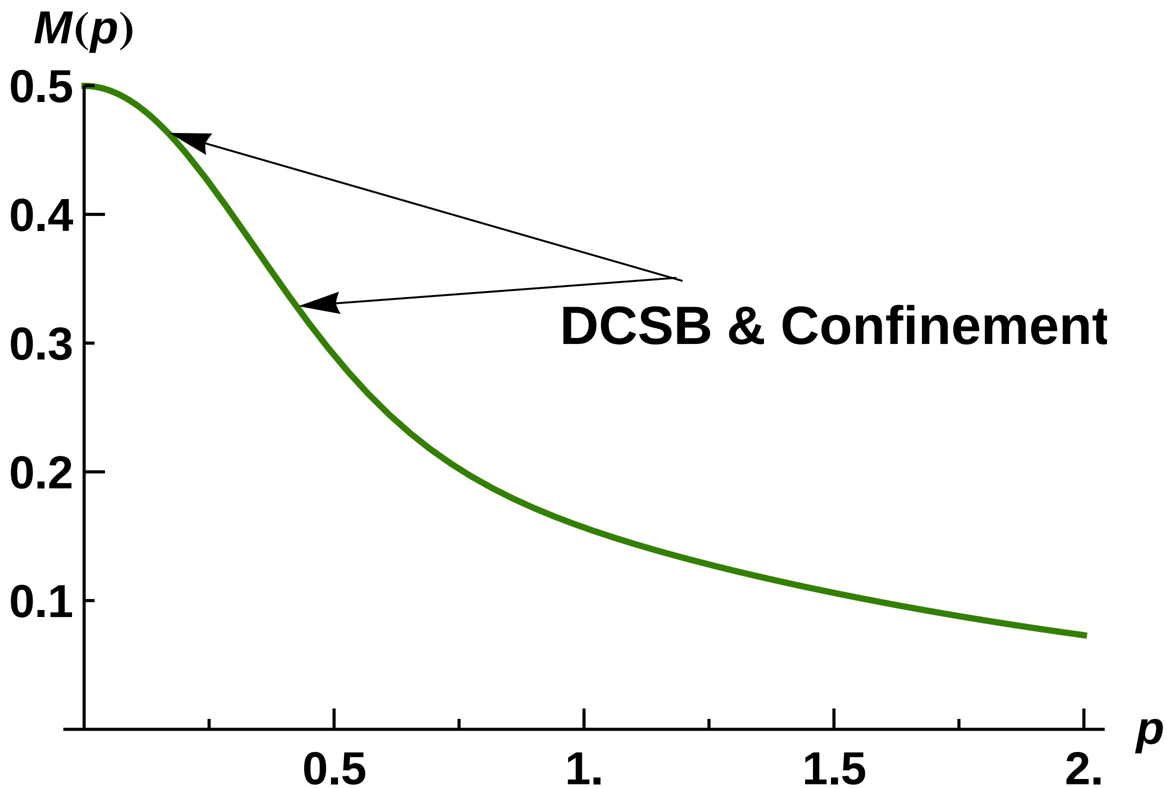
Empirically charting
Dynamical Chiral Symmetry Breaking

Dressed–quark Mass Function



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

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Universal Truths

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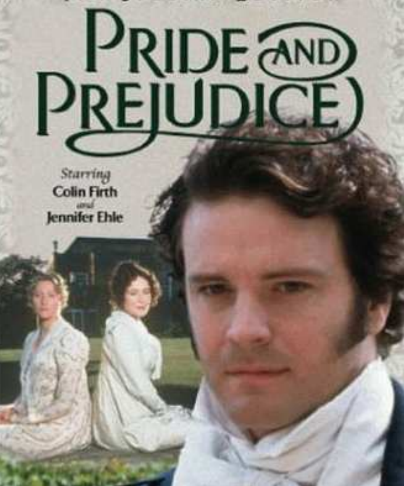

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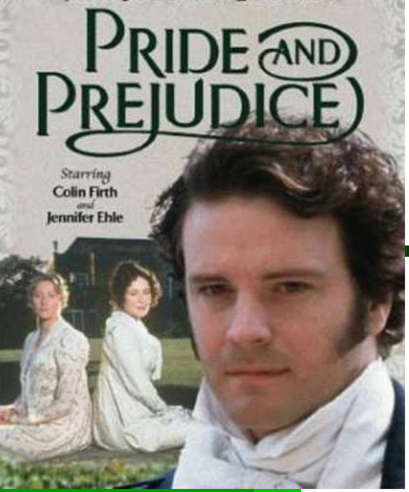
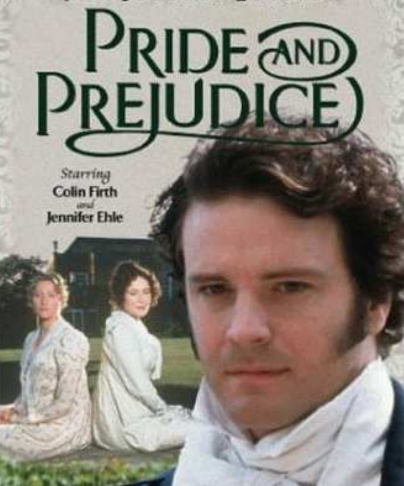


Universal Truths

- Spectrum of excited states, and elastic and transition form factors provide unique information about long-range interaction between light-quarks and distribution of hadron’s characterising properties amongst its QCD constituents.



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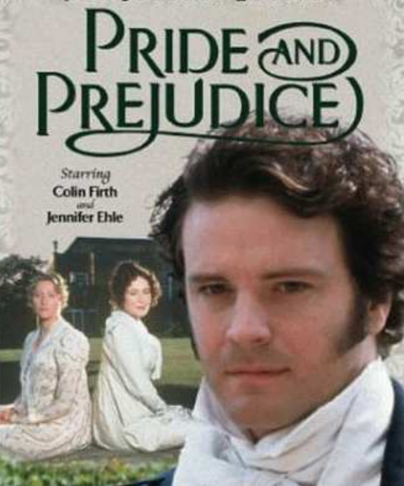

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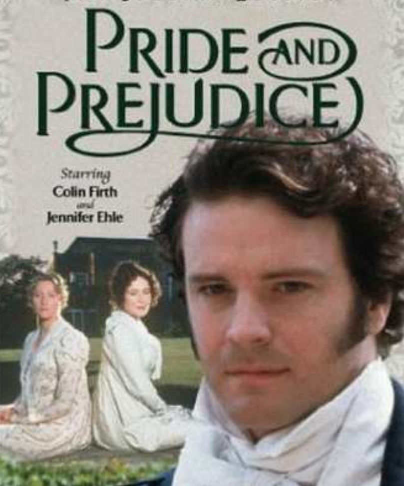

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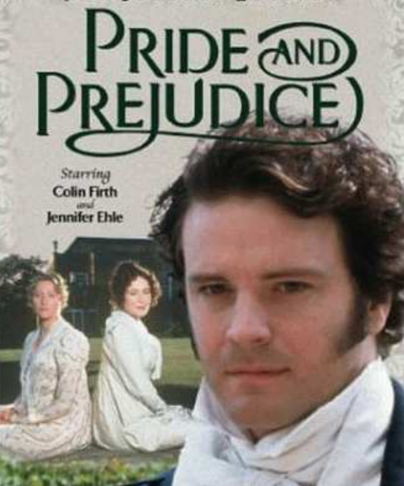

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- Running of quark mass entails that calculations at even modest Q^2 require a Poincaré-covariant approach. Covariance requires existence of quark orbital angular momentum in hadron's rest-frame wave function.

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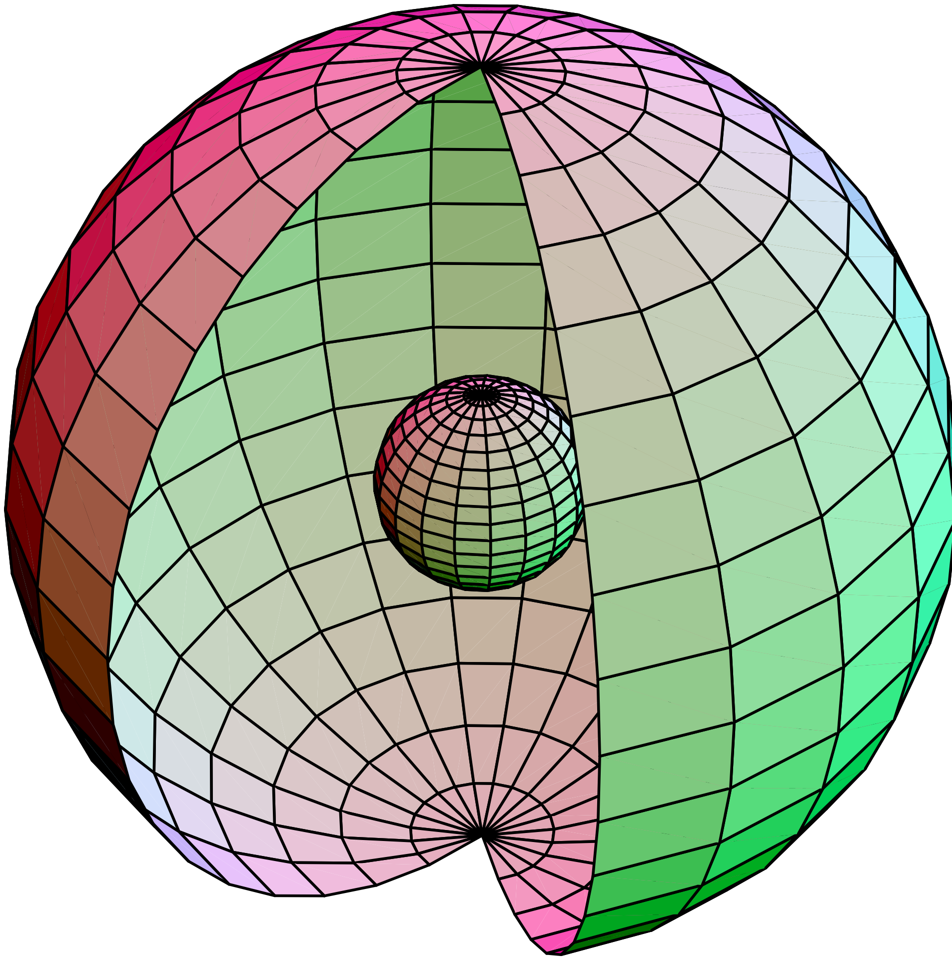
Intranucleon Interaction

Intranucleon Interaction



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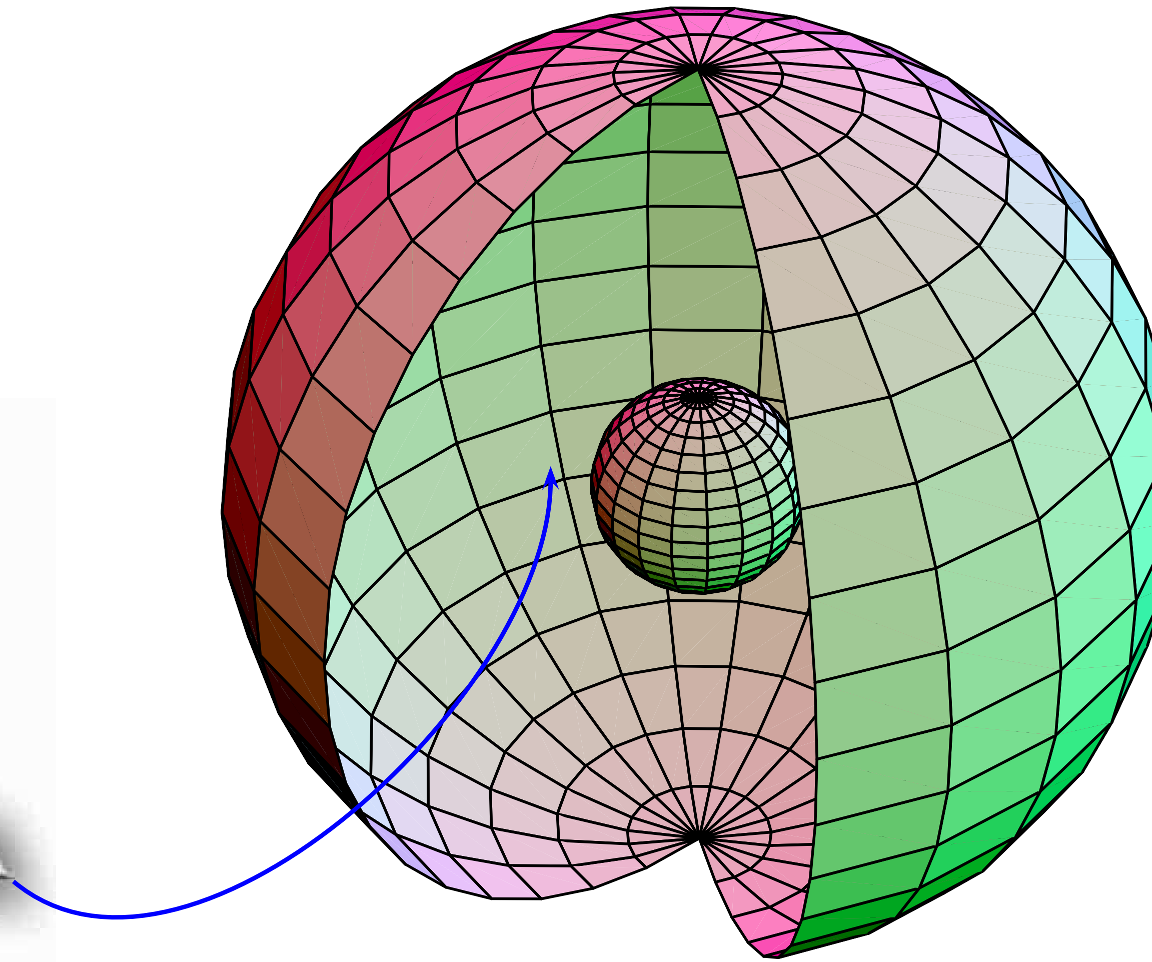
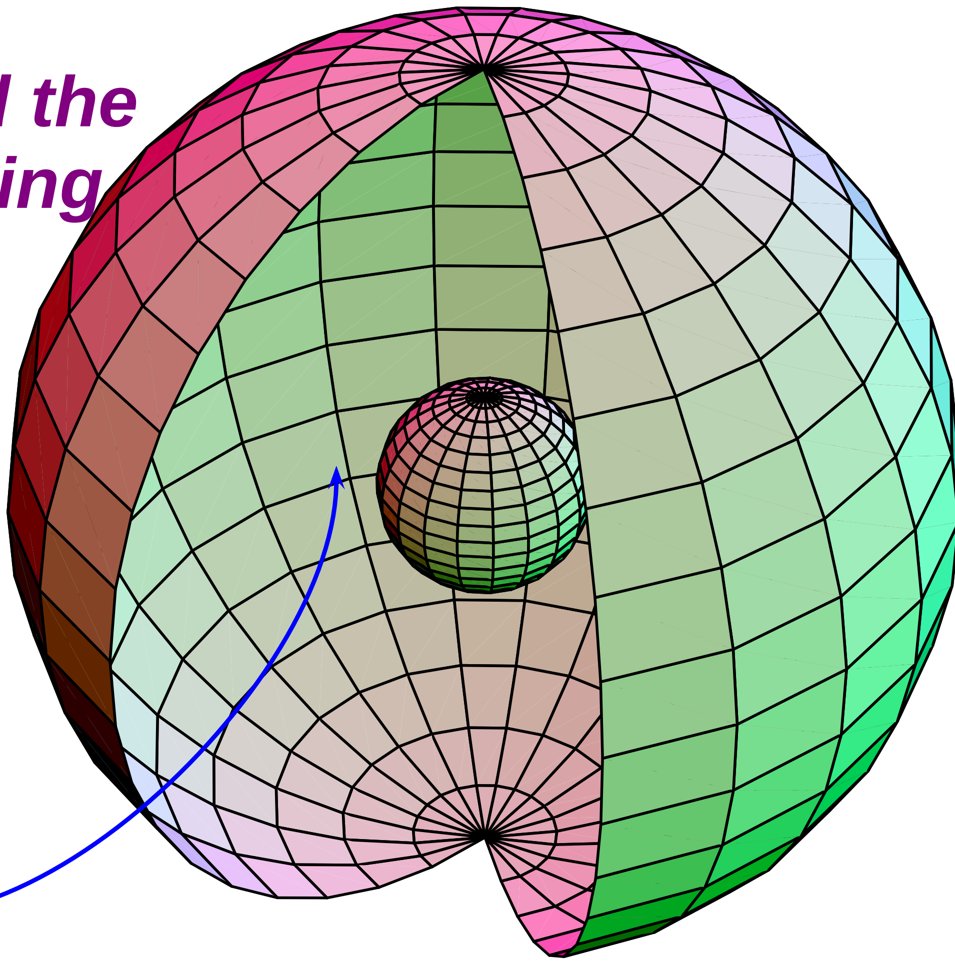


98% of the volume

What is the Intranucleon Interaction?

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



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What is the light-quark Long-Range Potential?

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What is the light-quark Long-Range Potential?

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

Euler-Lagrange equations for quantum field theory

- Well suited to Relativistic Quantum Field Theory

Dyson-Schwinger Equations

Euler-Lagrange equations for quantum field theory

- Well suited to Relativistic Quantum Field Theory
- Simplest level: Generating Tool for Perturbation Theory

  . . . . Materially Reduces Model Dependence

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    - 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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- Understanding $\Rightarrow$ InfraRed behaviour of $\alpha_s(Q^2)$
- Method yields Schwinger Functions $\equiv$ Propagators

Cross-Sections built from Schwinger Functions

Charting the Interaction between light-quarks

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Charting the Interaction between light-quarks

- Confinement can be related to the analytic properties of QCD's Schwinger functions

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Charting the Interaction between light-quarks

- Confinement can be related to the analytic properties of QCD's Schwinger functions
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  Of course, the behaviour of the β-function on the perturbative domain is well known.
- This is a well-posed problem whose solution is an elemental goal of modern hadron physics.

Charting the Interaction between light-quarks

- Through DSEs the pointwise behaviour of the β-function determines pattern of chiral symmetry breaking

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- Through DSEs the pointwise behaviour of the β-function determines pattern of chiral symmetry breaking
- DSEs connect β-function to experimental observables. Hence, comparison between computations and observations of, e.g.,
  - hadron mass spectrum;
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  can be used to chart β-function's long-range behaviour

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- Extant studies of mesons show that the properties of hadron excited states are a great deal more sensitive to the long-range behaviour of β-function than those of the ground state

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- DSEs connect β-function to experimental observables. Hence, comparison between computations and observations can be used to chart β-function's long-range behaviour
- To realise this goal, a nonperturbative symmetry-preserving DSE truncation is necessary
  - Steady quantitative progress is being made with a scheme that is systematically improvable

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Charting the Interaction between light-quarks

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- DSEs connect β-function to experimental observables. Hence, comparison between computations and observations can be used to chart β-function's long-range behaviour
- To realise this goal, a nonperturbative symmetry-preserving DSE truncation is necessary
  - On other hand, at present significant qualitative advances possible with symmetry-preserving kernel *Ansätze* that express important additional nonperturbative effects – $M(p^2)$ – difficult/impossible to capture in any finite sum of contributions

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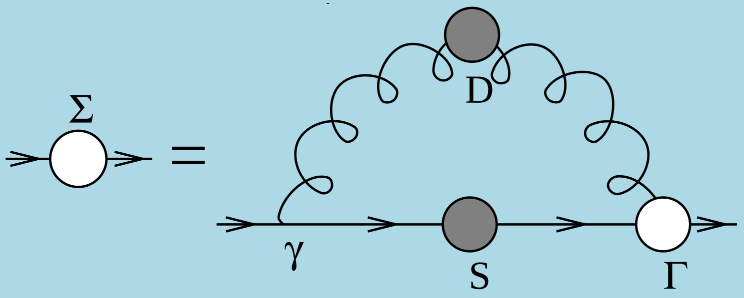
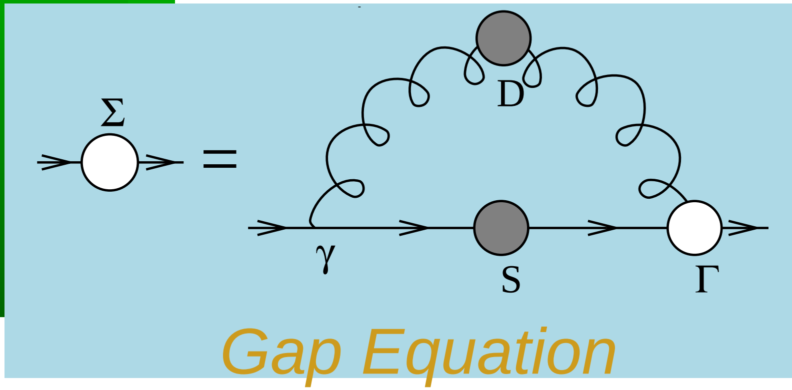
Frontiers of Nuclear Science:
A Long Range Plan (2007)

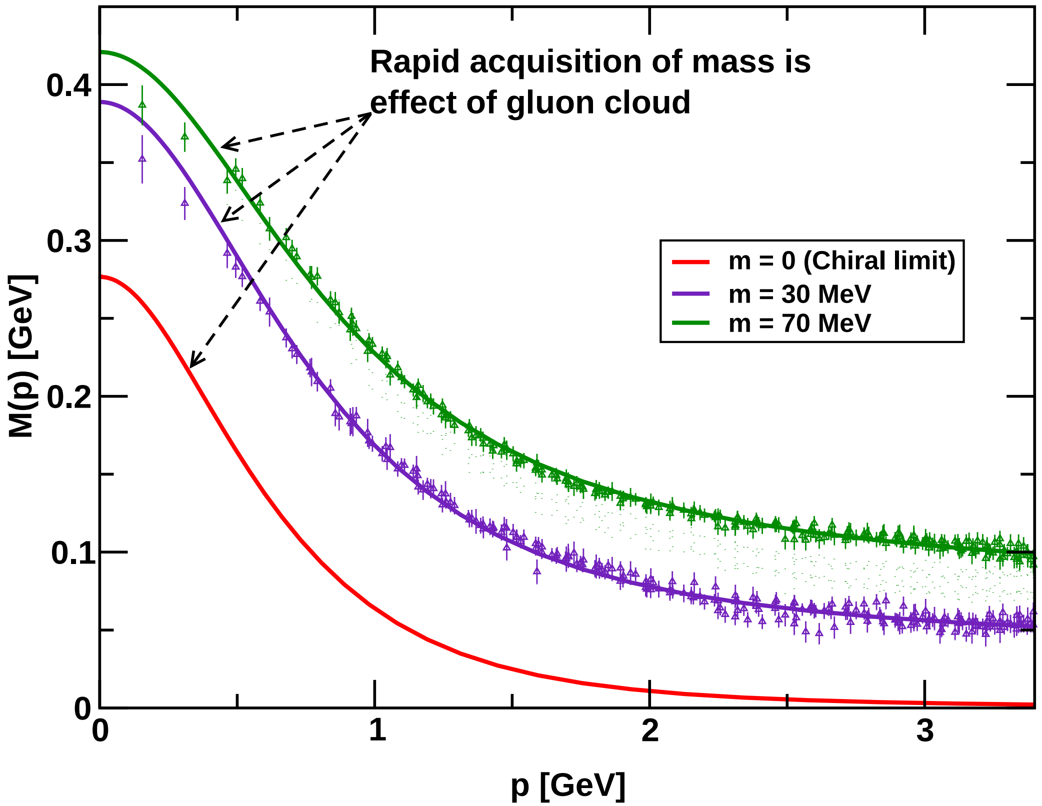
Frontiers of Nuclear Science: Theoretical Advances



Gap Equation



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



Mass from nothing.

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

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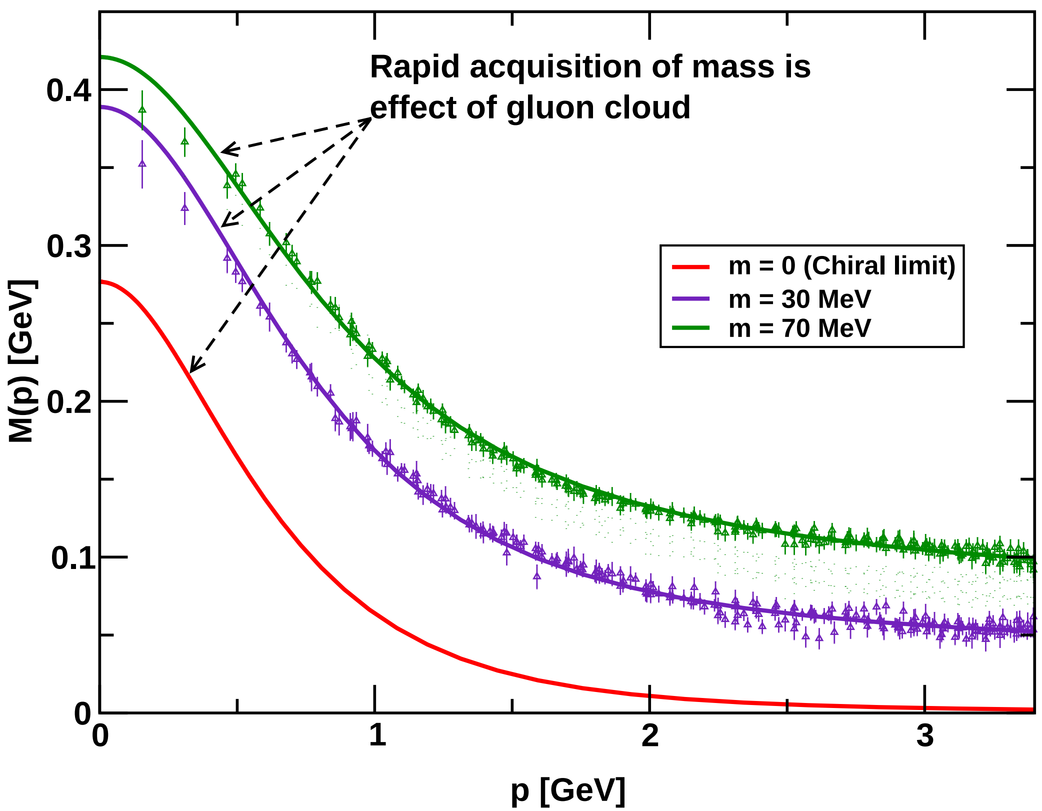

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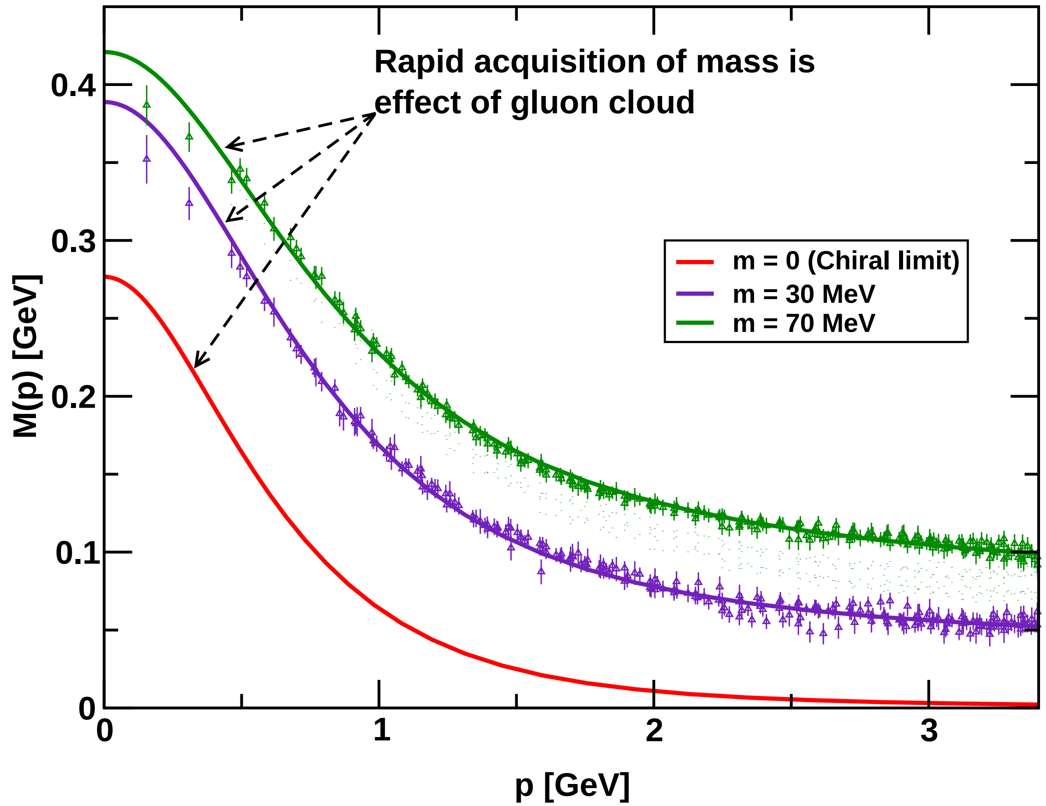

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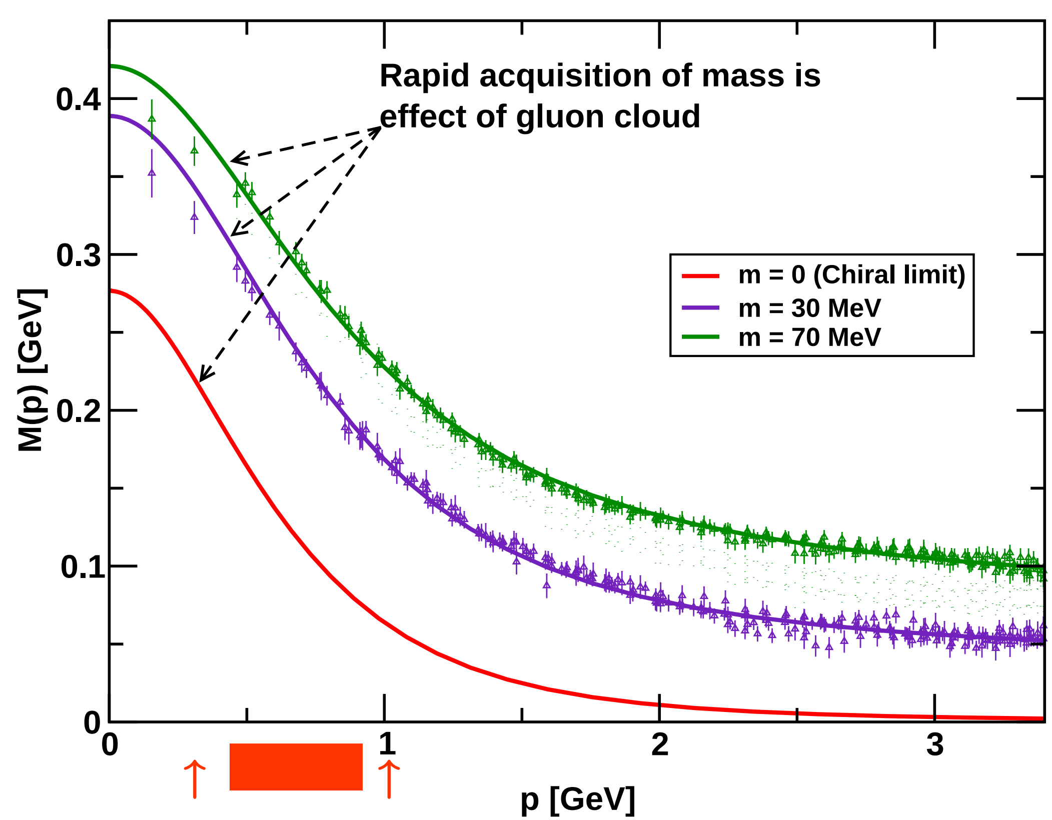

Scanned by $Q^2 \in [2, 9]\ \mathrm{GeV}^2$ Baryon Elastic and Transition Form Factors

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

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Satisfies BSE

Satisfies DSE

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but must be intimately related

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- Nontrivial constraint

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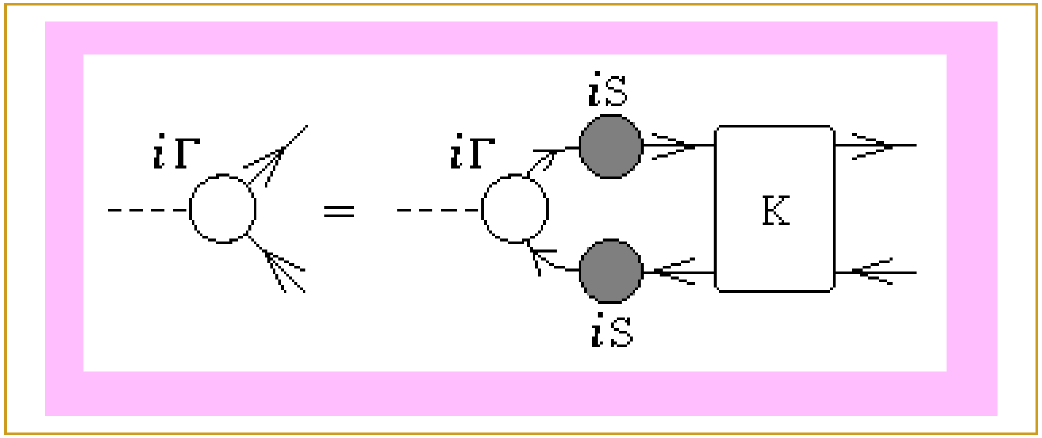
- Failure ⇒ Explicit Violation of QCD's Chiral Symmetry

Bound-state DSE

Bound-state DSE
Bethe-Salpeter Equation

- Standard form, familiar from textbooks

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



$K(q,k;P)$: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

Bound-state DSE
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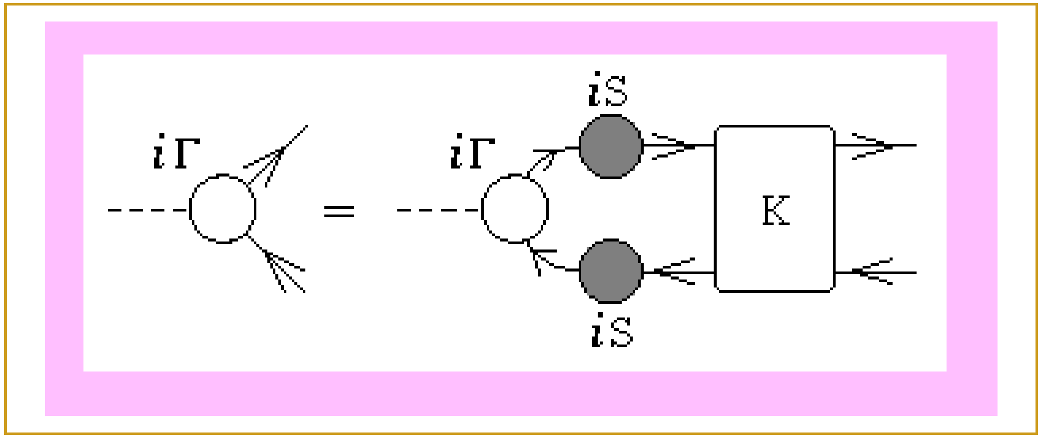

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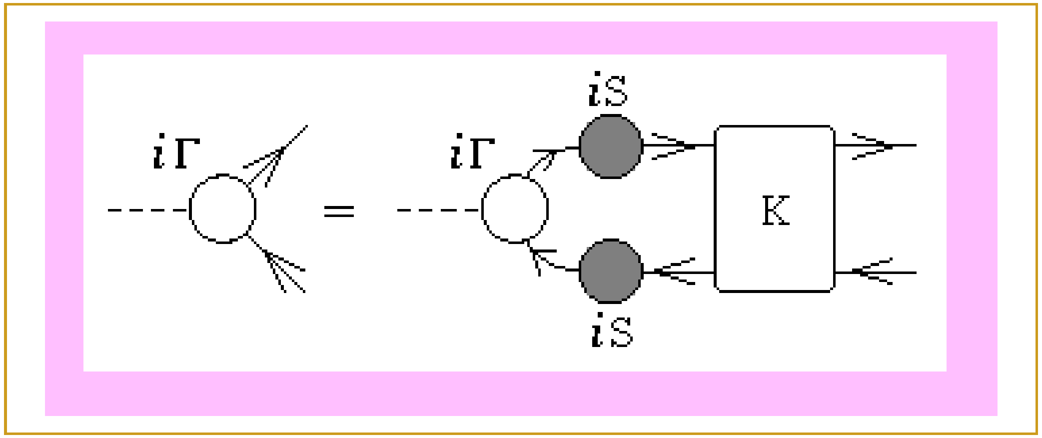

$K(q,k;P)$: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

- Compact. Visually appealing. Correct.
- Blocked progress for more than 60 years.

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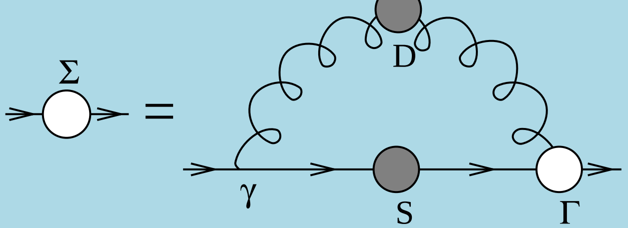
Gap Equation
General Form



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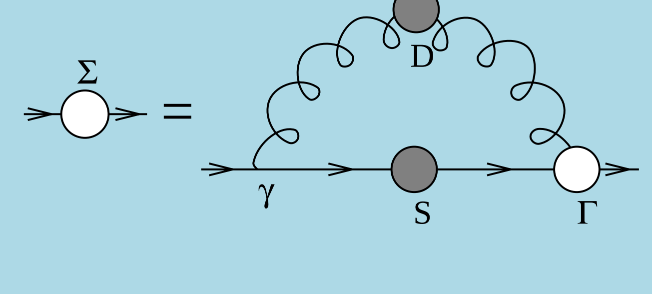
$$S_f(p)^{-1} = Z_2\,(i\gamma\cdot p + m_f^{\rm bm}) + \Sigma_f(p)\,,$$

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



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- $Z_{1,2}(\zeta^2,\Lambda^2)$ are respectively the vertex and quark wave function renormalisation constants, with ζ the renormalisation point
- $m^{\rm bm}(\Lambda)$ is the Lagrangian current-quark bare mass
- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma^f_\nu(q,p)$ is the dressed-quark-gluon vertex

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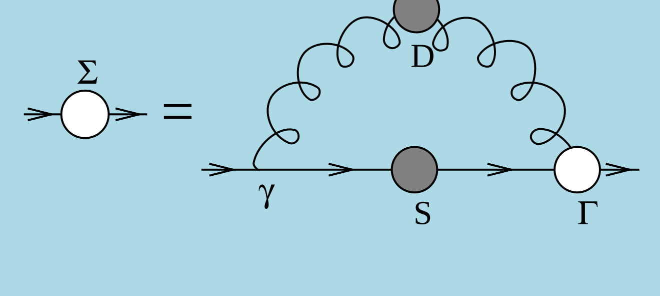

Gap Equation
General Form

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

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

- $Z_{1,2}(\zeta^2,\Lambda^2)$ are respectively the vertex and quark wave function renormalisation constants, with ζ the renormalisation point
- $m^{\rm bm}(\Lambda)$ is the Lagrangian current-quark bare mass
- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma^f_\nu(q,p)$ is the dressed-quark-gluon vertex
- Suppose one has in-hand the exact form of $\Gamma^f_\nu(q,p)$
  What is the associated
  Symmetry-preserving Bethe-Salpeter Kernel?

Bethe-Salpeter Equation
General Form

Bethe-Salpeter Equation
General Form

- Bender, Detmold, Roberts, Thomas:
  "*Bethe-Salpeter equation and a nonperturbative quark gluon vertex*,"
  Phys. Rev. C**65** (2002) 065203, nucl-th/0202082

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

(Poincaré covariance, hence $q_\pm = q \pm P/2$, etc., without loss of generality.)

- First exploration of effects arising from complete resummation of a diagrammatic subclass: ladder-gluon planar vertex corrections

Bethe-Salpeter Equation General Form

L. Chang and C. D. Roberts

0903.5461 [nucl-th], Phys. Rev. Lett. 103 (2009) 081601

- In fact, this is $K \to \Lambda$-equivalent exact form:

$$\Gamma^{fg}_{5\mu}(k;P) = Z_2 \gamma_5 \gamma_\mu$$

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

$$+ \int_q g^2 D_{\alpha\beta}(k-q) \, \frac{\lambda^a}{2} \, \gamma_\alpha S_f(q_+) \frac{\lambda^a}{2} \Lambda^{fg}_{5\mu\beta}(k,q;P),$$

(Poincaré covariance, hence $q_\pm = q \pm P/2$, etc., without loss of generality.)

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Bethe-Salpeter Equation General Form

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

- Equivalent exact form:

$$\Gamma^{fg}_{5\mu}(k;P) = Z_2\gamma_5\gamma_\mu$$

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

$$+ \int_q g^2 D_{\alpha\beta}(k-q)\,\frac{\lambda^a}{2}\,\gamma_\alpha S_f(q_+)\frac{\lambda^a}{2}\Lambda^{fg}_{5\mu\beta}(k,q;P),$$

(Poincaré covariance, hence $q_\pm = q \pm P/2$, etc., without loss of generality.)

- In this form ... $\Lambda^{fg}_{5\mu\beta}$
  is completely defined via the dressed-quark self-energy

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- E.g., in any reliable study of light-quark hadrons, axial-vector vertex must satisfy Ward-Takahashi identity

$$P_\mu \Gamma^{fg}_{5\mu}(k;P) = S_f^{-1}(k_+) i\gamma_5 + i\gamma_5 S_g^{-1}(k_-) - i\,[m_f(\zeta) + m_g(\zeta)]\, \Gamma_5^{fg}(k;P)\,,$$

Expresses chiral symmetry & pattern by which it's broken

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Expresses chiral symmetry & pattern by which it's broken

- The condition ($\Lambda^{fg}_{5\beta}$ pseudoscalar analogue of $\Lambda^{fg}_{5\mu\beta}$)

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

a new Ward-Takahashi identity, is Necessary & Sufficient to ensure $\boldsymbol{\Gamma^{fg}_{5\mu}(k;P)}$ Ward-Takahashi identity satisfied.

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- The condition ($\Lambda_{5\beta}^{fg}$ pseudoscalar analogue of $\Lambda_{5\mu\beta}^{fg}$)

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  a new Ward-Takahashi identity, is Necessary & Sufficient to ensure $\Gamma_{5\mu}^{fg}(k;P)$ Ward-Takahashi identity satisfied.

- Rainbow-ladder ...
  - $\Gamma_\beta^f(q,k) = \gamma_\mu$

    $\Rightarrow \Lambda_{5\mu\beta}^{fg}(k,q;P) = 0 = \Lambda_{5\beta}^{fg}(k,q;P)$

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- Bethe-Salpeter equation introduced in 1951

Bethe-Salpeter Kernel
60 year problem

L. Chang and C. D. Roberts
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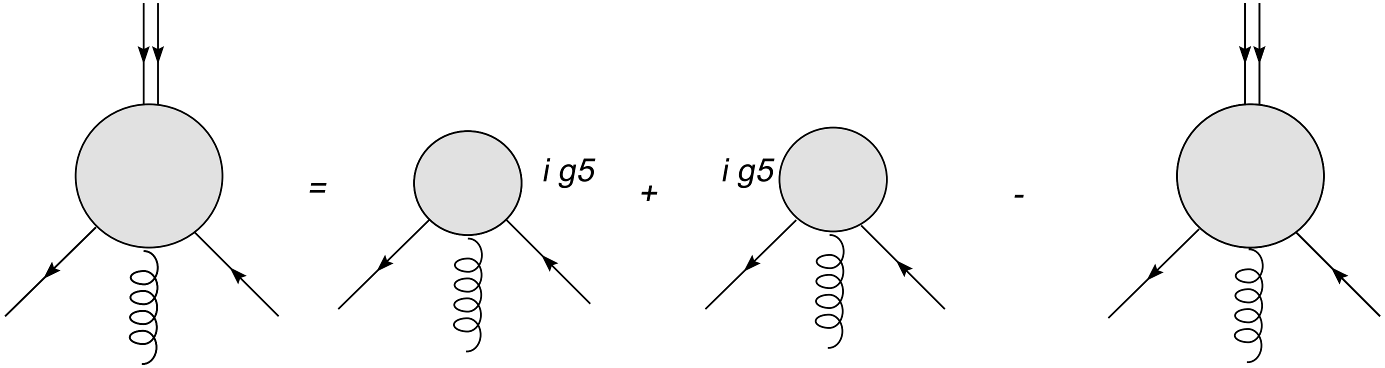
- Bethe-Salpeter equation introduced in 1951
- Newly-derived Ward-Takahashi identity



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

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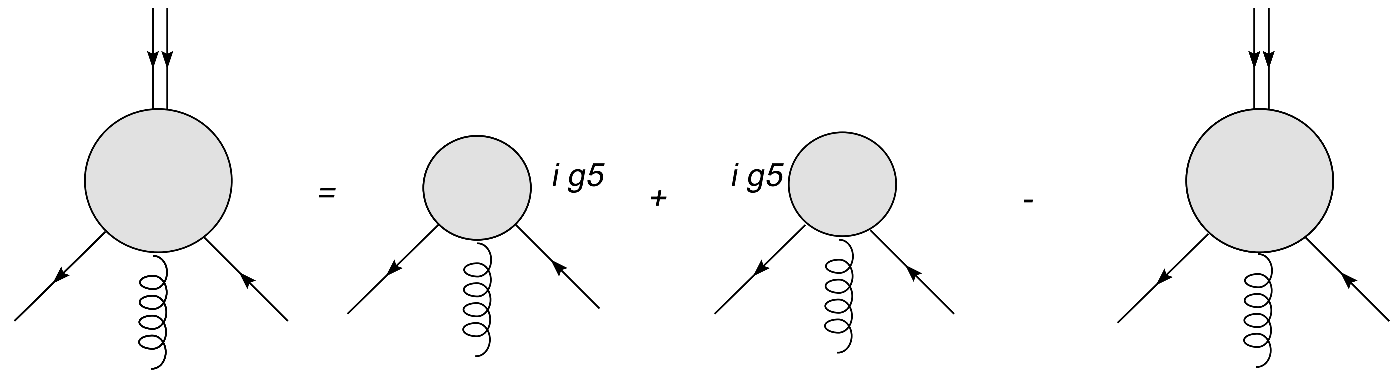

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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
  - Consistent means - all symmetries preserved!

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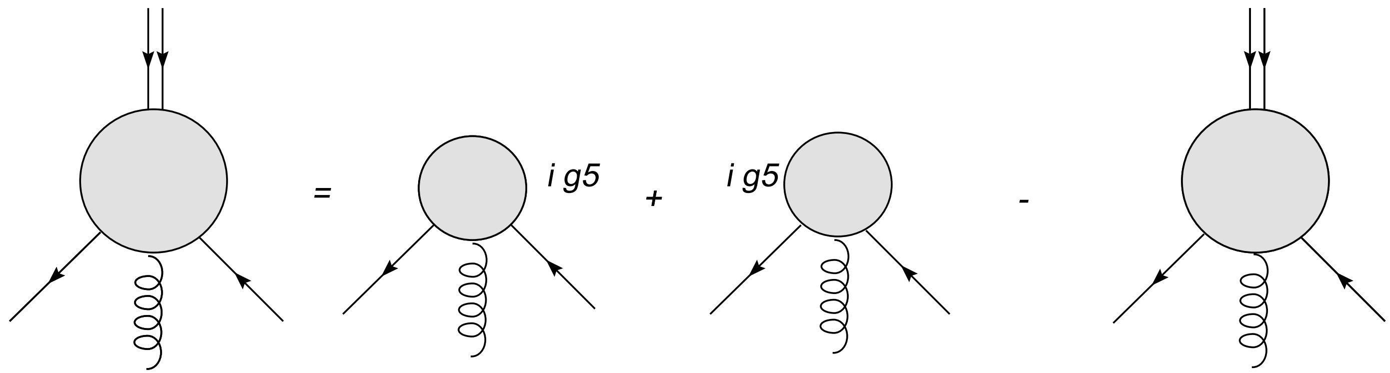

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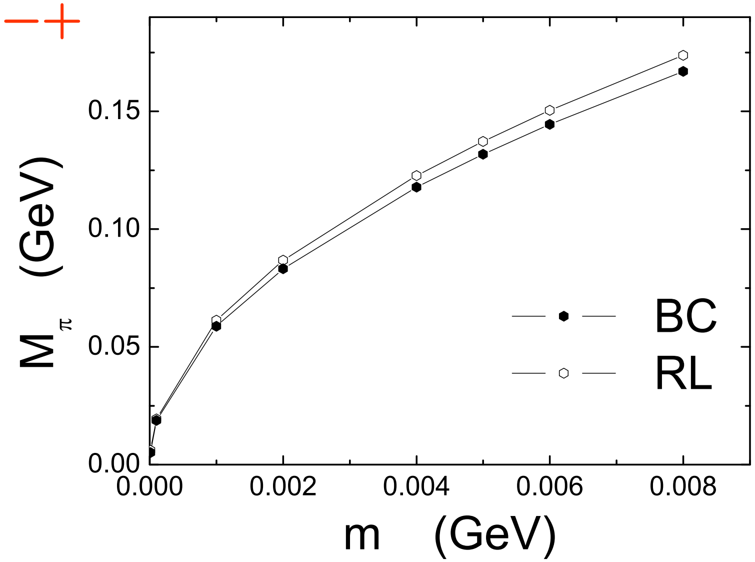
- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
- Exemplified the procedure and results to expect . . .

Numerical Illustration

π *cf.* σ

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

0^{-+}



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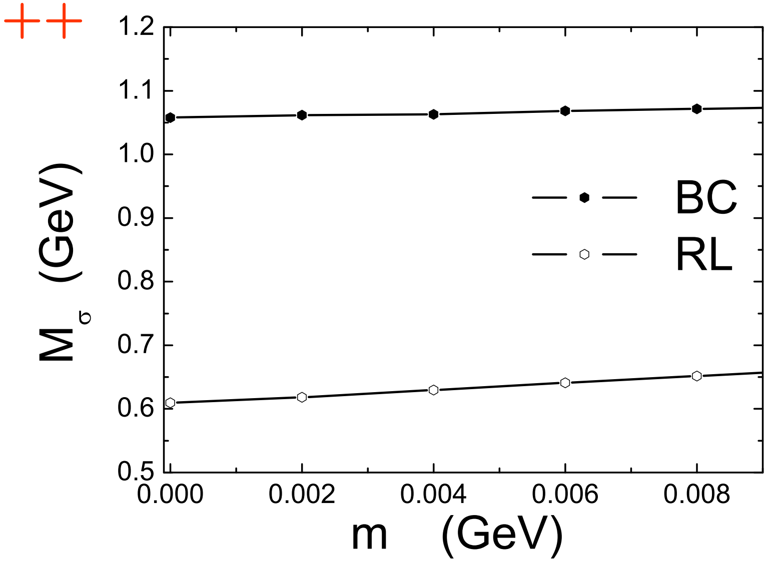

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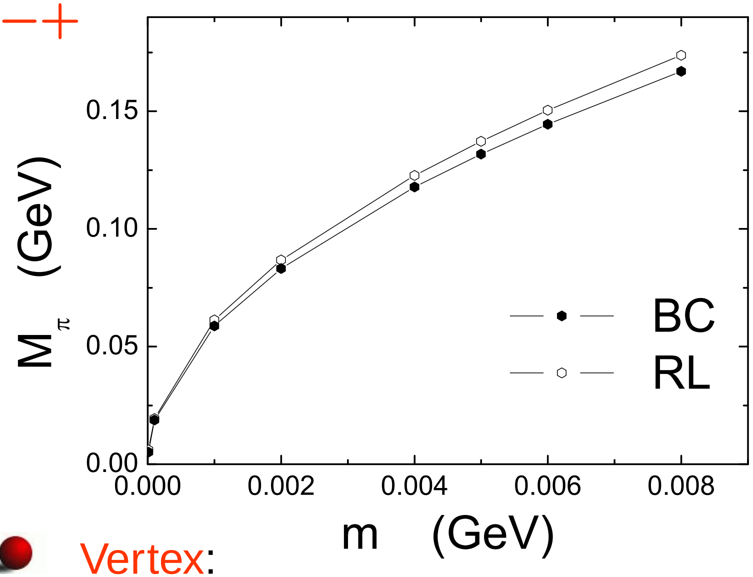

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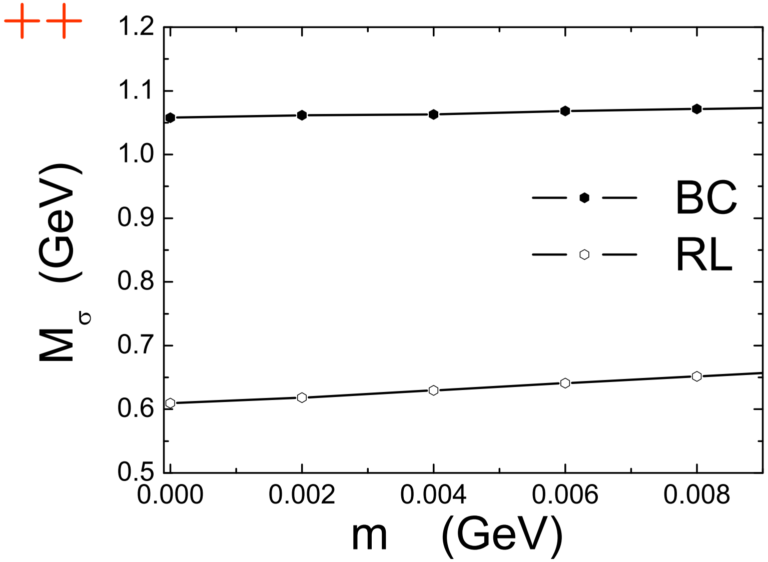

- Vertex:
  - leading-order rainbow-ladder truncation
  - cf. Ball-Chiu–consistent *Ansatz* – Essentially nonperturbative content; Expresses DCSB; Consistent with lattice-QCD simulations; Diagrammatic content unknown

Same interaction. One mass-scale in both truncations: $1/\omega = 0.4$ fm, defining border between IR & UV.

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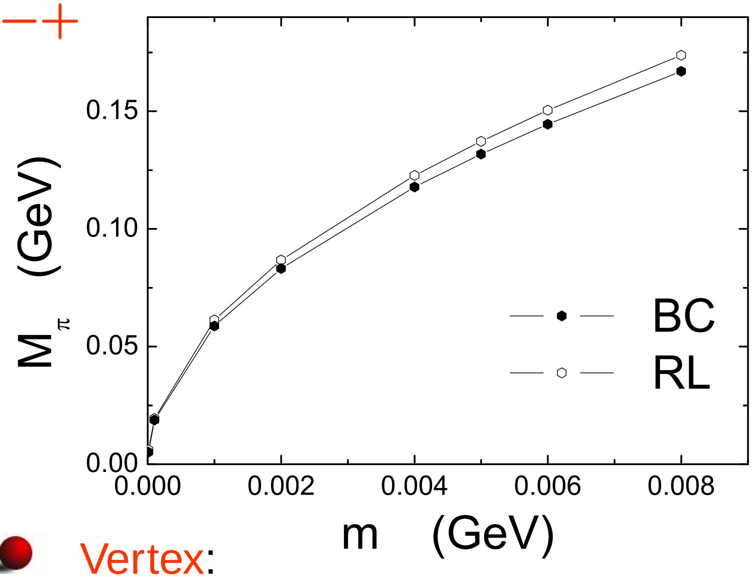

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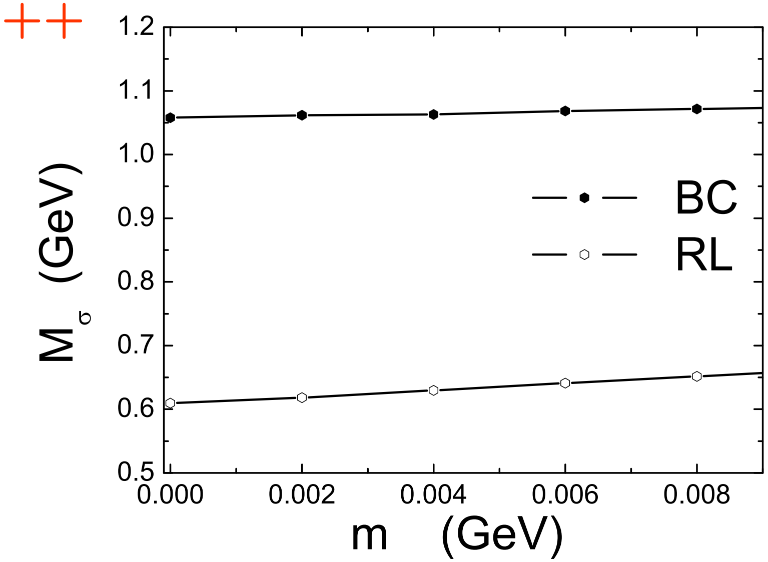

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  Same interaction. One mass-scale in both truncations: $1/\omega = 0.4$ fm, defining border between IR & UV.
- GMOR . . . plainly satisfied by both truncations
- A little attraction introduced in pseudoscalar channel
- Enormous repulsion introduced in scalar channel

Spin-orbit Interaction

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

- Rainbow-ladder DSE truncation, $\varepsilon_\sigma^{\rm RL} := \left.\dfrac{2M(0) - m_\sigma}{2M(0)}\right|_{\rm RL} = (0.3 \pm 0.1)\,.$
- BC-consistent Bethe-Salpeter kernel; viz., $\varepsilon_\sigma^{\rm BC} \lesssim 0.1\,.$

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- BC-consistent Bethe-Salpeter kernel; viz., $\varepsilon_\sigma^{\rm BC} \lesssim 0.1$.
- Scalar mesons $= {}^3P_0$ states: Constituents' spins aligned and one unit of constituent orbital angular momentum
  - From this viewpoint,
    scalar is a spin and orbital excitation of a pseudoscalar meson

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- Scalar mesons $=$ $^3P_0$ states: Constituents' spins aligned and one unit of constituent orbital angular momentum
- Extant studies of realistic corrections to the rainbow-ladder truncation show that they reduce hyperfine splitting in the absence of orbital angular momentum
- Clear sign that in a Poincaré covariant treatment the BC-consistent truncation magnifies spin-orbit interaction.
  - Effect owes to influence of quark's dynamically-enhanced scalar self-energy in the Bethe-Salpeter kernel.

Impossible to demonstrate effect without our new procedure

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Spin-orbit Interaction

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Impossible to demonstrate effect without our new procedure

- Expect this feature to have material impact

Especially on mesons with mass greater than 1 GeV.

prima facie . . . can overcome longstanding shortcoming of systematic, symmetry-preserving truncations;
viz., splitting between vector & axial-vector mesons is too small

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  Impossible to demonstrate effect without our new procedure
- Expect this feature to have material impact

  Especially on mesons with mass greater than 1 GeV.

  prima facie . . . can overcome longstanding shortcoming of systematic, symmetry-preserving truncations;
  viz., splitting between vector & axial-vector mesons is too small
- Promise of realistic meson spectroscopy . . . First time, also for mass > 1 GeV

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$[m_{a_1} - m_\rho]$ I . . .

- That was where things stood in March/09

$[m_{a_1} - m_\rho]$ I . . .

- That was where things stood in March/09
- Now, we've solved inhomogeneous vector and axial-vector Bethe-Salpeter equation at spacelike total momentum $\Rightarrow \Gamma_{qq}(k=0,P^2)$
- $$\boxed{\frac{1}{\Gamma_{qq}(k=0,P^2)}}$$ Exhibits a zero at ground-state mass-squared
- Padé approximant extrapolation to locate zero

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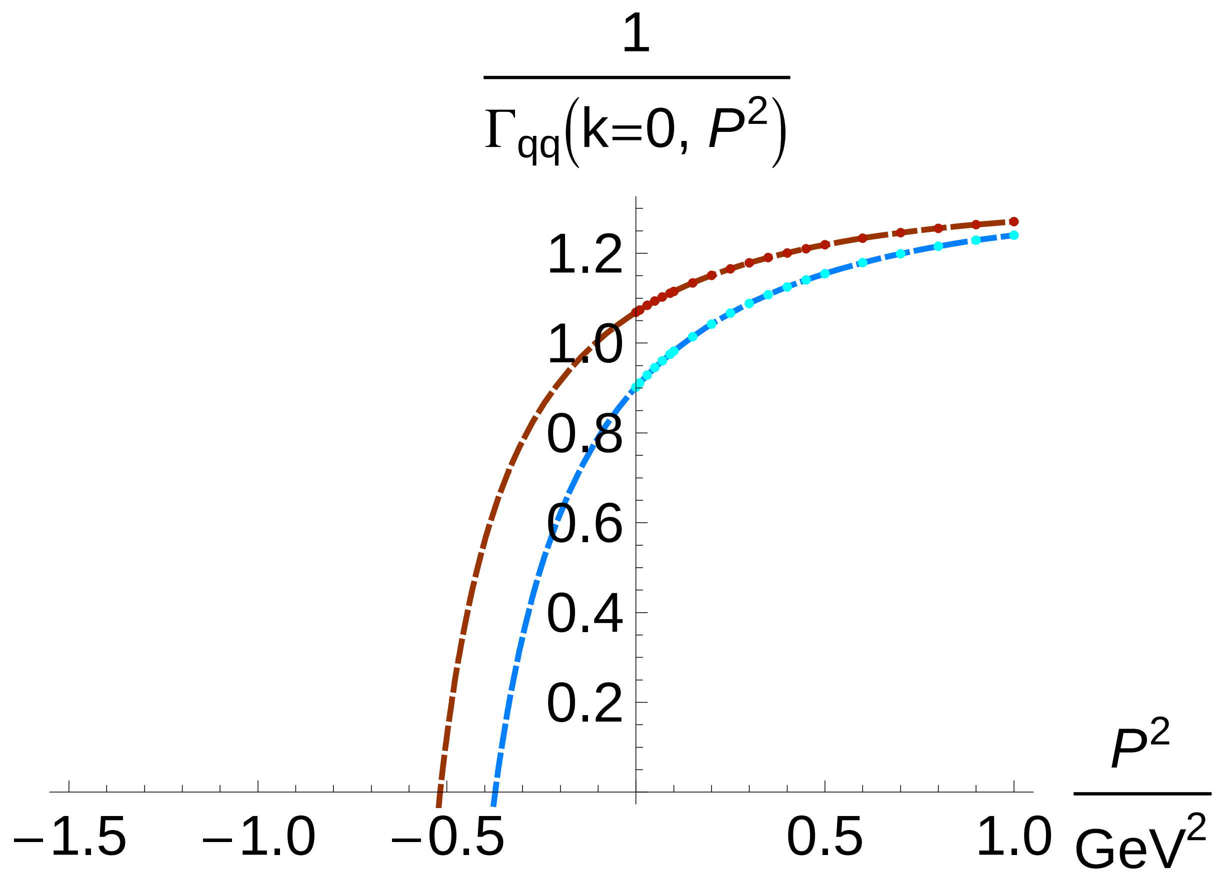
- $$\boxed{\frac{1}{\Gamma_{qq}(k=0,P^2)}}$$ Exhibits a zero at ground-state mass-squared
- Padé approximant extrapolation to locate zero
  - Almost precisely method used for ground-state masses in lattice-QCD
  - Intelligent use gives dependable results
    "Schwinger functions and light-quark bound states"
    Bhagwat, Höll, Krassnigg, Roberts & Wright,
    Few Body Syst. **40** (2007) 209, nucl-th/0701009

$\ldots\ [m_{a_1} - m_\rho]$ II $\ldots$

Rainbow-Ladder

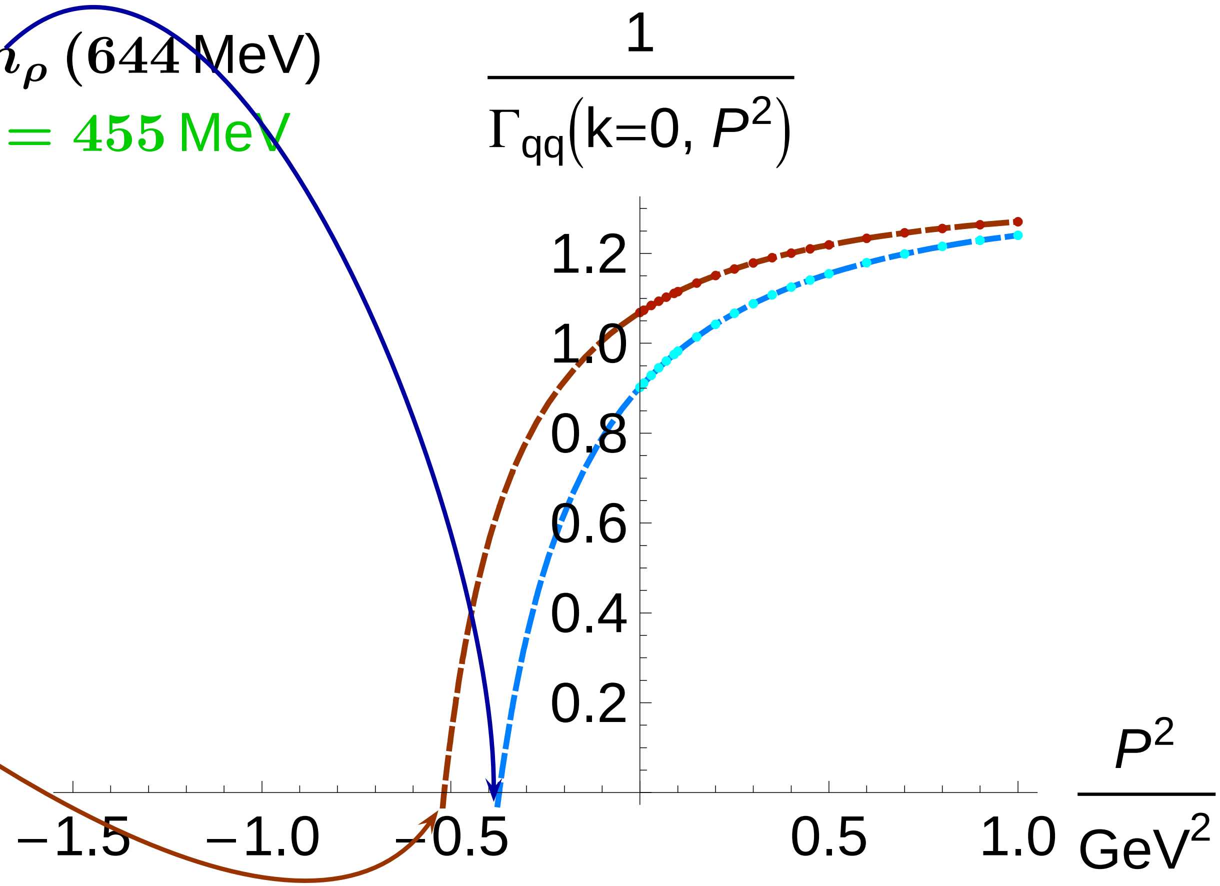
$$\Gamma_\mu(q,k) = \gamma_\mu$$



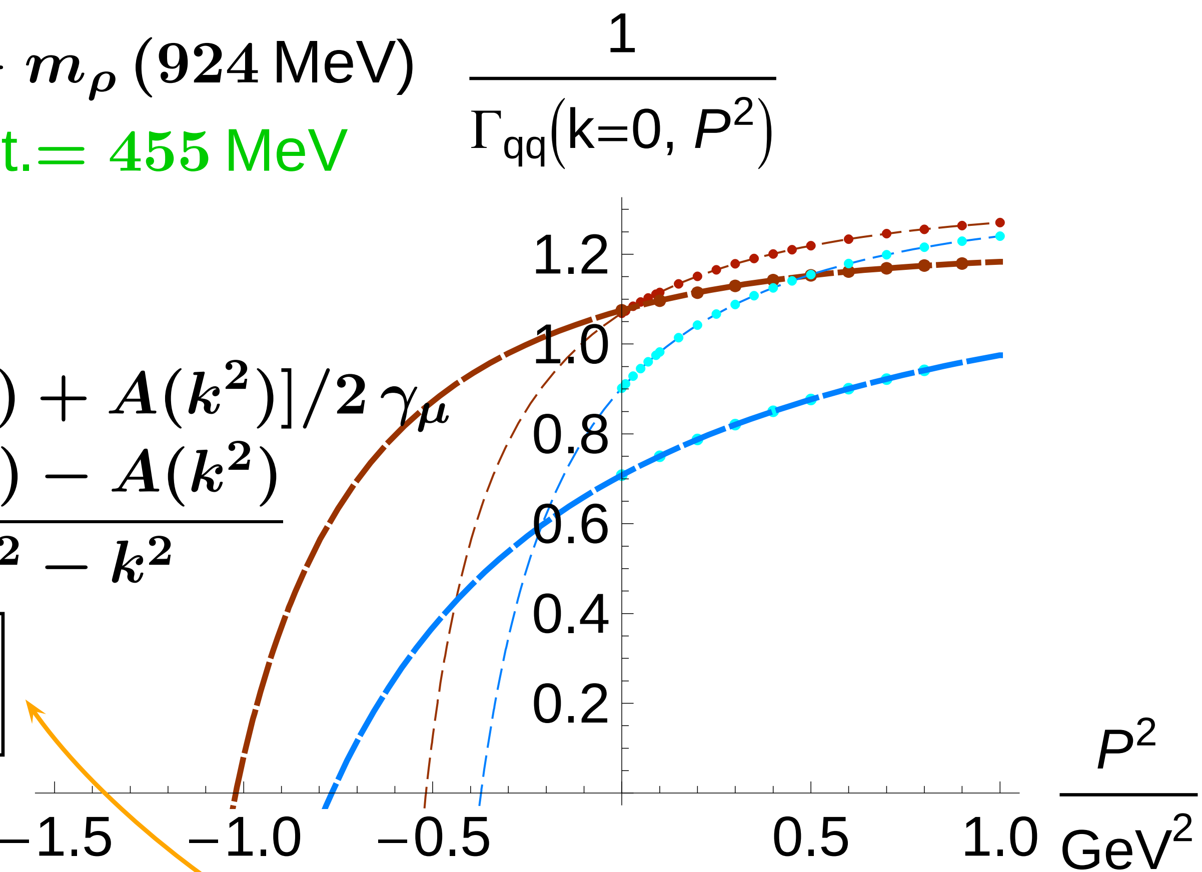
$\ldots\ [m_{a_1} - m_\rho]$ II $\ldots$

m_{a_1} (759 MeV) $-$ m_ρ (644 MeV)
$= 115$ MeV ... expt.$= 455$ MeV

Rainbow-Ladder
$\Gamma_\mu(q,k) = \gamma_\mu$



m_{a_1} (1066 MeV) $-\ m_\rho$ (924 MeV)
$=$ 142 MeV . . . expt.$=$ 455 MeV

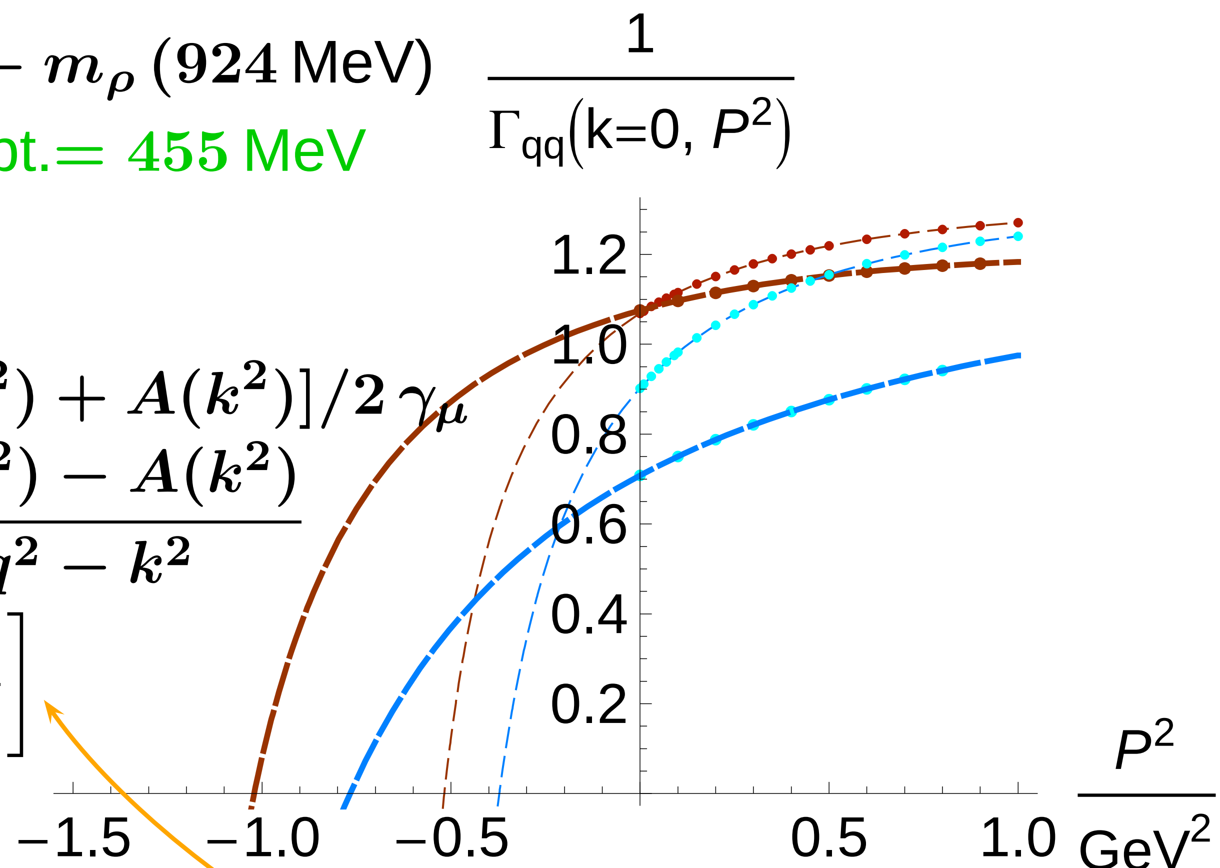


Ball-Chiu

$$\Gamma_\mu(q,k) = i[A(q^2)+A(k^2)]/2\,\gamma_\mu$$
$$+2k_\mu\left[i\gamma\cdot k\,\frac{A(q^2)-A(k^2)}{q^2-k^2}\right.$$
$$\left.+\frac{B(q^2)-B(k^2)}{q^2-k^2}\right]$$

DCSB enhanced spin-orbit interaction

m_{a_1} (1066 MeV) $- m_\rho$ (924 MeV)
$= 142$ MeV ... expt.$= 455$ MeV



Ball-Chiu

$$\Gamma_\mu(q,k) = i[A(q^2) + A(k^2)]/2\,\gamma_\mu$$
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DCSB enhanced spin-orbit interaction

What's missing?

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Missing Link

$$[m_{a_1} - m_\rho]$$

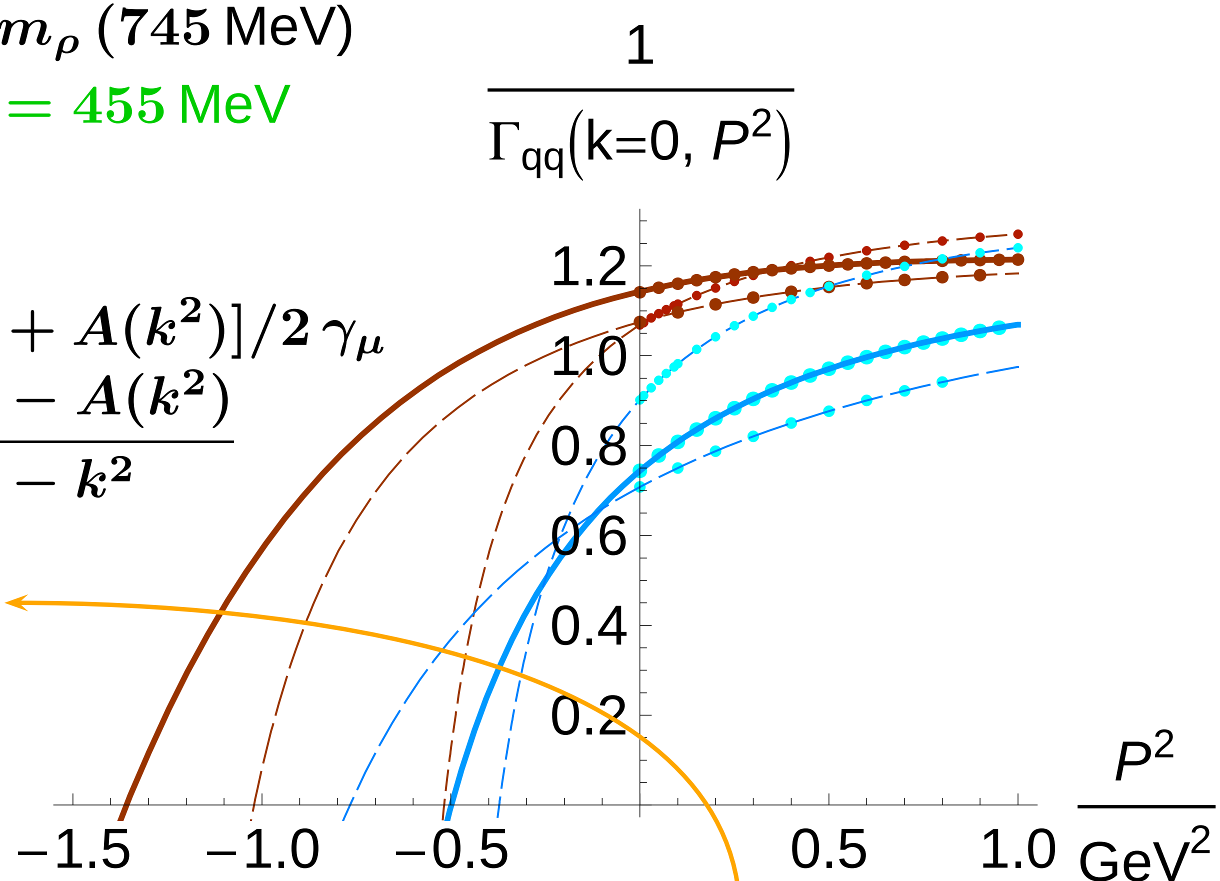
Chang Lei & CDR, in-preparation

Missing Link

$[m_{a_1} - m_\rho]$

Chang Lei & CDR, in-preparation

m_{a_1} (1230 MeV) $-$ m_ρ (745 MeV)
$= 485$ MeV ... expt.$= 455$ MeV



Ball-Chiu

$$\Gamma_\mu(q,k) = i[A(q^2) + A(k^2)]/2\,\gamma_\mu$$
$$+2k_\mu \left[i\gamma\cdot k\,\frac{A(q^2)-A(k^2)}{q^2-k^2} + \frac{B(q^2)-B(k^2)}{q^2-k^2} \right]$$

DCSB enhanced spin-orbit interaction

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Missing Link

$[m_{a_1} - m_\rho]$

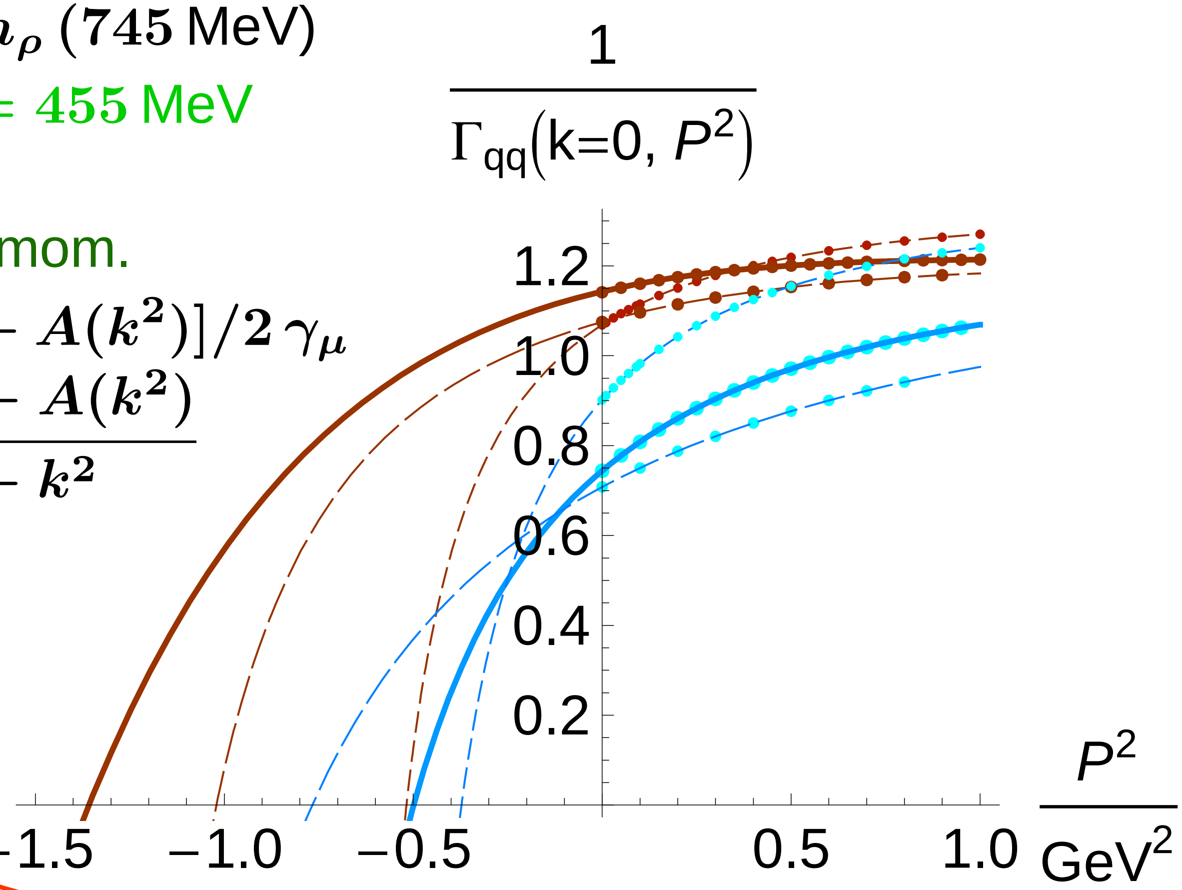
Chang Lei & CDR, in-preparation

m_{a_1} (1230 MeV) $- m_\rho$ (745 MeV)

$=$ 485 MeV ... expt.$=$ 455 MeV

Ball-Chiu + an. mag. mom.

$$\Gamma_\mu(q,k) = i[A(q^2)+A(k^2)]/2\,\gamma_\mu$$
$$+2k_\mu\left[i\gamma\cdot k\,\frac{A(q^2)-A(k^2)}{q^2-k^2} + \frac{B(q^2)-B(k^2)}{q^2-k^2}\right]$$
$$+\sigma_{\mu\nu}(q-k)_\nu\,\frac{B(q^2)-B(k^2)}{q^2-k^2}$$



DCSB enhanced anomalous chromomagnetic moment

Missing Link

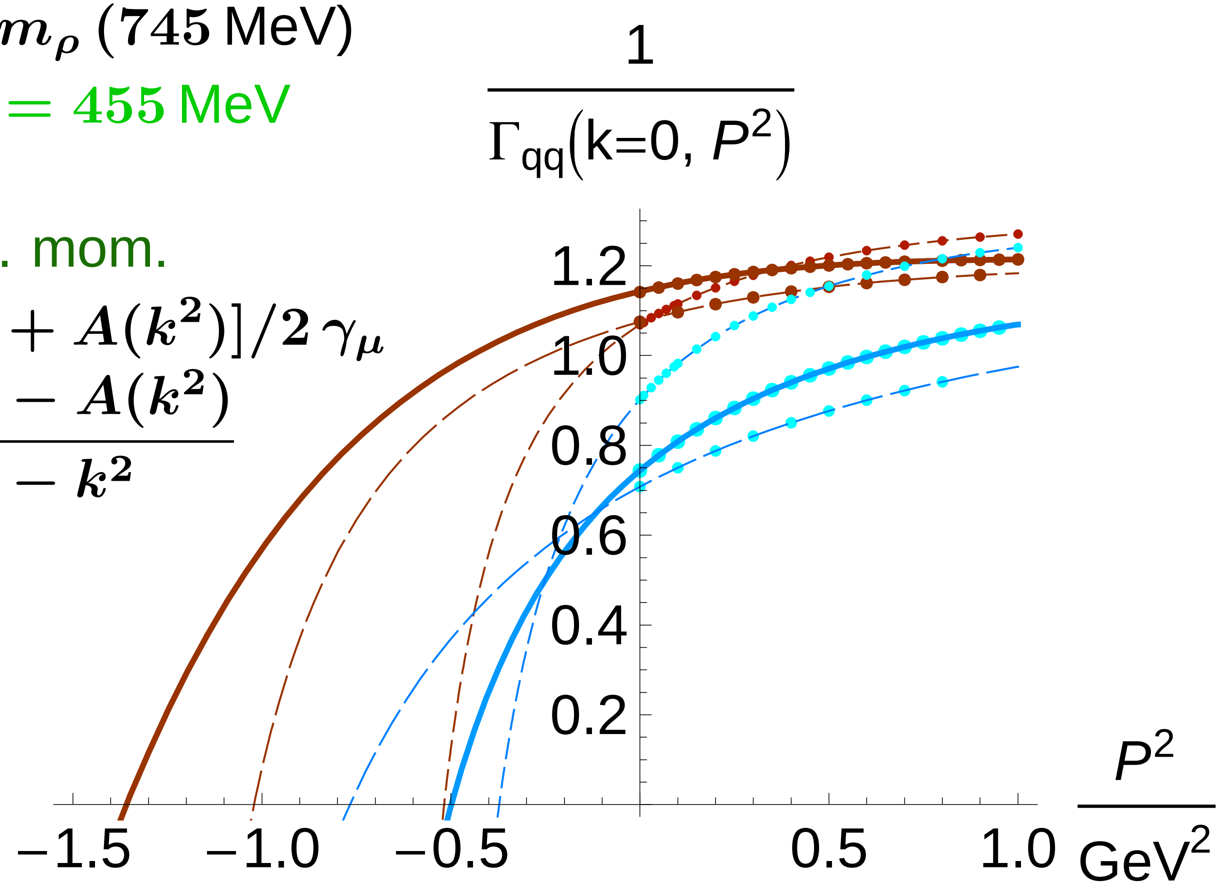
$$[m_{a_1} - m_\rho]$$

Chang Lei & CDR, in-preparation

m_{a_1} (1230 MeV) $- \, m_\rho$ (745 MeV)
$=$ 485 MeV . . . expt.$=$ 455 MeV

Ball-Chiu $+$ an. mag. mom.

$$\Gamma_\mu(q,k) = i[A(q^2)+A(k^2)]/2\,\gamma_\mu$$
$$+2k_\mu\left[i\gamma\cdot k\,\frac{A(q^2)-A(k^2)}{q^2-k^2}\right.$$
$$\left.+\frac{B(q^2)-B(k^2)}{q^2-k^2}\right]$$
$$+\sigma_{\mu\nu}(q-k)_\nu\,\frac{B(q^2)-B(k^2)}{q^2-k^2}$$



Inextricably connected
with DCSB.

DCSB enhanced anomalous chromomagnetic moment

Can't appear in chirally symmetric theory

Paves way for truly reliable light-quark meson spectrum

Ratio – Kaon/Pion
u-valence distribution

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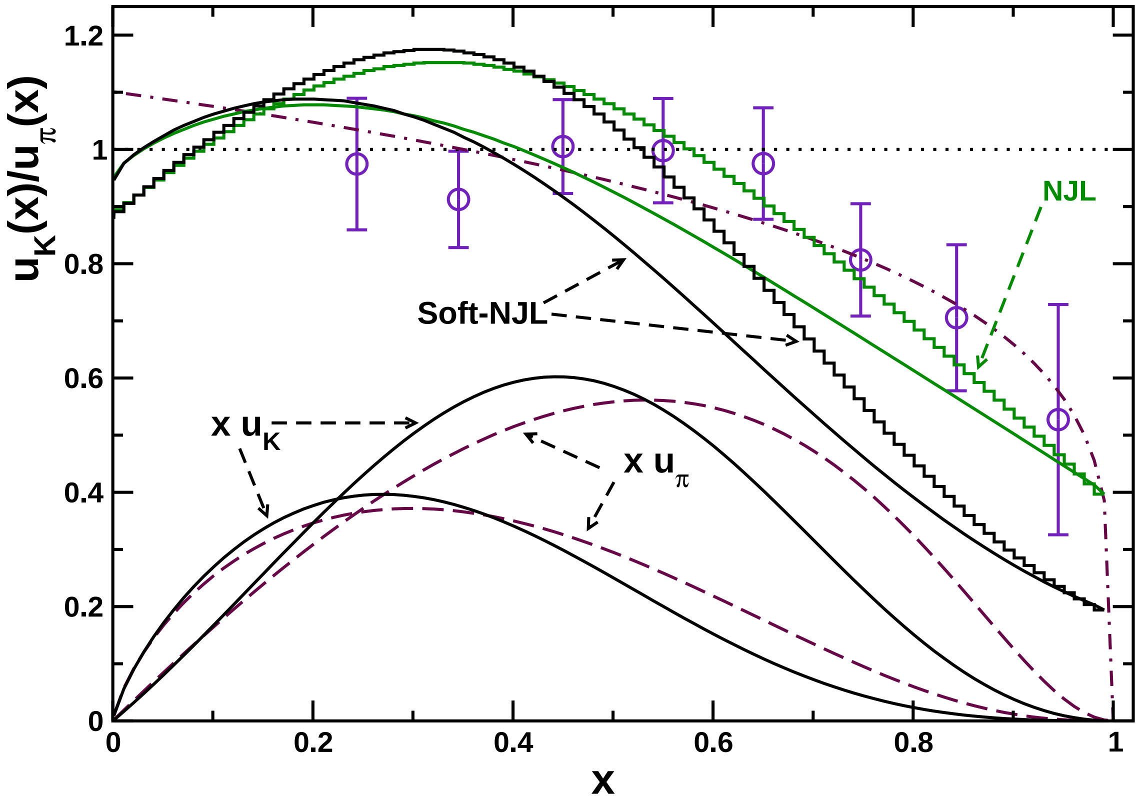

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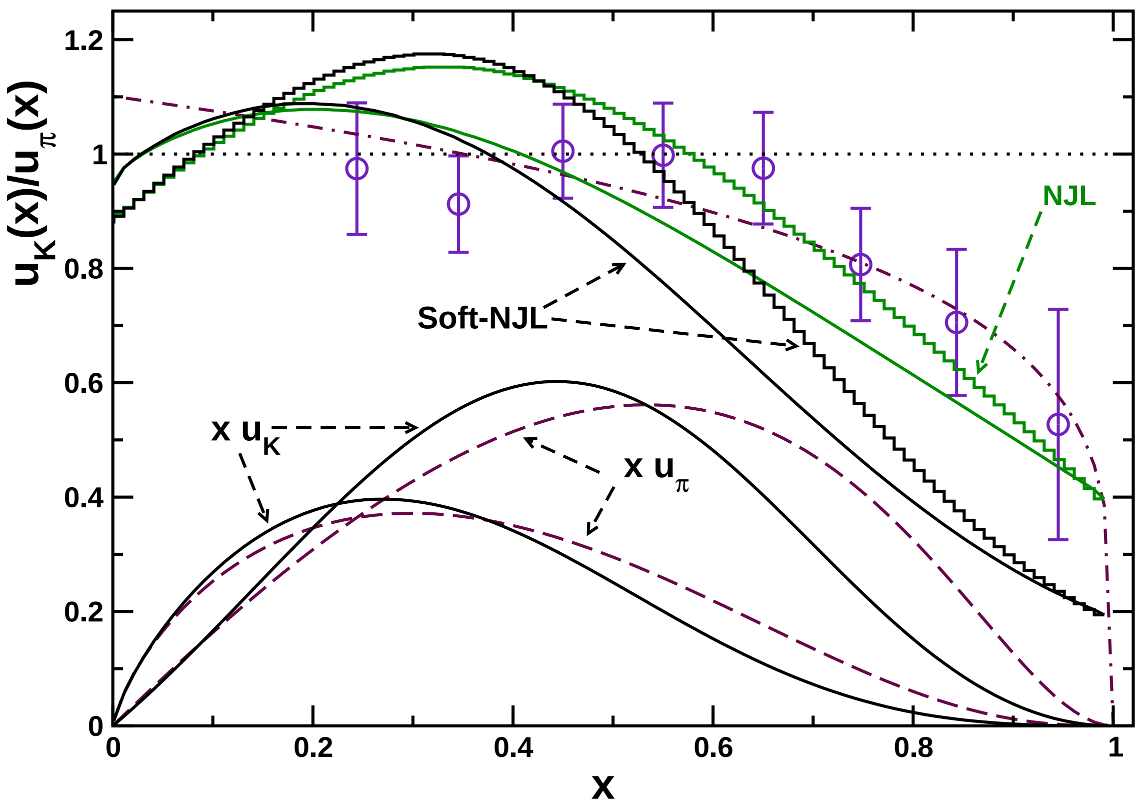
Ratio – Kaon/Pion u-valence distribution

- Hard-cutoff NJL model (constant mass) cf. QCD-DSE-based result $[M(p^2)$ plus $\Gamma_\pi(p;P)]$
- Influence of Mass-function felt strongly for $x > 0.5$
- Accessible at Upgraded JLab & Electron-Ion Collider




ARE WE THERE YET?

Unifying Study of Mesons and Baryons

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- How does one incorporate dressed-quark mass function, $M(p^2)$, in study of baryons? Behaviour of $M(p^2)$ is essentially a quantum field theoretical effect.

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  - Residue is proportional to nucleon's Faddeev amplitude
  - Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks

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  - Residue is proportional to nucleon's Faddeev amplitude
  - Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks
  - Tractable equation is founded on observation that an interaction which describes colour-singlet mesons also generates quark-quark (diquark) correlations in the colour-$\bar{3}$ (antitriplet) channel

Faddeev equation

R. T. Cahill *et al*. Austral. J. Phys. **42** (1989) 129

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Faddeev equation

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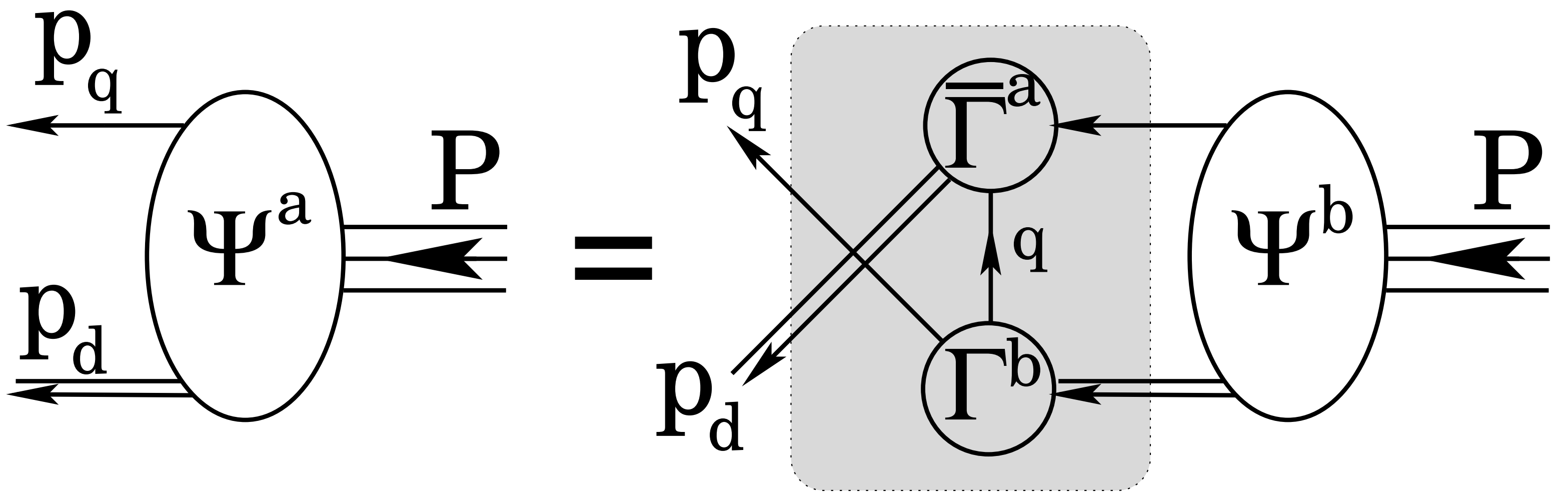

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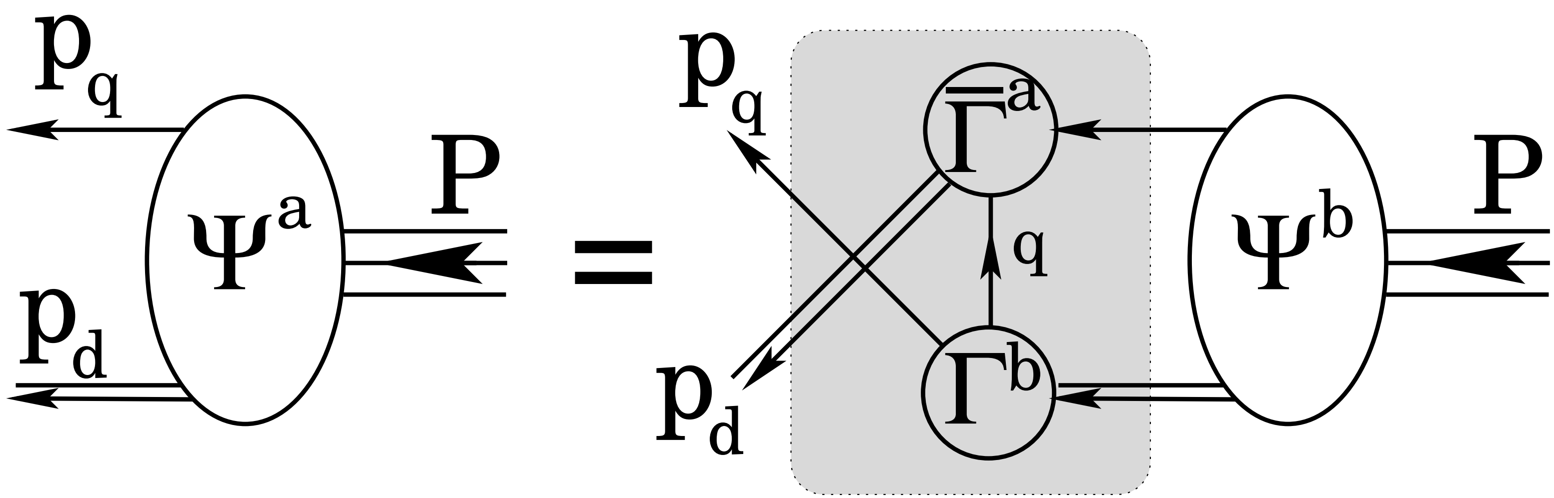

- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

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Nucleon-Photon Vertex

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

Nucleon-Photon Vertex

6 terms . . .

constructed systematically . . . current conserved automatically
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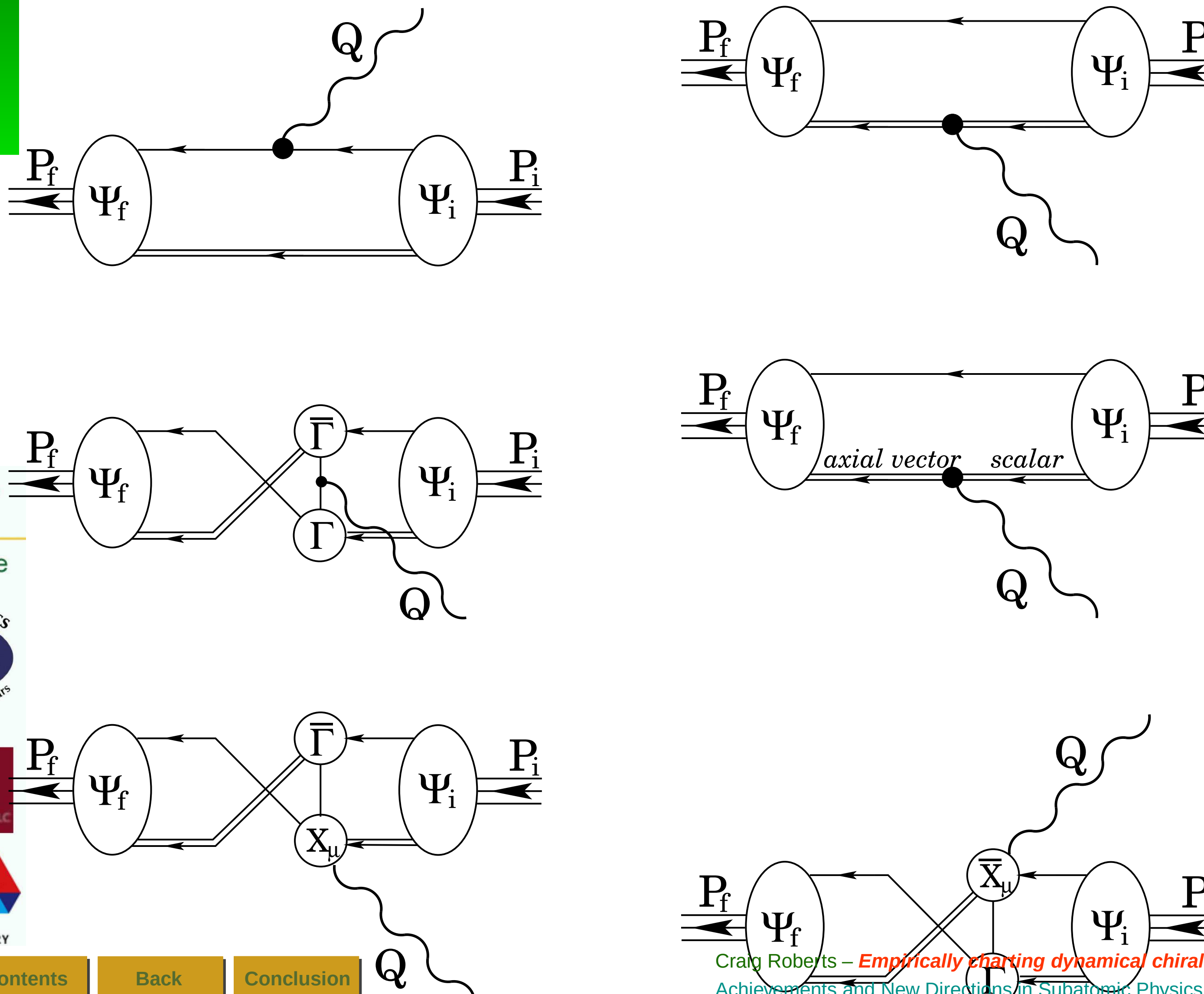

$$\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}$$

Cloët, Roberts *et al.*

– arXiv:0710.2059 [nucl-th]

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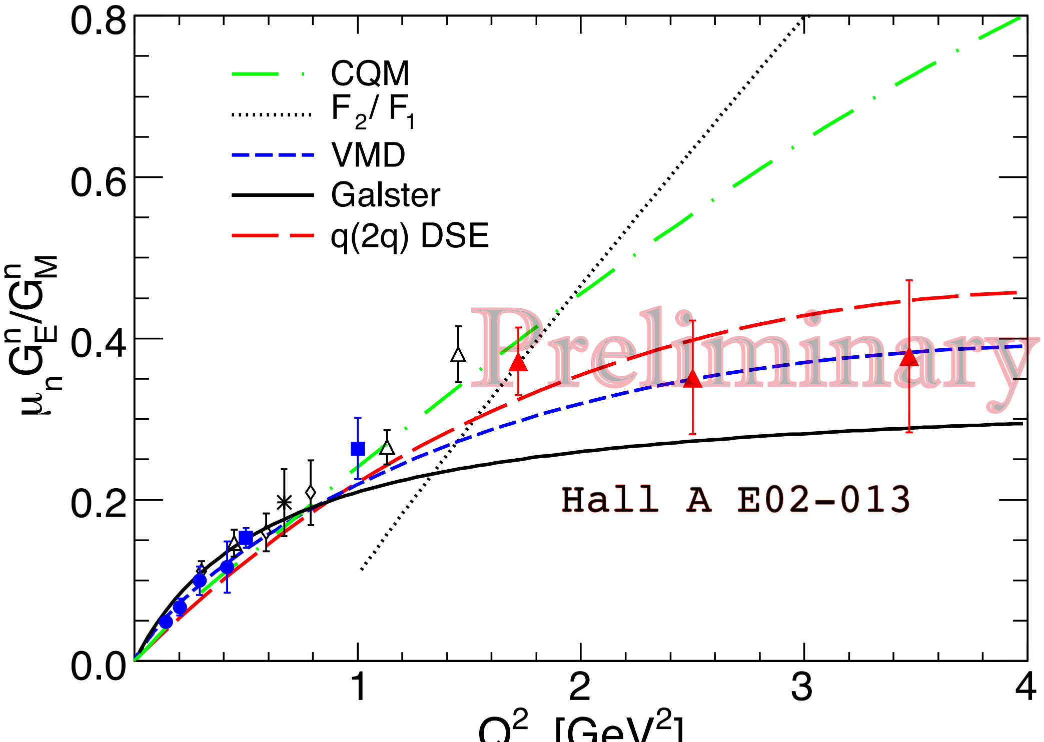

Jefferson Lab E02-013 Collaboration, *in preparation*.

Bogdan Wojtsekhowski

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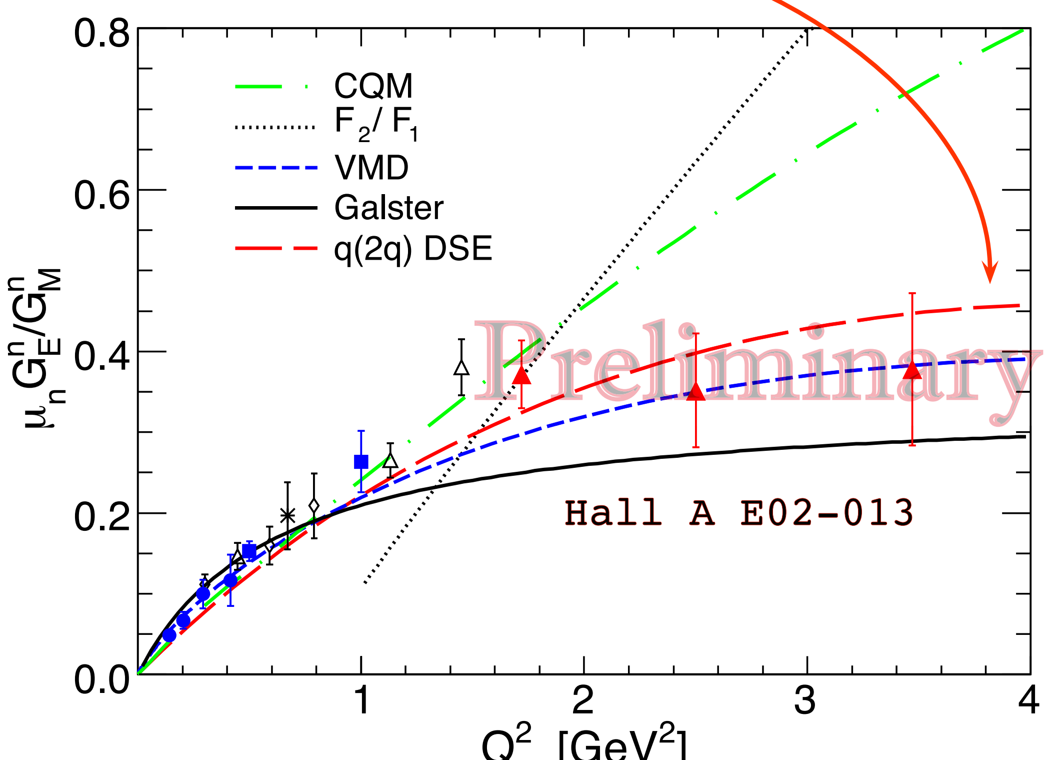

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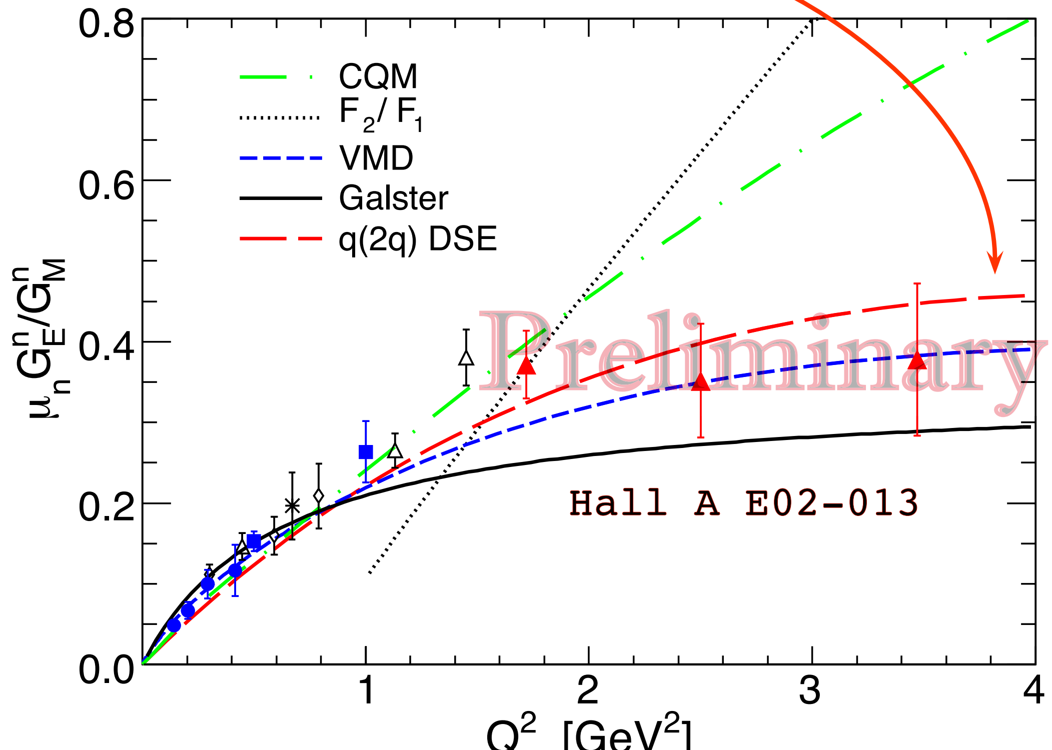

This evolution very sensitive to momentum -dependence dressed-quark propagator

Jefferson Lab E02-013 Collaboration, *in preparation*.
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Epilogue

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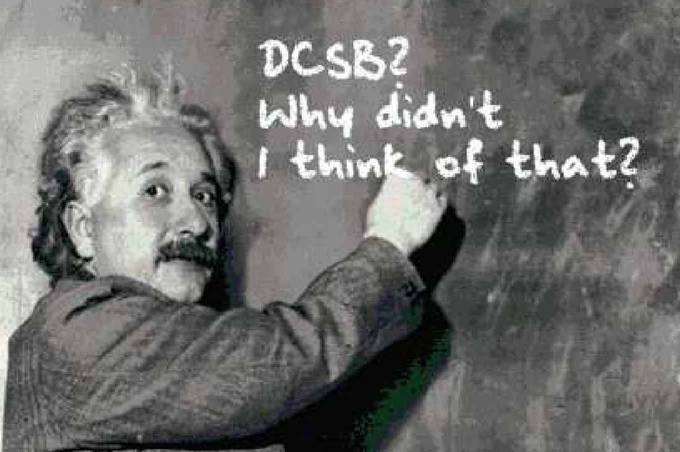

Epilogue

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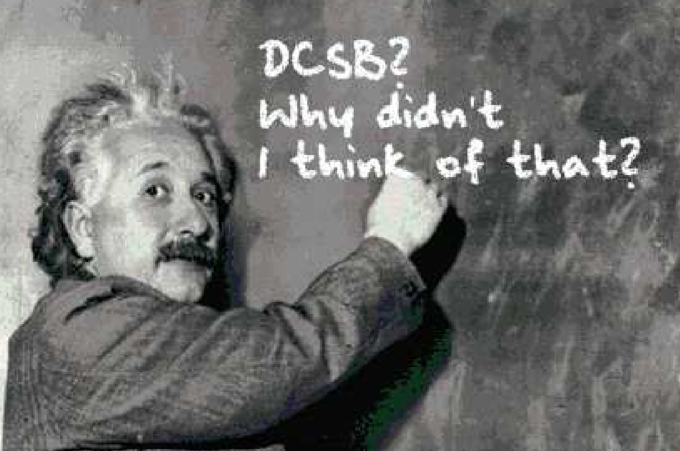

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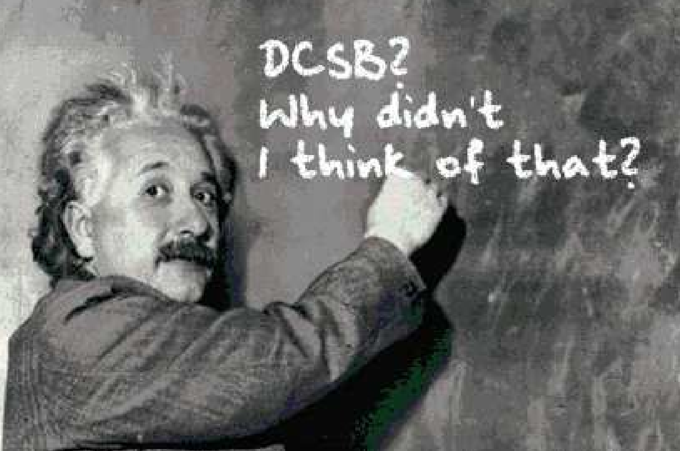
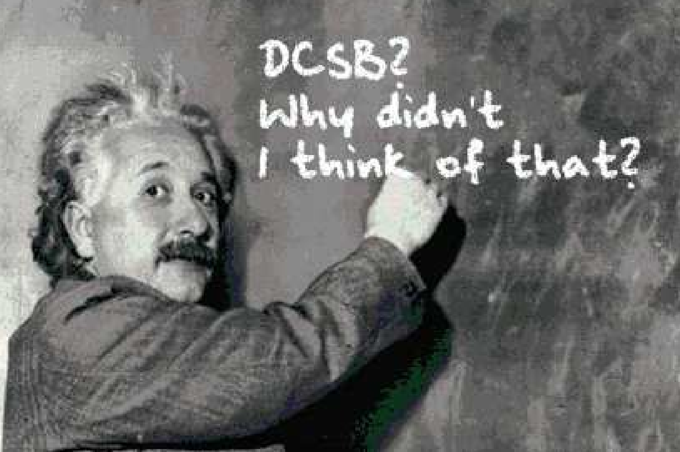


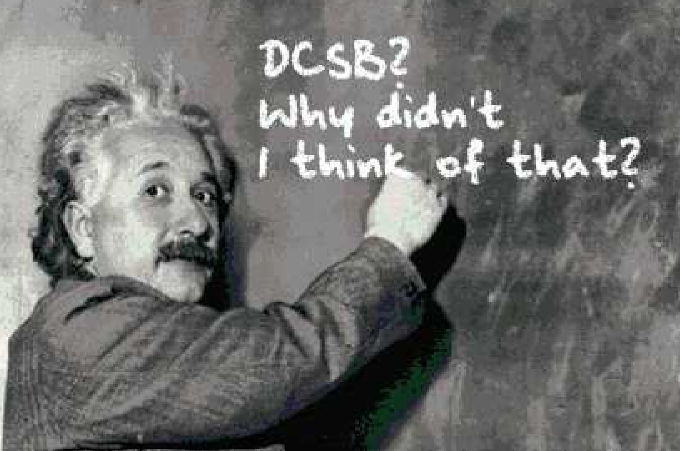
Epilogue

- DCSB exists in QCD.
  - It is manifest in dressed propagators and vertices
  - It predicts, amongst other things, that
    - light current-quarks become heavy constituent-quarks: 4 $\to$ 400 MeV
    - pseudoscalar mesons are unnaturally light: $m_\rho = 770$ cf. $m_\pi = 140$ MeV
    - pseudoscalar mesons couple unnaturally strongly to light-quarks: $g_{\pi\bar{q}q} \approx 4.3$
    - pseudscalar mesons couple unnaturally strongly to the lightest baryons $g_{\pi\bar{N}N} \approx 12.8 \approx 3 g_{\pi\bar{q}q}$



Epilogue

- DCSB impacts dramatically upon observables



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  - Spectrum; e.g., splittings: σ–π & a_1–ρ
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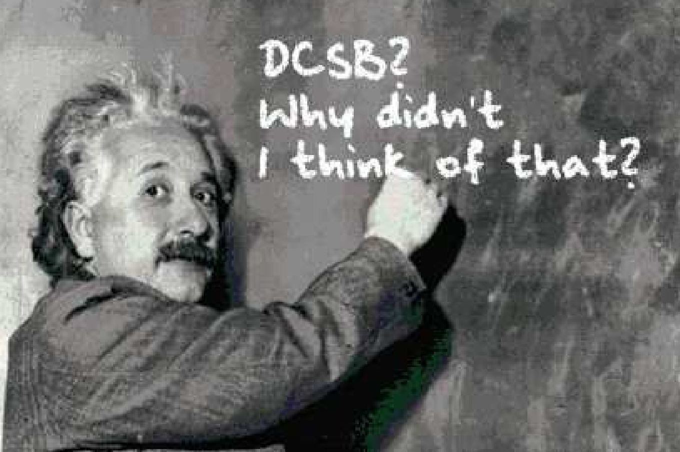

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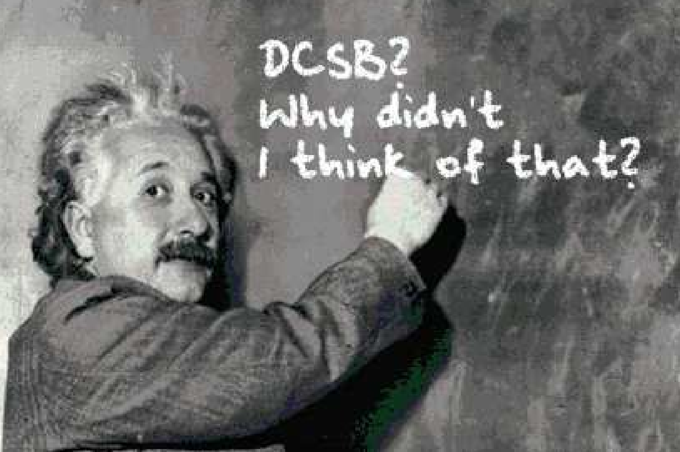

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  - Studies underway will identify observable signals of $M(p^2)$, the most important mass-generating mechanism for visible matter in the Universe

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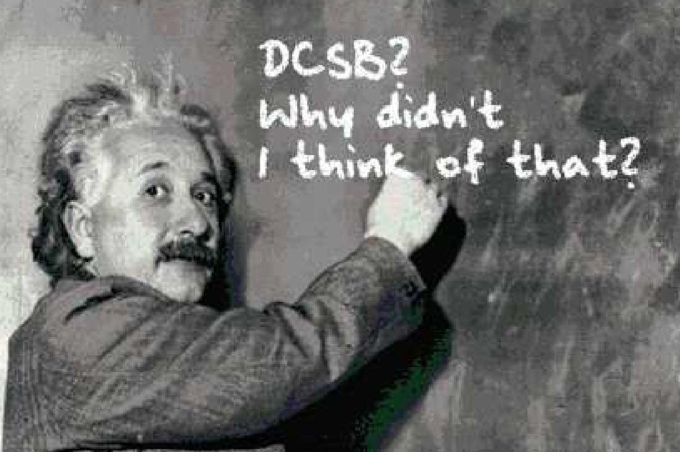

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  - Studies underway will identify observable signals of $M(p^2)$, the most important mass-generating mechanism for visible matter in the Universe
- DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks

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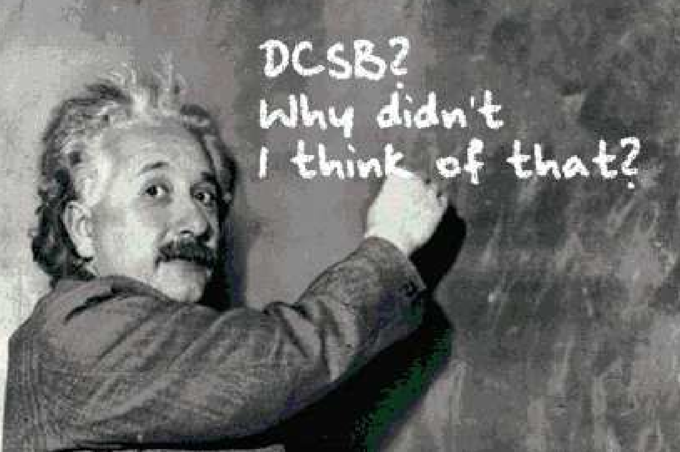
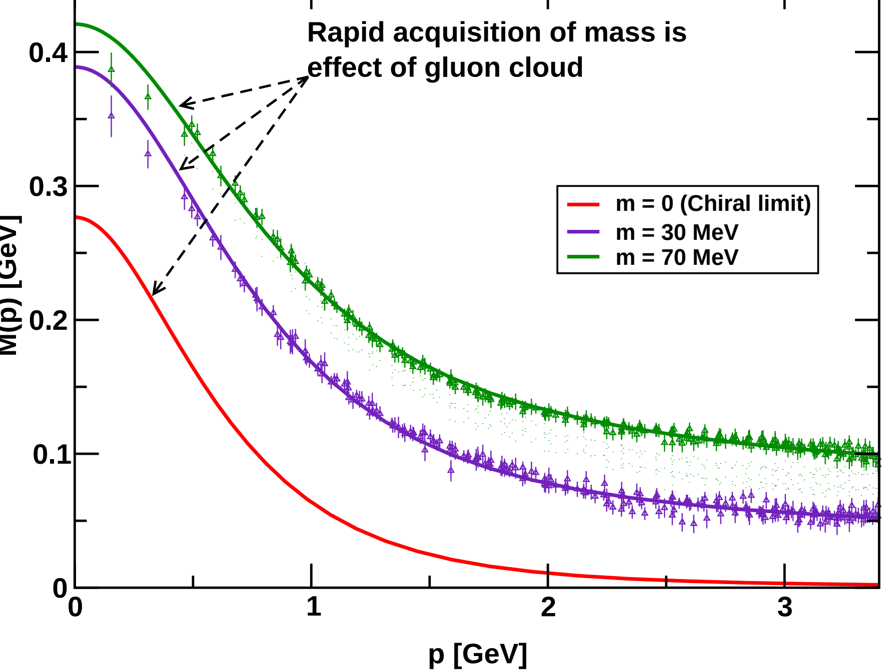


Epilogue

Now is an exciting time . . .

Positioned to unify phenomena as apparently disparate as

- Hadron spectrum
- Elastic and transition form factors, from small- to large-Q^2
- Parton distribution functions



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Key: an understanding of both the fundamental origin of nuclear mass and the far-reaching consequences of the mechanism responsible; namely, Dynamical Chiral Symmetry Breaking

Just the Basic Facts

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- Tony graduated from Flinders University in 1974.

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Just the Basic Facts

- Tony graduated from Flinders University in 1974. Whereafter he immediately left for British Columbia, in search of adventure.

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Just the Basic Facts

- And adventures he had . . .

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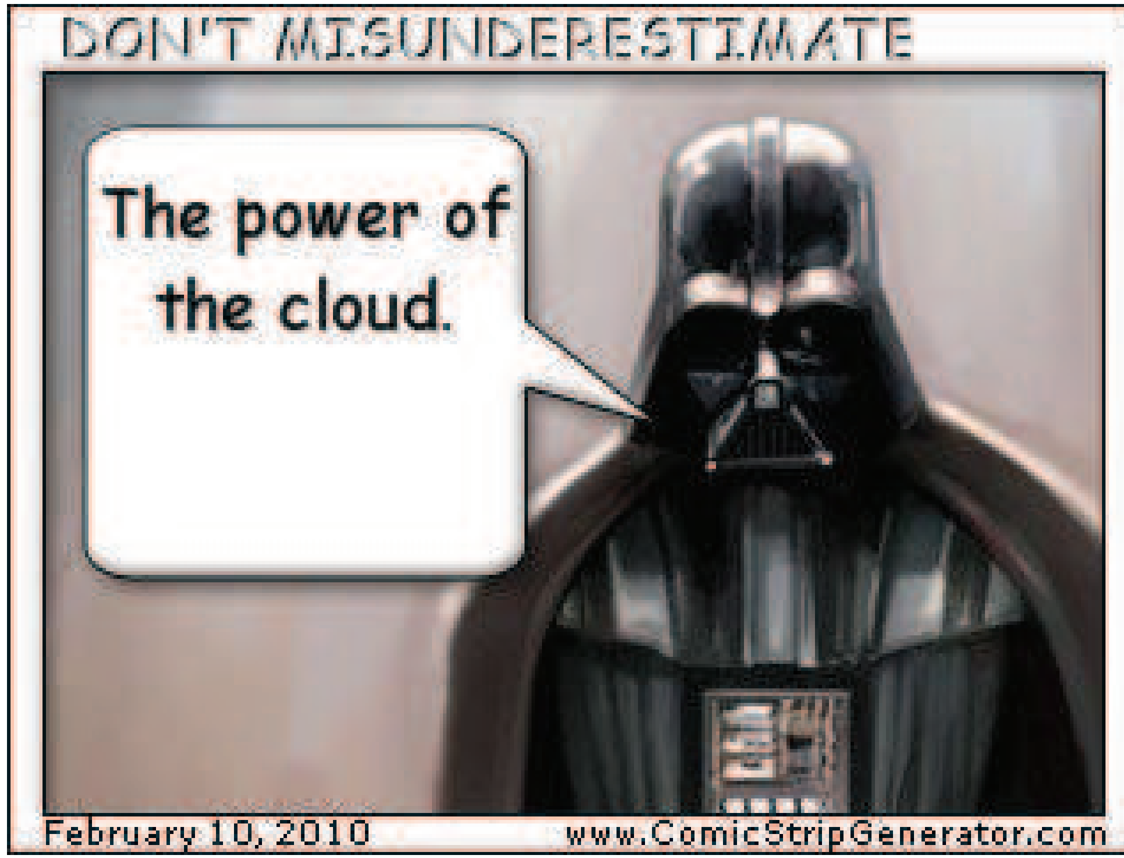

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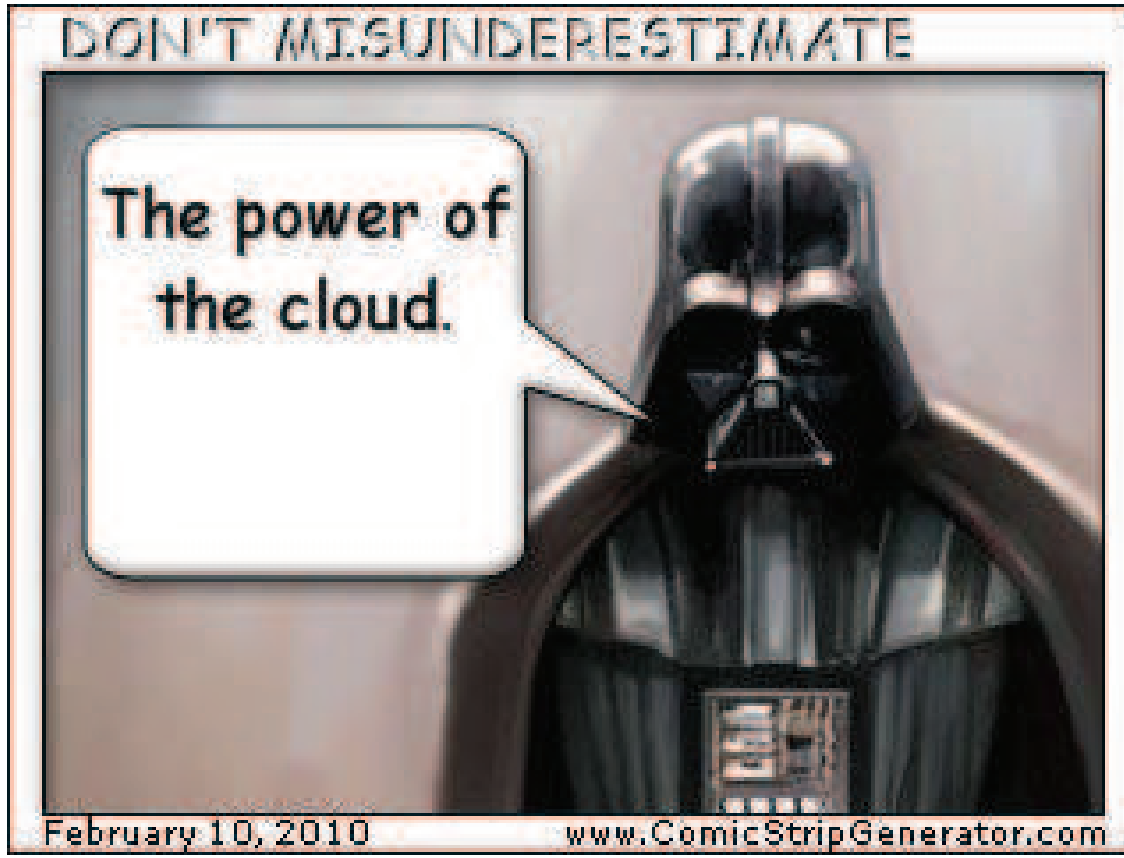

- In time, even I learnt to use it.

Just the Basic Facts

- But now Tony has returned to Australia
  and to the University of Adelaide.

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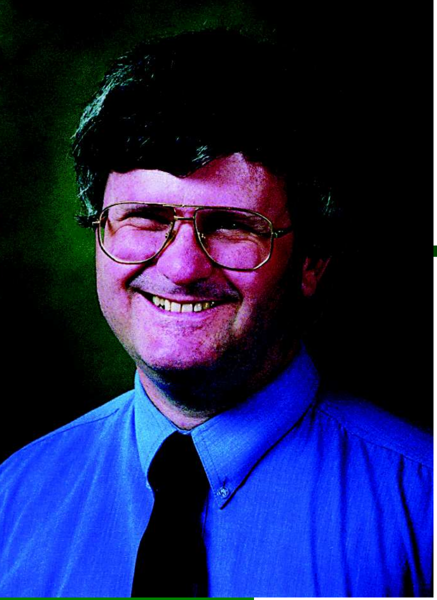
  - "*Eating, loving, singing and digesting are, in truth, the four acts of the comic opera known as life, and they pass like bubbles of a bottle of champagne. Whoever lets them break without having enjoyed them is a complete fool.*" Gioacchino Rossini



Just the Basic Facts

Tony:

Thankyou.

And a Belated Happy Birthday.

Contents

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Dichotomy of Pion
– *Goldstone Mode* and *Bound state*

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Must exhibit $m_\pi^2 \propto m_q$

Current Algebra . . . 1968

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The correct understanding of pion observables;
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Highly Nontrivial

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QCD’s Challenges

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- Quark and Gluon Confinement
  - No matter how hard one strikes the proton, one cannot liberate an individual quark or gluon

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QCD’s Challenges

Understand Emergent Phenomena

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- QCD – Complex behaviour

  arises from apparently simple rules

Confinement

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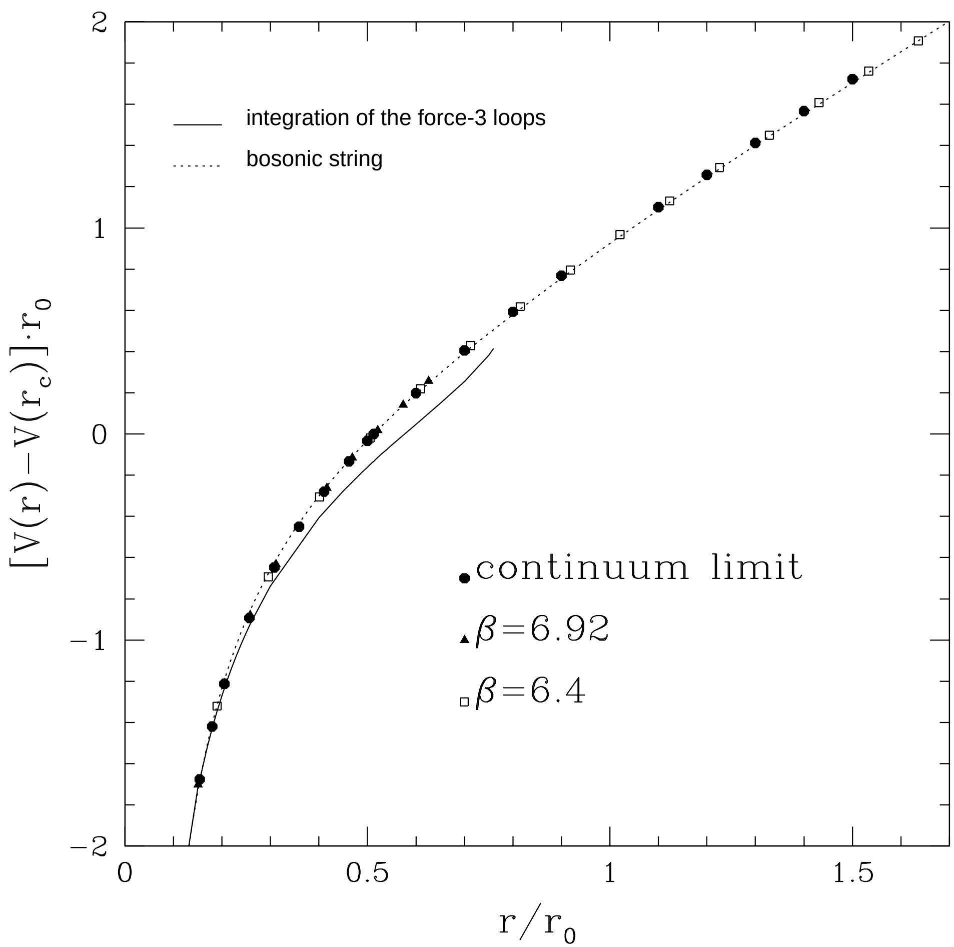
Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



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

$\sqrt{\sigma} \sim 470$ MeV

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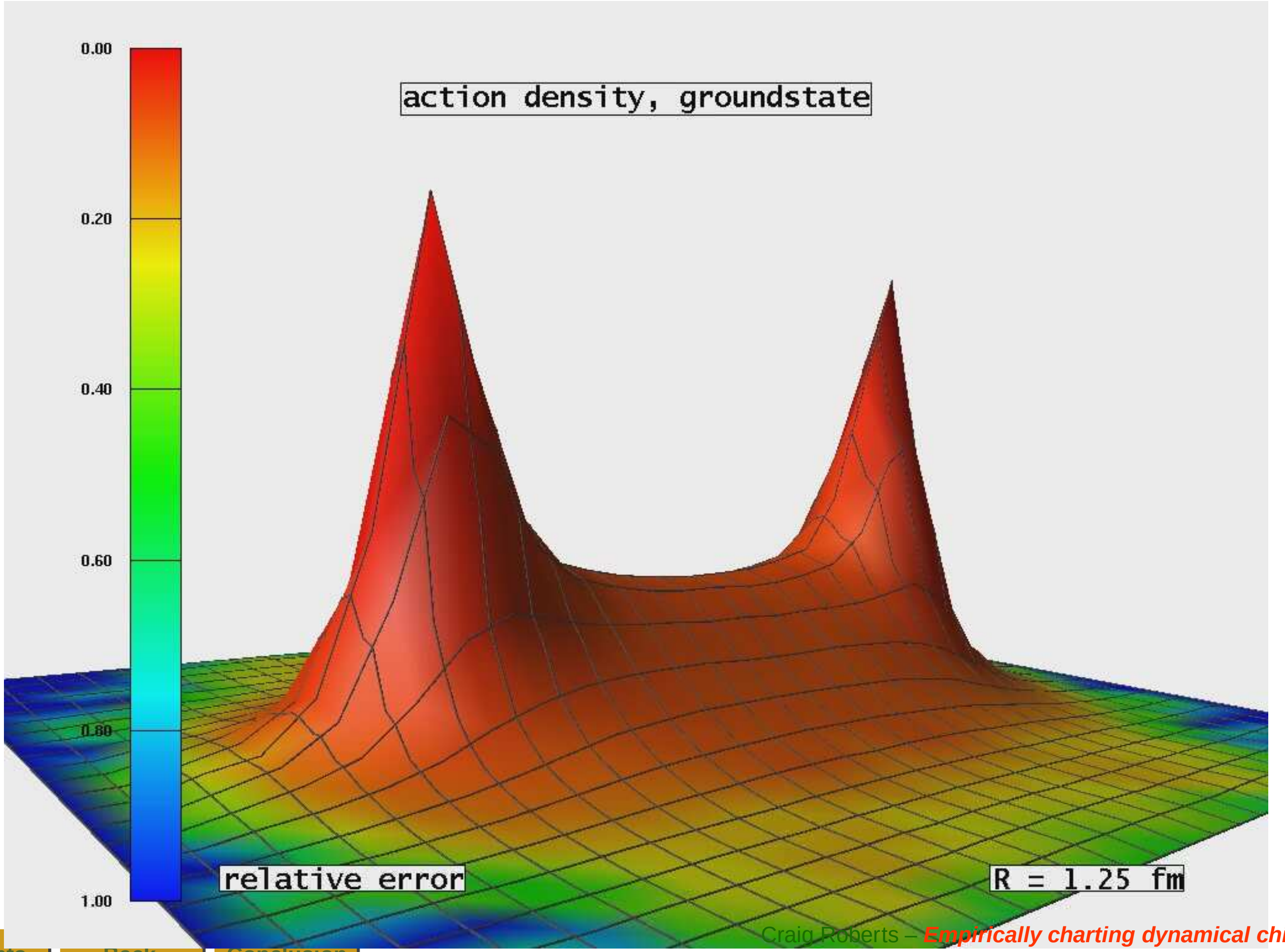
he-la/0108008

Confinement

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



Confinement

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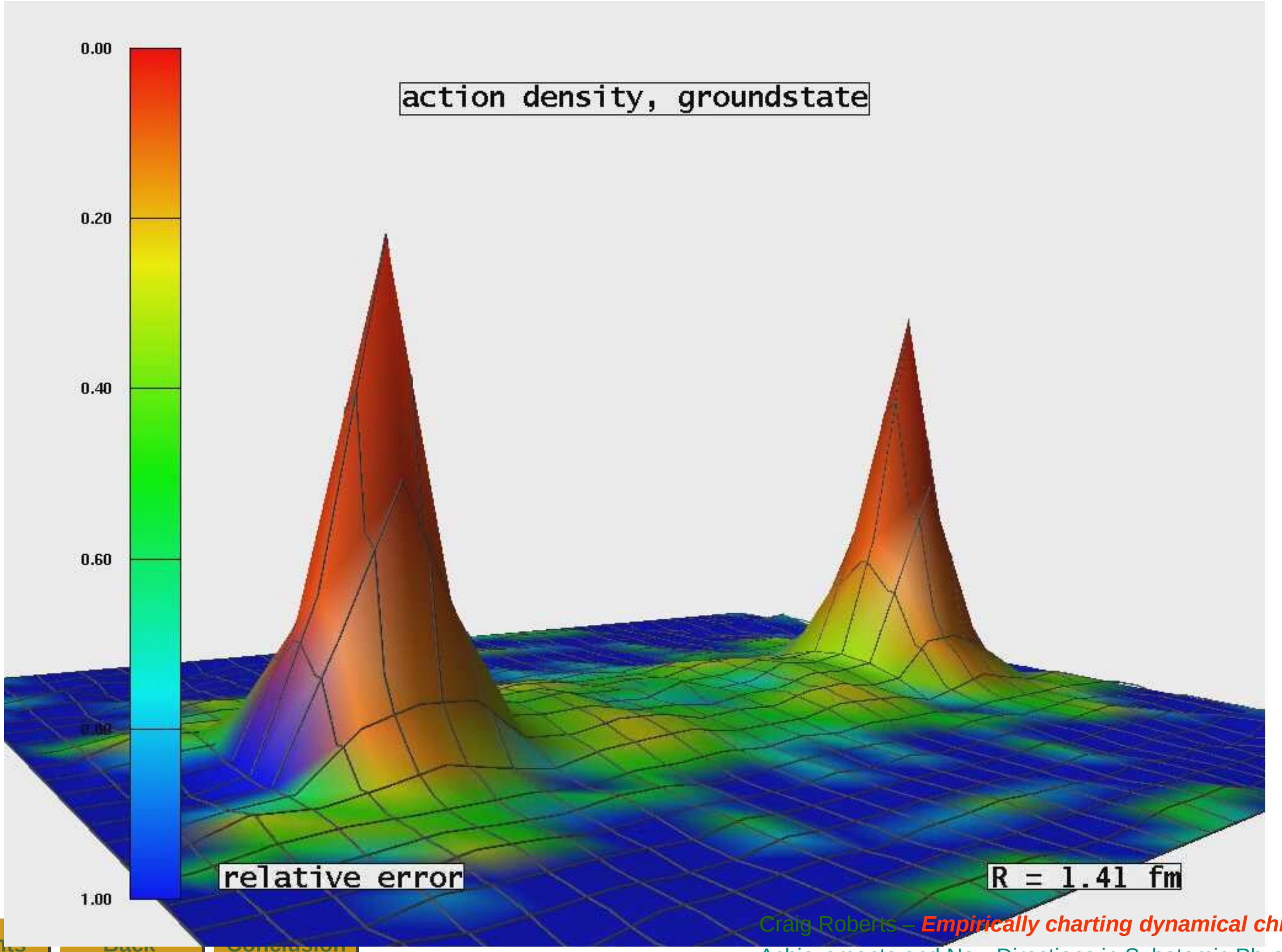

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he-la/0512018

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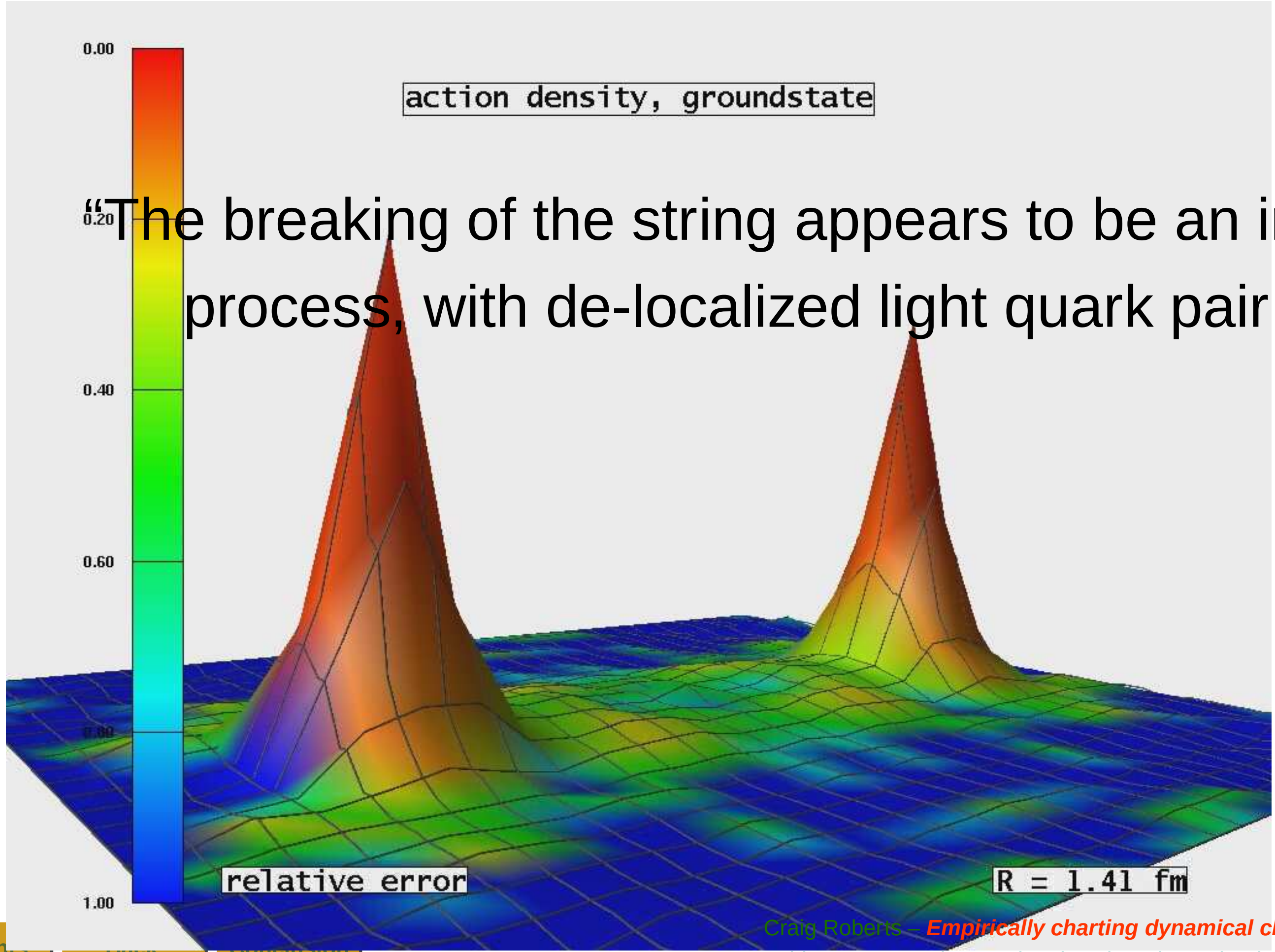

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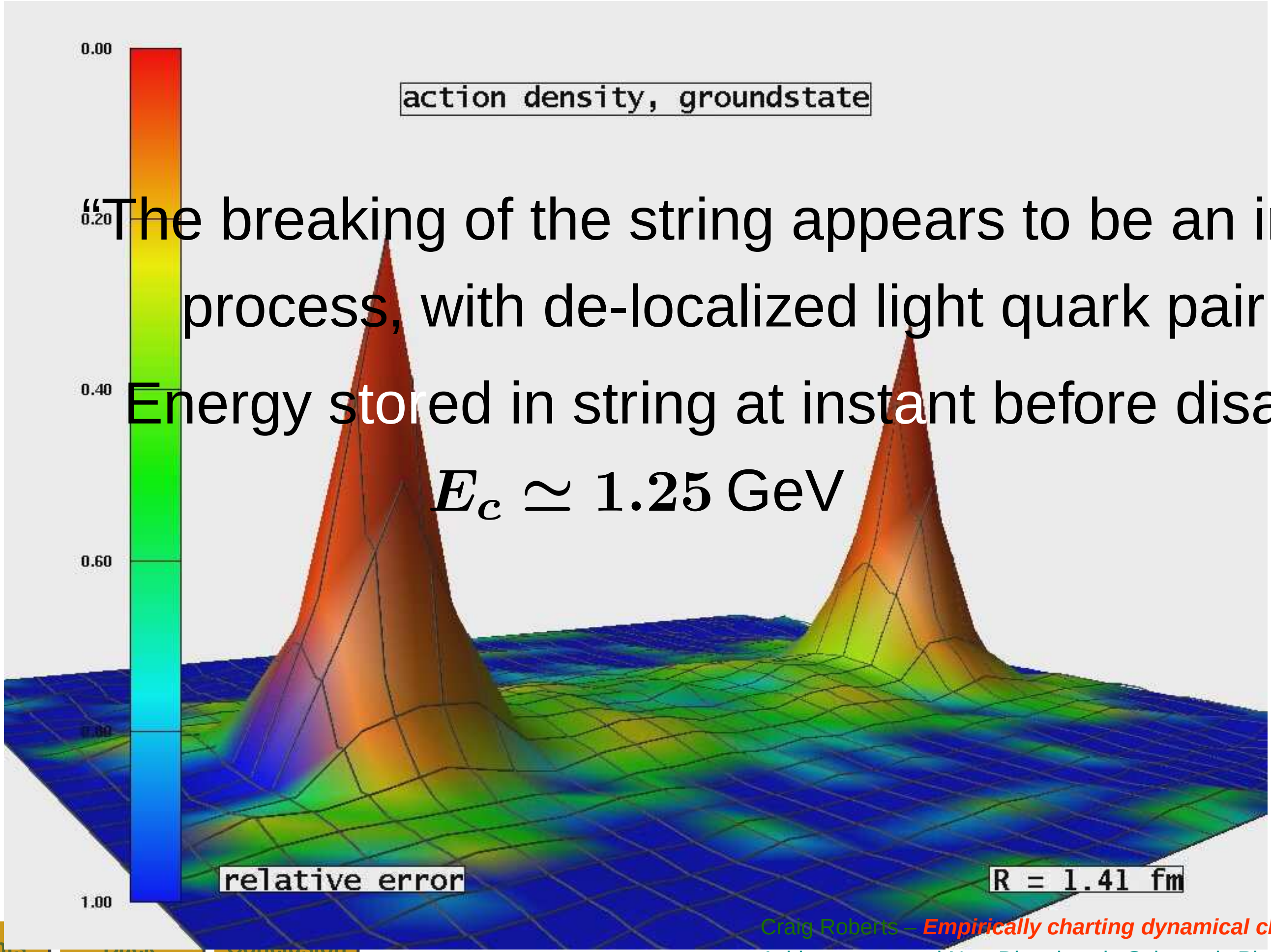

"The breaking of the string appears to be an instantaneous process, with de-localized light quark pair creation."

Energy stored in string at instant before disappearance:

$$E_c \simeq 1.25\,\text{GeV}$$

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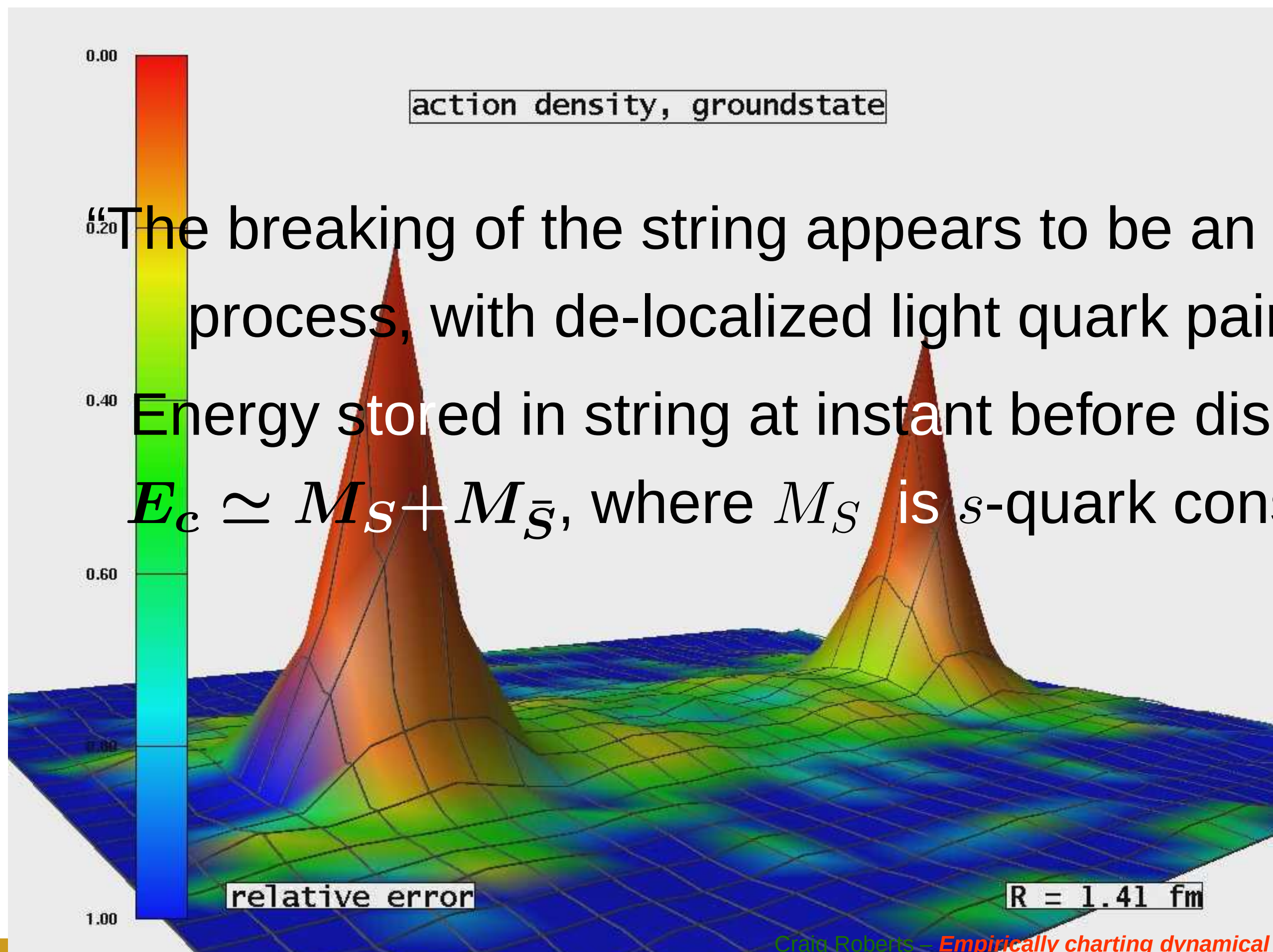

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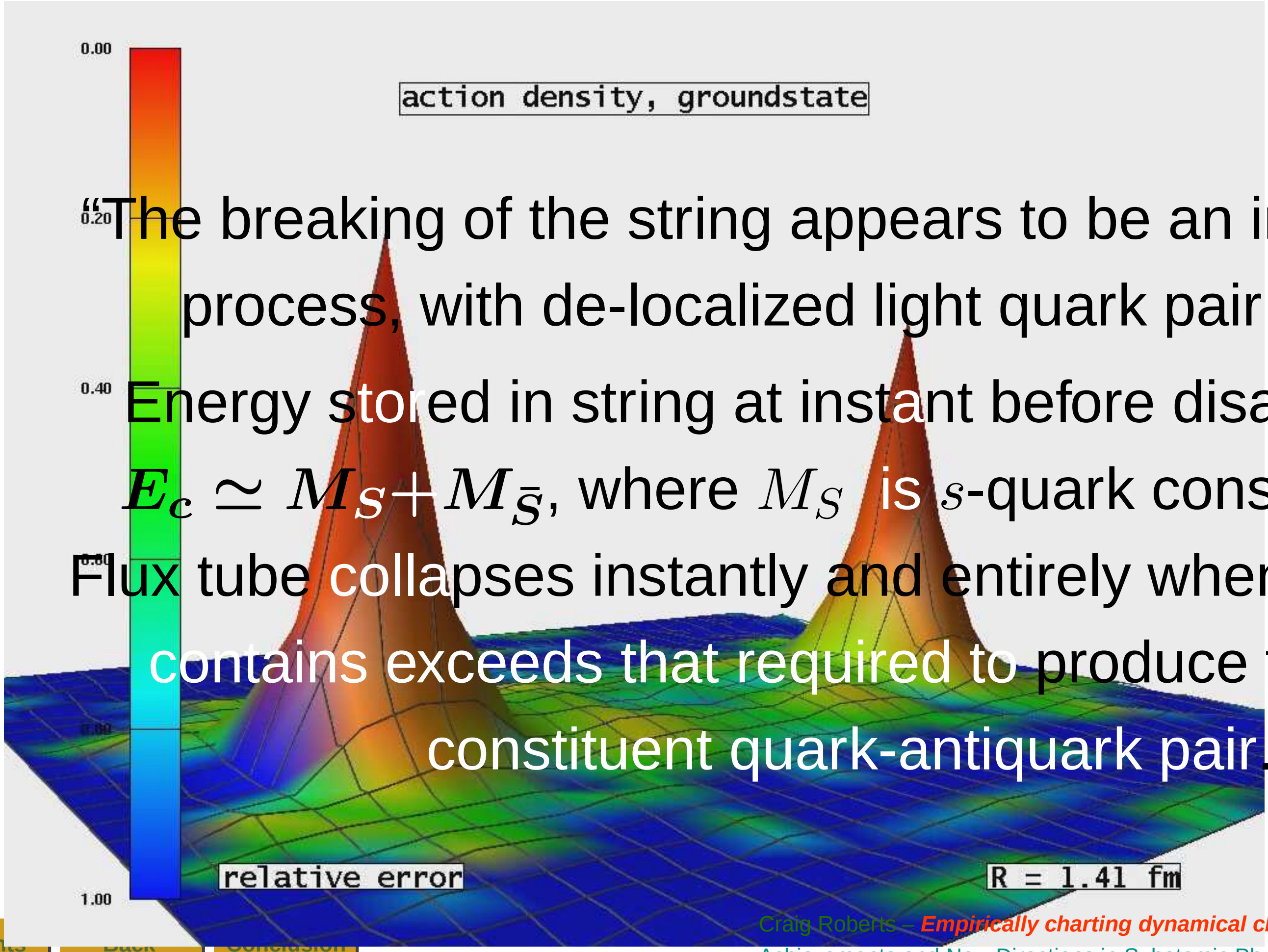

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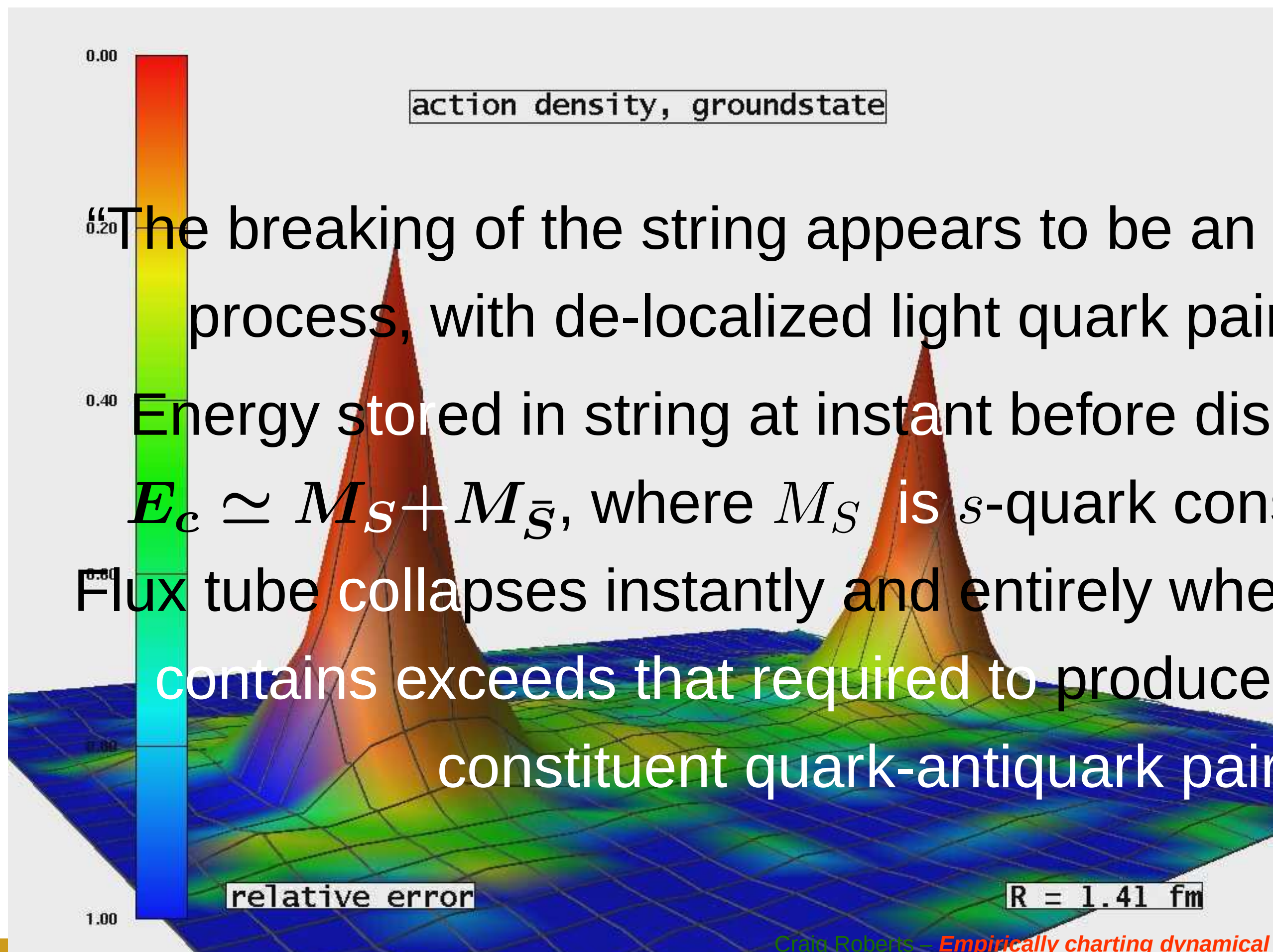
Flux tube collapses instantly and entirely when the energy it contains exceeds that required to produce the lightest constituent quark-antiquark pair.

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

- What happens in the real world; namely, in the presence of light-quarks? No one knows . . . but $\bar{Q}Q + 2 \times \bar{s}s$

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



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

Energy stored in string at instant before disappearance: $E_c \simeq M_S + M_{\bar{S}}$, where M_S is s-quark constituent-mass

Flux tube collapses instantly and entirely when the energy it contains exceeds that required to produce the lightest constituent quark-antiquark pair.


ALWAYS LOOK ON THE BRIGHT SIDE

- Established understanding of two- and three-point functions

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Hadrons

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

First Contents Back Conclusion

- Without bound states, Comparison with experiment is impossible

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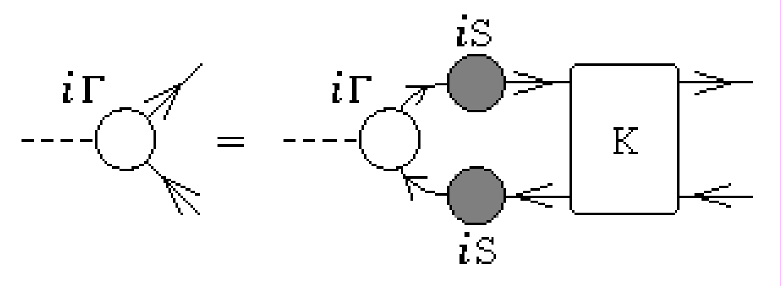
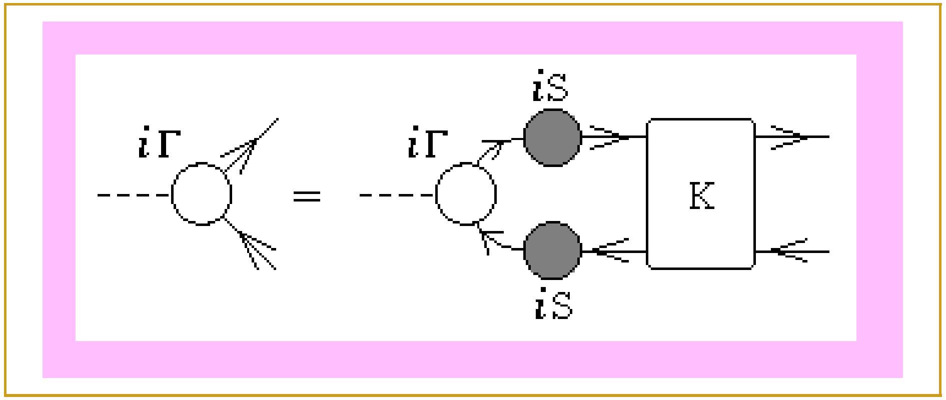
- They appear as pole contributions to $n \geq 3$-point colour-singlet Schwinger functions

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



QFT Generalisation of Lippmann-Schwinger Equation.

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



QFT Generalisation of Lippmann-Schwinger Equation.

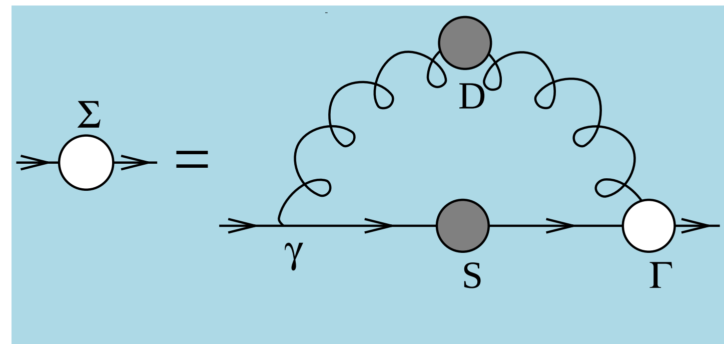
- What is the kernel, K?

  or What is the long-range potential in QCD?

Persistent Challenge

Persistent Challenge

- Infinitely Many Coupled Equations



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Persistent Challenge

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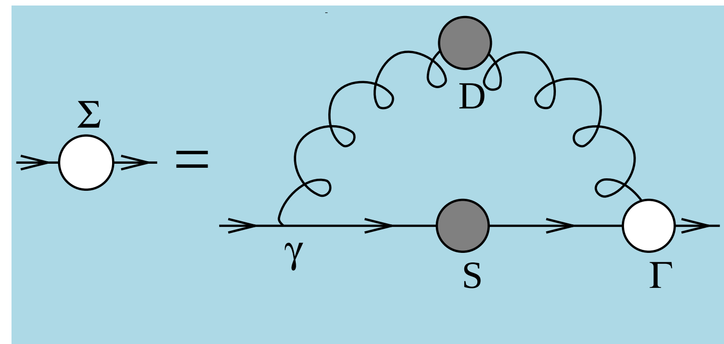

- Coupling between equations necessitates truncation

Persistent Challenge

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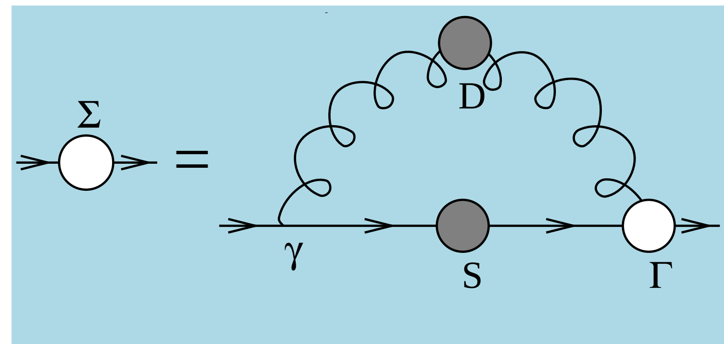

- Coupling between equations necessitates truncation
  - Weak coupling expansion ⇒ Perturbation Theory

Persistent Challenge

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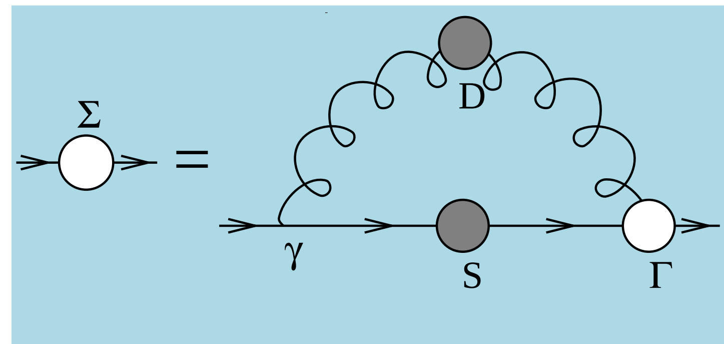

- Coupling between equations necessitates truncation
  - Weak coupling expansion $\Rightarrow$ Perturbation Theory
    Not useful for the nonperturbative problems
    in which we're interested

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Persistent Challenge

- Infinitely Many Coupled Equations
- 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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- Infinitely Many Coupled Equations
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- Has Enabled Proof of EXACT Results in QCD

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- And Formulation of Practical Phenomenological Tool to
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- Examples:

MIT – *The Net Advance of Physics*
Review Articles and Tutorials in an Encyclopædic Format
web.mit.edu/redingtn/www/netadv/Xdysonschw.html

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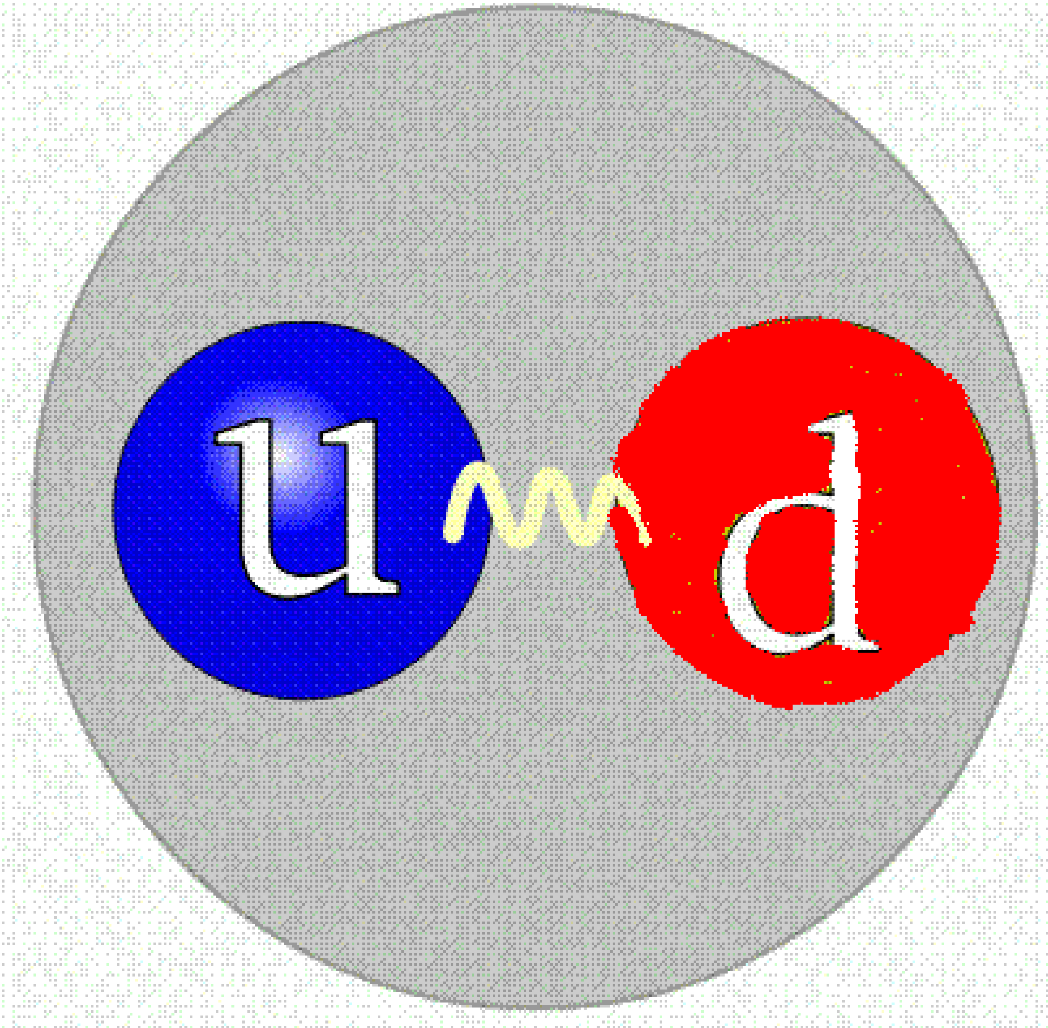
Diquark correlations



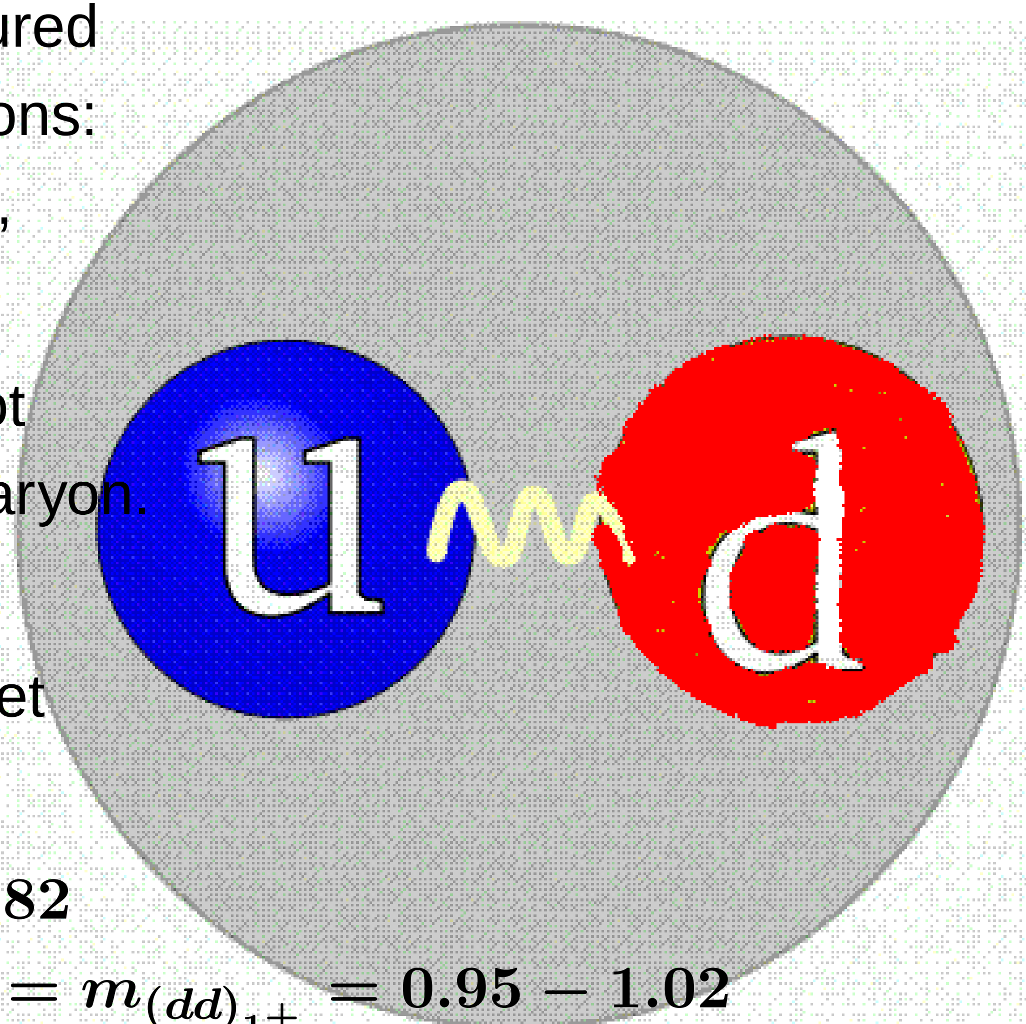
QUARK-QUARK

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

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Cloët, Roberts *et al*.
– arXiv:0710.2059 [nucl-th]
– arXiv:0710.5746 [nucl-th]
– arXiv:0804.3118 [nucl-th]
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$$\frac{G_M^n(Q^2)}{\mu_n G_D(Q^2)}$$

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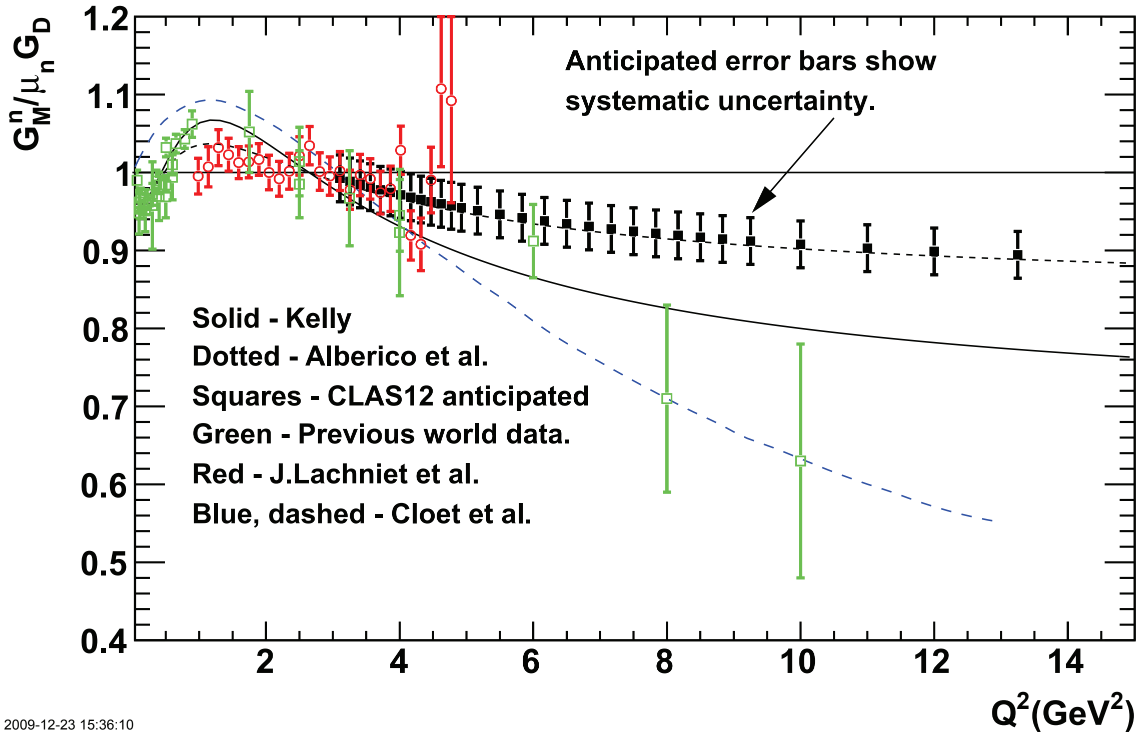

Jefferson Lab E12-07-104, *12GeV Proposal*.

Gilfoyle, Brooks, Hafidi for CLAS Collaboration

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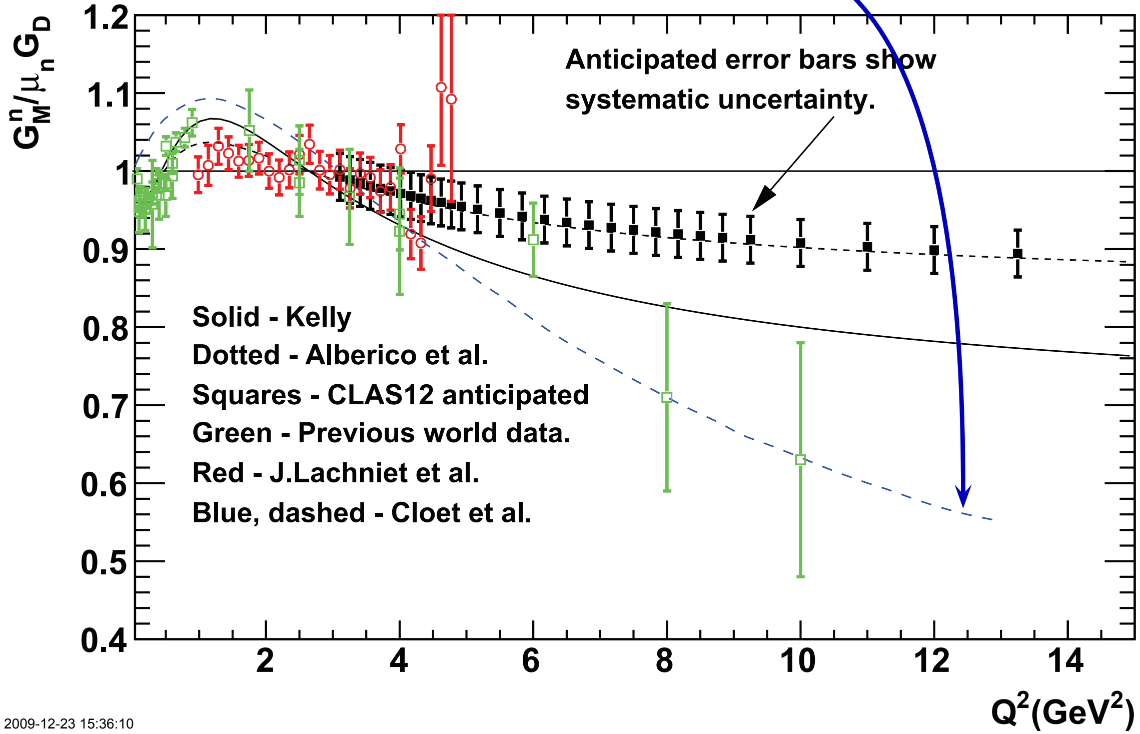

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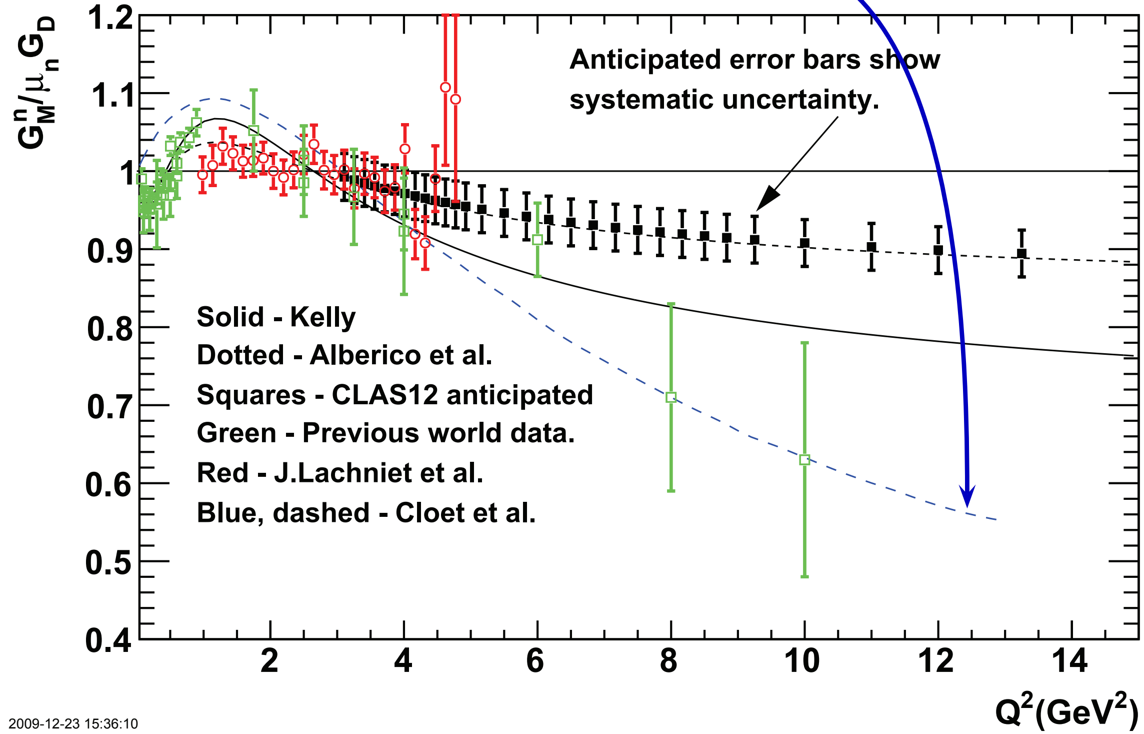

Sensitivity to $M(p^2)$ means experiments probe IR behaviour of strong running coupling

Jefferson Lab E12-07-104, *12GeV Proposal*.
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Maris, Roberts, Tandy
nucl-th/9707003

Goldberger-Treiman for pion

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nucl-th/9707003

Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

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

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

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- Axial-vector Ward-Takahashi identity

$\Rightarrow$

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

Maris, Roberts, Tandy
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$$\begin{aligned} f_\pi E_\pi(k;P=0) &= B(p^2) \\ F_R(k;0) + 2\, f_\pi F_\pi(k;0) &= A(k^2) \\ G_R(k;0) + 2\, f_\pi G_\pi(k;0) &= 2A'(k^2) \\ H_R(k;0) + 2\, f_\pi H_\pi(k;0) &= 0 \end{aligned}$$

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Pseudovector components necessarily nonzero

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

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$\Rightarrow$ Exact in Chiral QCD

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GT for pion – QCD and $F_\pi^{\rm em}(Q^2)$

Maris, Roberts
nucl-th/9804062

- What does this mean for observables?

Maris, Roberts
nucl-th/9804062

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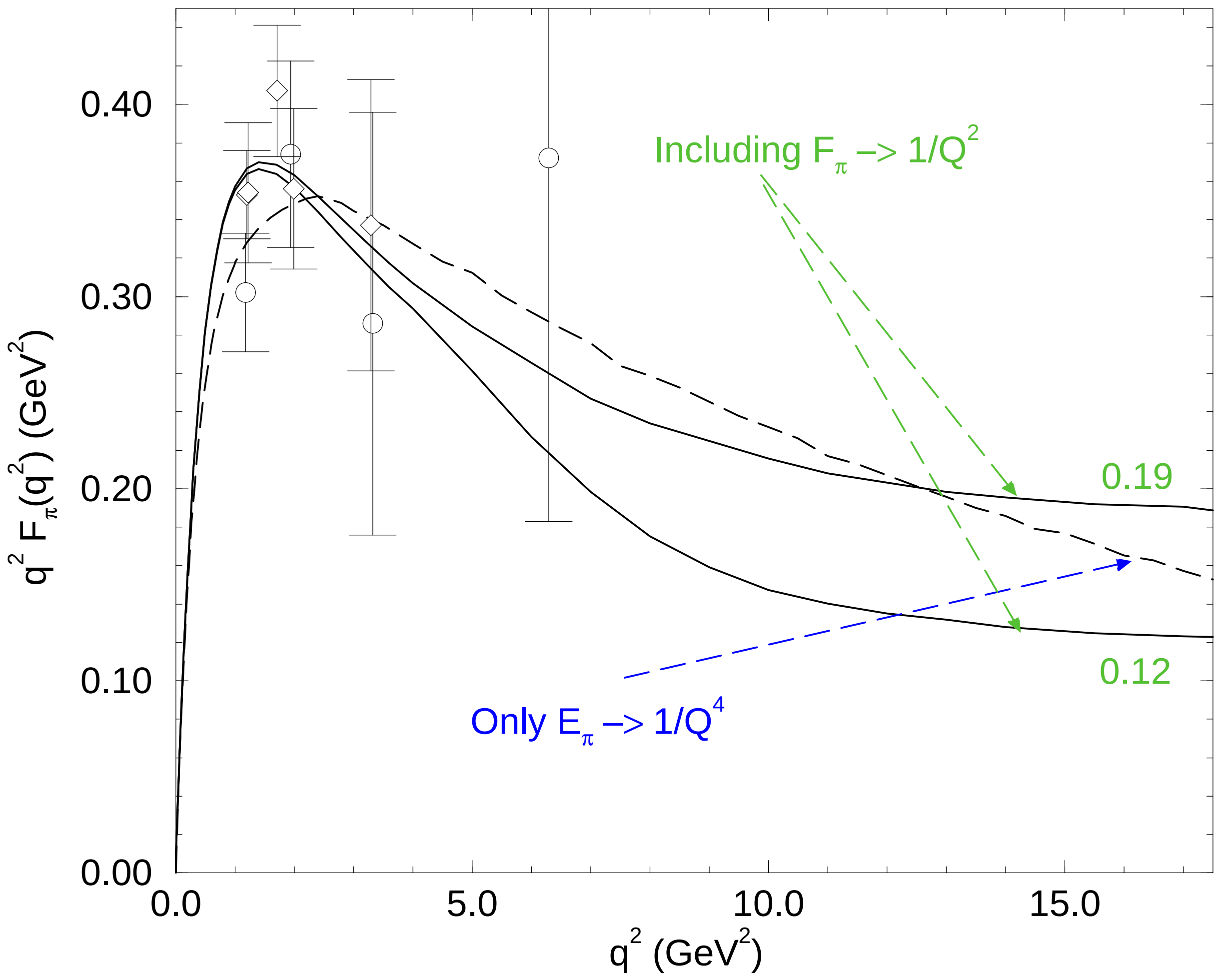

Maris, Roberts
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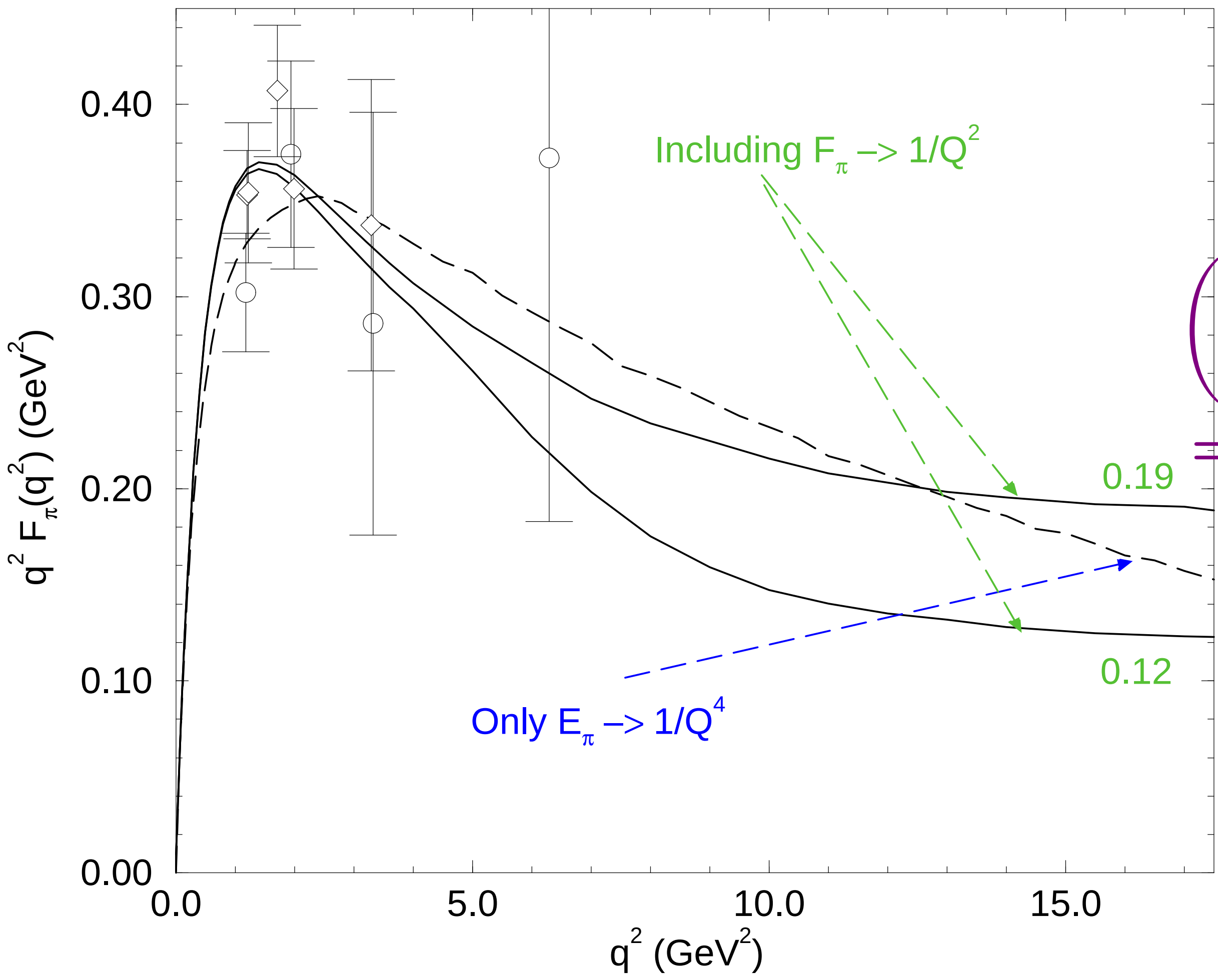

$$\left(\frac{Q}{2}\right)^2 = 2\,\mathrm{GeV}^2$$
$$\Rightarrow Q^2 = 8\,\mathrm{GeV}^2$$

- Pseudovector components dominate ultraviolet behaviour of electromagnetic form factor

GT for pion – Contact Interaction

Guttierez, Bashir, Cloët, Roberts:
in progress

GT for pion – Contact Interaction

- Bethe-Salpeter amplitude can't depend on relative momentum

  $\Rightarrow$ General Form $\boxed{\Gamma_\pi(P) = i\gamma_5 E_\pi(P) + \frac{1}{M_Q}\gamma \cdot P F_\pi(P)}$

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  $$P^2 = 0: \; M_Q = 0.40\,,\; E_\pi = 0.98\,,\; \frac{F_\pi}{M_Q} = 0.50$$

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  - RHS Bethe-Salpeter equation:

    $$\gamma_\mu S(k+P/2) i\gamma_5 E_\pi S(k-P/2)\gamma_\mu$$

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  - RHS Bethe-Salpeter equation:
    $\gamma_\mu S(k+P/2) i\gamma_5 E_\pi S(k-P/2)\gamma_\mu$
  - Has pseudovector component
    $\sim E_\pi[\sigma_S(k_+)\sigma_V(k_-) + \sigma_S(k_-)\sigma_V(k_+)]$

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    $\gamma_\mu S(k + P/2) i\gamma_5 E_\pi S(k - P/2)\gamma_\mu$
  - Hence F_π on LHS is forced to be nonzero because E_π on RHS is nonzero owing to DCSB

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GT for pion – Contact Interaction

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in progress

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    pion$(P = (0,0,-Q/2, iQ/2))$

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    $F^{\rm em}_{\pi\,EF}(Q^2) \sim 2\,S\gamma\cdot(P+Q)F_\pi S\gamma_4 S E_\pi$

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$$\Rightarrow F^{em}_{\pi\,EF}(Q^2) \propto \frac{Q^2}{M_Q^2}\frac{F_\pi}{E_\pi} \times E_\pi^2\text{-term} = \text{constant!}$$

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$$\Rightarrow F^{em}_{\pi\,EF}(Q^2) \propto \frac{Q^2}{M_Q^2}\frac{F_\pi}{E_\pi} \times E_\pi^2\text{-term} = \text{constant!}$$

- This behaviour dominates for $Q^2 \gtrsim M_Q^2 \dfrac{E_\pi}{F_\pi} > 0.8\,\text{GeV}^2$

Computation: Elastic Pion Form Factor

Guttierez, Bashir, Cloët, Roberts:
in progress

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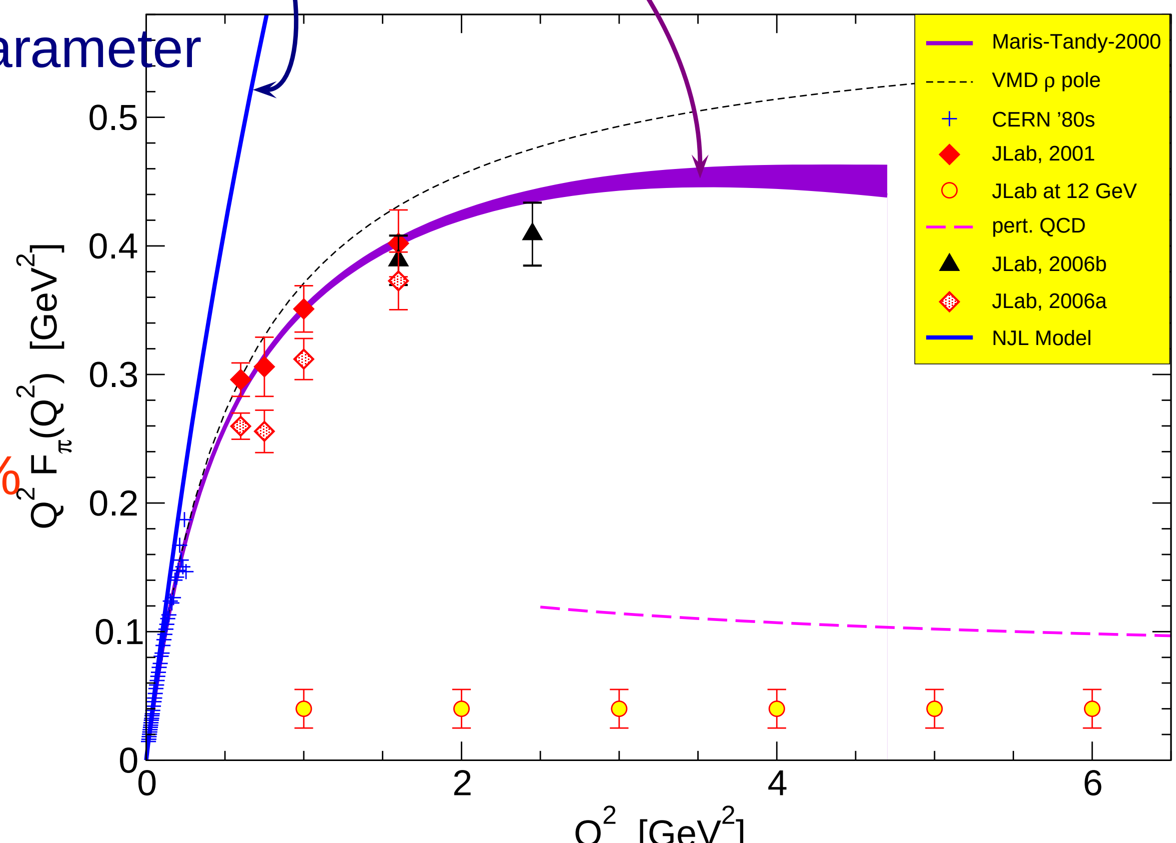
Same predictions for $Q^2 = 0$ properties

Disagreement $> 20\%$ for $Q^2 > M^2$



DSE-based Faddeev Equation

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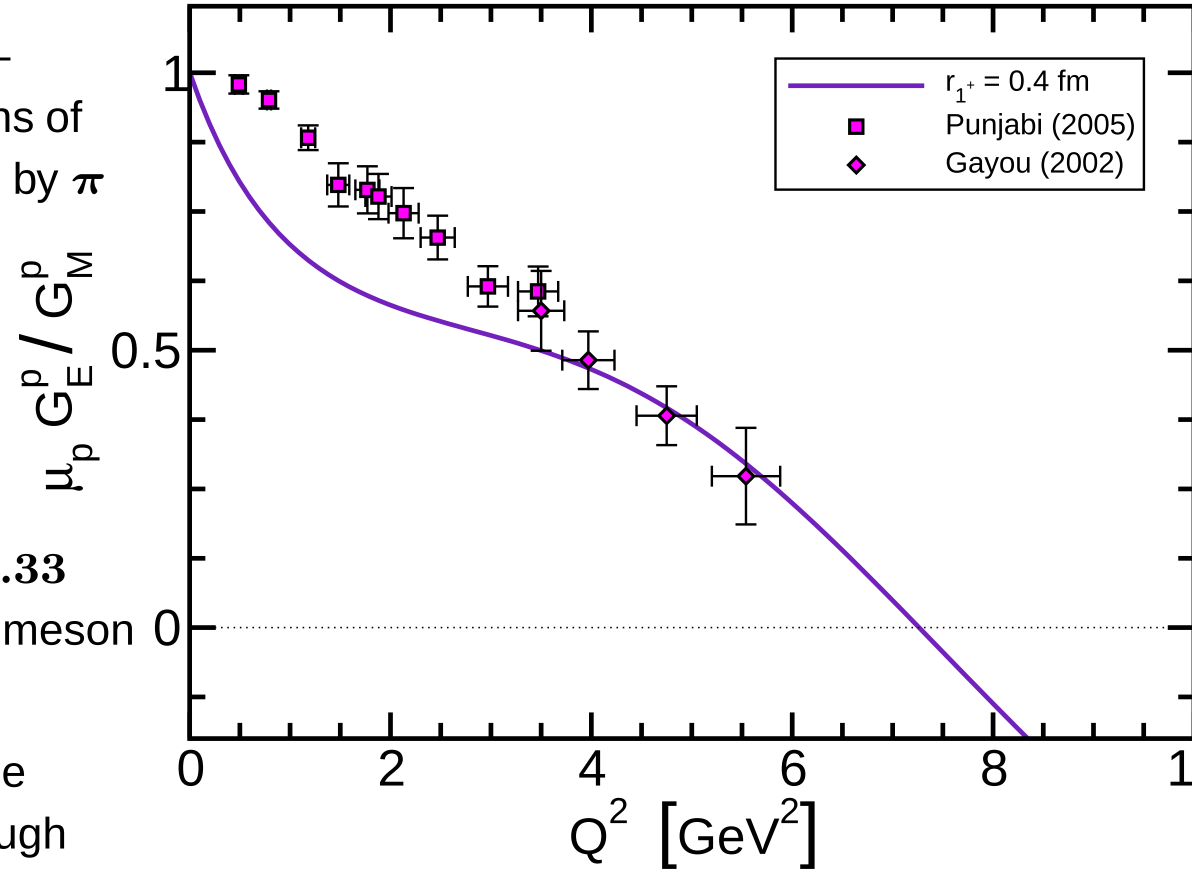

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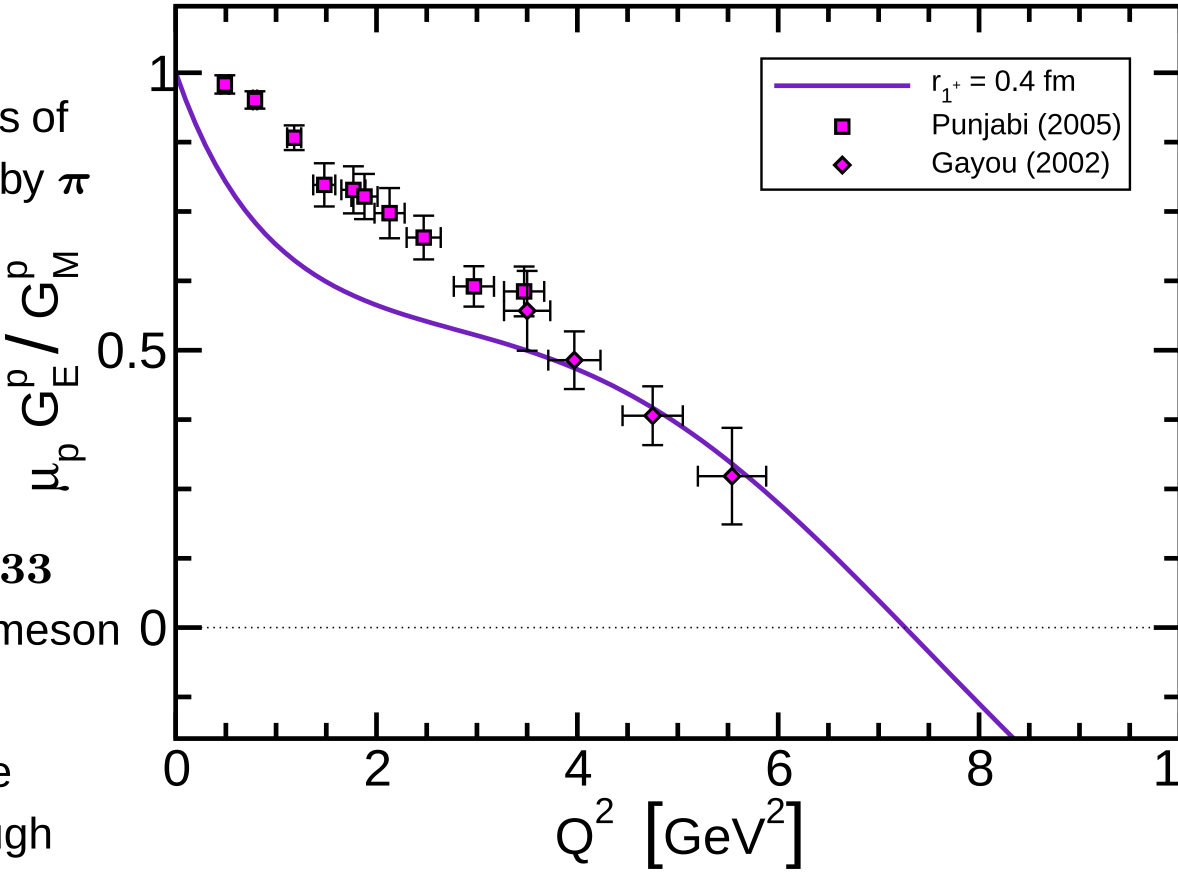

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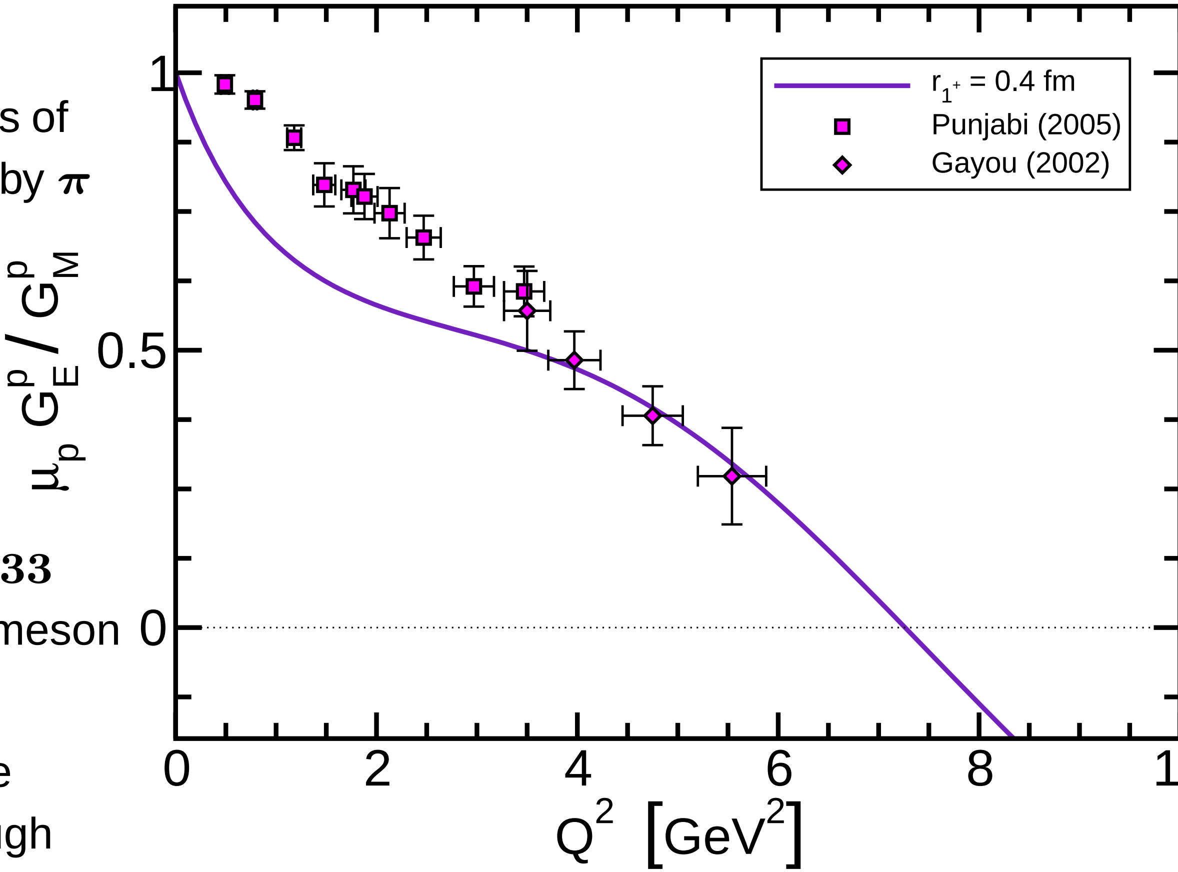

- On $Q^2 \lesssim 4$ GeV^2 result lies below experiment. This can be attributed to omission of pseudoscalar-meson-cloud contributions
- Always a zero but position depends on details of current

Harry Lee

Pions and Form Factors

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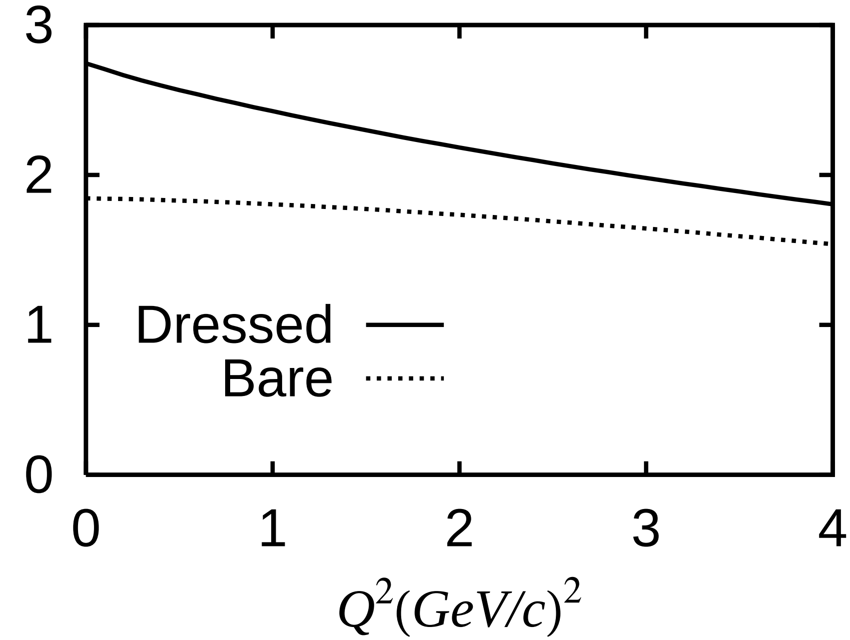
Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G^*_M(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



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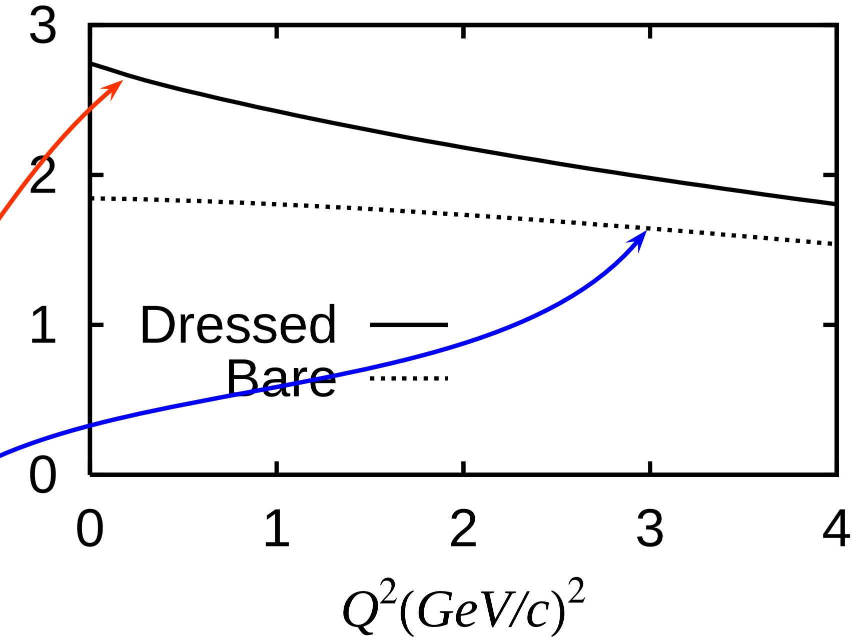
Quark Core



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

Pion Cloud

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Pion Cloud

F2 – neutron

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Pion Cloud
F2 – neutron

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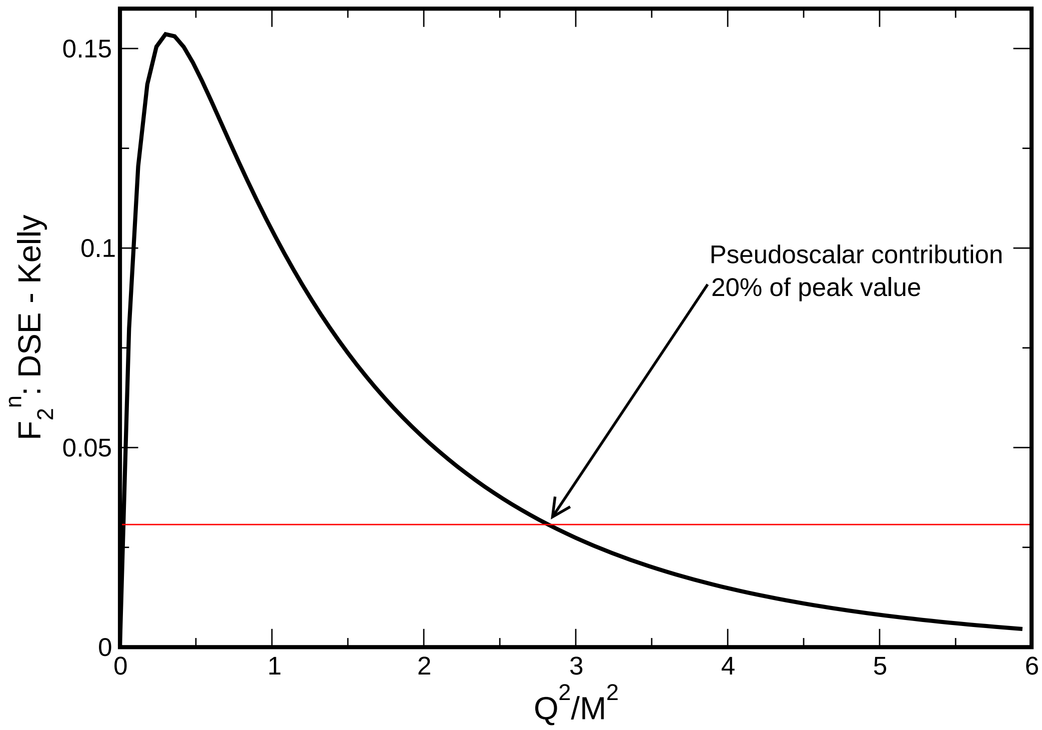

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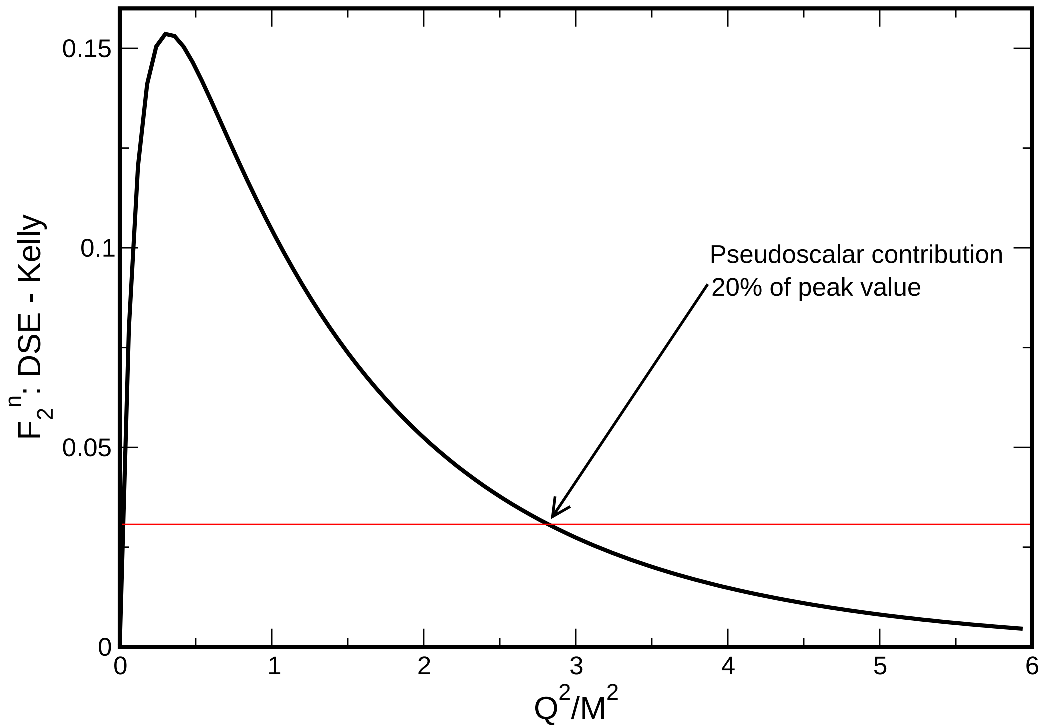

- Pseudoscalar meson cloud (and related effects) significant for $Q^2 \lesssim 3 - 4\, M_N^2$

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