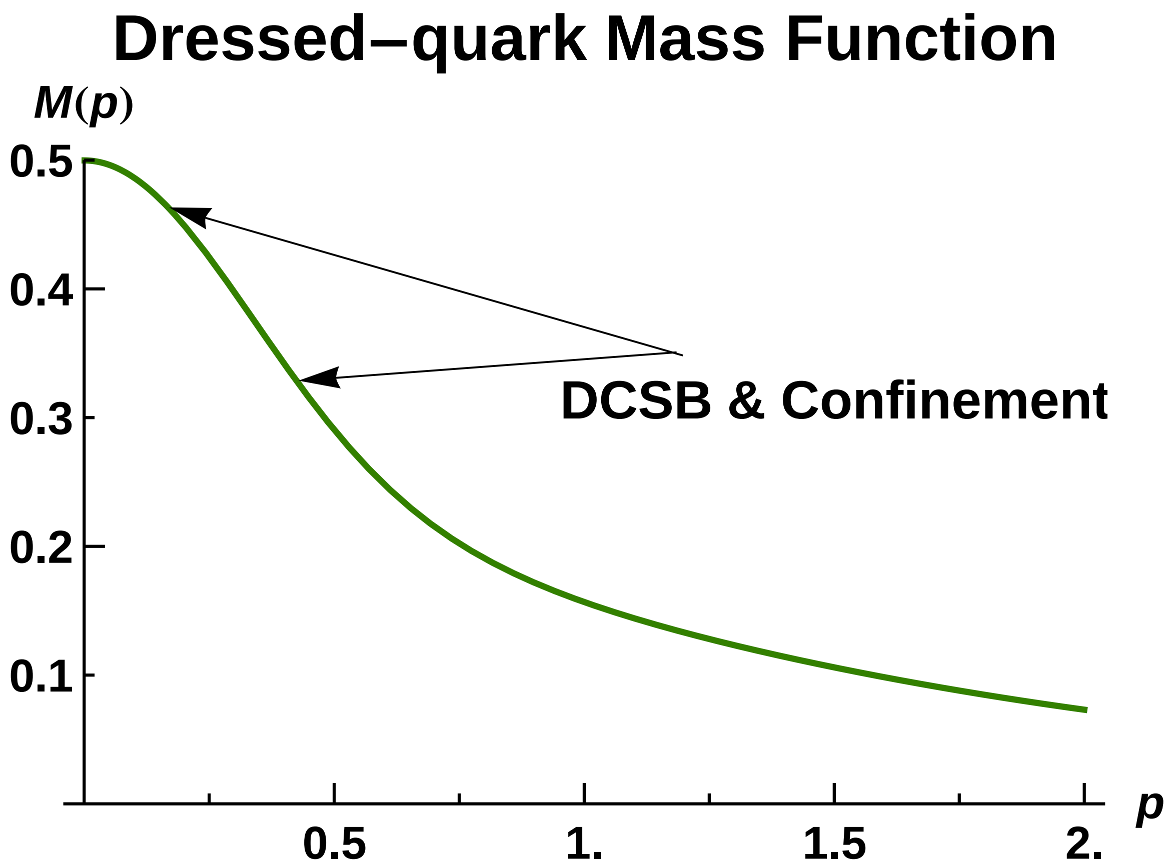
Impact of DCSB on Meson Structure and Interactions



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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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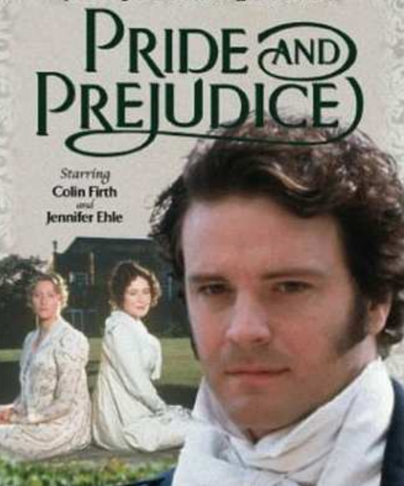

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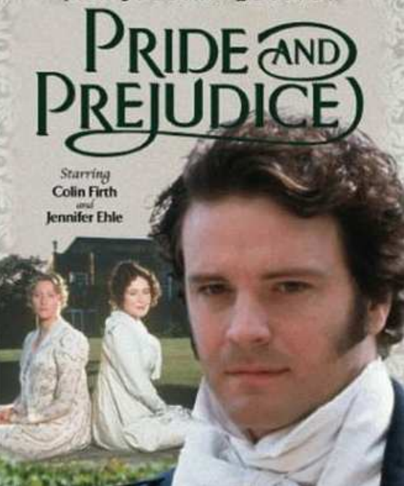

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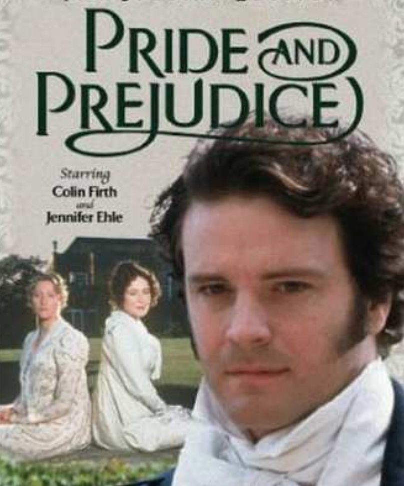

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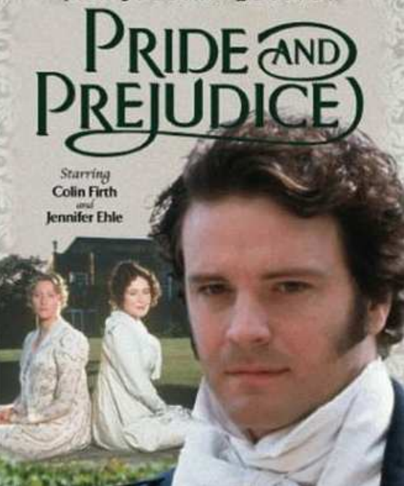

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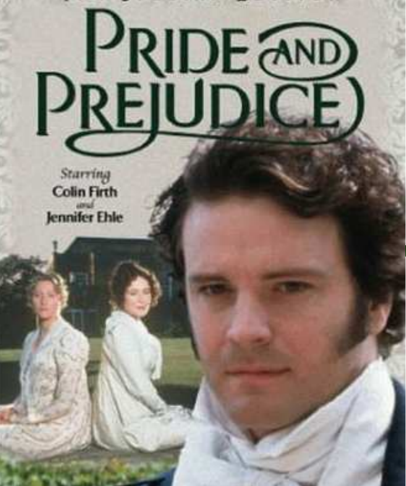

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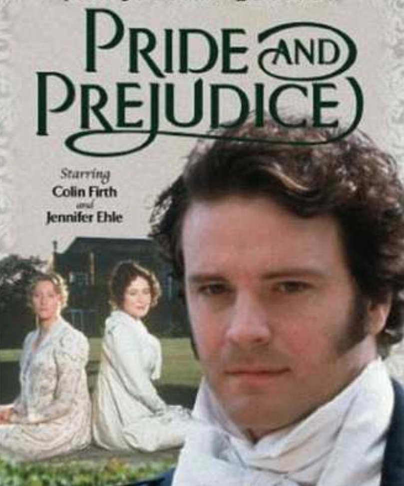

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- Running of quark mass entails that calculations at even modest Q^2 require a Poincaré-covariant approach. Covariance requires existence of quark orbital angular momentum in hadron's rest-frame wave function.

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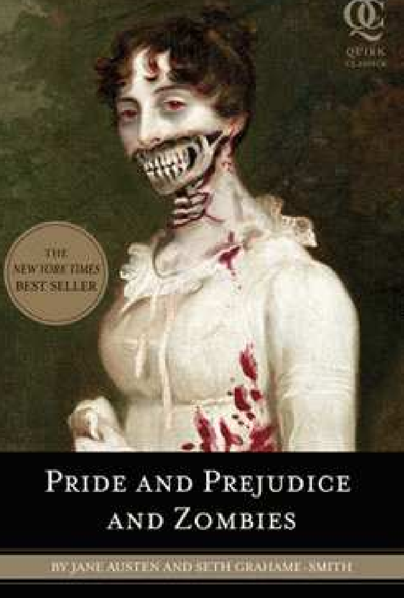

Universal Truths

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

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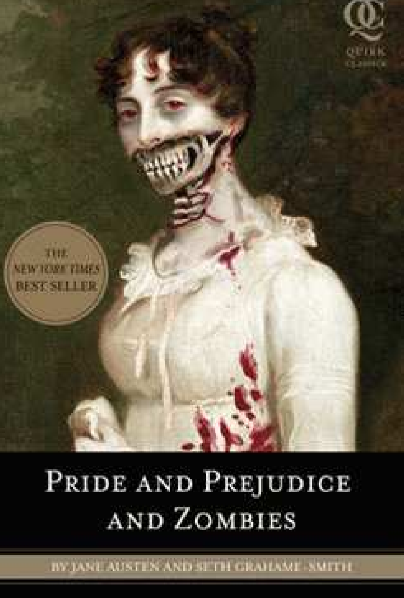

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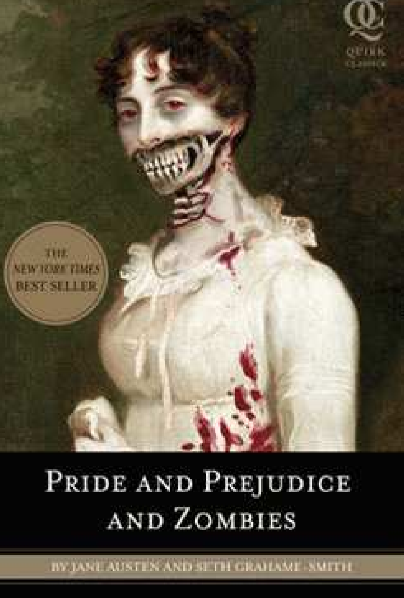

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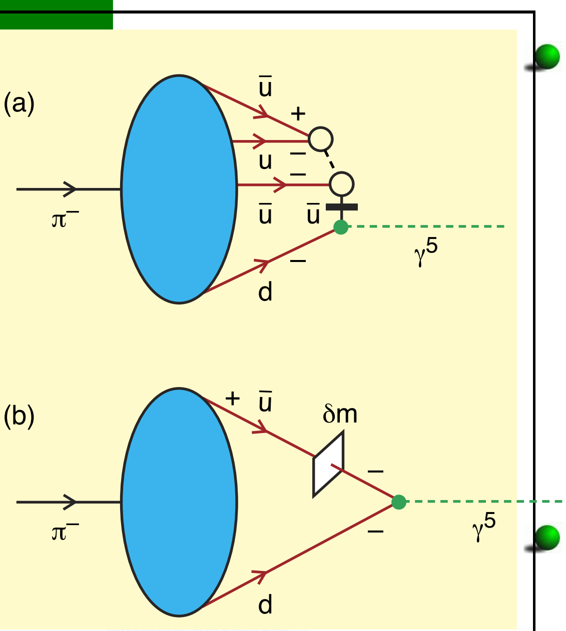
- E.g., one problem: DCSB - an established keystone of low-energy QCD and the origin of constituent-quark masses - has not yet been realised in the light-front formulation.
  - Resolution
    – *So-called* vacuum condensates can be understood as a property of hadrons themselves, which is expressed, for 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].



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

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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 known way to the light-quark interaction.

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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.

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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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  - Enabled proof or exact results in QCD: e.g., BRST – arXiv:1005.4610 [nucl-th]; and . . .

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Radial Excitations
& Chiral Symmetry

Radial Excitations & Chiral Symmetry

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

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

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- Mass^2 of pseudoscalar hadron

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Radial Excitations & Chiral Symmetry

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

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

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Radial Excitations & Chiral Symmetry

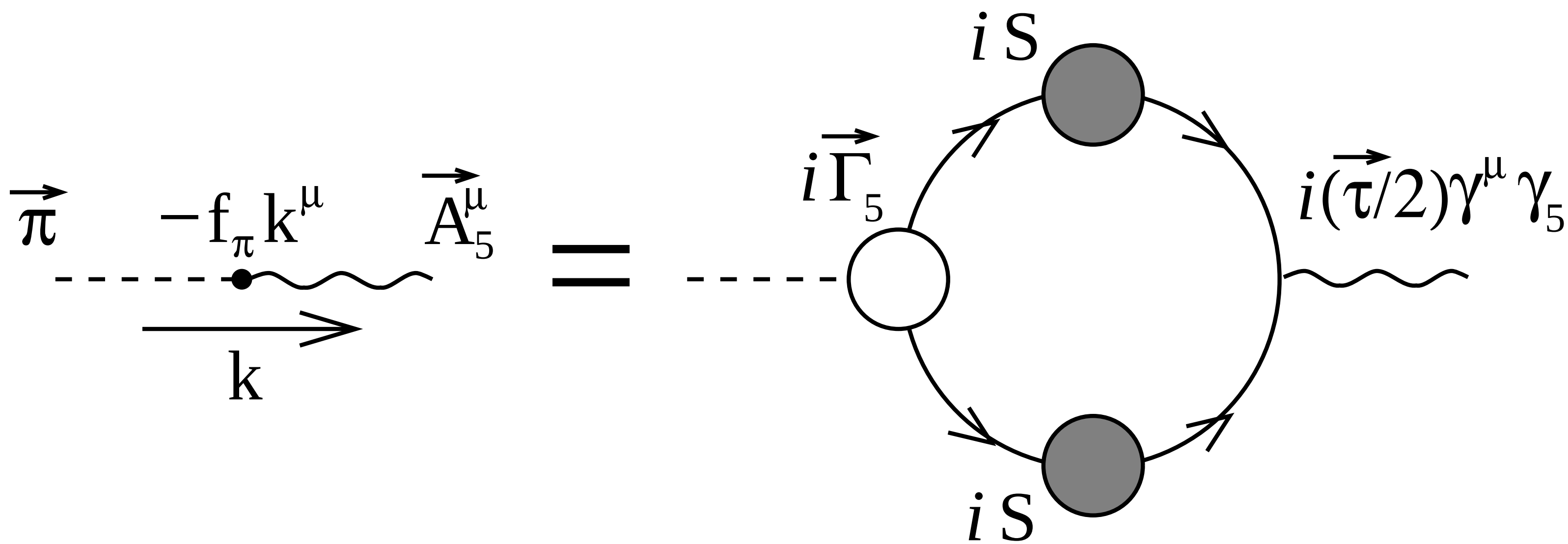
(Maris, Roberts, Tandy nu-th/9707003)

$-i\langle 0|\bar{q}\gamma_5\gamma_\mu q|\pi\rangle$

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

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

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



Radial Excitations & Chiral Symmetry

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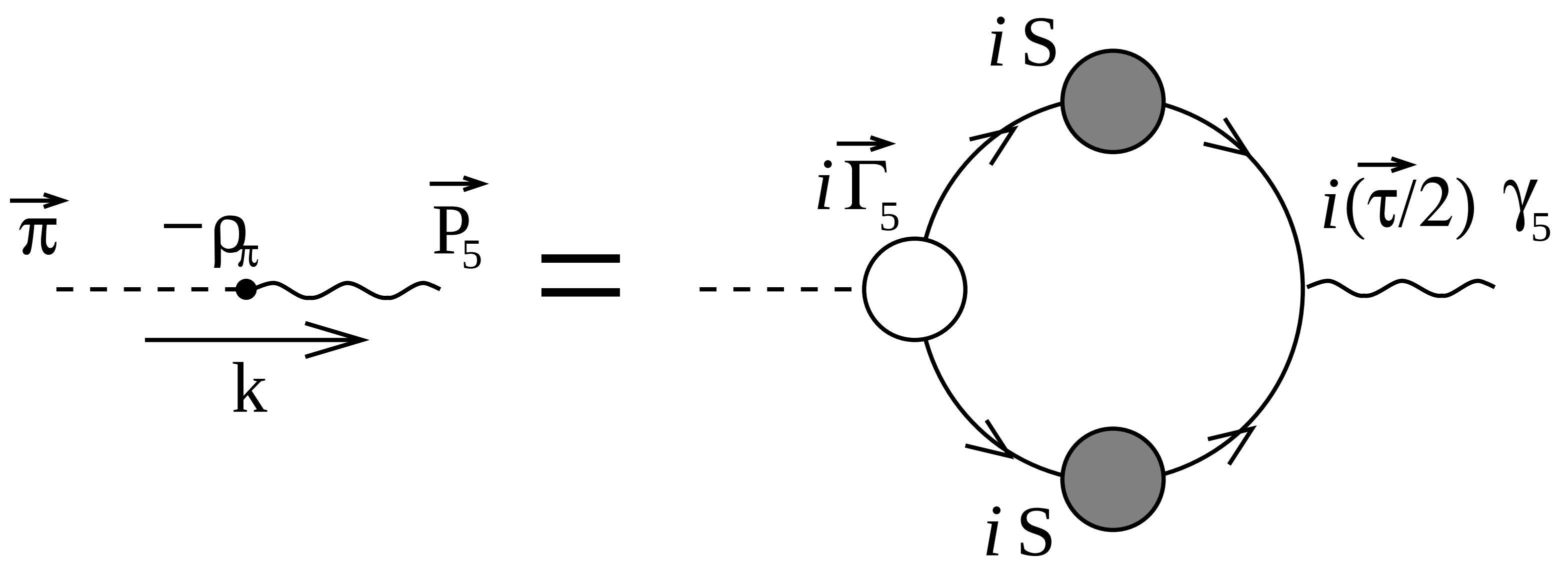

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- Heavy-quark + light-quark

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

  Hence, $m_H \propto m_q$

  ... QCD Proof of Potential Model result

Höll, Krassnigg, Roberts
nu-th/0406030

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- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

  impacts upon *every* pseudoscalar meson

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Radial Excitations & Lattice-QCD

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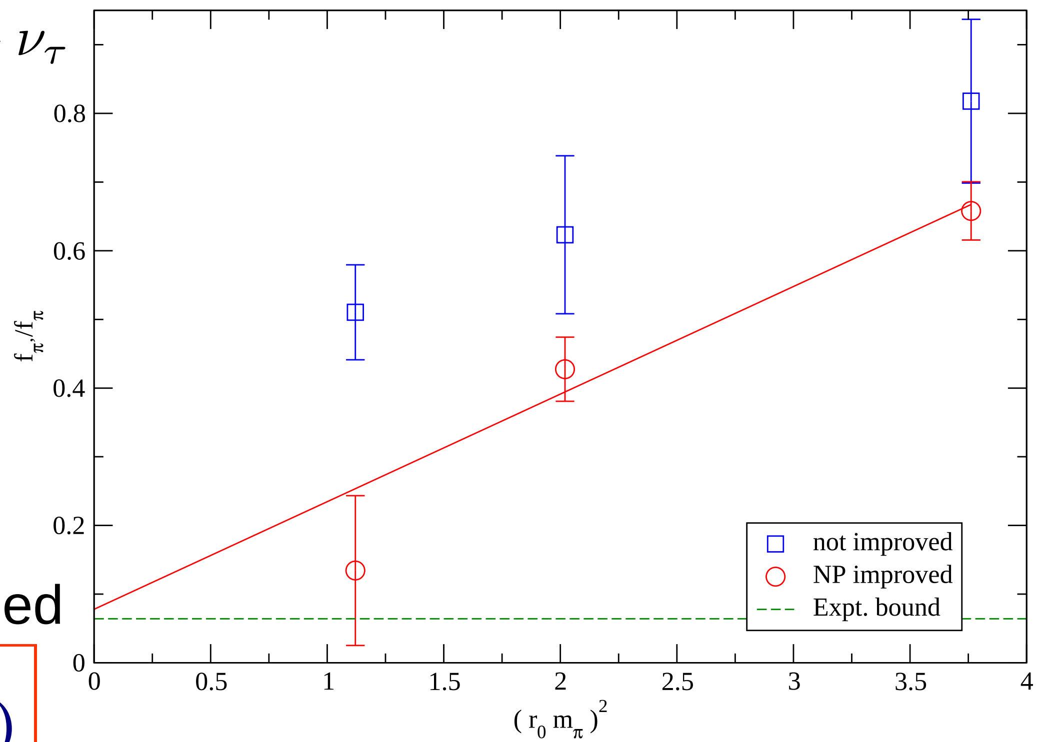

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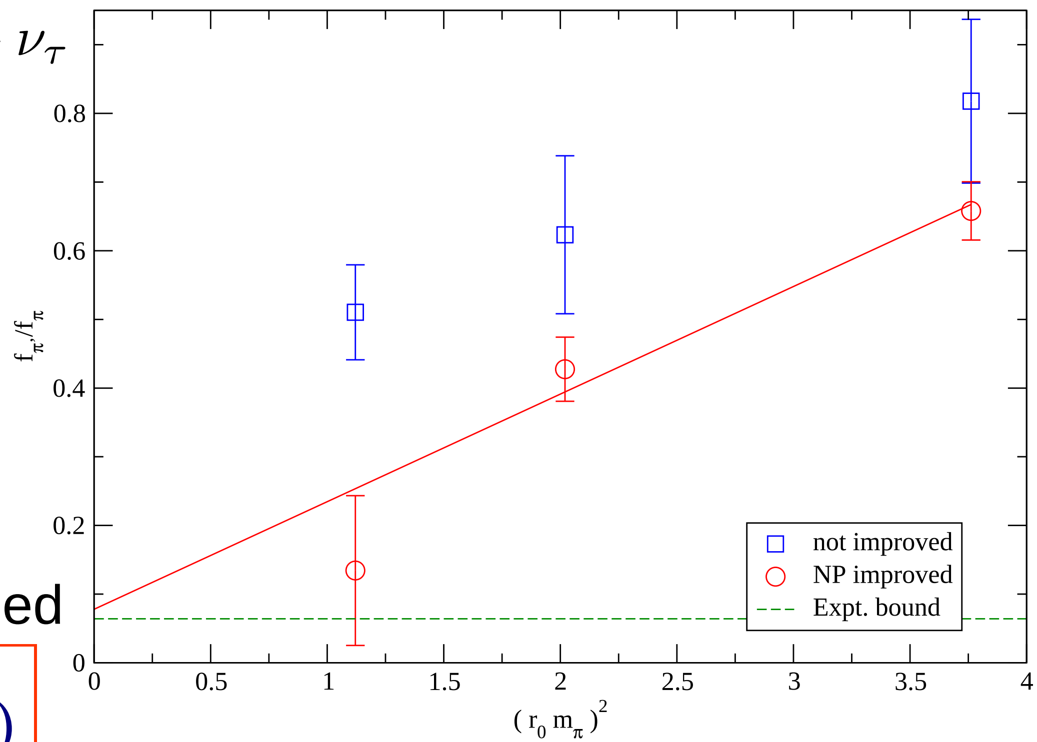

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

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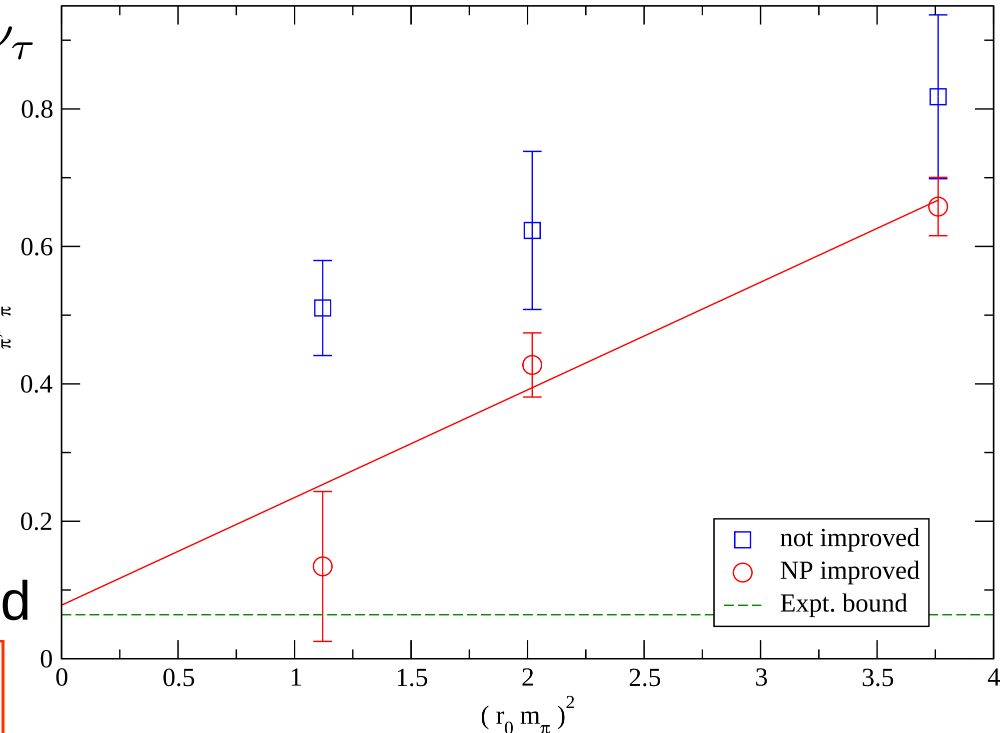

- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

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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)
  - Enabled proof or exact results in QCD, as we've just seen

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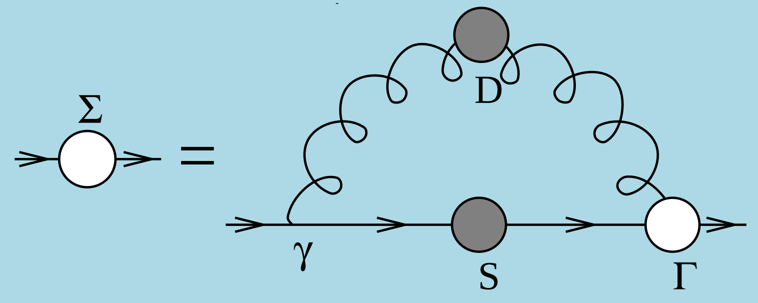
  - On other hand, at present significant qualitative advances possible with symmetry-preserving kernel *Ansätze* that express important additional nonperturbative effects – $M(p^2)$ – difficult/impossible to capture in any finite sum of contributions

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

Frontiers of Nuclear Science: Theoretical Advances



Gap Equation

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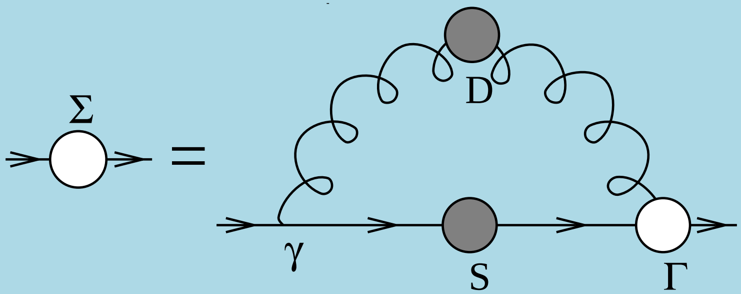
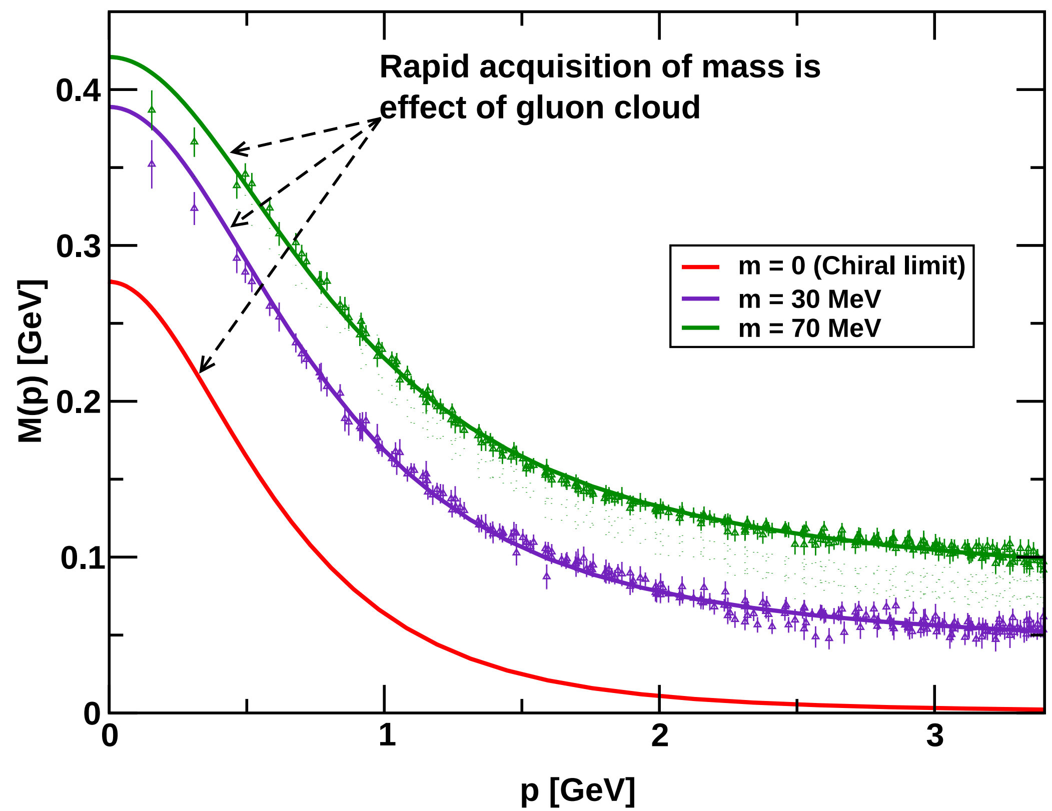
Frontiers of Nuclear Science: Theoretical Advances



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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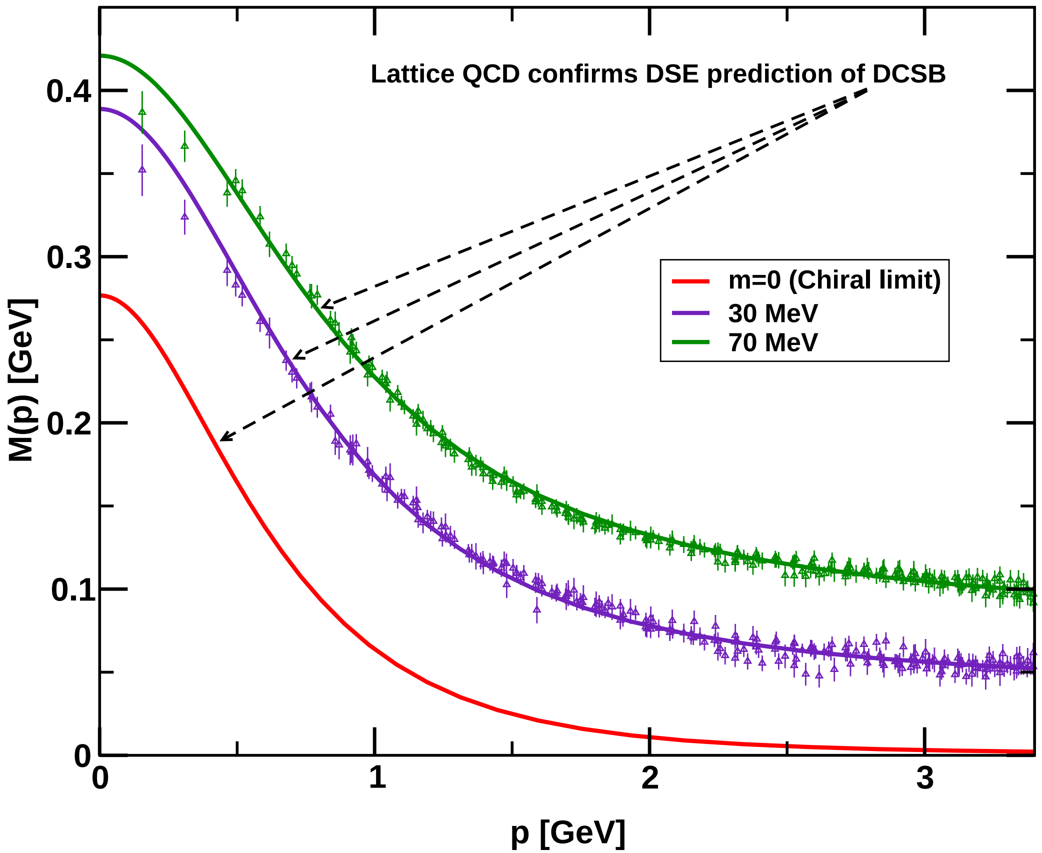

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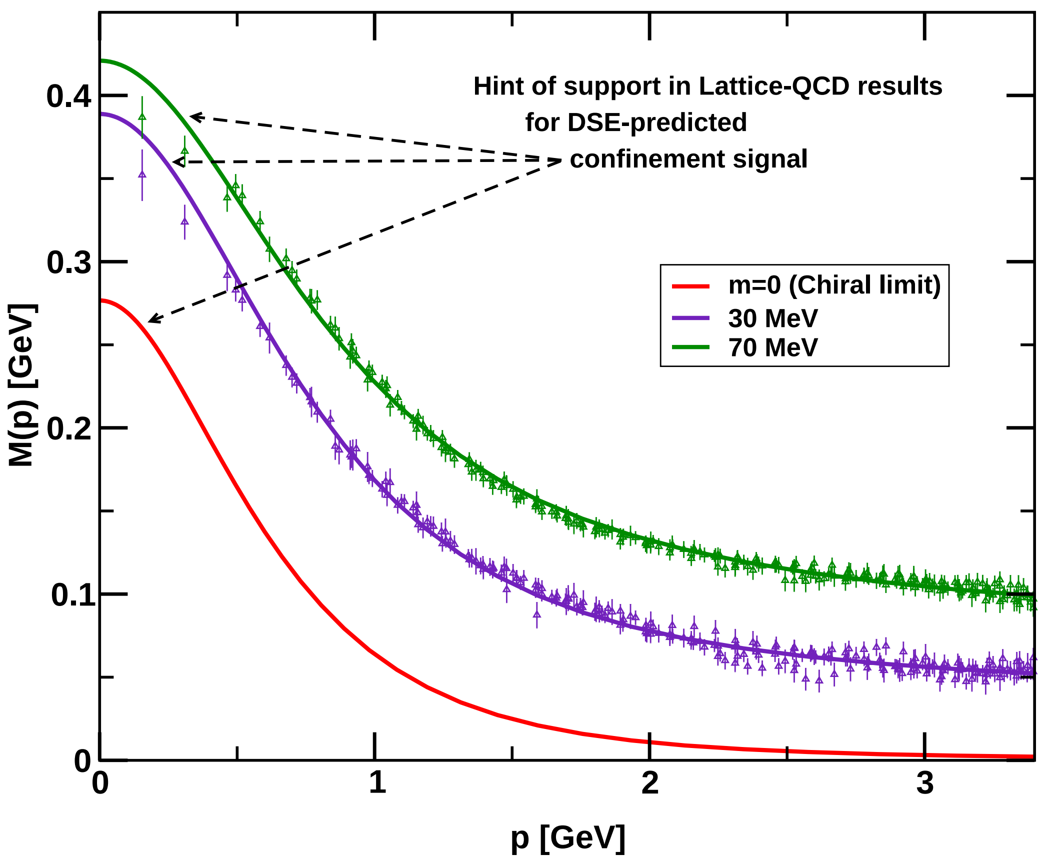

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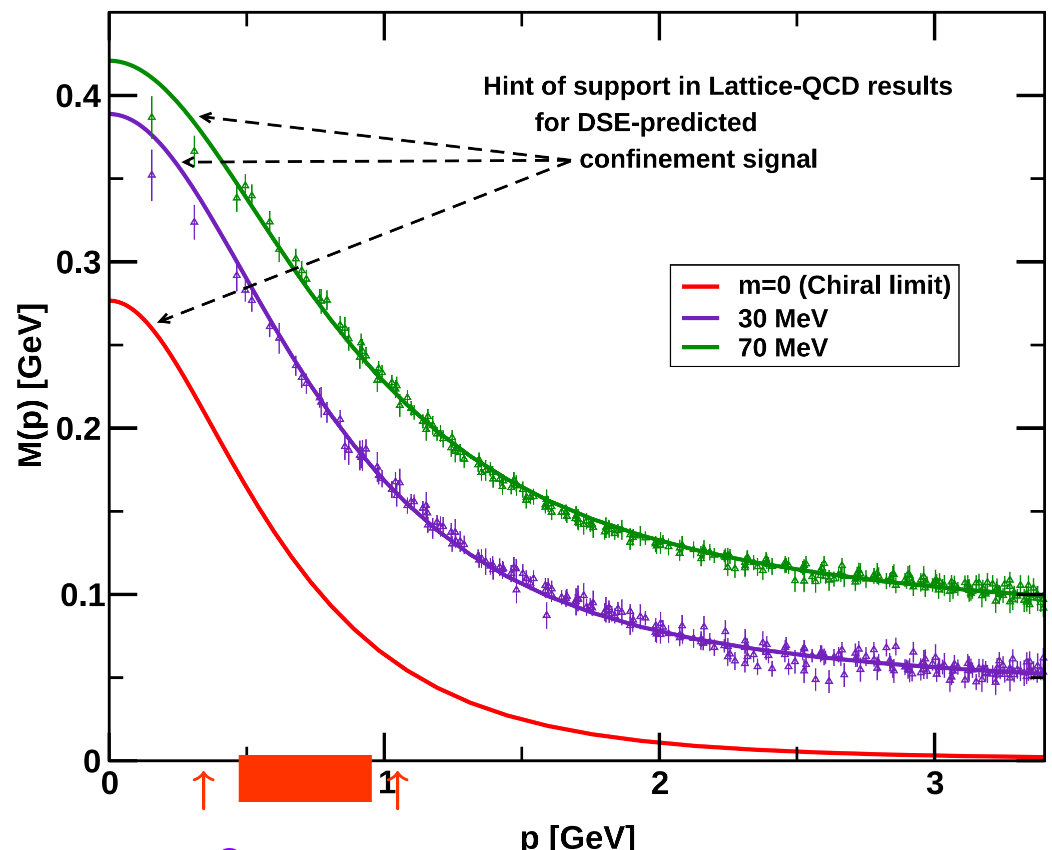

Scanned by $Q^2 \in [2, 9]\ \mathrm{GeV}^2$ Hadron Elastic and Transition Form Factors

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Gap Equation General Form

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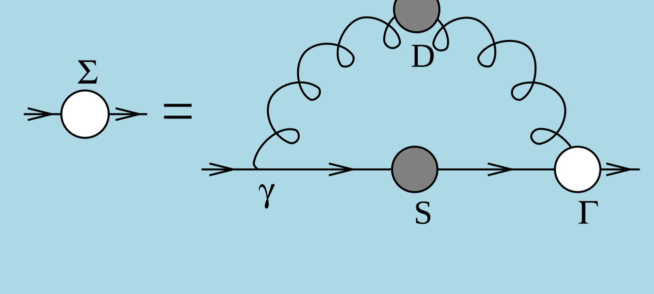

Gap Equation General Form

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

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

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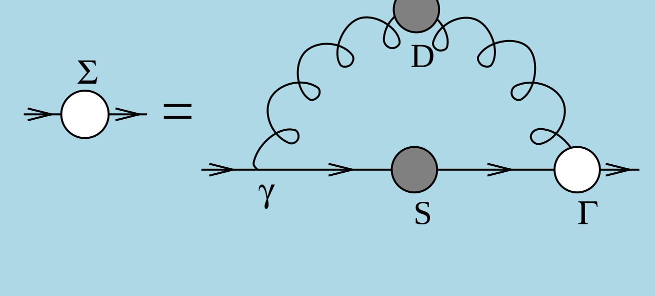

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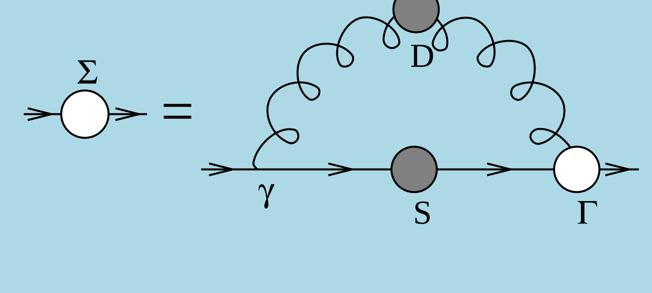
- $Z_{1,2}(\zeta^2,\Lambda^2)$ are respectively the vertex and quark wave function renormalisation constants, with ζ the renormalisation point
- $m^{\rm bm}(\Lambda)$ is the Lagrangian current-quark bare mass
- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma^f_\nu(q,p)$ is the dressed-quark-gluon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



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

Bound-state DSE

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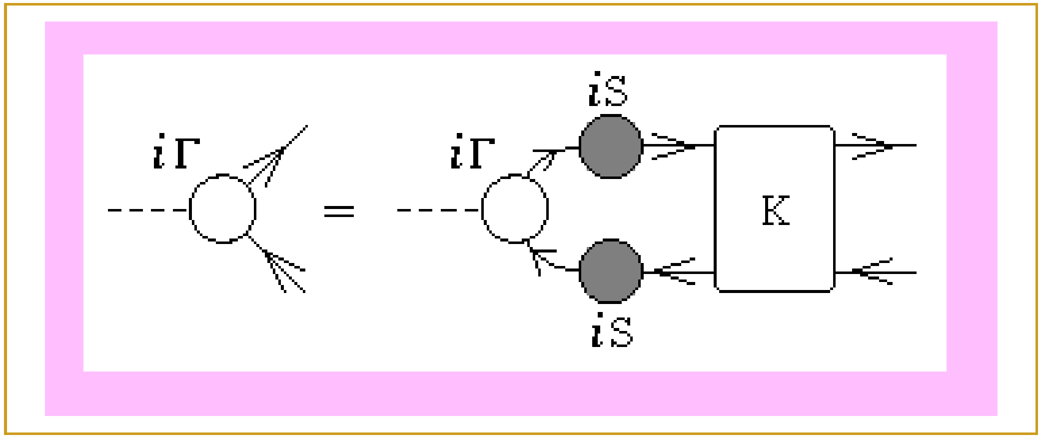
Bethe-Salpeter Equation

- 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

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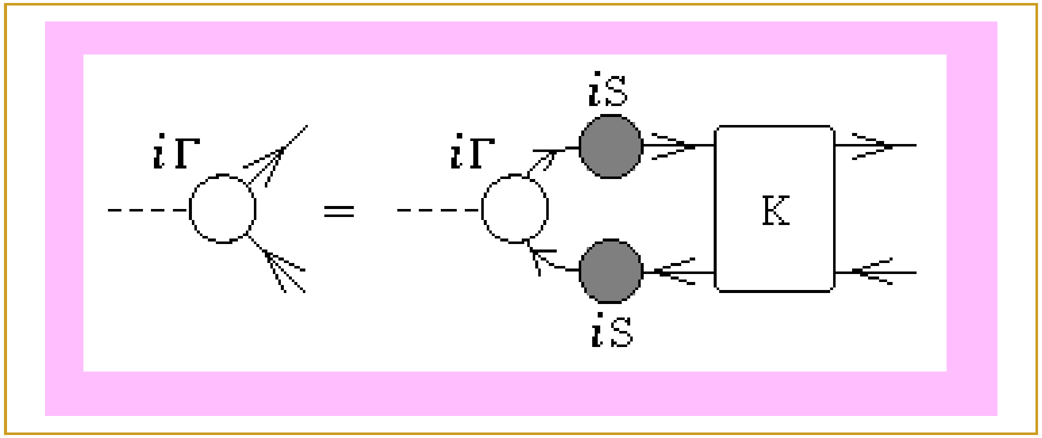

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- Compact. Visually appealing. Correct.

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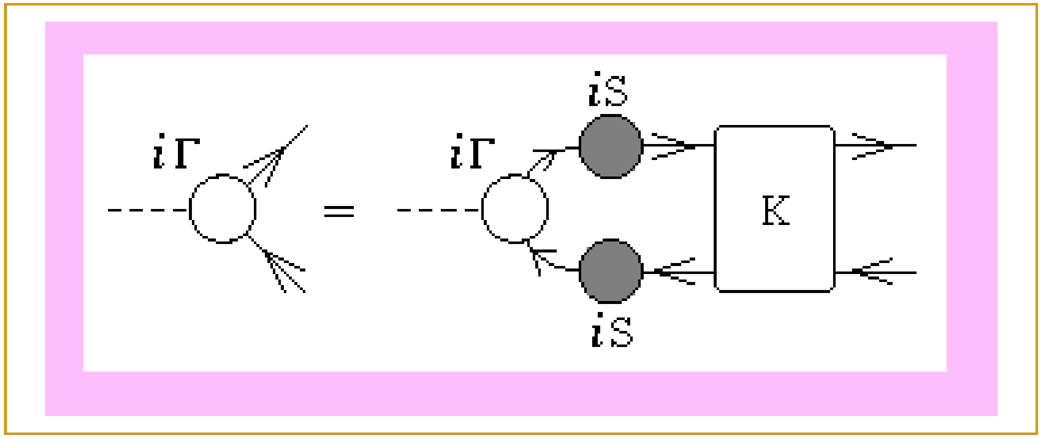

$K(q,k;P)$: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

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

Bethe-Salpeter Equation General Form

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

Bethe-Salpeter Equation General Form

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

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Bethe-Salpeter Kernel

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- Bethe-Salpeter equation introduced in 1951

Bethe-Salpeter Kernel
60 year problem

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- Bethe-Salpeter equation introduced in 1951
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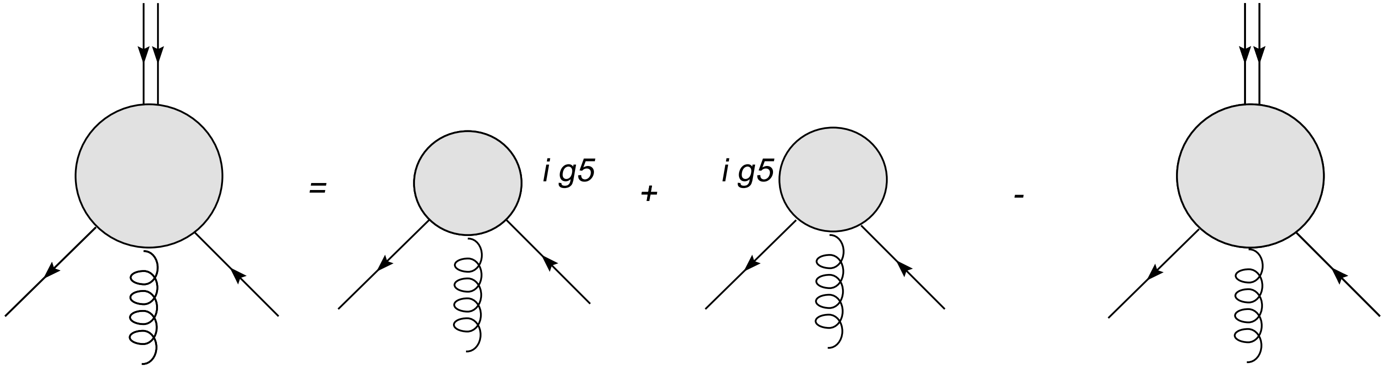

$$P_\mu \Lambda^{fg}_{5\mu\beta}(k,q;P) = \Gamma^f_\beta(q_+,k_+)\, i\gamma_5 + i\gamma_5\, \Gamma^g_\beta(q_-,k_-) - i[m_f(\zeta)+m_g(\zeta)]\Lambda^{fg}_{5\beta}(k,q;P),$$

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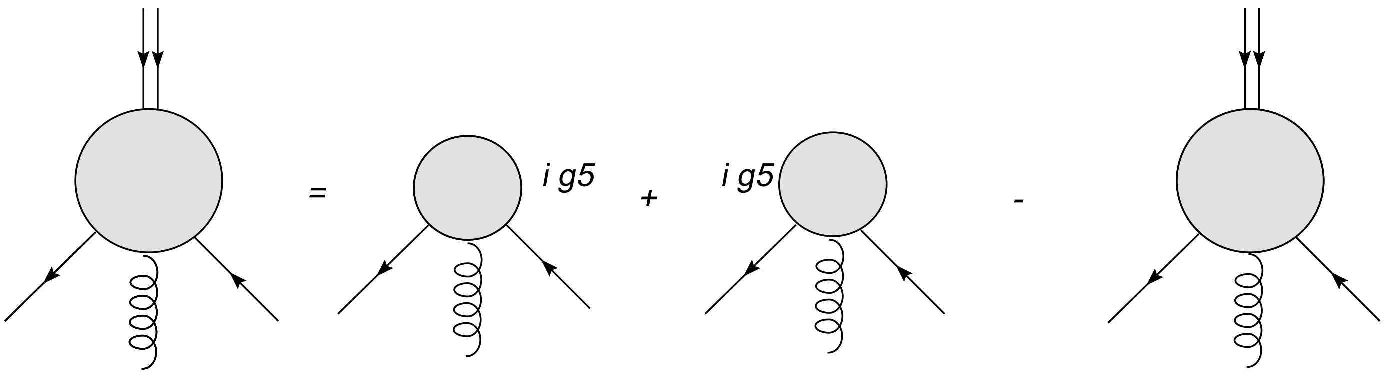

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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
  - Consistent means - all symmetries preserved!

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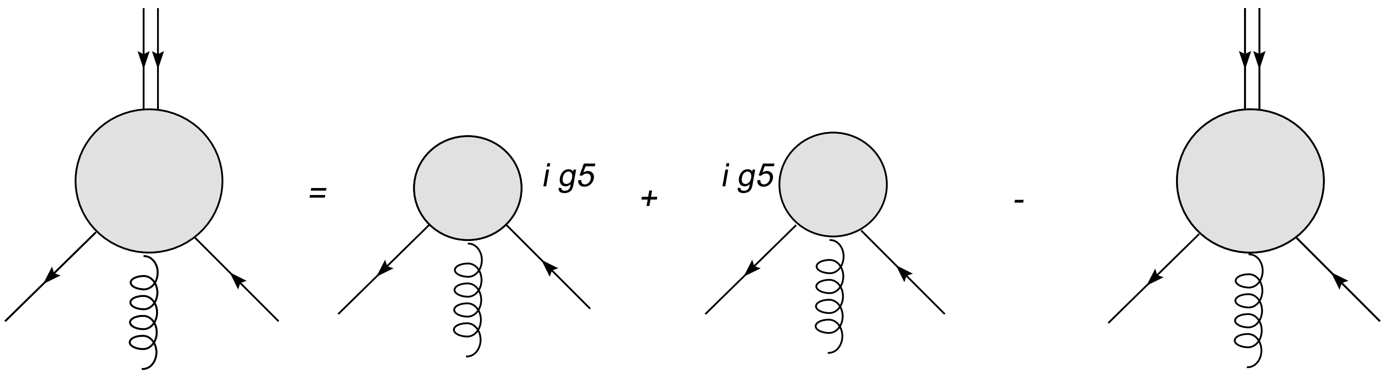

$$P_\mu \Lambda^{fg}_{5\mu\beta}(k,q;P) \;=\; \Gamma^f_\beta(q_+,k_+)\, i\gamma_5 + i\gamma_5\, \Gamma^g_\beta(q_-,k_-)$$
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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
- Procedure & 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!

$a_1 - \rho$

	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
  $$\Gamma_\mu^{BC}(k,p) = \ldots + (k+p)_\mu \frac{B(k)-B(p)}{k^2-p^2}$$
  - Some effects of DCSB built into vertex
  - Explains $\pi - \sigma$ splitting but not this problem

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$a_1 - \rho$

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

$a_1 - \rho$

Chang & Roberts arXiv:1003.5006 [nucl-th]

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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.

Quark Anomalous Magnetic Moments

Chang & Roberts, in progress

- Massless fermion can't possess an anomalous magnetic moment
  - Interaction term $\int d^4x \, \frac{1}{2} g \, \bar{\psi}(x) \sigma_{\mu\nu} \psi(x) F_{\mu\nu}(x)$ 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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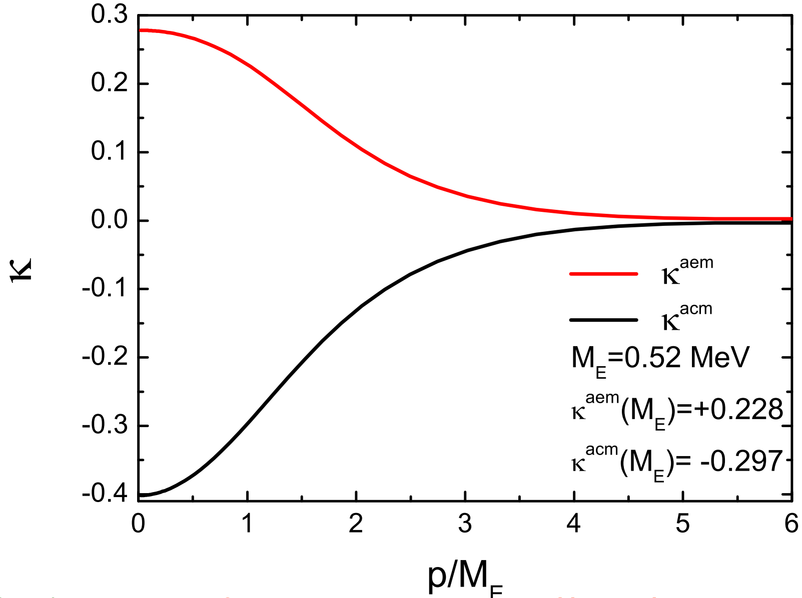
- $M(p^2) \Rightarrow \kappa(p^2)$
  - Preliminary result for μ distributions



Quark Anomalous Magnetic Moments

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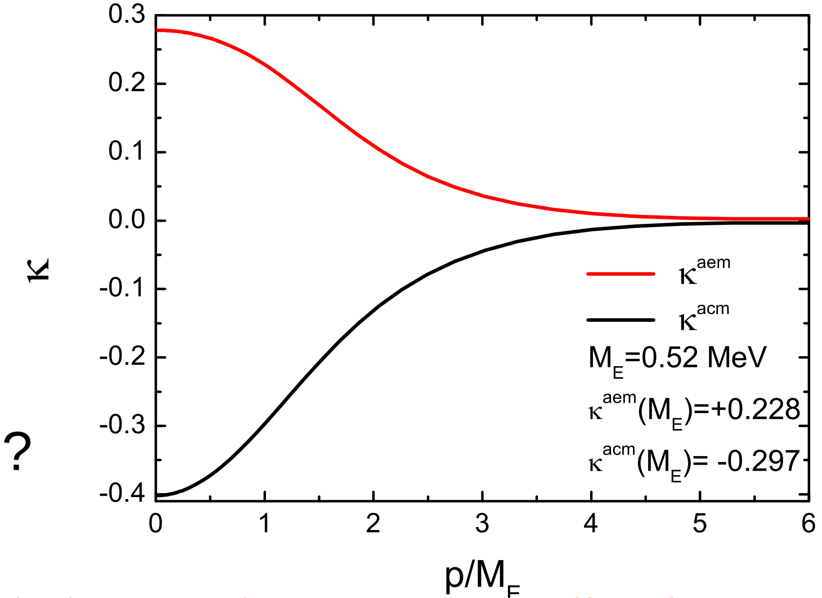
  - Preliminary result for μ distributions
- Cloët & Roberts
  Effect on hadron form factors?



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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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$\Rightarrow$

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

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Goldberger-Treiman for pion

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Pseudovector components necessarily nonzero

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

$\Rightarrow$ Exact in Chiral QCD

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

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

- What does this mean for observables?

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

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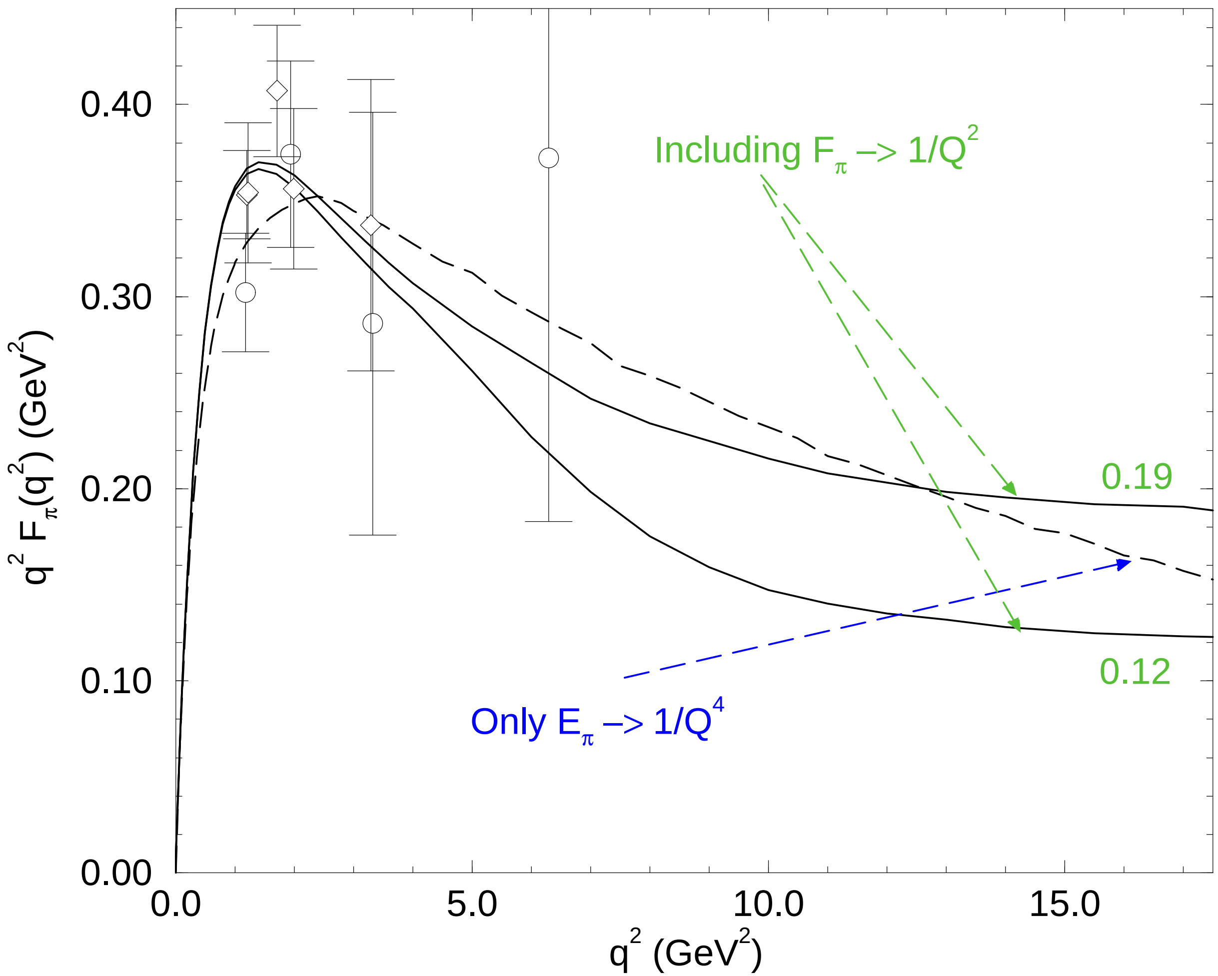

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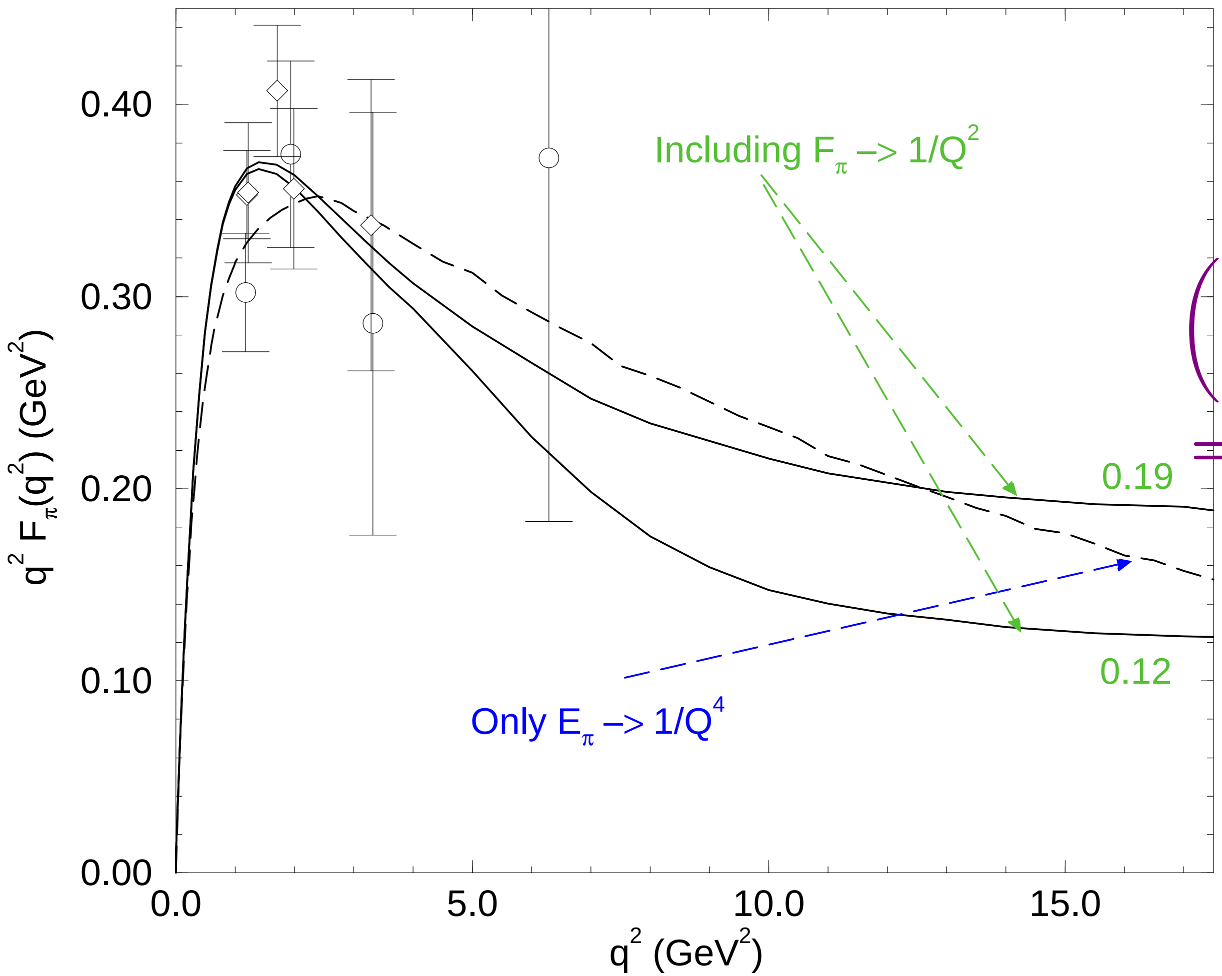
- What does this mean for observables?



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

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

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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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  - Has pseudovector component
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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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- Asymptotic form of electromagnetic pion form factor

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

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Computation: Elastic Pion Form Factor

Guttierez, Bashir, Cloët, Roberts:
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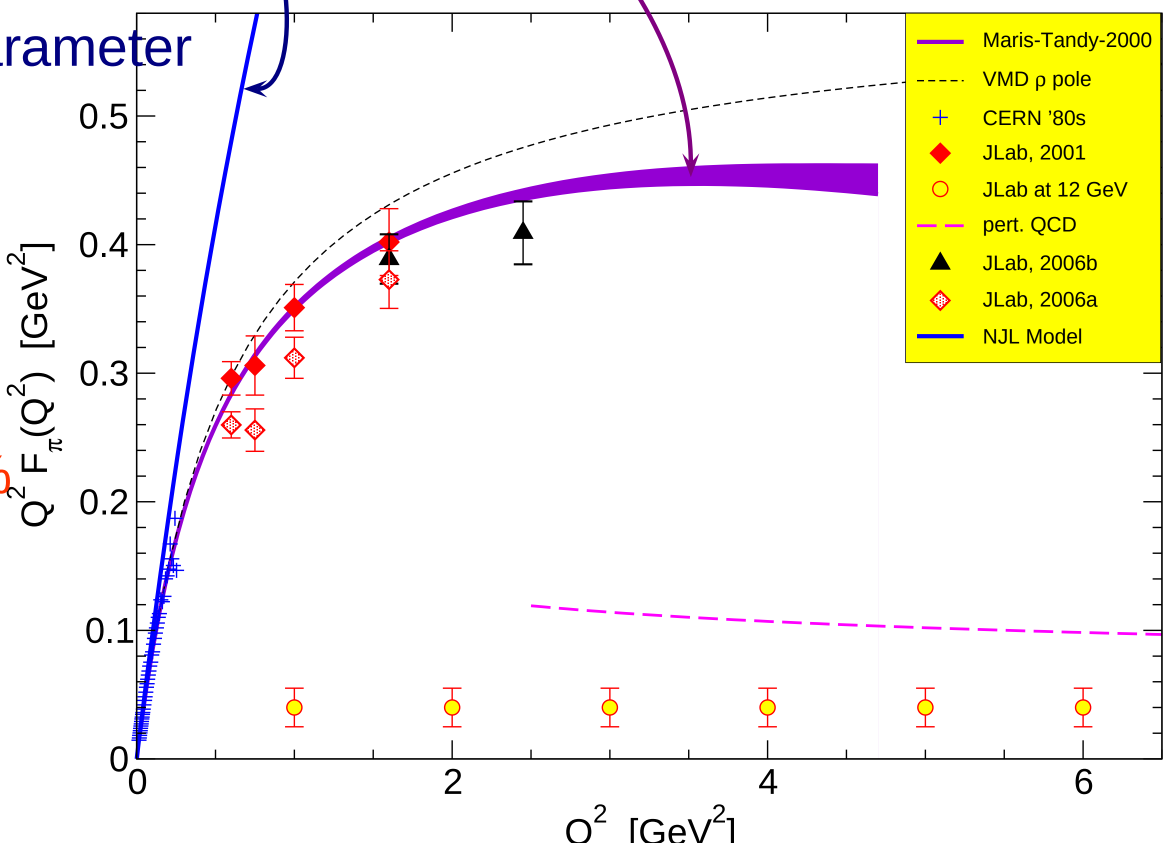
Disagreement $> 20\%$ for $Q^2 > M^2$



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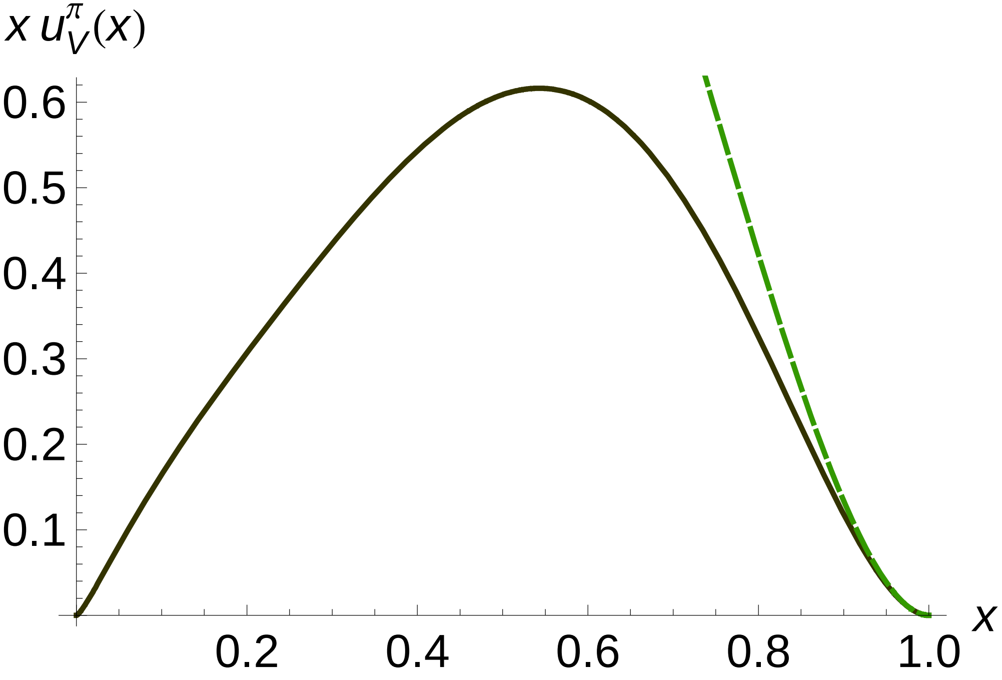
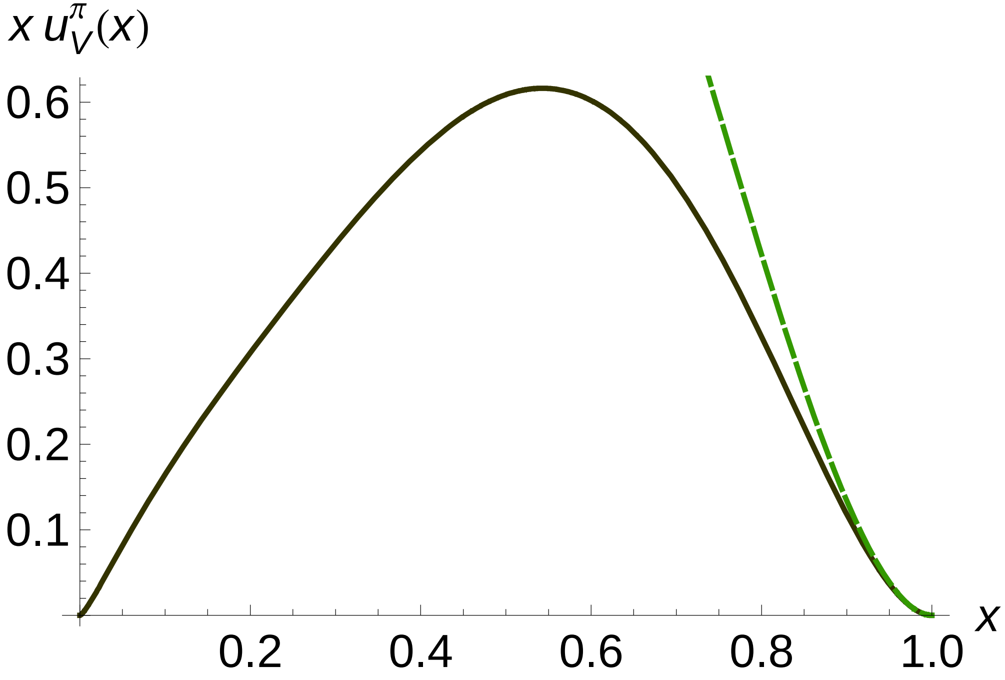
Pion's valence distribution



Pion's valence distribution

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

$$\frac{\alpha(q^2)}{q^2} \overset{q^2 \gtrsim M_D^2}{\propto} \left(\frac{1}{q^2}\right)^{1+\kappa}$$



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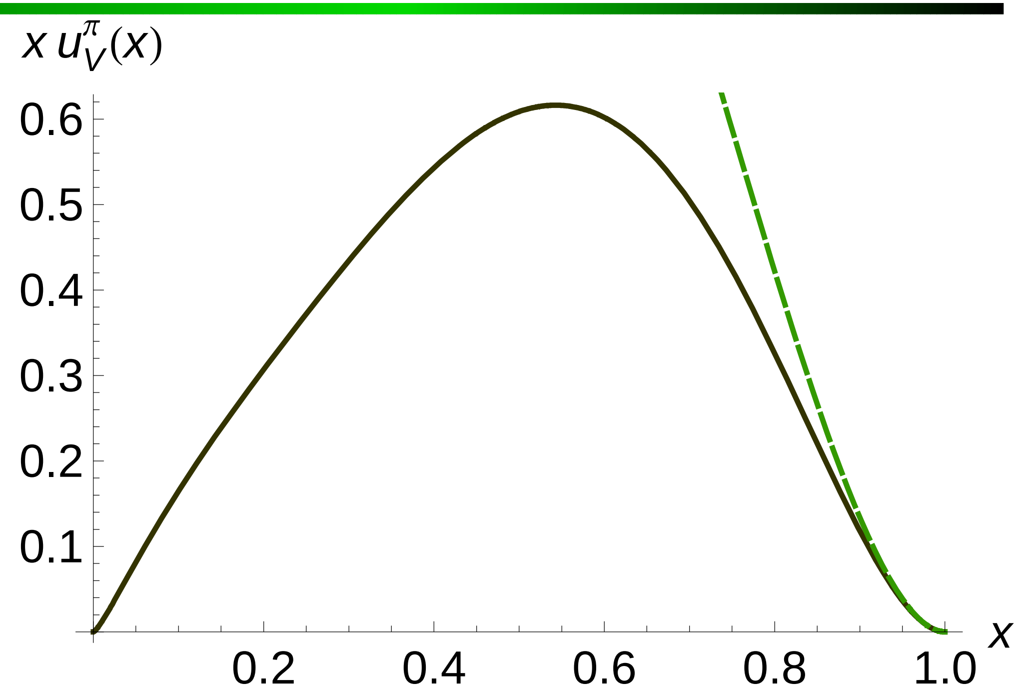

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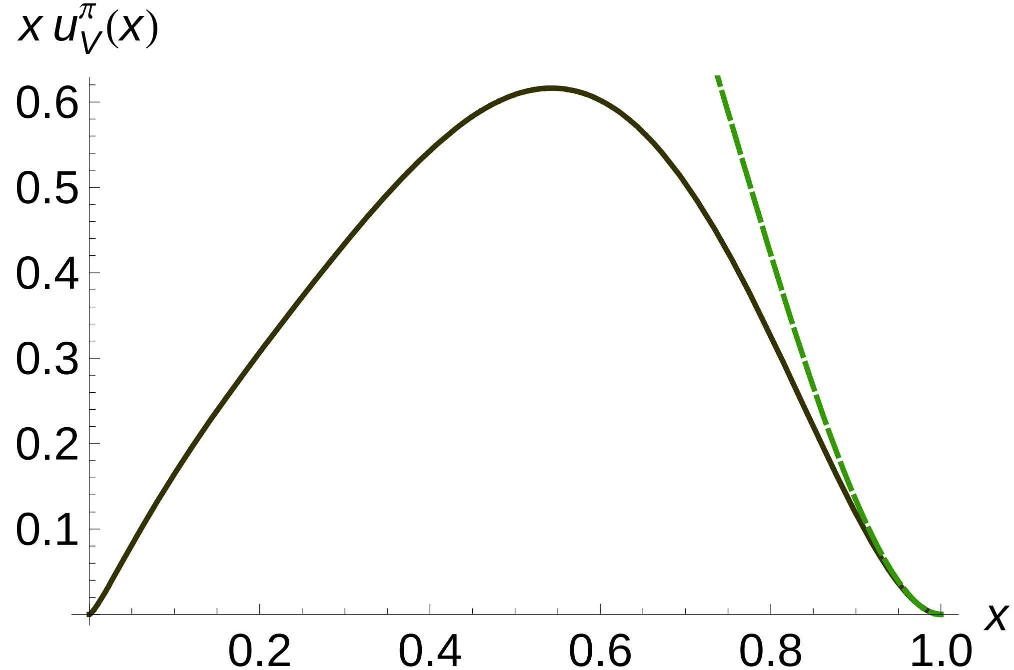

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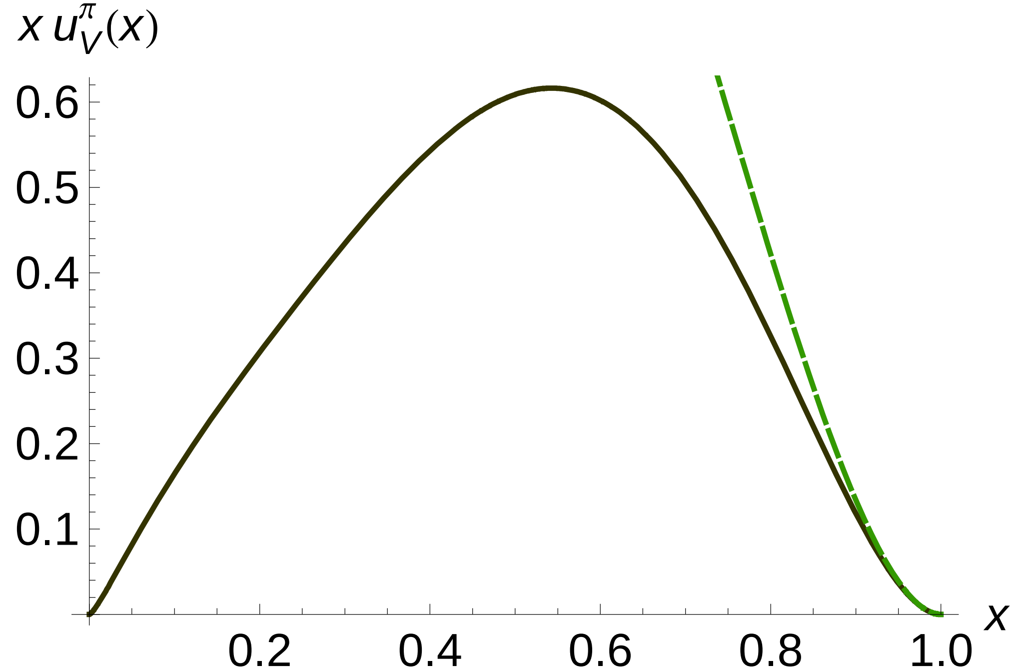

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- $M_D \approx 0.4$ GeV
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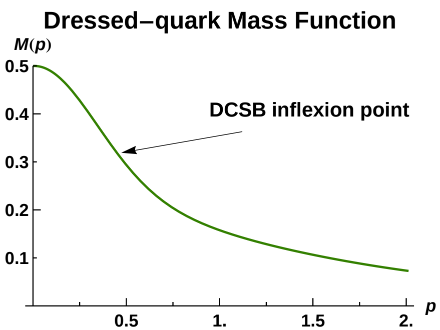

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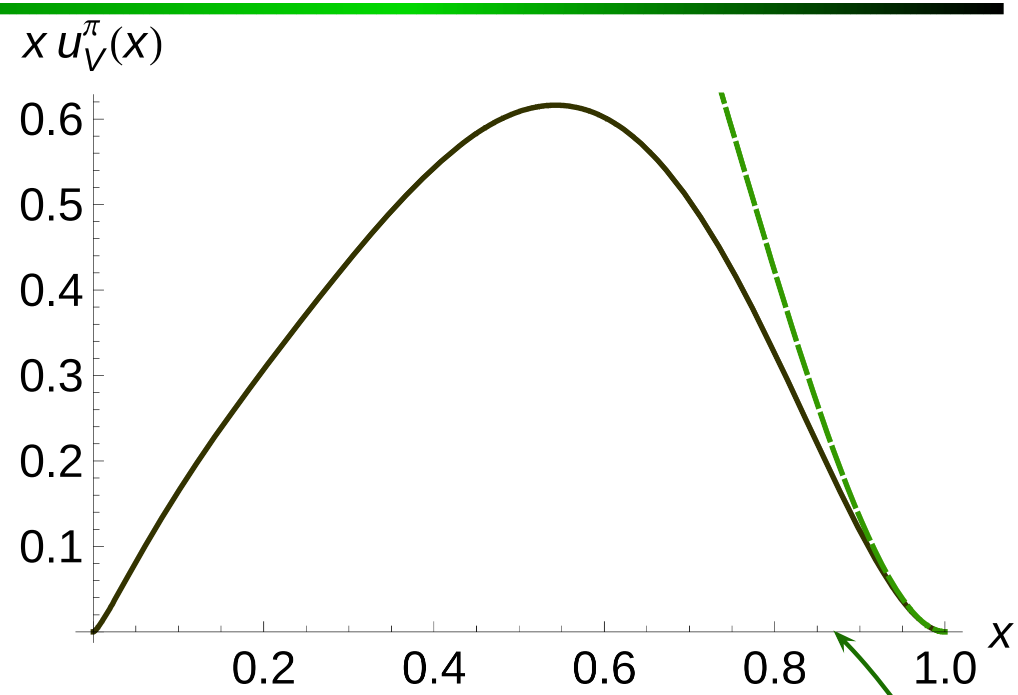

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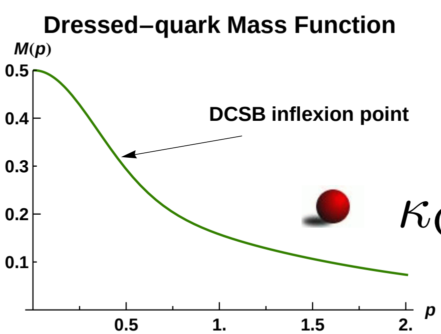
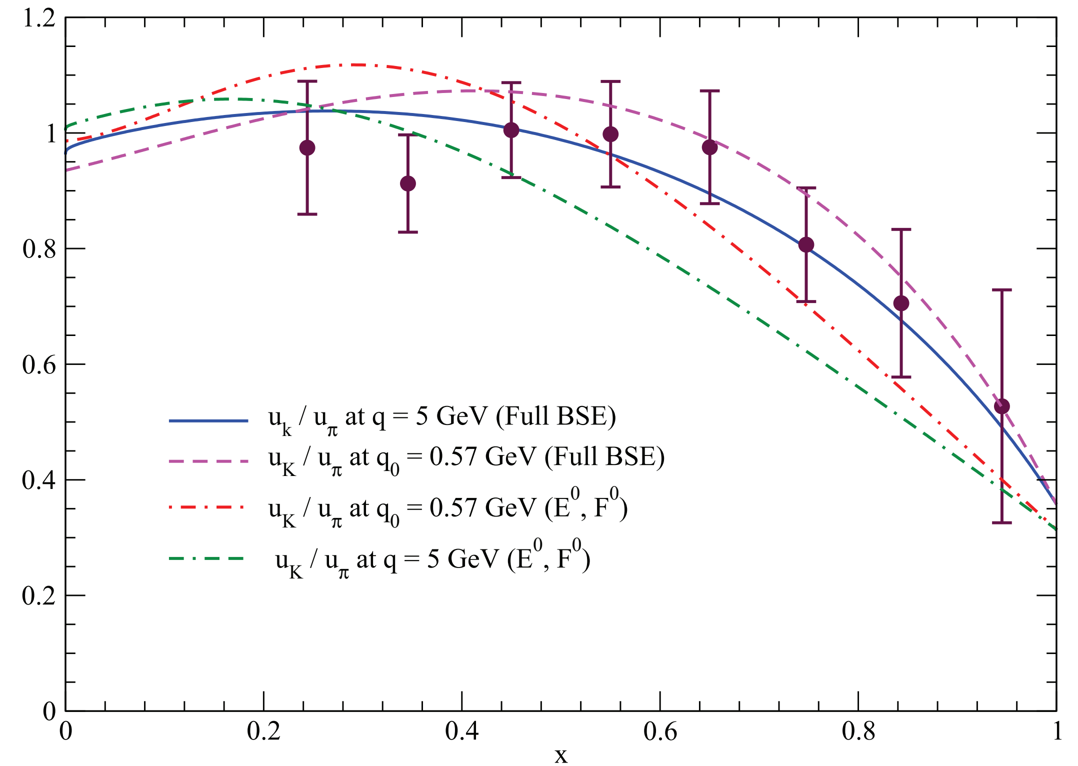


- $\kappa_{\mathrm{QCD}} = 0 \Rightarrow q_v^\pi(x; 1\,\mathrm{GeV}^2) \propto (1-x)^2$
  DSE calculation shows this valid for $\mathcal{L}_x = \{x | x > 0.86\}$.

Ratio – Kaon/Pion
u-valence distribution

T. Nguyen: PhD Thesis (Kent State U.)
Nguyen, 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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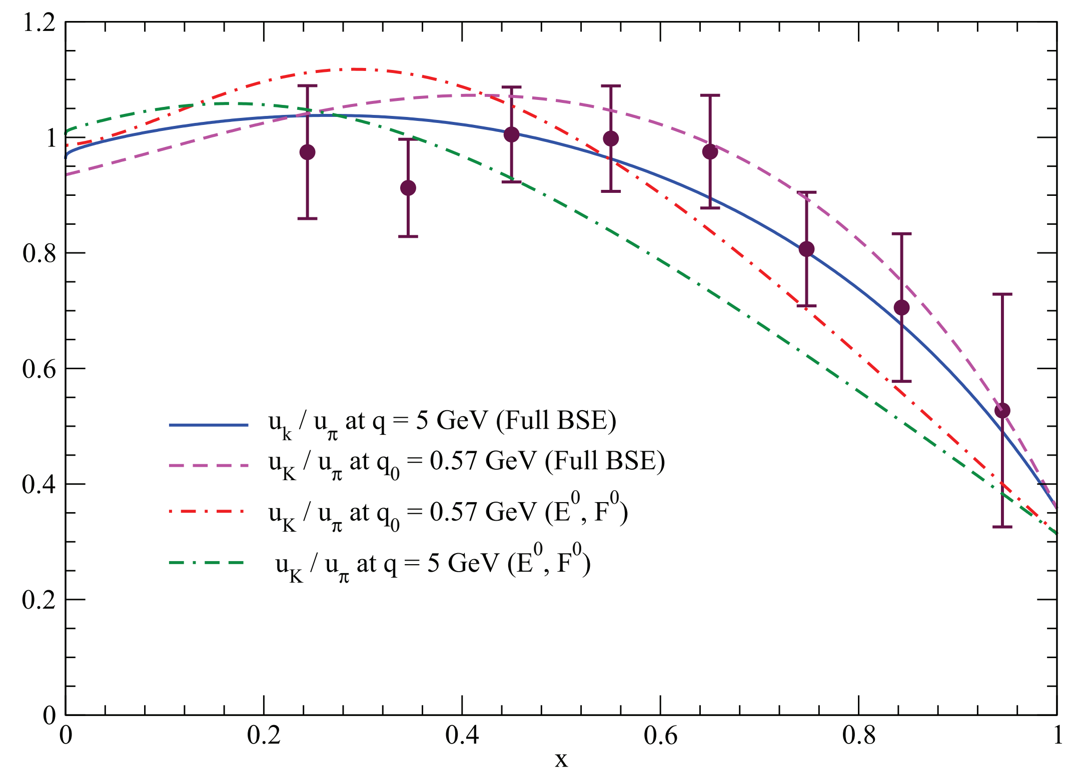

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- Influence of $M(p^2)$ felt strongly for $x > 0.5$
- QCD-$M(p^2) \Rightarrow$ prediction: $u_{\pi,K}(x) \propto (1-x)^2$ at resolving-scale $Q_0 = 0.6$ GeV

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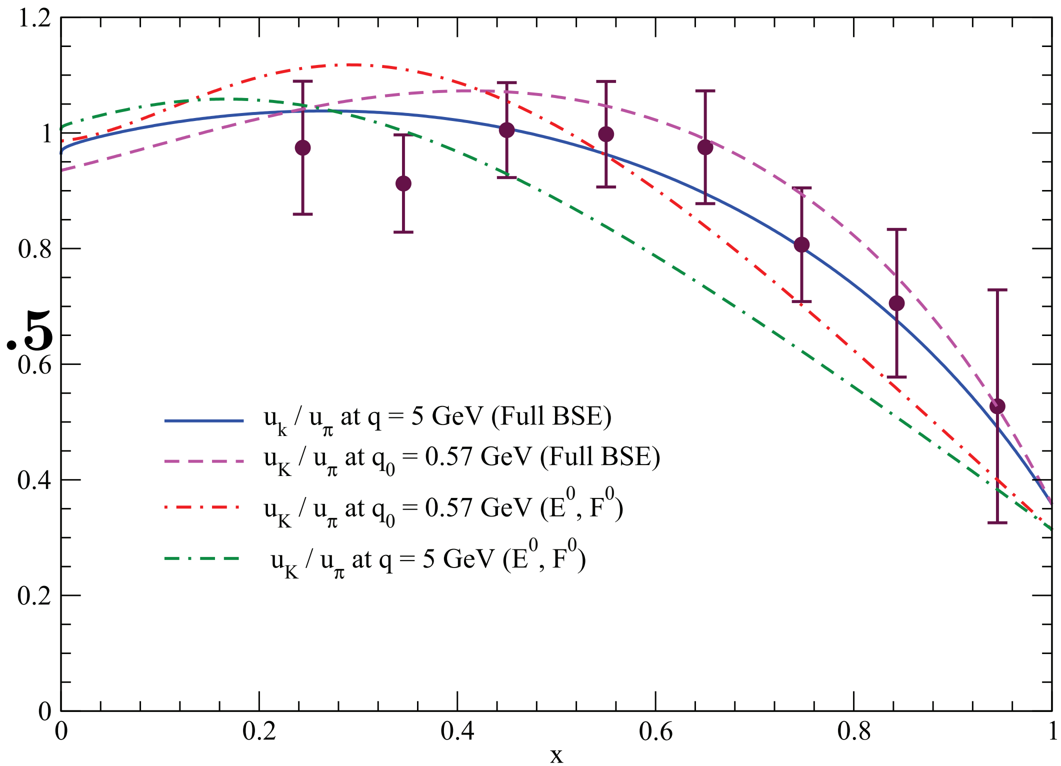

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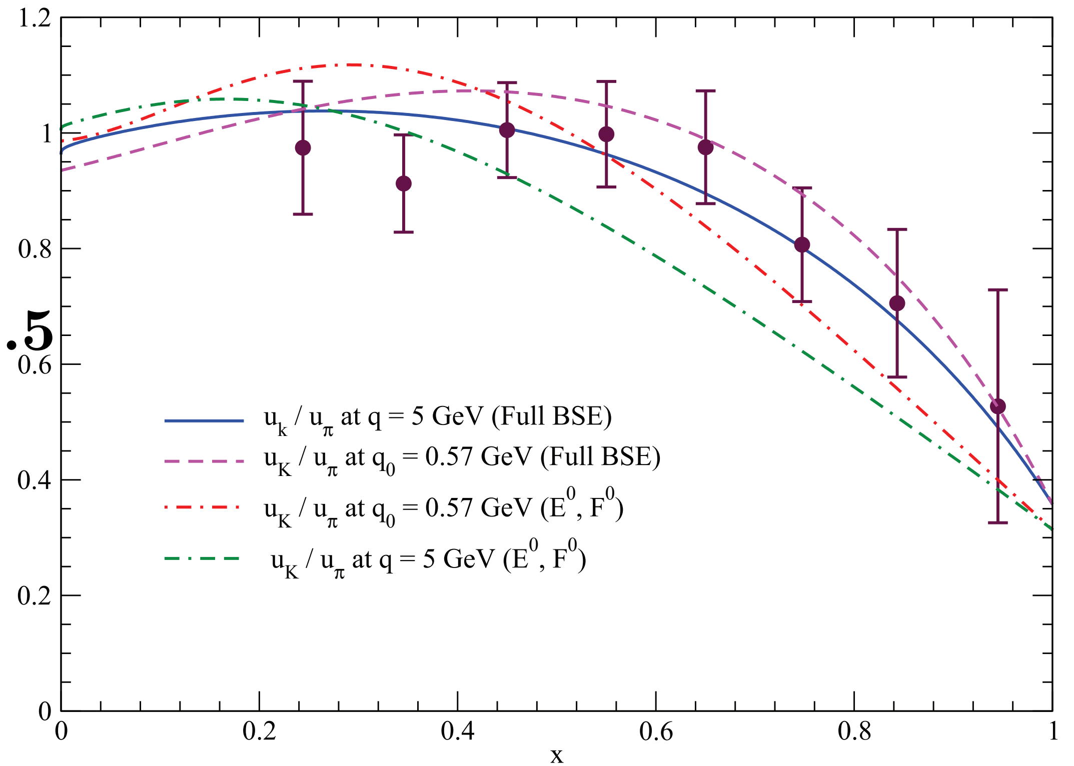

- $u_{\pi,K}(x=1)$ invariant under DGLAP-evolution

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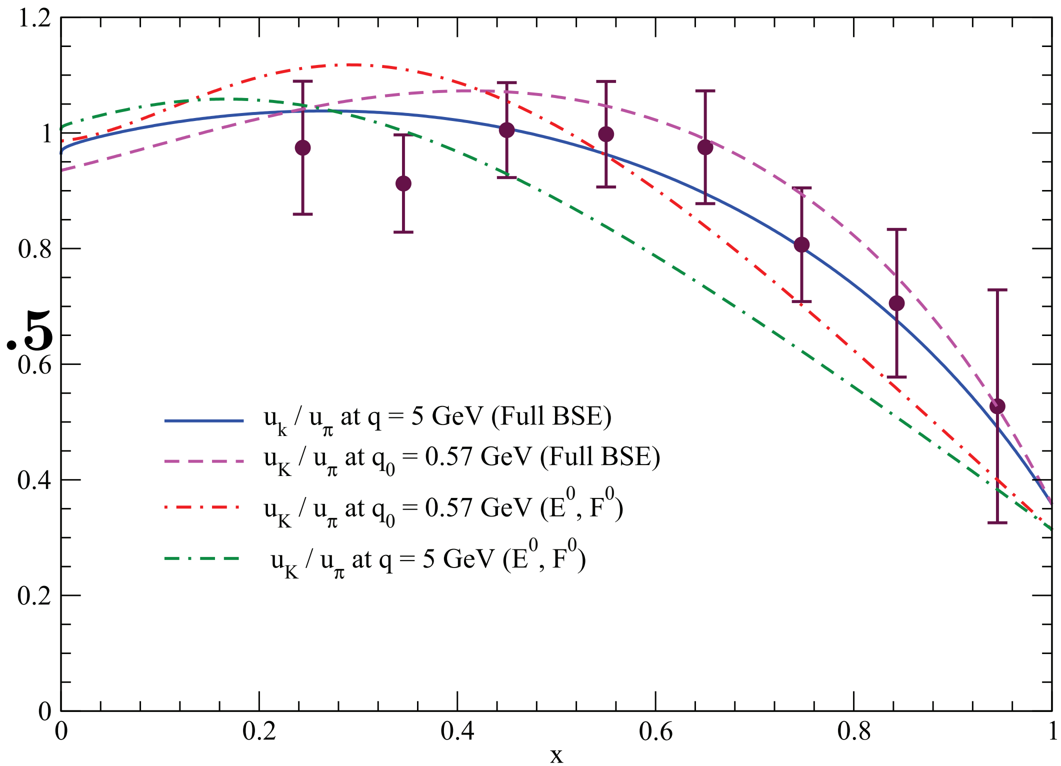

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- Accessible at Upgraded JLab & Electron-Ion Collider

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Some projects currently underway

- Elucidate effects of confinement & DCSB in
  - light-quark meson spectrum, including so-called hybrids and exotics, using Poincaré-covariant symmetry-preserving Bethe-Salpeter equation (*L. Chang, arXiv:0903.5461 [nucl-th]*)
  - hadron valence-quark distribution functions (*A. Bashir, P.C. Tandy*)

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  Survey of nucleon electromagnetic form factors
  I.C. Cloët *et al*., arXiv:0812.0416 [nucl-th], Few Body Syst. 46 (2009) pp. 1-36

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  - $N \to$ P11(1440)
  - $\kappa(p^2)$

  e.g., $F_1^{\rm d}(Q^2) = 0$ at $Q^2/M^2 \approx 5$

  (*M. Bhagwat, L. Chang, I. Cloët, H. Roberts*)

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  (*M. Bhagwat, L. Chang, I. Cloët, H. Roberts*)
- Incorporate "resonant contributions" (pion cloud) in kernels of bound-state equations (e.g., Eichmann, Roberts *et al*. – 0802.1948 [nucl-th] & Cloët, Roberts – 0811.2018 [nucl-th]; and *Fischer, Williams* – 0808.3372 [hep-ph])

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Epilogue

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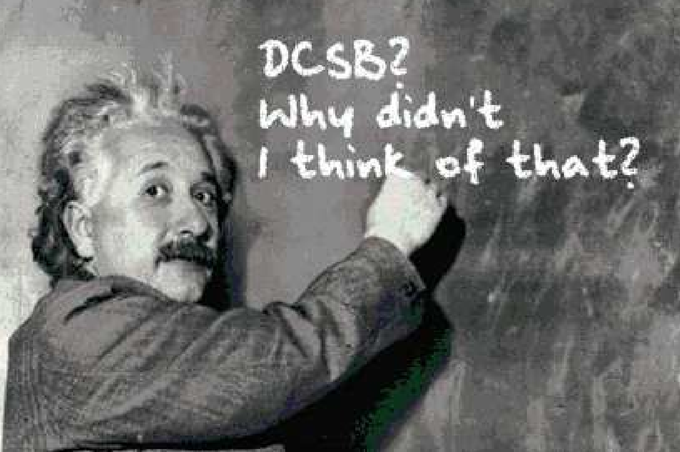

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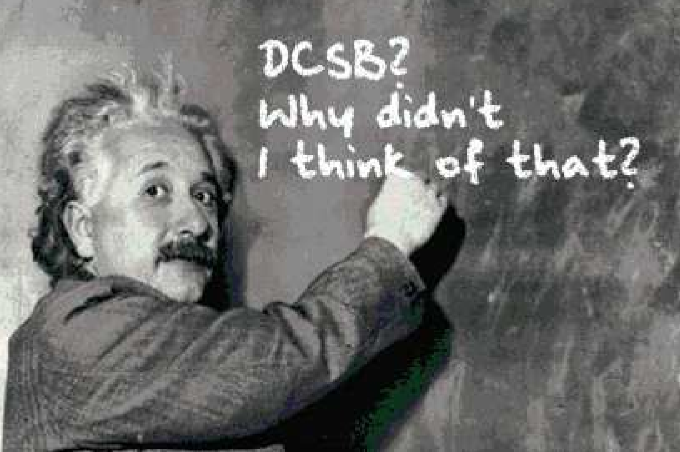
- DCSB exists in QCD.



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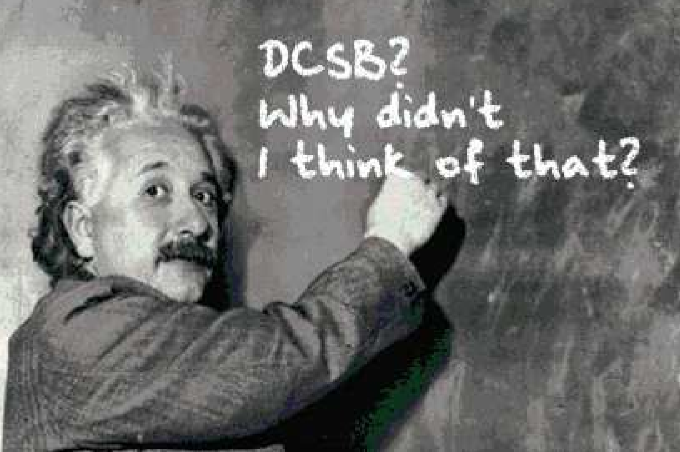

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- DCSB exists in QCD.
  - It is manifest in dressed propagators and vertices
  - It predicts, amongst other things, that
    - light current-quarks become heavy constituent-quarks: $4 \to 400\,\text{MeV}$
    - pseudoscalar mesons are unnaturally light: $m_\rho = 770$ cf. $m_\pi = 140\,\text{MeV}$
    - 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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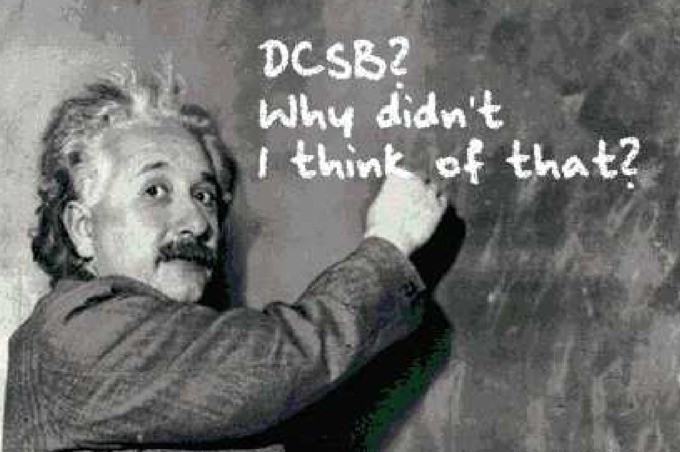
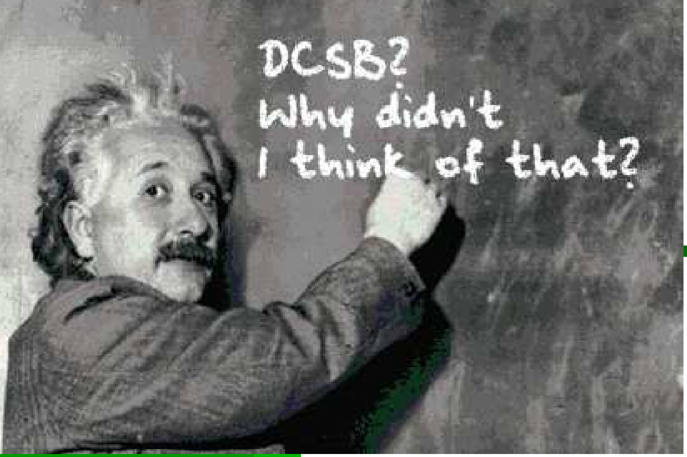


Epilogue

- DCSB impacts dramatically upon observables



Epilogue

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

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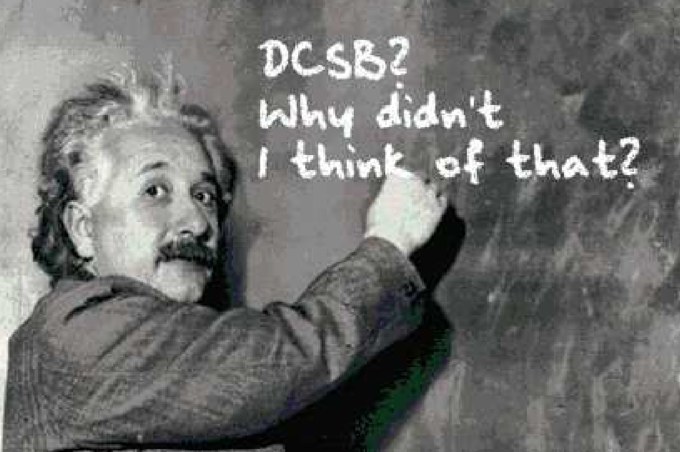

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  - Exposing & elucidating its effect in hadron physics requires nonperturbative, symmetry preserving framework; i.e., Poincaré covariance, chiral and e.m. current conservation, etc.

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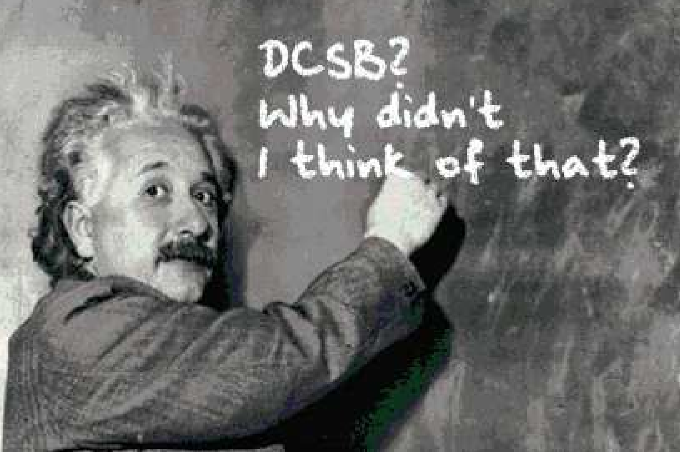

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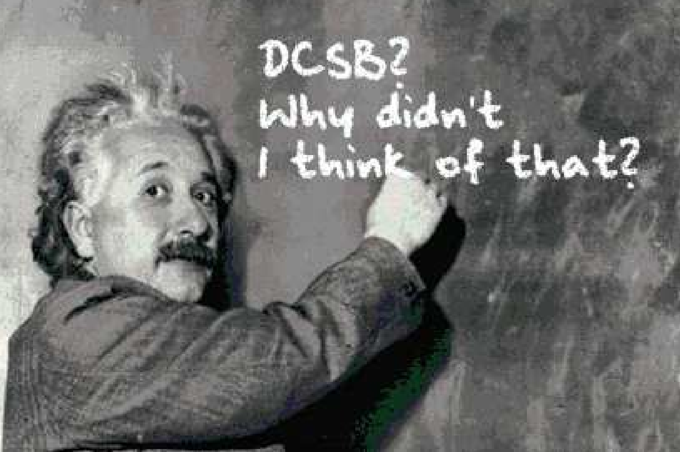
  - Studies underway will identify observable signals of $M(p^2)$, the most important mass-generating mechanism for visible matter in the Universe



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

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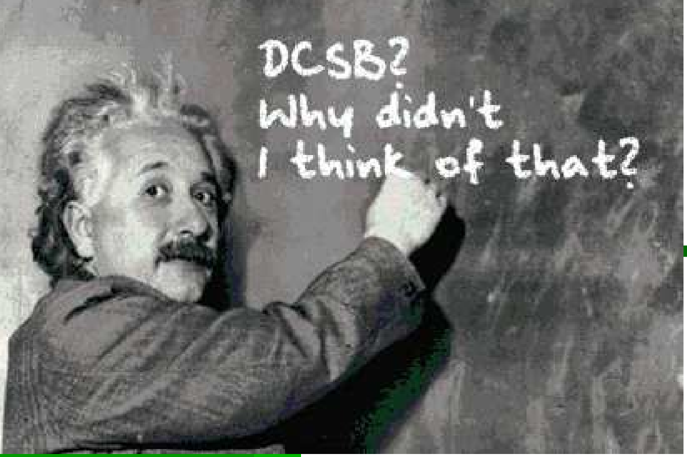

Epilogue

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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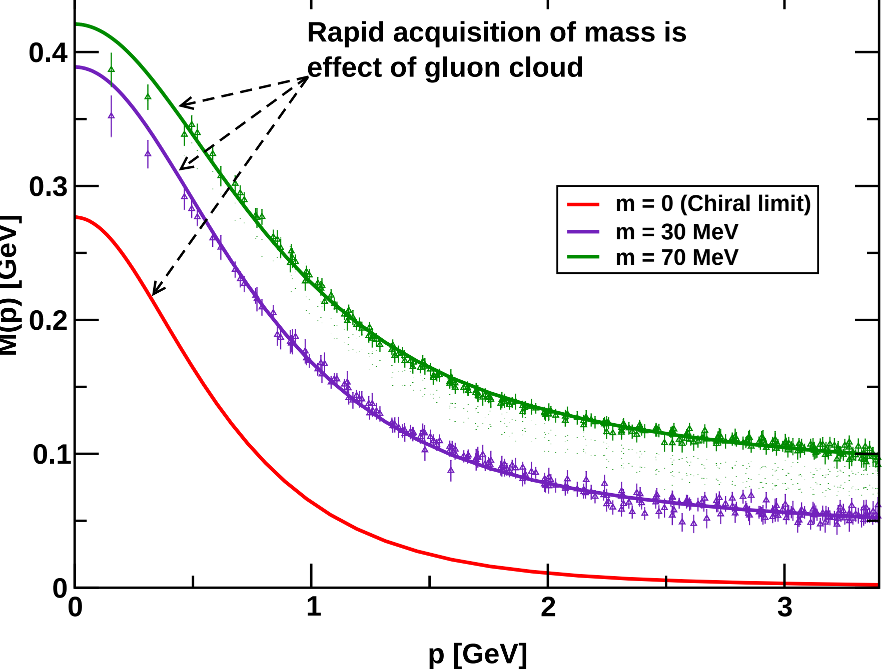

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Key: an understanding of both the fundamental origin of nuclear mass and the far-reaching consequences of the mechanism responsible; namely, Dynamical Chiral Symmetry Breaking

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