Unified description of mesons and baryons

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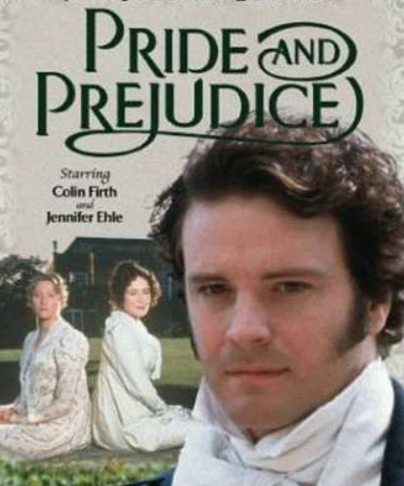
http://www.phy.anl.gov/theory/staff/cdr.html

Universal Truths



Universal Truths

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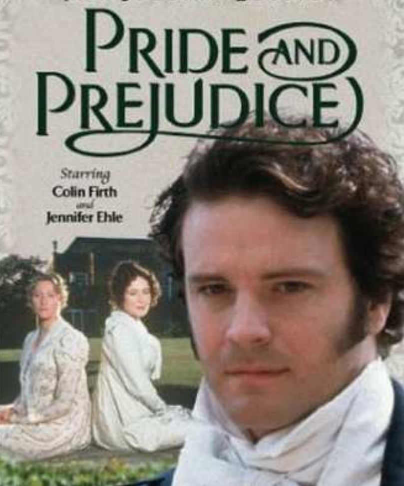

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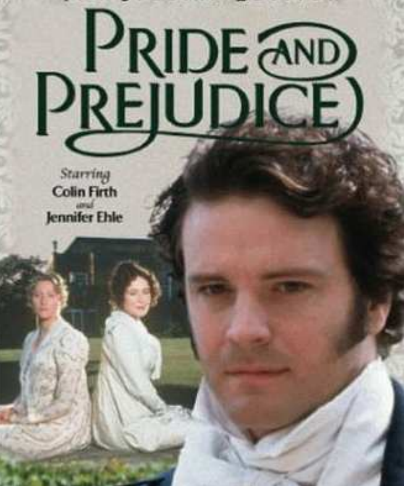

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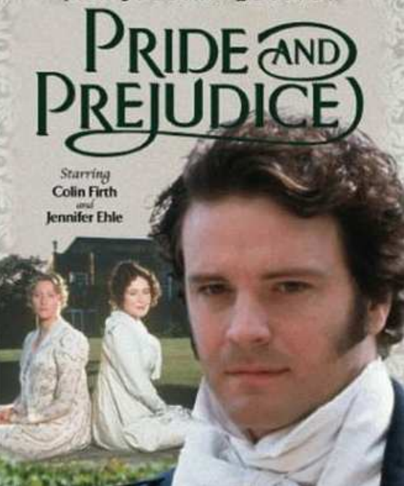

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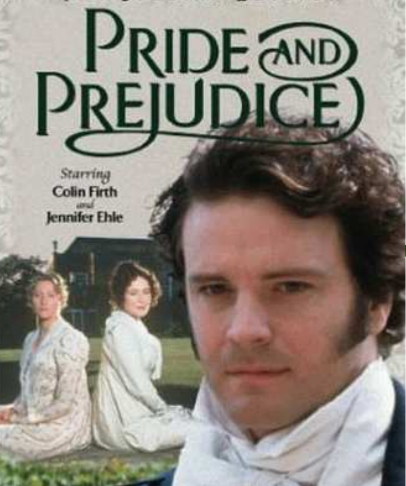

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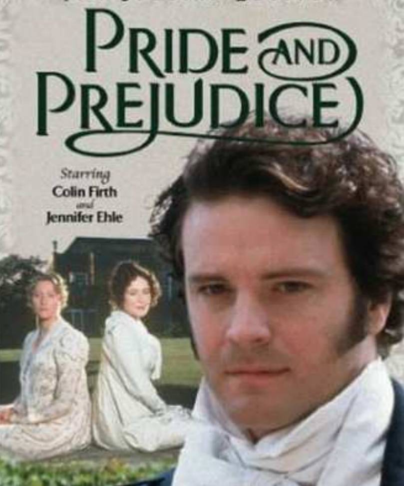

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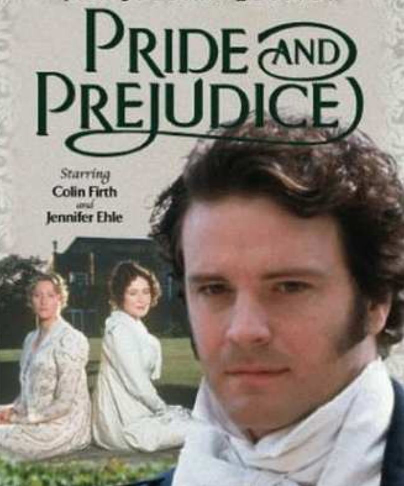

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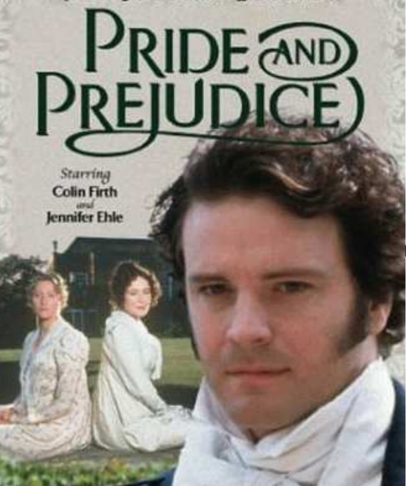

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- Dynamical Chiral Symmetry Breaking (DCSB) is most important mass generating mechanism for visible matter in the Universe. Higgs mechanism is irrelevant to light-quarks.
- Challenge: understand relationship between parton properties on the light-front 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.

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- QCD – Complex behaviour
  arises from apparently simple rules

Dichotomy of Pion
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Highly Nontrivial

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  - Interaction between quarks – the Interquark "Potential" – unknown throughout $> 98\%$ of a hadron's volume

Intranucleon Interaction

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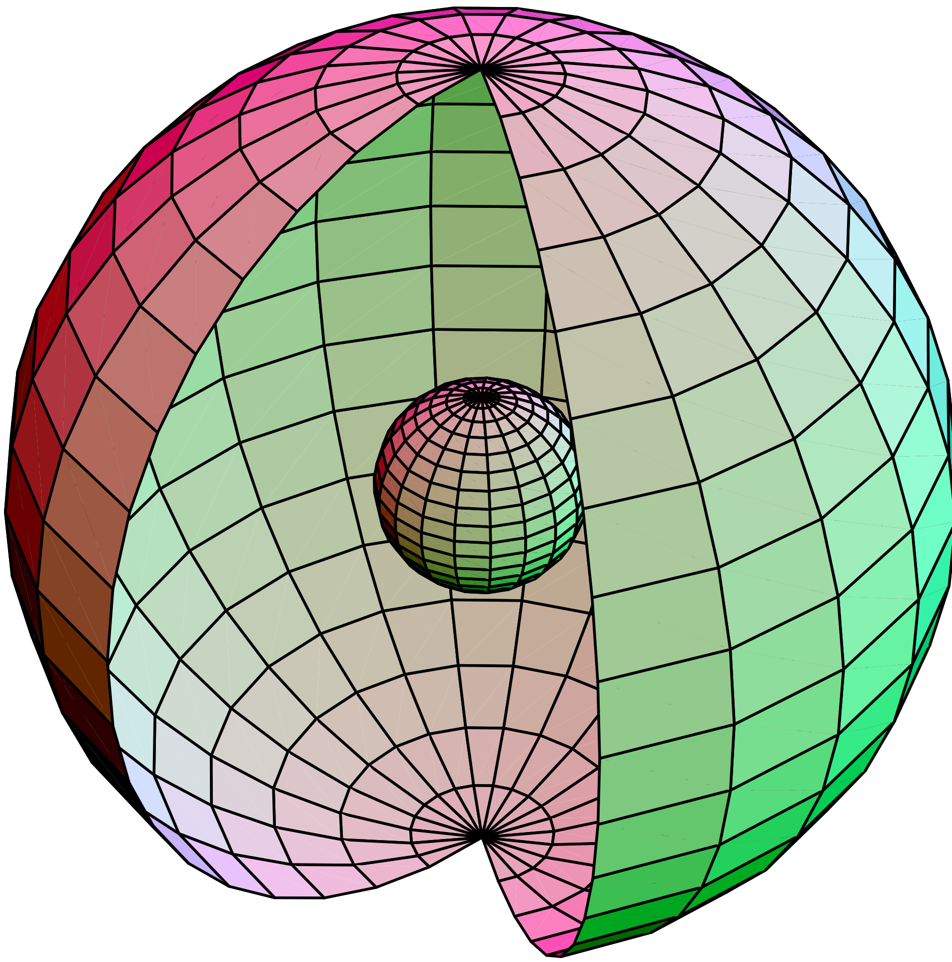

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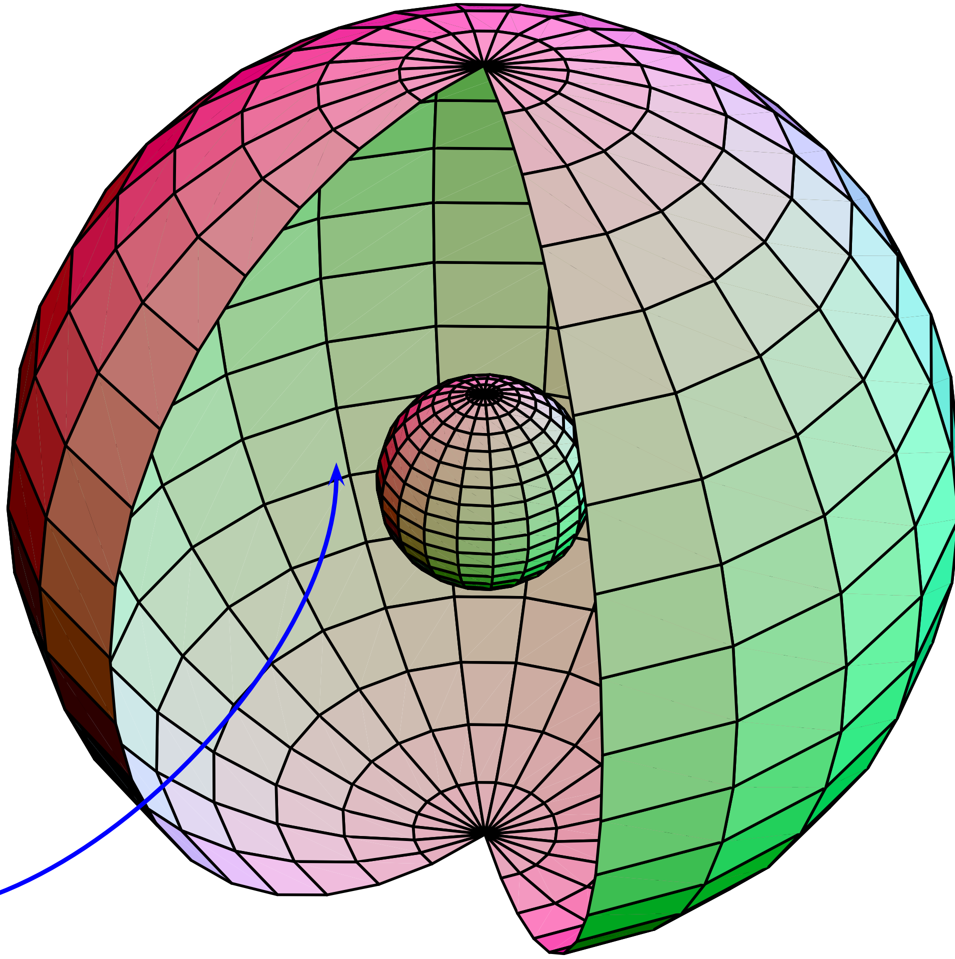
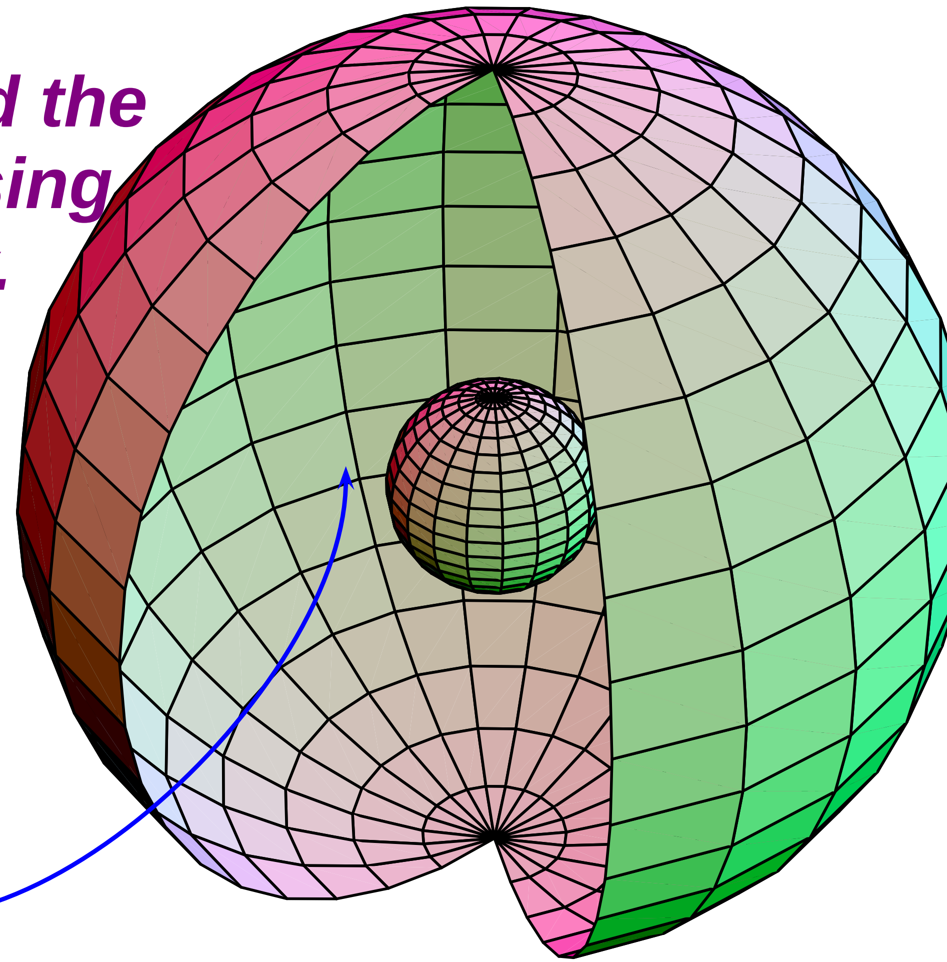


98% of the volume

What is the Intranucleon Interaction?

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



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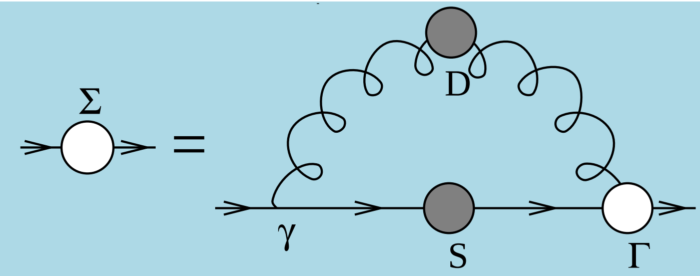

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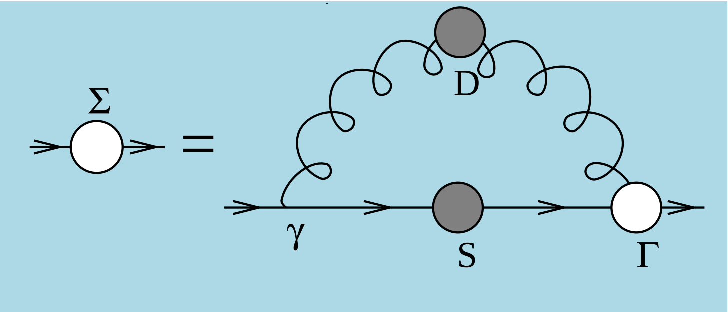
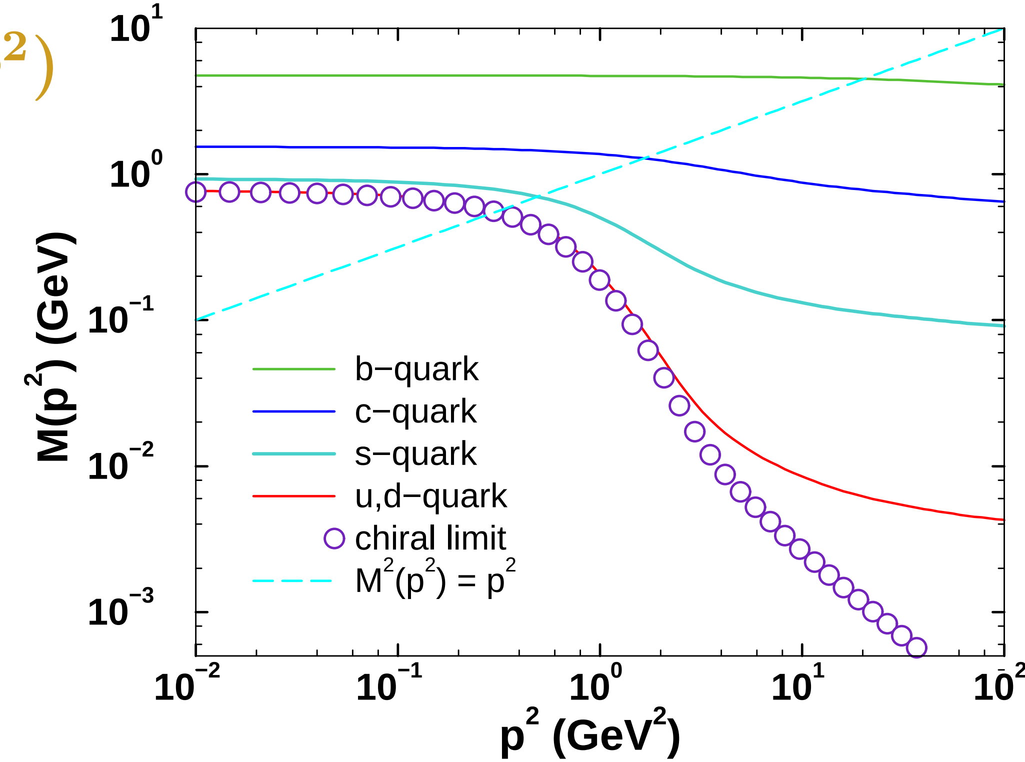


Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

$\Rightarrow$ IR Enhancement of $M(p^2)$



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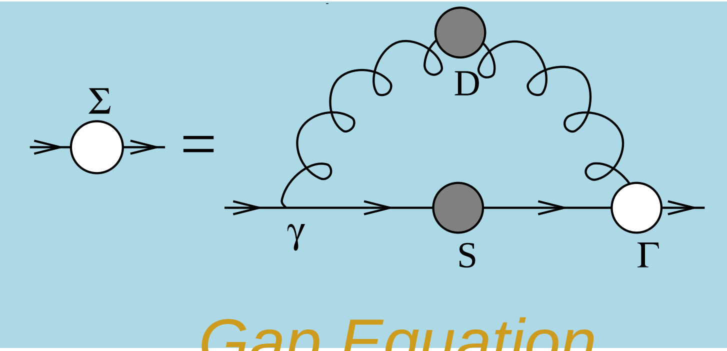

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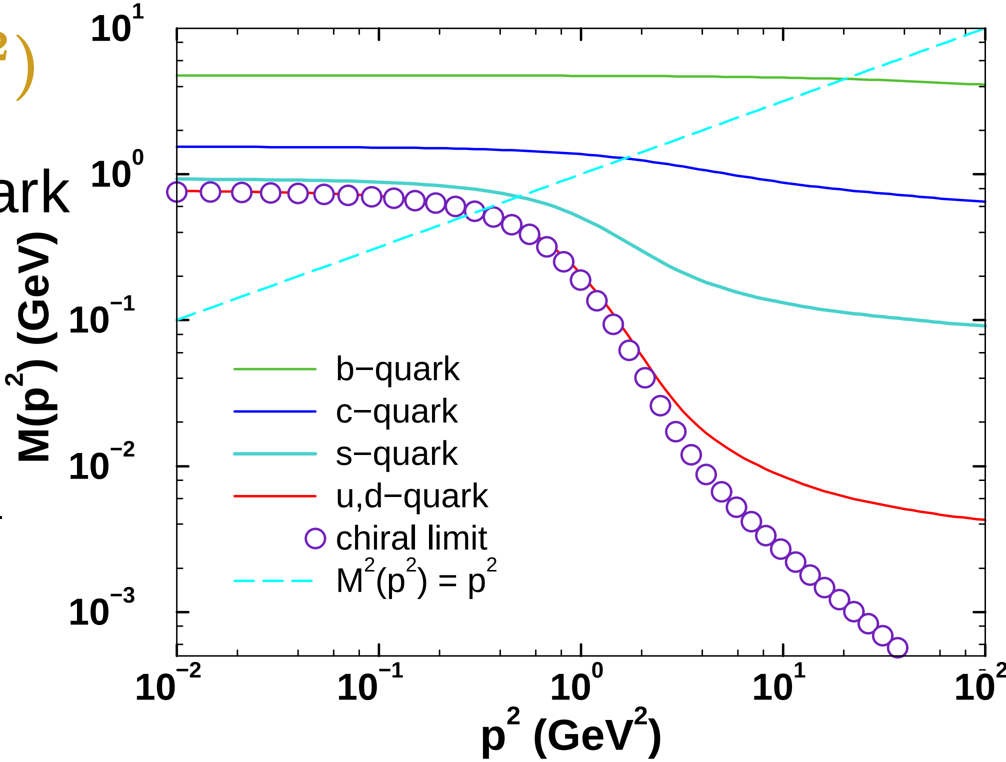
flavour	u/d	s	c	b
$\frac{M^E}{m_\zeta}$	$\sim 10^2$	~ 10	~ 1.5	~ 1.1



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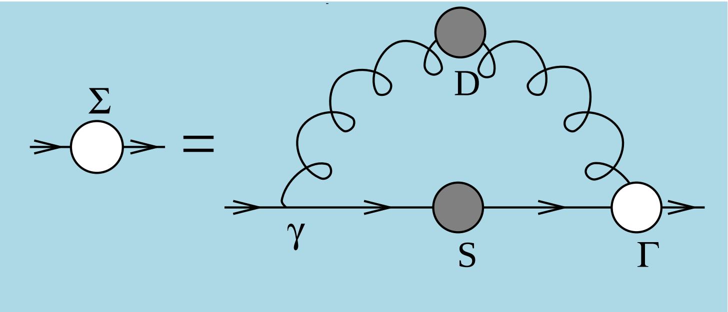

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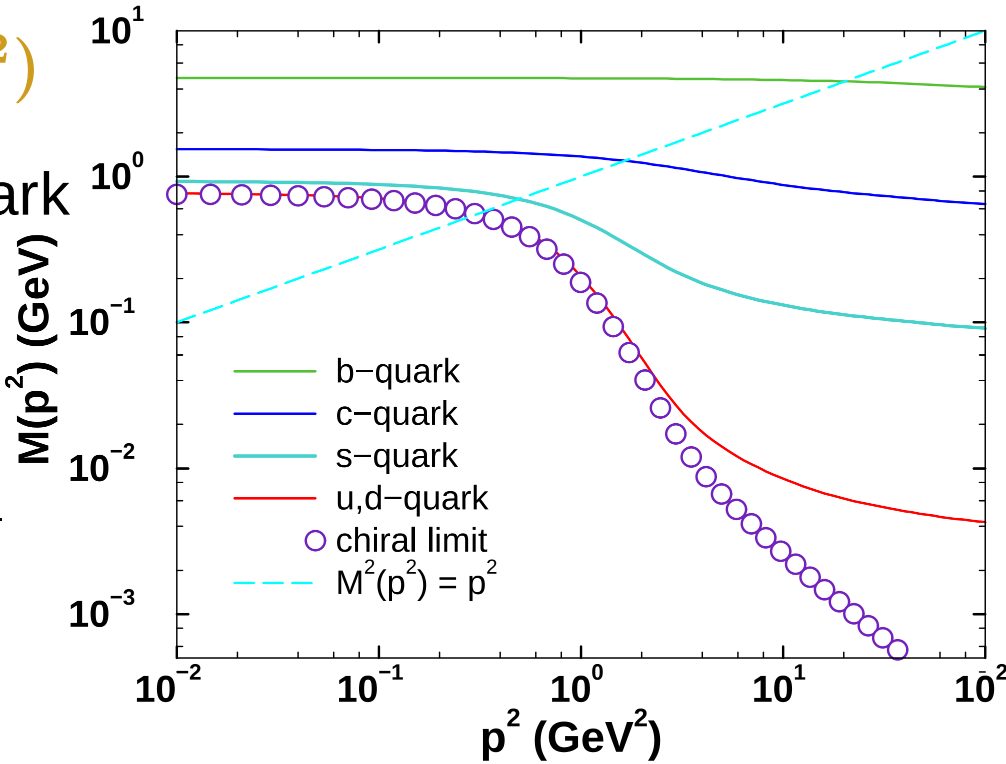
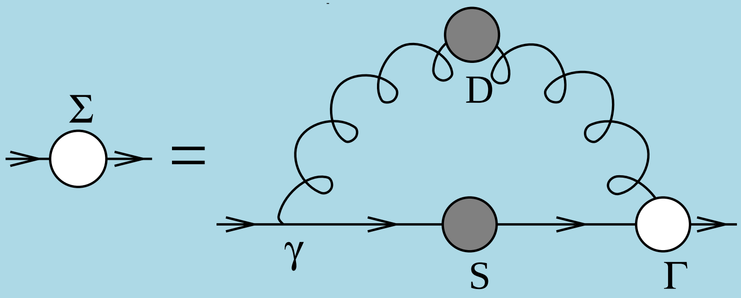


Predictions confirmed in numerical simulations of lattice-QCD

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

Frontiers of Nuclear Science: Theoretical Advances



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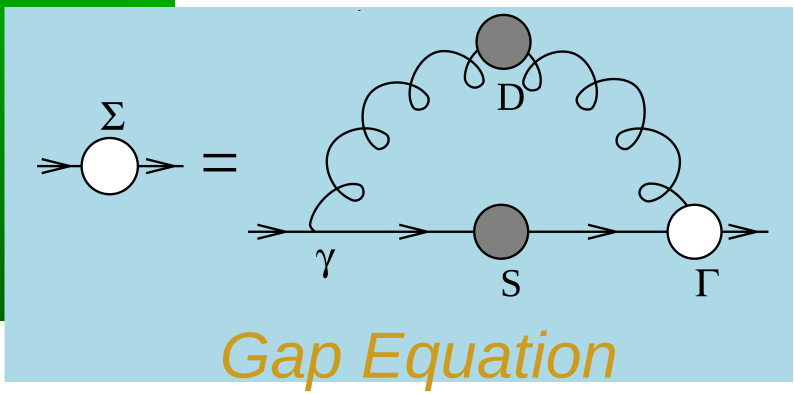

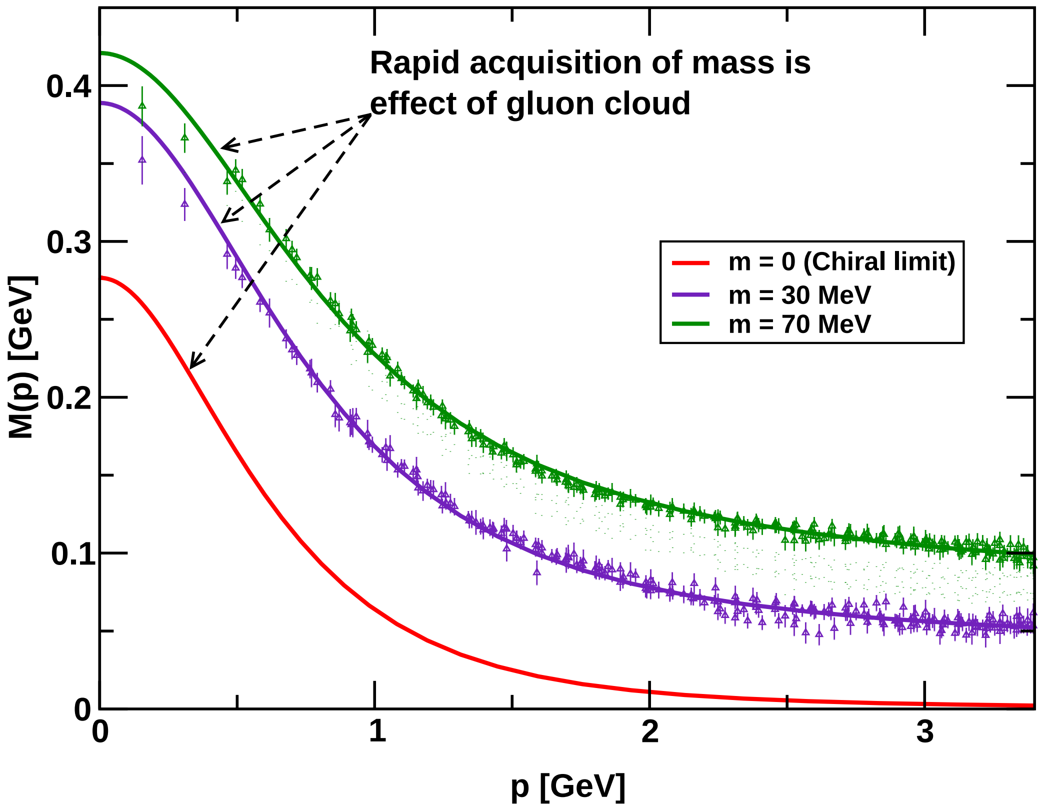

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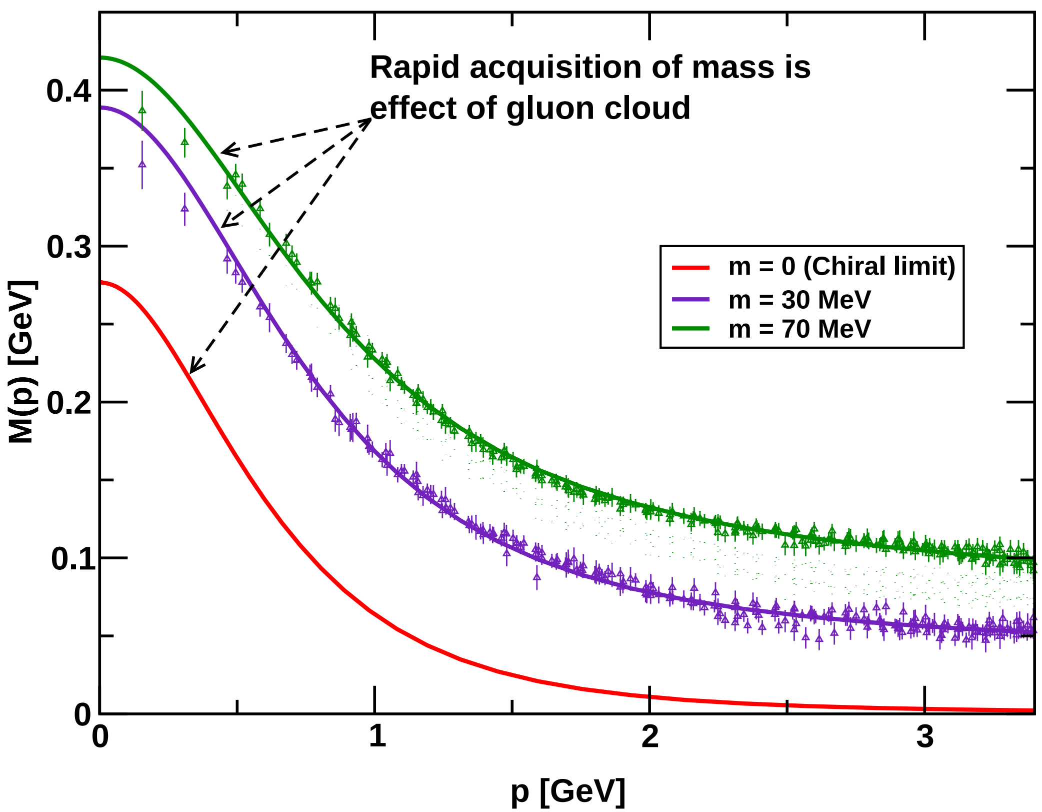
Mass from nothing.

In QCD a quark's effective mass depends on its momentum. The function describing this can be calculated and is depicted here. Numerical simulations of lattice QCD (data, at two different bare masses) have confirmed model predictions (solid curves) that the vast bulk of the constituent mass of a light quark comes from a cloud of gluons that are dragged along by the quark as it propagates. In this way, a quark that appears to be absolutely massless at high energies ($m = 0$, red curve) acquires a large constituent mass at low energies.



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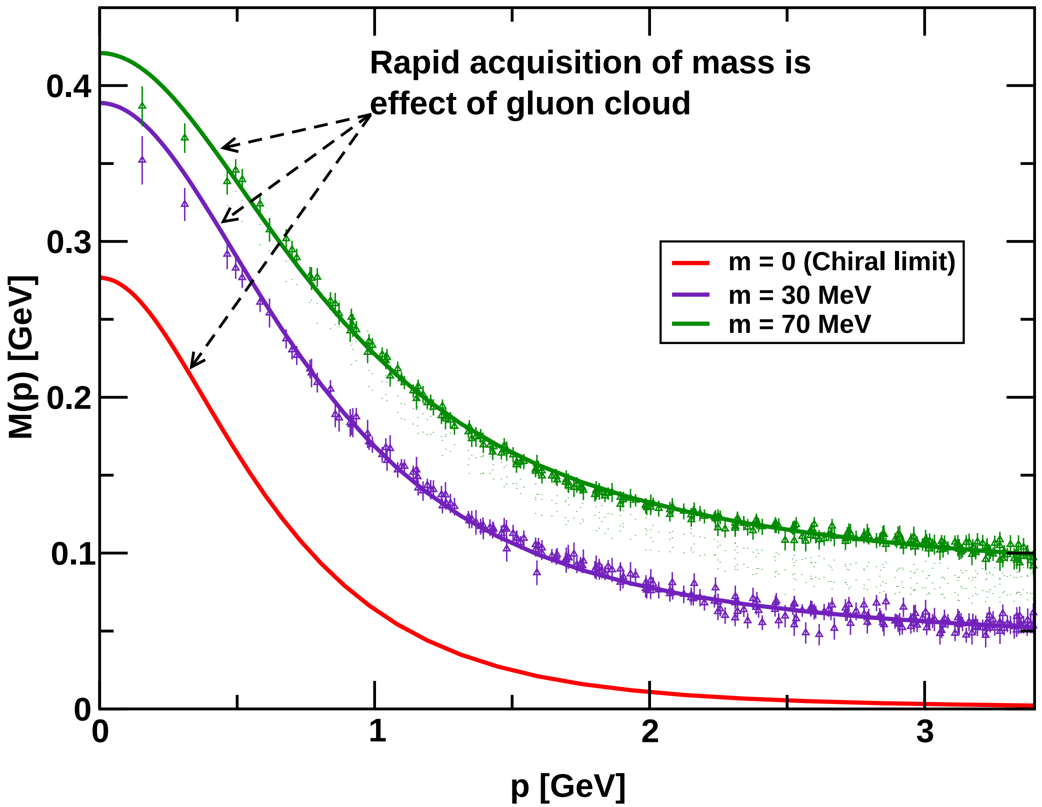


ALWAYS LOOK
ON THE
BRIGHT SIDE

- Established understanding of two- and three-point functions

Hadrons

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

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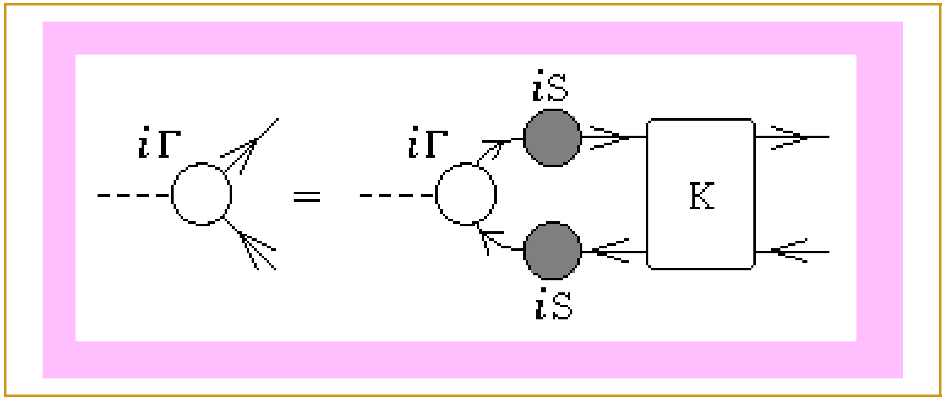

QFT Generalisation of Lippmann-Schwinger Equation.

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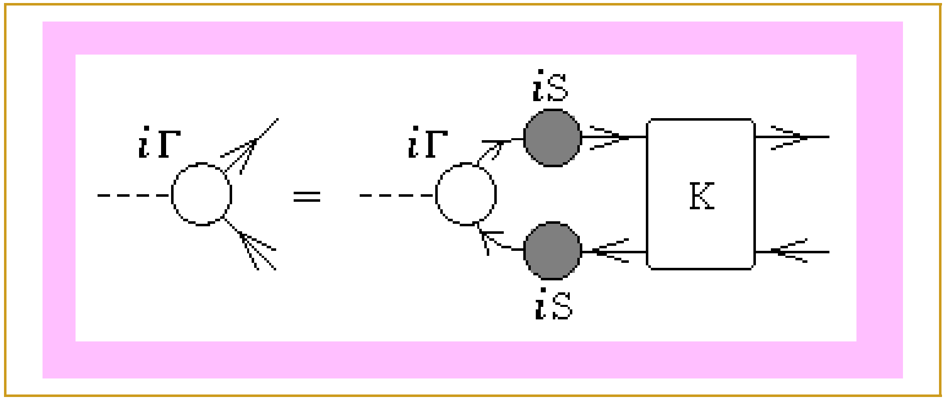

QFT Generalisation of Lippmann-Schwinger Equation.

- What is the kernel, K?

or

Confinement

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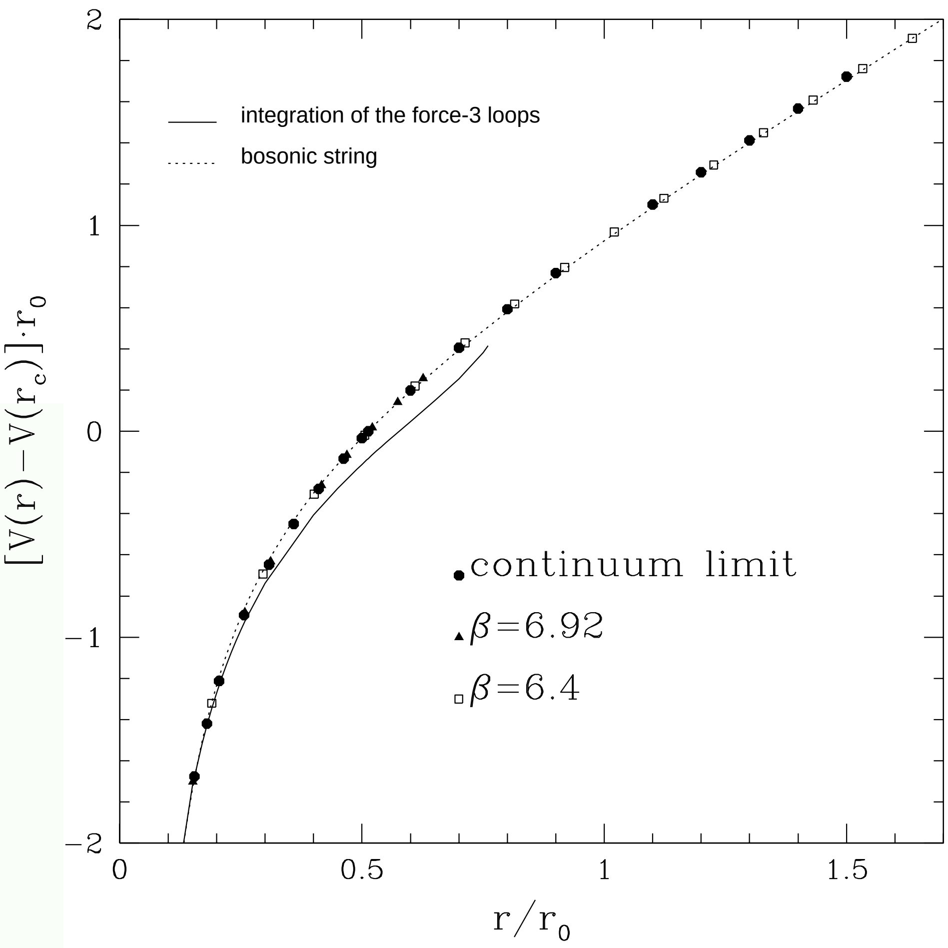
Confinement

- Infinitely Heavy Quarks . . . Picture in Quantum Mechanics



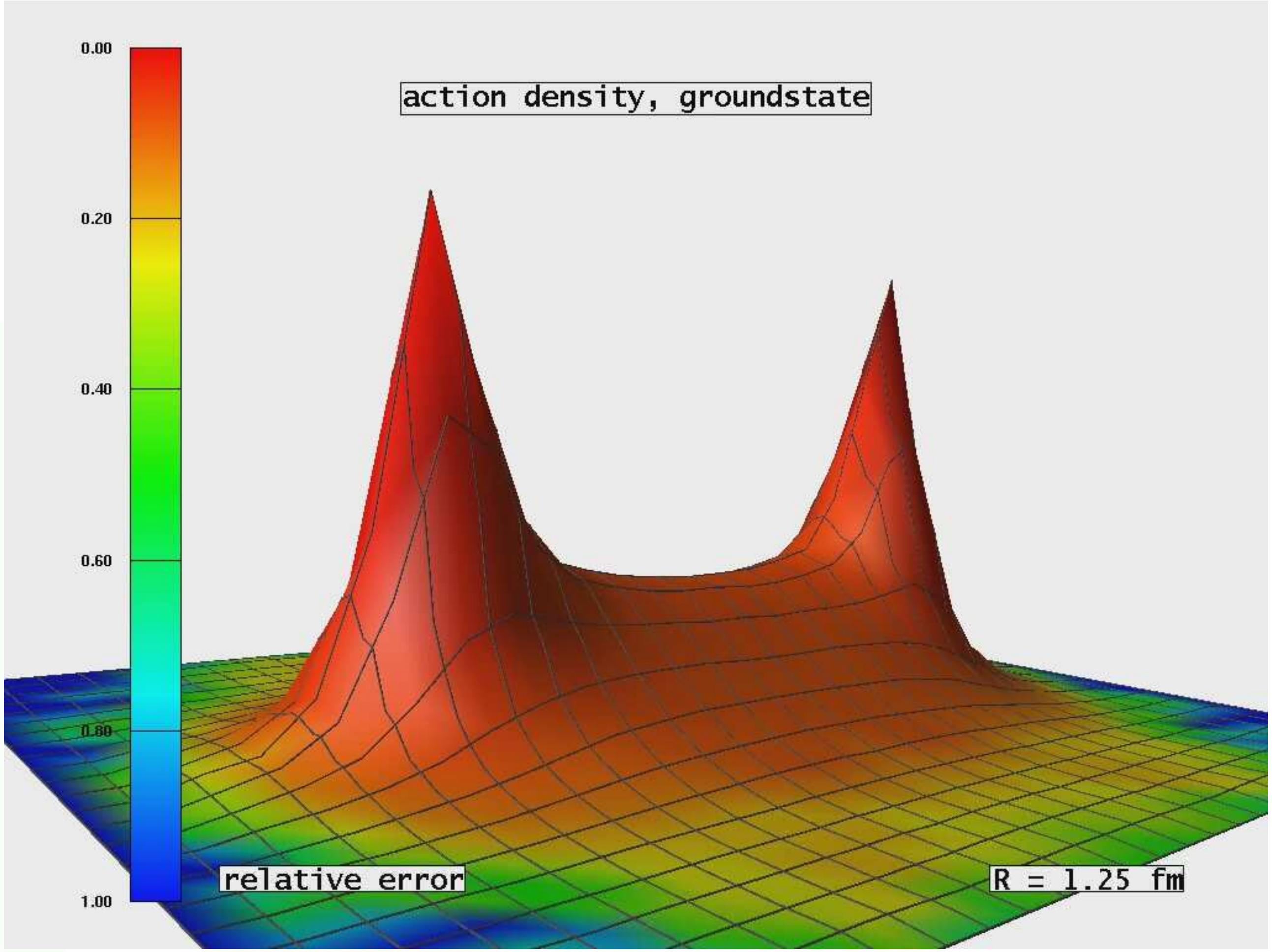
$$V(r) = \sigma\, r - \frac{\pi}{12}\,\frac{1}{r}$$

$\sigma \sim 470$ MeV

Necco & Sommer
he-la/0108008

Confinement

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



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

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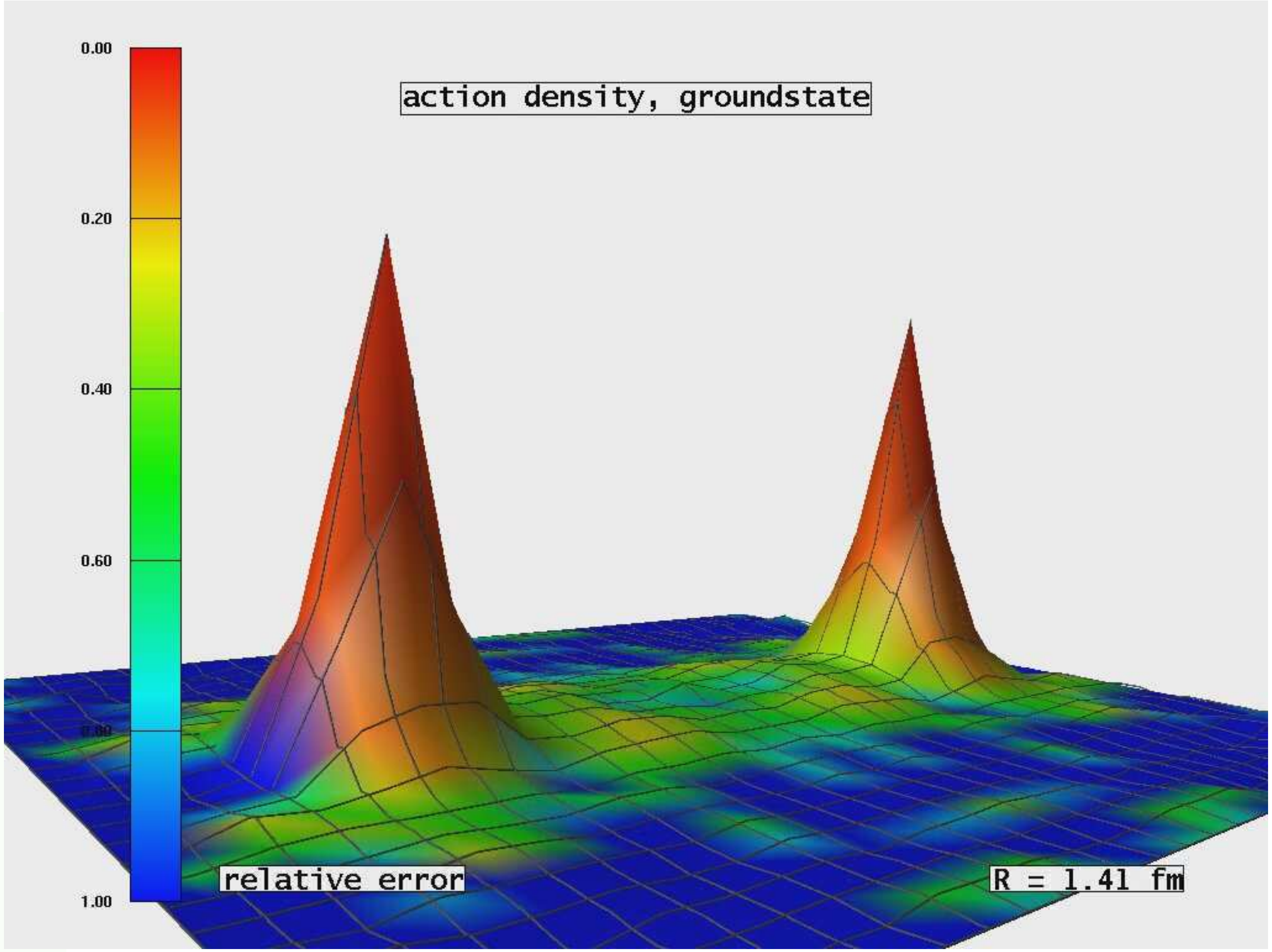

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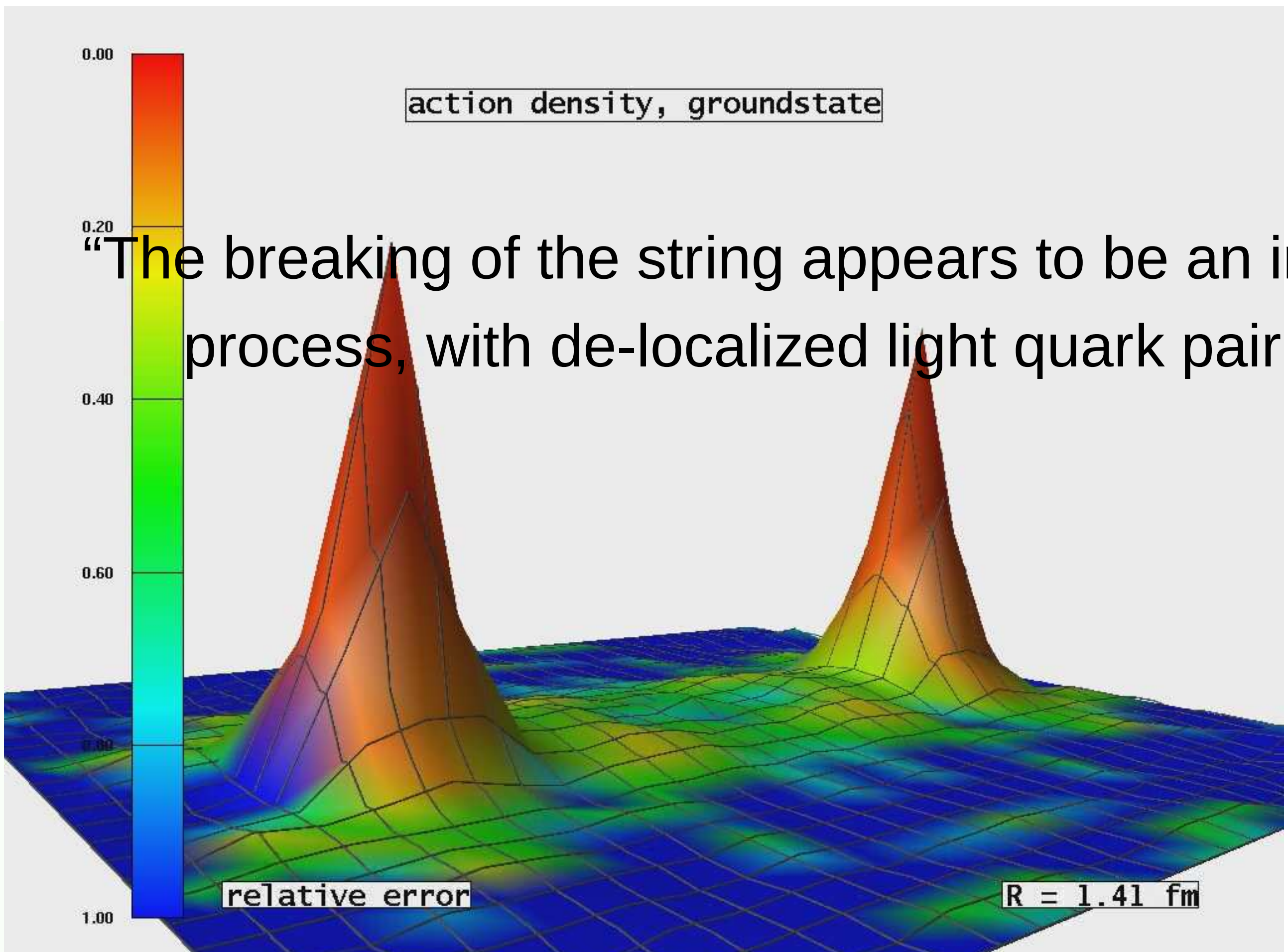

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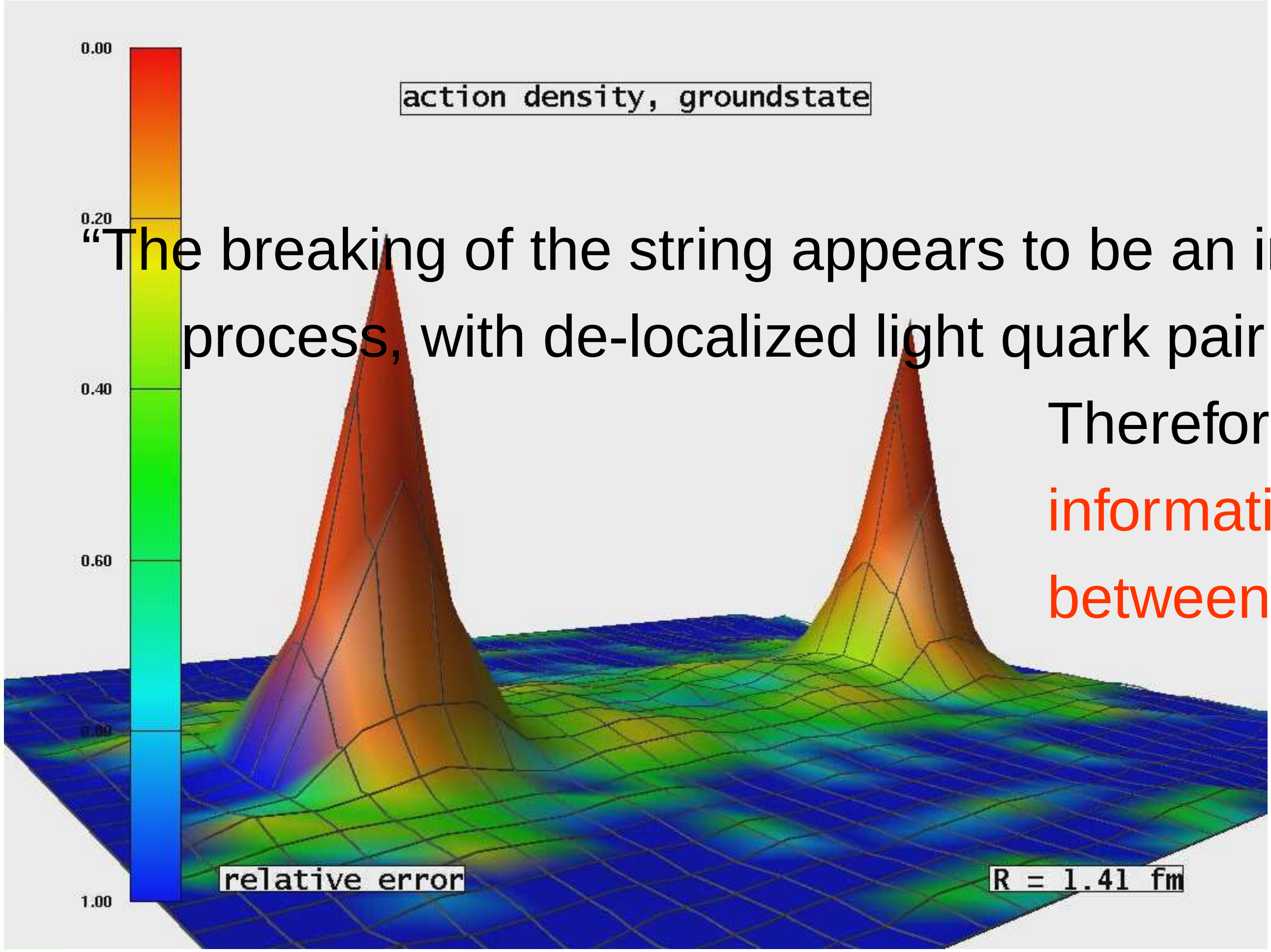

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Therefore ... No information on *potential* between light-quarks.

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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.

Bethe-Salpeter Kernel

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Bethe-Salpeter Kernel

- 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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- Failure $\Rightarrow$ Explicit Violation of QCD's Chiral Symmetry

Persistent Challenge

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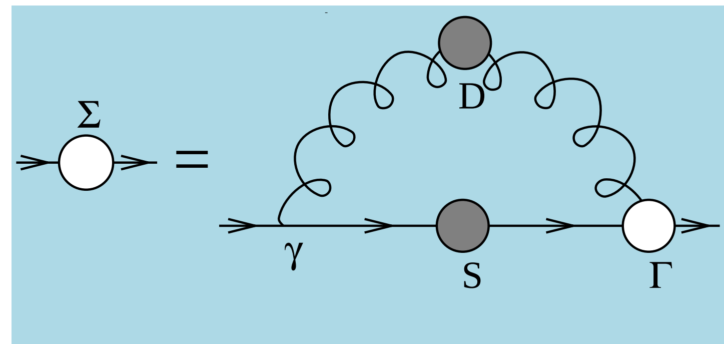
- Infinitely Many Coupled Equations



Persistent Challenge

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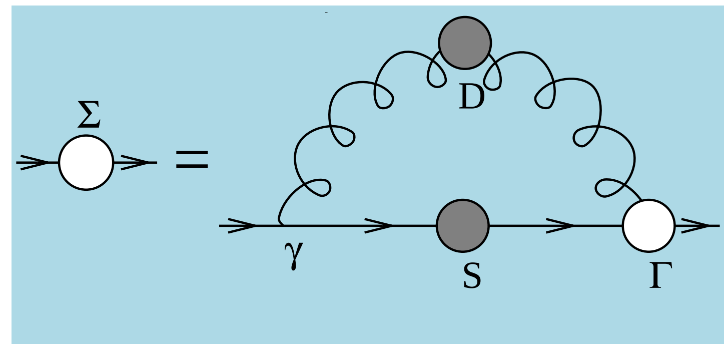

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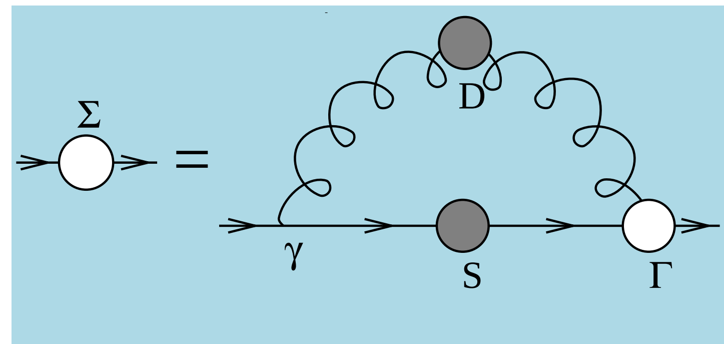

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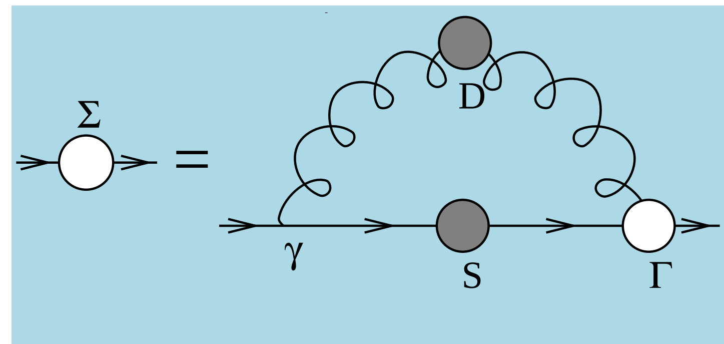

- Coupling between equations necessitates truncation
  - Weak coupling expansion $\Rightarrow$ Perturbation Theory
    Not useful for the nonperturbative problems
    in which we're interested

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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

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Radial Excitations
& Chiral Symmetry

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Radial Excitations & Chiral Symmetry

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

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

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- Mass^2 of pseudoscalar hadron

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

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

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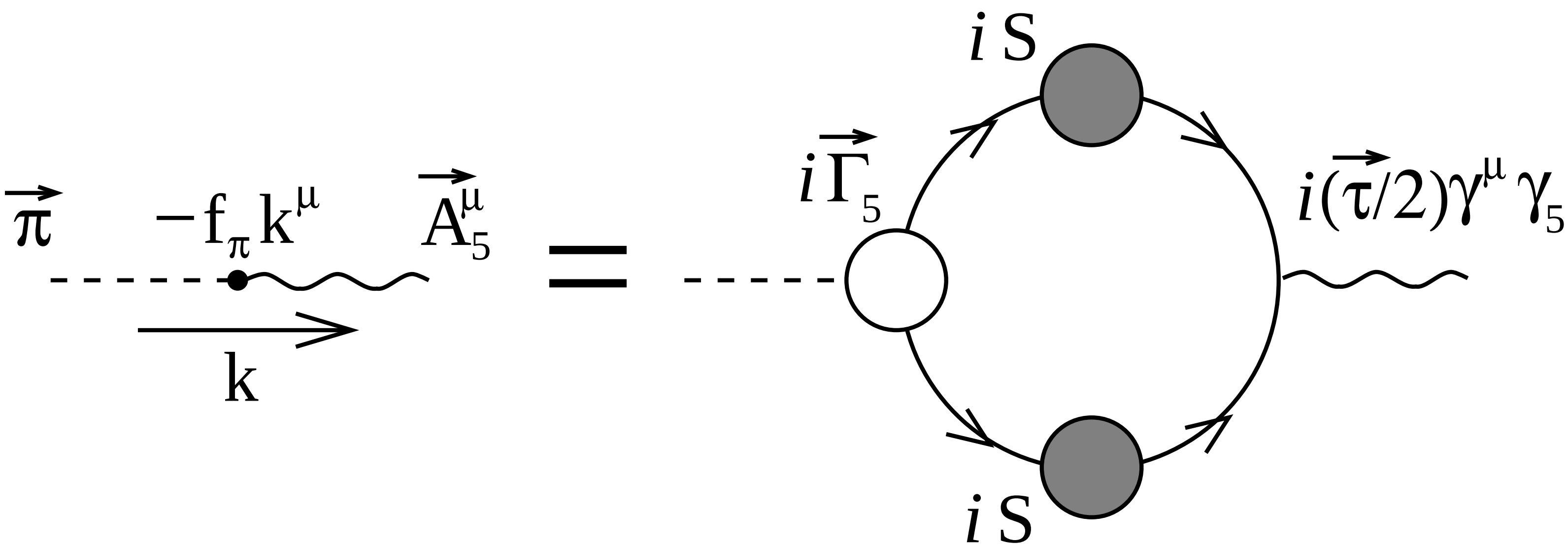
$$f_H\, p_\mu = Z_2 \int_q^\Lambda \tfrac{1}{2}\mathrm{tr}\left\{ \left(T^H\right)^{\mathrm{t}} \gamma_5\gamma_\mu \boxed{\mathcal{S}(q_+)\Gamma_H(q;P)\mathcal{S}(q_-)} \right\}$$

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



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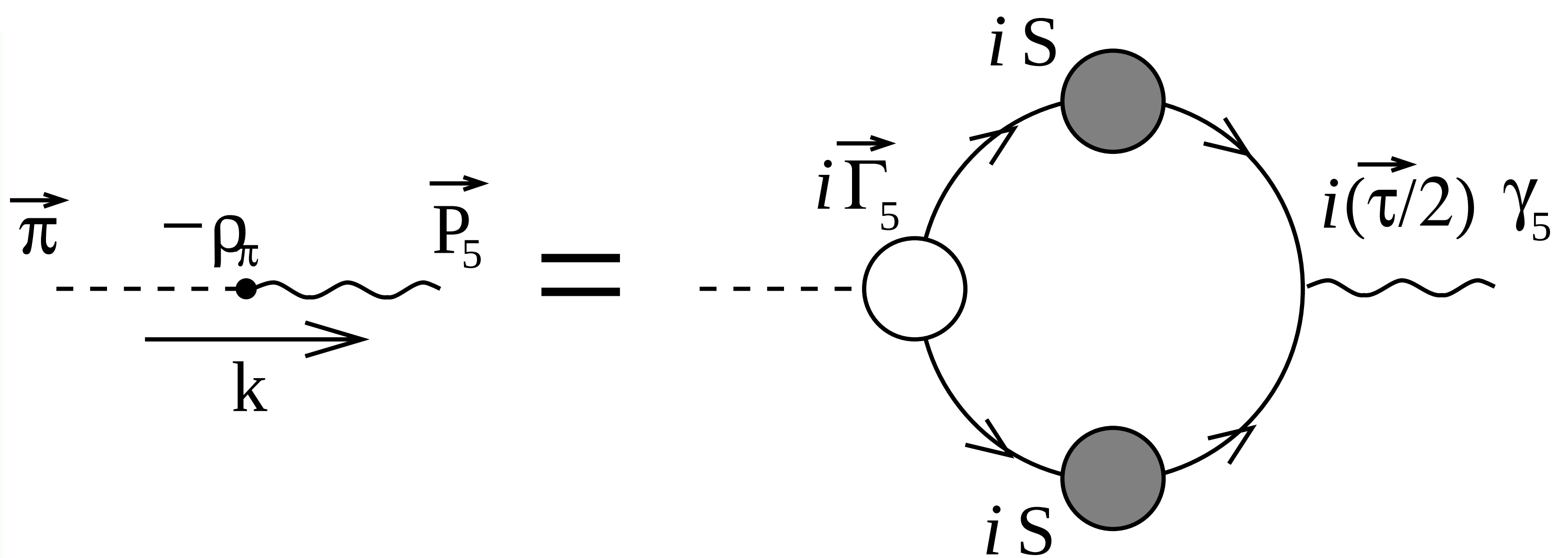

Radial Excitations & Chiral Symmetry

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Hence $\boxed{m_H^2 = \dfrac{-\langle \bar{q}q\rangle_\zeta^0}{(f_H^0)^2}\, m_q}$ …GMOR relation, a corollary

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- Heavy-quark + light-quark

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

Hence, $\boxed{m_H \propto m_q}$

. . . QCD Proof of Potential Model result

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Höll, Krassnigg, Roberts
nu-th/0406030

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- Dynamical Chiral Symmetry Breaking

  – Goldstone's Theorem –

  impacts upon *every* pseudoscalar meson

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Radial Excitations & Lattice-QCD

McNeile and Michael
he-la/0607032

Radial Excitations & Lattice-QCD

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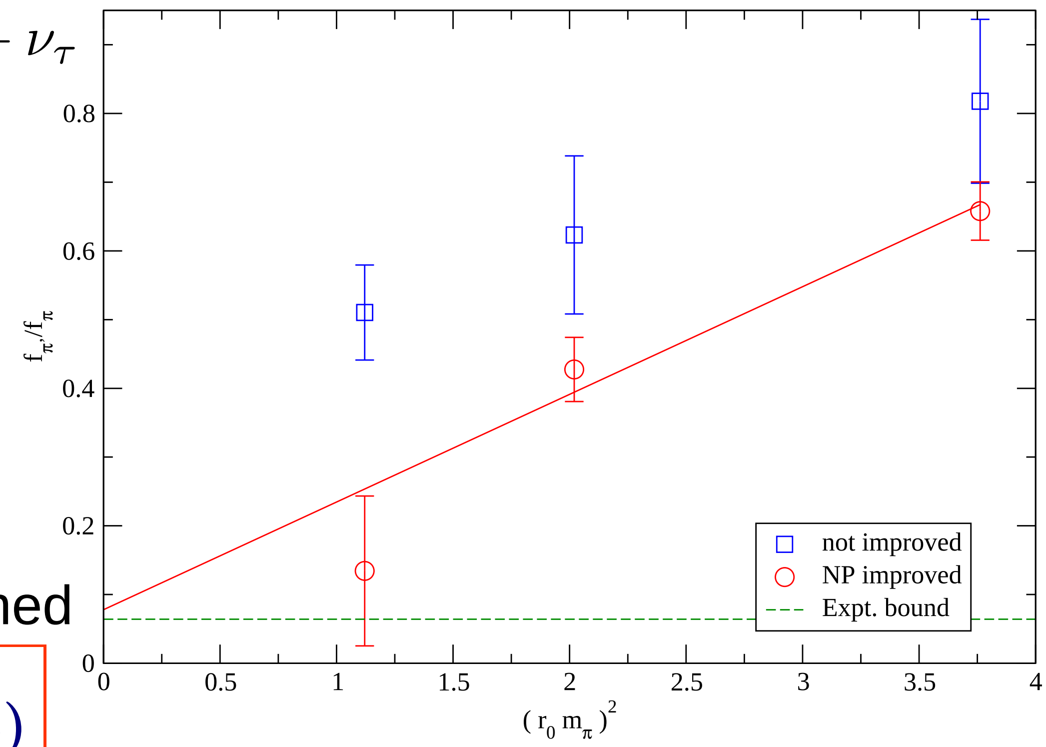
$$\boxed{\Rightarrow \frac{f_{\pi_1}}{f_\pi} = \mathbf{0.078\,(93)}}$$



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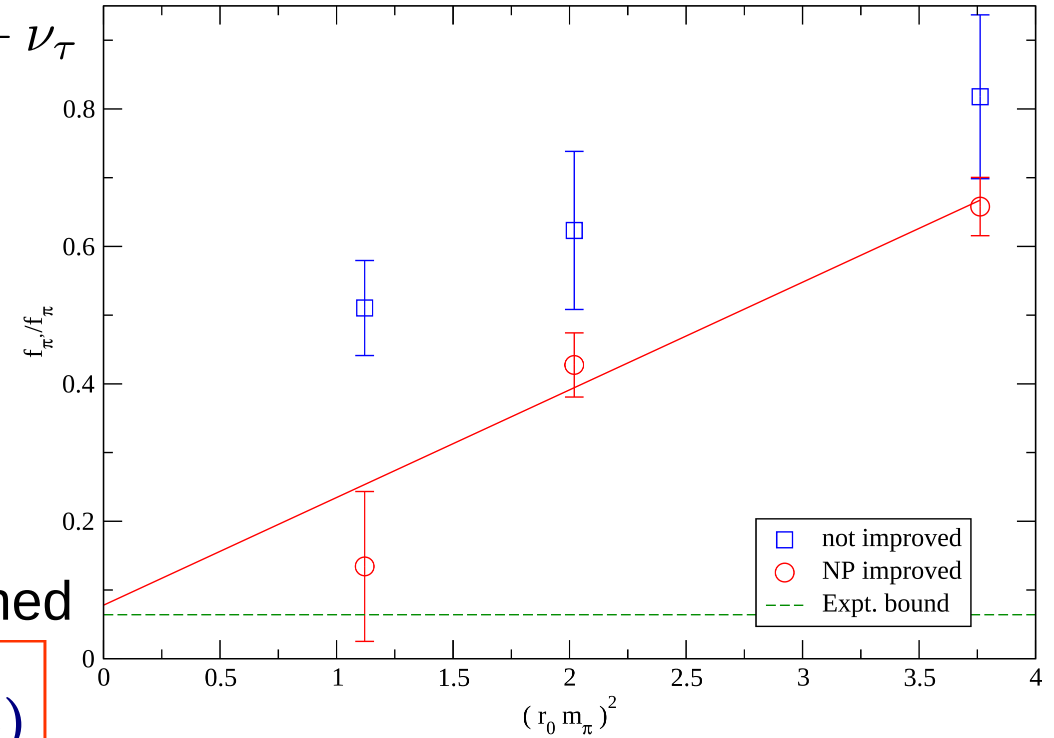

- Full ALPHA formulation is required to see suppression, because PCAC relation is at the heart of the conditions imposed for improvement (determining coefficients of irrelevant operators)

Radial Excitations & Lattice-QCD

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he-la/0607032

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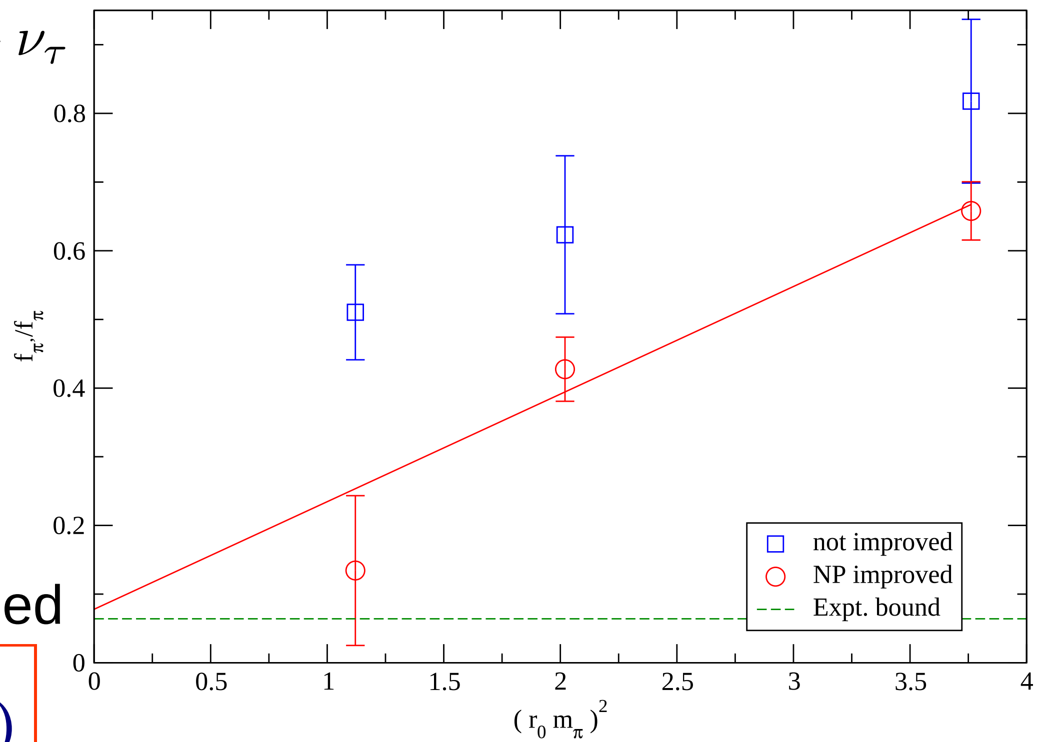


- *The suppression of f_{π_1} is a useful benchmark that can be used to tune and validate lattice QCD techniques that try to determine the properties of excited states mesons.*

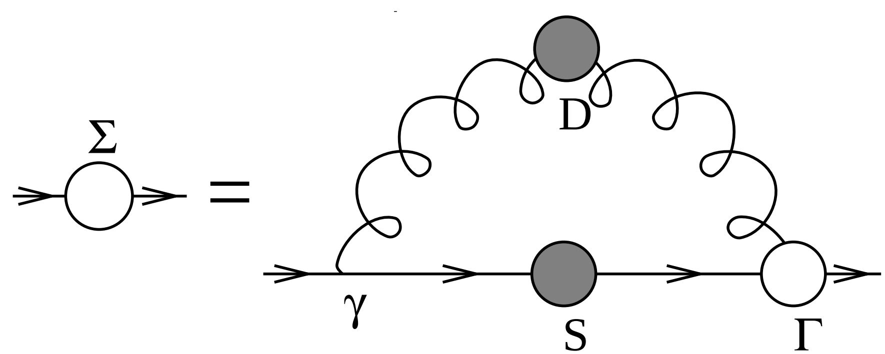
Pion Form Factor

Procedure Now Straightforward

Pion Form Factor

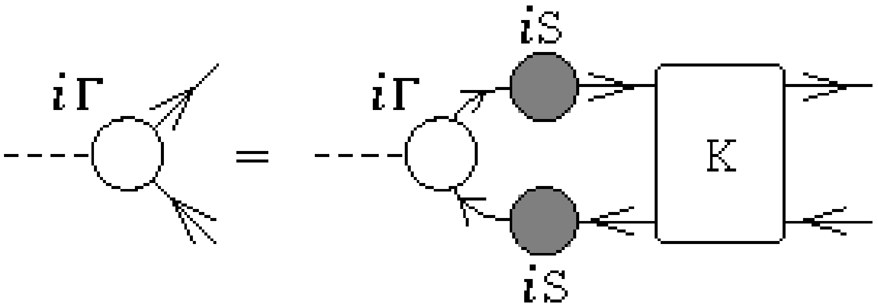
- Solve Gap Equation

  $\Rightarrow$ Dressed-Quark Propagator, $S(p)$



Pion Form Factor

- Use that to Complete Bethe Salpeter Kernel, K
- Solve Homogeneous Bethe-Salpeter Equation for Pion Bethe-Salpeter Amplitude, Γ_π



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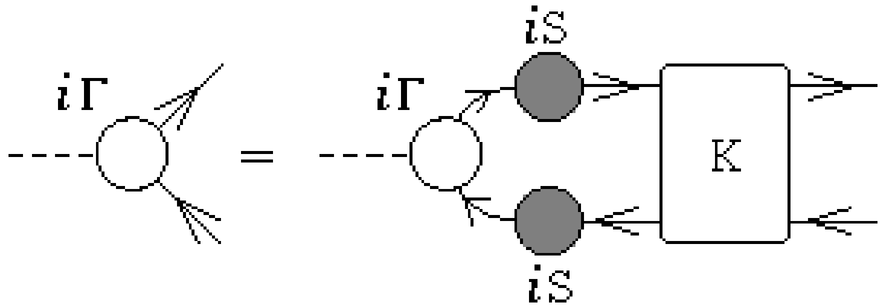
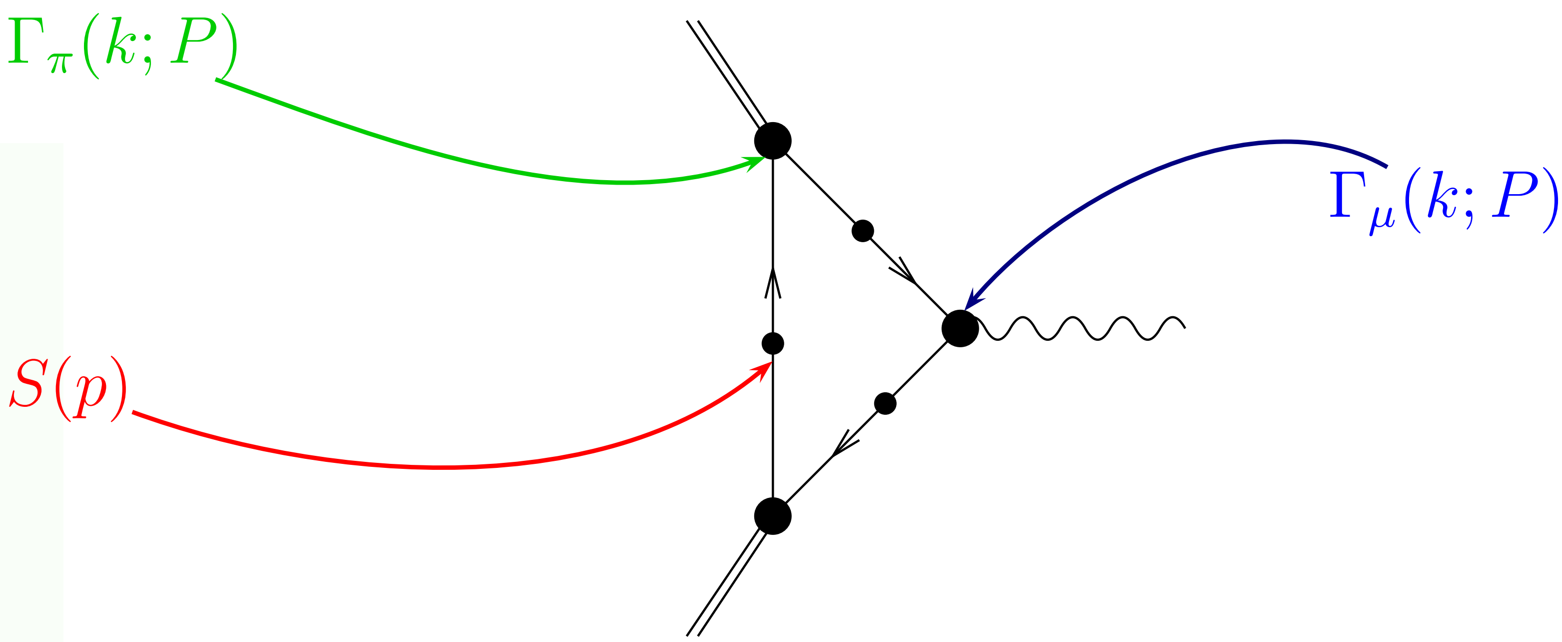


- Solve Inhomogeneous Bethe-Salpeter Equation for Dressed-Quark-Photon Vertex, Γ_μ

Pion Form Factor

- Now have all elements for Impulse Approximation to Electromagnetic Pion Form factor



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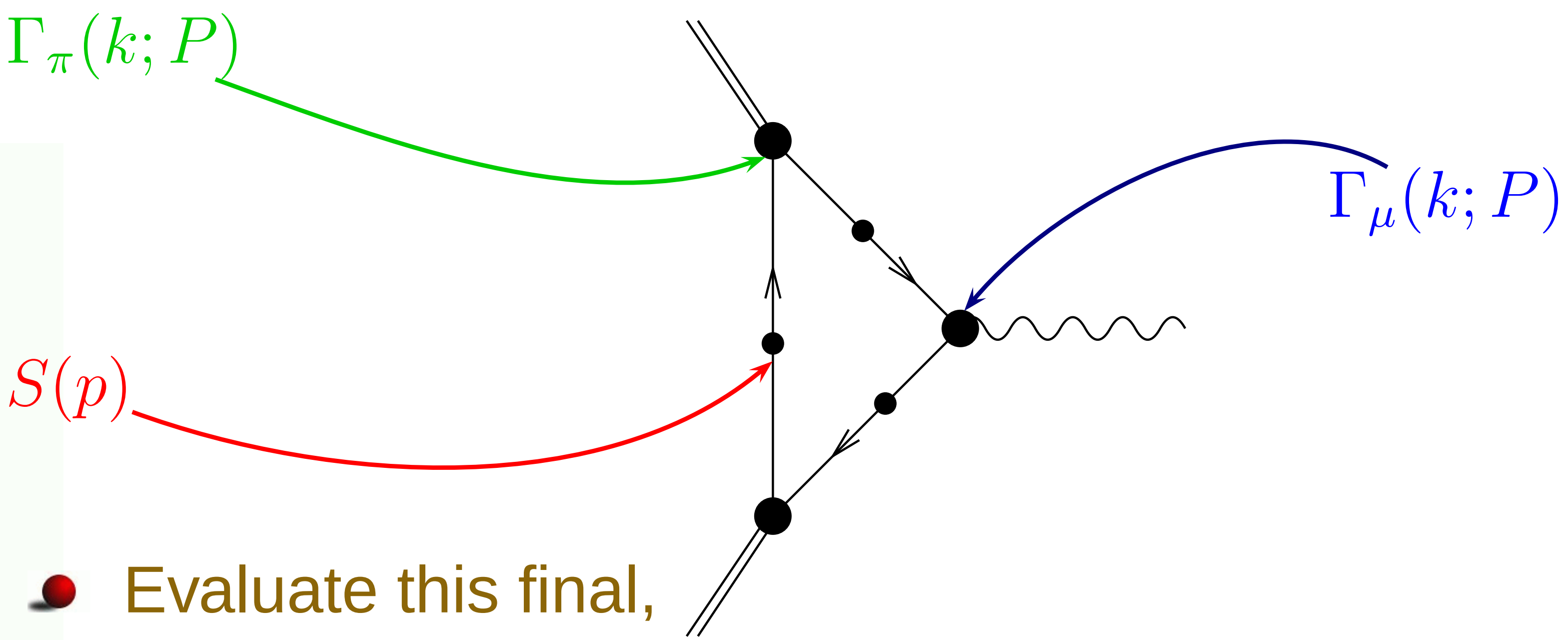
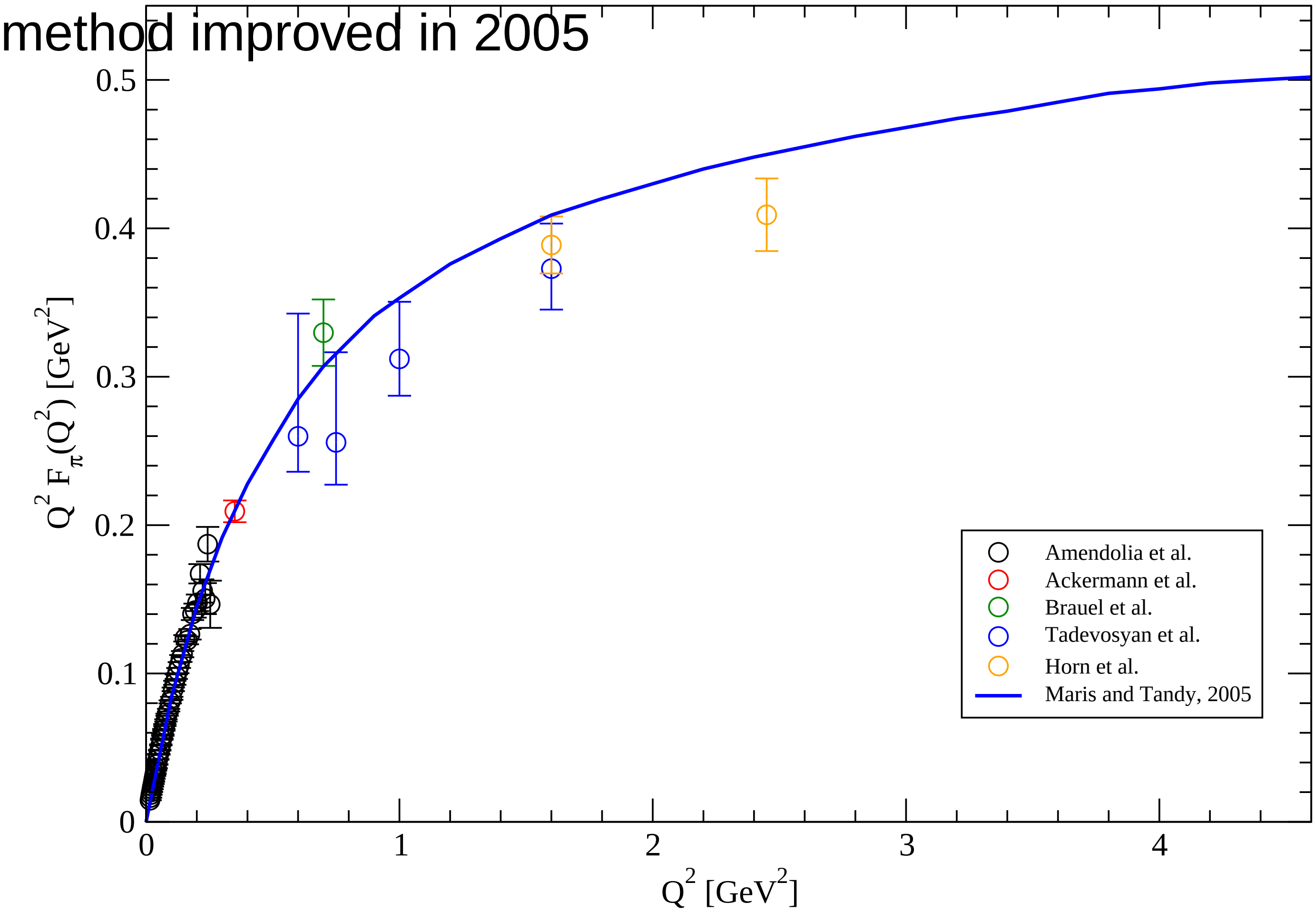


- Evaluate this final, three-dimensional integral

Calculated Pion Form Factor

Calculation first published in 1999; No Parameters Varied

Numerical method improved in 2005



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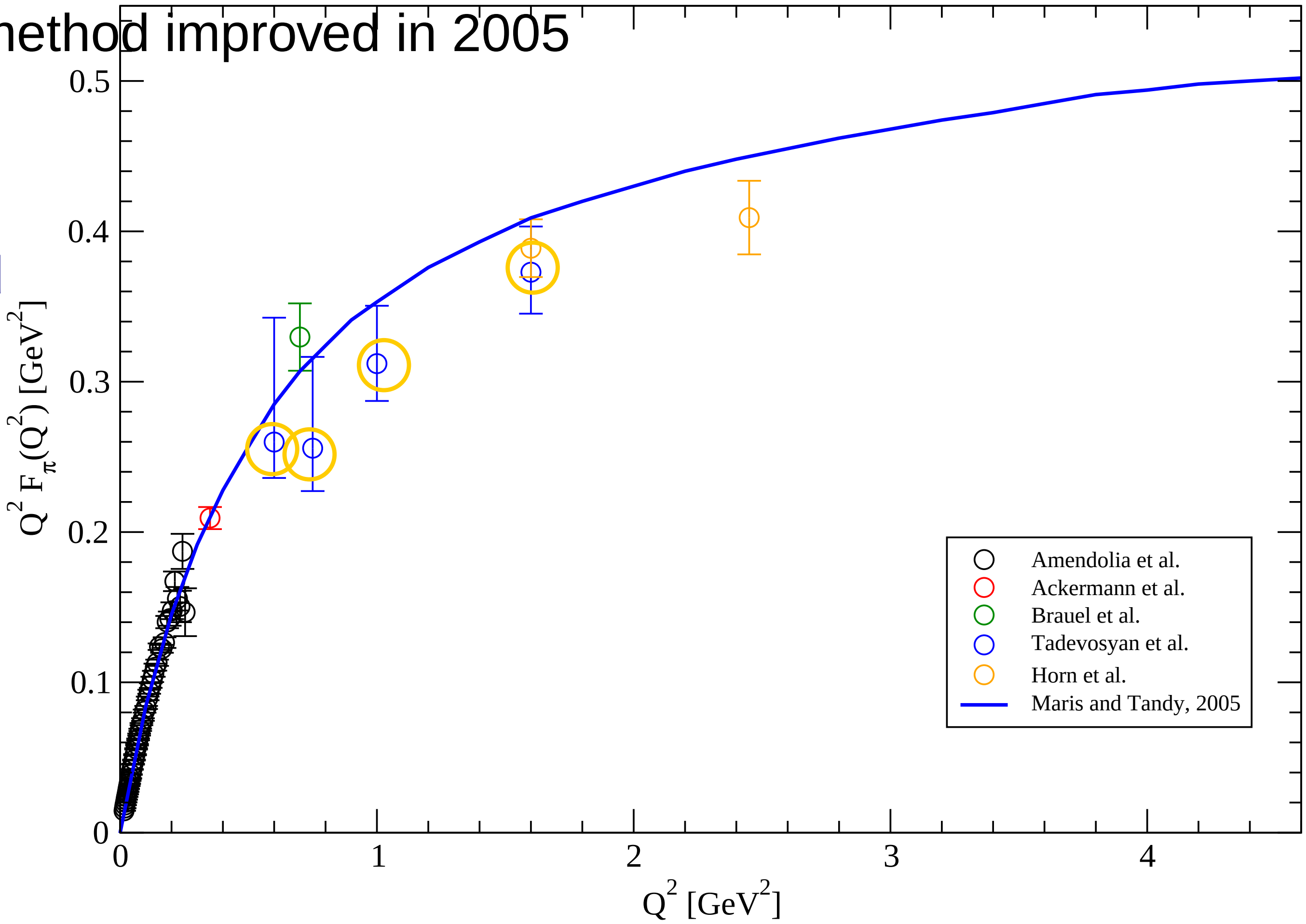
Data published in 2001. Subsequently revised



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Timelike Pion Form Factor

Ab initio calculation into timelike region. Deeper than ground-state ρ-meson pole

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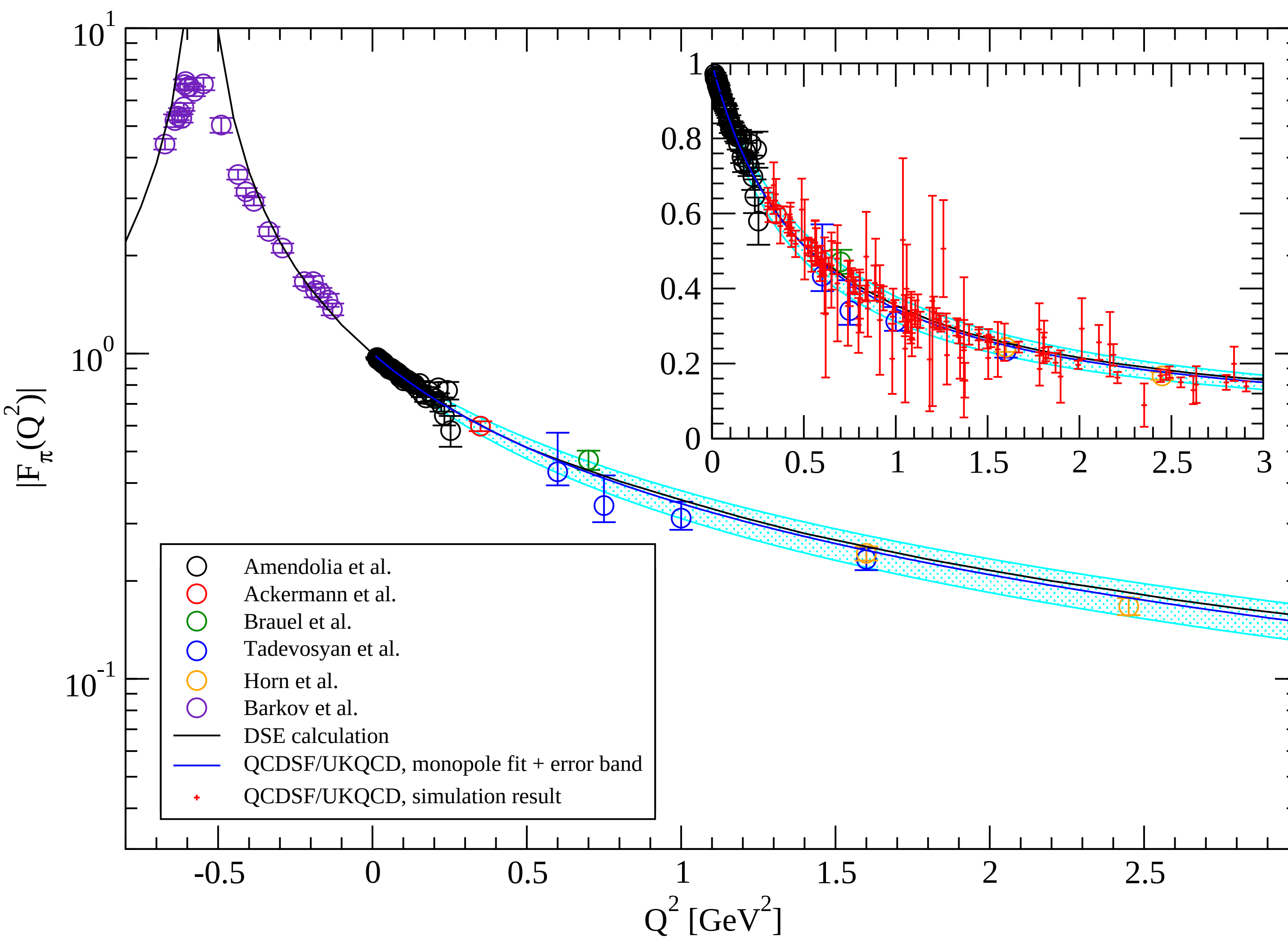
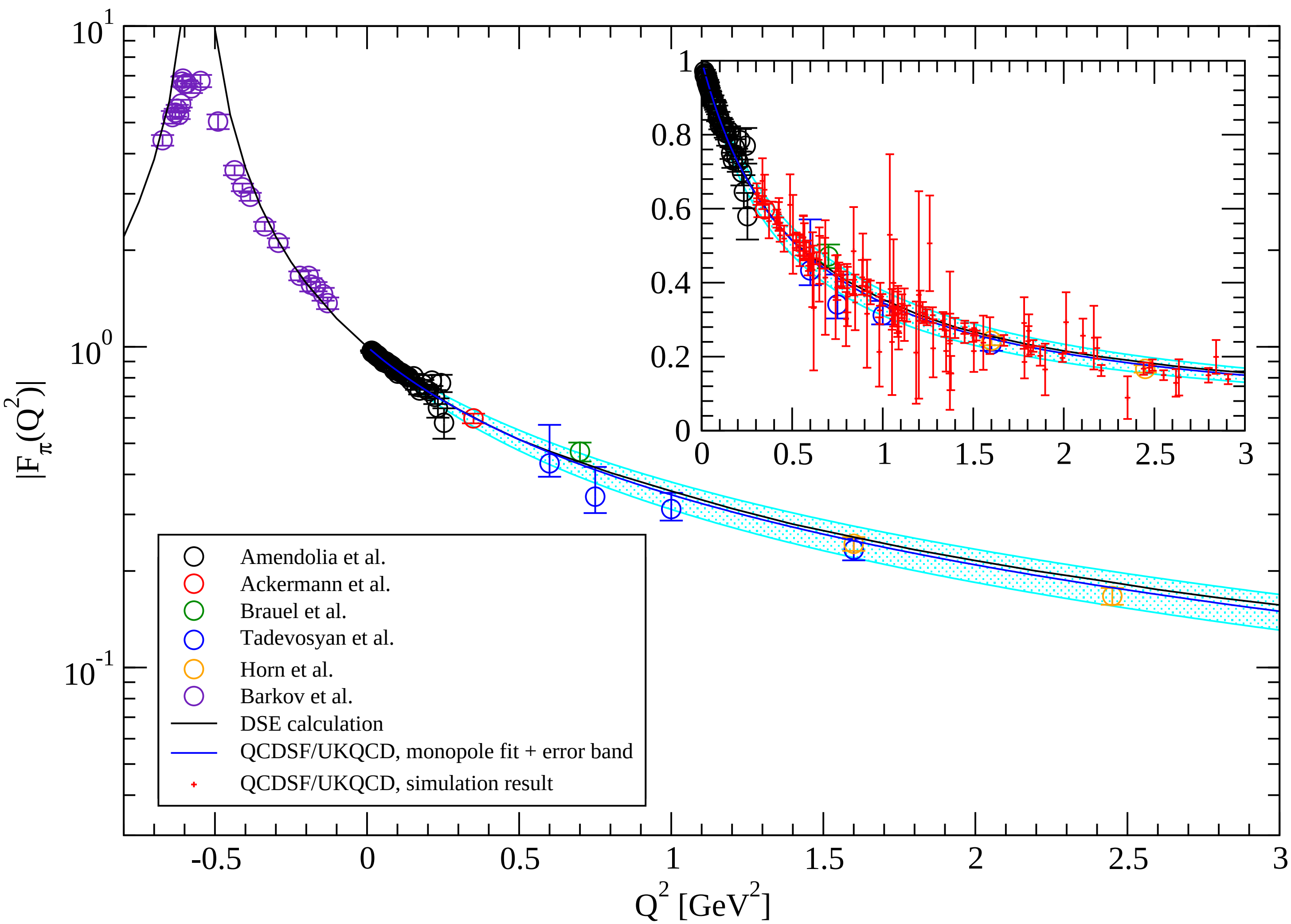


Ab initio calculation into timelike region. Deeper than ground-state ρ-meson pole

Timelike Pion Form Factor

ρ-meson not put in "by hand" – generated dynamically as a bound-state of dressed-quark and dressed-antiquark



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Pion Form Factors

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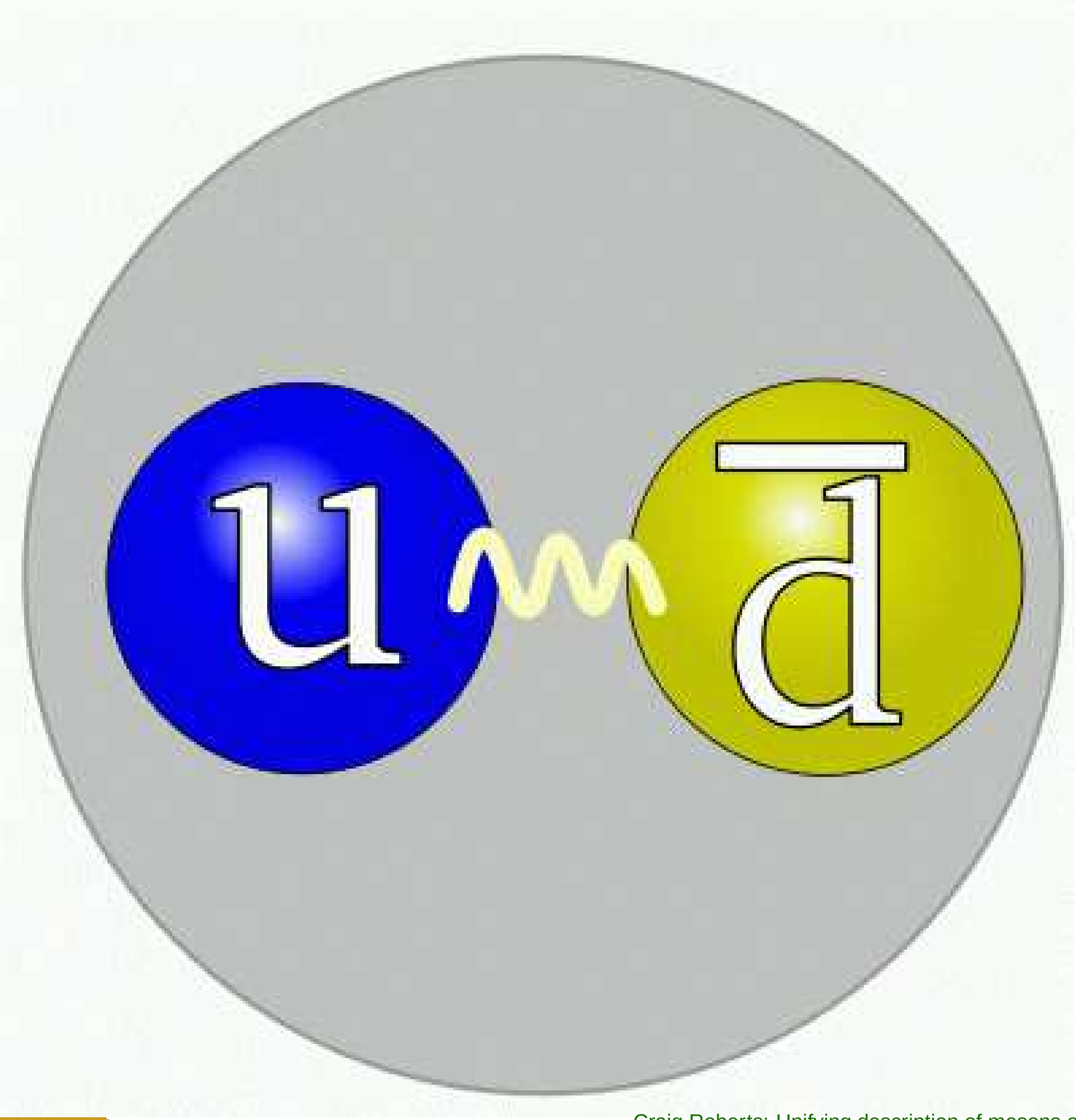
- Must similarly require prediction of $\gamma^*\pi \to \pi\pi$ and all other anomalous processes

Answer for the pion



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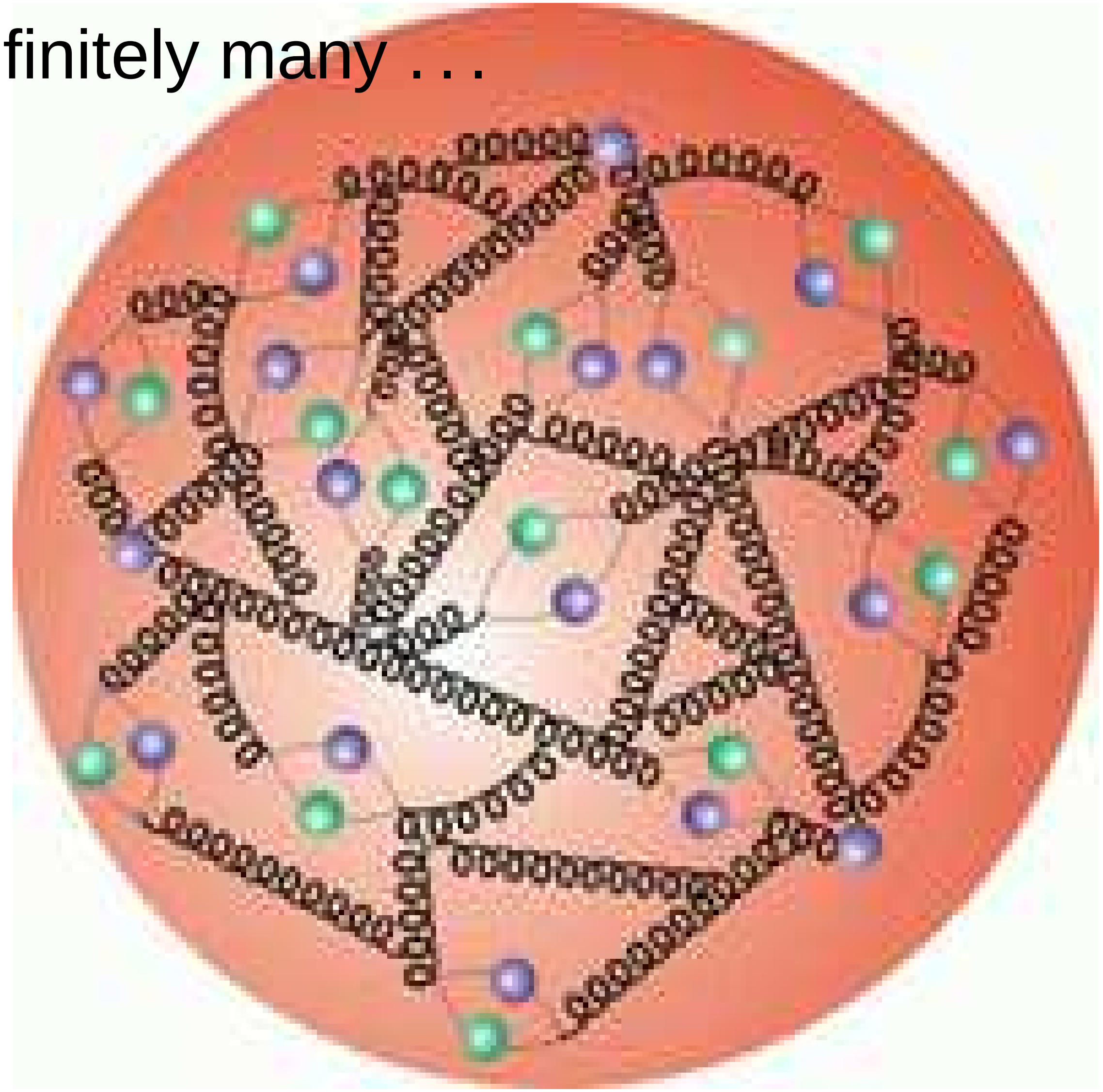
Two → Infinitely many . . .



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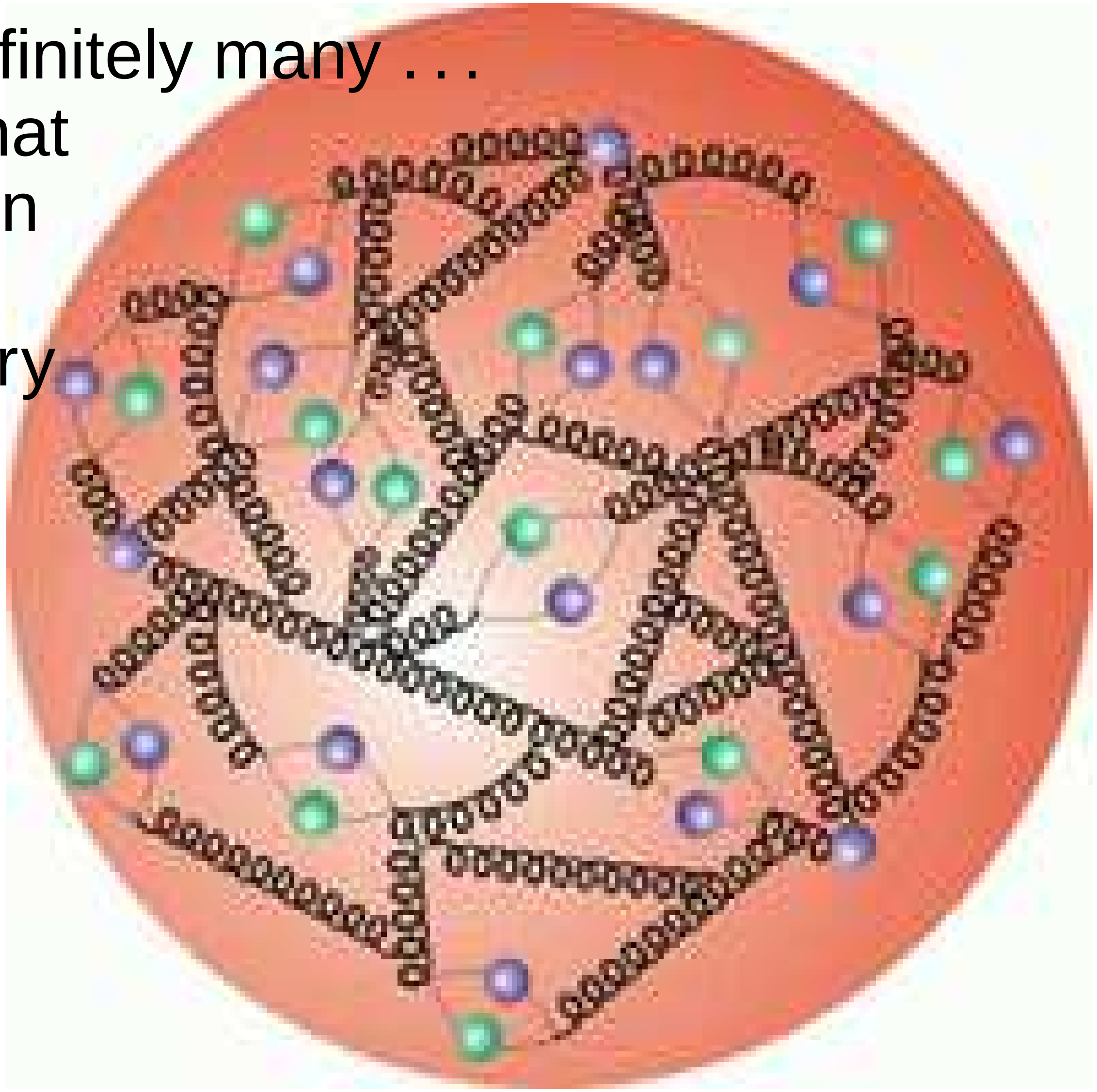

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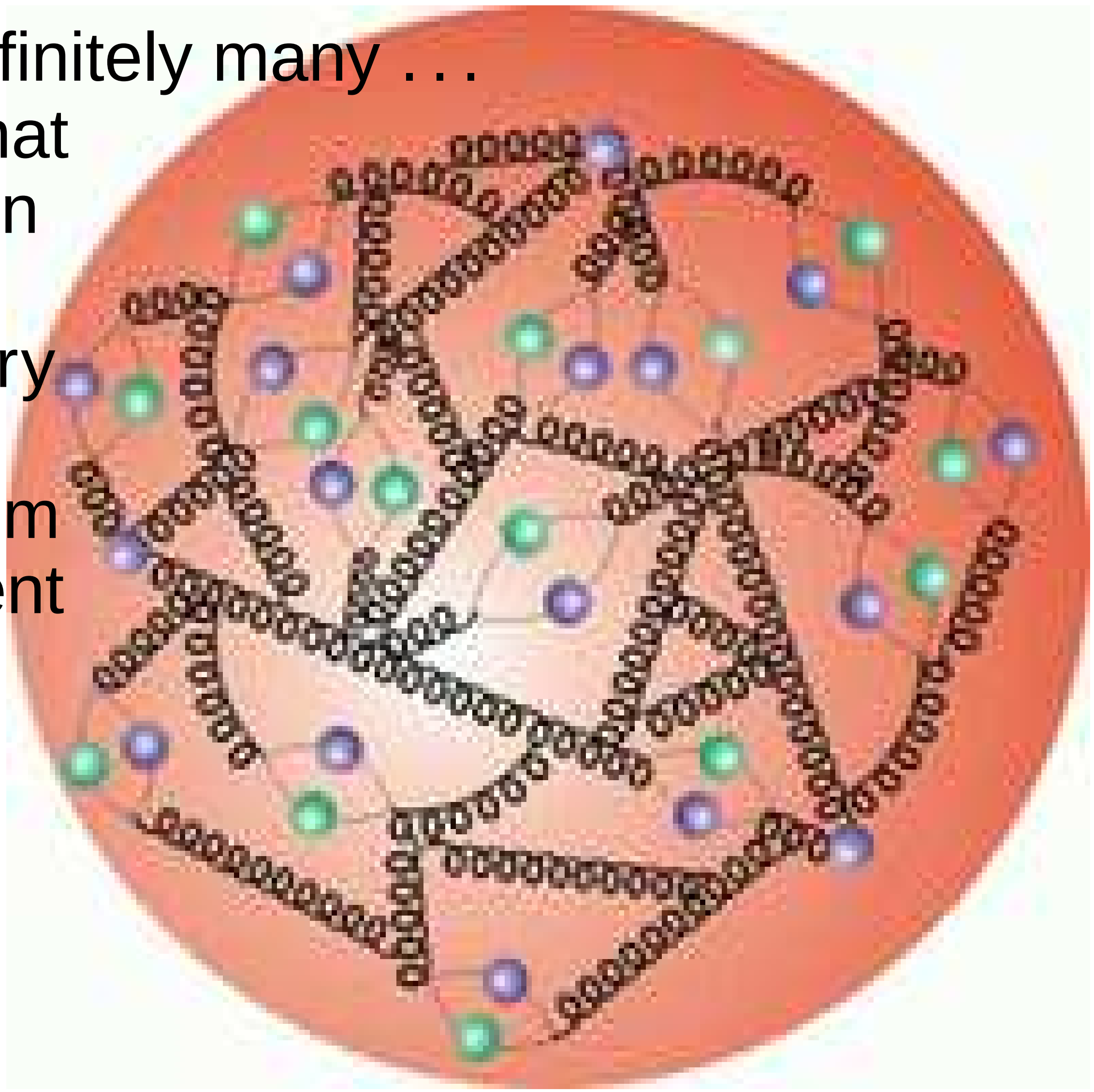

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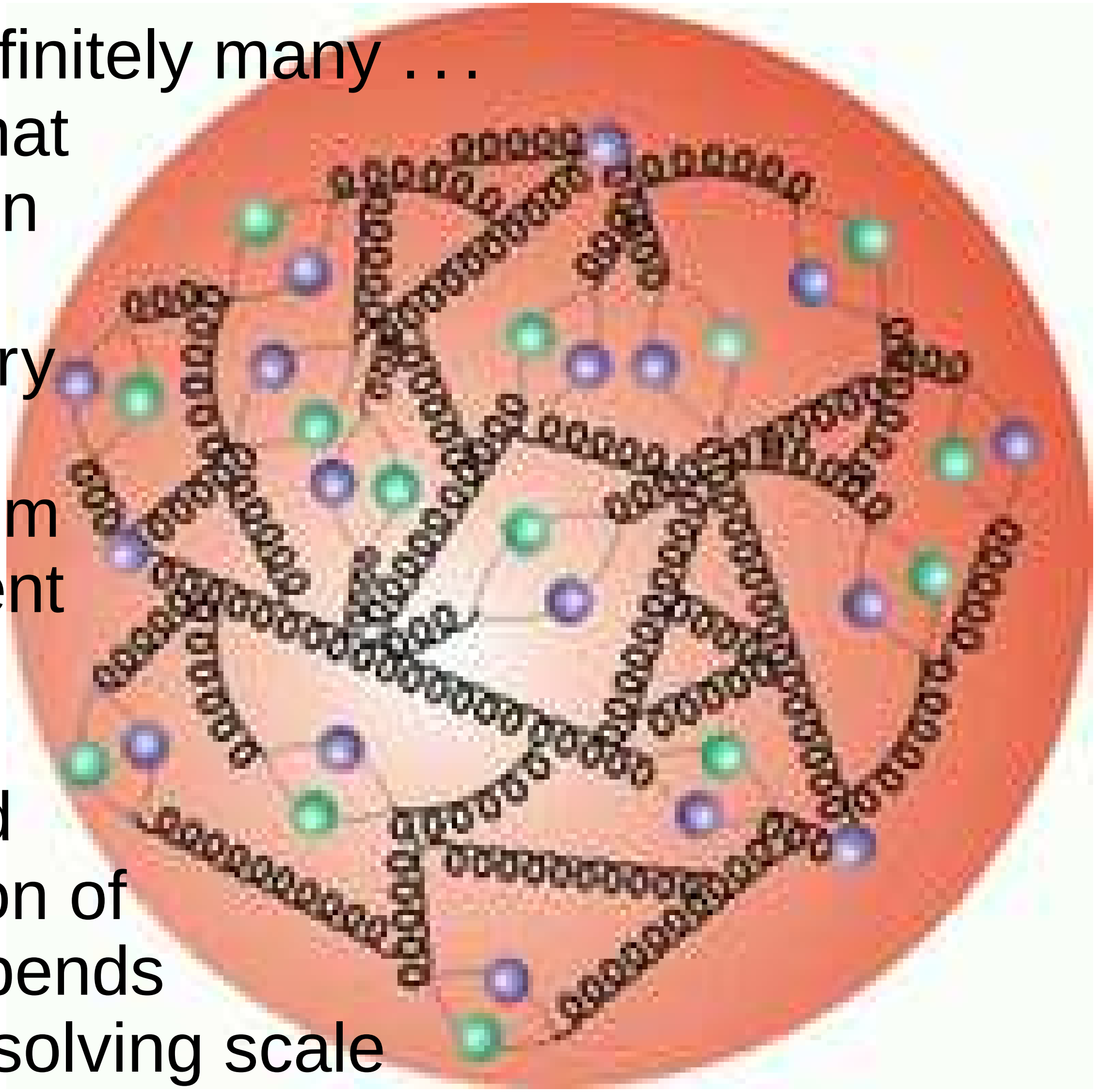


ARE WE THERE YET?

New Challenges

New Challenges

- Next Steps . . . Applications to excited states and axial-vector mesons, e.g., will improve understanding of confinement interaction between light-quarks.

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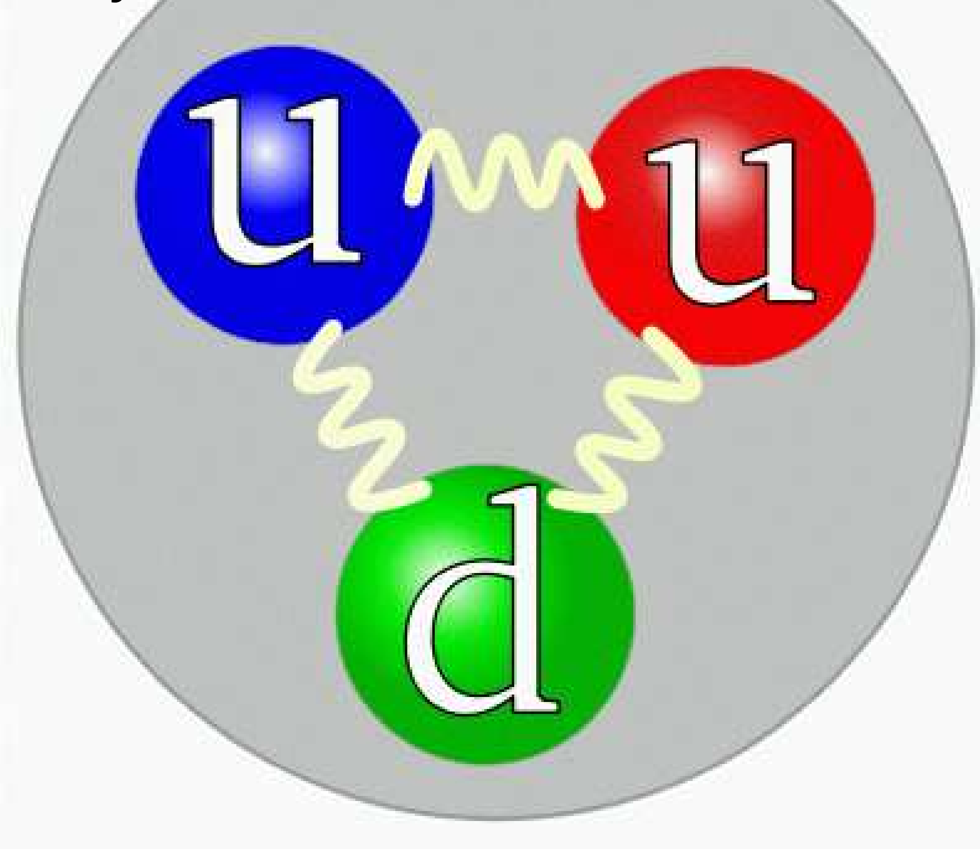
- Next Steps . . . Applications to excited states and axial-vector mesons, e.g., will improve understanding of confinement interaction between light-quarks.
- Move on to the problem of a symmetry preserving treatment of hybrids and exotics.

New Challenges

- Another Direction . . . Also want/need information about three-quark systems



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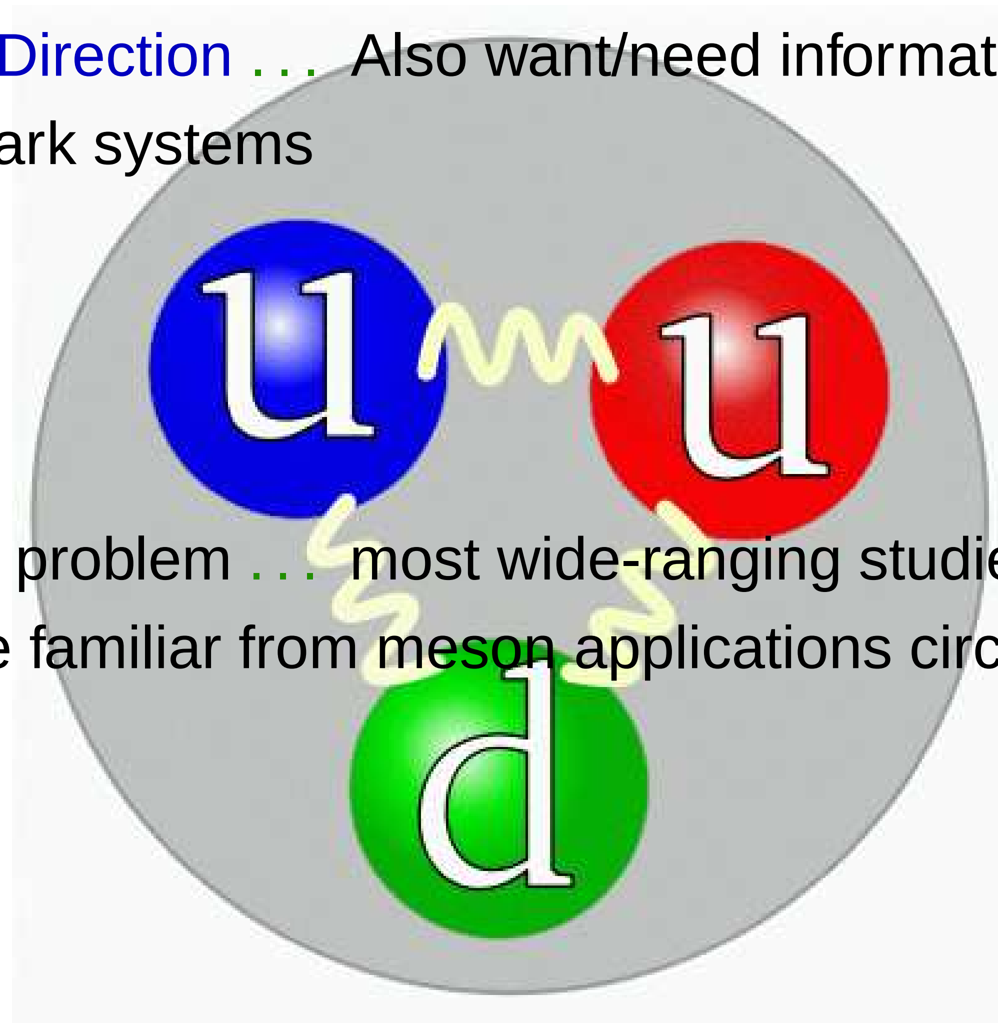

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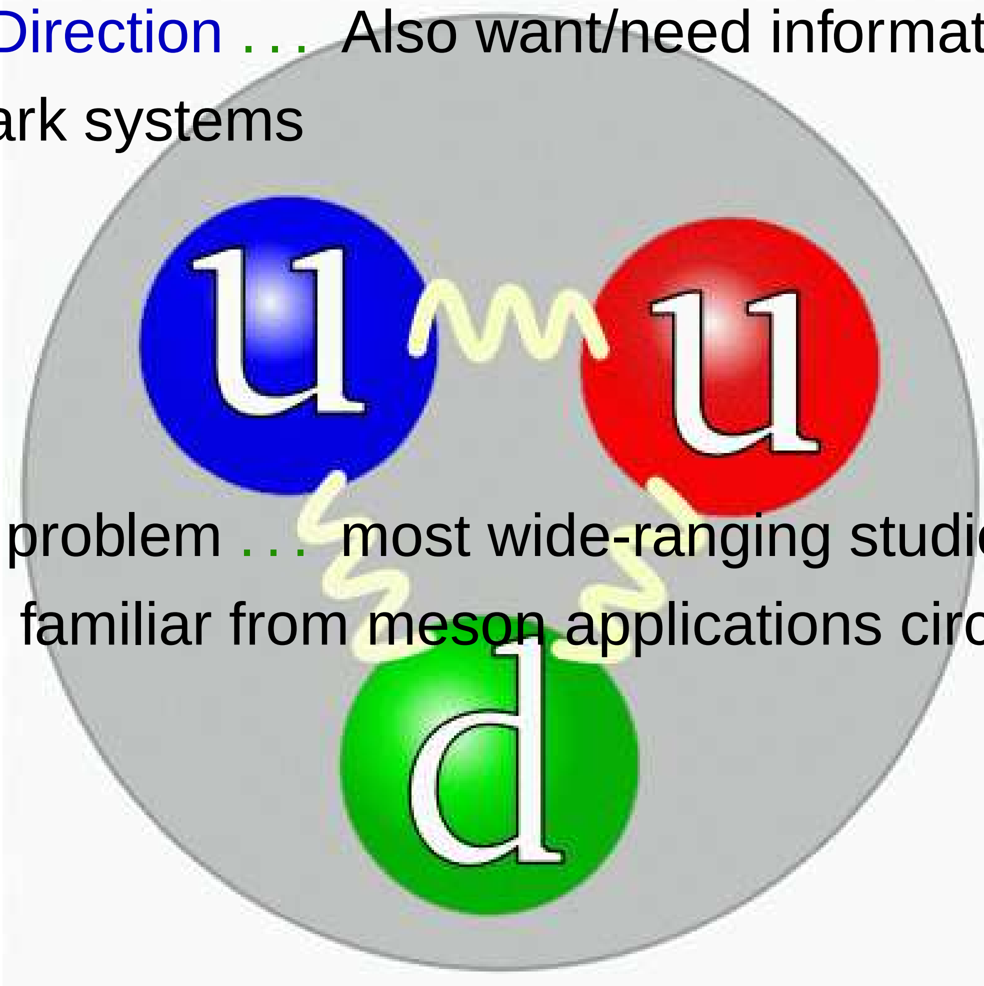

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- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.

New Challenges

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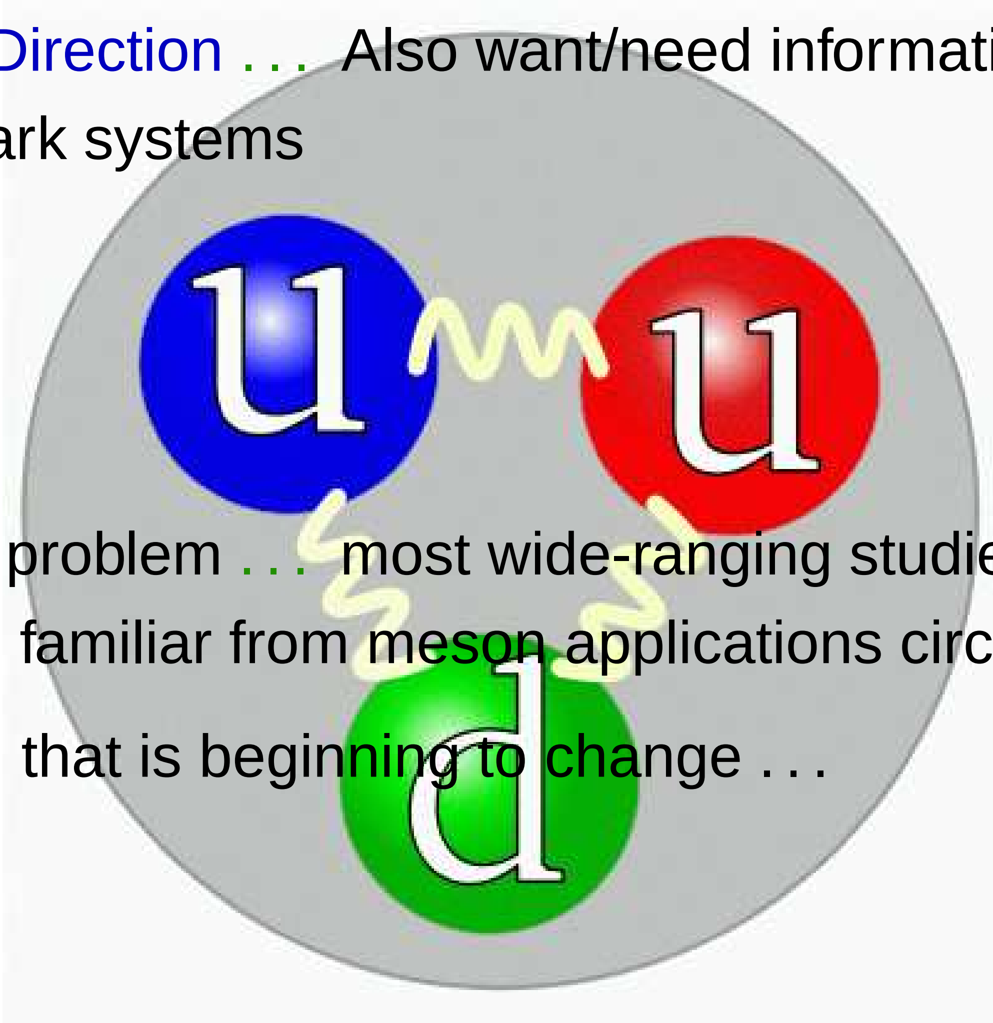

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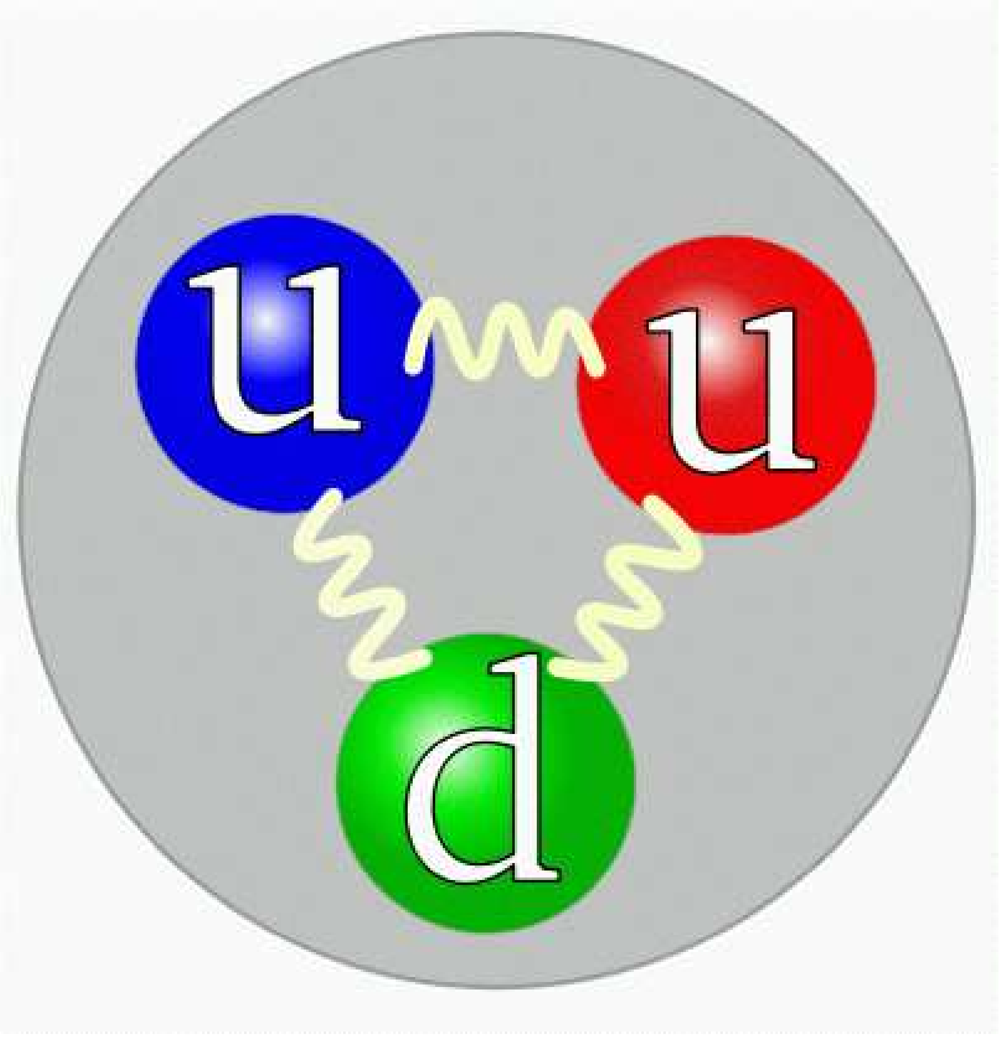
Nucleon . . .

Three-body Problem?



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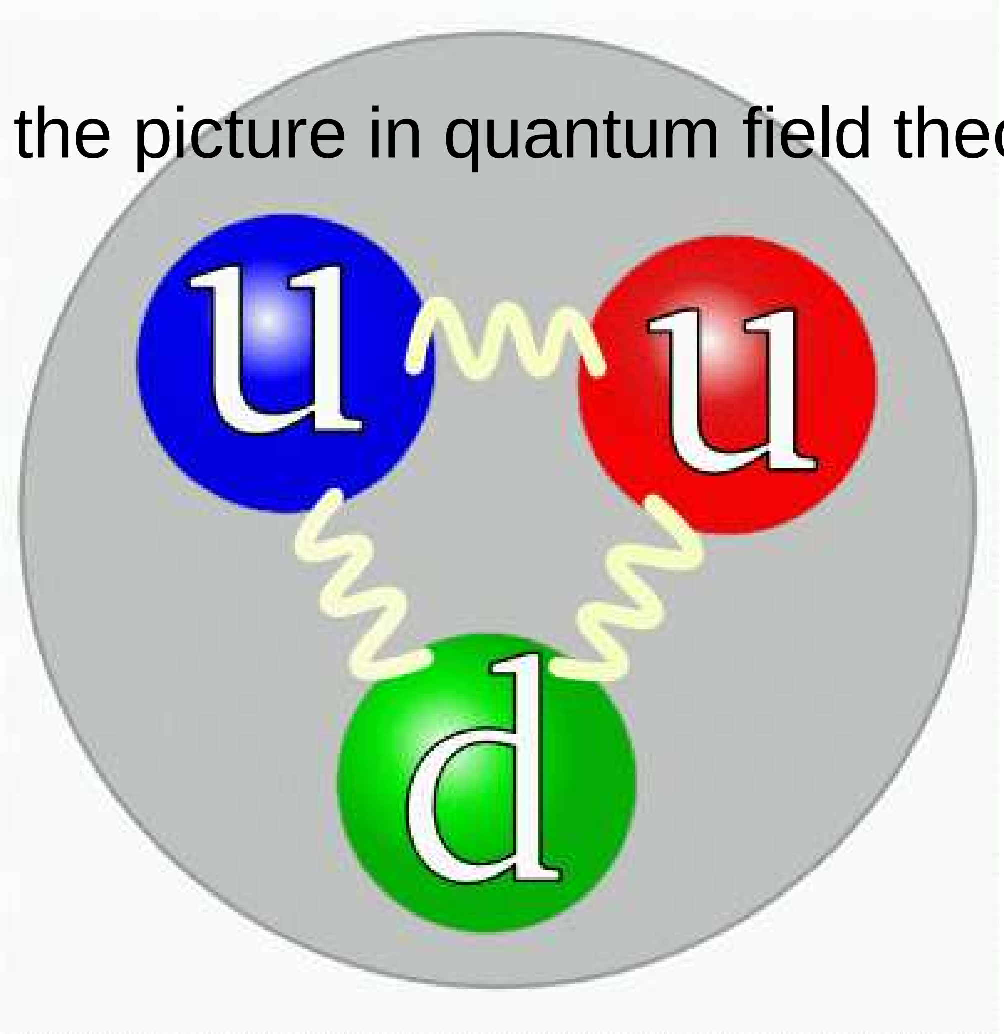

Three-body Problem?

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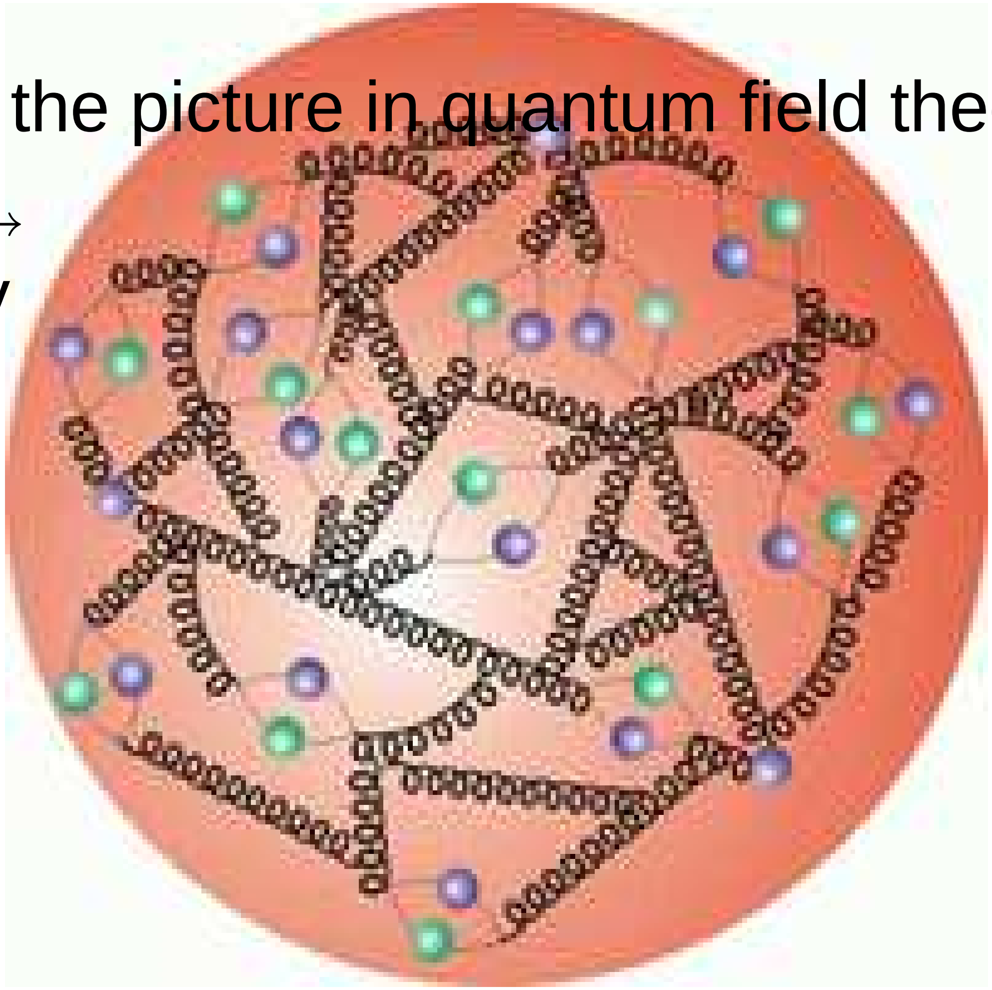

Unifying Study of Mesons and Baryons

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  - Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks

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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.
- 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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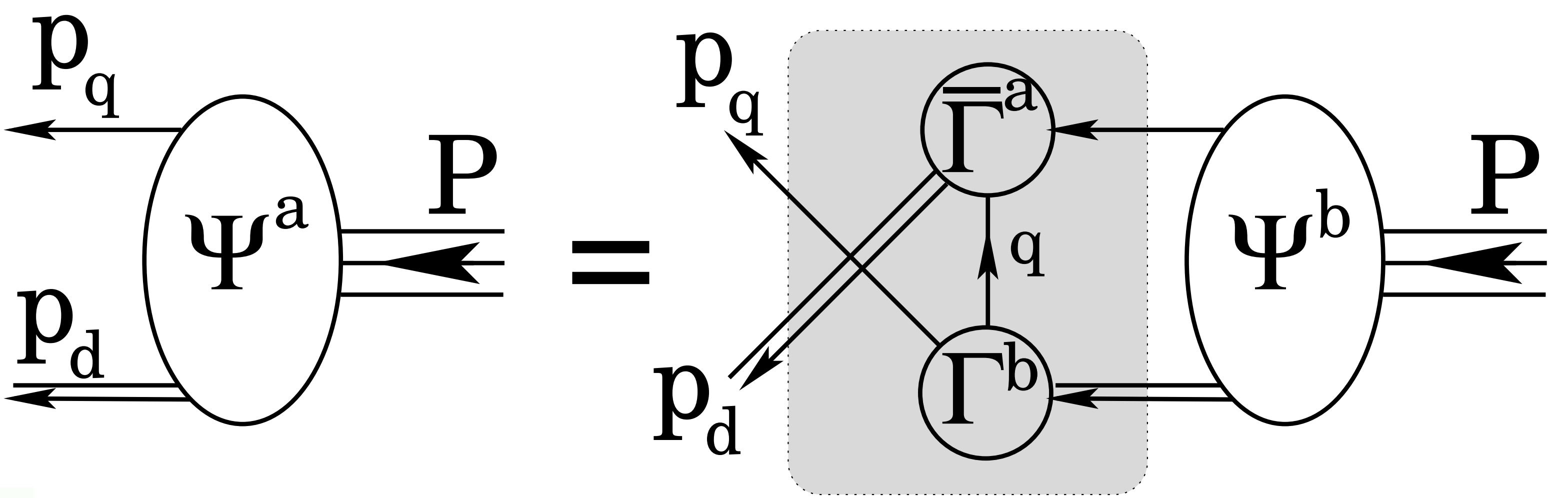
Faddeev equation

Faddeev equation



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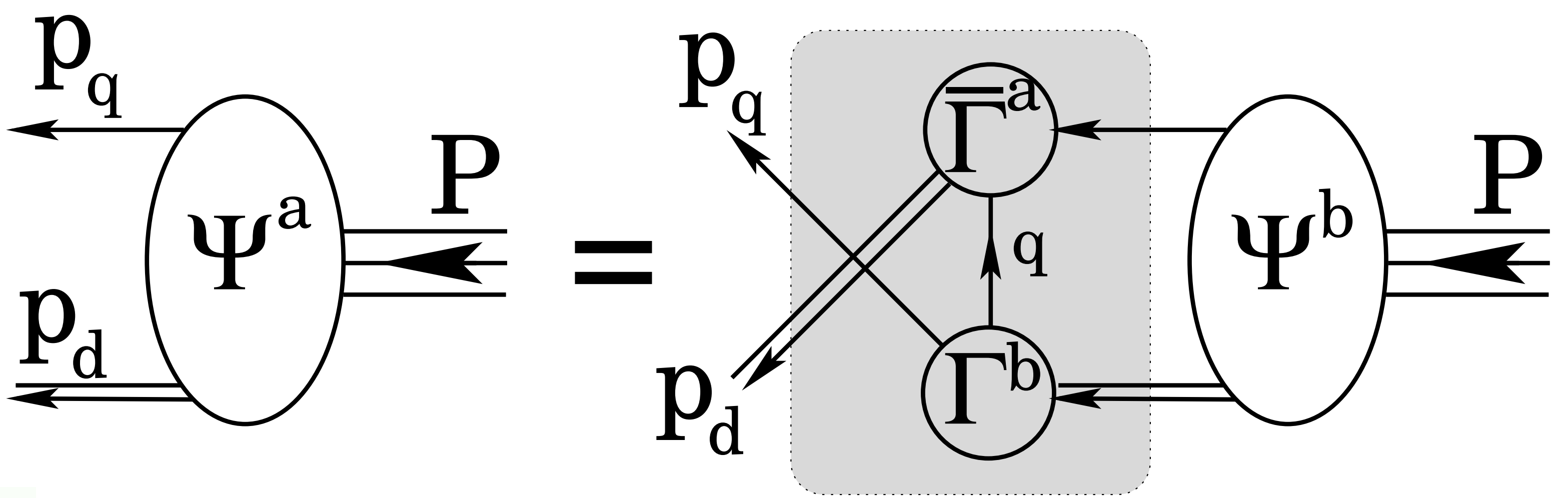

- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

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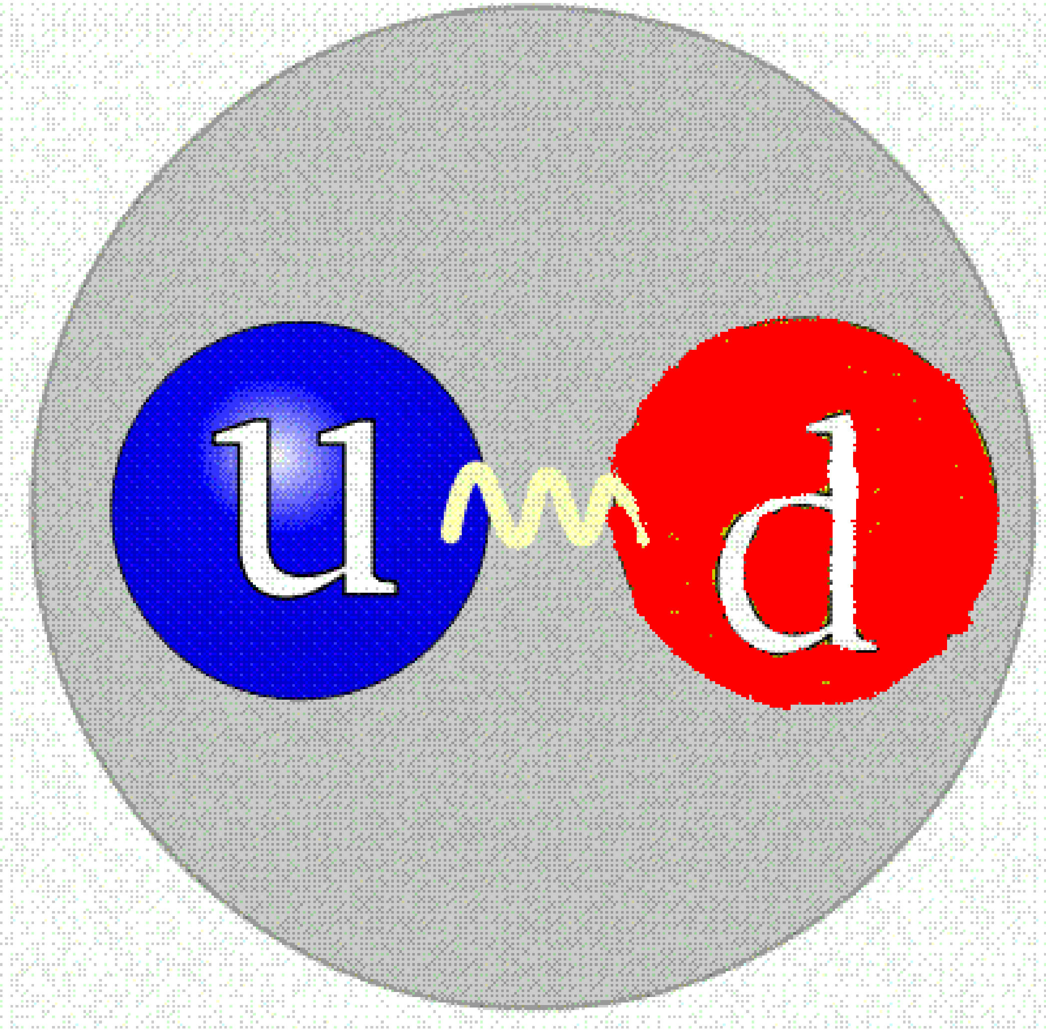
Diquark correlations



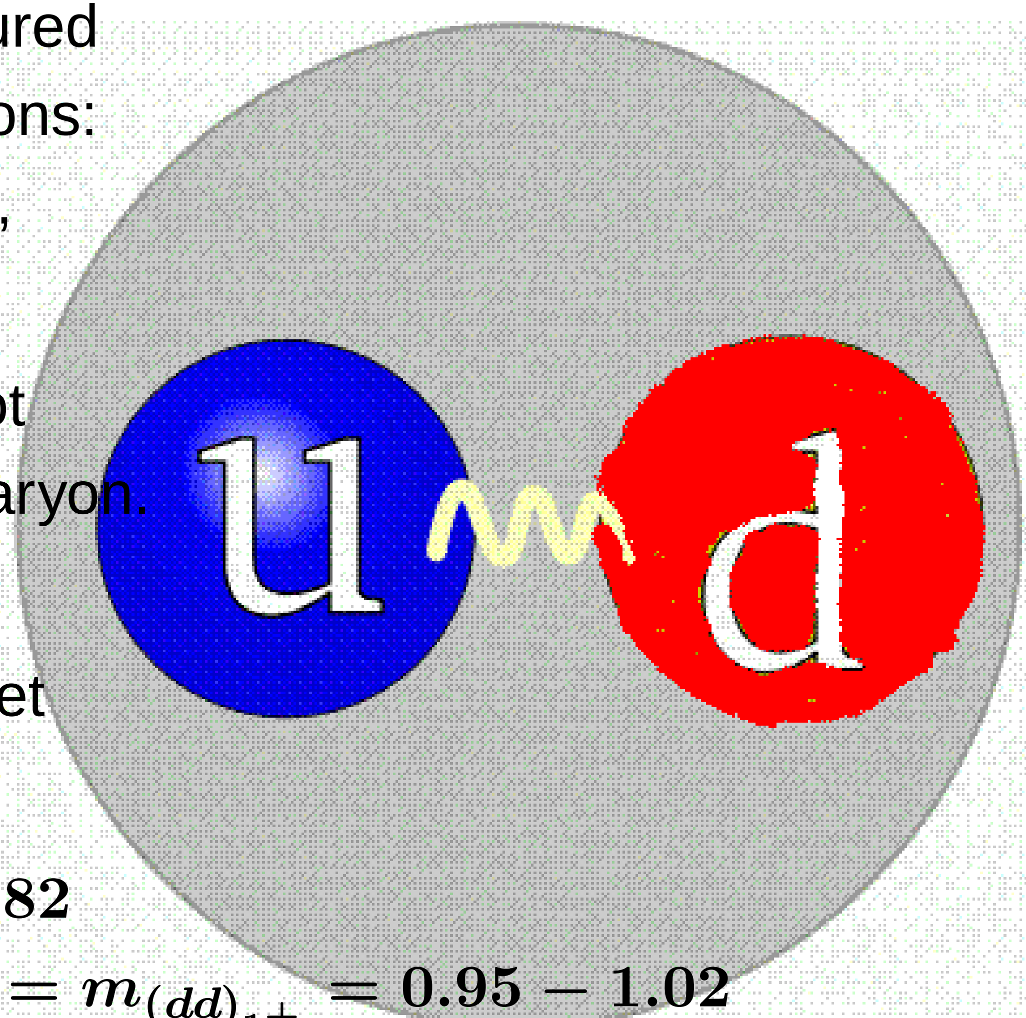
QUARK-QUARK

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

Ab-initio study
of mesons & nucleons

Eichmann *et al*.
– arXiv:0802.1948 [nucl-th]
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Ab-initio study of mesons & nucleons

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Ab-initio study of mesons & nucleons

- Leading-order truncation of DSEs – rainbow-ladder

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  - Roughly 50/50-split between nonresonant and resonant (pseudoscalar meson loop) contributions

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- Symmetry preserving and systematic approach can elucidate and account for these effects
  - Use this knowledge to constrain interaction in infrared
  - Interaction in ultraviolet predicted by perturbative expansion of DSEs

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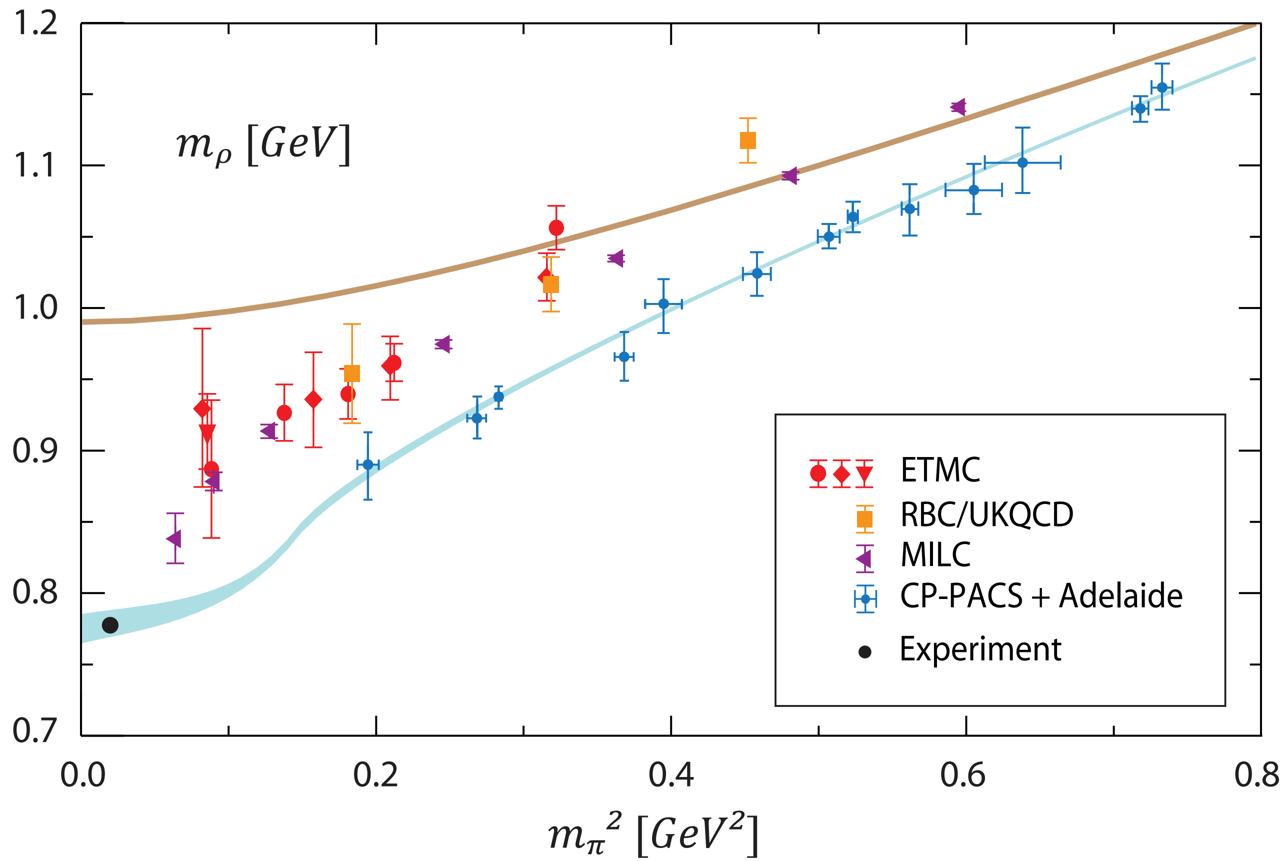

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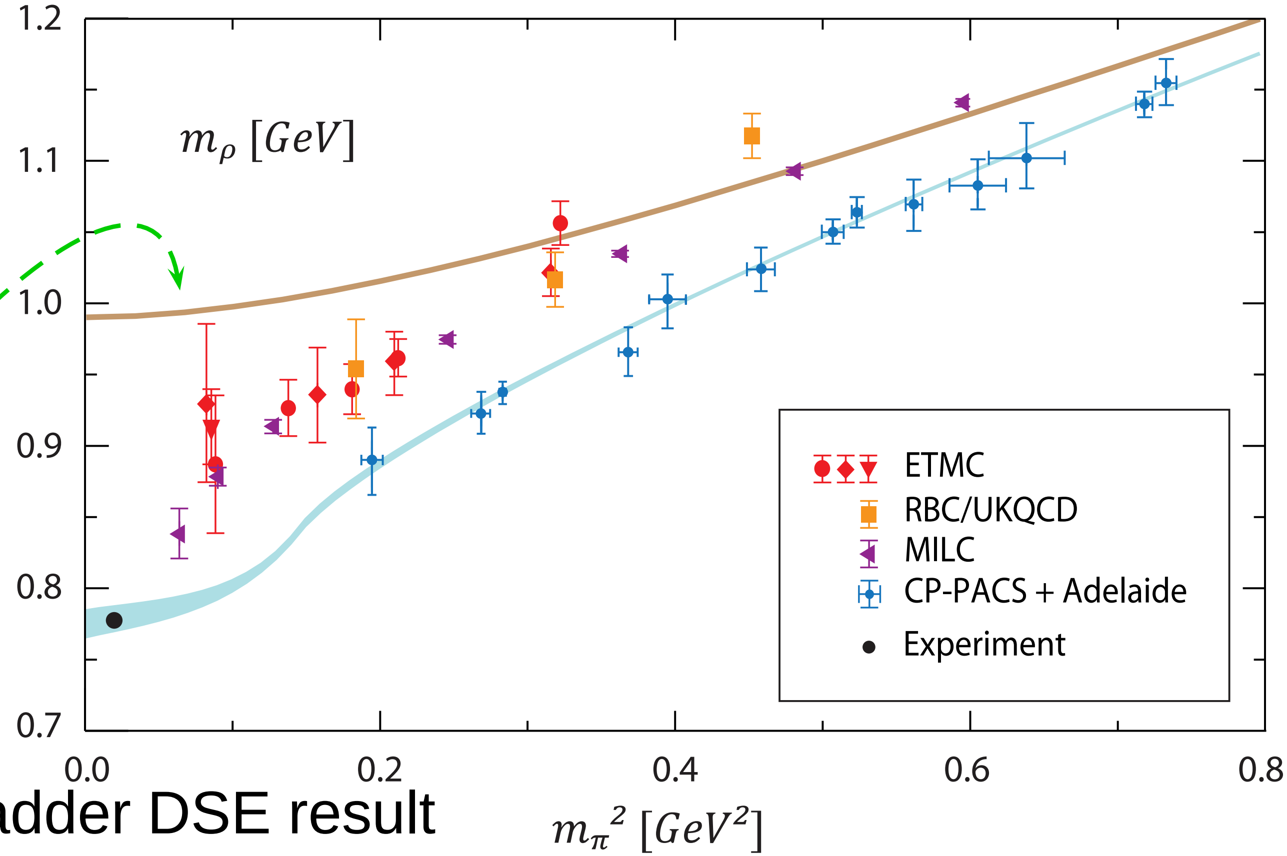

- Rainbow-Ladder DSE result

one parameter for IR – "confinement radius"

Results insensitive to value on material domain

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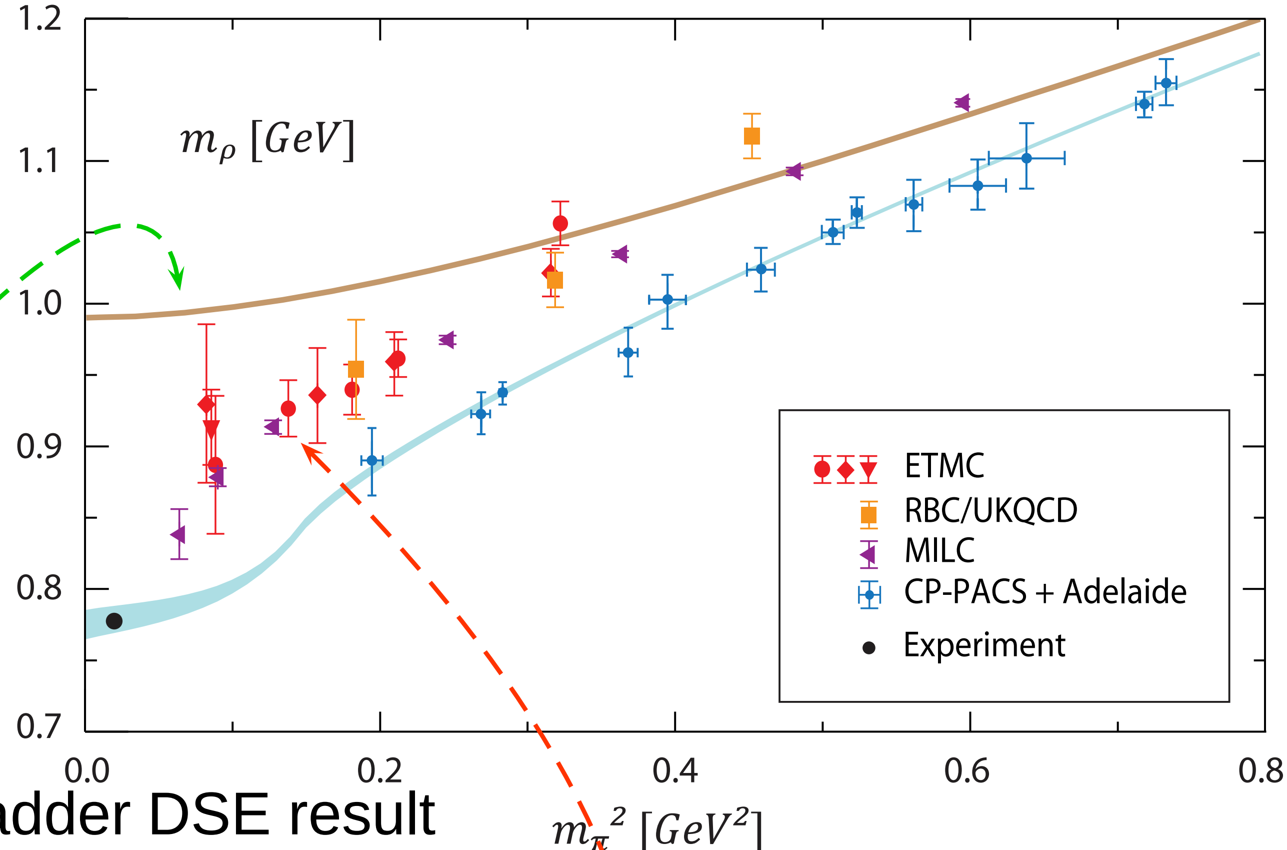

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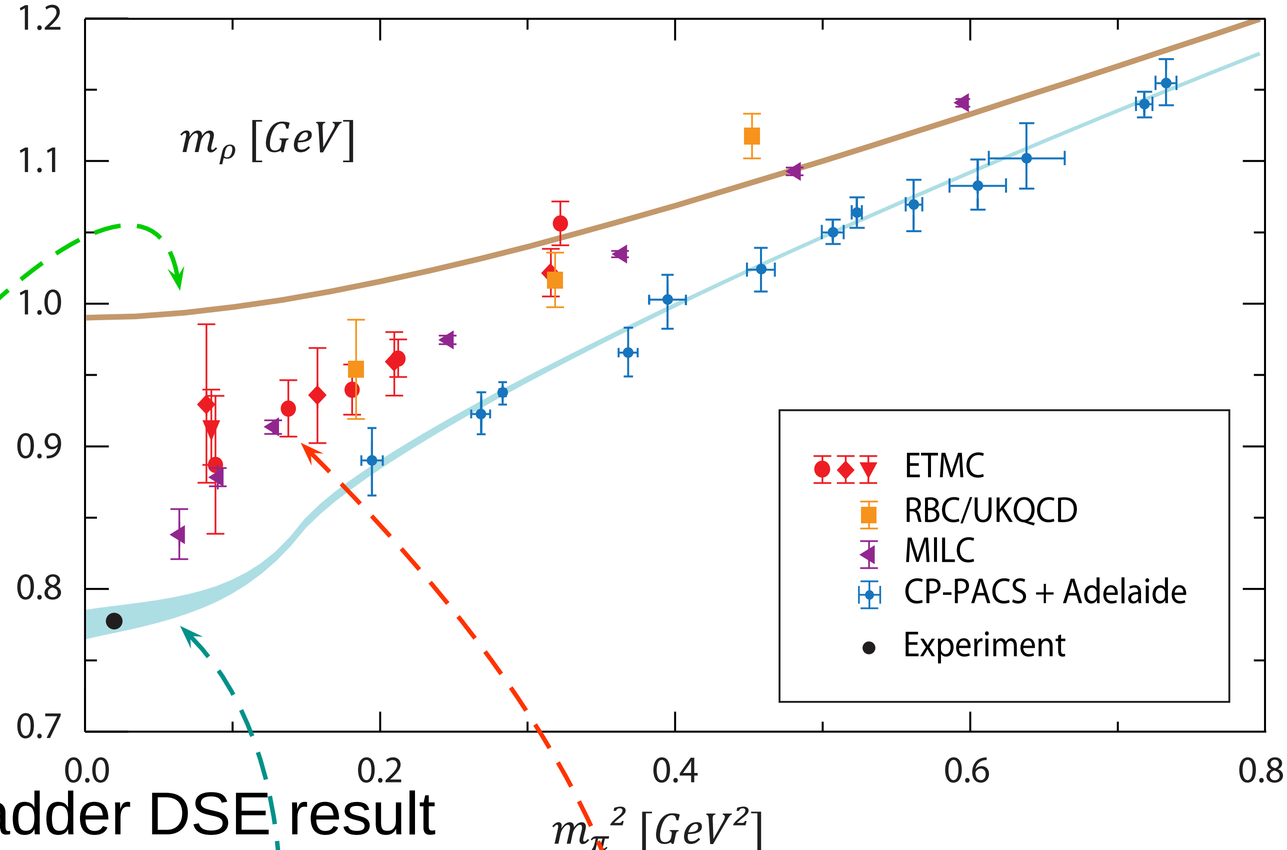

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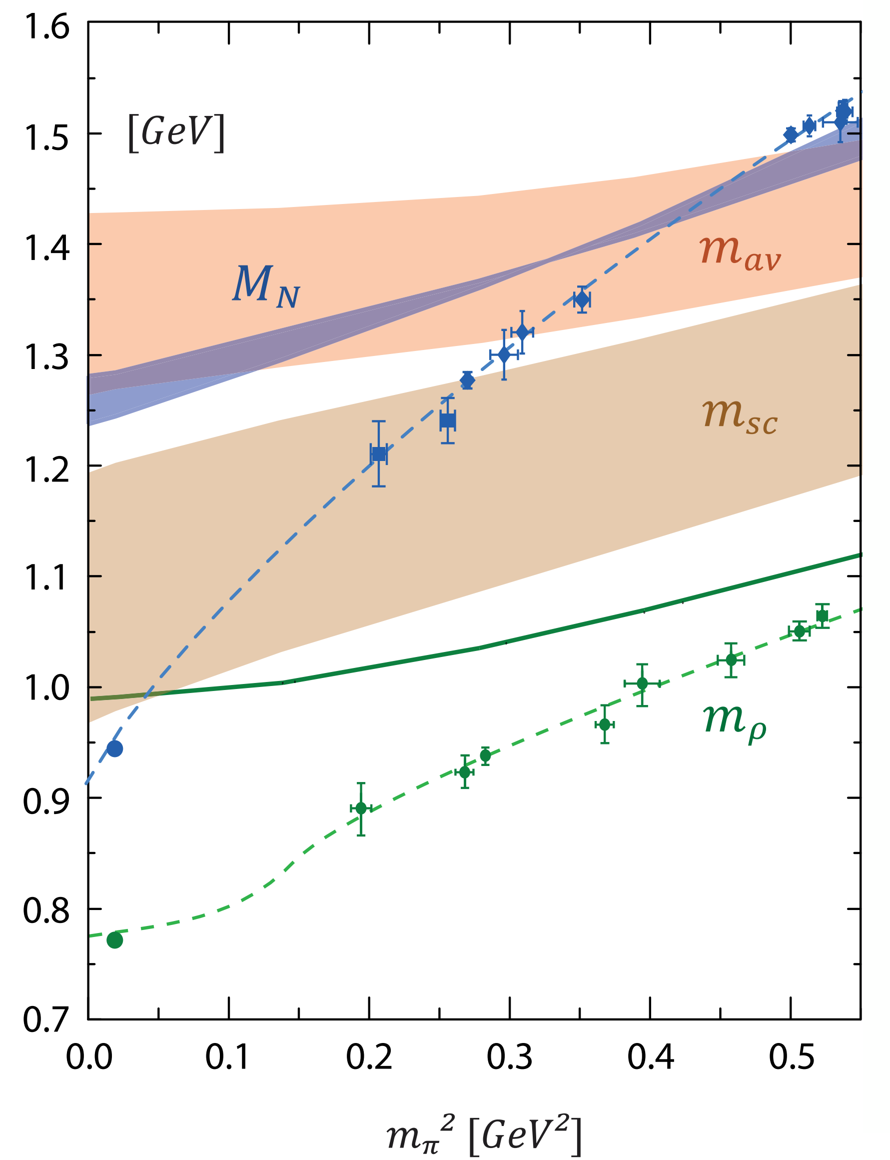

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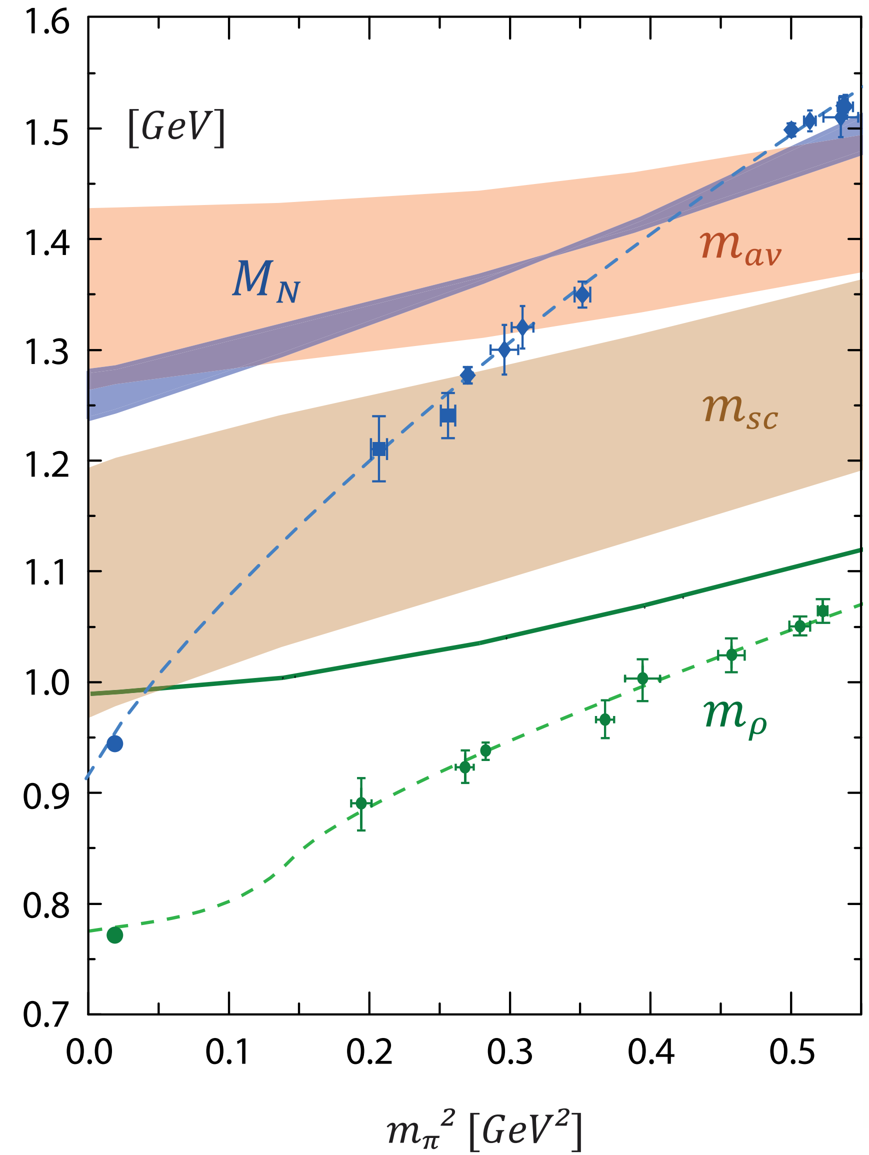

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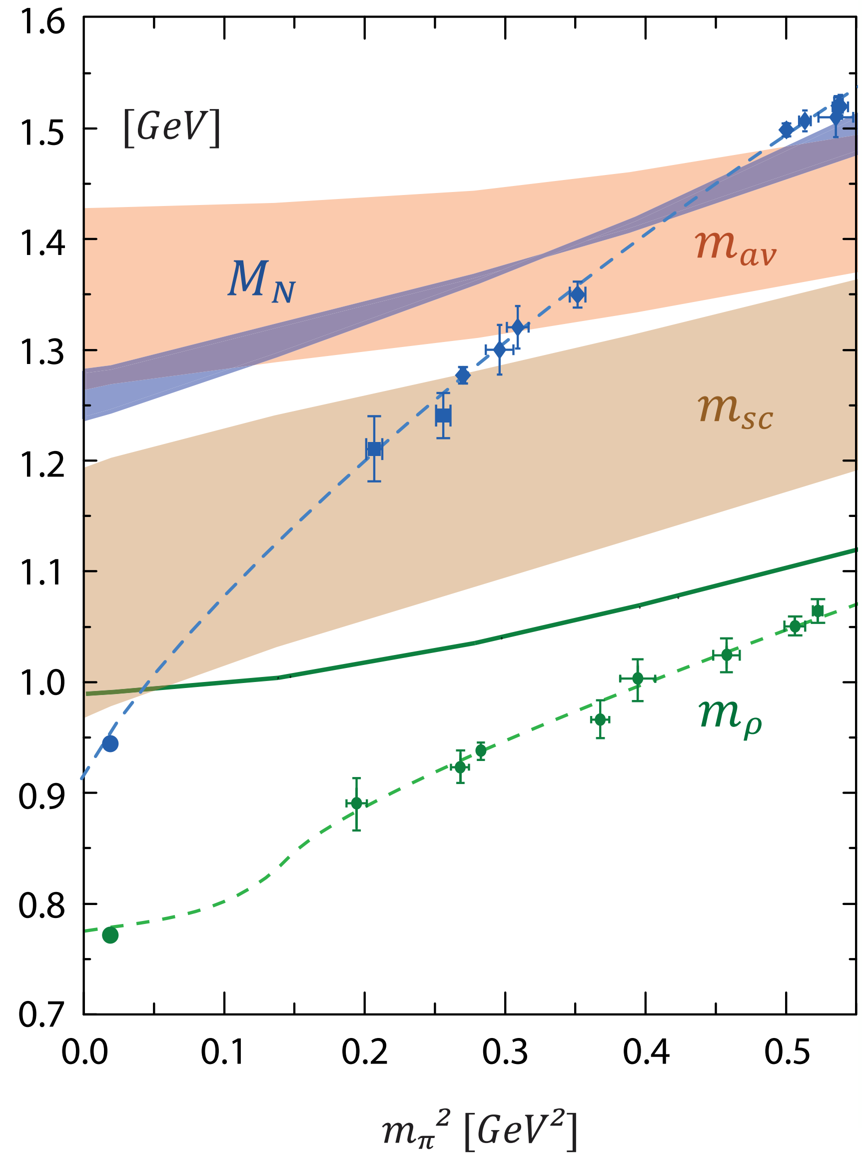
- But … $[m_{av} - m_{sc}]$, m_ρ & M_N … are *independent* of that parameter



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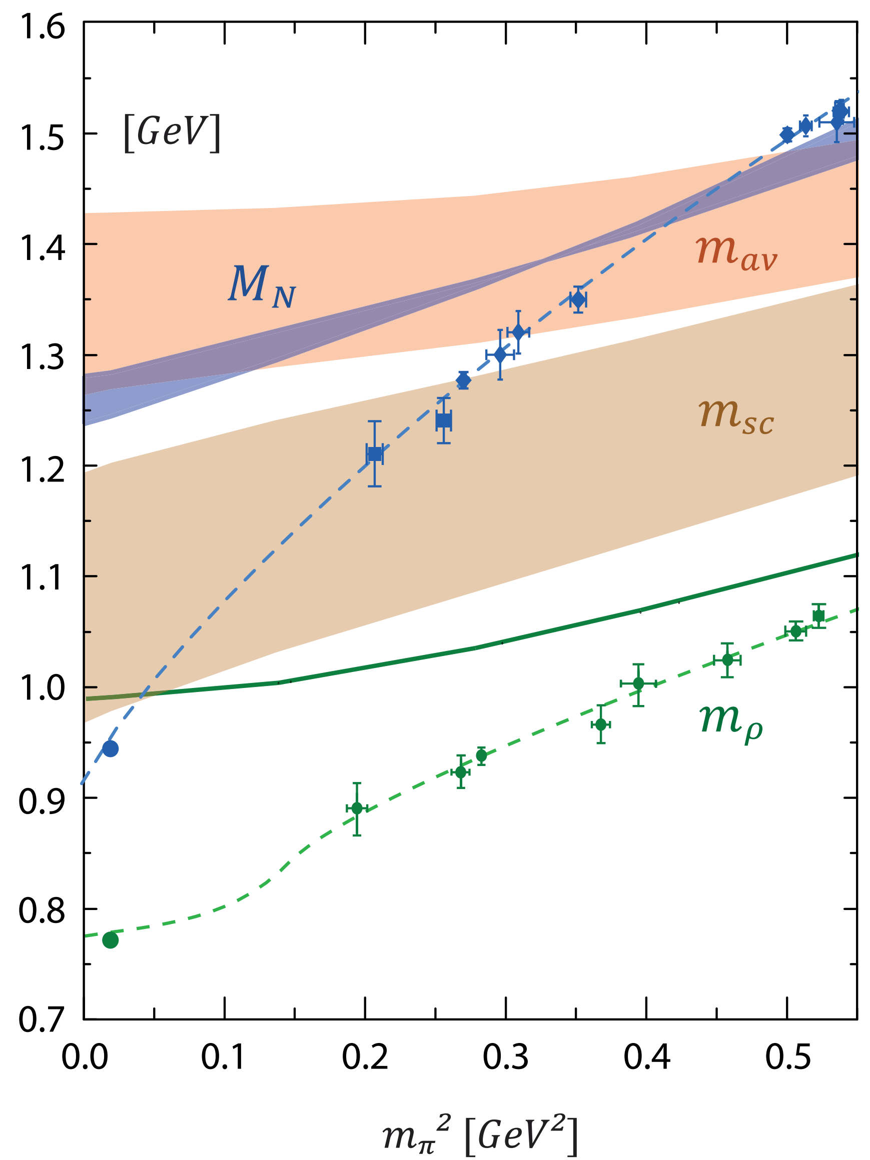

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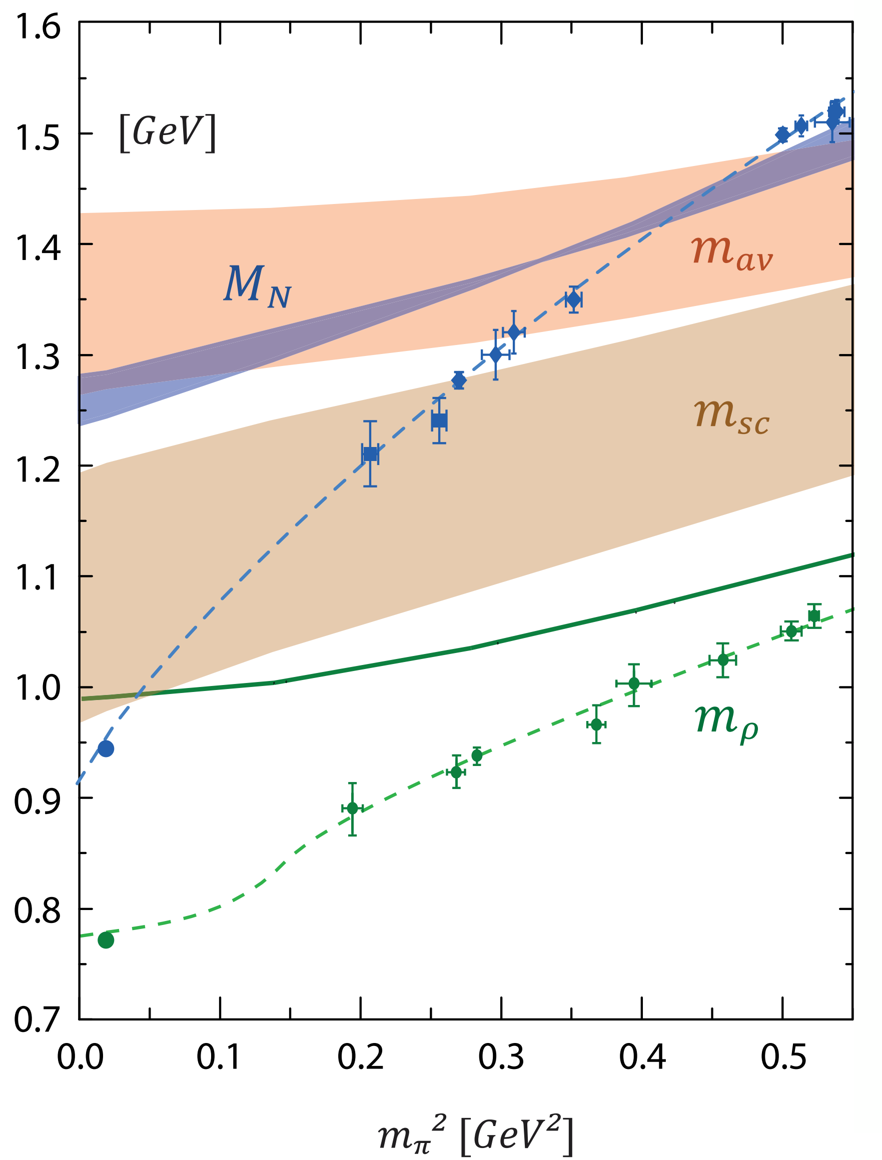

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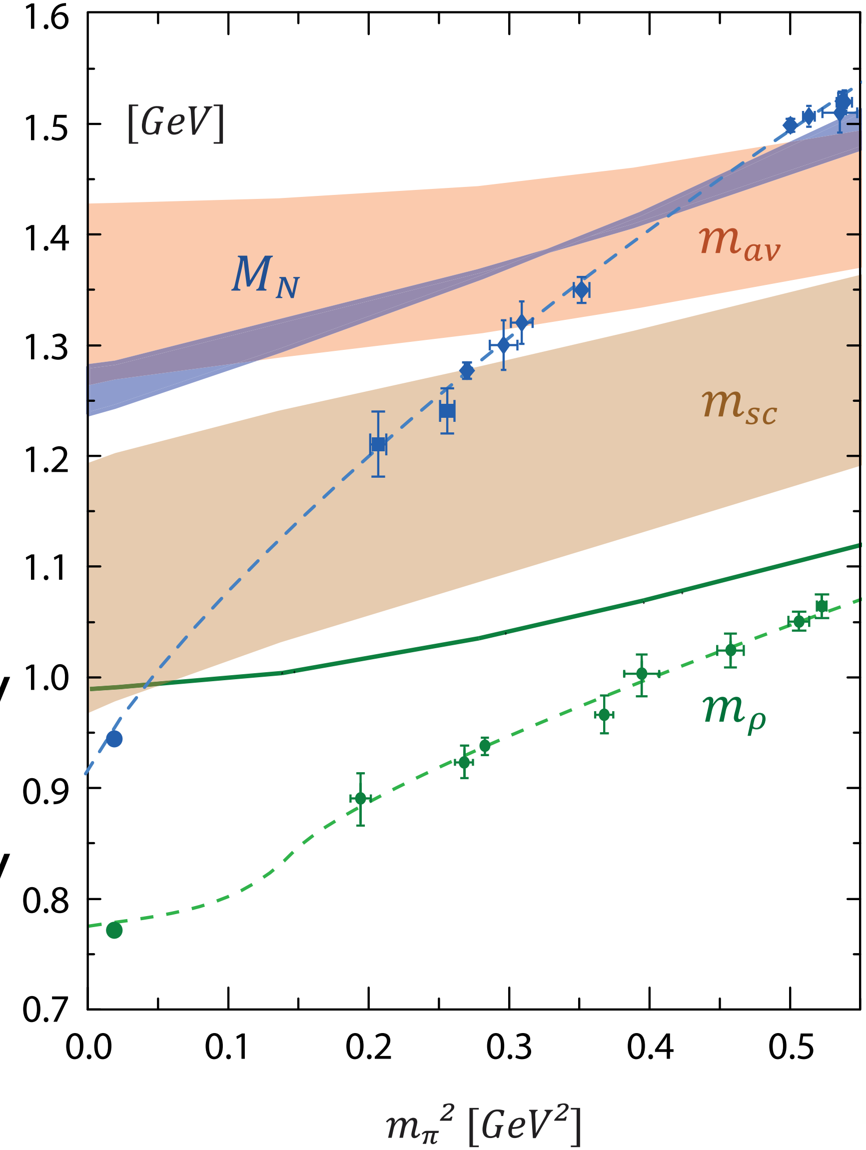
- Prediction: at physical m_π^2, $M_N^{\text{quark}-\text{core}} = 1.26(2)$ GeV cf. FRR+lattice-QCD, $M_N^{\text{quark}-\text{core}} = 1.27(2)$ GeV

$\Rightarrow$ subleading corrections, including 0^--meson loops, $\delta M_N = -320$ MeV, $\delta m_\rho = -220$ MeV



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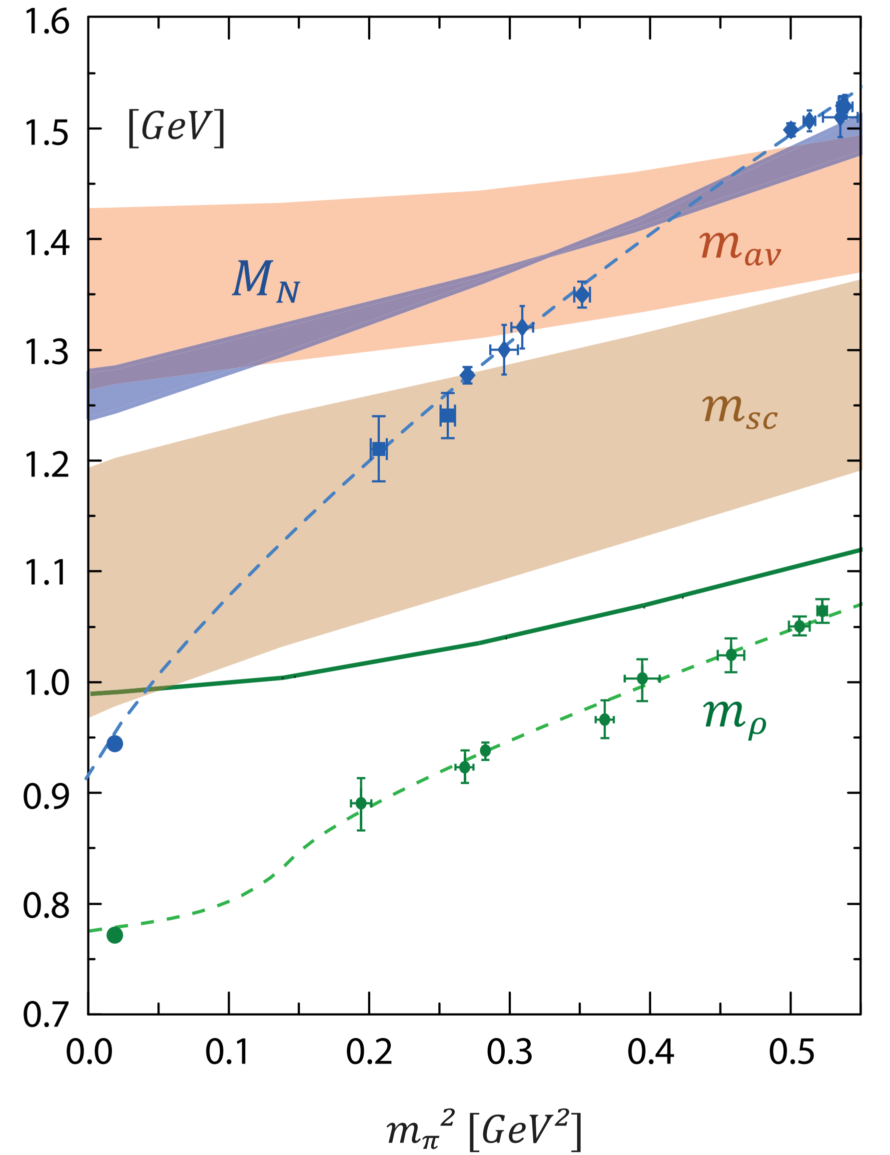

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Office of Nuclear Physics
Argonne NATIONAL LABORATORY

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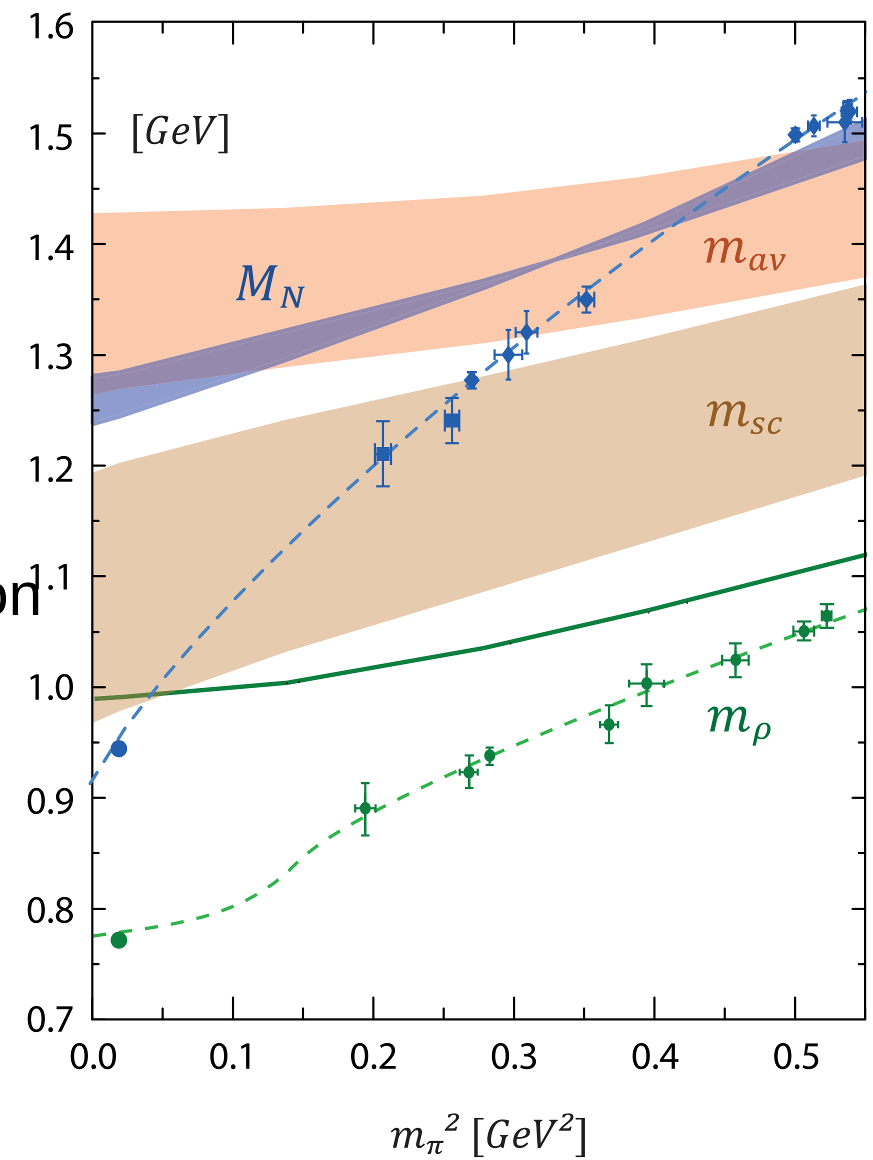

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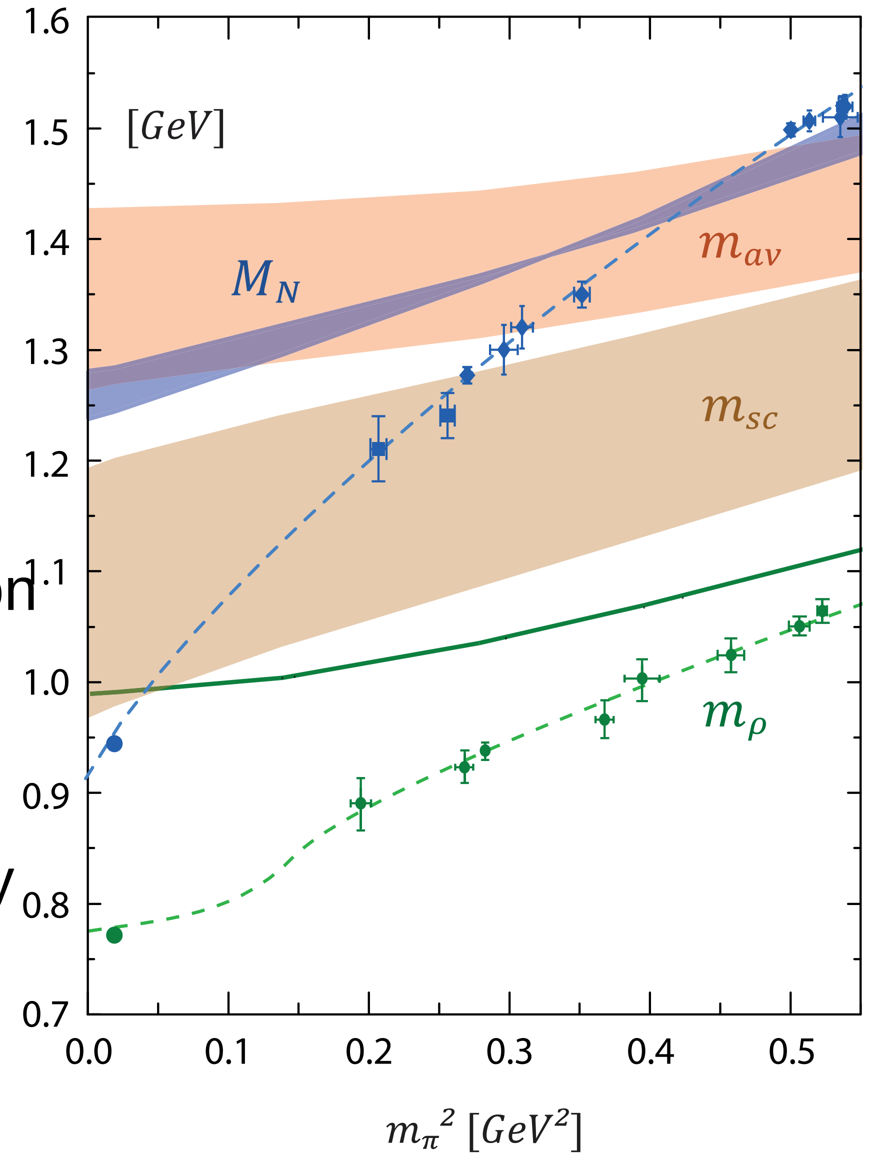

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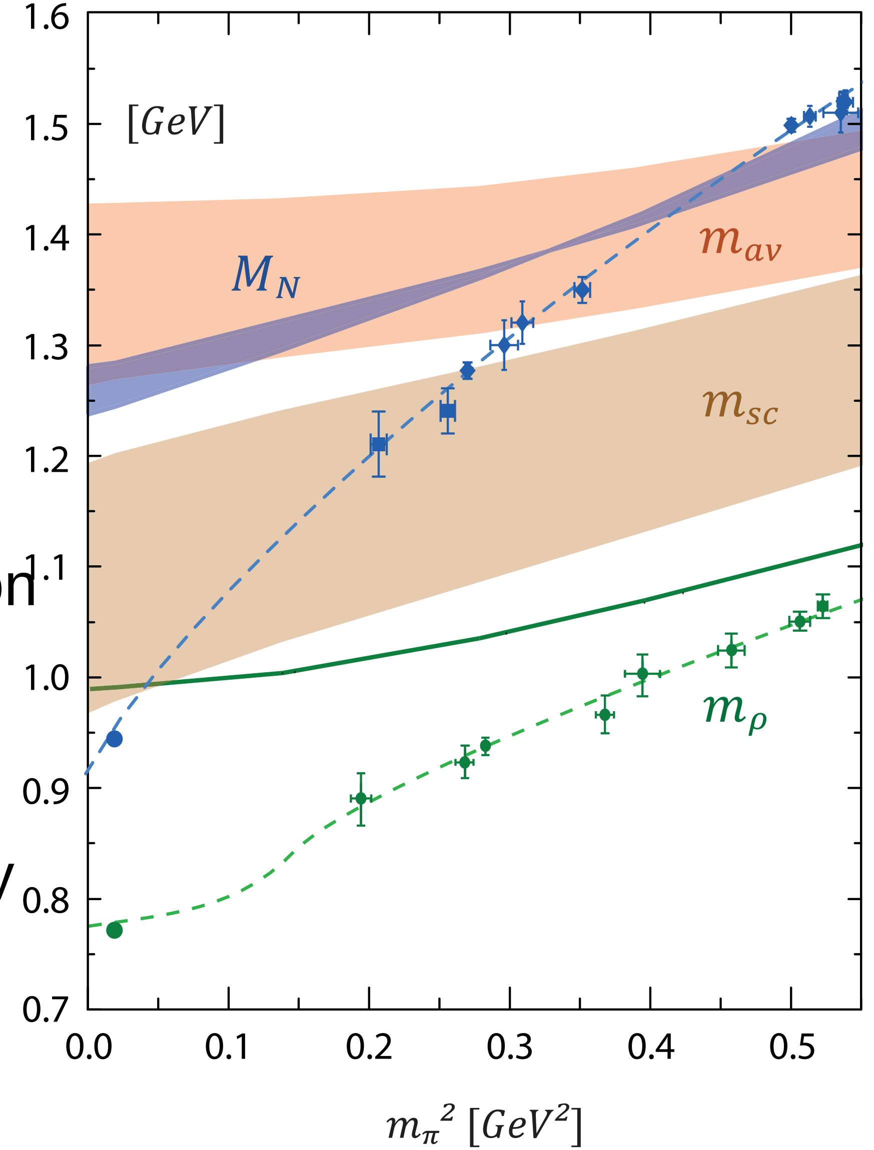

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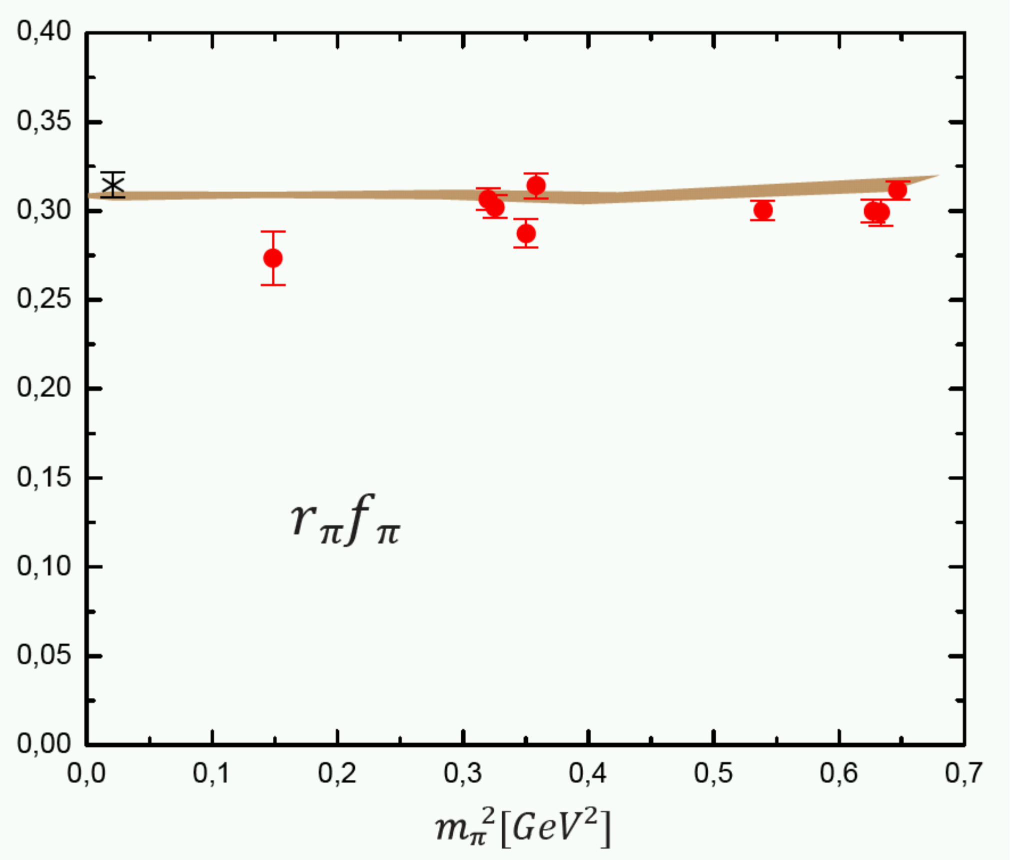

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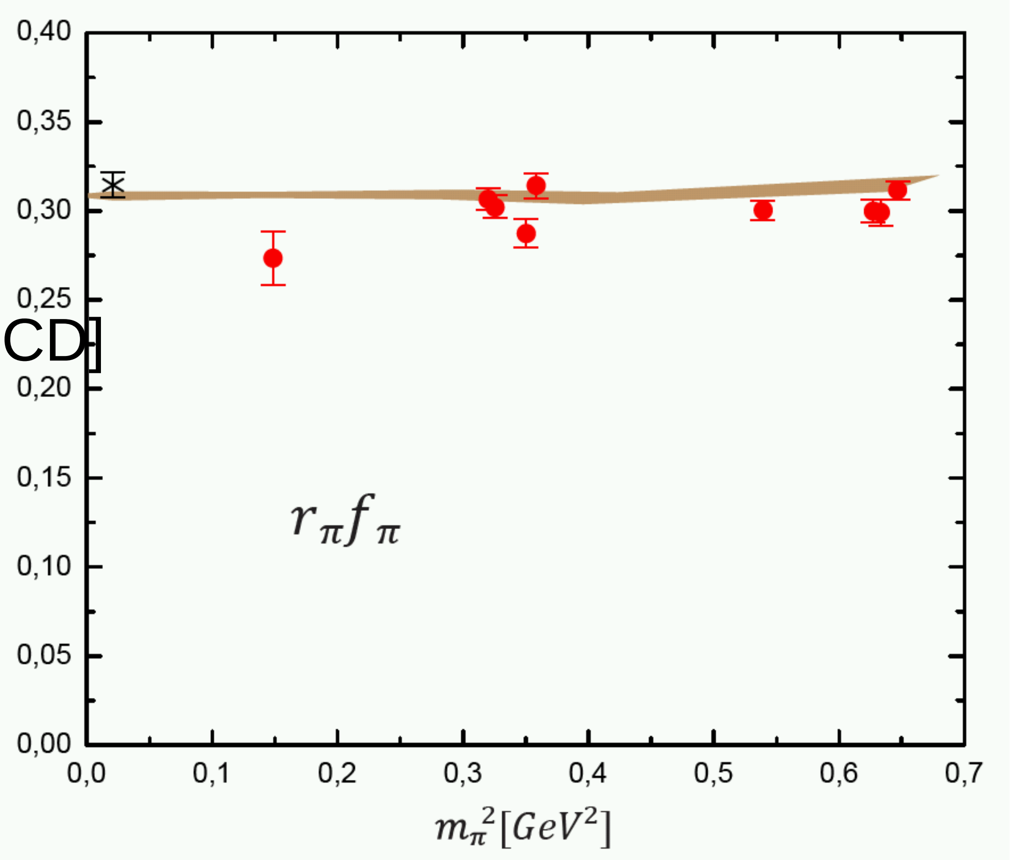

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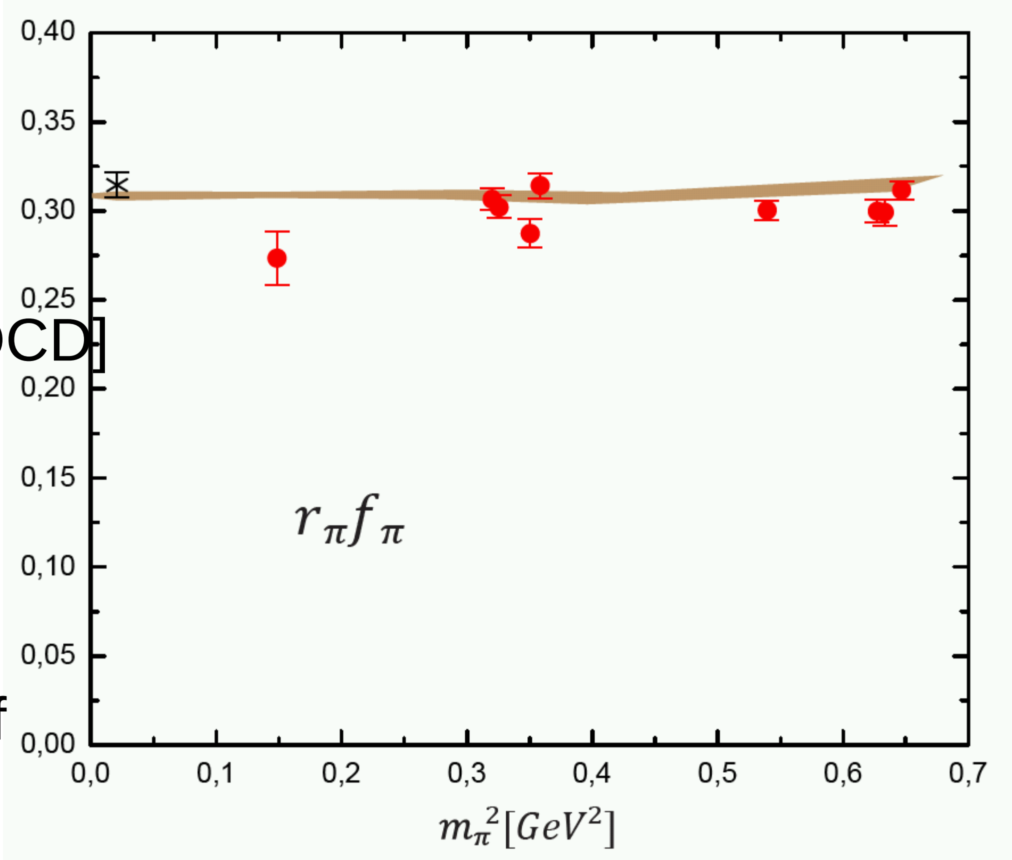

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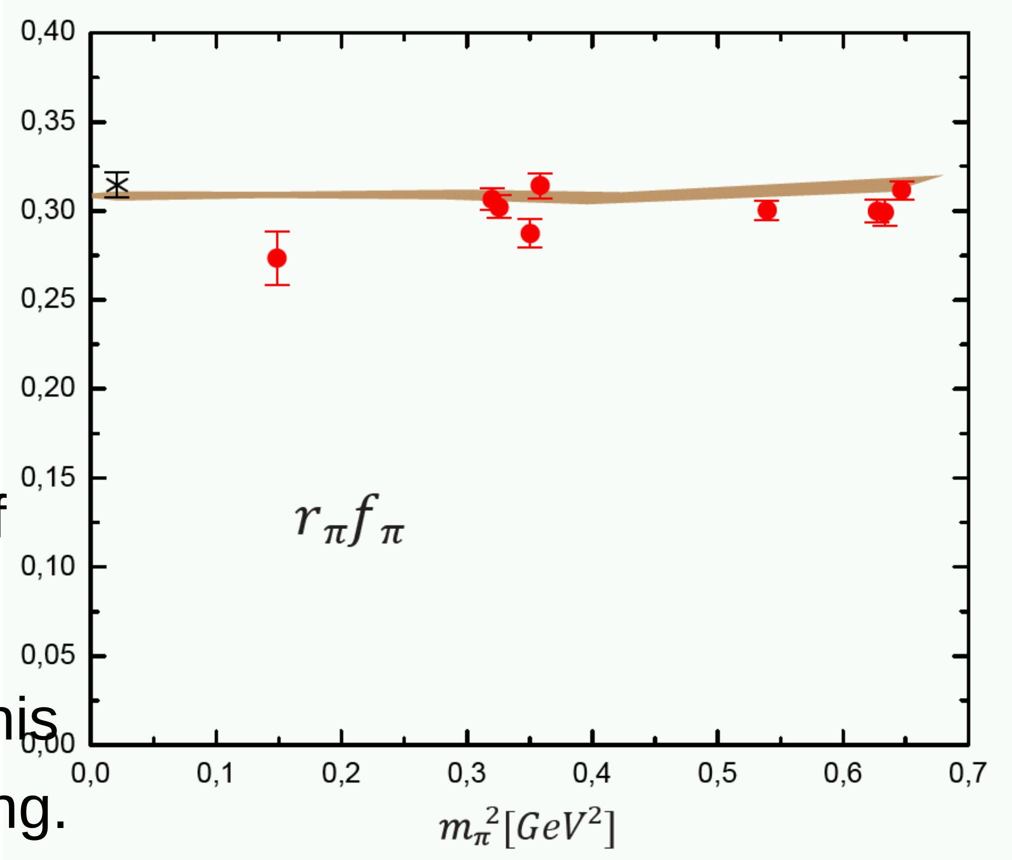

- DSE prediction
- Fascinating result:
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  obtains independent of
  current-quark mass.
- We have understood this.
  Implications far-reaching.

Nucleon-Photon Vertex

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

Nucleon-Photon Vertex

6 terms . . .

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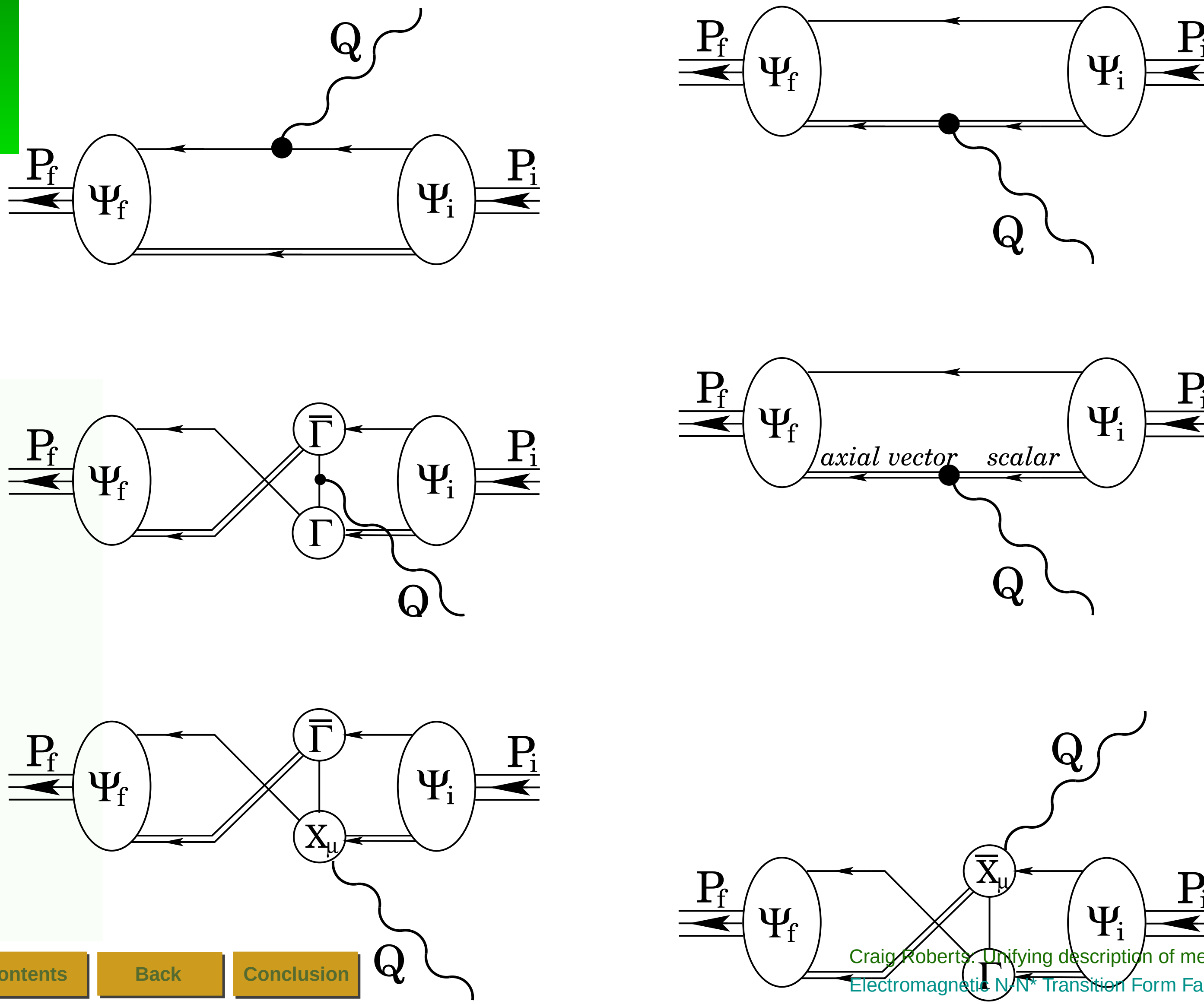

DSE-based
Faddeev Equation

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Cloët *et al.*
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  – $M_{0^+} = 0.8$ GeV,
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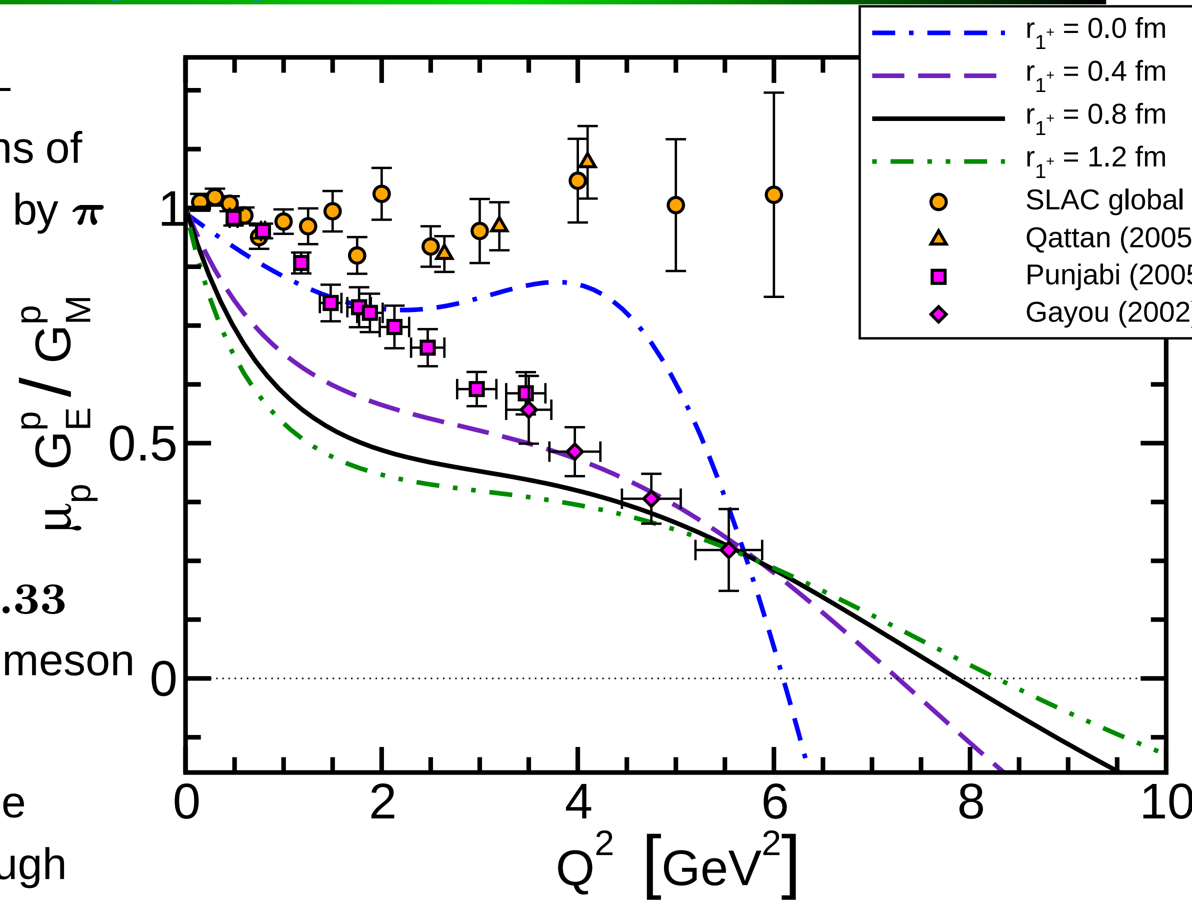

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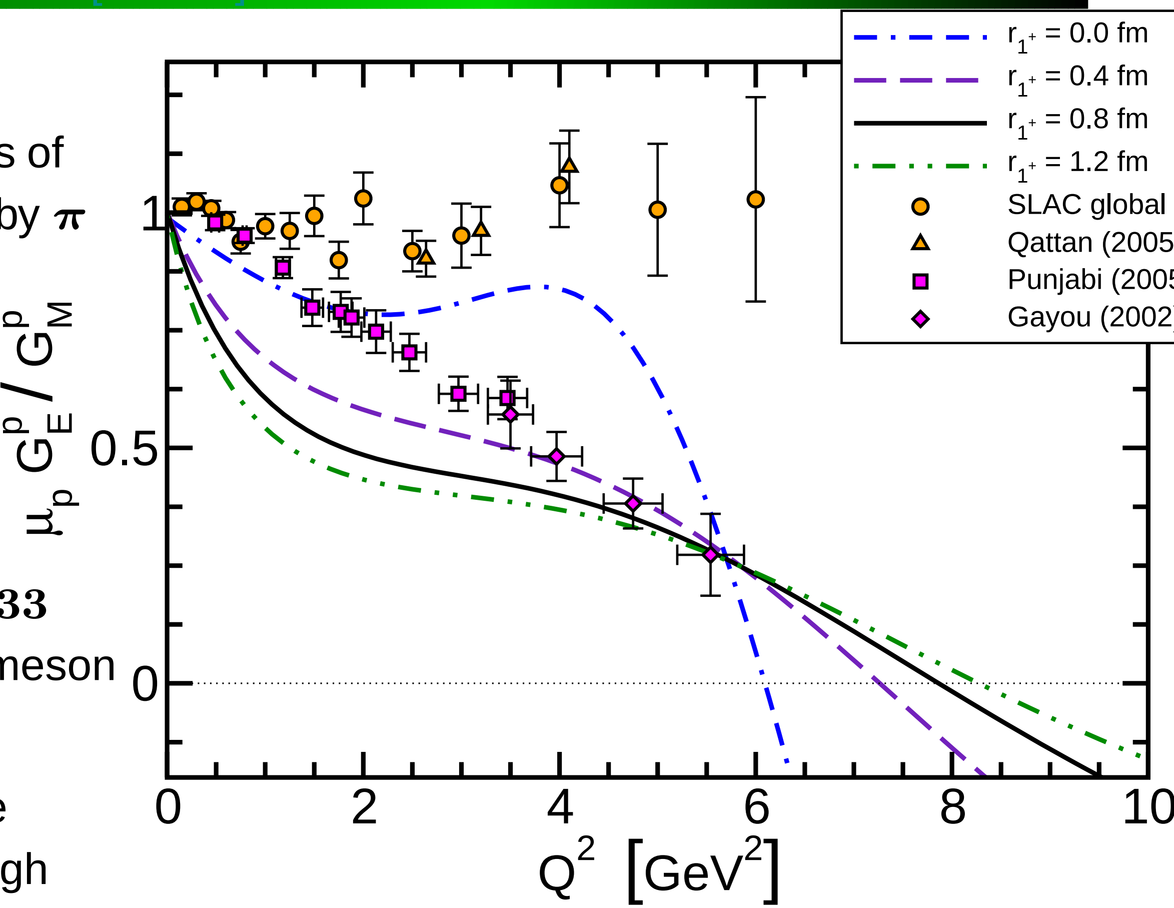

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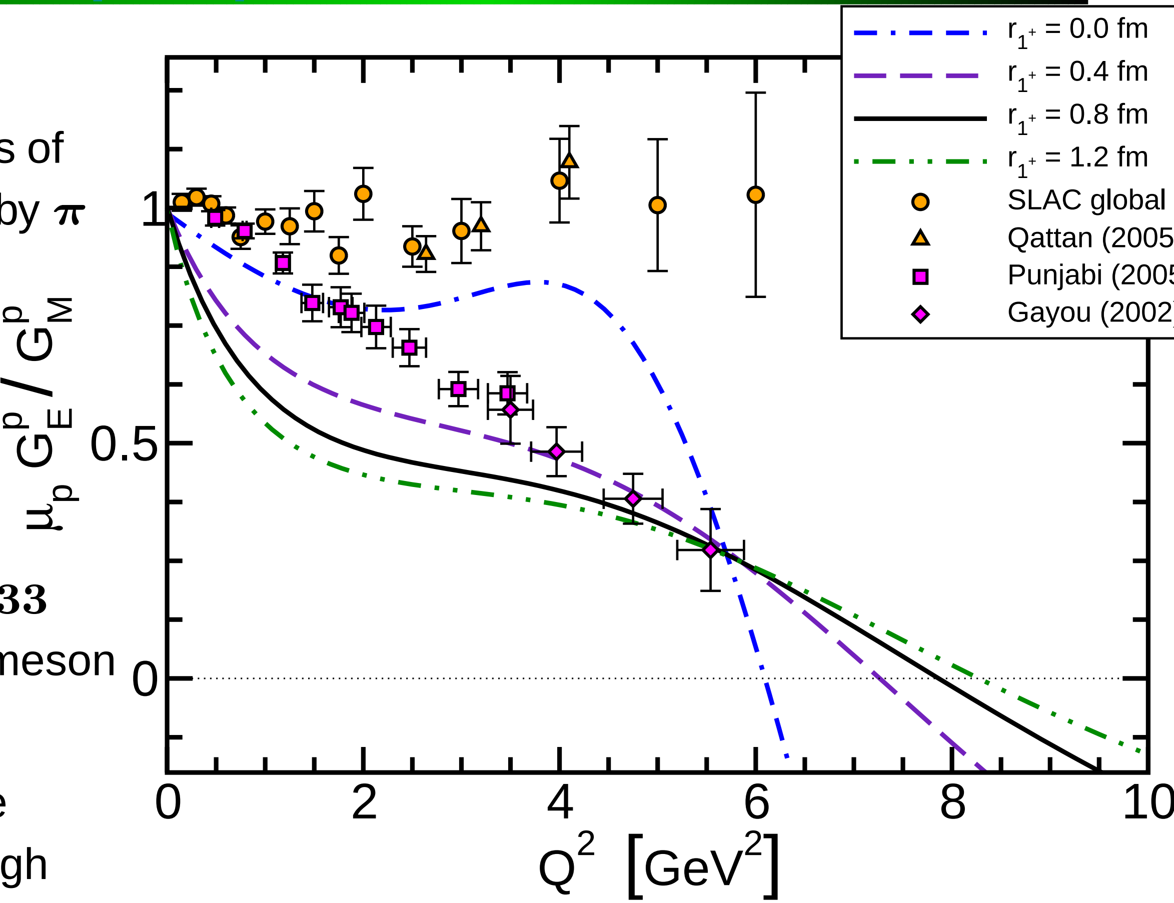

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ab initio
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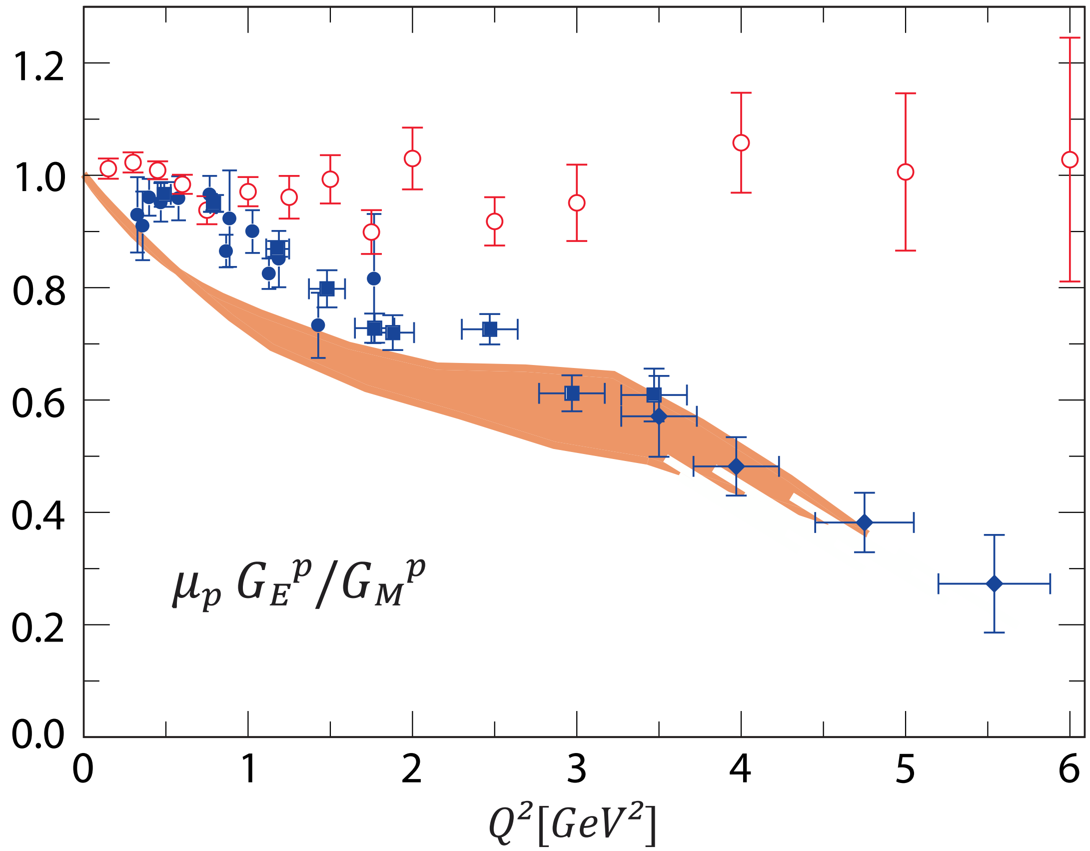

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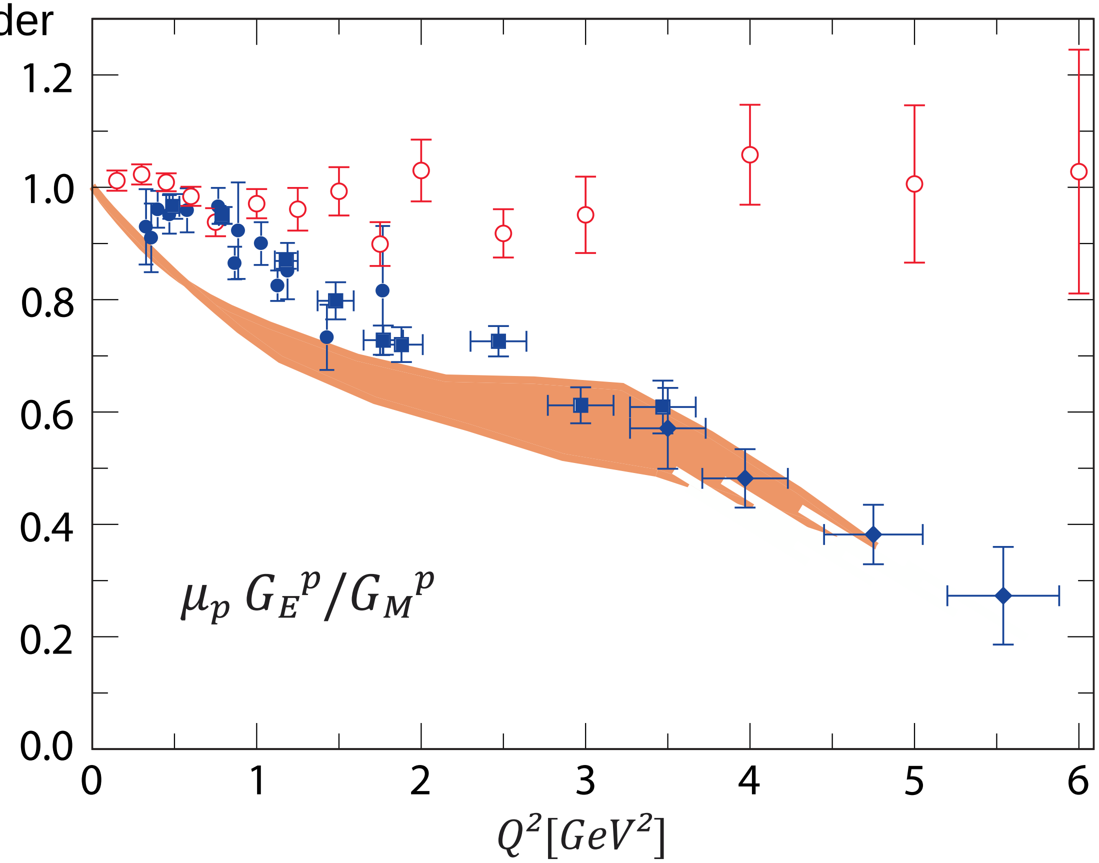

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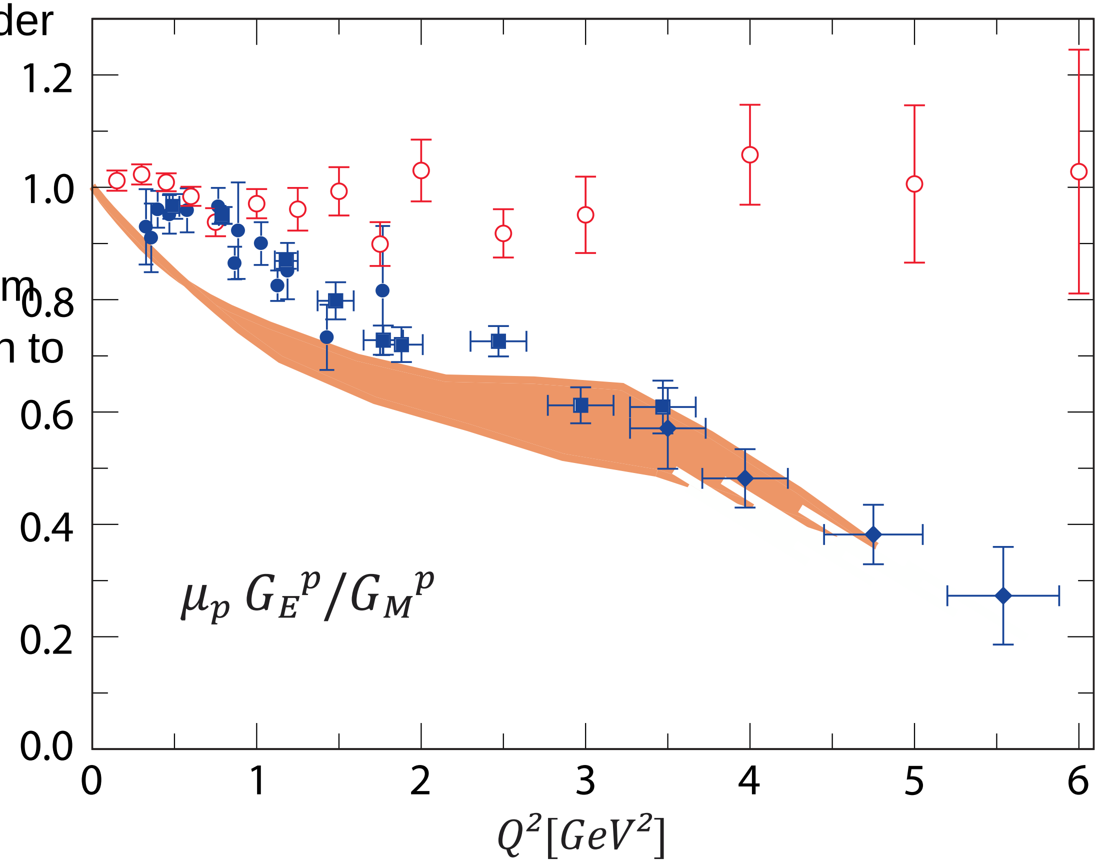

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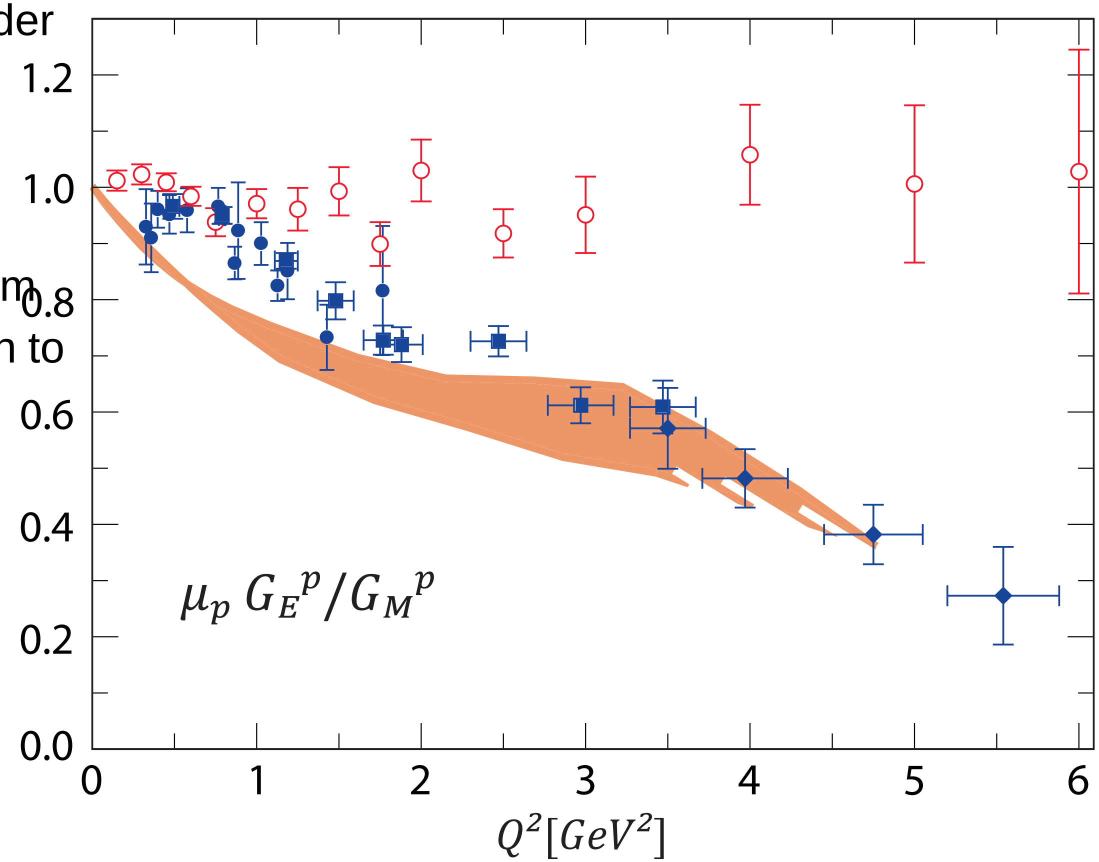

- Calculation unifies π, ρ and nucleon properties – keystone is behaviour of dressed-quark mass function and hence veracious description of QCD's Goldstone mode

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Ratio of Neutron Pauli & Dirac Form Factors

- $$\frac{\hat{Q}^2}{(\ln \hat{Q}^2/\hat{\Lambda})^2} \frac{F_2^n(\hat{Q}^2)}{F_1^n(\hat{Q}^2)}$$

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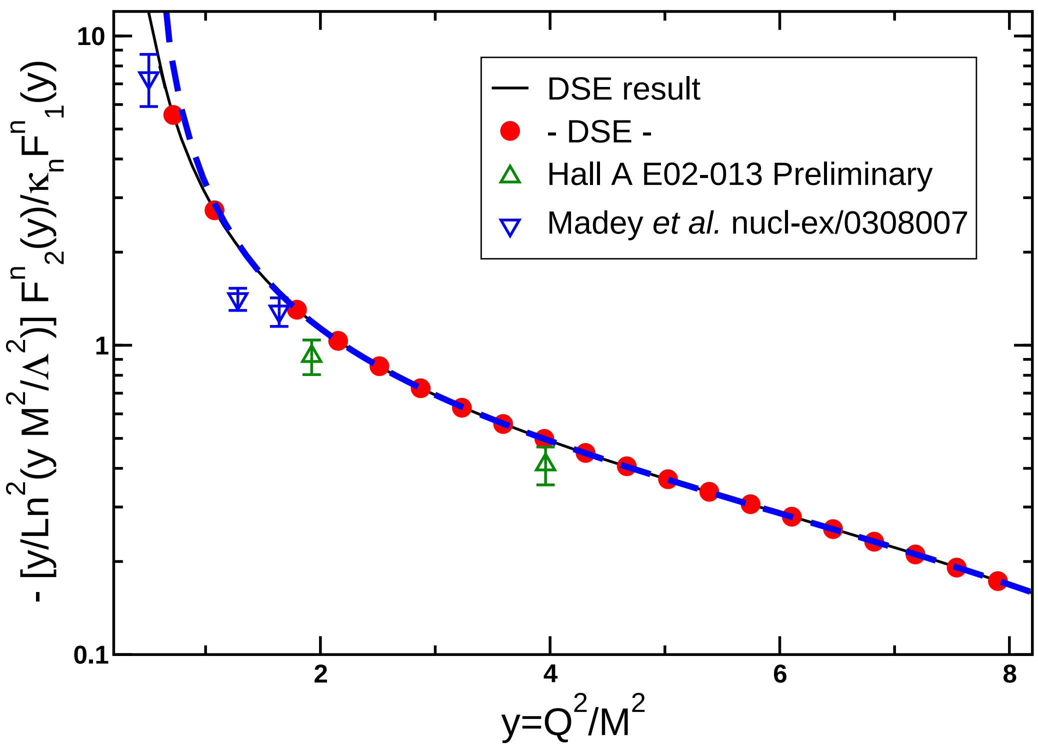

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Ratio of Neutron Pauli & Dirac Form Factors

- $$\frac{\hat{Q}^2}{(\ln \hat{Q}^2/\hat{\Lambda})^2} \frac{F_2^n(\hat{Q}^2)}{F_1^n(\hat{Q}^2)}$$

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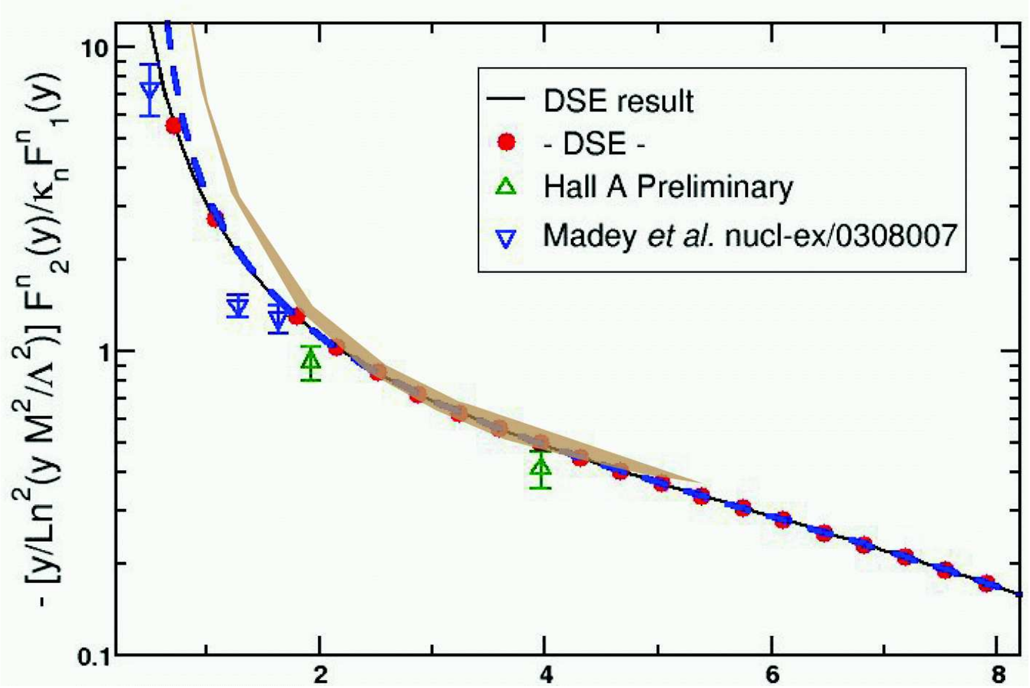
- Brown band
  – *ab initio* RL result



Pion Cloud

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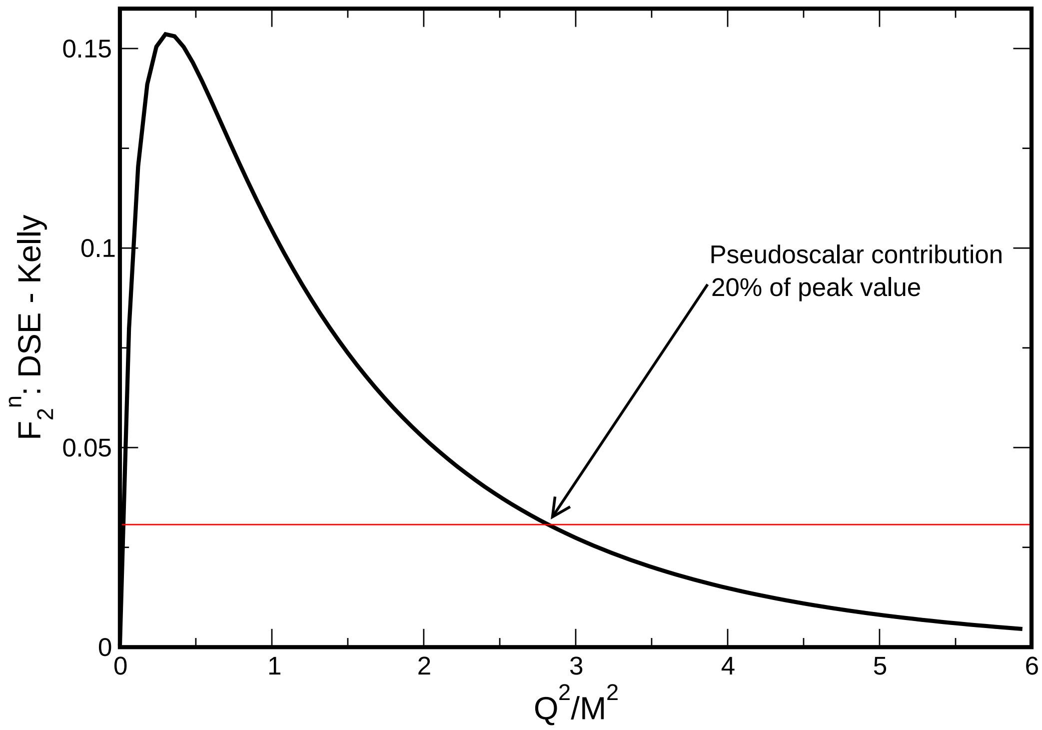

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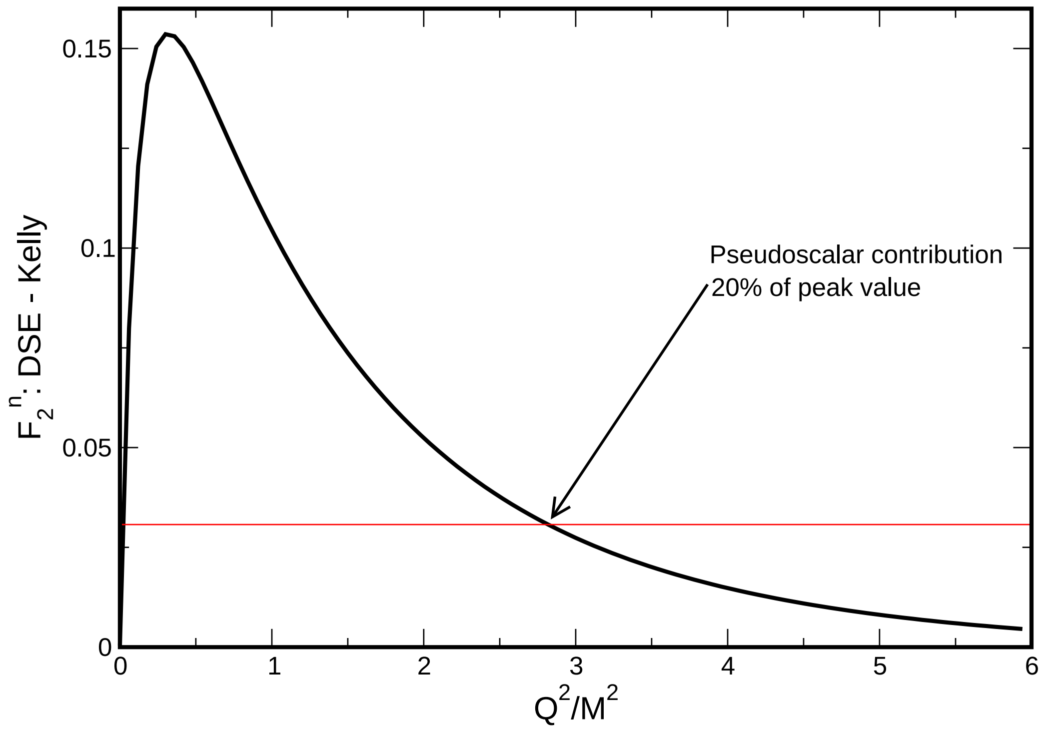

- Faddeev equation set-up to describe dressed-quark core
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- Tool enabling insight to be drawn from experiment into long-range piece of interaction between light-quarks

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