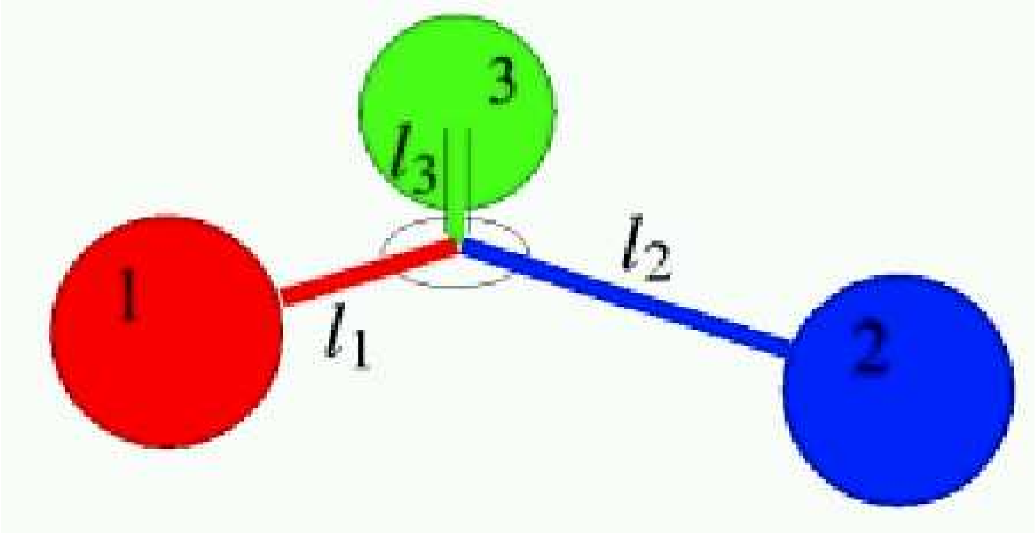
- Confinement
  – No quark ever seen in isolation
- Weightlessness
  – 2004 Nobel Prize in Physics:
  Mass of $u-$ & $d-$quarks,
  each just 5 MeV;
  Proton Mass is 940 MeV
  $\Rightarrow$ No Explanation Apparent
  for 98.4 % of Mass



Meson Spectrum

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$	STRANGE ($S = \pm1$, $C = B = 0$)	$I(J^P)$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$	• $K^\pm$	$1/2(0^-)$
• 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	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$	$K^*_0(800)$	$1/2(0^+)$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$	• $K^*(892)$	$1/2(1^-)$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$	• $K_1(1270)$	$1/2(1^+)$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$	• $K_1(1400)$	$1/2(1^+)$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$	• $K^*(1410)$	$1/2(1^-)$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$	• $K^*_0(1430)$	$1/2(0^+)$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$	• $K^*_2(1430)$	$1/2(2^+)$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$	$K(1460)$	$1/2(0^-)$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$	$K_2(1580)$	$1/2(2^-)$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$	$K(1630)$	$1/2(?^?)$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$	$K_1(1650)$	$1/2(1^+)$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$	• $K^*(1680)$	$1/2(1^-)$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$	• $K_2(1770)$	$1/2(2^-)$

- proton = three constituent quarks



Modern Miracles in Hadron Physics

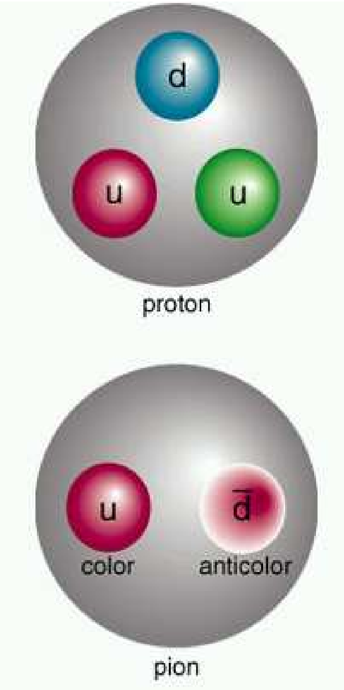
- proton $=$ three constituent quarks
- $M_{\mathbf{proton}} \approx \mathbf{1\,GeV}$

Modern Miracles in Hadron Physics

- proton = three constituent quarks
- $M_{\mathbf{proton}} \approx \mathbf{1\,GeV}$
- guess $M_{\mathbf{constituent-quark}} \approx \frac{\mathbf{1\,GeV}}{\mathbf{3}} \approx \mathbf{350\,MeV}$

Modern Miracles in Hadron Physics

- proton $=$ three constituent quarks
- $M_{\rm proton} \approx 1\,{\rm GeV}$
- guess $M_{\rm constituent-quark} \approx \frac{1\,{\rm GeV}}{3} \approx 350\,{\rm MeV}$
- pion $=$
  constituent quark $+$ constituent antiquark



- proton $=$ three constituent quarks
- $M_{\mathbf{proton}} \approx \mathbf{1\,GeV}$
- guess $M_{\mathbf{constituent-quark}} \approx \dfrac{\mathbf{1\,GeV}}{\mathbf{3}} \approx \mathbf{350\,MeV}$
- pion $=$
  constituent quark $+$ constituent antiquark
- guess $M_{\mathbf{pion}} \approx \mathbf{2} \times \dfrac{M_{\mathbf{proton}}}{\mathbf{3}} \approx \mathbf{700\,MeV}$

- proton = three constituent quarks
- $M_{\rm proton} \approx 1\,{\rm GeV}$
- guess $M_{\rm constituent-quark} \approx \frac{1\,{\rm GeV}}{3} \approx 350\,{\rm MeV}$
- pion =
  constituent quark + constituent antiquark
- guess $M_{\rm pion} \approx 2 \times \frac{M_{\rm proton}}{3} \approx 700\,{\rm MeV}$
- WRONG . . . . $M_{\rm pion} = 140\,{\rm MeV}$

- proton = three constituent quarks
- $M_{\mathbf{proton}} \approx \mathbf{1\,GeV}$
- guess $M_{\mathbf{constituent-quark}} \approx \frac{\mathbf{1\,GeV}}{\mathbf{3}} \approx \mathbf{350\,MeV}$
- pion = constituent quark + constituent antiquark
- guess $M_{\mathbf{pion}} \approx \mathbf{2} \times \frac{M_{\mathbf{proton}}}{\mathbf{3}} \approx \mathbf{700\,MeV}$
- WRONG . . . . $M_{\mathbf{pion}} = \mathbf{140\,MeV}$
- Another meson:

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

- proton = three constituent quarks
- $M_{\rm proton} \approx 1\,{\rm GeV}$
- guess $M_{\rm constituent-quark} \approx \frac{1\,{\rm GeV}}{3} \approx 350\,{\rm MeV}$
- pion =
  constituent quark + constituent antiquark
- guess $M_{\rm pion} \approx 2 \times \frac{M_{\rm proton}}{3} \approx 700\,{\rm MeV}$
- WRONG .... $M_{\rm pion} = 140\,{\rm MeV}$
- What is "wrong" with the pion?

Is this . . . Mass Destruction?

Dichotomy of the Pion

First Contents Back Conclusion

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First Contents Back Conclusion

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Using DSEs, we've provided this.

QCD's Emergent Phenomena

First Contents Back Conclusion

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- NSAC – Understanding these phenomena is one of the greatest intellectual challenges in physics

Why should You care?

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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- How do such changes affect Big Bang Nucleosynthesis?

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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?

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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- Modern Physics & Mathematics
  – Still quite some way from being able to do that

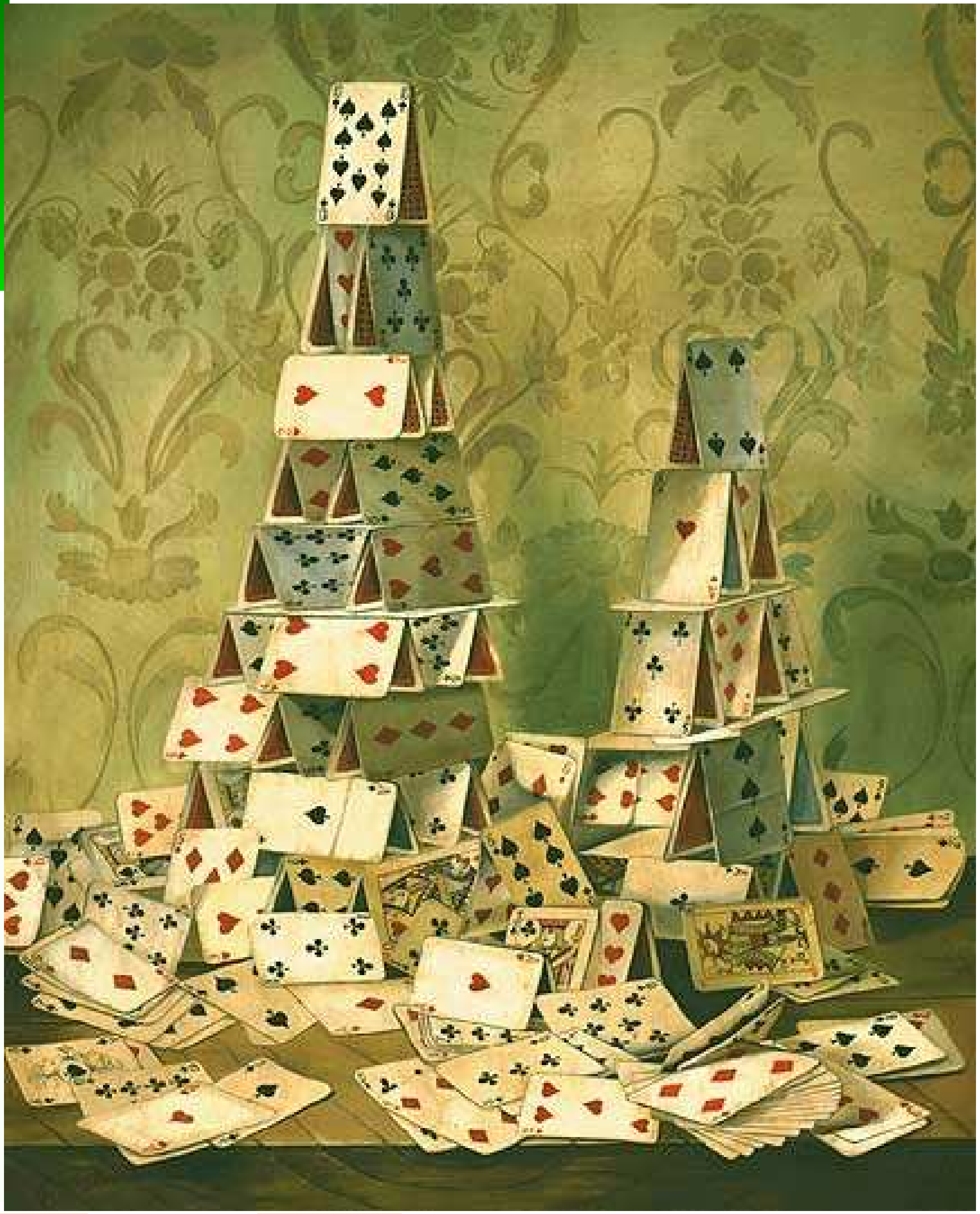
Model QCD

Traditional approach to strong force problem

Model QCD

Traditional approach to strong force problem

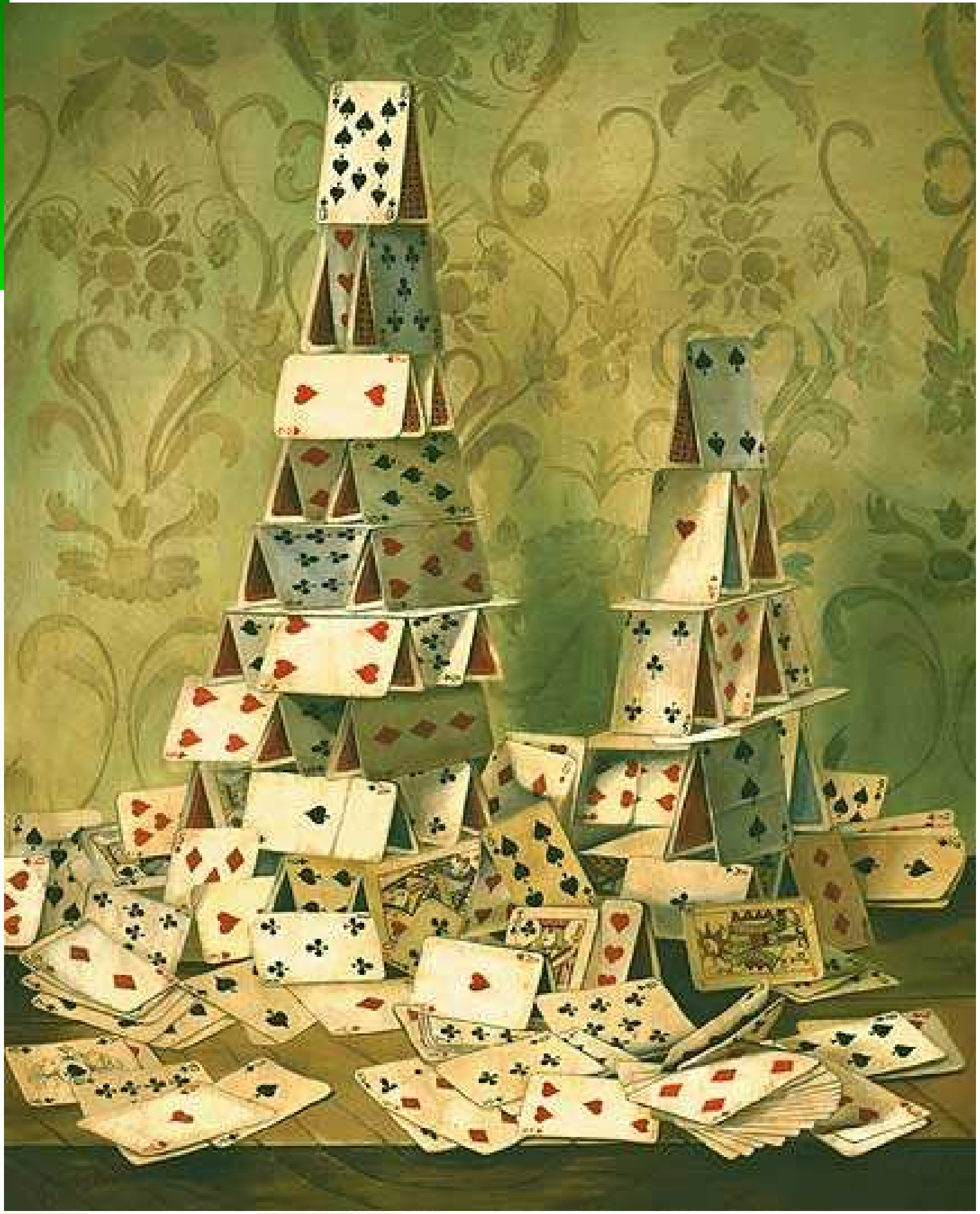
Model QCD

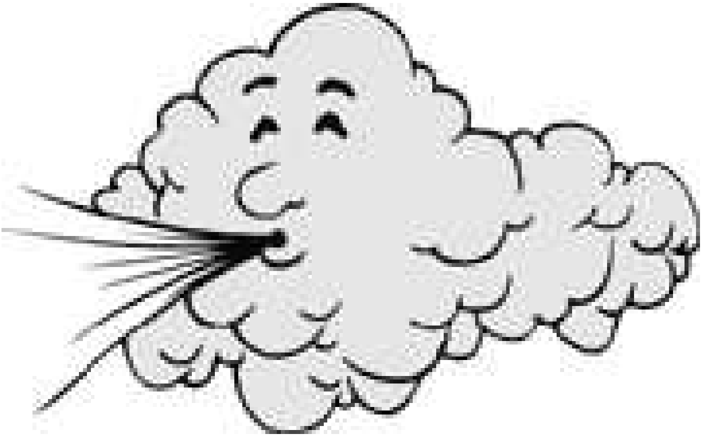


First Contents Back Conclusion

Traditional approach to strong force problem

Model QCD





Lattice QCD

First Contents Back Conclusion

One modern nonperturbative approach *Lattice QCD*

First Contents Back Conclusion

One modern nonperturbative approach *Lattice QCD*

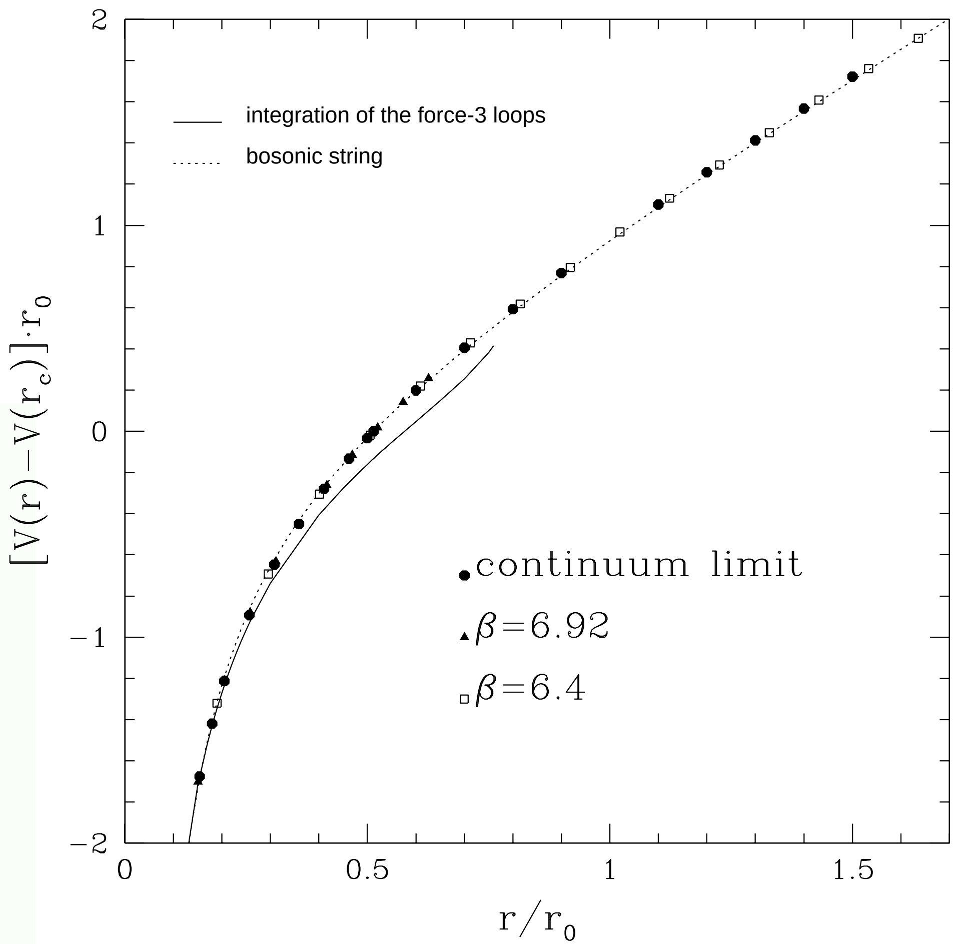
First Contents Back Conclusion

Confinement

First Contents Back Conclusion

Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



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

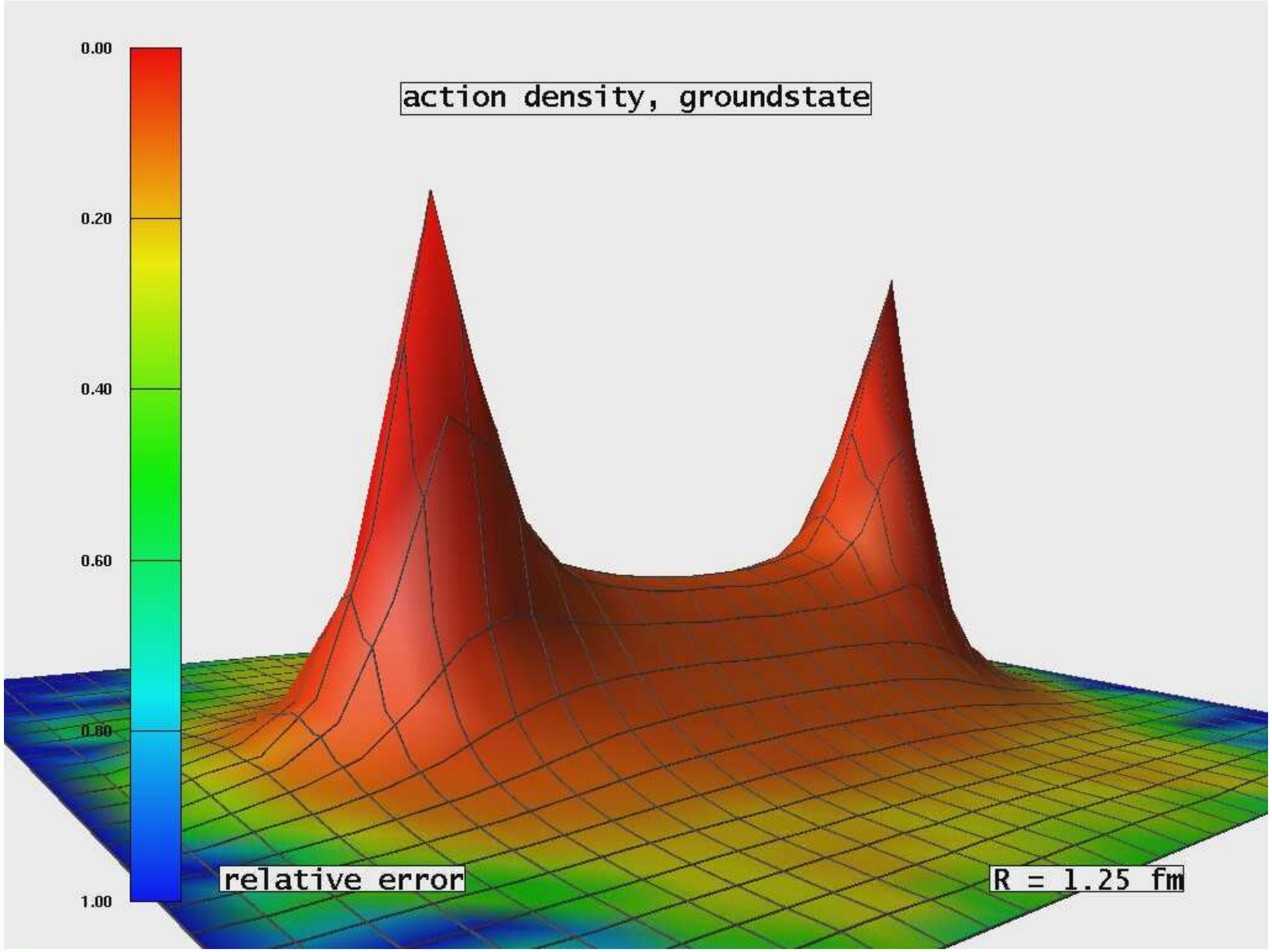
$\sigma \sim 470$ MeV

Necco & Sommer
he-la/0108008

First | Contents | Back | Conclusion

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

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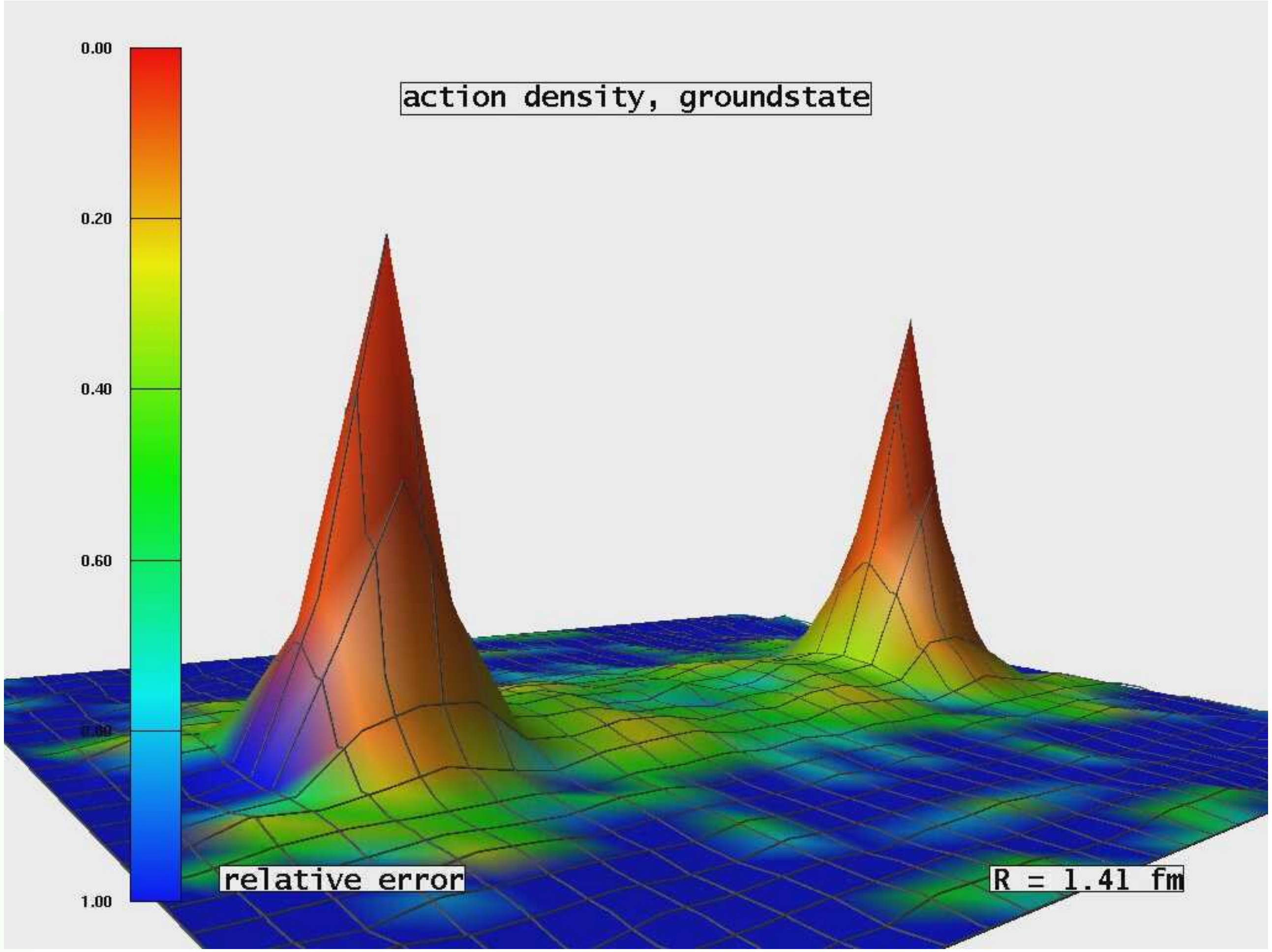

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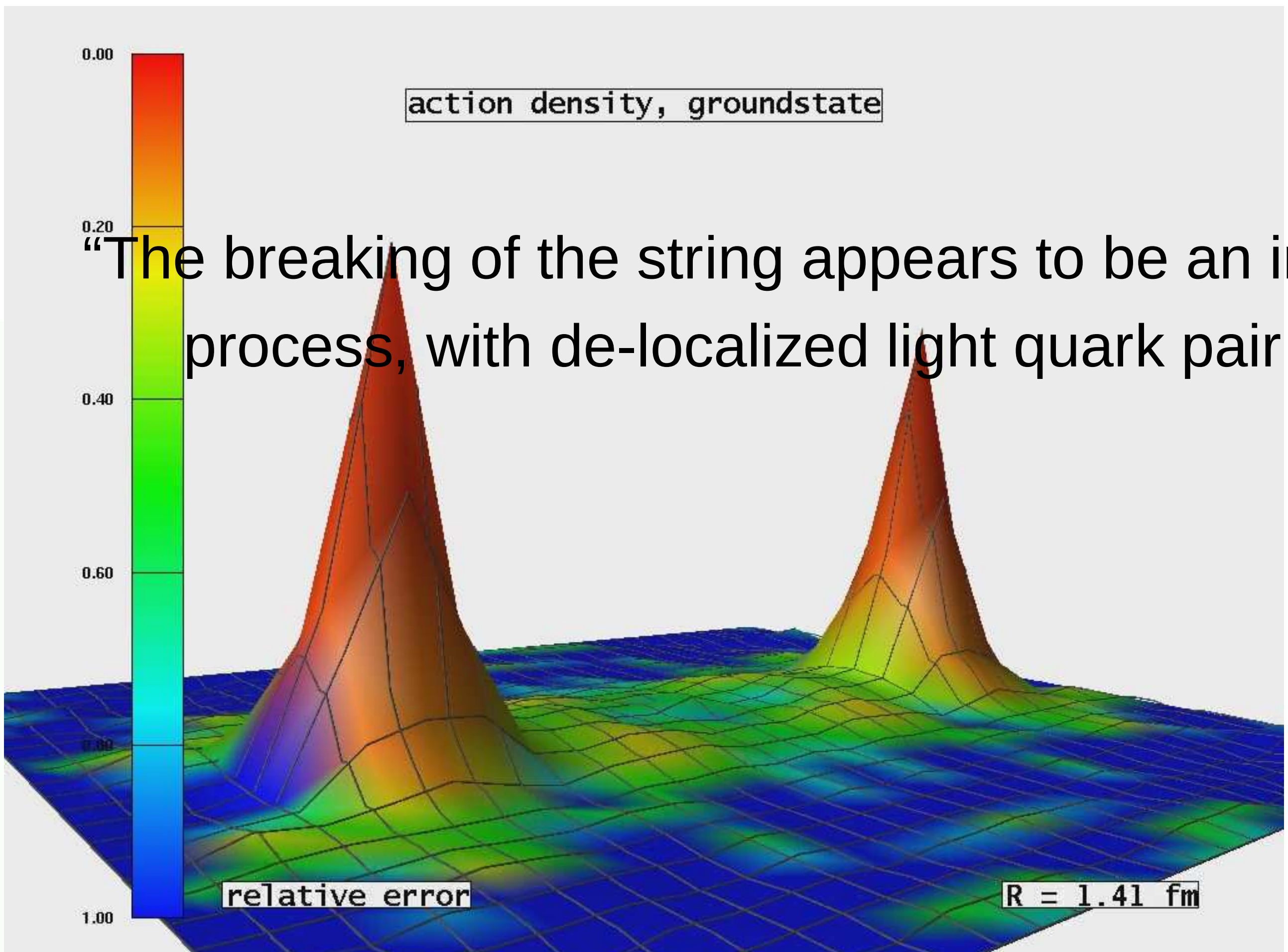

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First Contents Back Conclusion

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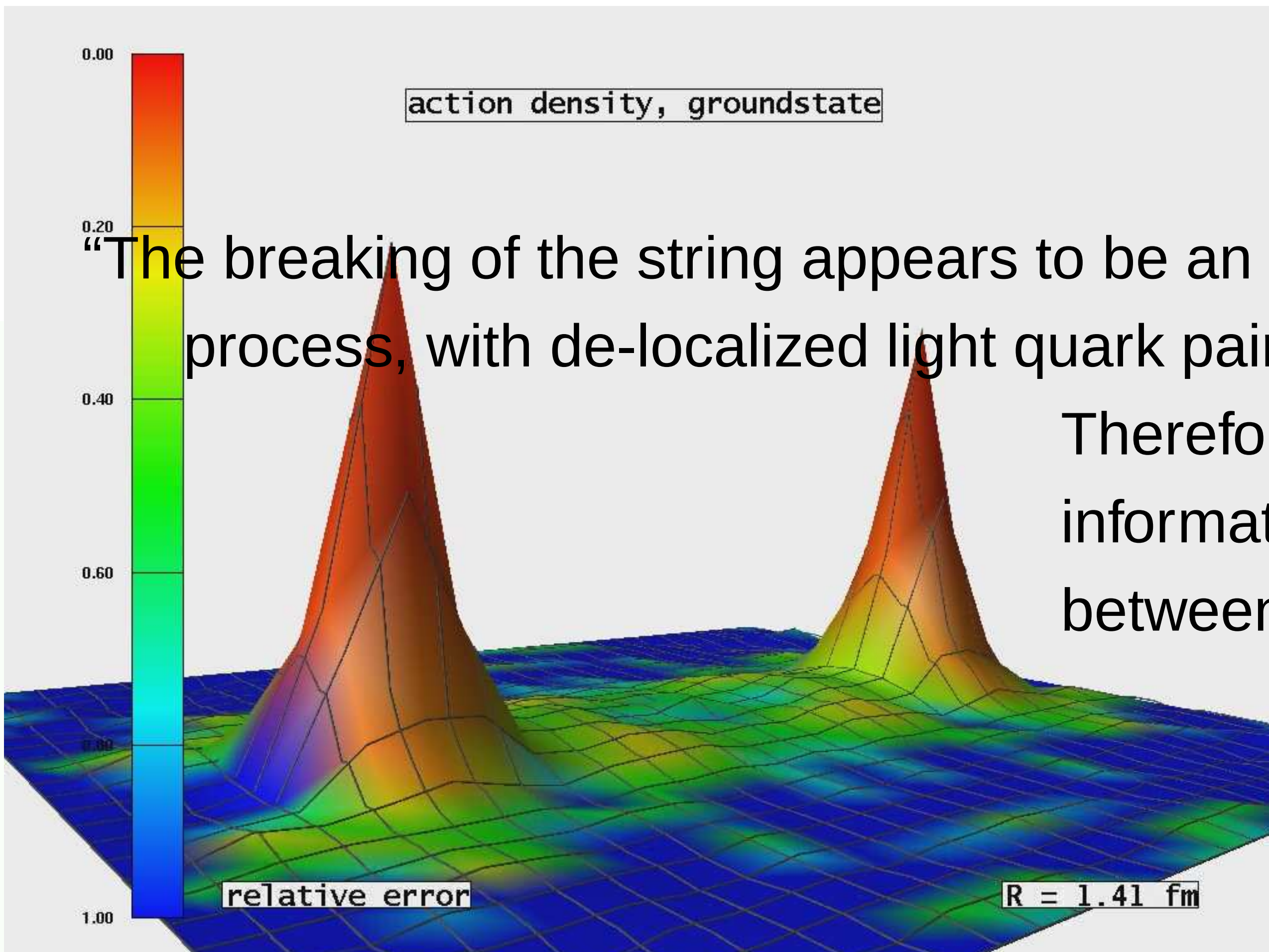

“The breaking of the string appears to be an instantaneous process, with de-localized light quark pair creation.”

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

A Compromise?

Dyson-Schwinger Equations

First Contents Back Conclusion

- 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]. . . . .*"

A Compromise?

Dyson-Schwinger Equations

- 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. . . .*"

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First Contents Back Conclusion

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First Contents Back Conclusion

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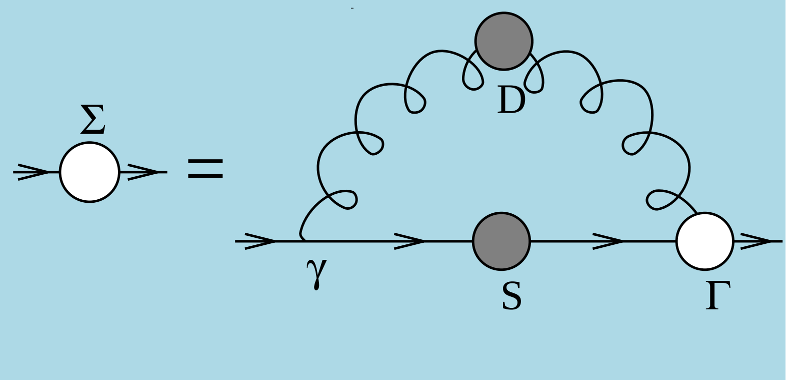

First Contents Back Conclusion

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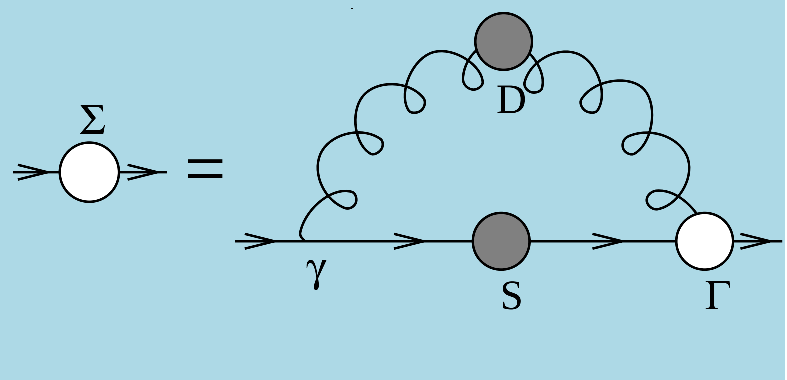

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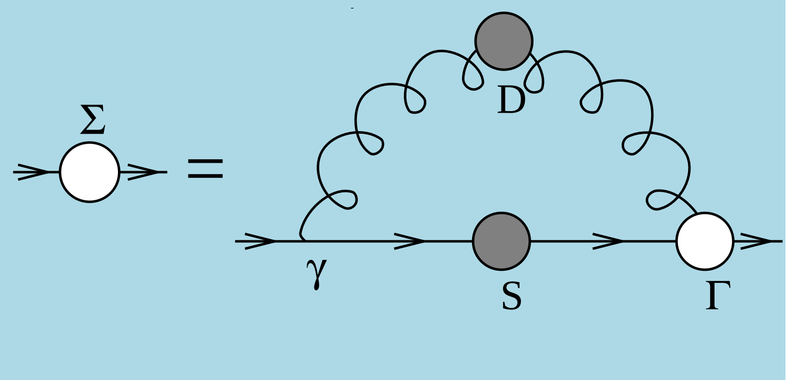

- These are nonperturbative equivalents in quantum field theory to the Lagrange equations of motion.
- Essential in simplifying the general proof of renormalisability of gauge field theories.

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First Contents Back Conclusion

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First Contents Back Conclusion

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First Contents Back Conclusion

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- ⇒ Understanding InfraRed (long-range)

  . . . . behaviour of $\alpha_s(Q^2)$

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- Method yields Schwinger Functions $\equiv$ Propagators

First Contents Back Conclusion

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Cross-Sections built from Schwinger Functions

First Contents Back Conclusion

Persistent Challenge

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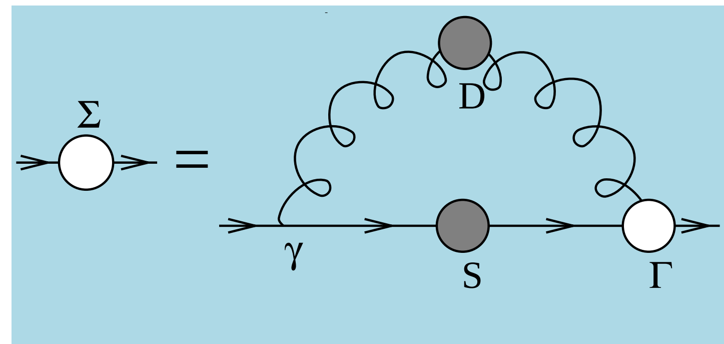

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Persistent Challenge

- Infinitely Many Coupled Equations
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  - Not all are Schwinger functions are experimentally observable but all are same VEVs measured in Lattice-QCD simulations . . . opportunity for comparisons at pre-experimental level . . . cross-fertilisation

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    Not useful for the nonperturbative problems in which we're interested

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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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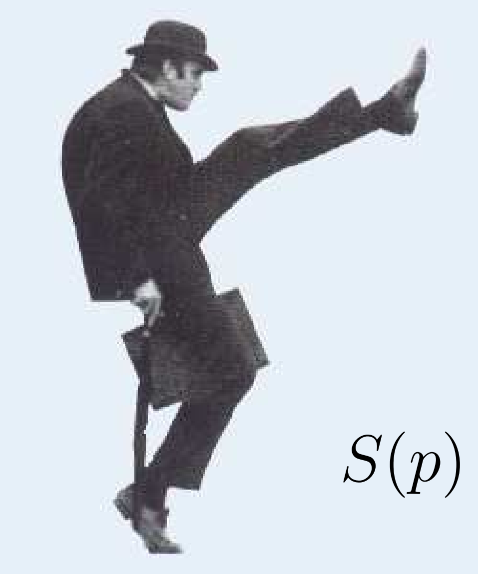
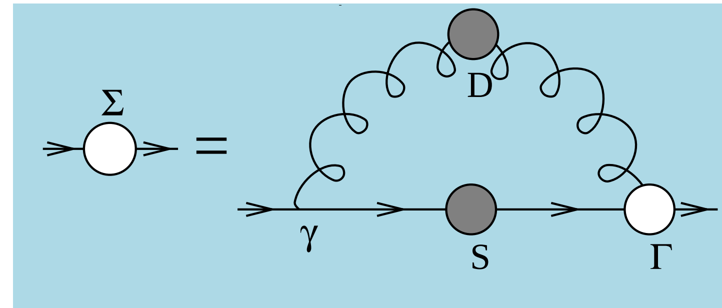
Perturbative Dressed-quark Propagator



Perturbative Dressed-quark Propagator

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



Gap Equation

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First | Contents | Back | Conclusion

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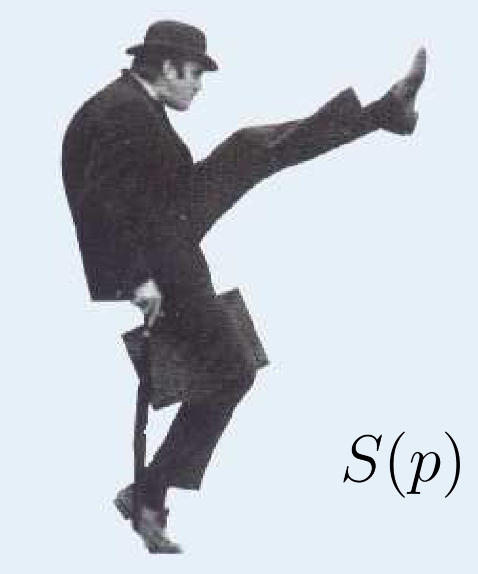

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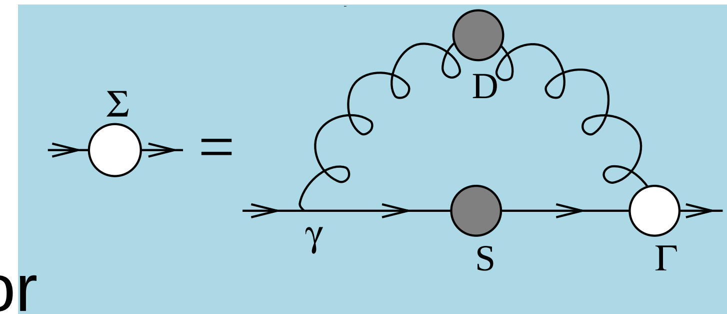
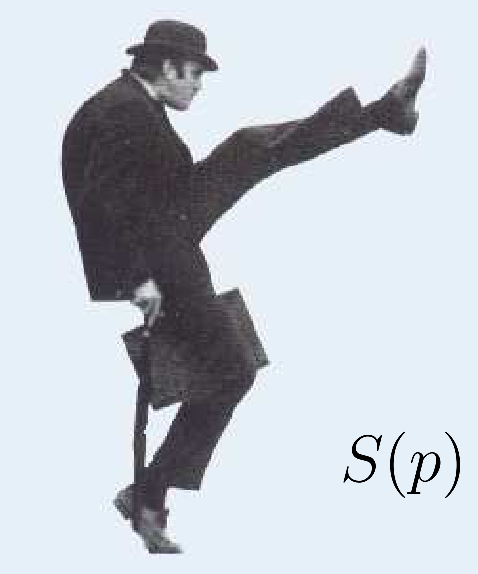


Gap Equation

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



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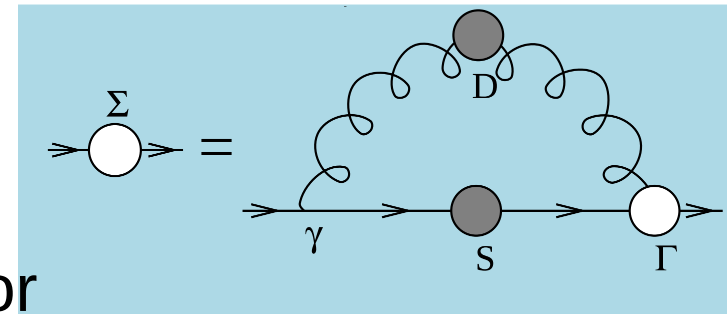

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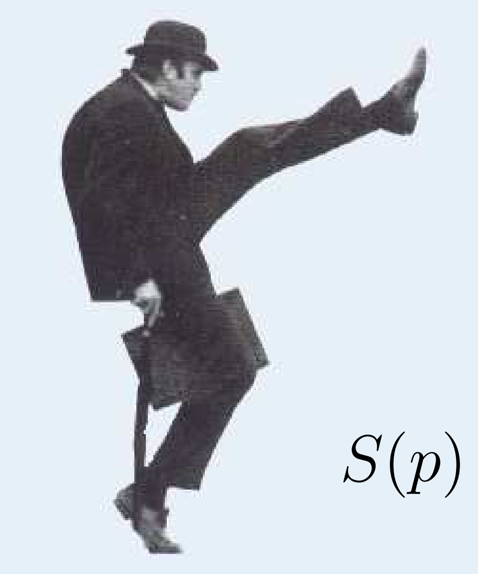
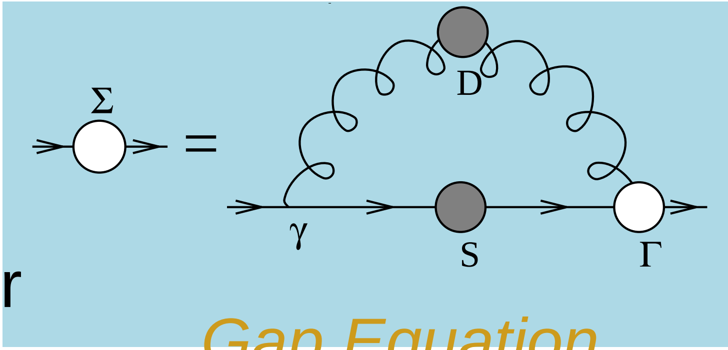
- Weak Coupling Expansion

  Reproduces Every Diagram in Perturbation Theory

Perturbative Dressed-quark Propagator



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



Gap Equation

- dressed-quark propagator

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

- Weak Coupling Expansion

  Reproduces Every Diagram in Perturbation Theory

- 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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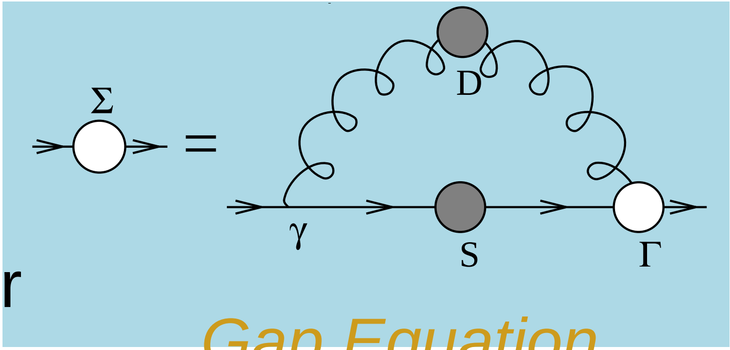

Gap Equation

- dressed-quark propagator

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No DCSB Here!

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Dressed-Quark Propagator

First Contents Back Conclusion

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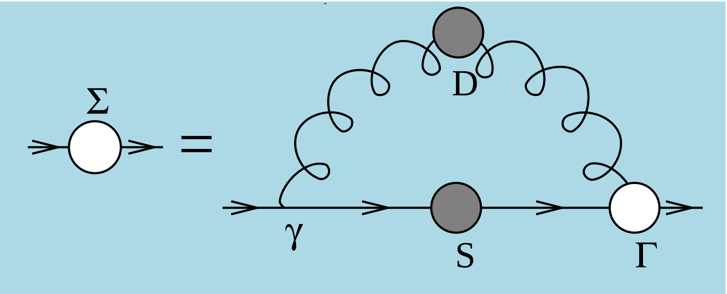

Gap Equation

First Contents Back Conclusion

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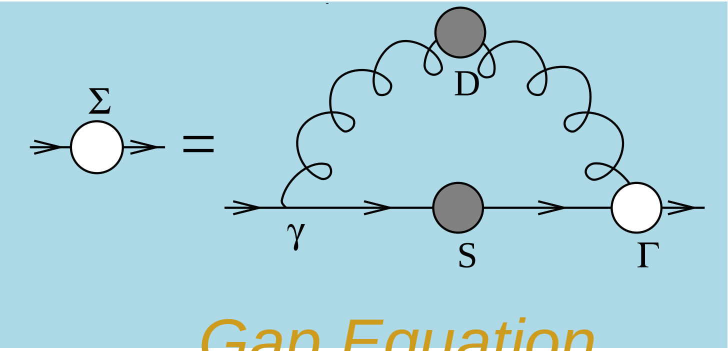
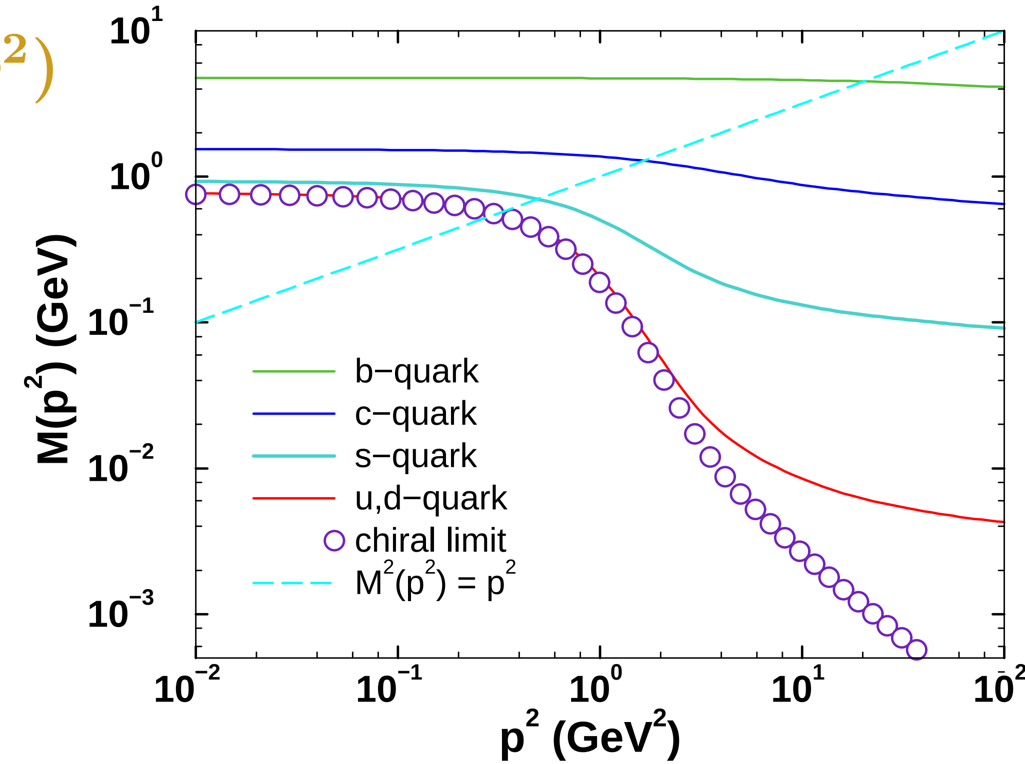


Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

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



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First | Contents | Back | Conclusion

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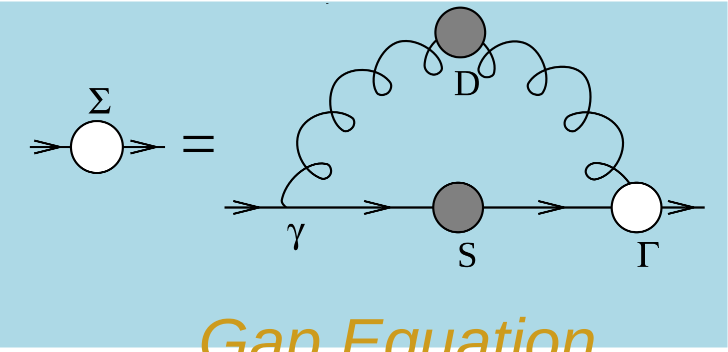

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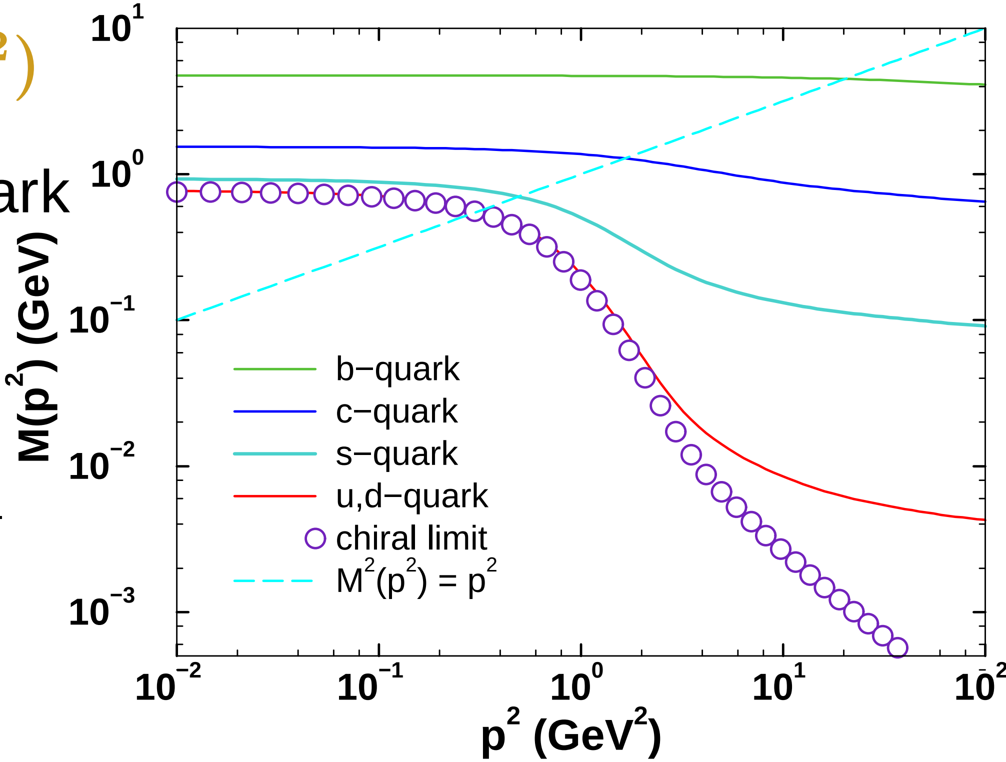

- Euclidean Constituent–Quark Mass: M_f^E: $p^2 = M(p^2)^2$

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

Dressed-Quark Propagator

- Longstanding Prediction of Dyson-Schwinger Equation Studies

First Contents Back Conclusion

Dressed-Quark Propagator

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  - E.g., *Dyson-Schwinger equations and their application to hadronic physics*,
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    33 (1994) 477

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First Contents Back Conclusion

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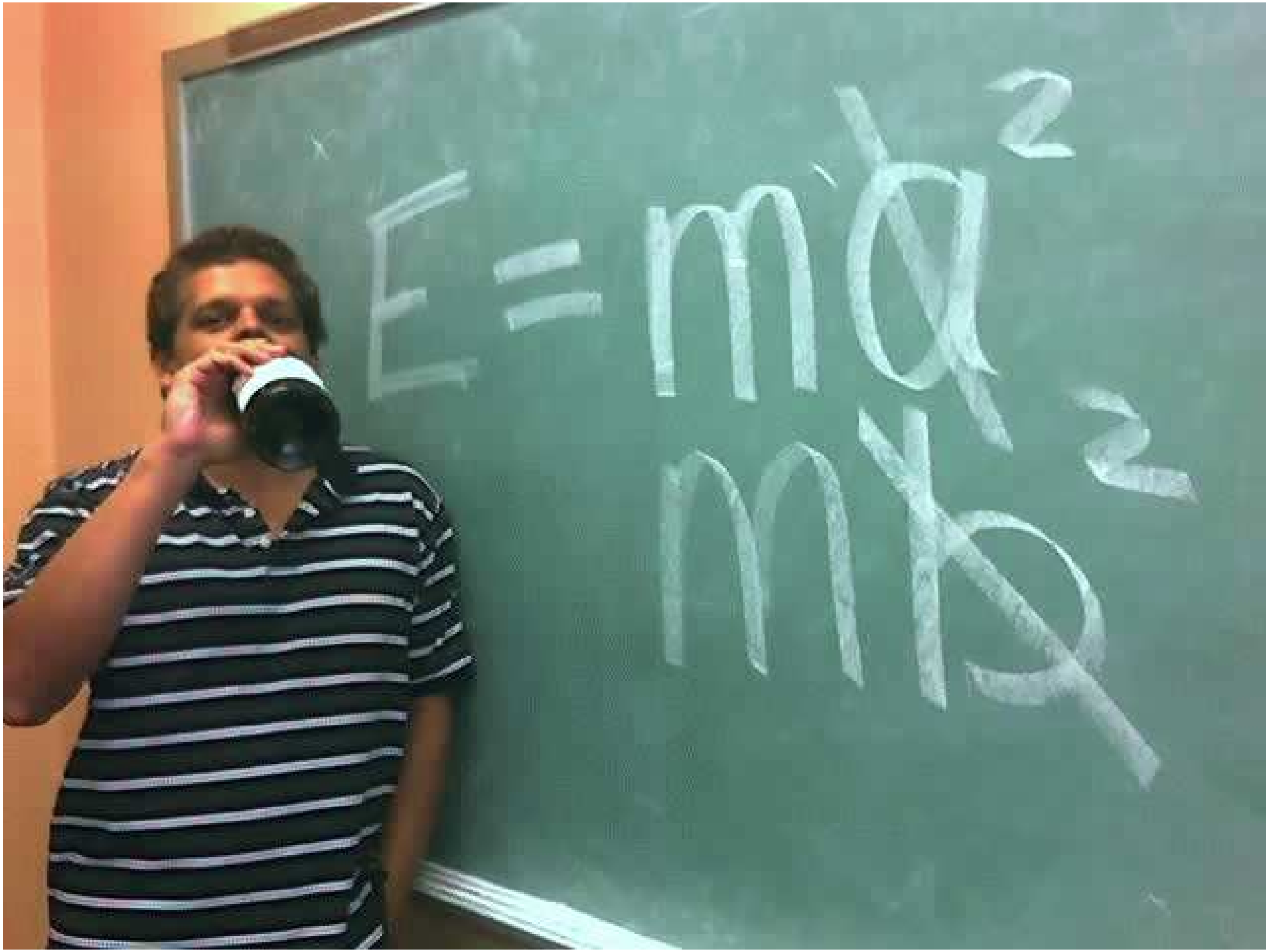
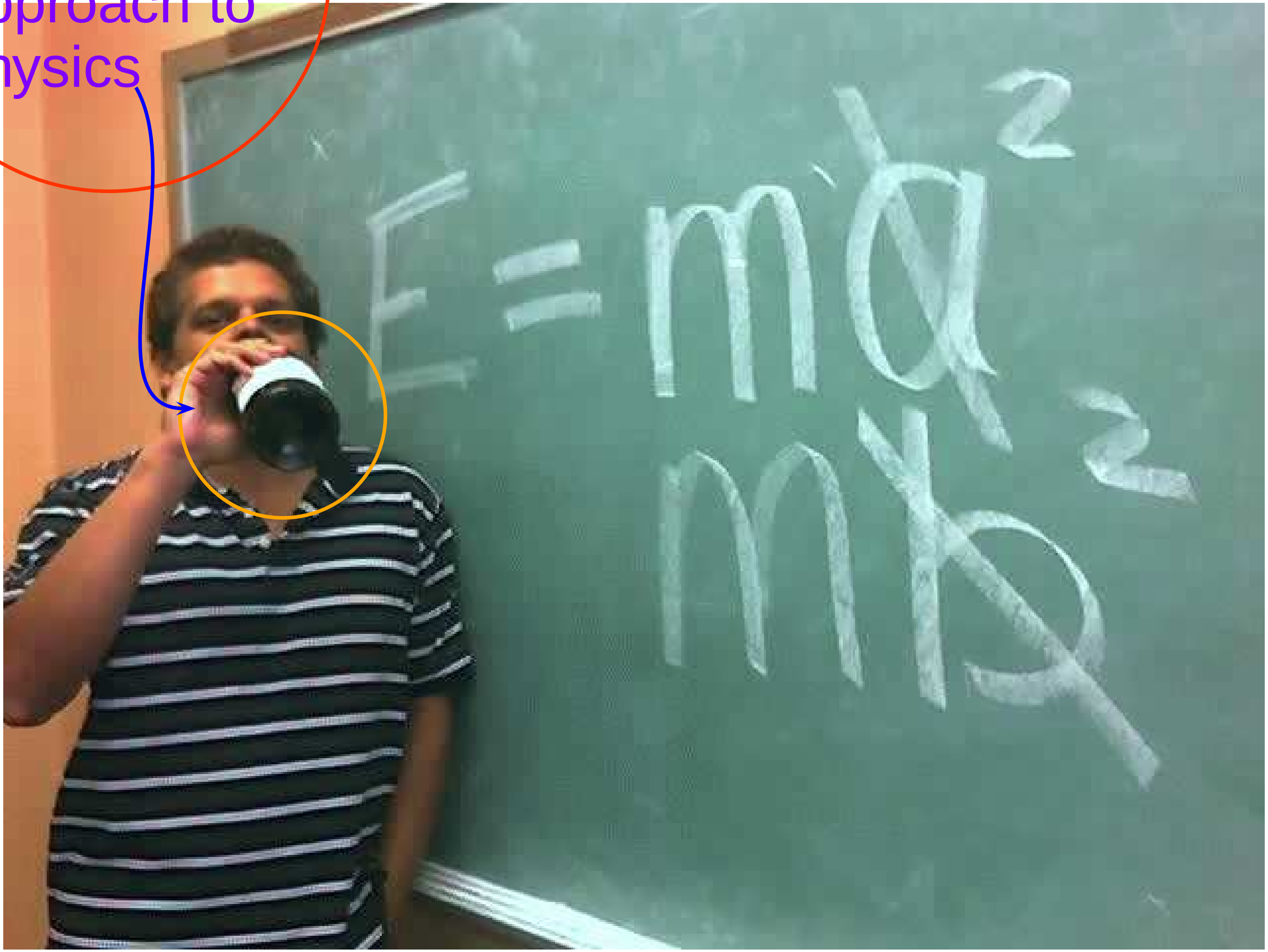
First | Contents | Back | Conclusion

Mandar Bhagwat



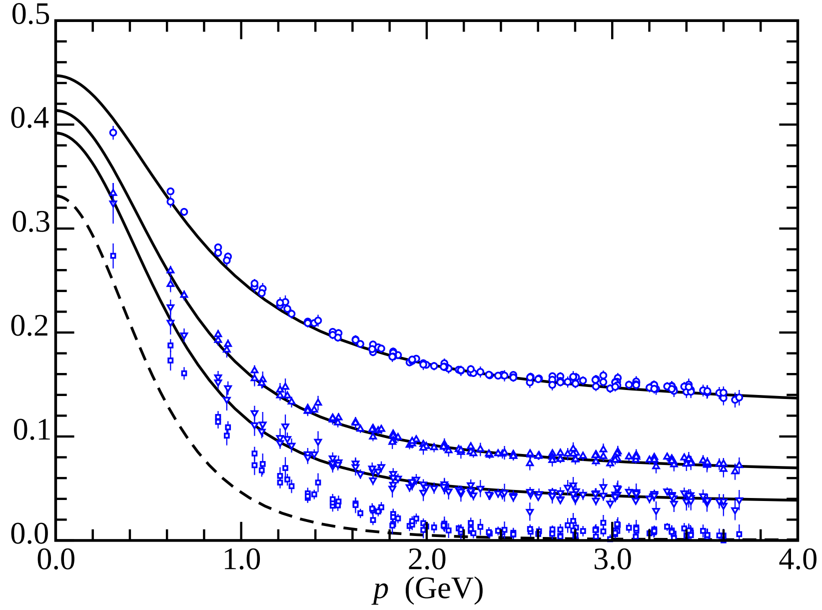
Mandar Bhagwat

Emulating supervisor's approach to physics

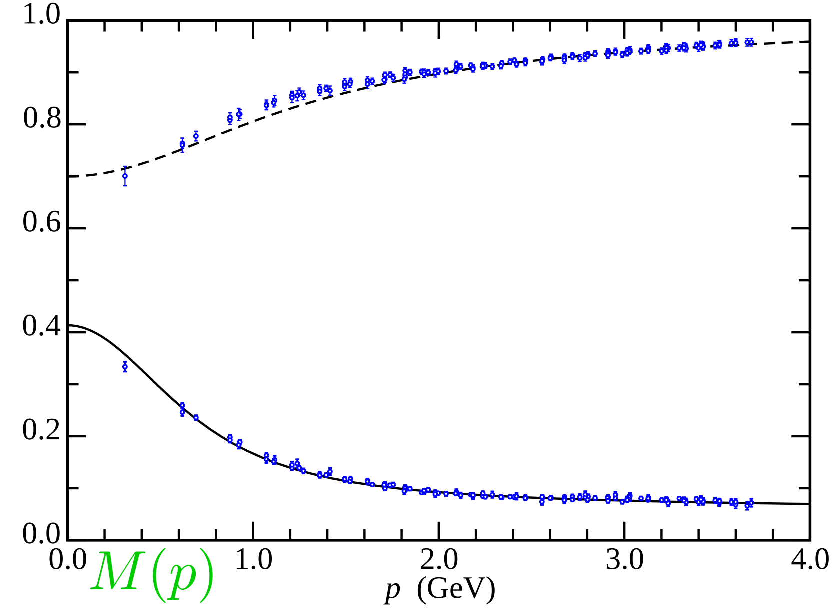


Quenched-QCD Dressed-Quark Propagator

$M(p)$



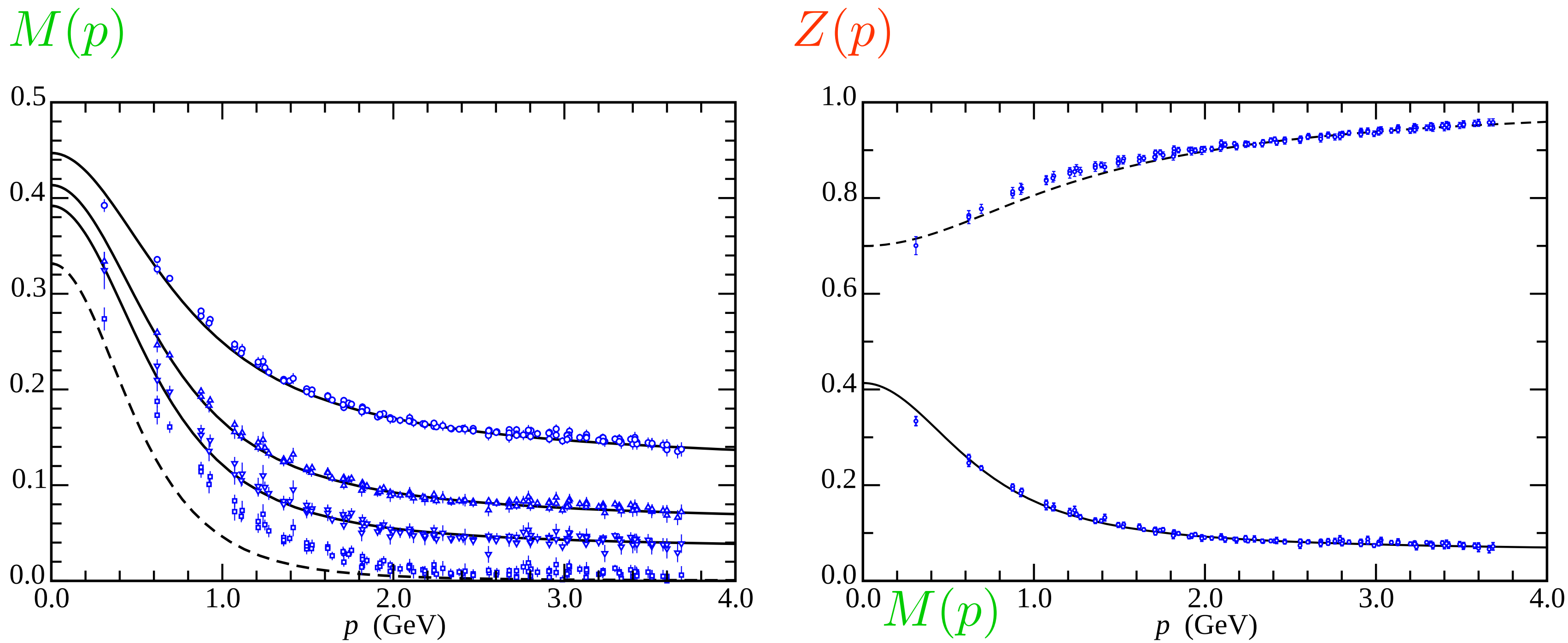
$Z(p)$



First Contents Back Conclusion

Quenched-QCD Dressed-Quark Propagator

2002



- "*data*:" Quenched Lattice Meas.
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2002

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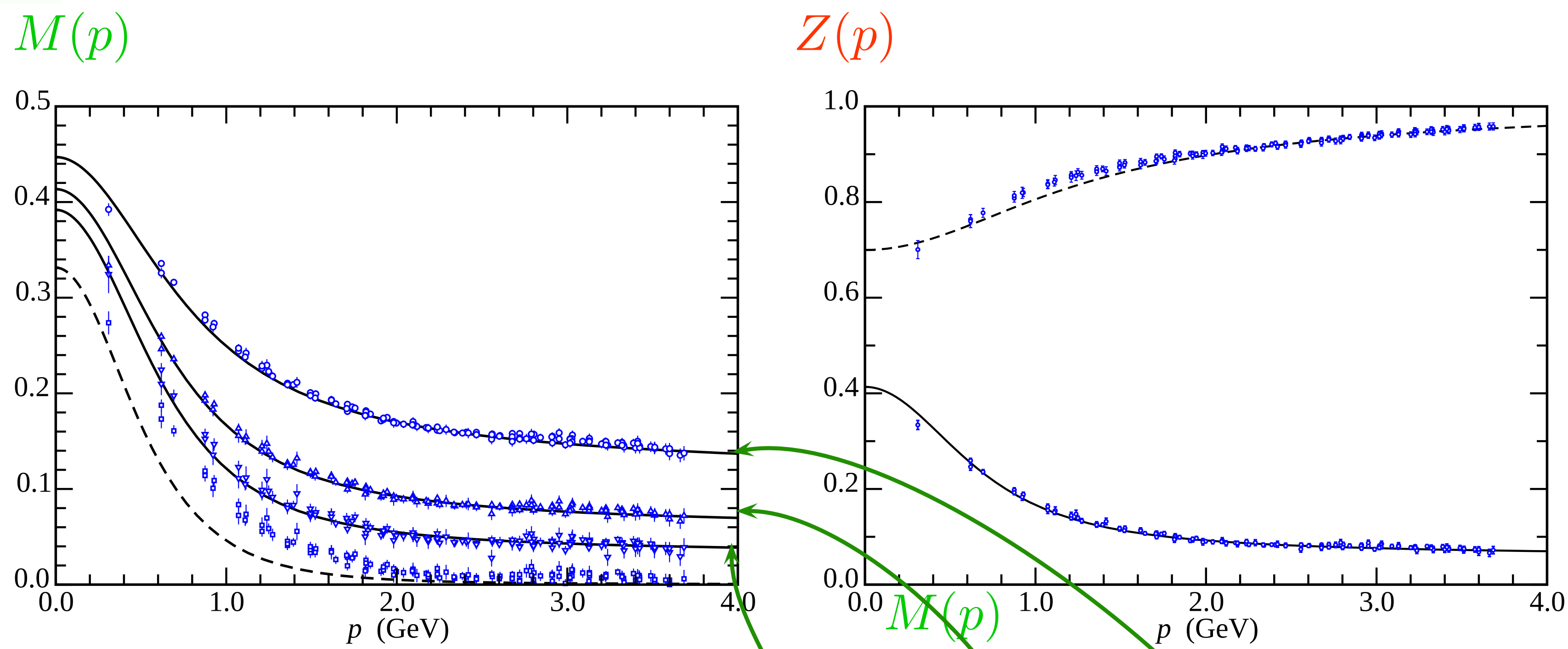

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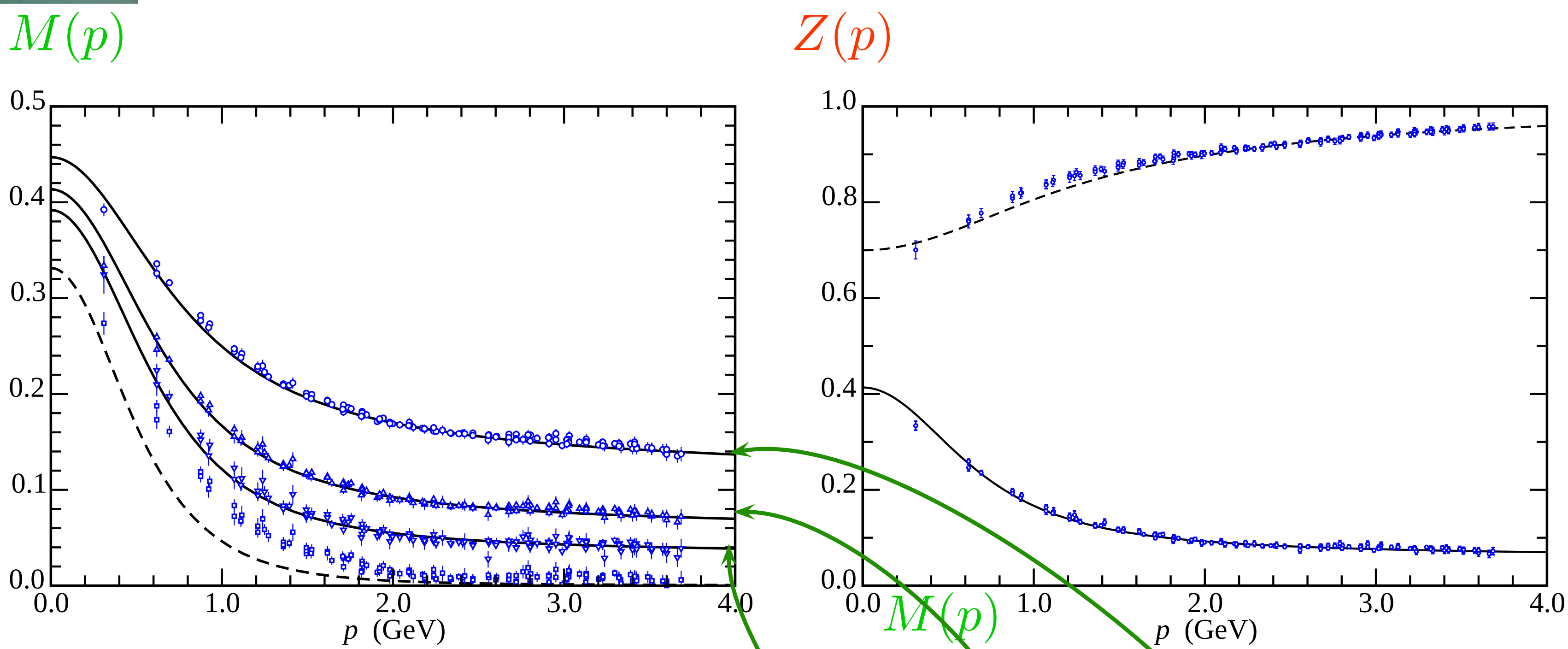

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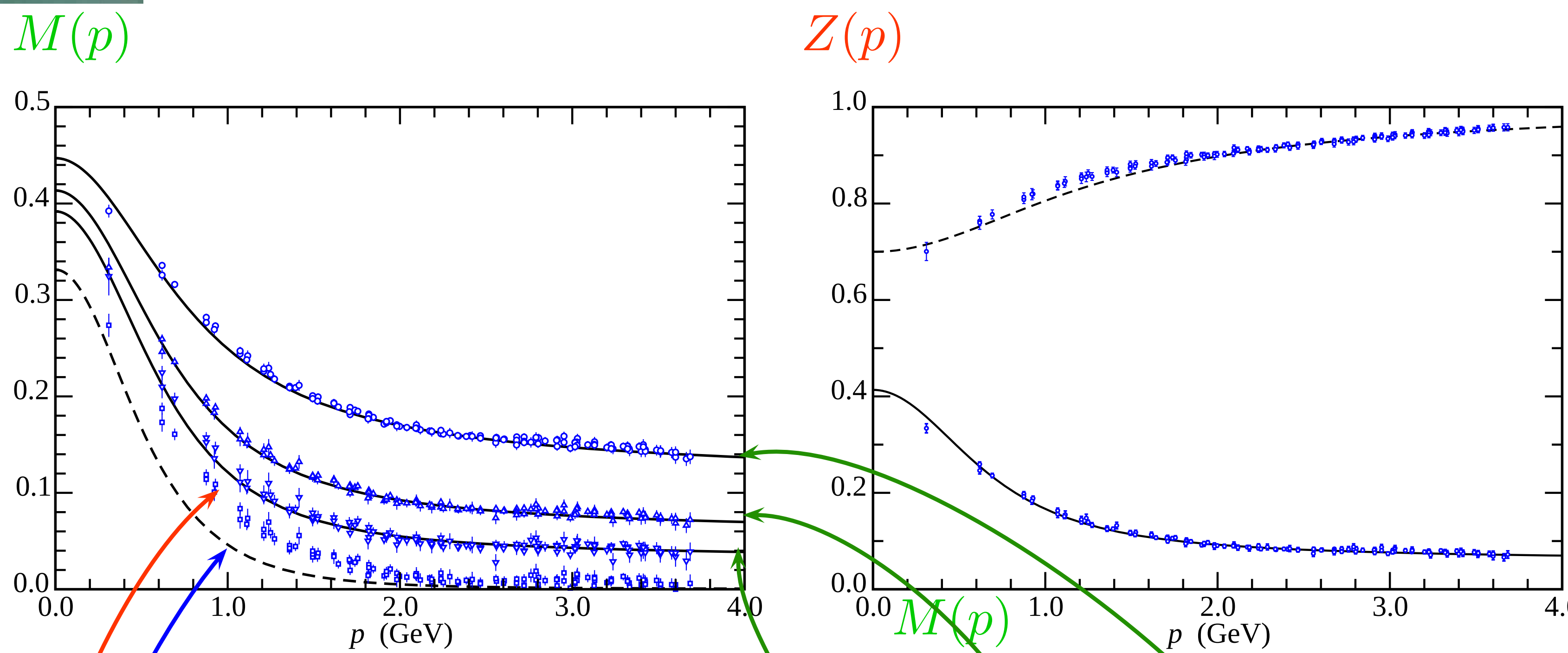
2002

Quenched-QCD Dressed-Quark Propagator



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- Linear extrapolation of lattice data to chiral limit is inaccurate

First | Contents | Back | Conclusion

QCD & Interaction Between Light-Quarks

- Kernel of Gap Equation: $D_{\mu\nu}(p-q)\,\Gamma_\nu(q)$
  Dressed-gluon propagator and dressed-quark-gluon vertex
- Reliable DSE studies of Dressed-gluon propagator:
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- Dressed-gluon propagator – lattice-QCD simulations confirm that behaviour:
  - D. B. Leinweber, J. I. Skullerud, A. G. Williams and C. Parrinello [UKQCD Collaboration], *Asymptotic scaling and infrared behavior of the gluon propagator*, Phys. Rev. D **60**, 094507 (1999) [Erratum-ibid. D **61**, 079901 (2000)].
- Exploratory DSE and lattice-QCD studies of dressed-quark-gluon vertex

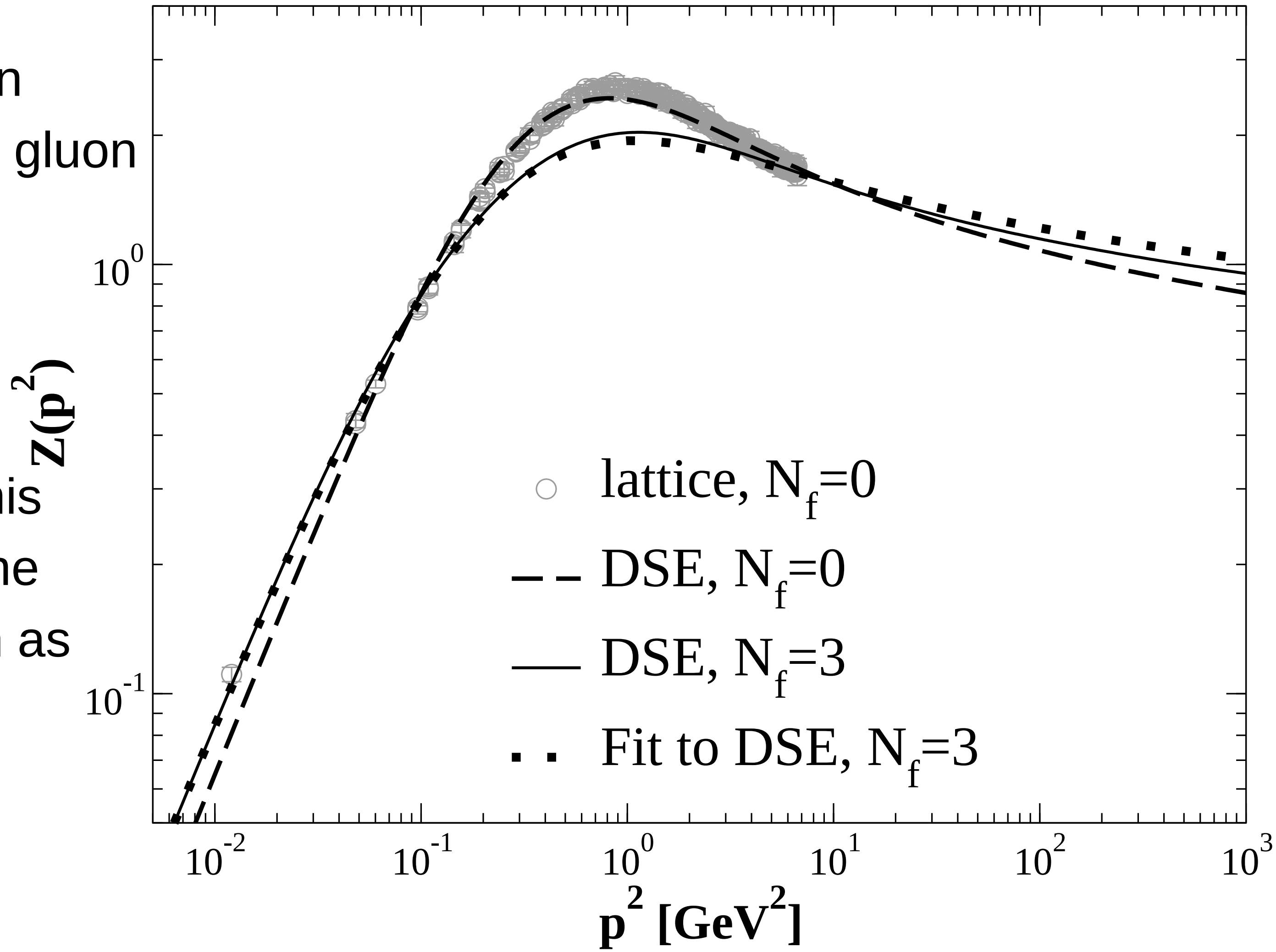
Alkofer, Detmold, Fischer, Maris: he-ph/0309078

Dressed-gluon Propagator

- $$D_{\mu\nu}(k) = \left(\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}\right)\frac{Z(k^2)}{k^2}$$

- Suppression means $\exists$ IR gluon mass-scale ≈ 1 GeV

- Naturally, this scale has the same origin as $\Lambda_{\rm QCD}$



First Contents Back Conclusion

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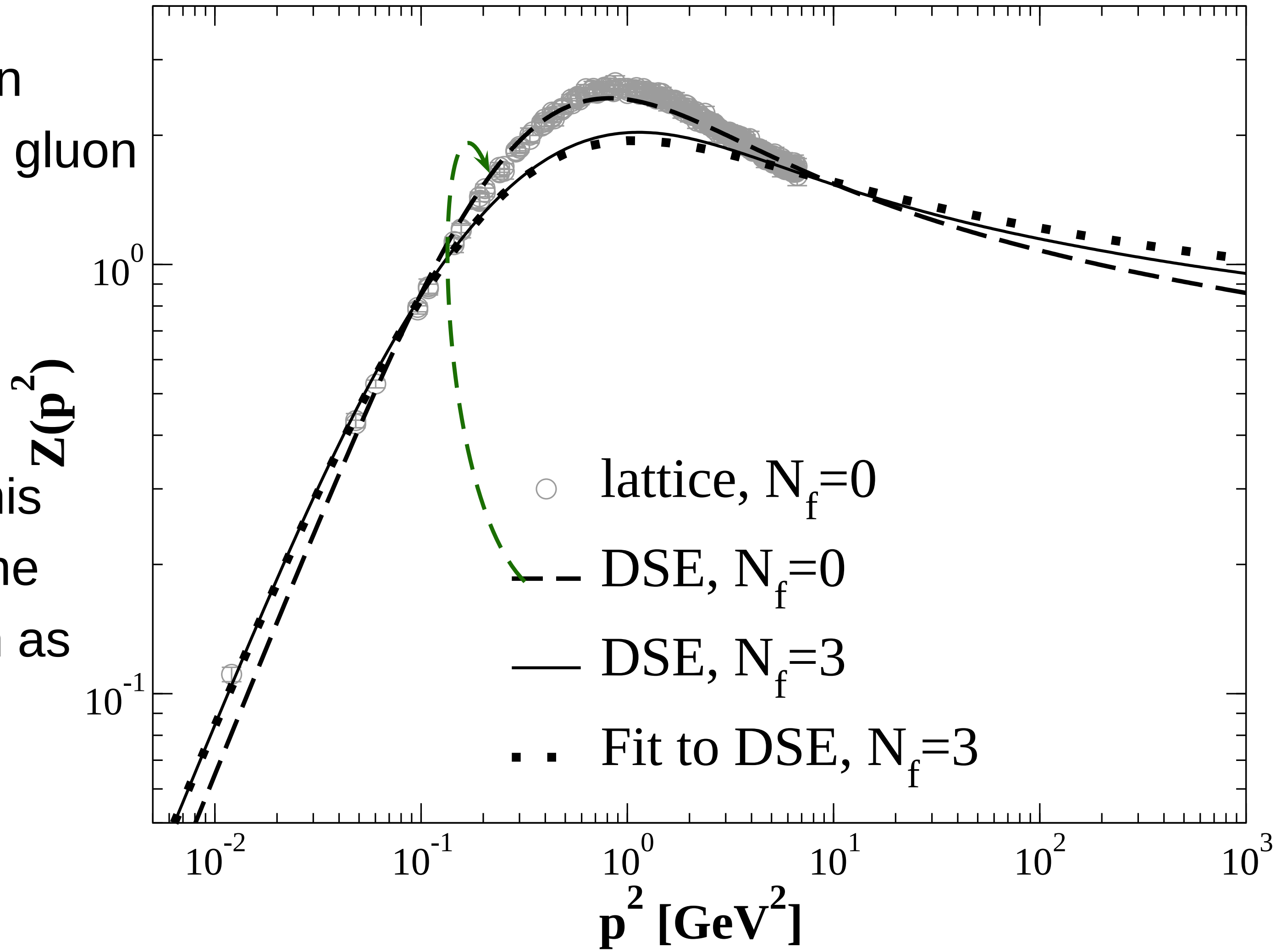

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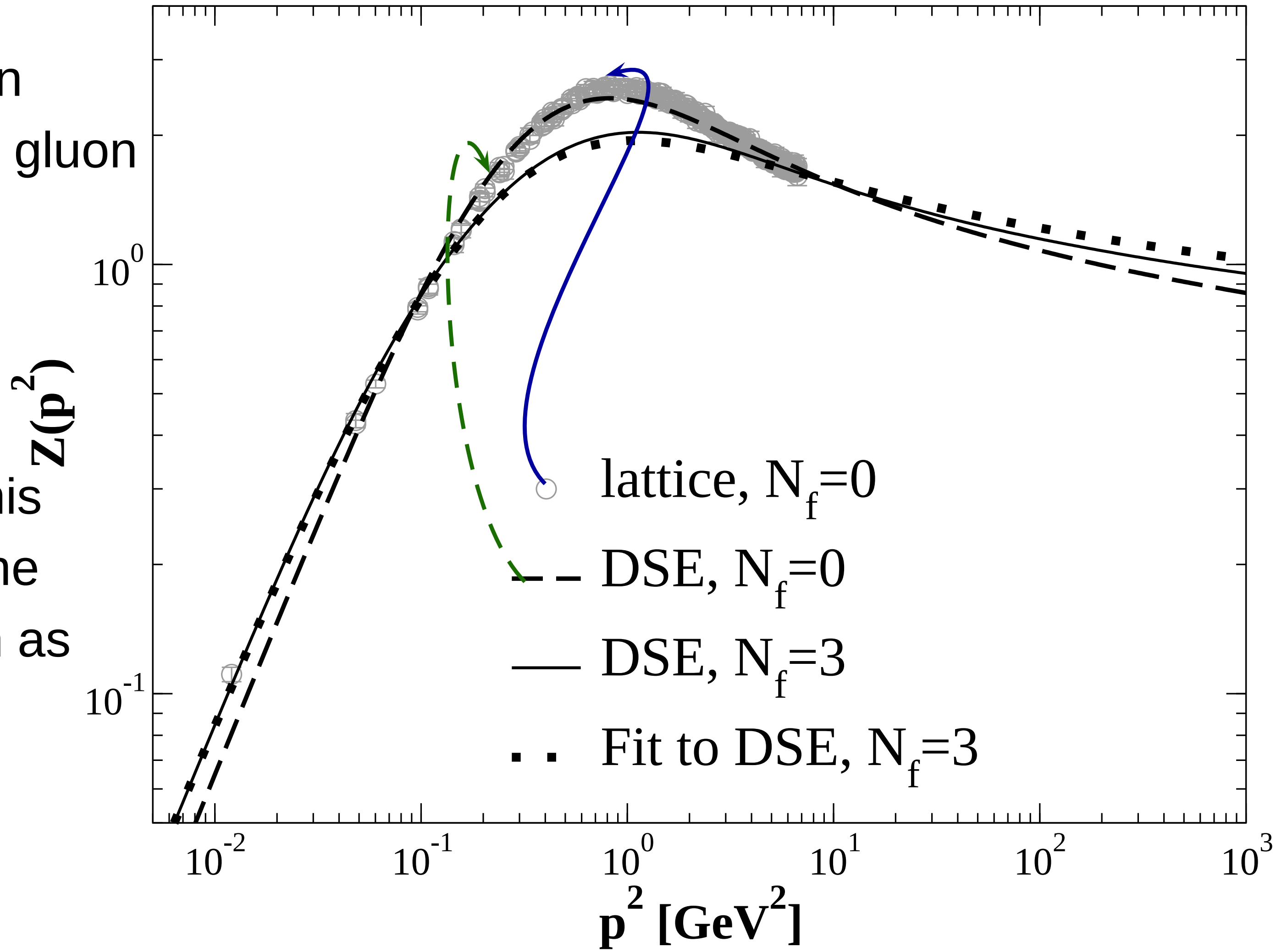

First Contents Back Conclusion

Hadrons

- Established understanding of two- and three-point functions

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- What about bound states?

- Without bound states, Comparison with experiment is impossible

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  Comparison with experiment is
  impossible
- They appear as pole contributions to $n \geq 3$-point colour-singlet Schwinger functions

- Without bound states, Comparison with experiment is impossible

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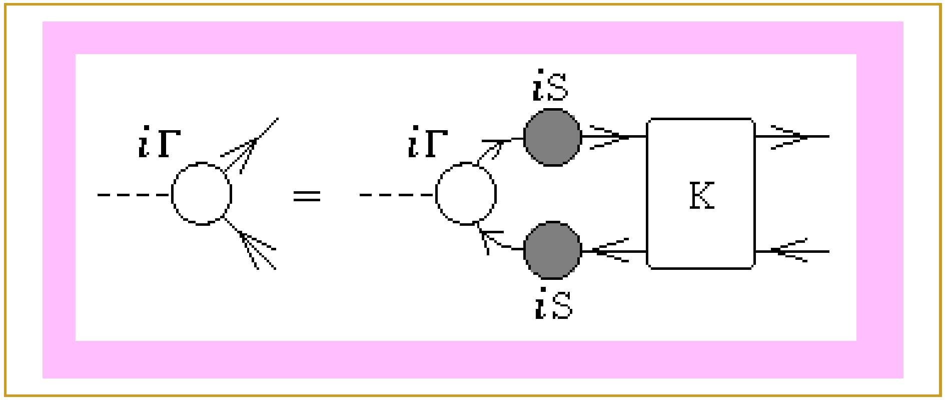

QFT Generalisation of Lippmann-Schwinger Equation.

- Without bound states, Comparison with experiment is impossible
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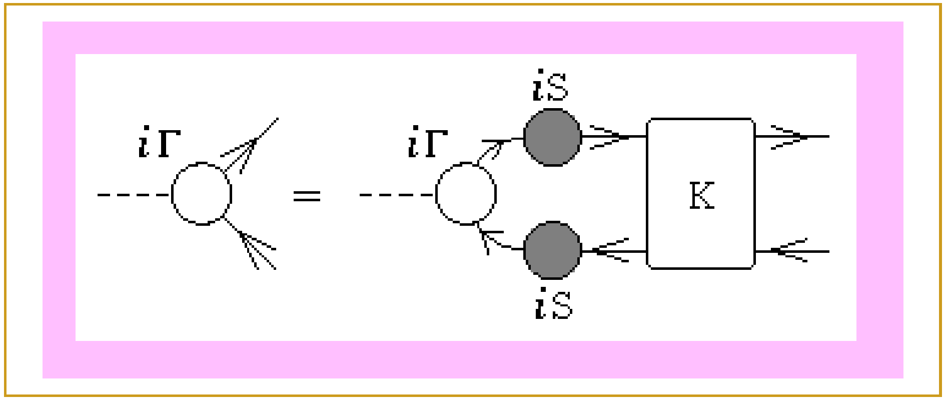

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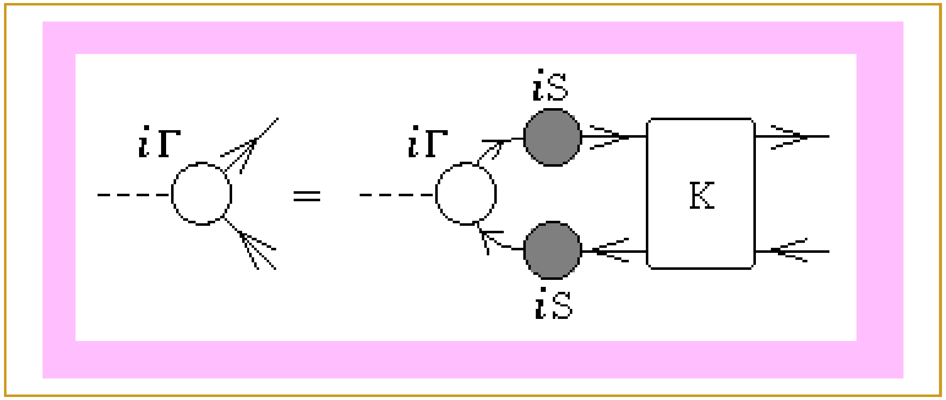

QFT Generalisation of Lippmann-Schwinger Equation.

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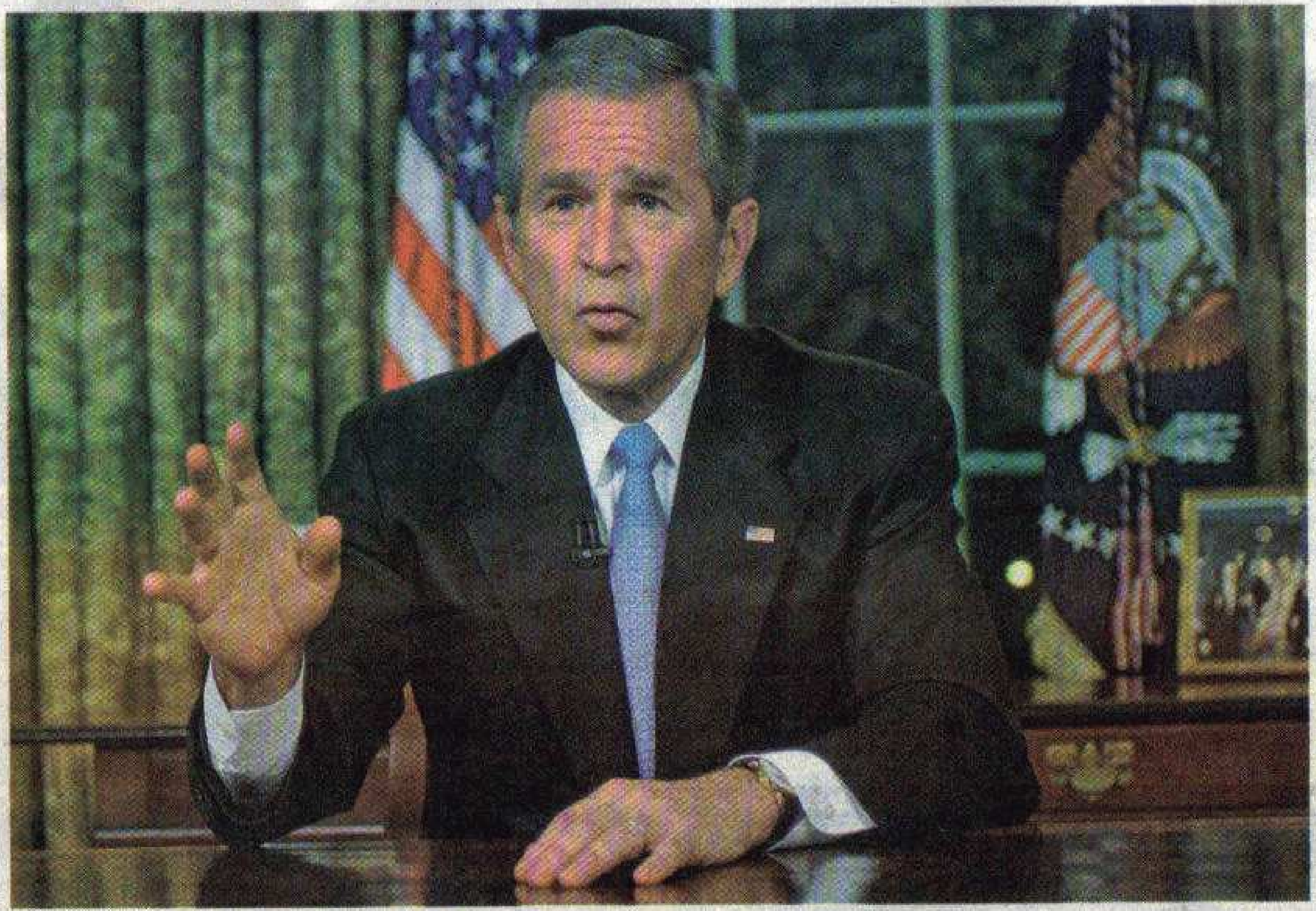
or

What is the Long-Range Potential?

First Contents Back Conclusion

What is the Long-Range Potential?

Bush Urges Nation To Be Quiet For A Minute While He Tries To Think



In a televised address to the nation, Bush called for "a little peace and quiet."

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First | Contents | Back | Conclusion

Bethe-Salpeter Kernel

Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

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

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

QFT Statement of Chiral Symmetry

Bethe-Salpeter Kernel

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Satisfies BSE — Satisfies DSE

Kernels must be intimately related

First · Contents · Back · Conclusion

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Satisfies BSE — Satisfies DSE

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- Nontrivial constraint

First | Contents | Back | Conclusion

Bethe-Salpeter Kernel

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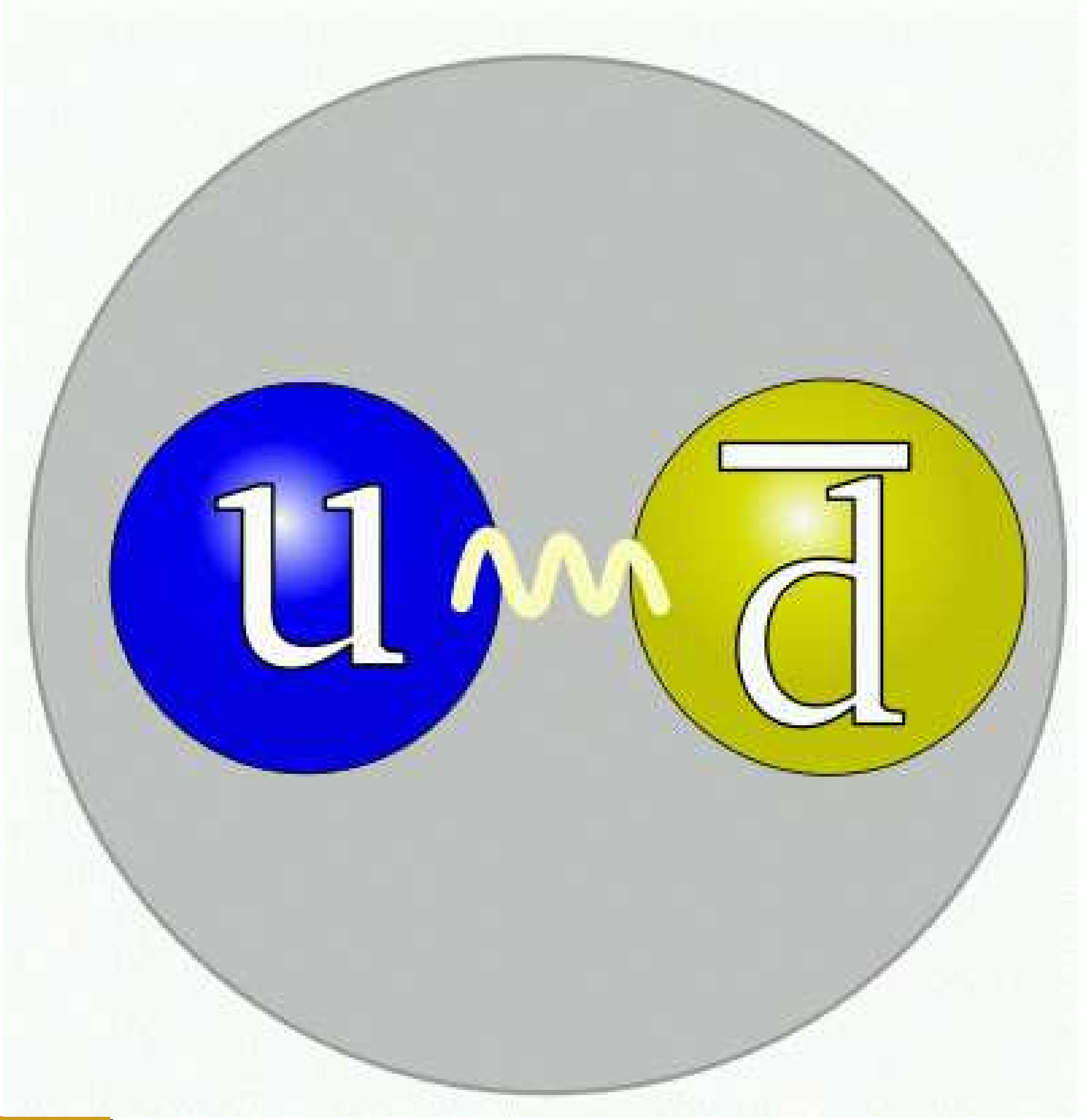
- Relation must be preserved by truncation
- Failure $\Rightarrow$ Explicit Violation of QCD's Chiral Symmetry

First | Contents | Back | Conclusion

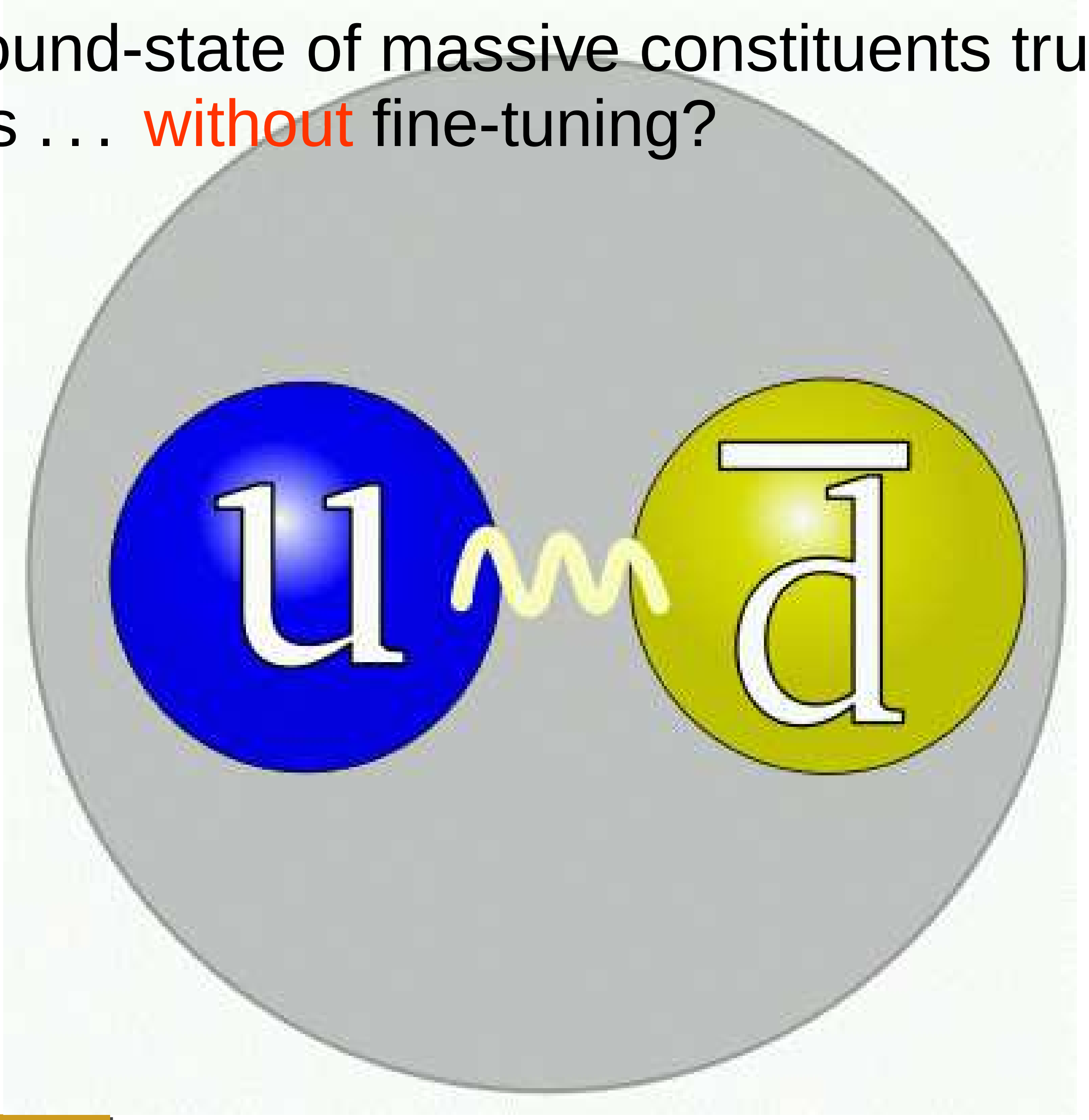
Pion and . . .

Pseudoscalar Mesons?



First Contents Back Conclusion

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



Radial Excitations & Chiral Symmetry

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$$f_H \; m_H^2 = - \; \rho_\zeta^H \; \mathcal{M}_H$$

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- Mass^2 of pseudoscalar hadron

Radial Excitations & Chiral Symmetry

$$f_H \; m_H^2 = - \; \rho_\zeta^H \; \mathcal{M}_H$$

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

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

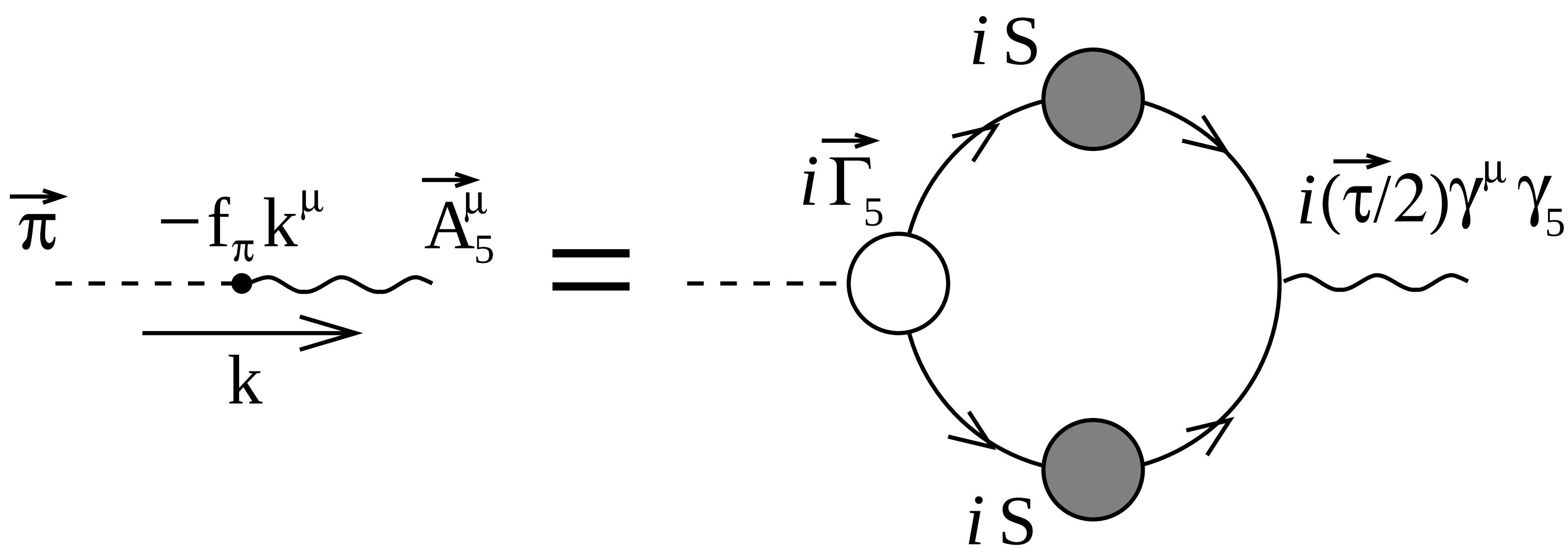
First Contents Back Conclusion

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

$$f_H \, m_H^2 = - \, \rho_\zeta^H \, \mathcal{M}_H$$

$$f_H \, p_\mu = Z_2 \int_q^\Lambda \tfrac{1}{2} \mathrm{tr} \left\{ \left(T^H\right)^{\mathrm{t}} \gamma_5 \gamma_\mu \, \mathcal{S}(q_+) \Gamma_H(q;P) \mathcal{S}(q_-) \right\}$$

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



Radial Excitations & Chiral Symmetry

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First Contents Back Conclusion

Radial Excitations & Chiral Symmetry

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

$$f_H \; m_H^2 = - \; \rho_\zeta^H \; \mathcal{M}_H$$

- Light-quarks; i.e., $m_q \sim 0$
  - $f_H \to f_H^0$ & $\rho_\zeta^H \to \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{f_H^0}$, Independent of m_q

Hence $m_H^2 = \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{(f_H^0)^2} m_q$ ...GMOR relation, a corollary

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

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  Hence $m_H^2 = \dfrac{-\langle \bar{q}q \rangle_\zeta^0}{(f_H^0)^2}\, m_q$ ...GMOR relation, a corollary
- Heavy-quark + light-quark

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

  Hence, $m_H \propto m_q$

  ... QCD Proof of Potential Model result

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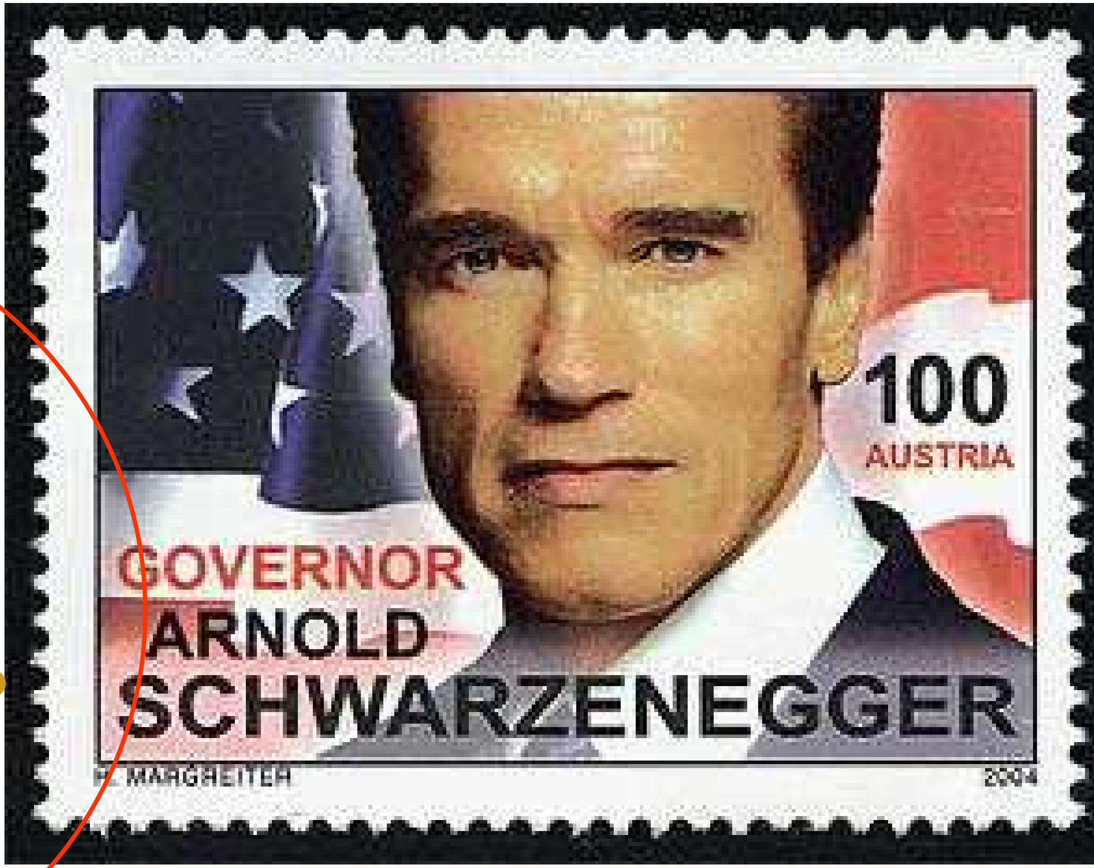
First Contents Back Conclusion

Andreas Krassnigg

FWF "Erwin Schrödinger Fellow," ANL 2003-2005

First | Contents | Back | Conclusion

Almost Blood Relative of Arnold
. . . Future
President?
. . . Executioner?



Radial Excitations & Chiral Symmetry

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- Valid for ALL Pseudoscalar mesons

Höll, Krassnigg, Roberts
nu-th/0406030

Radial Excitations & Chiral Symmetry

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Höll, Krassnigg, Roberts
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- "radial" excitation of π-meson,
  $\boldsymbol{m^2_{\pi_{n\neq 0}} > m^2_{\pi_{n=0}} = 0}$, in chiral limit

First Contents Back Conclusion

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- $\Rightarrow \boldsymbol{f_H = 0}$
  ALL pseudoscalar mesons except $\boldsymbol{\pi(140)}$ in chiral limit

First | Contents | Back | Conclusion

Höll, Krassnigg, Roberts
nu-th/0406030

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$$f_H \; m_H^2 = - \; \rho_\zeta^H \; \mathcal{M}_H$$

- Valid for ALL Pseudoscalar mesons
- $\rho_H \Rightarrow$ finite, nonzero value in chiral limit, $\mathcal{M}_H \to 0$
- "radial" excitation of π-meson,
  $\boldsymbol{m^2_{\pi_{n\neq 0}} > m^2_{\pi_{n=0}} = 0}$, in chiral limit
- $\Rightarrow \boldsymbol{f_H = 0}$
  ALL pseudoscalar mesons except $\boldsymbol{\pi(140)}$ in chiral limit
- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

  impacts upon *every* pseudoscalar meson

Radial Excitations

First Contents Back Conclusion

Radial Excitations

- Spectrum contains 3 pseudoscalars [$I^G(J^P)L = 1^-(0^-)S$]

  masses below 2 GeV: $\boldsymbol{\pi(140)}$; $\boldsymbol{\pi(1300)}$; and $\boldsymbol{\pi(1800)}$

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  $S_{\bar{Q}Q} = 1 \oplus L_F = 1 \Rightarrow J = 0$
  & $L_F = 1 \Rightarrow\ {}^3S_1 \oplus\ {}^3S_1$ ($\bar{Q}Q$) decays suppressed?

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- NSAC Long-Range Plan, 2002: . . . an understanding of confinement "remains one of the greatest intellectual challenges in physics"

Radial Excitations & Chiral Symmetry

First Contents Back Conclusion

Radial Excitations & Chiral Symmetry

- Fundamental properties of QCD

Radial Excitations & Chiral Symmetry

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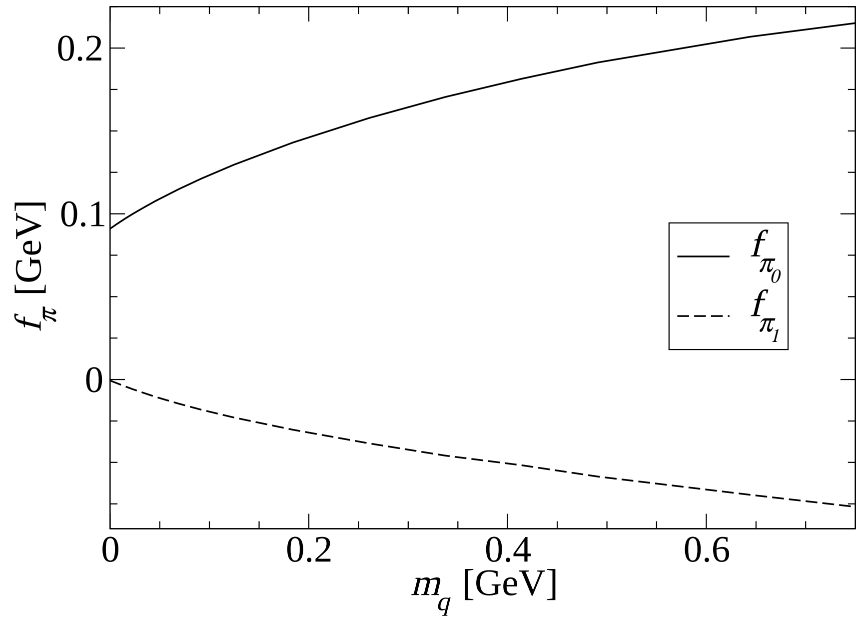
  - If chiral symmetry is dynamically broken, then in the chiral limit every pseudoscalar meson is blind to the weak interaction *except* $\pi(140)$.



Radial Excitations & Chiral Symmetry

- Fundamental properties of QCD
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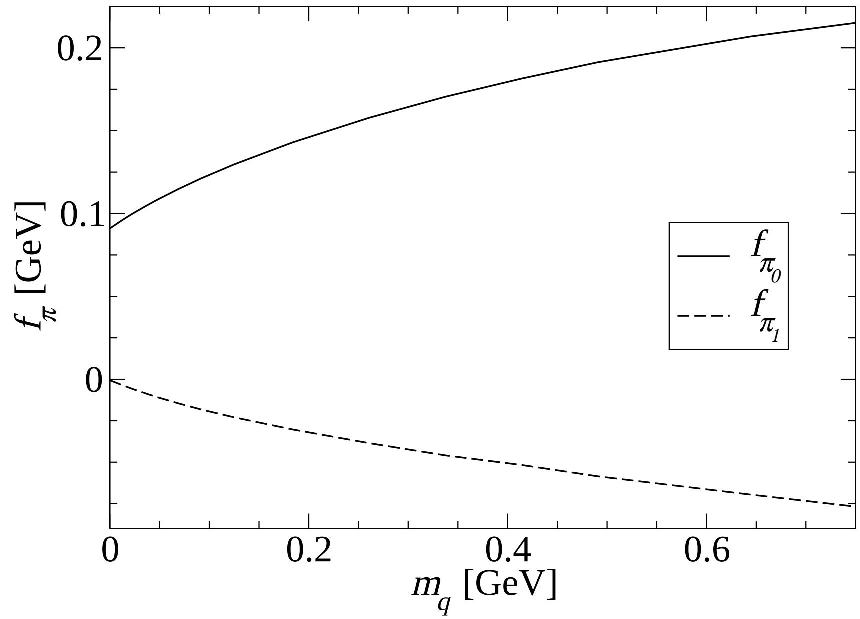
  - If chiral symmetry is not broken, then *NO pseudoscalar meson experiences the weak interaction.*



McNeile and Michael
he-la/0607032

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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

Radial Excitations & Lattice-QCD

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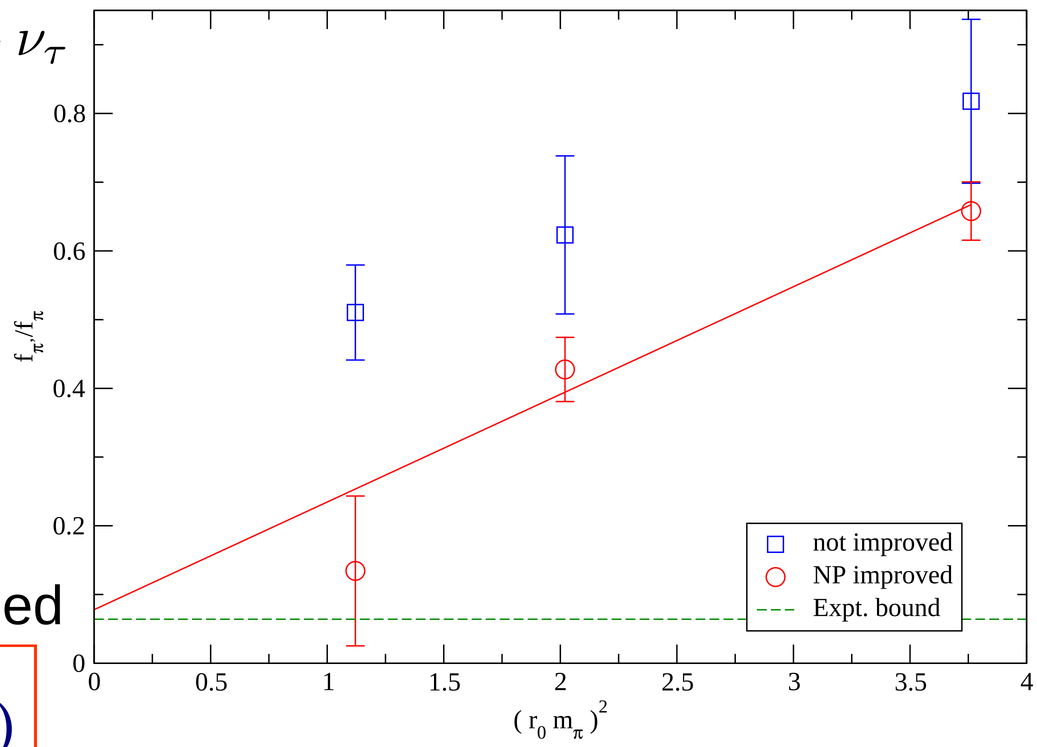
$$\Rightarrow \frac{f_{\pi_1}}{f_\pi} = \mathbf{0.078\,(93)}$$



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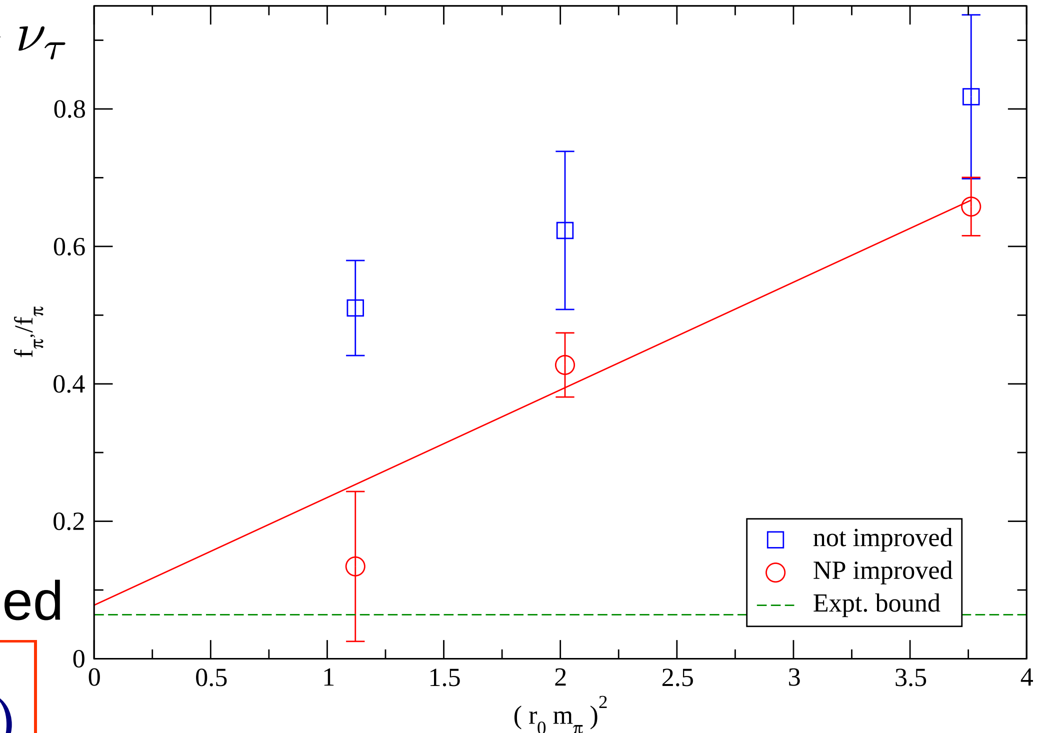

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

Radial Excitations & Lattice-QCD

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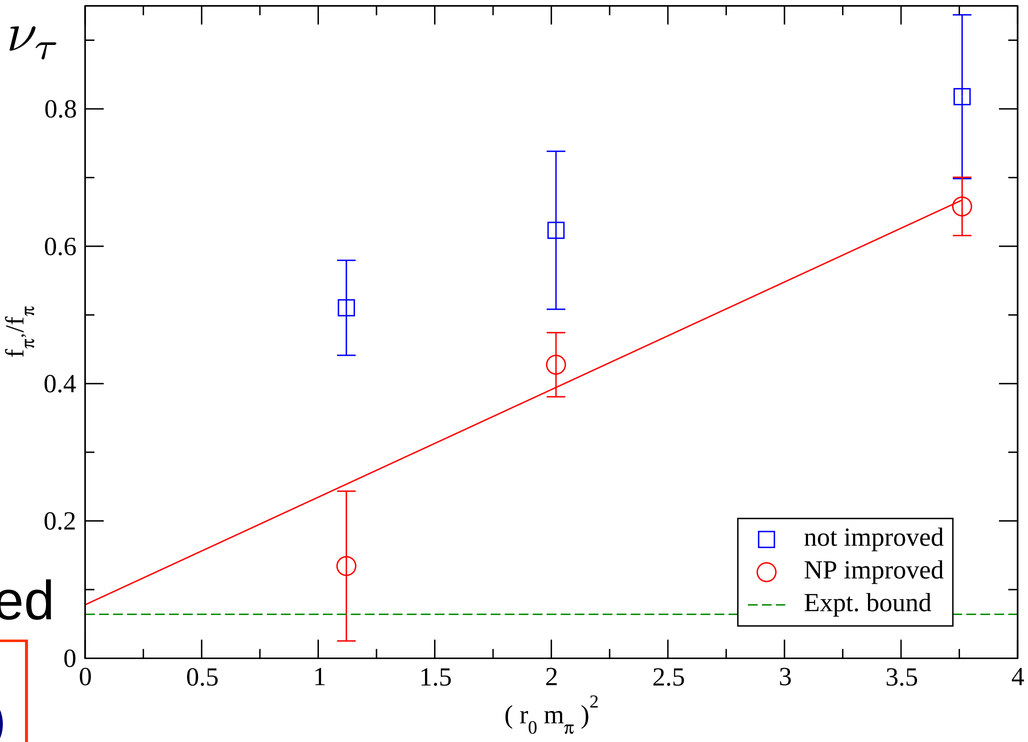
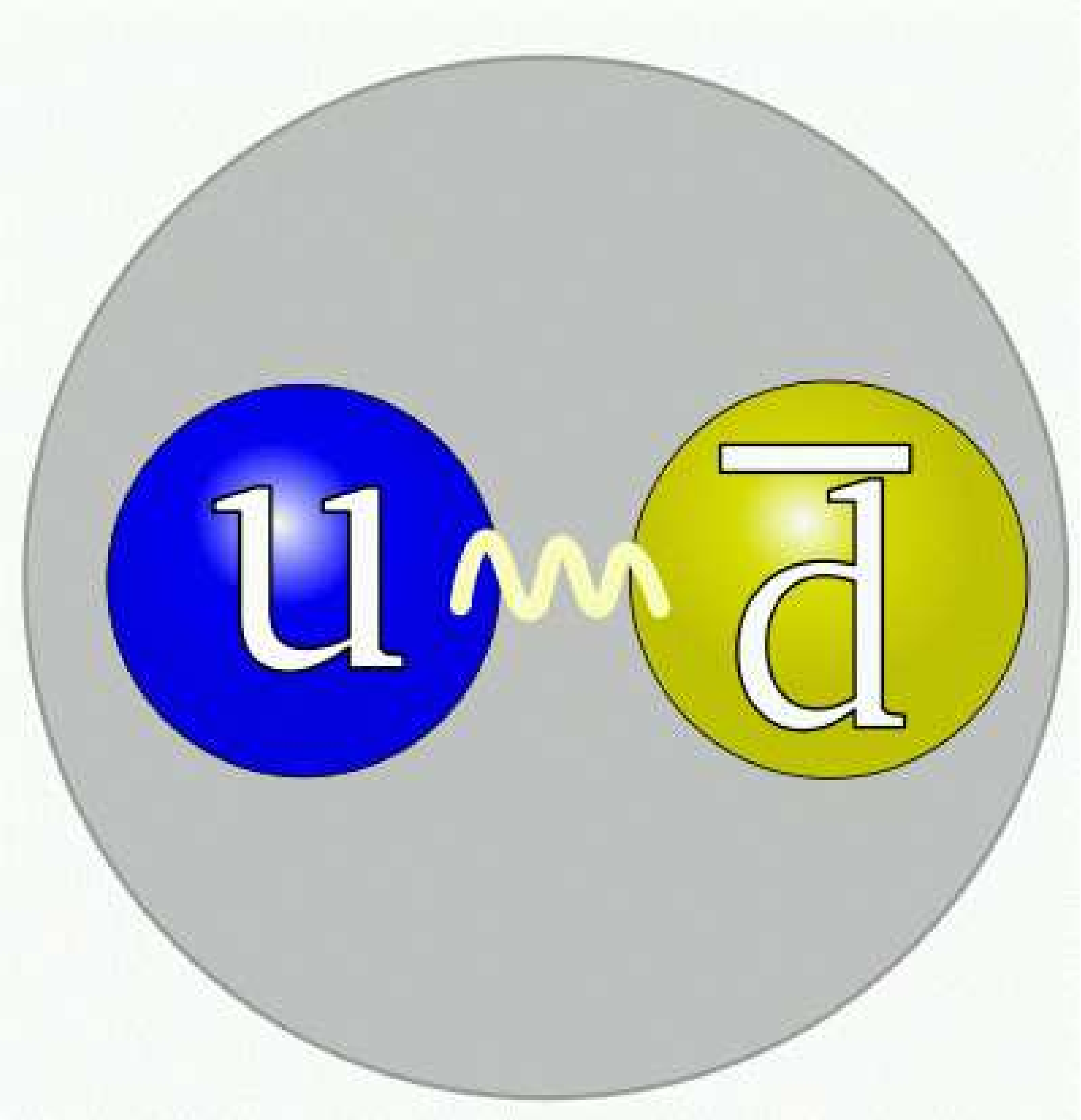


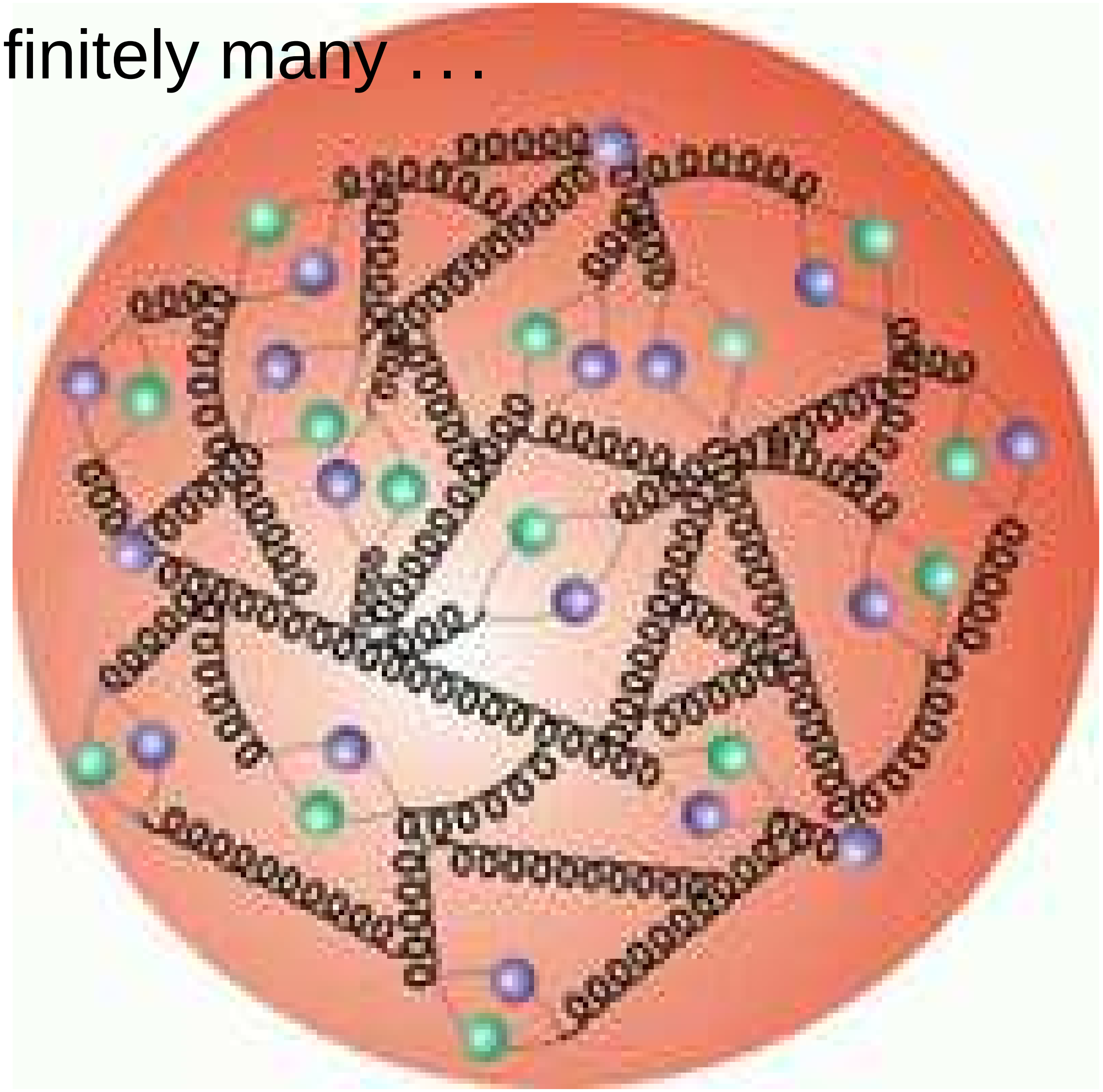
- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

Answer for the pion



Answer for the pion

Two → Infinitely many . . .



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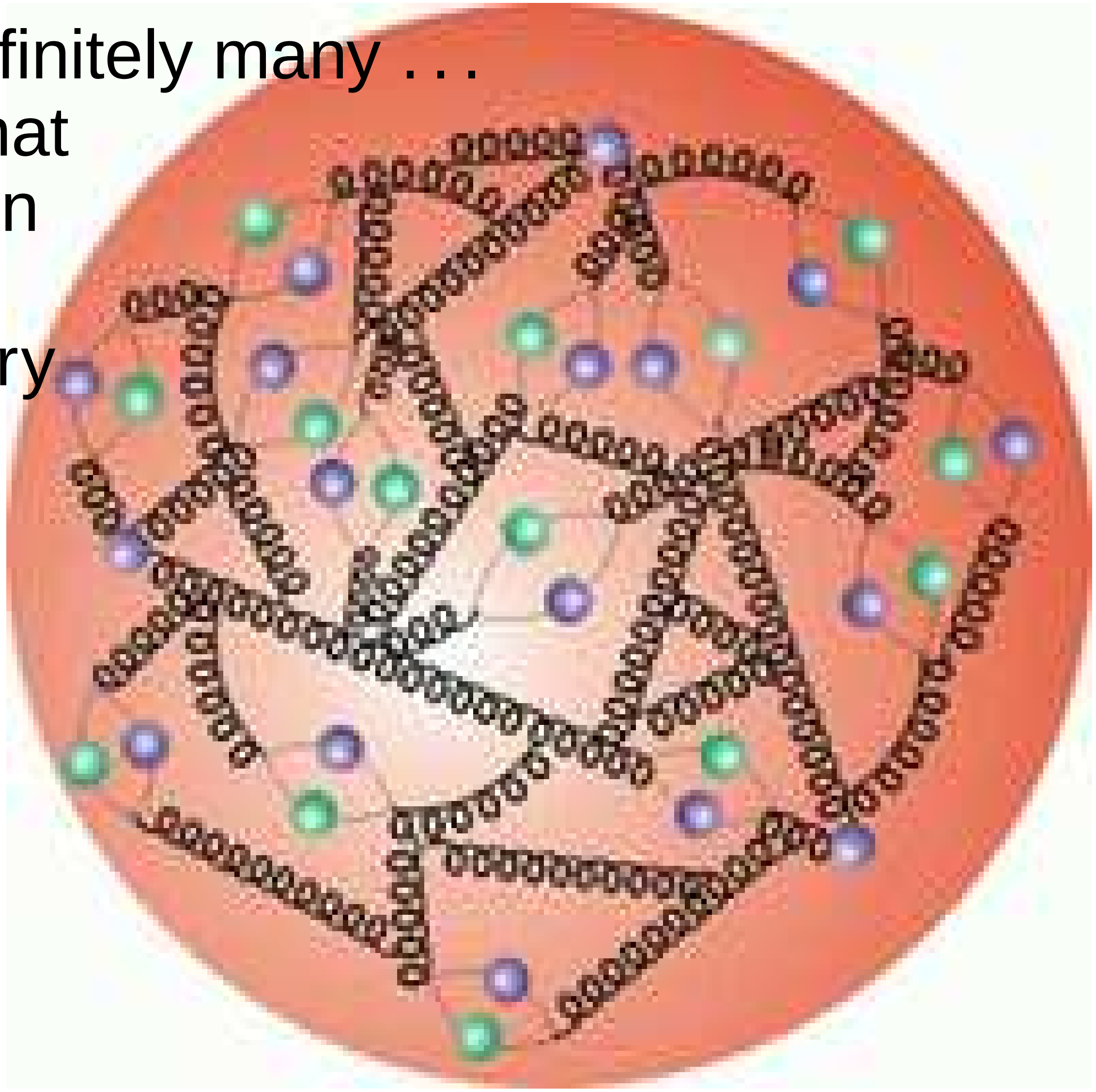

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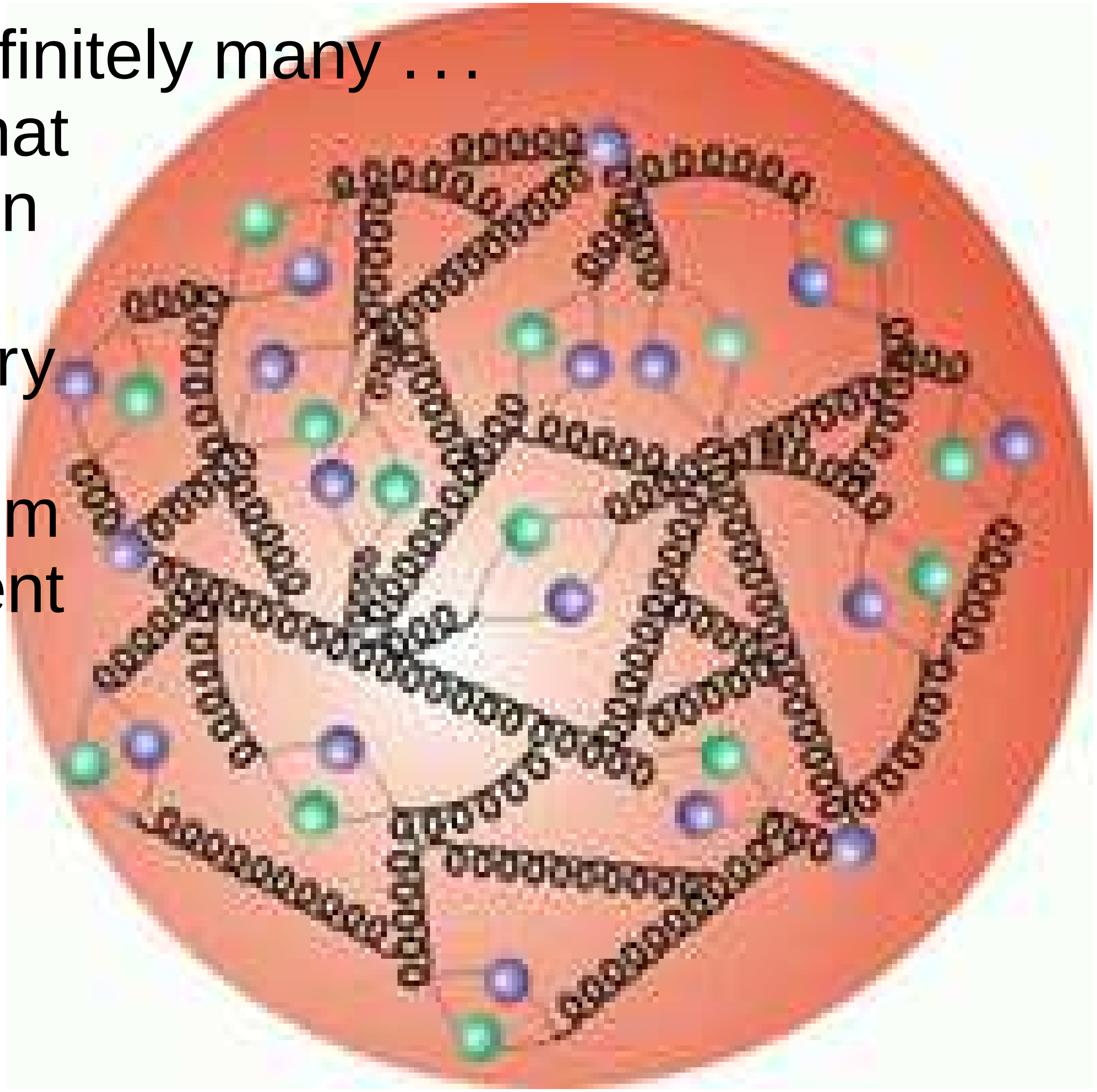

First Contents Back Conclusion

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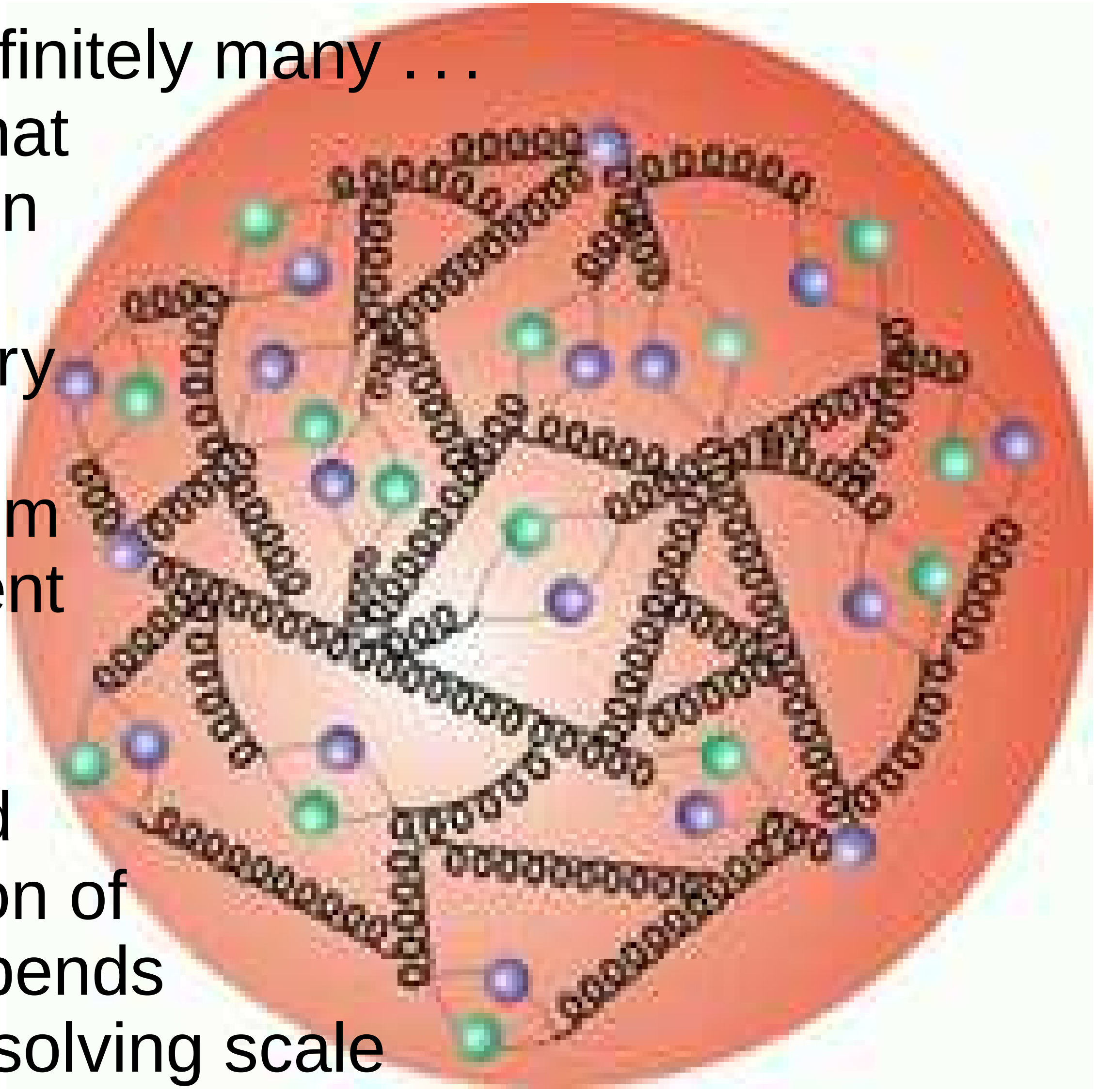
perceived distribution of mass depends on the resolving scale



Are we there yet?

Crocs emerge in town twice bitten

On the croc's back: Tony and Trent DeWith negotiate a flooded street in Katherine's town centre in a snappy canoe yesterday Picture: Patrina Malo

New Challenges

New Challenges

- Maris & Tandy . . . series of five papers . . . excellent description of light pseudoscalar and vector mesons . . . basket of 31 masses/couplings/radii with r.m.s. error of 15% . . . moreover, prediction of $F_\pi(Q^2)$ measured in Hall C.

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Peter Tandy

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- One parameter model . . . parameter specifies long-range interaction between light-quarks . . . model-independent results in ultraviolet

First Contents Back Conclusion

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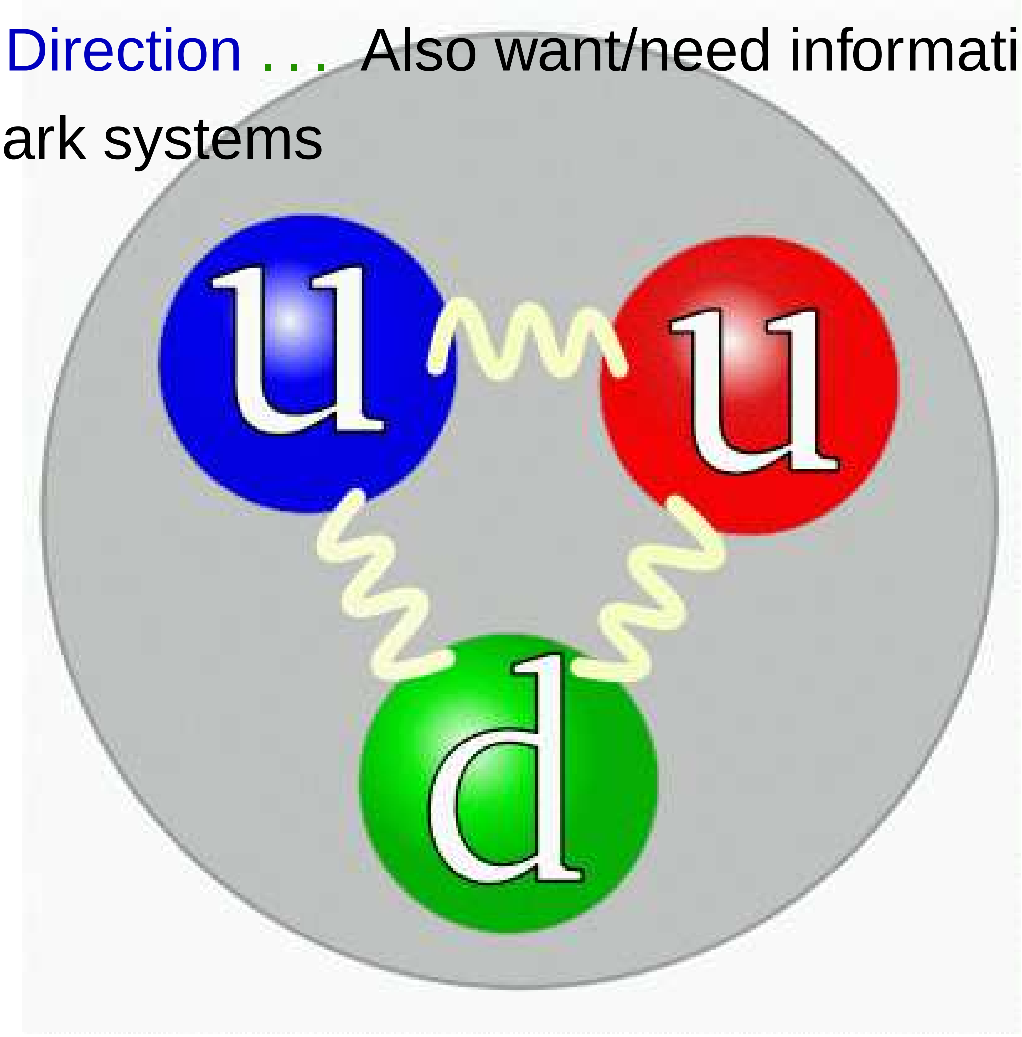
- One parameter model . . . parameter specifies long-range interaction between light-quarks . . . model-independent results in ultraviolet
- Next Steps . . . Applications to excited states and axial-vector mesons, e.g., will improve understanding of confinement interaction between light-quarks

- Another Direction . . . Also want/need information about three-quark systems



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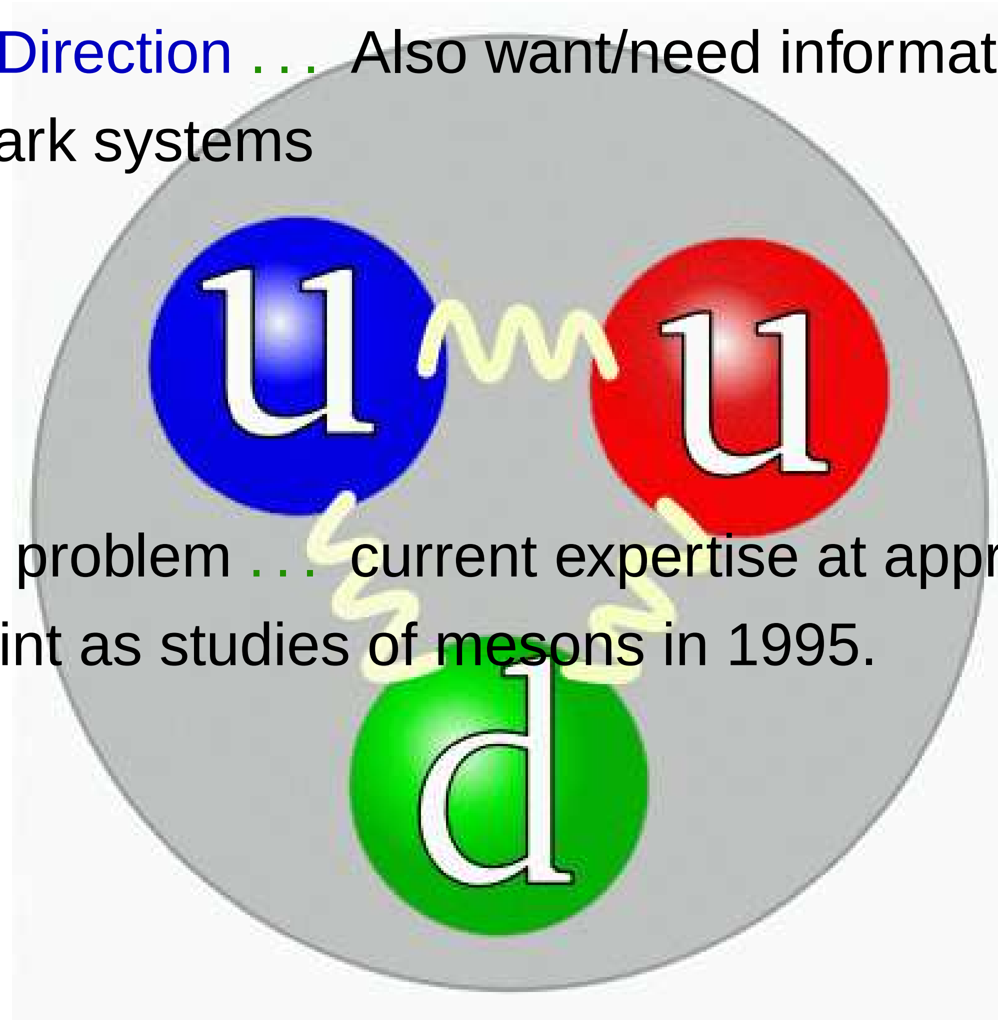

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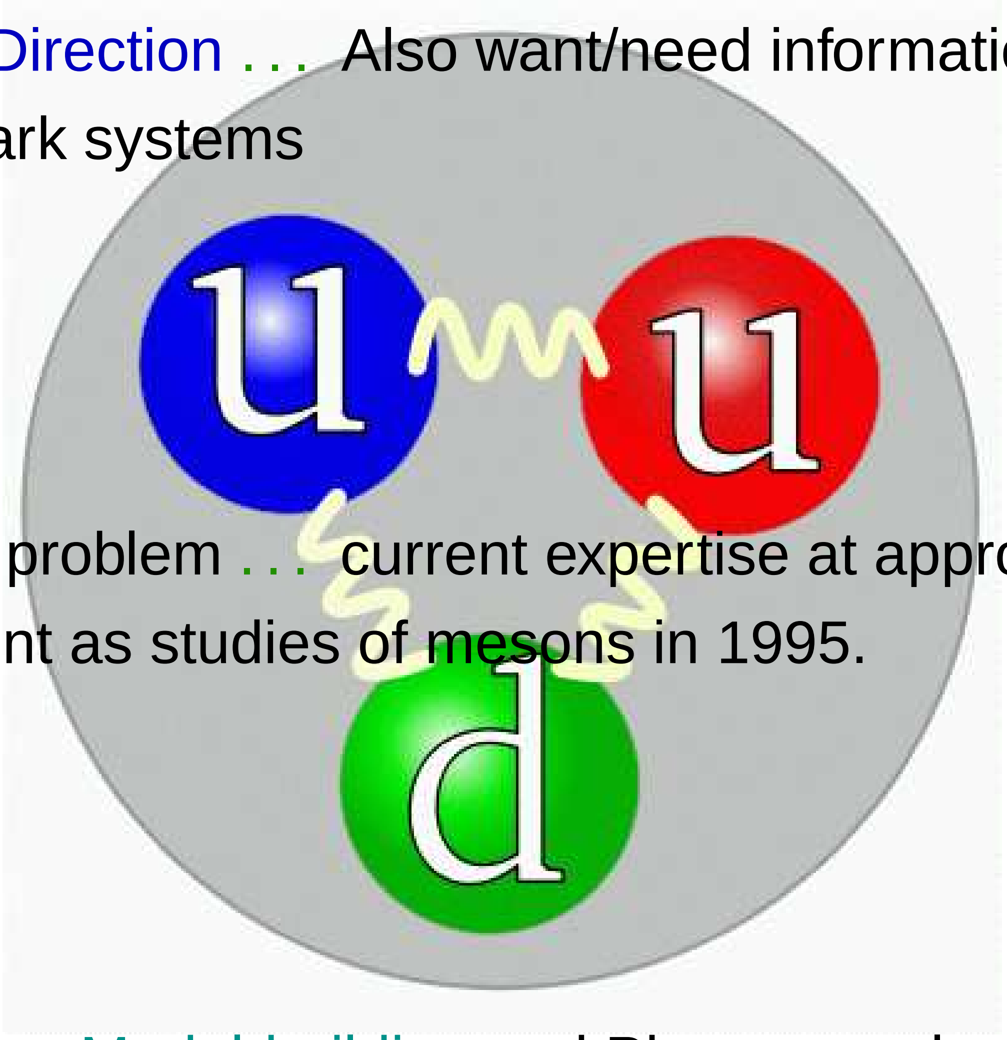
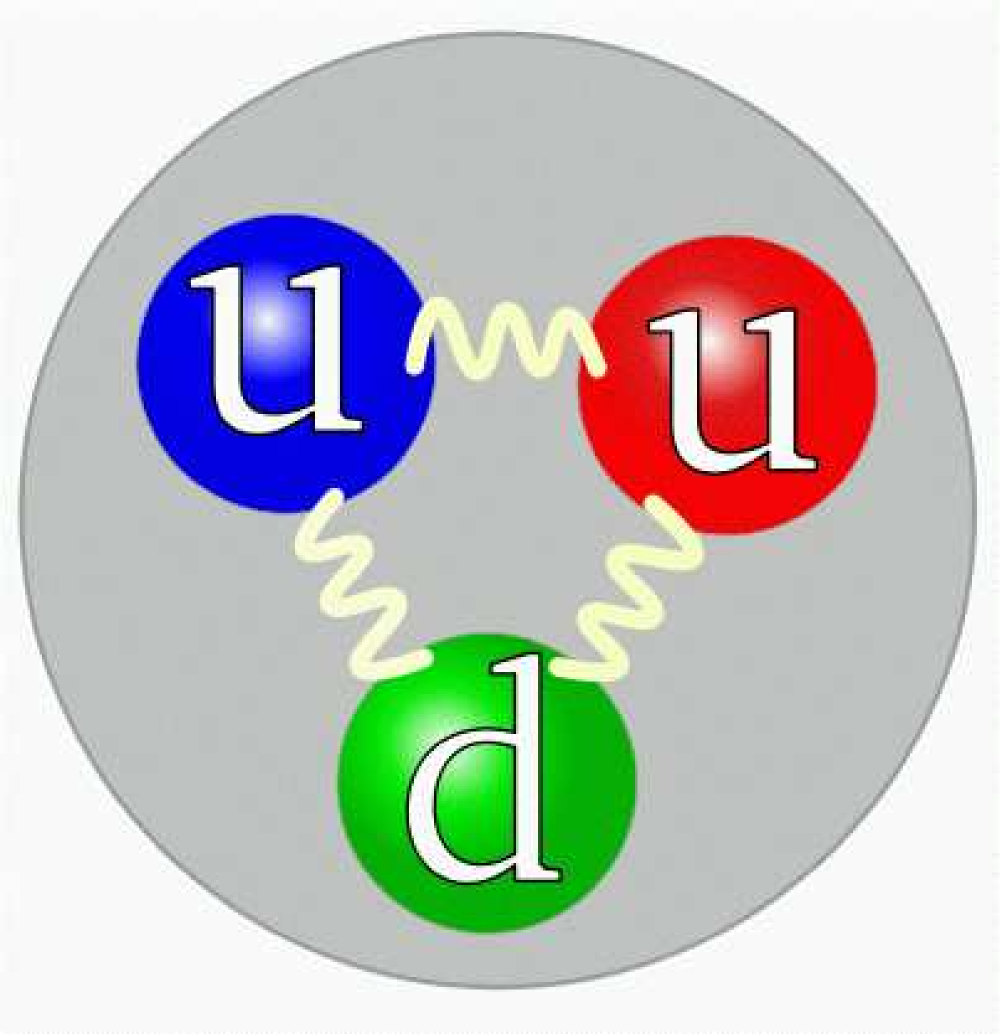


- With this problem . . . current expertise at approximately same point as studies of mesons in 1995.

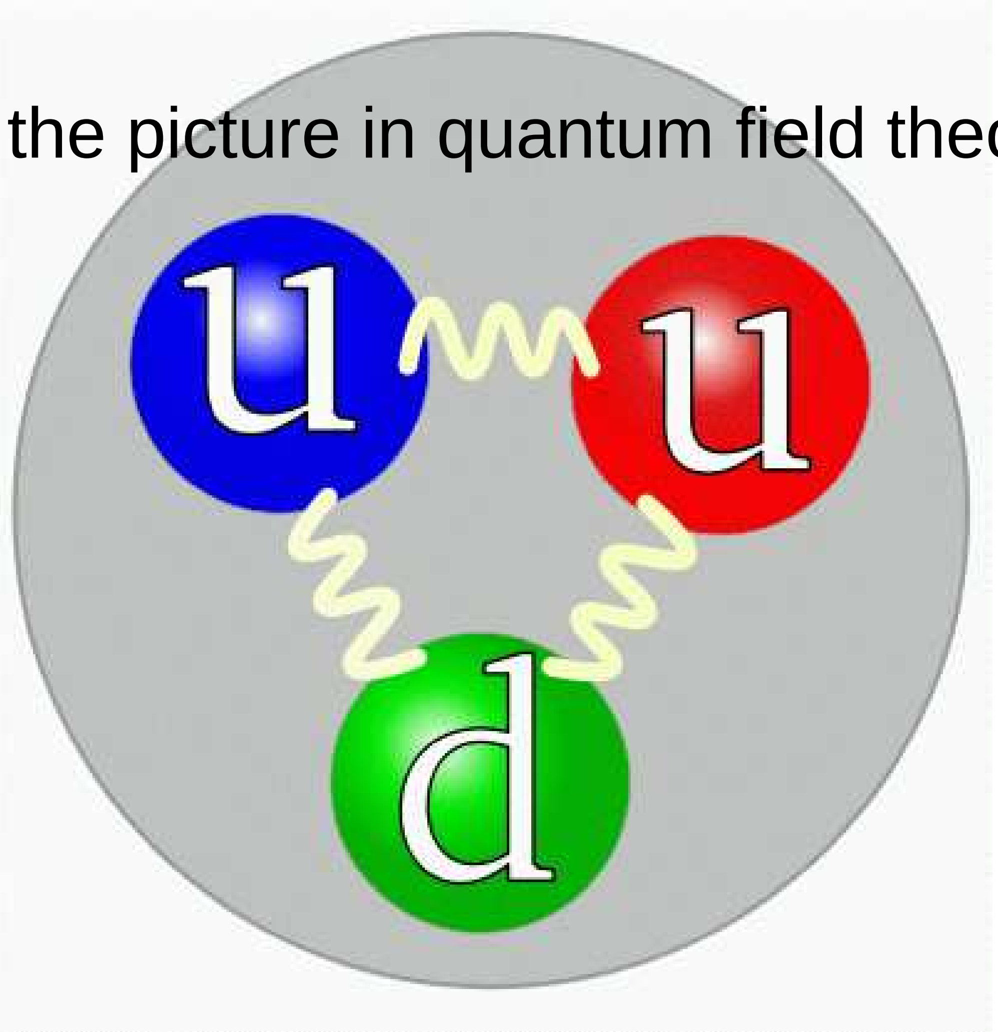
- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.

Nucleon . . .
Three-body Problem?



Three-body Problem?

- What is the picture in quantum field theory?



Nucleon . . .
Three-body Problem?

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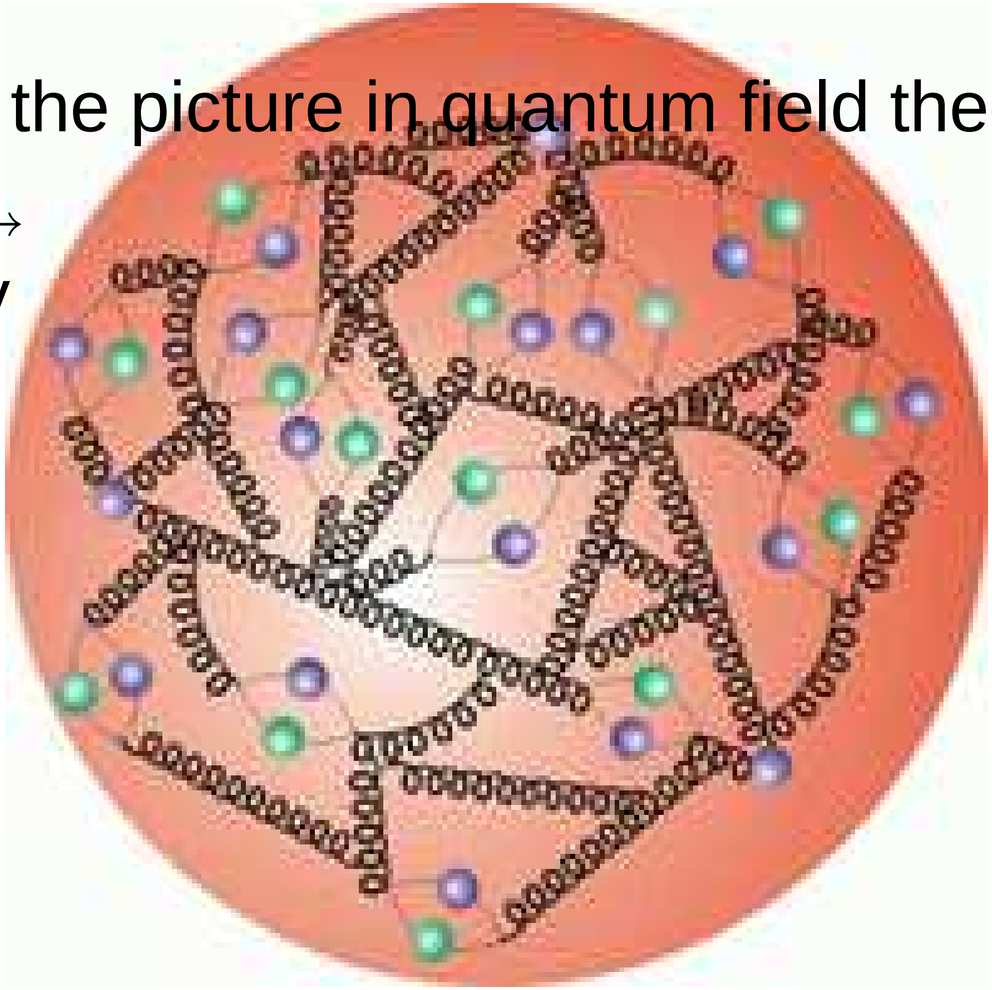
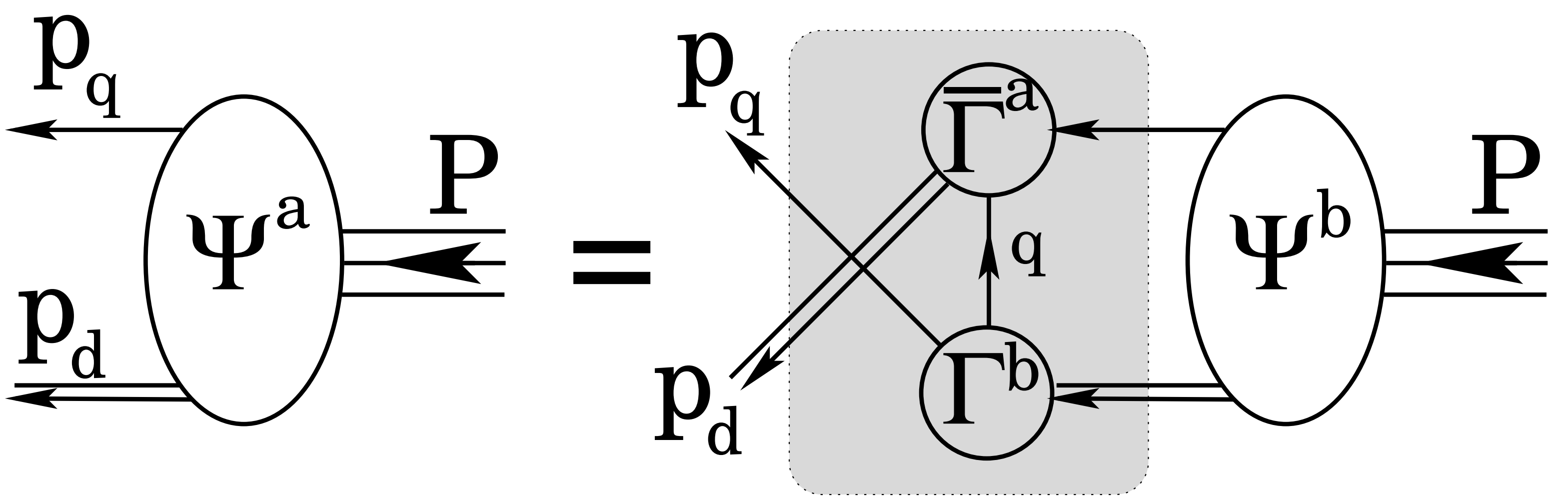
- Three → infinitely many!



Faddeev equation

First Contents Back Conclusion

Faddeev equation



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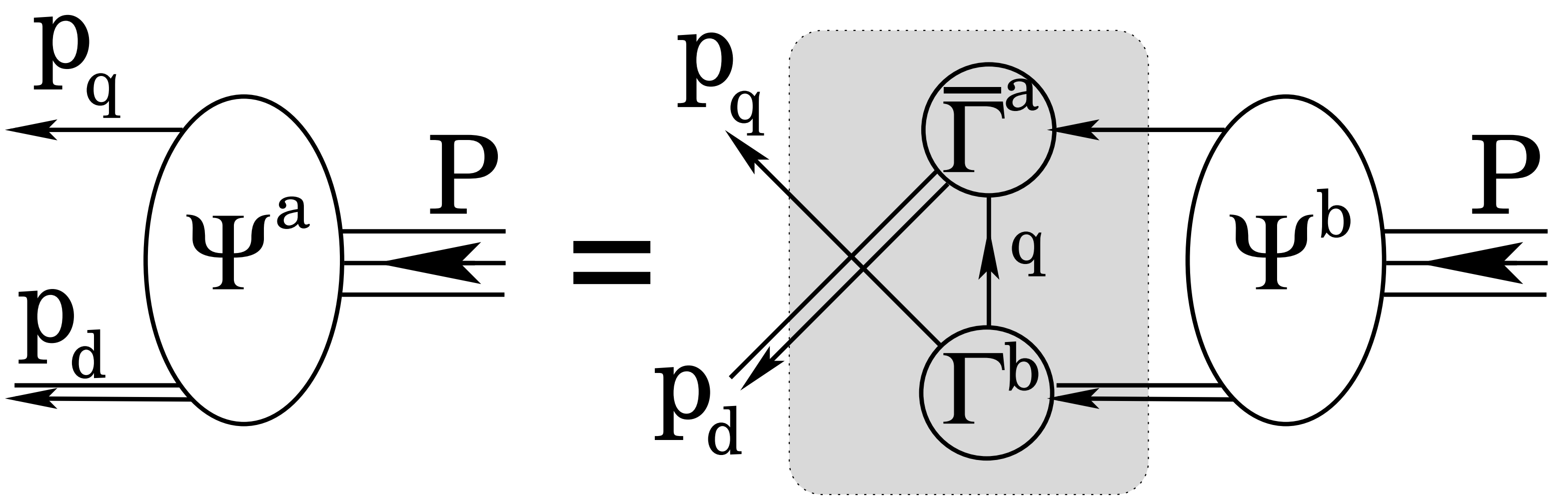
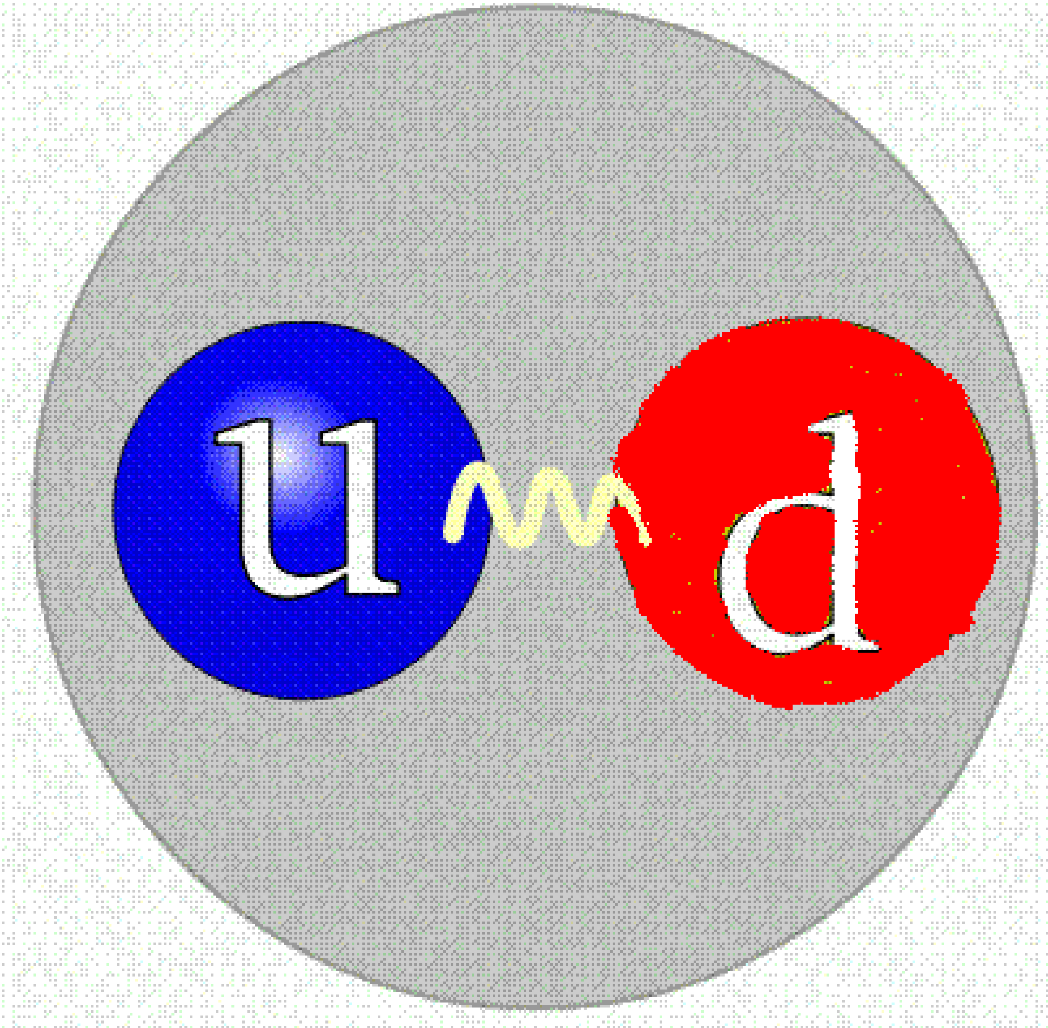


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks ... In Nucleon's Rest Frame Amplitude has ... $s-$, $p-$ & $d-$wave correlations

First Contents Back Conclusion

Diquark correlations



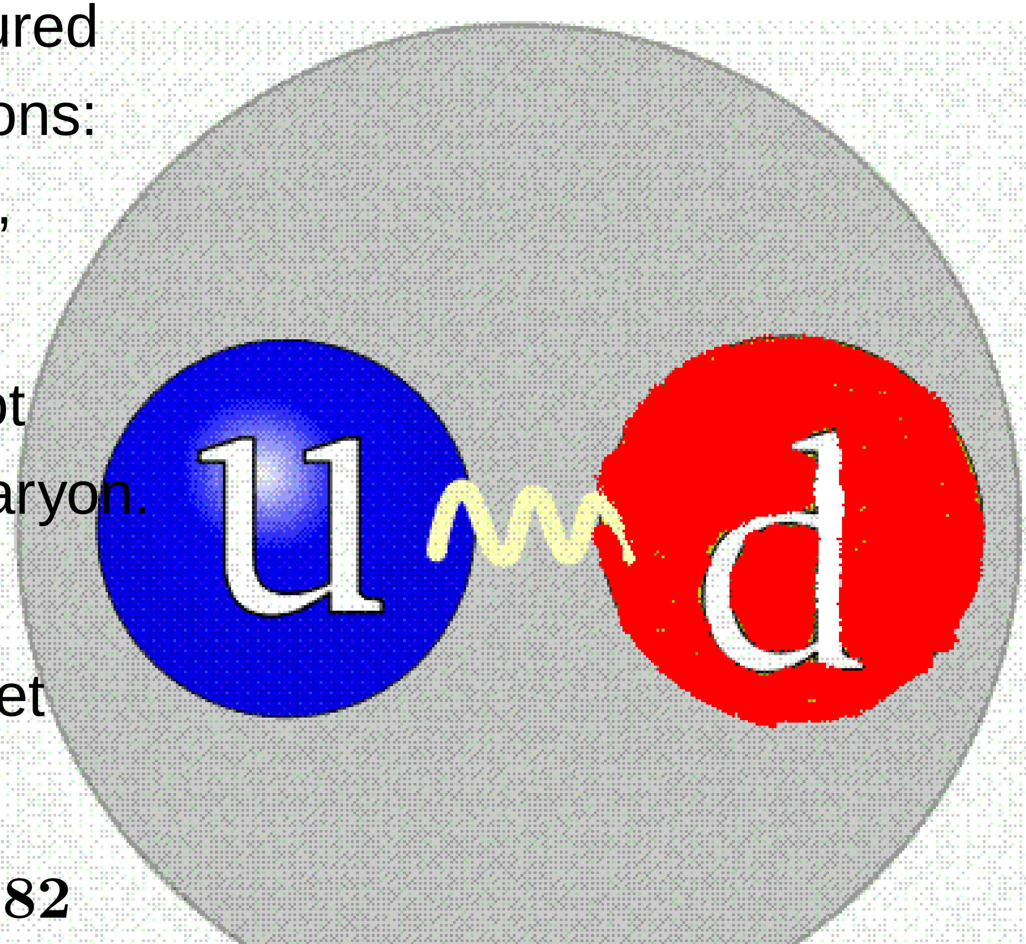
QUARK-QUARK

Diquark correlations

- Same interaction that describes mesons also generates three coloured quark-quark correlations: blue–red, blue–green, green–red
- Confined . . . Does not escape from within baryon.
- Scalar is isosinglet, Axial-vector is isotriplet
- DSE and lattice-QCD

$$m_{[ud]_{0^+}} = 0.74 - 0.82$$

$$m_{(uu)_{1^+}} = m_{(ud)_{1^+}} = m_{(dd)_{1^+}} = 0.95 - 1.02$$



QUARK-QUARK

Nucleon EM Form Factors: A Précis

Höll, Kloker, *et al.*: nu-th/0412046 & nu-th/0501033

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First Contents Back Conclusion

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First Contents Back Conclusion

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(Oettel, Hellstern, Alkofer, Reinhardt: nucl-th/9805054)

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First Contents Back Conclusion

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  - Cloudy Bag: $\delta M_+^{\pi-\rm loop} = -300$ to -400 MeV!
- Critical to anticipate pion cloud effects

  Roberts, Tandy, Thomas, *et al.*, nu-th/02010084

Pions and Form Factors

- Dynamical coupled-channels model . . . Analyzed extensive JLab data . . . Completed a study of the $\Delta(1236)$
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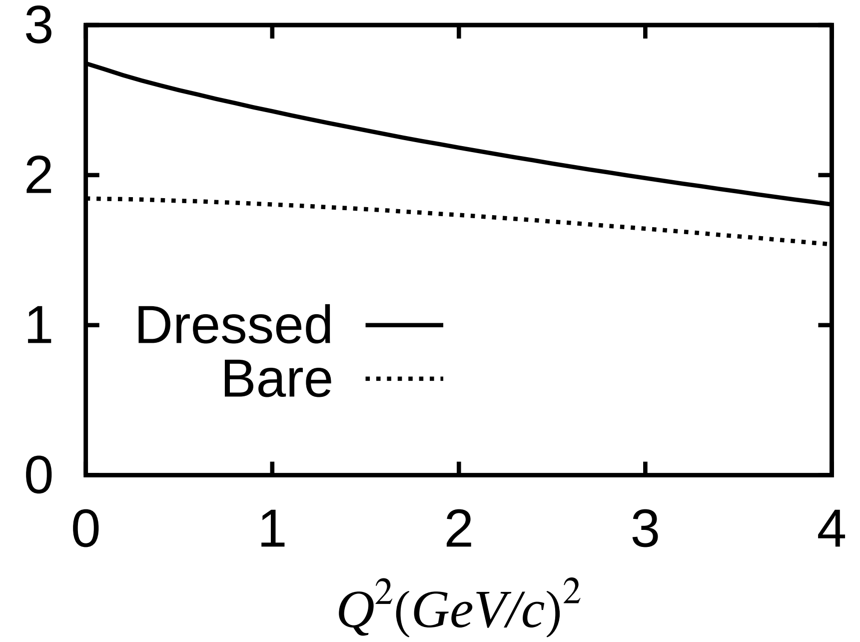
Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G^*_M(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



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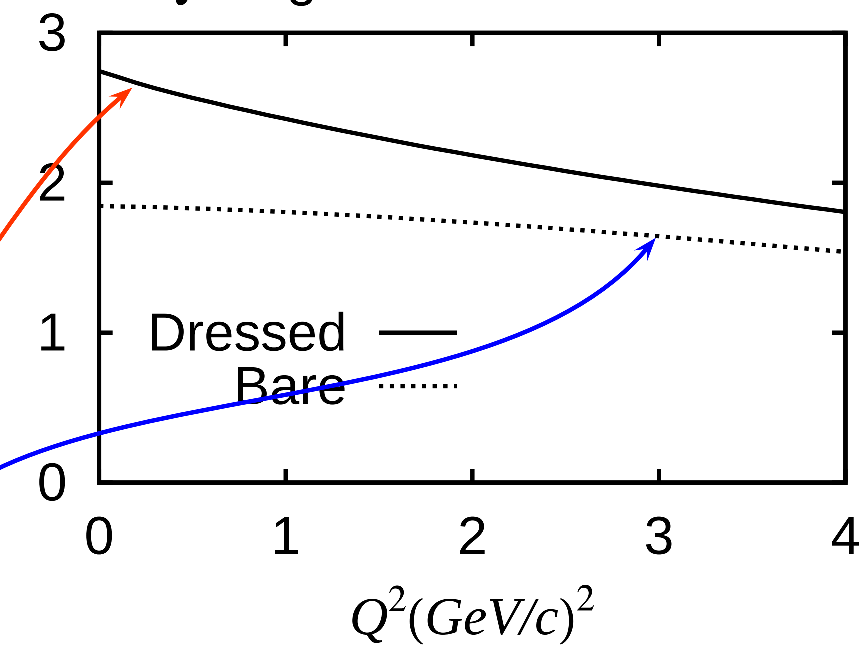
Quark Core



- Responsible for only 2/3 of result at small Q^2
- Dominant for $Q^2 > 2 - 3\,\text{GeV}^2$

Results: Nucleon and Δ Masses

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Mass-scale parameters (in GeV) for the scalar and axial-vector diquark correlations, fixed by fitting nucleon and Δ masses

Set A – fit to the actual masses was required; whereas for
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set	M_N	M_Δ	m_{0^+}	m_{1^+}	ω_{0^+}	ω_{1^+}
A	0.94	1.23	0.63	0.84	0.44=1/(0.45 fm)	0.59=1/(0.33 fm)
B	1.18	1.33	0.79	0.89	0.56=1/(0.35 fm)	0.63=1/(0.31 fm)

- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV

First Contents Back Conclusion

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- Axial-vector diquark provides significant attraction

First Contents Back Conclusion

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- Constructive Interference: 1^{++}-diquark $+ \, \partial_\mu \pi$

Nucleon-Photon Vertex

M. Oettel, M. Pichowsky
and L. von Smekal, nu-th/9909082

6 terms . . .

Nucleon-Photon Vertex

constructed systematically . . . current conserved automatically

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First Contents Back Conclusion

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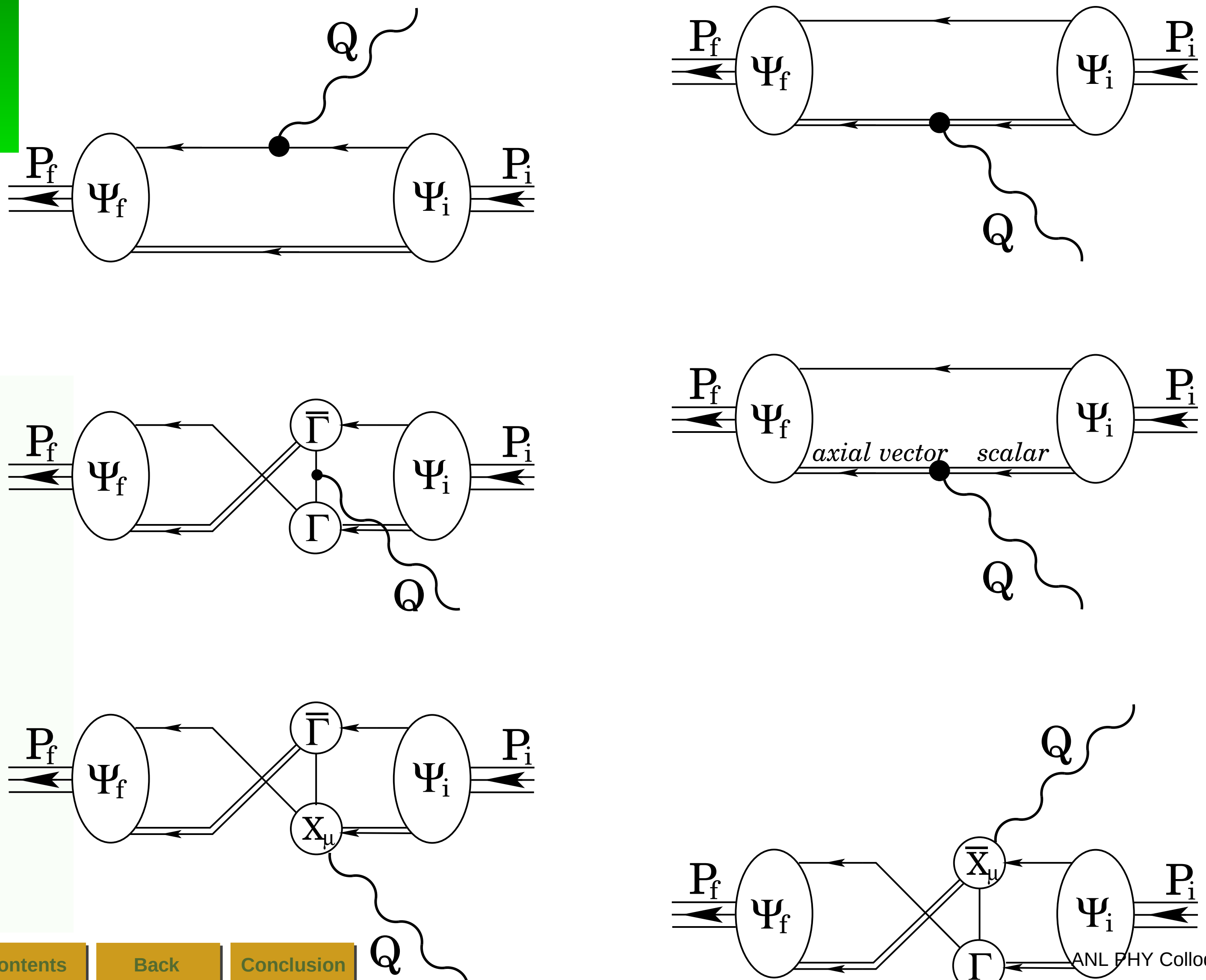
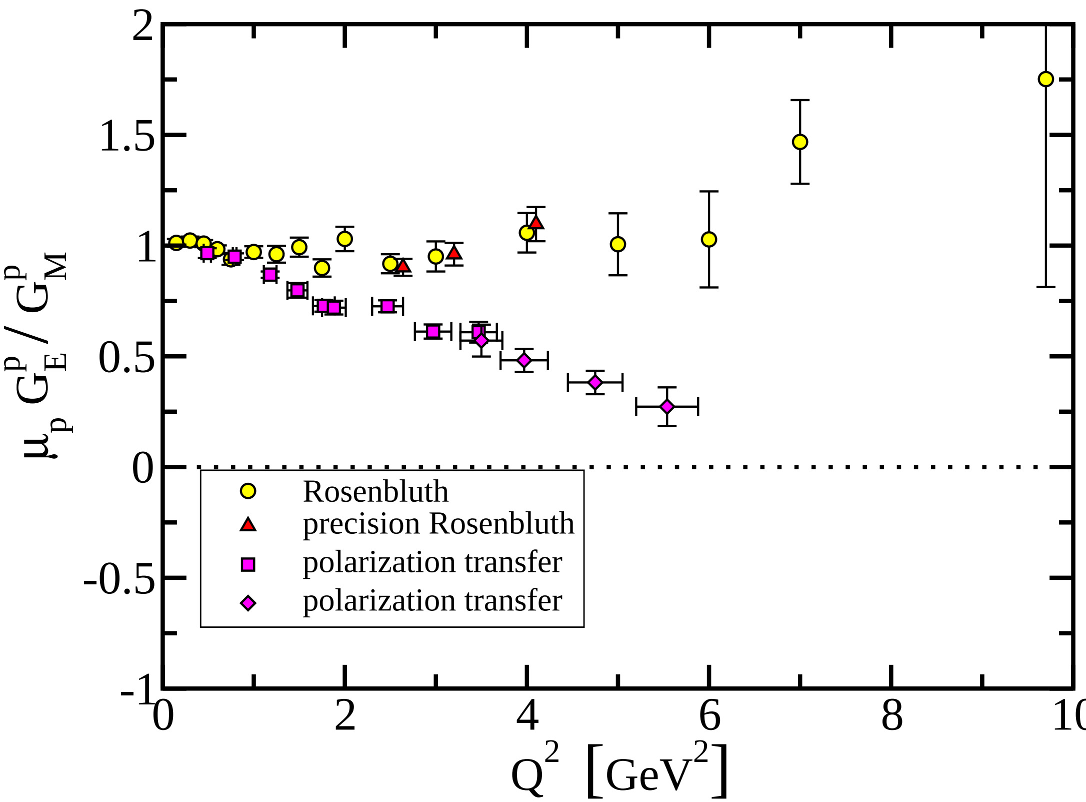


Form Factor Ratio: GE/GM



First Contents Back Conclusion

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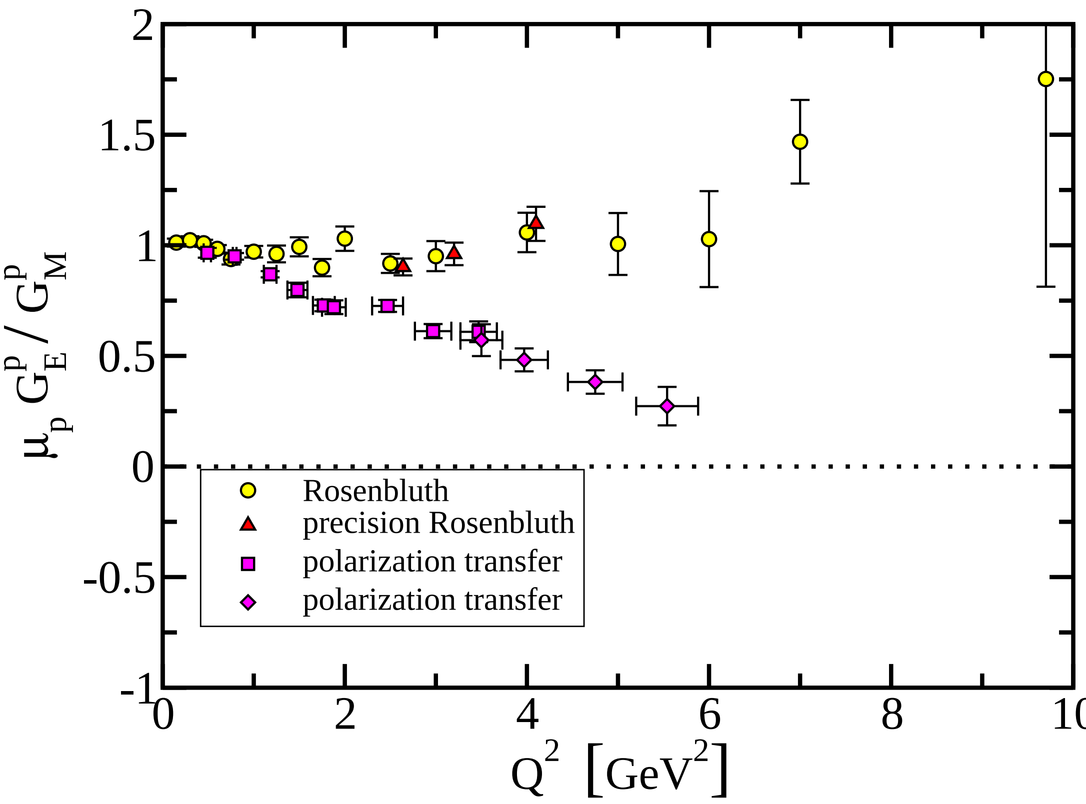

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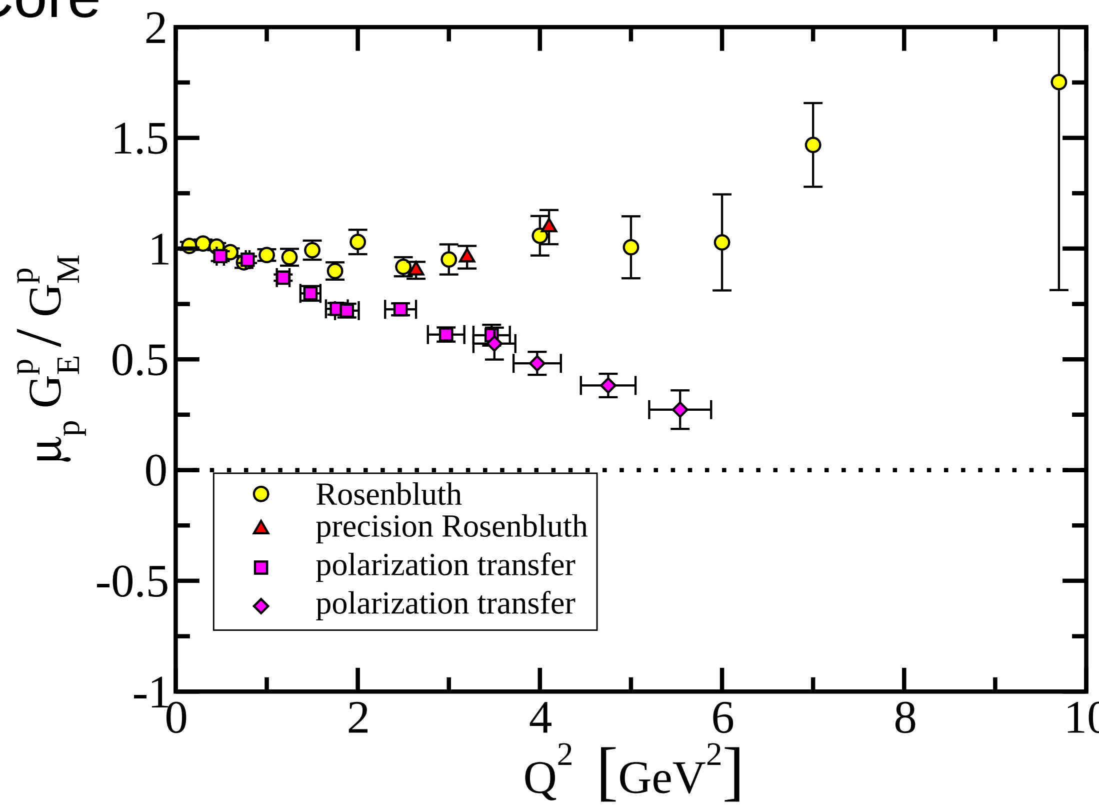

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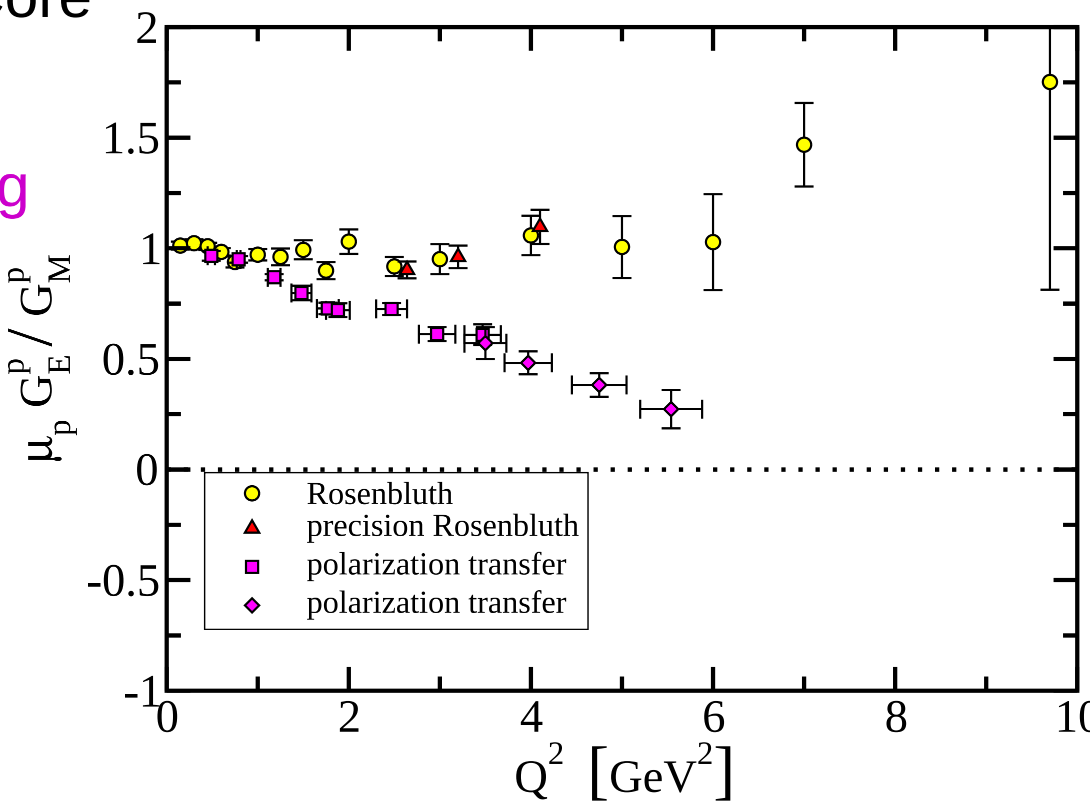

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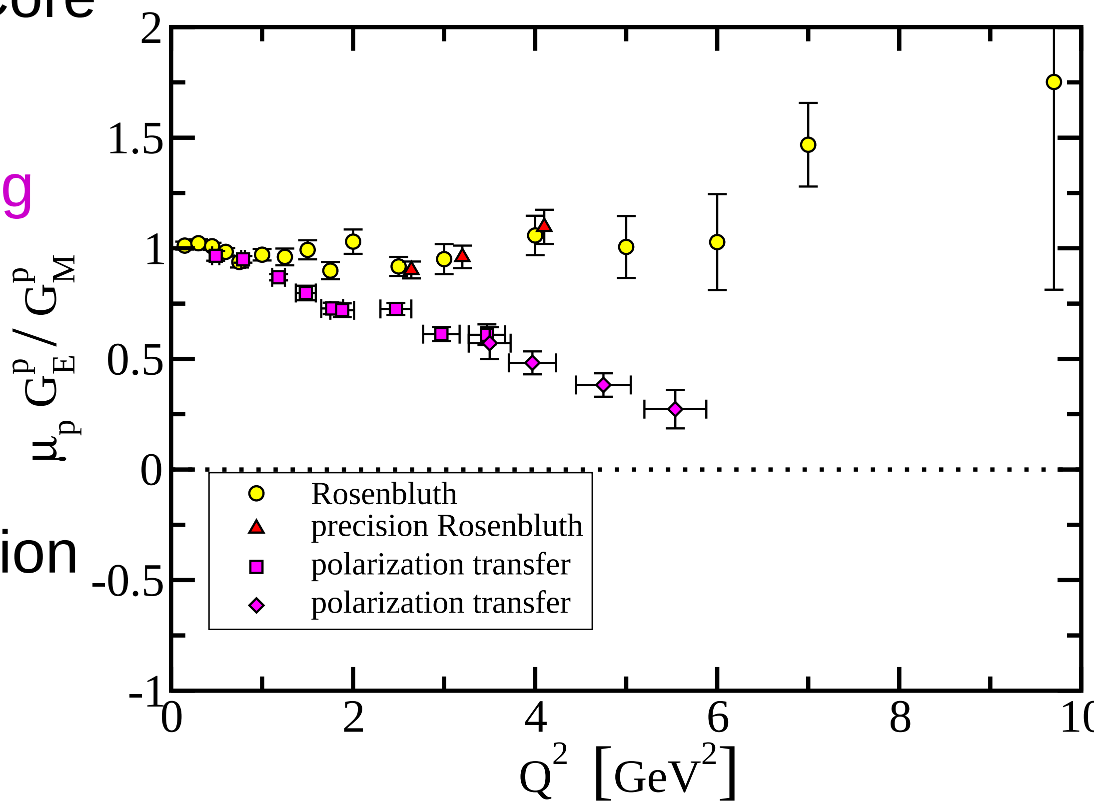

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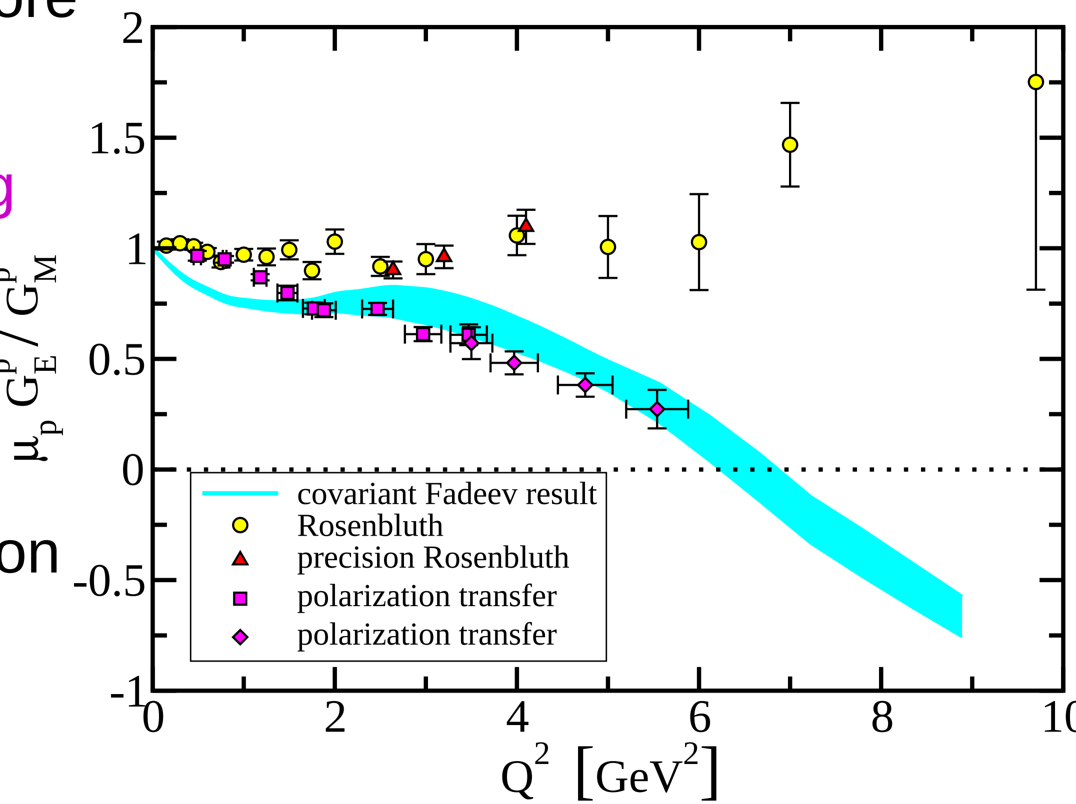

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First Contents Back Conclusion

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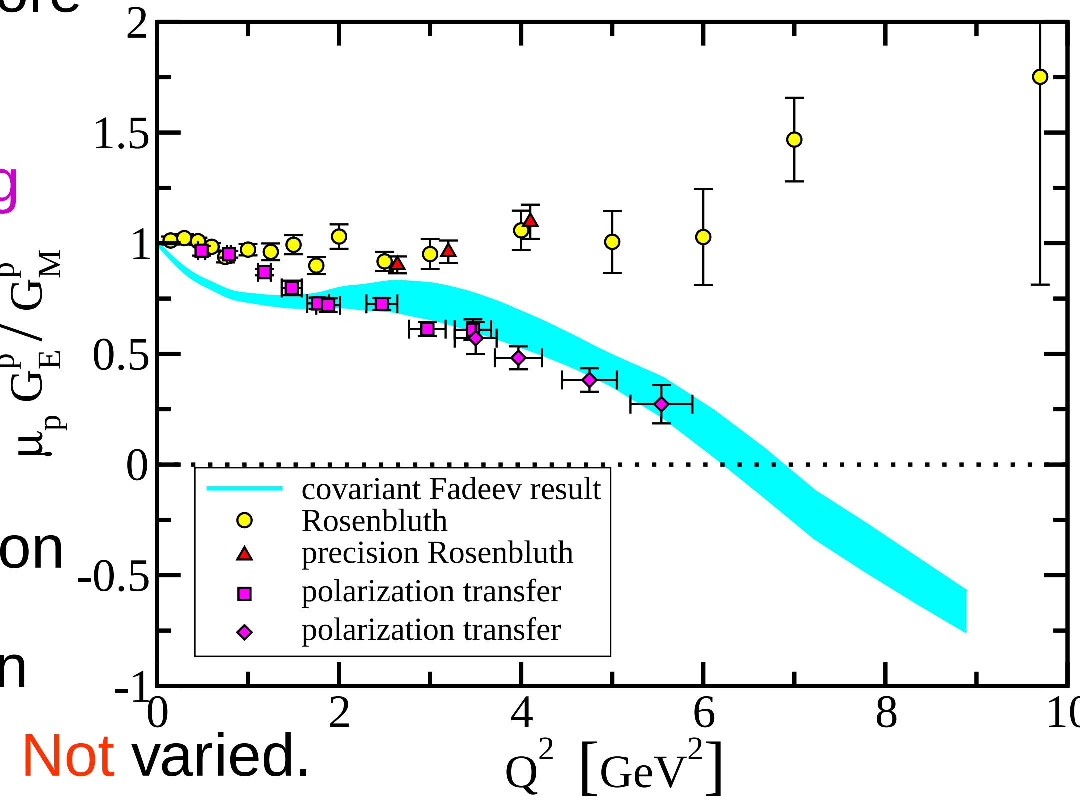

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First Contents Back Conclusion

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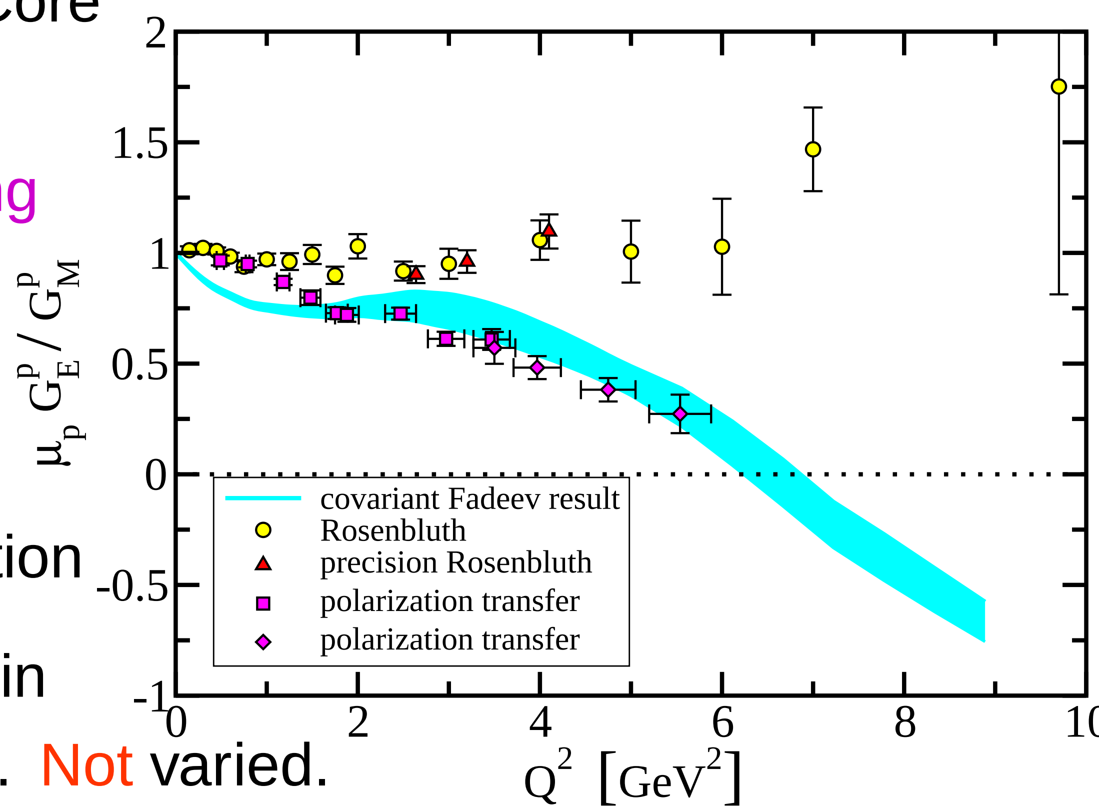

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First Contents Back Conclusion

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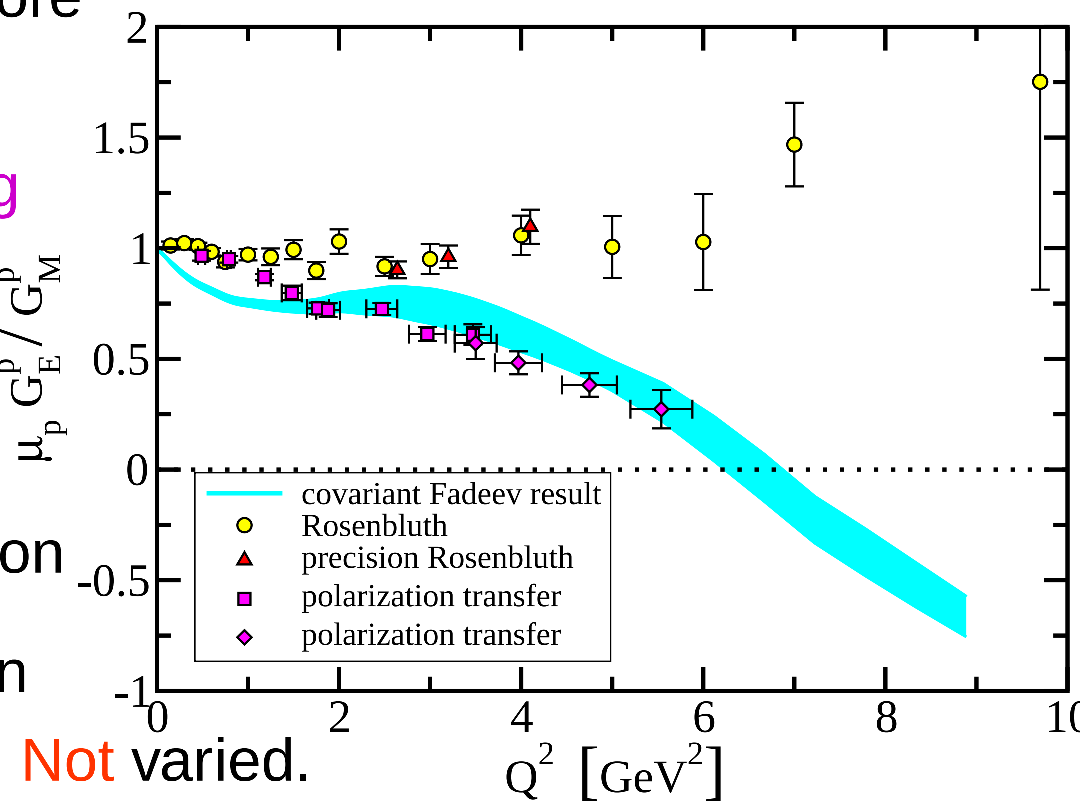

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First Contents Back Conclusion

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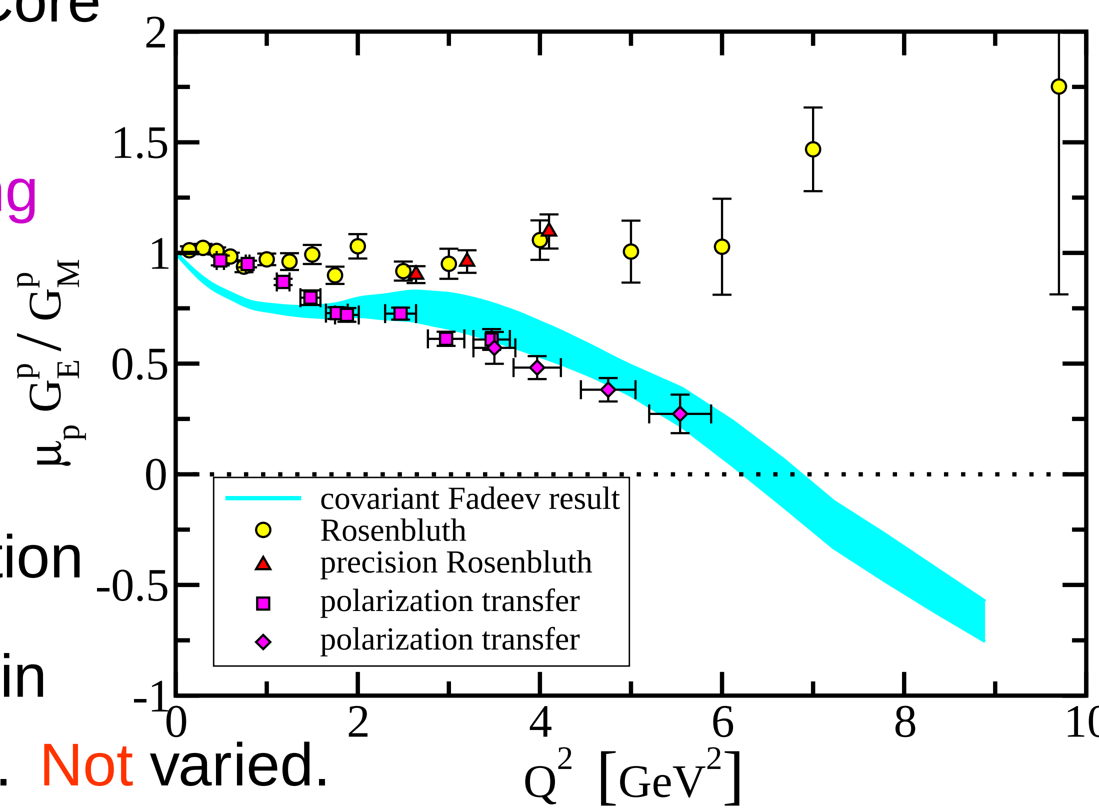

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Chiral Corrections

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First Contents Back Conclusion

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First | Contents | Back | Conclusion

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$$\langle r^2_{\substack{p\\n}} \rangle^{1-loop^R}_{NA} = \mp \frac{1+5g_A^2}{32\pi^2 f_\pi^2} \ln\left(\frac{m_\pi^2}{m_\pi^2+\lambda^2}\right),$$

$$\langle (r^\mu_N)^2 \rangle^{1-loop^R}_{NA} = -\frac{1+5g_A^2}{32\pi^2 f_\pi^2} \ln\left(\frac{m_\pi^2}{m_\pi^2+\lambda^2}\right) + \frac{g_A^2 M_N}{16\pi f_\pi^2 \mu_v} \frac{1}{m_\pi} \frac{2}{\pi} \arctan\left(\frac{\lambda}{m_\pi}\right),$$

$$(\mu_{\substack{p\\n}})^{1-loop^R}_{NA} = \mp \frac{g_A^2 M_N}{4\pi^2 f_\pi^2} m_\pi \frac{2}{\pi} \arctan\left(\frac{\lambda^3}{m_\pi^3}\right),$$

First | Contents | Back | Conclusion

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	r_p	r_n	r_p^μ	r_n^μ	μ_p	$-\mu_n$	ς
q-(qq) core	0.595	0.169	0.449	0.449	3.63	2.13	0.39
$+\pi$-loop correction	0.762	0.506	0.761	0.761	3.05	1.55	0.23
experiment	0.847	0.336	0.836	0.889	2.79	1.91	

First Contents Back Conclusion

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$r_p \approx r_p^\mu \Rightarrow$ ratio varies $< 10\%$ on $0 < Q^2 < 0.6$ GeV^2

First Contents Back Conclusion

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- Complements nucleon mass considerations

  ... veracious understanding of all nucleon properties

  ... impossible without intelligent incorporation

  of chiral corrections

Epilogue

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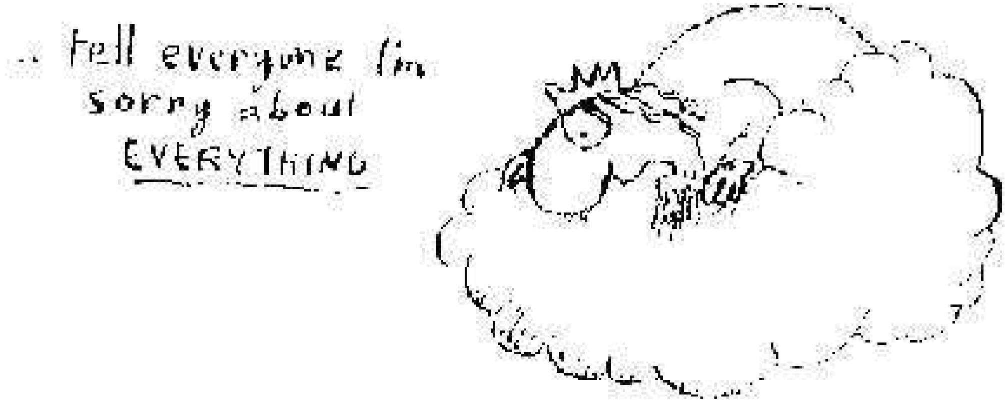

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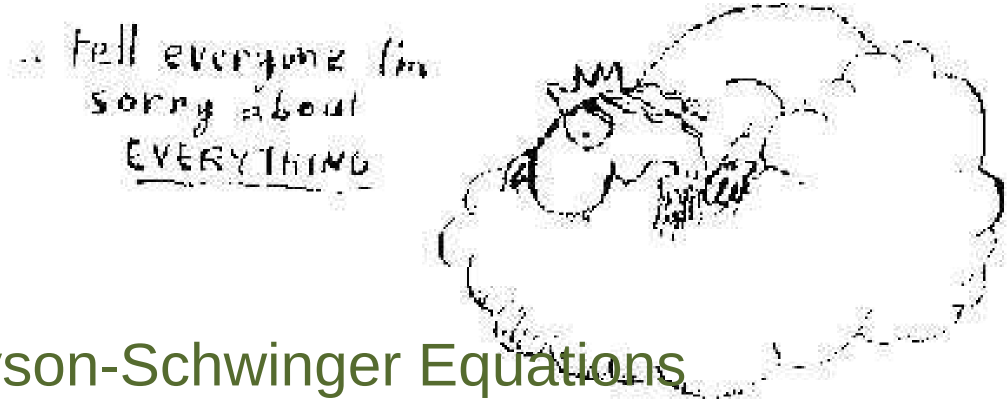

Dyson-Schwinger Equations

- Provide Understanding of
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  $\Rightarrow$ π is quark-antiquark Bound State

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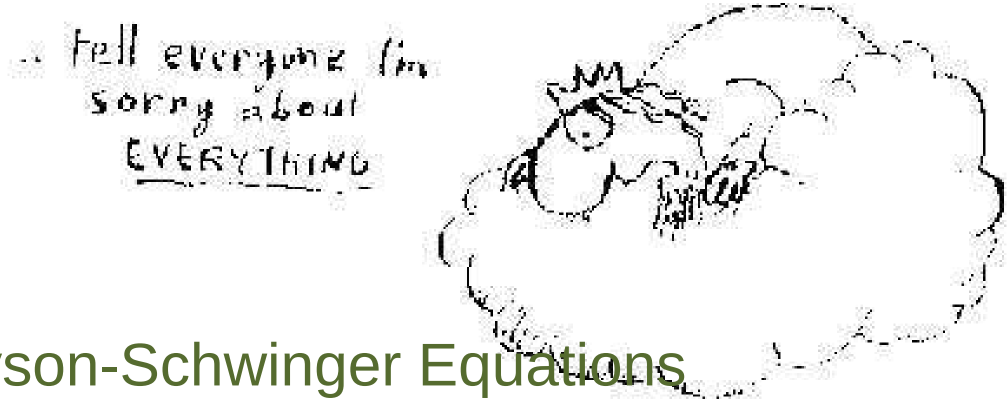

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- Foundation for Proof of
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  e.g., Quark Goldberger-Treiman
  Properties of Pseudoscalar Mesons

First Contents Back Conclusion

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- Poincaré Covariant Faddeev Equation

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First Contents Back Conclusion

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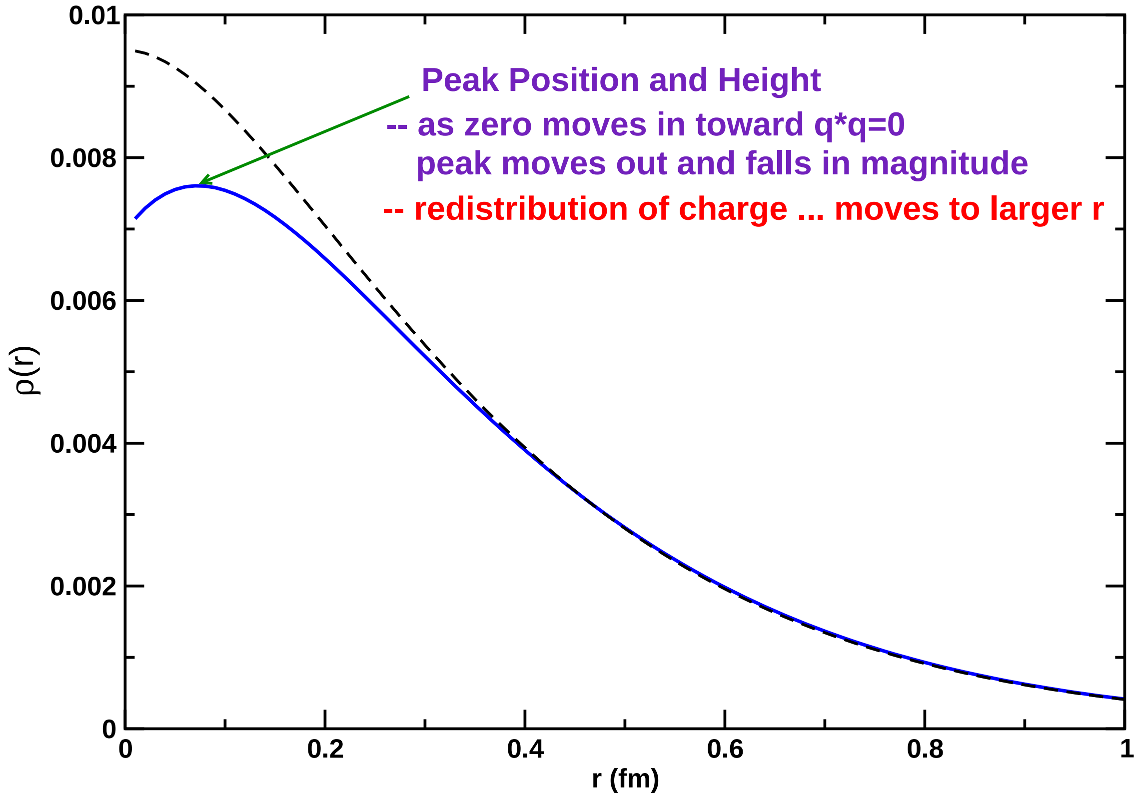

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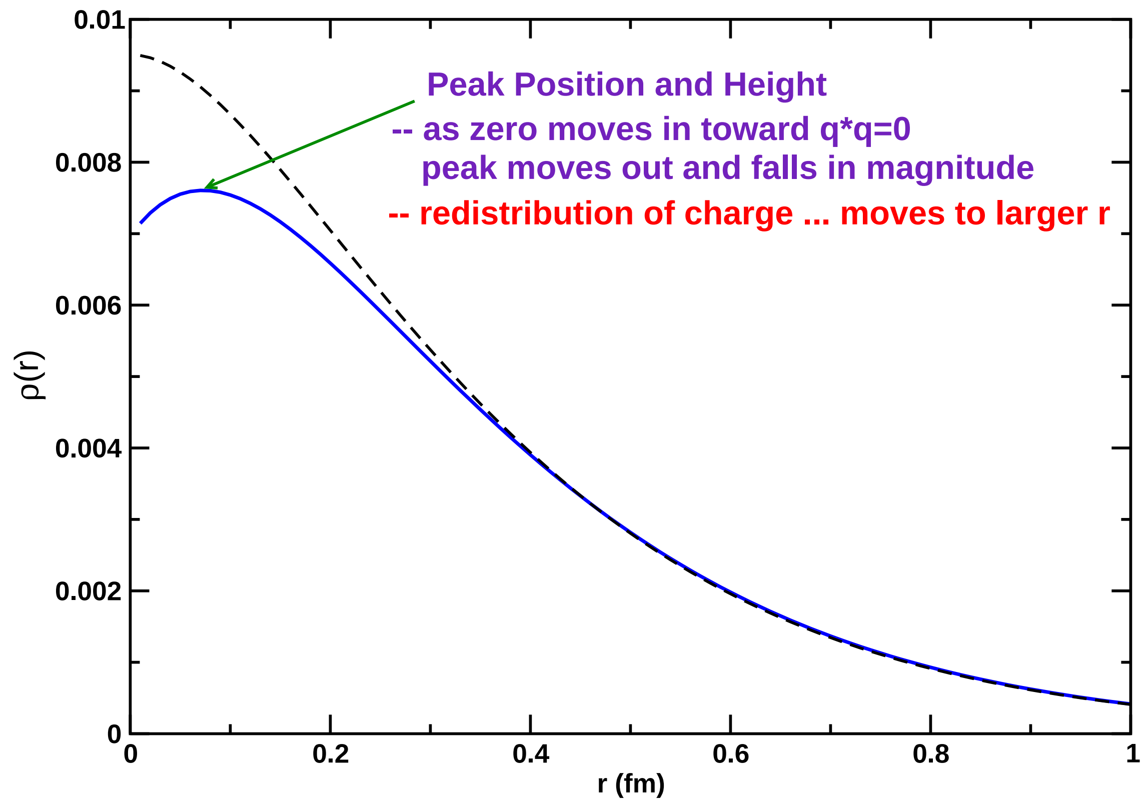


- However, Current Density remains peaked at $r = 0$!

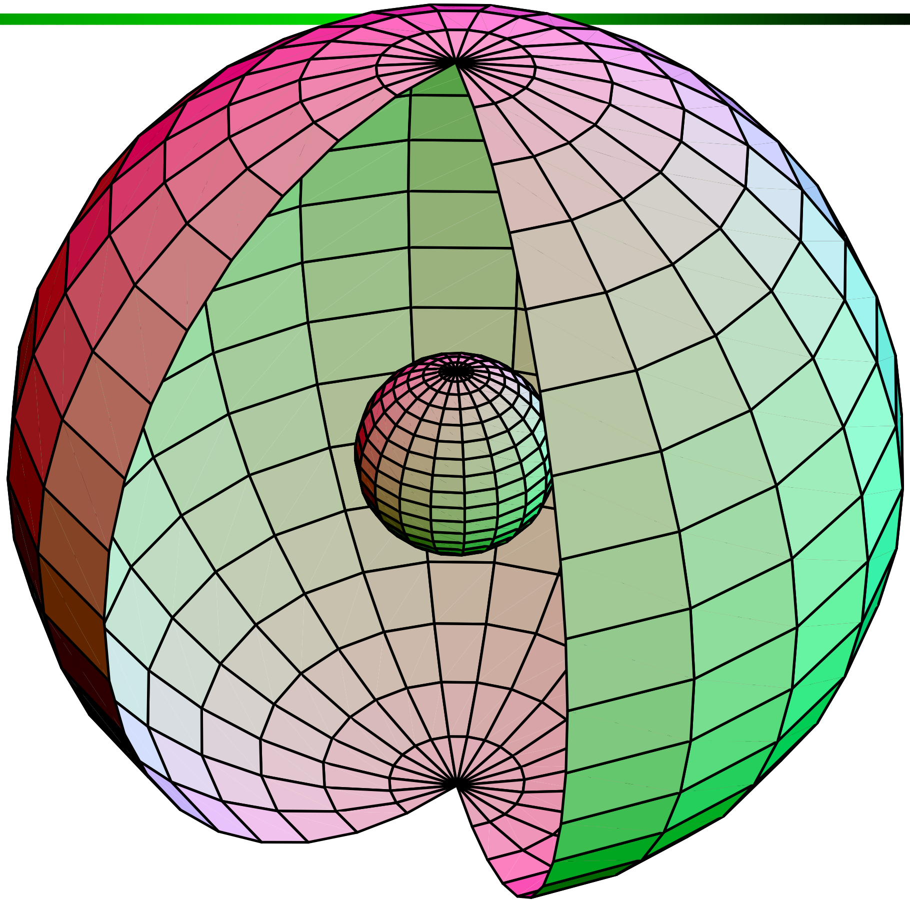
Epilogue

- Appearance of a zero in $G_E(Q^2)$ – Completely Unexpected
- Wave Function is complex and correlated mix of virtual particles and antiparticles: $s-$, $p-$ and $d-$waves

Future?

First Contents Back Conclusion

Future?



First Contents Back Conclusion

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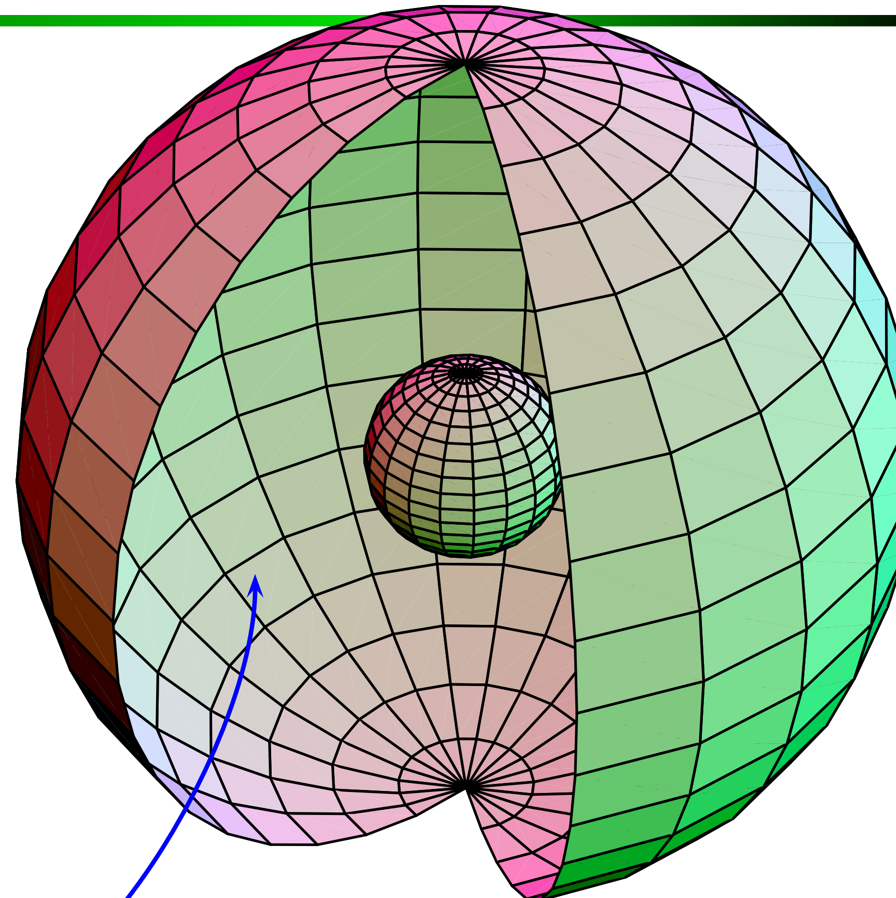

98% of the volume

It that is more than a parton is not for many,

And it that is less than an hadron,
many are not for it.

Anon.

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Office of Nuclear Physics

Argonne NATIONAL LABORATORY

First Contents Back Conclusion

Contents

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First Contents Back Conclusion

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First Contents Back Conclusion

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  Widths fixed by "asymptotic freedom" condition –

$$\frac{d}{dK^2}\left(\frac{1}{m_{J^P}^2}\mathcal{F}(K^2/\omega_{J^P}^2)\right)^{-1}\Bigg|_{K^2=0} = 1 \;\Rightarrow\; \omega_{J^P}^2 = \frac{1}{2}\,m_{J^P}^2\,,$$

  Only two parameters; viz., diquark "masses": m_{J^P}

Contemporary Reviews

- Dyson-Schwinger Equations: Density, Temperature and Continuum Strong QCD
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  Prog. Part. Nucl. Phys. **45** (2000) S1
- The IR behavior of QCD Green's functions: Confinement, DCSB, and hadrons . . .
  R. Alkofer and L. von Smekal, he-ph/0007355,
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- Dyson-Schwinger equations: A Tool for Hadron Physics
  P. Maris and C.D. Roberts, nu-th/0301049,
  Int. J. Mod. Phys. **E 12** (2003) pp. 297-365
- Infrared properties of QCD from Dyson-Schwinger equations.
  C. S. Fischer, he-ph/0605173,
  J. Phys. **G 32** (2006) pp. R253-R291

First Contents Back Conclusion