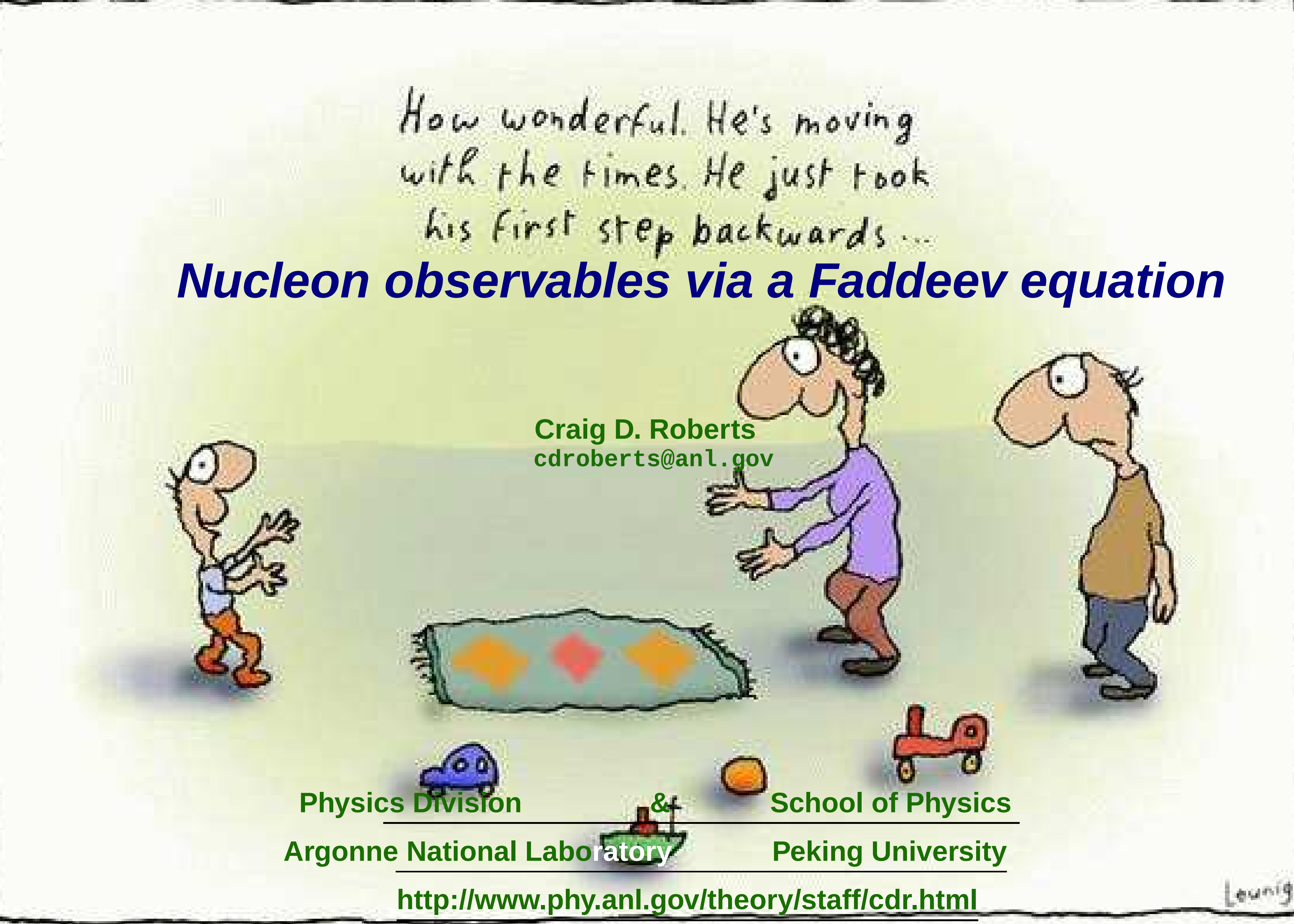

Nucleon observables via a Faddeev equation

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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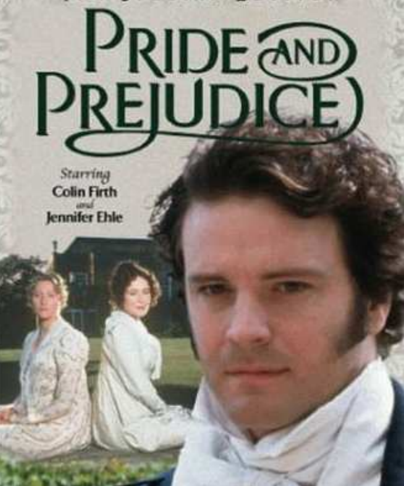

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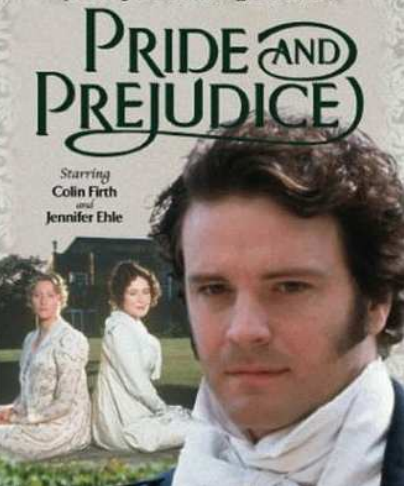

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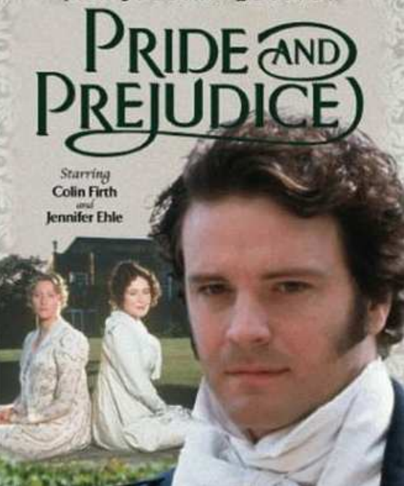

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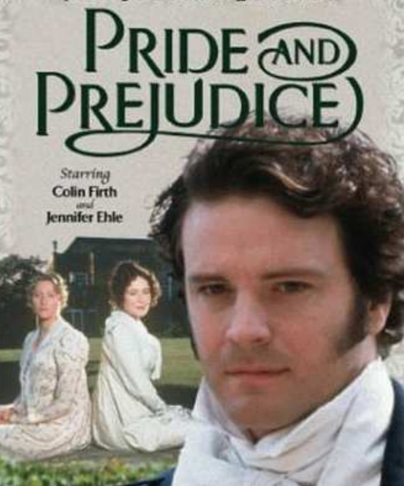

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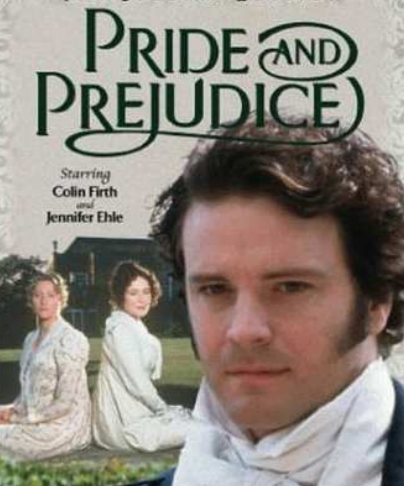

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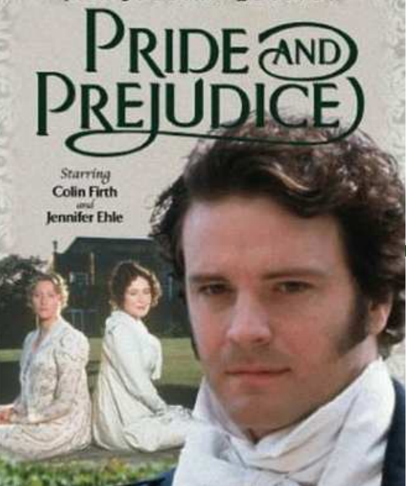

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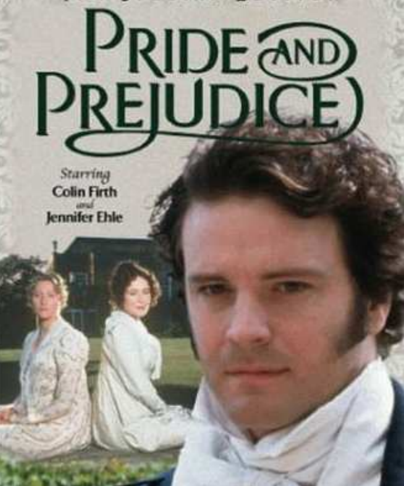

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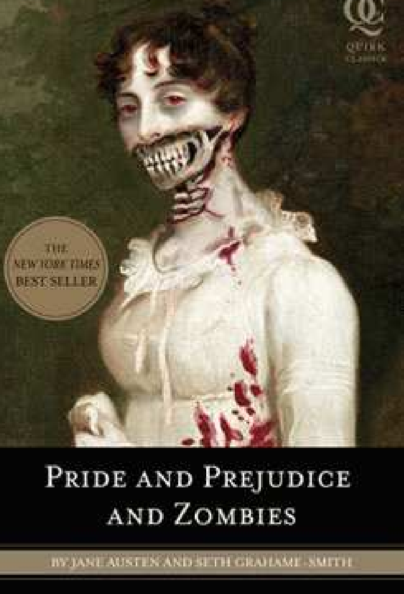

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- Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons. Problem because, e.g., DCSB - an established keystone of low-energy QCD and the origin of constituent-quark masses - has not been realised in the light-front formulation.

QCD’s Challenges

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

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QCD's Challenges

Understand Emergent Phenomena

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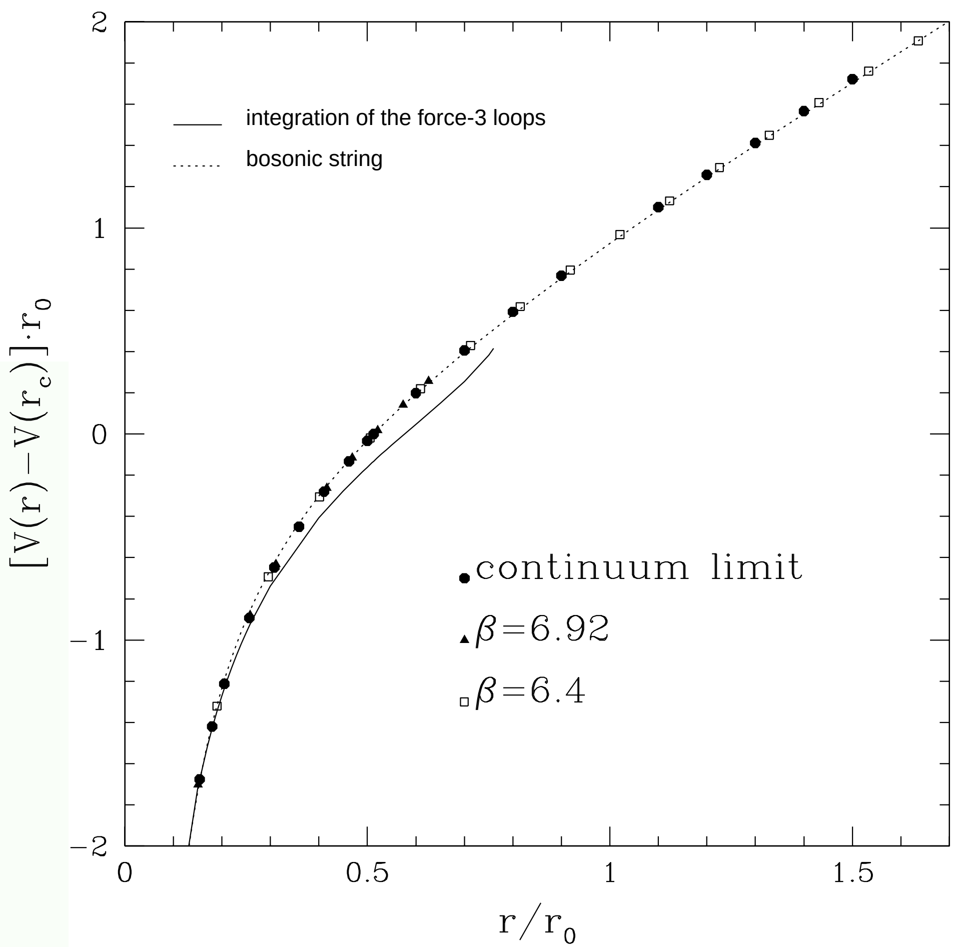
- QCD – Complex behaviour

  arises from apparently simple rules

Confinement

Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



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

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

Necco & Sommer
he-la/0108008

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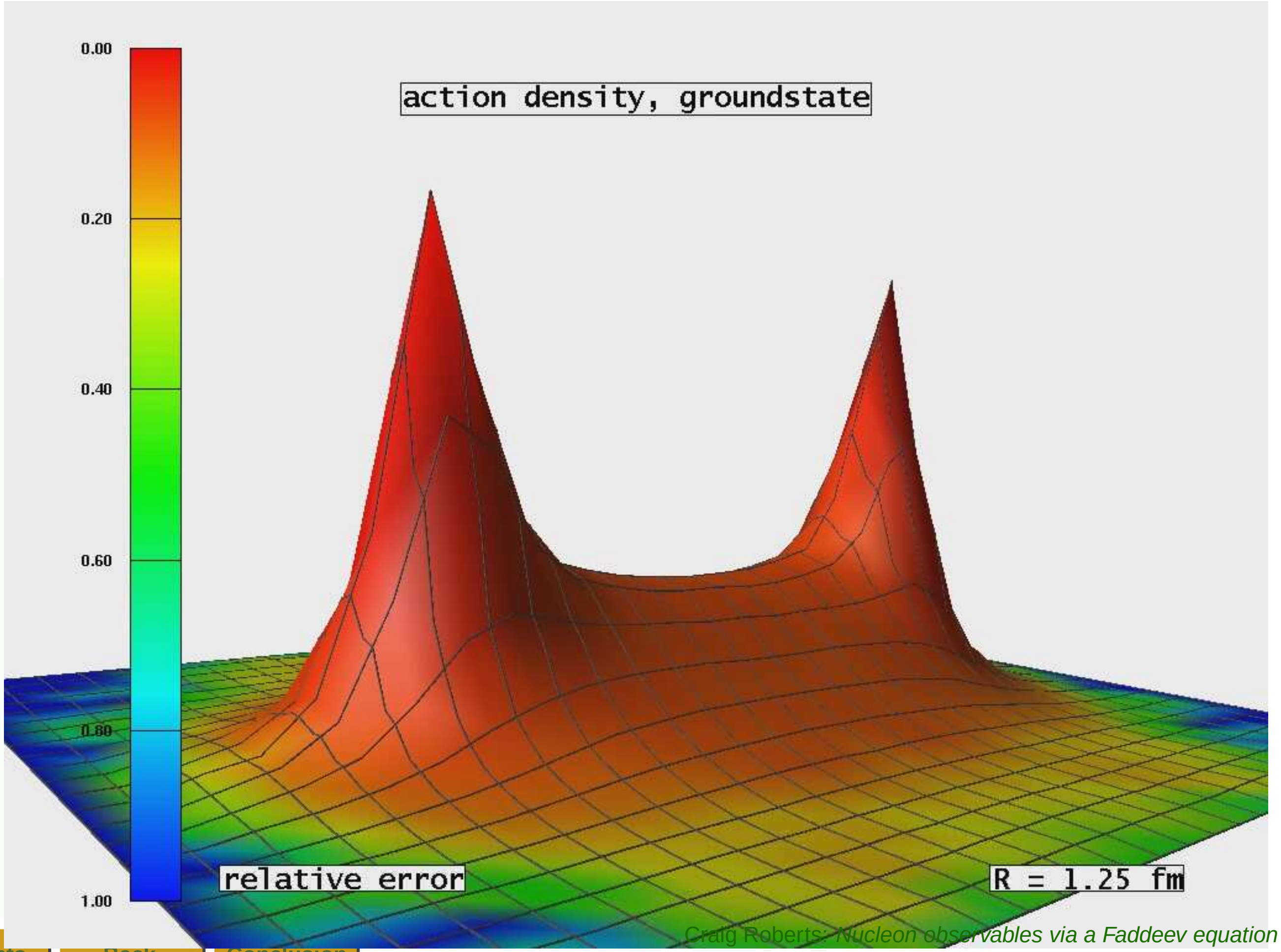
- Illustrate this in terms of the action density ... analogous to plotting the Force $= F_{\bar{Q}Q}(r) = \sigma + \frac{\pi}{12}\frac{1}{r^2}$



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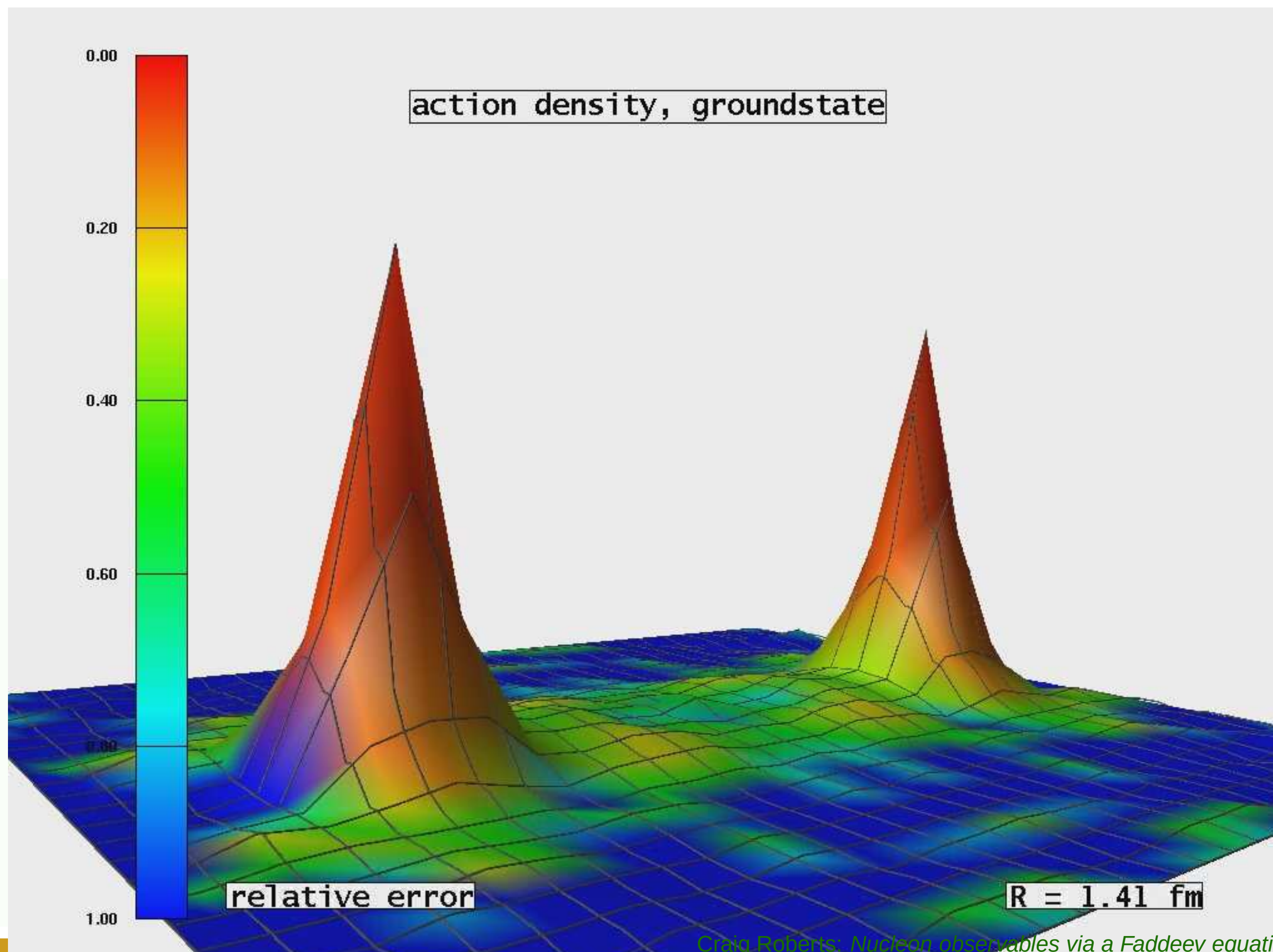

Bali, *et al*.
he-la/0512018

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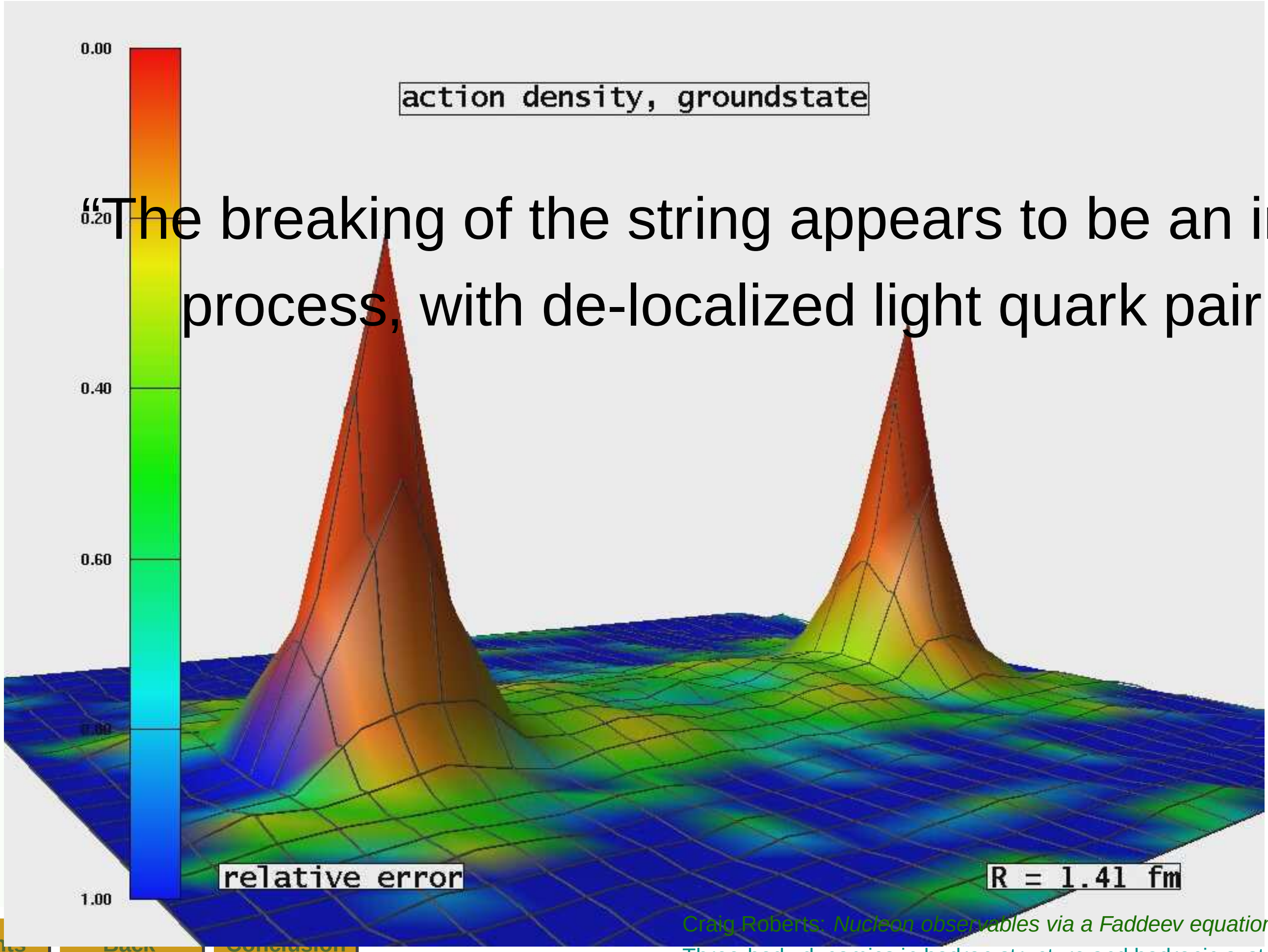

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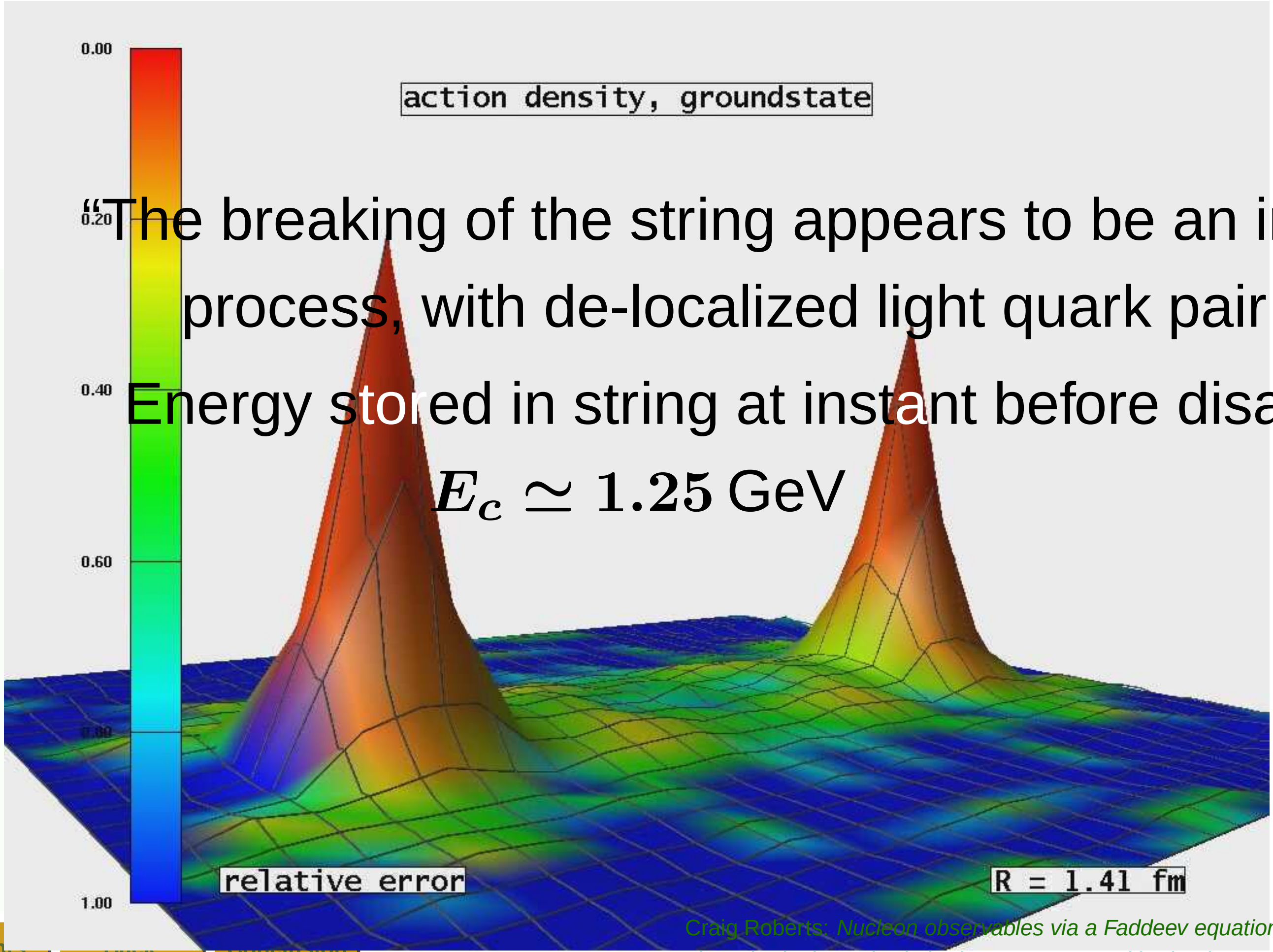

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Energy stored in string at instant before disappearance:

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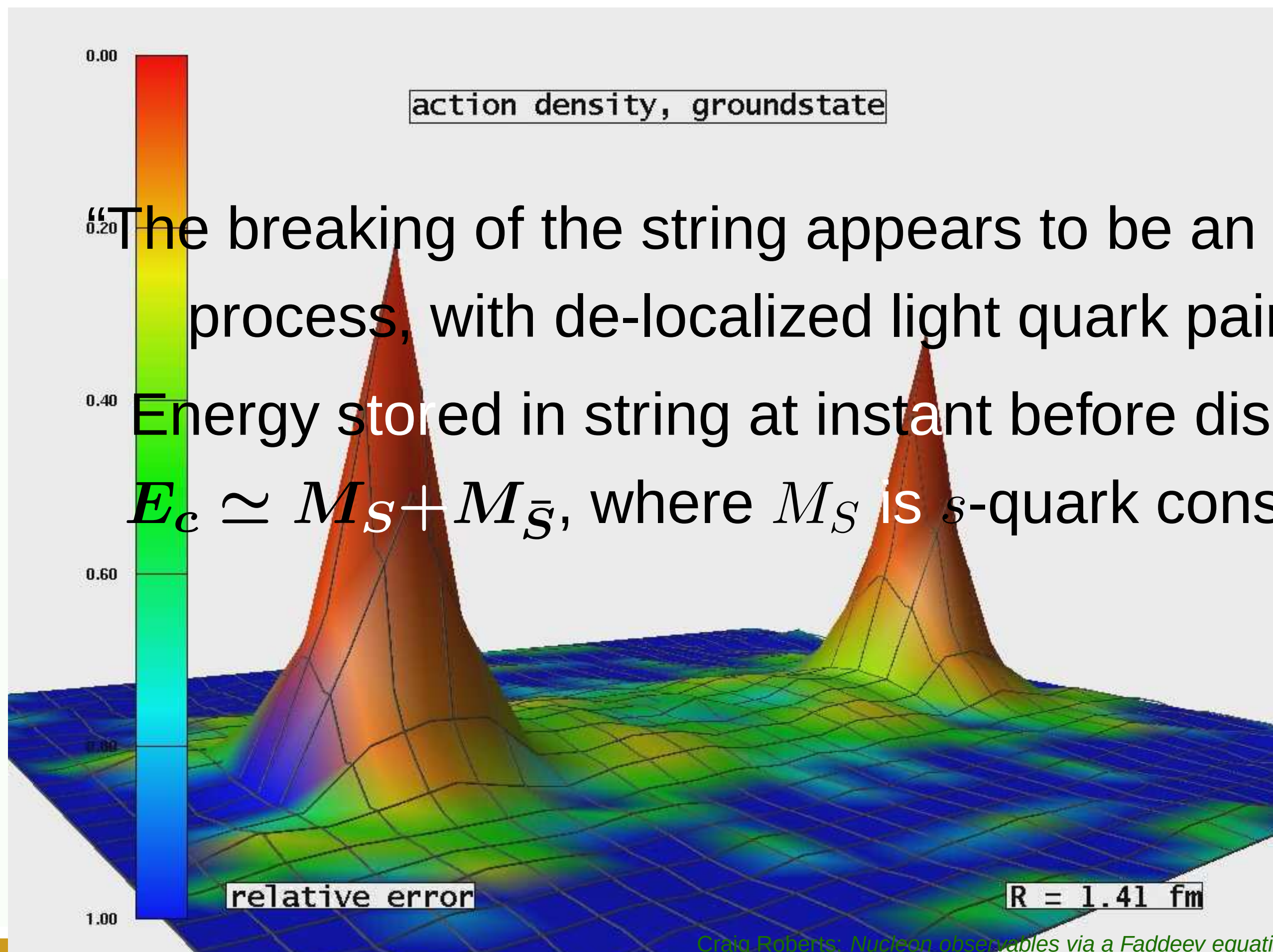

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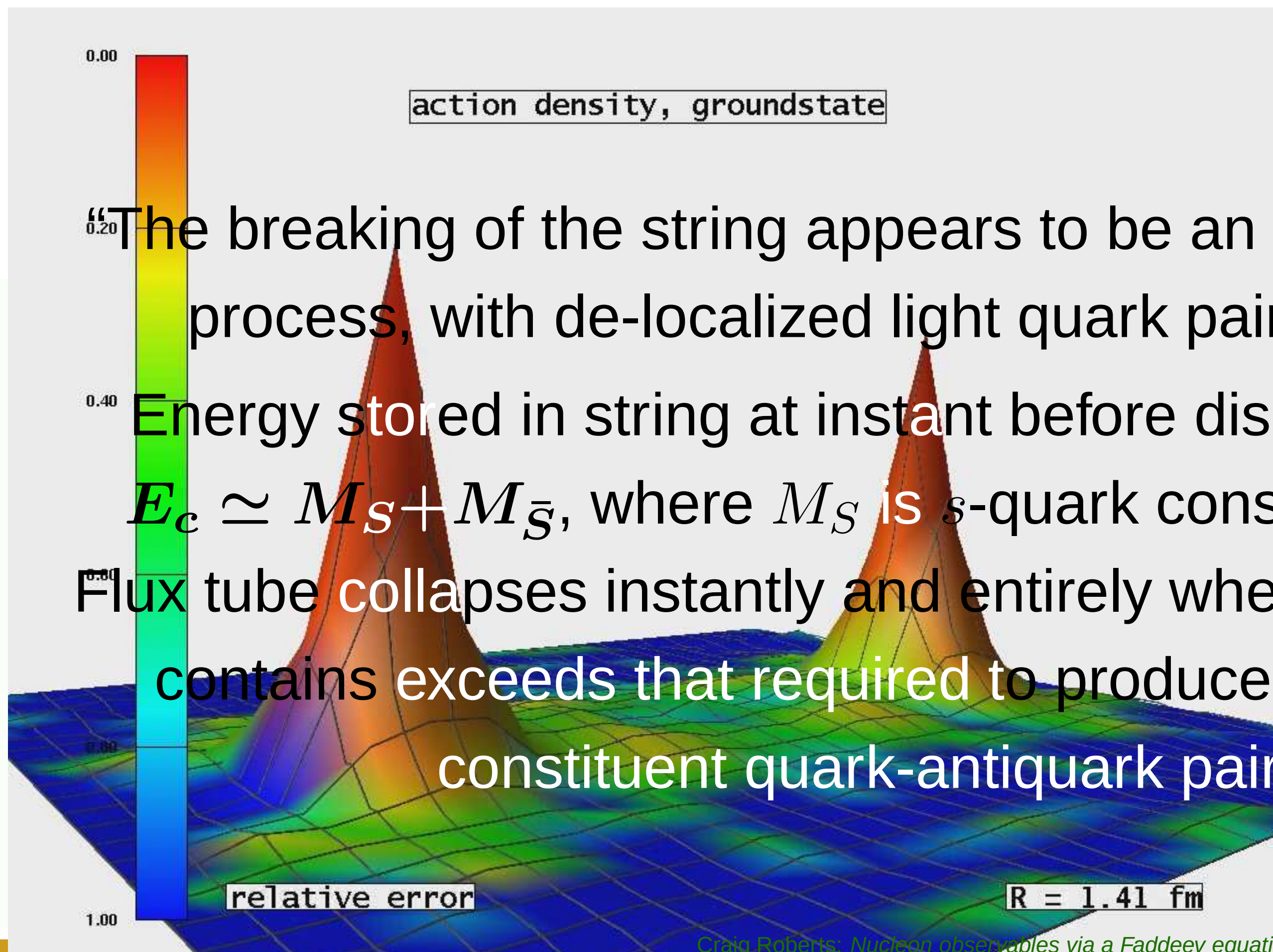

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Therefore . . . No information on *potential* between light-quarks. **Confinement**

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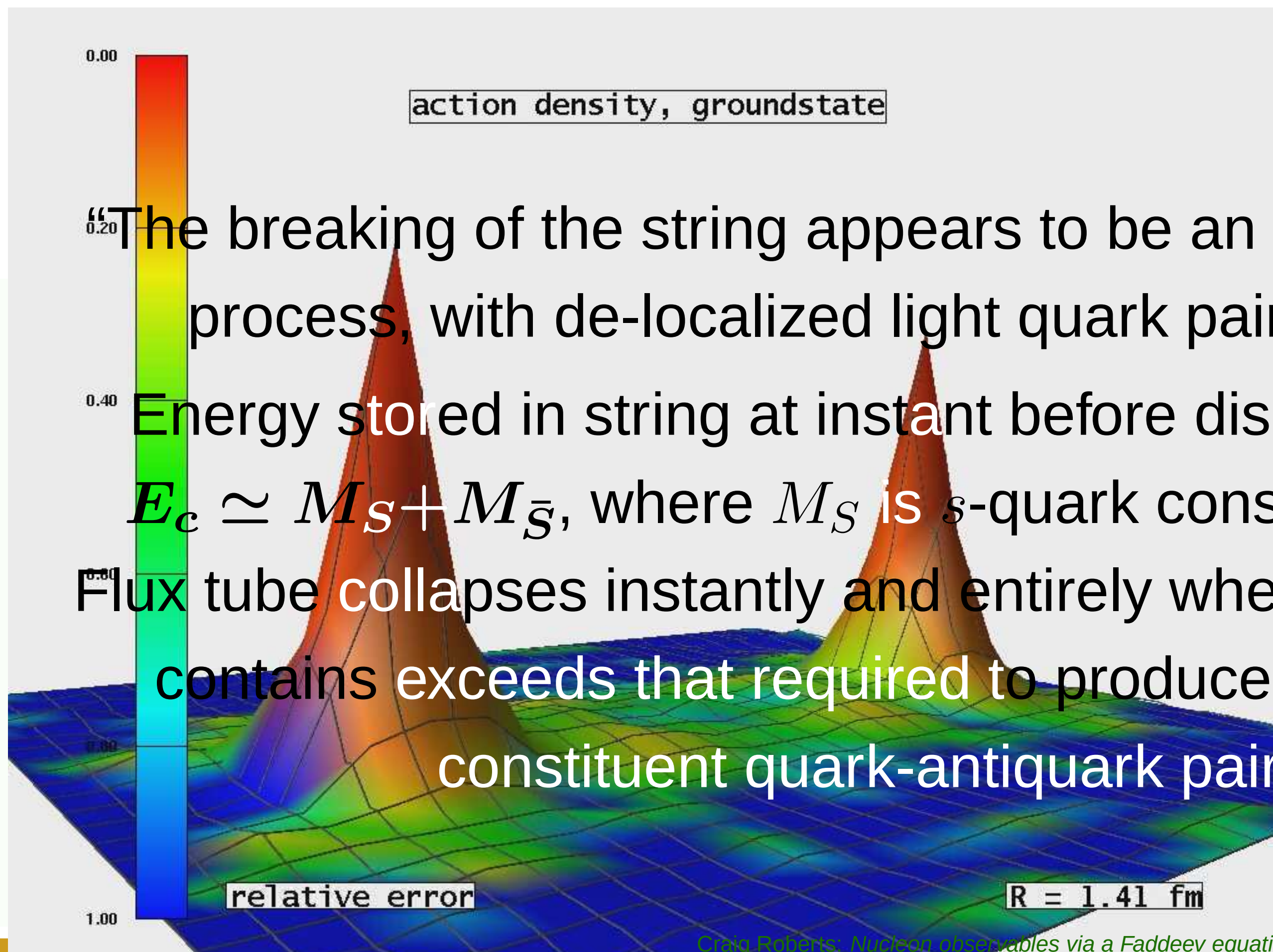

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What is the light-quark Long-Range Potential?

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What is the light-quark Long-Range Potential?

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

Dyson-Schwinger Equations

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- Well suited to Relativistic Quantum Field Theory

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Cross-Sections built from Schwinger Functions

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Charting the Interaction between light-quarks

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

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  - On other hand, at present significant qualitative advances possible with symmetry-preserving kernel *Ansätze* that express important additional nonperturbative effects, difficult to capture in any finite sum of contributions

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

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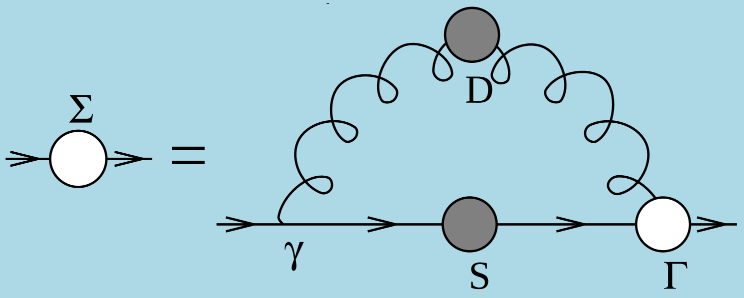
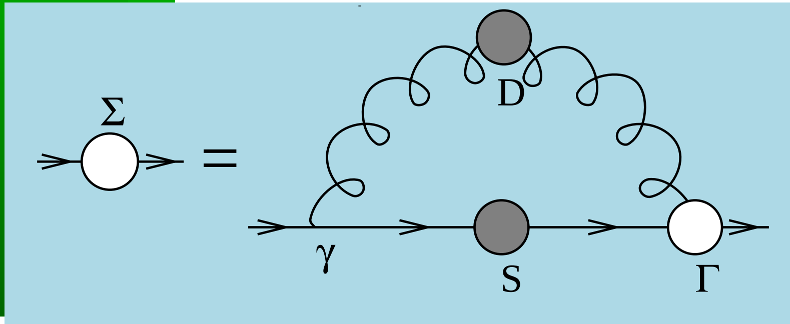


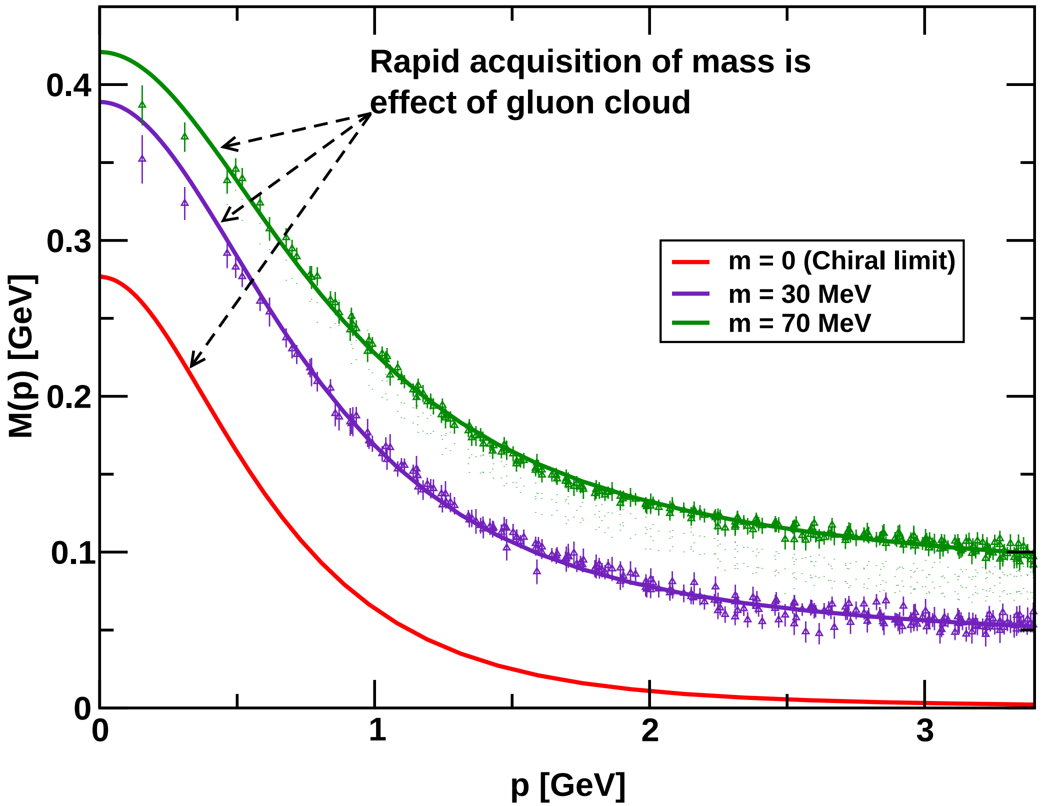
Gap Equation

Frontiers of Nuclear Science: Theoretical Advances



Gap Equation

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



Mass from nothing.

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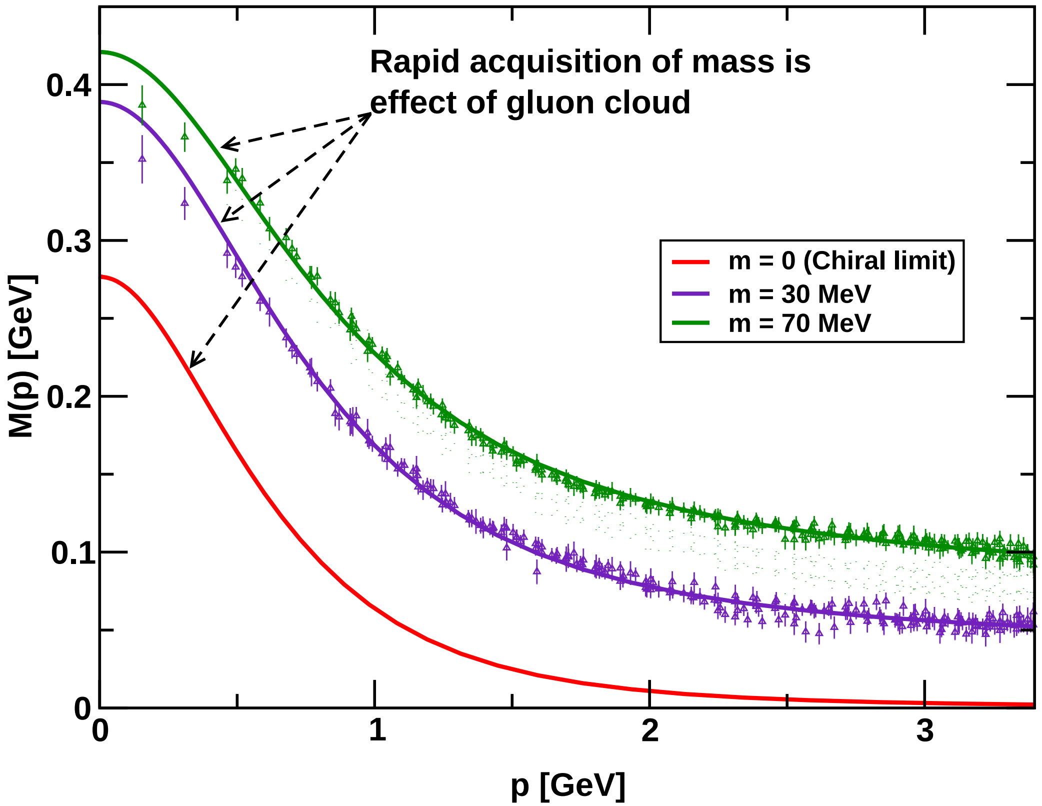
In QCD a quark's effective mass depends on its momentum. The function describing this can be calculated and is depicted here. Numerical simulations of lattice QCD (data, at two different bare masses) have confirmed model predictions (solid curves) that the vast bulk of the constituent mass of a light 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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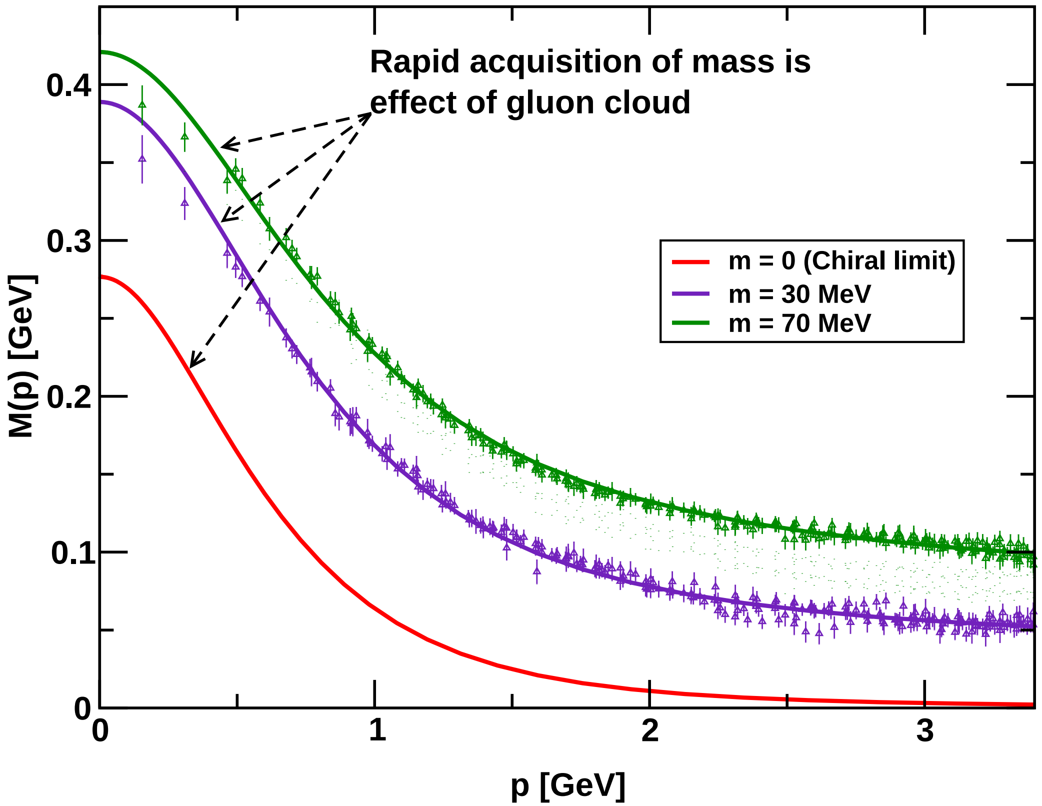


ALWAYS LOOK
ON THE
BRIGHT SIDE

- Established understanding of two- and three-point functions

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Hadrons

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

- Without bound states, Comparison with experiment is impossible

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- Without bound states, Comparison with experiment is impossible
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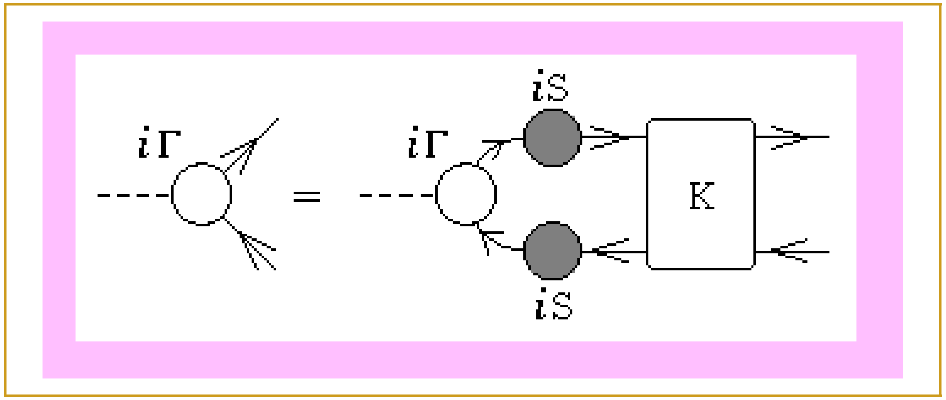

QFT Generalisation of Lippmann-Schwinger Equation.

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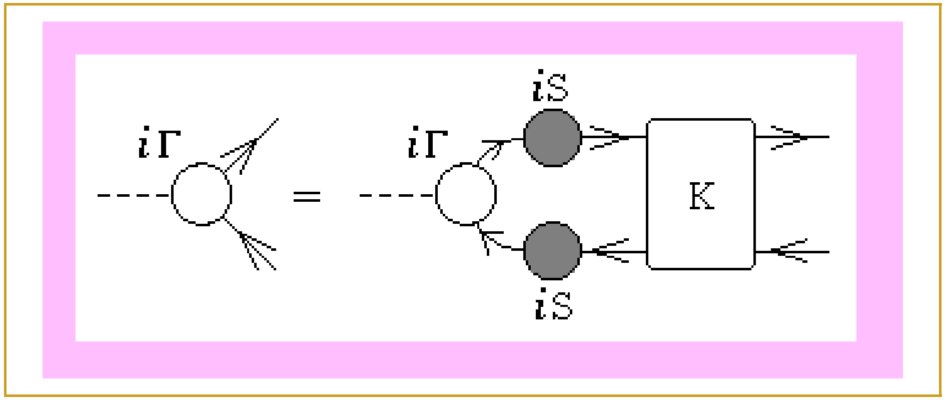

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

or What is the long-range potential in QCD?

Bethe-Salpeter Kernel

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- Axial-vector Ward-Takahashi identity

$$P_\mu \; \Gamma^l_{5\mu}(k;P) \quad = \quad \mathcal{S}^{-1}(k_+)\,\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5 \; \mathcal{S}^{-1}(k_-)$$

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QFT Statement of Chiral Symmetry

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Bethe-Salpeter Kernel

- Axial-vector Ward-Takahashi identity

$$P_\mu \Gamma^l_{5\mu}(k;P) = \mathcal{S}^{-1}(k_+)\frac{1}{2}\lambda^l_f i\gamma_5 + \frac{1}{2}\lambda^l_f i\gamma_5 \mathcal{S}^{-1}(k_-)$$

$$-M_\zeta\, i\Gamma^l_5(k;P) - i\Gamma^l_5(k;P)\, M_\zeta$$

Satisfies BSE　　　　Satisfies DSE

Kernels very different

but must be intimately related

- Relation must be preserved by truncation
- Nontrivial constraint

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Satisfies BSE Satisfies DSE

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

Persistent Challenge

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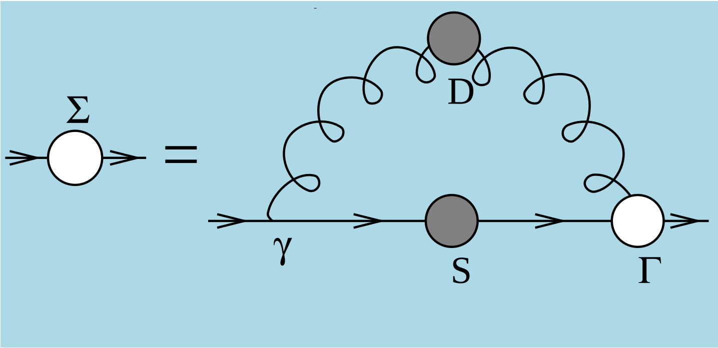
Persistent Challenge

- Infinitely Many Coupled Equations



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Persistent Challenge

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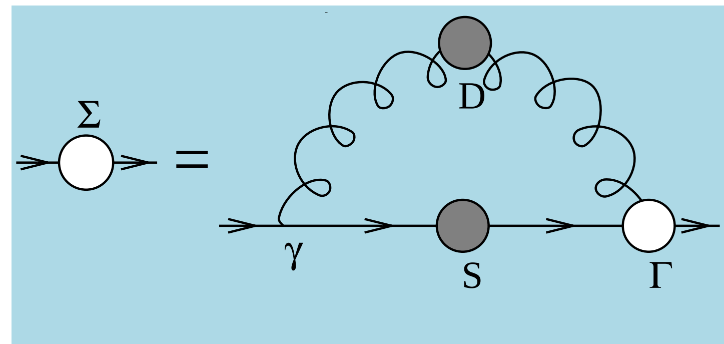

- Coupling between equations necessitates truncation

Persistent Challenge

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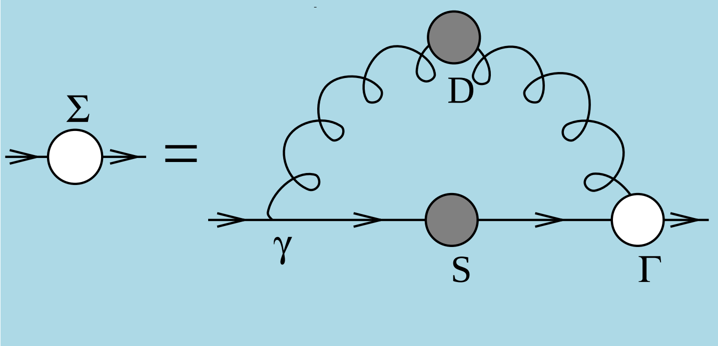

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Persistent Challenge

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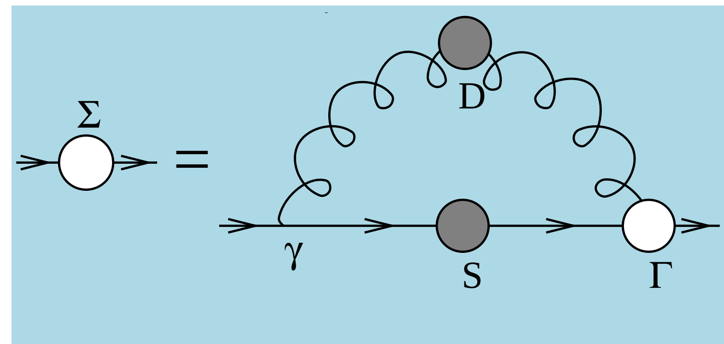

- Coupling between equations necessitates truncation
  - Weak coupling expansion $\Rightarrow$ Perturbation Theory
    Not useful for the nonperturbative problems
    in which we're interested

Persistent Challenge

- Infinitely Many Coupled Equations
- There is at least one systematic nonperturbative, symmetry-preserving truncation scheme
  H.J. Munczek Phys. Rev. D **52** (1995) 4736
  Dynamical chiral symmetry breaking, Goldstone's theorem and the consistency of the Schwinger-Dyson and Bethe-Salpeter Equations
  A. Bender, C. D. Roberts and L. von Smekal, Phys. Lett. B **380** (1996) 7
  Goldstone Theorem and Diquark Confinement Beyond Rainbow Ladder Approximation

Persistent Challenge

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  - Make Predictions with Readily Quantifiable Errors

Gap Equation
General Form

First Contents Back Conclusion

- Return to general bound-state problem . . .

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- To study the Poincaré covariant bound-state problem for mesons, one must first solve the gap equation

$$
\begin{aligned}
S_f(p)^{-1} &= Z_2\,(i\gamma\cdot p + m_f^{\rm bm}) + \Sigma_f(p)\,,\\
\Sigma_f(p) &= Z_1 \int_q^\Lambda g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S_f(q)\frac{\lambda^a}{2}\Gamma_\nu^f(q,p),
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\end{aligned}
$$

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

Bethe-Salpeter Equation
General Form

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- Pseudoscalar and axial-vector mesons appear as poles in the inhomogeneous Bethe-Salpeter equation.

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

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- $\Lambda^{fg}_{5\mu\beta}$ is defined completely via the dressed-quark self-energy and, owing to Poincaré covariance, one can employ, e.g., $q_\pm = q \pm P/2$, etc., without loss of generality

Ward-Takahashi Identity
Bethe-Salpeter Kernel

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Ward-Takahashi Identity
Bethe-Salpeter Kernel

- In any reliable study of light-quark hadrons, axial-vector vertex must satisfy

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P_\mu \Gamma^{fg}_{5\mu}(k;P) &= S_f^{-1}(k_+) i\gamma_5 + i\gamma_5 S_g^{-1}(k_-) \\
&\quad - i\left[m_f(\zeta) + m_g(\zeta)\right] \Gamma^{fg}_5(k;P)\,,
\end{aligned}
$$

expresses chiral symmetry & pattern by which it's broken

First Contents Back Conclusion

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expresses chiral symmetry & pattern by which it's broken

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

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

NECESSARY & SUFFICIENT

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NECESSARY & SUFFICIENT

to ensure Ward-Takahashi identity satisfied.

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

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

Bethe-Salpeter Kernel

Bethe-Salpeter Kernel
60 year problem

- Bethe-Salpeter equation introduced in 1951

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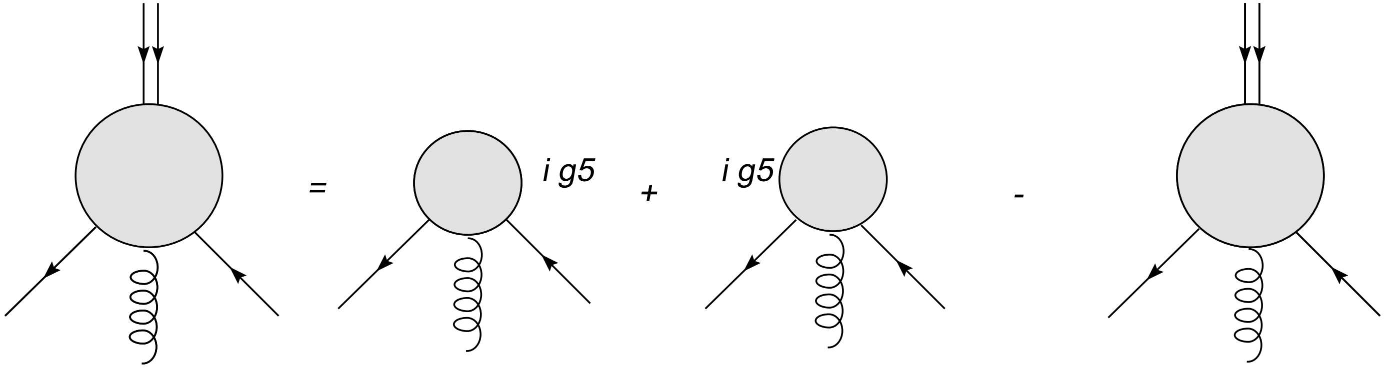

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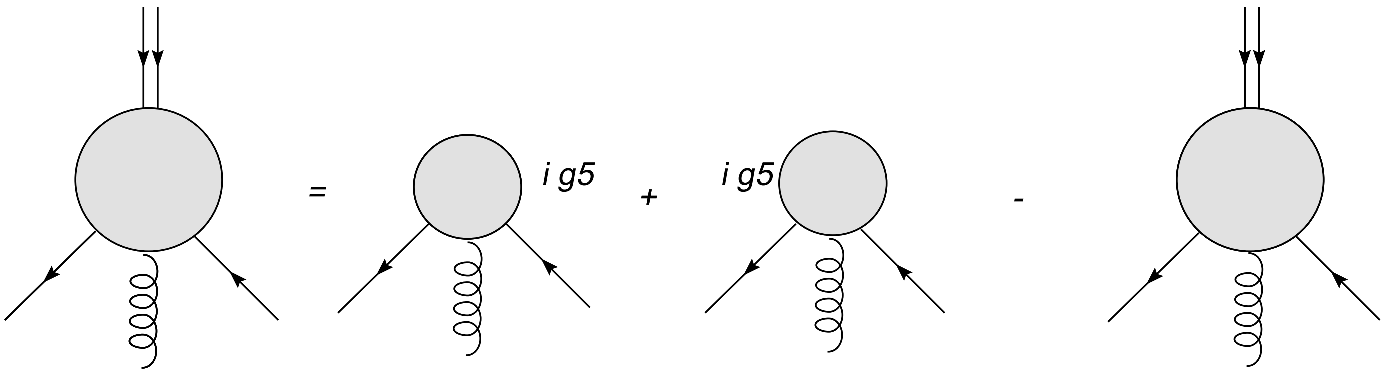

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- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
  - Consistent means - all symmetries preserved!

Bethe-Salpeter Kernel
60 year problem

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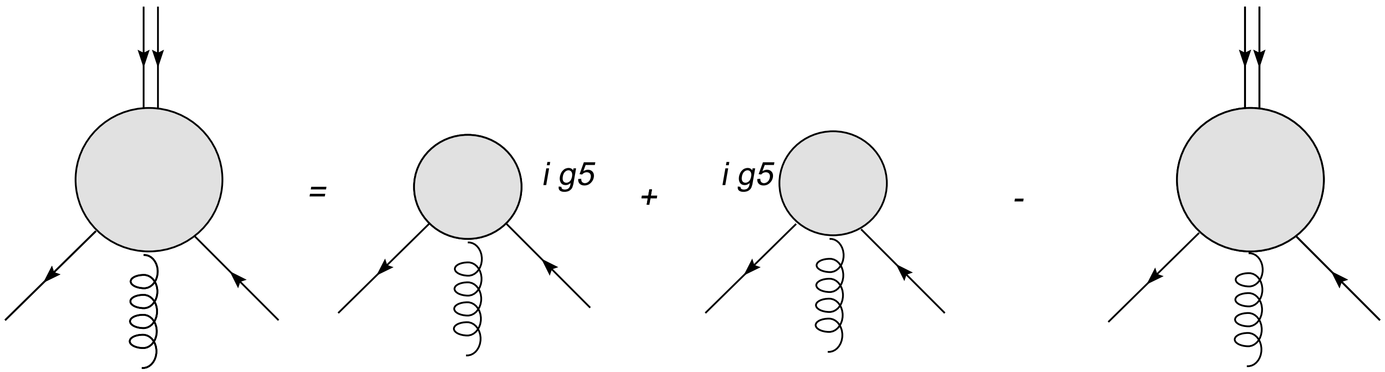

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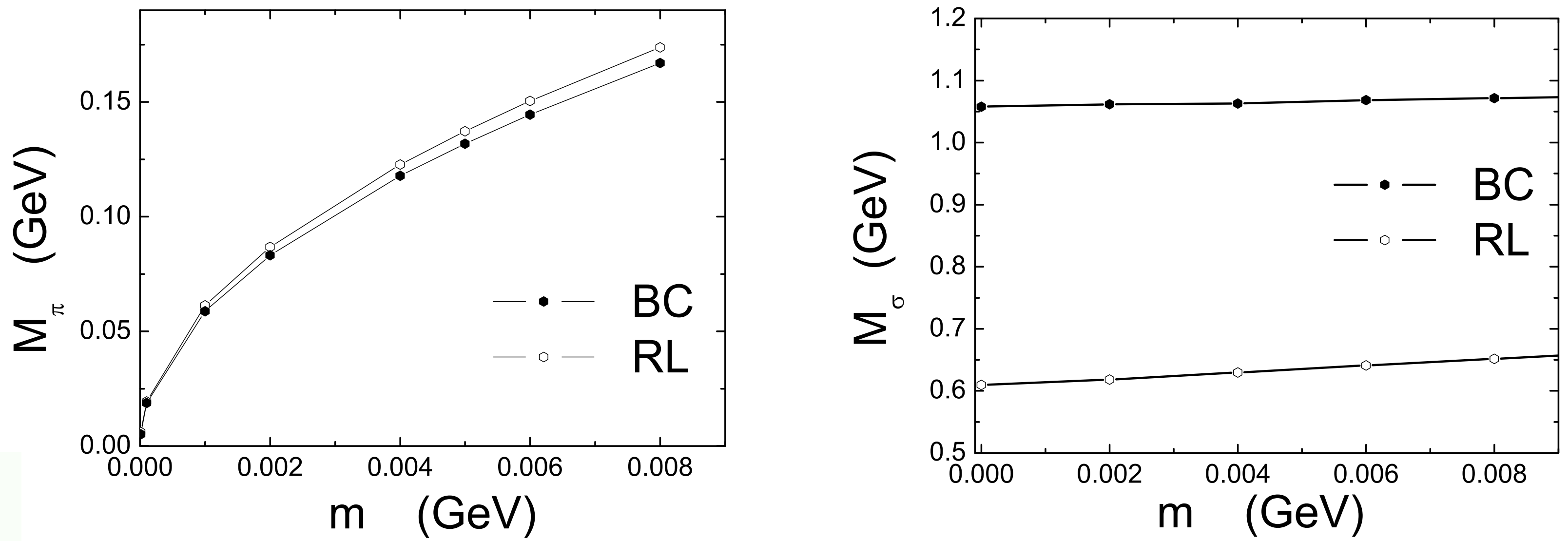
- For first time: can construct *Ansatz* for Bethe-Salpeter kernel consistent with any reasonable quark-gluon vertex
- Exemplified the procedure and results to expect . . .

Numerical Illustration

Chang Lei & CDR, arXiv:0903.5461 [nucl-th]



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Numerical Illustration

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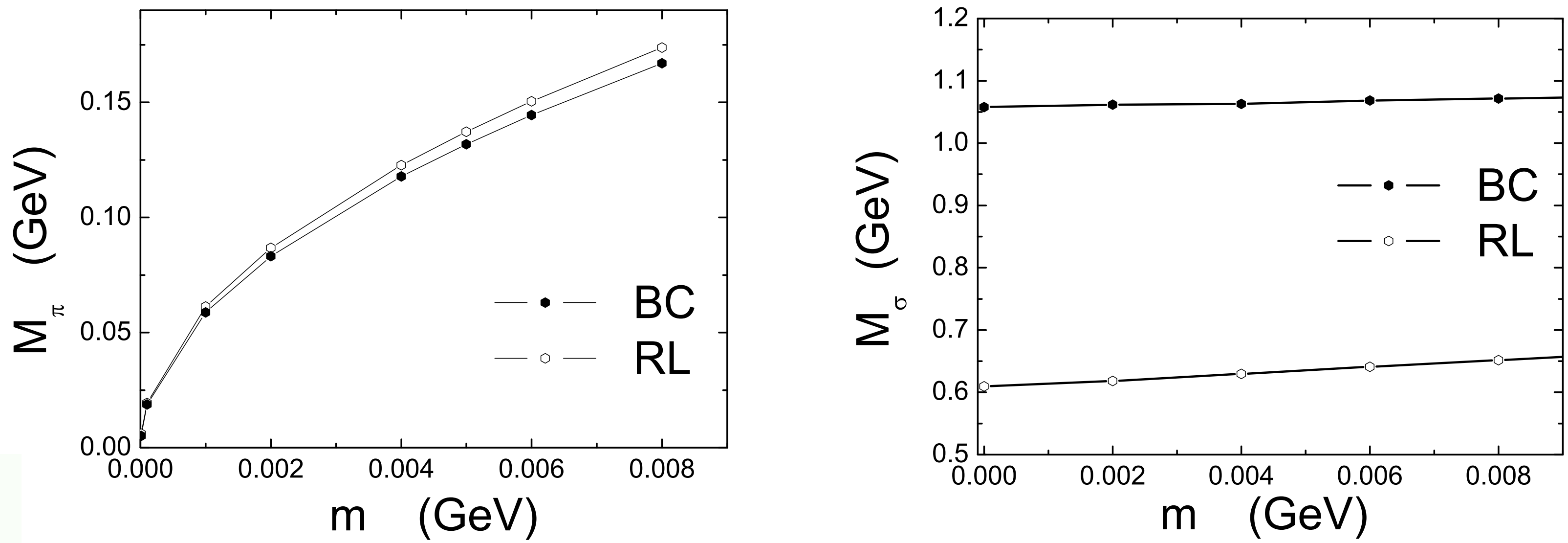

- Single interaction, common mass scale: rainbow-ladder cf. BC-consistent truncation

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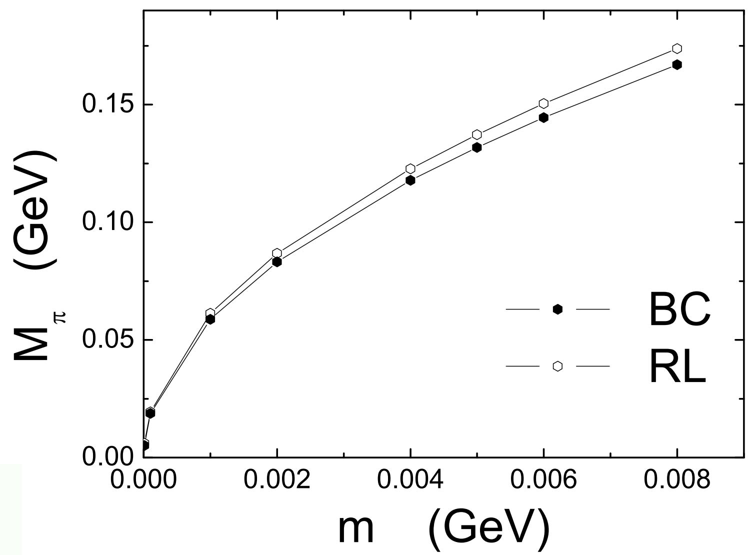
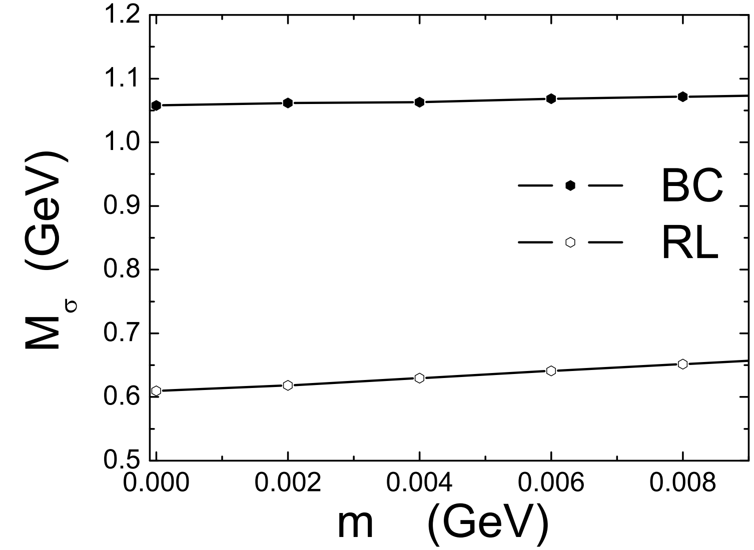
Numerical Illustration





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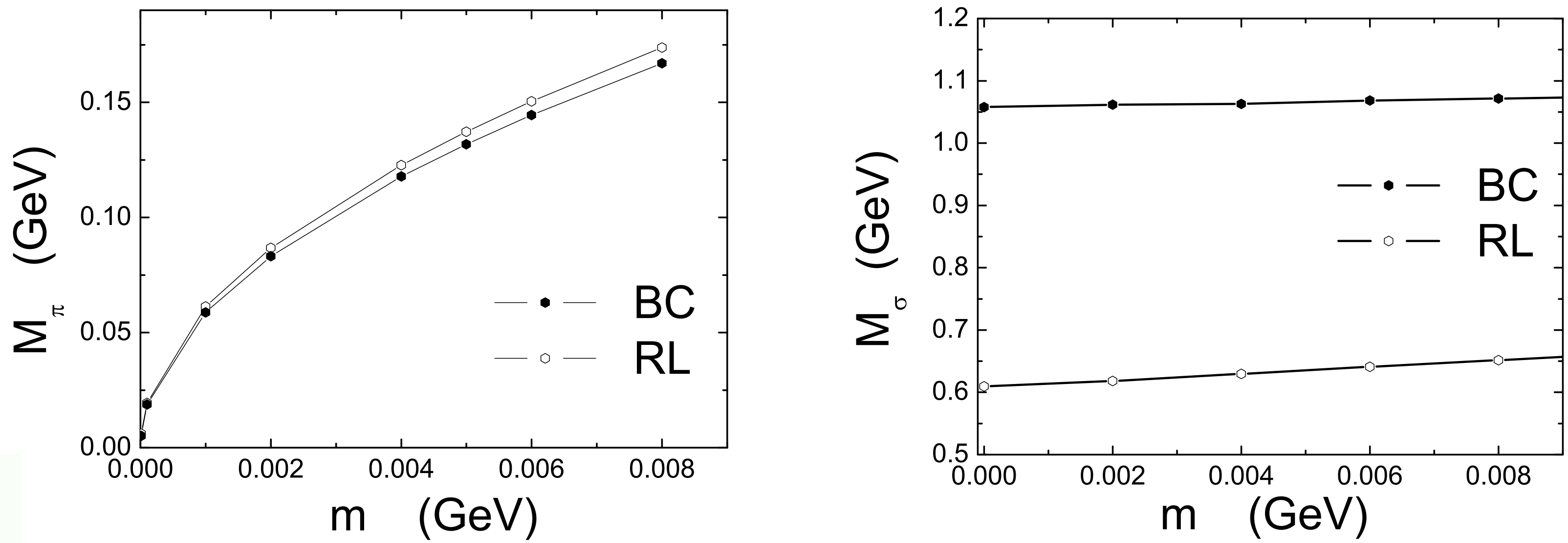

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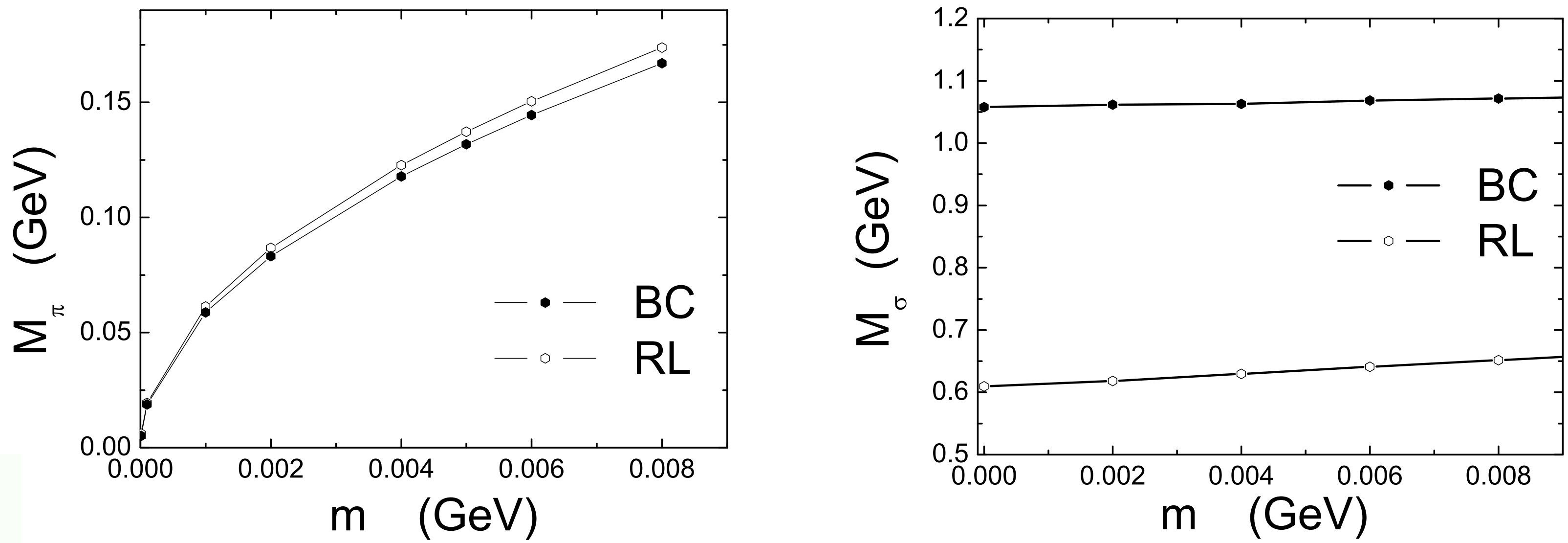

- Single interaction, common mass scale: rainbow-ladder cf. BC-consistent truncation
  - GMOR . . . plainly satisfied by both truncations
  - Added attraction in pseudoscalar channel
  - Added repulsion in scalar channel

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Spin-orbit Interaction

Chang Lei & CDR, arXiv:0903.5461 [nucl-th]

- Rainbow-ladder DSE truncation,
$$\varepsilon_\sigma^{\rm RL} := \left.\frac{2M(0) - m_\sigma}{2M(0)}\right|_{\rm RL} = (0.3 \pm 0.1)\,.$$
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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

Spin-orbit Interaction

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- Scalar mesons $= {}^3P_0$ states: Constituents' spins aligned and one unit of constituent orbital angular momentum
- Clear sign that in a Poincaré covariant treatment the BC-consistent truncation magnifies spin-orbit splitting. 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

Spin-orbit Interaction

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- Expect this feature to have material impact on mesons with mass greater than 1 GeV.

  prima facie ... can overcome longstanding shortcoming of RL truncation; viz., splitting between vector & axial-vector mesons is too small

Spin-orbit Interaction

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- Clear sign that in a Poincaré covariant treatment the BC-consistent truncation magnifies spin-orbit splitting.
- Expect this feature to have material impact on mesons with mass greater than 1 GeV.
- Promise of realistic meson spectroscopy
  First time, also for mass > 1 GeV

$a_1 - \rho$ mass splitting

$a_1 - \rho$ mass splitting

- Solve 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"
    S.V. Wright, *et al*., Few Body Syst. **40** (2007) 209, nucl-th/0701009

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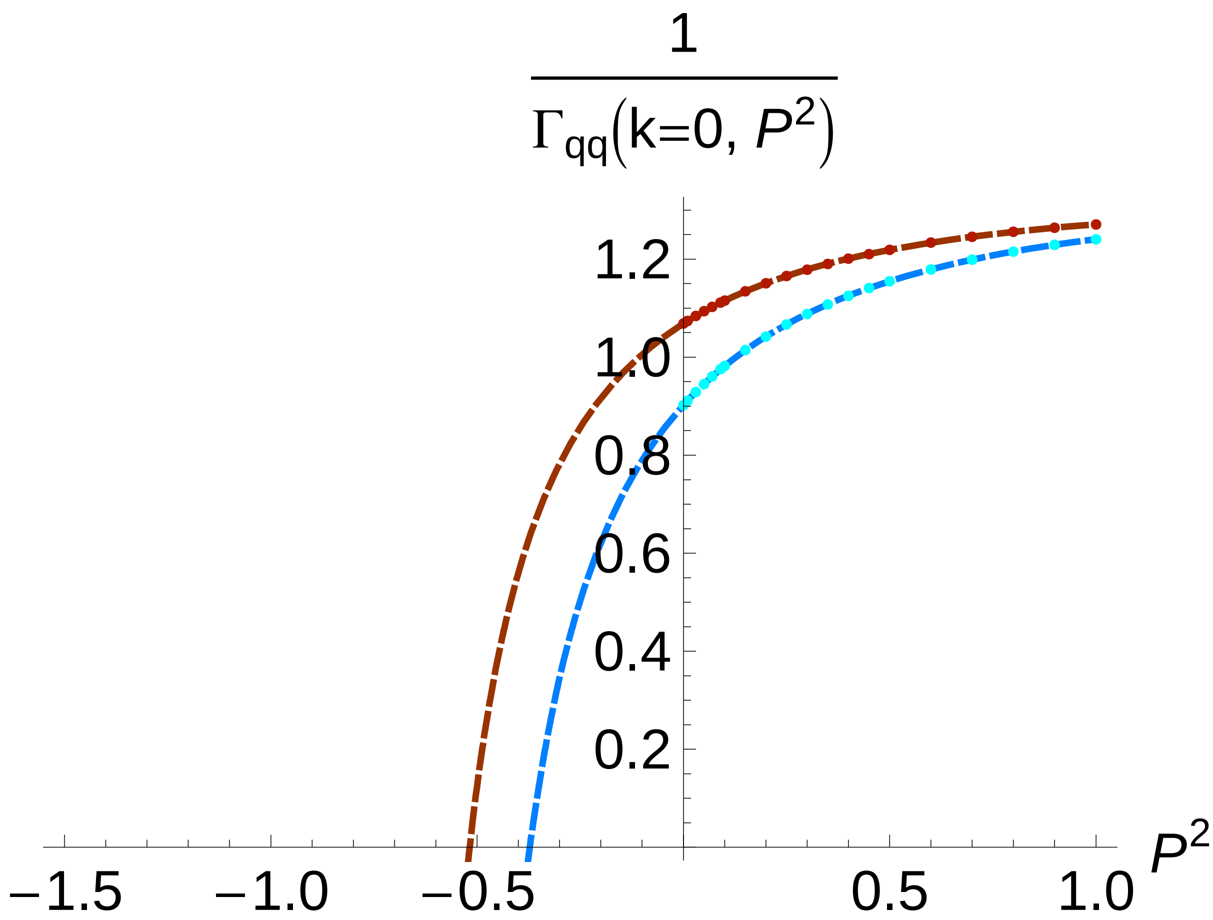
$a_1 - \rho$ mass splitting



Chang Lei & CDR, in-preparation

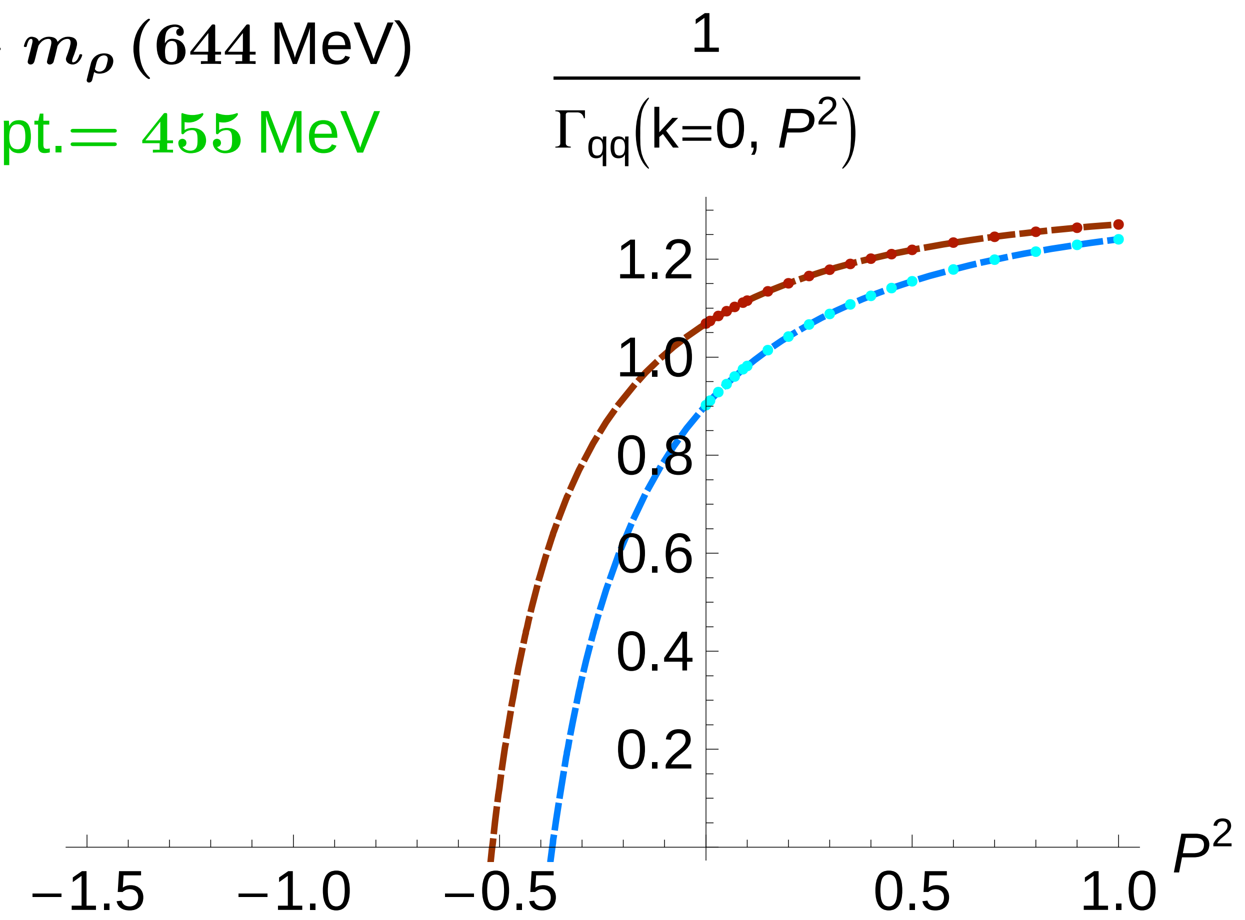
$a_1 - \rho$ mass splitting

$m_{a_1}\,(759\,\text{MeV}) - m_\rho\,(644\,\text{MeV})$

$= 115\,\text{MeV}$ . . . expt.$= 455\,\text{MeV}$

Rainbow-Ladder

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



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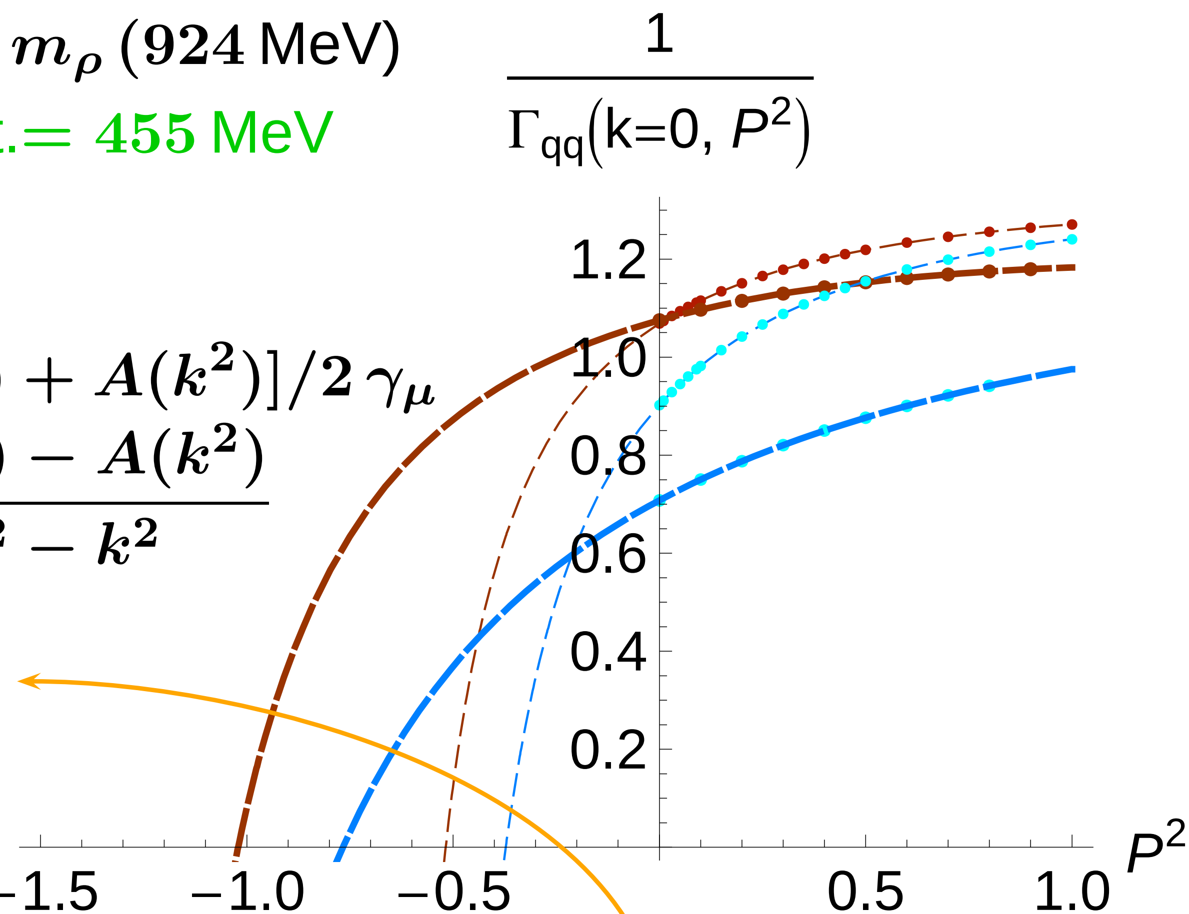
$a_1 - \rho$ mass splitting

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



Ball-Chiu

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

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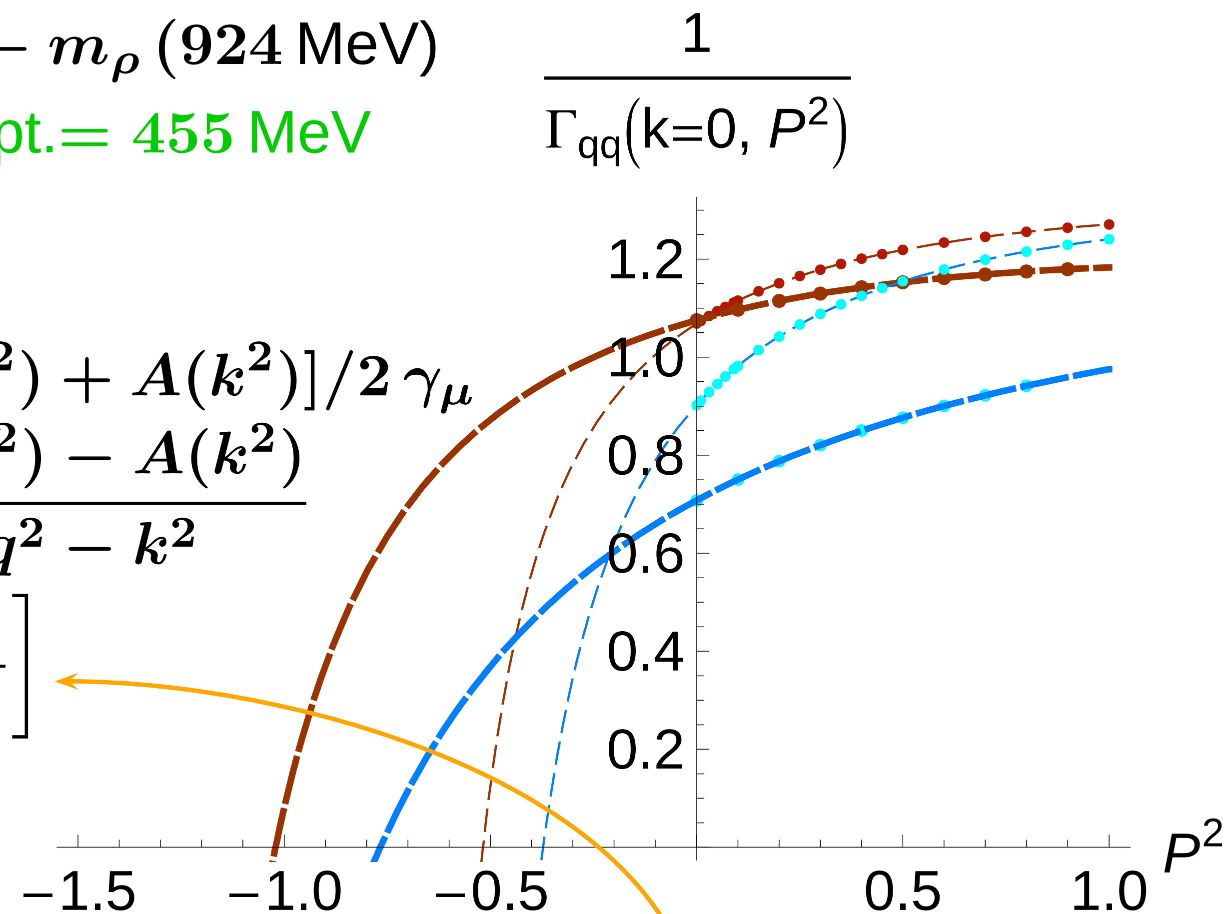

Ball-Chiu

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What's missing?

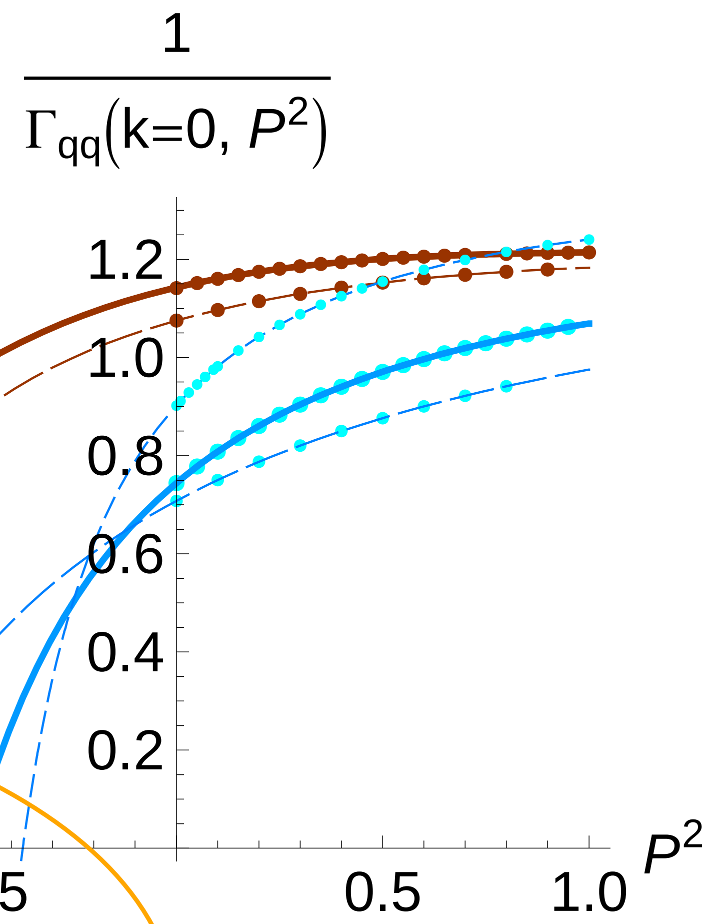
DCSB enhanced spin-orbit interaction

$a_1 - \rho$ mass splitting

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

Ball-Chiu + an. mag. mom.

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



DCSB enhanced spin-orbit interaction

DCSB enhanced anomalous magnetic moment

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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?

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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

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Faddeev equation

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

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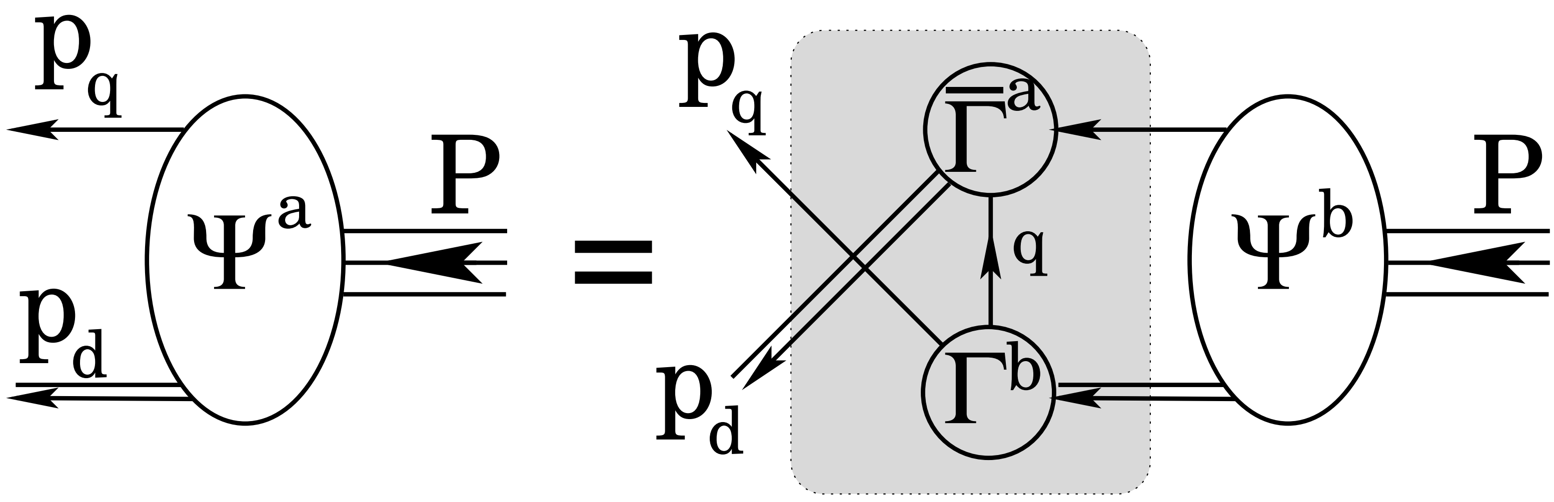
R. T. Cahill *et al*. Austral. J. Phys. **42** (1989) 129

Faddeev equation



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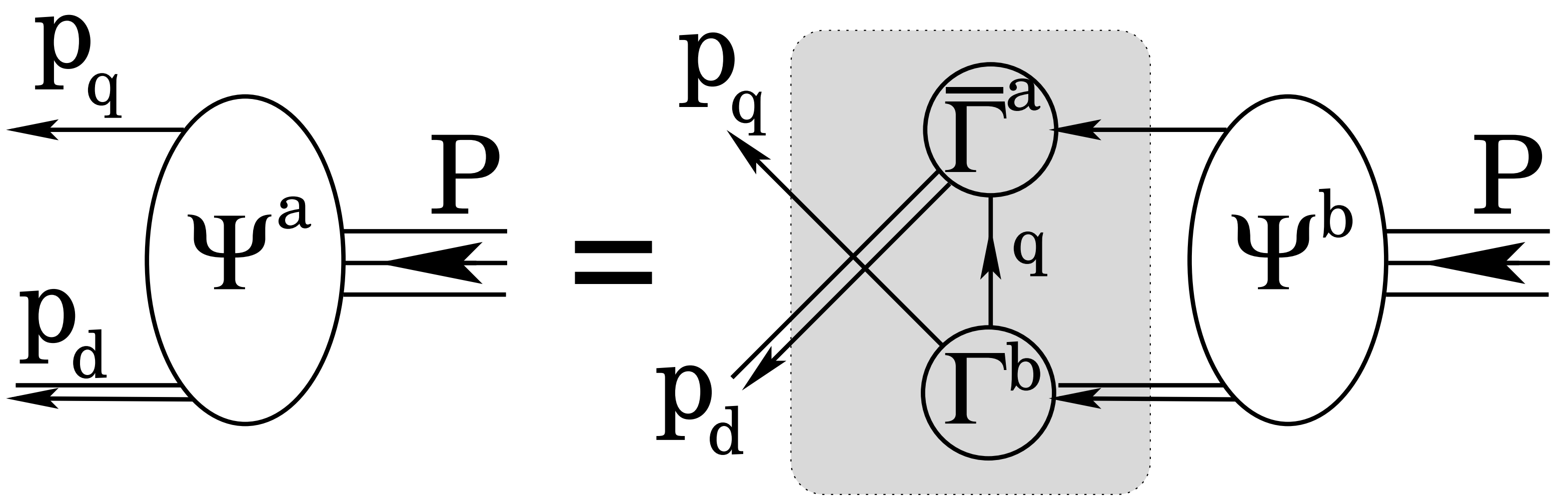
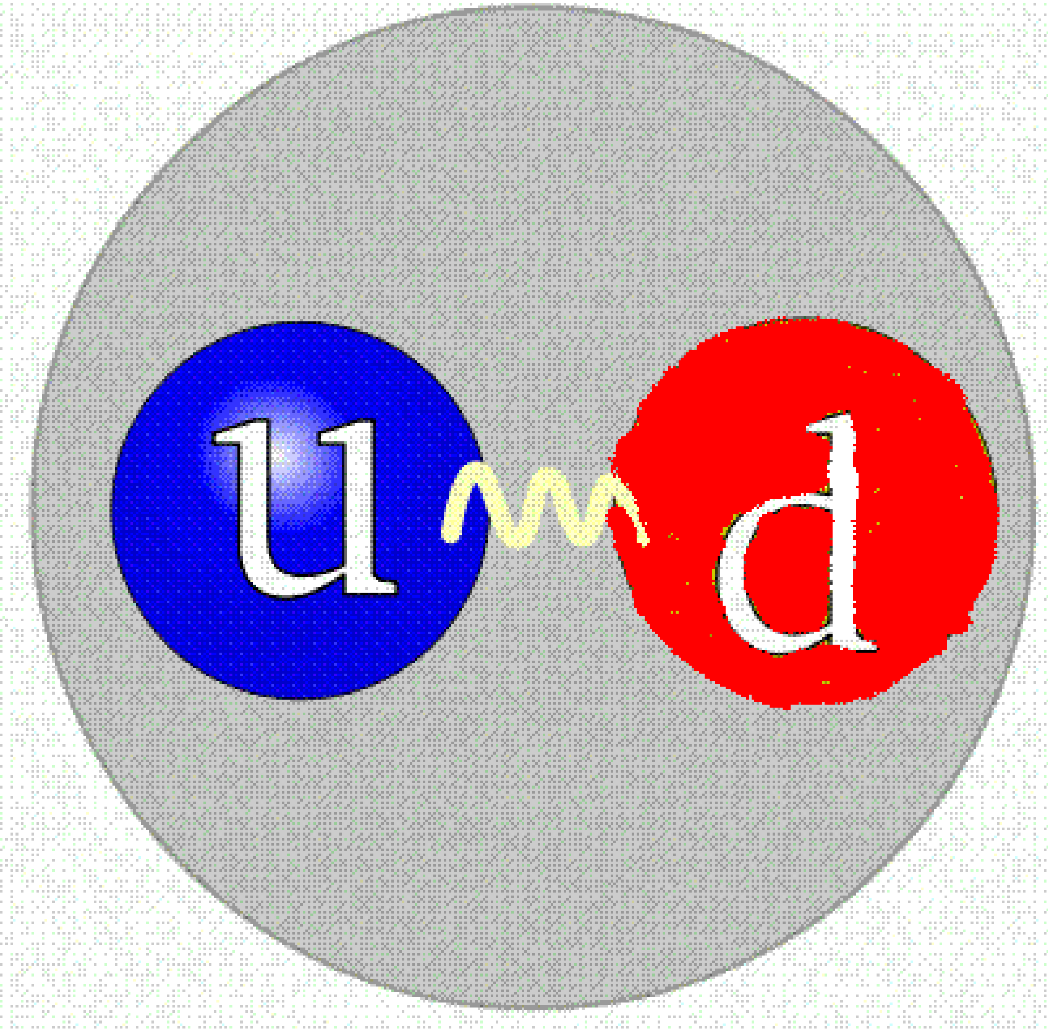


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Diquark correlations



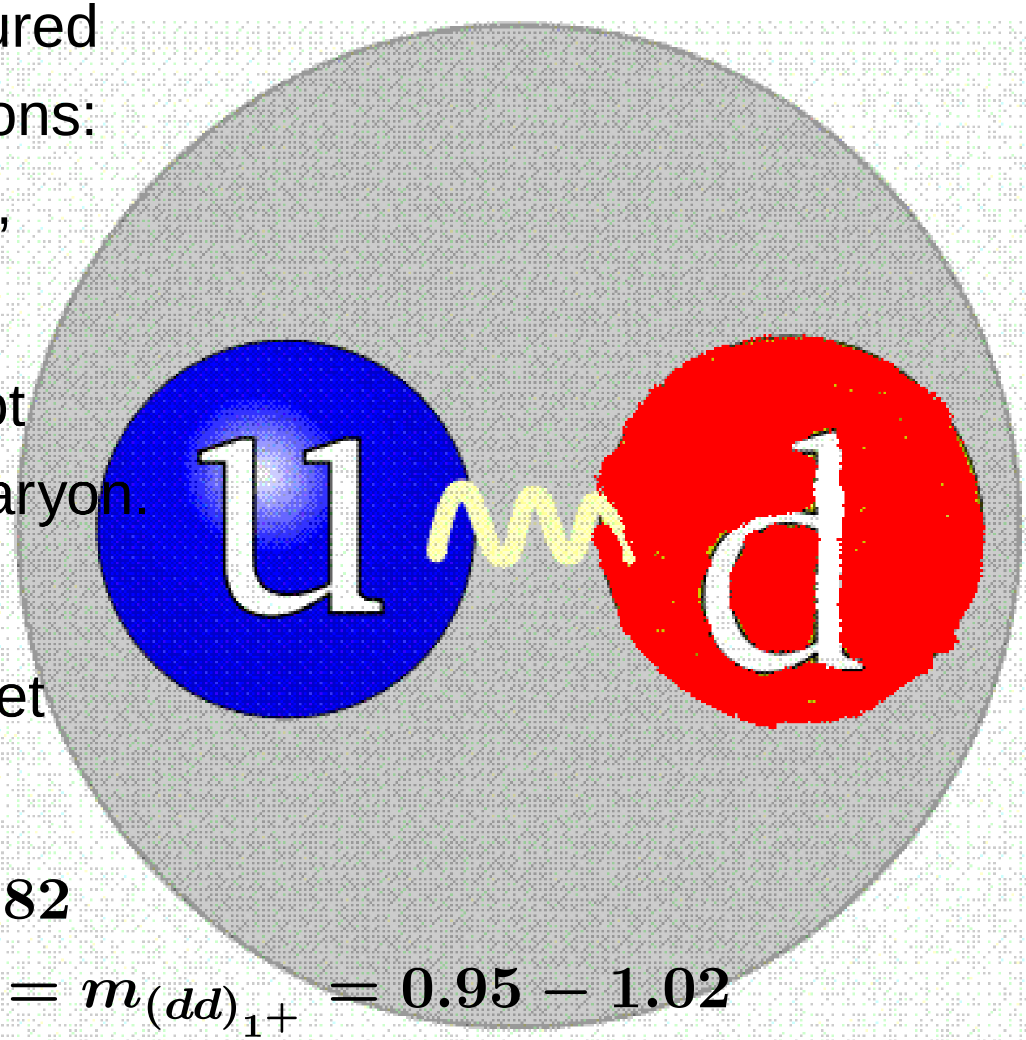
QUARK-QUARK

Diquark correlations

- Same interaction that describes mesons also generates three coloured quark-quark correlations: blue–red, blue–green, green–red
- Confined . . . Does not escape from within baryon.
- Scalar is isosinglet, Axial-vector is isotriplet
- DSE and lattice-QCD

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

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



QUARK-QUARK

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Nucleon-Photon Vertex

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M. Oettel, M. Pichowsky
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6 terms . . .

Nucleon-Photon Vertex

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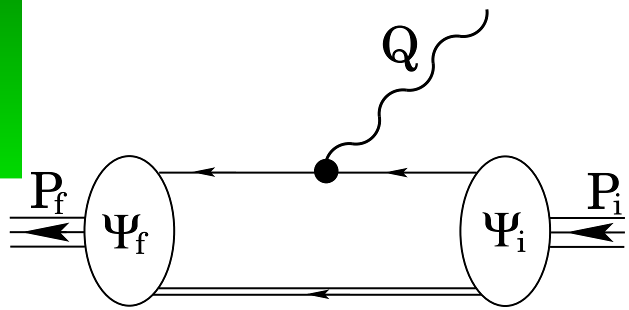

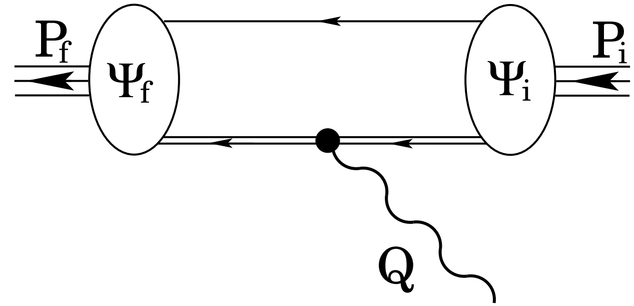

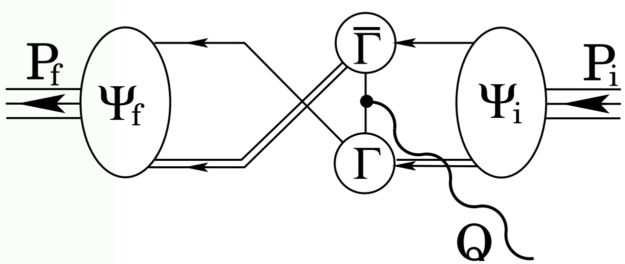

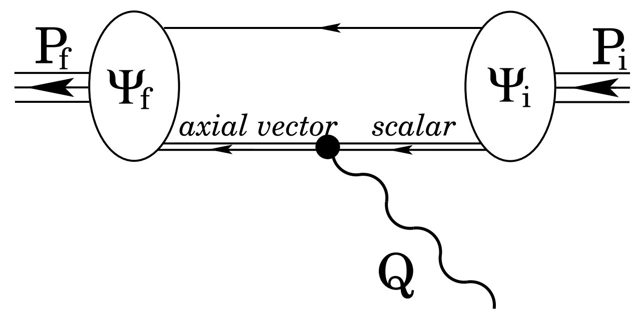

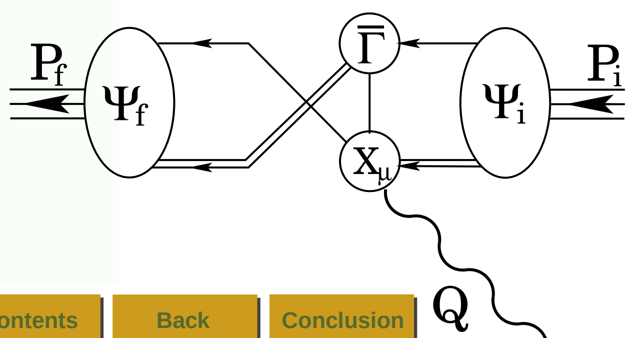

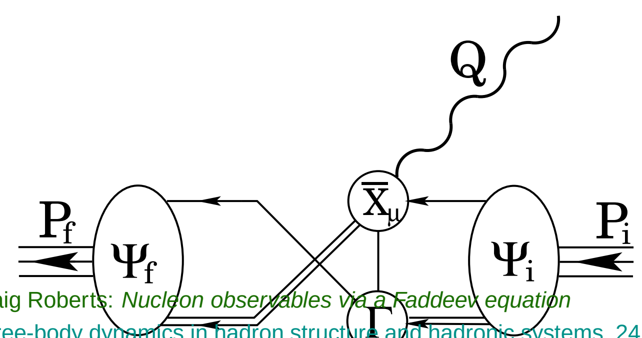

DSE-based Faddeev Equation

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Cloët *et al.*

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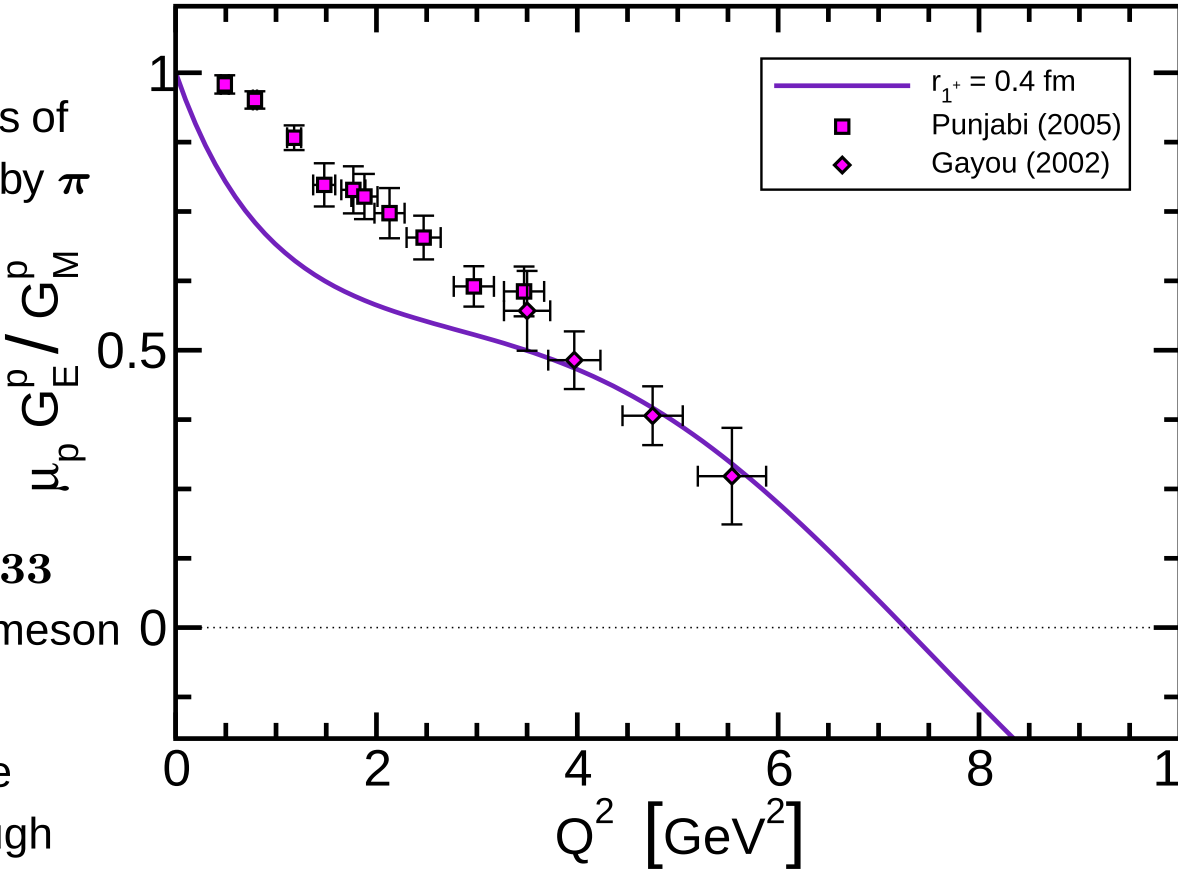

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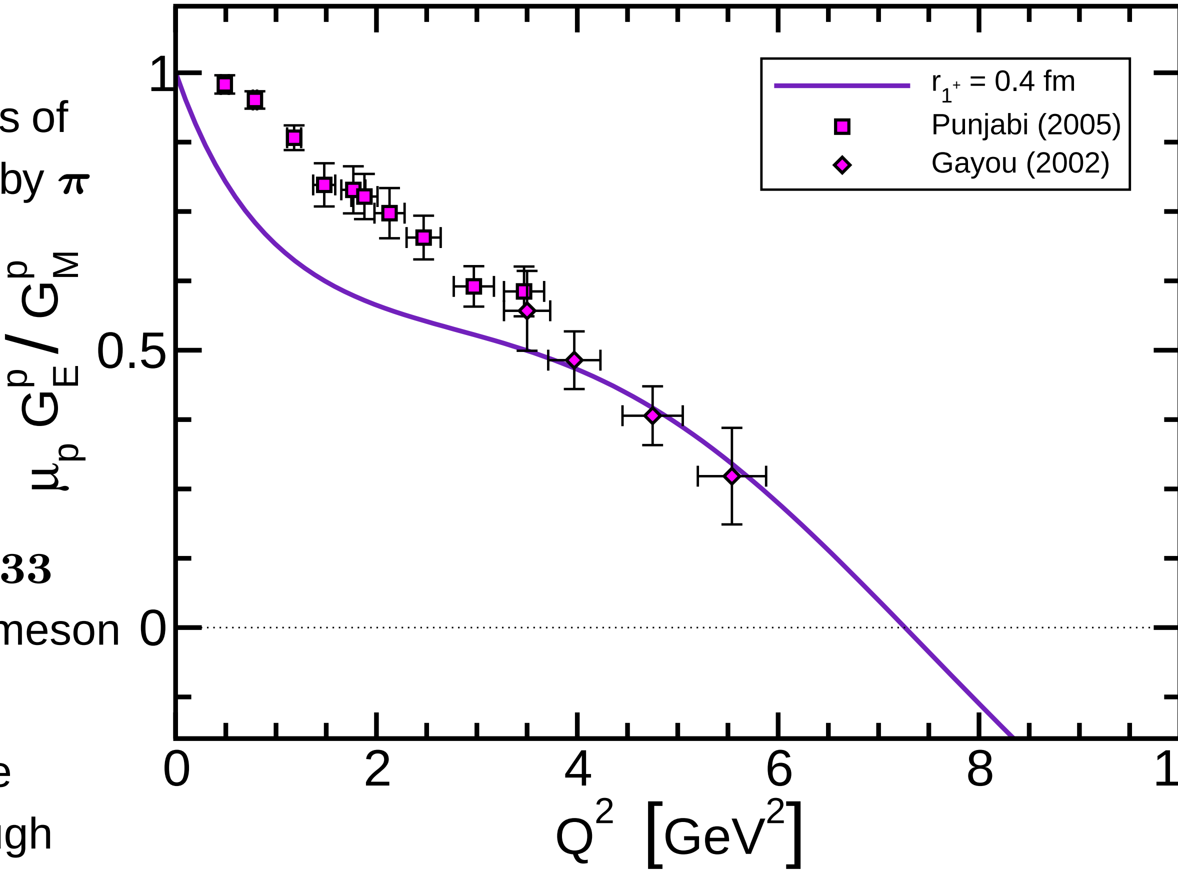

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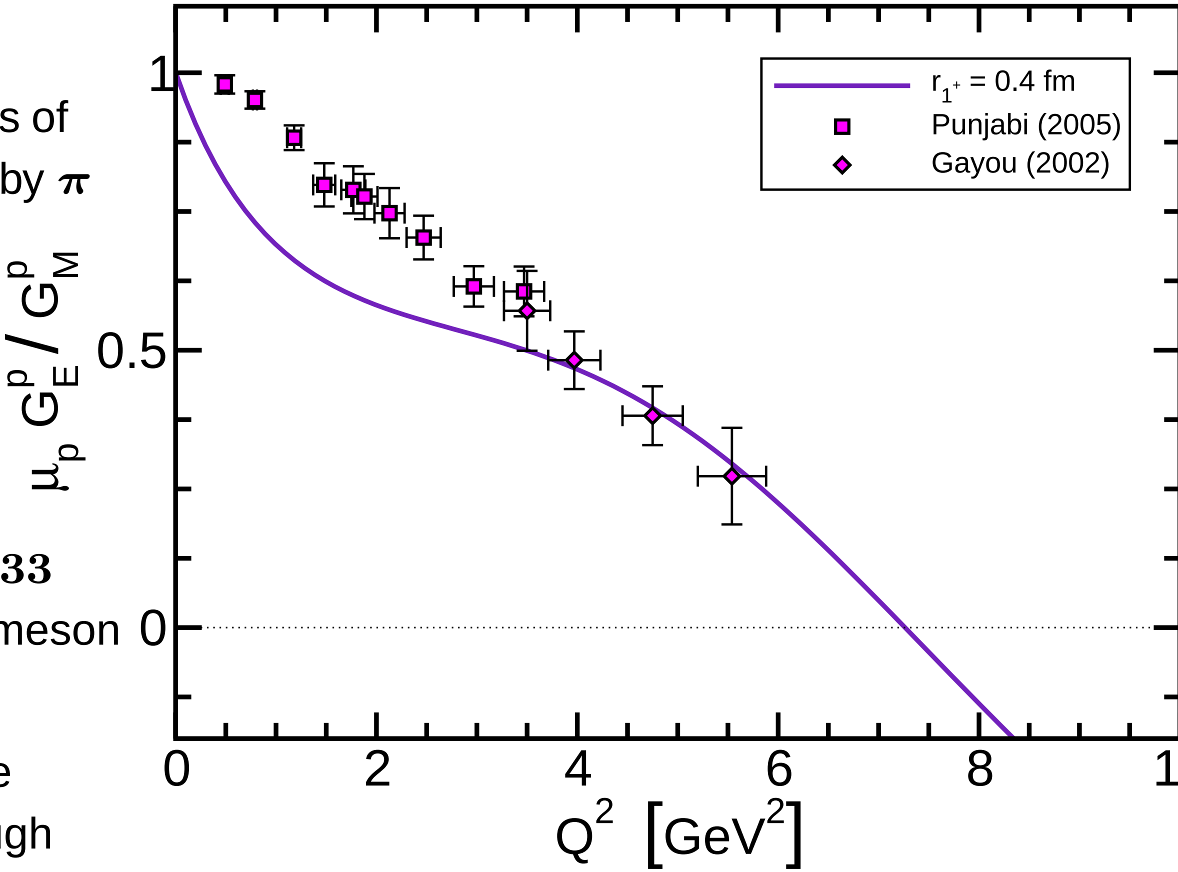

- On $Q^2 \lesssim 4$ GeV^2 result lies below experiment. This can be attributed to omission of pseudoscalar-meson-cloud contributions
- Always a zero but position depends on details of current

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

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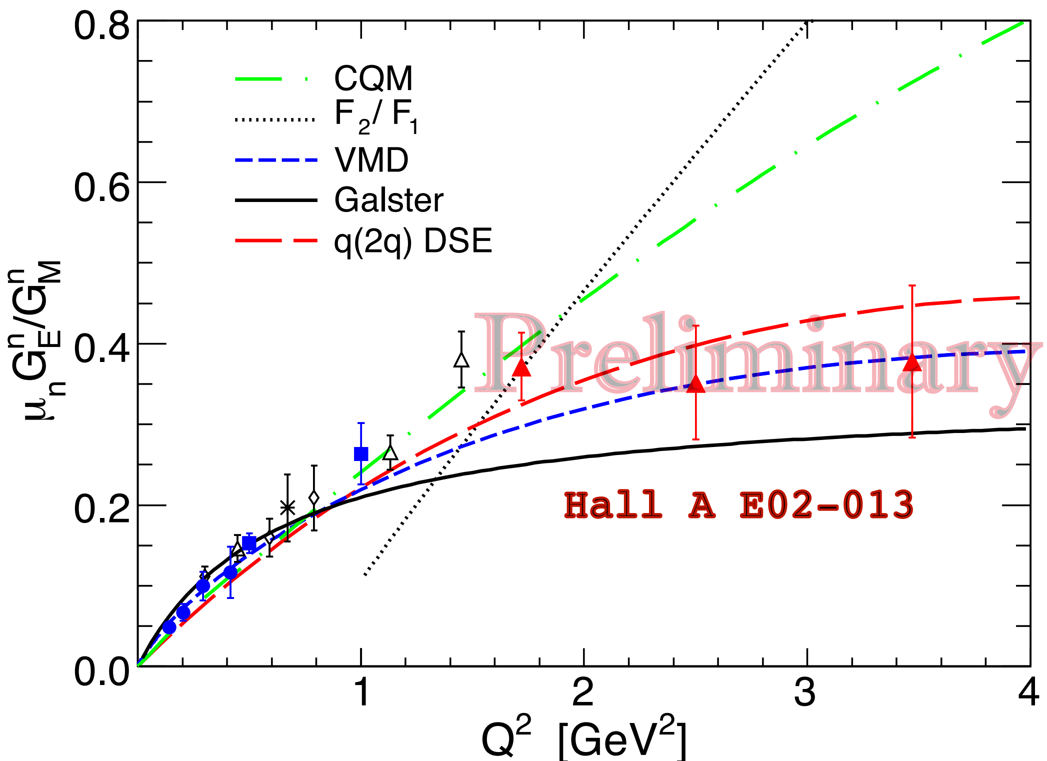

Jefferson Lab E02-013 Collaboration, *in preparation*.

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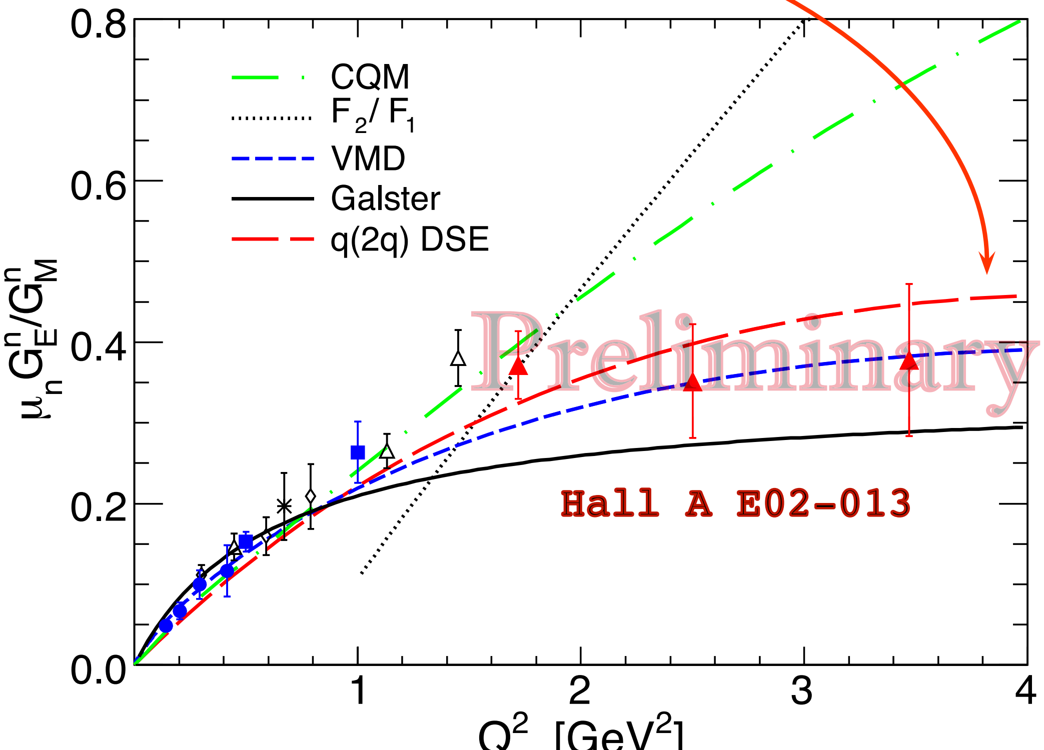
Red long-dashed curve



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Pion Cloud

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Pion Cloud
F2 – neutron

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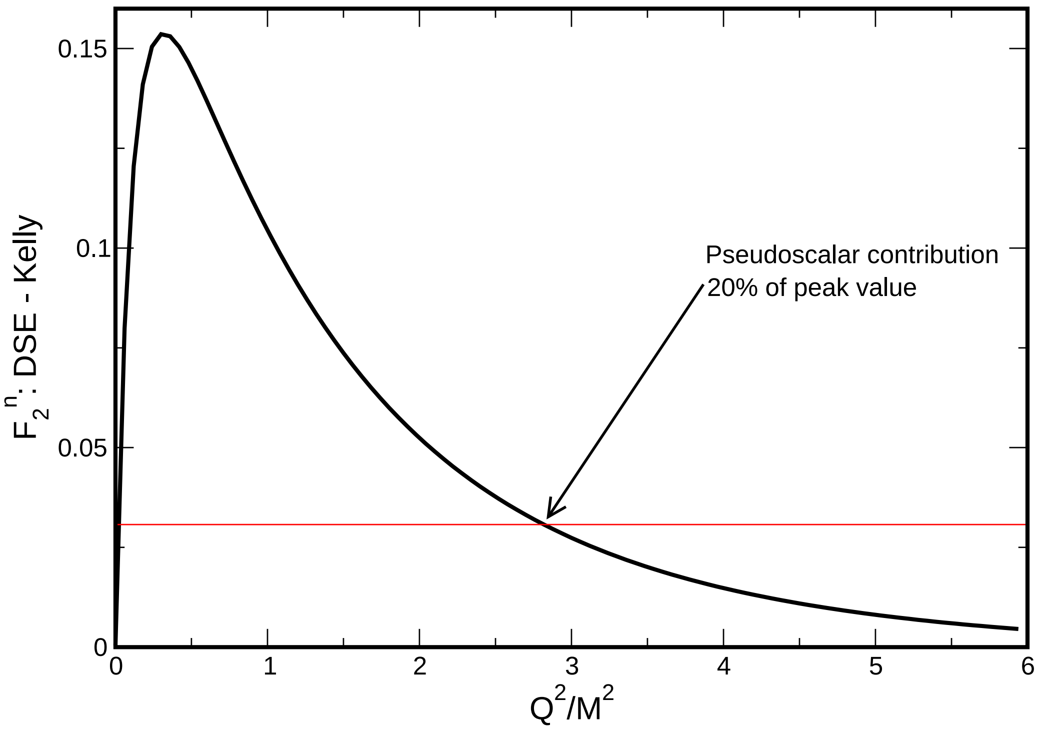

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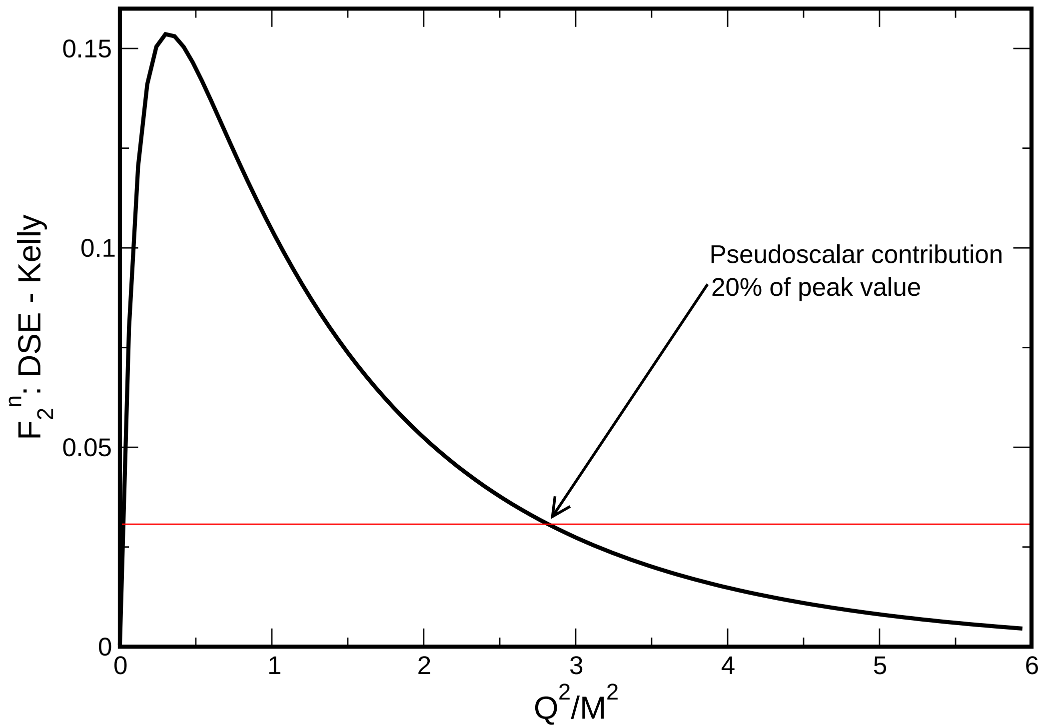
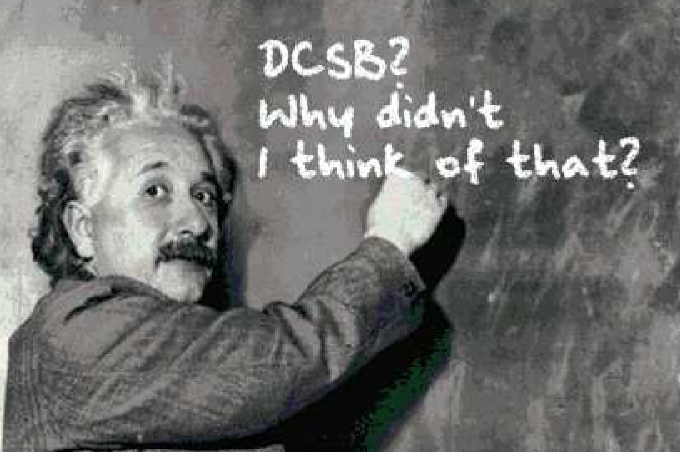


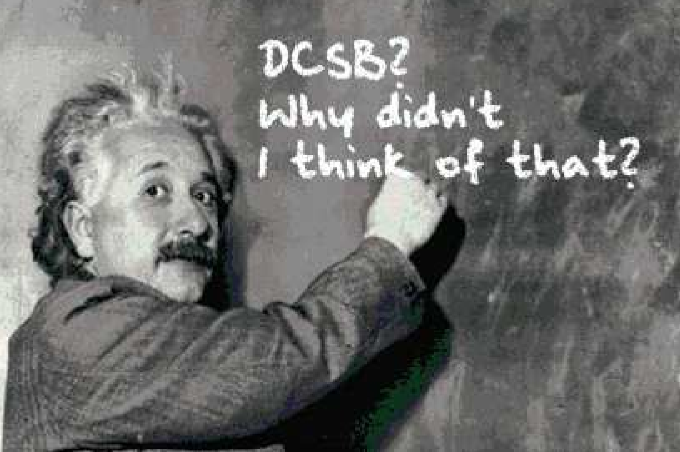
- Pseudoscalar meson cloud (and related effects) significant for $Q^2 \lesssim 3 - 4\, M_N^2$

Epilogue



Epilogue

- DCSB exists in QCD.



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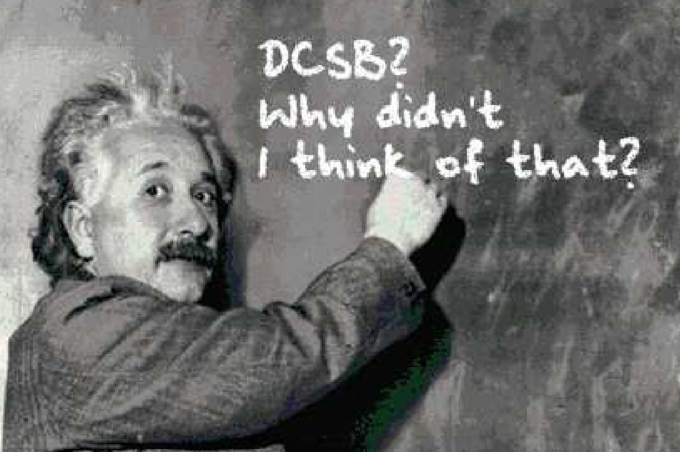

Epilogue

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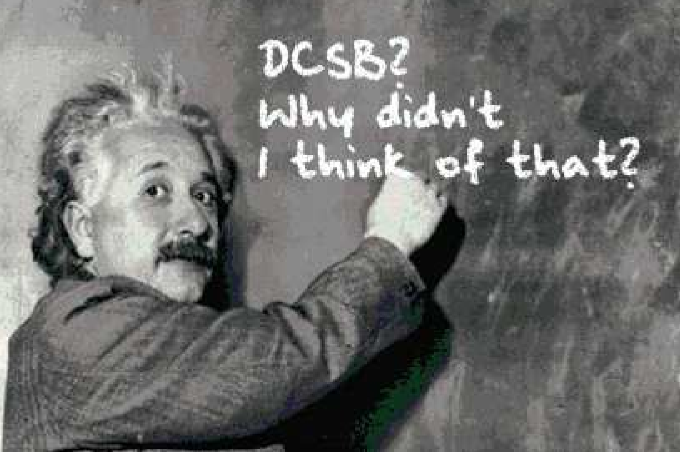
  - It predicts, amongst other things, that
    - light current-quarks become heavy constituent-quarks: $4 \rightarrow 400\,$MeV
    - pseudoscalar mesons are unnaturally light: $m_\rho = 770$ cf. $m_\pi = 140\,$MeV
    - pseudoscalar mesons couple unnaturally strongly to light-quarks: $g_{\pi\bar{q}q}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



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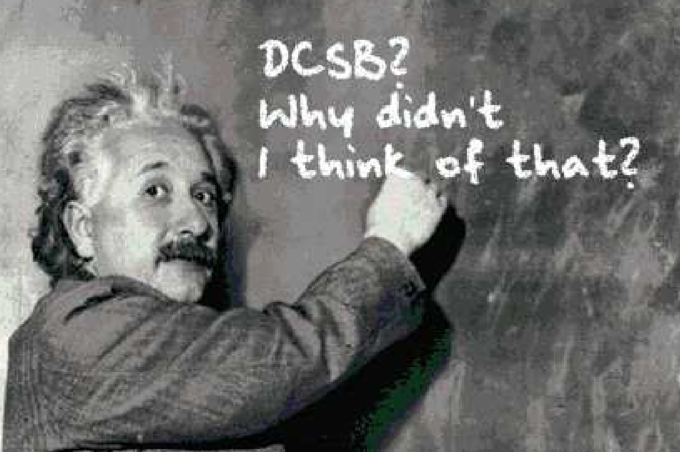
  - It impacts dramatically upon observables.



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- Dyson-Schwinger Equations
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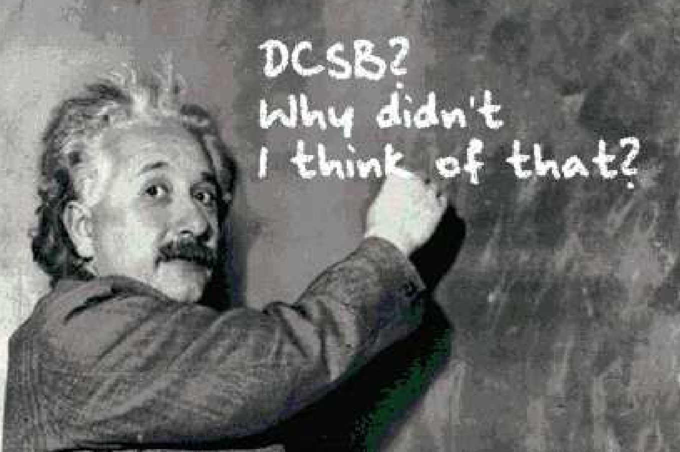

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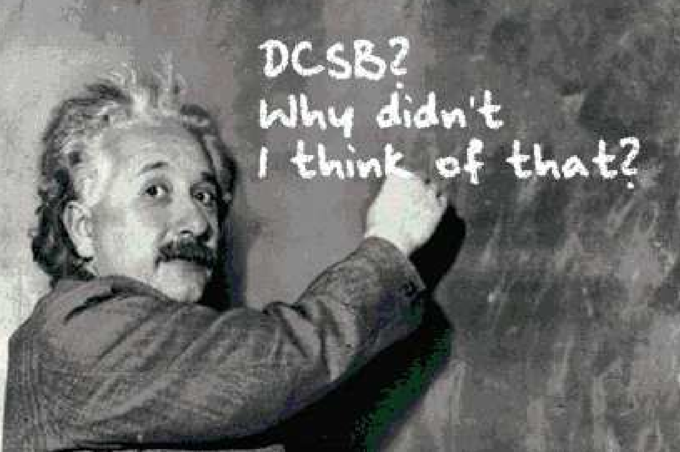

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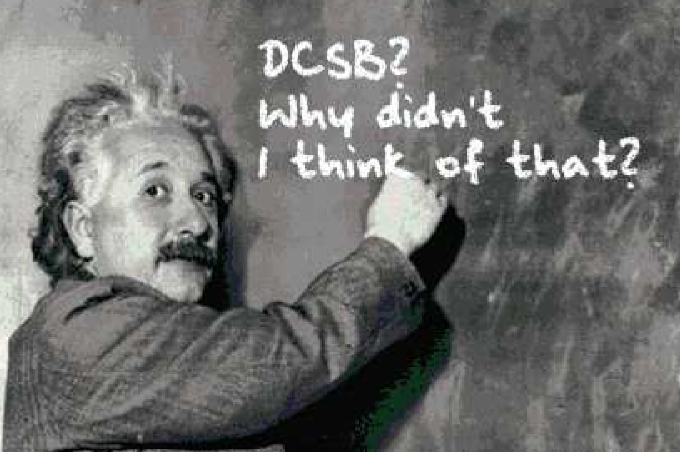
  - Solved a_1-ρ problem. Now positioned to provide first unified and reliable symmetry-preserving prediction of complete meson spectrum



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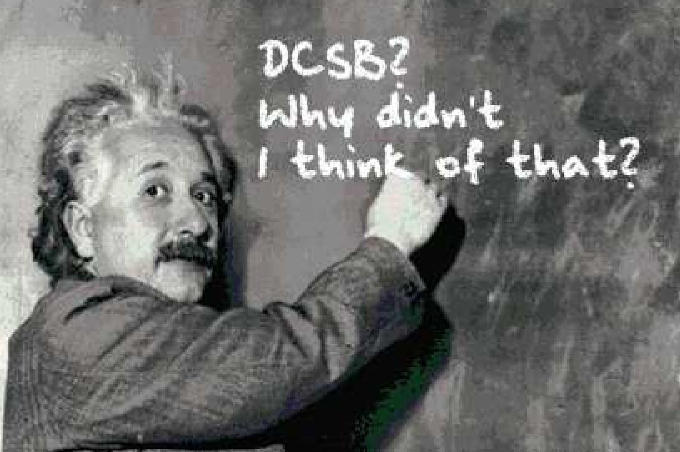

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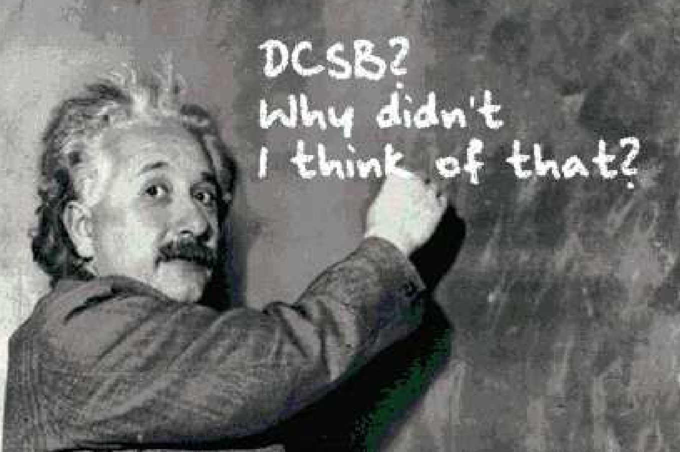

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- DSEs: Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks

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