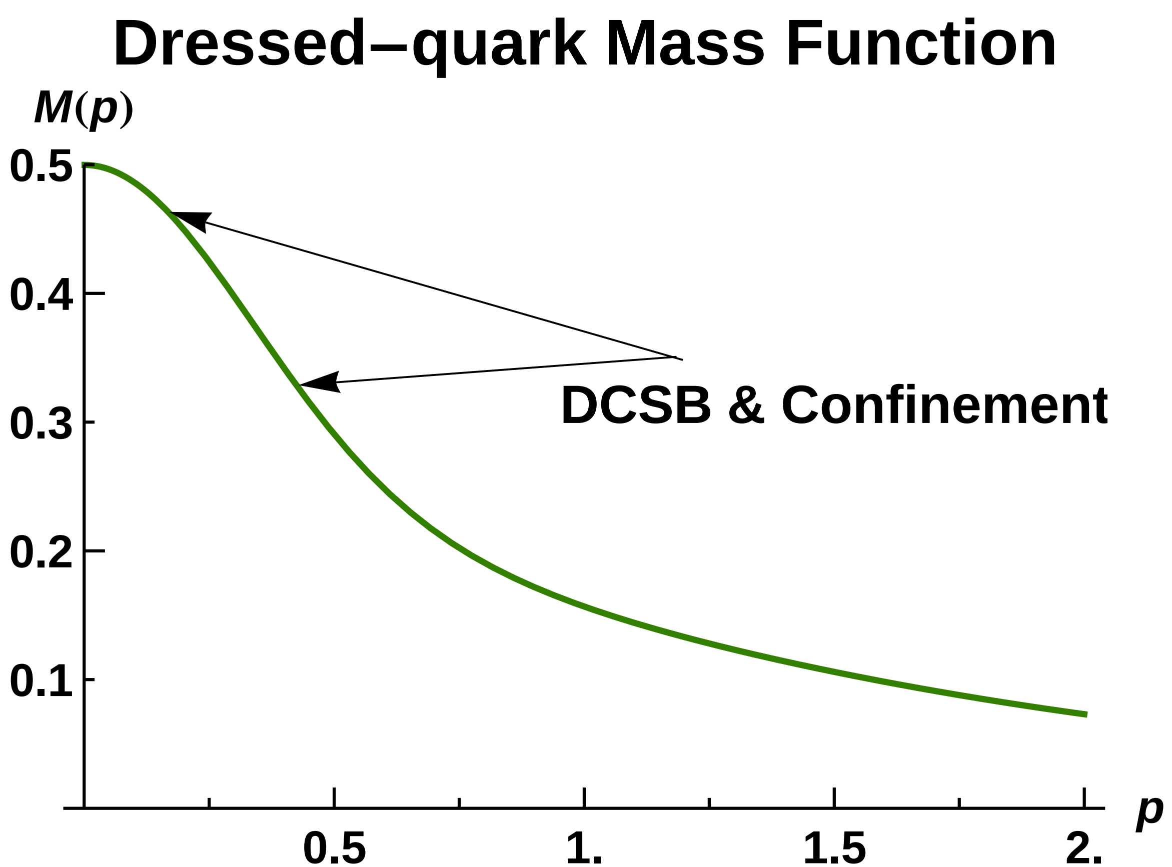
Dyson-Schwinger equations: Recent successes & future perspective



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Argonne National Laboratory Peking University

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

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Universal Truths

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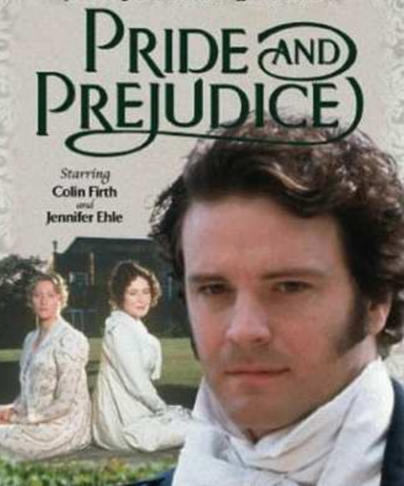

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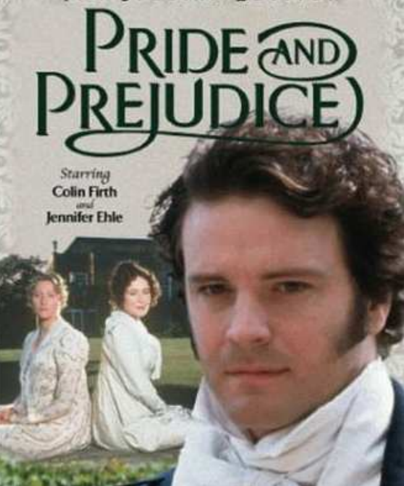

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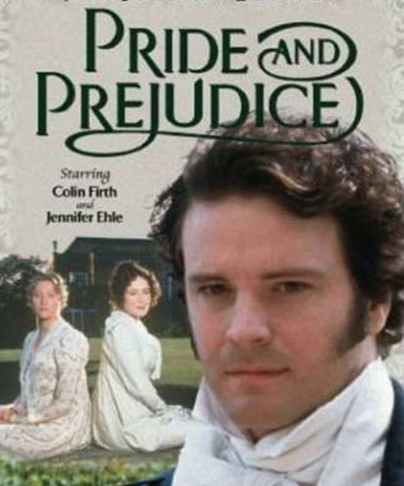

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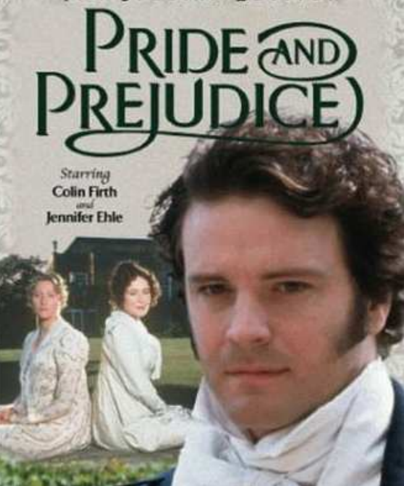

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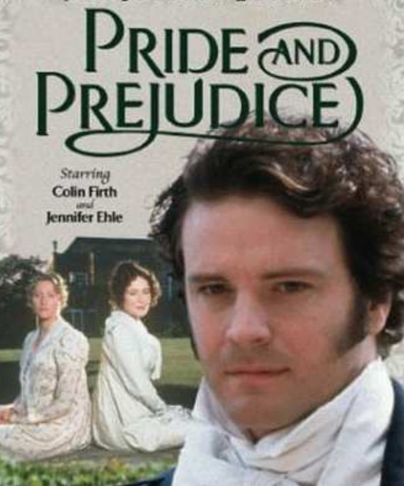

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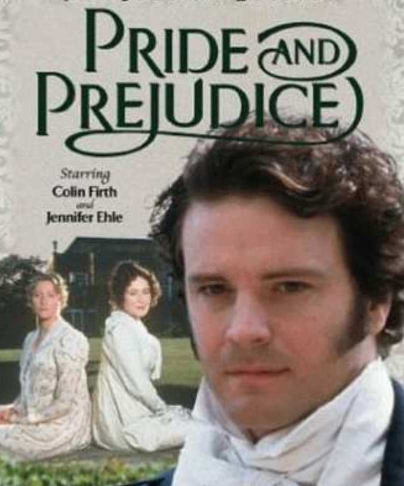

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- Running of quark mass entails that calculations at even modest Q^2 require a Poincaré-covariant approach. Covariance requires existence of quark orbital angular momentum in hadron's rest-frame wave function.

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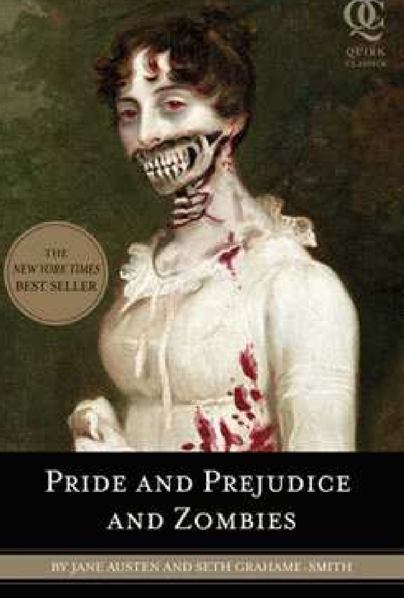
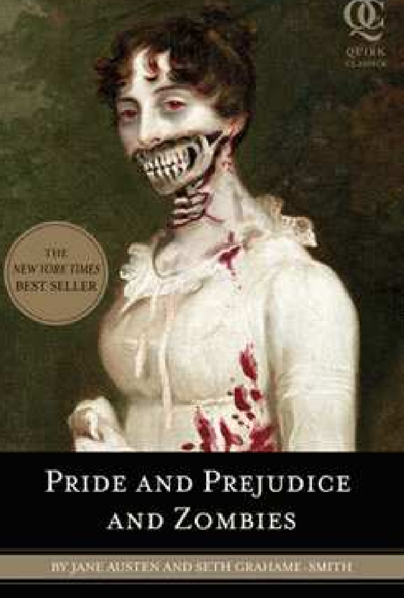


Universal Truths

- Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons.



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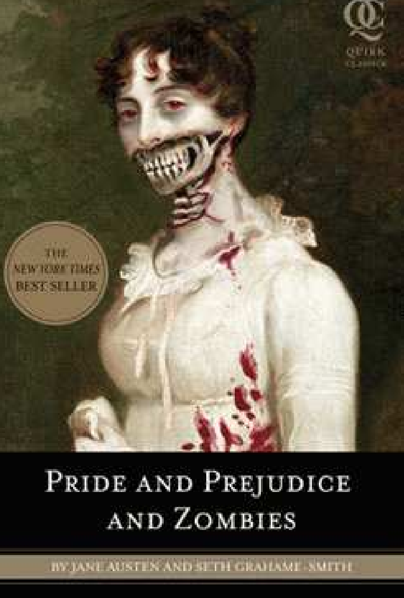

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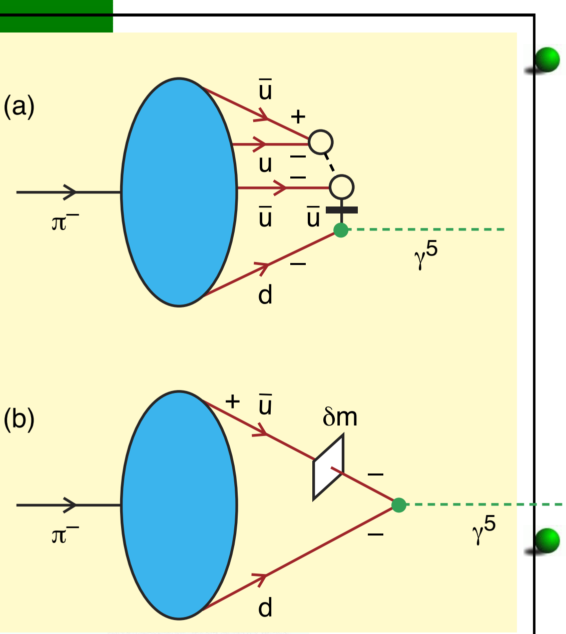
  - Resolution
    – *So-called* vacuum condensates can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wavefunctions.
    – DCSB obtained via coherent contribution from countable infinity of higher Fock-state components in LF-wavefunction.
  - Brodsky, Roberts, Shrock, Tandy – arXiv:1005.4610 [nucl-th].



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QCD's Challenges

Understand Emergent Phenomena

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

  arises from apparently simple rules

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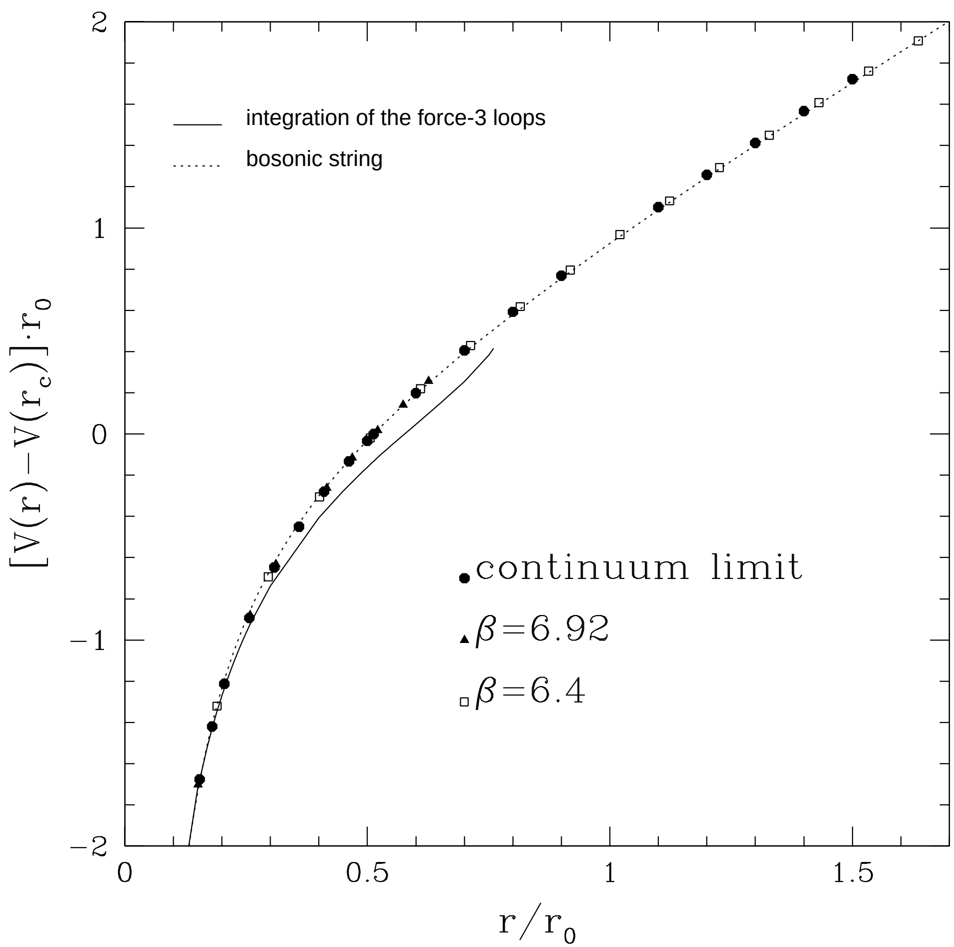
Confinement

Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



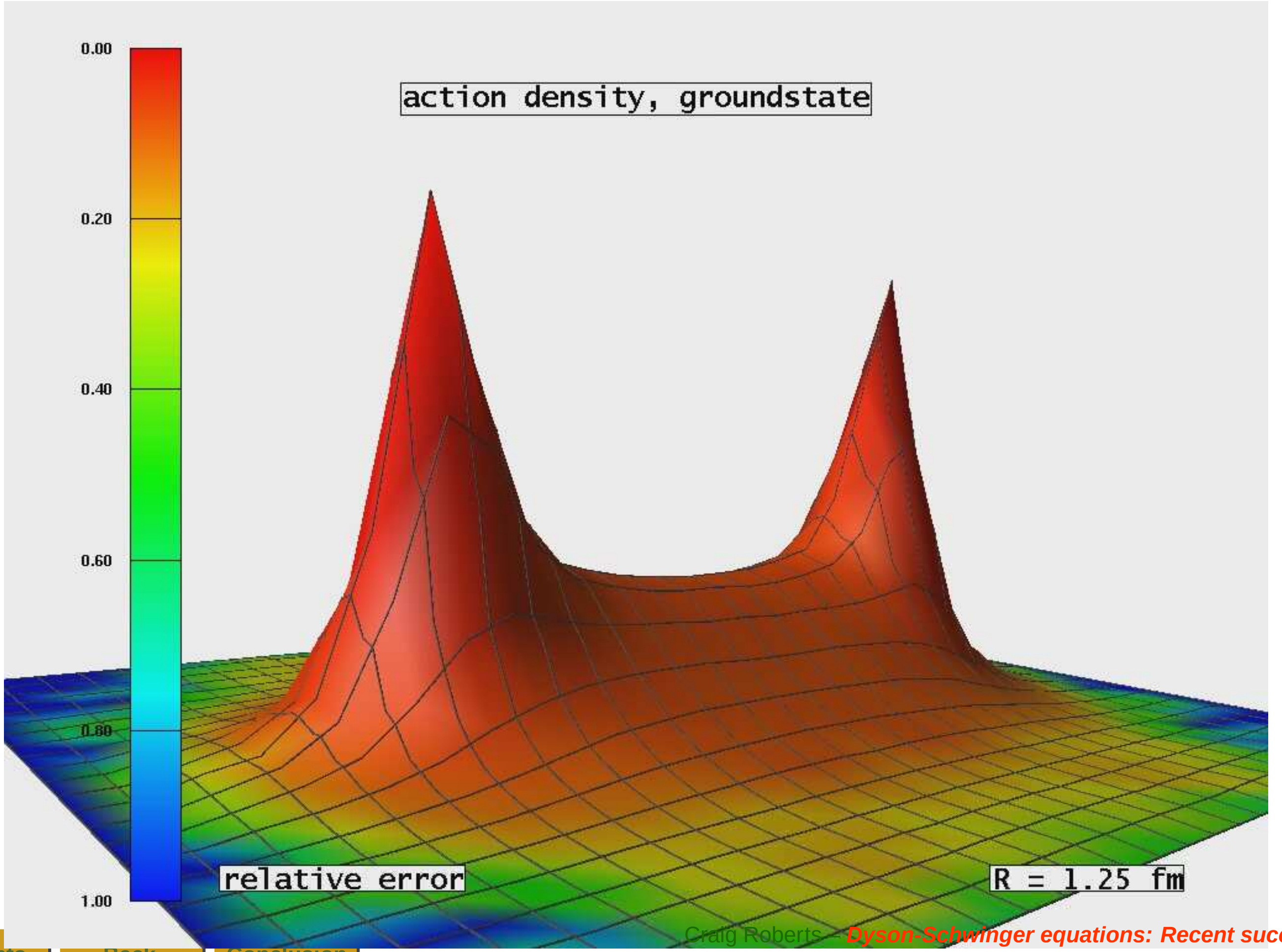
$$V(r) = \sigma\, r - \frac{\pi}{12}\,\frac{1}{r}$$

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

Necco & Sommer
he-la/0108008

Confinement

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



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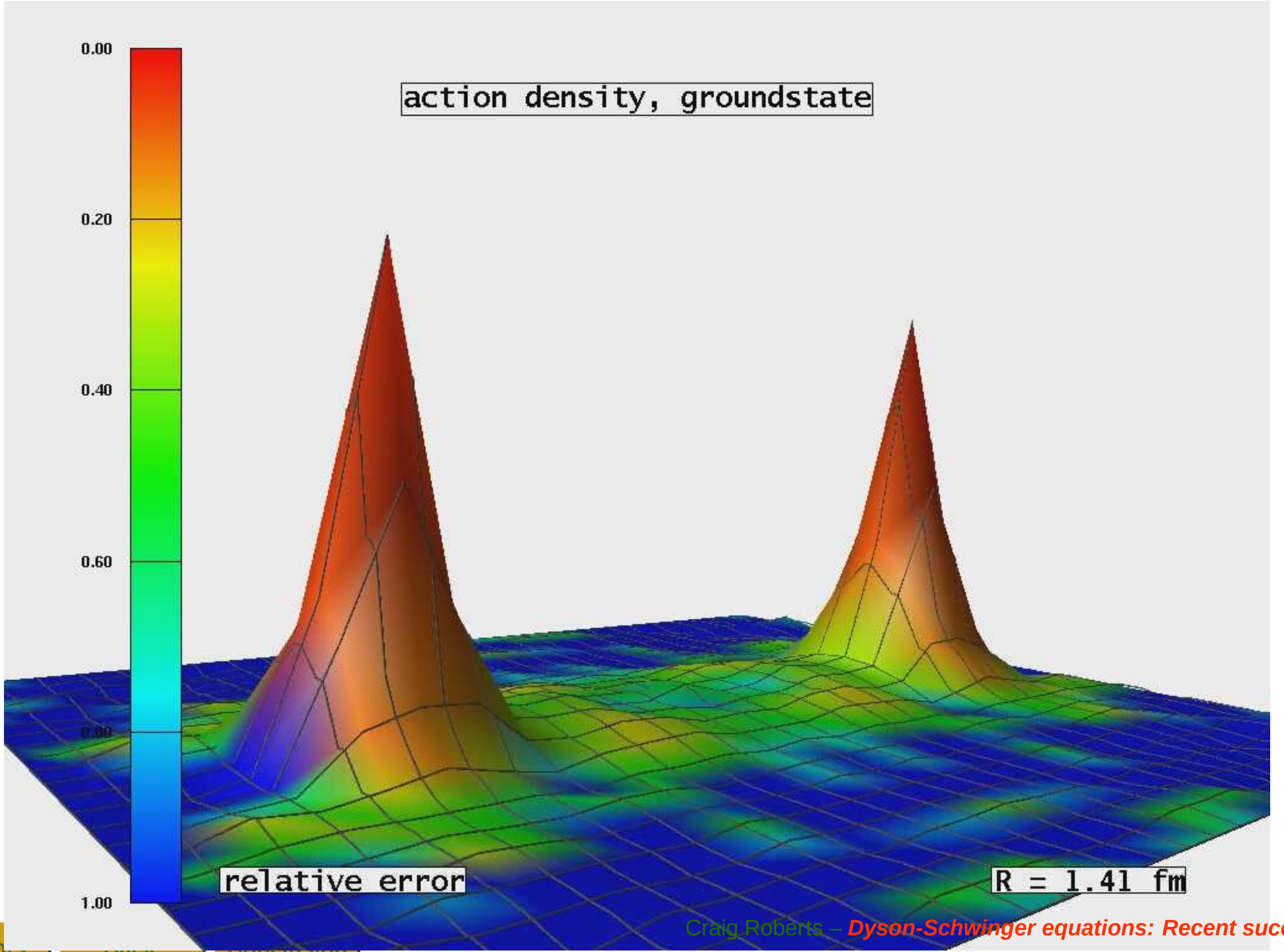

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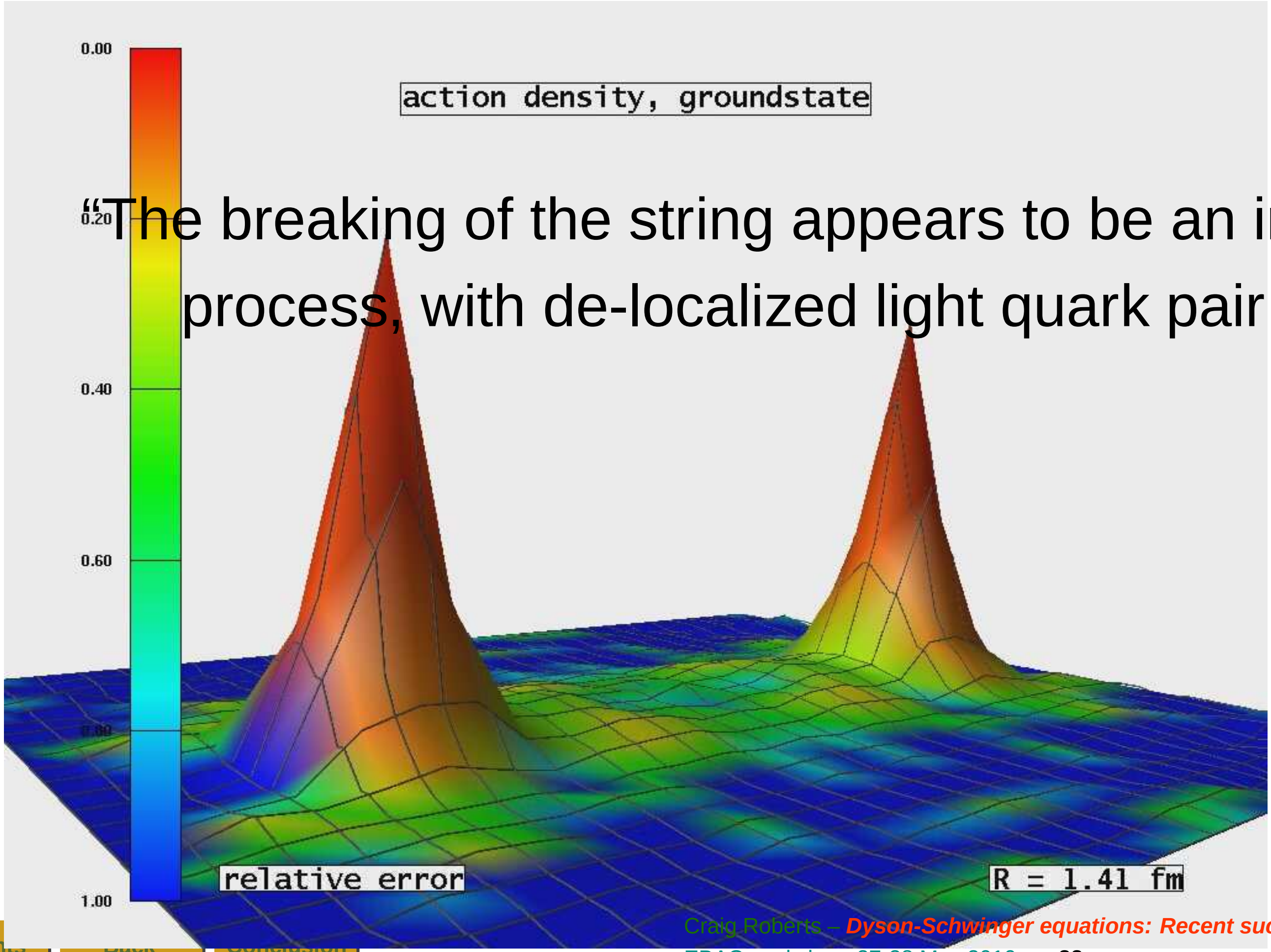

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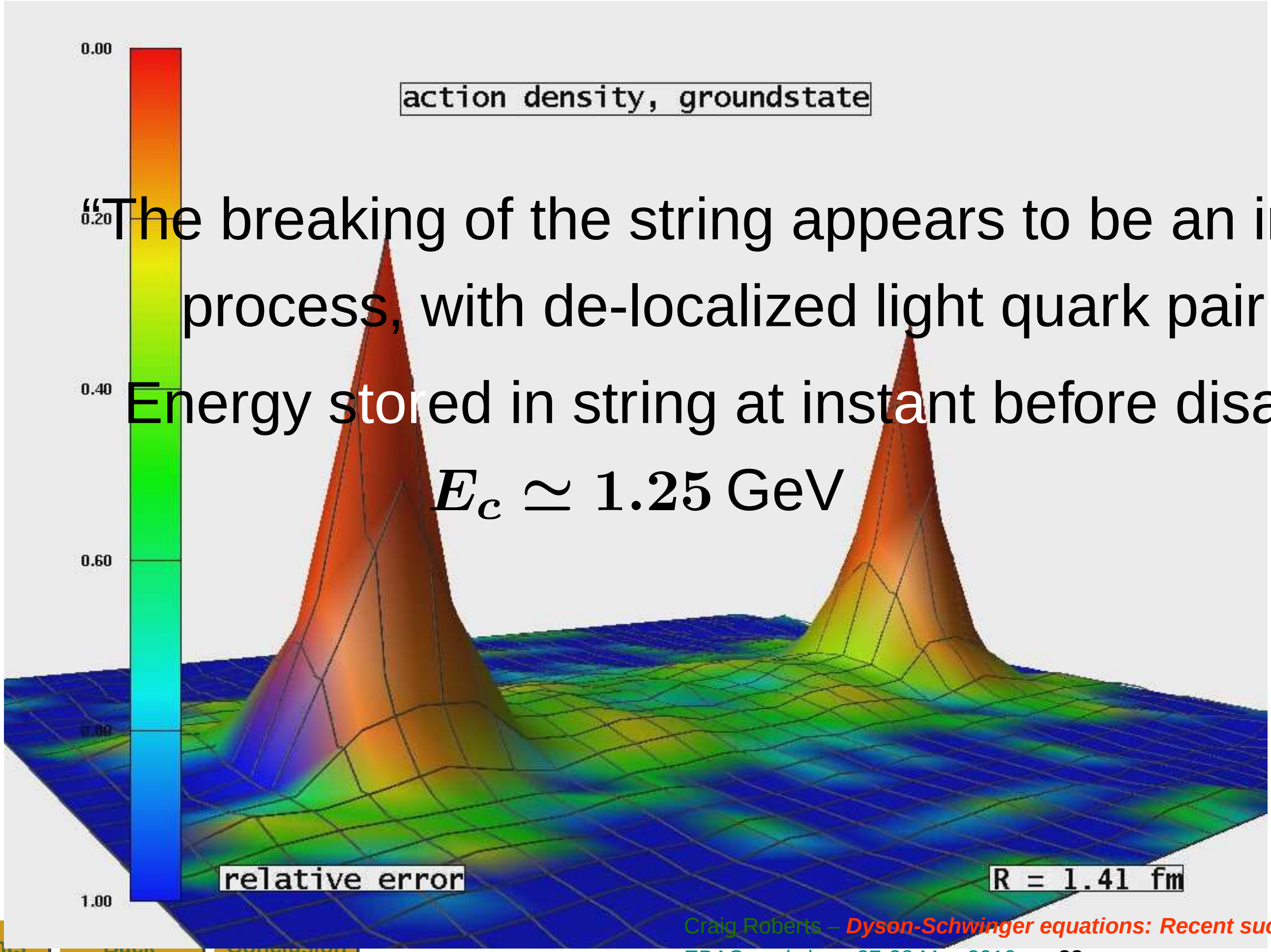

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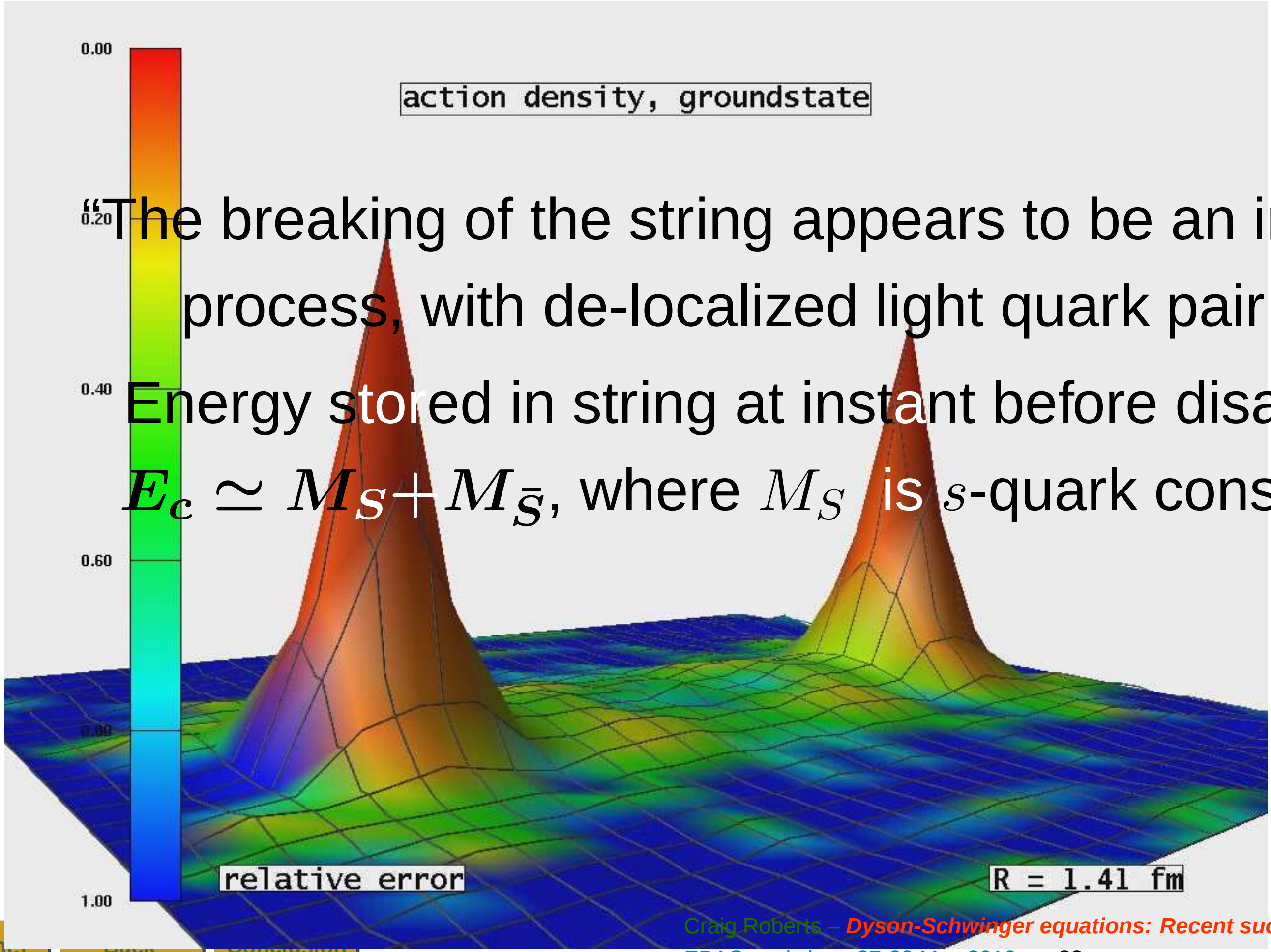

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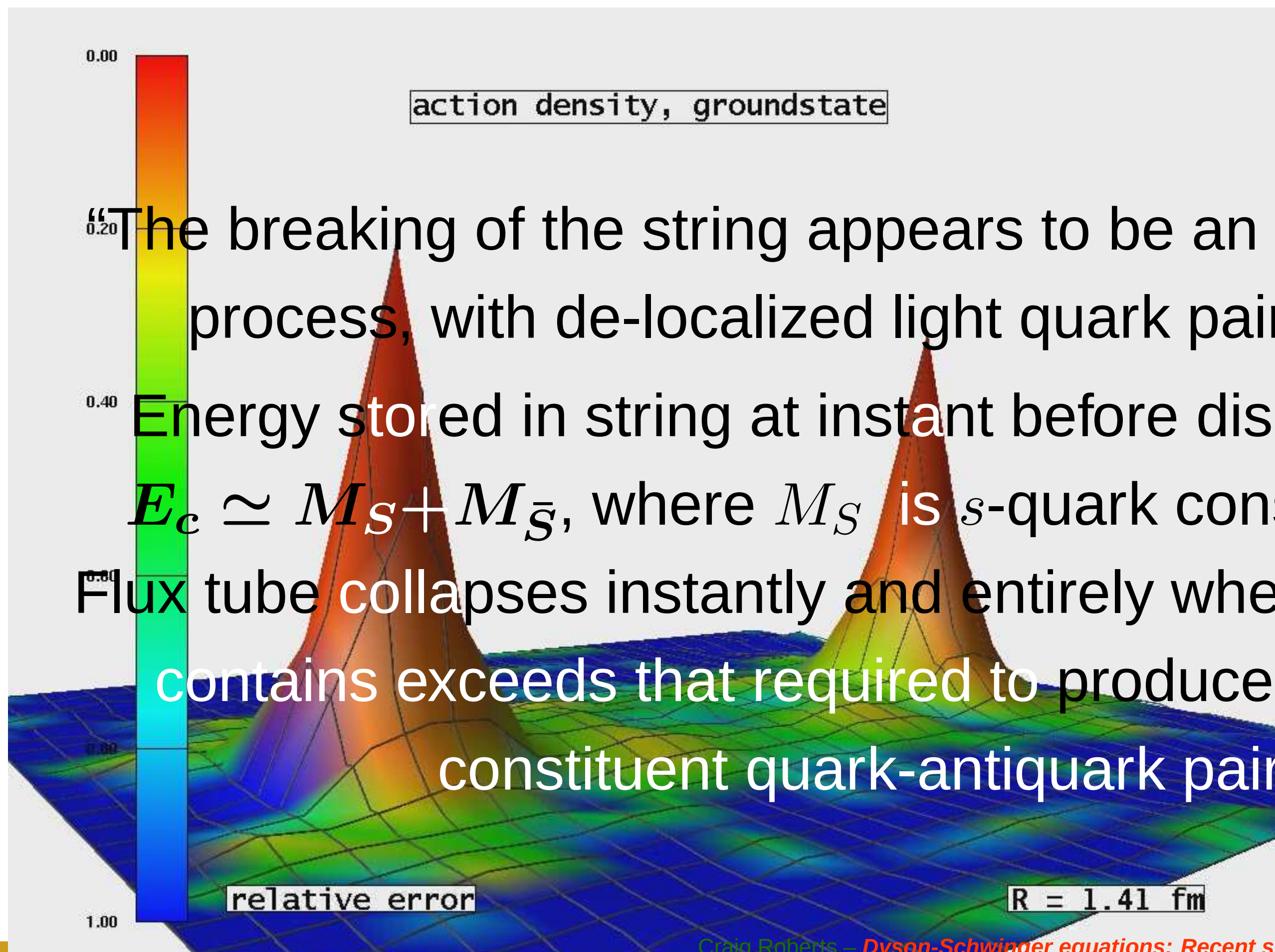

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Flux tube collapses instantly and entirely when the energy it contains exceeds that required to produce the lightest constituent quark-antiquark pair.

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

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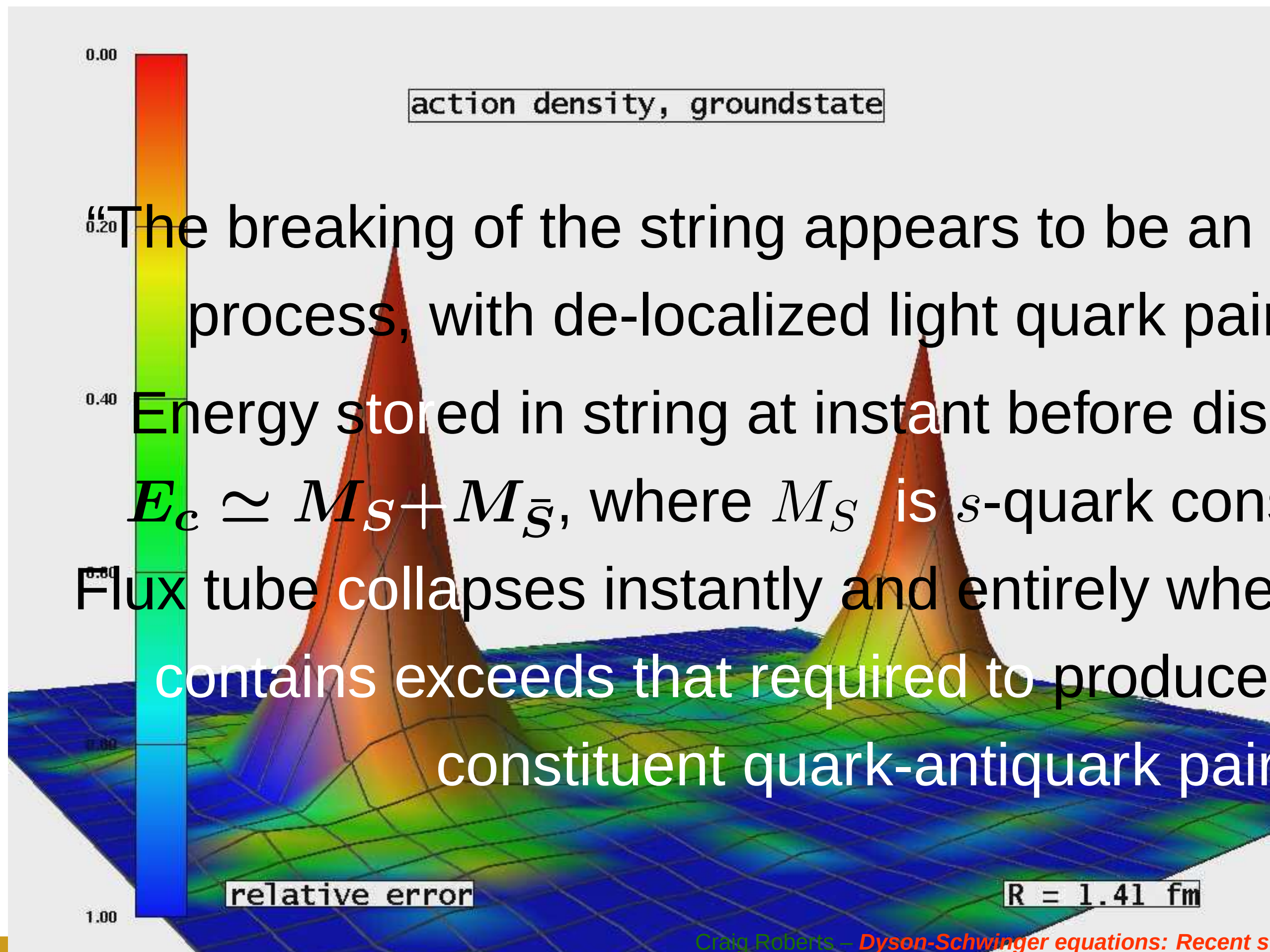

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  Of course, the behaviour of the β-function on the perturbative domain is well known.
- This is a well-posed problem whose solution is an elemental goal of modern hadron physics.

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 known way to the light-quark interaction.

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- E.g.: 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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- 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 (See nucl-th/9602012 and references thereto)

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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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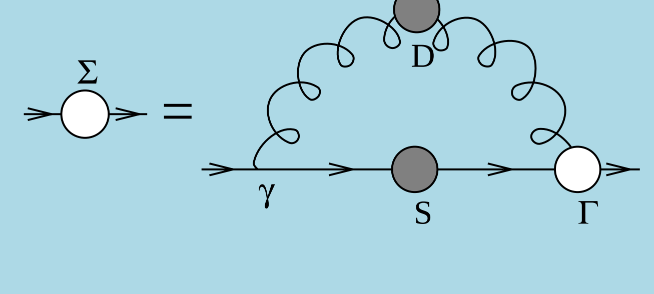
Gap Equation
General Form



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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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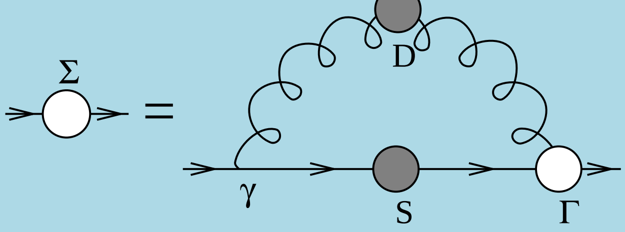

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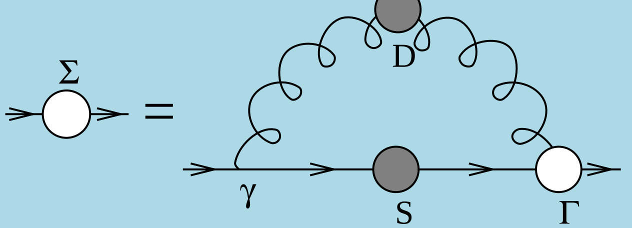
- $m^{\rm bm}(\Lambda)$ is the Lagrangian current-quark bare mass
- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma_\nu^f(q,p)$ is the dressed-quark-gluon vertex



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- $\Gamma^f_\nu(q,p)$ 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?

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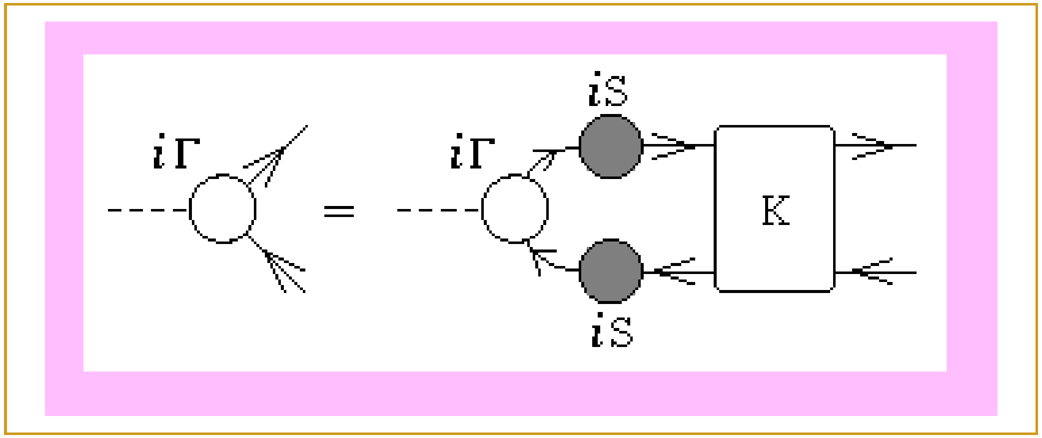
Bethe-Salpeter Equation

- Standard form, familiar from textbooks

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



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

Bound-state DSE
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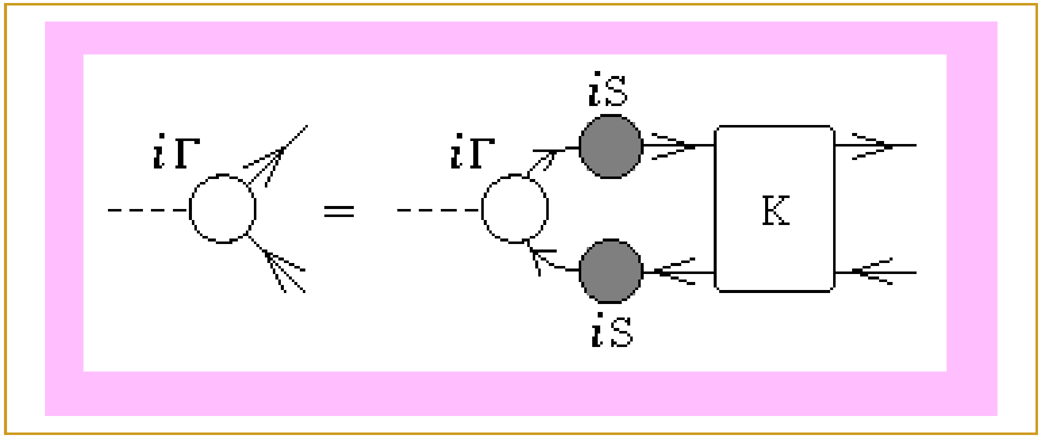

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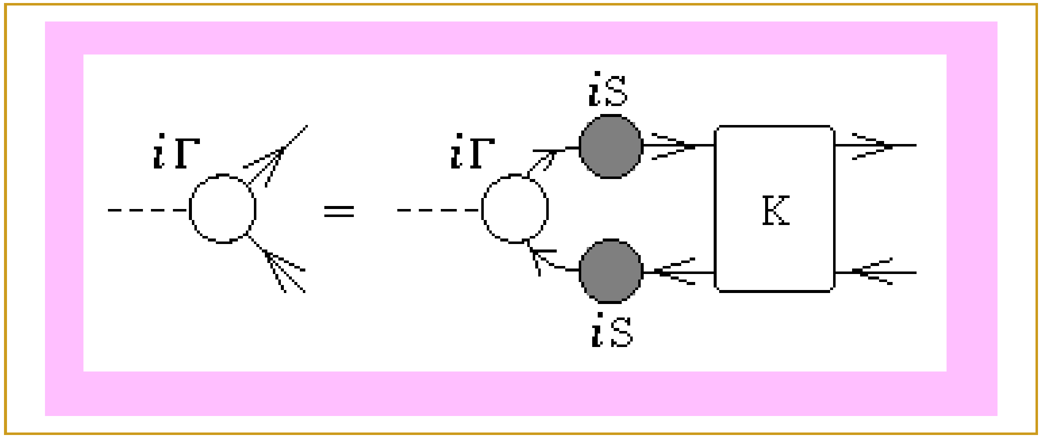

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- Blocked progress for more than 60 years.

Bethe-Salpeter Equation General Form

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

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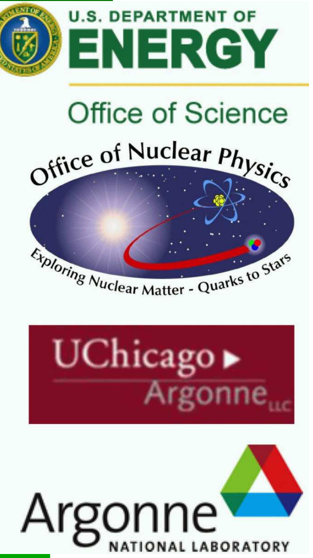

- Equivalent exact form:

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

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

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

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

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

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

- Bethe-Salpeter equation introduced in 1951

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Bethe-Salpeter Kernel
60 year problem

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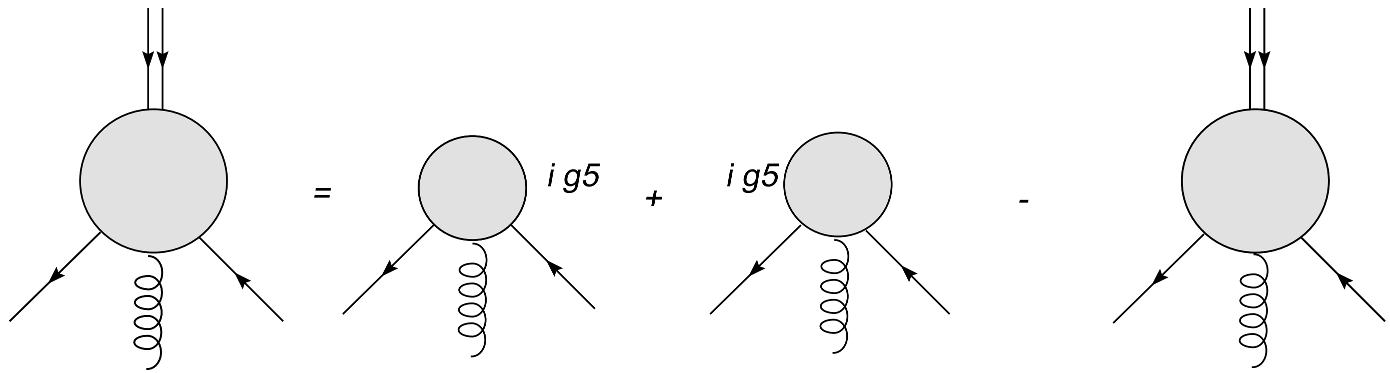

$$P_\mu \Lambda^{fg}_{5\mu\beta}(k,q;P) = \Gamma^f_\beta(q_+,k_+)\, i\gamma_5 + i\gamma_5\, \Gamma^g_\beta(q_-,k_-) - i[m_f(\zeta)+m_g(\zeta)]\Lambda^{fg}_{5\beta}(k,q;P),$$

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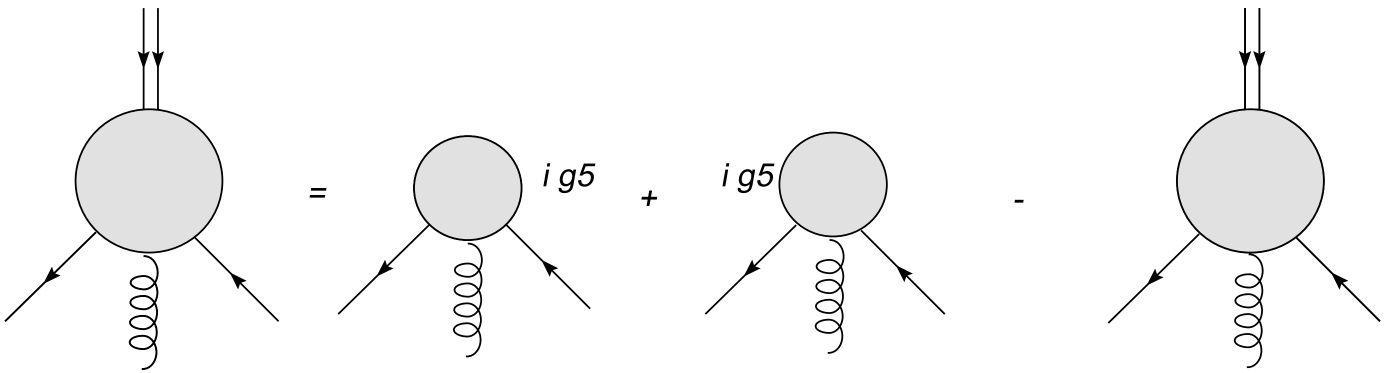

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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
  - Consistent means - all symmetries preserved!

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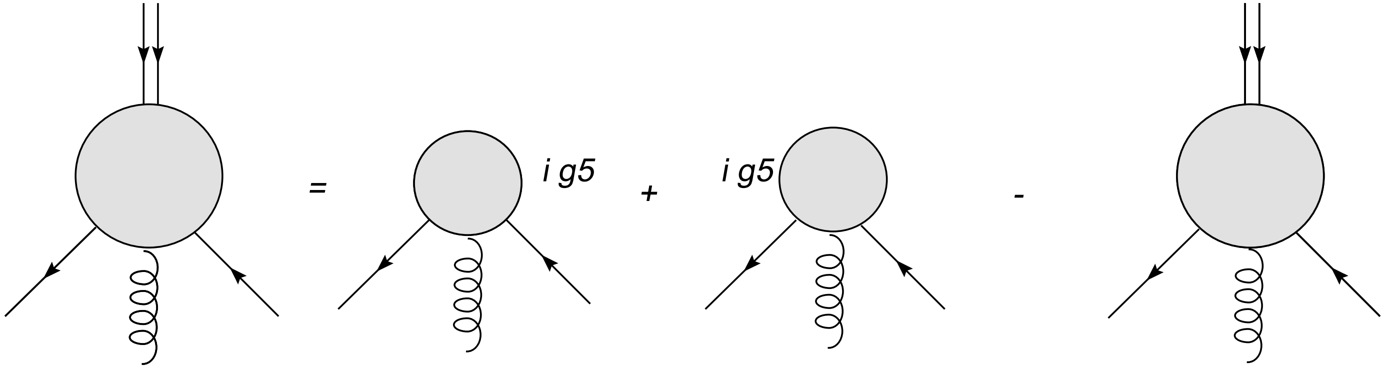

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- Procedure & results to expect . . .

see arXiv:1003.5006 [nucl-th]

Mass Splitting

$a_1 - \rho$

	exp.			
mass a_1	1230			
mass ρ	775			
mass-splitting	455			

- Splitting known experimentally for more than 35 years.
- Hitherto, no explanation.

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Mass Splitting

$a_1 - \rho$

	exp.	rainbow-ladder	one-loop		
mass a_1	1230	759	885		
mass ρ	775	644	764		
mass-splitting	455	115	121		

- Systematic, symmetry-preserving, Poincaré-covariant DSE truncation scheme of nucl-th/9602012.
- Never better than $\sim \frac{1}{4}$ of splitting.
- Constructing kernel skeleton-diagram-by-diagram, DCSB cannot be faithfully expressed: $M(p^2)$ is absent!

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Mass Splitting

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	exp.	rainbow-ladder	one-loop	Ball-Chiu consistent
mass a_1	1230	759	885	1066
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- New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]
- Ball-Chiu *Ansatz* for quark-gluon vertex

$$\Gamma_\mu^{BC}(k,p) = \ldots + (k+p)_\mu \frac{B(k)-B(p)}{k^2-p^2}$$

  - Some effects of DCSB built into vertex
  - Explains $\pi - \sigma$ splitting but not this problem

Mass Splitting

$a_1 - \rho$

Chang & Roberts arXiv:1003.5006 [nucl-th]

	exp.	rainbow-ladder	one-loop	Ball-Chiu consistent	Ball-Chiu plus anom. cm mom.
mass a_1	1230	759	885	1066	1230
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- New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]
- Ball-Chiu augmented by *quark anomalous chromomagnetic moment* term: $\Gamma_\mu(k,p) = \Gamma_\mu^{\rm BC} + \sigma_{\mu\nu}(k-p)_\nu \frac{B(k)-B(p)}{k^2-p^2}$

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- New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]
- DCSB is the answer. Subtle interplay between competing effects, which can only now be explicated
- Promise of first reliable prediction of light-quark meson spectrum, including the so-called hybrid and exotic states.

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Quark Anomalous Magnetic Moments

Chang & Roberts, in progress

- Massless fermion can't possess an anomalous magnetic moment
  - Interaction term $\boxed{\int d^4x \, \frac{1}{2} g \, \bar{\psi}(x) \sigma_{\mu\nu} \psi(x) F_{\mu\nu}(x)}$

    explicitly breaks chiral symmetry

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- However, DCSB can generate a large anomalous chromomagnetic moment even in chiral limit
  – This explains the a_1-ρ mass-splitting

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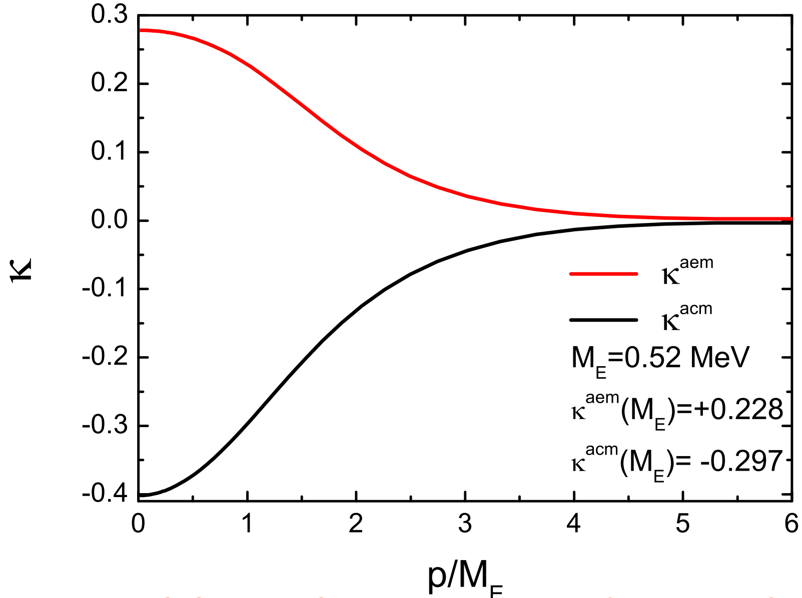
  - Preliminary result for μ distributions



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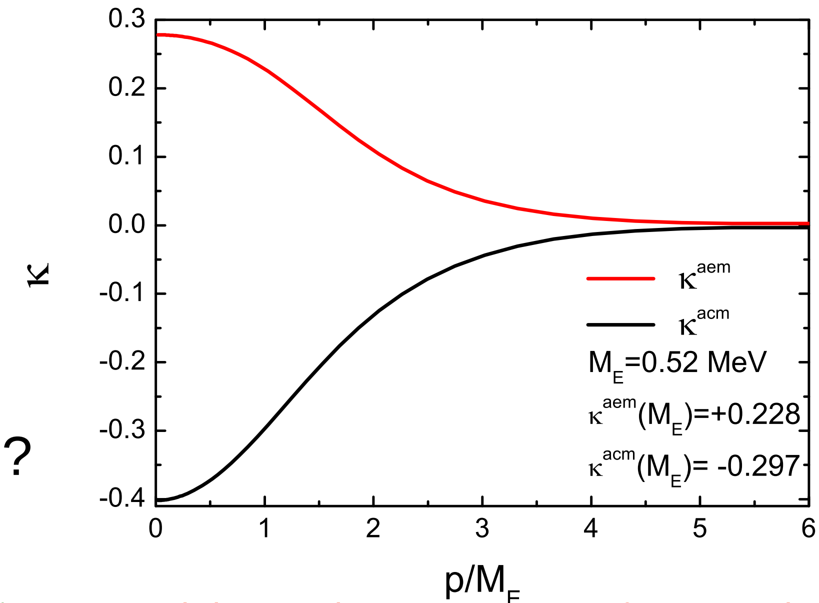
- Cloët & Roberts
  Effect on hadron form factors?



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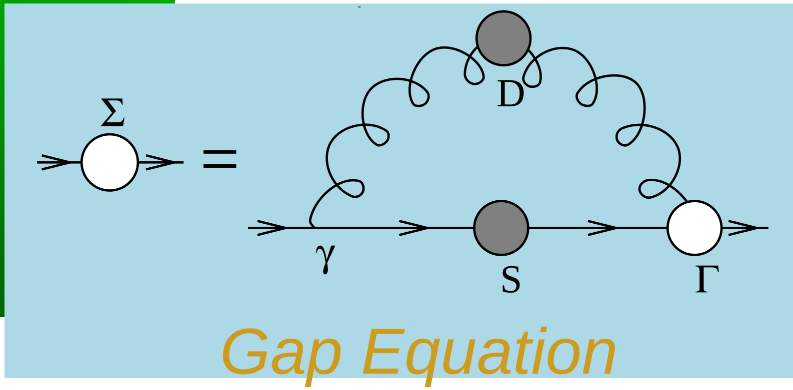
Frontiers of Nuclear Science: Theoretical Advances



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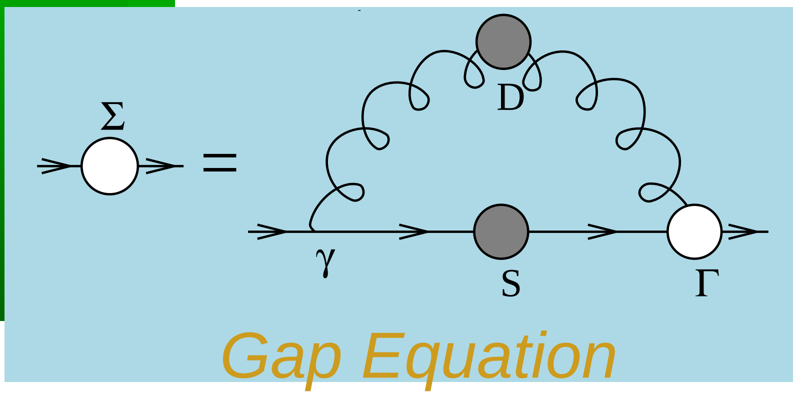
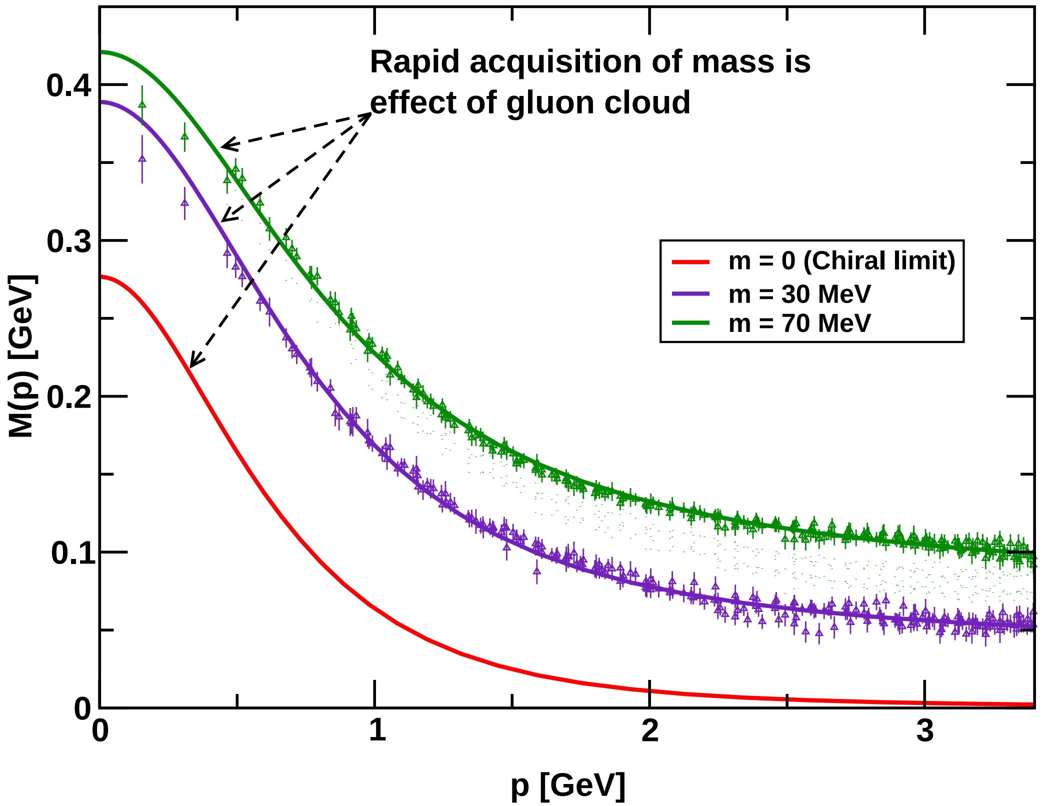


$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



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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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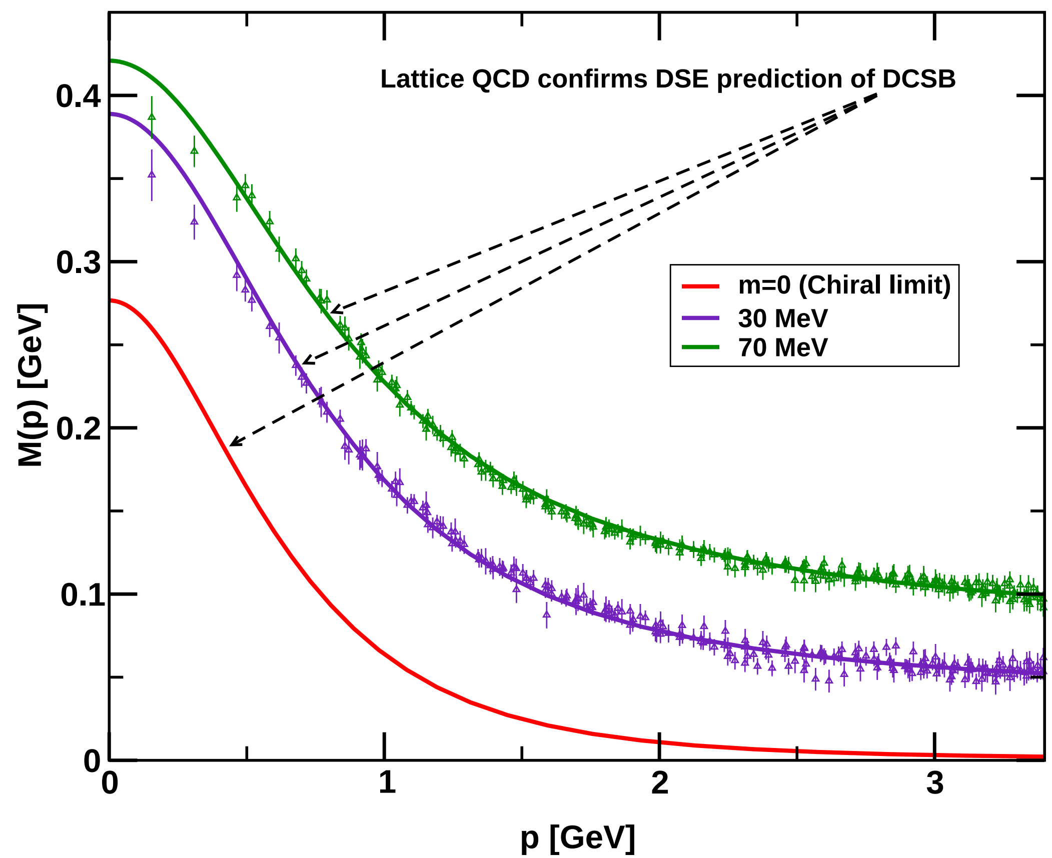

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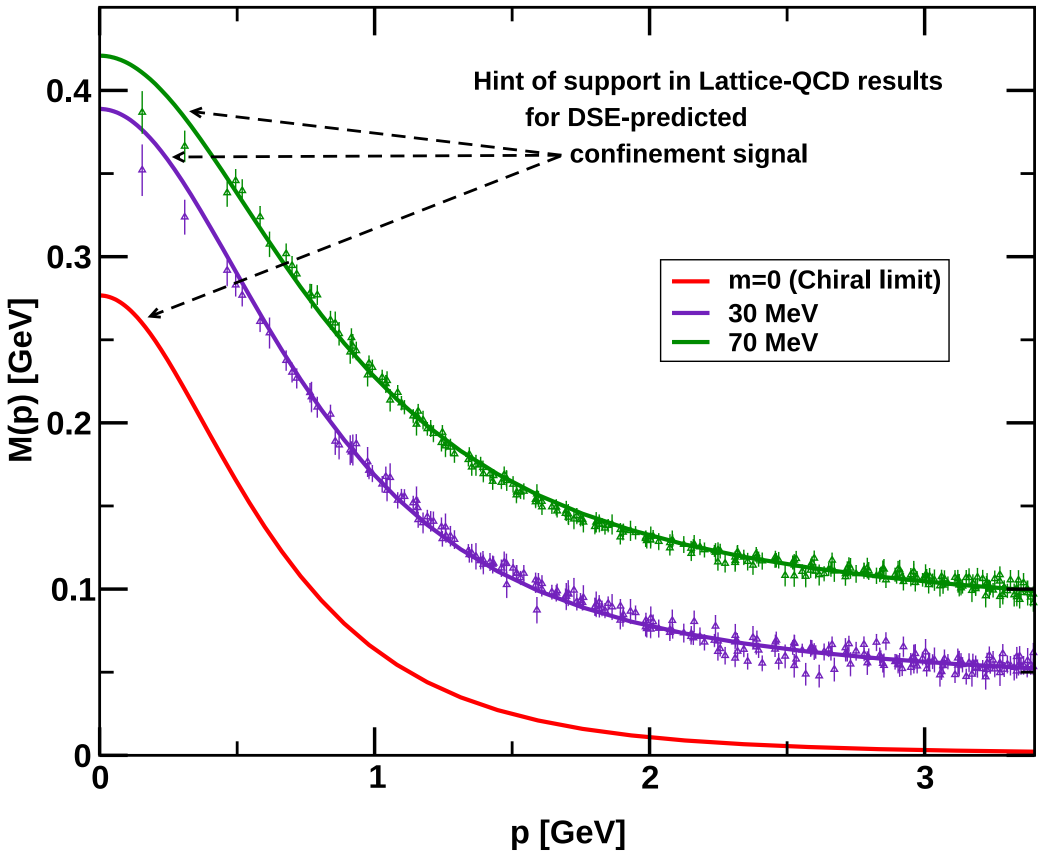

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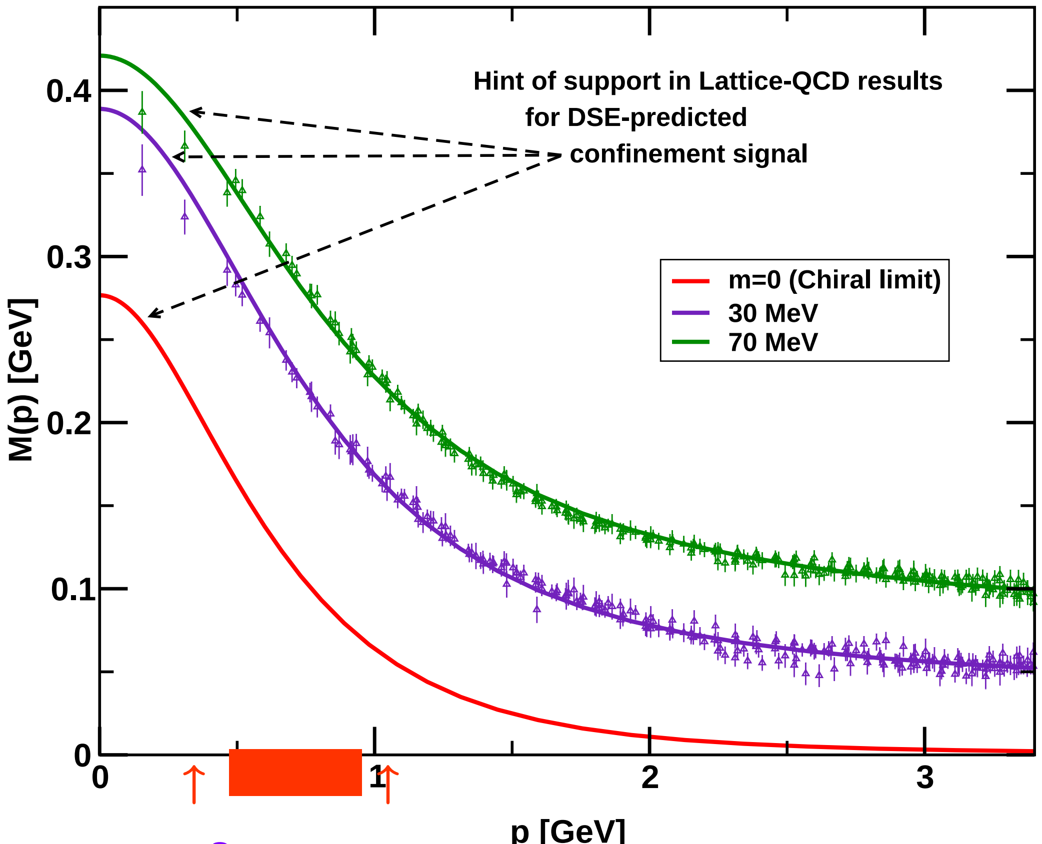

Scanned by $Q^2 \in [2,9]\,\mathrm{GeV}^2$ Baryon Elastic and Transition Form Factors

Goldberger-Treiman for pion

Maris, Roberts, Tandy
nucl-th/9707003

Goldberger-Treiman for pion

- Pseudoscalar Bethe-Salpeter amplitude

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

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

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Pseudovector components necessarily nonzero

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- What does this mean for observables?

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Maris, Roberts
nucl-th/9804062

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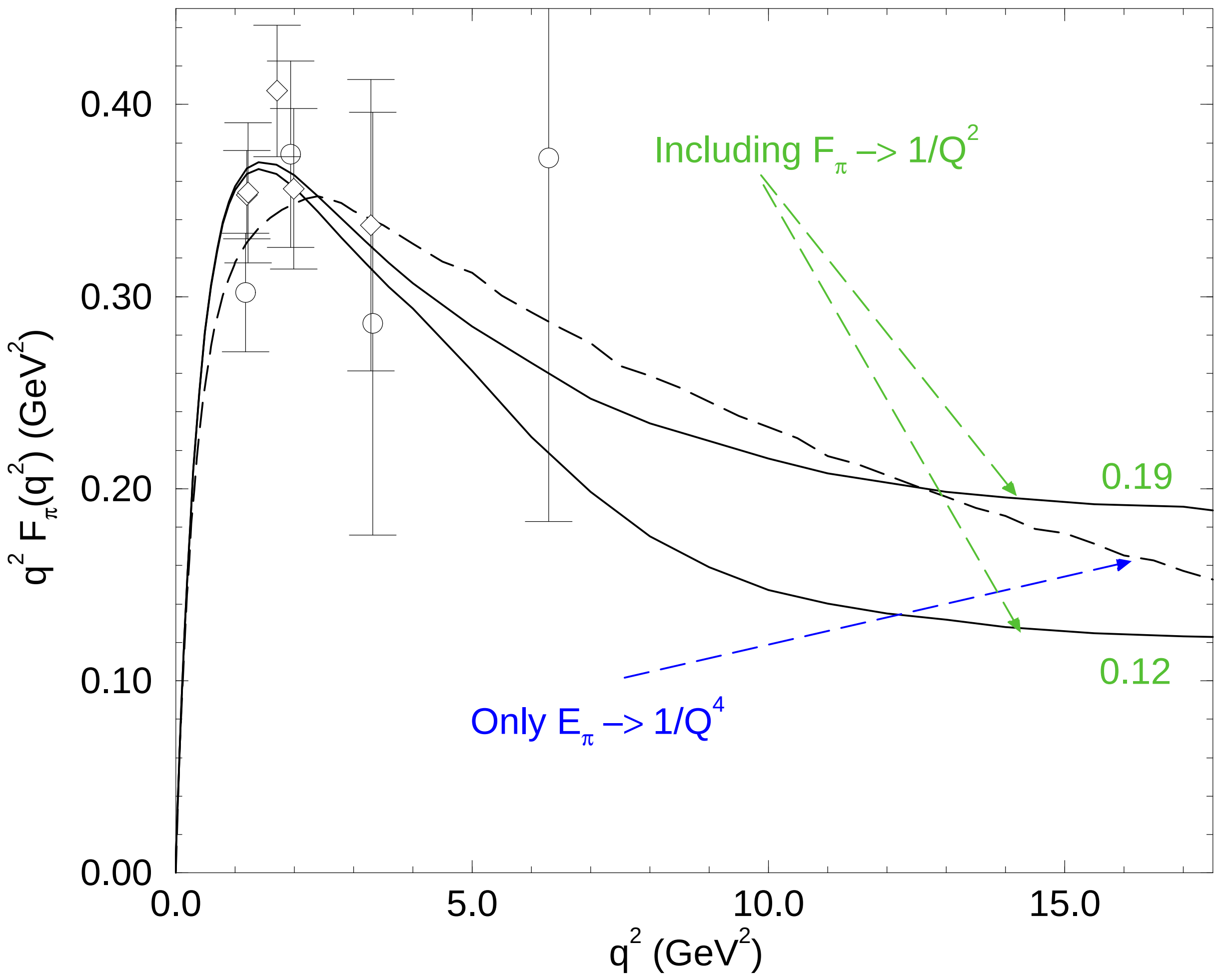

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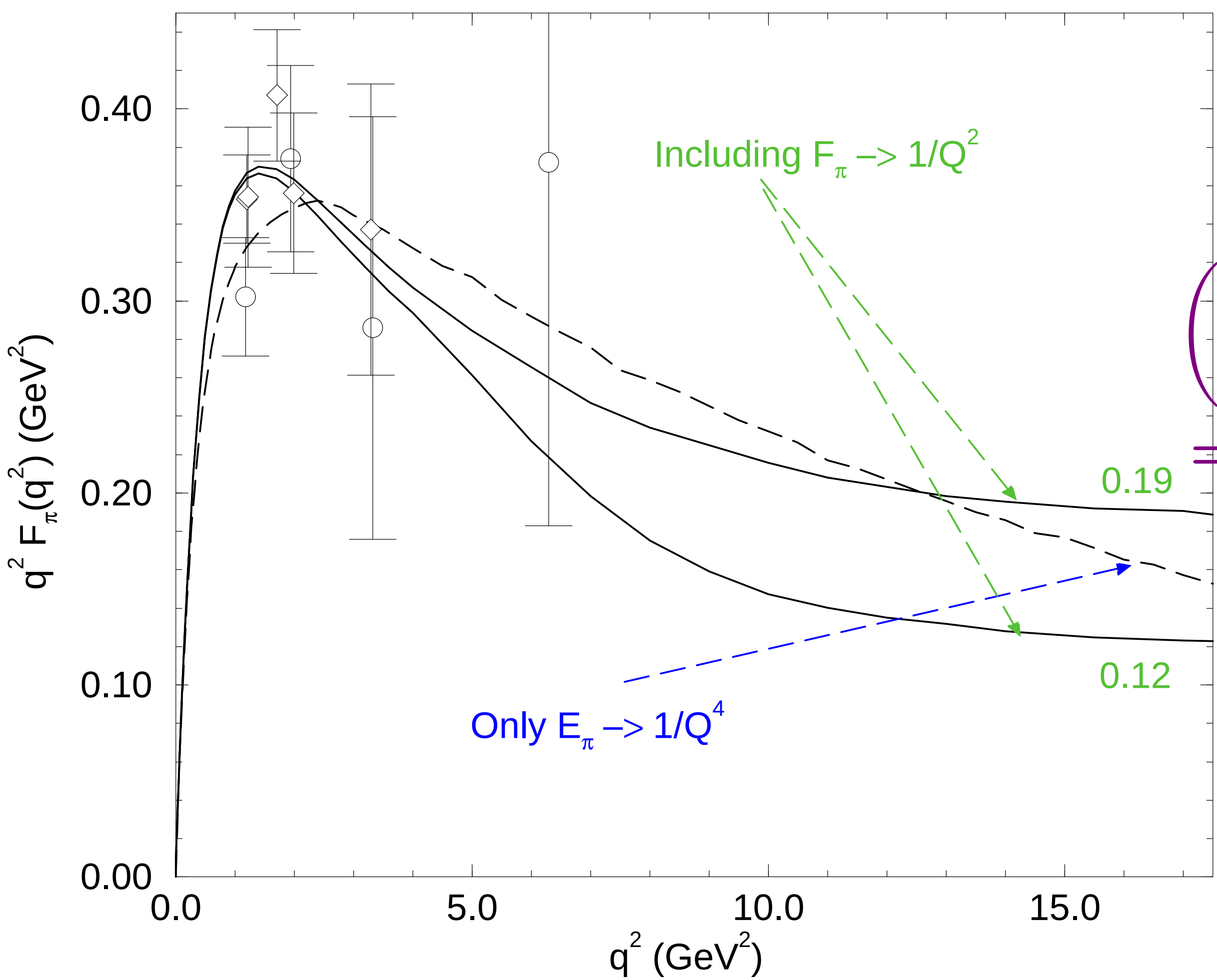

$$\left(\frac{Q}{2}\right)^2 = 2\,\mathrm{GeV}^2$$
$$\Rightarrow Q^2 = 8\,\mathrm{GeV}^2$$

- Pseudovector components dominate ultraviolet behaviour of electromagnetic form factor

GT for pion – Contact Interaction

Guttierez, Bashir, Cloët, Roberts:
arXiv:1002.1968 [nucl-th]

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  - Has pseudovector component
    $\sim E_\pi[\sigma_S(k_+)\sigma_V(k_-) + \sigma_S(k_-)\sigma_V(k_+)]$

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    - Hence F_π on LHS is forced to be nonzero because E_π on RHS is nonzero owing to DCSB

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  - $E_\pi F_\pi$-term. Breit Frame: pion$(P=(0,0,-Q/2,iQ/2))$

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GT for pion – Contact Interaction

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arXiv:1002.1968 [nucl-th]

- Bethe-Salpeter amplitude: General Form

$$\Gamma_\pi(P) = \gamma_5[iE_\pi(P) + \frac{1}{M_Q}\gamma \cdot P F_\pi(P)]$$

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  - E_π^2-term $\Rightarrow F^{\rm em}_{\pi\,E}(Q^2) \sim \frac{M^2}{Q^2}$, photon$(Q)$
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- This behaviour dominates for $Q^2 \gtrsim M_Q^2 \dfrac{E_\pi}{F_\pi} > 0.8\,\mathrm{GeV}^2$

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Computation: Elastic Pion Form Factor

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- DSE prediction: $M(p^2)$; i.e., interaction $\dfrac{1}{|x-y|^2}$
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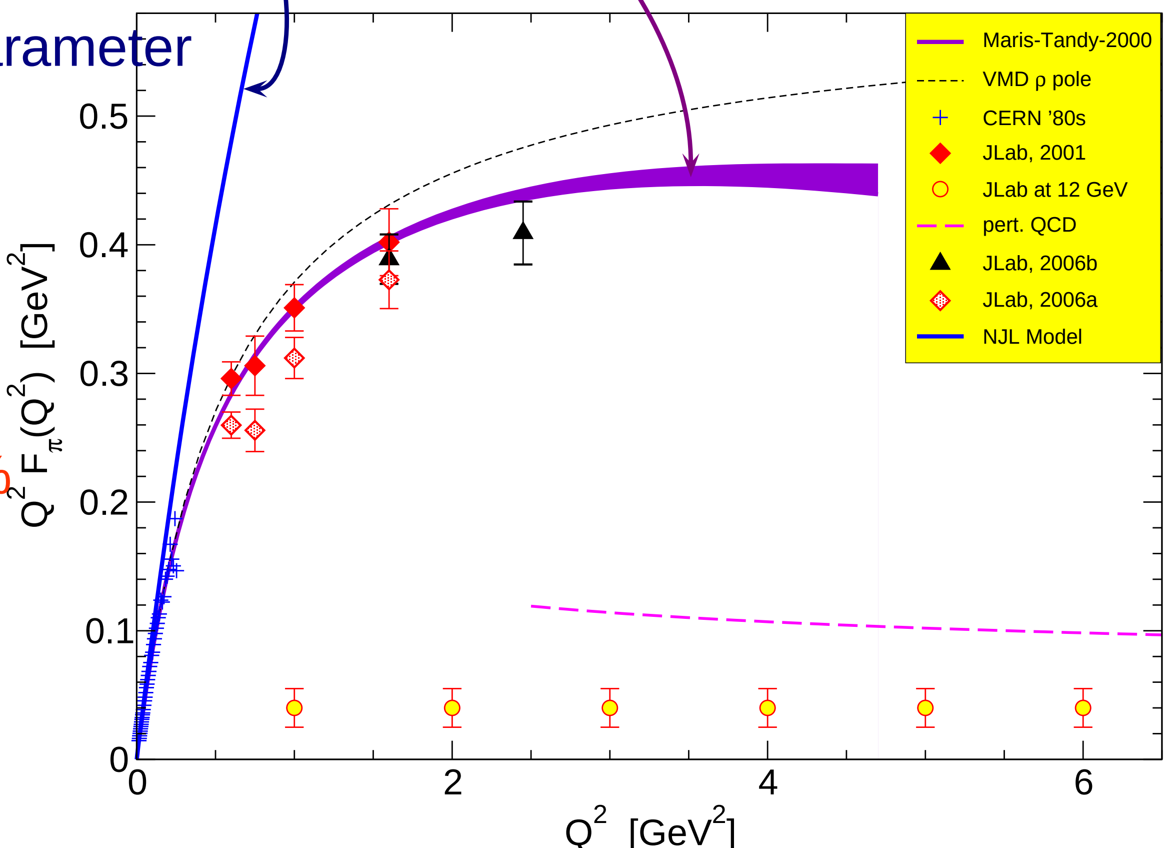
Disagreement $> 20\%$ for $Q^2 > M^2$



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Ratio – Kaon/Pion
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Trang: PhD Thesis (Kent State U.)
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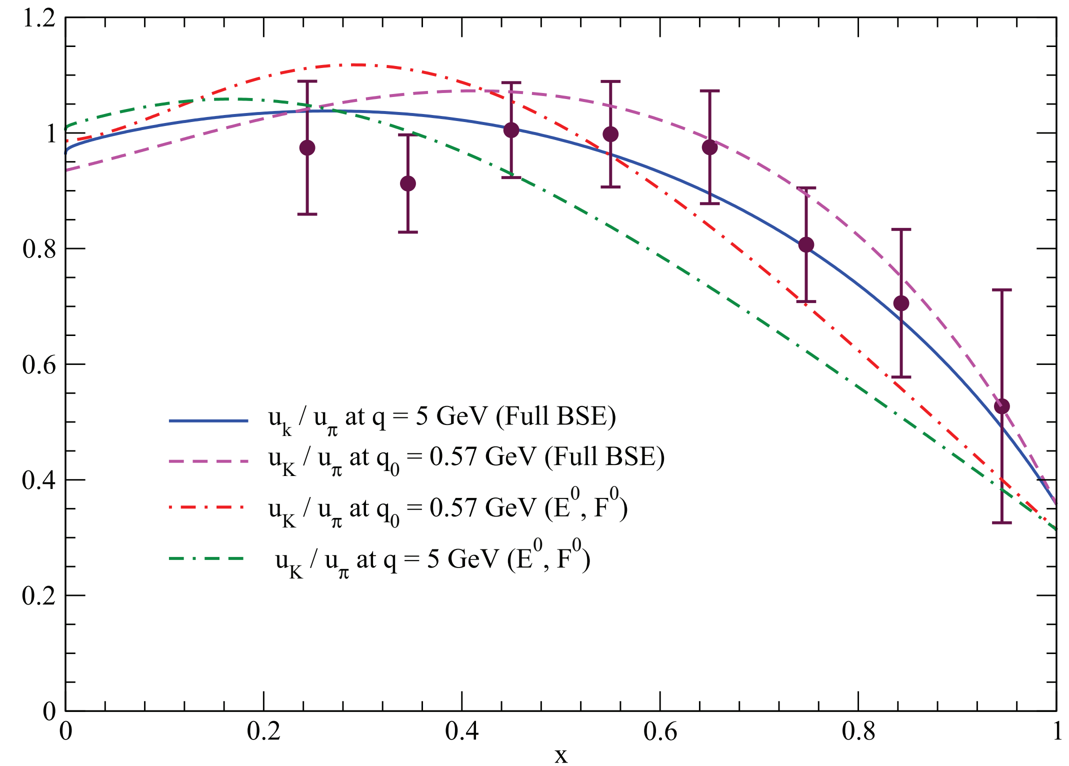
data: Badier, *et al.* , Phys. Lett. **B 93** (1980) 354



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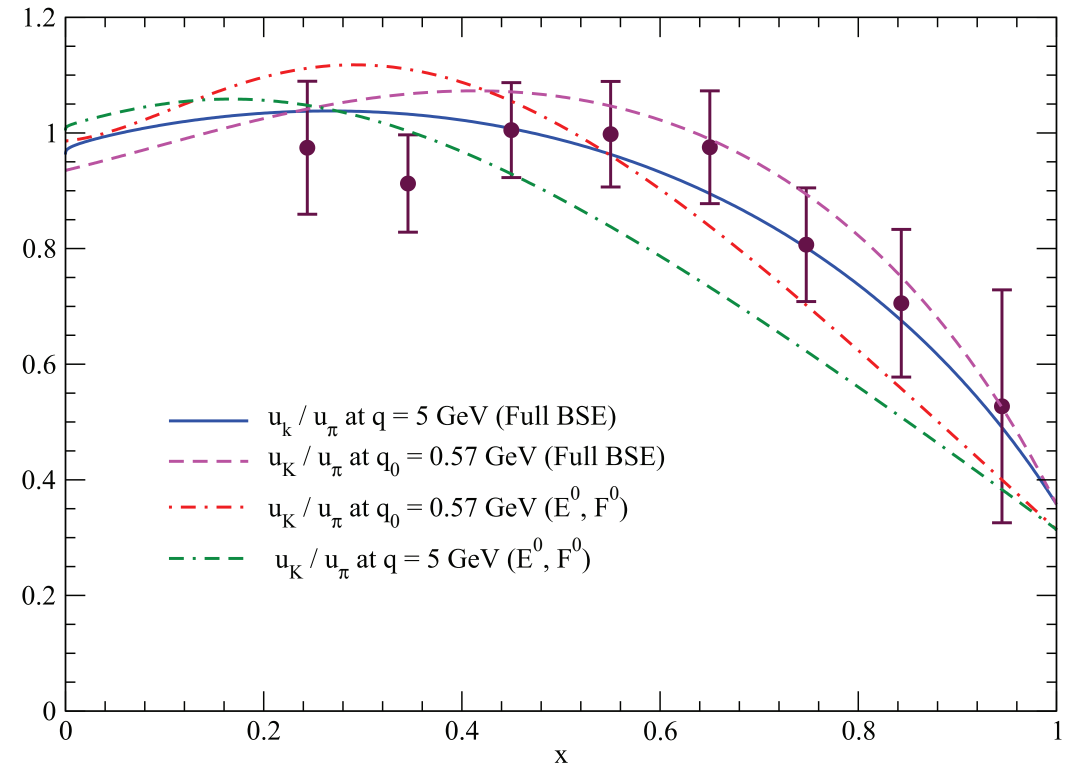

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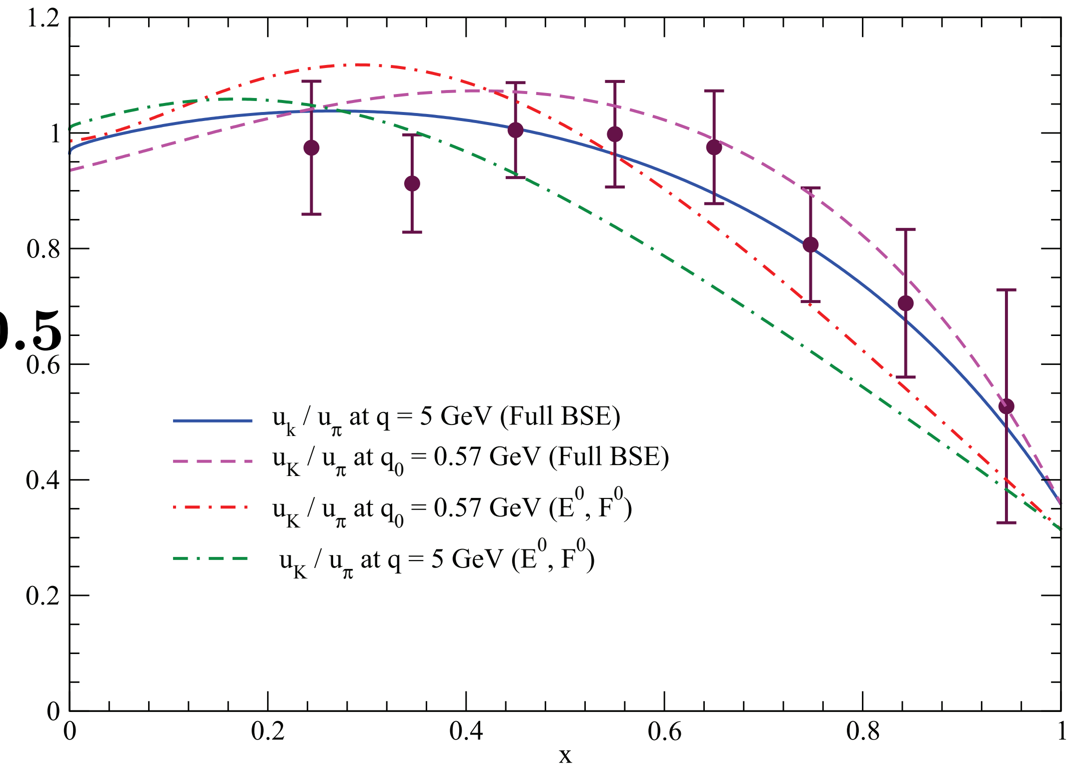

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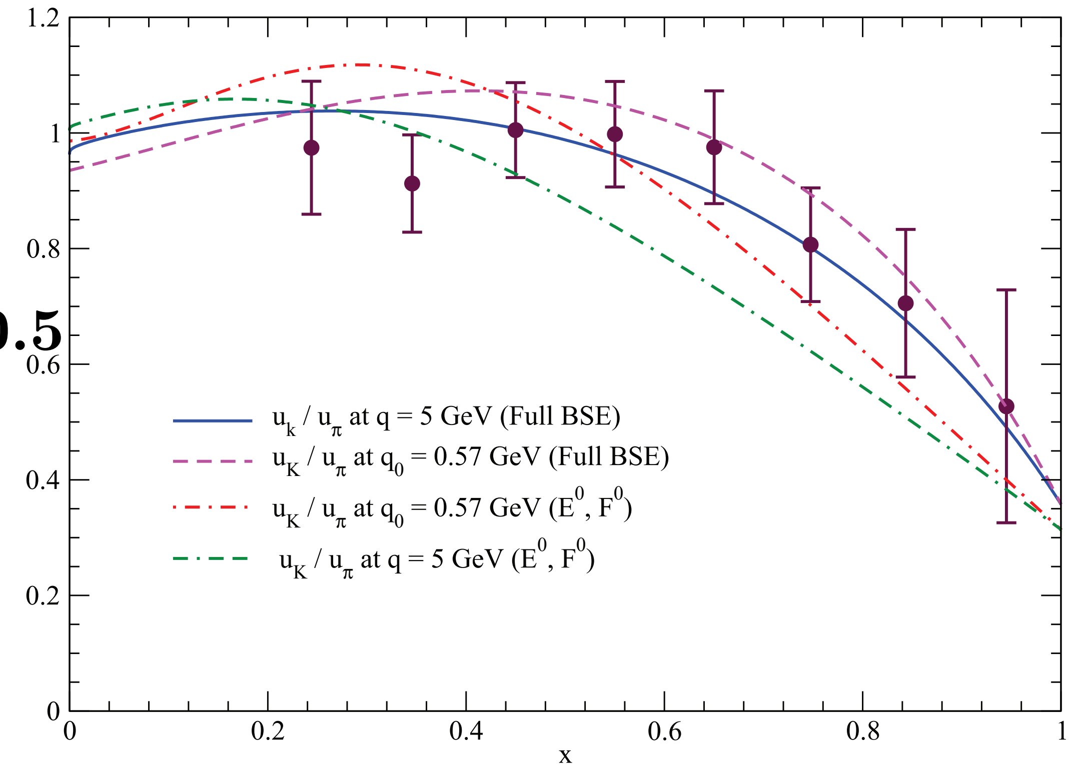

- $u_{\pi,K}(x=1)$ invariant under DGLAP-evolution

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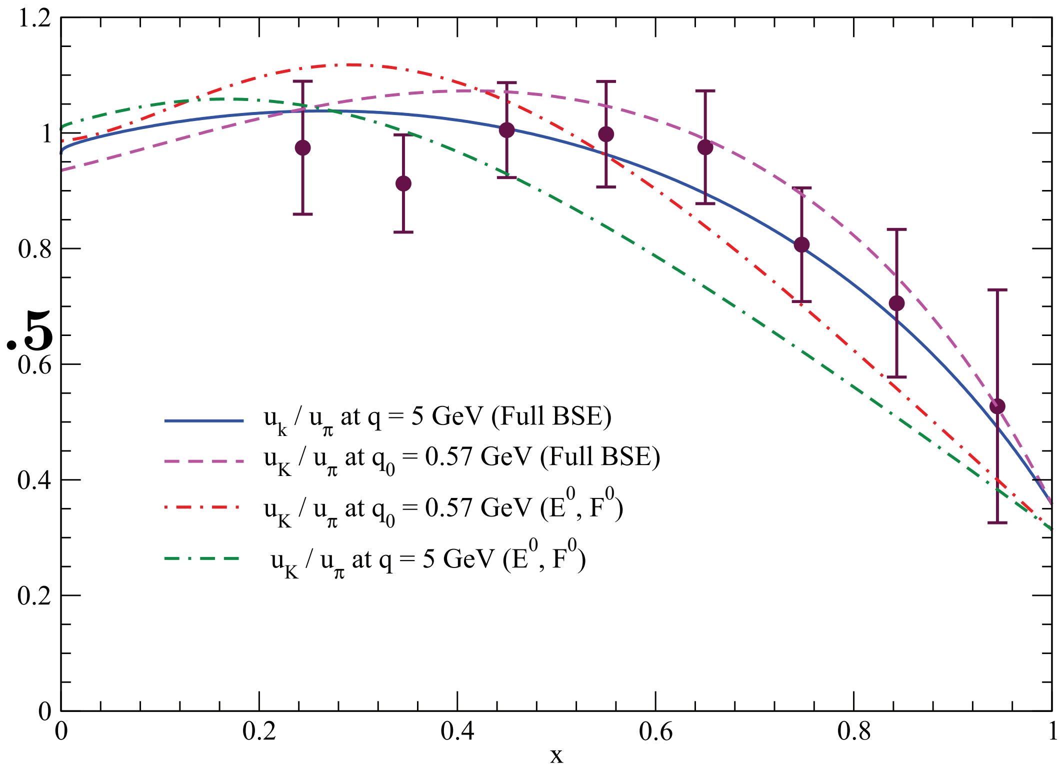

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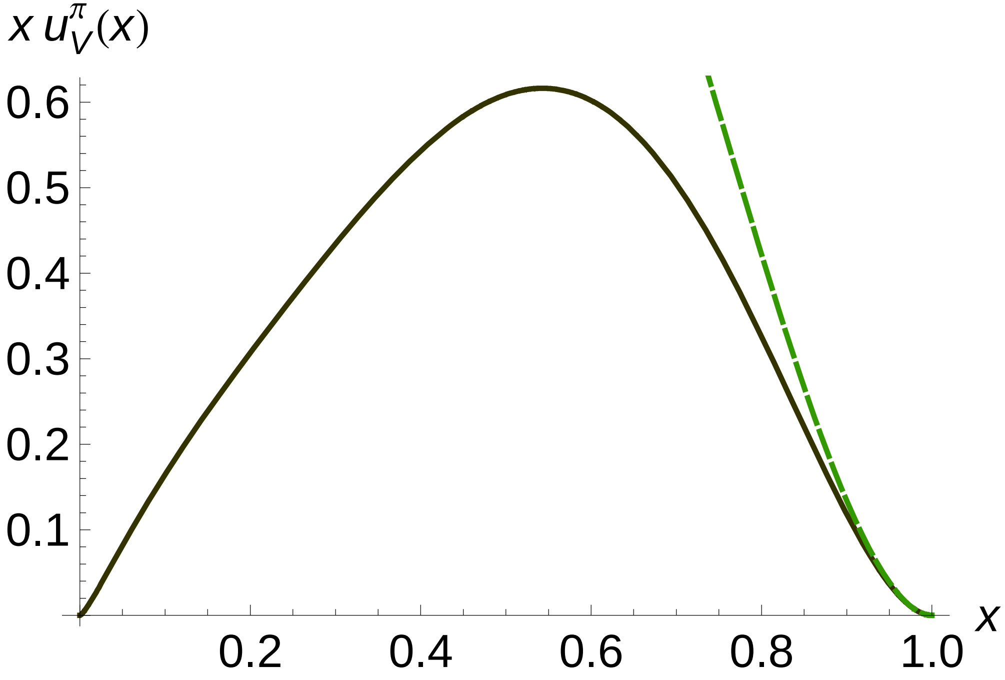
- Accessible at Upgraded JLab & Electron-Ion Collider

Pion's valence distribution

Holt & Roberts: arXiv:1002.4666 [nucl-th]



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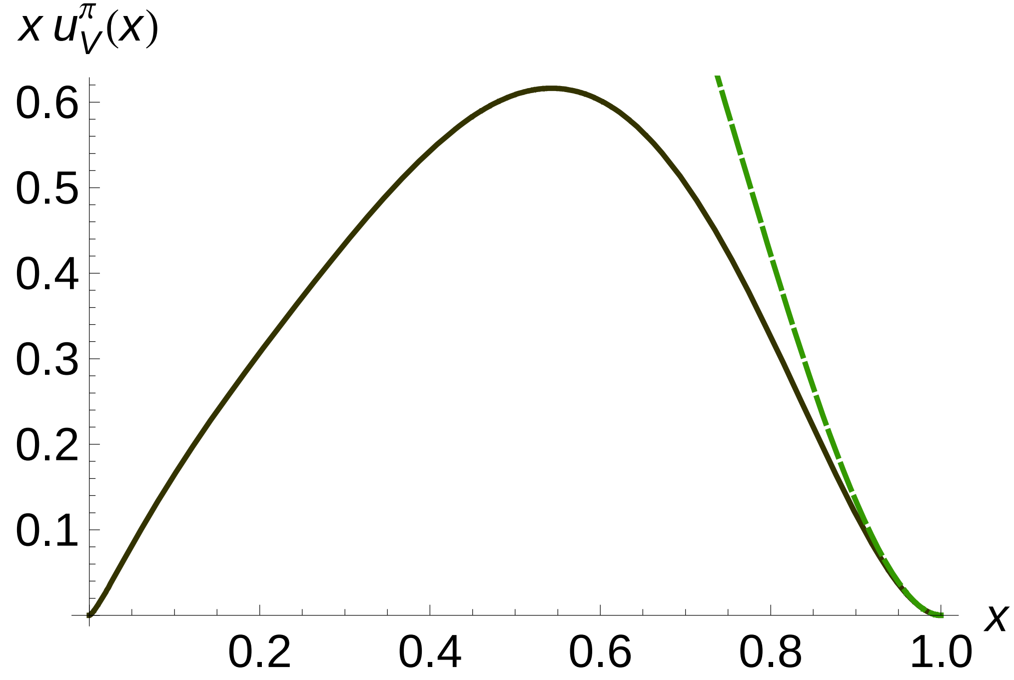

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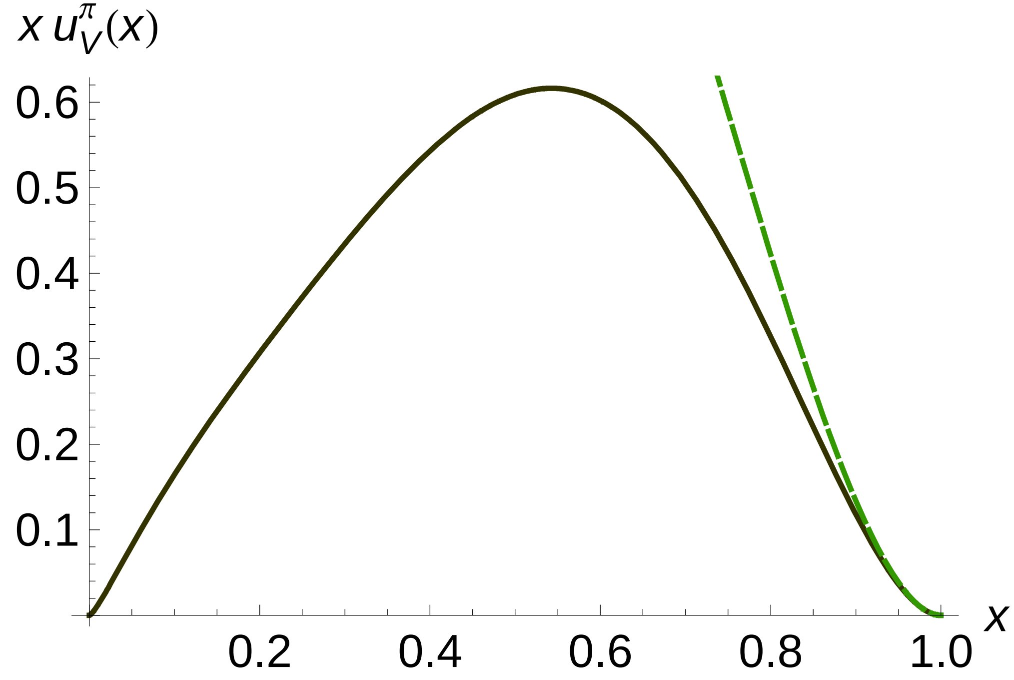

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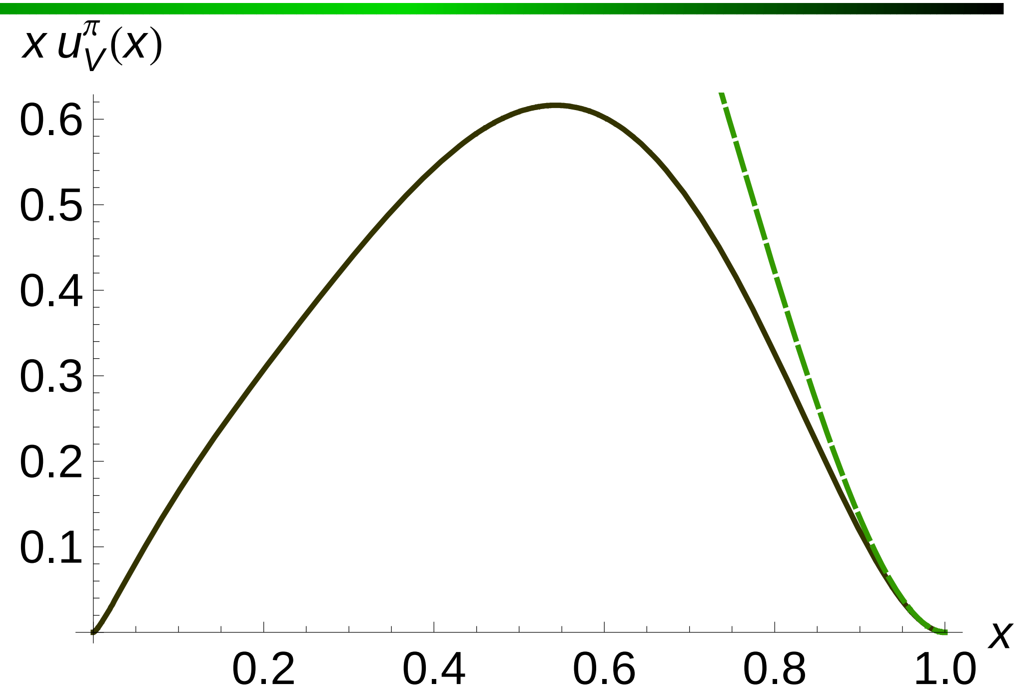

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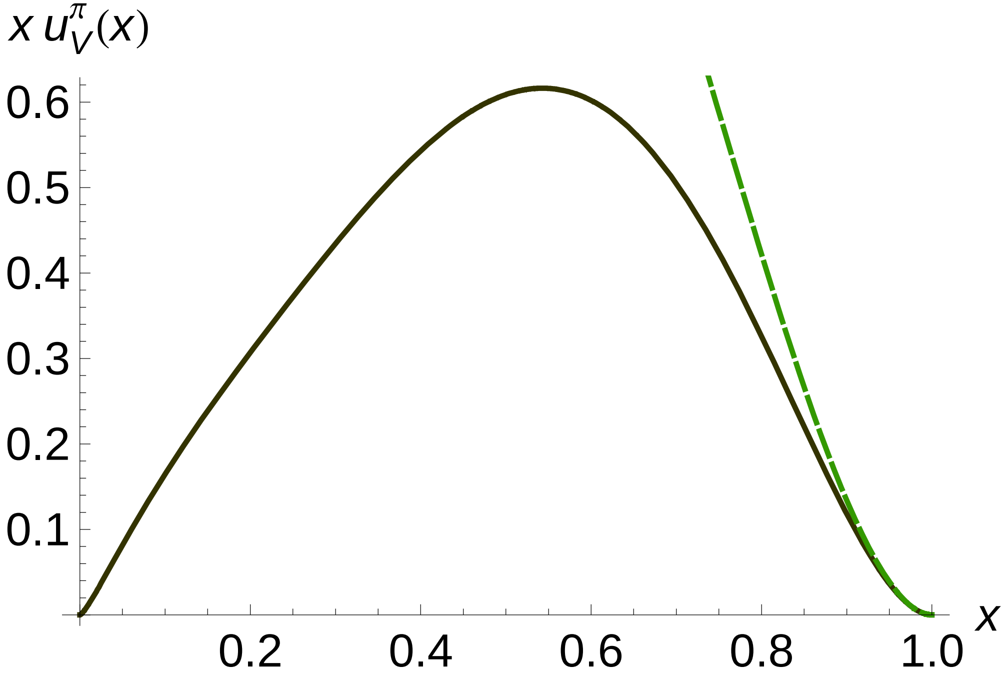

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  – location of largest-p^2 inflexion point in $M(p^2)$

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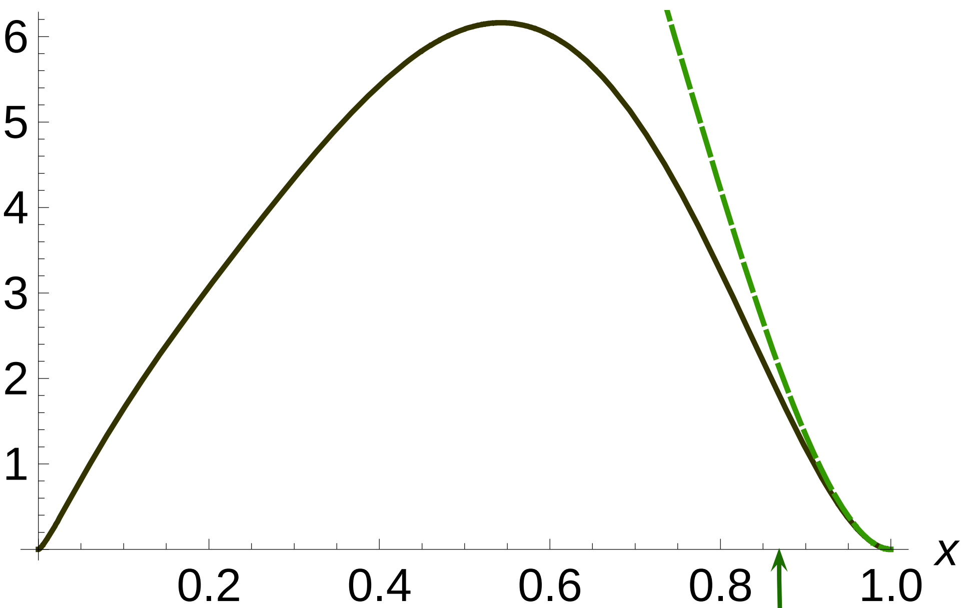

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- $M_D \approx 0.4$ GeV
  – location of largest-p^2 inflexion point in $M(p^2)$
- $\kappa_{\rm QCD} = 0 \Rightarrow q_v^\pi(x; 1\,{\rm GeV}^2) \propto (1-x)^2$
  DSE calculation shows this valid for $\mathcal{L}_x = \{x | x > 0.86\}$.

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Unifying Study
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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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- In quantum field theory a nucleon appears as a pole in a six-point quark Green function.
  - 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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  - 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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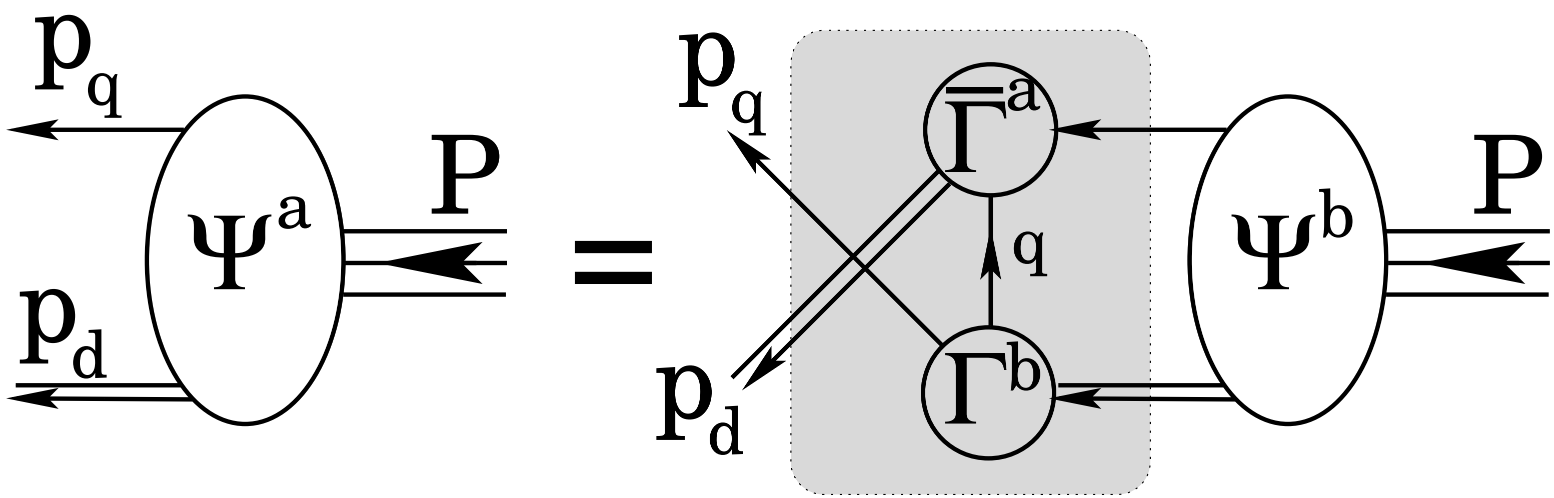

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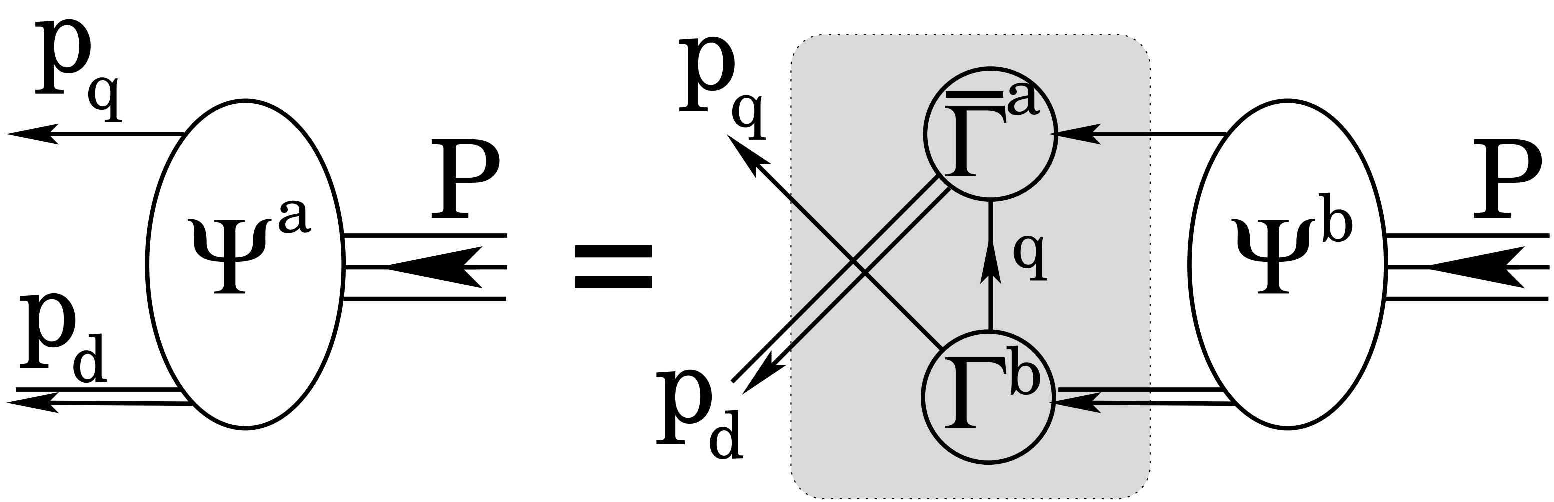
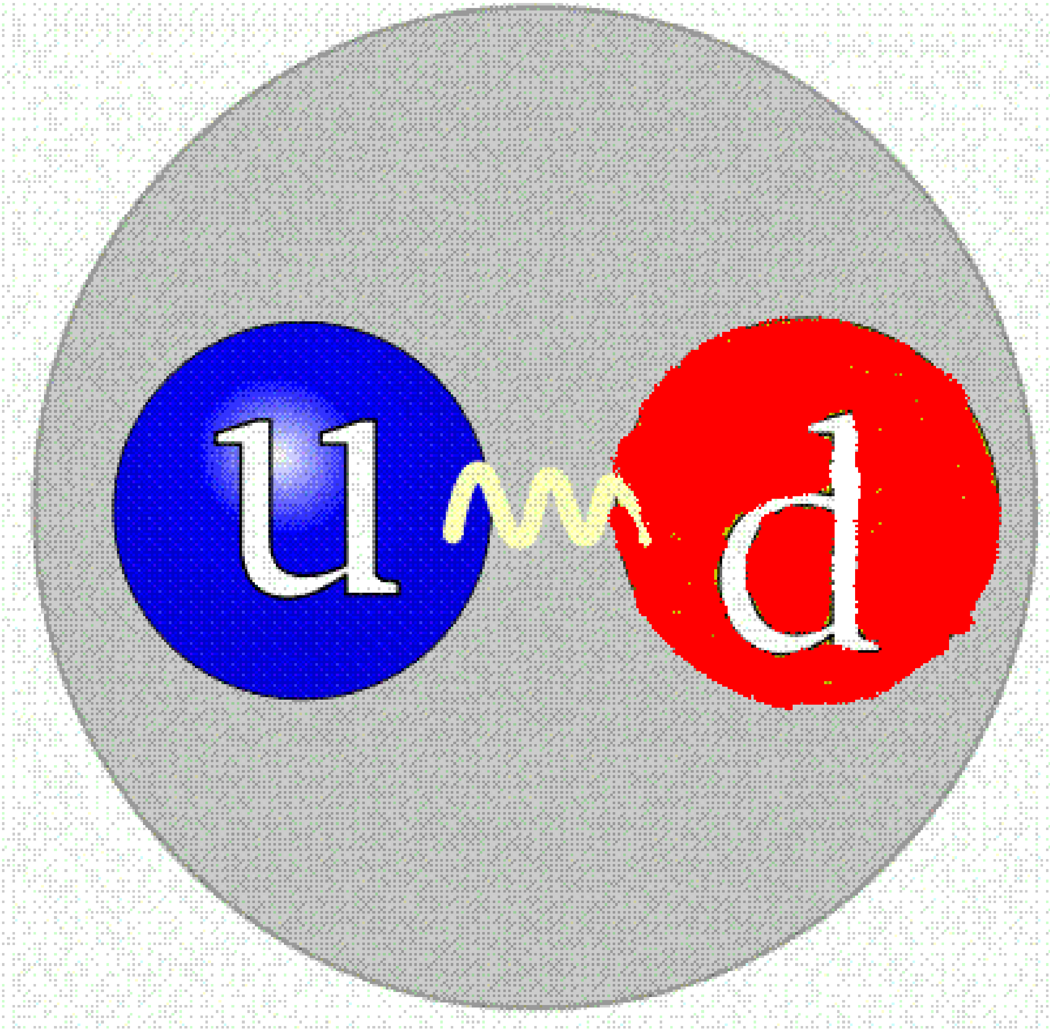


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Diquark correlations



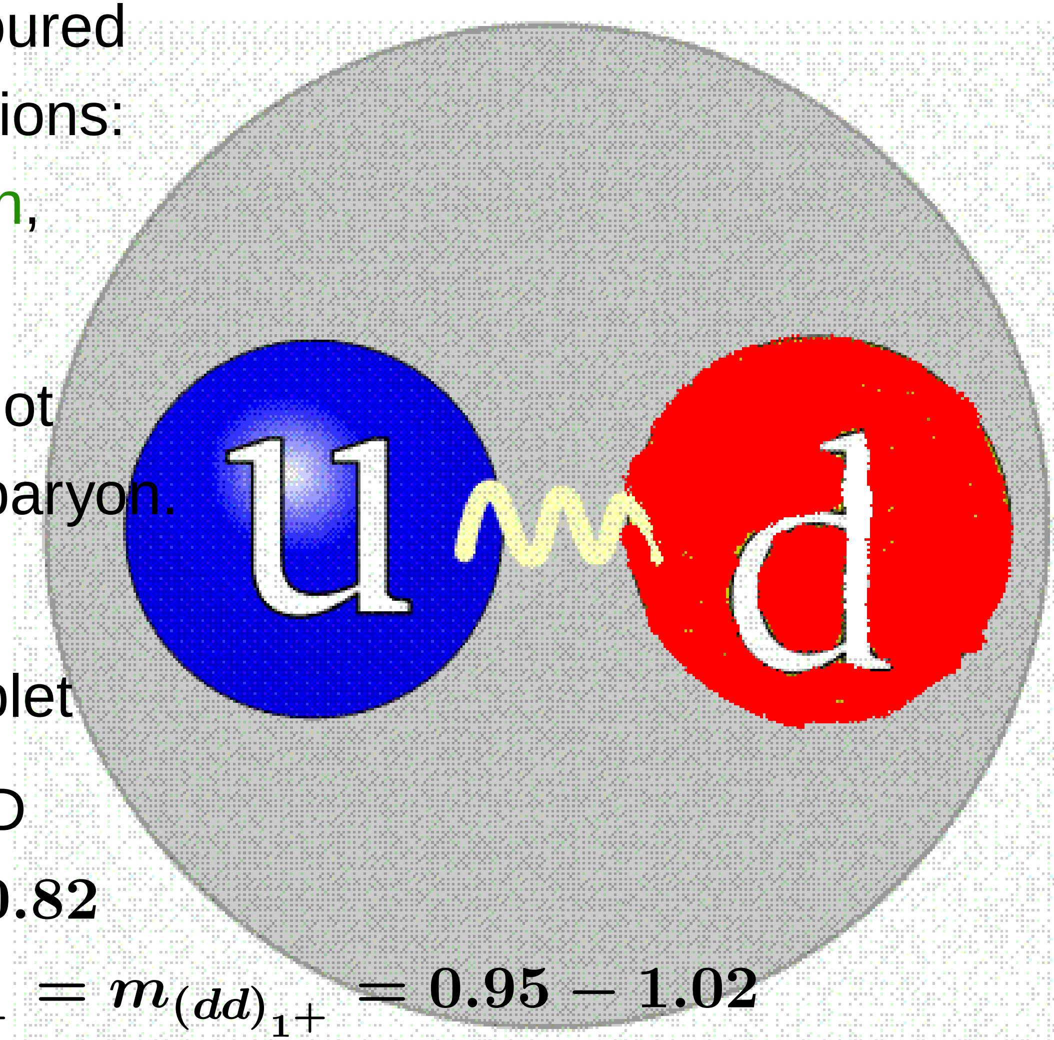
QUARK-QUARK

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

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

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



QUARK-QUARK

Nucleon-Photon Vertex

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

6 terms . . .

Nucleon-Photon Vertex

constructed systematically . . . current conserved automatically
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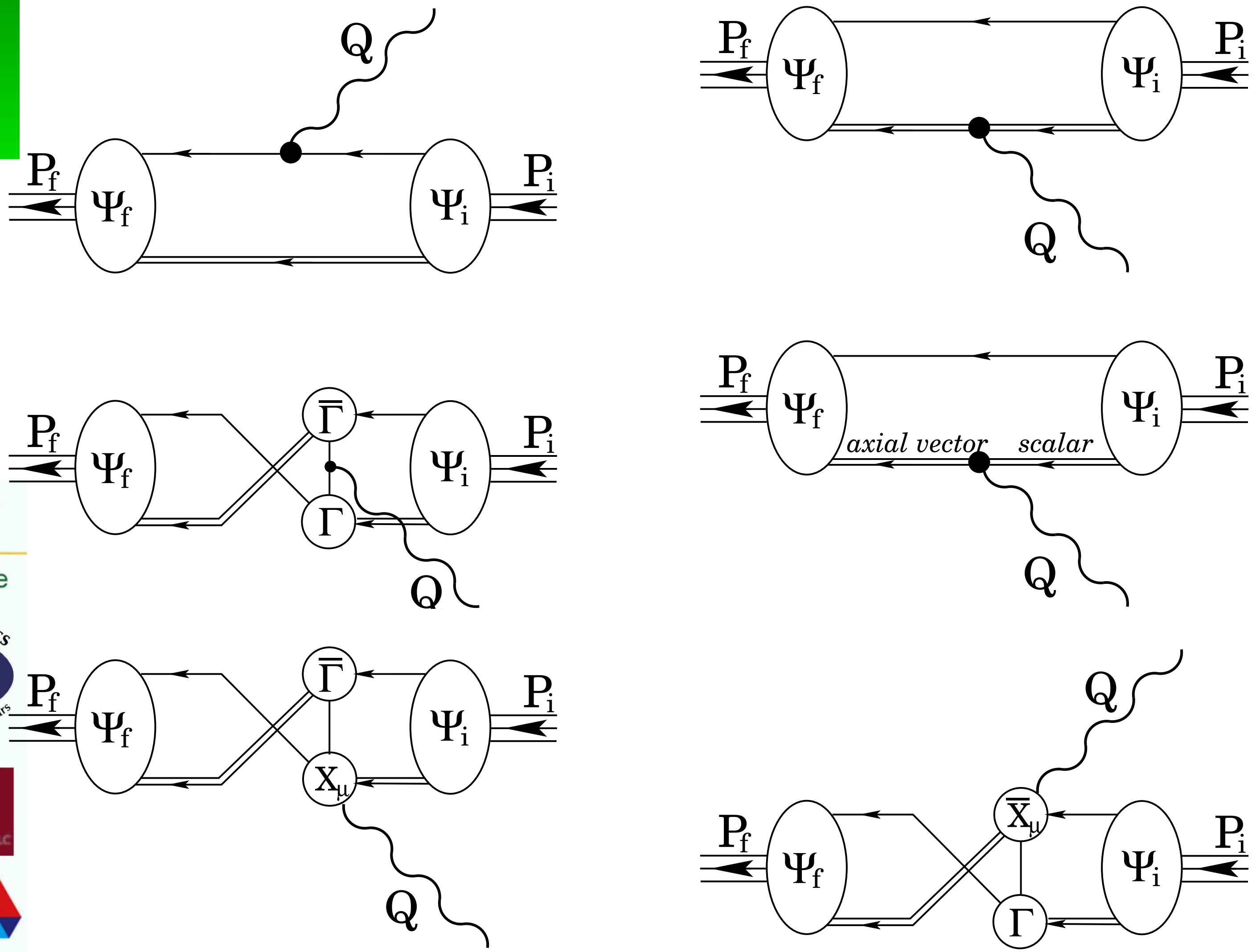

$$\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}$$

Cloët, Roberts *et al*.

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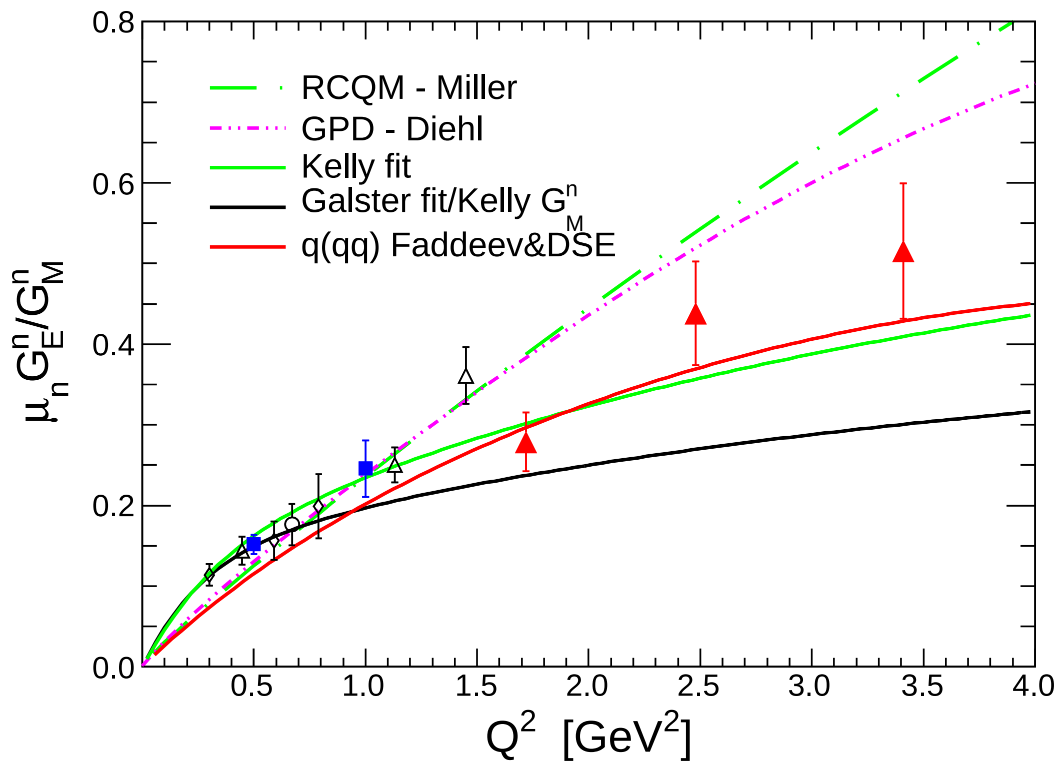

B. Wojtsekhowski, Jefferson Lab E02-013 Collaboration, *in preparation*.
Figure courtesy S. Riordan

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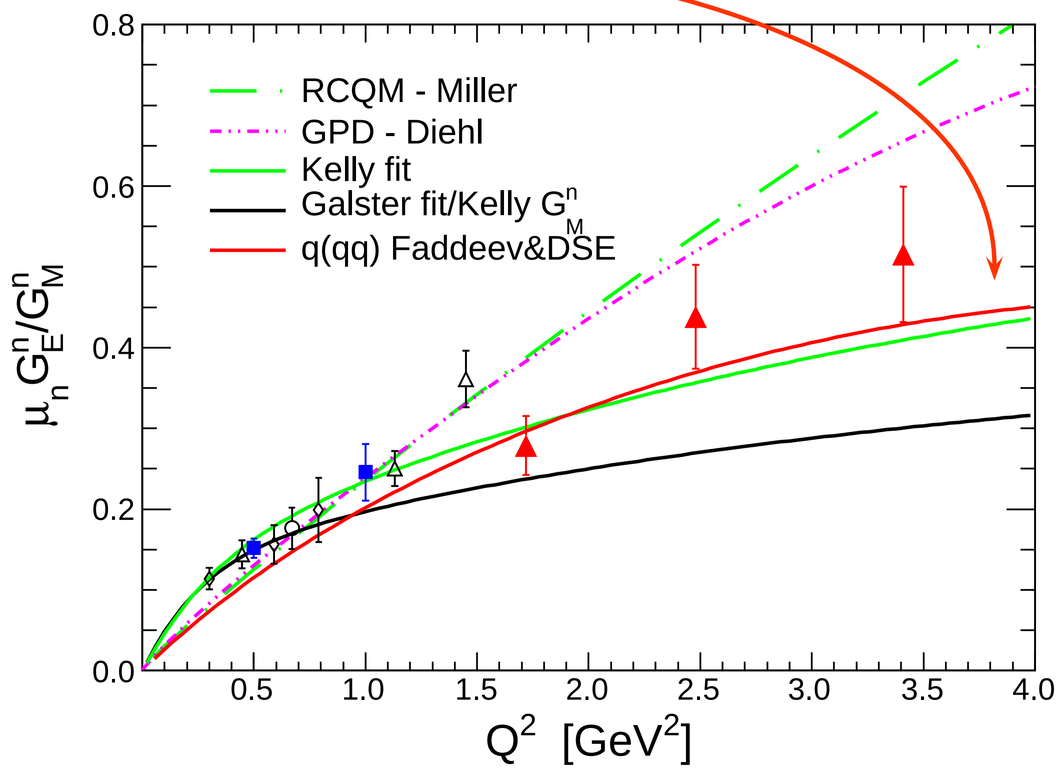
Red solid curve



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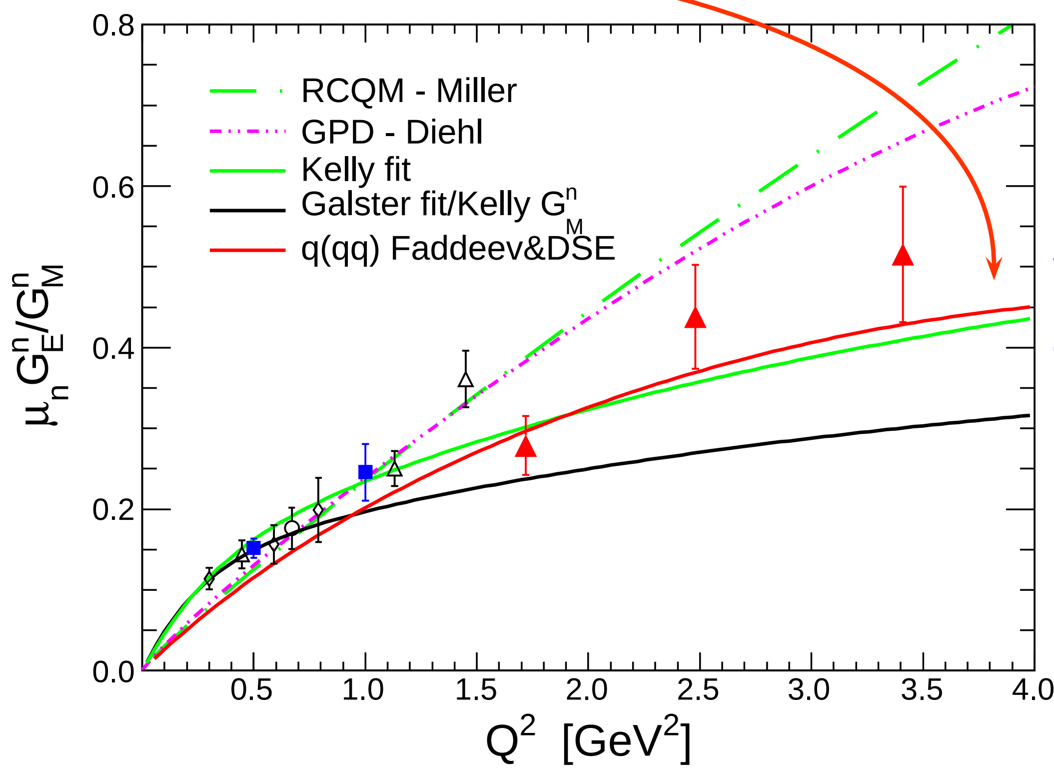

This evolution very sensitive to momentum -dependence dressed-quark propagator

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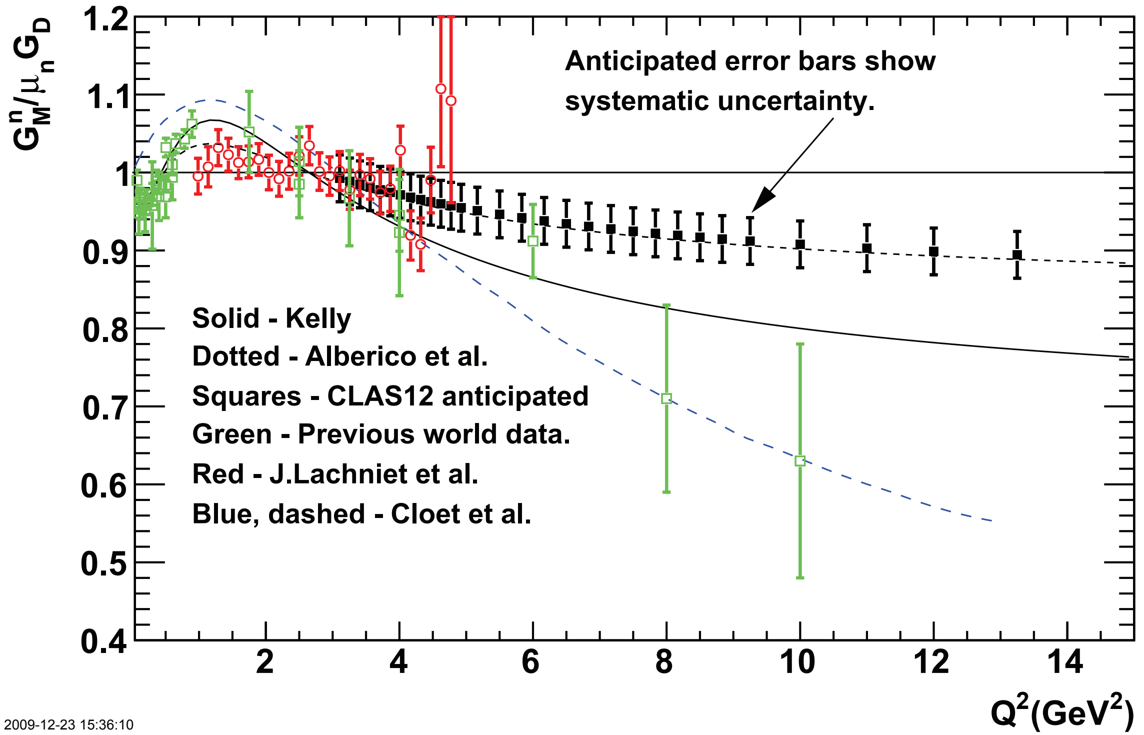

Jefferson Lab E12-07-104, *12GeV Proposal*.
Gilfoyle, Brooks, Hafidi for CLAS Collaboration

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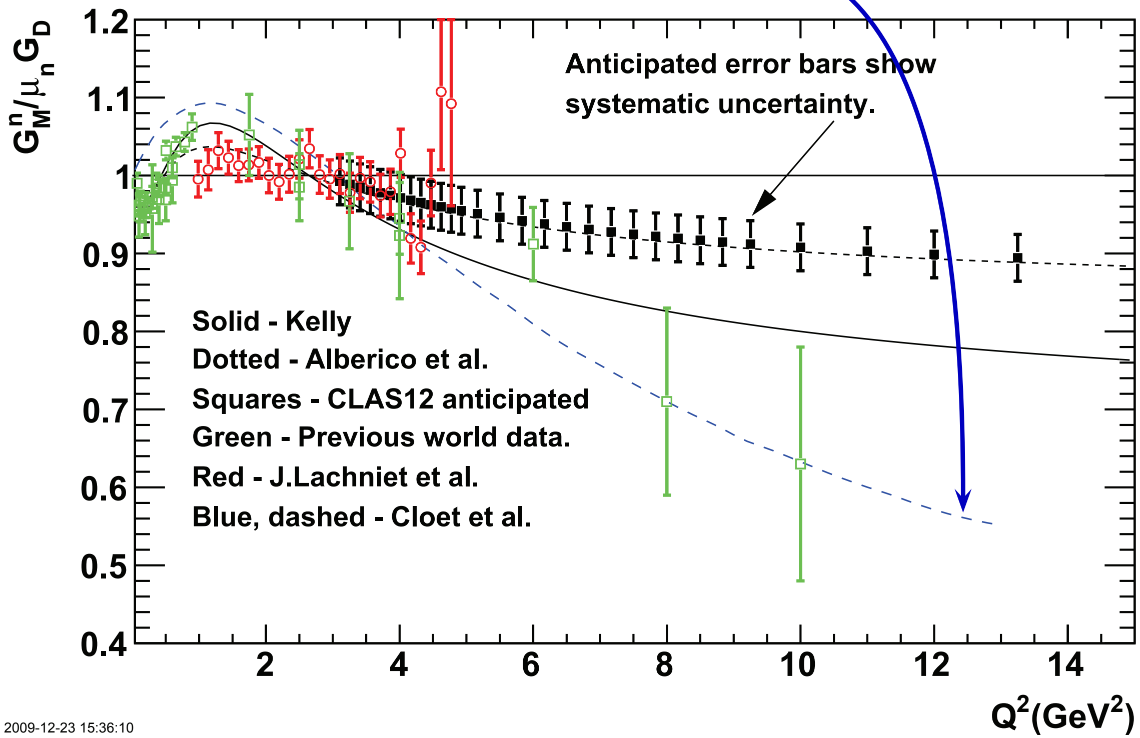
  Blue long-dashed curve



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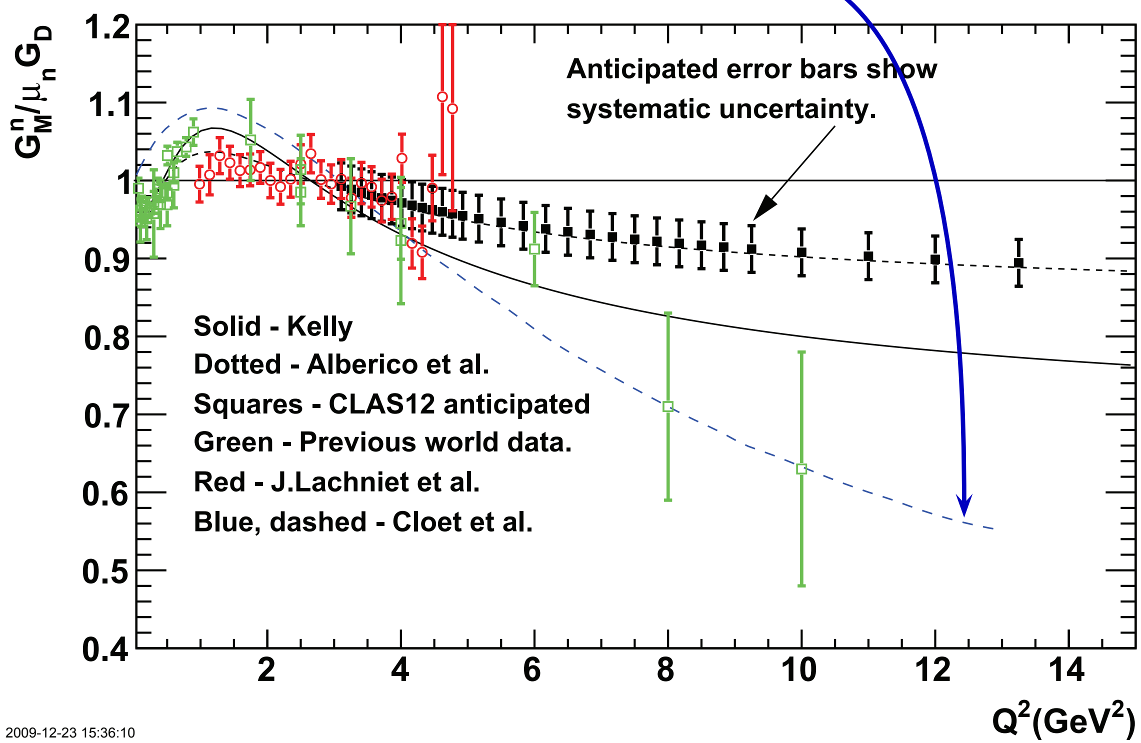

Sensitivity to $M(p^2)$ means experiments probe IR behaviour of strong running coupling

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

Gilfoyle, Brooks, Hafidi for CLAS Collaboration

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Cloët, Roberts *et al.*
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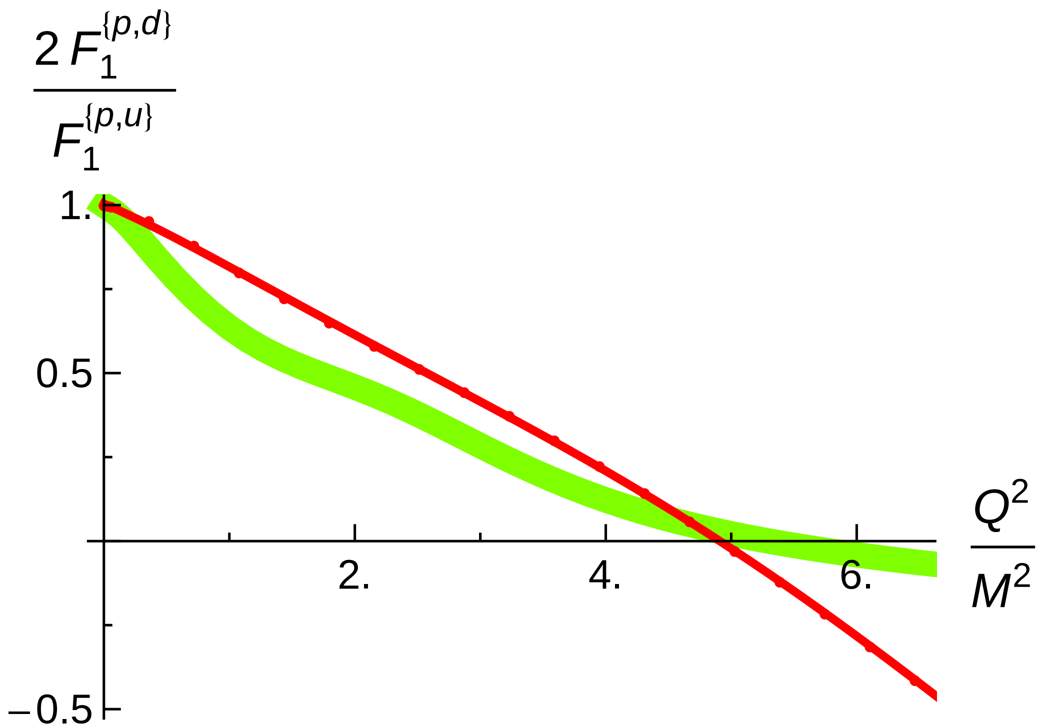

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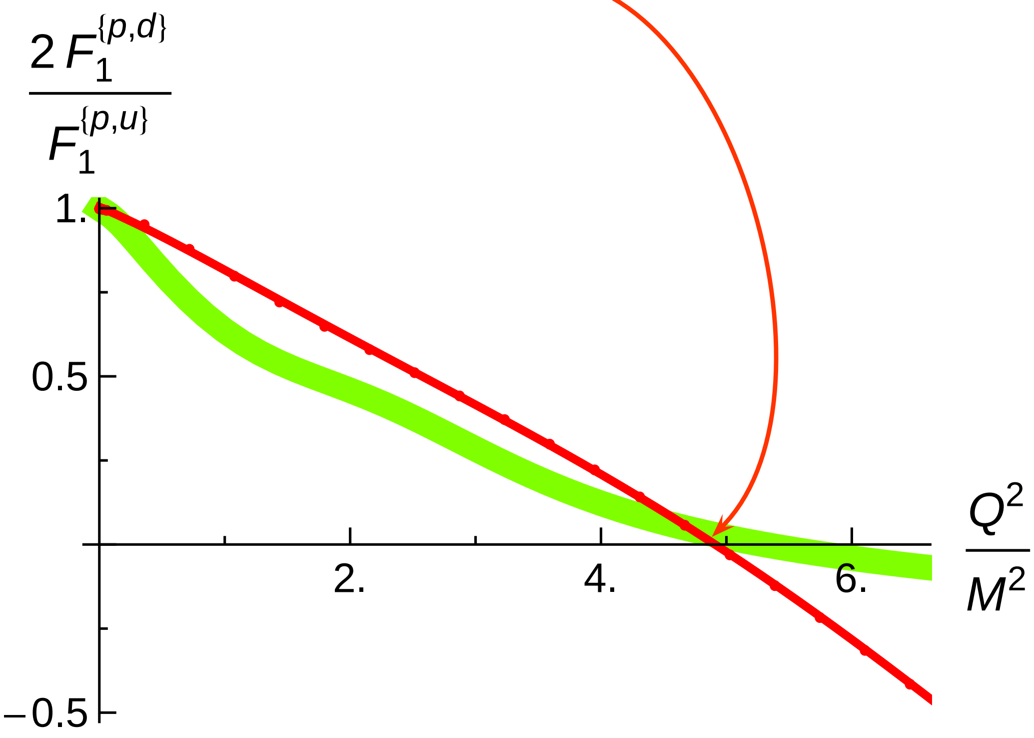

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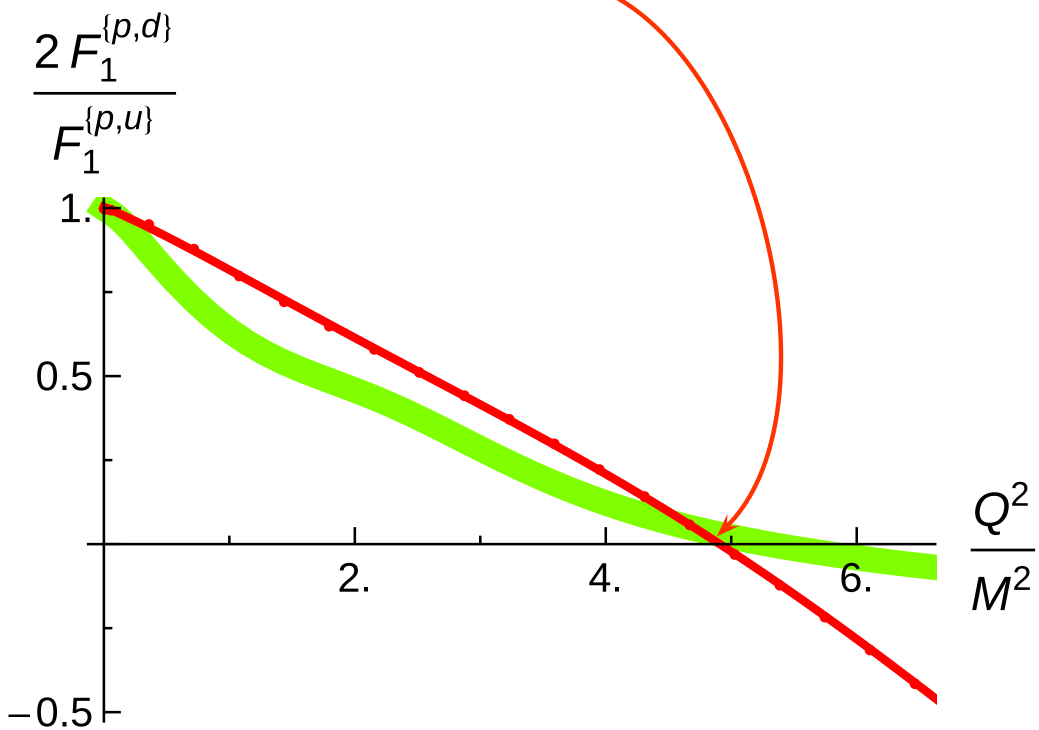

Brooks, Bodek, Budd, Arrington fit to data hep-ex/0602017.

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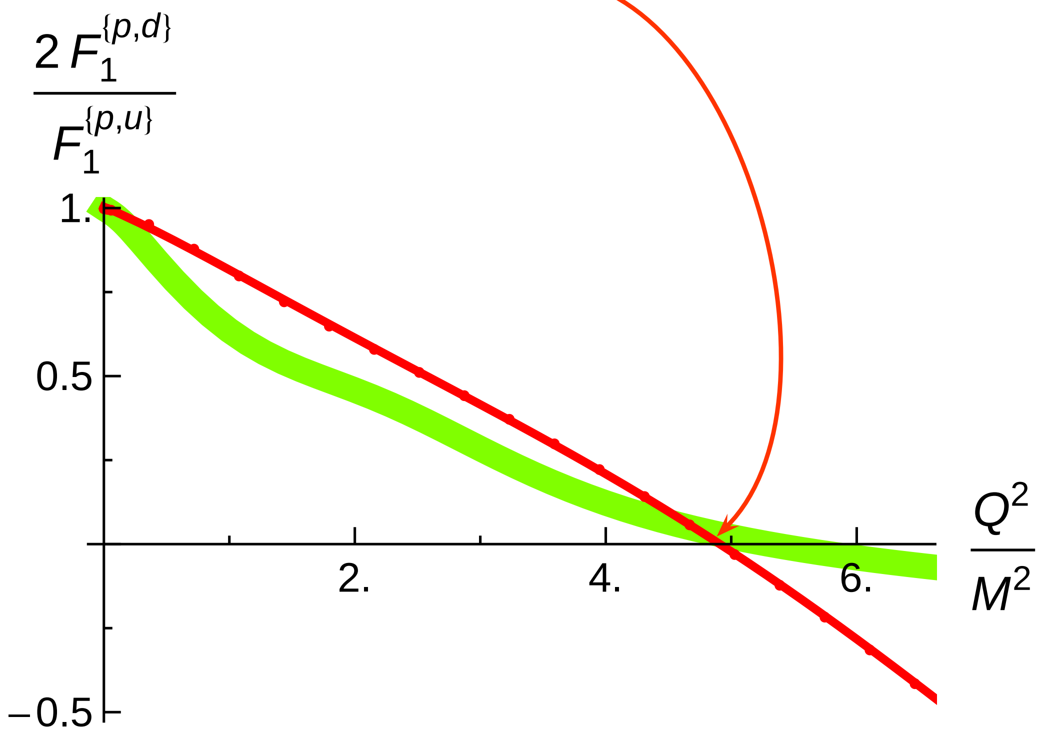

Location of zero measures relative strength of scalar and axial-vector qq-correlations

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Some current 12 GeV-related projects

- Elucidate signals of $M(p^2)$ in Q^2-evolution of nucleon elastic and transition form factors; viz.,
  - $N \to \Delta$
  - $N \to$ P11(1440)
  - $\kappa(p^2)$

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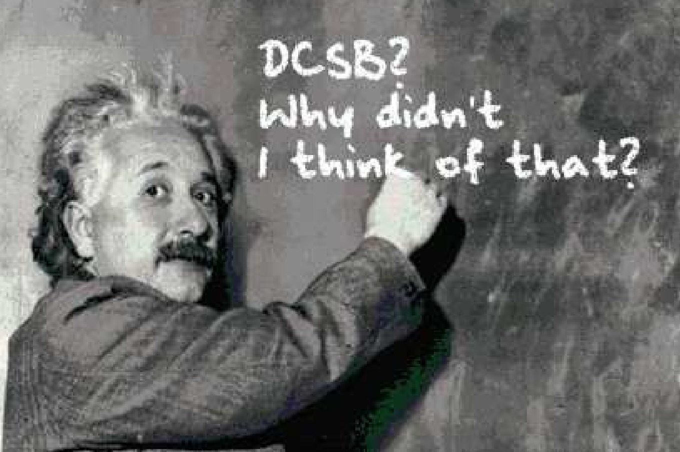
- Incorporate "resonant contributions" (pion cloud) in kernels of bound-state equations (e.g., arXiv:0802.1948 [nucl-th] & arXiv:0811.2018 [nucl-th]; and *C.S. Fischer et al.*)

Epilogue



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- DCSB exists in QCD.

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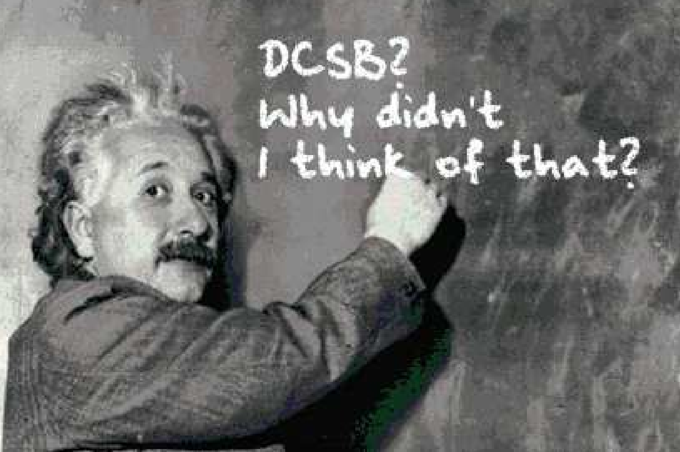

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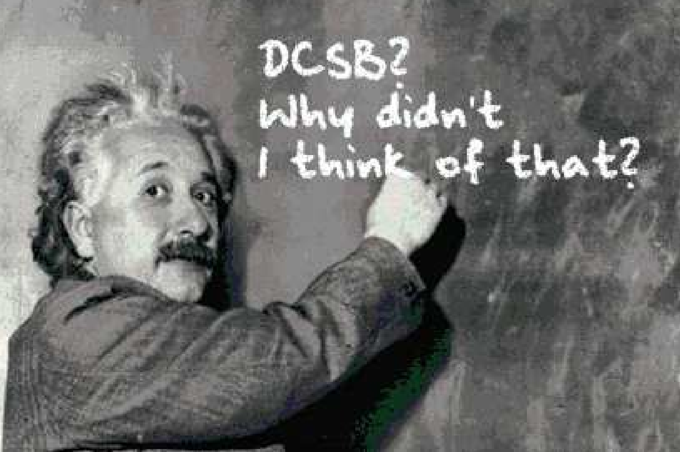

Epilogue

- 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 $\rightarrow$ 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 $g_{\pi\bar{N}N} \approx 12.8 \approx 3g_{\pi\bar{q}q}$

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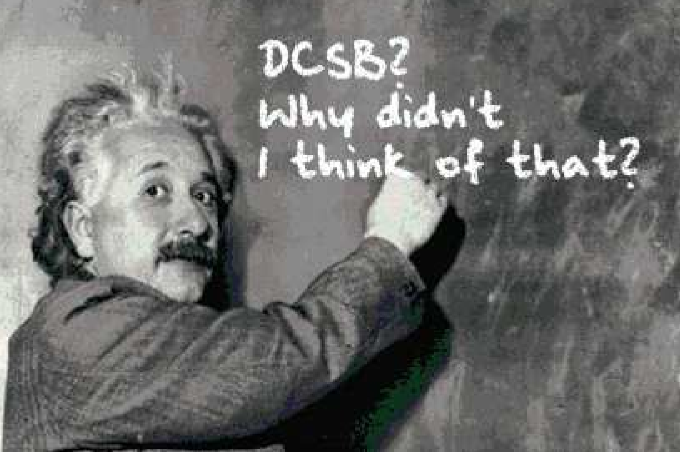

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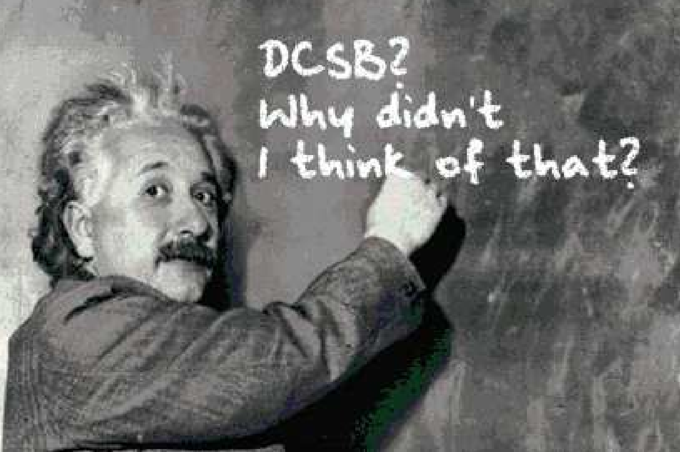

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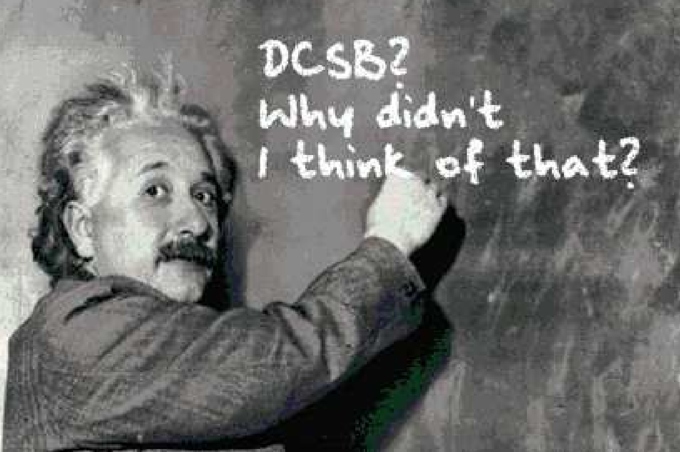

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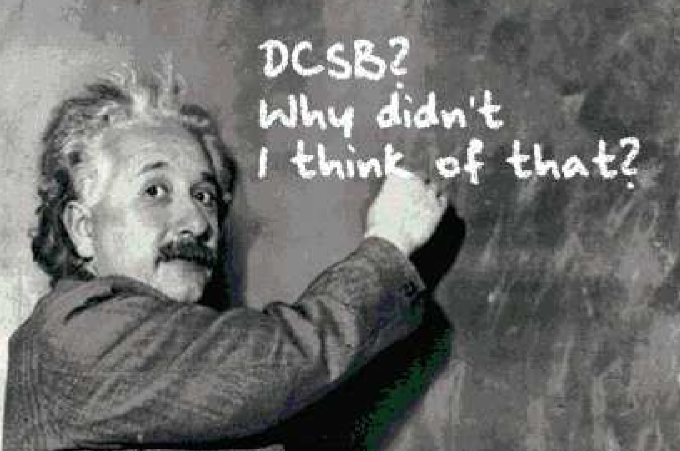

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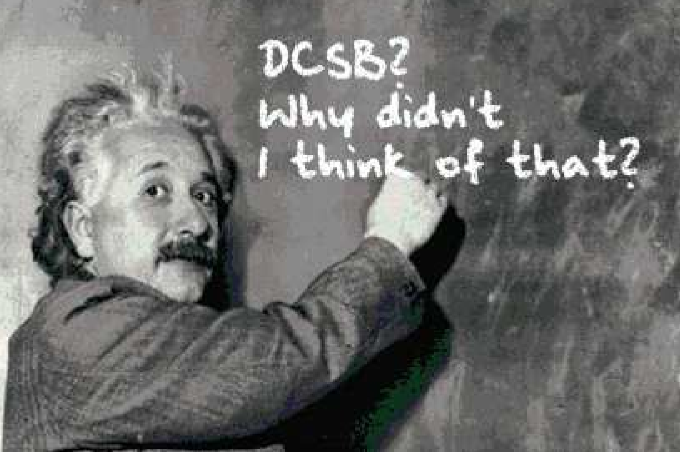

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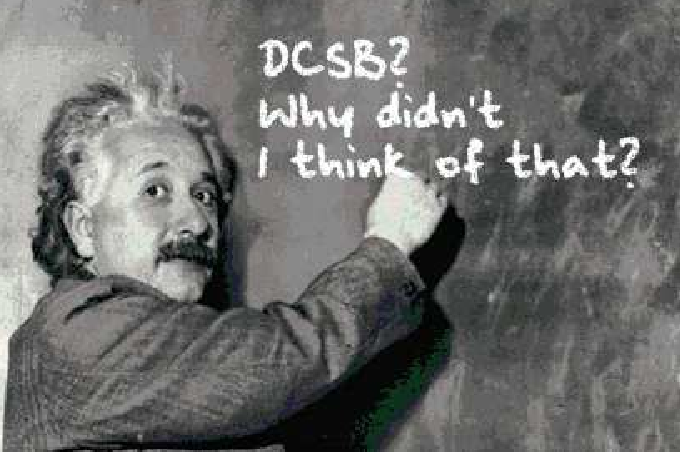
- DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks

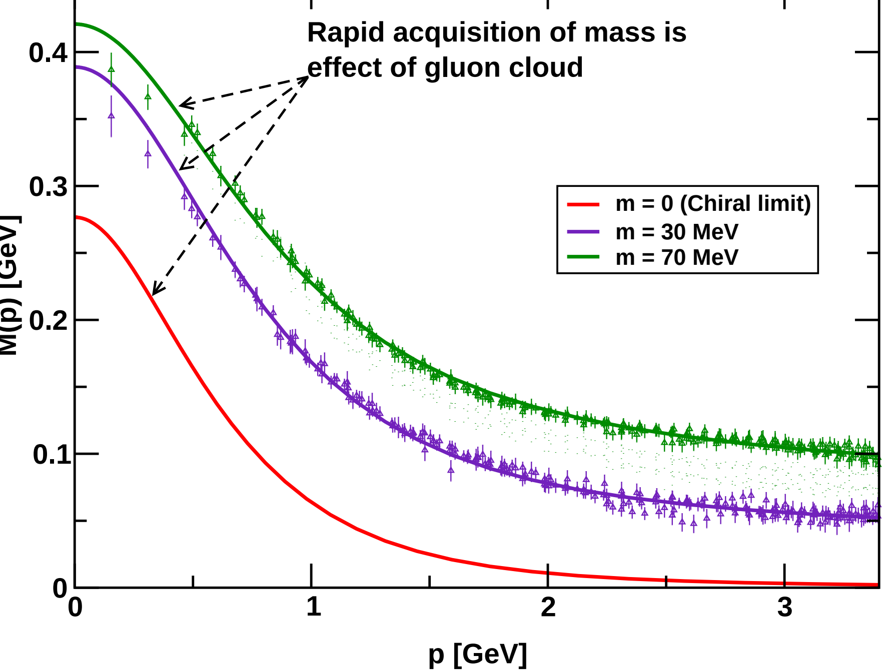


Epilogue

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

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