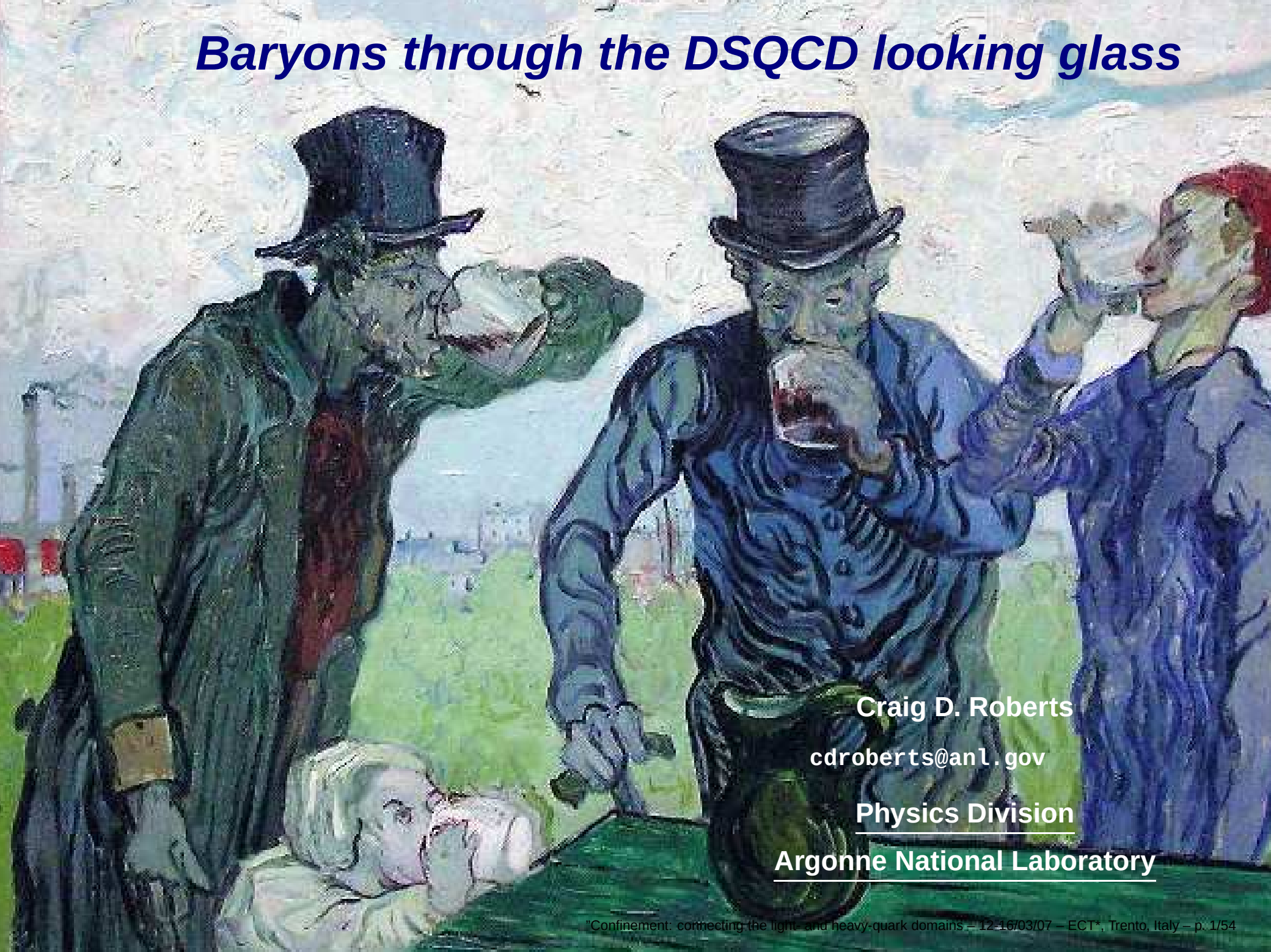
Baryons through the DSQCD looking glass



Craig D. Roberts

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Physics Division

Argonne National Laboratory

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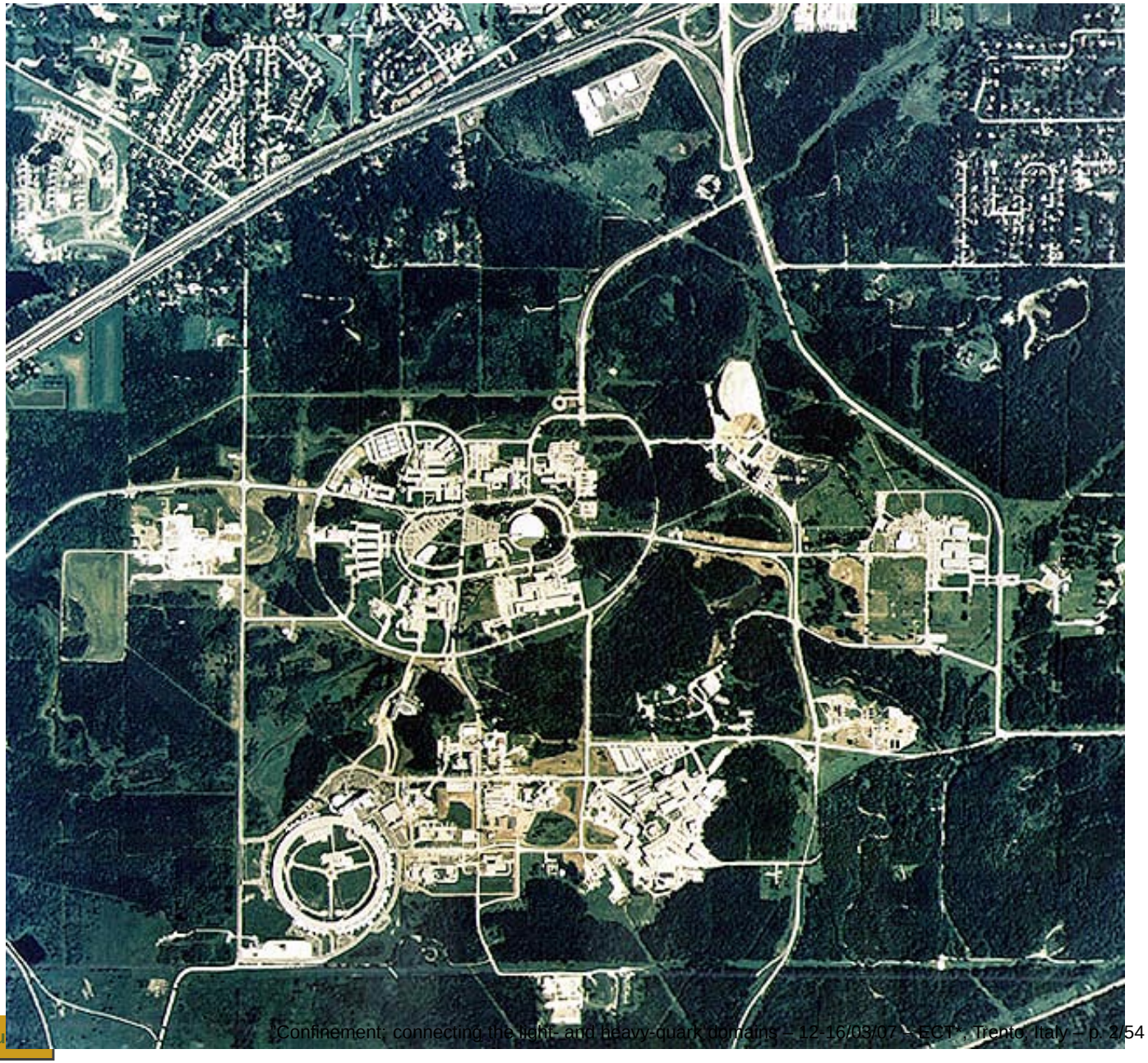

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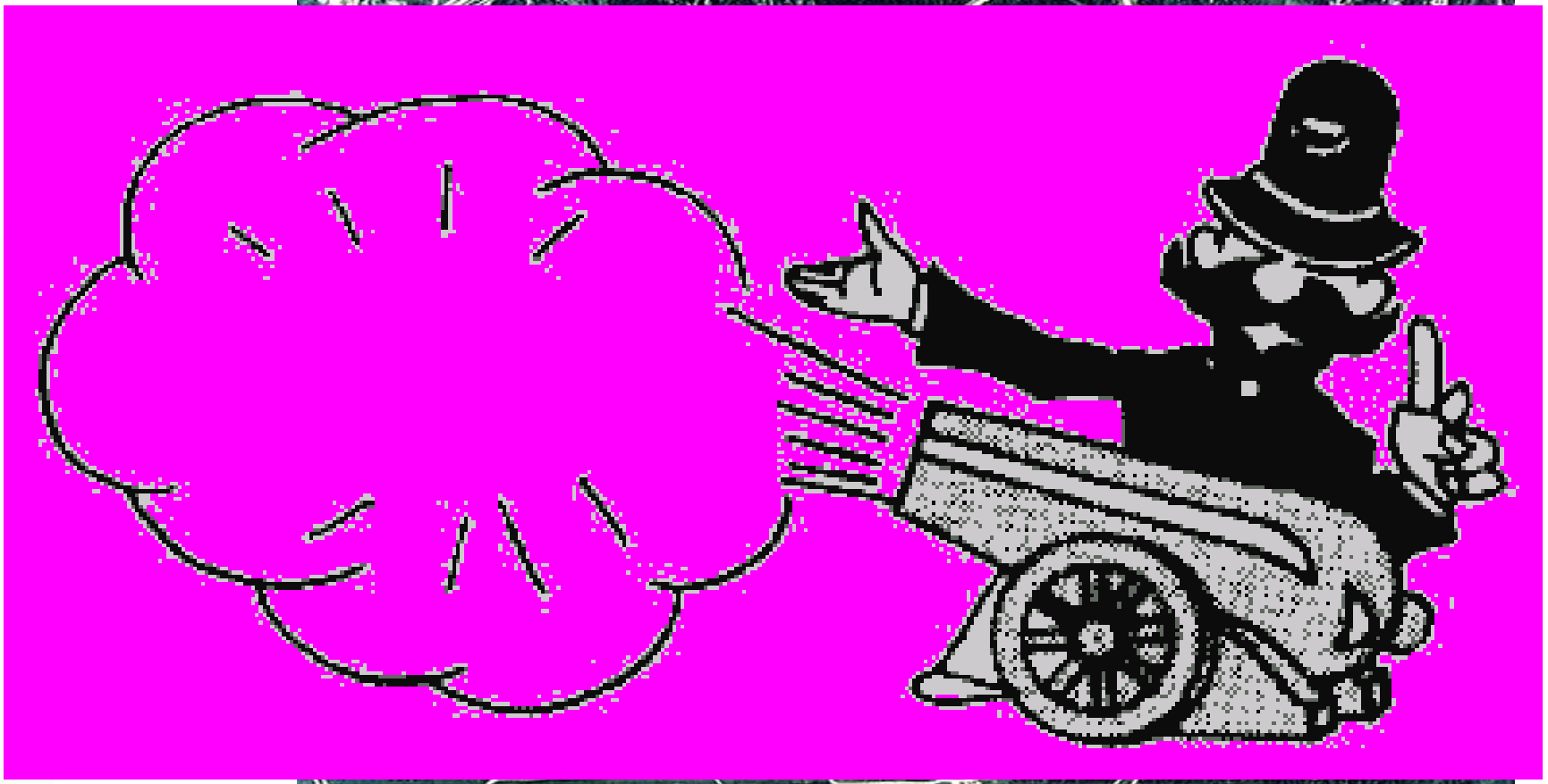

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And so . . .


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And so . . . We gather in Trento

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And so . . . We gather in Trento

One thing was certain, that the WHITE kitten had had nothing to do with it:
– it was the black kitten's fault entirely.

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Nucleon . . . 2 Key Hadrons

= Proton and Neutron

Nucleon . . . 2 Key Hadrons = Proton and Neutron

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- 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

QED cf. QCD

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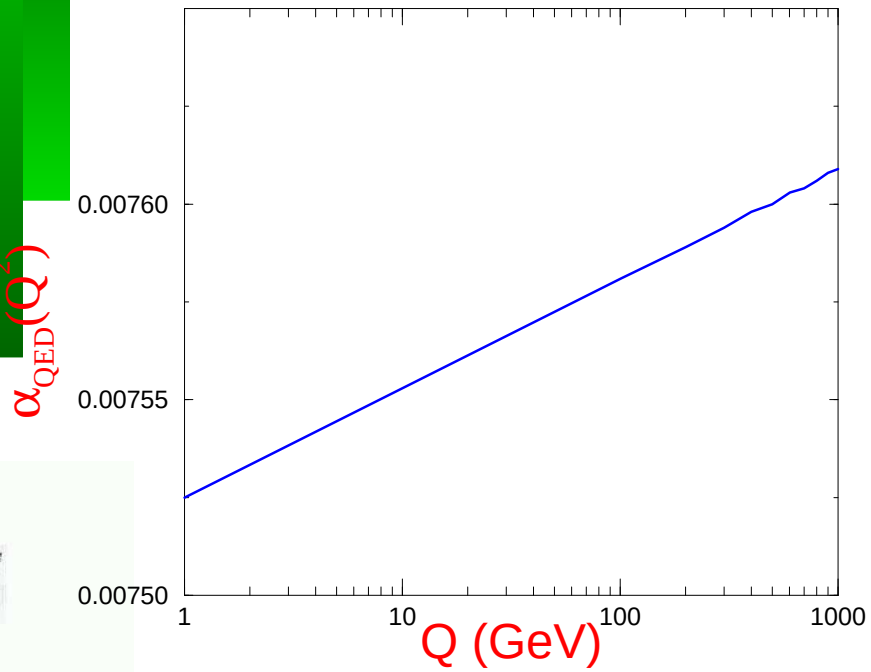
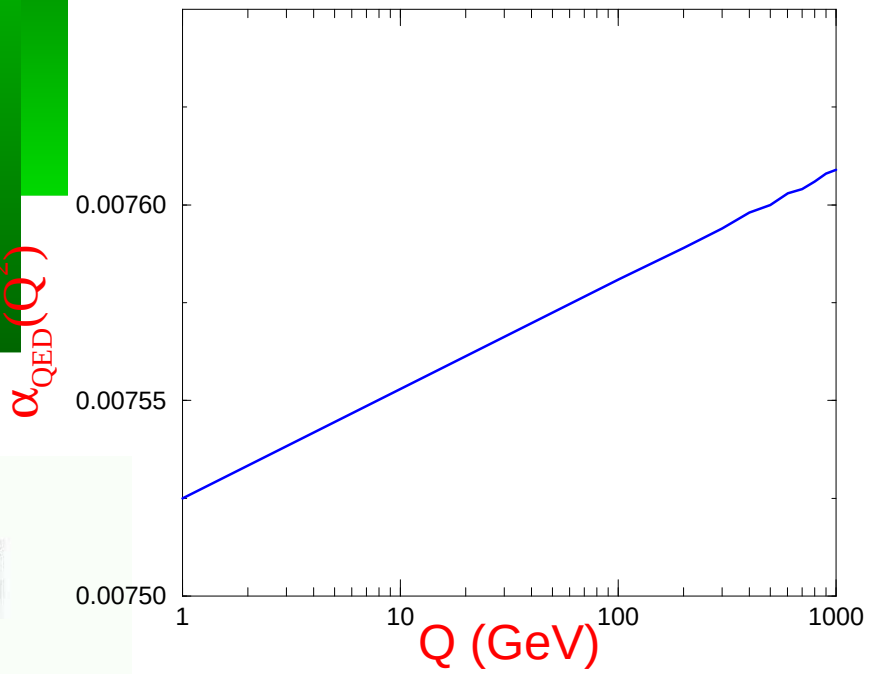
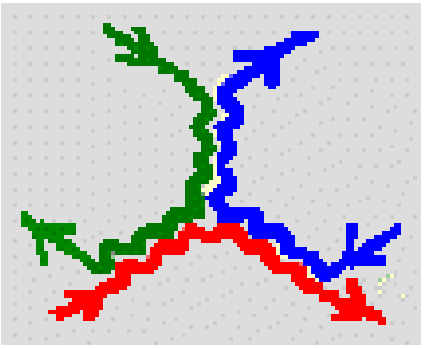


$$\alpha_{\mathrm{QED}} = \frac{\alpha}{1 - \alpha/3\pi \ln\left(Q^2/m_e^2\right)}$$

QED cf. QCD

Add three-gluon interaction





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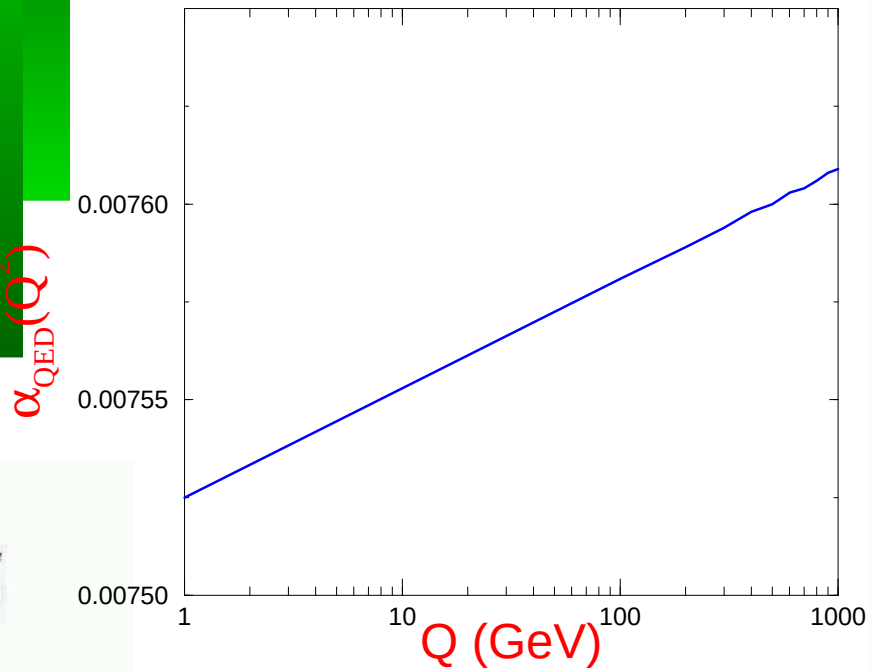

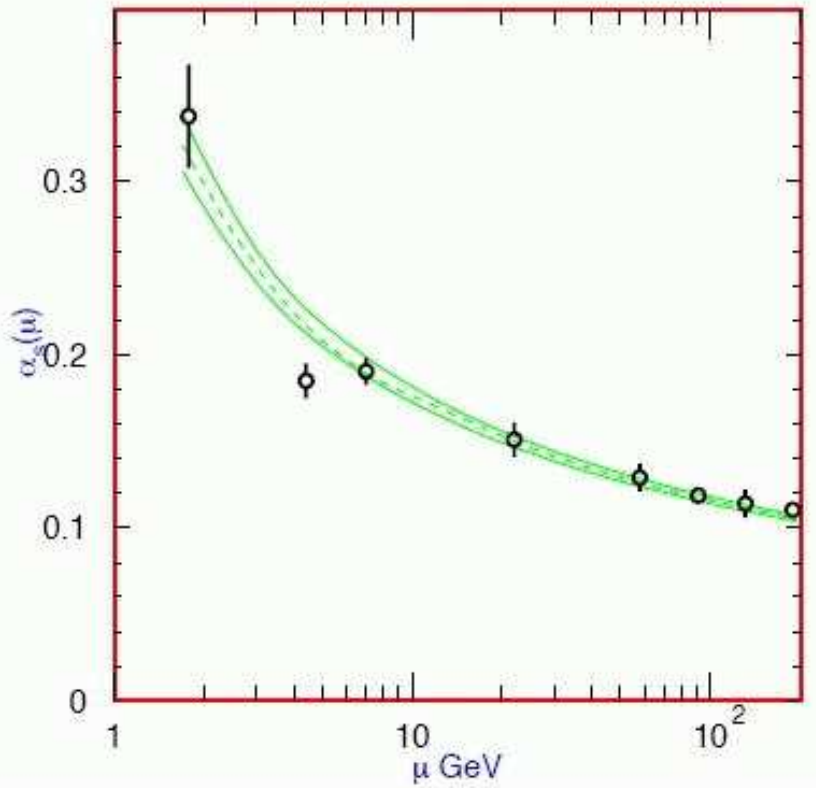

Figure 9.2: Summary of the values of $\alpha_s(\mu)$ at the values of μ where they are measured. The lines show the central values and the $\pm 1\sigma$ limits of our average. The figure clearly shows the decrease in $\alpha_s(\mu)$ with increasing μ. The data are, in increasing order of μ, τ width,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

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

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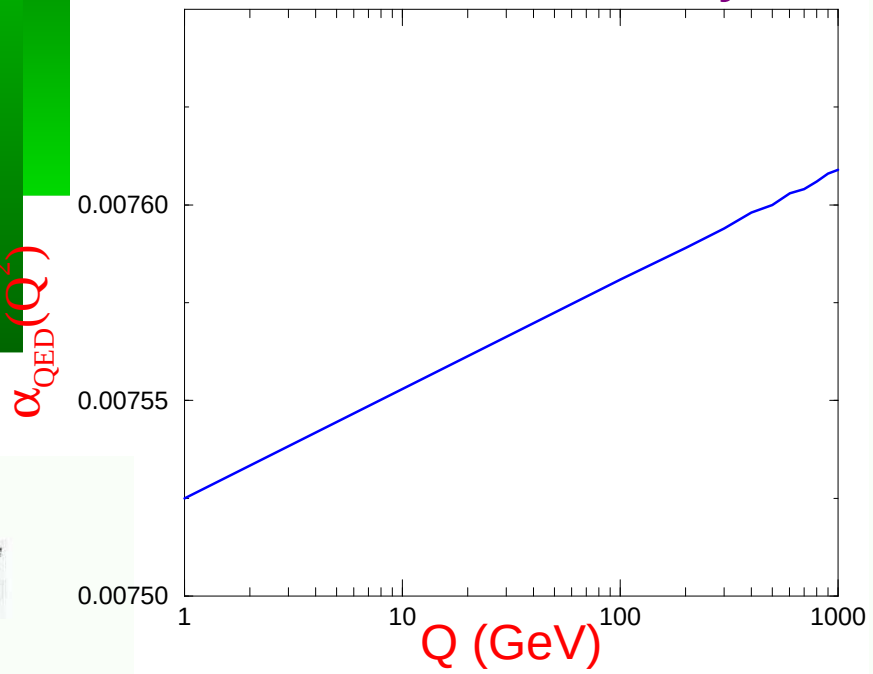
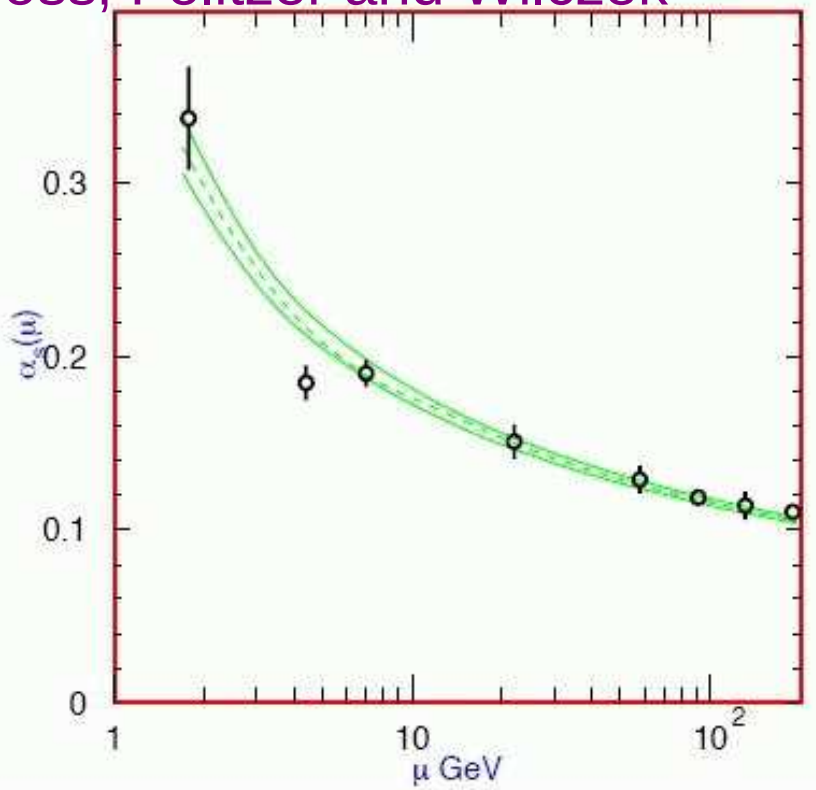
QED cf. QCD

2004 Nobel Prize in Physics: Gross, Politzer and Wilczek





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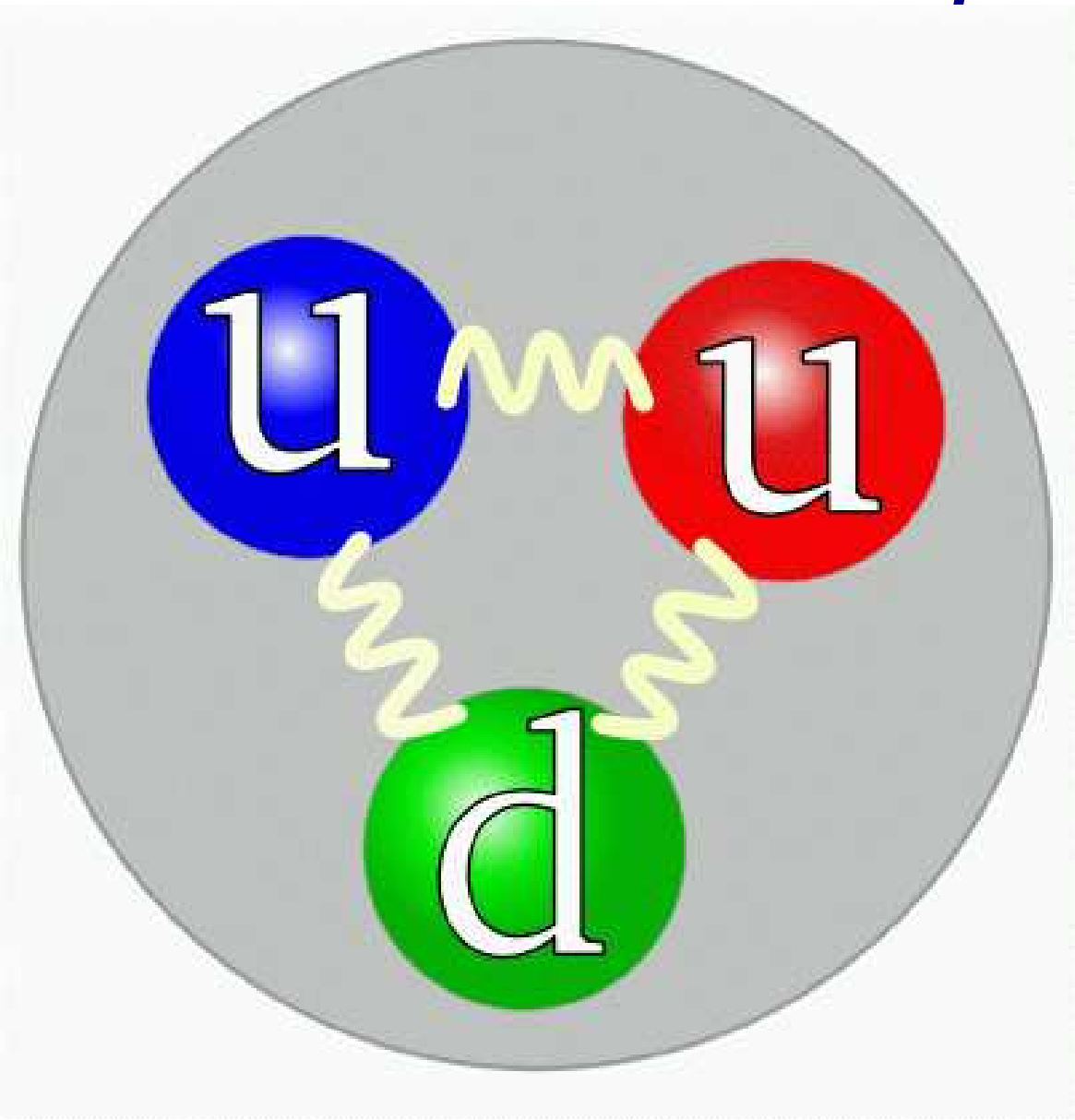
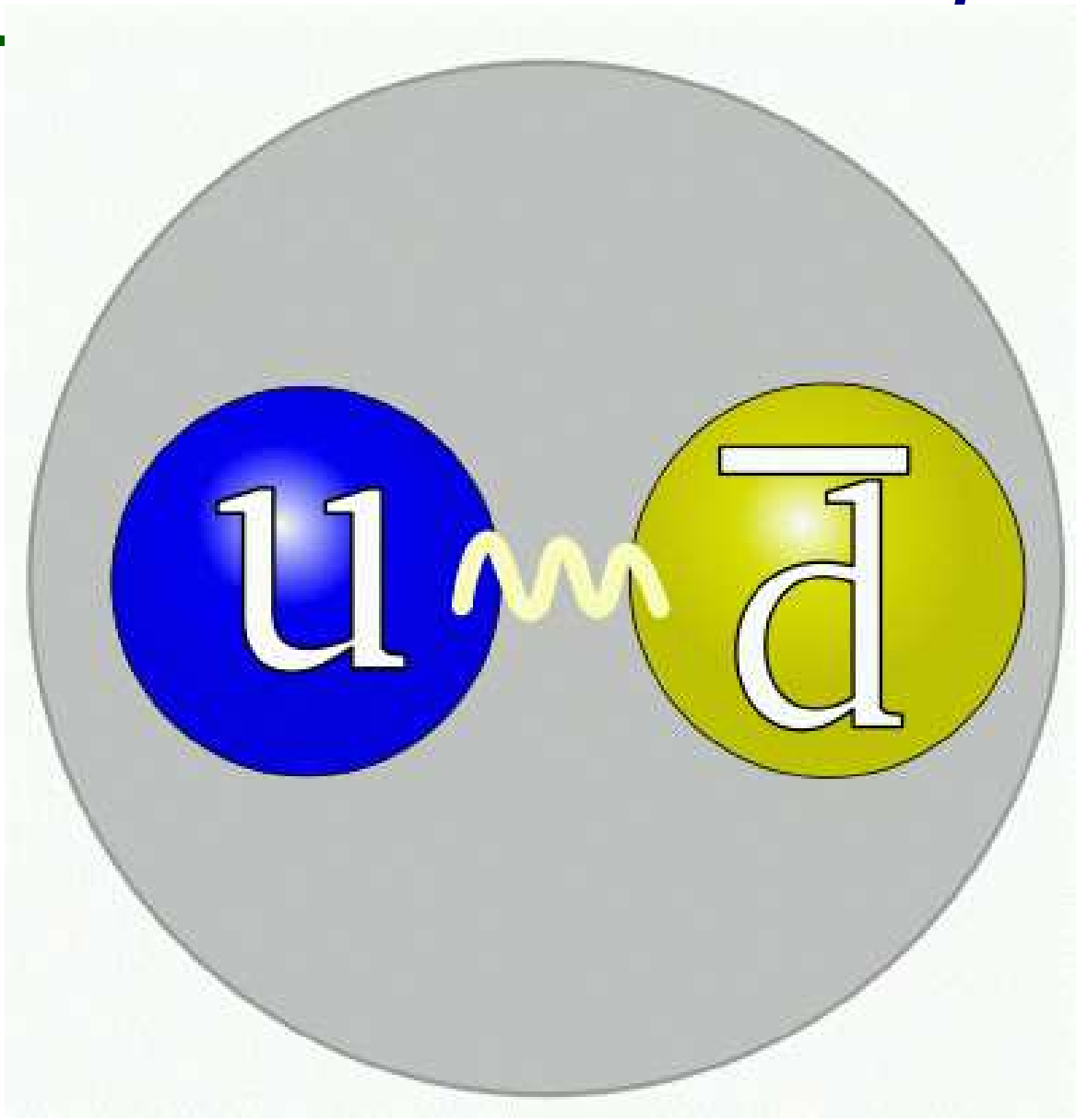


PROTON

Simple Picture



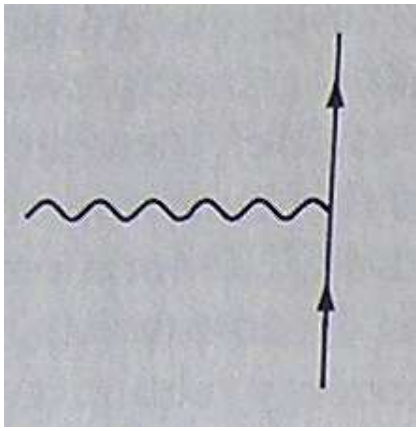
PION

Study Structure via Nucleon Form Factors

Study Structure via Nucleon Form Factors

- Electron's relativistic electromagnetic current:

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



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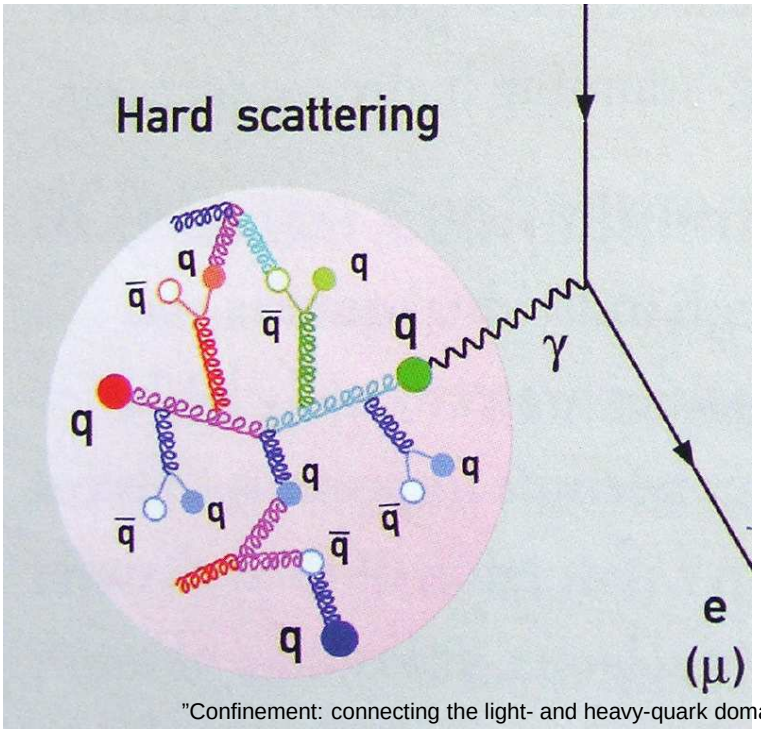

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Point-particle: $\boldsymbol{F_2\equiv 0\Rightarrow G_E\equiv G_M}$

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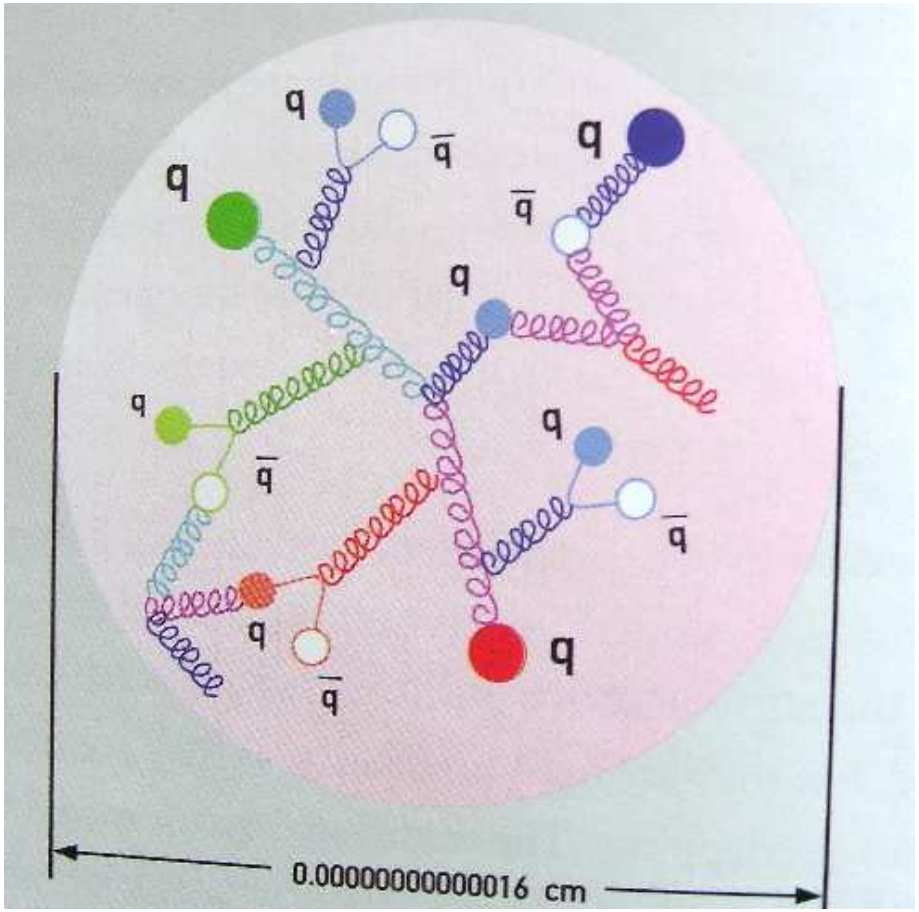
NSAC Long Range Plan

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



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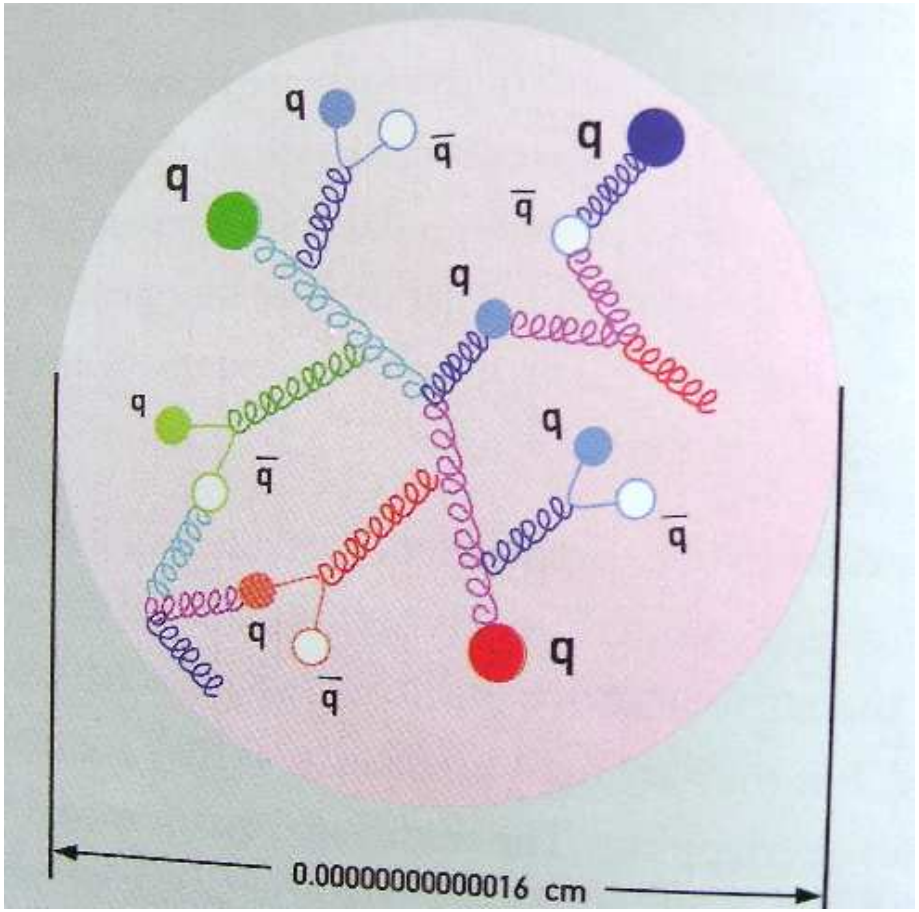

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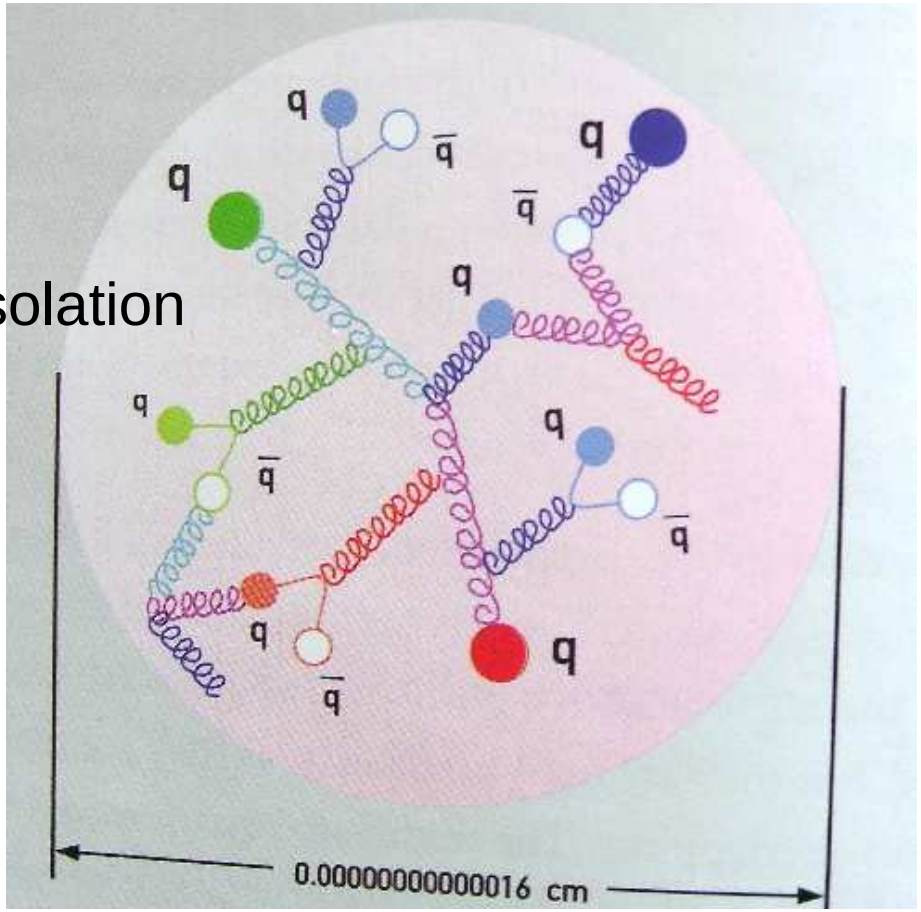

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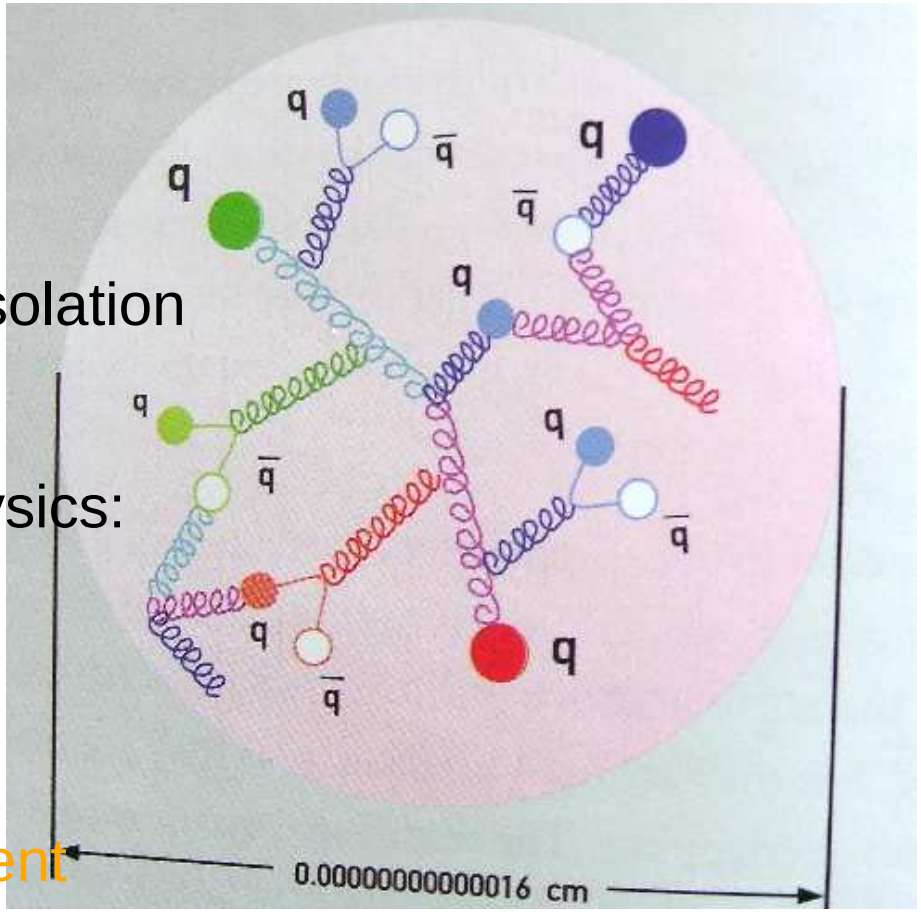
- Weightlessness
  – 2004 Nobel Prize in Physics:
  Mass of $u-$ & $d-$quarks,
  each just 5 MeV;
  Proton Mass is 940 MeV
  $\Rightarrow$ No Explanation Apparent
  for 98.4% of Mass



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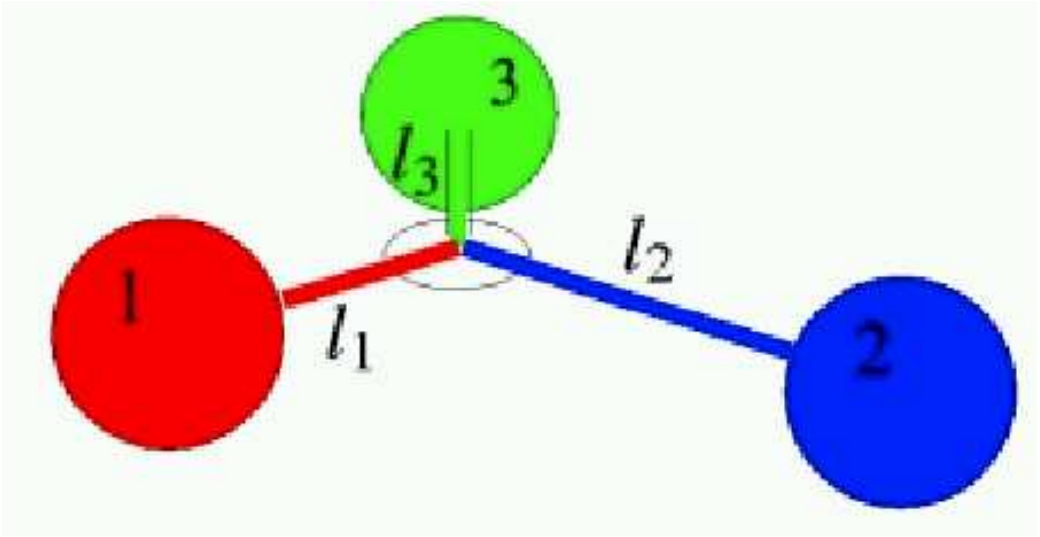
Modern Miracles in Hadron Physics

- proton = three constituent quarks



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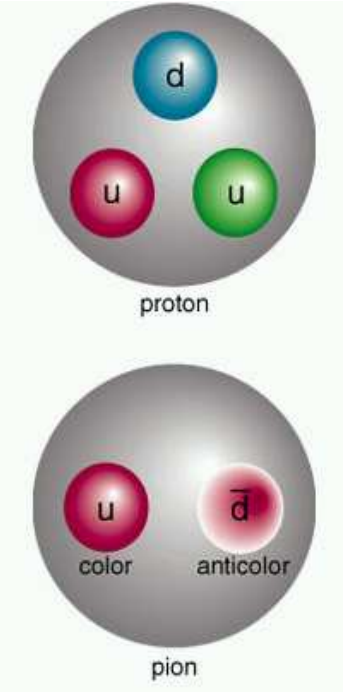

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- Another meson:
  ..... $M_{\rho} = 770\,\mathrm{MeV}$ ..... No Surprises Here

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- What is "wrong" with the pion?

Is this . . . Mass Destruction?

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Dichotomy of the Pion

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Current Algebra . . . 1968

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

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Using DSEs, we've provided this.

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QCD's Emergent Phenomena

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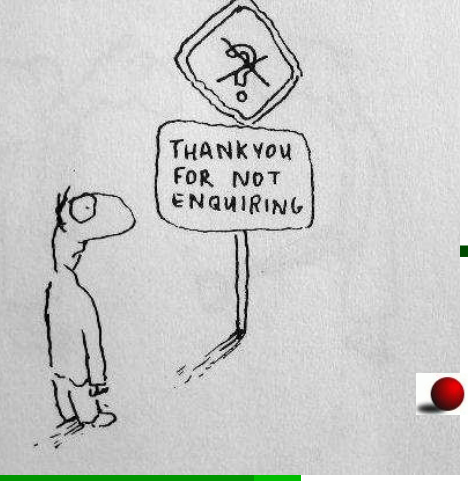

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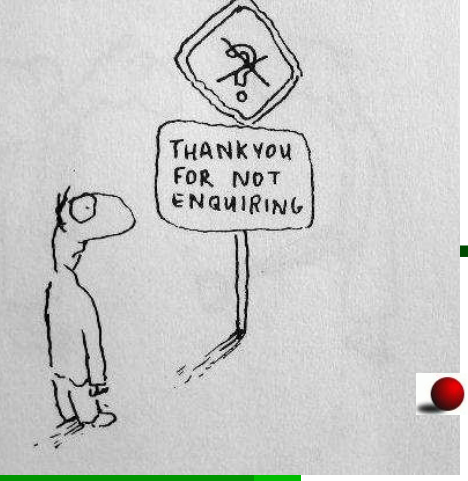

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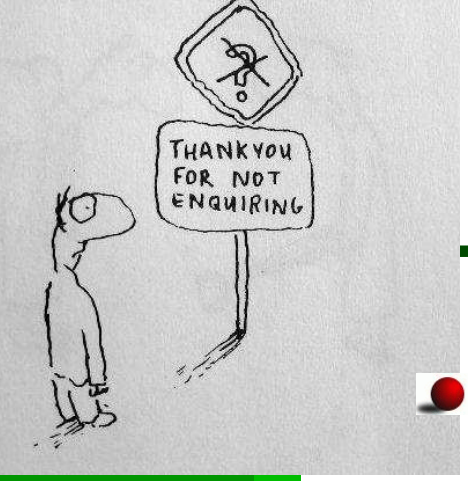

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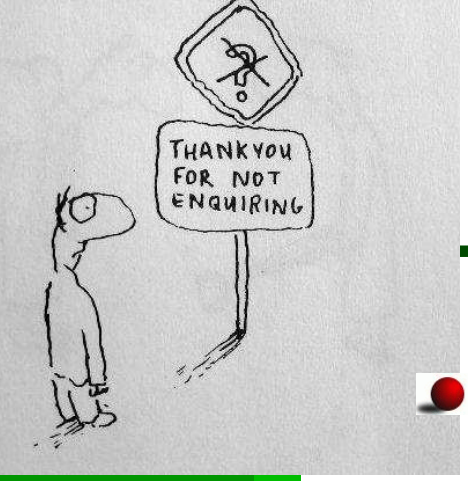

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- NSAC – Understanding these phenomena is one of the greatest intellectual challenges in physics

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What's the Problem?

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- Must calculate the hadron's *wave function*
  – Can't be done using perturbation theory

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- Must calculate the hadron's *wave function*
  – Can't be done using perturbation theory
  - So what? Same is true of hydrogen atom

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

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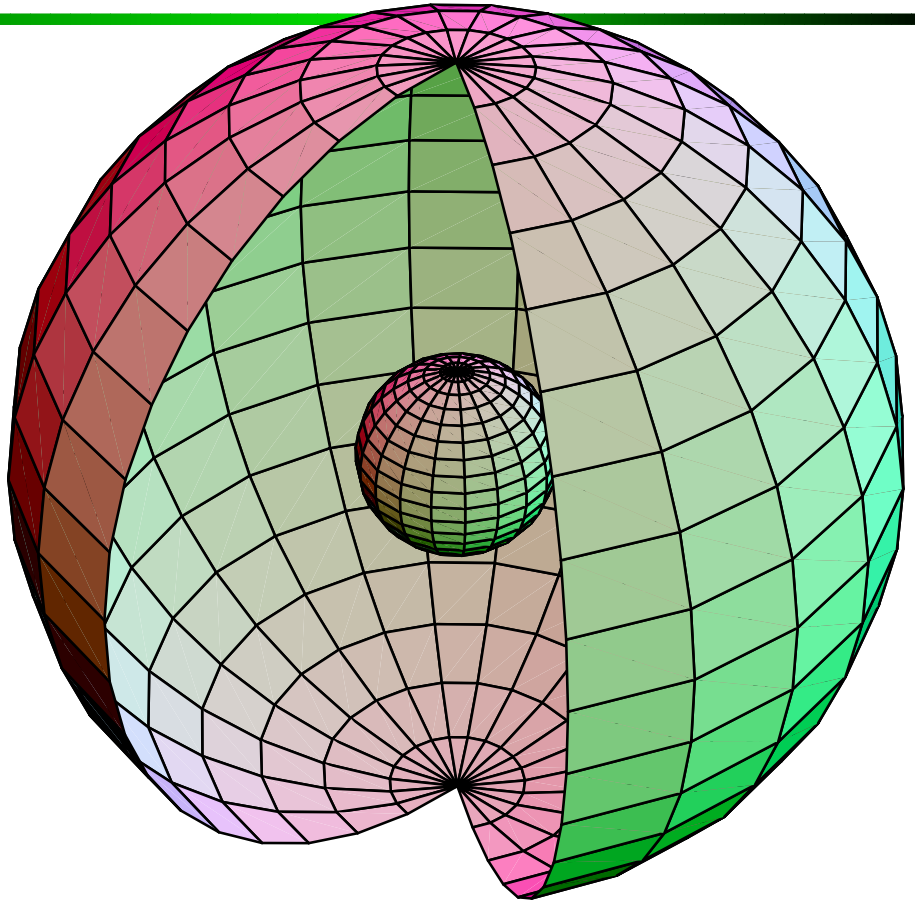
Intranucleon Interaction

Intranucleon Interaction



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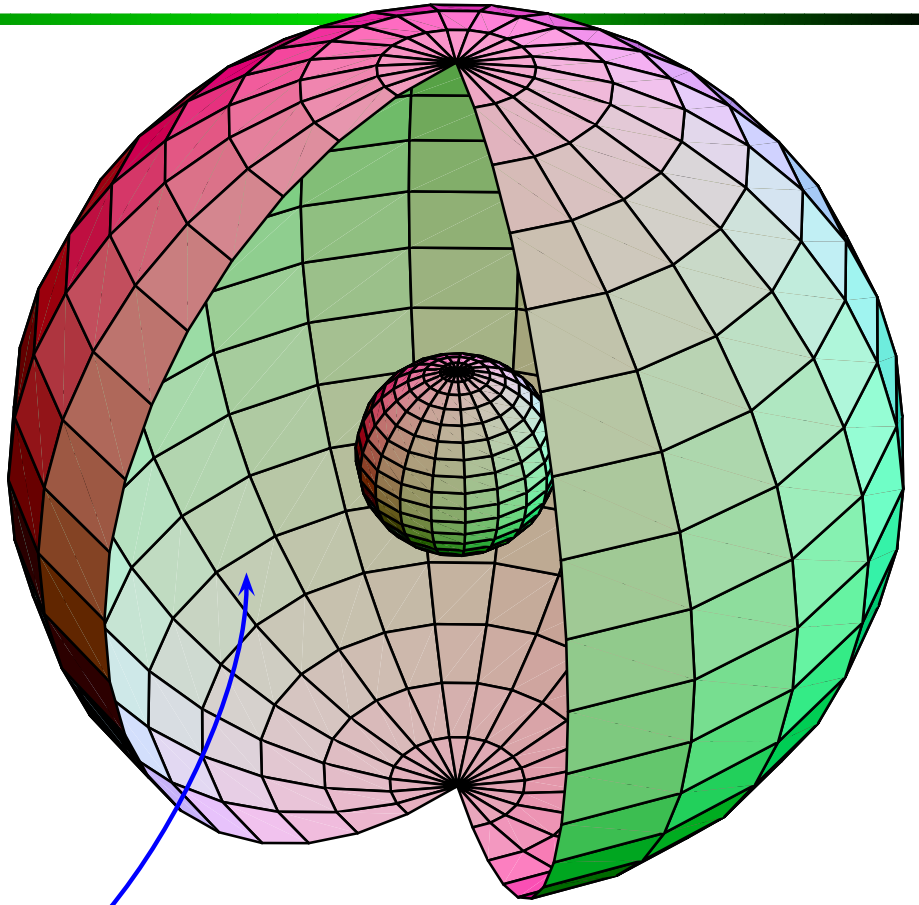

98% of the volume

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Why should You care?

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Absent DCSB: $m_\pi = m_\rho \Rightarrow$ repulsive and attractive forces in nucleon-nucleon interaction both have SAME range and there is No intermediate range attraction!

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- Is ^{12}C stable?
  - Probably not, if range range $\sim \frac{1}{2\,M_Q}$

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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?

Model QCD


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Traditional approach to strong force problem

Model QCD

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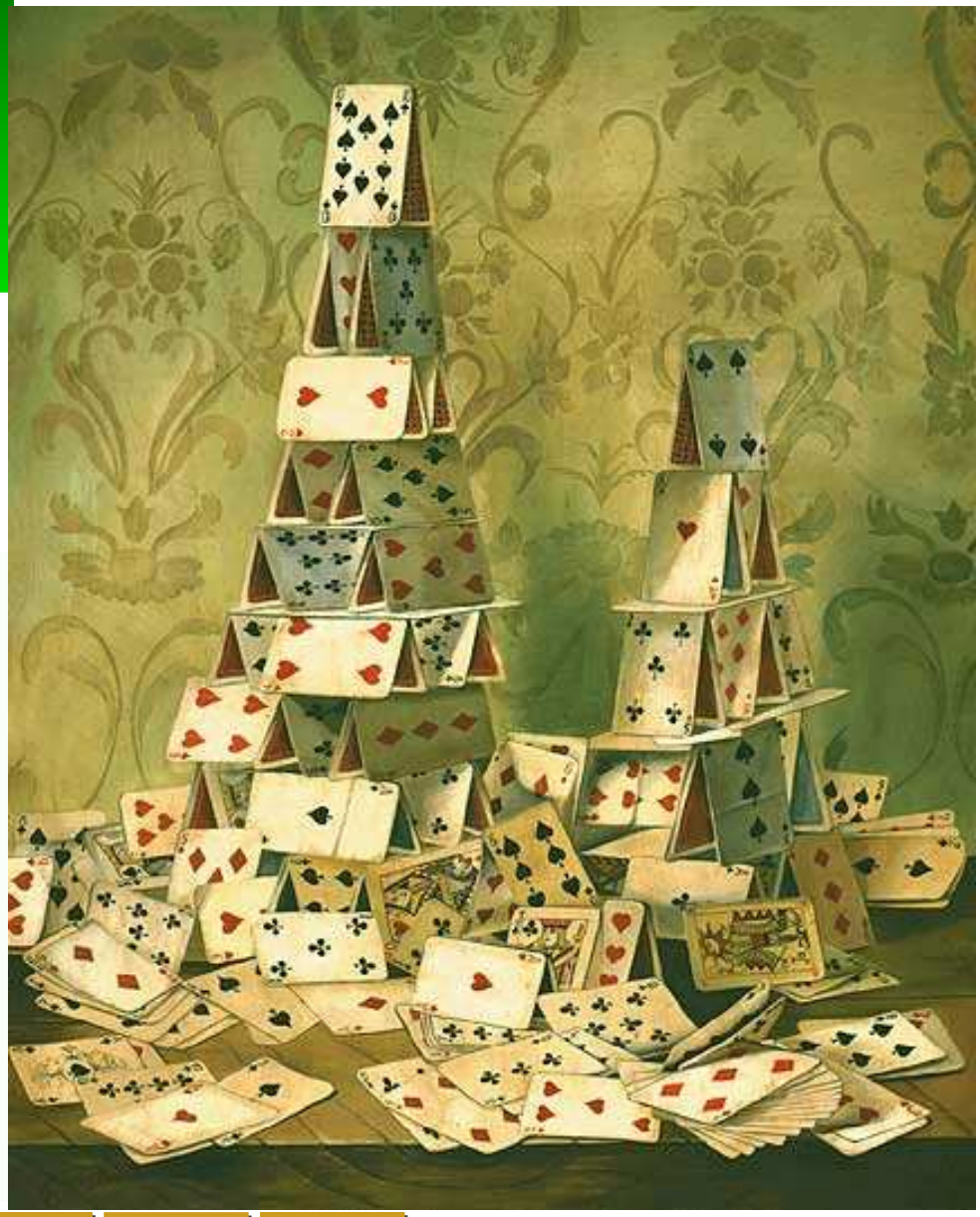

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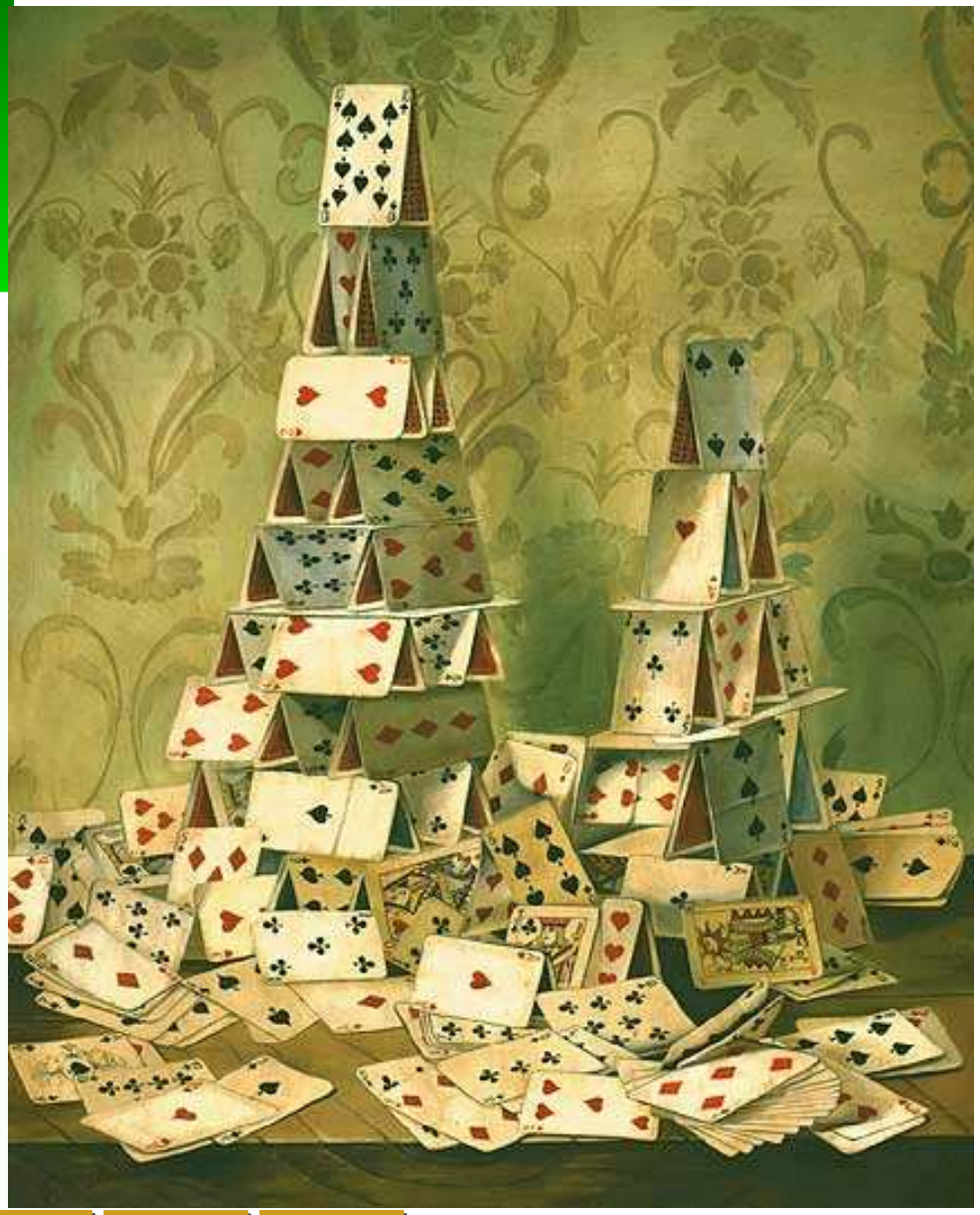

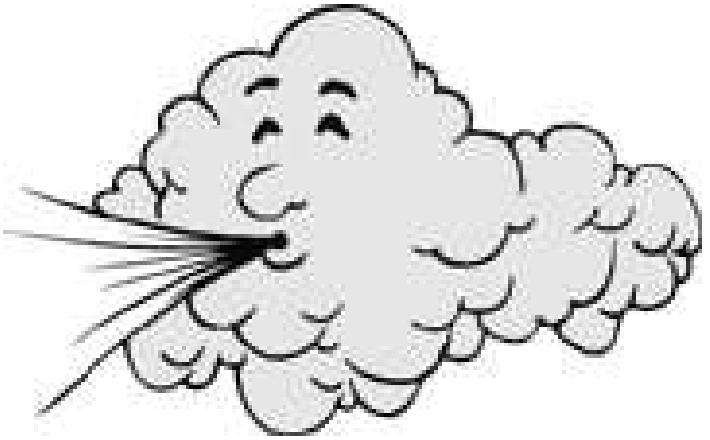

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Lattice QCD


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One modern nonperturbative approach ***Lattice QCD***

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Dyson-Schwinger Equations

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- NonPerturbative, Continuum approach to QCD
  - Hadrons as Composites of Quarks and Gluons
    - Qualitative and Quantitative Importance of:
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        – Generation of fermion mass from *nothing*
      - Quark & Gluon Confinement

        – Coloured objects not detected, not detectable?

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- $\Rightarrow$ Understanding InfraRed (long-range)

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

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- Method yields Schwinger Functions ≡ Propagators

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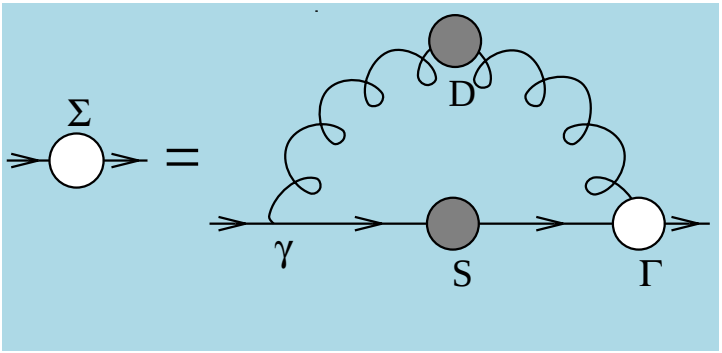
Cross-Sections built from Schwinger Functions

Persistent Challenge

Persistent Challenge

- Infinitely Many Coupled Equations



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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  - Weak coupling expansion $\Rightarrow$ Perturbation Theory

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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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- There is at least one systematic nonperturbative, symmetry-preserving truncation scheme

  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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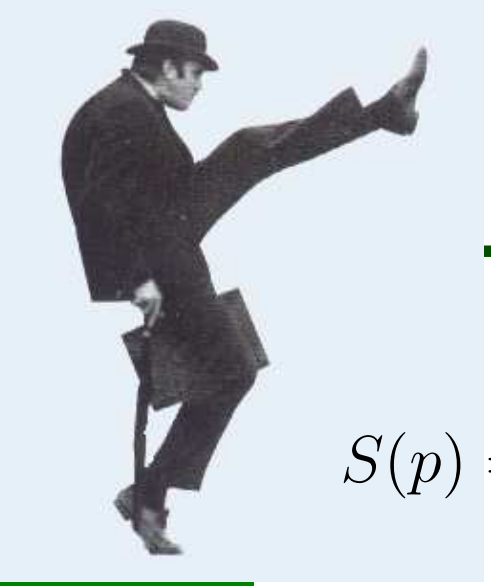
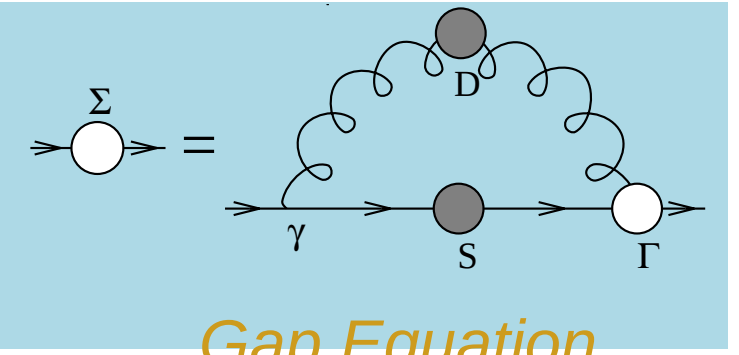
Perturbative Dressed-quark Propagator

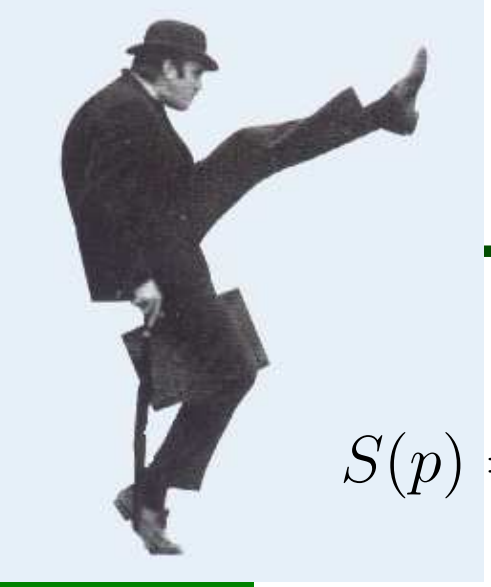


Perturbative Dressed-quark Propagator

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



Gap Equation



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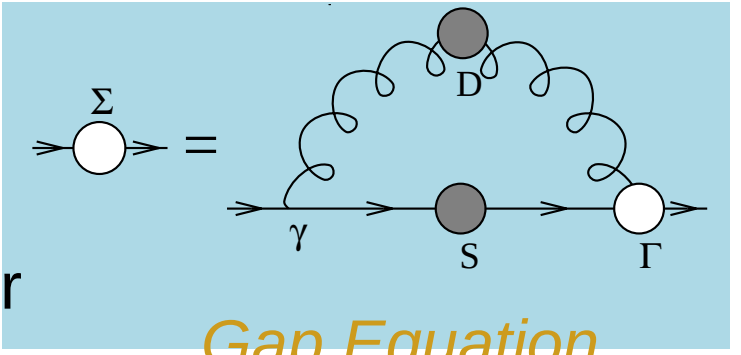

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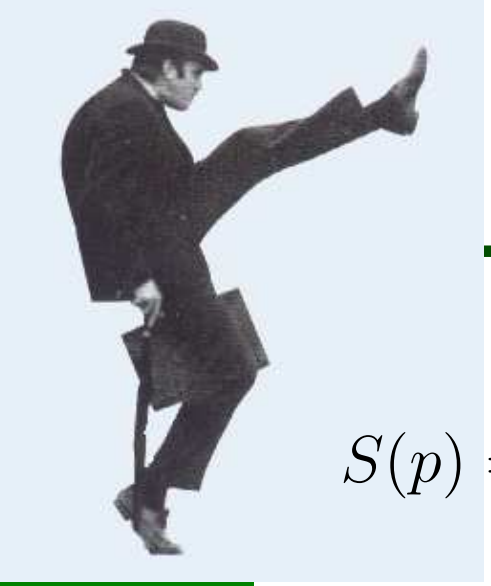

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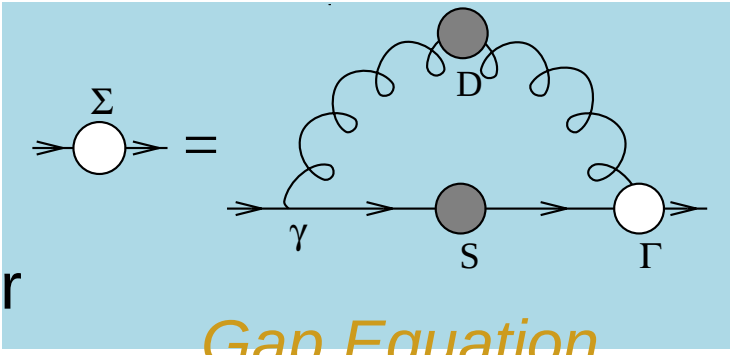

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  Reproduces Every Diagram in Perturbation Theory

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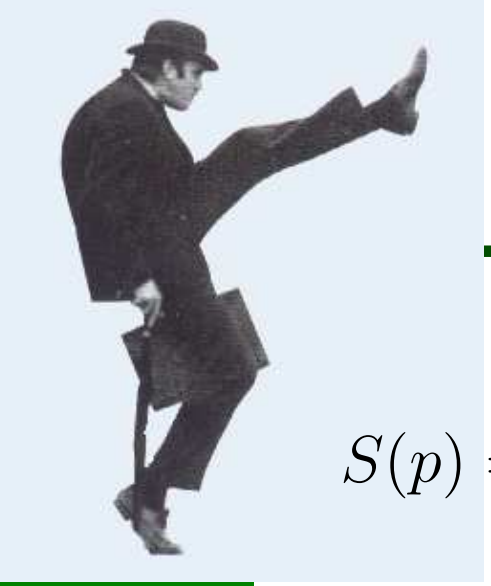

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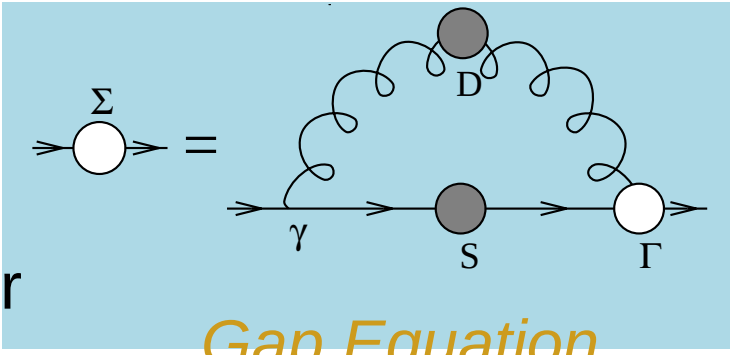

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- But in Perturbation Theory

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

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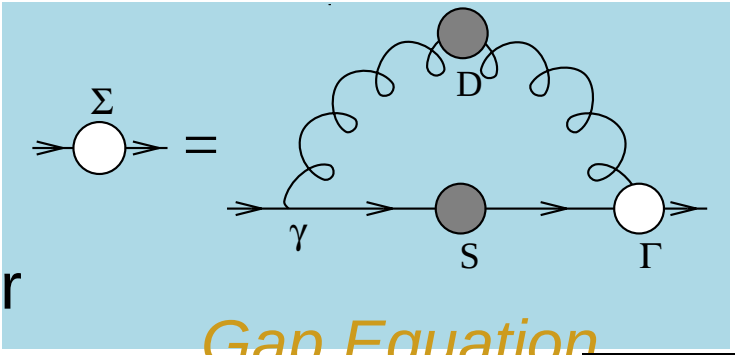

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No DCSB Here!

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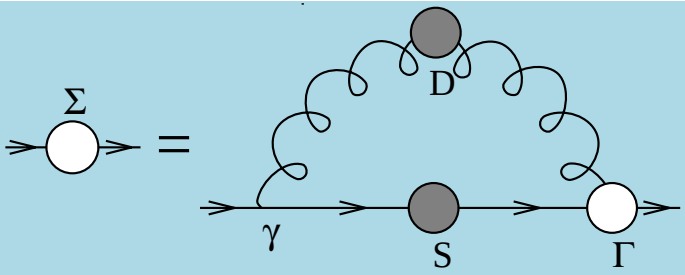

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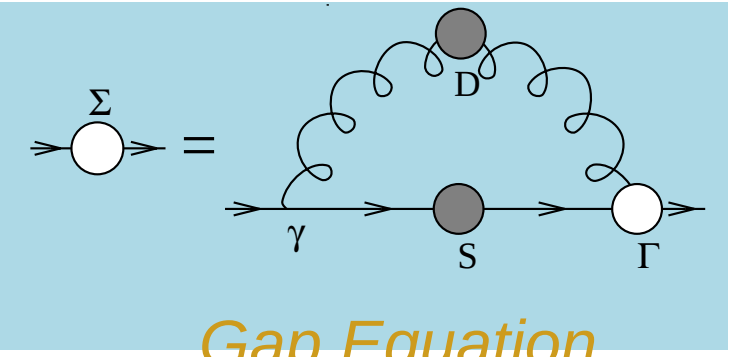
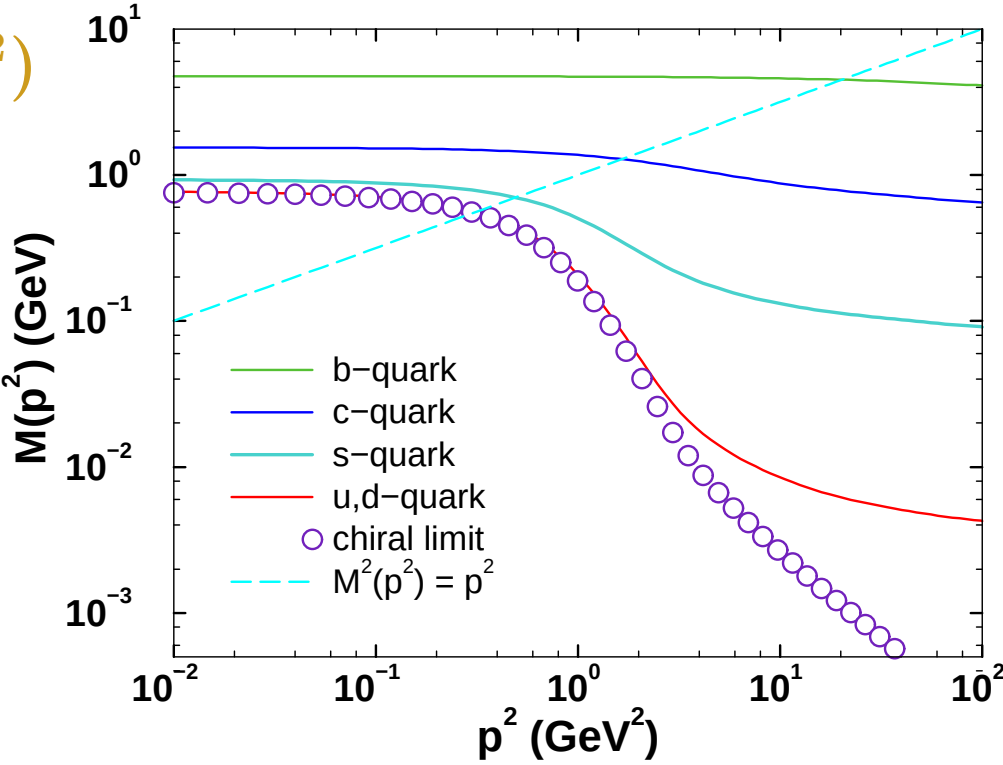


Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

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



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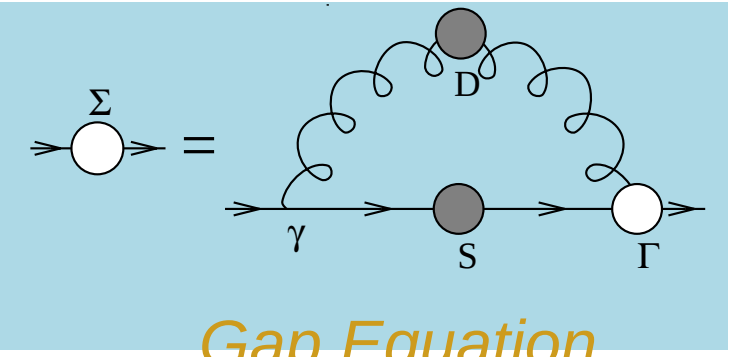

Gap Equation

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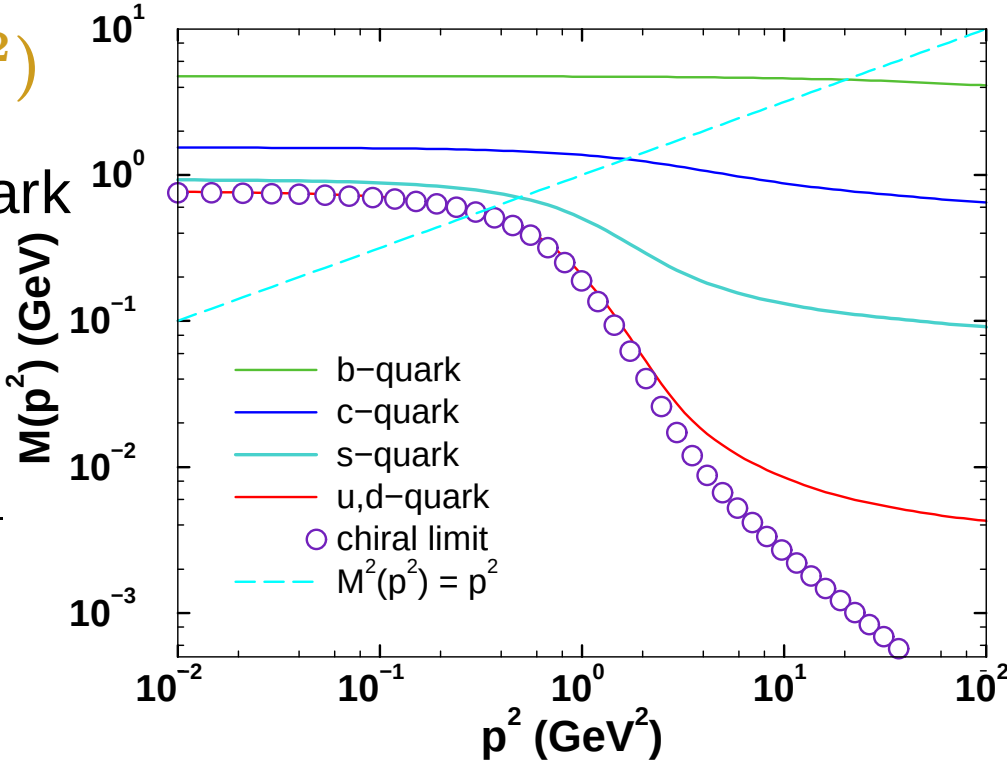
$\Rightarrow$ IR Enhancement of $M(p^2)$

- 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



Dressed-Quark Propagator

- Longstanding Prediction of Dyson-Schwinger Equation Studies

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Dressed-Quark Propagator

- Longstanding Prediction of Dyson-Schwinger Equation Studies
  - E.g., *Dyson-Schwinger equations and their application to hadronic physics*, C. D. Roberts and A. G. Williams, Prog. Part. Nucl. Phys. **33** (1994) 477

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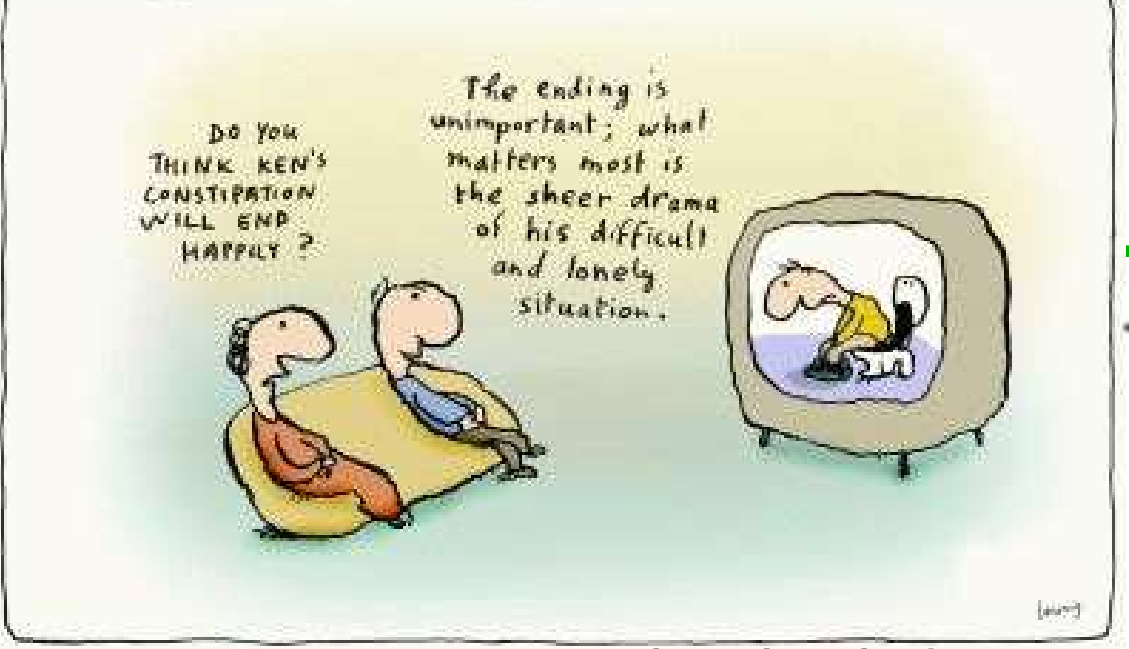

- Long used as basis for efficacious hadron physics phenomenology

- Longstanding Prediction of Dyson-Schwinger Equation Studies
  - E.g., *Dyson-Schwinger equations and their application to hadronic physics*, C. D. Roberts and A. G. Williams, Prog. Part. Nucl. Phys. **33** (1994) 477

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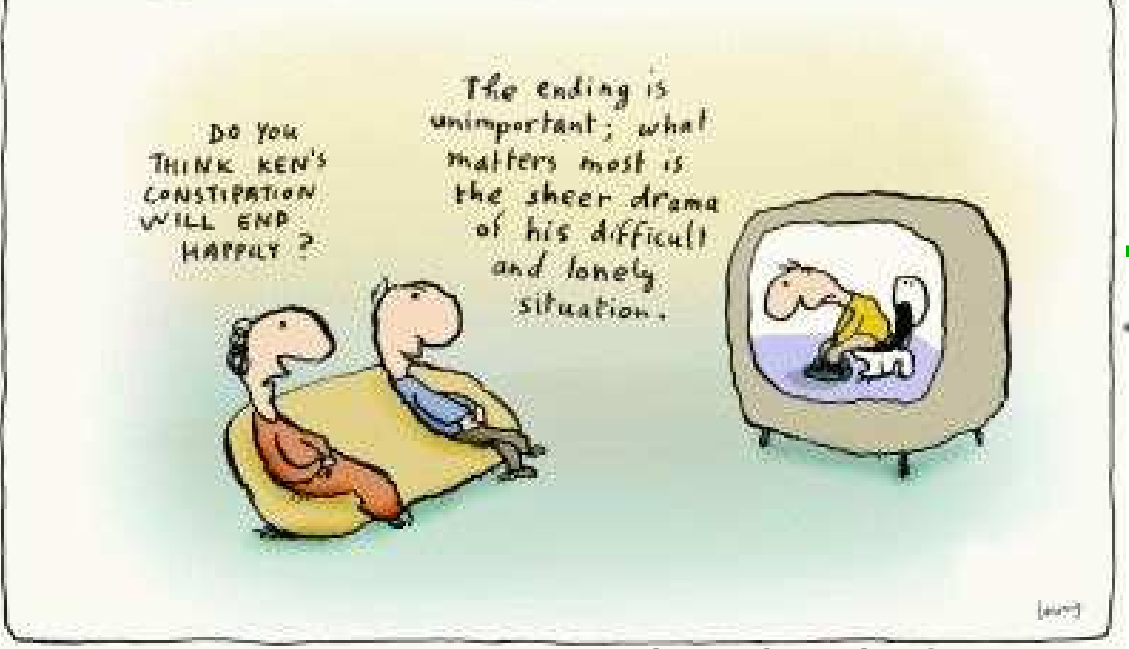
Dressed-Quark Propagator



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Mandar Bhagwat

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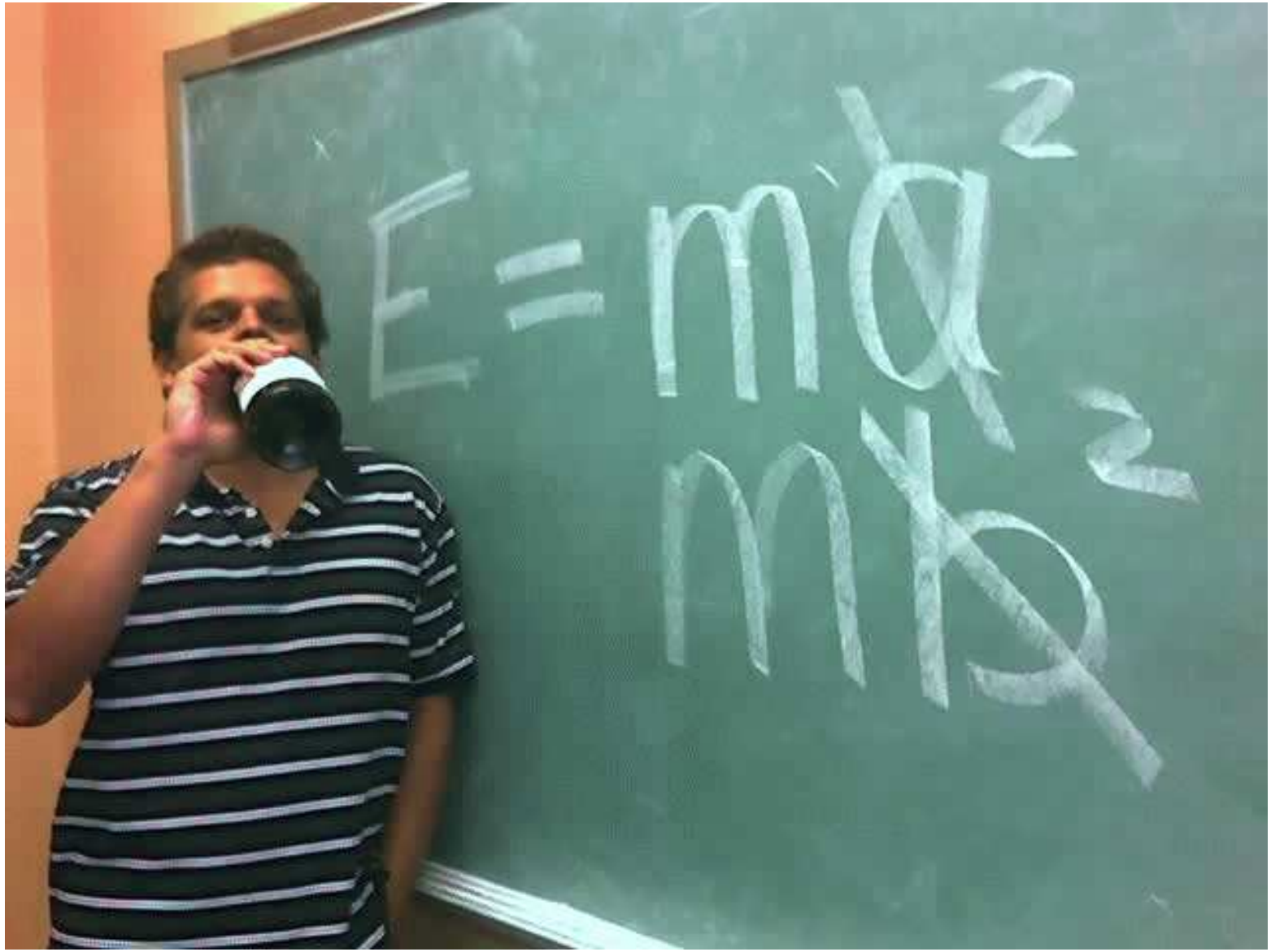

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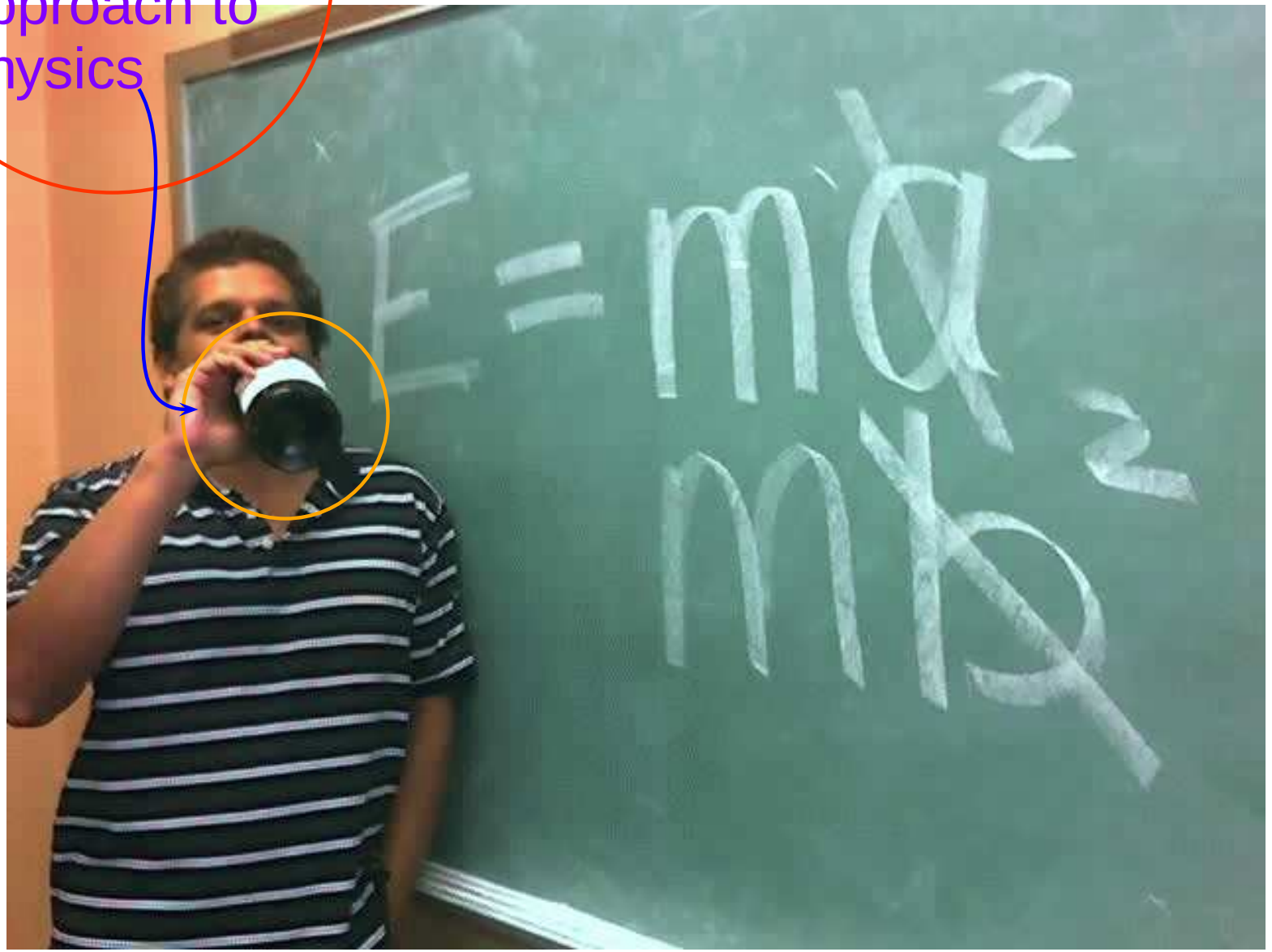
Emulating supervisor's approach to physics

Mandar Bhagwat



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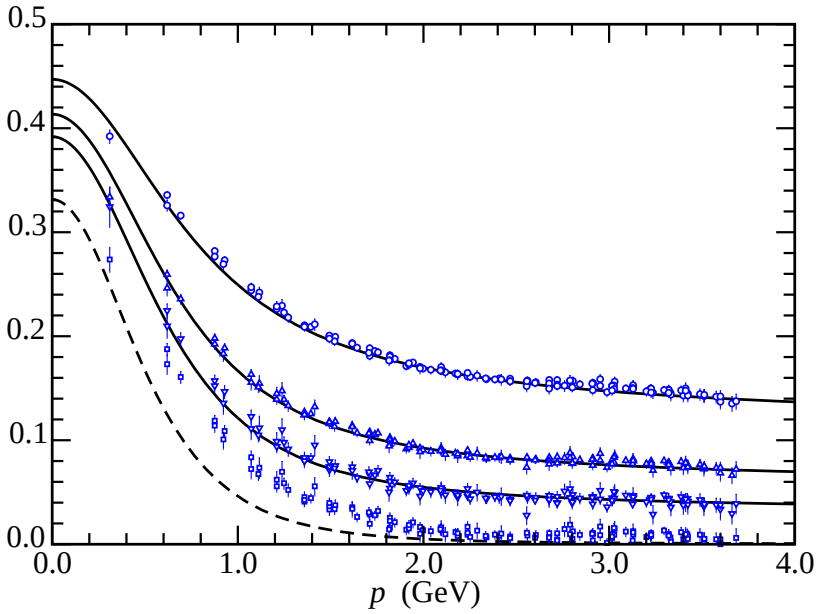
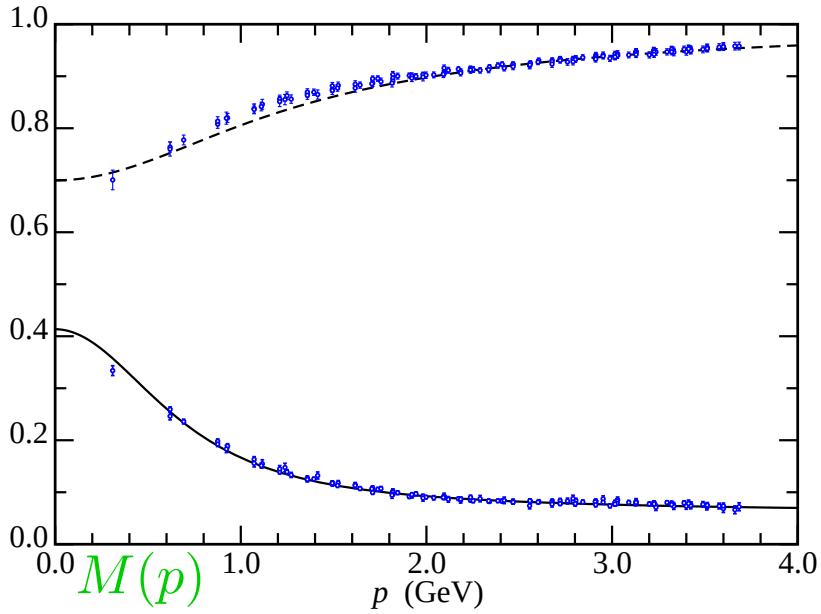
Quenched-QCD Dressed-Quark Propagator

$M(p)$



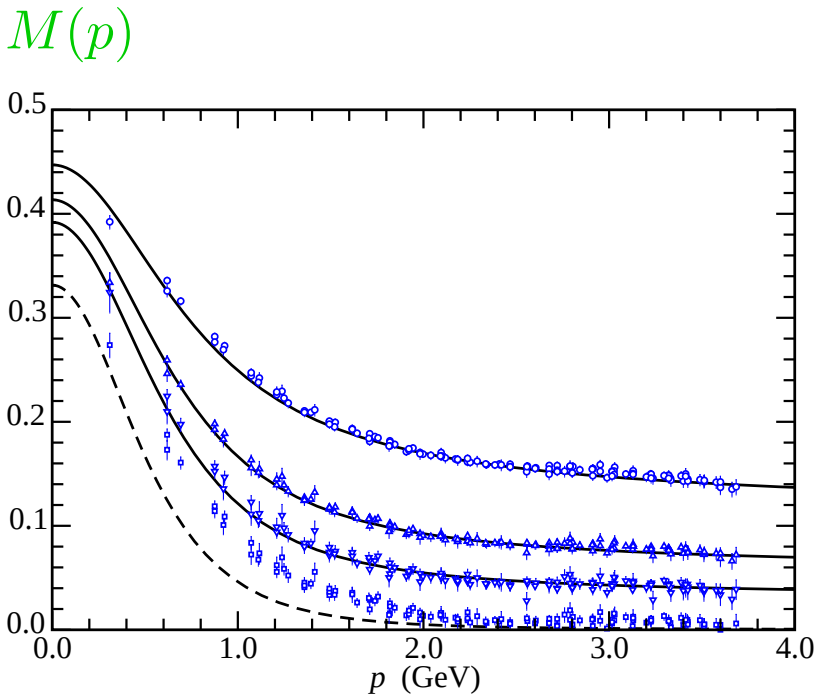
$Z(p)$

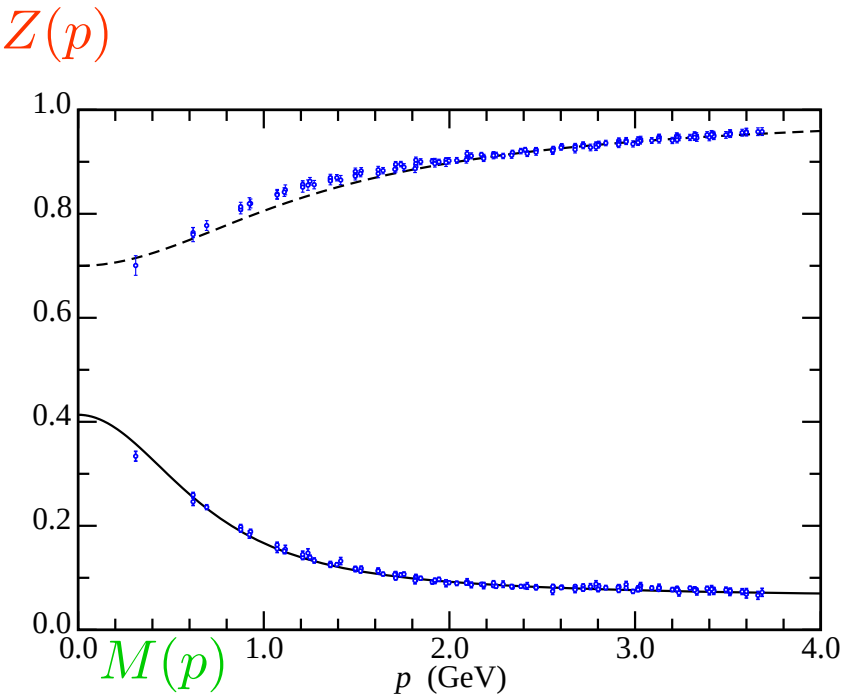


$M(p)$

Quenched-QCD Dressed-Quark Propagator

2002





- "*data*:" Quenched Lattice Meas.
  – Bowman, Heller, Leinweber, Williams: he-lat/0209129

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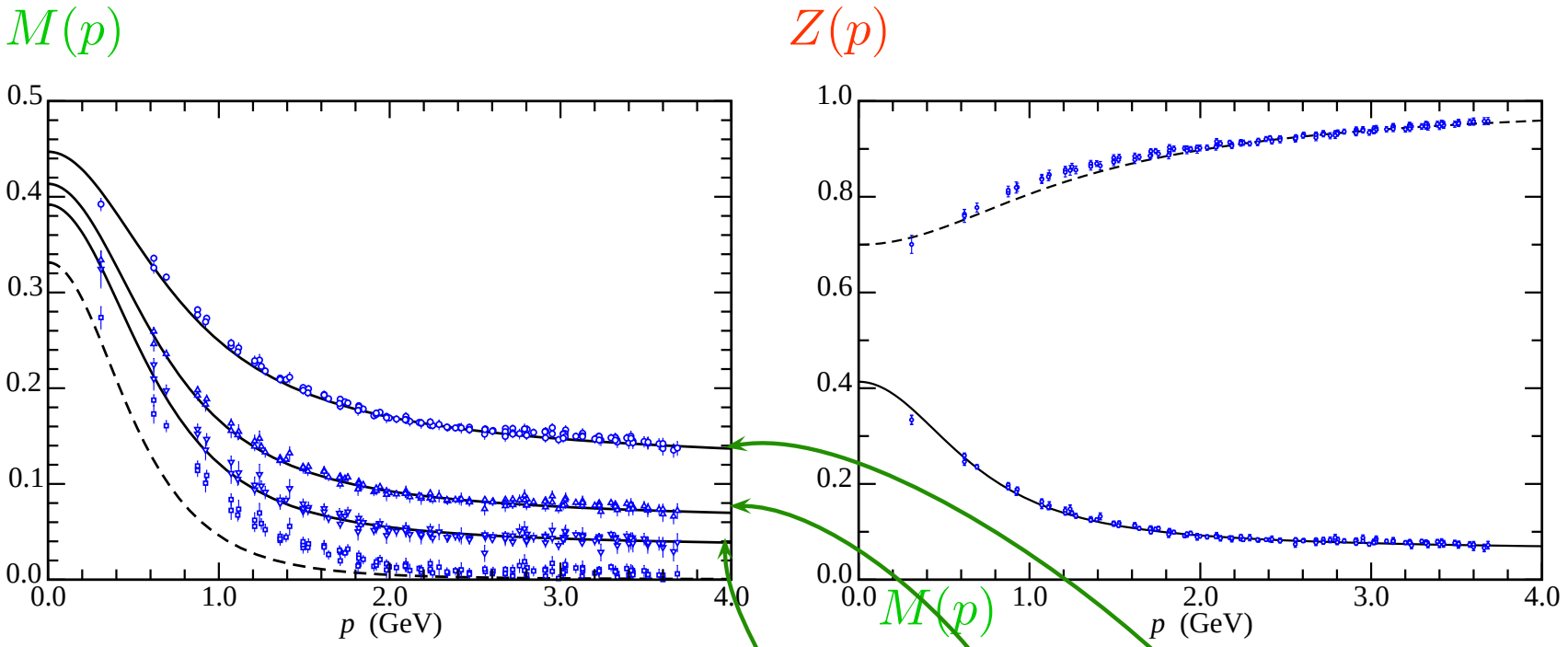
Quenched-QCD Dressed-Quark Propagator

2002



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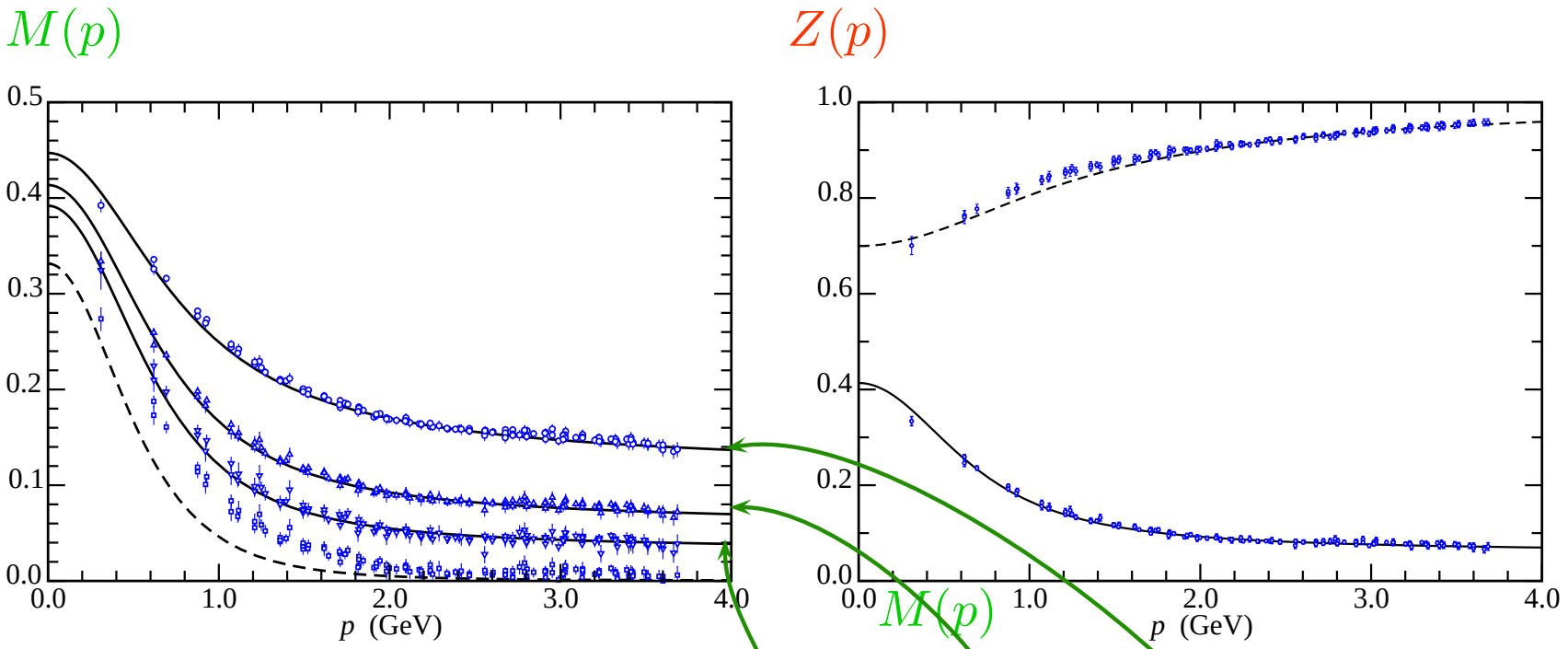

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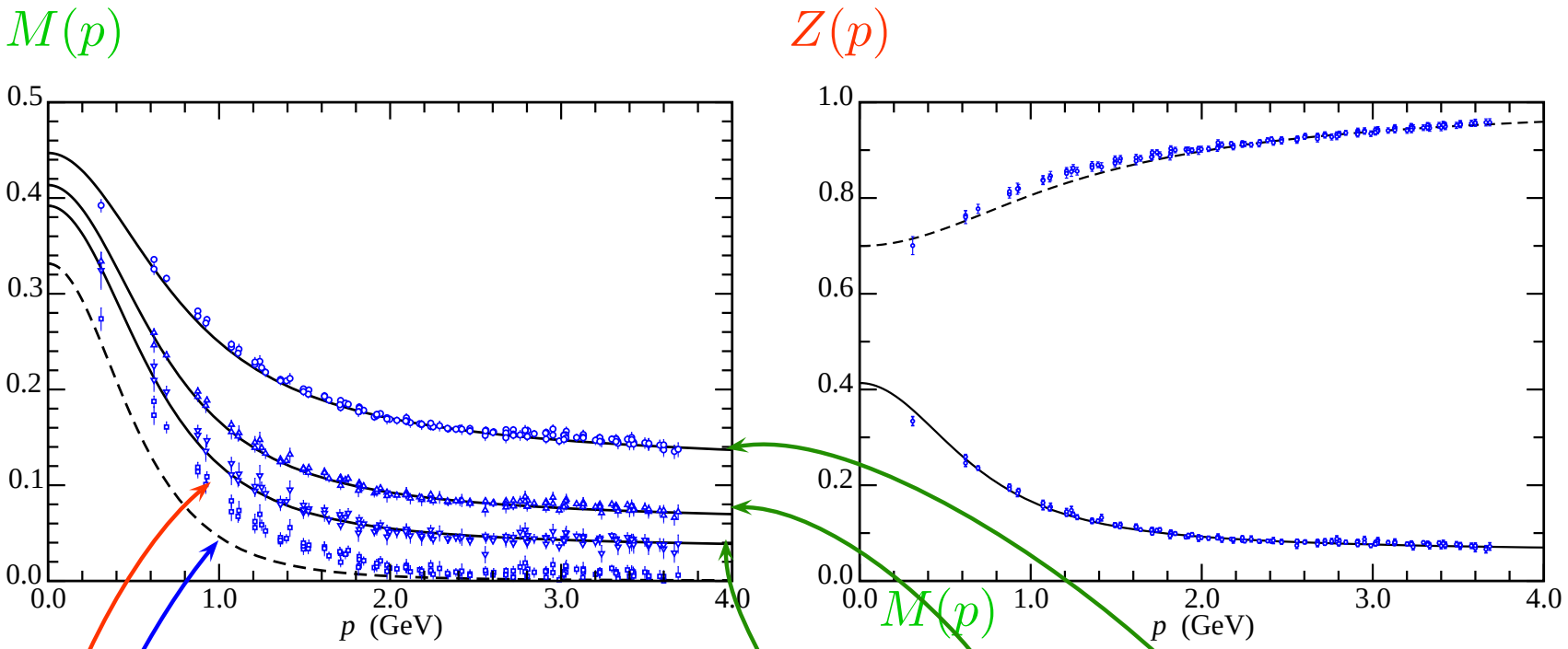
Quenched-QCD Dressed-Quark Propagator



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- Linear extrapolation of lattice data to chiral limit is inaccurate

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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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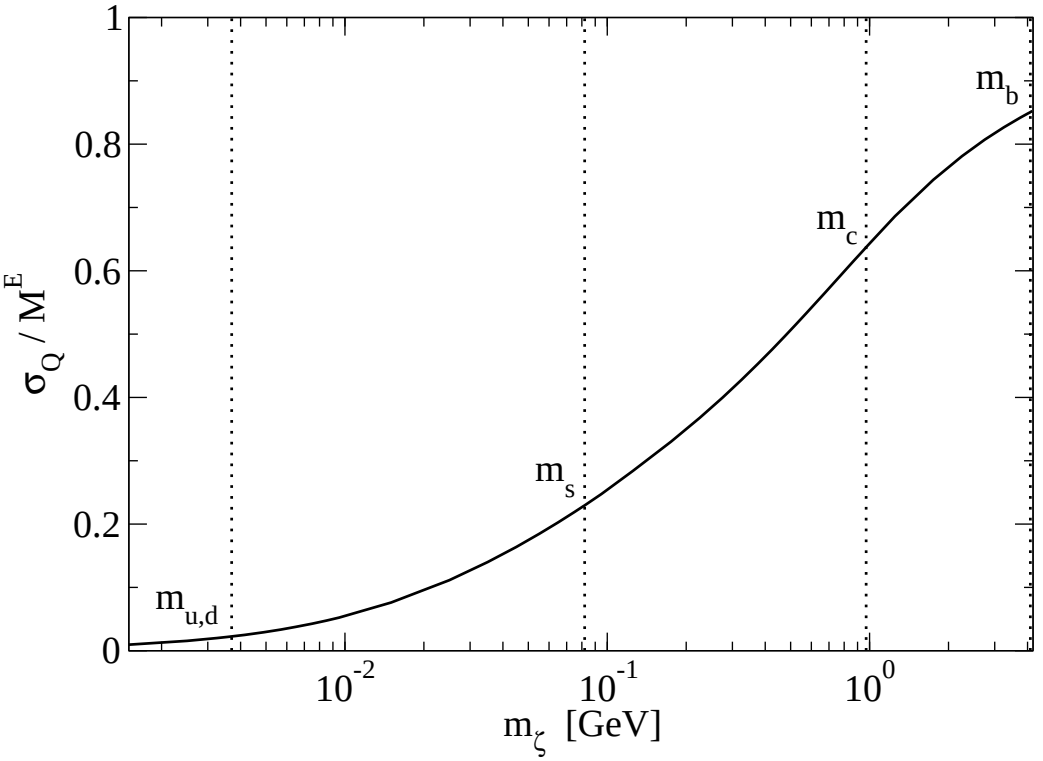

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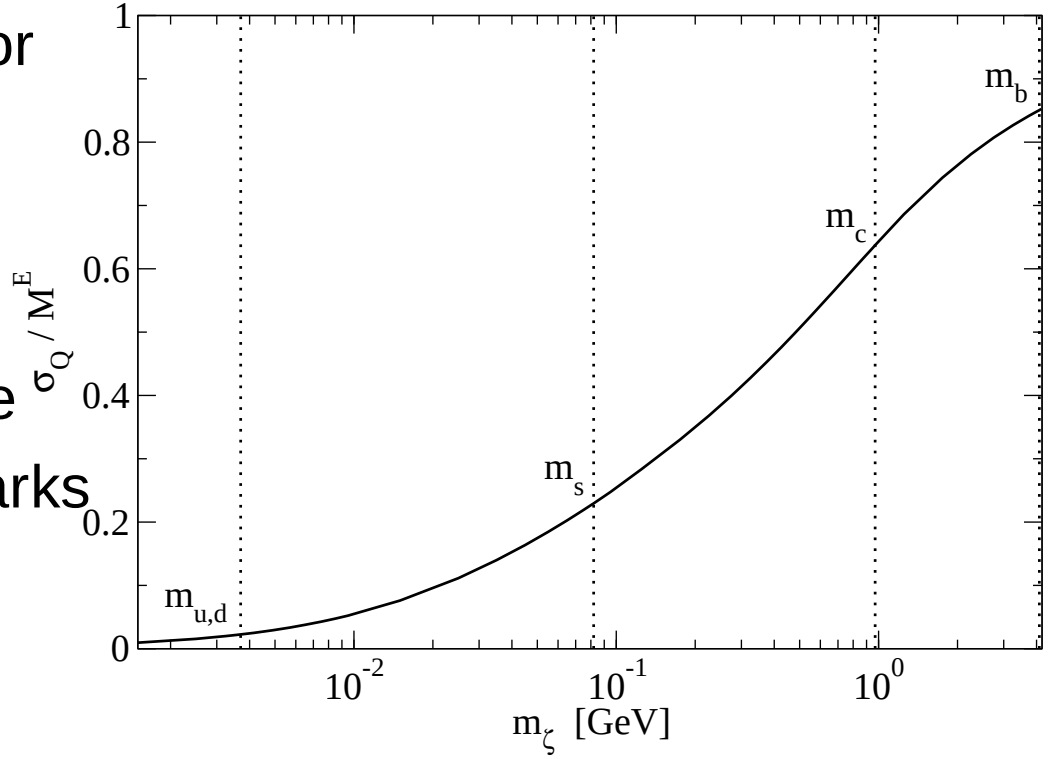
Obvious: ratio vanishes for light-quarks because magnitude of their constituent-mass owes primarily to DCSB. On the other hand, for heavy-quarks it approaches one.



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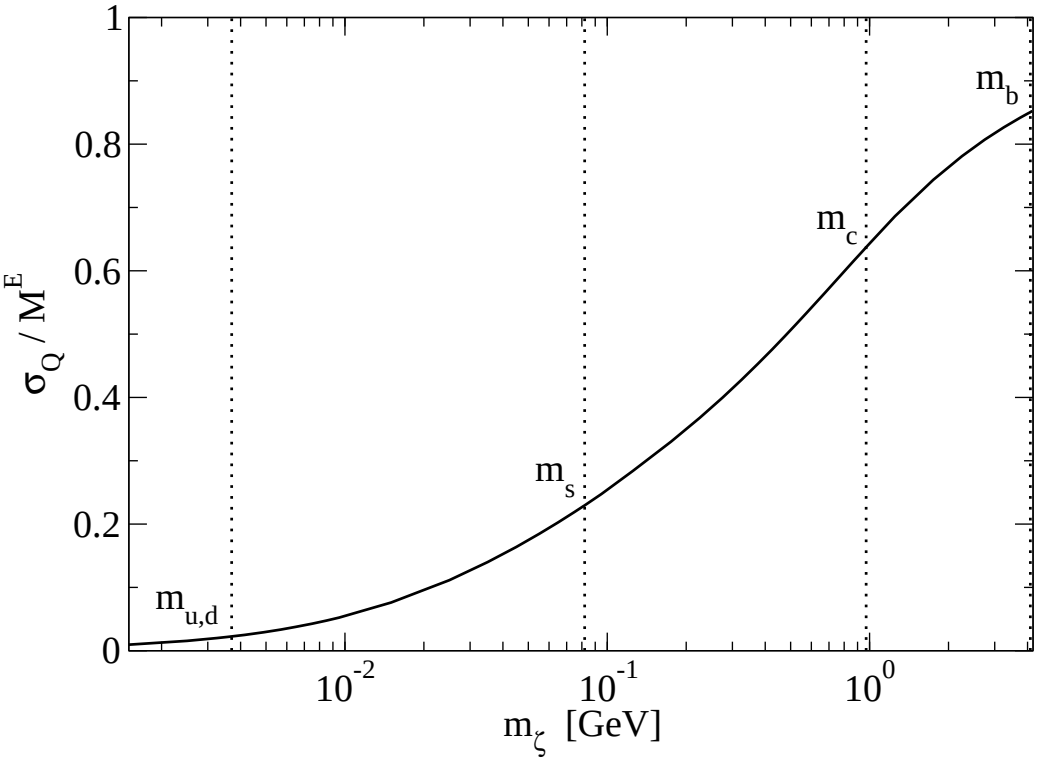
Essentially dynamical component of chiral symmetry breaking, and manifestation in all its order parameters, vanishes with increasing current-quark mass



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Hadrons

- Established understanding of two- and three-point functions

Hadrons

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

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Hadrons

- Without bound states, Comparison with experiment is impossible

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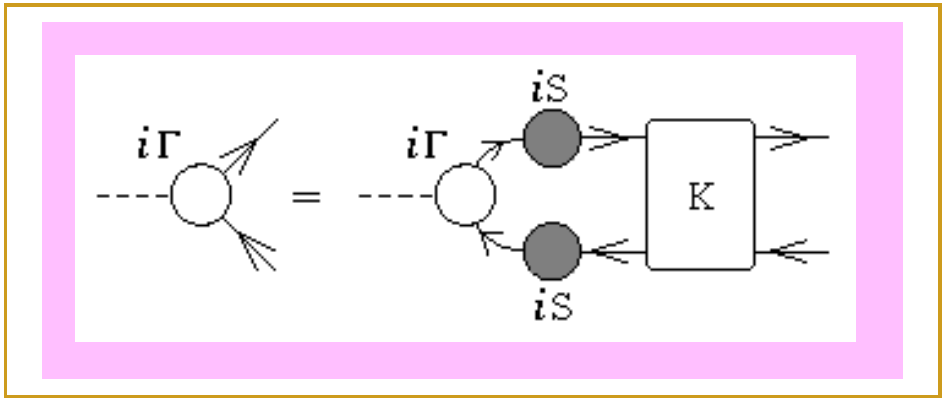
Hadrons

- Without bound states, Comparison with experiment is impossible
- They appear as pole contributions to $n \geq 3$-point colour-singlet Schwinger functions

Hadrons

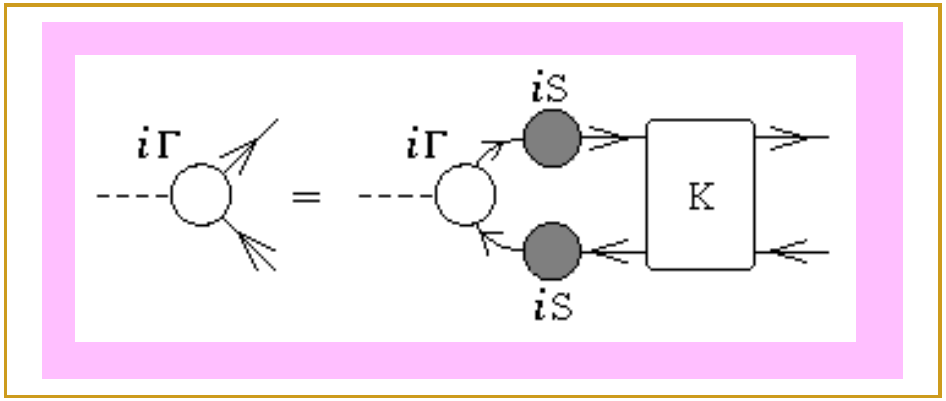
- Without bound states, Comparison with experiment is impossible
- Bethe-Salpeter Equation



QFT Generalisation of Lippmann-Schwinger Equation.

Hadrons

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



QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

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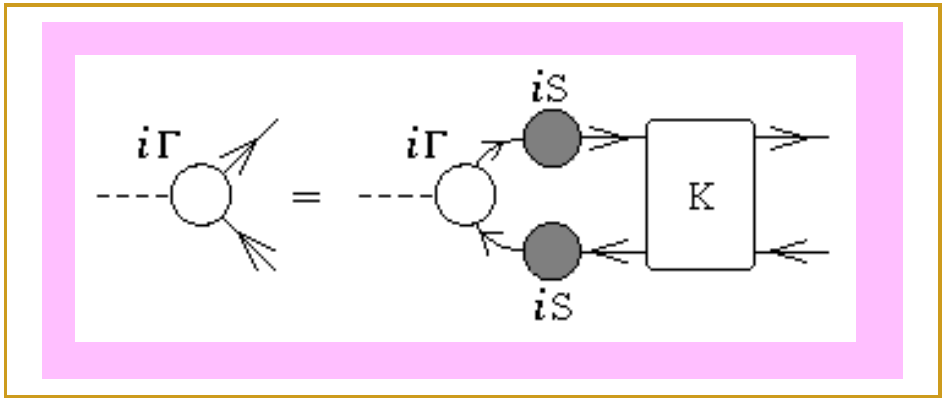


QFT Generalisation of Lippmann-Schwinger Equation.

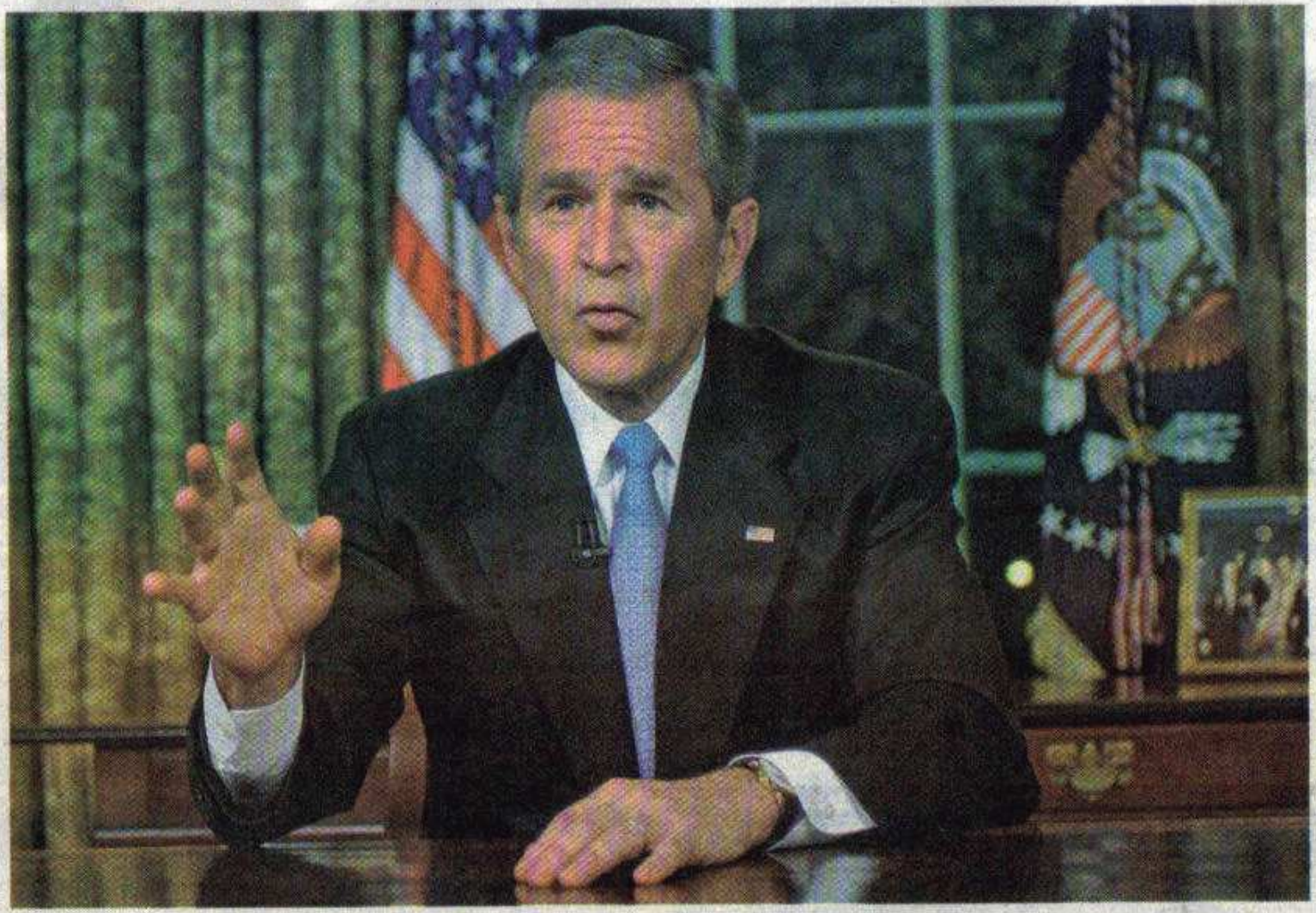
- What is the kernel, K?

or

What is the Long-Range Potential?

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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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

- Axial-vector Ward-Takahashi identity

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

Satisfies DSE

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Satisfies BSE — Satisfies DSE

Kernels must be intimately related

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Satisfies BSE — Satisfies DSE

Kernels must be intimately related

- Relation must be preserved by truncation
- Nontrivial constraint

Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma^l_{5\mu}(k;P) = \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5\,\mathcal{S}^{-1}(k_-) - M_\zeta\, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\, M_\zeta$$

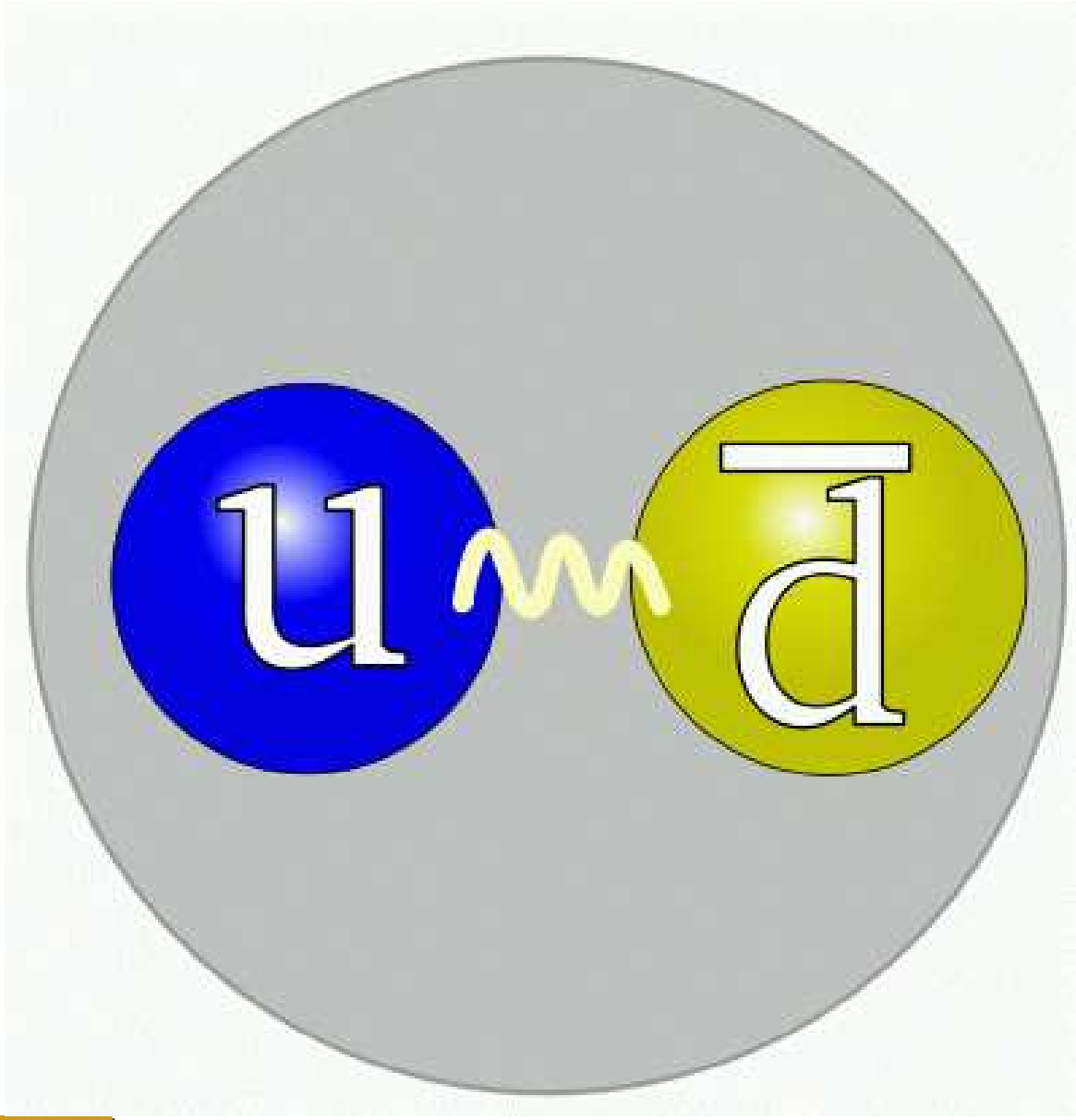
Satisfies BSE — Satisfies DSE

Kernels must be intimately related

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

Pion and . . .

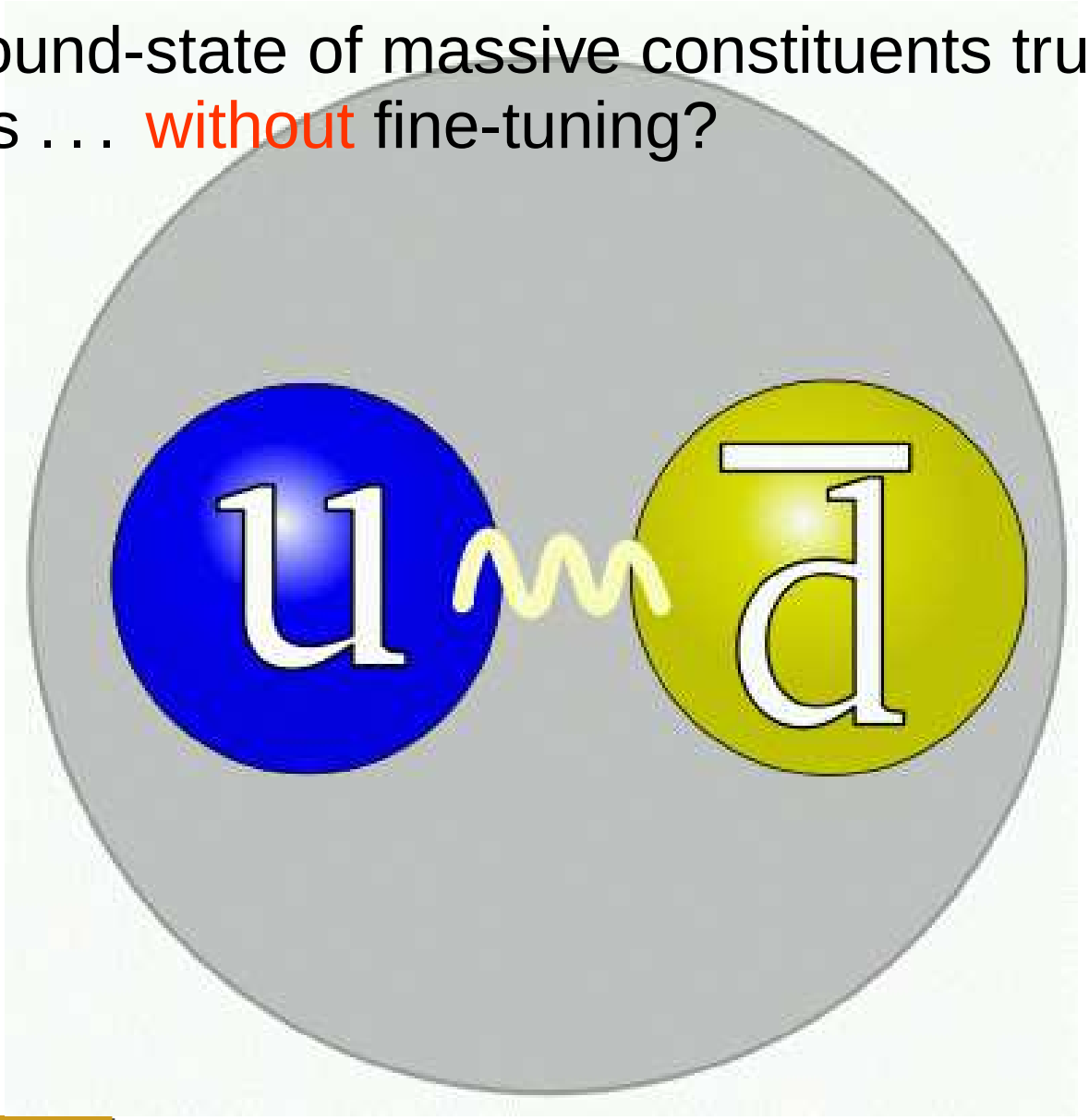
Pseudoscalar Mesons?



Pion and . . .

Pseudoscalar Mesons?

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



Radial Excitations & Chiral Symmetry

Radial Excitations & Chiral Symmetry

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

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

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., $T^{K^+} = \frac{1}{2}\left(\lambda^4 + i\lambda^5\right)$

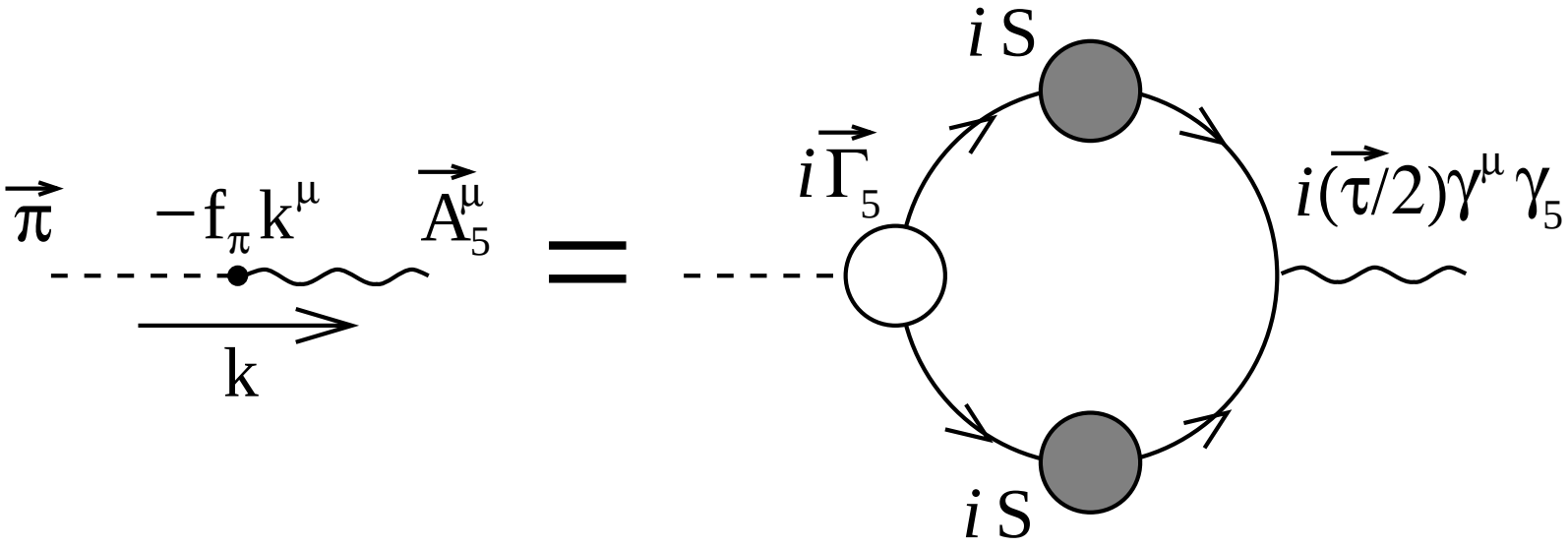
Radial Excitations & Chiral Symmetry

(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



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Radial Excitations & Chiral Symmetry

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

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

Radial Excitations & Chiral Symmetry

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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, $\boxed{m_H \propto m_q}$

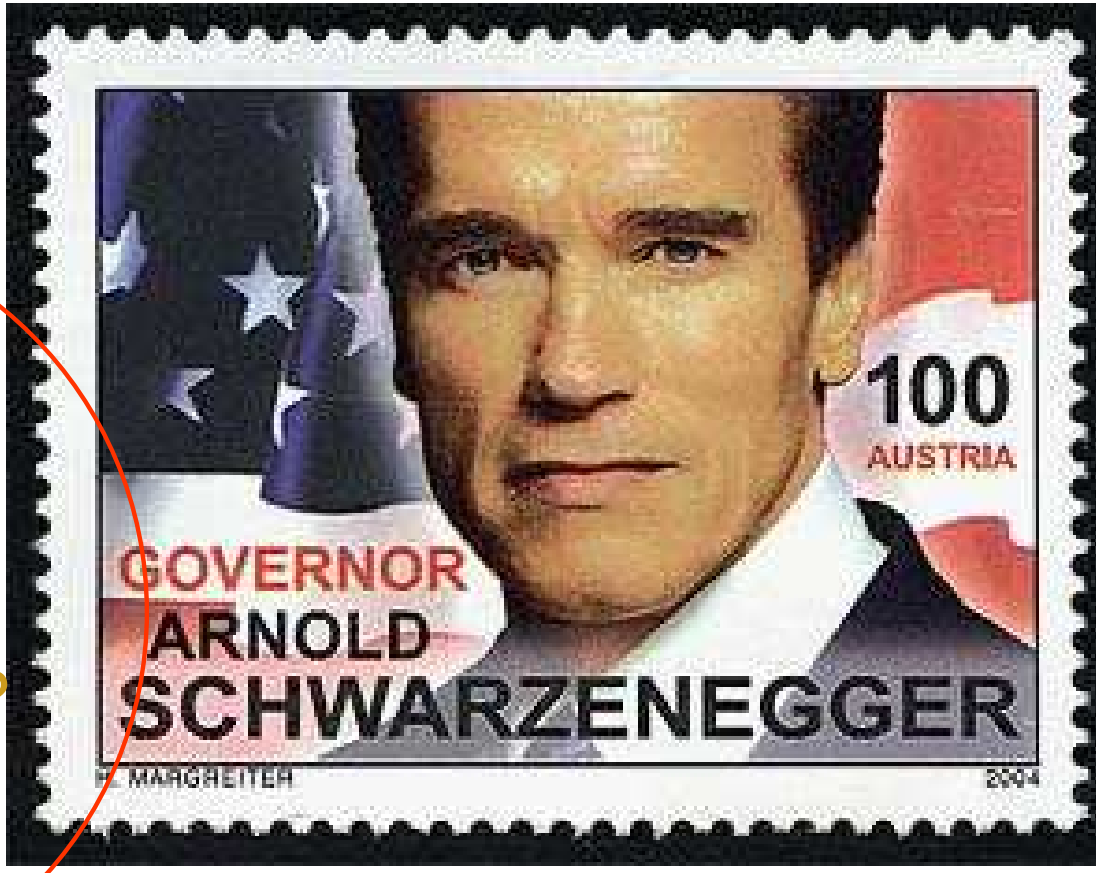
. . . QCD Proof of Potential Model result

Andreas Krassnigg

FWF “Erwin Schrödinger Fellow,” ANL 2003-2005

Andreas Krassnigg

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



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Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
nu-th/0406030

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- Valid for ALL Pseudoscalar mesons

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nu-th/0406030

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

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Radial Excitations & Chiral Symmetry

Höll, Krassnigg, Roberts
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- $\Rightarrow f_H = 0$
  ALL pseudoscalar mesons except $\pi(140)$ in chiral limit
- Dynamical Chiral Symmetry Breaking
  – Goldstone's Theorem –
  impacts upon *every* pseudoscalar meson

Radial Excitations

Radial Excitations

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

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

Radial Excitations

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

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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 & Lattice-QCD

McNeile and Michael
he-la/0607032

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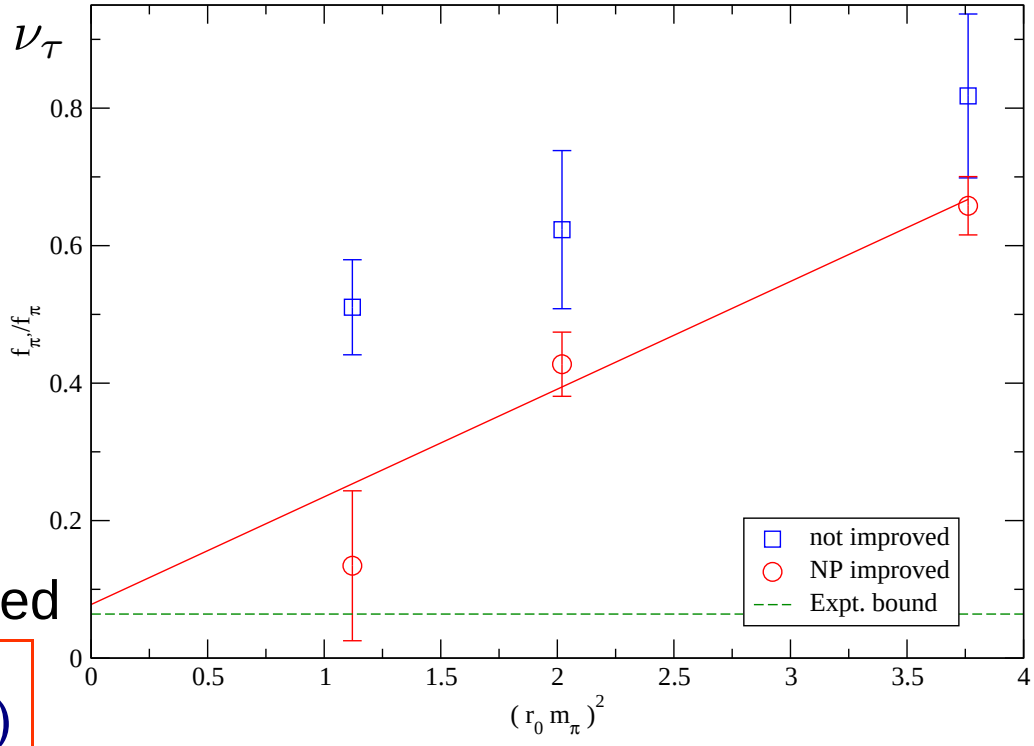
- Lattice-QCD check:
  $16^3 \times 32$,
  $a \sim 0.1$ fm,
  two-flavour, unquenched

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



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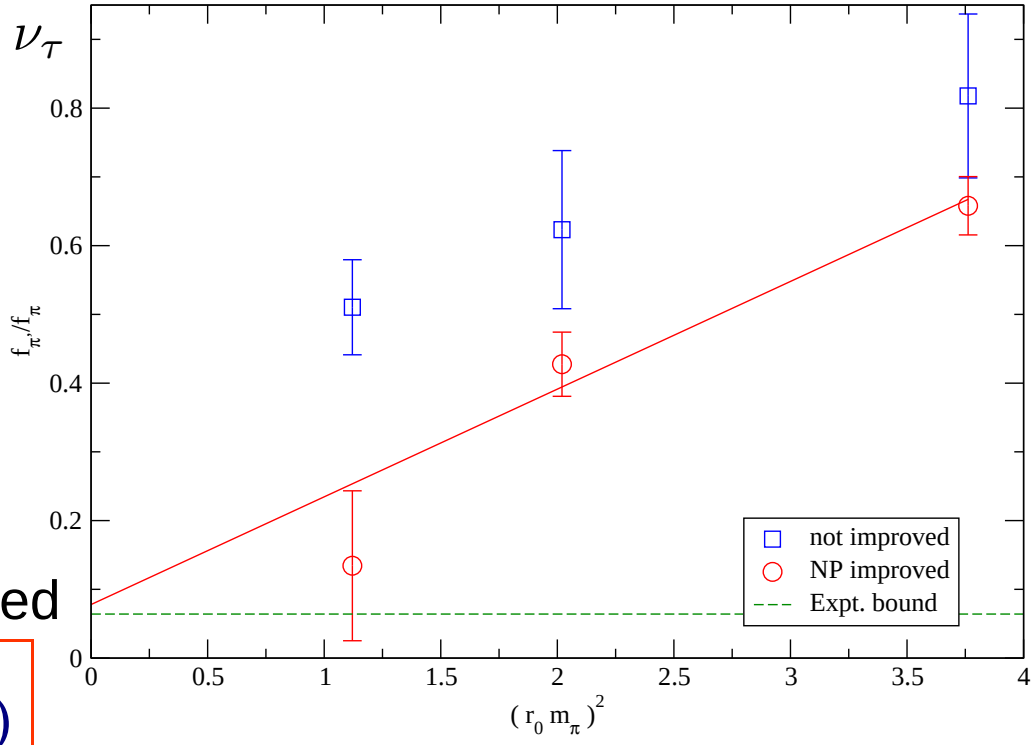

$$\Rightarrow \frac{f_{\pi_1}}{f_\pi} = 0.078\,(93)$$

- 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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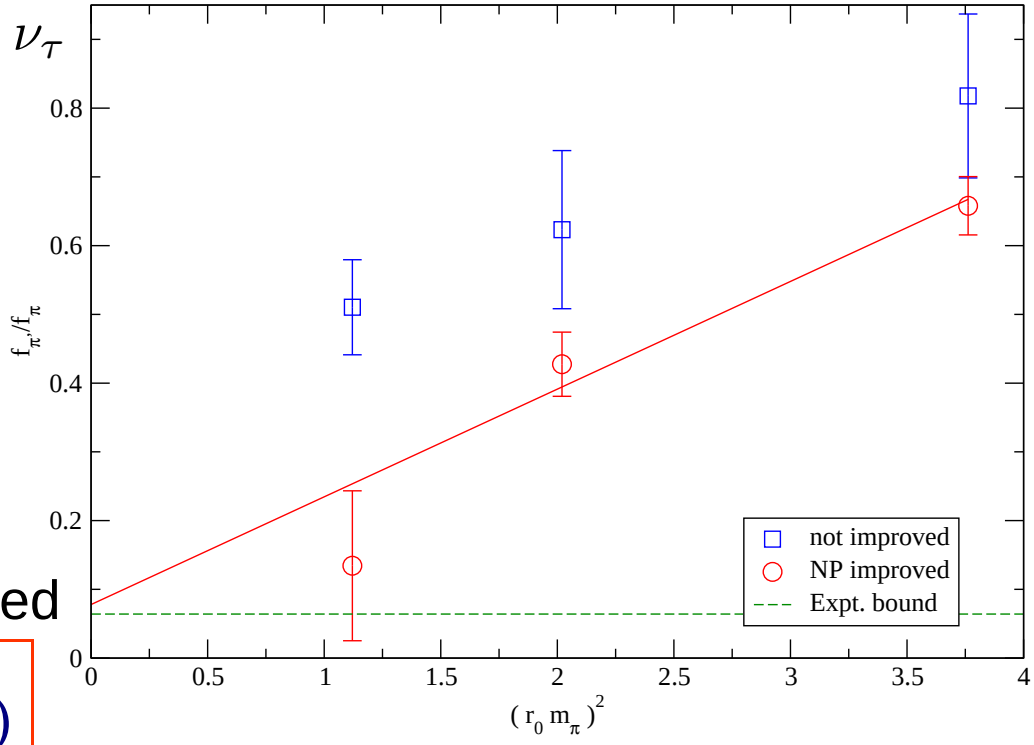

$$\Rightarrow \frac{f_{\pi_1}}{f_\pi} = 0.078\,(93)$$

- *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.*

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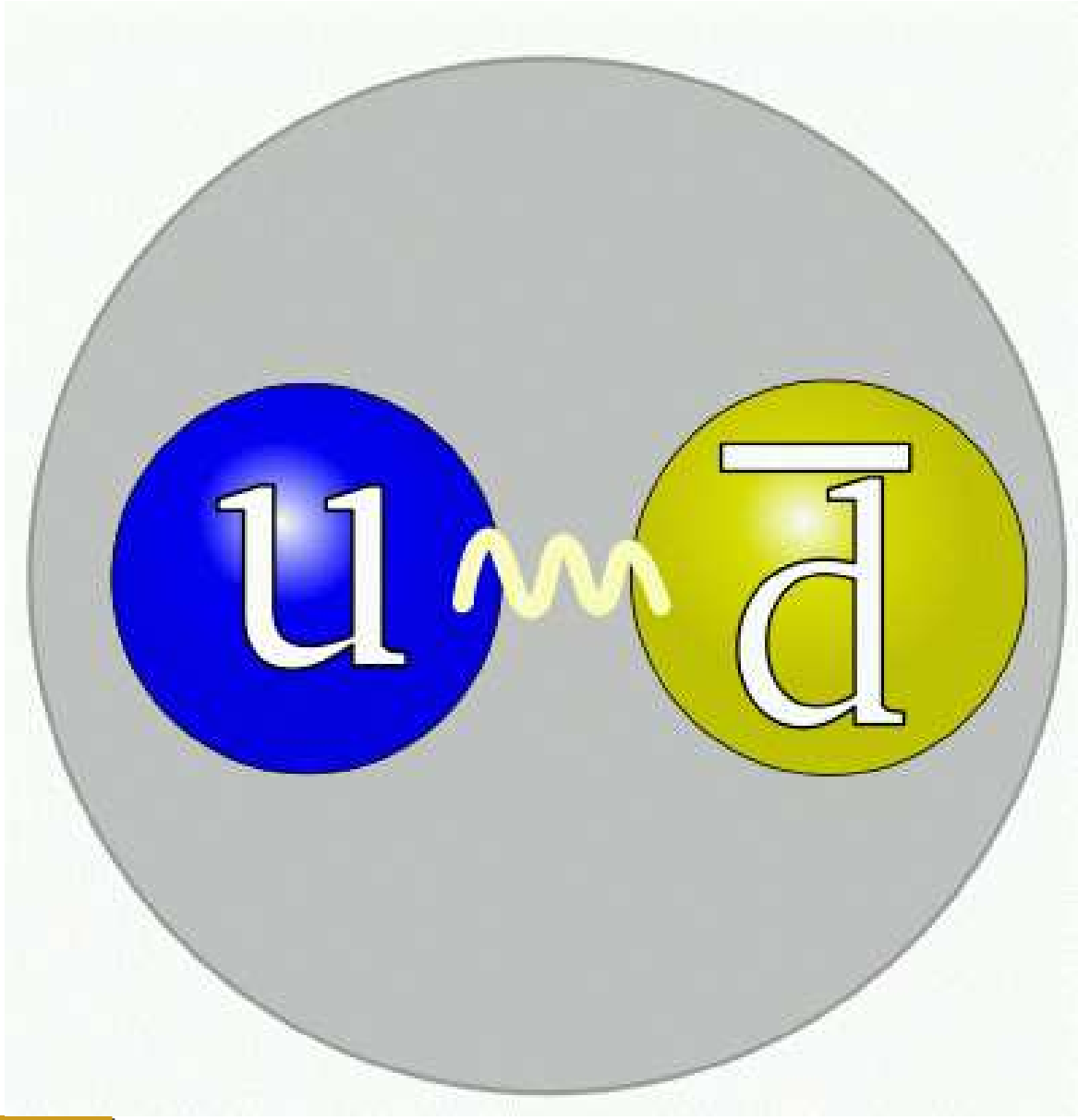
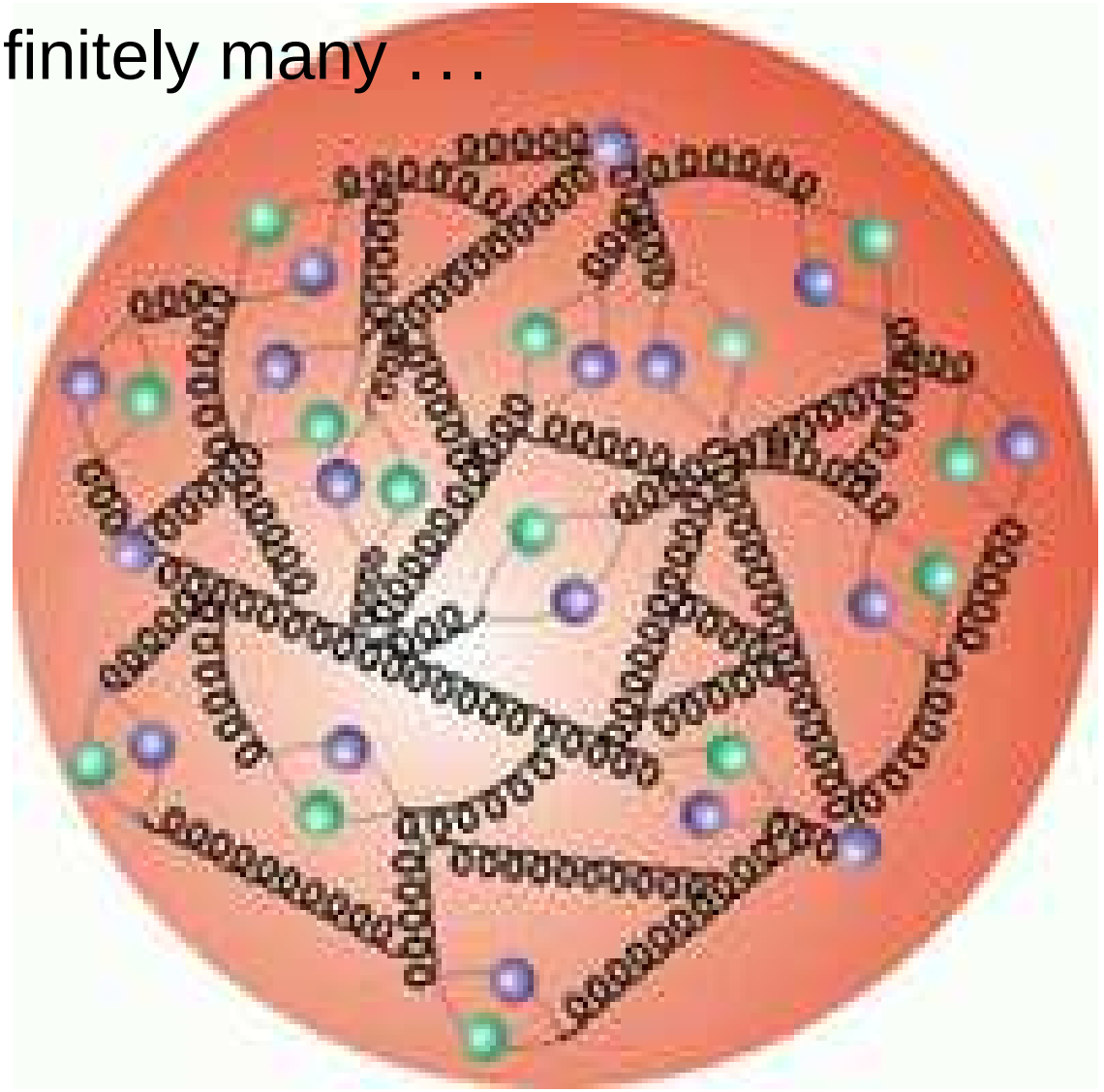
Answer for the pion



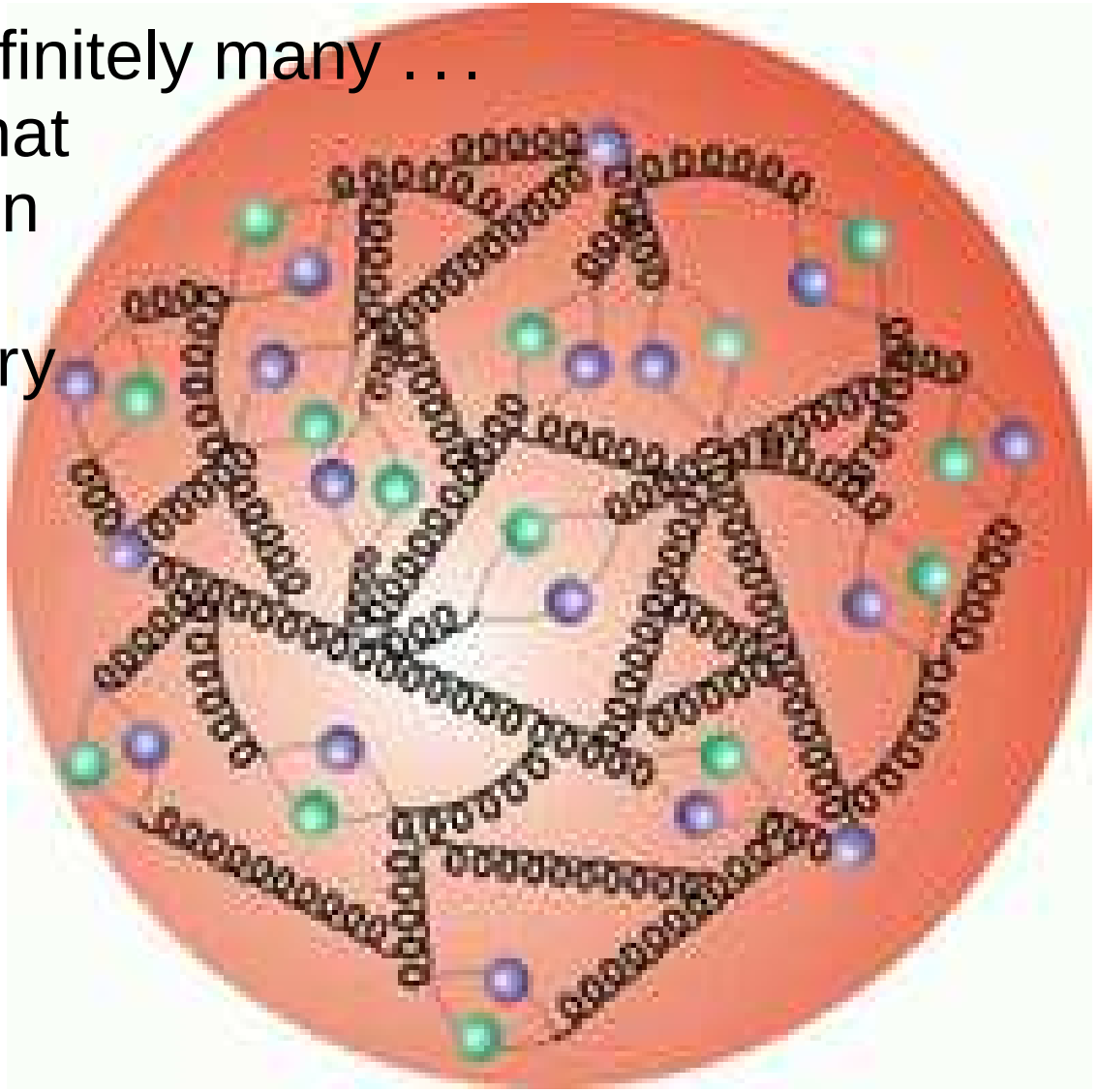
Answer for the pion

Two $\longrightarrow$ Infinitely many . . .



Answer for the pion

Two $\longrightarrow$ Infinitely many . . .
Handle that properly in quantum field theory



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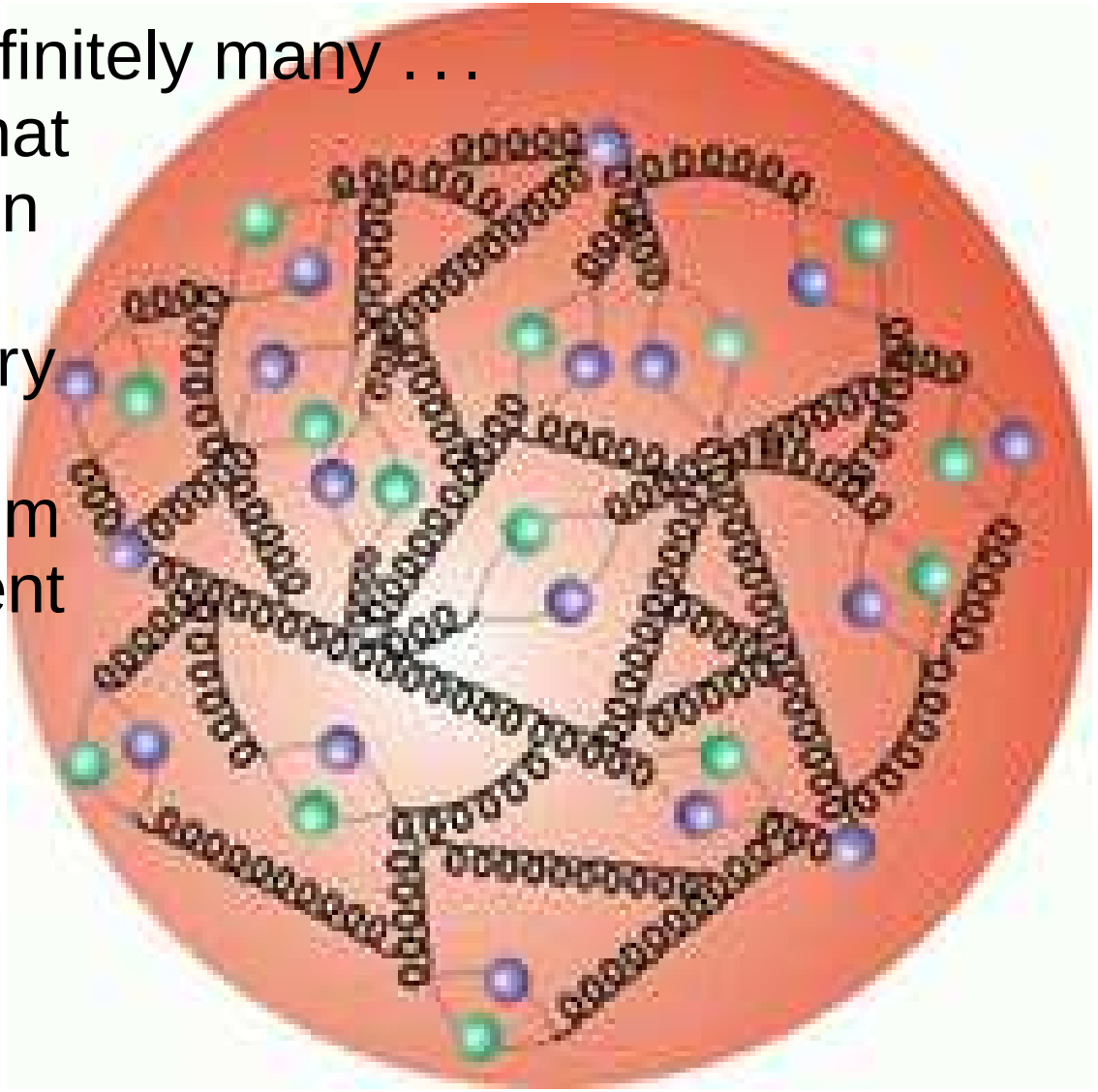

Answer for the pion

Two $\longrightarrow$ Infinitely many . . .
Handle that properly in quantum field theory
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momentum -dependent dressing
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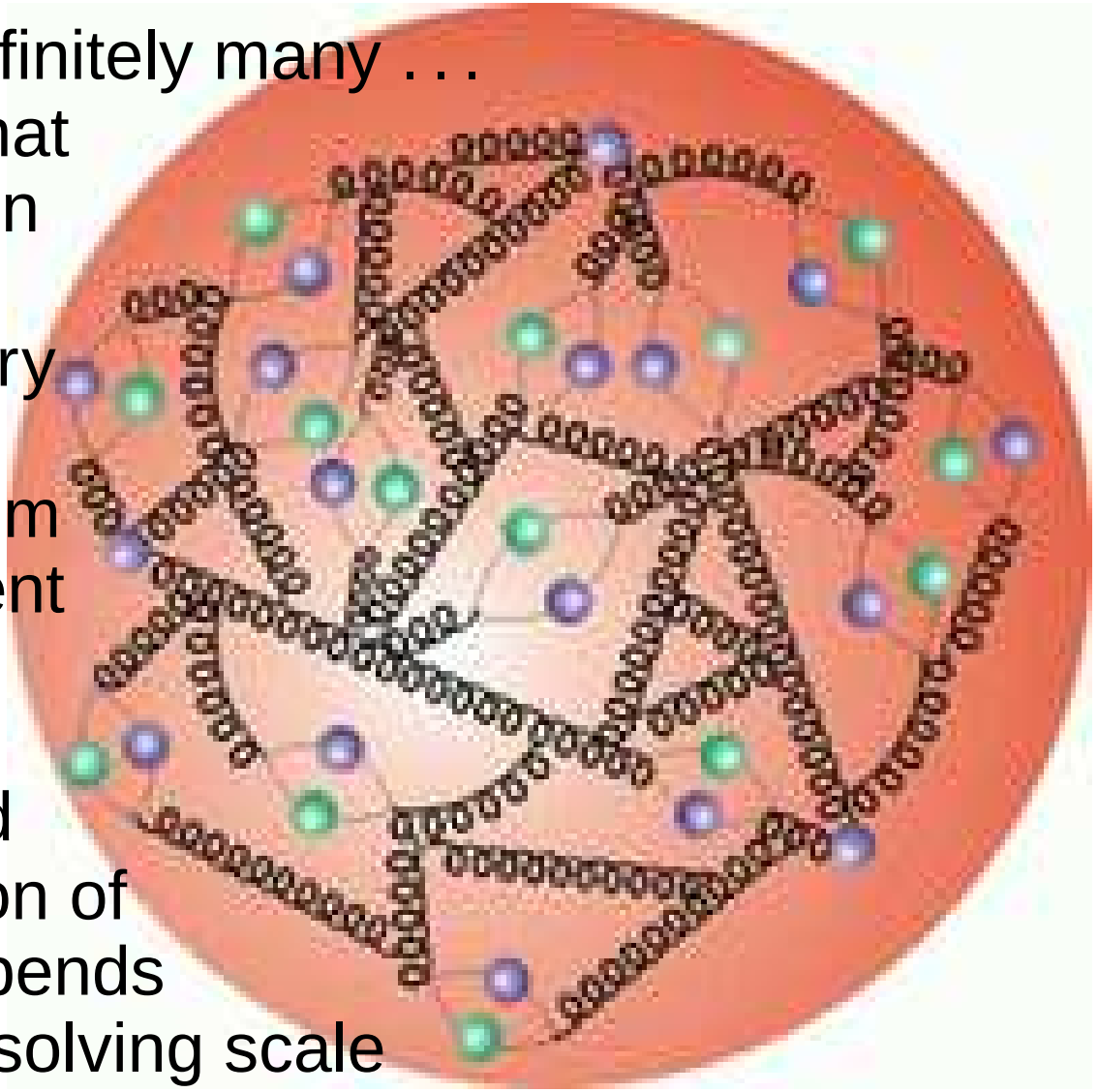
perceived distribution of mass depends on the resolving scale



Pion ... $J = 0$

but ...

- Orbital angular momentum is not a Poincaré invariant. However, if absent in a particular frame, it will appear in another frame related via a Poincaré transformation.

Pion . . . $J = 0$

but . . .

- Nonzero quark orbital angular momentum is thus a necessary outcome of a Poincaré covariant description.

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Pion ... $J = 0$ but ...

- Pseudoscalar meson Bethe-Salpeter amplitude

$$\chi_\pi(k;P) = \gamma_5 \left[i\mathcal{E}_{\pi_n}(k;P) + \gamma\cdot P \mathcal{F}_{\pi_n}(k;P) \right.$$
$$\left. \gamma\cdot k\, k\cdot P\, \mathcal{G}_{\pi_n}(k;P) + \sigma_{\mu\nu}\, k_\mu P_\nu\, \mathcal{H}_{\pi_n}(k;P) \right]$$

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- $J = 0$ . . . *but* while $\mathcal{E}$ and $\mathcal{F}$ are purely $L = 0$ in the rest frame, the $\mathcal{G}$ and $\mathcal{H}$ terms are associated with $L = 1$. Thus a pseudoscalar meson Bethe-Salpeter wave function *always* contains both S- and P-wave components.

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Introduce mixing angle θ_π such that

$$\chi_\pi \sim \cos\theta_\pi |L = 0\rangle + \sin\theta_\pi |L = 1\rangle$$

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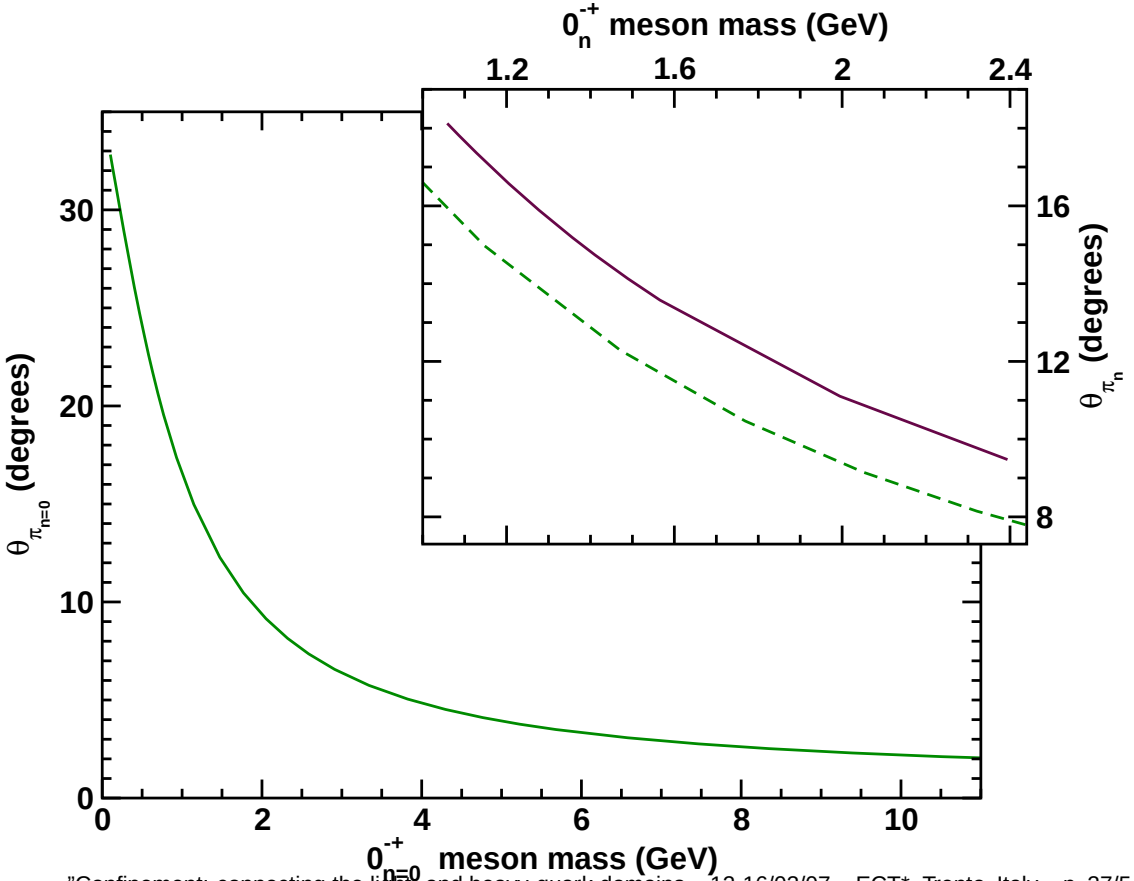

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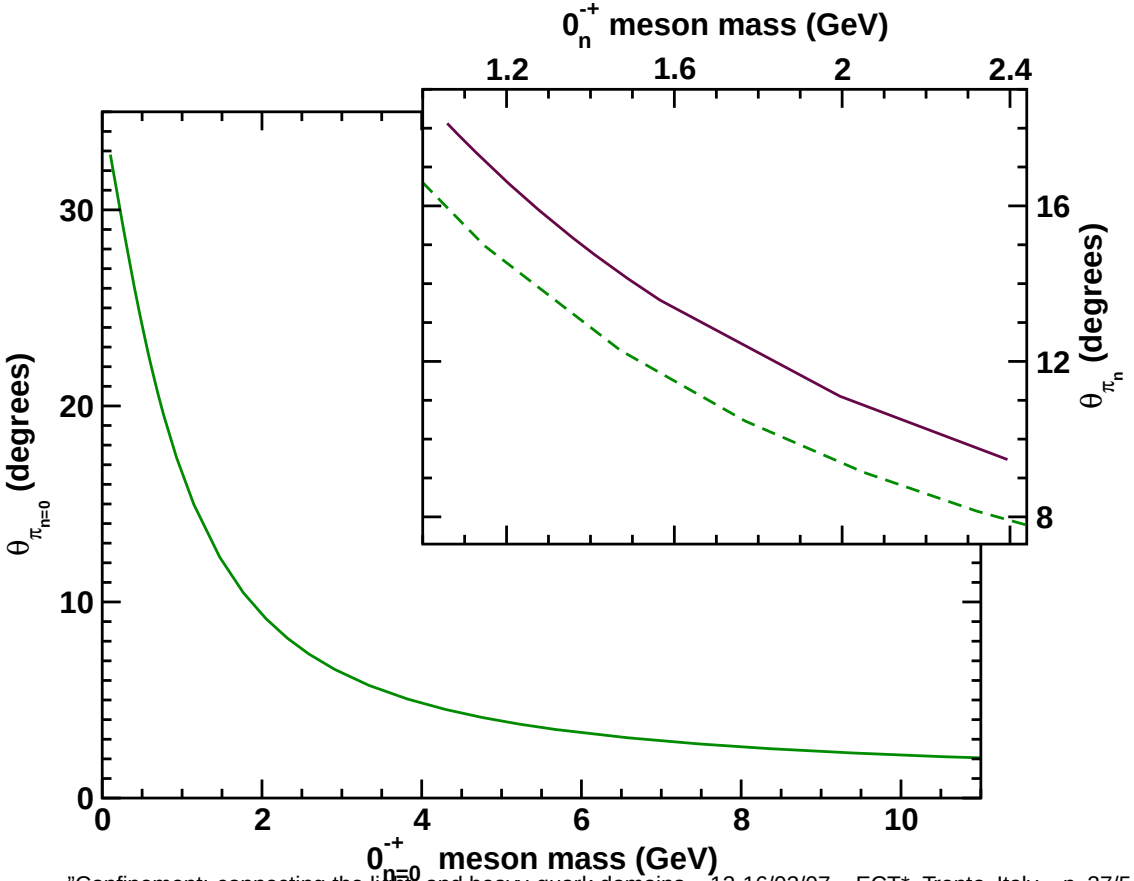
L is significant in the neighbourhood of the chiral limit, and decreases with increasing current-quark mass.



Are we there yet?

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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.

Pieter Maris

Peter Tandy

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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

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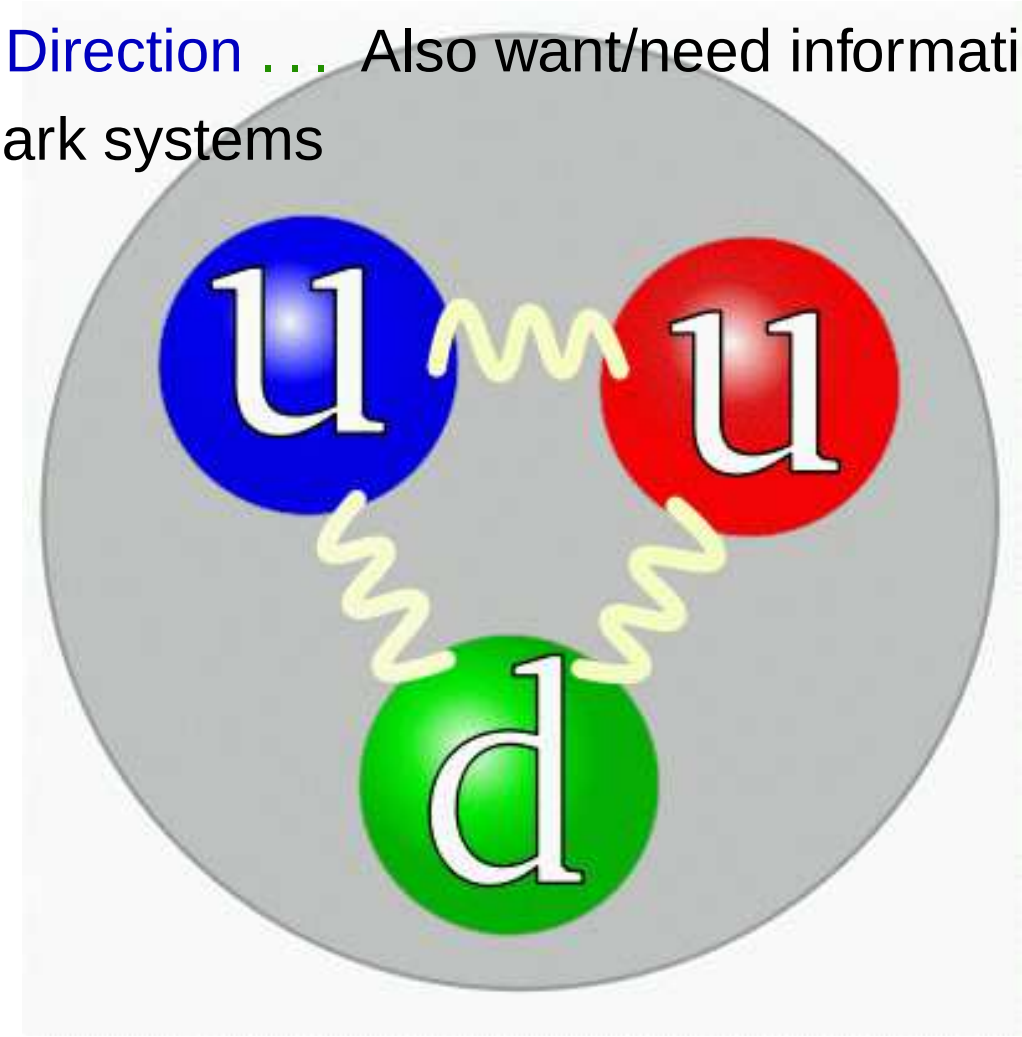
New Challenges

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



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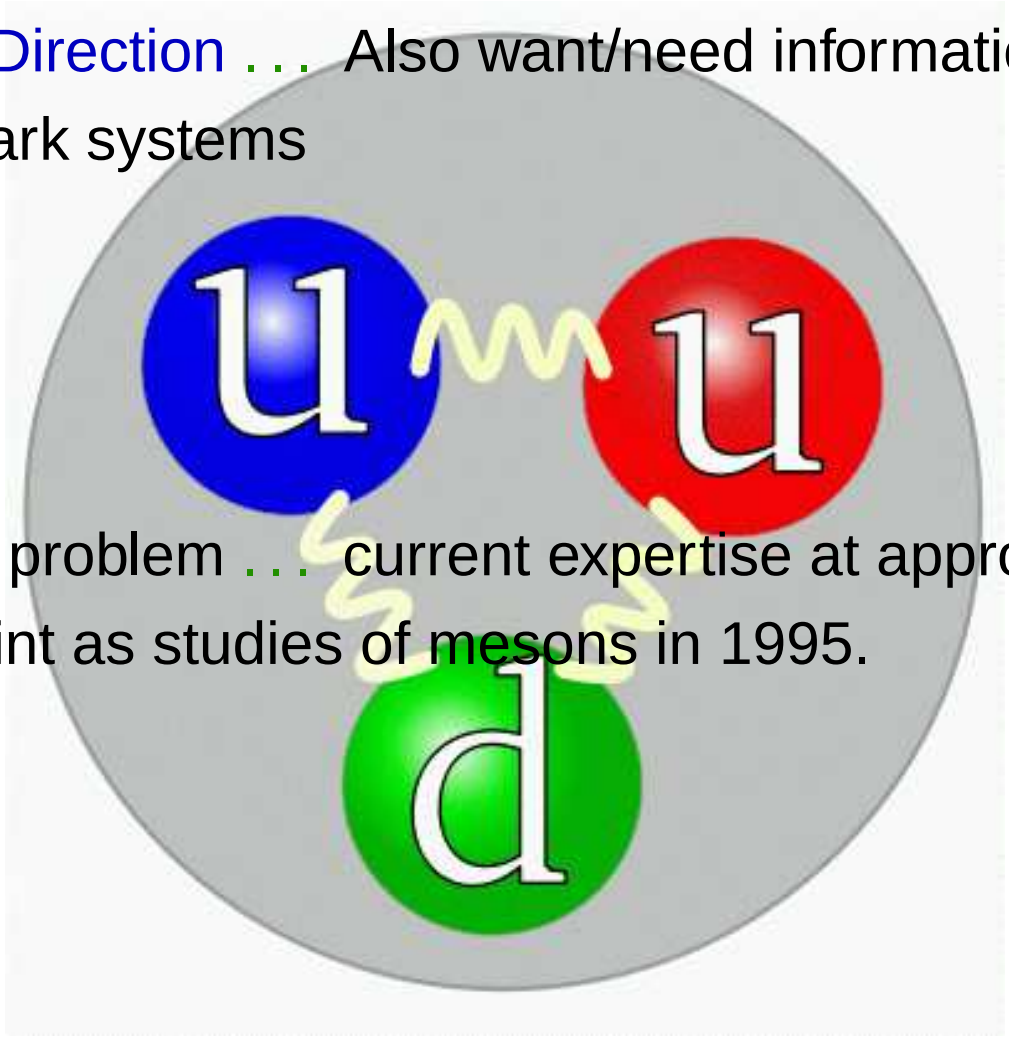

- With this problem . . . current expertise at approximately same point as studies of mesons in 1995.

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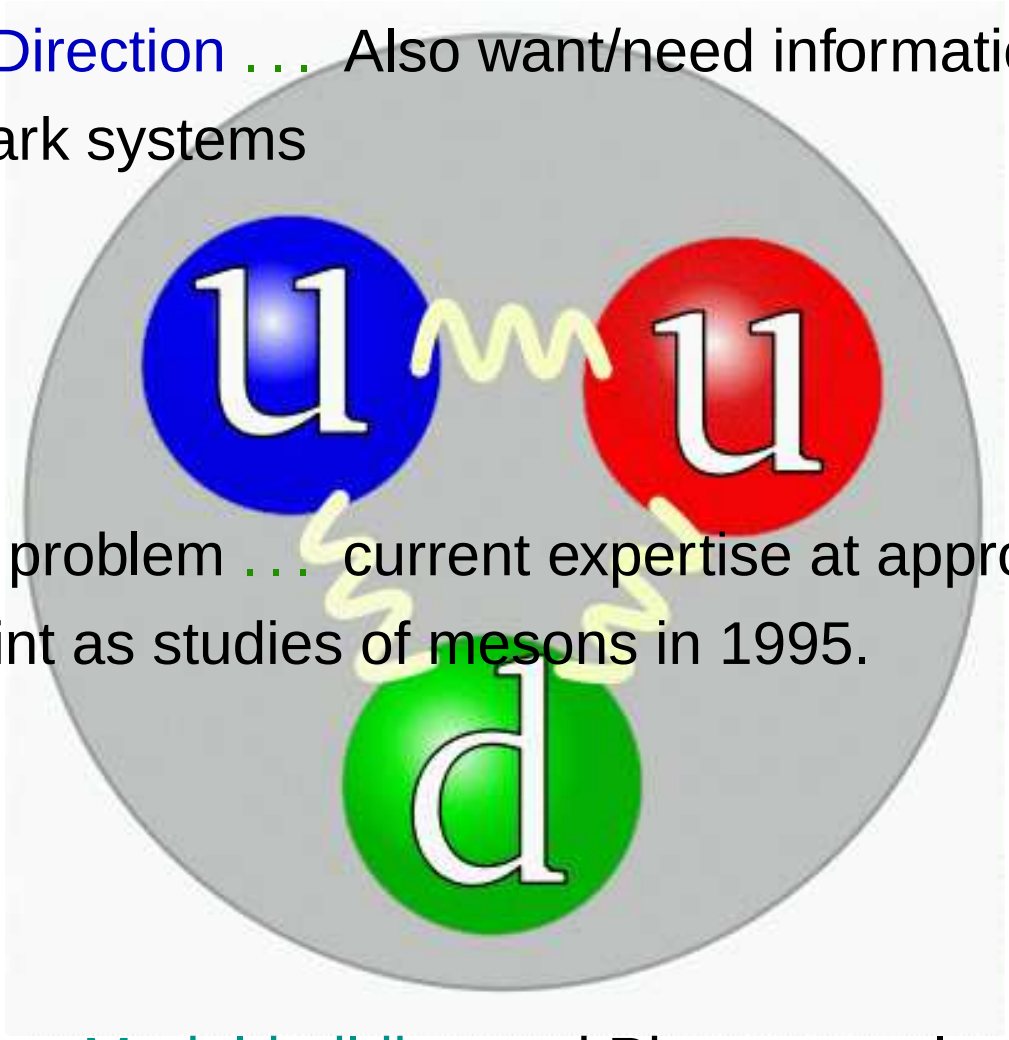

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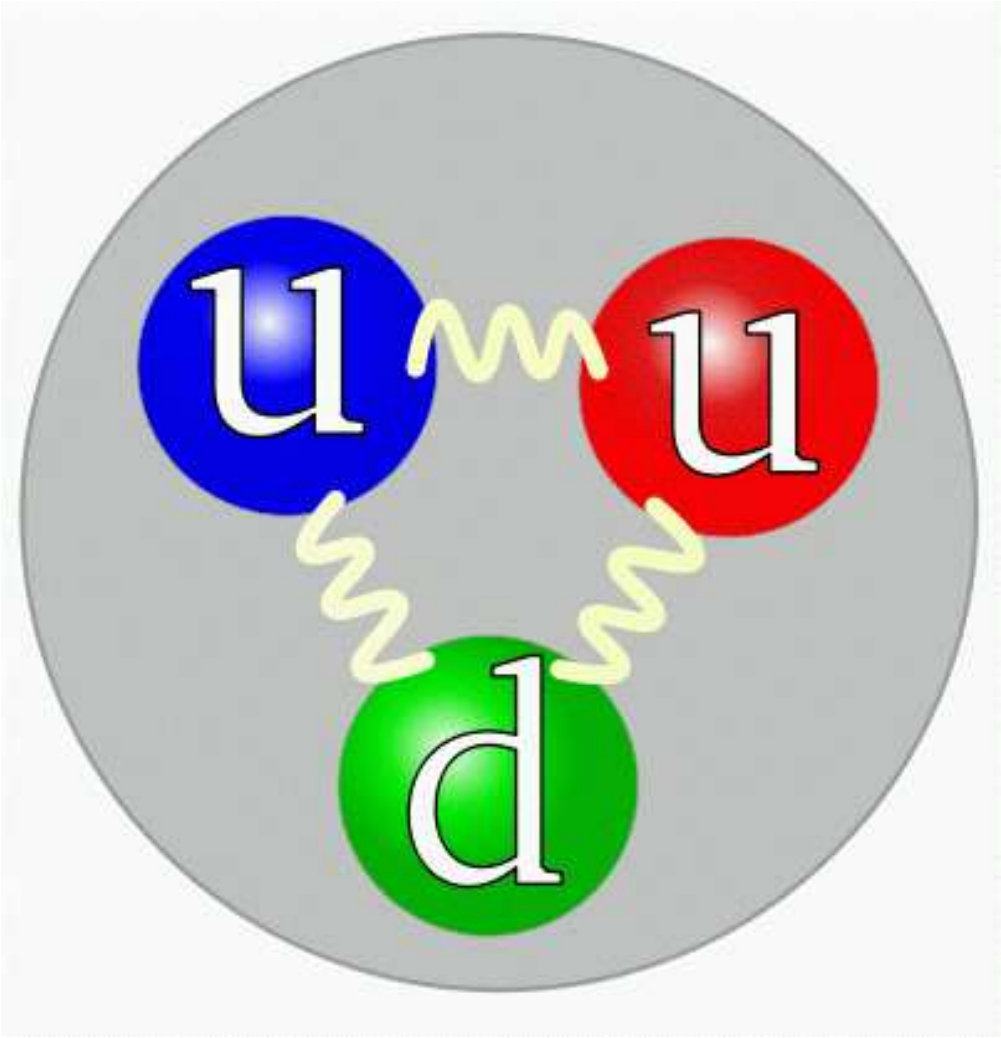
- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.

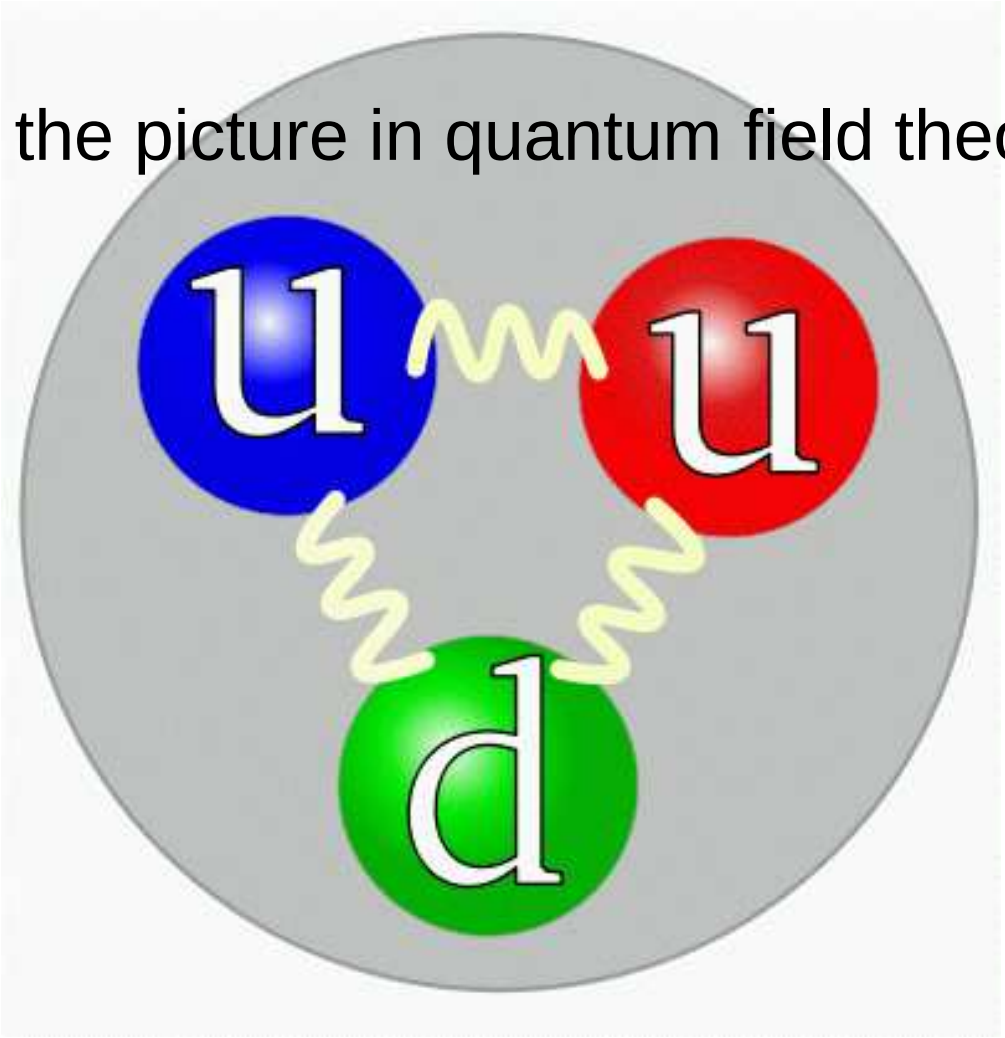
Nucleon . . .

Three-body Problem?



Nucleon . . .
Three-body Problem?

- What is the picture in quantum field theory?



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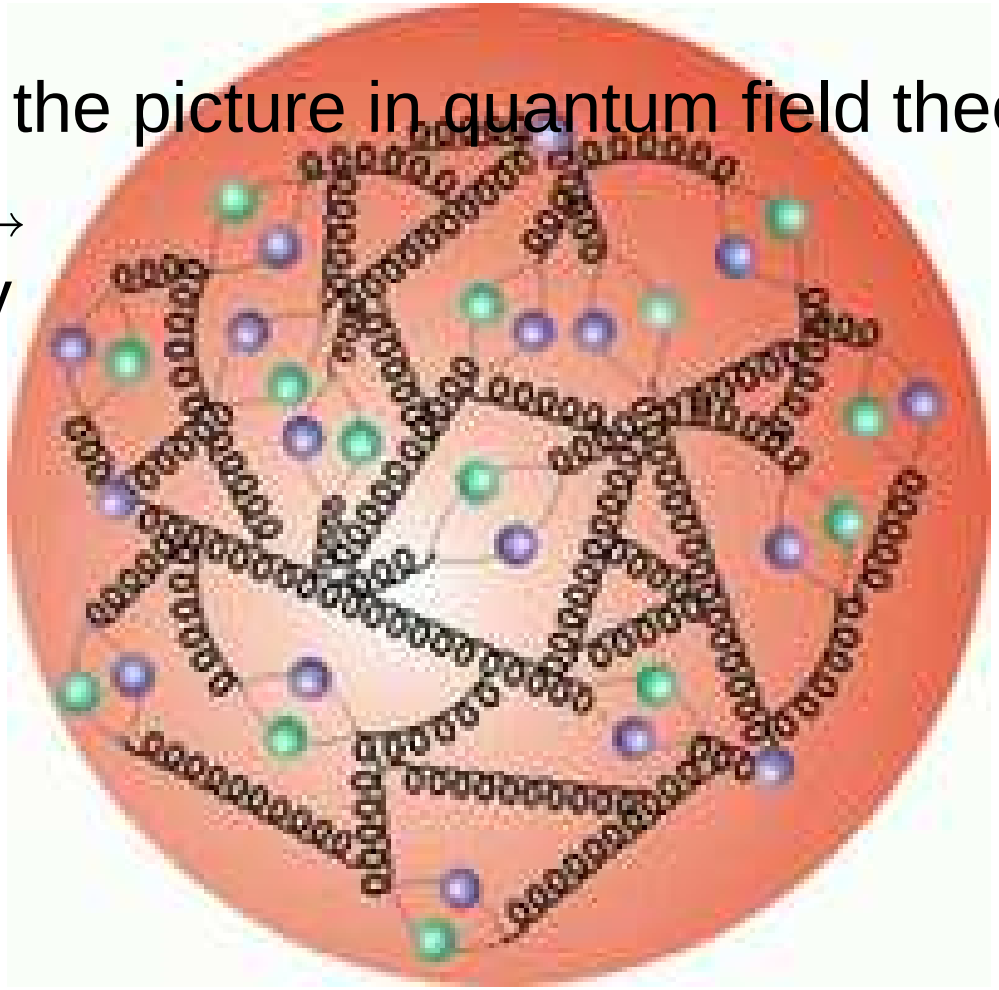
Nucleon . . .

Three-body Problem?

- What is the picture in quantum field theory?
- Three → infinitely many!



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Faddeev equation

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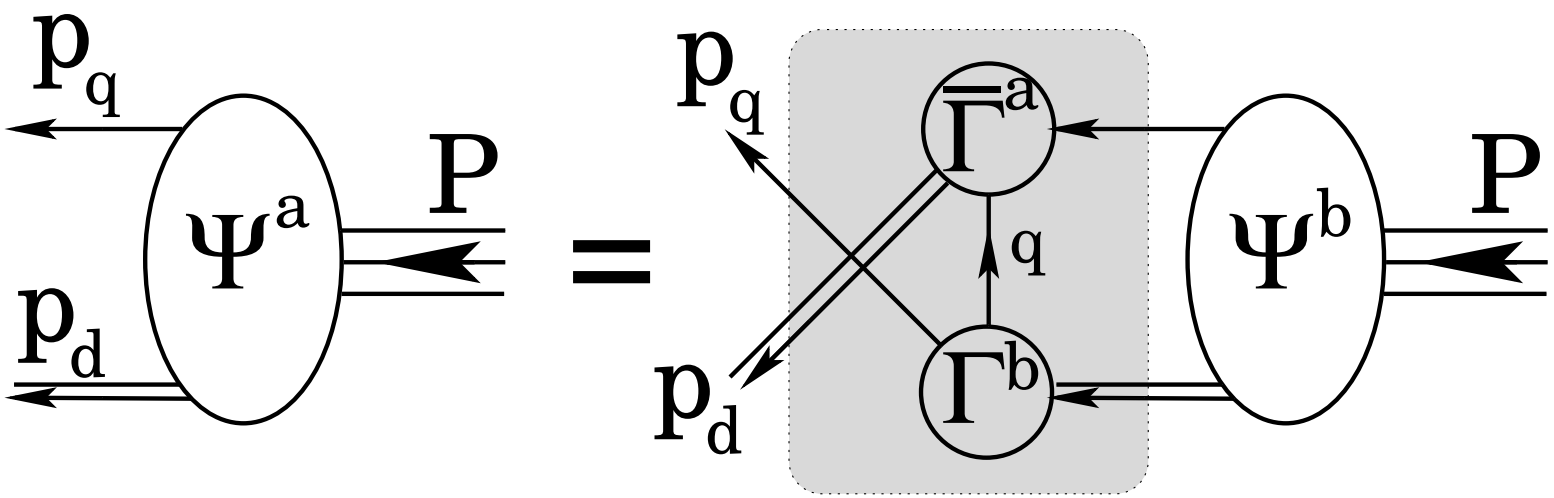

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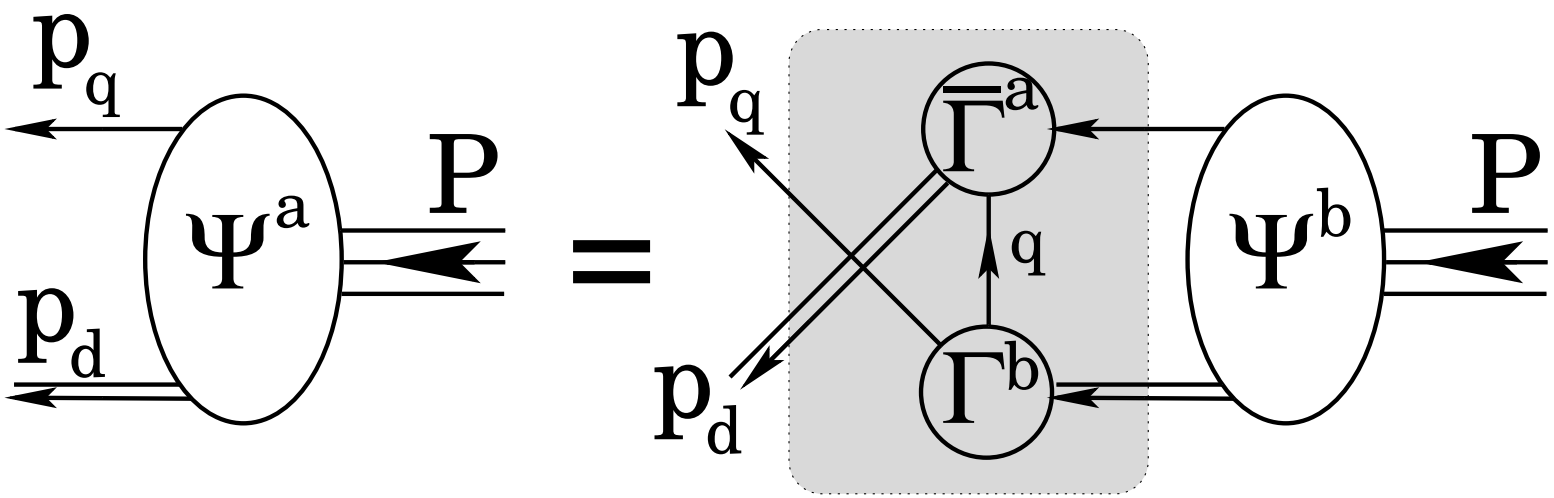
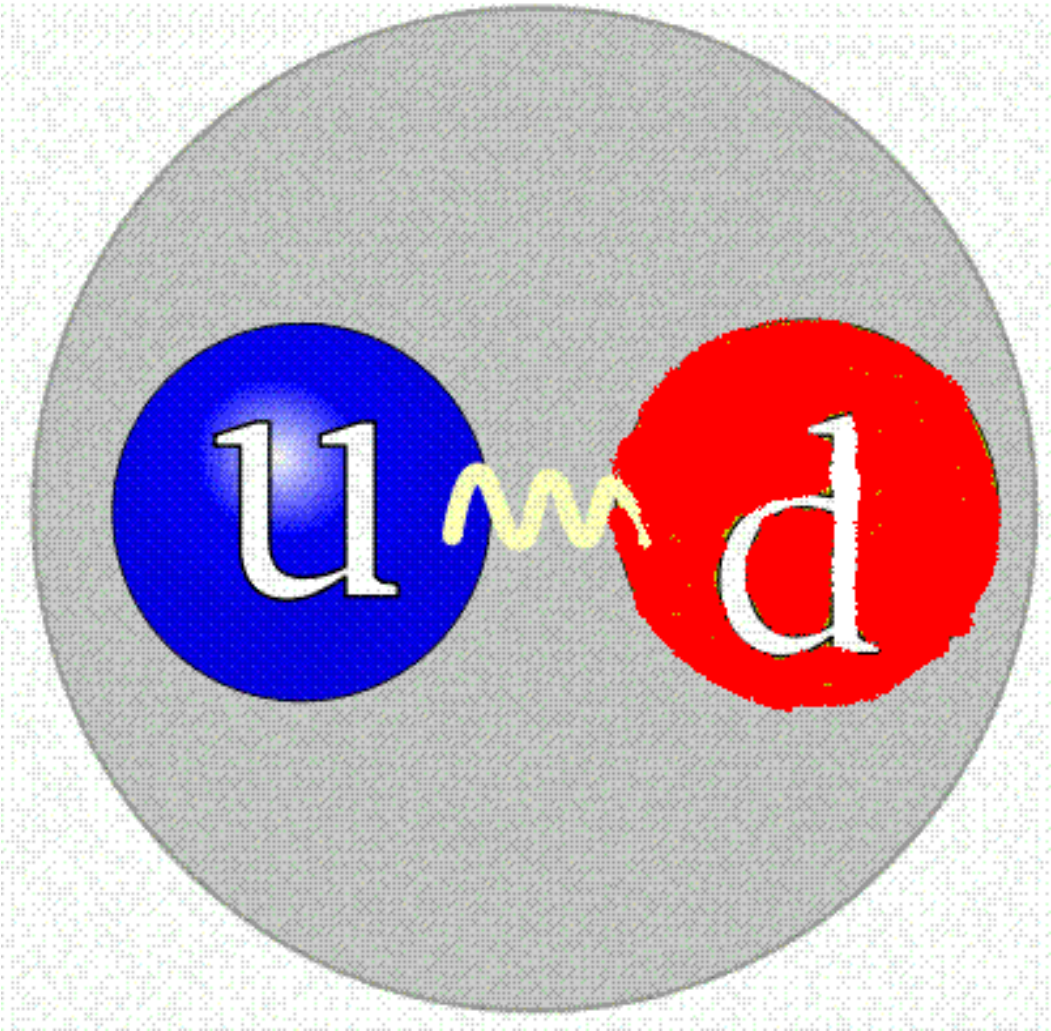


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Diquark correlations



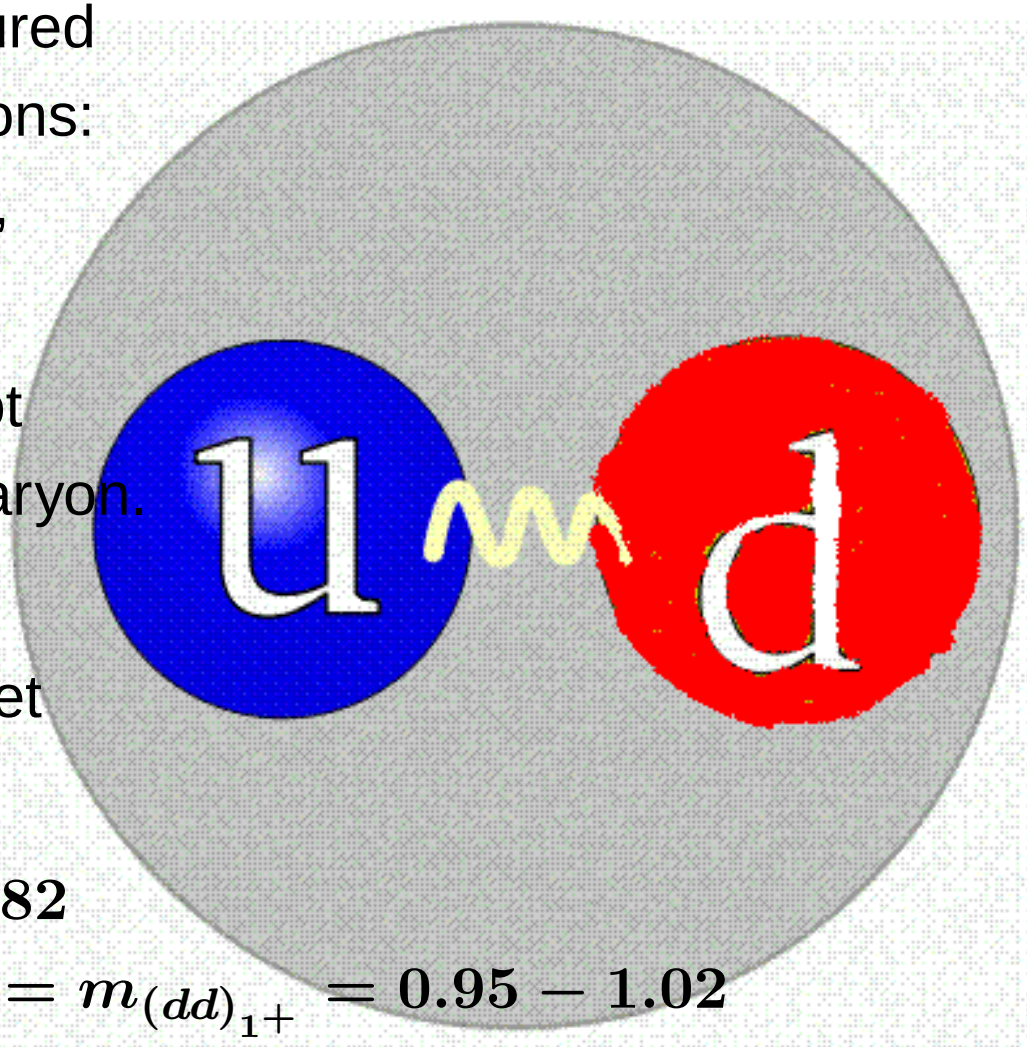
QUARK-QUARK

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

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

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



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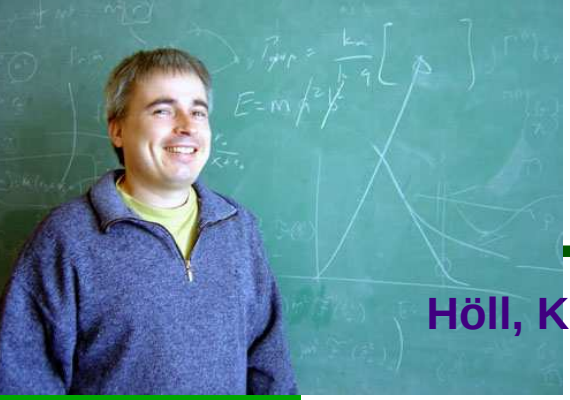
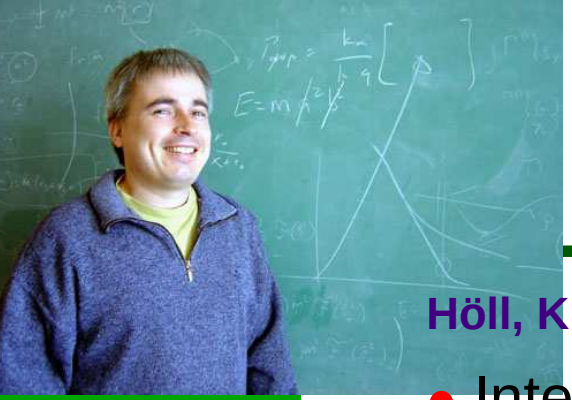


Nucleon EM Form Factors: A Précis

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



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- Interpreting expts. with GeV electromagnetic probes requires Poincaré covariant treatment of baryons

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

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- Critical to anticipate pion cloud effects
  Roberts, Tandy, Thomas, *et al.*, nu-th/02010084

Pions and Form Factors

Pions and Form Factors

- Dynamical coupled-channels model . . . Analyzed extensive JLab data . . . Completed a study of the $\Delta(1236)$
  - *Meson Exchange Model for πN Scattering and $\gamma N \to \pi N$ Reaction*, T. Sato and T.-S. H. Lee, Phys. Rev. C **54**, 2660 (1996)
  - *Dynamical Study of the Δ Excitation in $N(e, e'\pi)$ Reactions*, T. Sato and T.-S. H. Lee, Phys. Rev. C 63, 055201/1-13 (2001)

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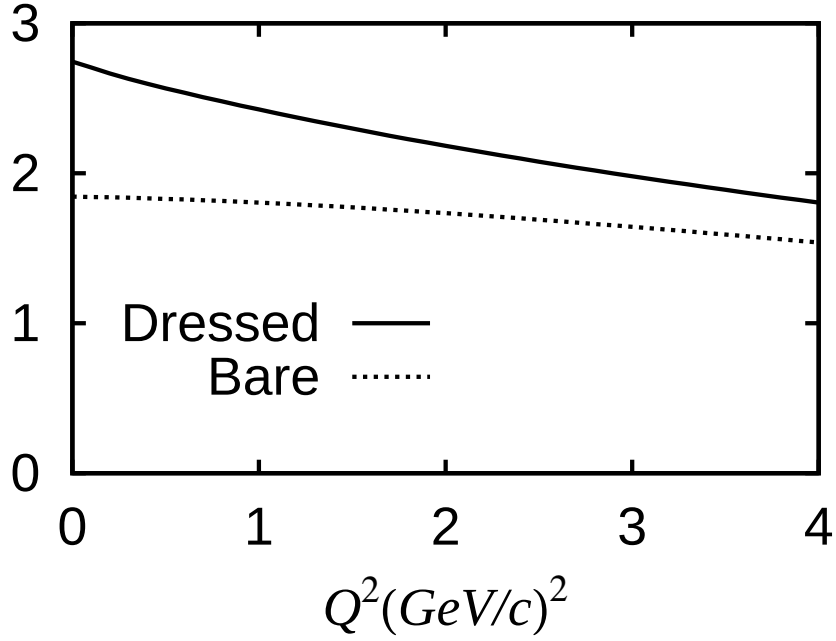
Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G_M^*(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



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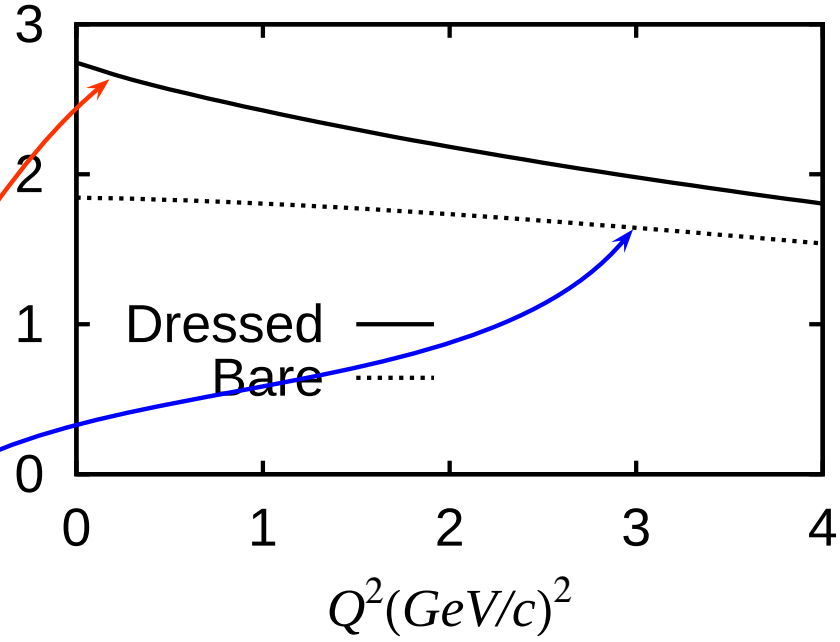

Quark Core

- Responsible for only 2/3 of result at small Q^2
- Dominant for $Q^2 >$2 – 3 GeV^2

Results: Nucleon and Δ Masses

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Results: Nucleon and Δ Masses

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

Set B – fitted mass was offset to allow for "π-cloud" contributions

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)

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

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- Axial-vector diquark provides significant attraction

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

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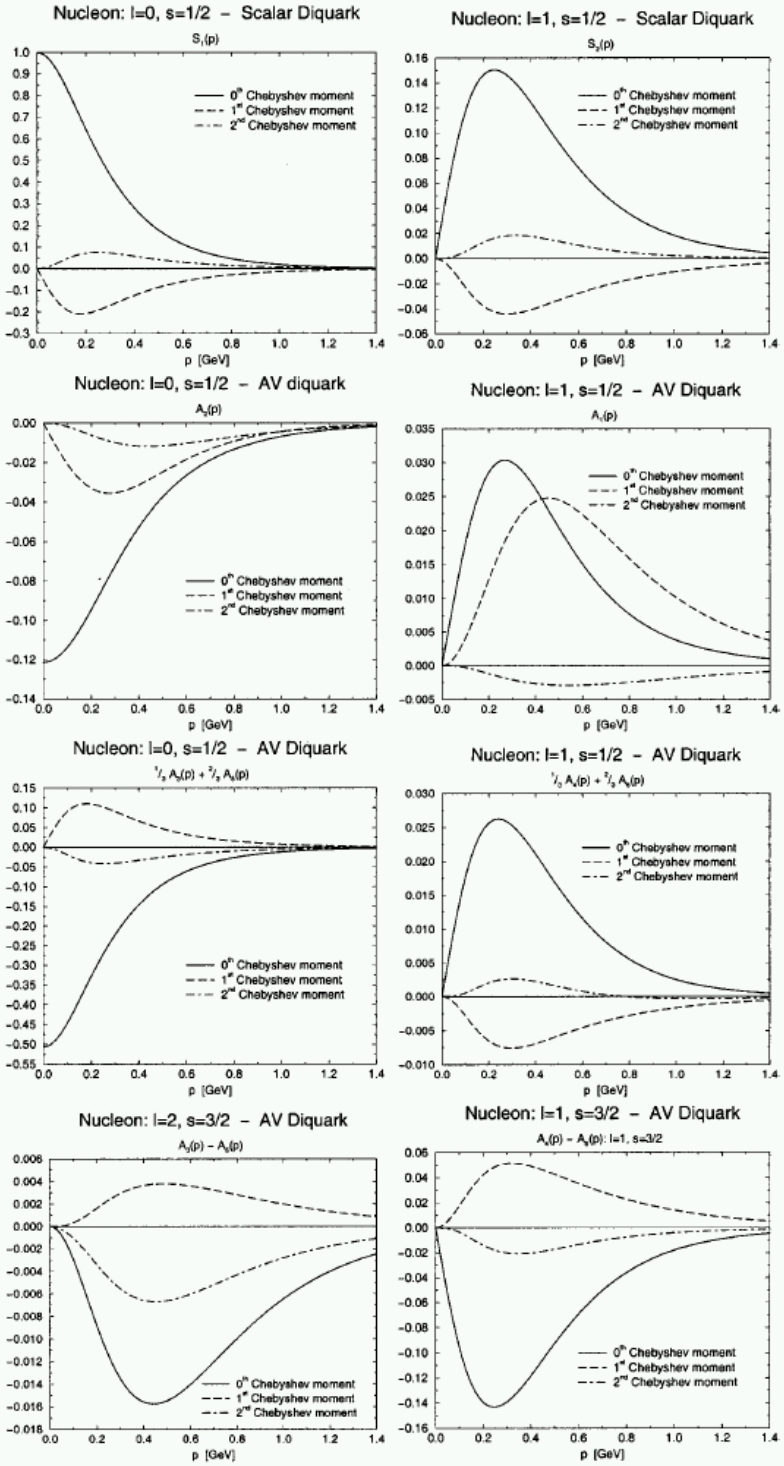

Angular Momentum Rest Frame

M. Oettel, *et al.* nucl-th/9805054

Crude estimate based on magnitudes $\Rightarrow$ probability for a u-quark to carry the proton's spin is $P_{u\uparrow} \sim 80\,\%$, with $P_{u\downarrow} \sim 5\,\%$, $P_{d\uparrow} \sim 5\,\%$, $P_{d\downarrow} \sim 10\,\%$.

Hence, by this reckoning $\sim 30\%$ of proton's rest-frame spin is located in dressed-quark angular momentum.

Nucleon-Photon Vertex

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

Nucleon-Photon Vertex

6 terms . . .

constructed systematically . . . current conserved automatically

for on-shell nucleons described by Faddeev Amplitude

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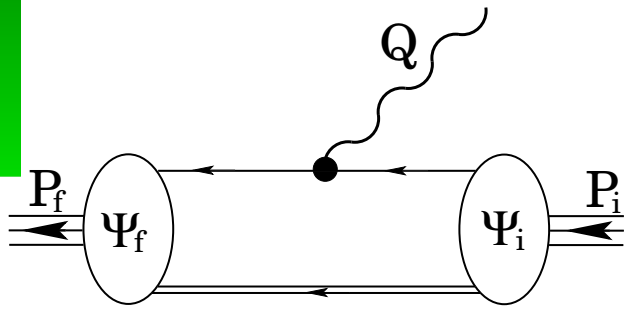
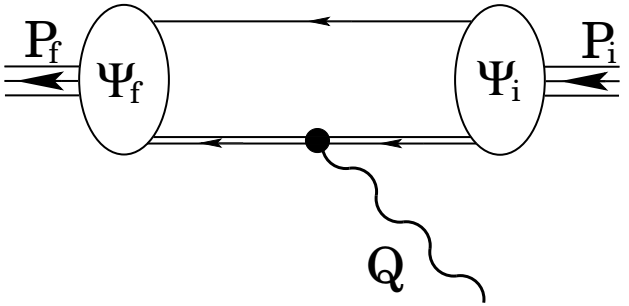
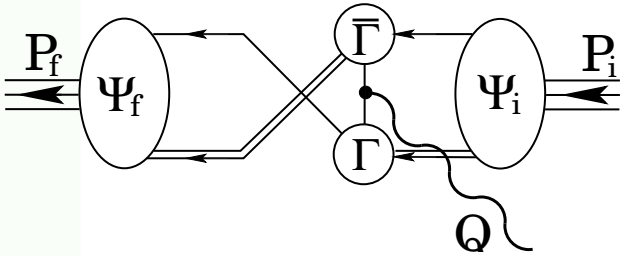
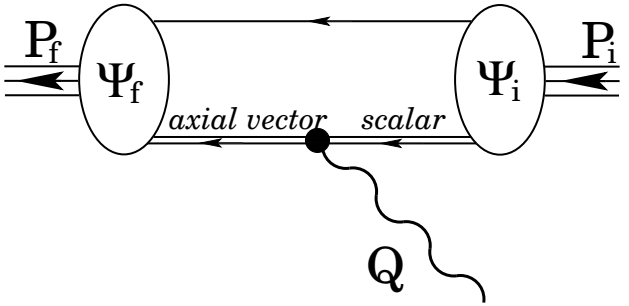
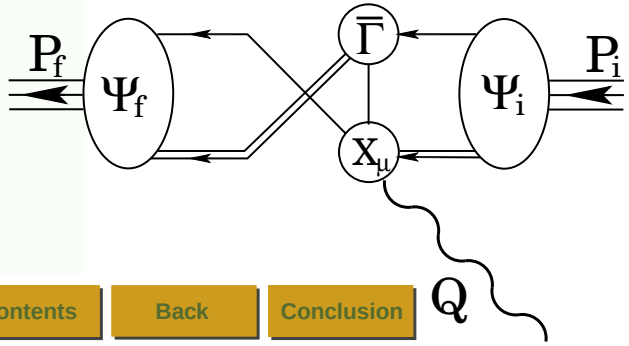
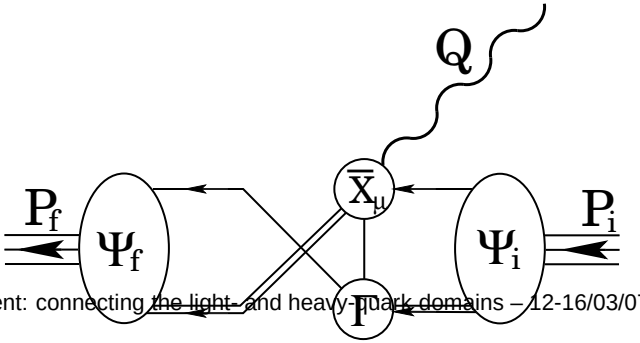




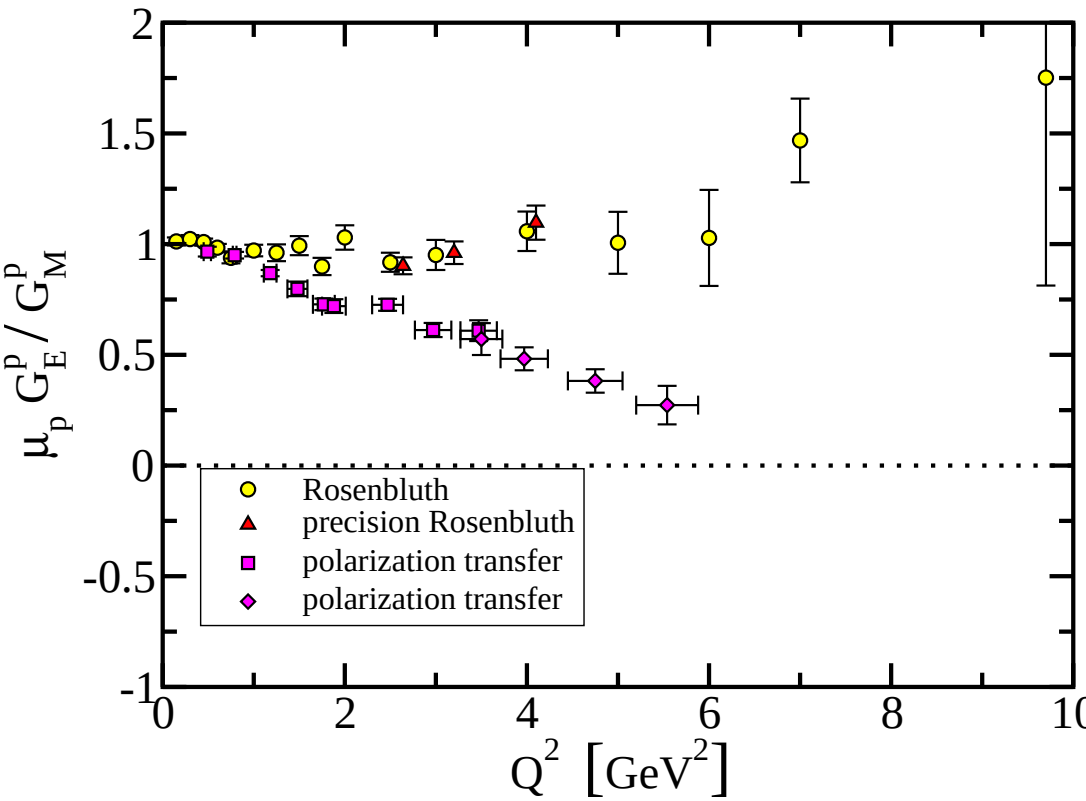








Form Factor Ratio: GE/GM



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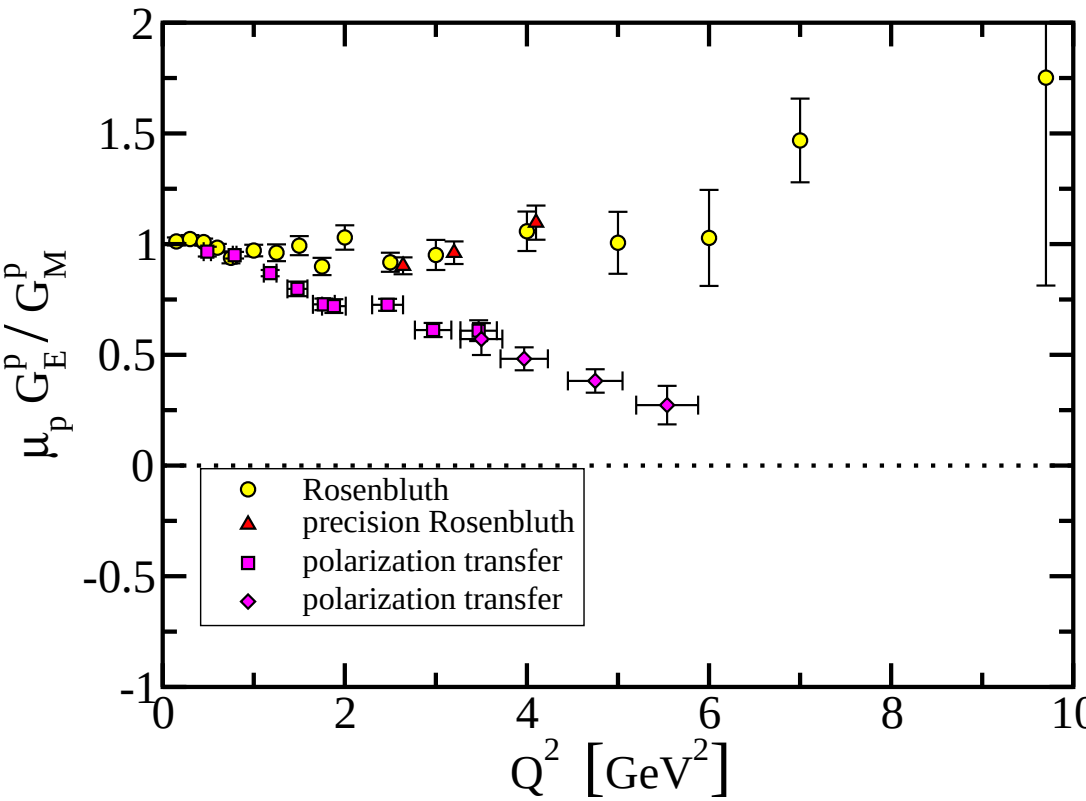
Form Factor Ratio: GE/GM

- Combine these elements . . .



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- Combine these elements . . .
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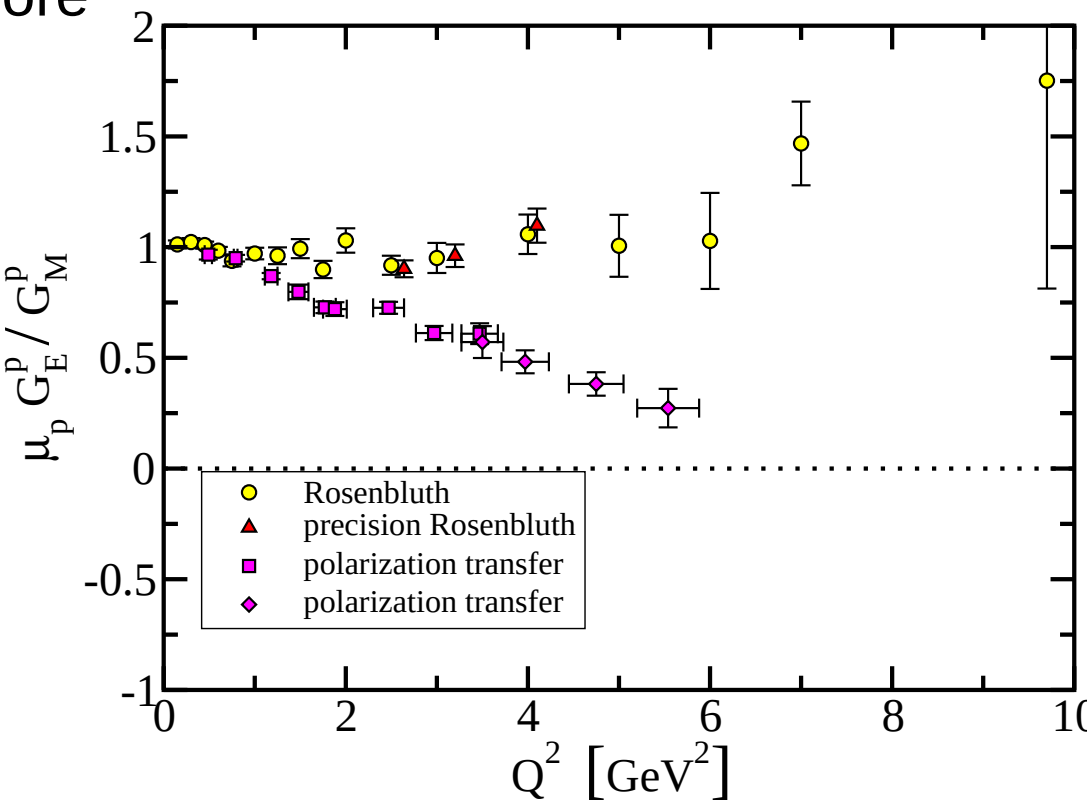

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- Combine these elements . . .
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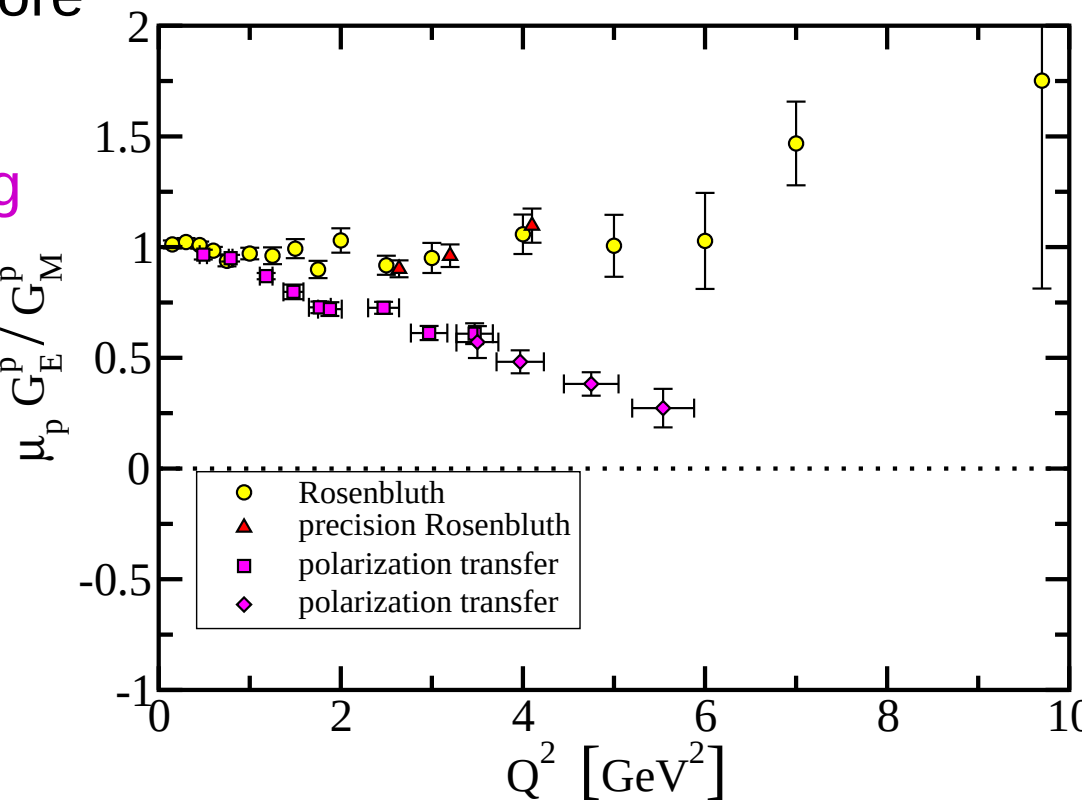

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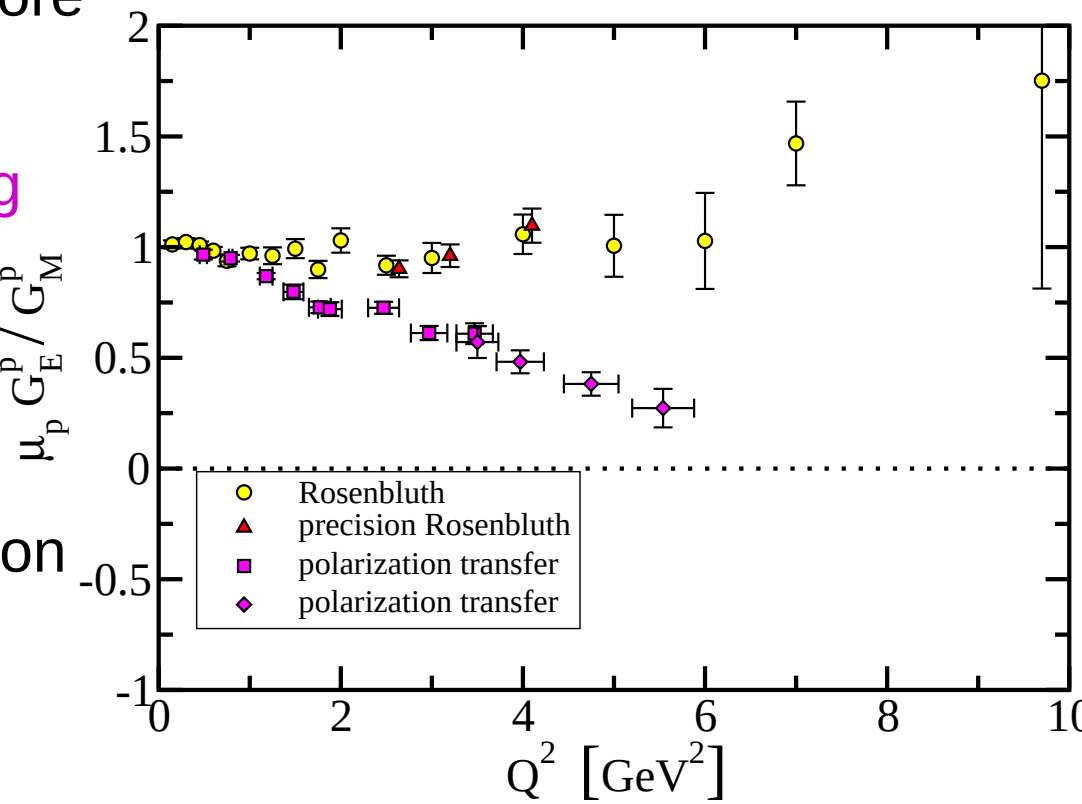

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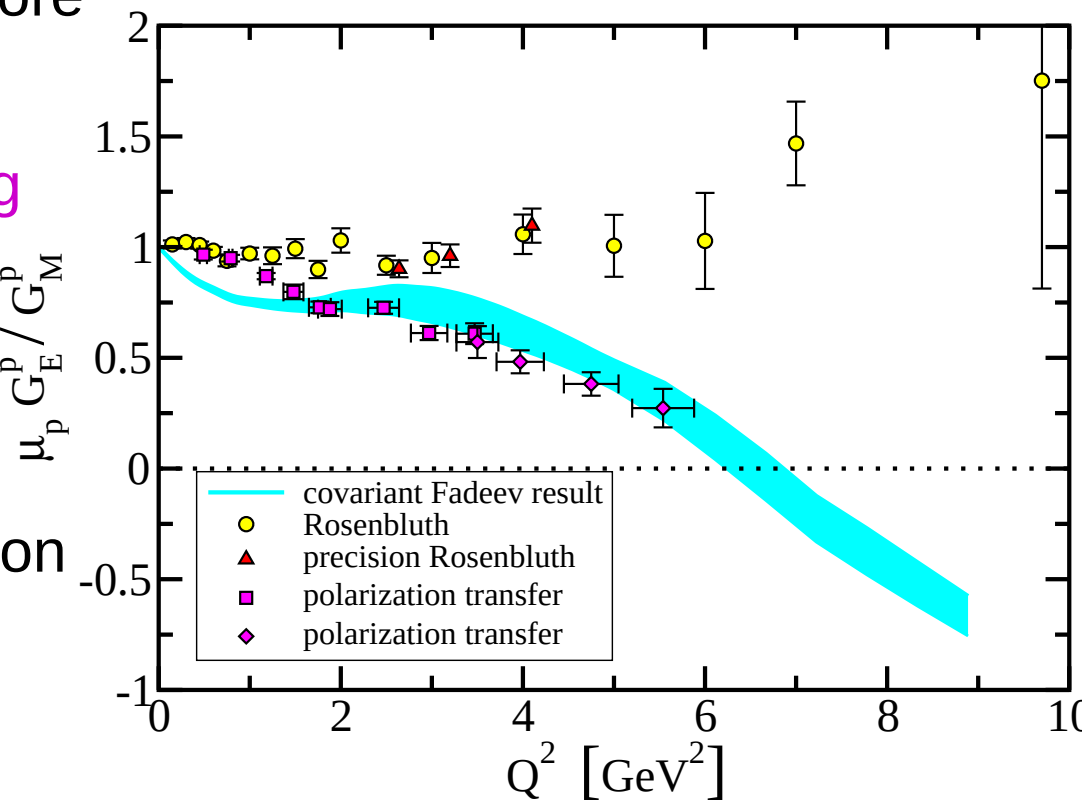

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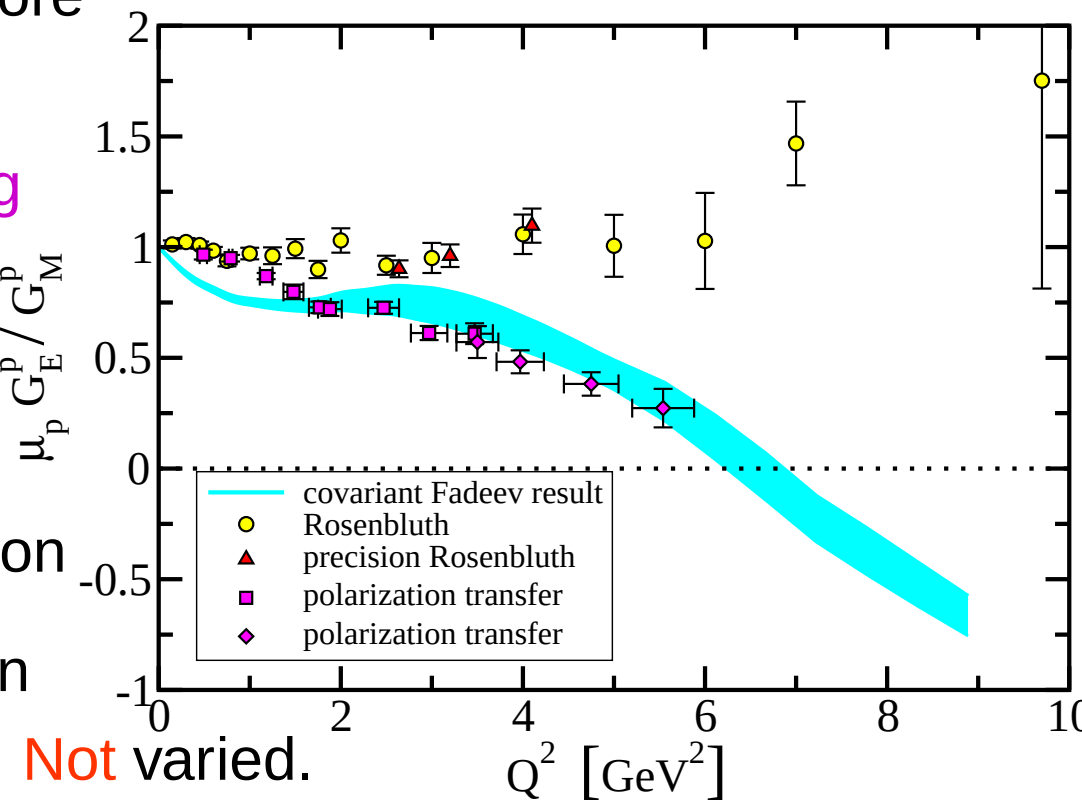

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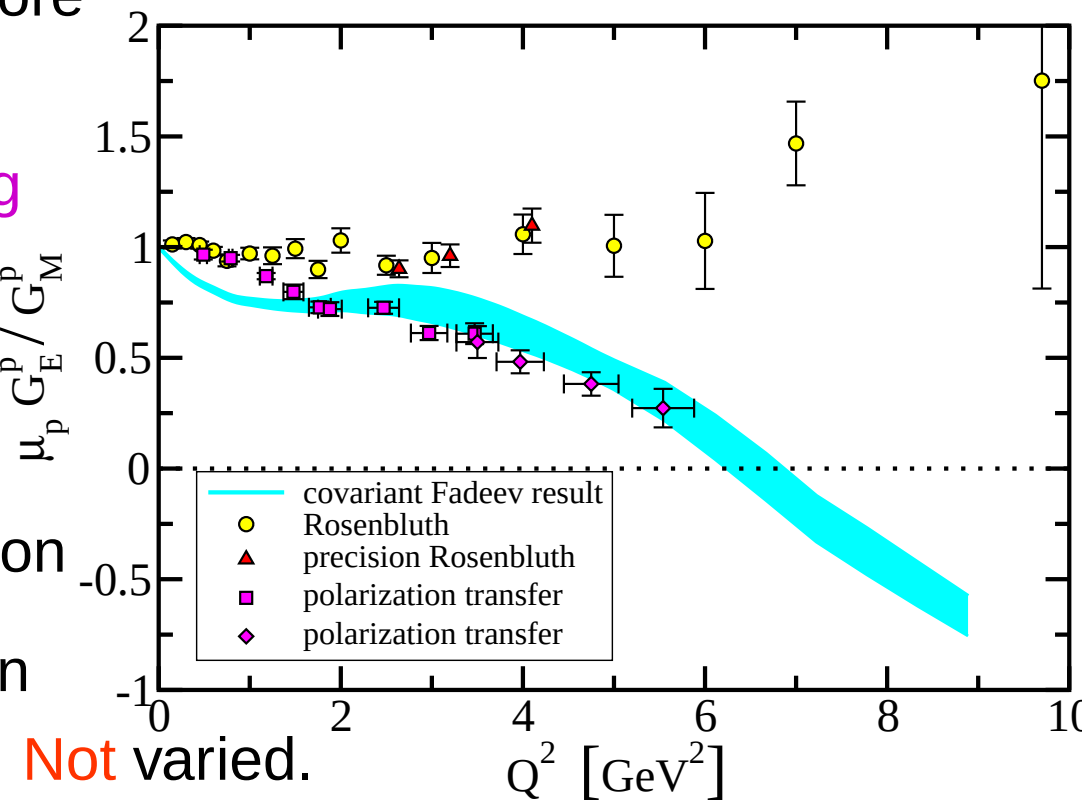

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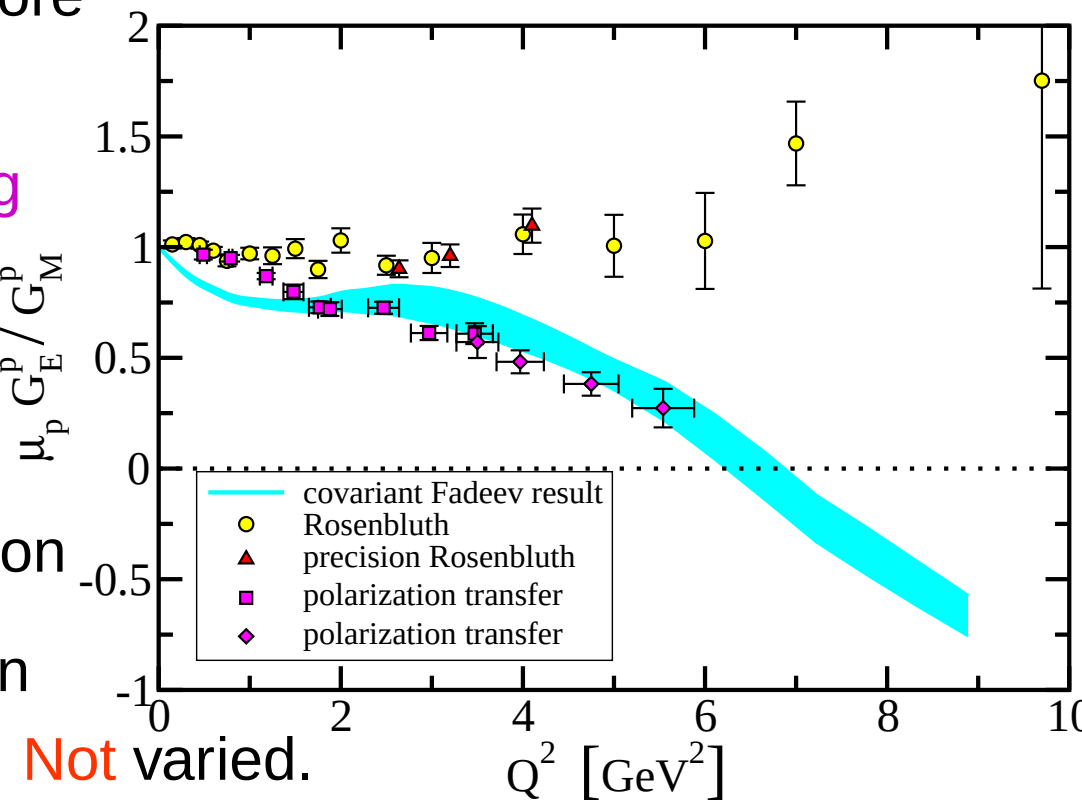

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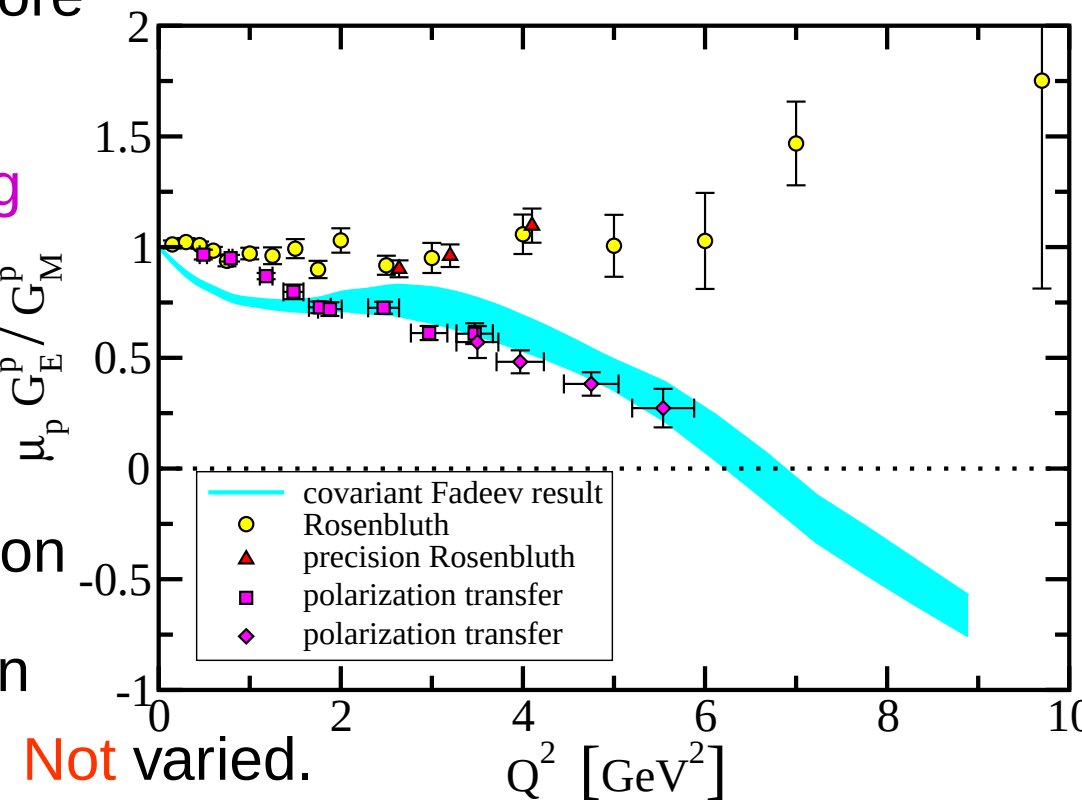

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  - Correlations in Faddeev amplitude – quark orbital angular momentum – essential to that agreement
  - Predict Zero at $Q^2 \approx 6.5\mathrm{GeV}^2$

Chiral Corrections

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- Thus far, omitted pion cloud contribution to current

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- Include loops following method of
  - . . . Ashley, Leinweber, Thomas, Young, he-lat/0308024
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$$\langle r^2_{\substack{p\\n}} \rangle^{1-loop^R}_{NA} = \mp \frac{1+5g_A^2}{32\pi^2 f_\pi^2} \ln(\frac{m_\pi^2}{m_\pi^2+\lambda^2}) ,$$

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

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

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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	

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$$\mu_p \frac{G_E^p(Q^2)}{G_M^p(Q^2)} = 1 - \frac{Q^2}{6}\left[(r_p)^2 - (r_p^\mu)^2\right]$$

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

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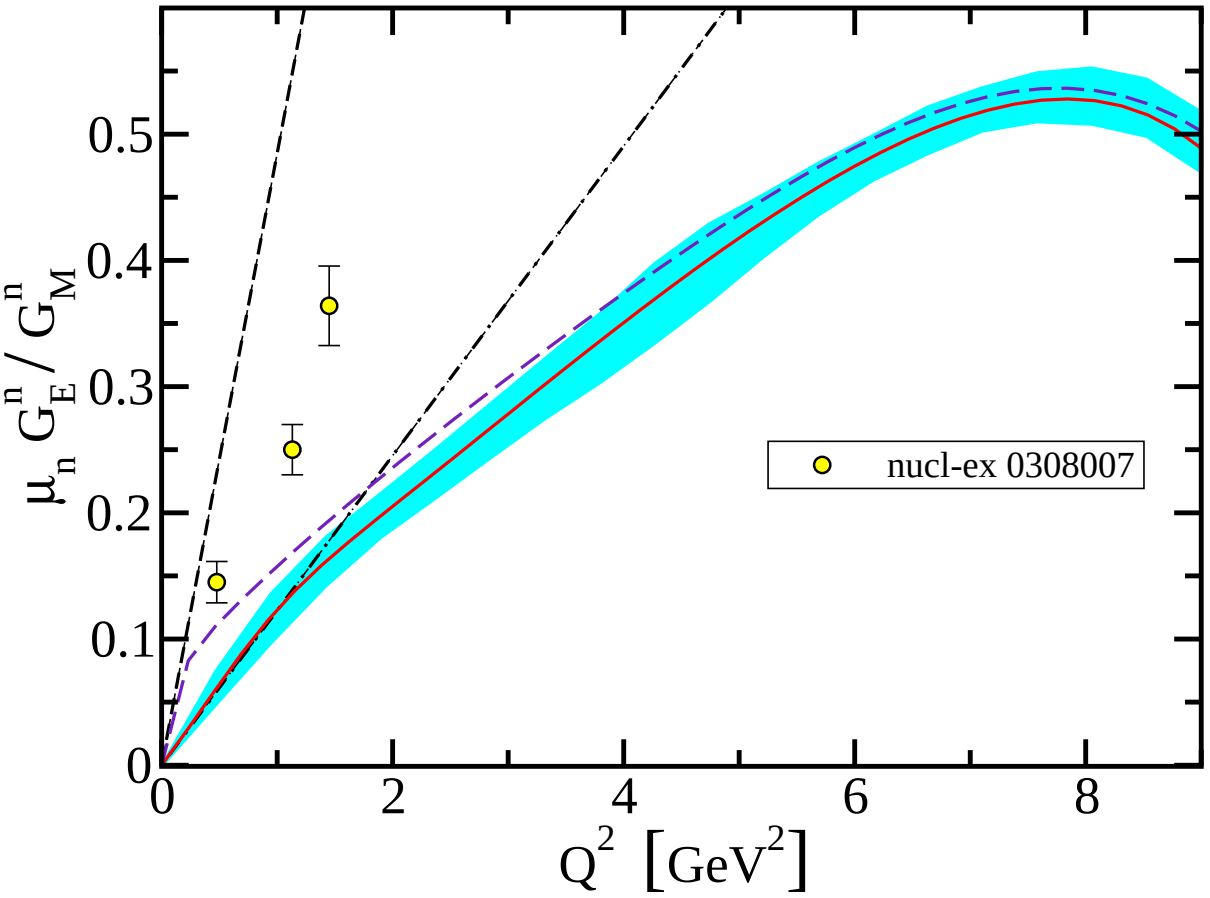
- Complements nucleon mass considerations
  - . . . veracious understanding of all nucleon properties
  - . . . impossible without intelligent incorporation of chiral corrections

Neutron Form Factors



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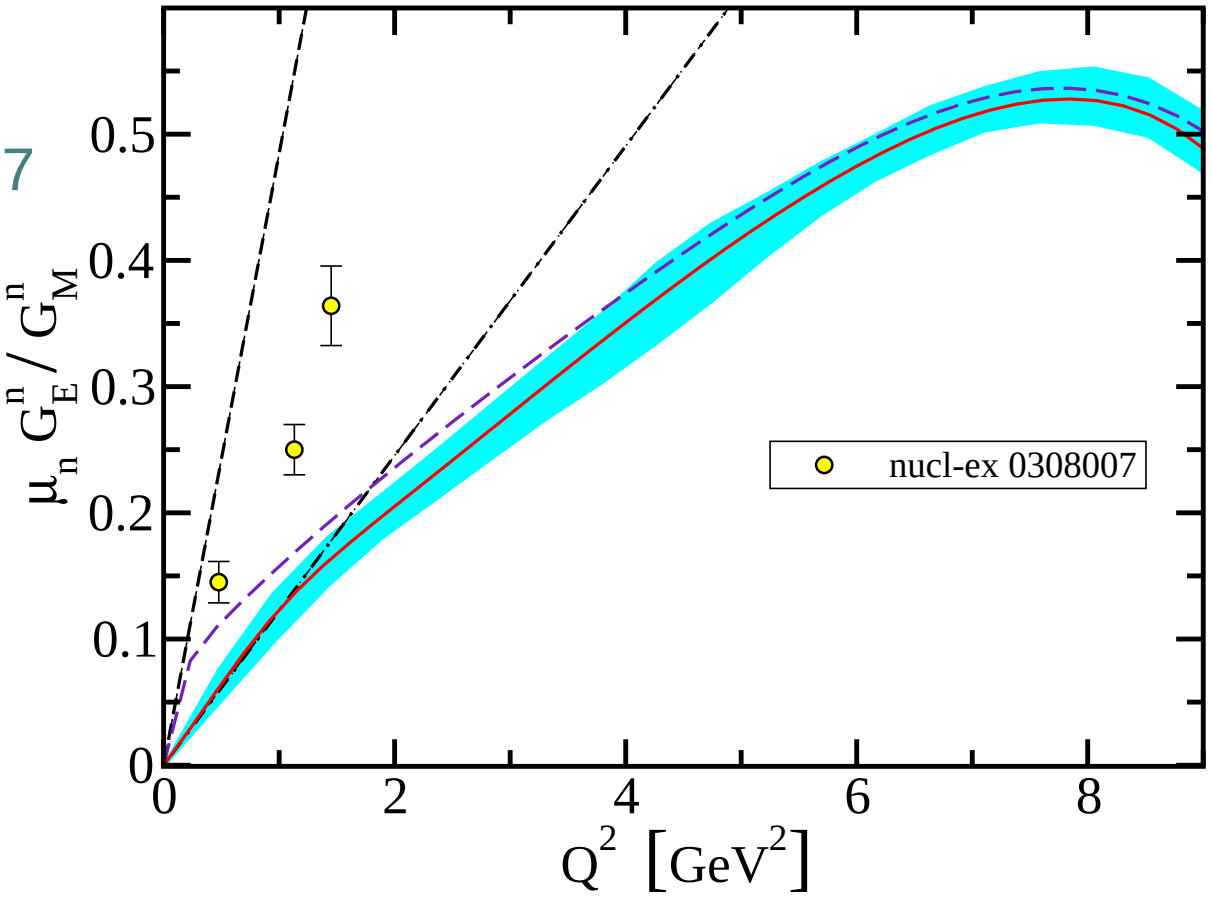

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Neutron Form Factors

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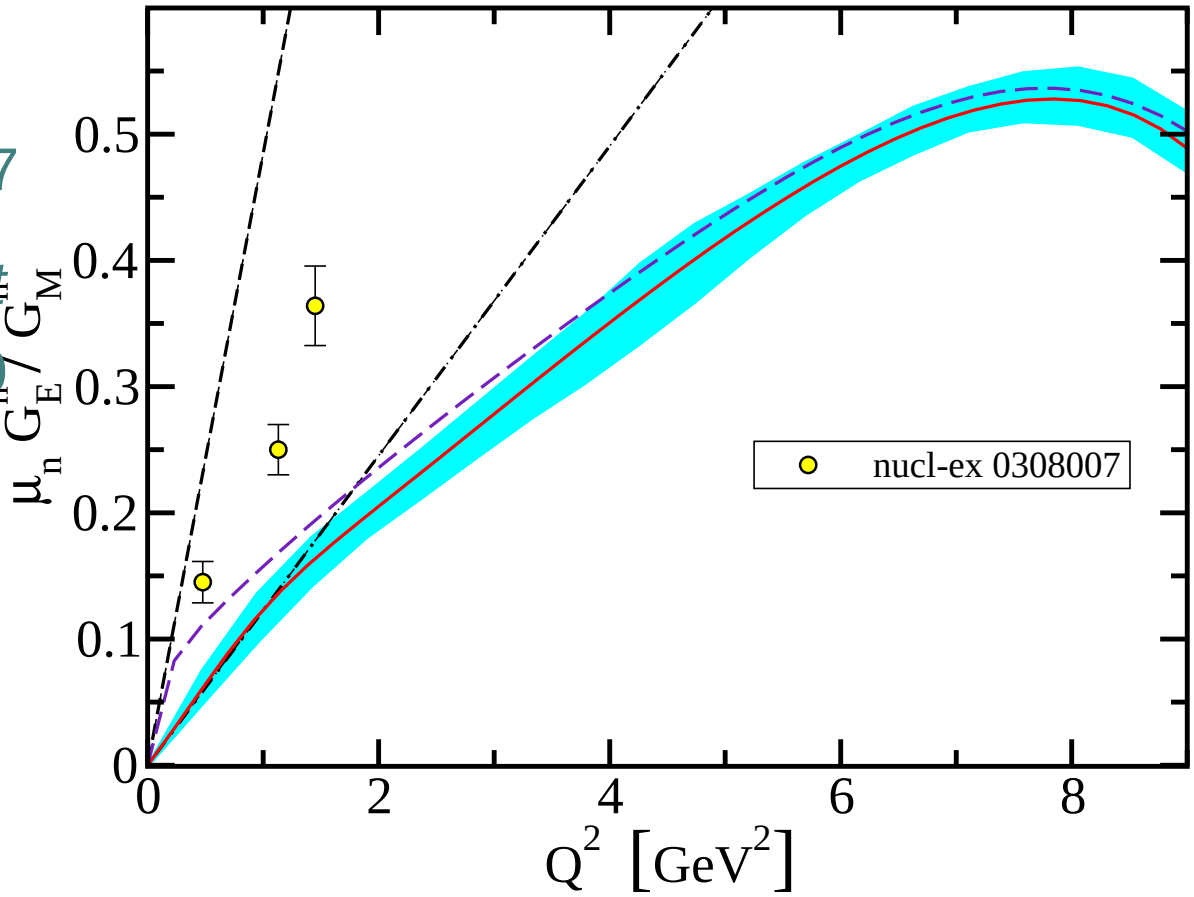
- Calc. Bhagwat, *et al.* nu-th/0610080
- $\mu_p \dfrac{G_E^n(Q^2)}{G_M^n(Q^2)} = -\dfrac{r_n^2}{6} Q^2$

Valid for $r_n^2 Q^2 \lesssim 1$



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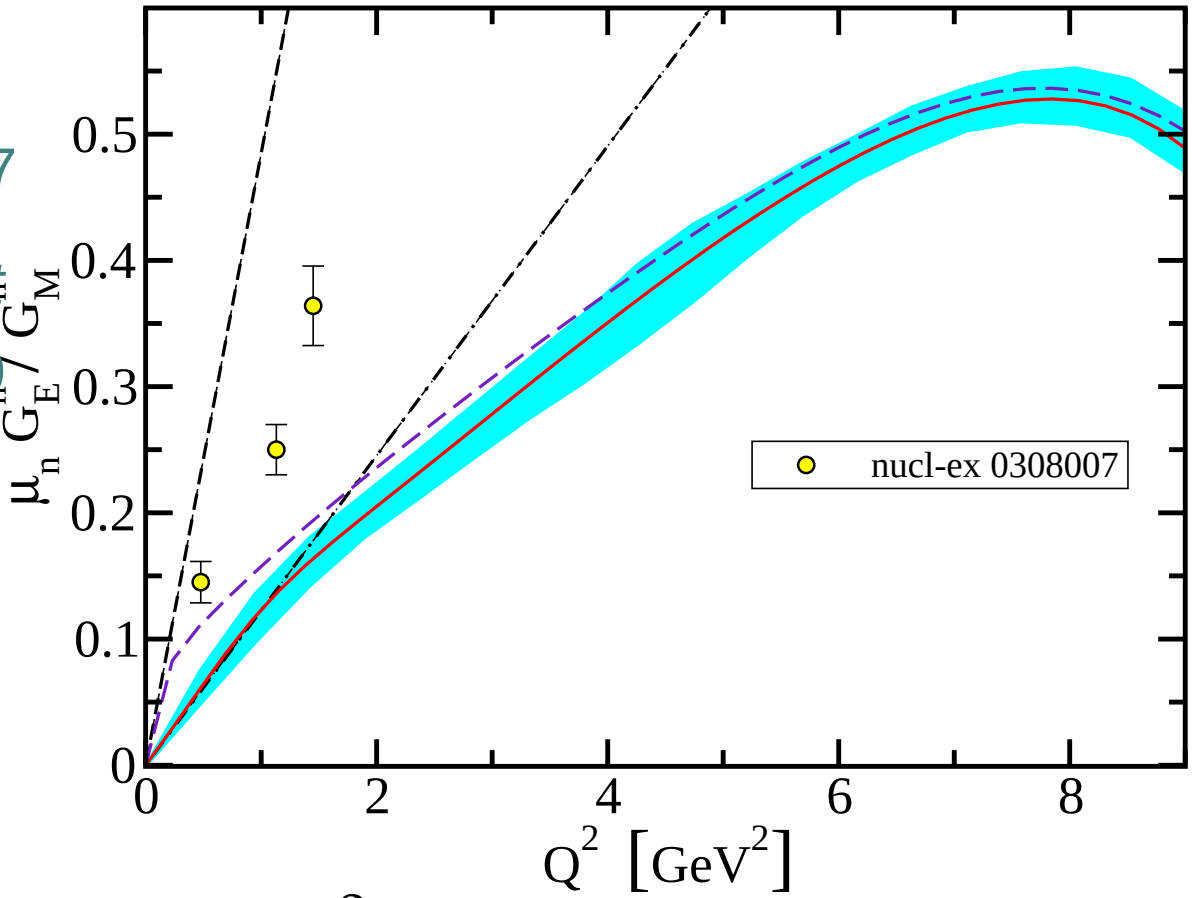

- No sign yet of a zero in $G_E^n(Q^2)$, even though calculation predicts $G_E^p(Q^2 \approx 6.5\,\mathrm{GeV}^2) = 0$
- Data to $Q^2 = 3.4\,\mathrm{GeV}^2$ is being analysed (JLab E02-013)

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Epilogue


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Epilogue

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- DCSB exists in QCD.
  - It is manifest in the dressed light-quark propagator.
  - It impacts dramatically upon observables.

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- Confinement

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  - Observables can be used to explore model realisations

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- An excellent way to test conjectures and constrain the possibilities

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  - Observables can be used to explore model realisations
- An excellent way to test conjectures and constrain the possibilities
- Physics is an Experimental science

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  - Confining propagators . . . mass for each – m_{J^P}

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
  C.D. Roberts and S.M. Schmidt, nu-th/0005064,
  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,
  Phys. Rept. **353** (2001) 281
- 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

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