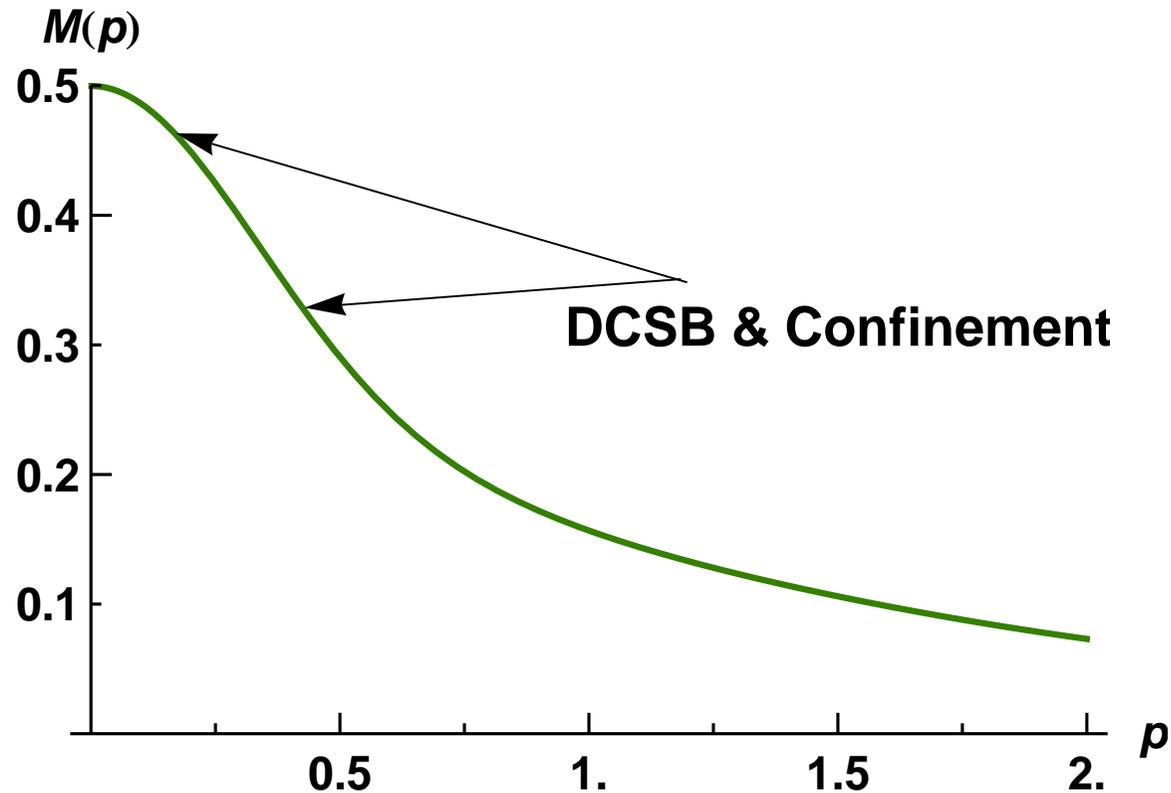


Empirically charting Dynamical Chiral Symmetry Breaking

Dressed-quark Mass Function

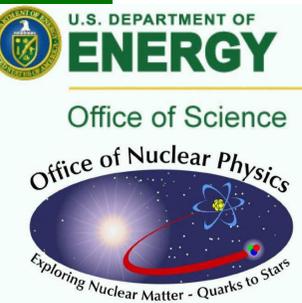


Craig D. Roberts
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Physics Division & School of Physics

Argonne National Laboratory & Peking University

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



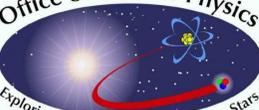
Universal Truths



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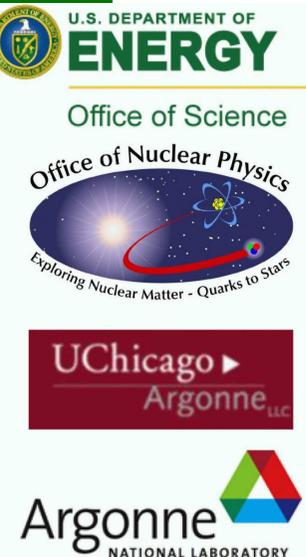
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Universal Truths

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



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- Spectrum of excited states, and elastic and transition form factors provide unique information about long-range interaction between light-quarks and distribution of hadron's characterising properties amongst its QCD constituents.
- Dynamical Chiral Symmetry Breaking (DCSB) is most important mass generating mechanism for visible matter in the Universe.



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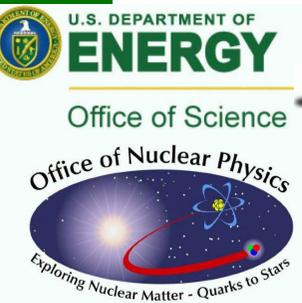
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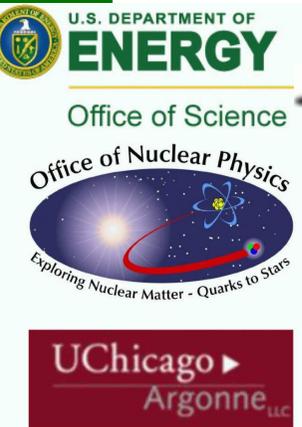
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- Running of quark mass entails that calculations at even modest Q^2 require a Poincaré-covariant approach. **Covariance requires existence of quark orbital angular momentum in hadron's rest-frame wave function.**



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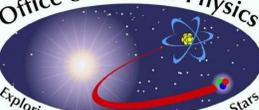
Intranucleon Interaction



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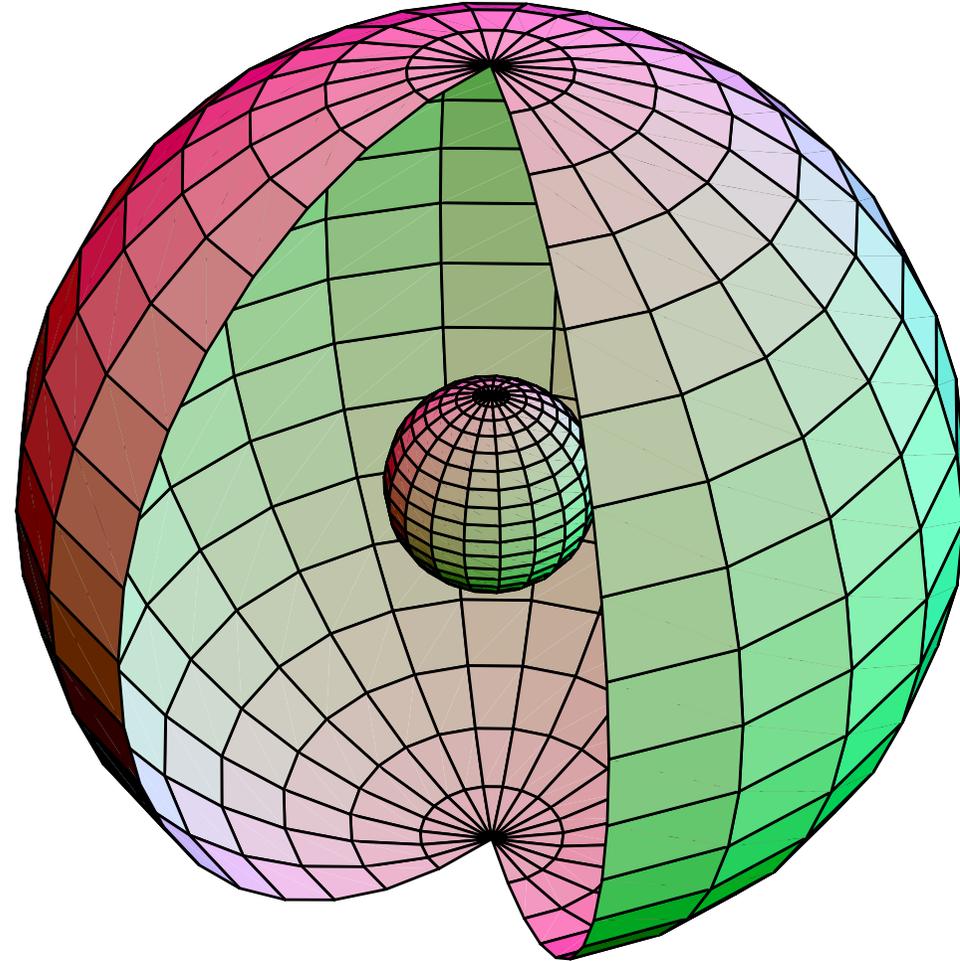
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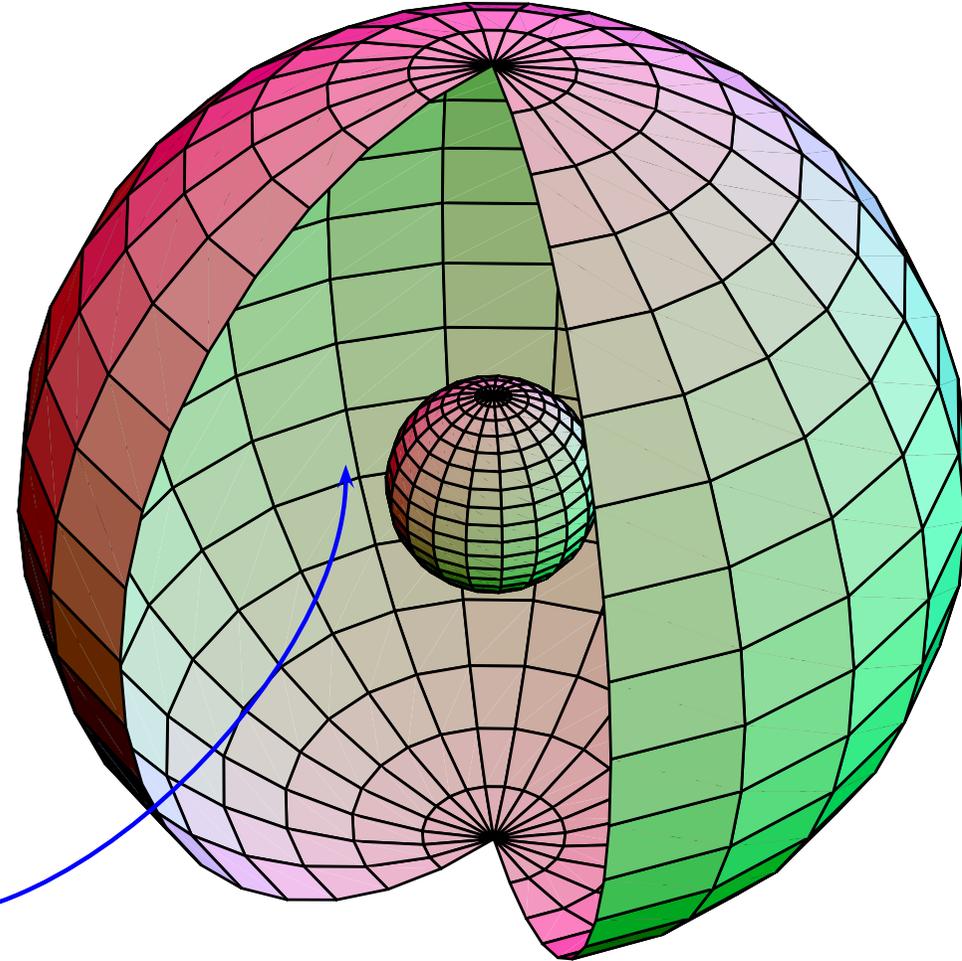
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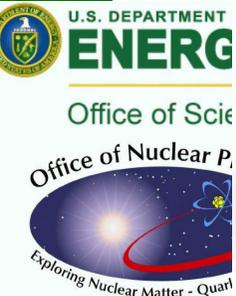
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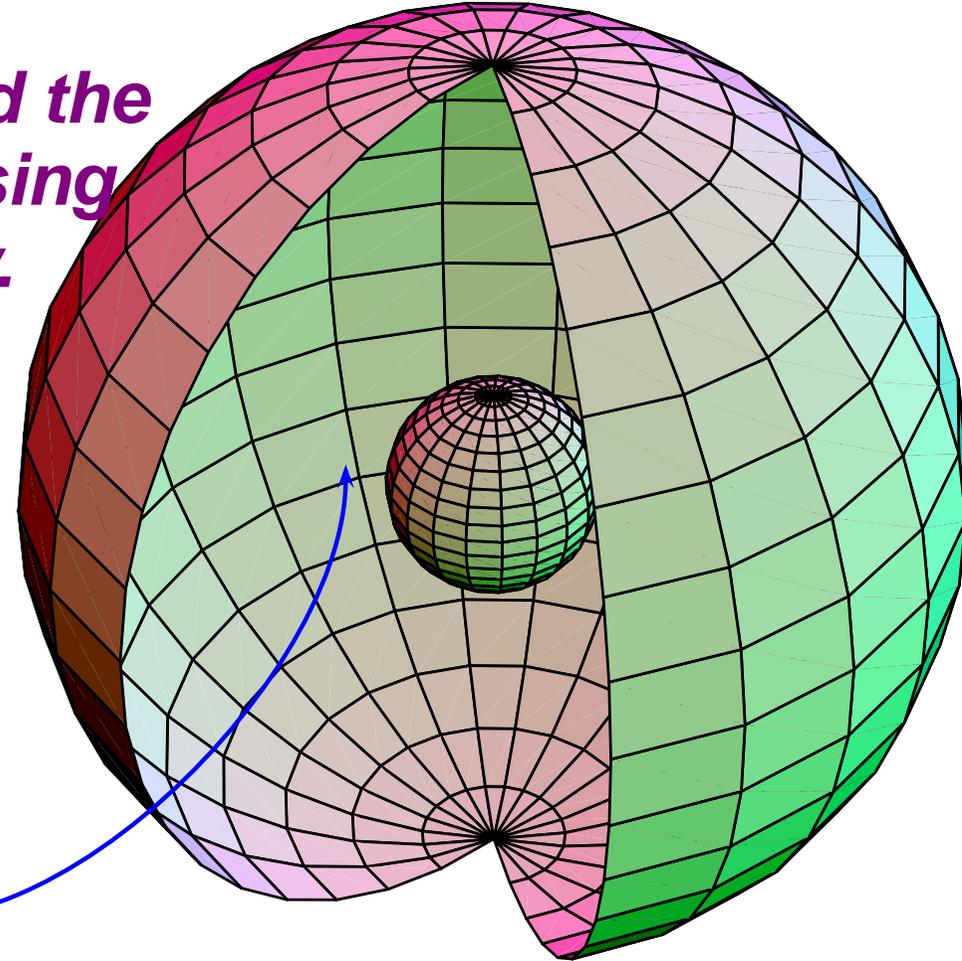


98% of the volume



What is the Intranucleon Interaction?

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



98% of the volume



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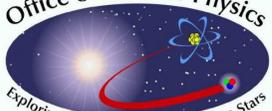
What is the light-quark Long-Range Potential?



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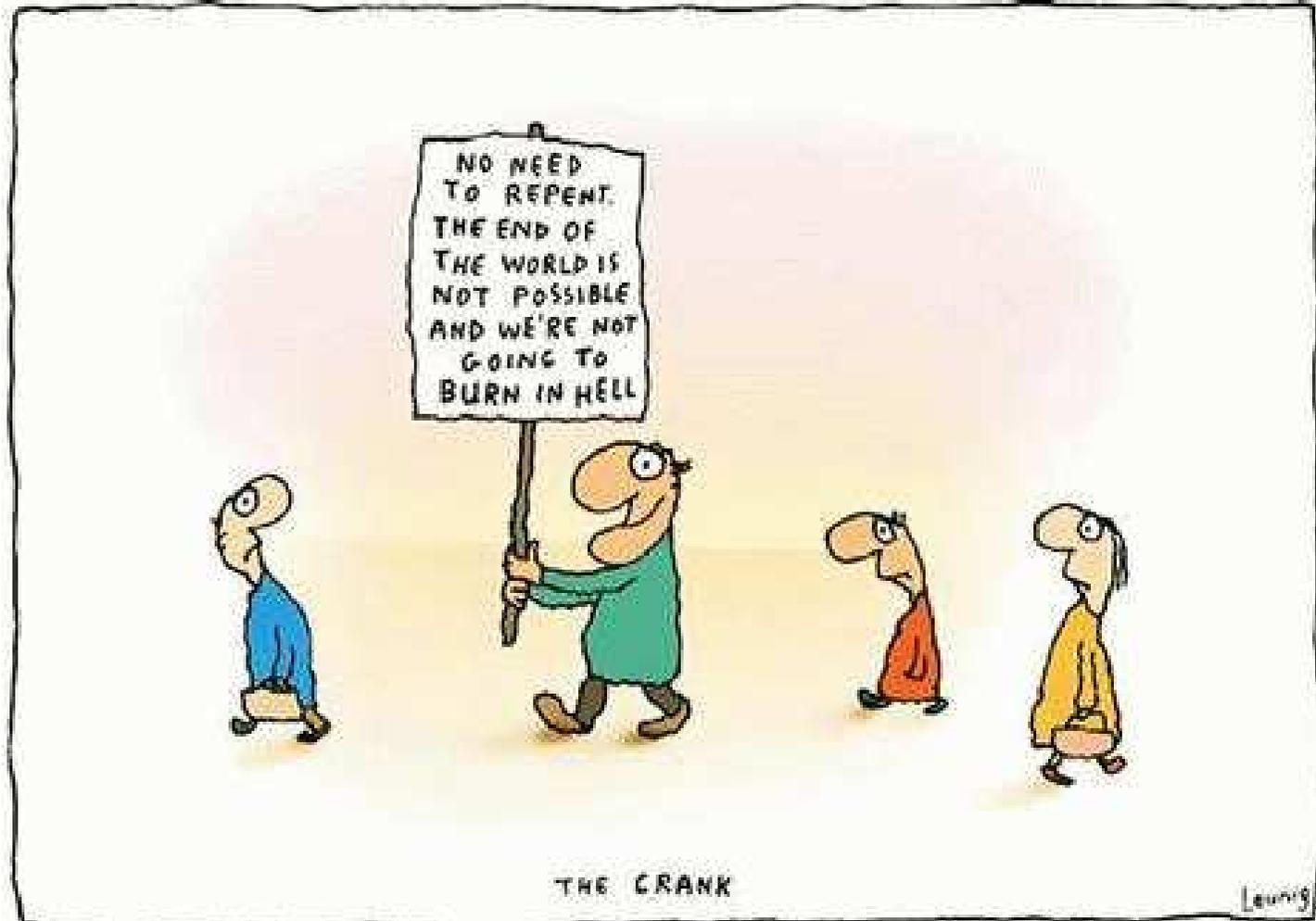
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What is the light-quark Long-Range Potential?



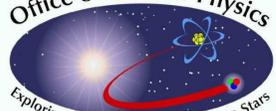
Potential between static (infinitely heavy) quarks measured in simulations of lattice-QCD **is not related** in any simple way to the light-quark interaction.



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Dyson-Schwinger Equations

Euler-Lagrange equations for quantum field theory

- Well suited to Relativistic Quantum Field Theory



Dyson-Schwinger Equations

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- Simplest level: **Generating Tool for Perturbation Theory**
..... **Materially Reduces** Model Dependence

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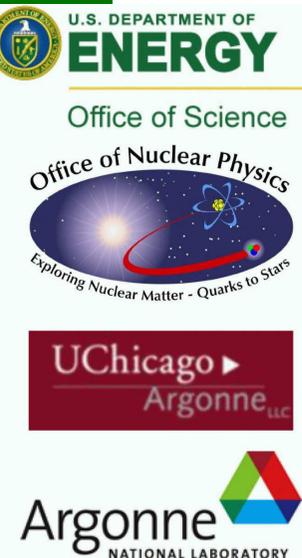
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Dyson-Schwinger Equations

Euler-Lagrange equations for quantum field theory

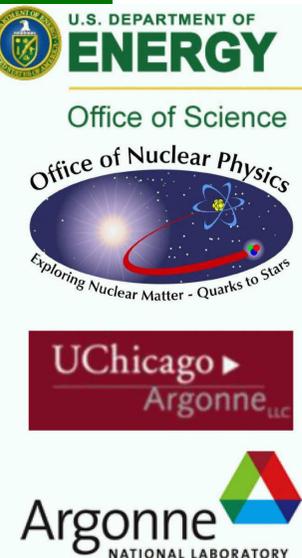
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 - Hadrons as Composites of **Quarks** and **Gluons**
 - Qualitative and Quantitative Importance of:
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- Method yields Schwinger Functions \equiv Propagators

Cross-Sections built from Schwinger Functions



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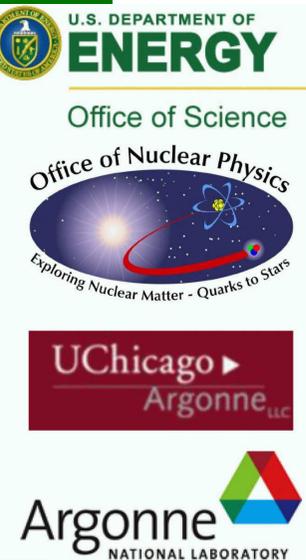
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Charting the Interaction between light-quarks



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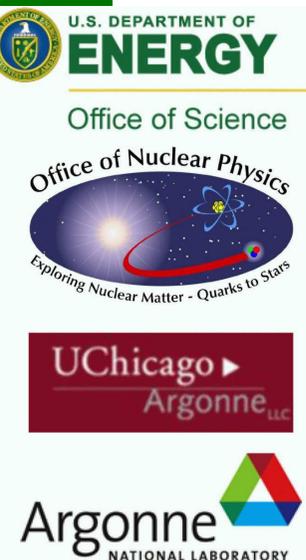
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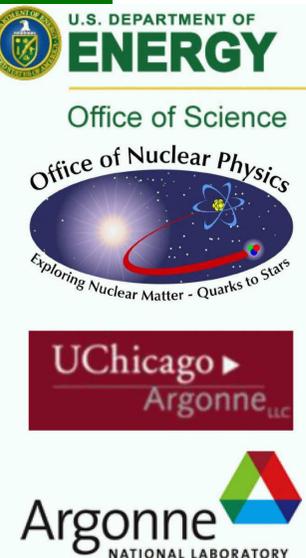
Charting the Interaction between light-quarks

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



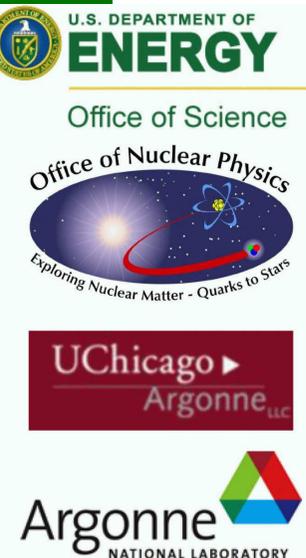
Charting the Interaction between light-quarks

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Of course, the behaviour of the β -function on the perturbative domain is well known.



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Charting the Interaction between light-quarks

- Confinement can be related to the analytic properties of QCD's Schwinger functions
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Of course, the behaviour of the β -function on the perturbative domain is well known.

- This is a well-posed problem whose solution is an elemental goal of modern hadron physics.

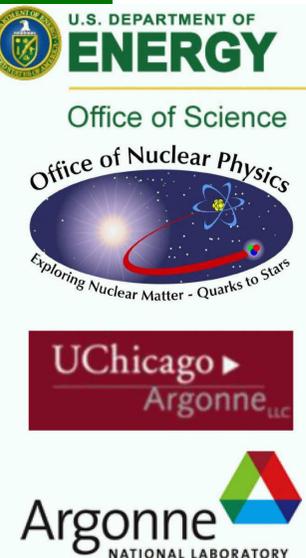


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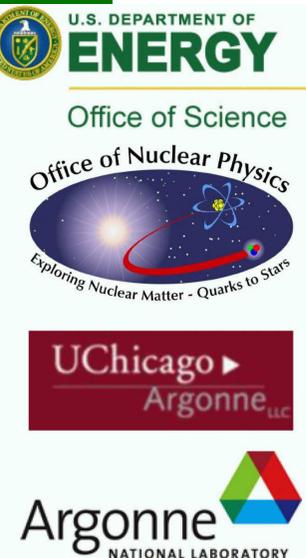
Charting the Interaction between light-quarks

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



Charting the Interaction between light-quarks

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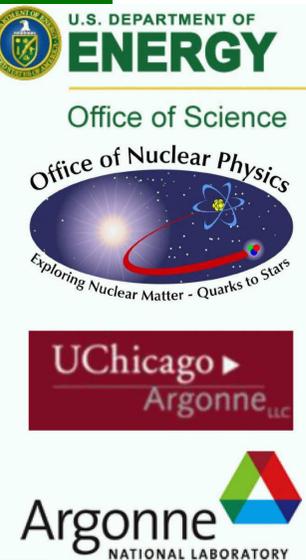


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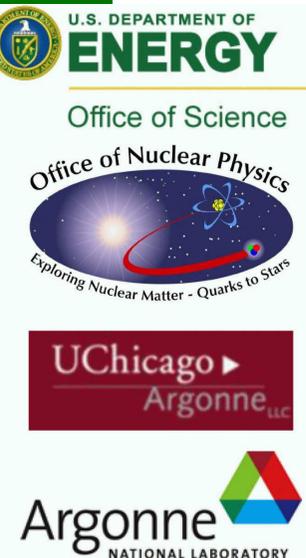
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- Extant studies of mesons show that the properties of hadron excited states are a great deal more sensitive to the long-range behaviour of β -function than those of the ground state



Charting the Interaction between light-quarks

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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
 - Steady quantitative progress is being made with a scheme that is systematically improvable



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Charting the Interaction between light-quarks

- 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



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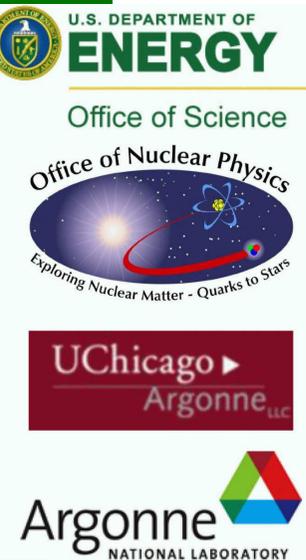
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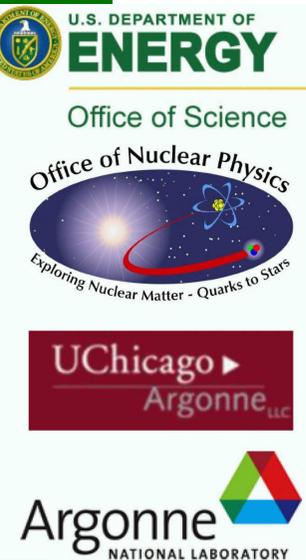
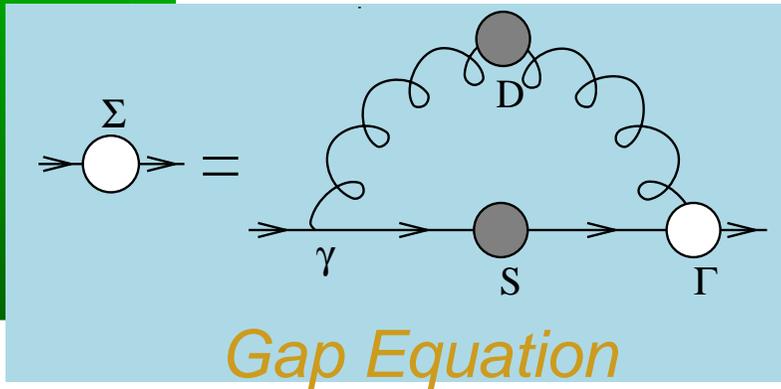
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Frontiers of Nuclear Science: Theoretical Advances



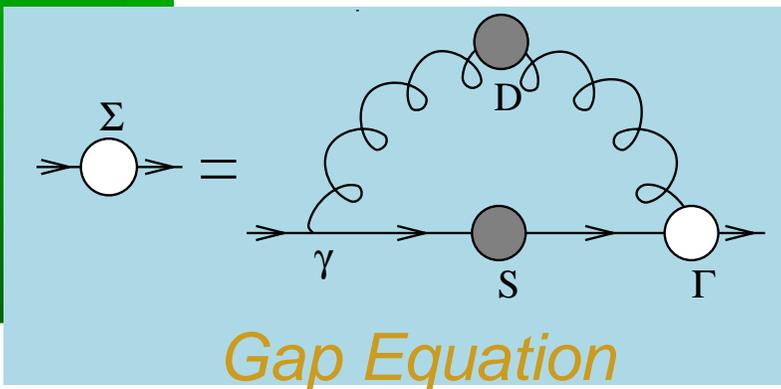
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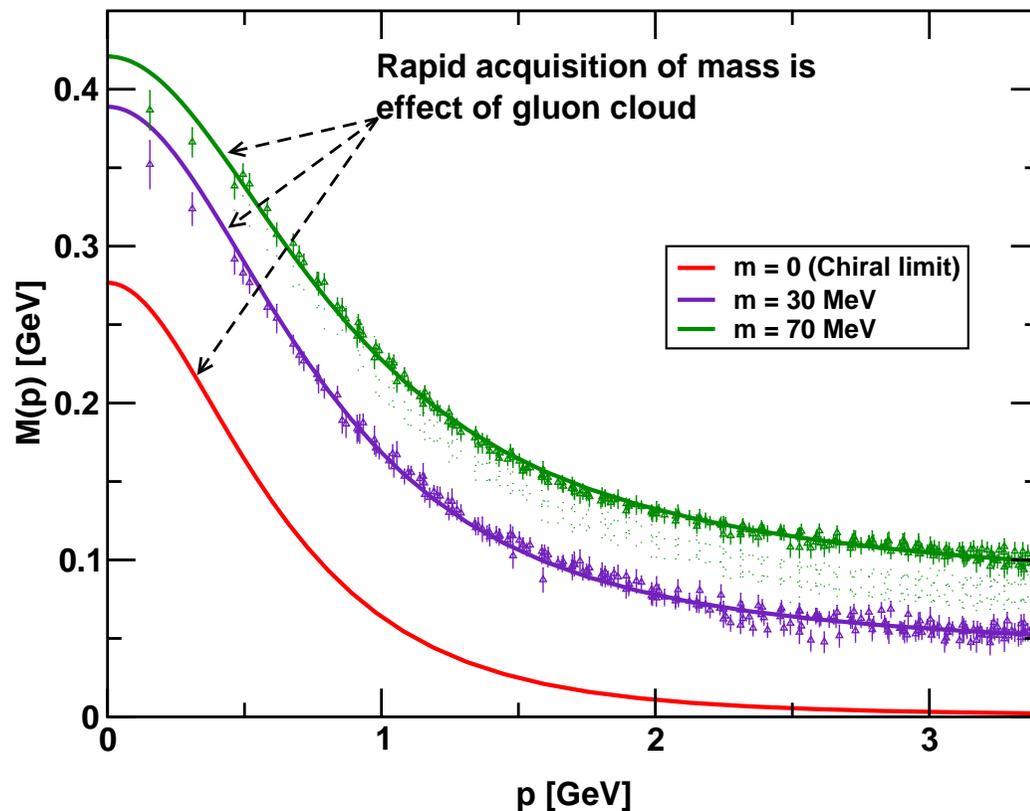
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Frontiers of Nuclear Science: Theoretical Advances



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



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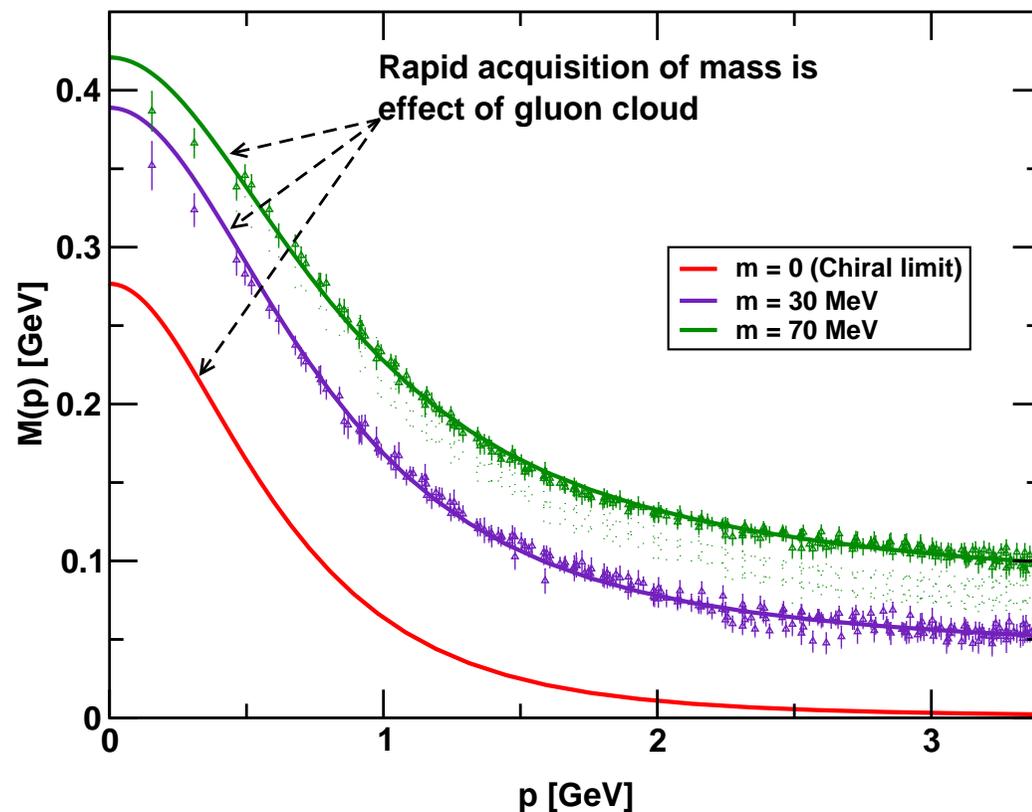
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Frontiers of Nuclear Science: Theoretical Advances

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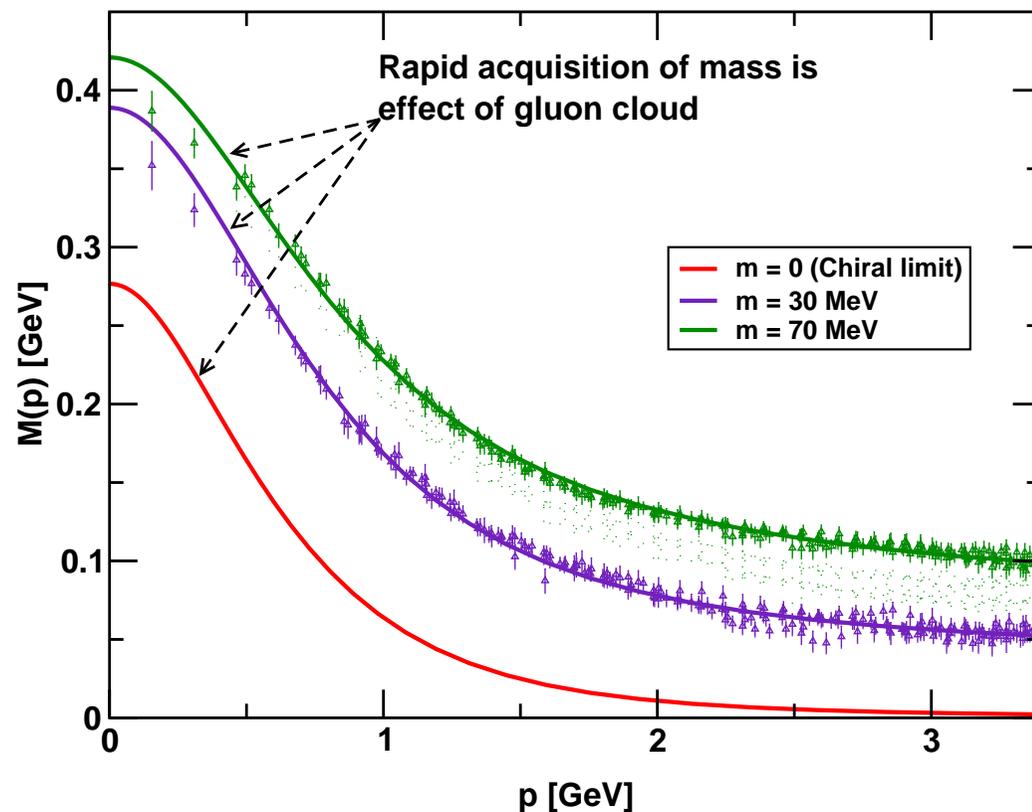
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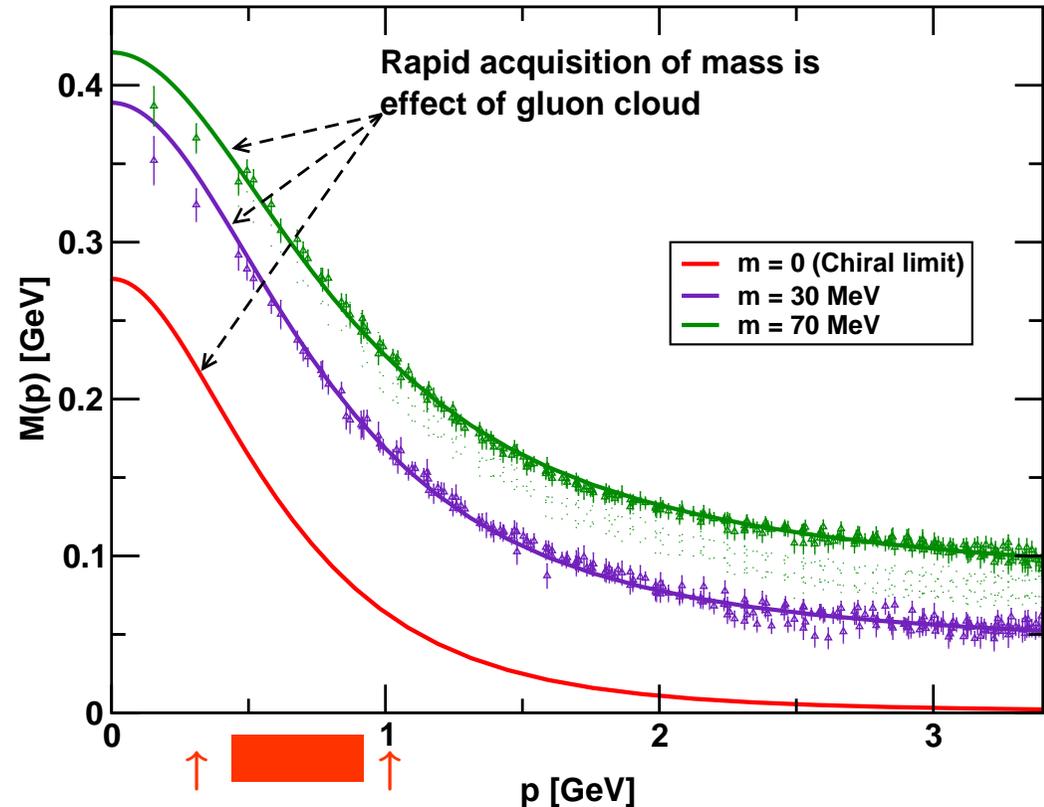
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Scanned by $Q^2 \in [2, 9] \text{ GeV}^2$ Baryon Elastic and Transition Form Factors



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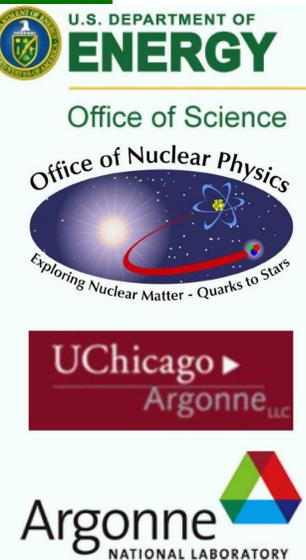
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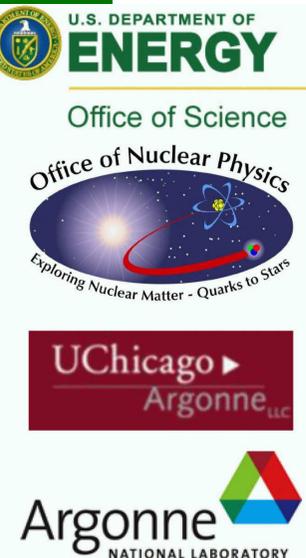
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Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma_{5\mu}^l(k; P) = \mathcal{S}^{-1}(k_+) \frac{1}{2} \lambda_f^l i\gamma_5 + \frac{1}{2} \lambda_f^l i\gamma_5 \mathcal{S}^{-1}(k_-) \\ - M_\zeta i\Gamma_5^l(k; P) - i\Gamma_5^l(k; P) M_\zeta$$

QFT Statement of Chiral Symmetry



Bethe-Salpeter Kernel

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Satisfies BSE

Satisfies DSE



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Kernels very different

but must be *intimately* related



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Satisfies BSE

Satisfies DSE

Kernels very different

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- Relation **must** be preserved by truncation
- **Nontrivial** constraint



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Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma_{5\mu}^l(k; P) = \mathcal{S}^{-1}(k_+) \frac{1}{2} \lambda_f^l i\gamma_5 + \frac{1}{2} \lambda_f^l i\gamma_5 \mathcal{S}^{-1}(k_-) - M_\zeta i\Gamma_5^l(k; P) - i\Gamma_5^l(k; P) M_\zeta$$

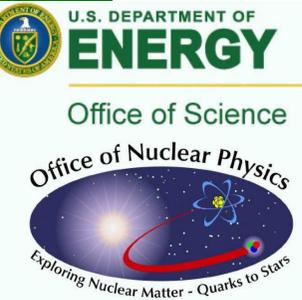
Satisfies BSE

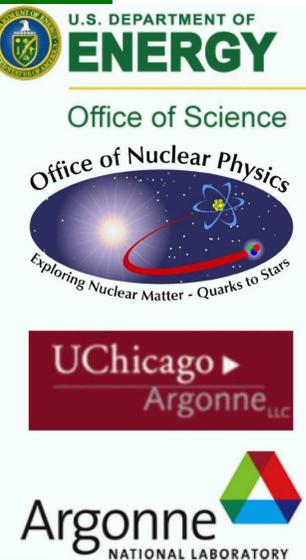
Satisfies DSE

Kernels very different

but must be *intimately* related

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





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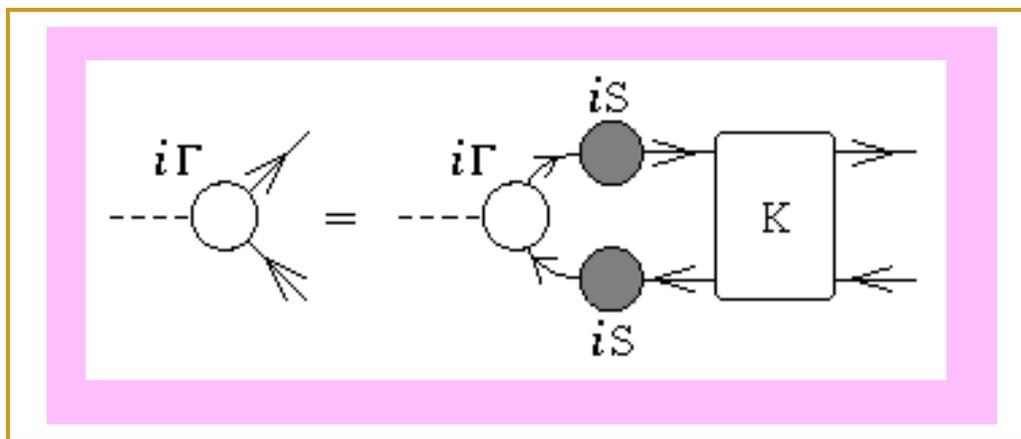
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Bound-state DSE

Bethe-Salpeter Equation

- Standard form, familiar from textbooks

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



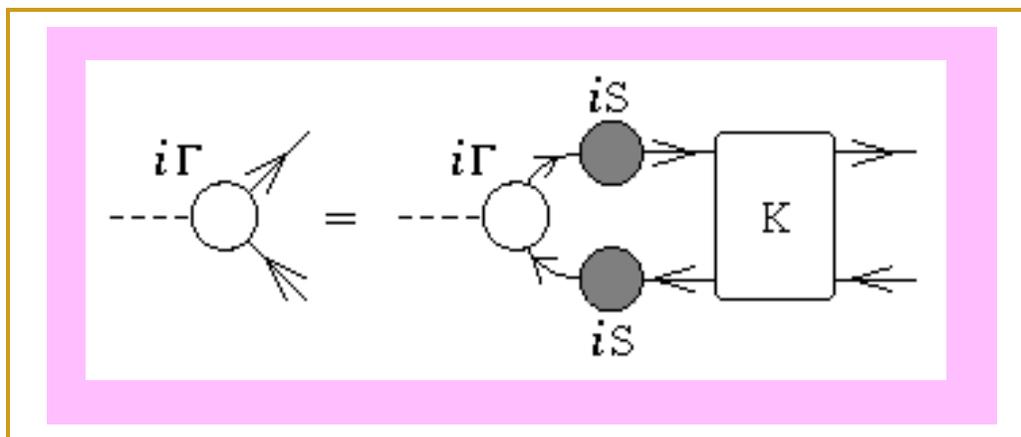
$K(q, k; P)$: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

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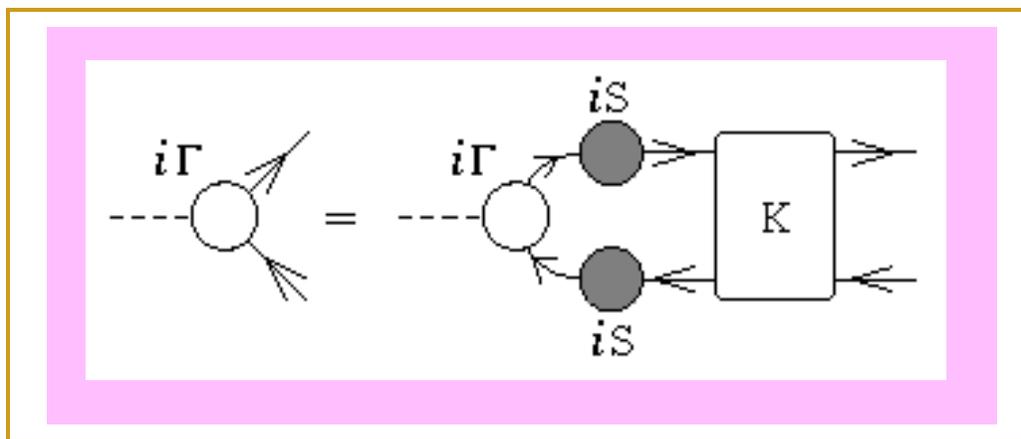
- Compact. Visually appealing. Correct.

Bound-state DSE

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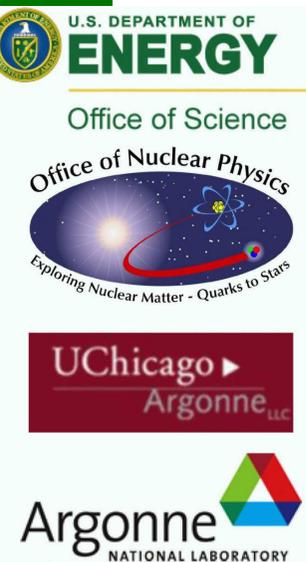


$K(q, k; P)$: Fully-amputated, 2-particle-irreducible, quark-antiquark scattering kernel

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

Gap Equation

General Form



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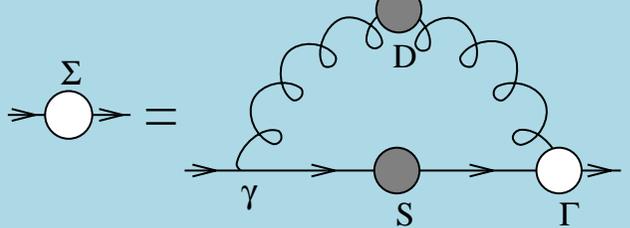
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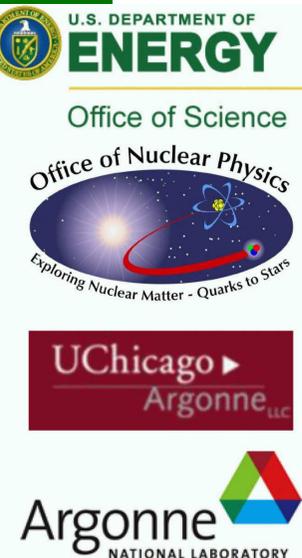
Gap Equation

General Form



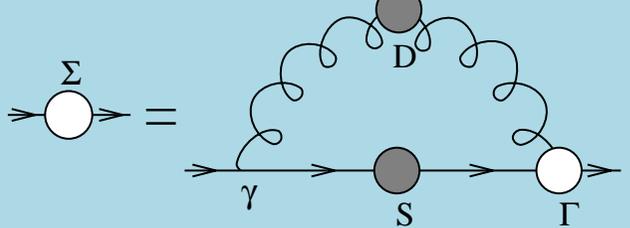
$$S_f(p)^{-1} = Z_2 (i\gamma \cdot p + m_f^{\text{bm}}) + \Sigma_f(p),$$

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



Gap Equation

General Form



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

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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
- $m^{\text{bm}}(\Lambda)$ 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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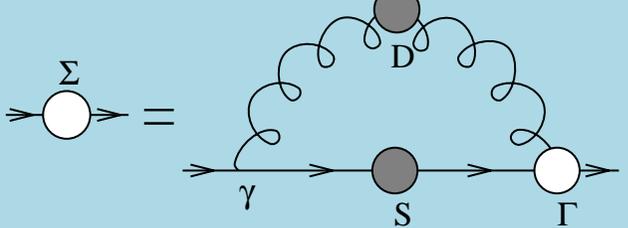
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General Form



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- $D_{\mu\nu}(k)$ is the dressed-gluon propagator
- $\Gamma_\nu^f(q,p)$ is the dressed-quark-gluon vertex
- Suppose one has in-hand the exact form of $\Gamma_\nu^f(q,p)$

What is the associated

Symmetry-preserving Bethe-Salpeter Kernel?

Craig Roberts – Empirically charting dynamical chiral symmetry breaking

Achievements and New Directions in Subatomic Physics, 15-19 Feb 2010 ... 29 – p. 12/31



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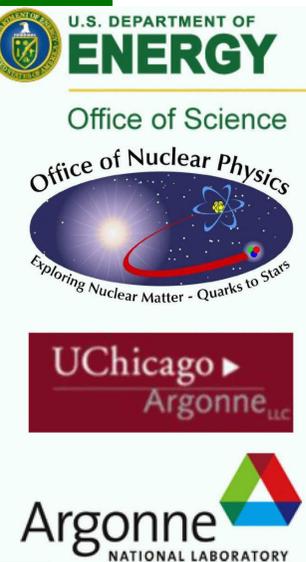
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General Form



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Bethe-Salpeter Equation

General Form

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

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

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

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



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Bethe-Salpeter Equation

General Form

L. Chang and C. D. Roberts

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



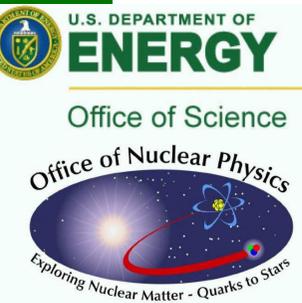
- In fact, this is $K \rightarrow \Lambda$ -equivalent exact form:

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

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

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

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



Bethe-Salpeter Equation

General Form

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- Equivalent exact form:

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

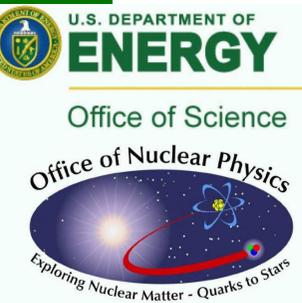
$$- \int_q g^2 D_{\alpha\beta}(k - q) \frac{\lambda^a}{2} \gamma_\alpha S_f(q_+) \Gamma_{5\mu}^{fg}(q; P) S_g(q_-) \frac{\lambda^a}{2} \Gamma_\beta^g(q_-, k_-)$$

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

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

- In this form ... $\Lambda_{5\mu\beta}^{fg}$

is completely defined via the dressed-quark self-energy

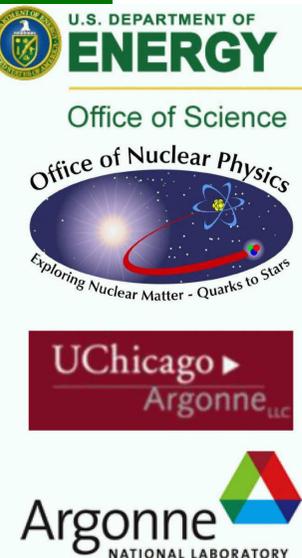


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0903.5461 [nucl-th], Phys. Rev. Lett. 103 (2009) 081601

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

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

Expresses chiral symmetry & pattern by which it's broken



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Expresses chiral symmetry & pattern by which it's broken

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

$$P_\mu \Lambda_{5\mu\beta}^{fg}(k, q; P) = \Gamma_\beta^f(q_+, k_+) i\gamma_5 + i\gamma_5 \Gamma_\beta^g(q_-, k_-) - i [m_f(\zeta) + m_g(\zeta)] \Lambda_{5\beta}^{fg}(k, q; P),$$

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



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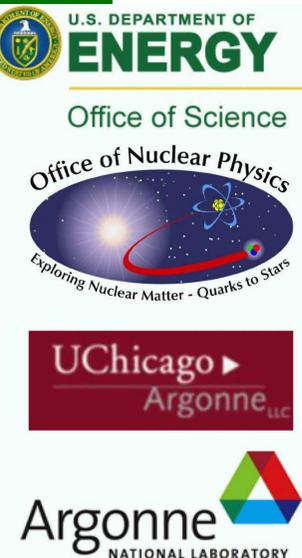
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- Rainbow-ladder ...

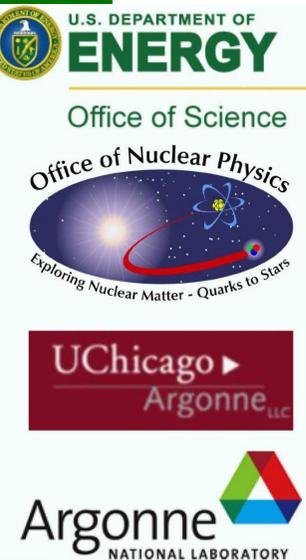
- $\Gamma_\beta^f(q, k) = \gamma_\mu$
 $\Rightarrow \Lambda_{5\mu\beta}^{fg}(k, q; P) = 0 = \Lambda_{5\beta}^{fg}(k, q; P)$



Bethe-Salpeter Kernel

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- Bethe-Salpeter equation introduced in 1951

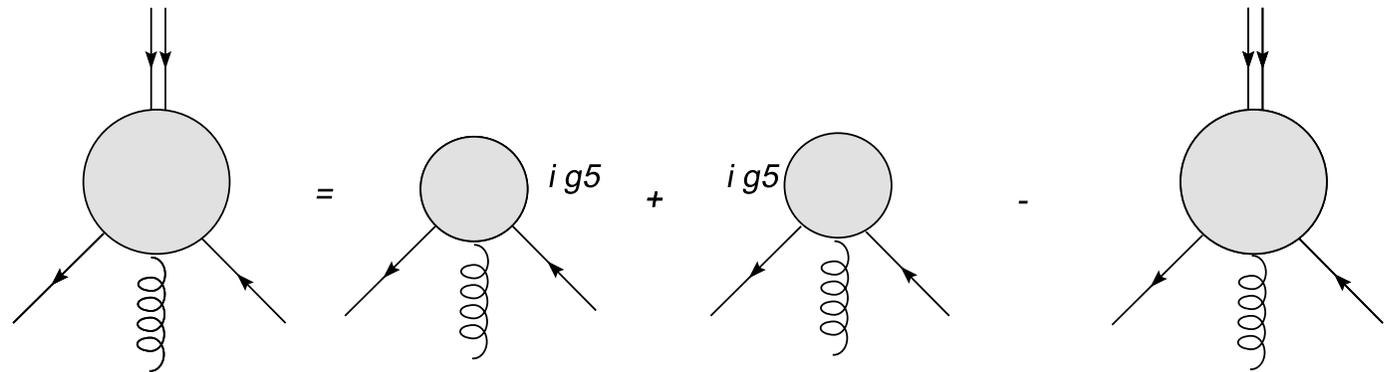


Bethe-Salpeter Kernel

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

60 year problem

- Bethe-Salpeter equation introduced in 1951
- Newly-derived Ward-Takahashi identity



$$P_\mu \Lambda_{5\mu\beta}^{fg}(k, q; P) = \Gamma_\beta^f(q_+, k_+) i\gamma_5 + i\gamma_5 \Gamma_\beta^g(q_-, k_-) - i[m_f(\zeta) + m_g(\zeta)] \Lambda_{5\beta}^{fg}(k, q; P),$$



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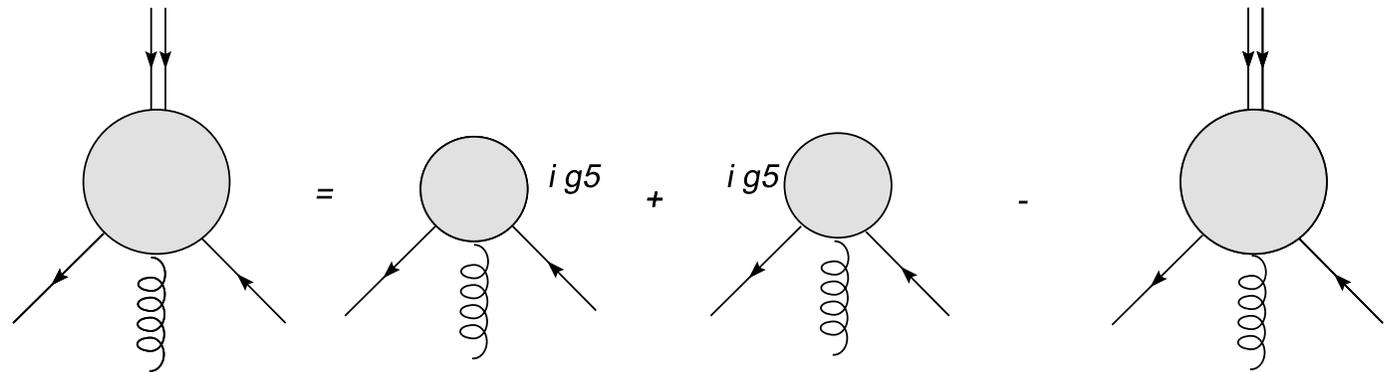
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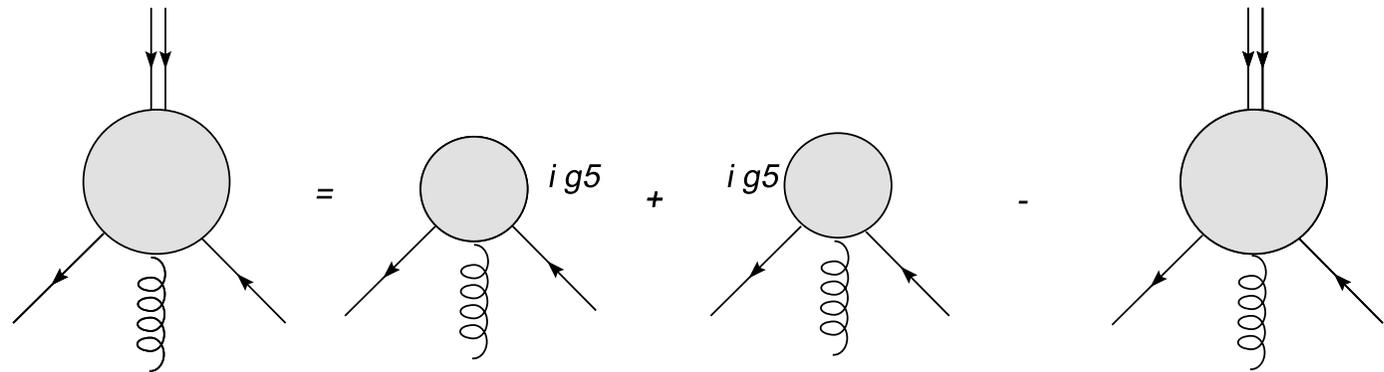
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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
 - Consistent means - all symmetries preserved!

- Bethe-Salpeter equation introduced in 1951
- Newly-derived Ward-Takahashi identity



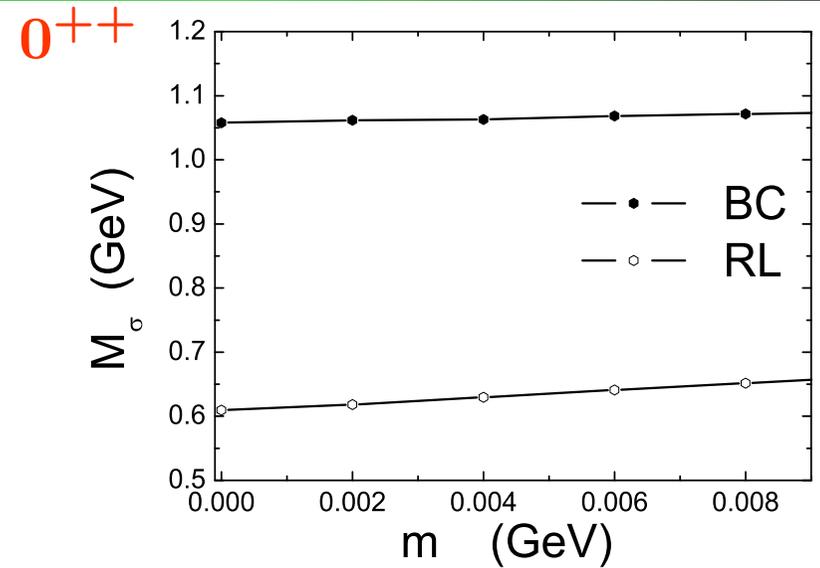
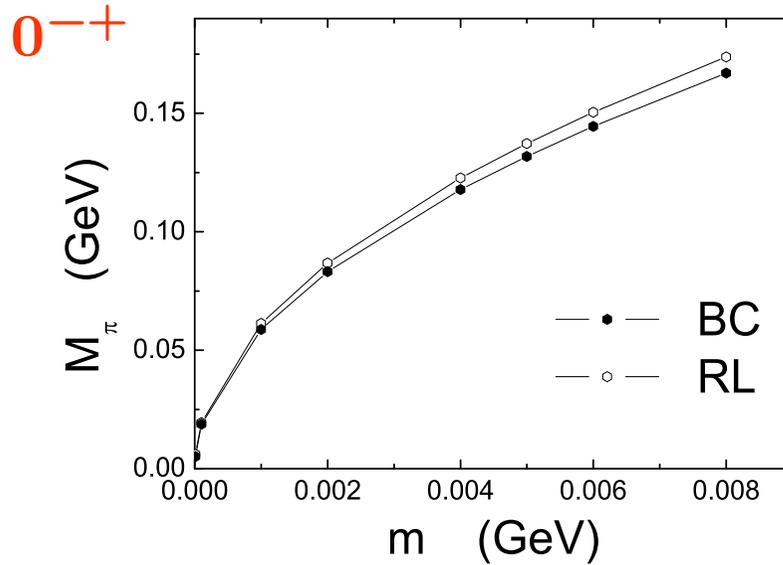
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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
- Exemplified the procedure and results to expect ...

Numerical Illustration

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π *cf.* σ



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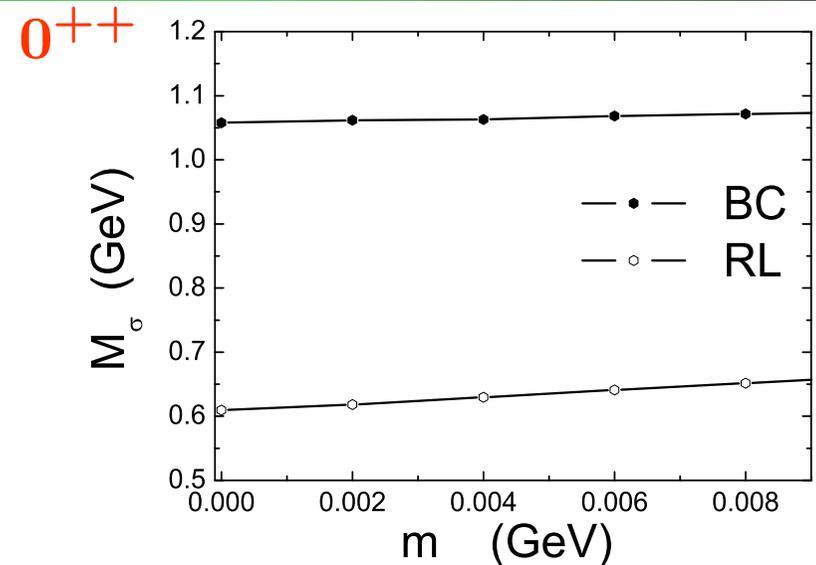
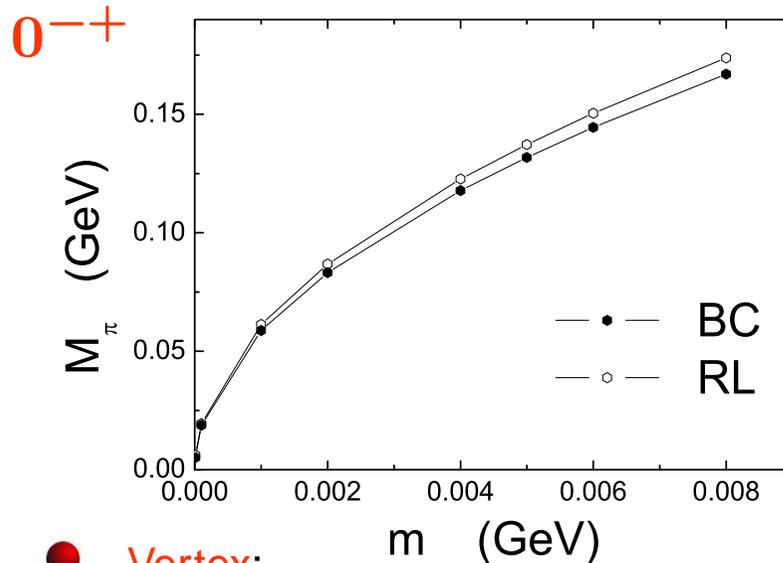
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π *cf.* σ



Vertex:

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

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



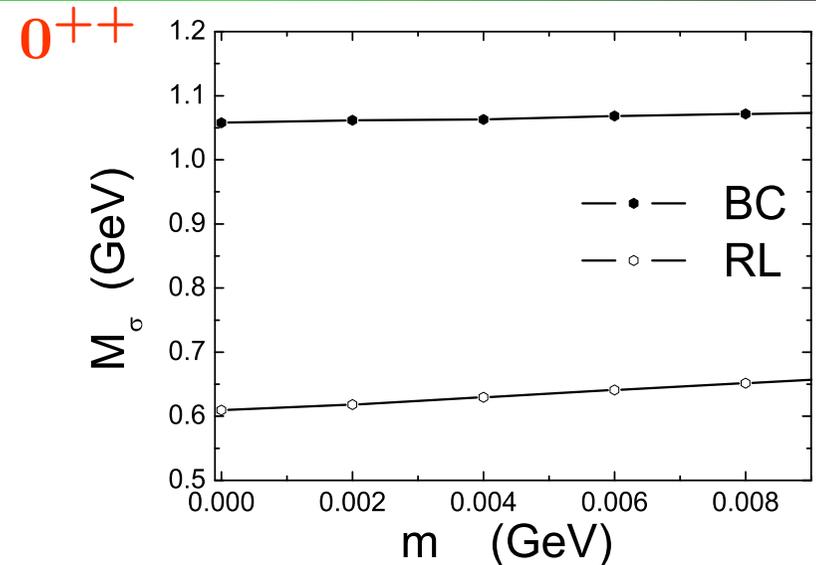
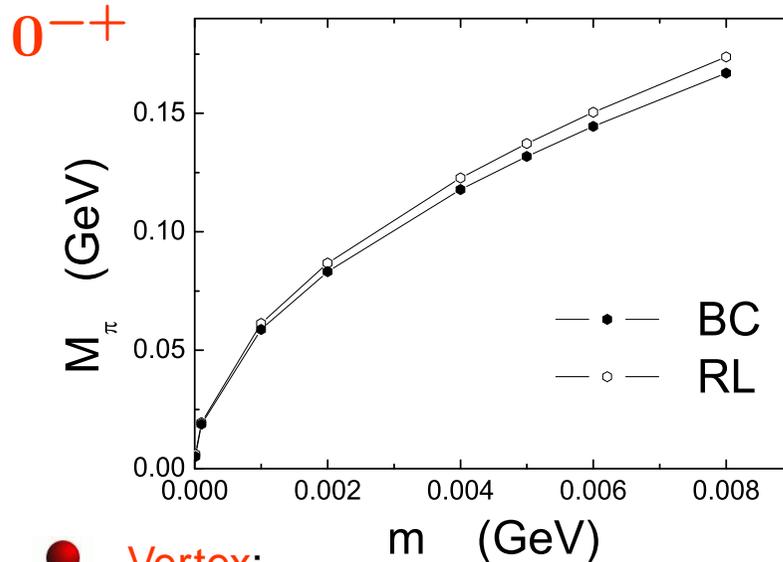
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Same interaction. One mass-scale in both truncations: $1/\omega = 0.4$ fm, defining border between **IR** & **UV**.

- GMOR ... plainly satisfied by both truncations
- A little **attraction** introduced in pseudoscalar channel
- **Enormous repulsion** introduced in scalar channel



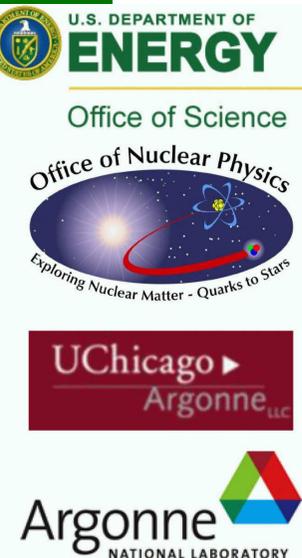
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Spin-orbit Interaction

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- Rainbow-ladder DSE truncation, $\epsilon_{\sigma}^{\text{RL}} := \frac{2M(0) - m_{\sigma}}{2M(0)}_{\text{RL}} = (0.3 \pm 0.1)$.
- BC-consistent Bethe-Salpeter kernel; viz., $\epsilon_{\sigma}^{\text{BC}} \lesssim 0.1$.



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- Scalar mesons = 3P_0 states: Constituents' spins aligned and one unit of constituent orbital angular momentum
 - From this viewpoint,
scalar is a spin and orbital excitation of a pseudoscalar meson



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Spin-orbit Interaction

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

Impossible to demonstrate effect without our new procedure



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- Impossible to demonstrate effect without our new procedure
- Expect this feature to have material impact
 - Especially on mesons with mass greater than 1 GeV.
- prima facie* ... can overcome longstanding shortcoming of systematic, symmetry-preserving truncations;
viz., splitting between vector & axial-vector mesons is too small



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



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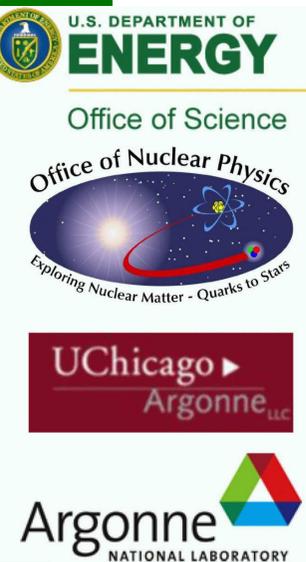
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$$[m_{a_1} - m_\rho] / \dots$$

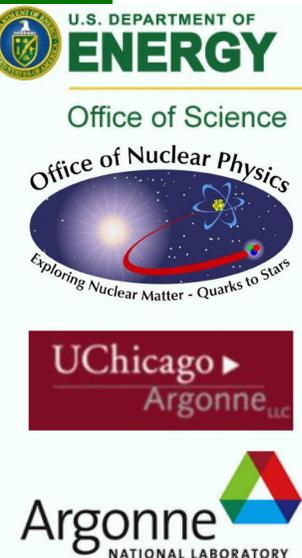
- That was where things stood in March/09



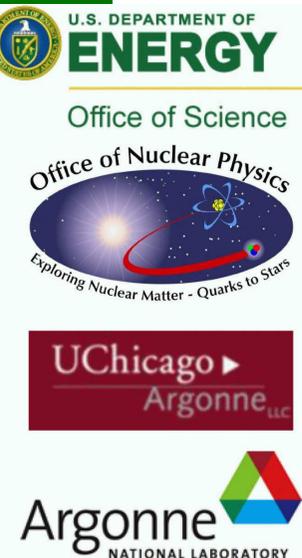
$$[m_{a_1} - m_\rho] / \dots$$

Chang Lei & CDR, in-preparation

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

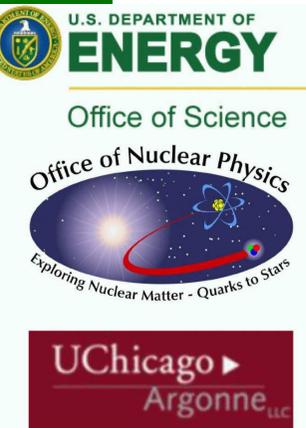
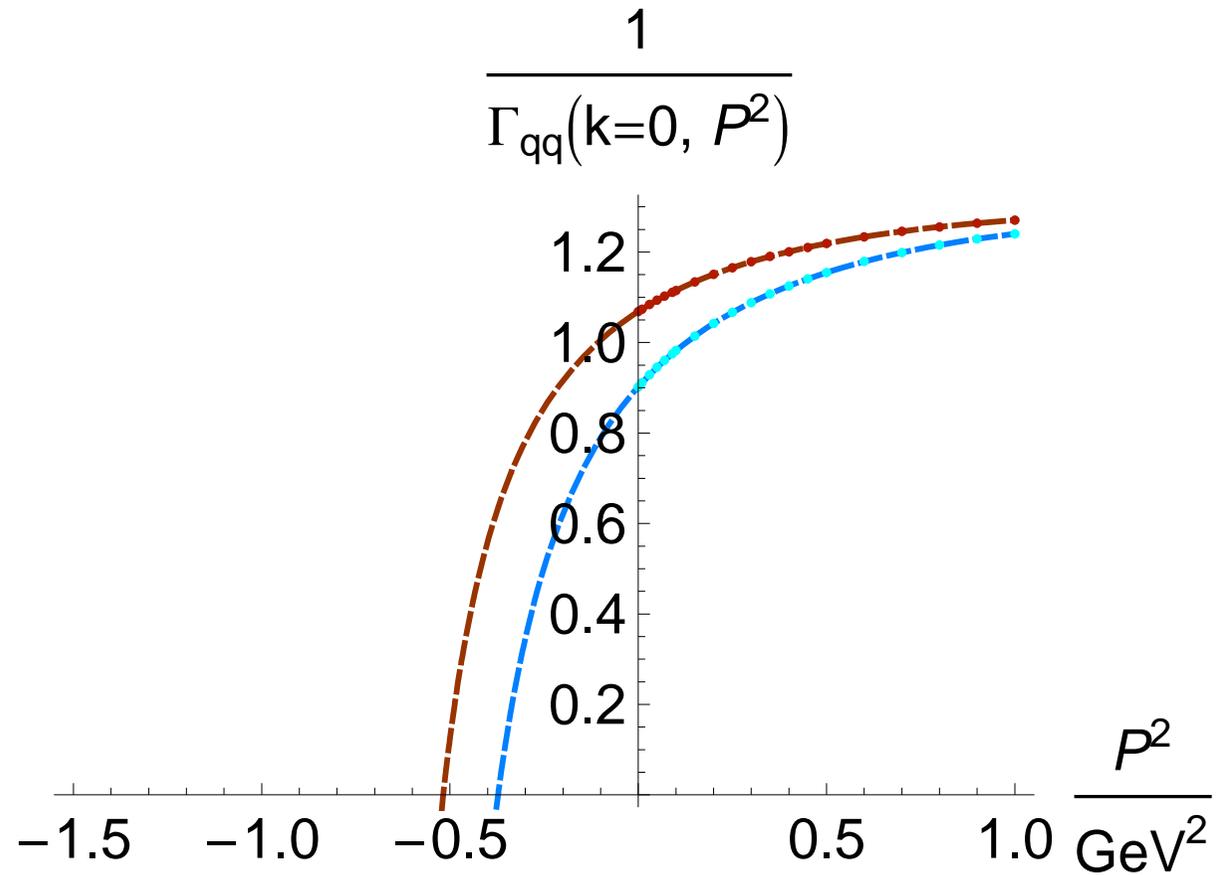


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- Now, we've solved inhomogeneous vector and axial-vector Bethe-Salpeter equation at spacelike total momentum
 $\Rightarrow \Gamma_{qq}(k = 0, P^2)$
- $\frac{1}{\Gamma_{qq}(k = 0, P^2)}$ Exhibits a zero at ground-state mass-squared
- Padé approximant extrapolation to locate zero
 - Almost precisely method used for ground-state masses in lattice-QCD
 - Intelligent use gives dependable results
 “Schwinger functions and light-quark bound states”
[Bhagwat](#), [Höll](#), [Krassnigg](#), [Roberts](#) & [Wright](#),
 Few Body Syst. **40** (2007) 209, nucl-th/0701009



Rainbow-Ladder

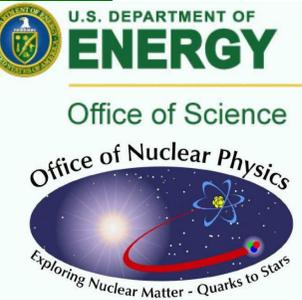
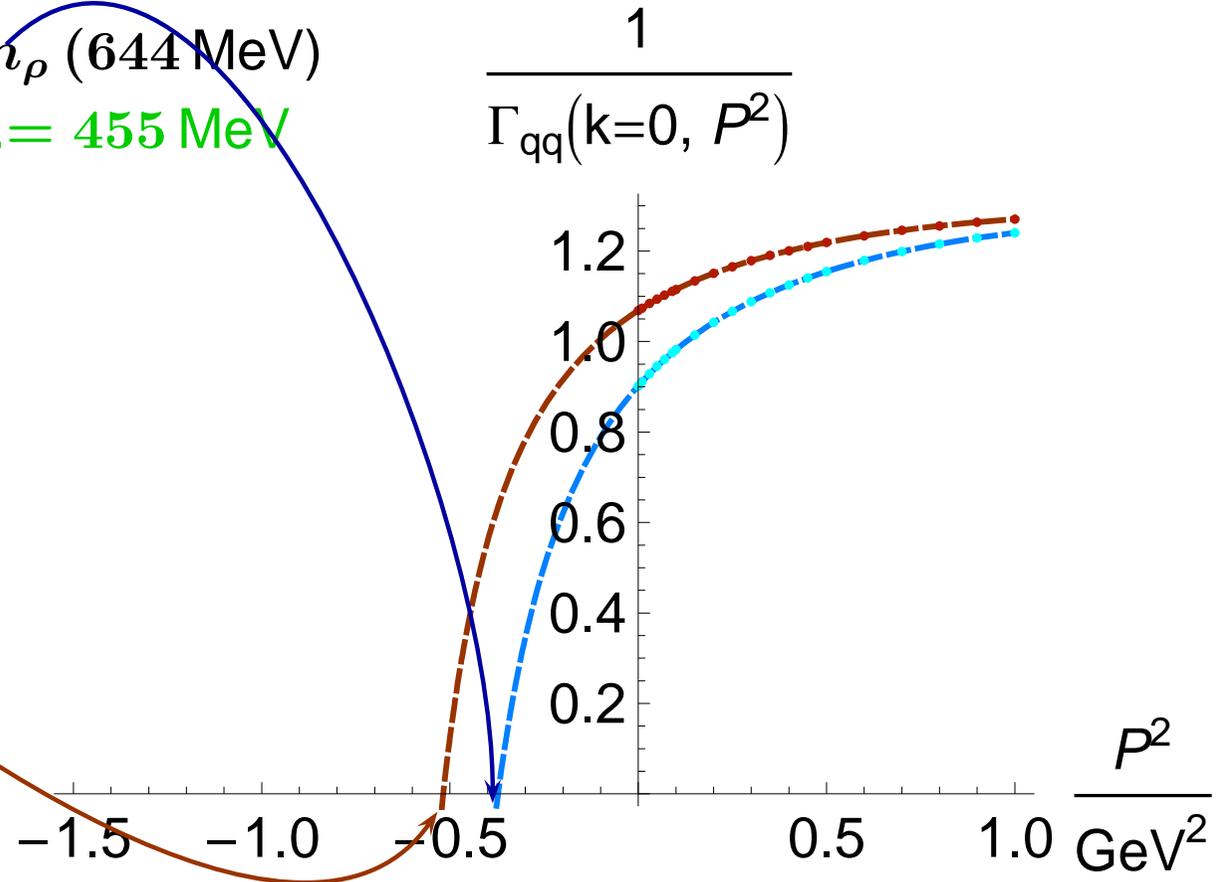
$$\Gamma_\mu(q, k) = \gamma_\mu$$



$m_{a_1} (759 \text{ MeV}) - m_\rho (644 \text{ MeV})$
 $= 115 \text{ MeV} \dots \text{expt.} = 455 \text{ MeV}$

Rainbow-Ladder

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

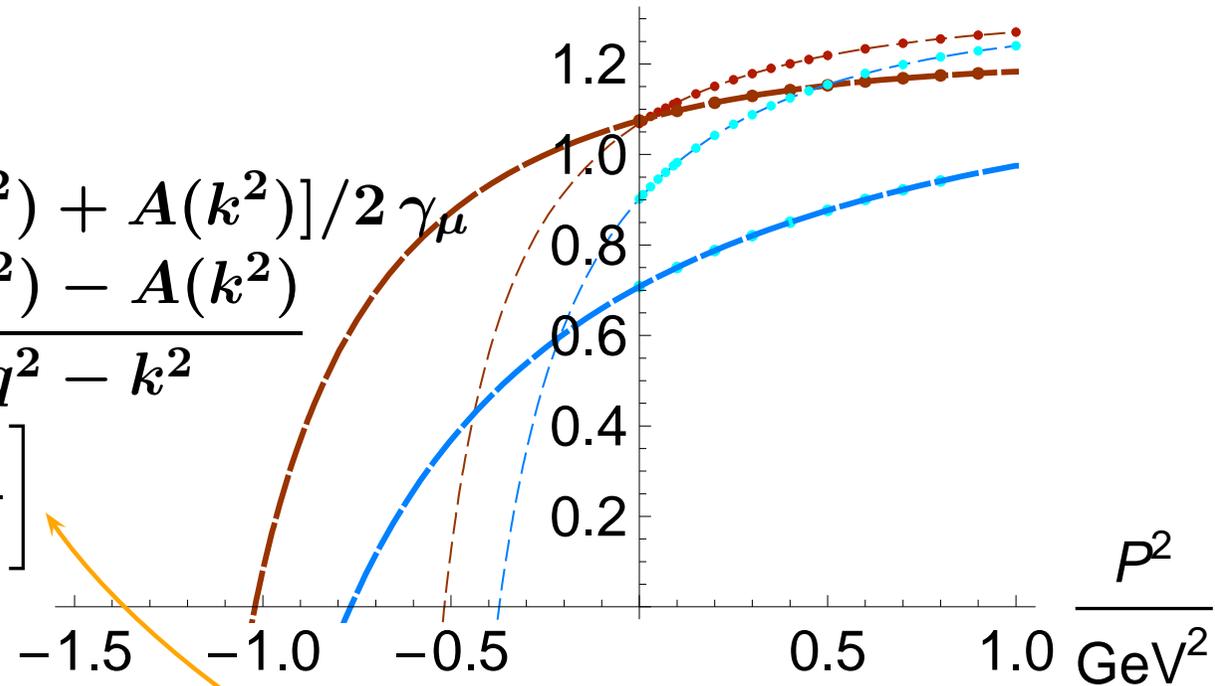


$$m_{a_1} (1066 \text{ MeV}) - m_\rho (924 \text{ MeV}) = 142 \text{ MeV} \dots \text{expt.} = 455 \text{ MeV}$$

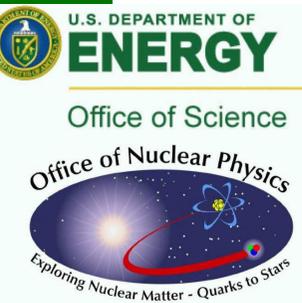
$$\frac{1}{\Gamma_{qq}(k=0, P^2)}$$

Ball-Chiu

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



DCSB enhanced spin-orbit interaction

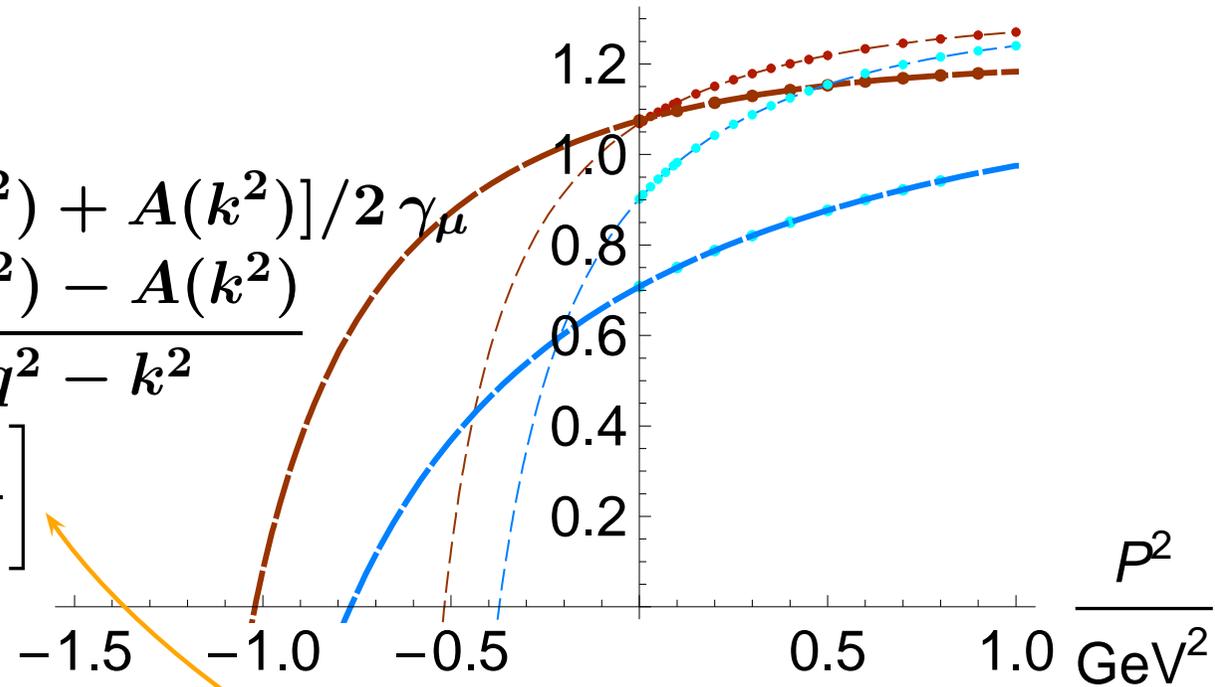


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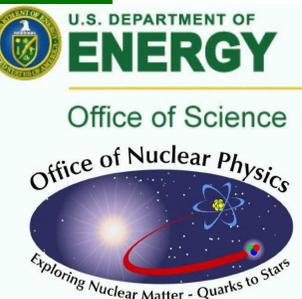
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$$\Gamma_\mu(q, k) = i[A(q^2) + A(k^2)]/2 \gamma_\mu + 2k_\mu \left[i\gamma \cdot k \frac{A(q^2) - A(k^2)}{q^2 - k^2} + \frac{B(q^2) - B(k^2)}{q^2 - k^2} \right]$$



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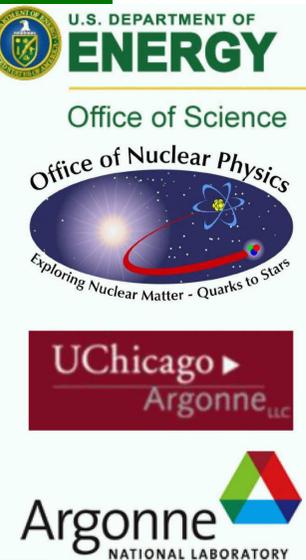
What's missing?



Missing Link

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

Chang Lei & CDR, in-preparation



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

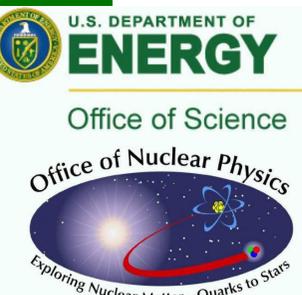
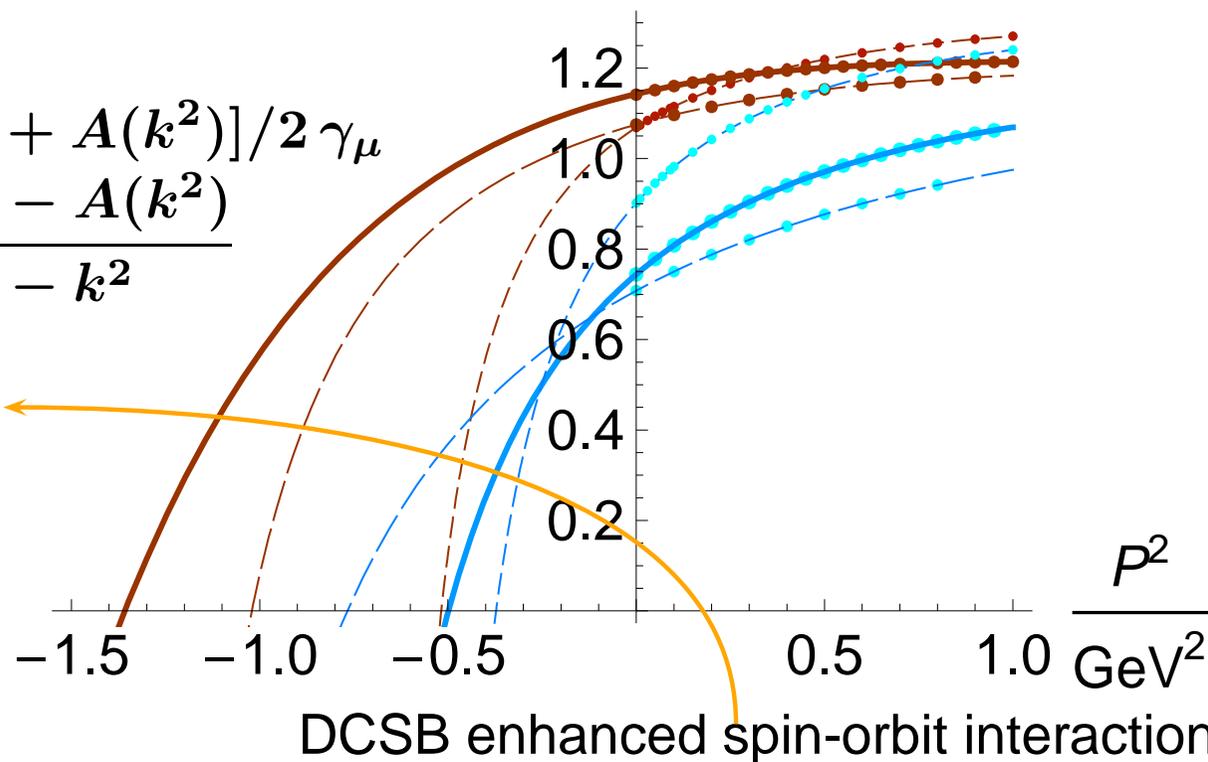
Chang Lei & CDR, in-preparation

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

Ball-Chiu

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

$$\frac{1}{\Gamma_{qq}(k=0, P^2)}$$



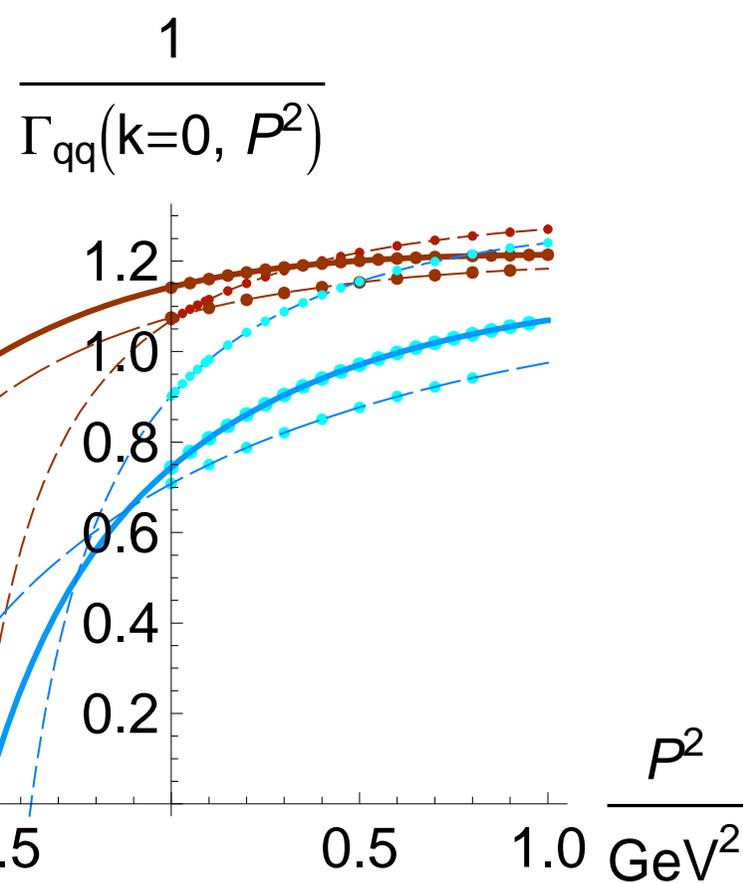
$$[m_{a_1} - m_\rho]$$

Chang Lei & CDR, in-preparation

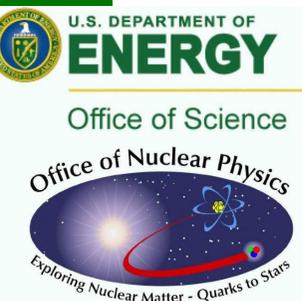
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Ball-Chiu + an. mag. mom.

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



DCSB enhanced anomalous chromomagnetic moment



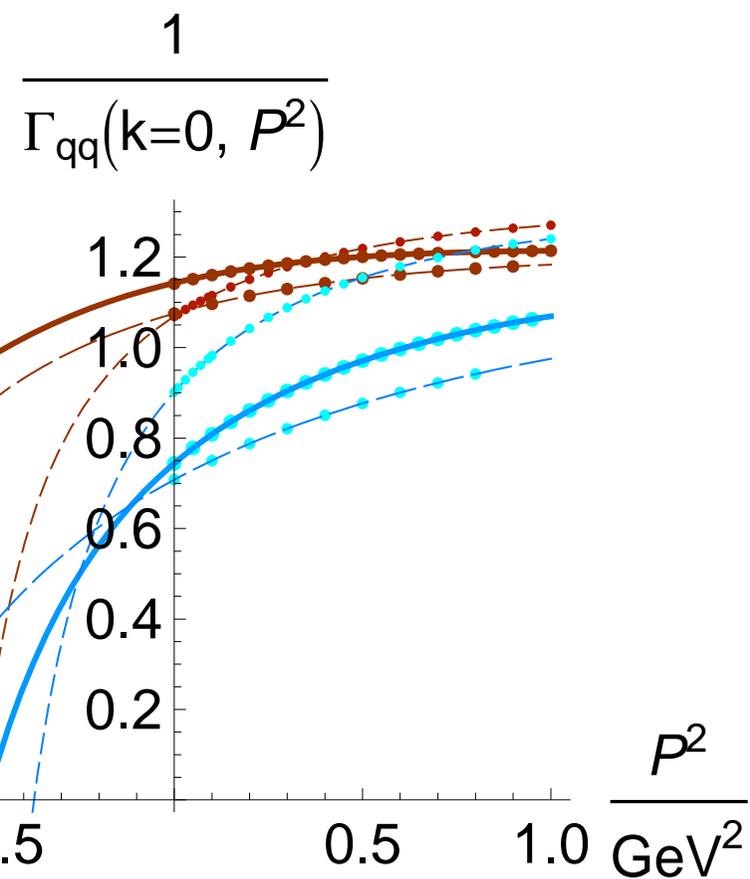
$$[m_{a_1} - m_\rho]$$

Chang Lei & CDR, in-preparation

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

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



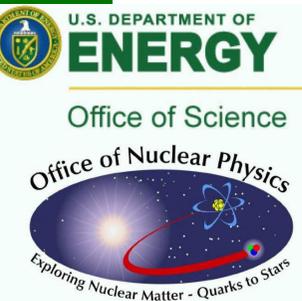
Inextricably connected

with DCSB.

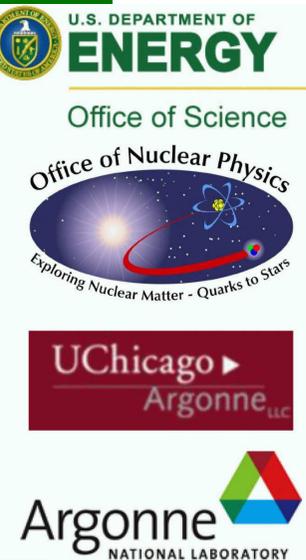
DCSB enhanced anomalous chromomagnetic moment

Can't appear in chirally symmetric theory

Paves way for truly reliable light-quark meson spectrum



Ratio – Kaon/Pion *u*-valence distribution



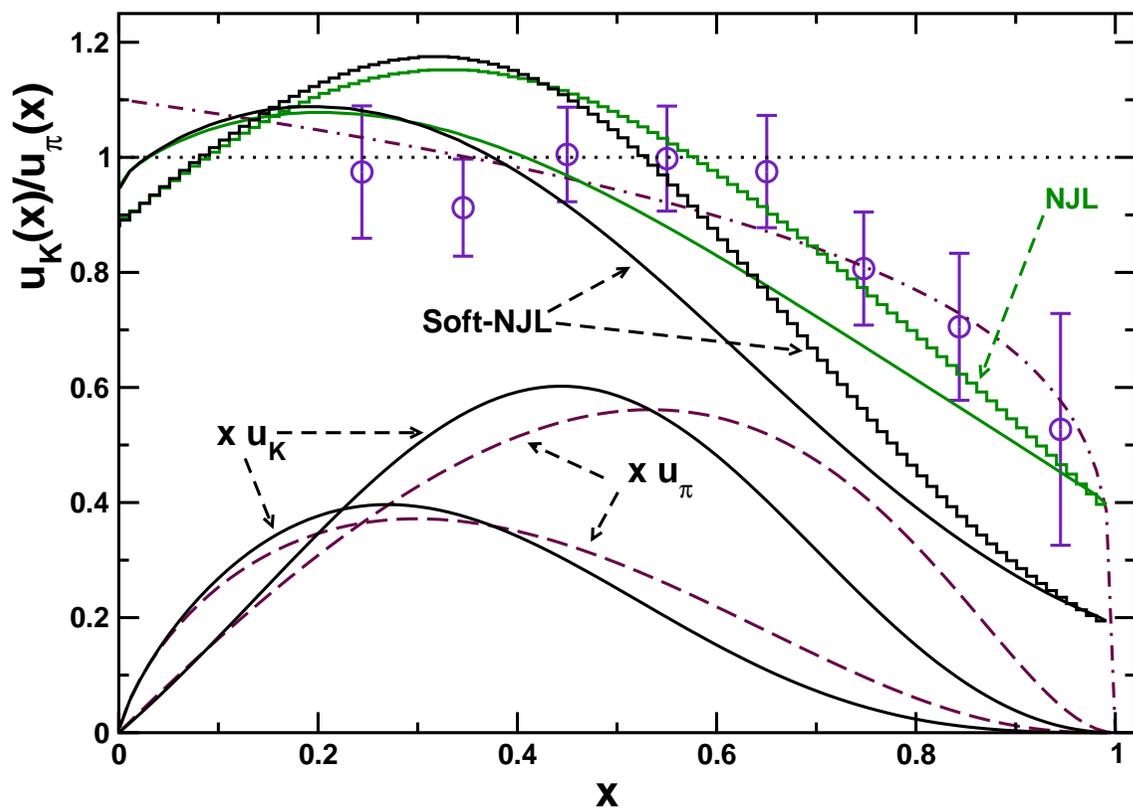
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Ratio – Kaon/Pion u -valence distribution



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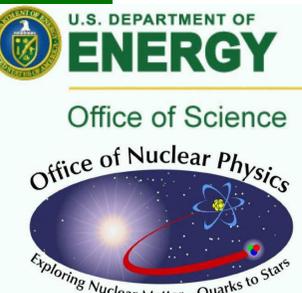
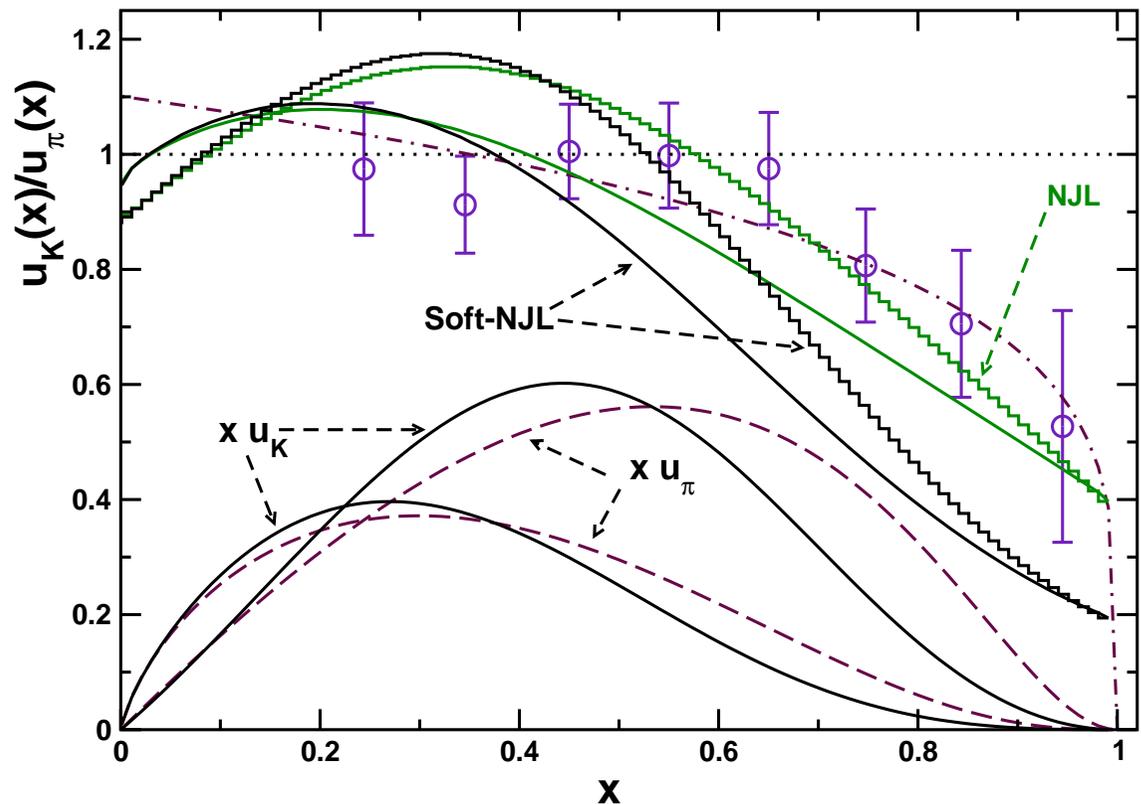
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Ratio – Kaon/Pion *u*-valence distribution

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

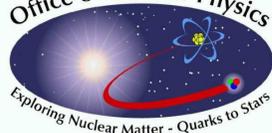




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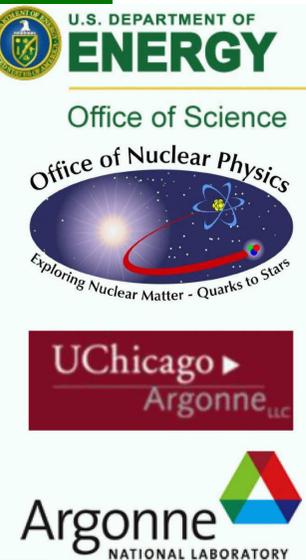
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Unifying Study of Mesons and Baryons



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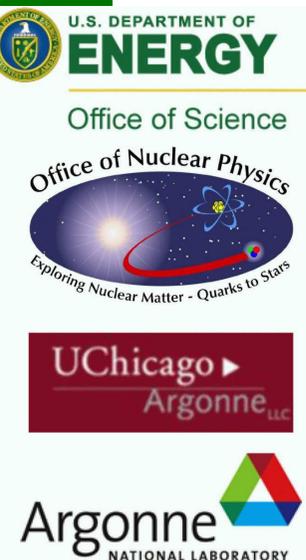
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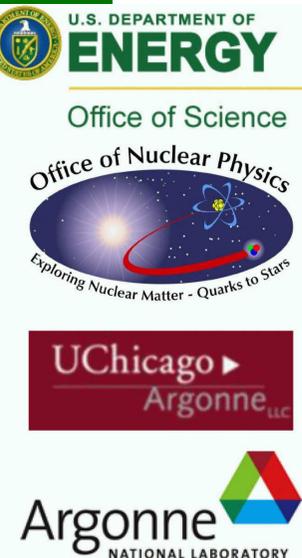
Unifying Study of Mesons and Baryons

- 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.



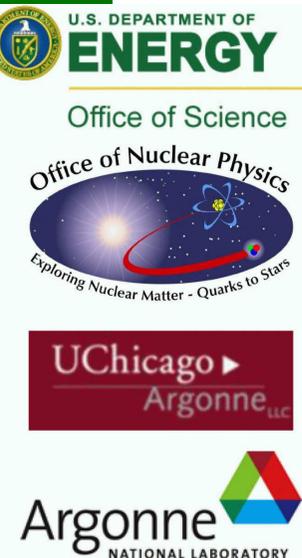
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- In quantum field theory a nucleon appears as a pole in a six-point quark Green function.
 - Residue is proportional to nucleon's Faddeev amplitude
 - Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks



Unifying Study of Mesons and Baryons

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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
 - 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

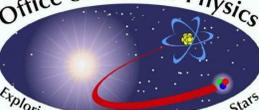
R. T. Cahill *et al.* Austral. J. Phys. **42** (1989) 129



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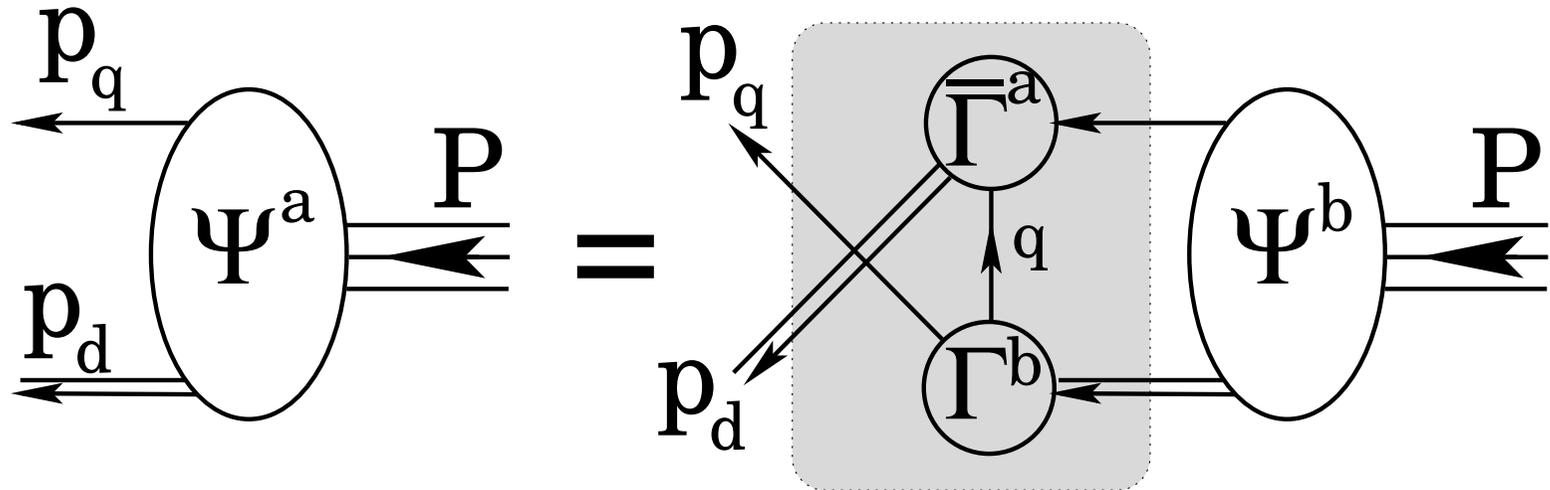
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Faddeev equation

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



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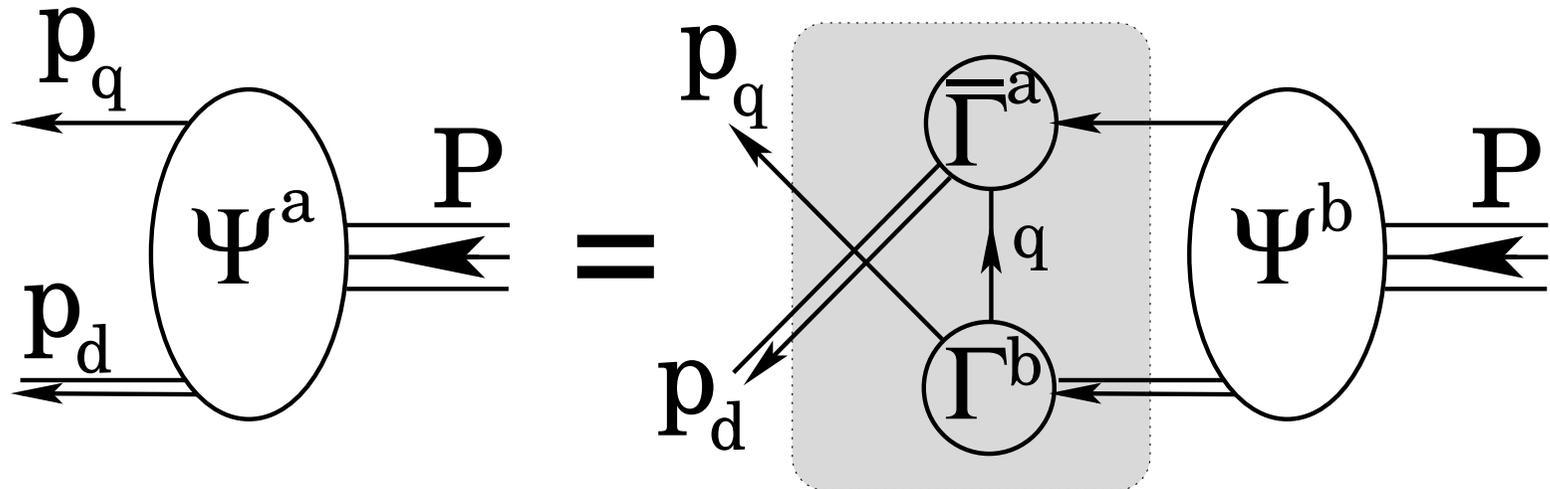
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Faddeev equation

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



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



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Nucleon-Photon Vertex



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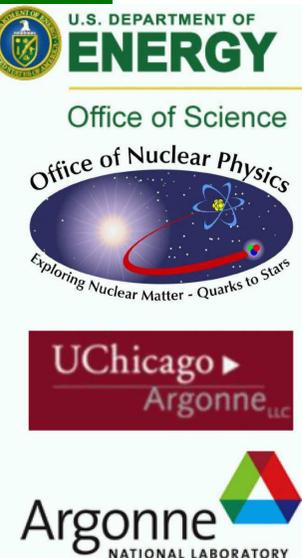
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M. Oettel, M. Pichowsky
and L. von Smekal, nu-th/9909082

6 terms ...

Nucleon-Photon Vertex

constructed systematically ... current conserved automatically
for on-shell nucleons described by Faddeev Amplitude



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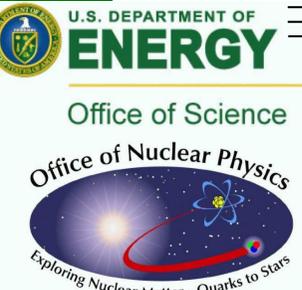
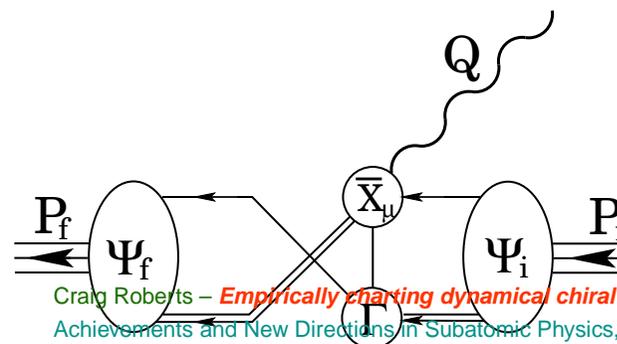
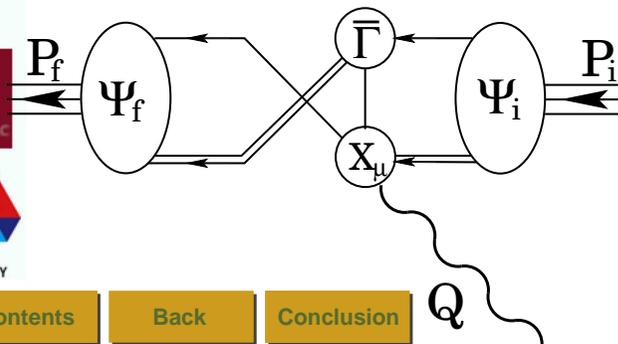
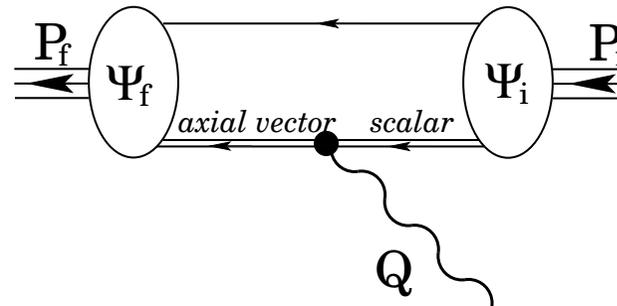
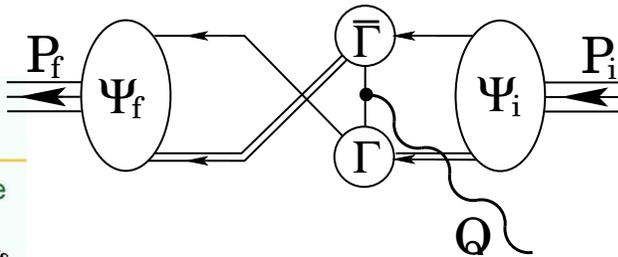
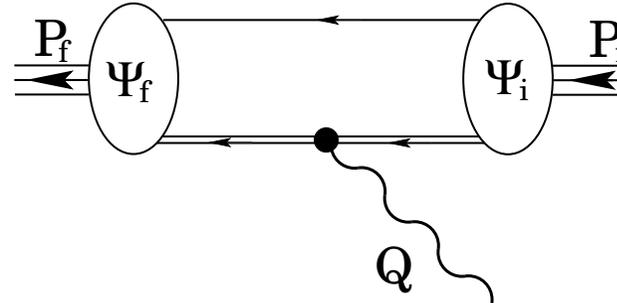
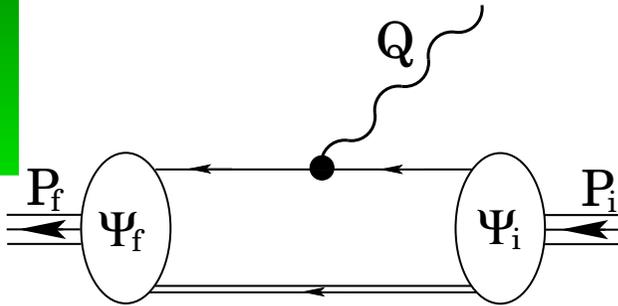
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6 terms ...

Nucleon-Photon Vertex

constructed systematically ... current conserved automatically
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Cloët, Roberts *et al.*

- arXiv:0710.2059 [nucl-th]
- arXiv:0710.5746 [nucl-th]
- arXiv:0804.3118 [nucl-th]

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

- arXiv:0812.0416 [nucl-th] – *Survey of nucleon EM form factors*



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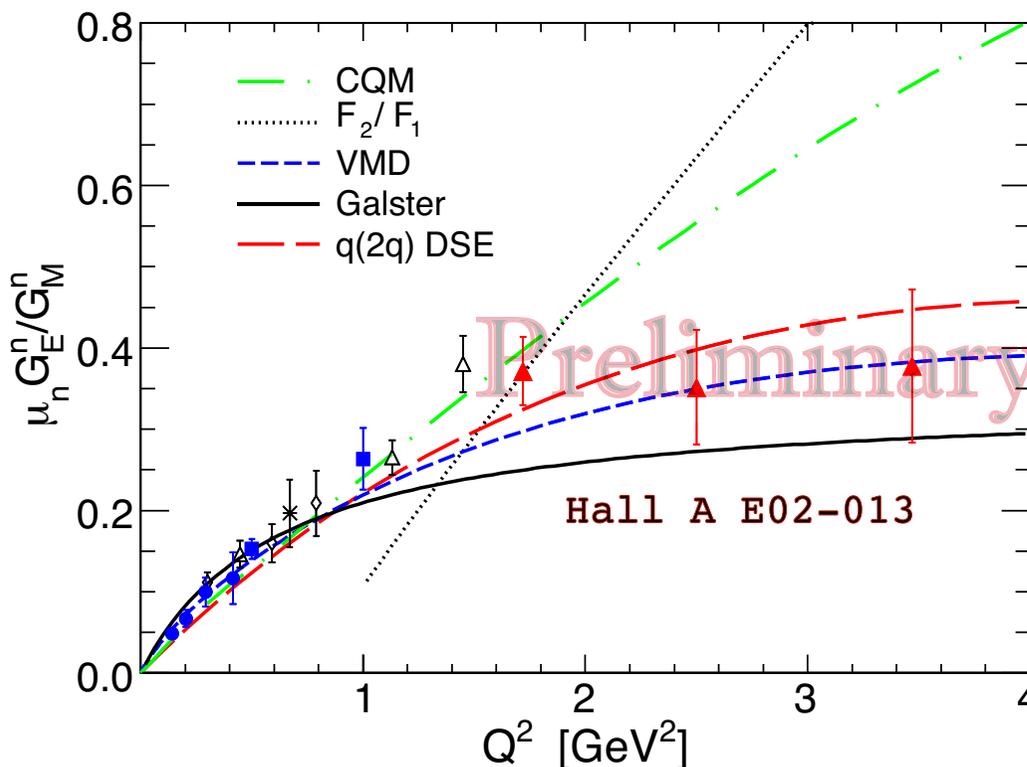
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● DSE-Faddeev Equation prediction



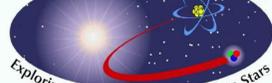
Jefferson Lab E02-013 Collaboration, *in preparation.*

Bogdan Wojtsekhowski



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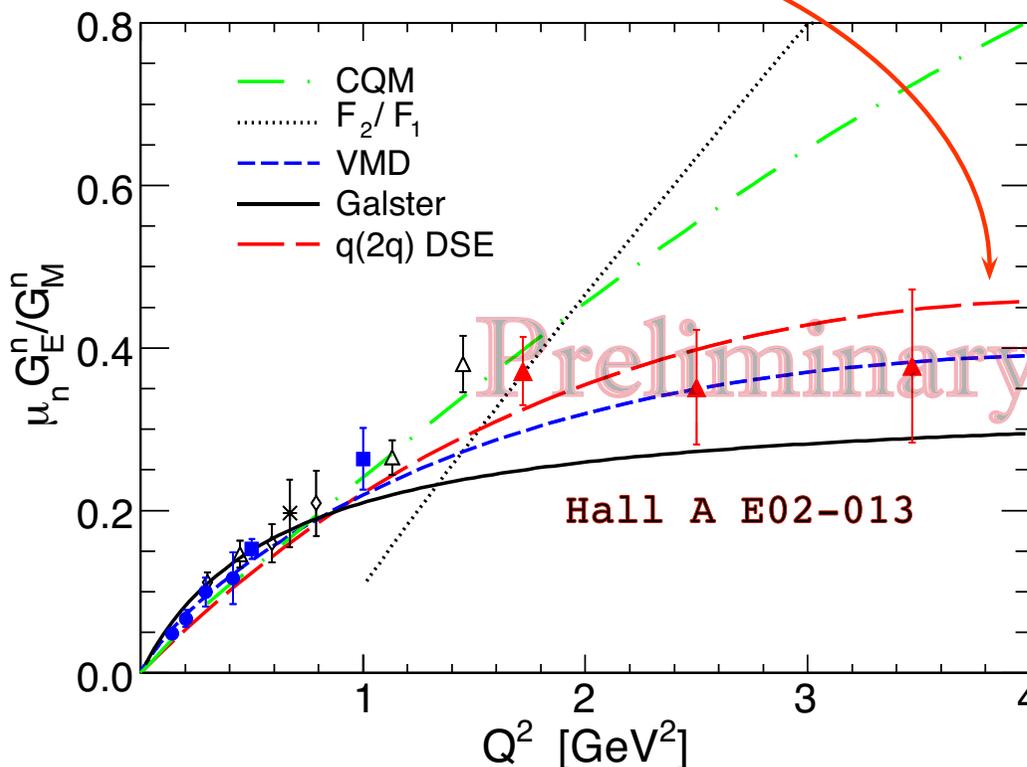
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● DSE-Faddeev Equation prediction

Red long-dashed curve



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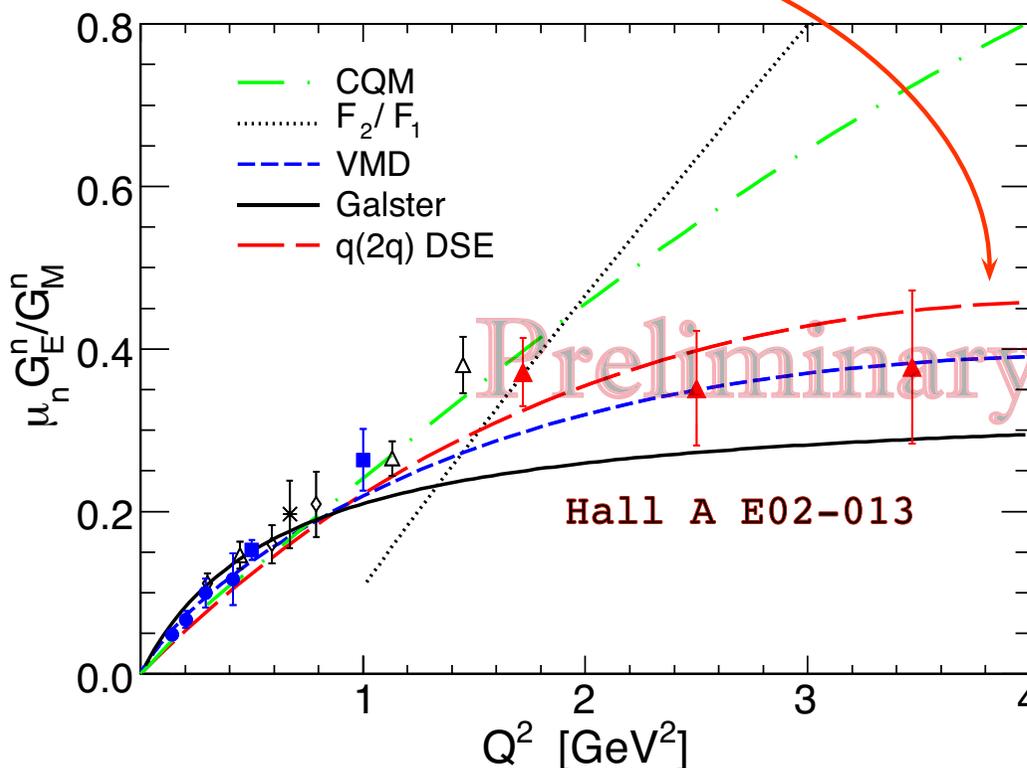
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● DSE-Faddeev Equation prediction

Red long-dashed curve



This evolution
very sensitive
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-dependence
dressed-quark
propagator

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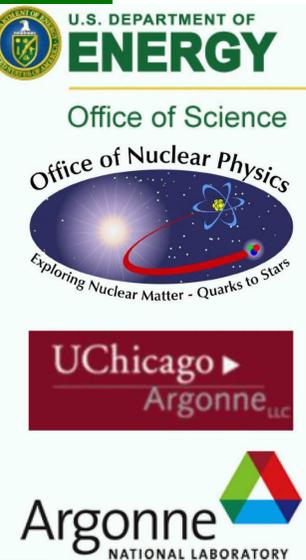
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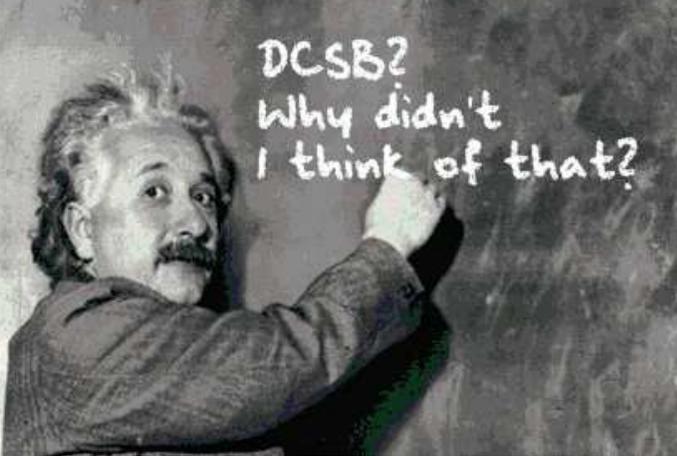


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- DCSB exists in QCD.

Epilogue

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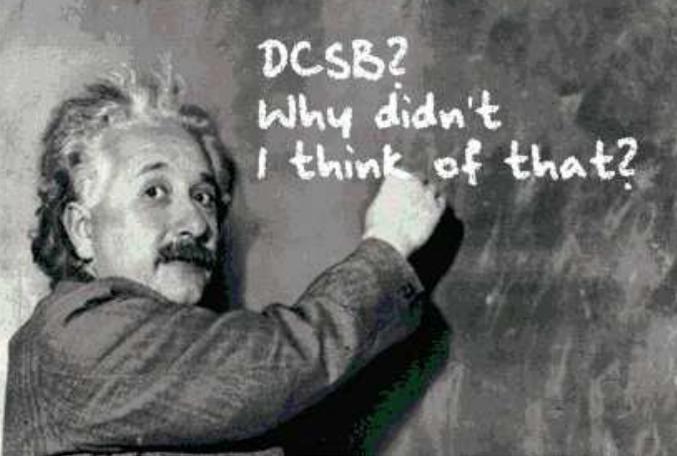
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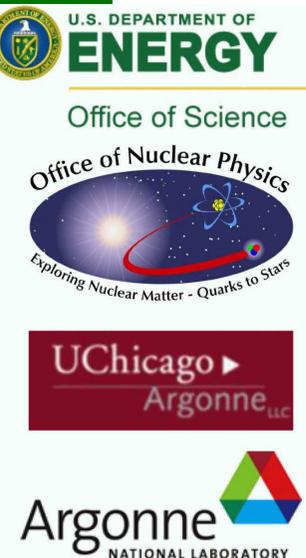
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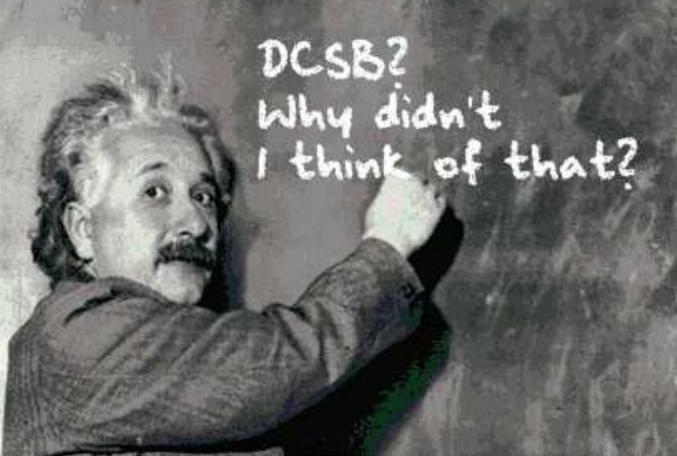


Epilogue

● DCSB exists in QCD.

- It is manifest in dressed propagators and vertices



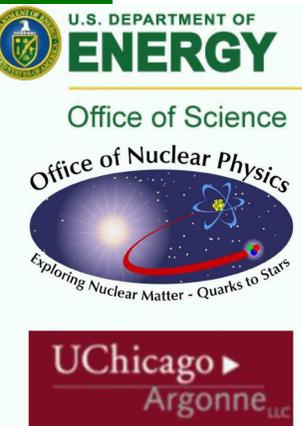


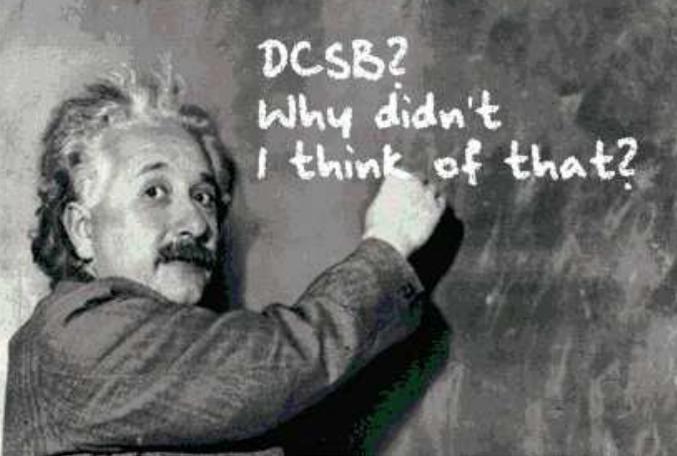
Epilogue

● 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: $4 \rightarrow 400 \text{ MeV}$
 - pseudoscalar mesons are unnaturally light: $m_\rho = 770$ cf. $m_\pi = 140 \text{ MeV}$
 - pseudoscalar mesons couple unnaturally strongly to light-quarks: $g_{\pi\bar{q}q} \approx 4.3$
 - pseudoscalar mesons couple unnaturally strongly to the lightest baryons

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





Epilogue

- DCSB impacts dramatically upon observables

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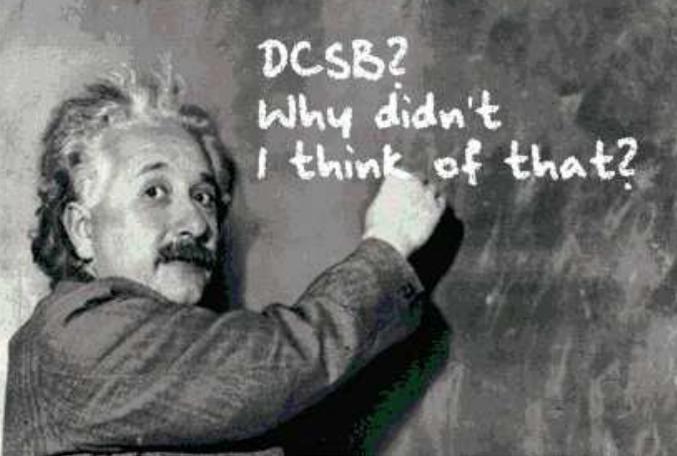
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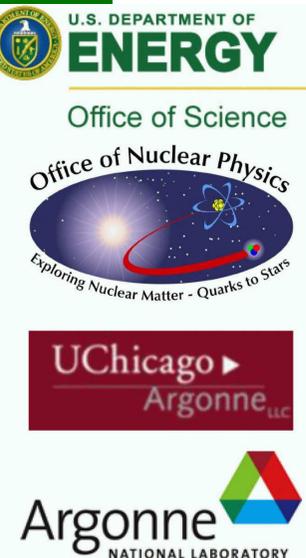
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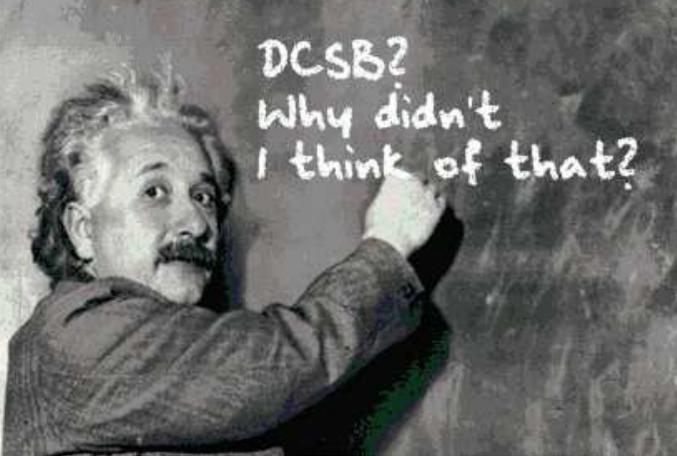
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Epilogue

- DCSB impacts dramatically upon observables
 - Spectrum; e.g., splittings: $\sigma-\pi$ & $a_1-\rho$
 - Elastic and Transition Form Factors





Epilogue

- DCSB impacts dramatically upon observables
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- But $M(p^2)$ is an *essentially* quantum field theoretical effect
 - 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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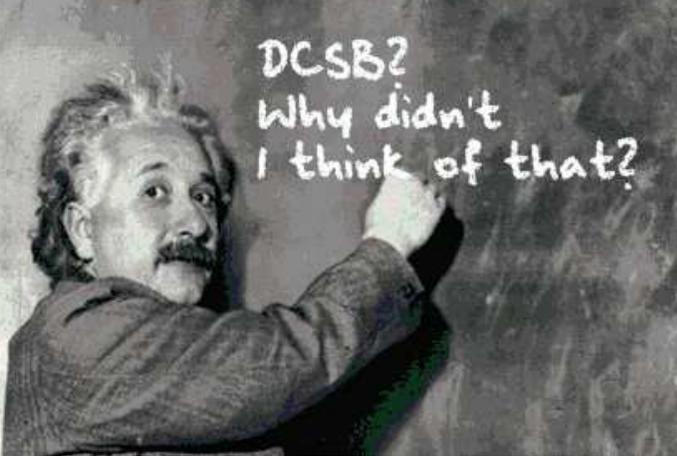


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Epilogue

- DCSB impacts dramatically upon observables
 - Spectrum; e.g., splittings: $\sigma-\pi$ & $a_1-\rho$
 - Elastic and Transition Form Factors
- But $M(p^2)$ is an *essentially* quantum field theoretical effect
 - Exposing & elucidating its effect in hadron physics requires nonperturbative, symmetry preserving framework; i.e., Poincaré covariance, chiral and e.m. current conservation, etc.
- 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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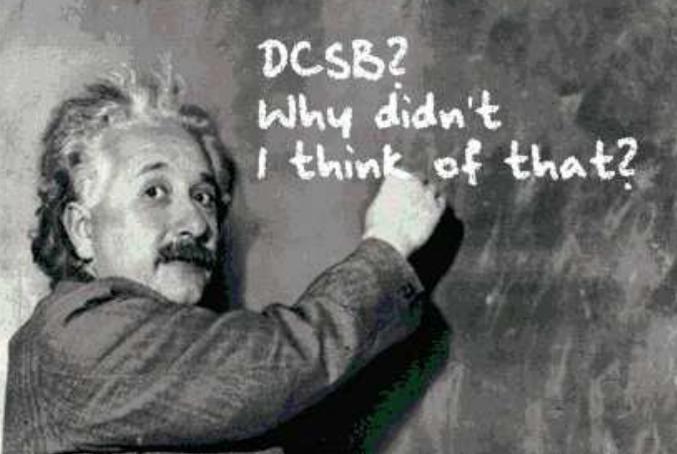


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Epilogue

- DCSB impacts dramatically upon observables
 - Spectrum; e.g., splittings: $\sigma-\pi$ & $a_1-\rho$
 - Elastic and Transition Form Factors
- But $M(p^2)$ is an *essentially* quantum field theoretical effect
 - Exposing & elucidating its effect in hadron physics requires nonperturbative, symmetry preserving framework; i.e., Poincaré covariance, chiral and e.m. current conservation, etc.
- 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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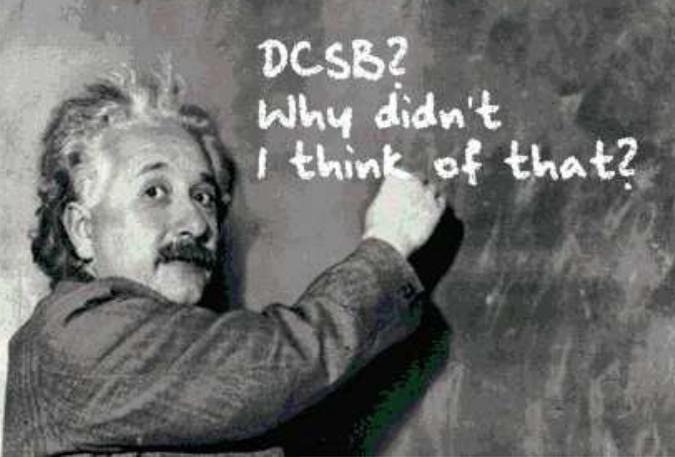


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Now is an exciting time . . .

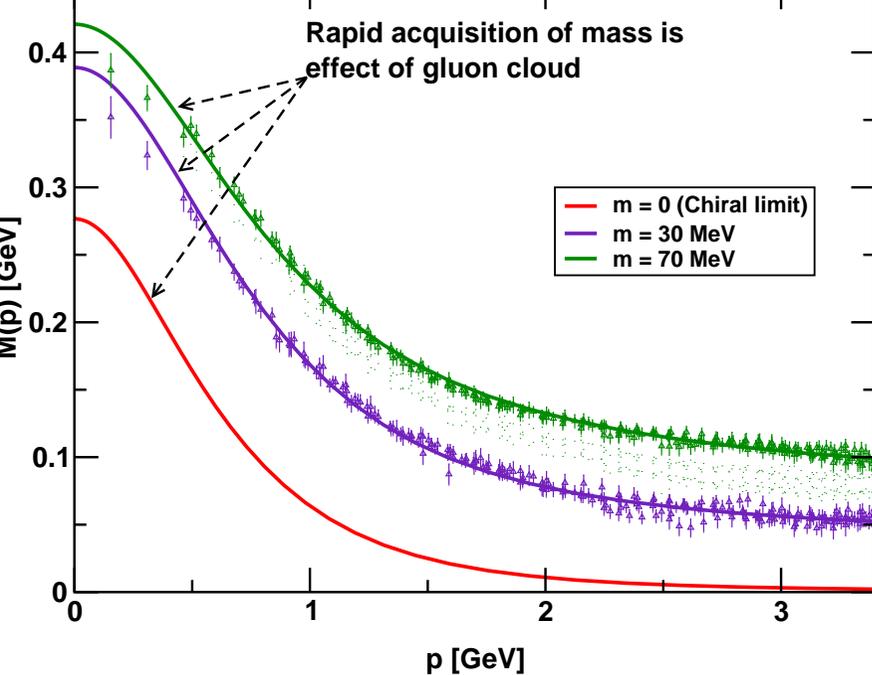
Positioned to unify phenomena as apparently disparate as

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



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Now is an exciting time . . .

Positioned to unify phenomena as apparently disparate as

- Hadron spectrum
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- Parton distribution functions

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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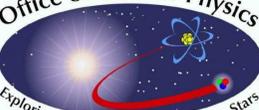
Just the Basic Facts



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Just the Basic Facts

- Tony graduated from Flinders University in 1973.

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Just the Basic Facts

- Tony graduated from Flinders University in 1973. Whereafter he immediately left for British Columbia, in search of adventure.



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Just the Basic Facts

- And adventures he had ...



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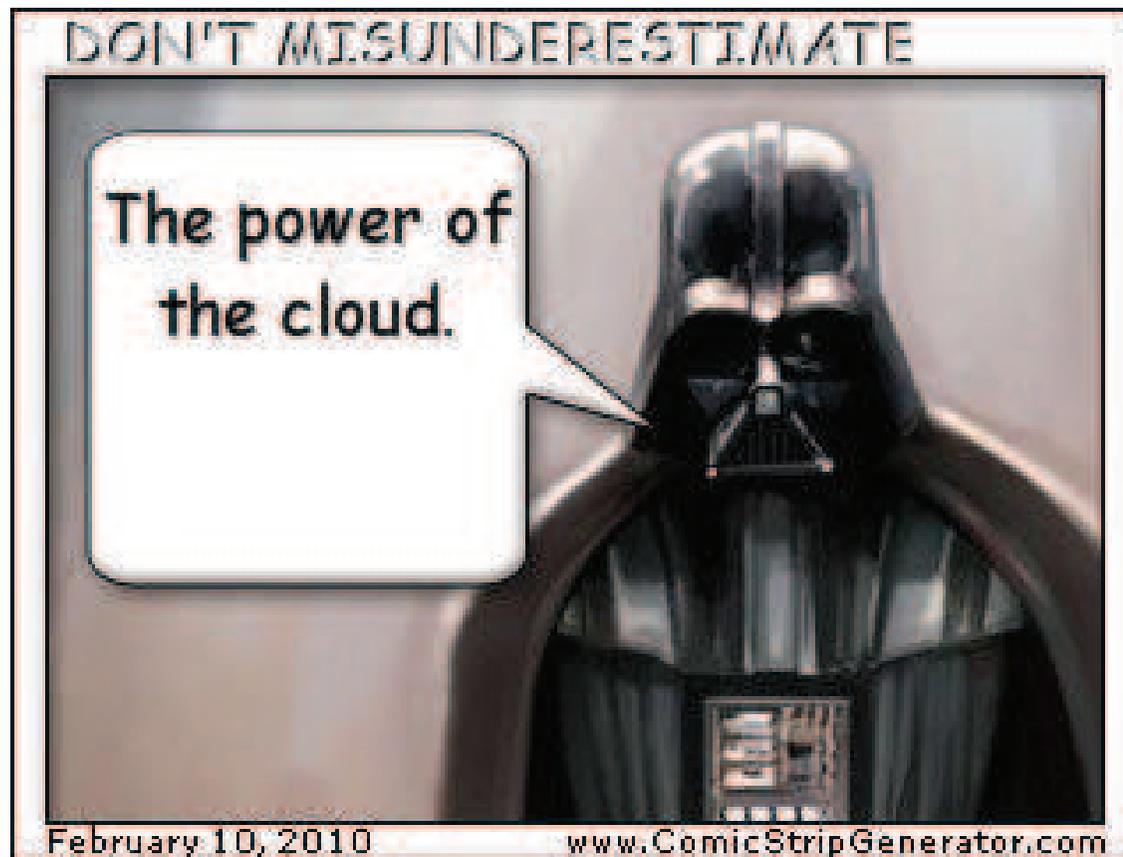
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Just the Basic Facts

- And adventures he had ...



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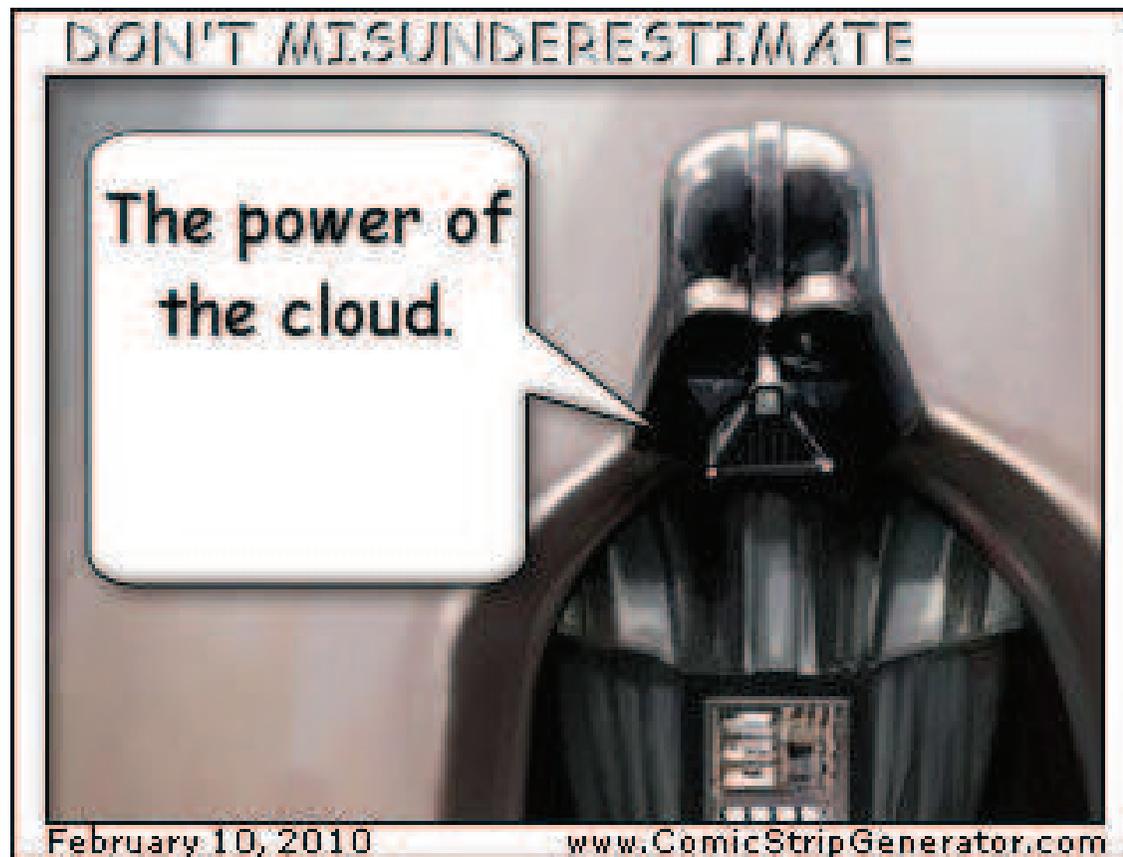
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Just the Basic Facts

- And adventures he had ...



- In time, even I learnt to use it.



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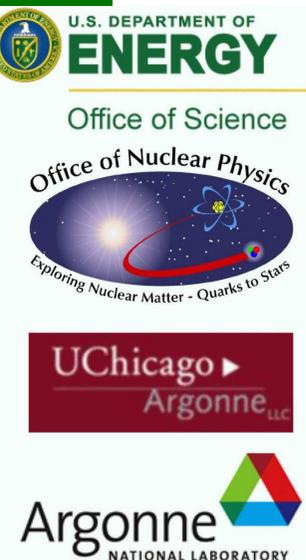
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Just the Basic Facts

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



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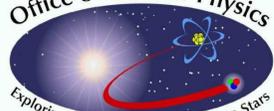
Just the Basic Facts

- But now Tony has returned to Australia and to the University of Adelaide.
- Part of the answer lies in the lead-off for the Faculty of Science at the University of Adelaide . . .



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Just the Basic Facts

- But now Tony has returned to Australia and to the University of Adelaide.
- Part of the answer lies in the lead-off for the Faculty of Science at the University of Adelaide . . .



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



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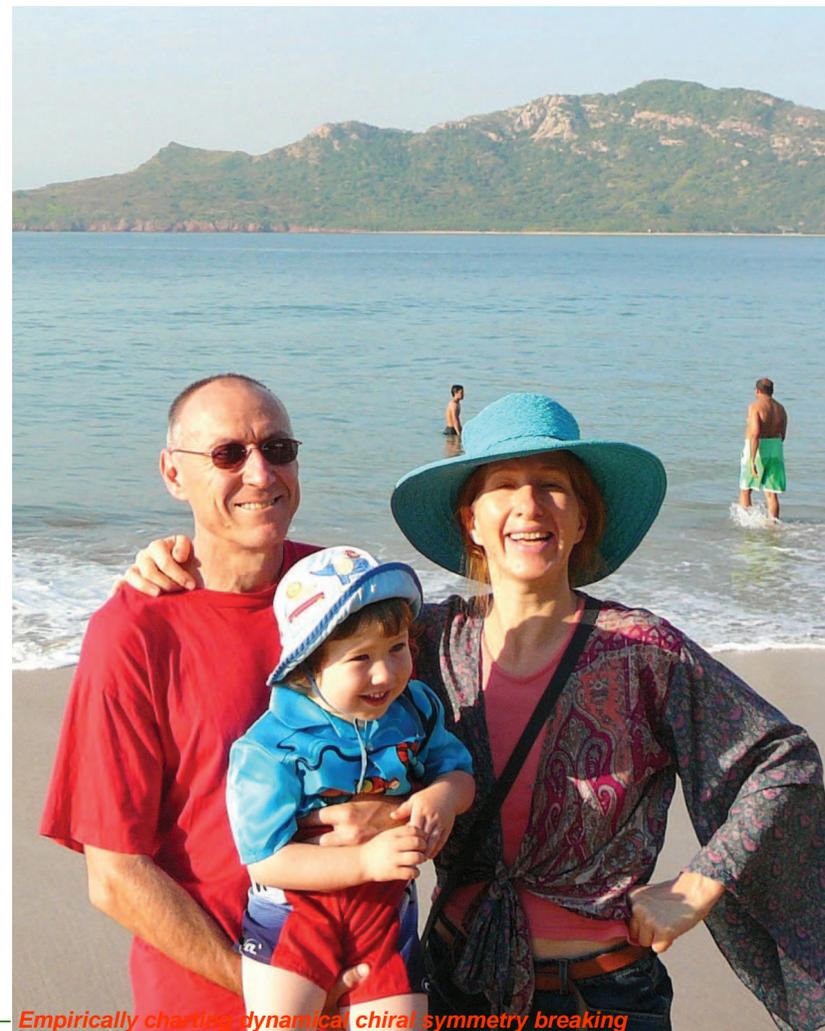
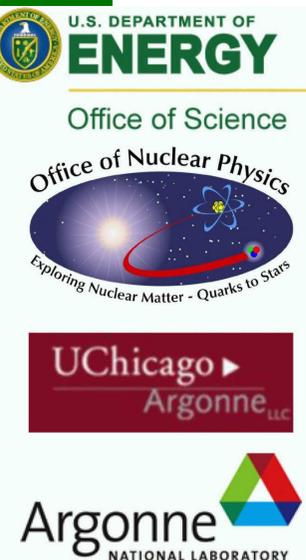


Tony:

Just the Basic Facts

Thankyou.

And a Belated Happy Birthday.



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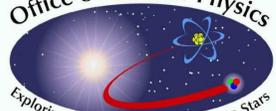
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