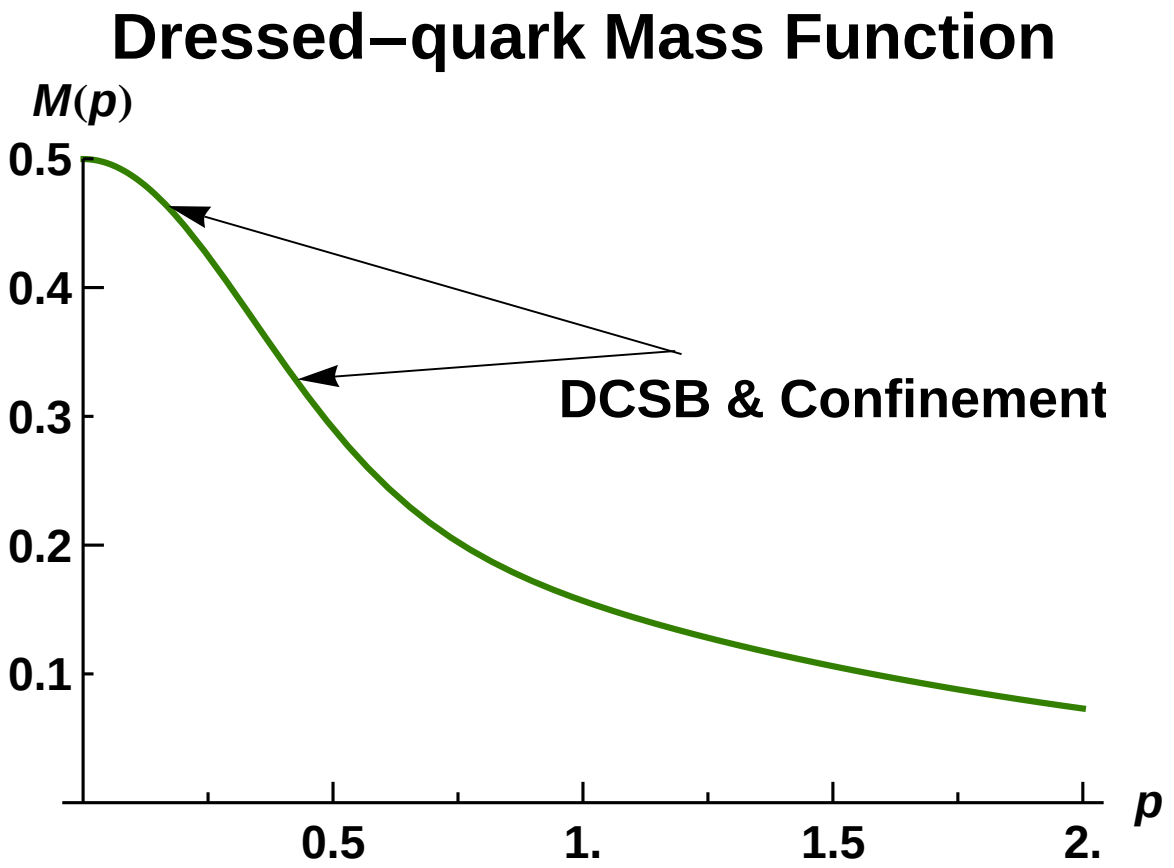
Exposing the Dressed Quark's mass



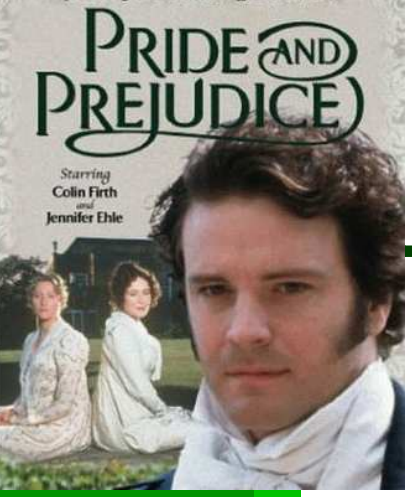
Craig D. Roberts
cdroberts@anl.gov

Physics Division & **School of Physics**

Argonne National Laboratory **Peking University**

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

Universal Truths



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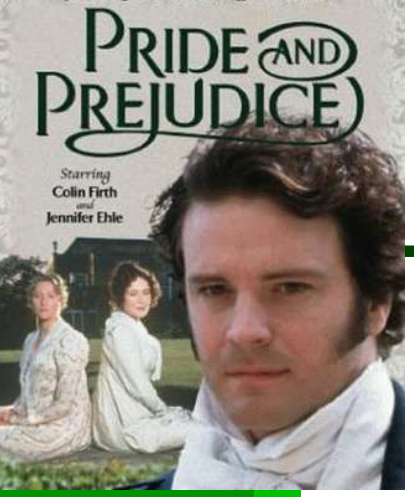

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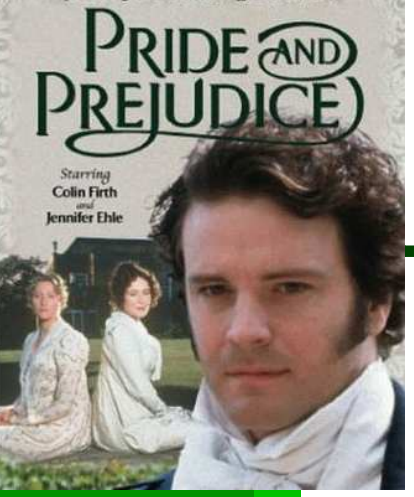

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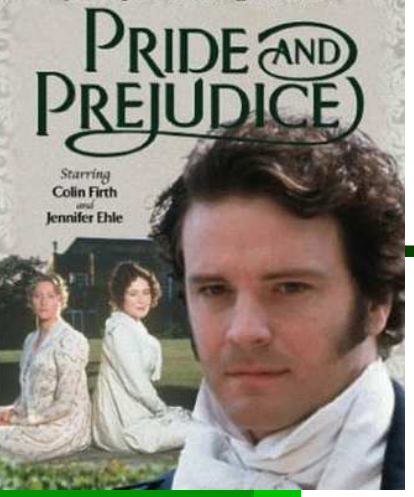

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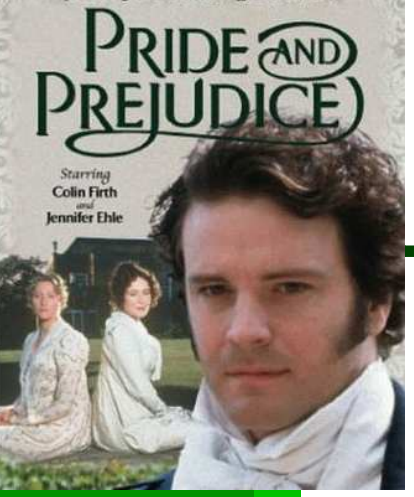

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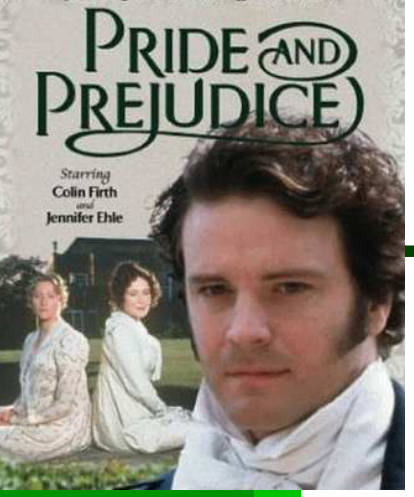

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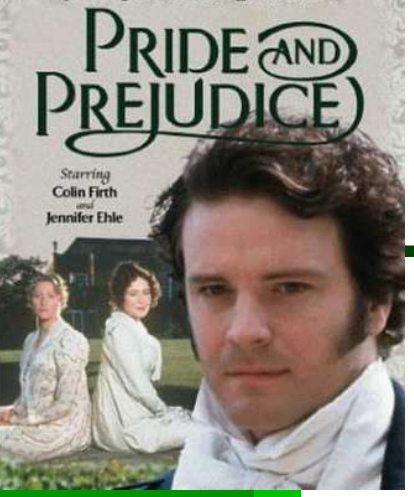

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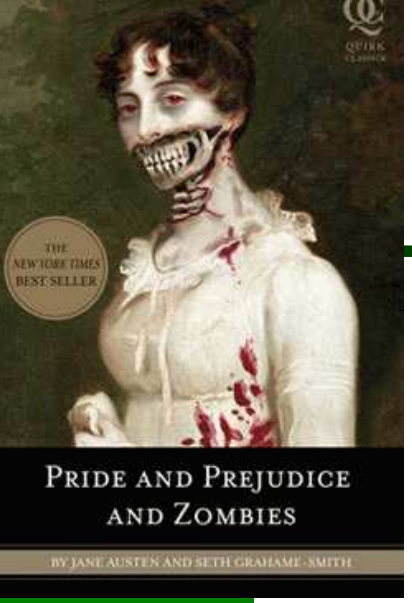

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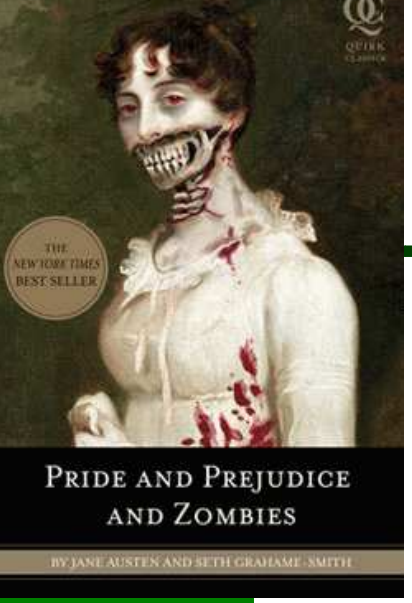

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QCD's Challenges

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QCD's Challenges

Understand Emergent Phenomena

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- QCD – Complex behaviour arises from apparently simple rules

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Charting the Interaction between light-quarks

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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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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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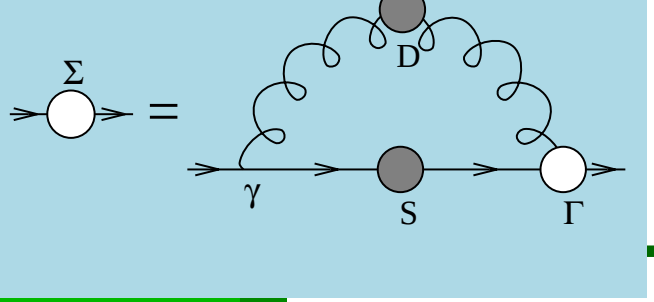
- Through DSEs the pointwise behaviour of the β-function determines pattern of chiral symmetry breaking
- DSEs connect β-function to experimental observables. Hence, comparison between computations and observations can be used to chart β-function's long-range behaviour
- To realise this goal, a nonperturbative 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

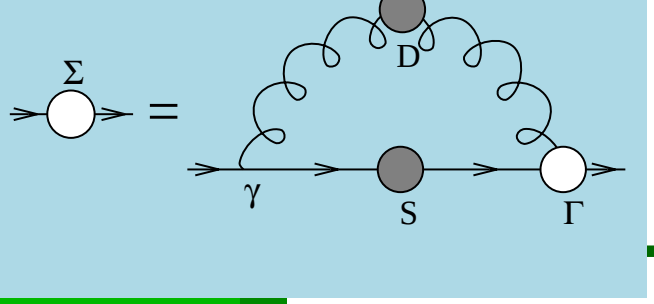
Gap Equation
General Form



Gap Equation
General Form

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

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



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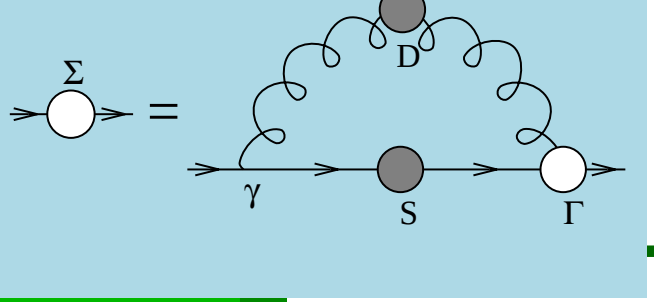
- $Z_{1,2}(\zeta^2,\Lambda^2)$ are respectively the vertex and quark wave function renormalisation constants, with ζ the renormalisation point
- $m^{\rm bm}(\Lambda)$ is the Lagrangian current-quark bare mass
- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma^f_\nu(q,p)$ is the dressed-quark-gluon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



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- Suppose one has in-hand the exact form of $\Gamma^f_\nu(q,p)$

What is the associated

Symmetry-preserving Bethe-Salpeter Kernel?

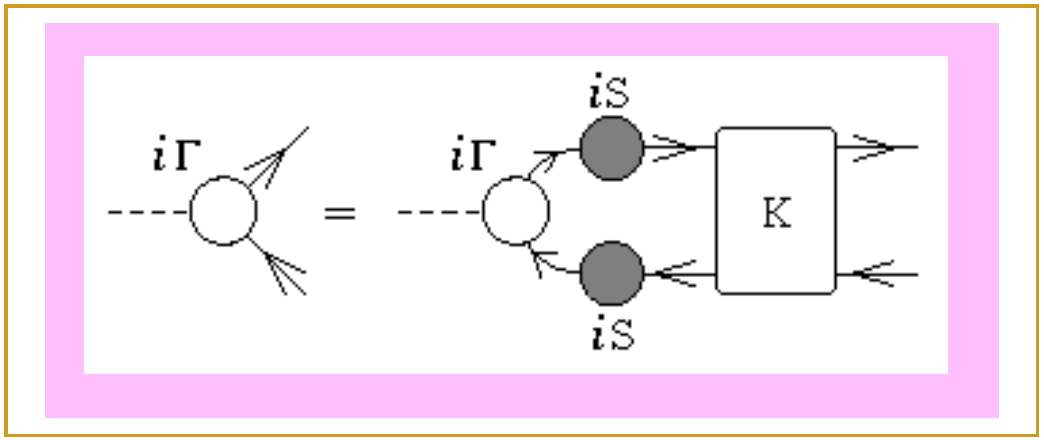
Bound-state DSE

Bound-state DSE

Bethe-Salpeter Equation

- Standard form, familiar from textbooks

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



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

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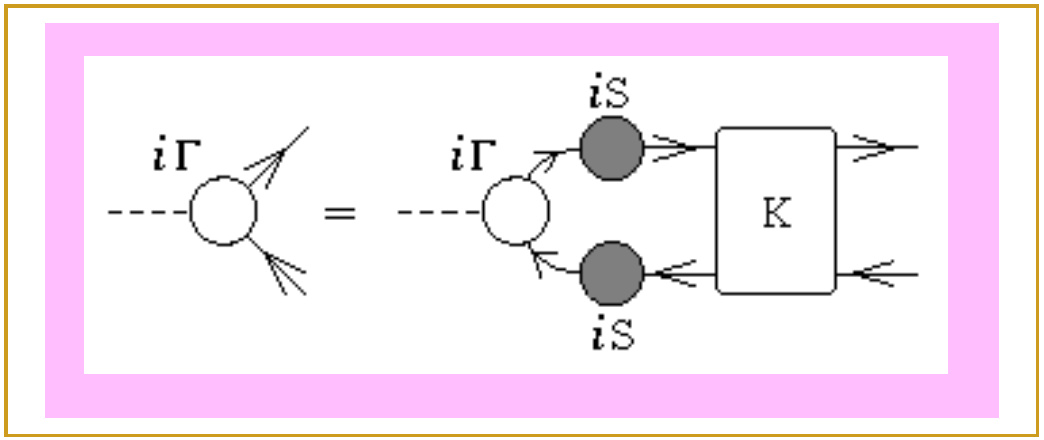

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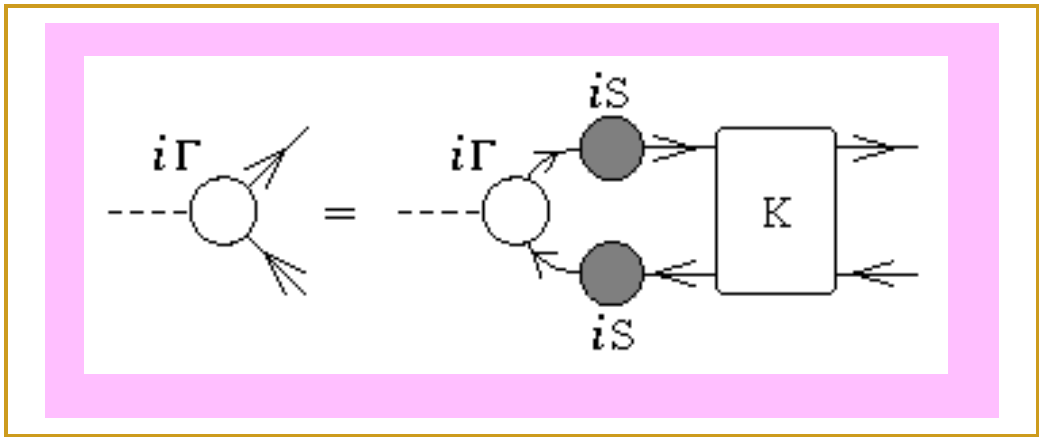

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- Compact. Visually appealing. Correct.
- Blocked progress for more than 60 years.

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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(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

Bethe-Salpeter Kernel

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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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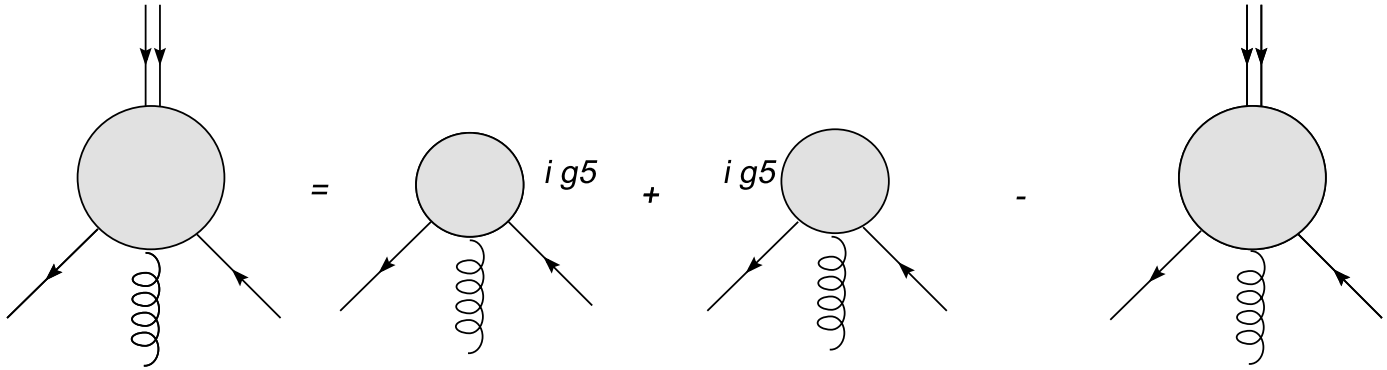

$$P_\mu \Lambda^{fg}_{5\mu\beta}(k,q;P) = \Gamma^f_\beta(q_+,k_+)\, i\gamma_5 + i\gamma_5\, \Gamma^g_\beta(q_-,k_-) - i[m_f(\zeta)+m_g(\zeta)]\Lambda^{fg}_{5\beta}(k,q;P),$$

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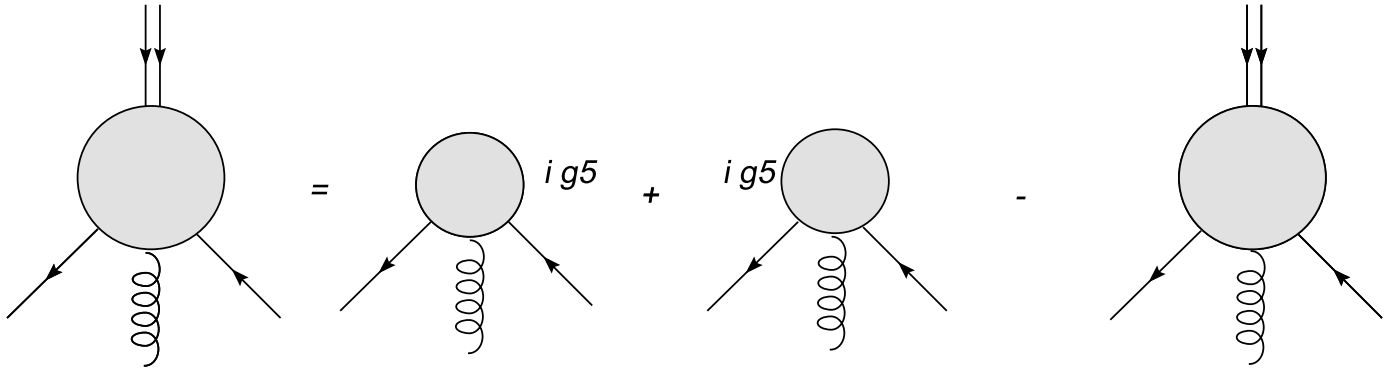

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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
  - Consistent means - all symmetries preserved!

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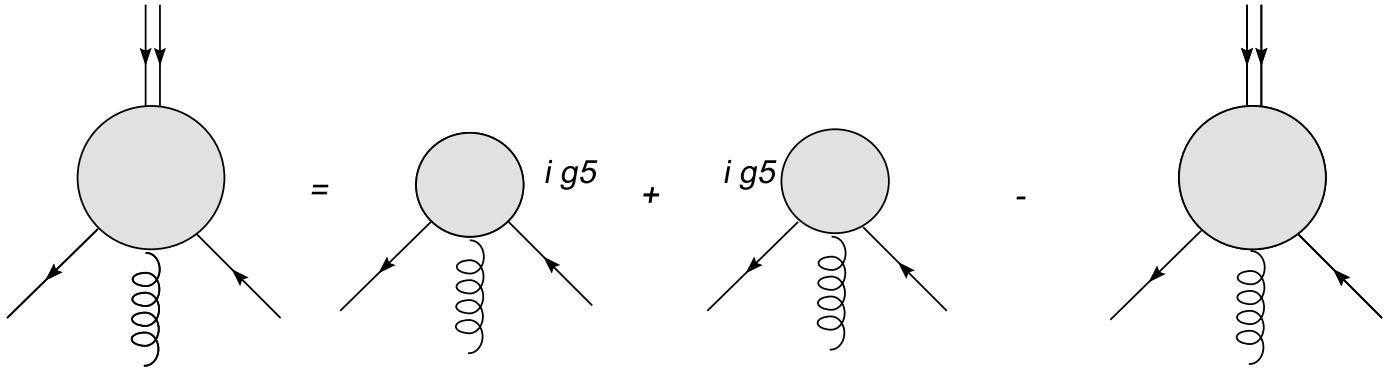

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- Procedure & results to expect . . .

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.

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!

Mass Splitting

$a_1 - \rho$

	exp.	rainbow-ladder	one-loop	Ball-Chiu consistent	
mass a_1	1230	759	885	1066	
mass ρ	775	644	764	924	
mass-splitting	455	115	121	142	

- New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]
- Ball-Chiu *Ansatz* for quark-gluon vertex

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

  - 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
mass ρ	775	644	764	924	745
mass-splitting	455	115	121	142	485

- 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: $\Gamma_\mu(k,p) = \Gamma^{\rm BC}_\mu + \sigma_{\mu\nu}(k-p)_\nu \frac{B(k)-B(p)}{k^2-p^2}$

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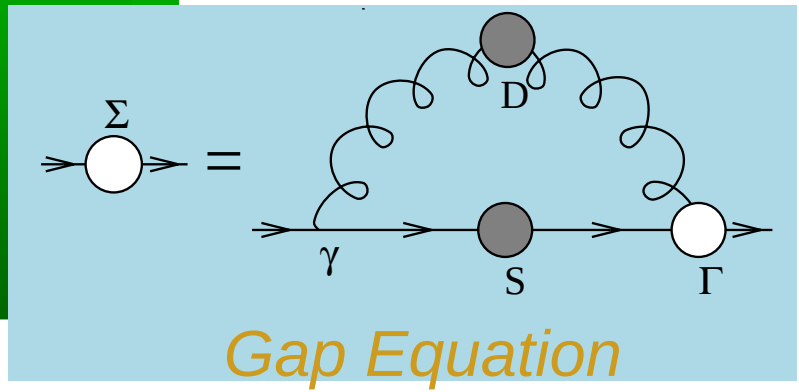
- New nonperturbative, symmetry-preserving Poincaré-covariant Bethe-Salpeter equation formulation of arXiv:0903.5461 [nucl-th]
- DCSB is the answer. Subtle interplay between competing effects, which can only now be explicated
- Promise of first reliable prediction of light-quark meson spectrum, including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

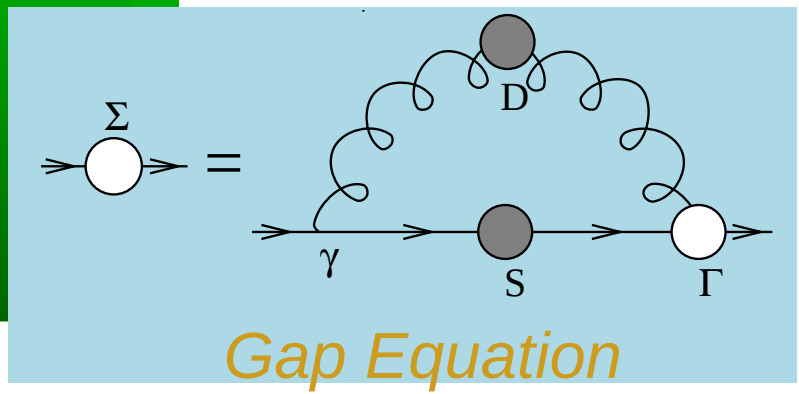
Frontiers of Nuclear Science: A Long Range Plan (2007)

Frontiers of Nuclear Science: Theoretical Advances



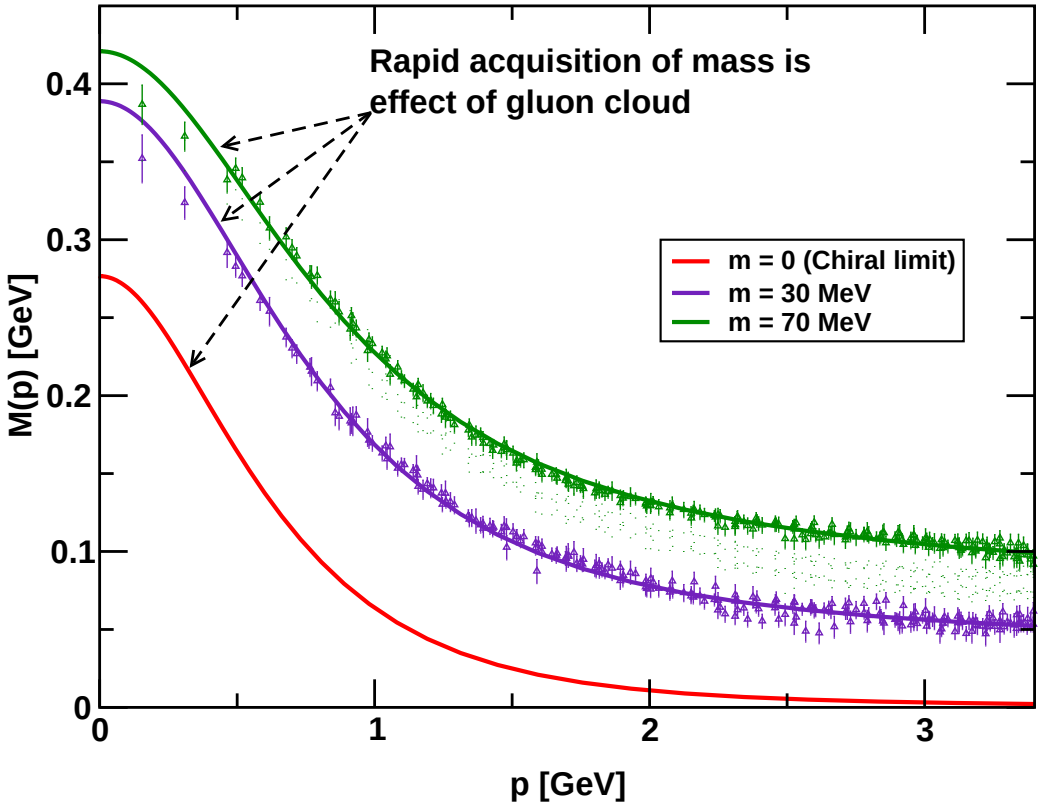
Gap Equation

Frontiers of Nuclear Science: Theoretical Advances



Gap Equation

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



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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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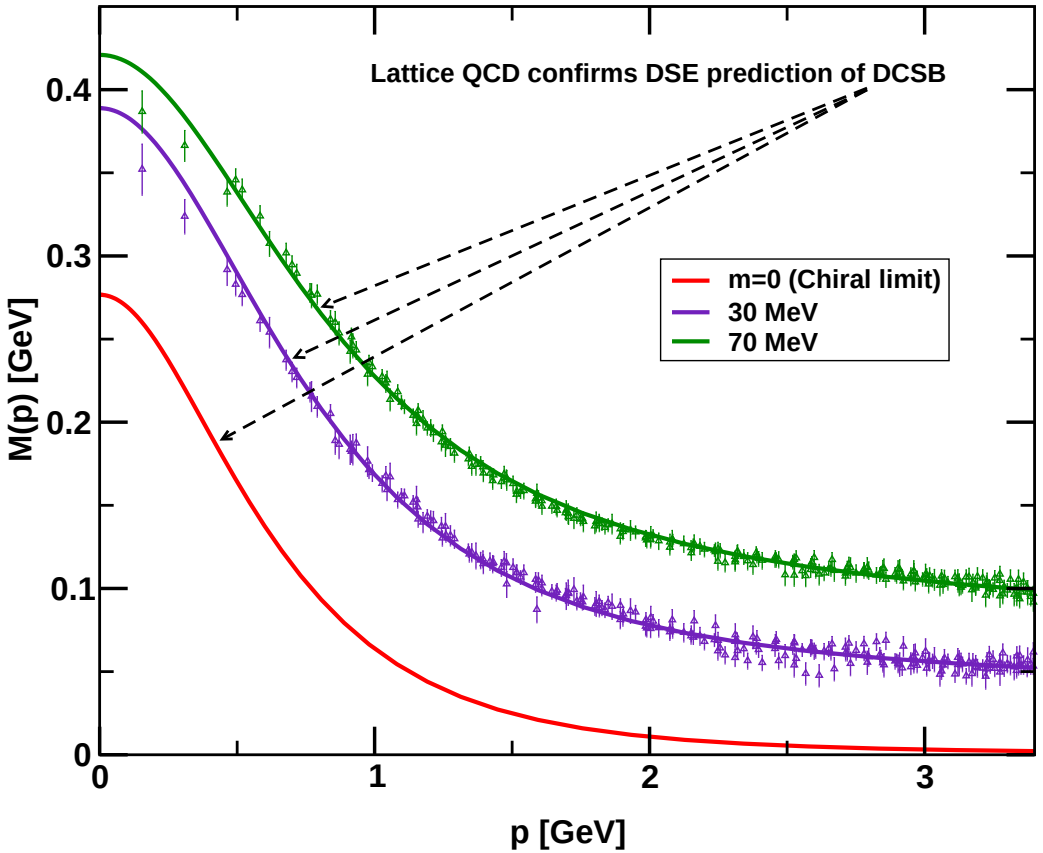

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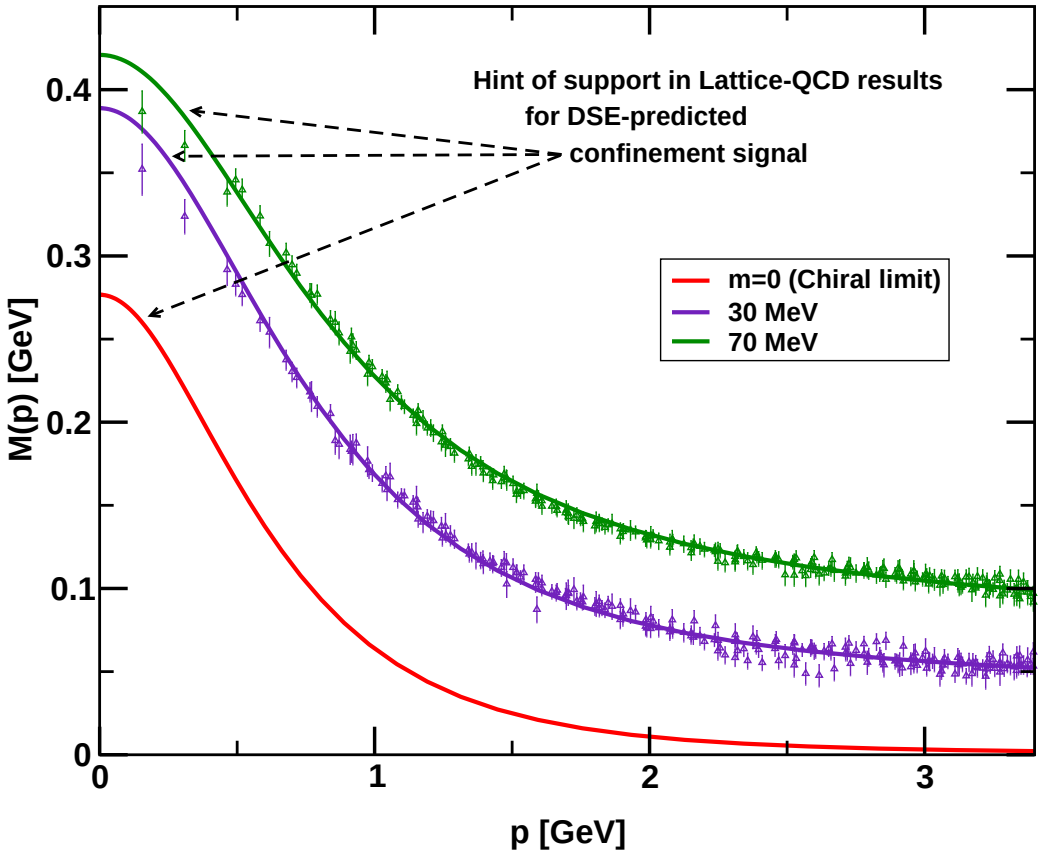

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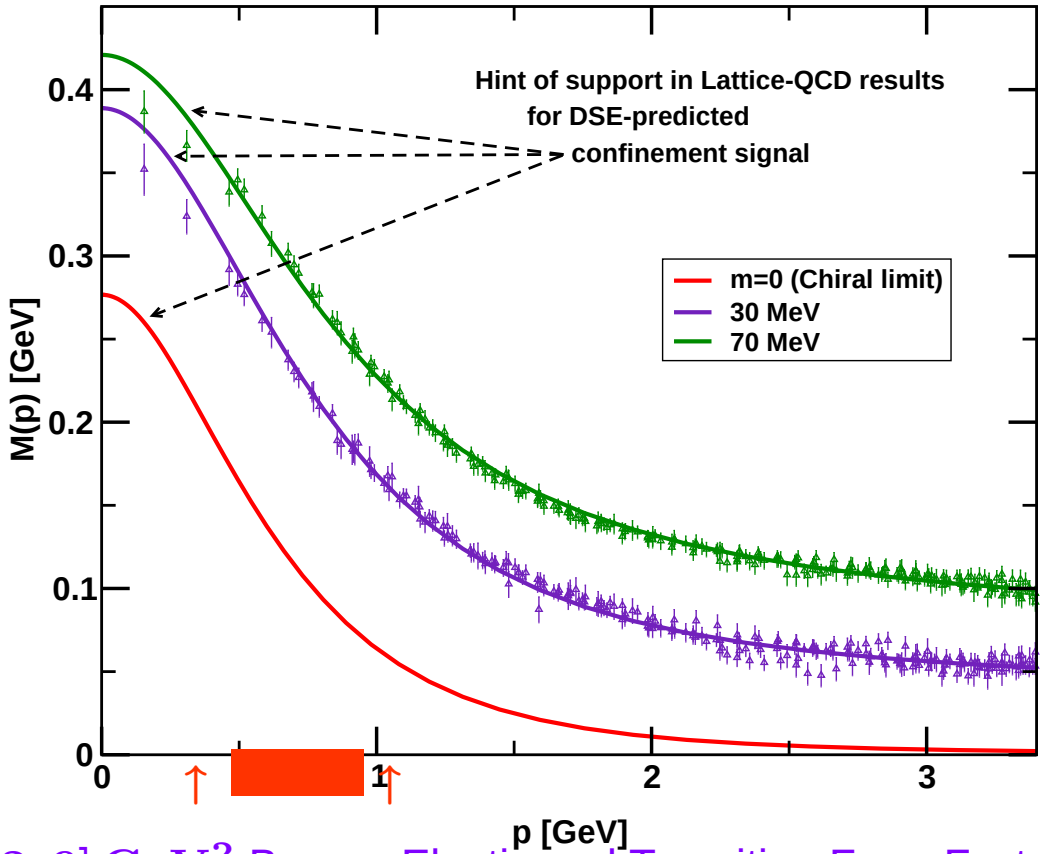
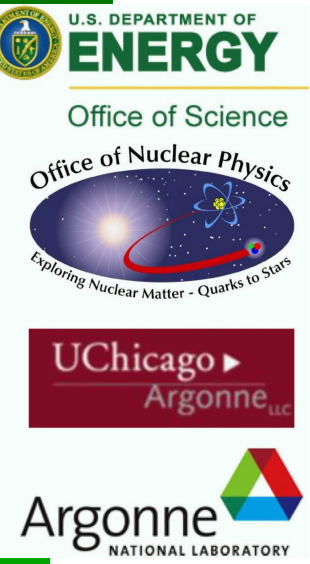


Scanned by $Q^2 \in [2, 9]\,\mathrm{GeV}^2$ Baryon Elastic and Transition Form Factors

Maris, Roberts, Tandy
nucl-th/9707003

Goldberger-Treiman for pion



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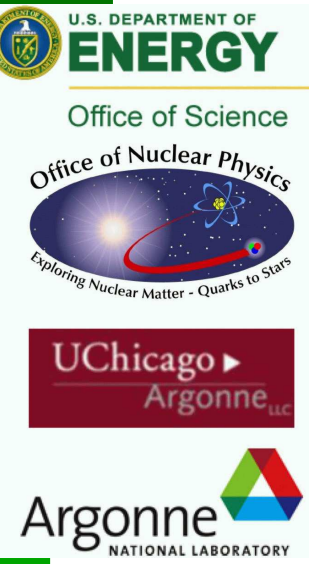
- Dressed-quark Propagator: $S(p) = \dfrac{1}{i\gamma\cdot p\, A(p^2) + B(p^2)}$



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- Axial-vector Ward-Takahashi identity

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

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$\Rightarrow$

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

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Pseudovector components necessarily nonzero

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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?

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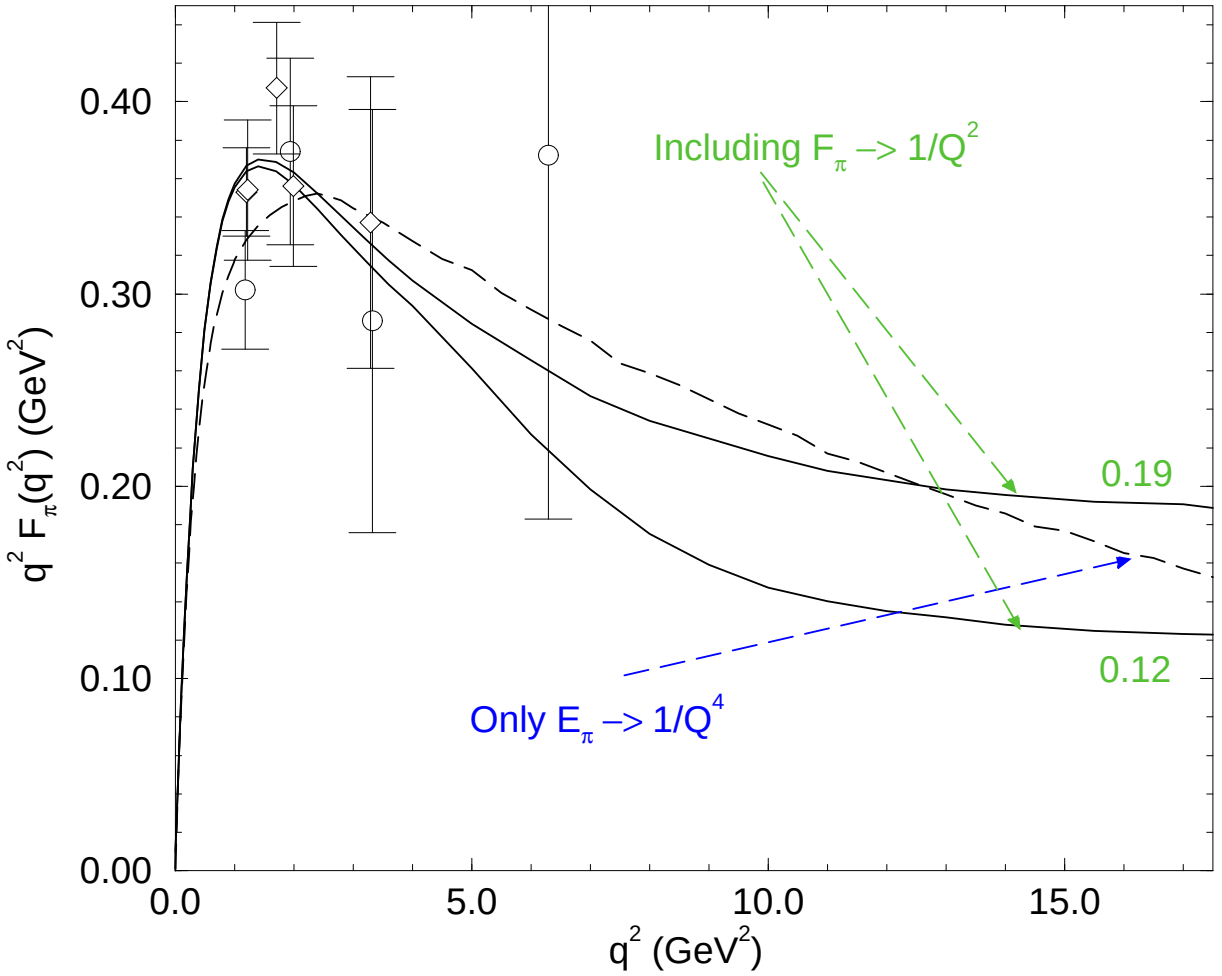

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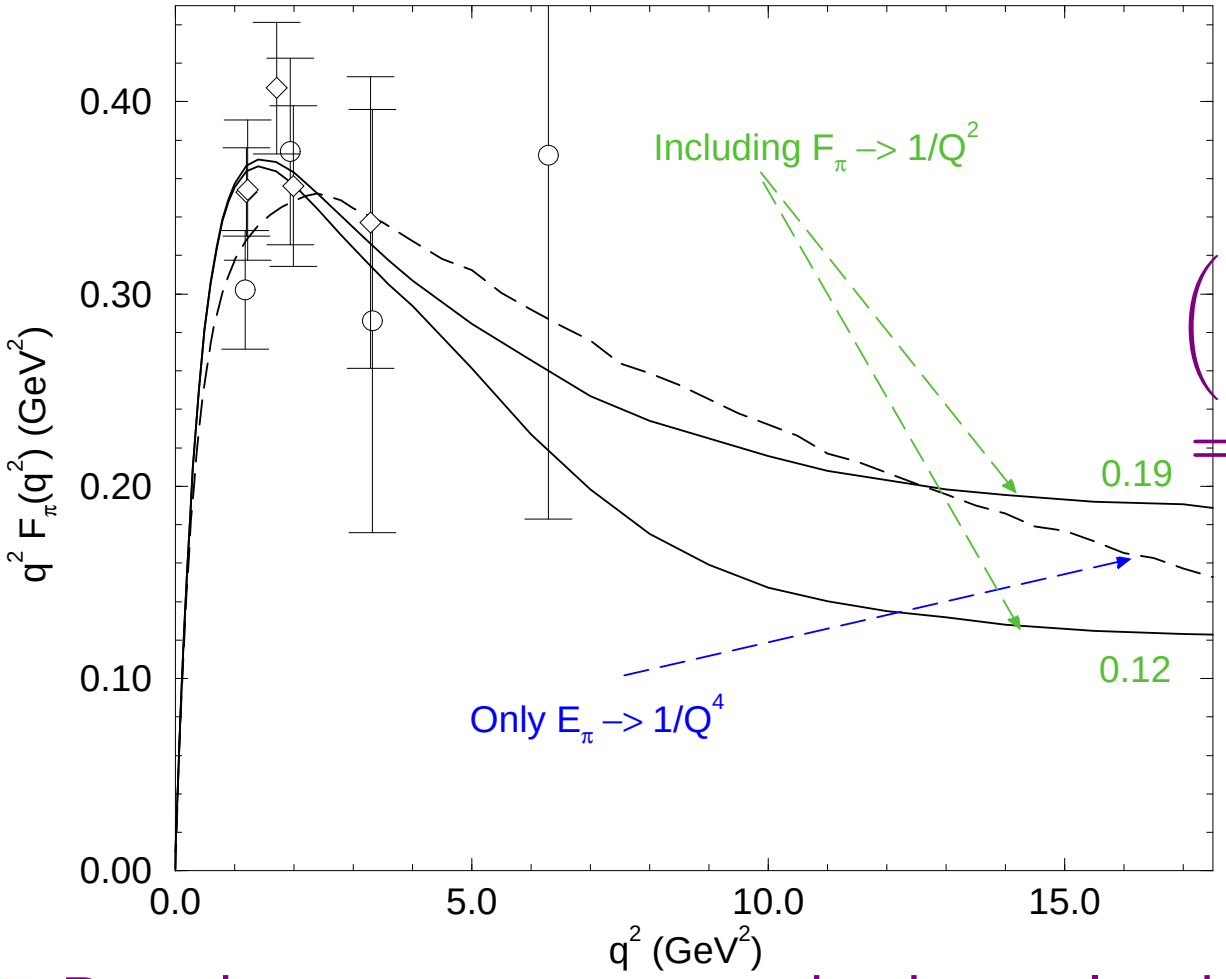

$$\left(\frac{Q}{2}\right)^2 = 2\,\mathrm{GeV}^2$$
$$\Rightarrow Q^2 = 8\,\mathrm{GeV}^2$$

- 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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- Solve chiral-limit gap and Bethe-Salpeter equations

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

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

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

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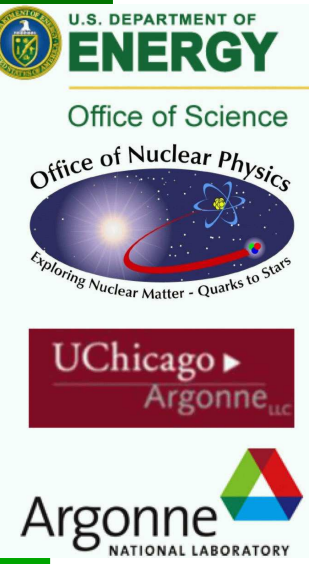
- This behaviour dominates for $Q^2 \gtrsim M_Q^2 \dfrac{E_\pi}{F_\pi} > 0.8\,\text{GeV}^2$

Computation: Elastic Pion Form Factor

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

- DSE prediction: $M(p^2)$; i.e., interaction $\dfrac{1}{|x-y|^2}$
- cf. $M(p^2) =$ Constant; i.e., interaction $\delta^4(x-y)$



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Single mass-scale parameter
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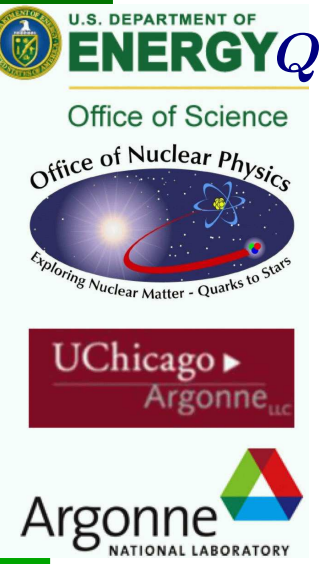

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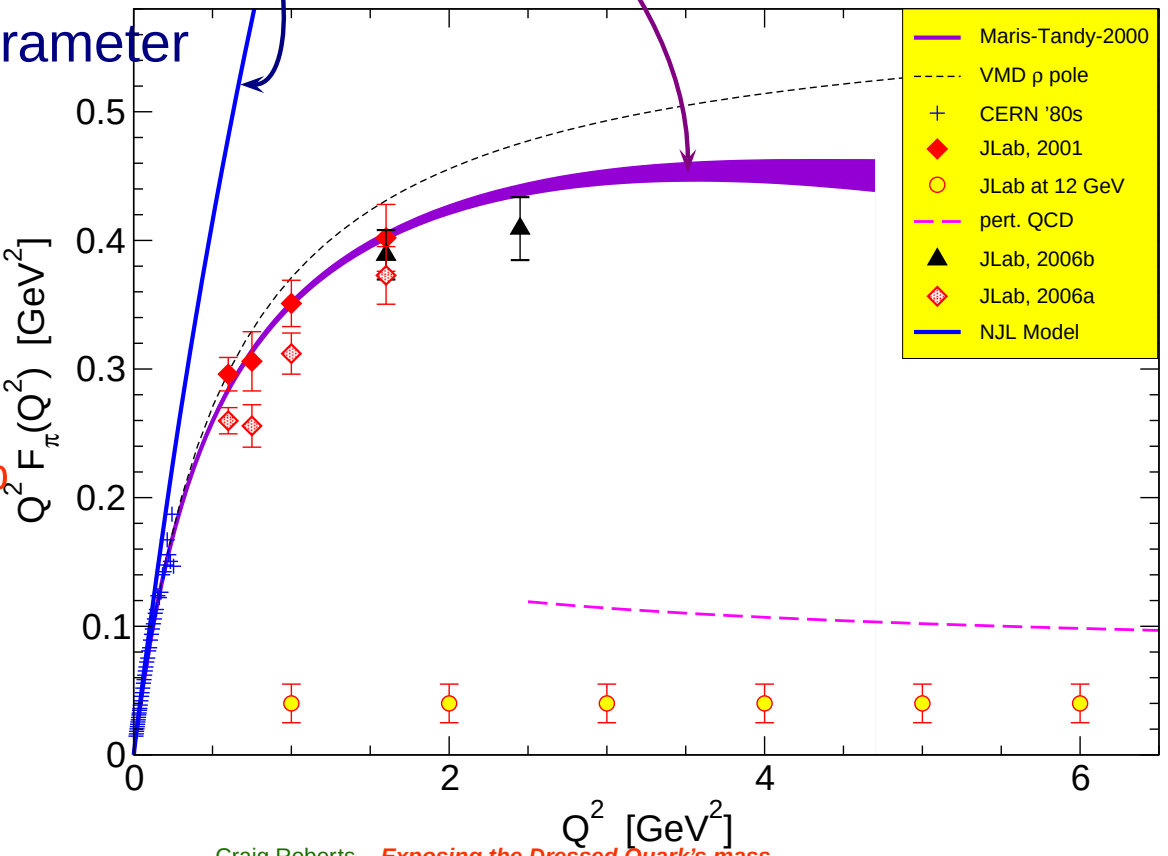
Same predictions for $Q^2 = 0$ properties

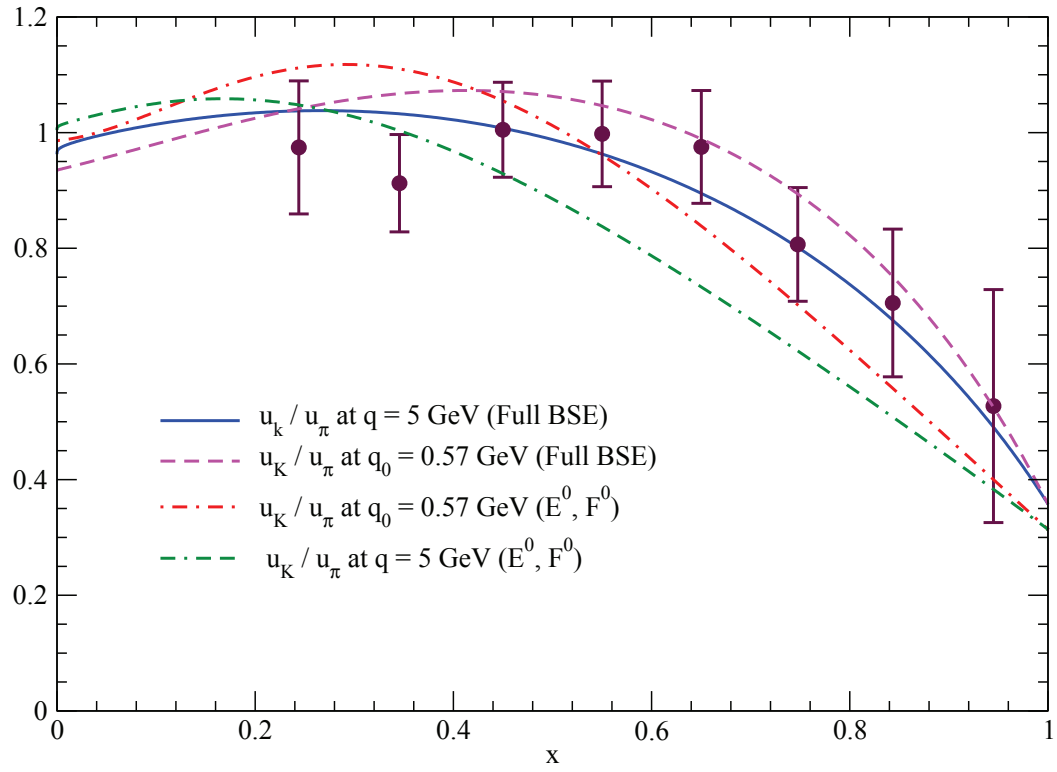
Disagreement $> 20\%$ for $Q^2 > M^2$



Ratio – Kaon/Pion u-valence distribution

Trang: PhD Thesis (Kent State U.)
Trang, Tandy, Bashir, Roberts, in progress
Holt & Roberts: arXiv:1002.4666 [nucl-th]

data: Badier, *et al.* , Phys. Lett. **B 93** (1980) 354



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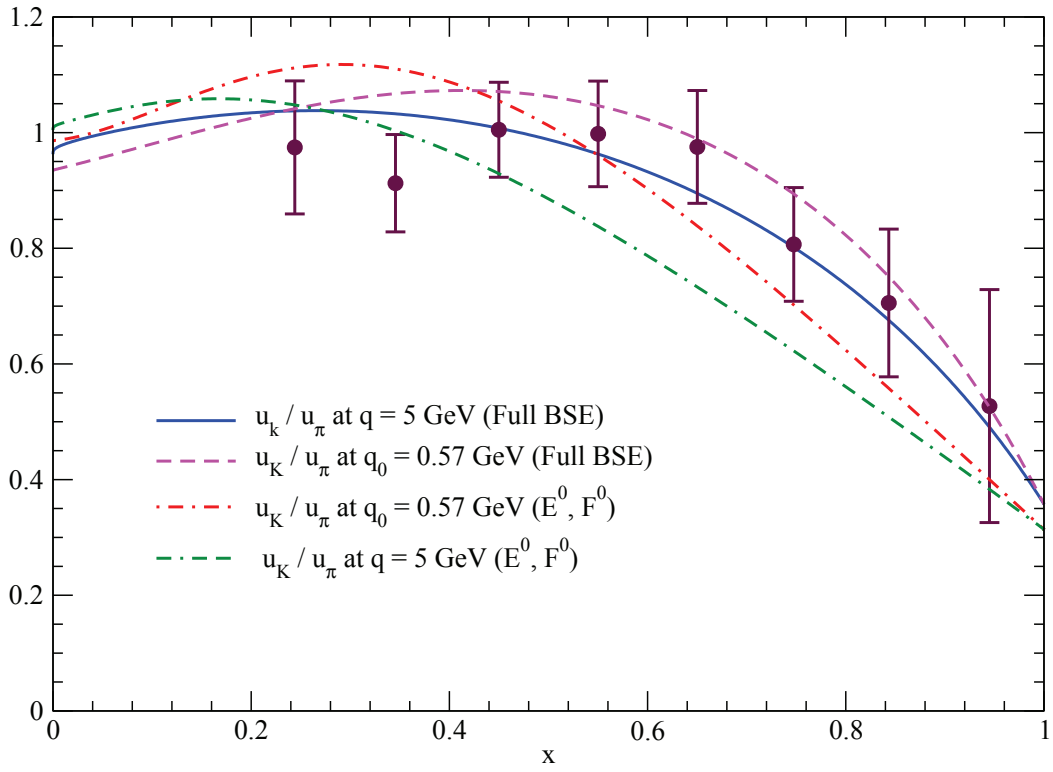

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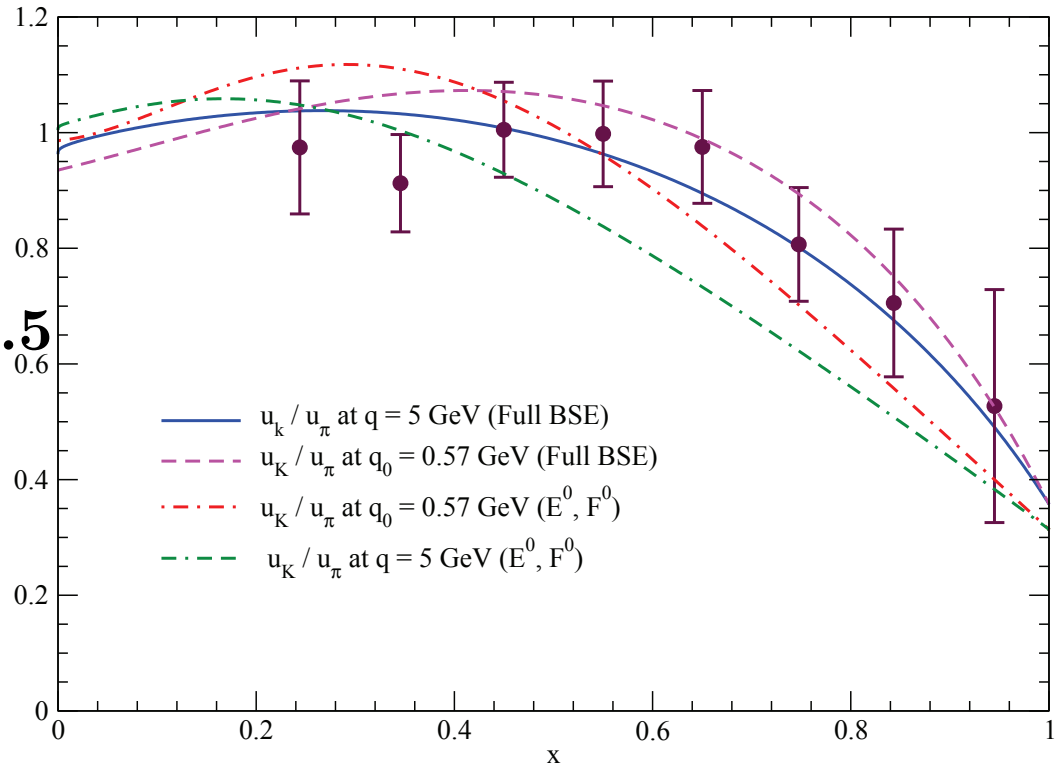

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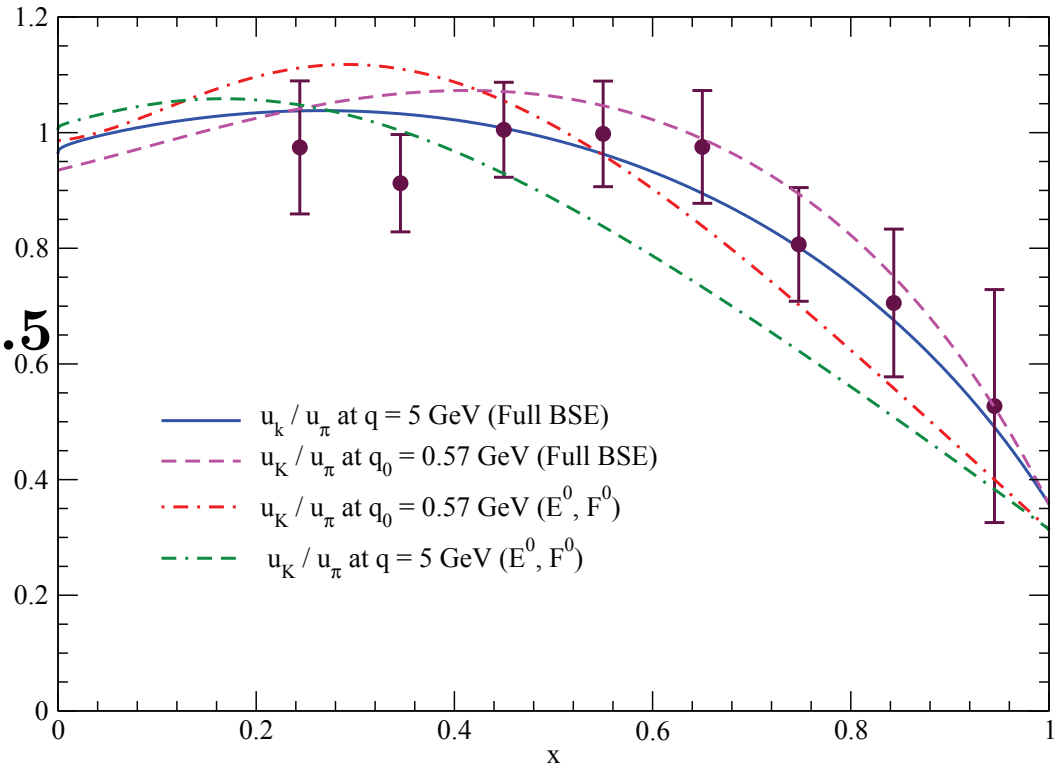

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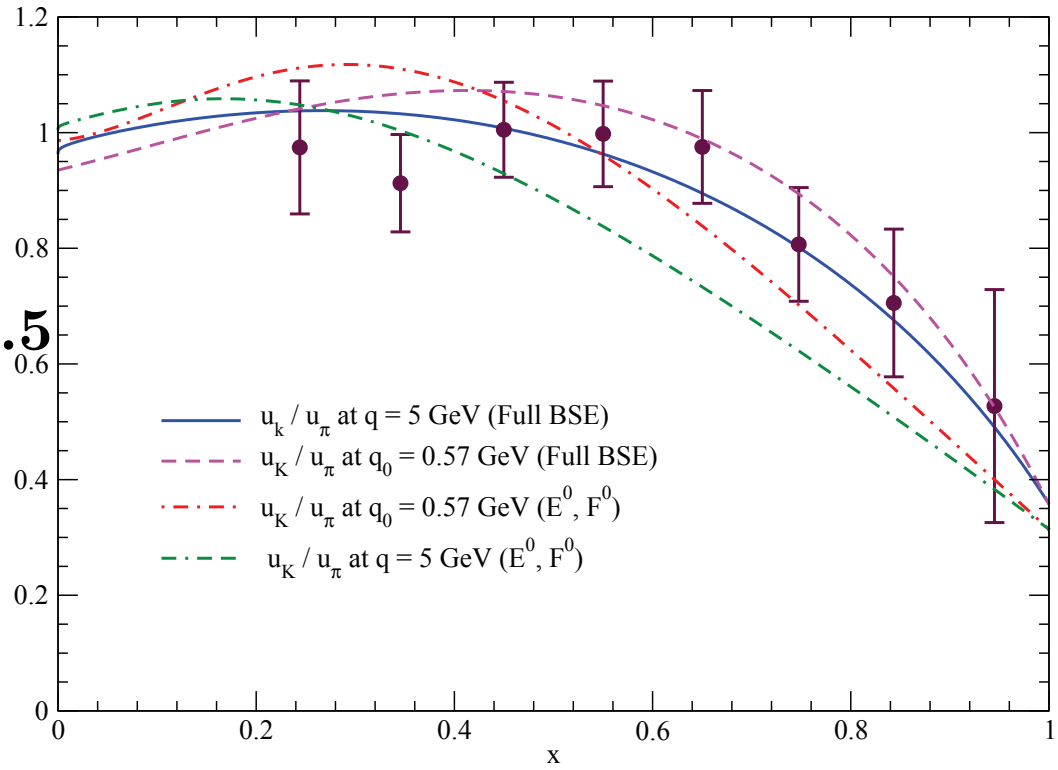

Unifying Study of Mesons and Baryons

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  - Tractable equation is founded on observation that an interaction which describes colour-singlet mesons also generates quark-quark (diquark) correlations in the colour-$\overline{3}$ (antitriplet) channel

Faddeev equation

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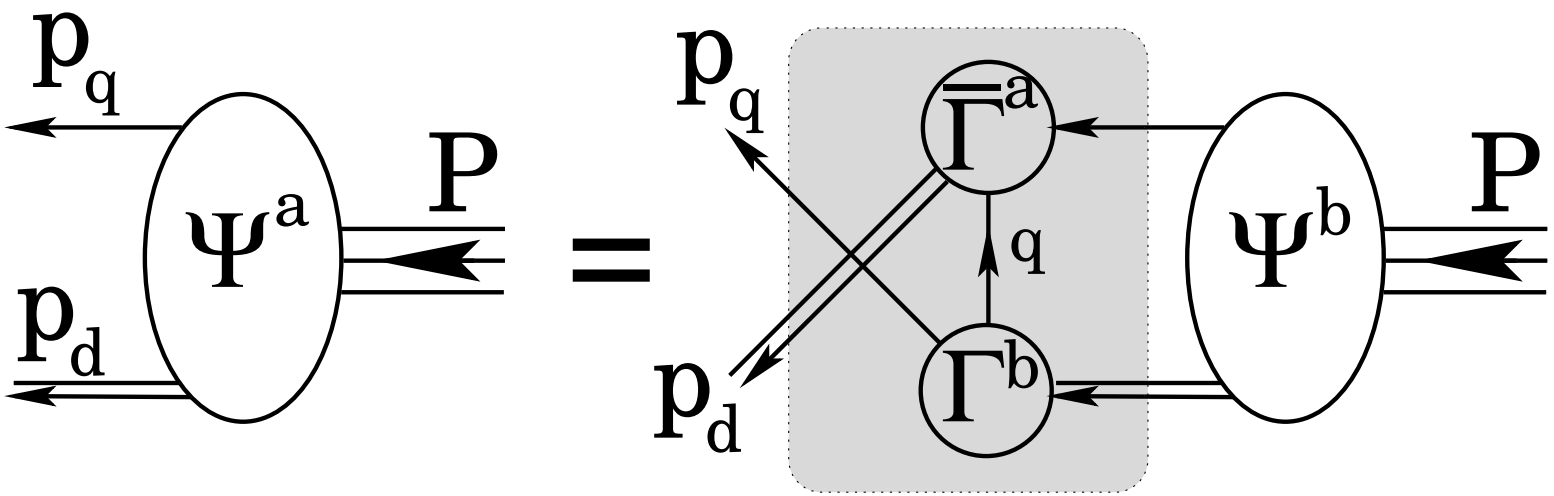

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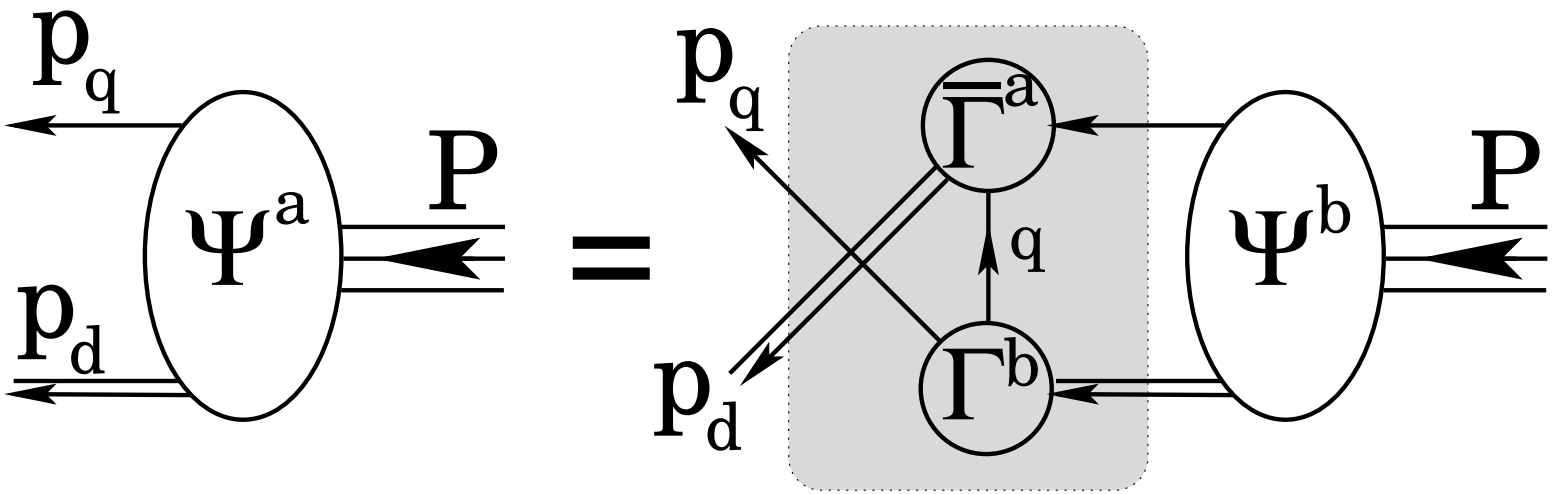

- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Nucleon-Photon Vertex

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

Nucleon-Photon Vertex

6 terms . . .

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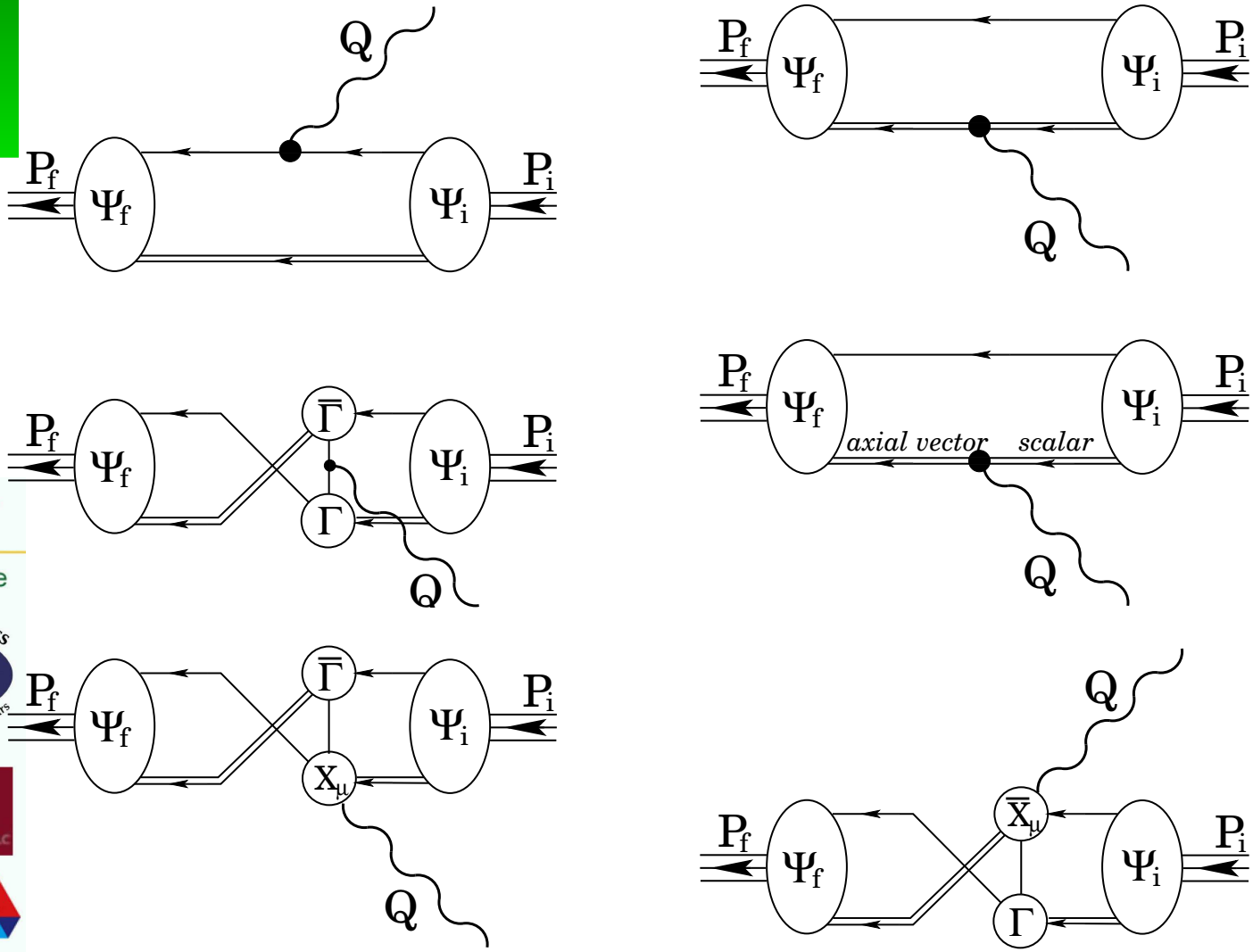

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$$\frac{\mu_n G_E(Q^2)}{G_M(Q^2)}$$

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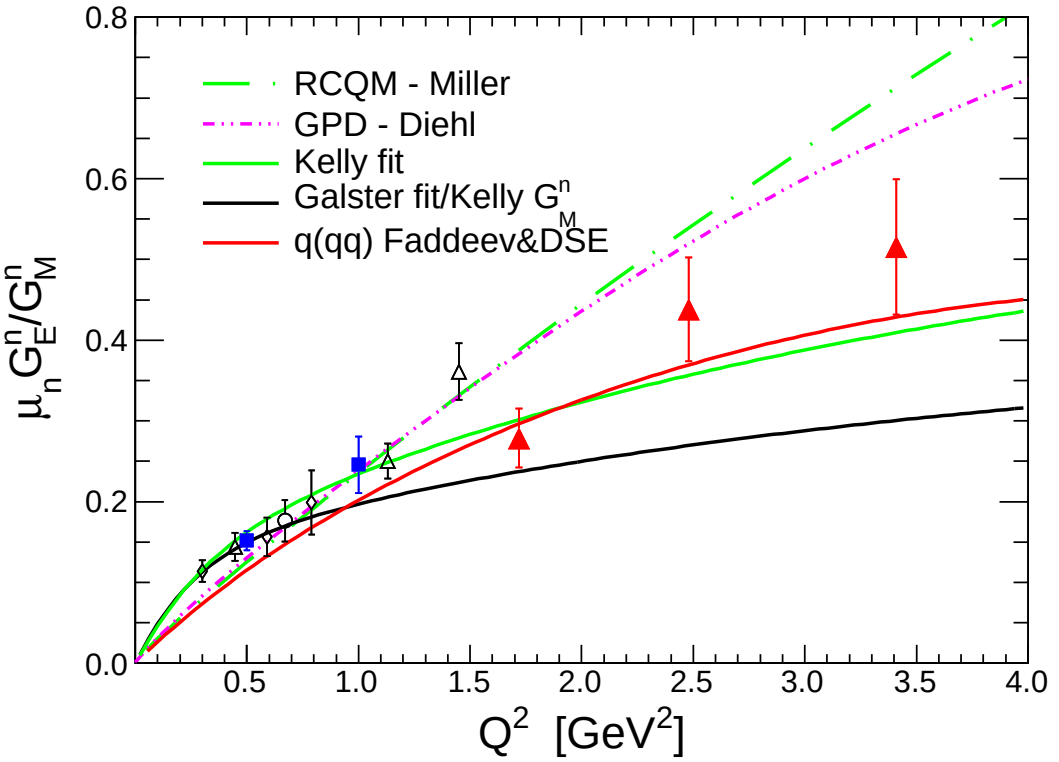

B. Wojtsekhowski, Jefferson Lab E02-013 Collaboration, *in preparation*.

Figure courtesy S. Riordan

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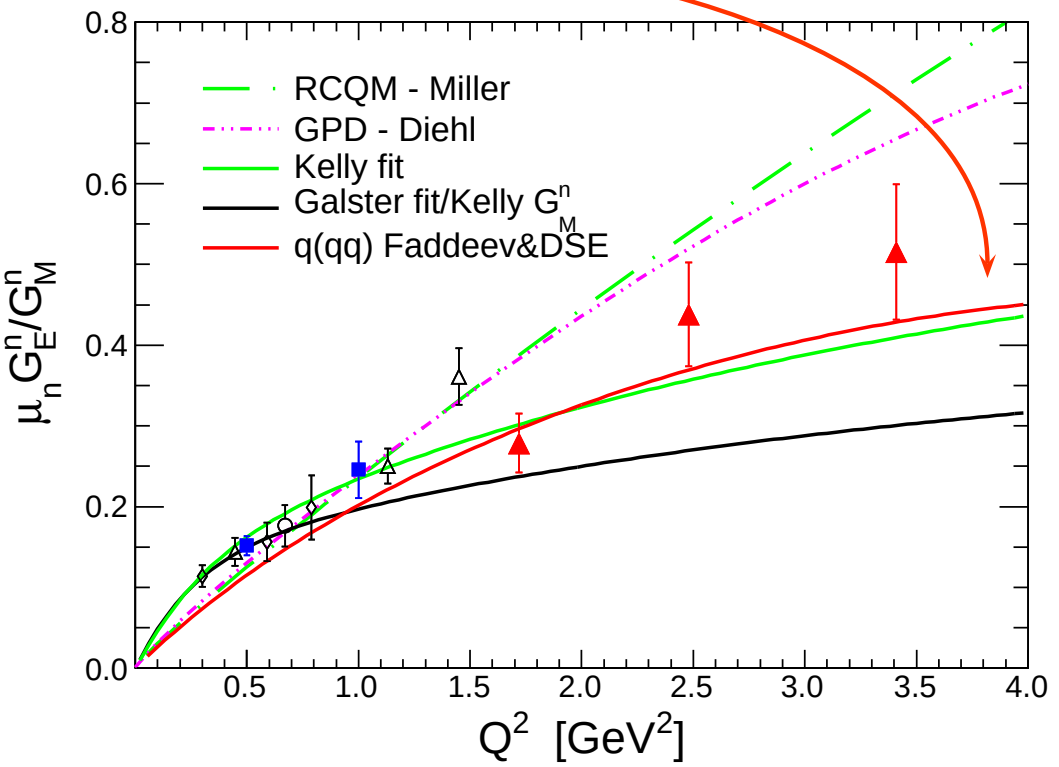

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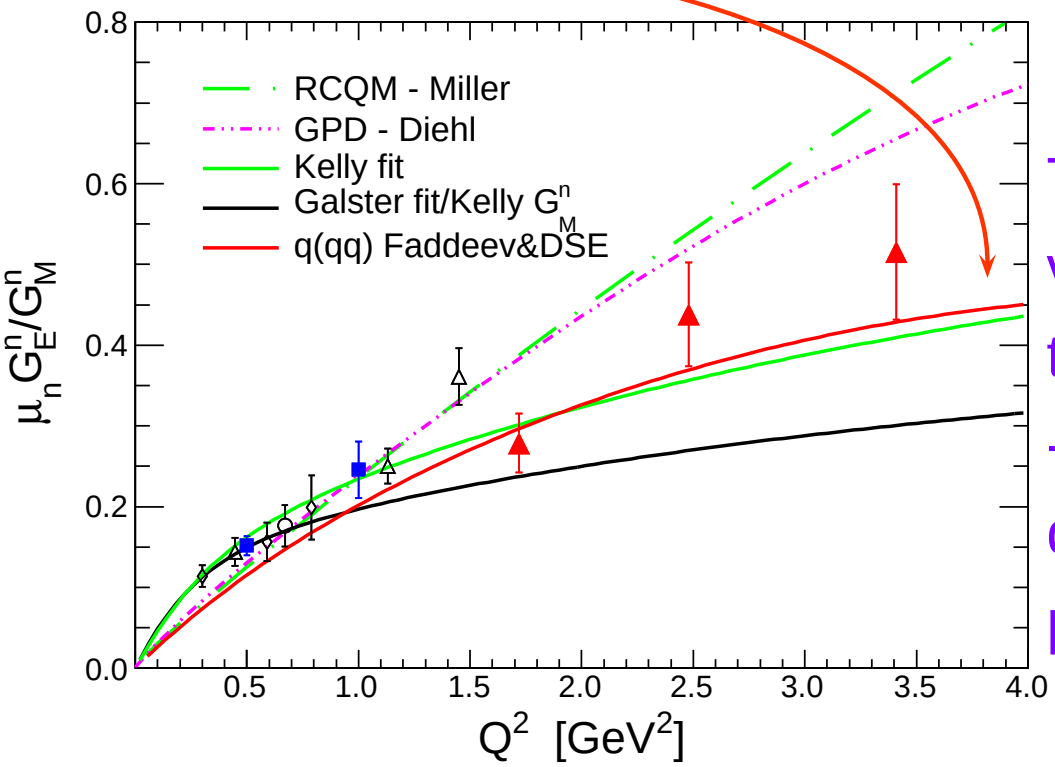

This evolution very sensitive to momentum -dependence dressed-quark propagator

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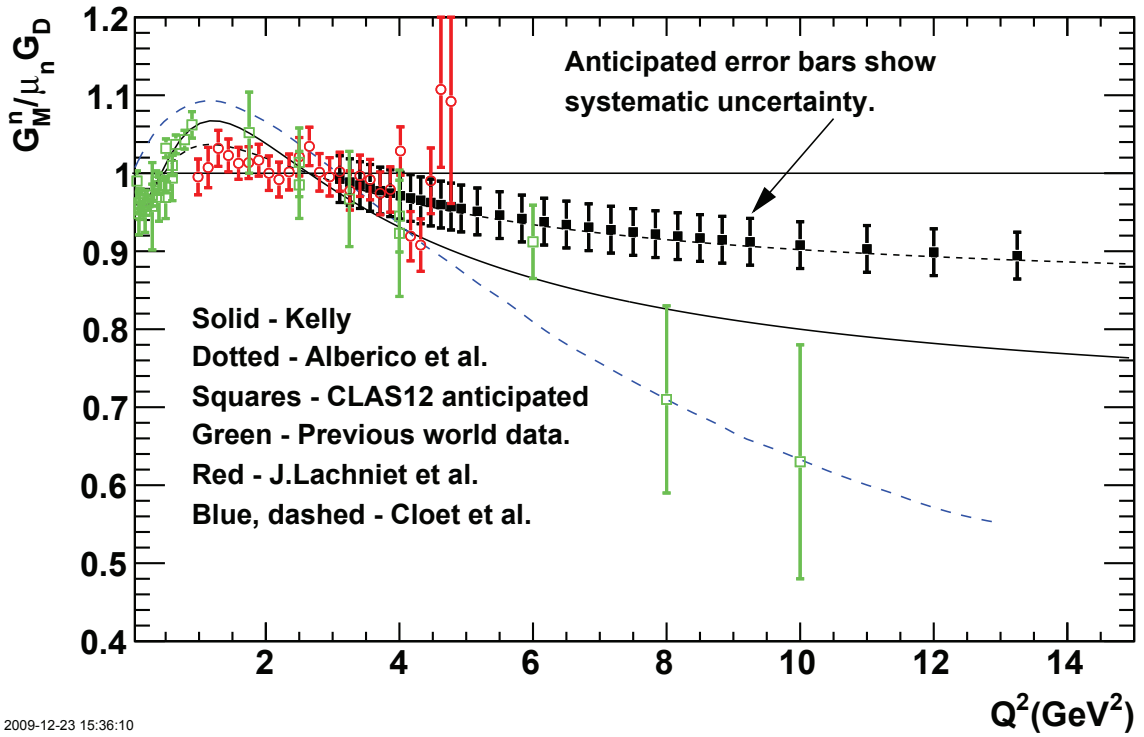

Jefferson Lab E12-07-104, *12GeV Proposal*.

Gilfoyle, Brooks, Hafidi for CLAS Collaboration

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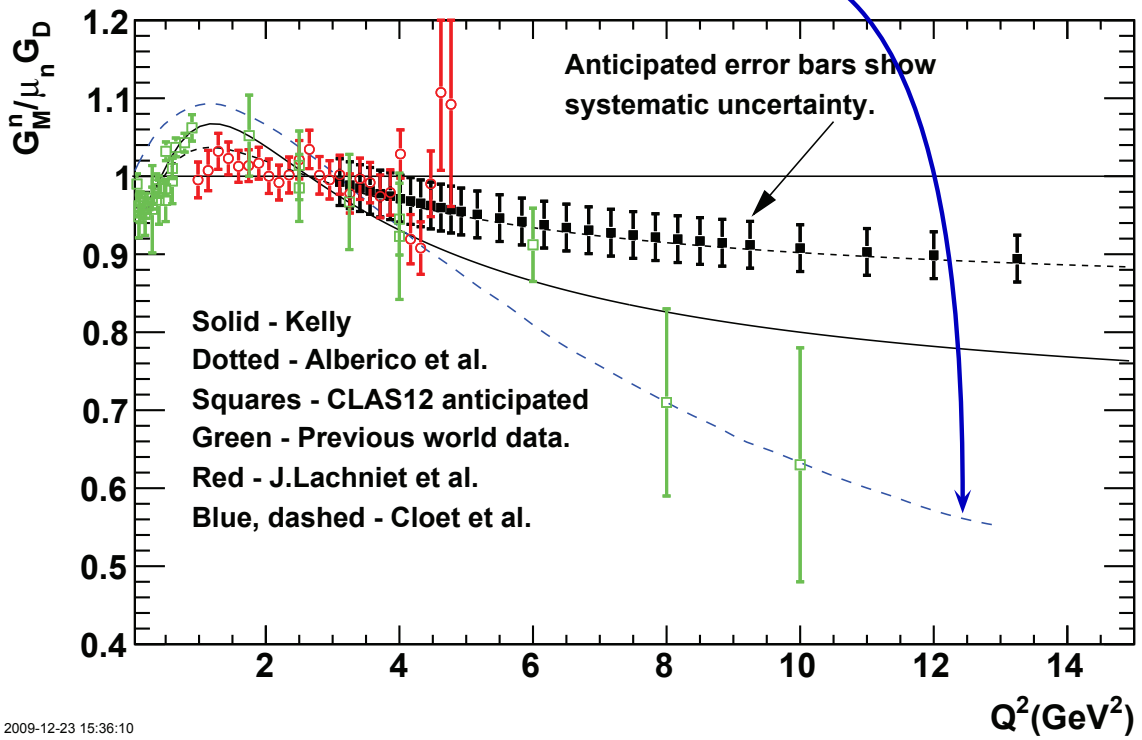

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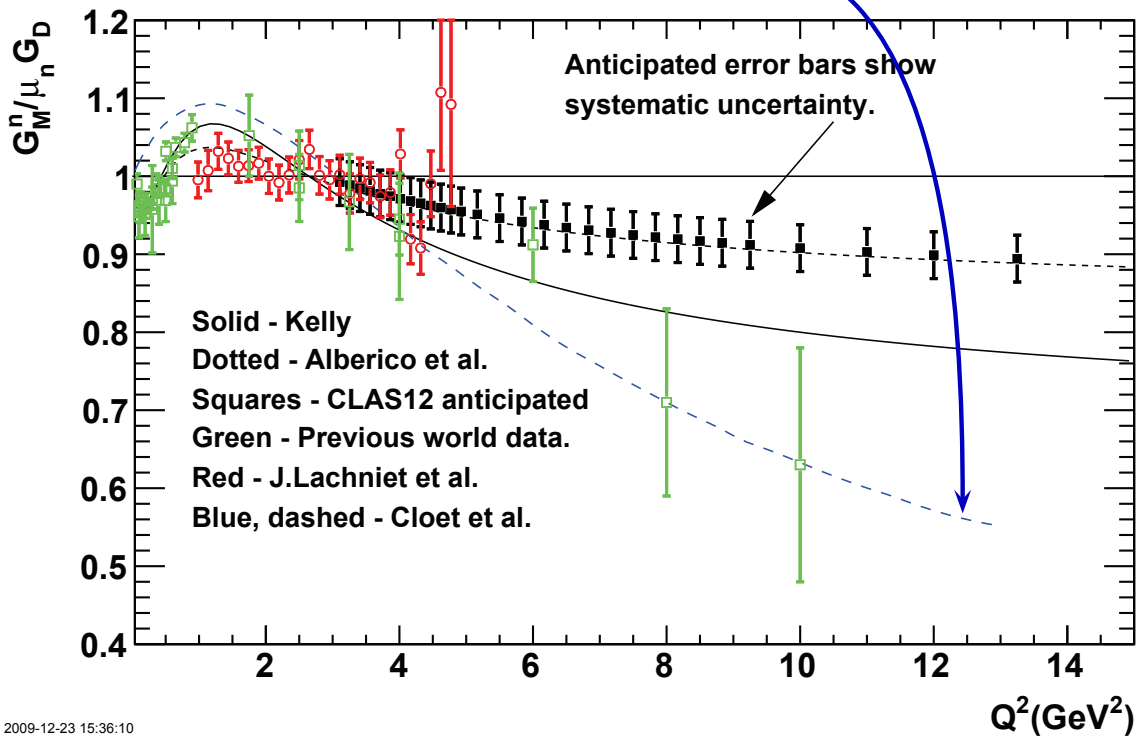

Sensitivity to $M(p^2)$ means experiments probe IR behaviour of strong running coupling

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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.,
  - $N \to \Delta$
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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.*)

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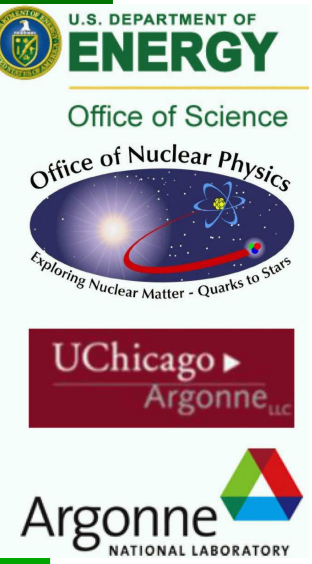
Epilogue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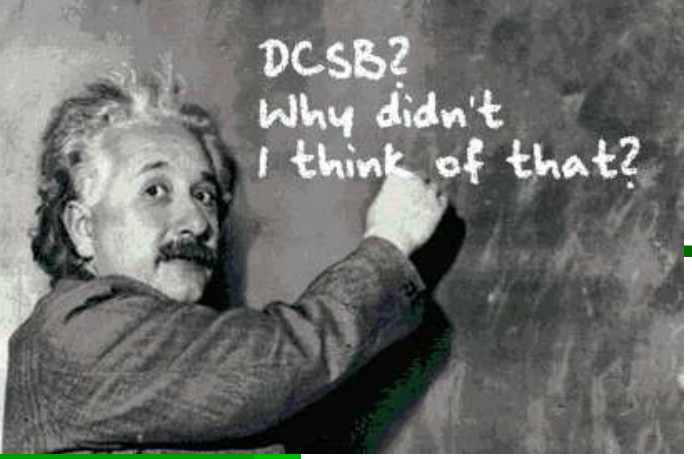

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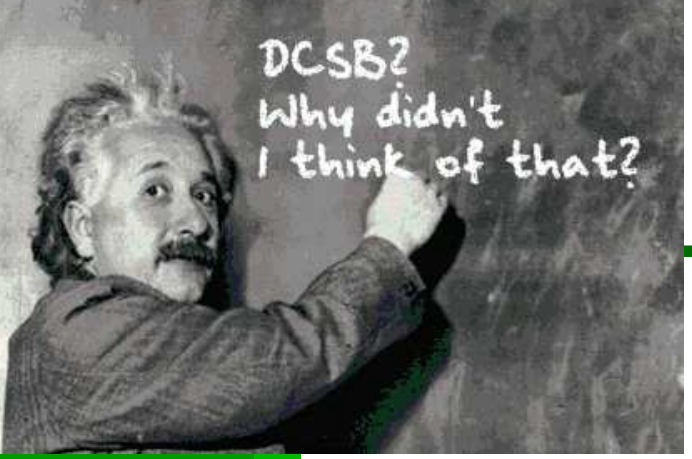

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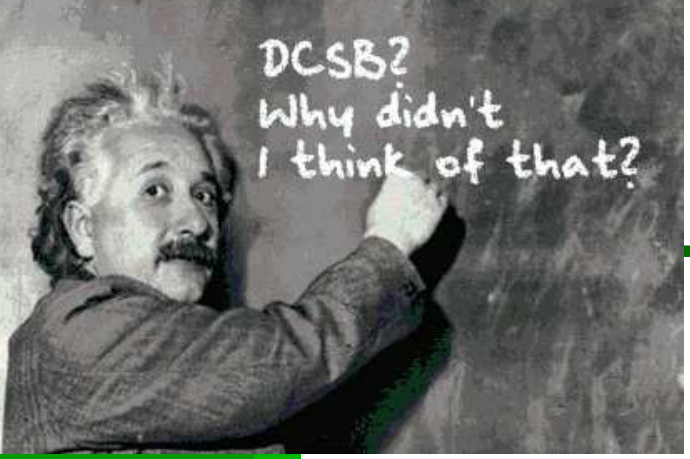
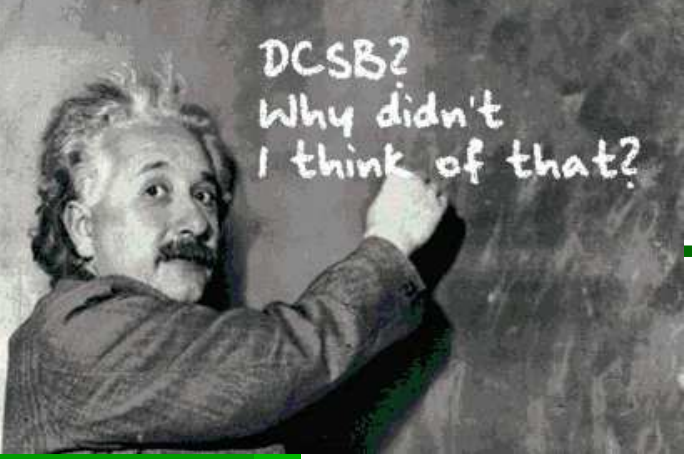


Epilogue

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



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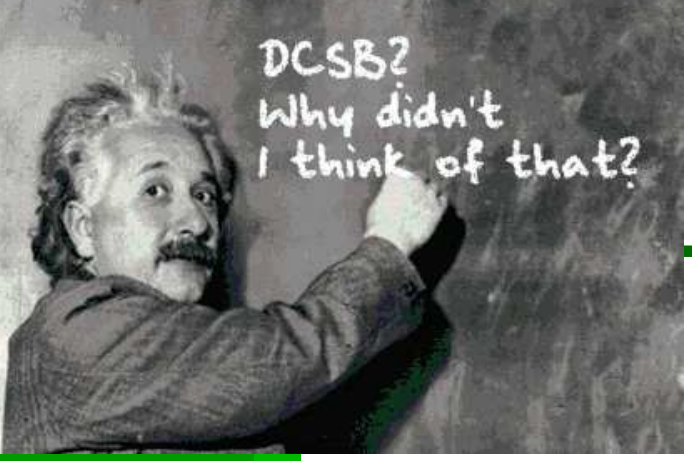
- DCSB impacts dramatically upon observables



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- DCSB impacts dramatically upon observables
  - Spectrum; e.g., splittings: σ–π & a_1–ρ
  - Elastic and Transition Form Factors

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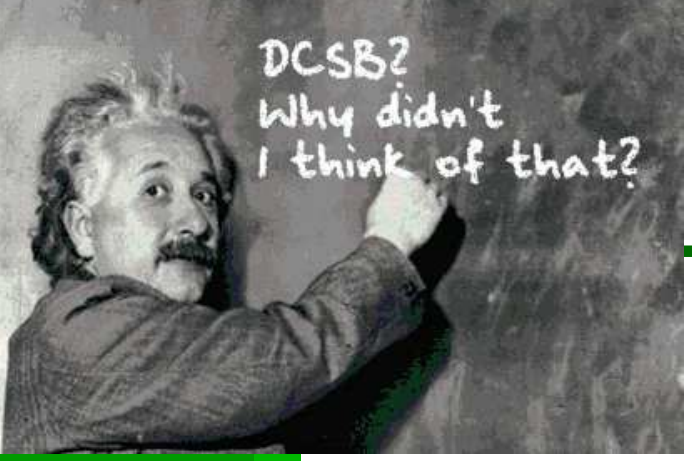

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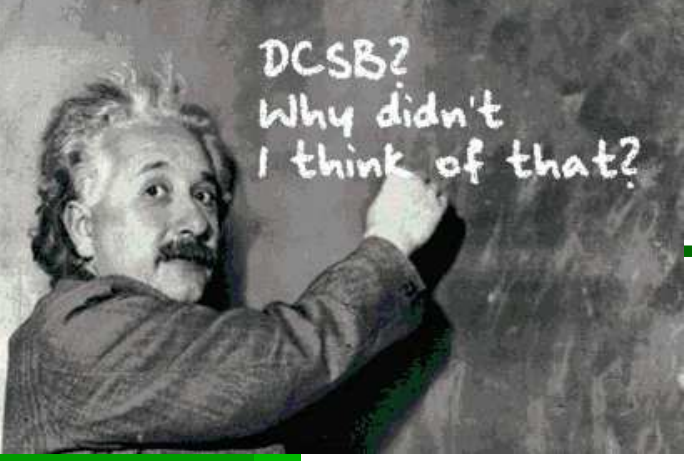

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- DSEs provide such a framework.
  - Studies underway will identify observable signals of $M(p^2)$, the most important mass-generating mechanism for visible matter in the Universe

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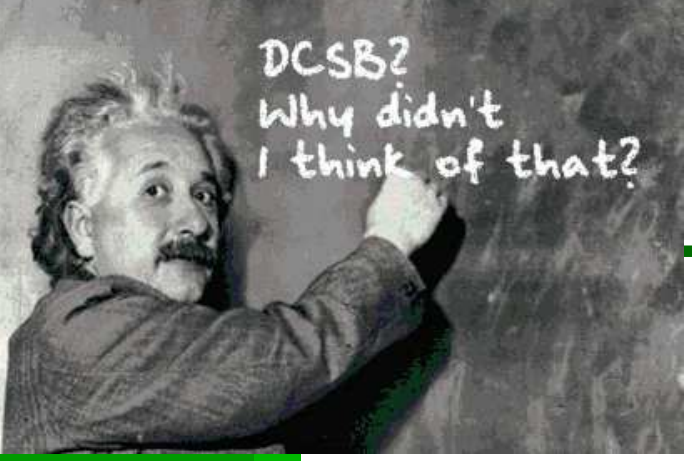

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- DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks

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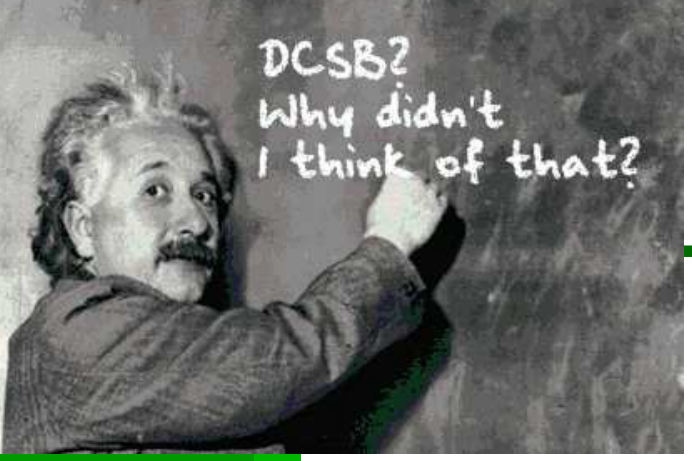

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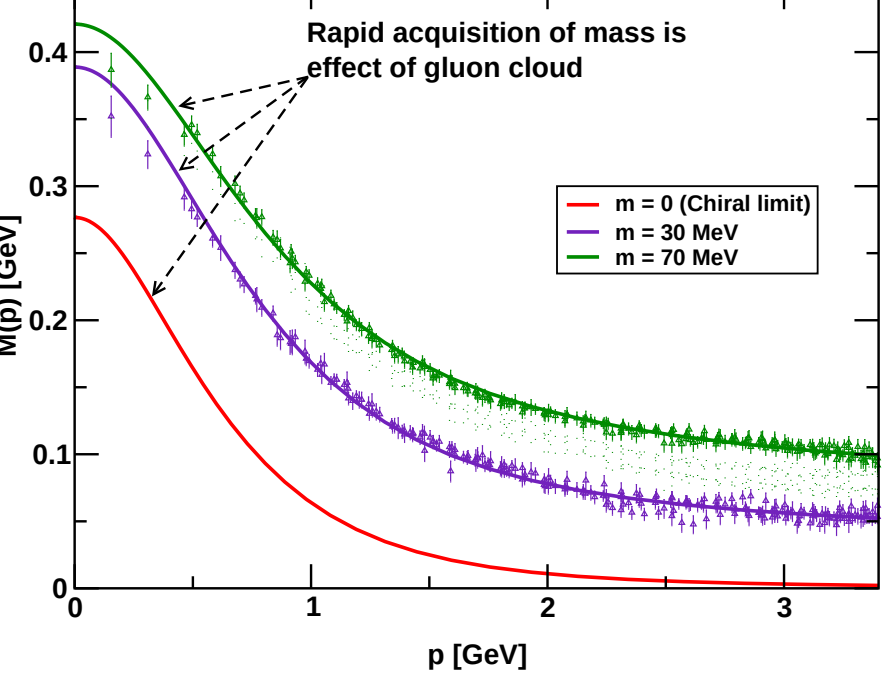
Now is an exciting time . . .

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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