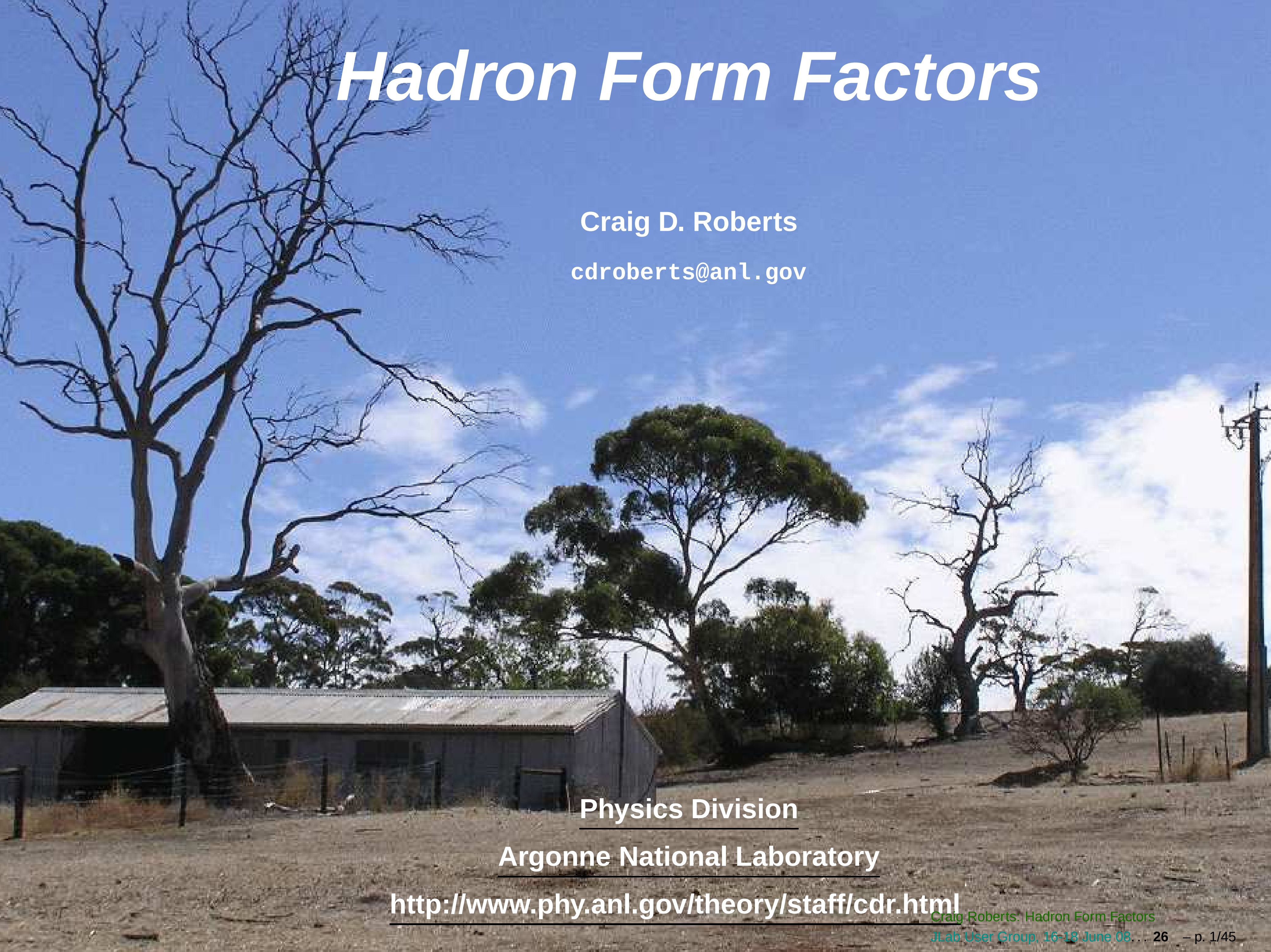

Hadron Form Factors

Craig D. Roberts

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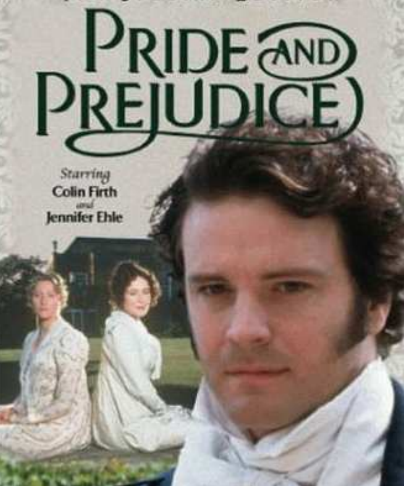
Physics Division

Argonne National Laboratory

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

Universal Truths



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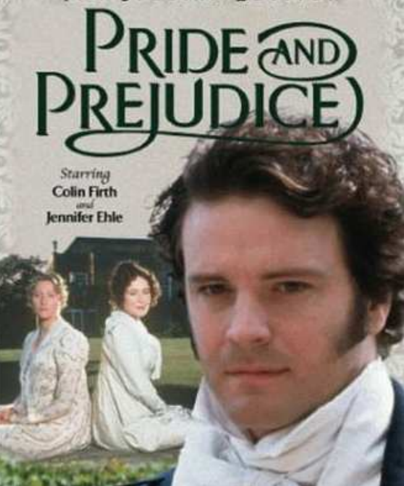

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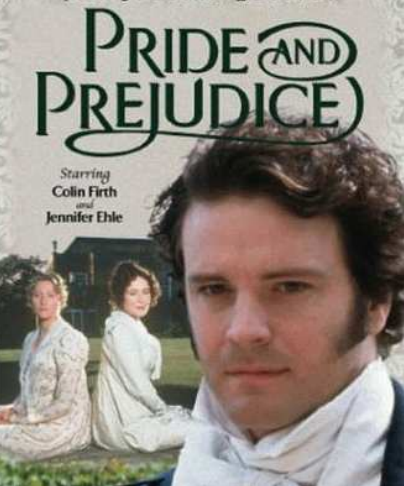

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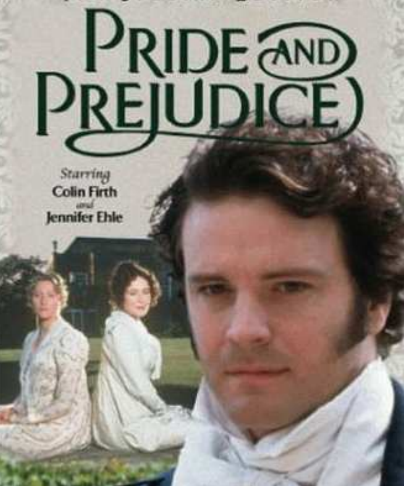

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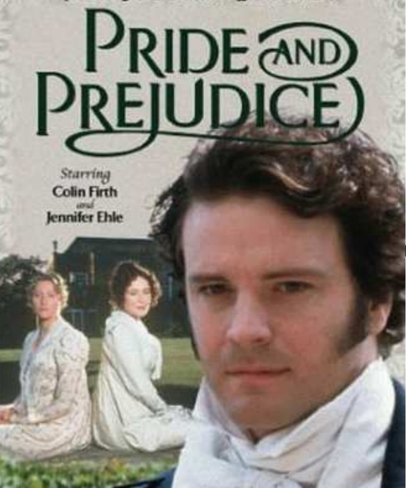

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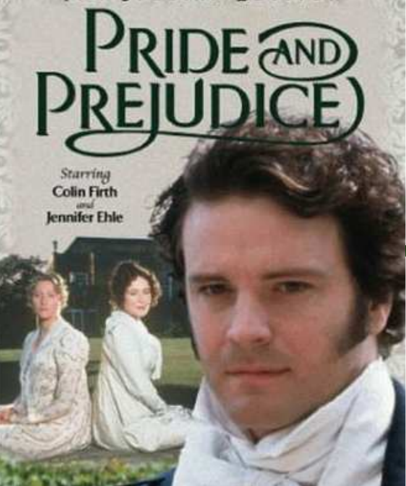

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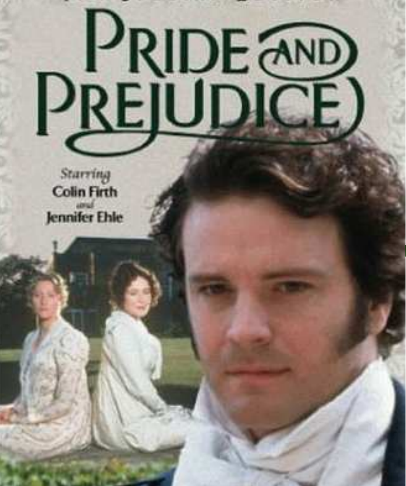

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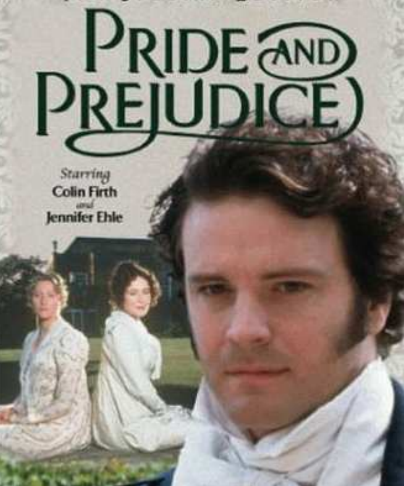

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- DCSB is most important mass generating mechanism for matter in the Universe. Higgs mechanism is irrelevant to light-quarks.
- Challenge: understand relationship between parton properties on the light-front and rest frame structure of hadrons. Problem 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.

QCD’s Challenges

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QCD's Challenges

Understand Emergent Phenomena

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- QCD – Complex behaviour

  arises from apparently simple rules

Why?

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- Experimental and theoretical studies of nucleon electromagnetic form factors have made rapid and significant progress during the last several years, including new data in the time like region, and material gains have been made in studying the pion form factor.
- Despite this, many urgent questions remain unanswered.

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Office of Nuclear Physics Exploring Nuclear Matter - Quarks to Stars
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Some Questions

- What is the role of pion cloud in nucleon electromagnetic structure?
- Can we understand the pion cloud in a more quantitative and, perhaps, model-independent way?

Some Questions

- Where is the transition from non-pQCD to pQCD in the pion and nucleon electromagnetic form factors?

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Some Questions

- Do we understand the high Q^2 behavior of the proton form factor ratio in the space-like region?
- Can we make model-independent statements about the role of relativity or orbital angular momentum in the nucleon?

Some Questions

- Can we understand the rich structure of the time-like proton form factors in terms of resonances?
- What do we expect for the proton form factor ratio in the time-like region?
- What is the relation between proton and neutron form factor in the time-like region?
- How do we understand the ratio between time-like and space-like form factors?

Some Questions

- What is the role of two-photon exchange contributions in understanding the discrepancy between the polarization and Rosenbluth measurements of the proton form factor ratio?
- What is the impact of these contributions on other form factor measurements?

- How accurately can the pion form factor be extracted from the $ep \to e' n \pi^+$ reaction?

Status

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  - J. Arrington, C. D. Roberts and J. M. Zanotti "Nucleon electromagnetic form factors," J. Phys. G **34**, S23 (2007); [arXiv:nucl-th/0611050].
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- Most recently:
  "ECT* Workshop on Hadron Electromagnetic Form Factors"
  Organisers: Alexandrou, Arrington, Friedrich, Maas, Roberts
  Presentations, etc., available on-line
  http://ect08.phy.anl.gov/

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

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

Intranucleon Interaction

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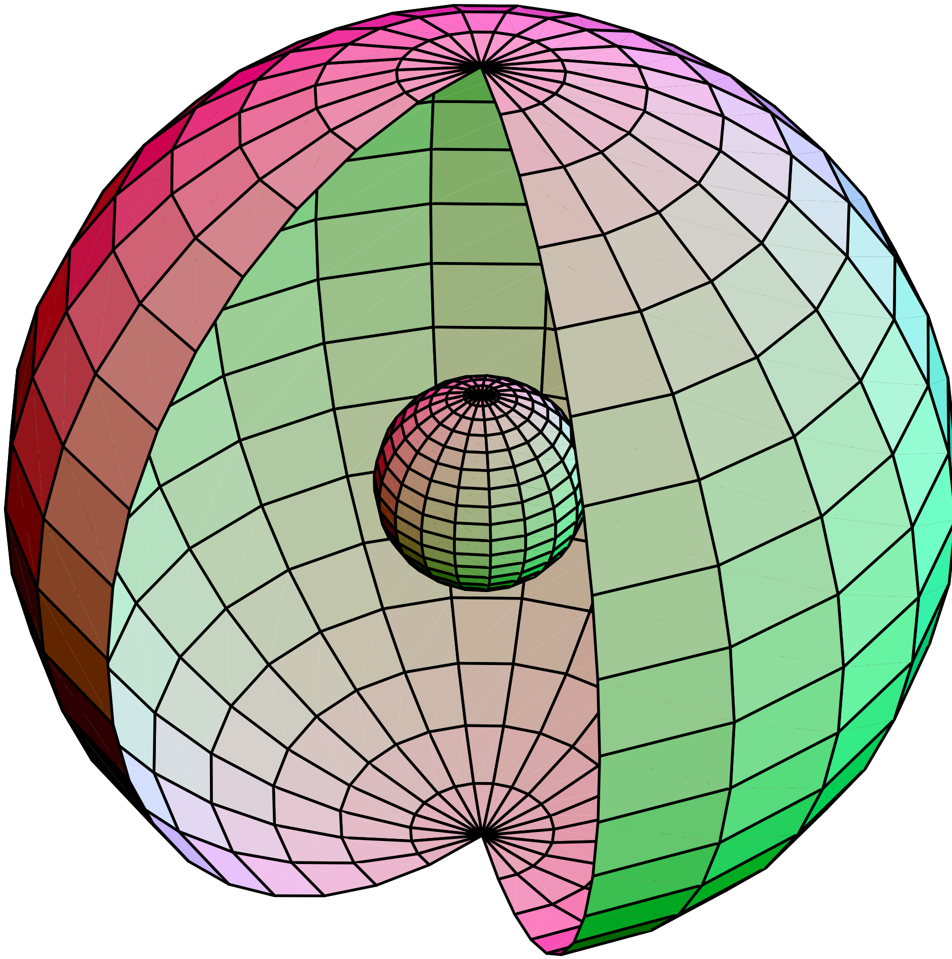
Intranucleon Interaction



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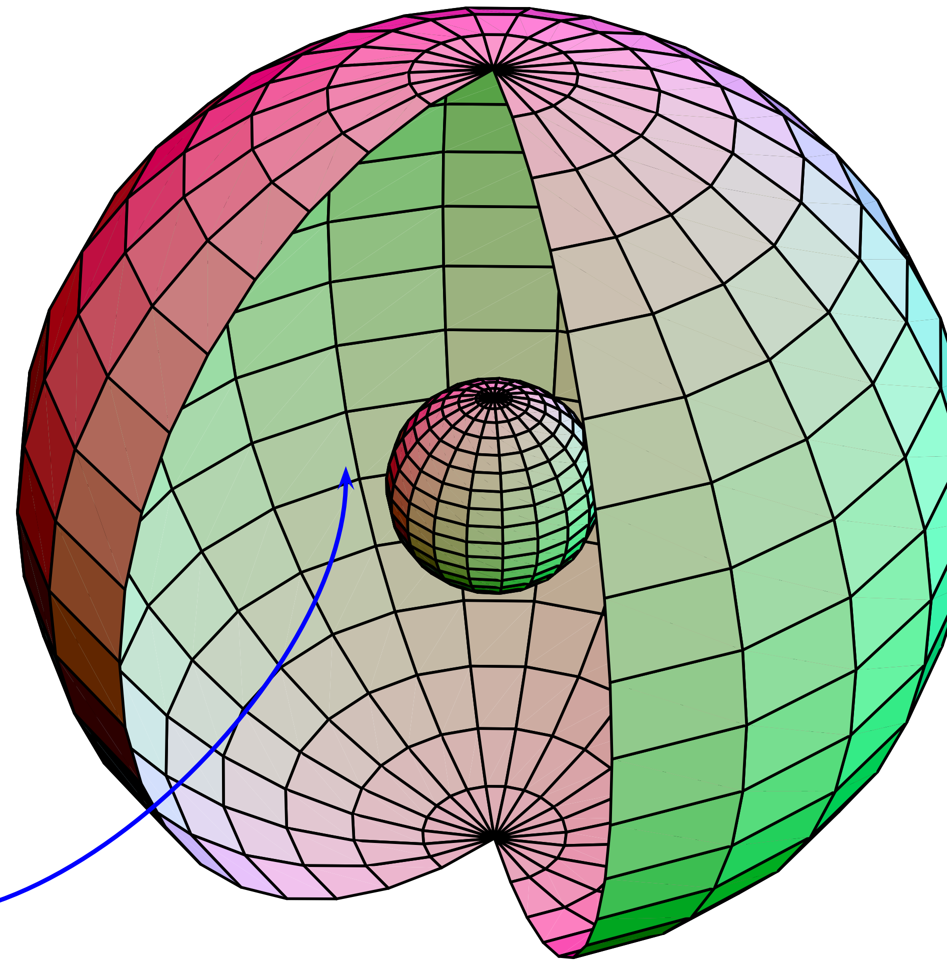
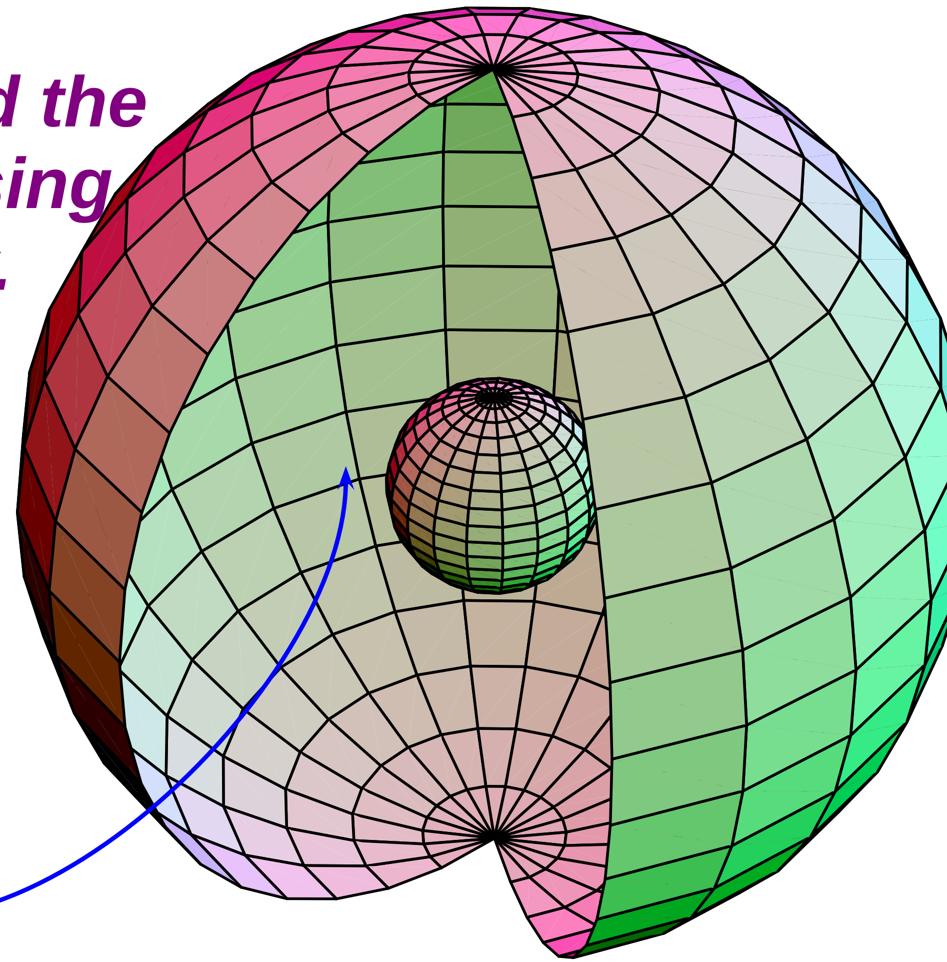


98% of the volume

What is the Intranucleon Interaction?

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



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Dyson-Schwinger Equations

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Dyson-Schwinger Equations
Dressed-Quark Propagator

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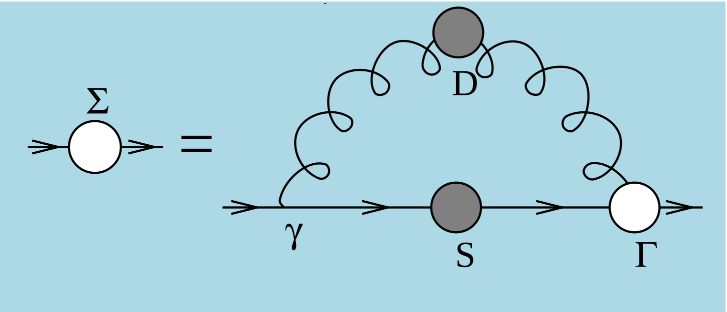

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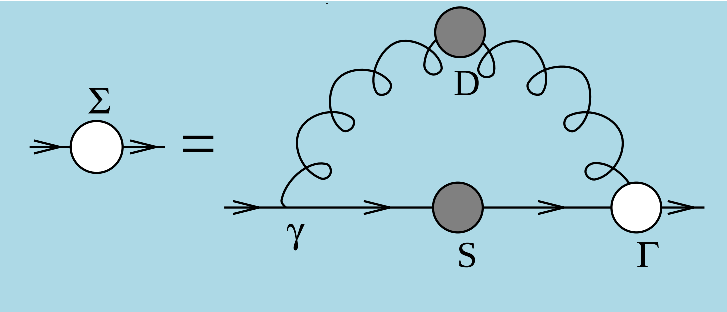

Gap Equation

- Gap Equation's Kernel Enhanced on IR domain

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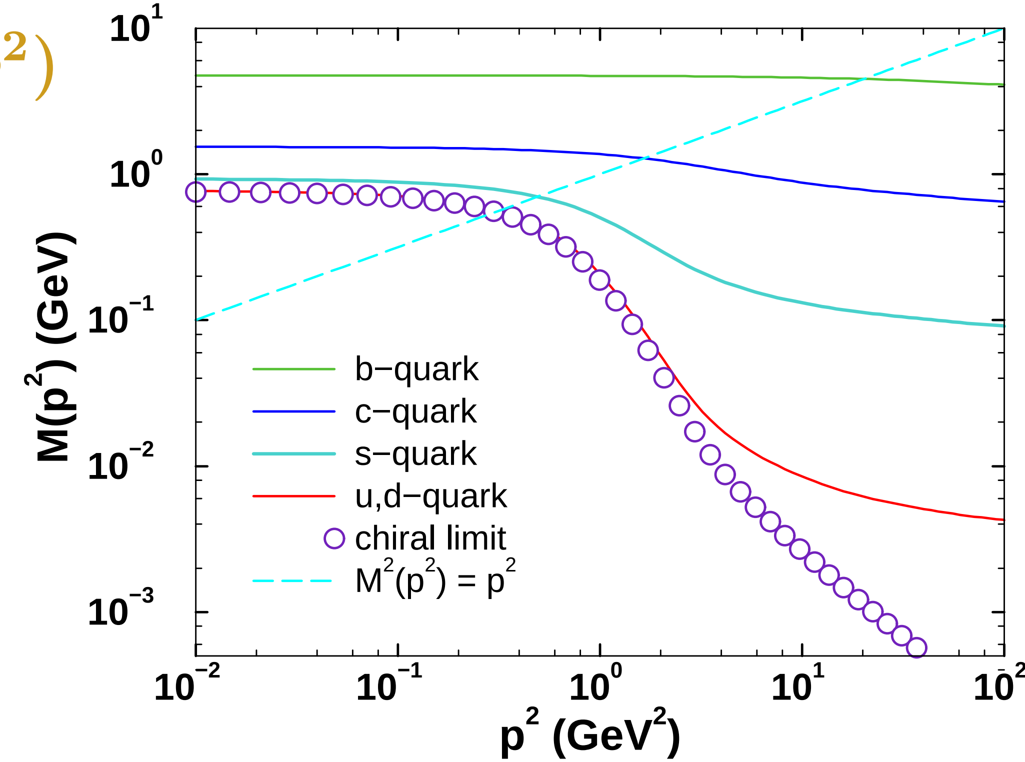

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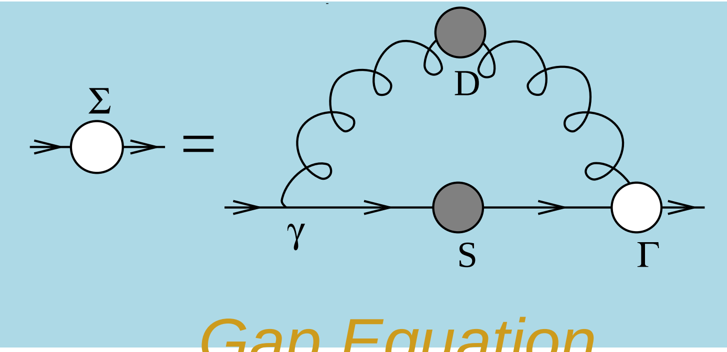

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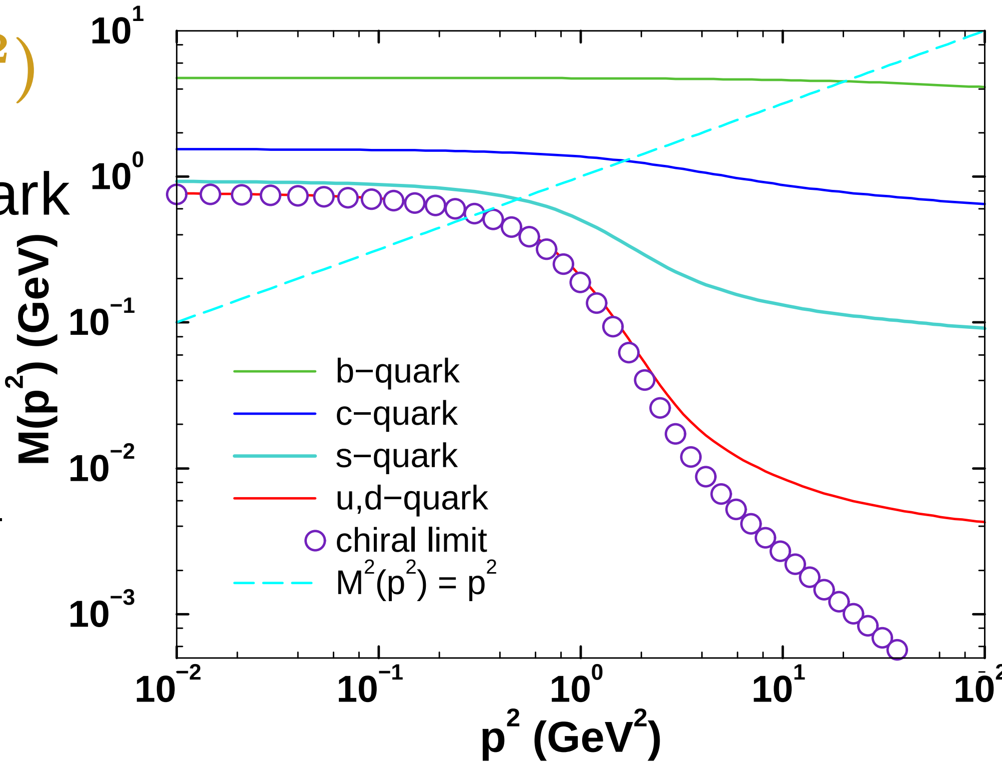
flavour	u/d	s	c	b
$\frac{M^E}{m_\zeta}$	$\sim 10^2$	~ 10	~ 1.5	~ 1.1



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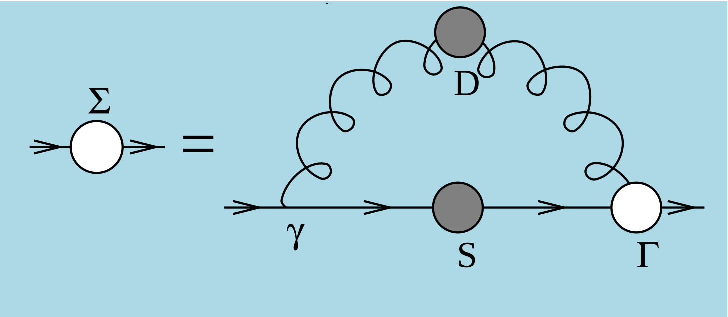

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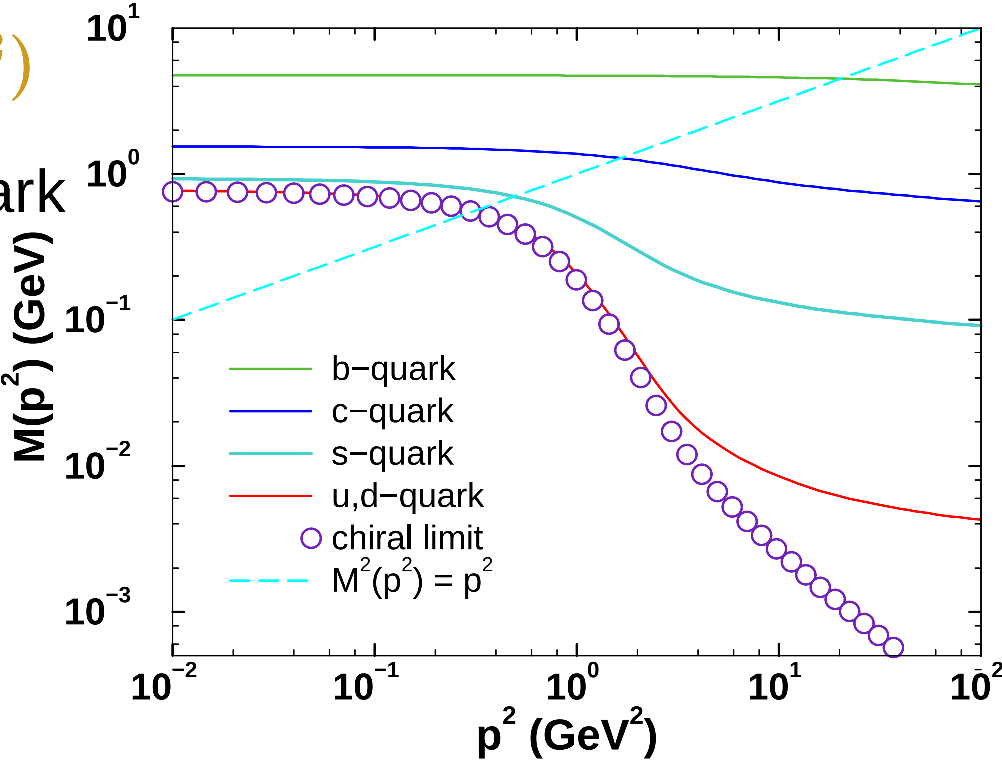

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Predictions confirmed in numerical simulations of lattice-QCD

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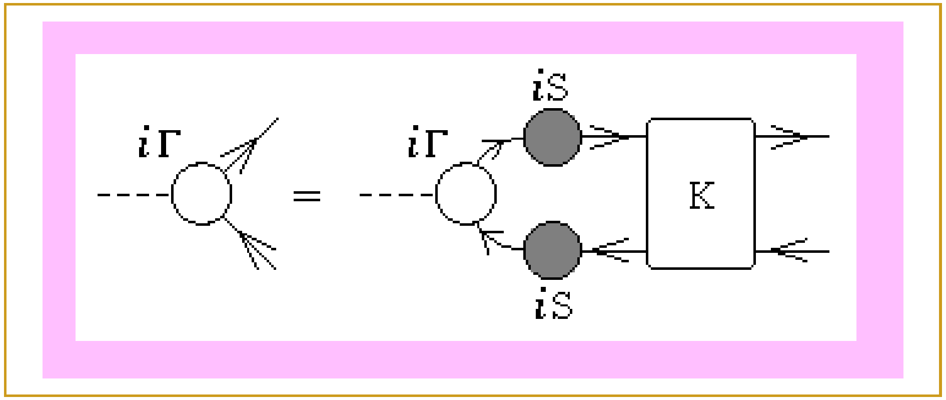

QFT Generalisation of Lippmann-Schwinger Equation.

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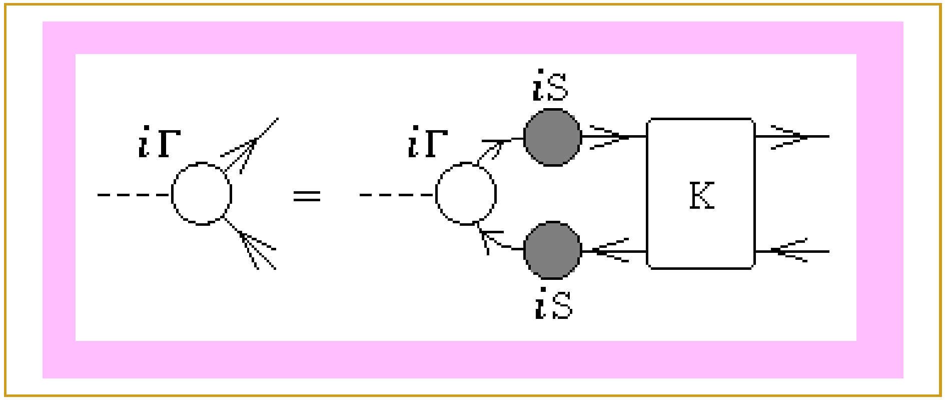

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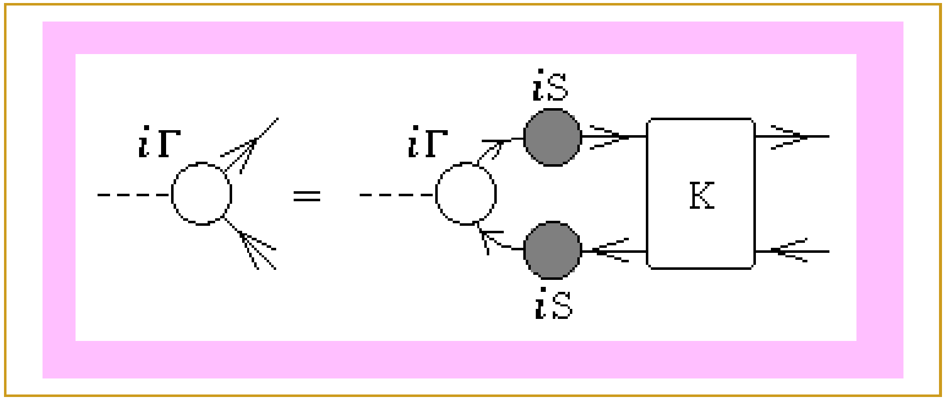

QFT Generalisation of Lippmann-Schwinger Equation.

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or

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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- 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 ⇒ Explicit Violation of QCD's Chiral Symmetry

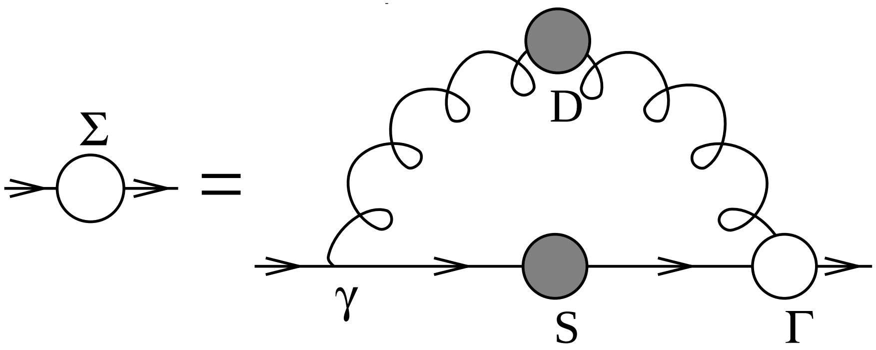
Pion Form Factor

Procedure Now Straightforward

Pion Form Factor

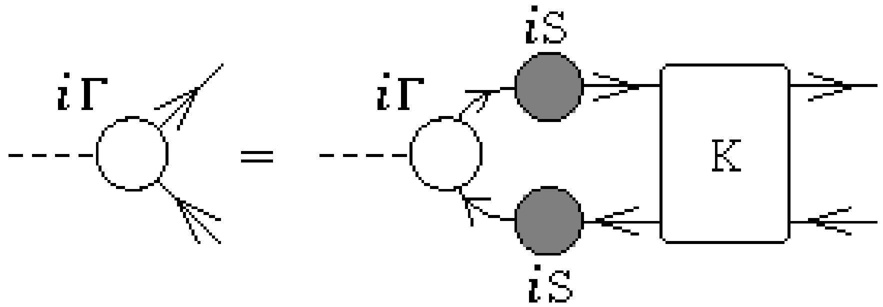
- Solve Gap Equation

  $\Rightarrow$ 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



Pion Form Factor

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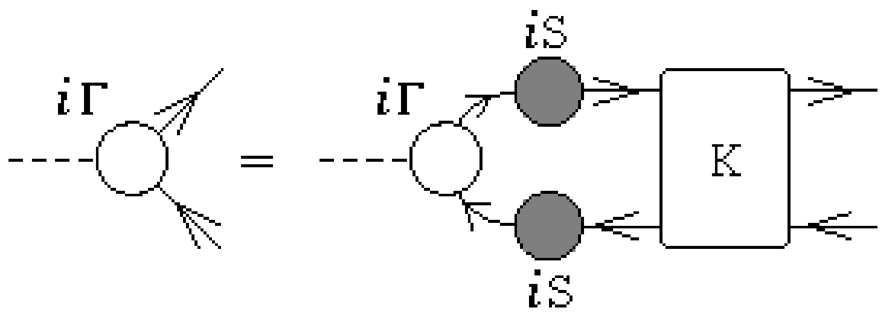

- Solve Inhomogeneous Bethe-Salpeter Equation for Dressed-Quark-Gluon Vertex, Γ_μ

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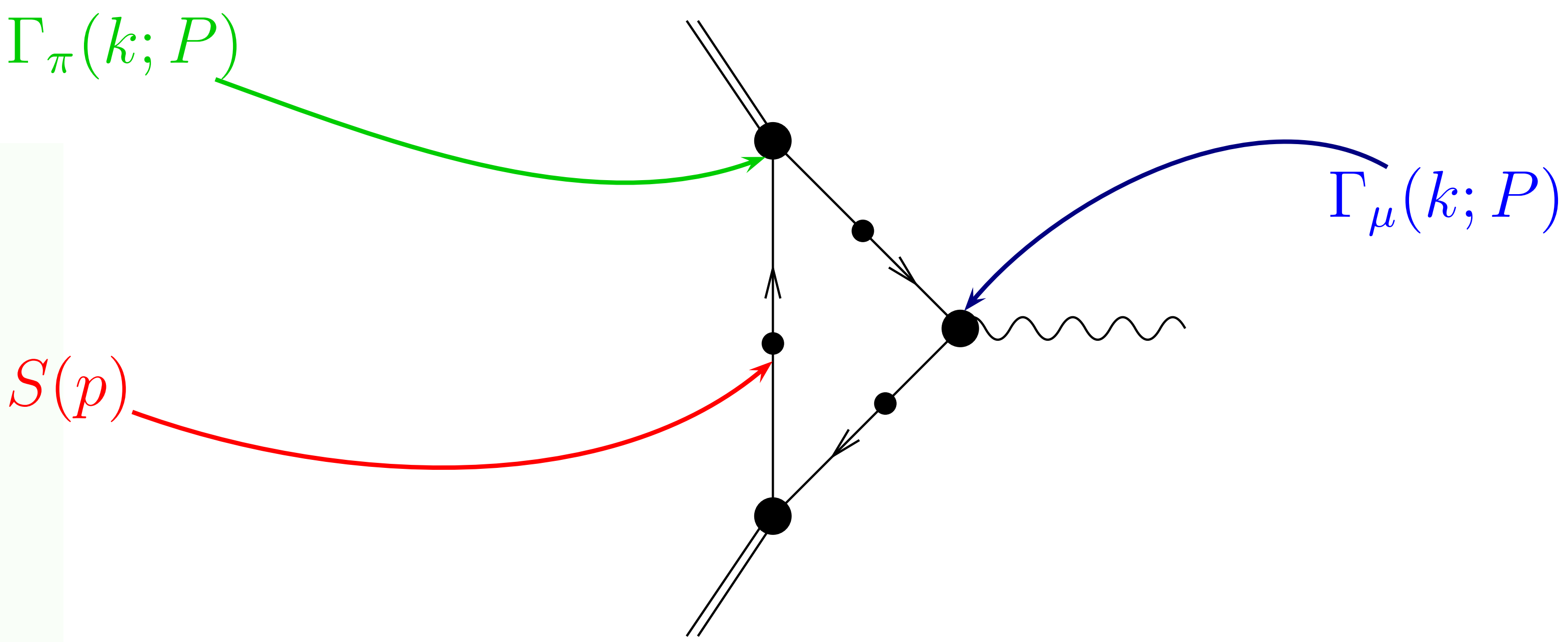
Pion Form Factor

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



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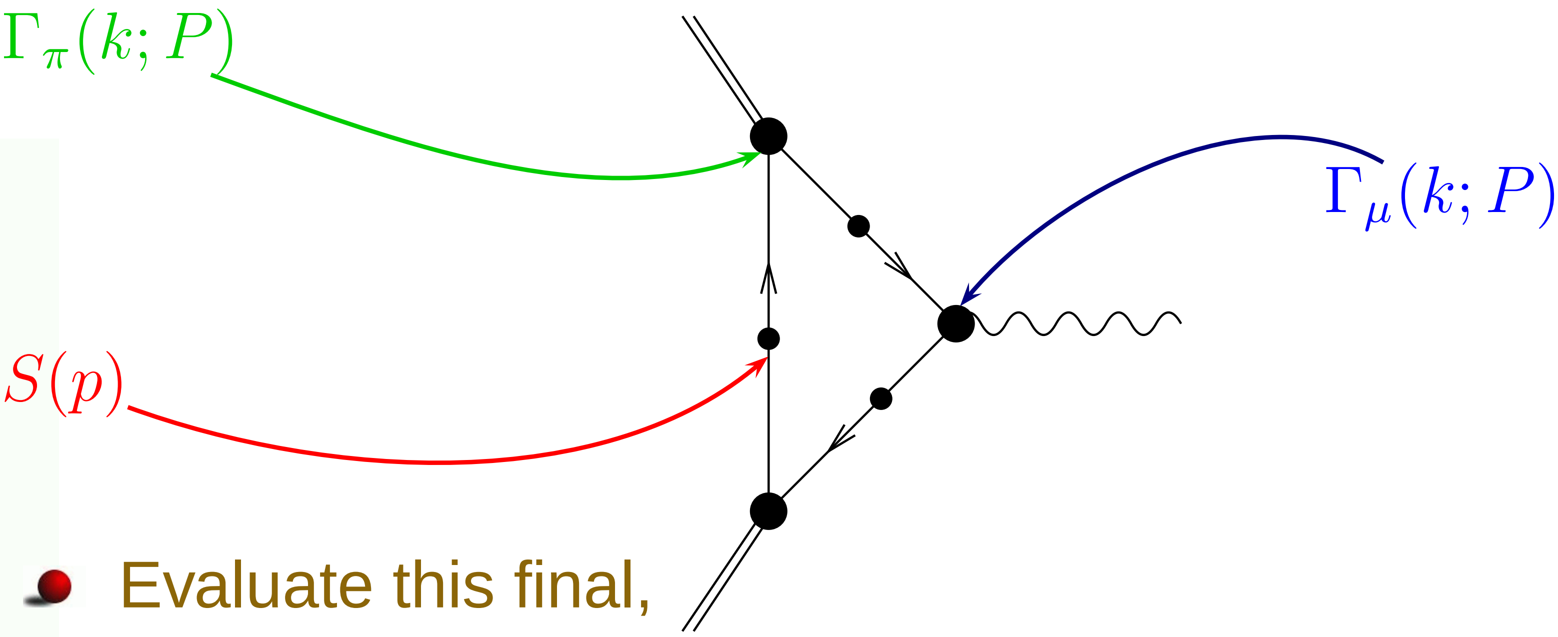

- Evaluate this final, three-dimensional integral

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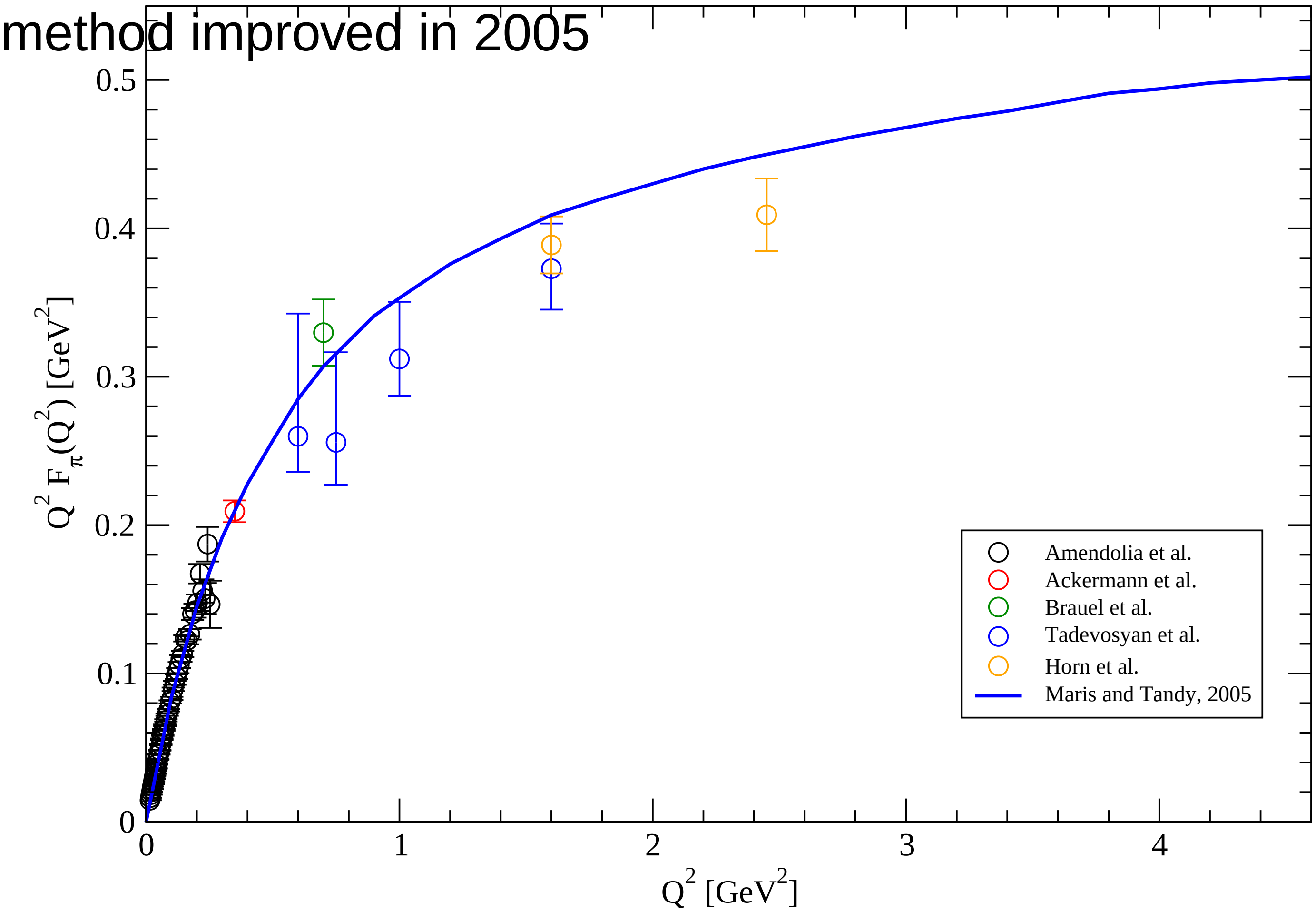
Calculated Pion Form Factor

Calculation first published in 1999; No Parameters Varied

Numerical method improved in 2005



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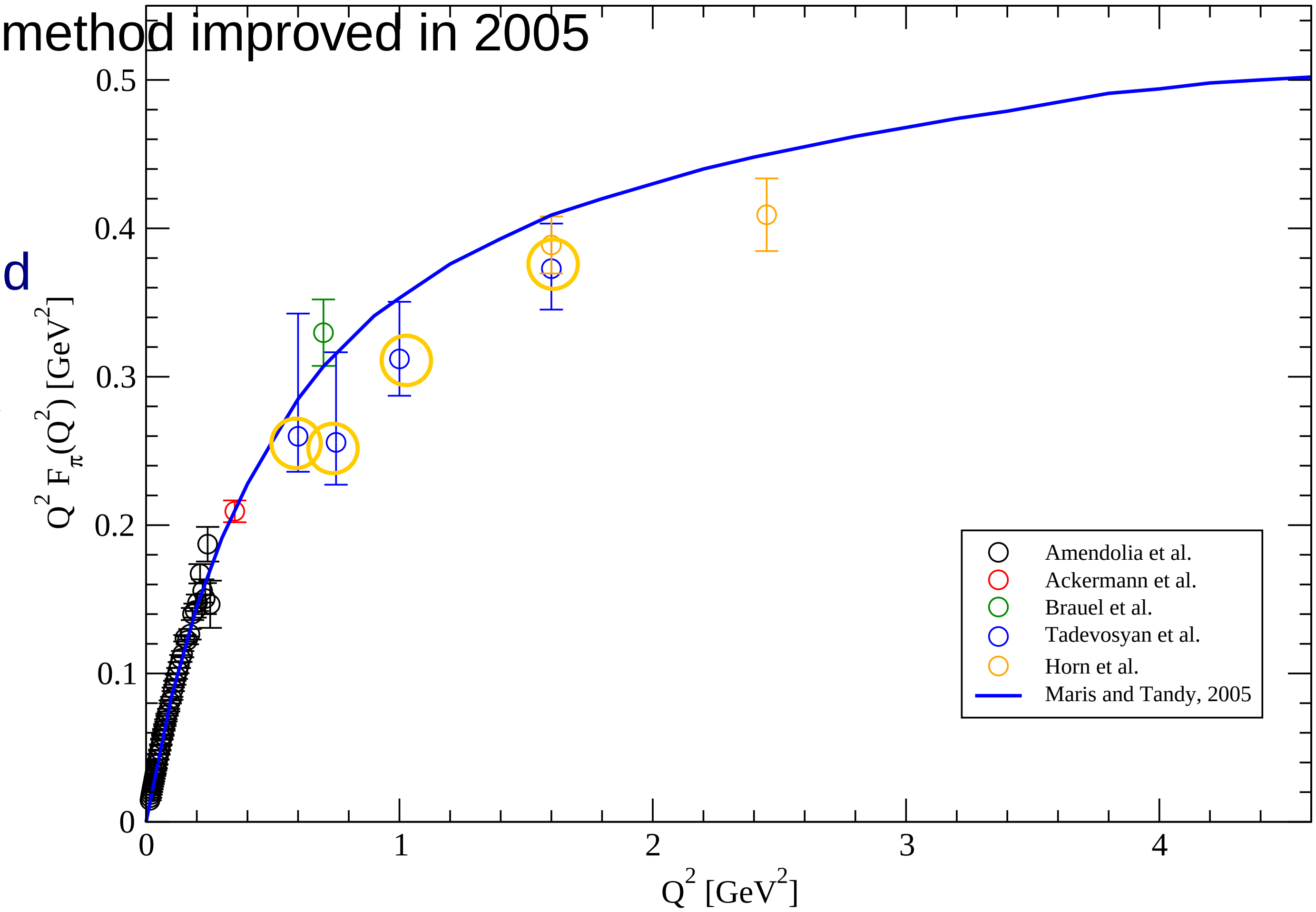

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Timelike Pion Form Factor

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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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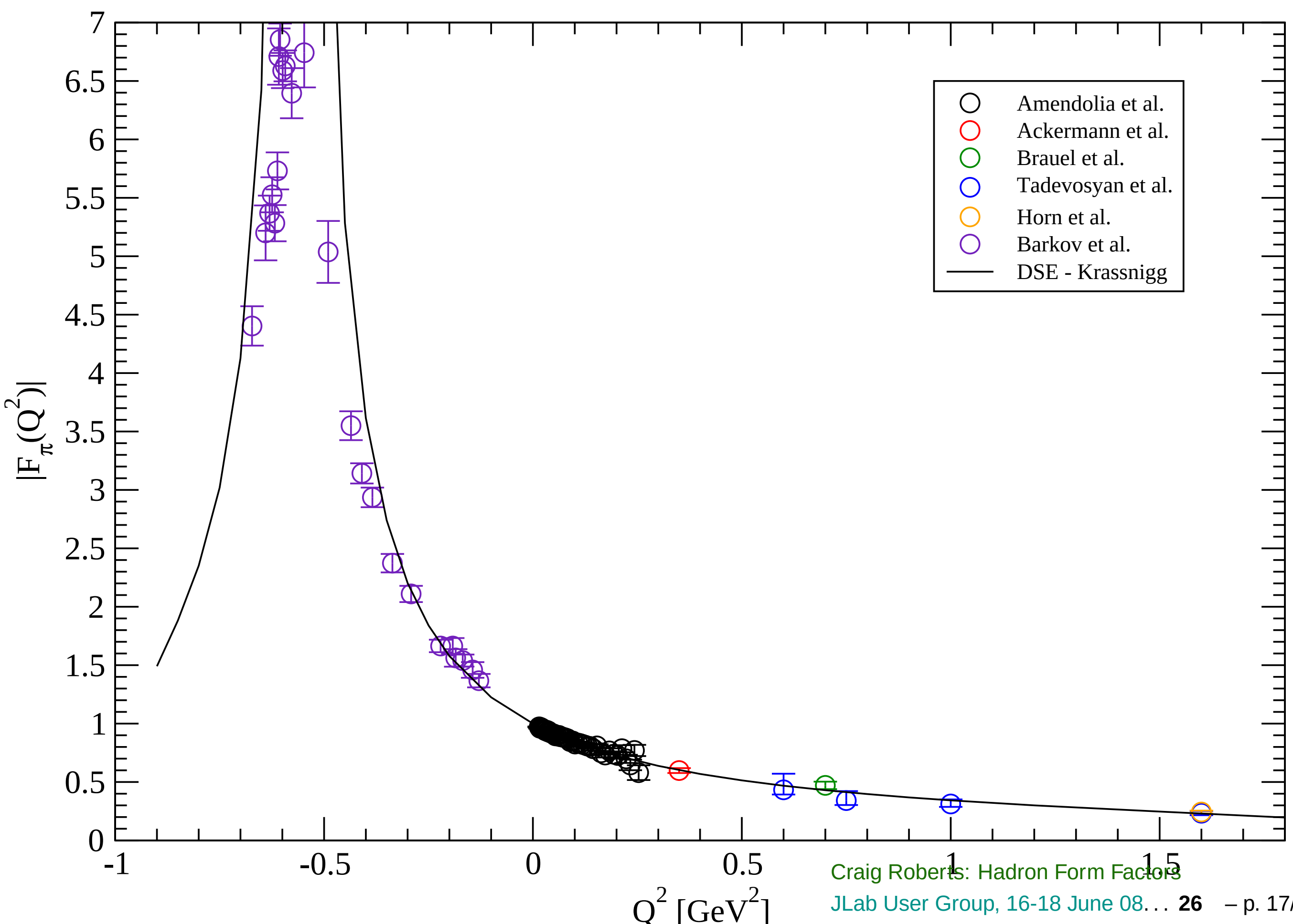
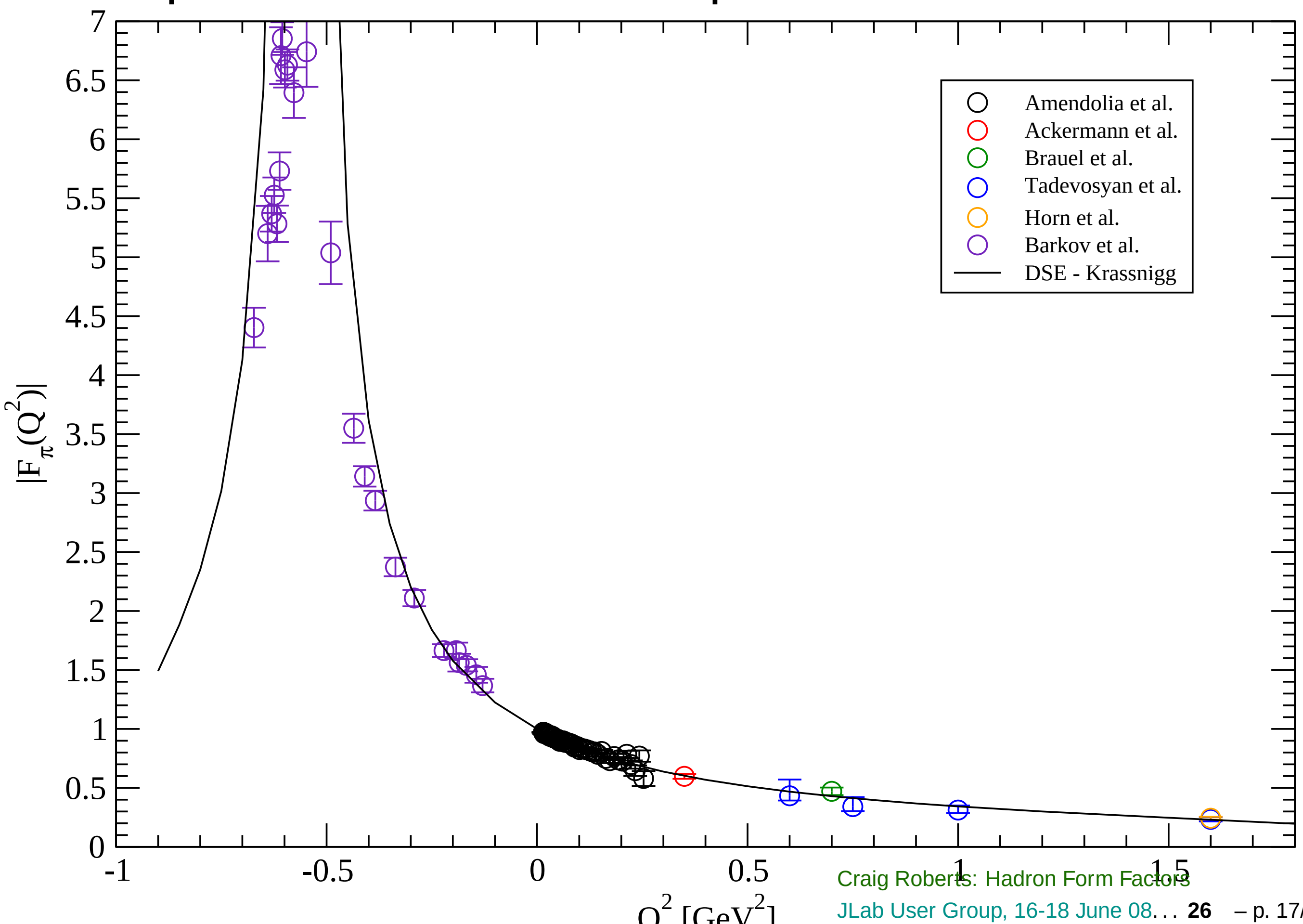


Timelike **Pion Form Factor**

Ab initio calculation into timelike region

Deeper than ground-state ρ-meson pole

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



Nucleon Challenge

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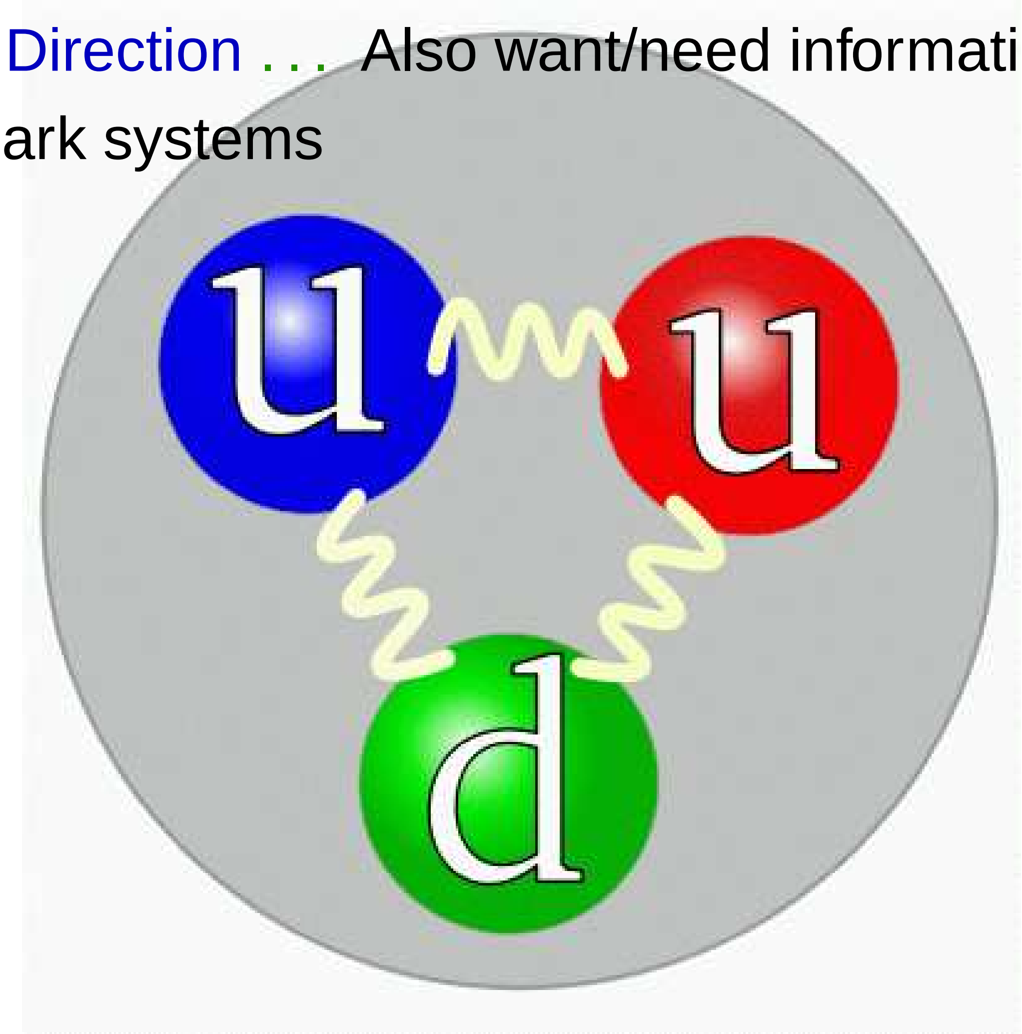

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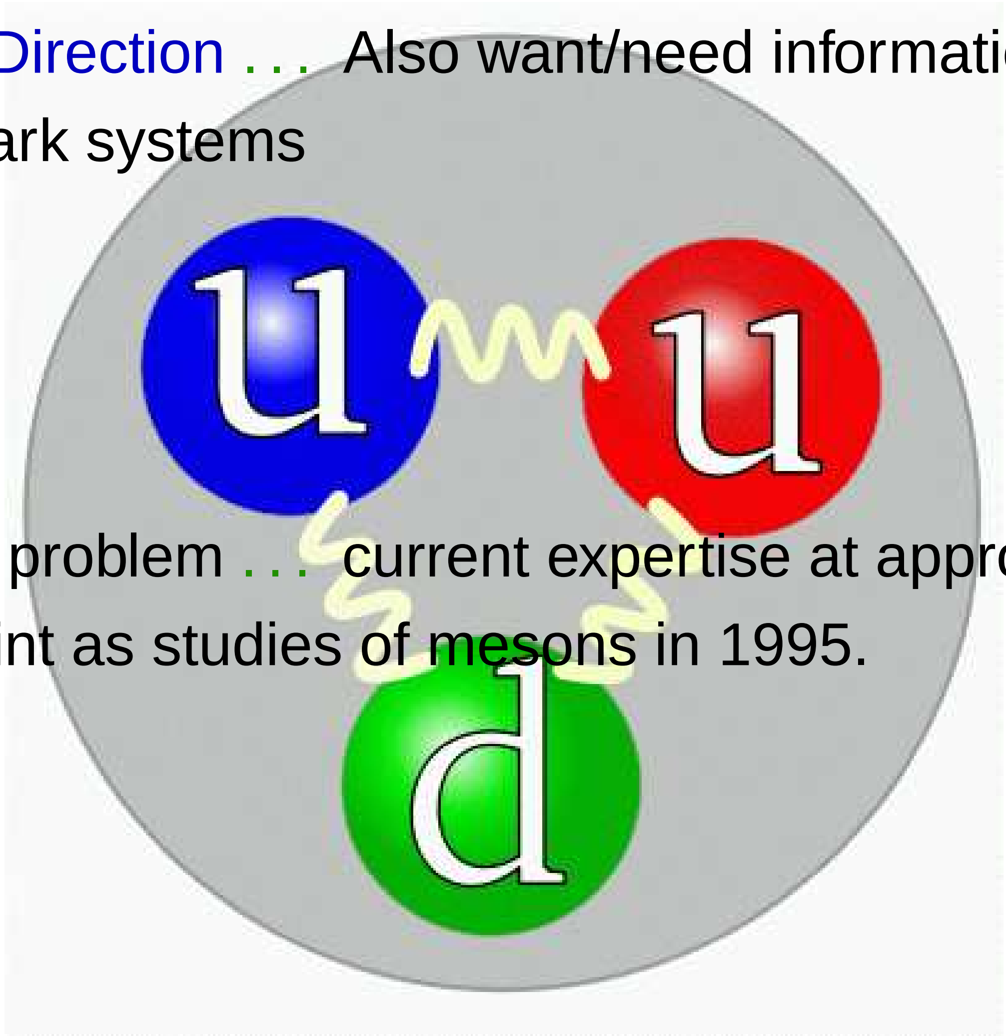

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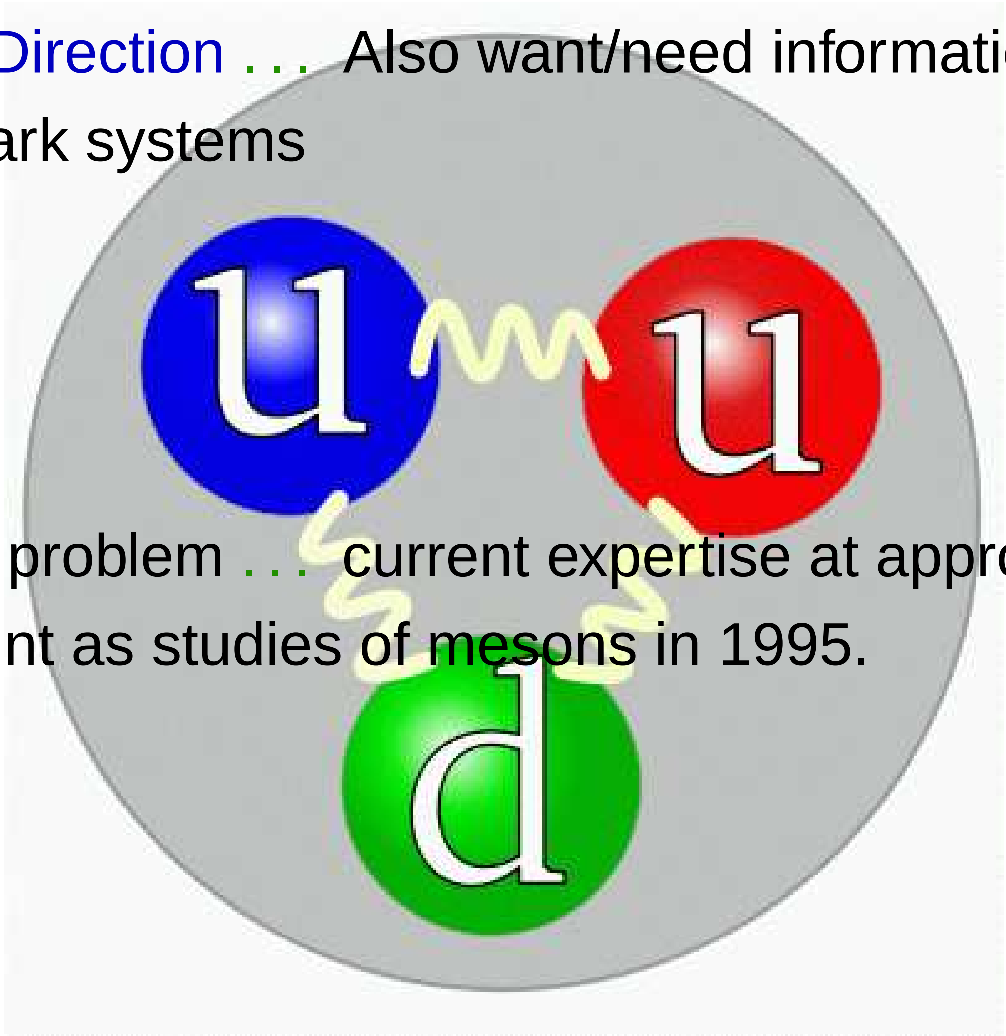

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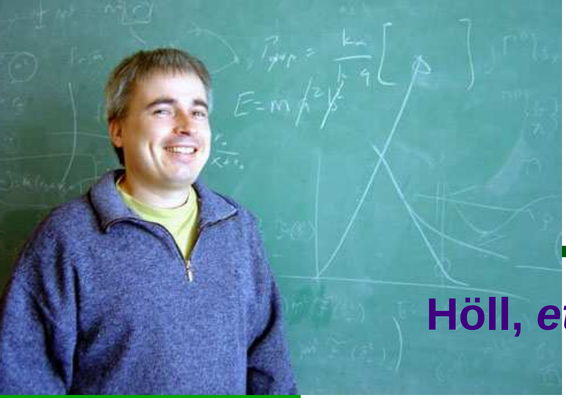
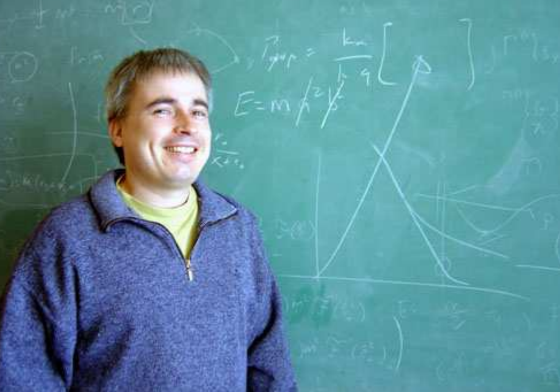
- Namely . . . Model-building and Phenomenology, constrained by the DSE results outlined already.



Nucleon EM Form Factors: A Précis

Höll, *et al.*: nu-th/0412046 & nu-th/0501033



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(Oettel, Hellstern, Alkofer, Reinhardt: nucl-th/9805054)

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- Critical to anticipate pion cloud effects
  Roberts, Tandy, Thomas, *et al.*, nu-th/02010084

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Faddeev equation

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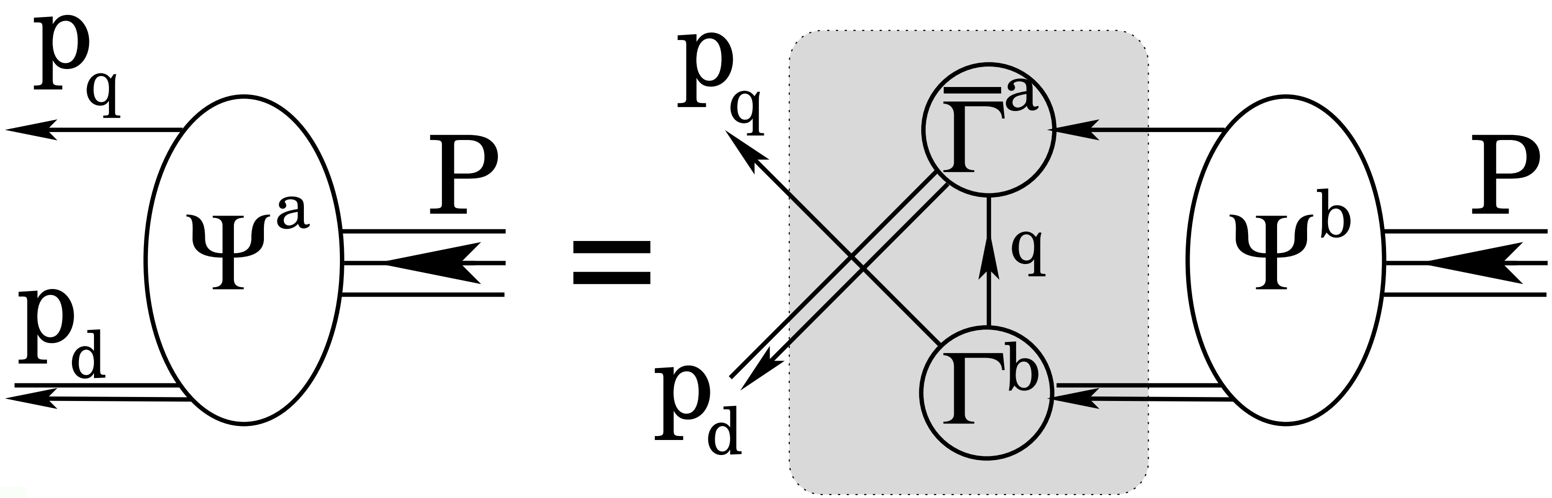

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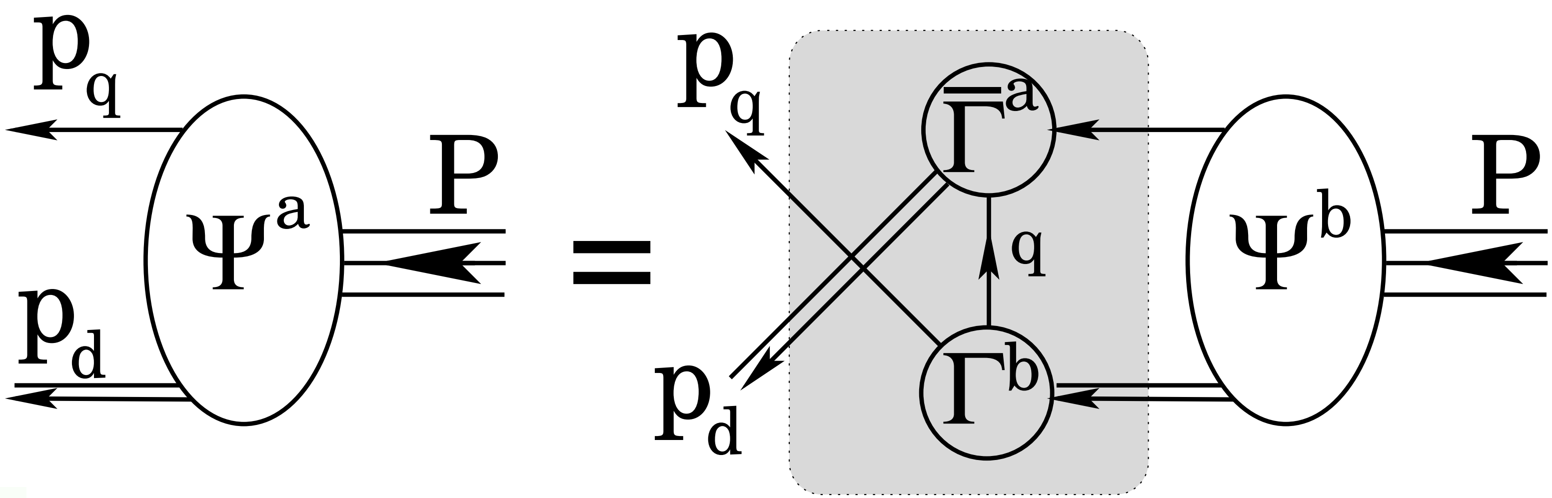
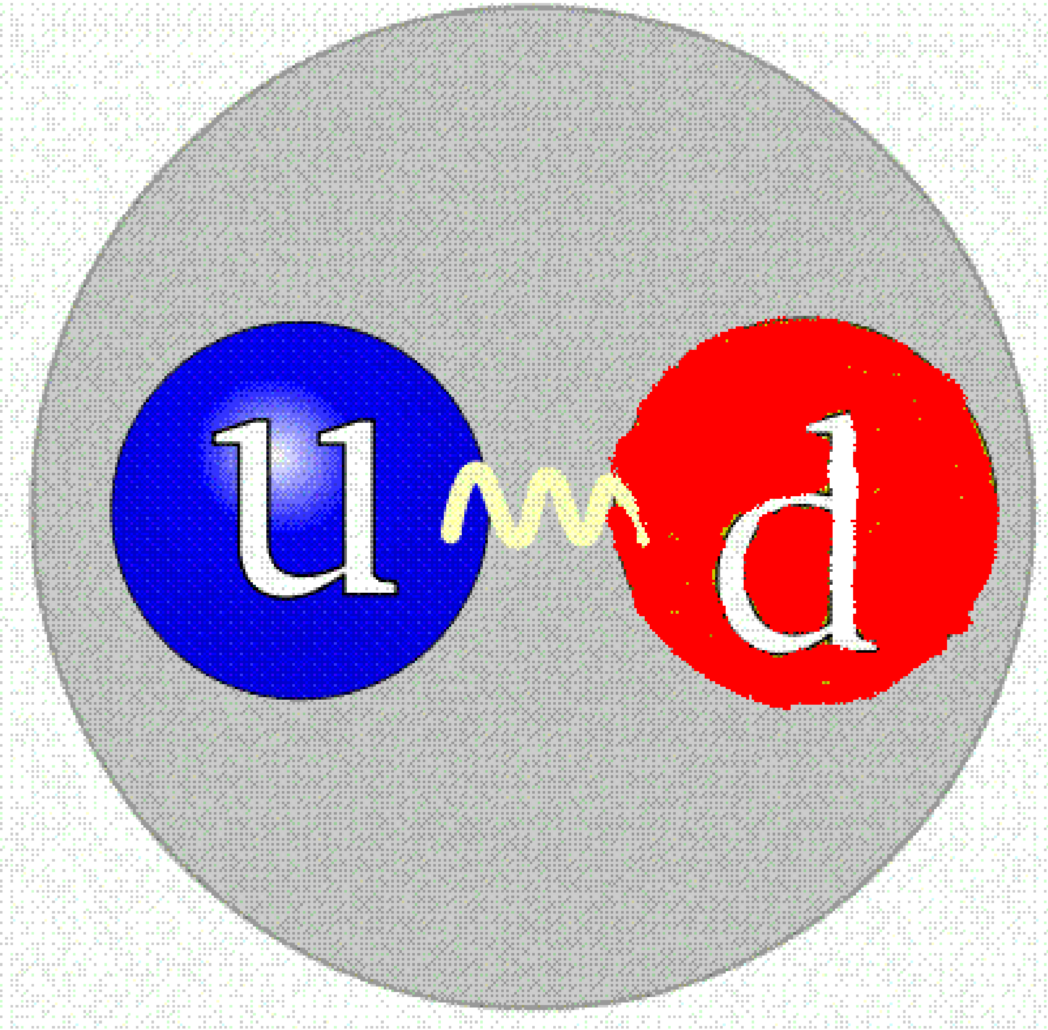


- Linear, Homogeneous Matrix equation
  - Yields *wave function* (Poincaré Covariant Faddeev Amplitude) that describes quark-diquark relative motion within the nucleon
- Scalar and Axial-Vector Diquarks . . . In Nucleon's Rest Frame Amplitude has . . . $s-$, $p-$ & $d-$wave correlations

Diquark correlations



QUARK-QUARK

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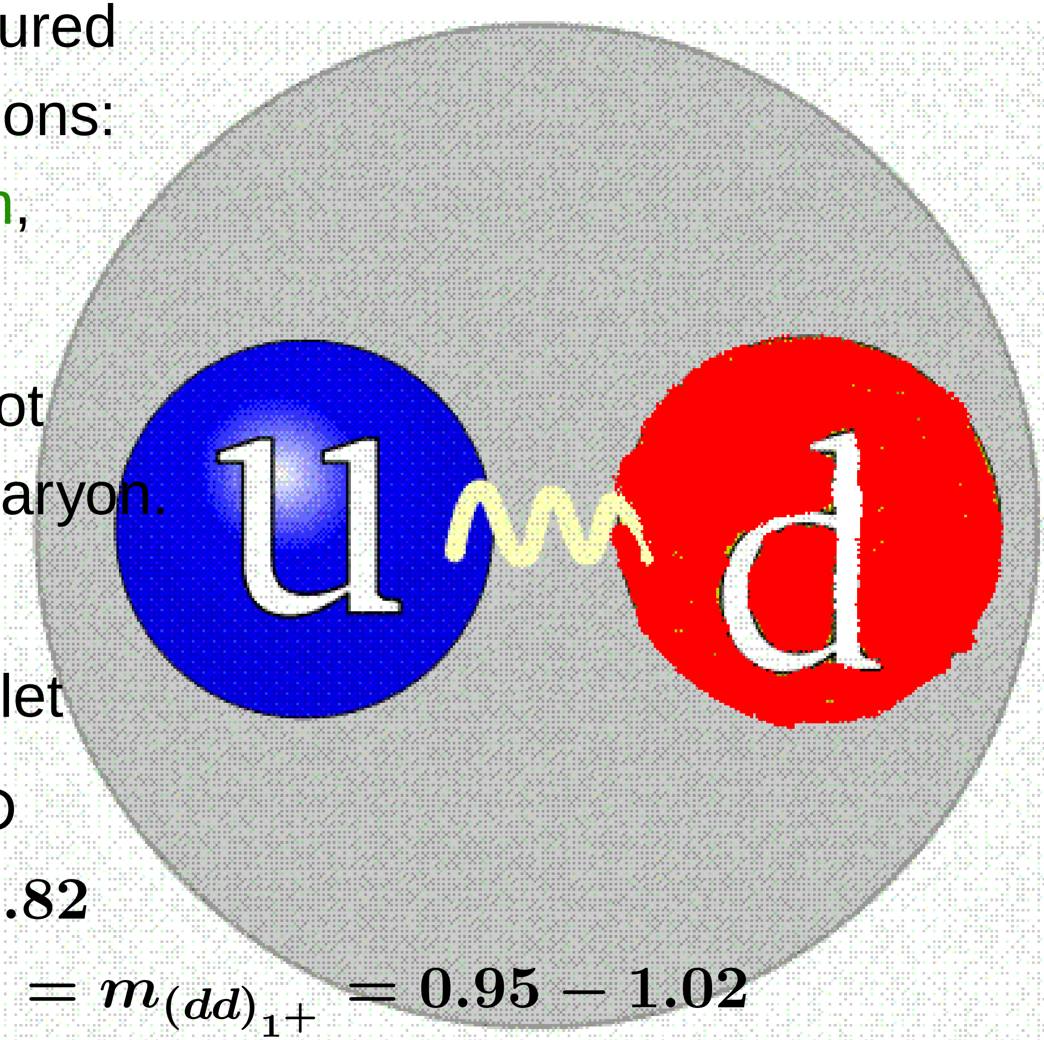
Diquark correlations

- 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

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

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



QUARK-QUARK

Nucleon-Photon Vertex

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

Nucleon-Photon Vertex

6 terms . . .

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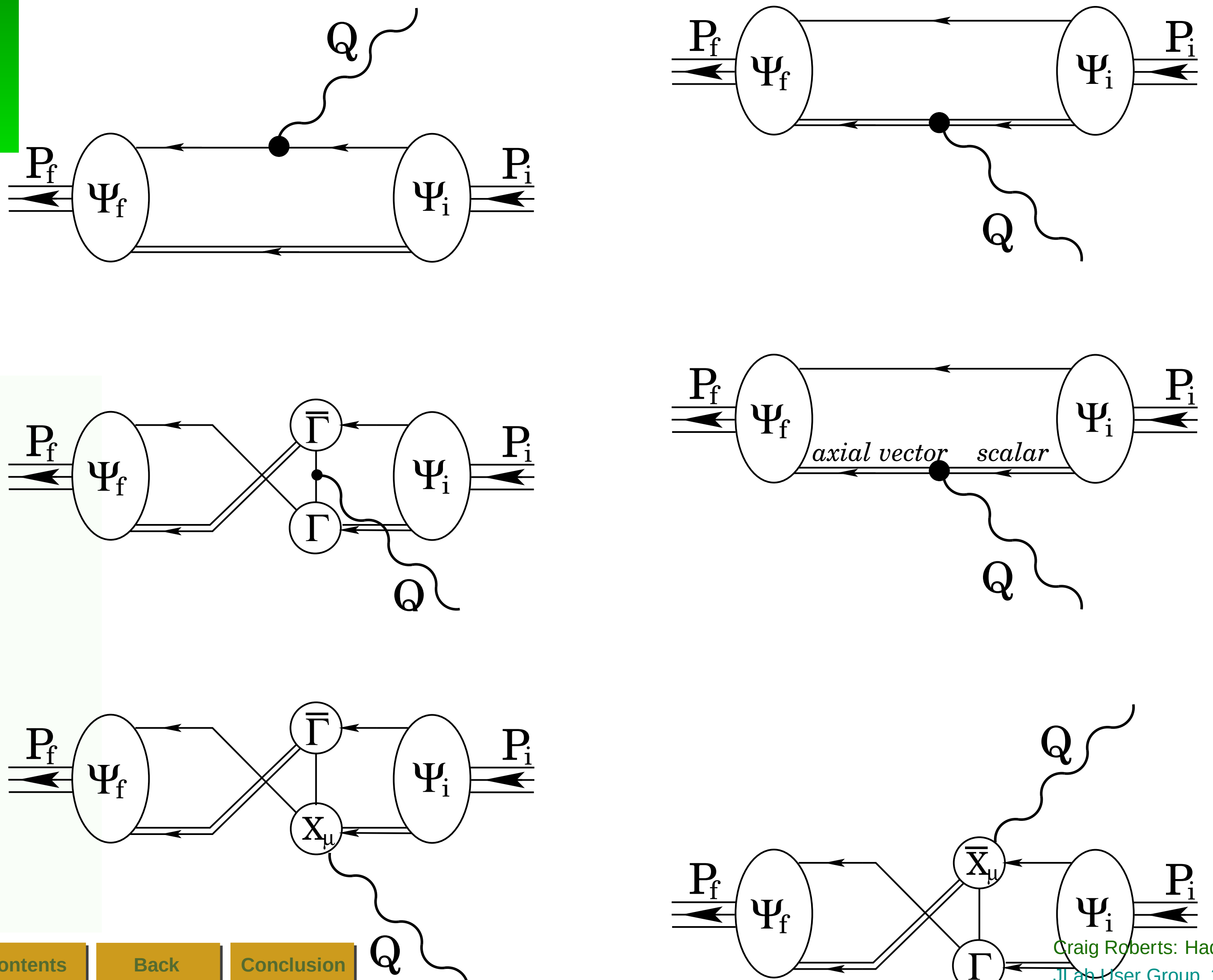
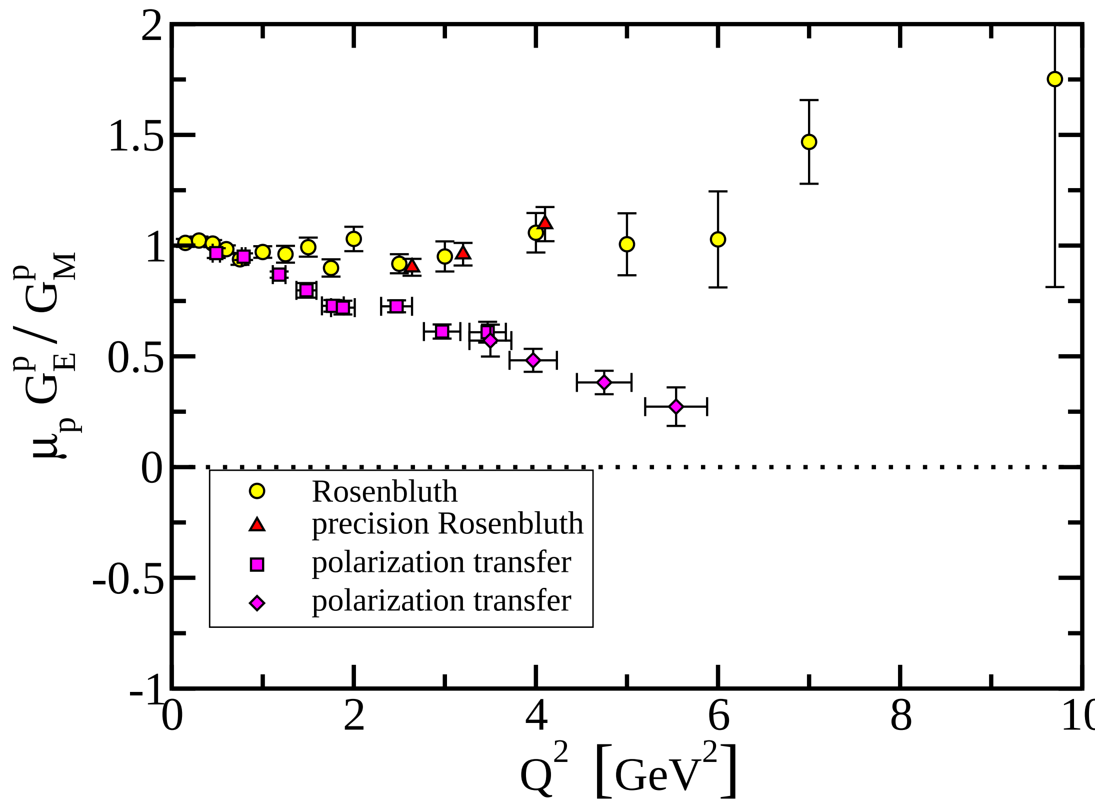


Form Factor Ratio: GE/GM



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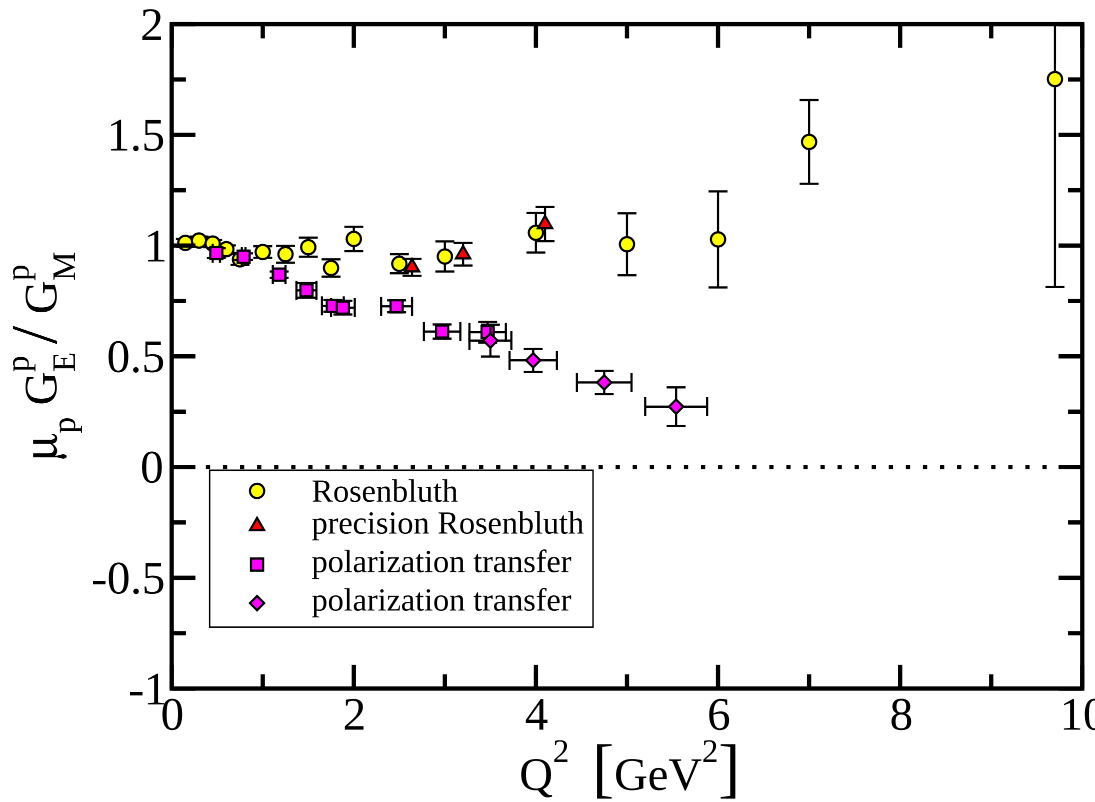

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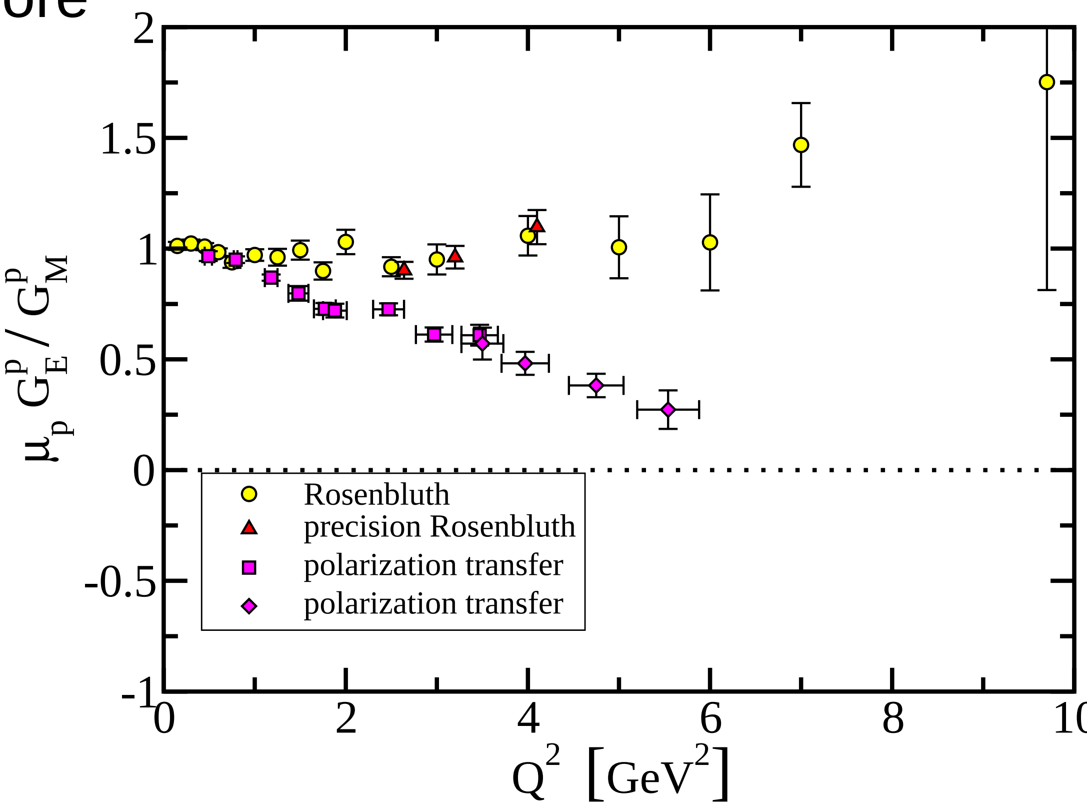

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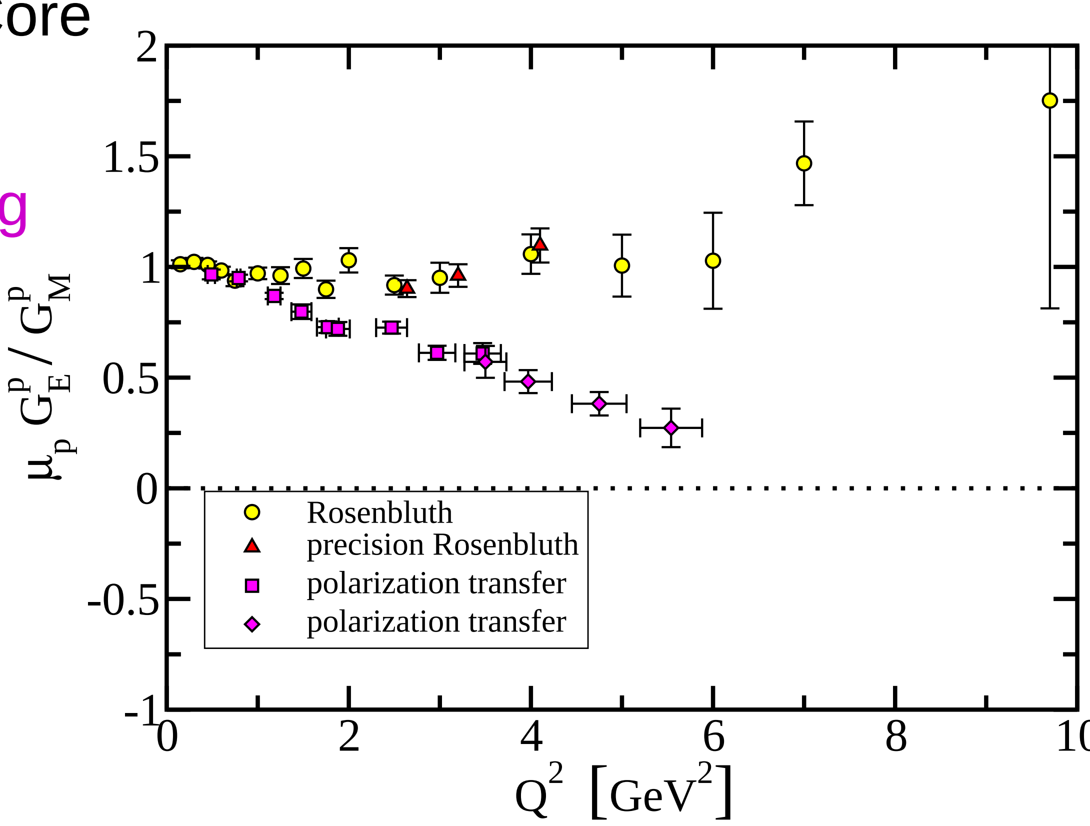

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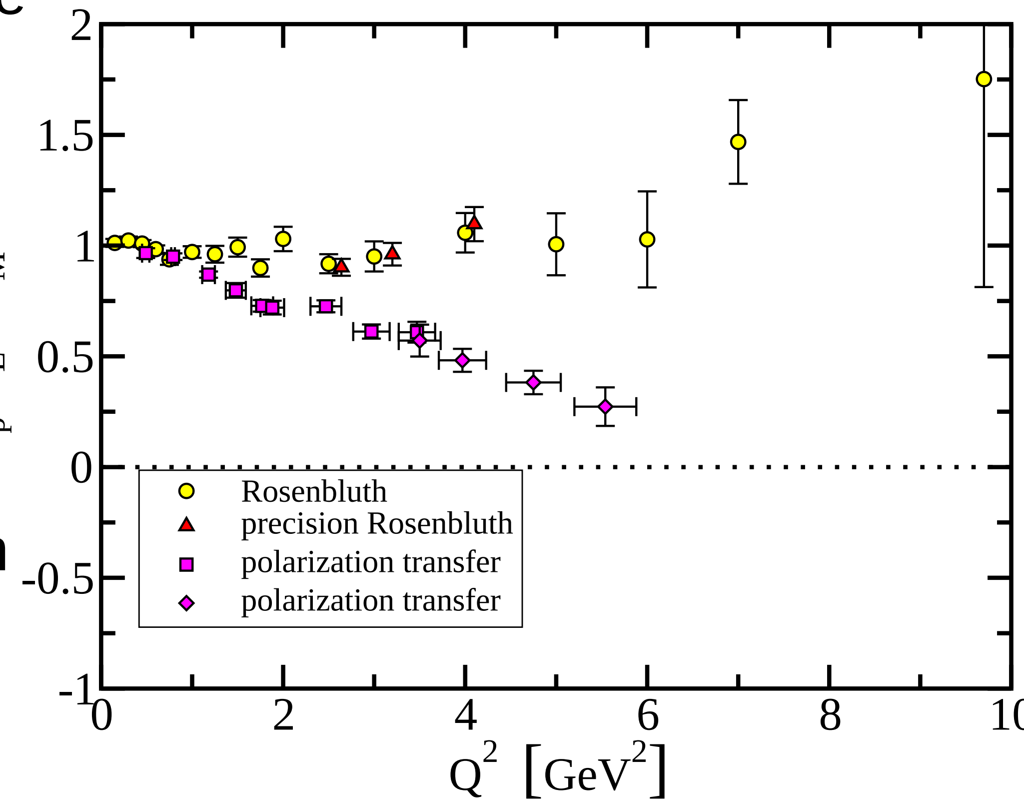

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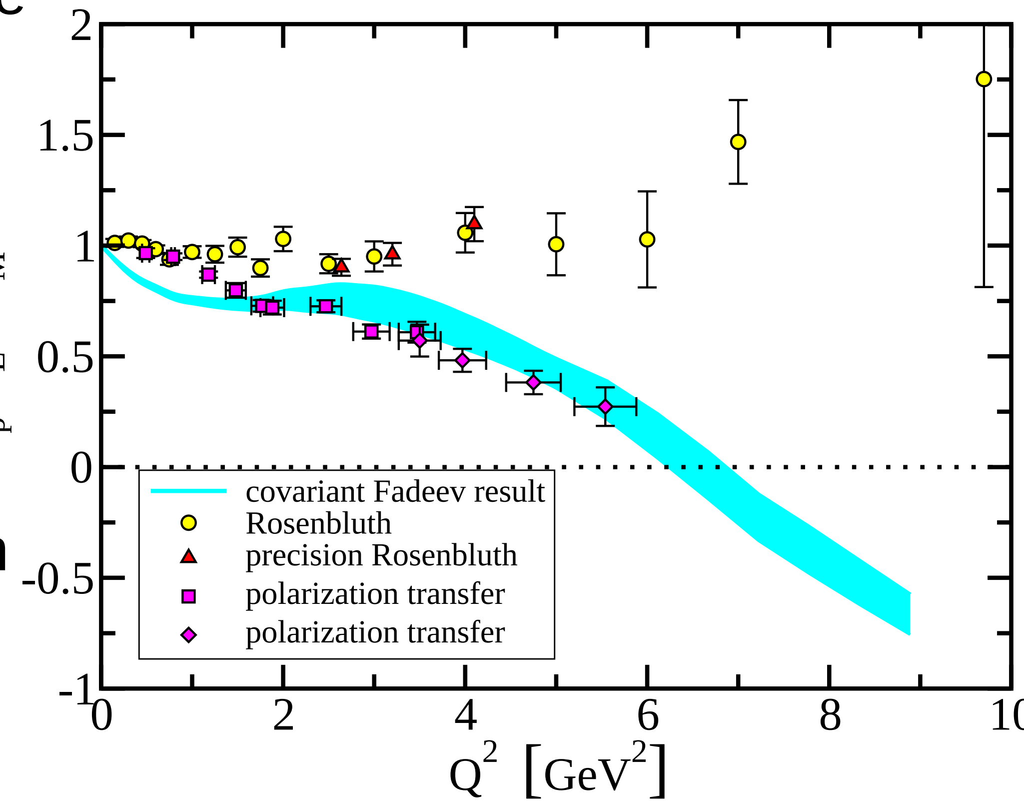

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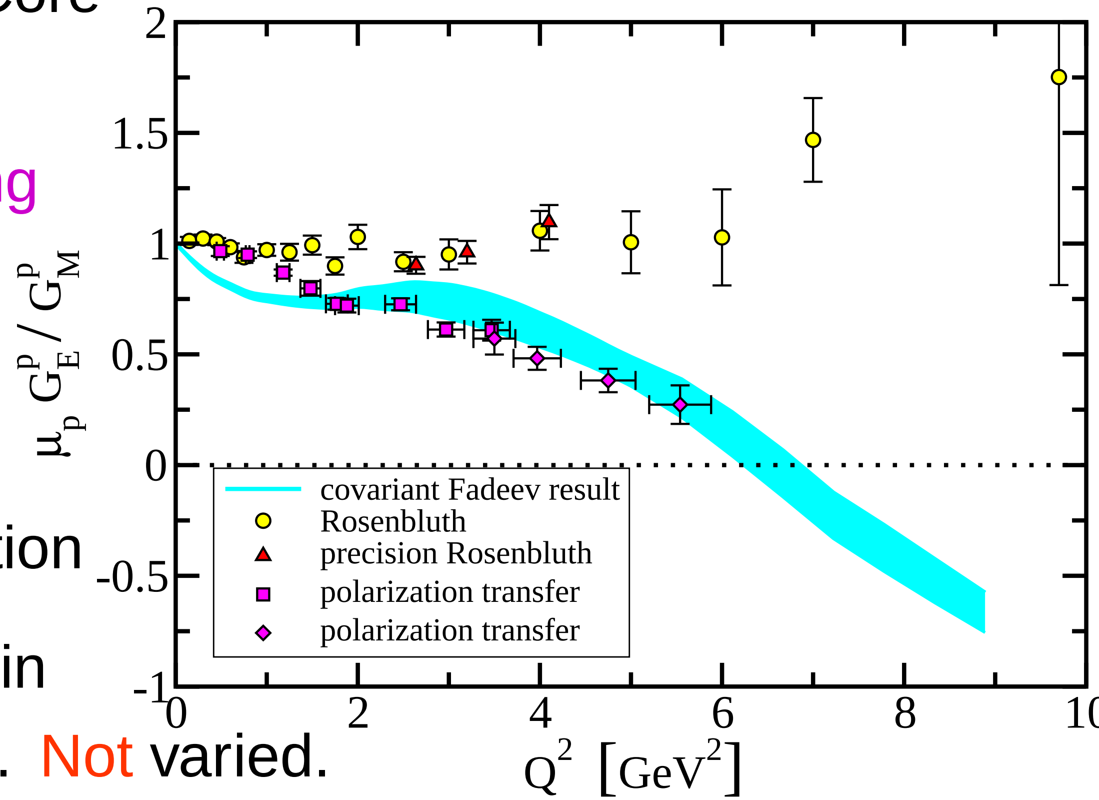

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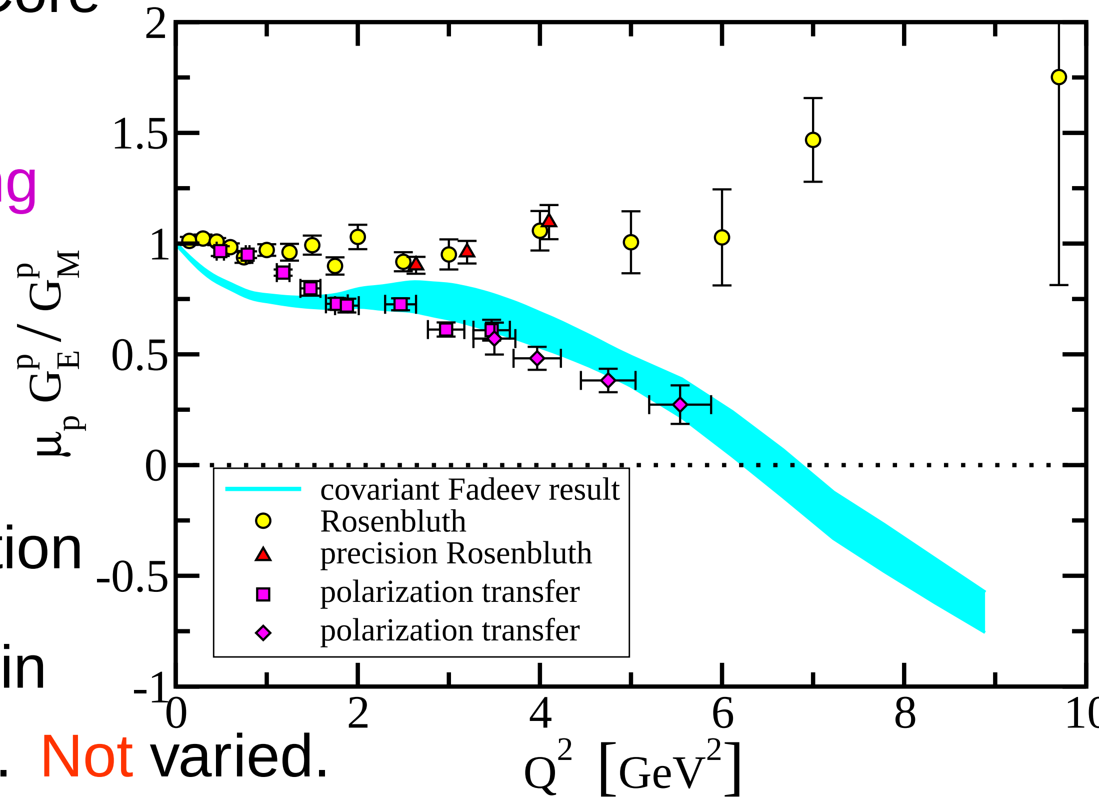

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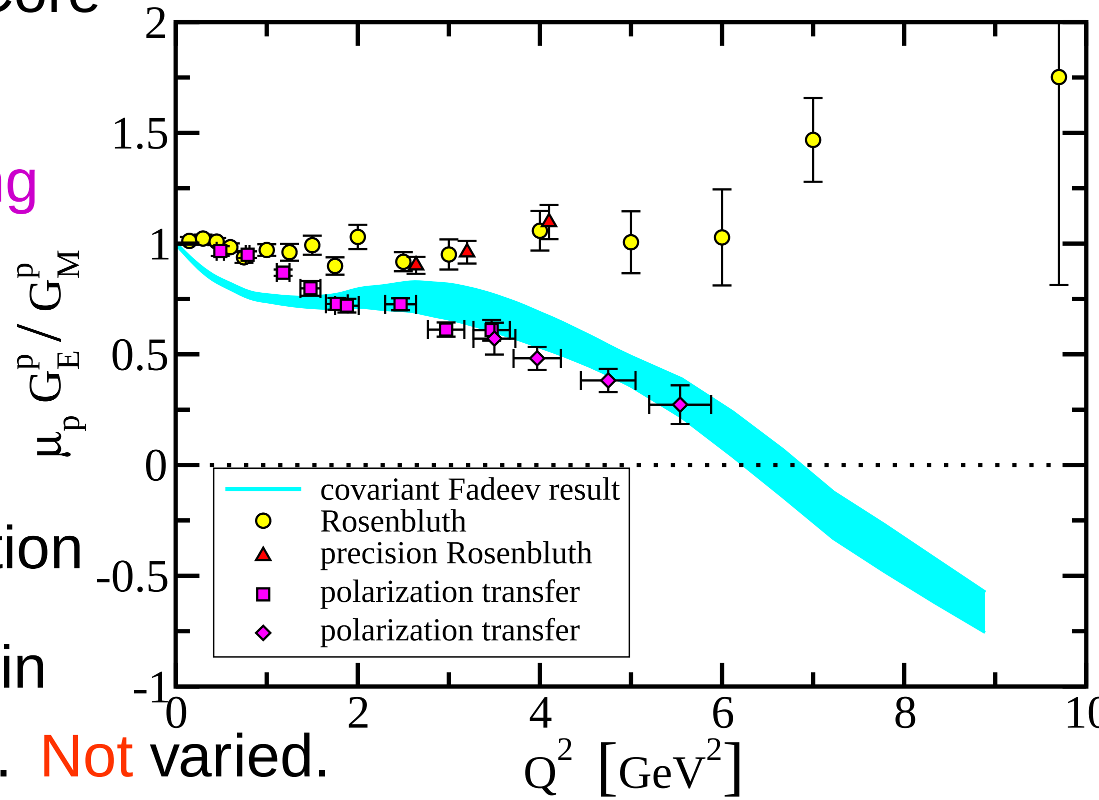

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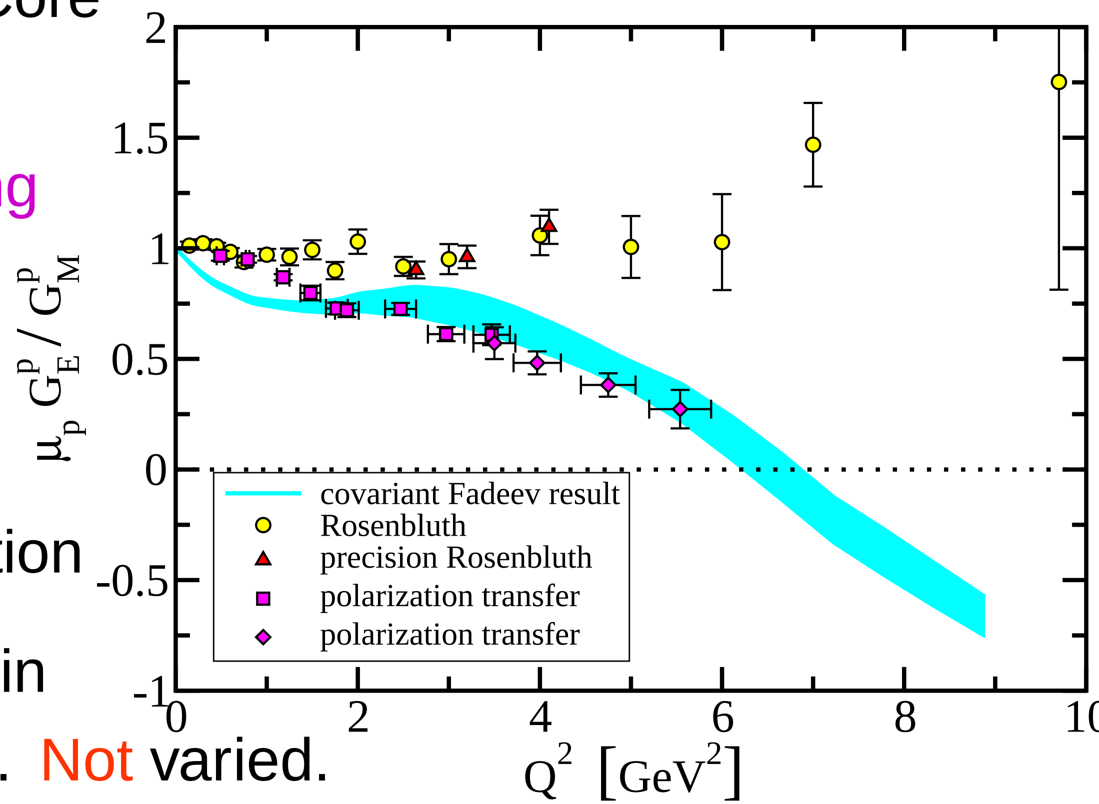

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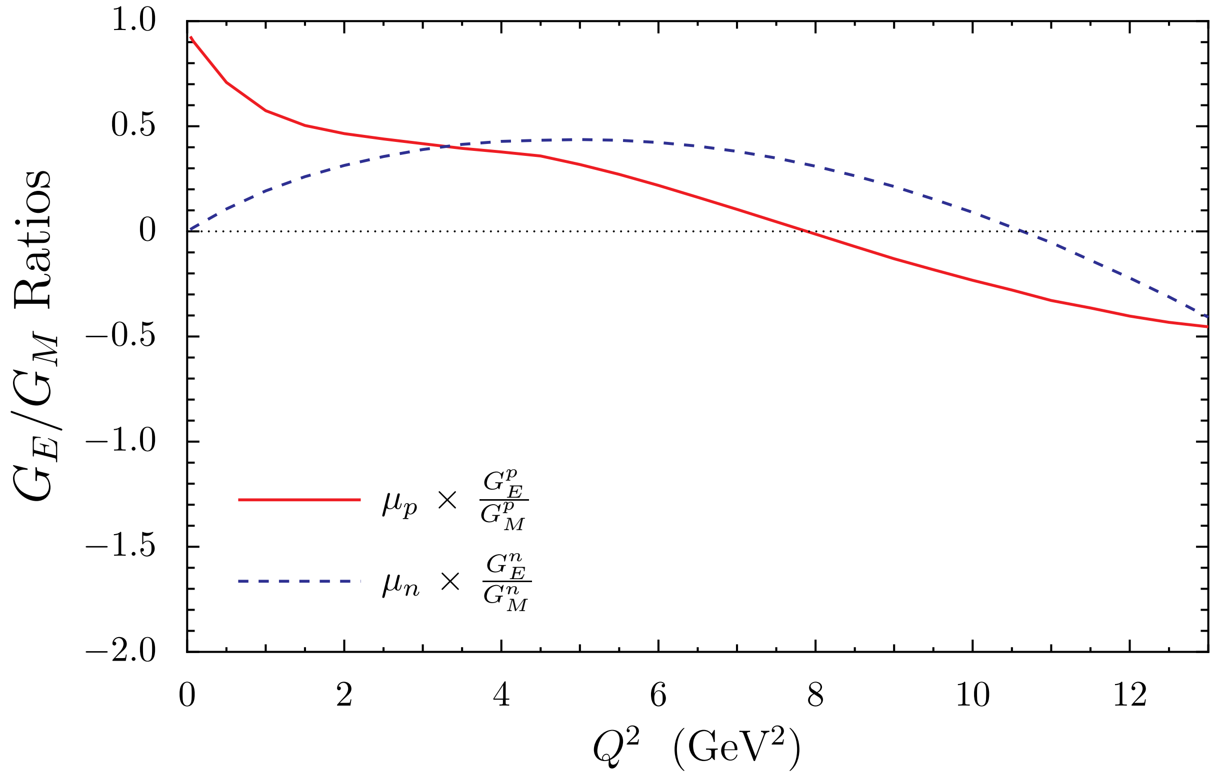

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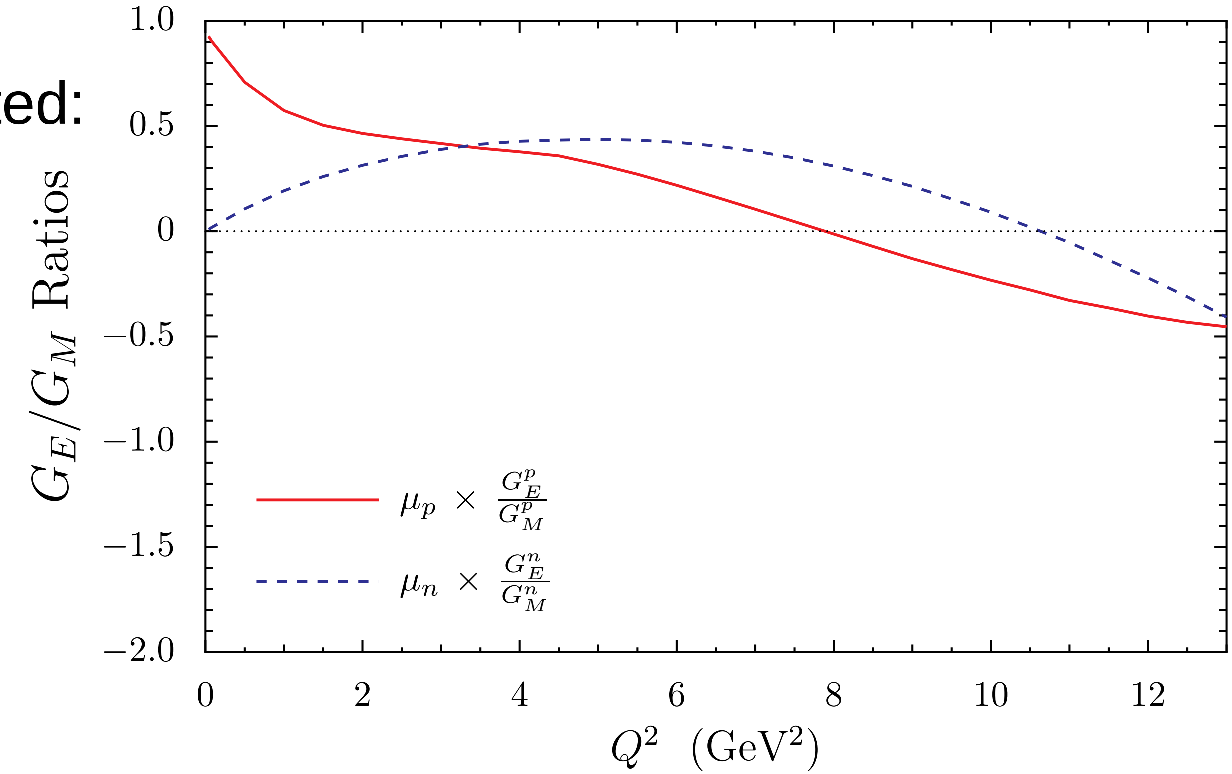

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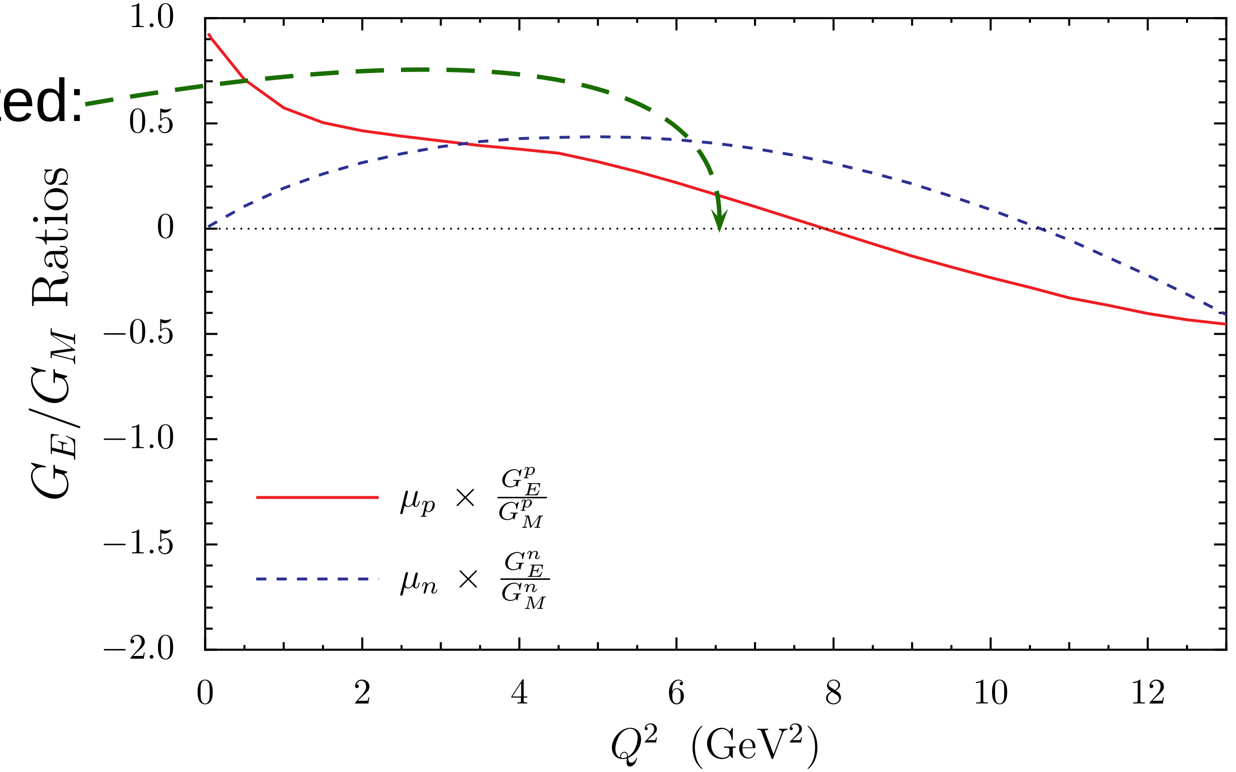

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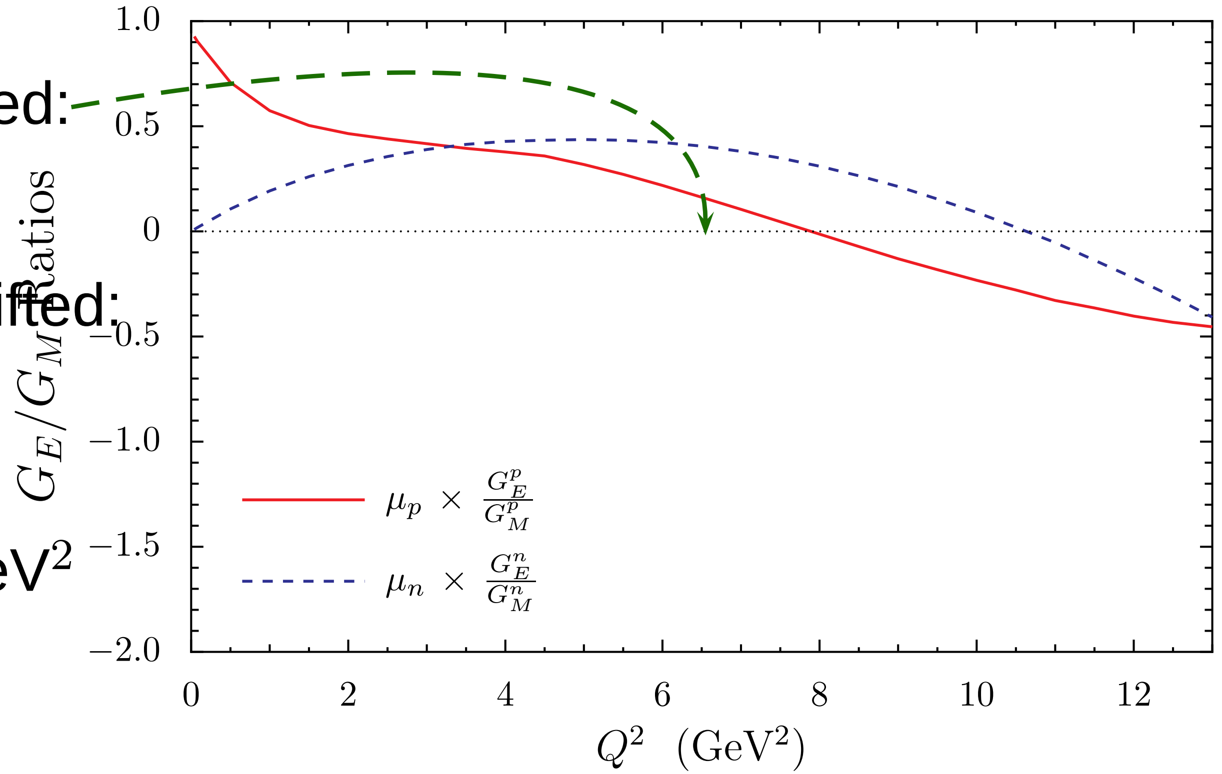

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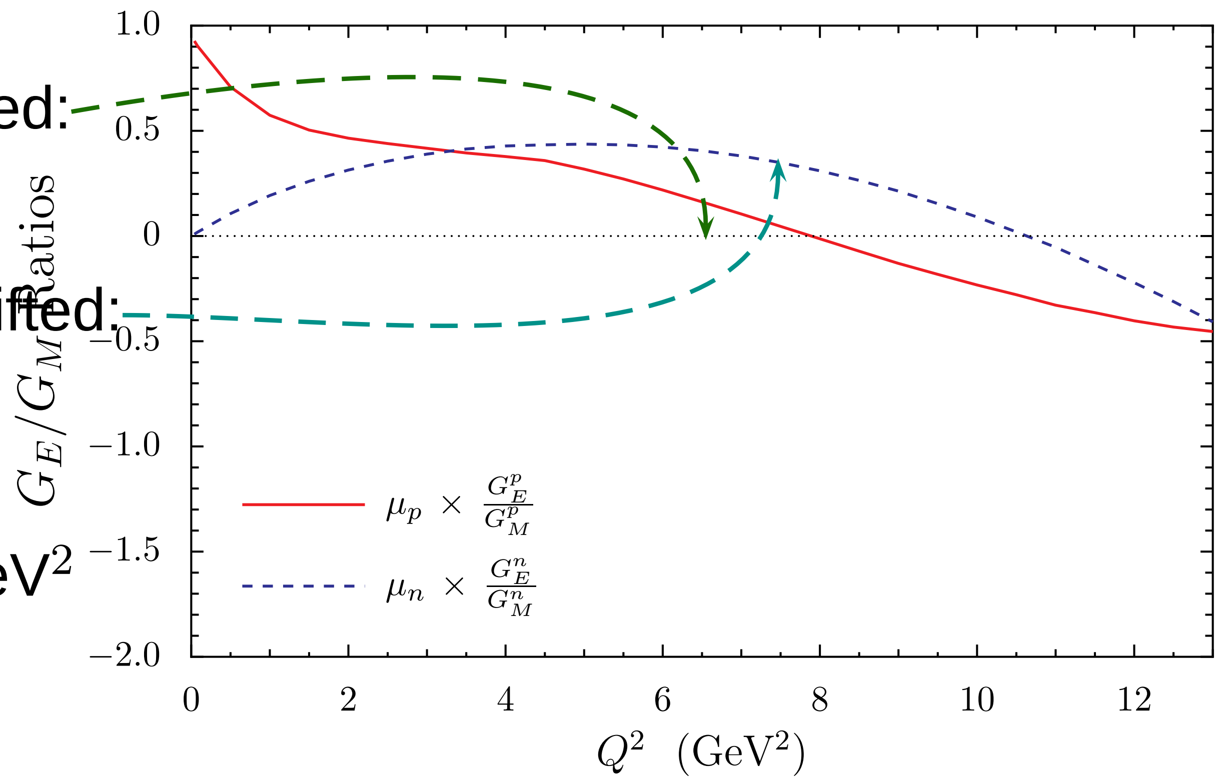

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Pion Cloud

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Pion Cloud
F1 – neutron

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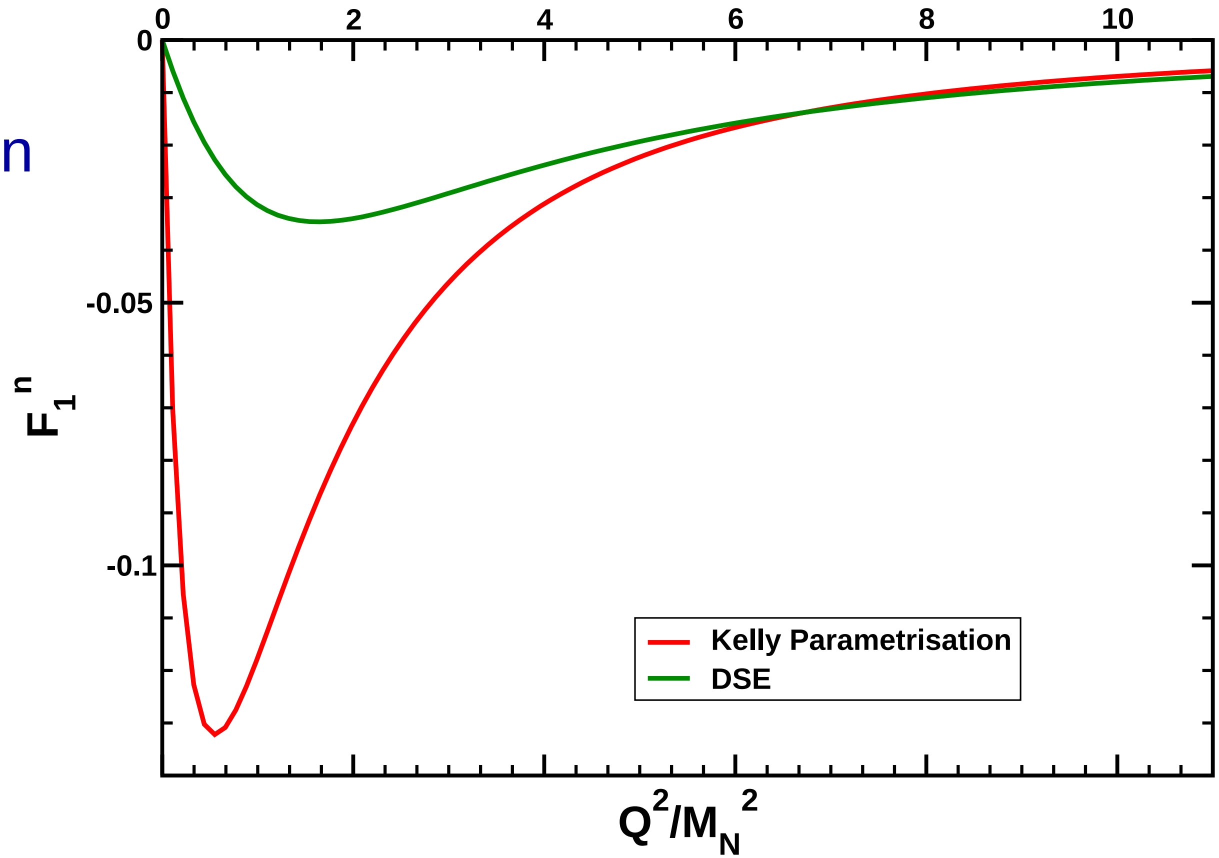

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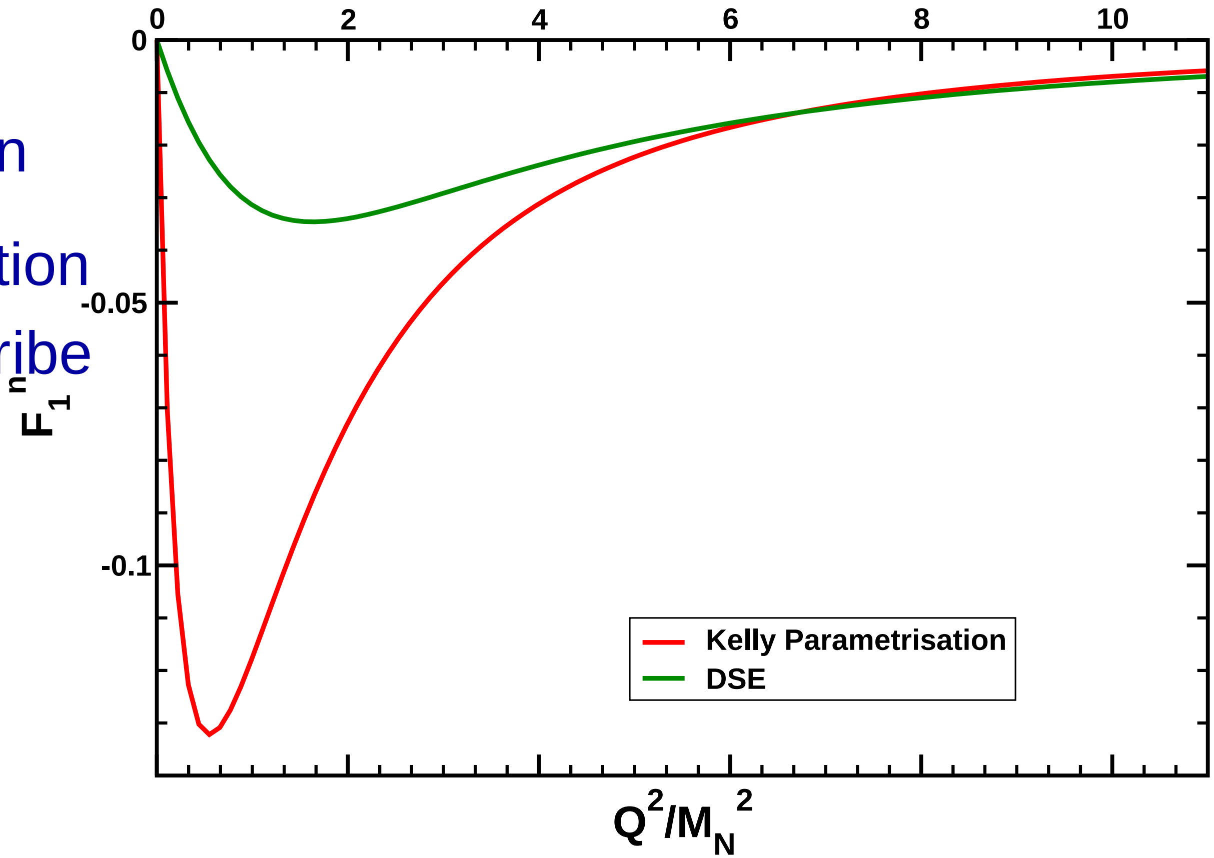

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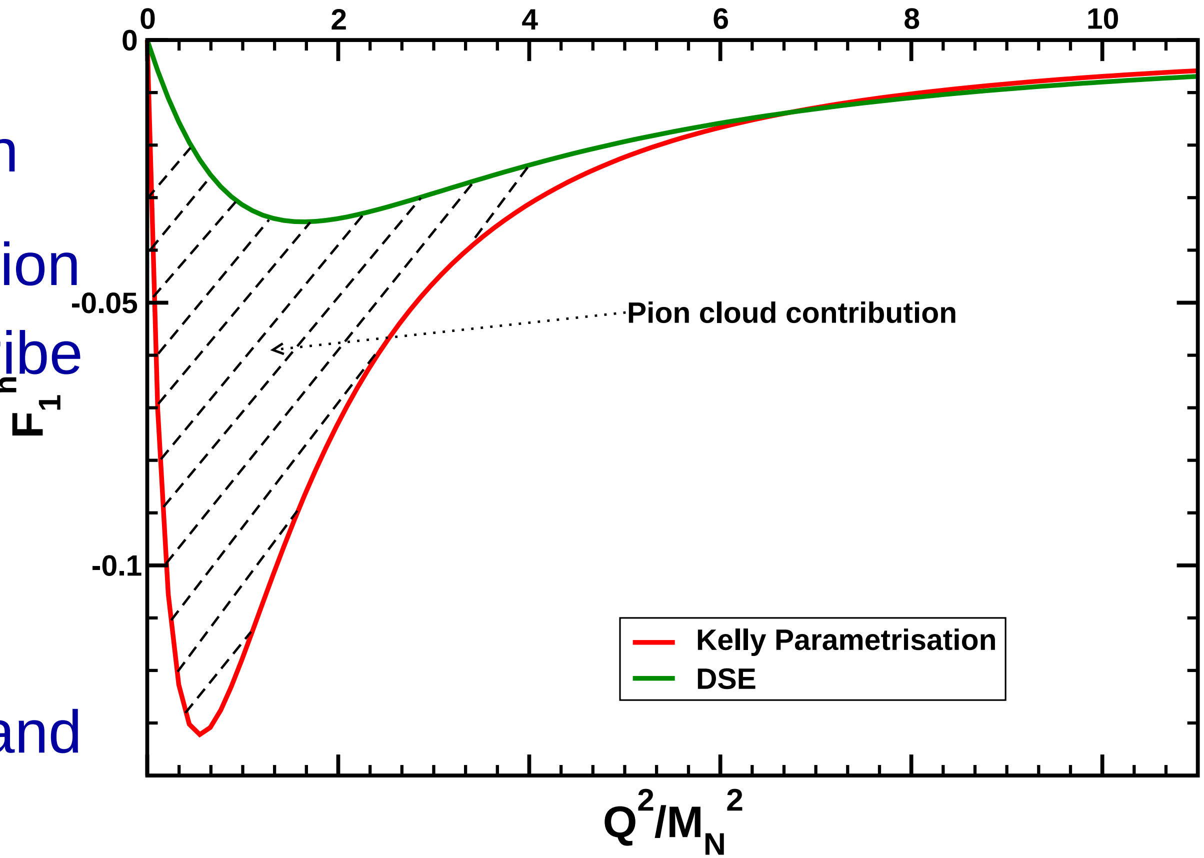

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Epilogue

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Epilogue

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Contents

Dyson-Schwinger Equations

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- Well suited to Relativistic Quantum Field Theory

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- Simplest level: Generating Tool for Perturbation Theory

  .... Materially Reduces Model Dependence

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Cross-Sections built from Schwinger Functions

Schwinger Functions

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Schwinger Functions

- Solutions are Schwinger Functions (Euclidean Green Functions)

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- Proving fruitful.

Persistent Challenge

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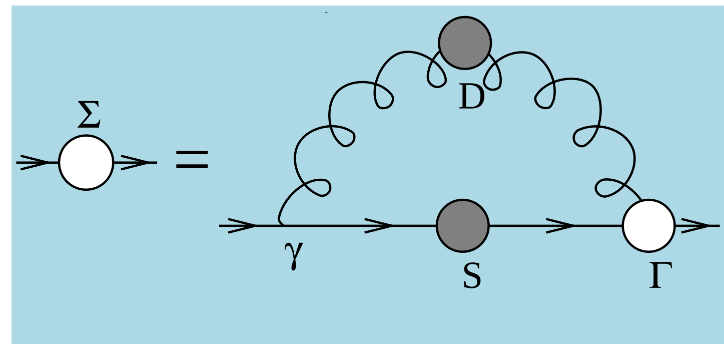
Persistent Challenge

- Infinitely Many Coupled Equations



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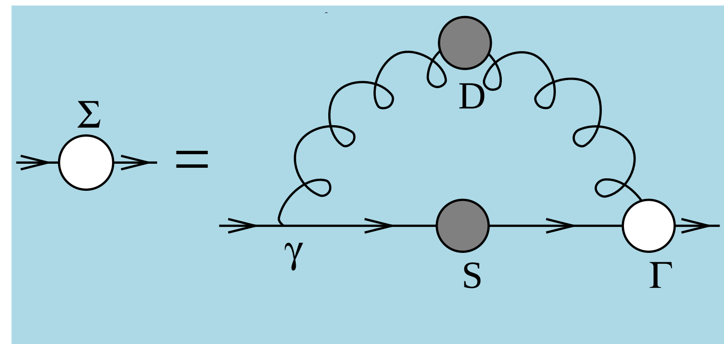

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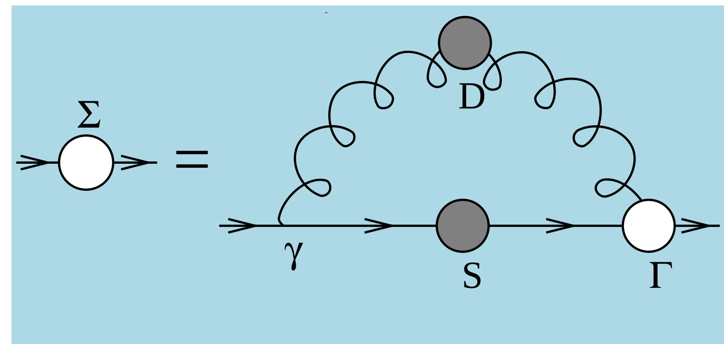

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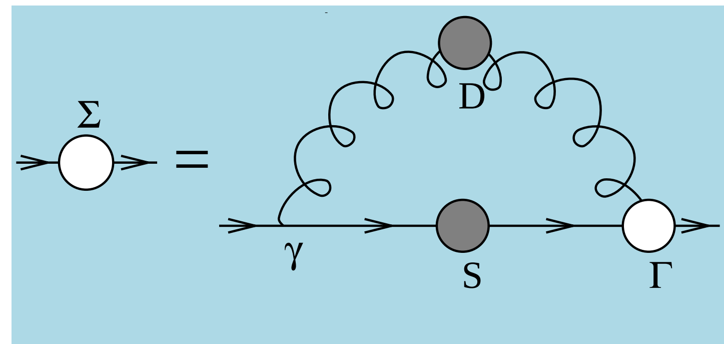

- Coupling between equations necessitates truncation
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    Not useful for the nonperturbative problems
    in which we're interested

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

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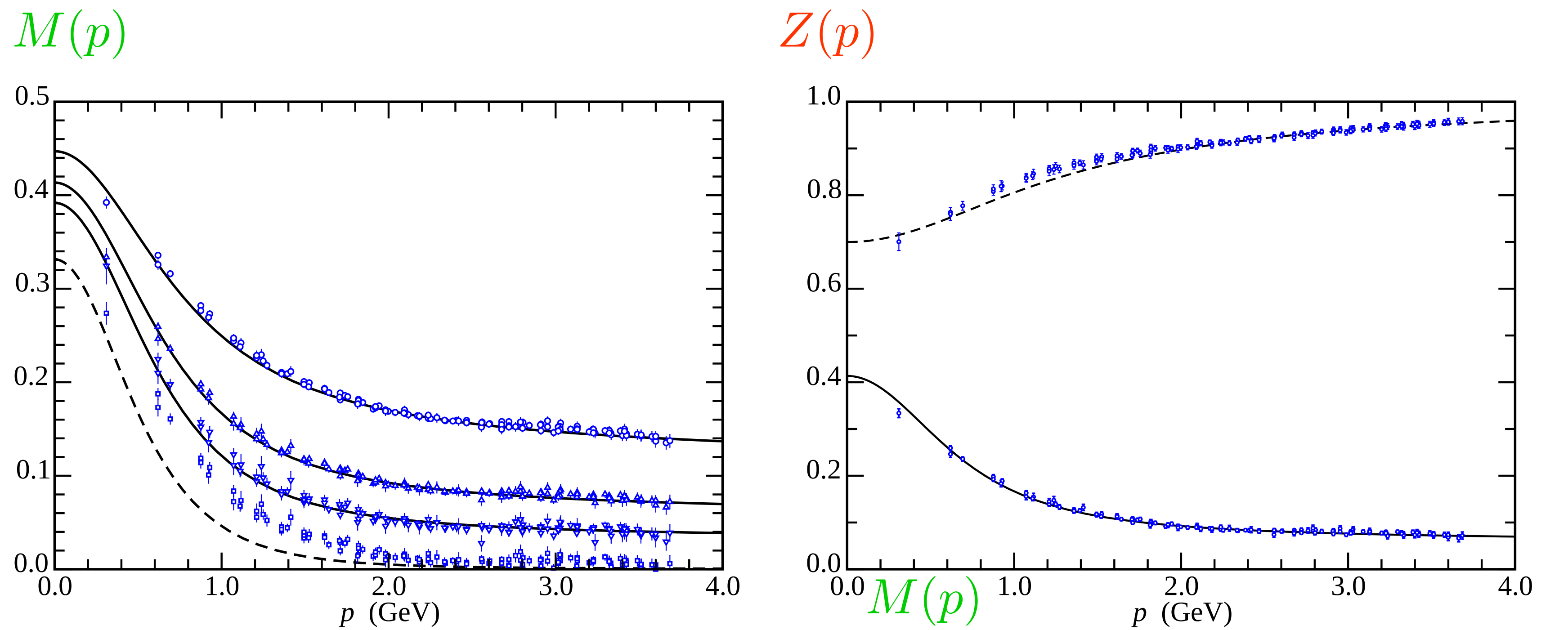
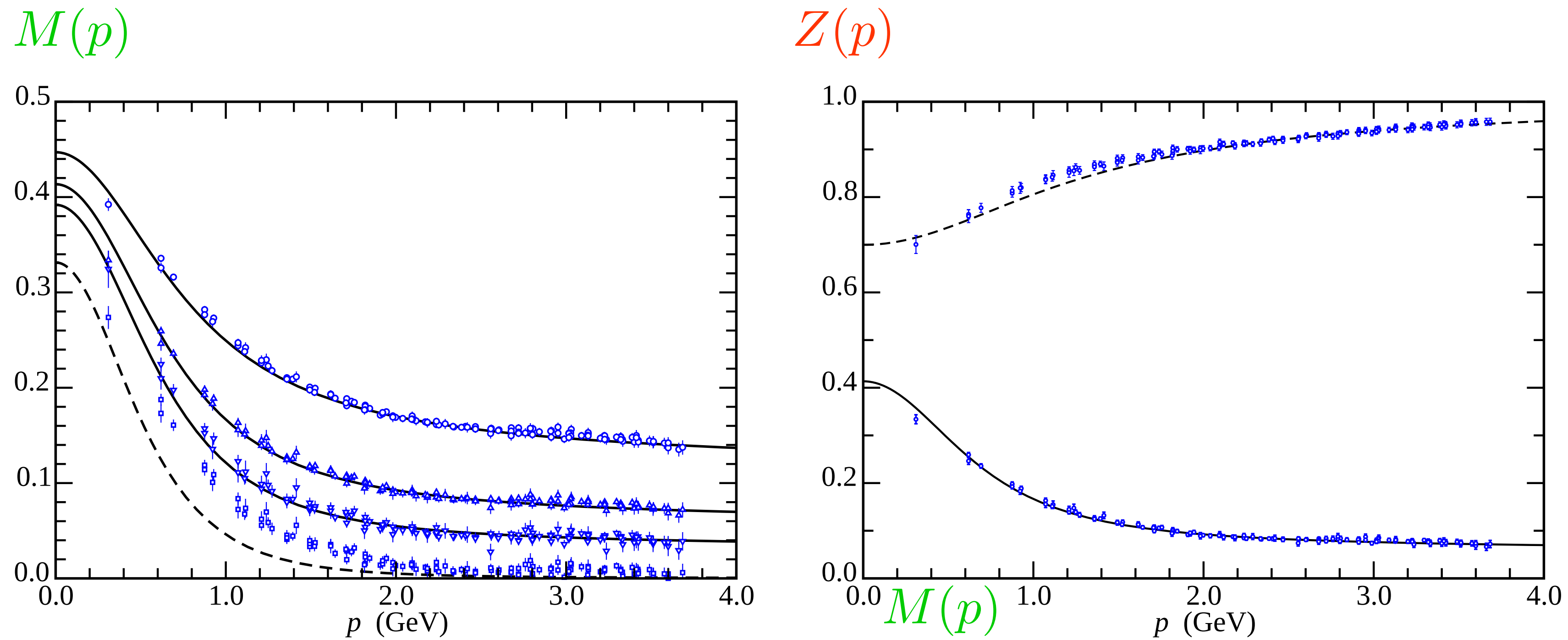
Quenched-QCD
Dressed-Quark Propagator



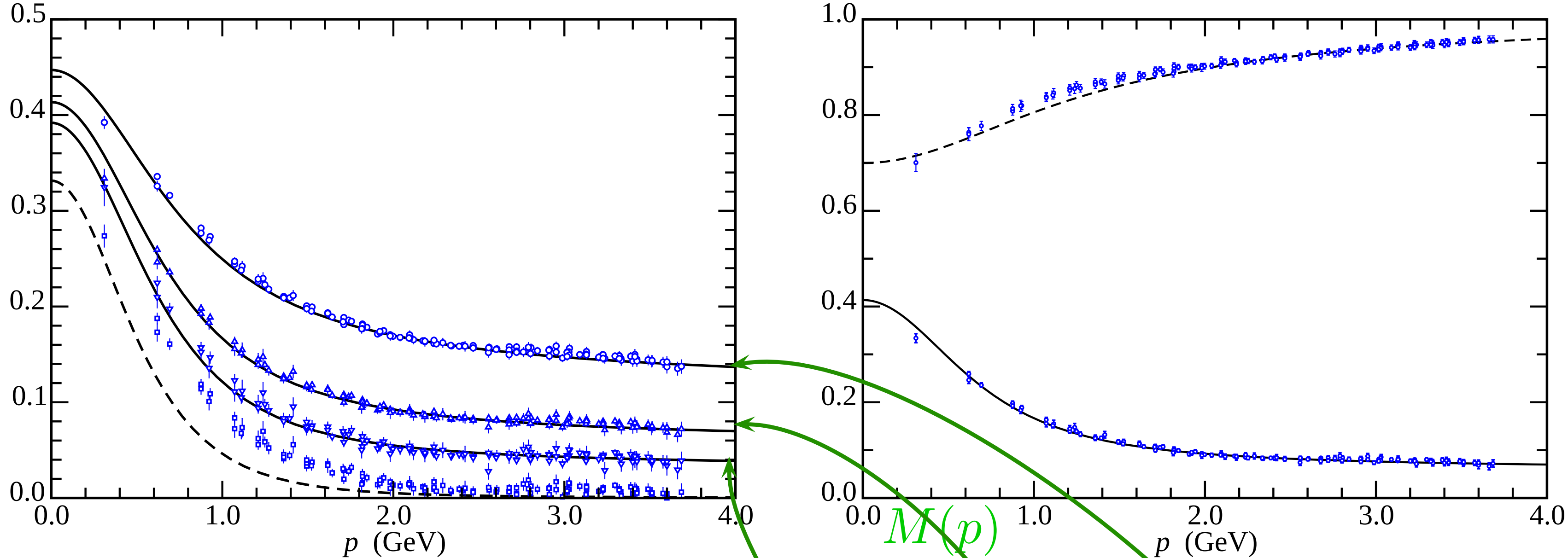
2002 Quenched-QCD Dressed-Quark Propagator



- "*data*:" Quenched Lattice Meas.
  – Bowman, Heller, Leinweber, Williams: he-lat/0209129

Quenched-QCD Dressed-Quark Propagator

$M(p)$ $Z(p)$



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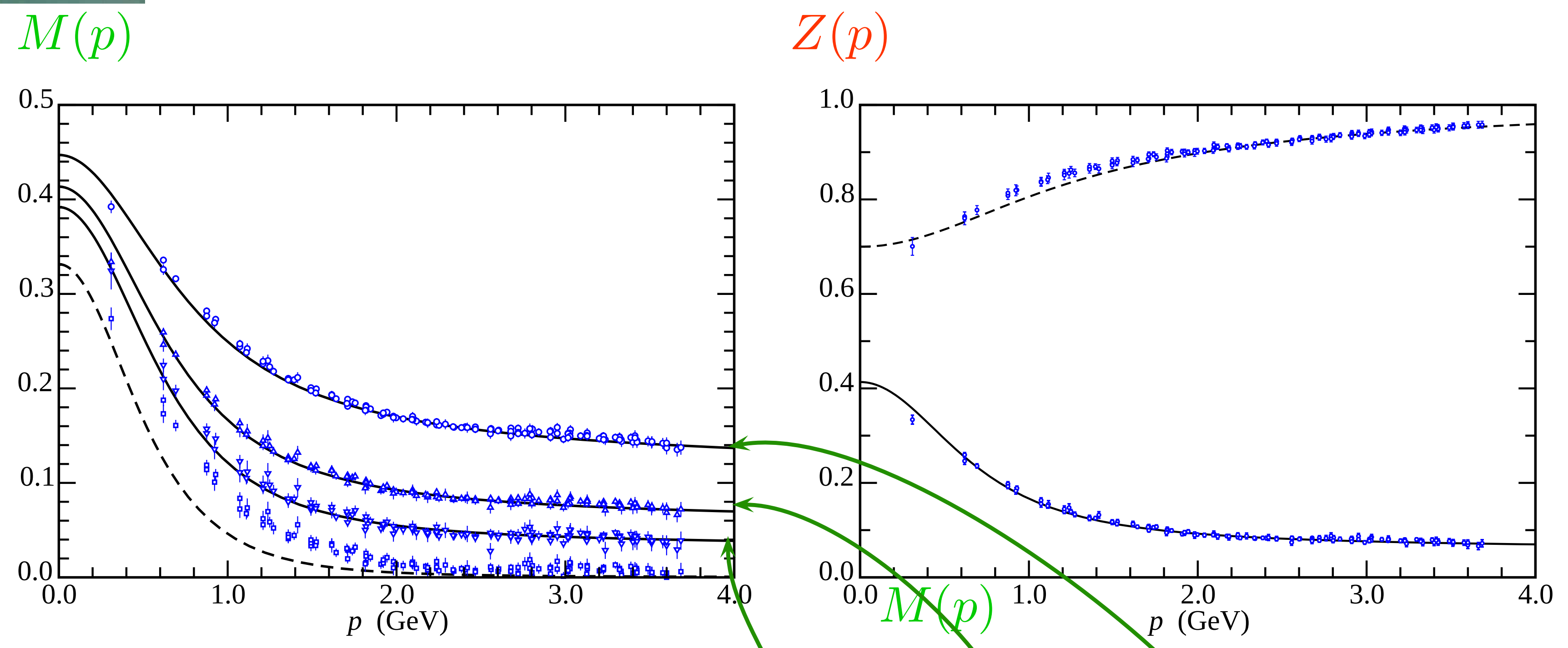
Quenched-QCD Dressed-Quark Propagator

2002



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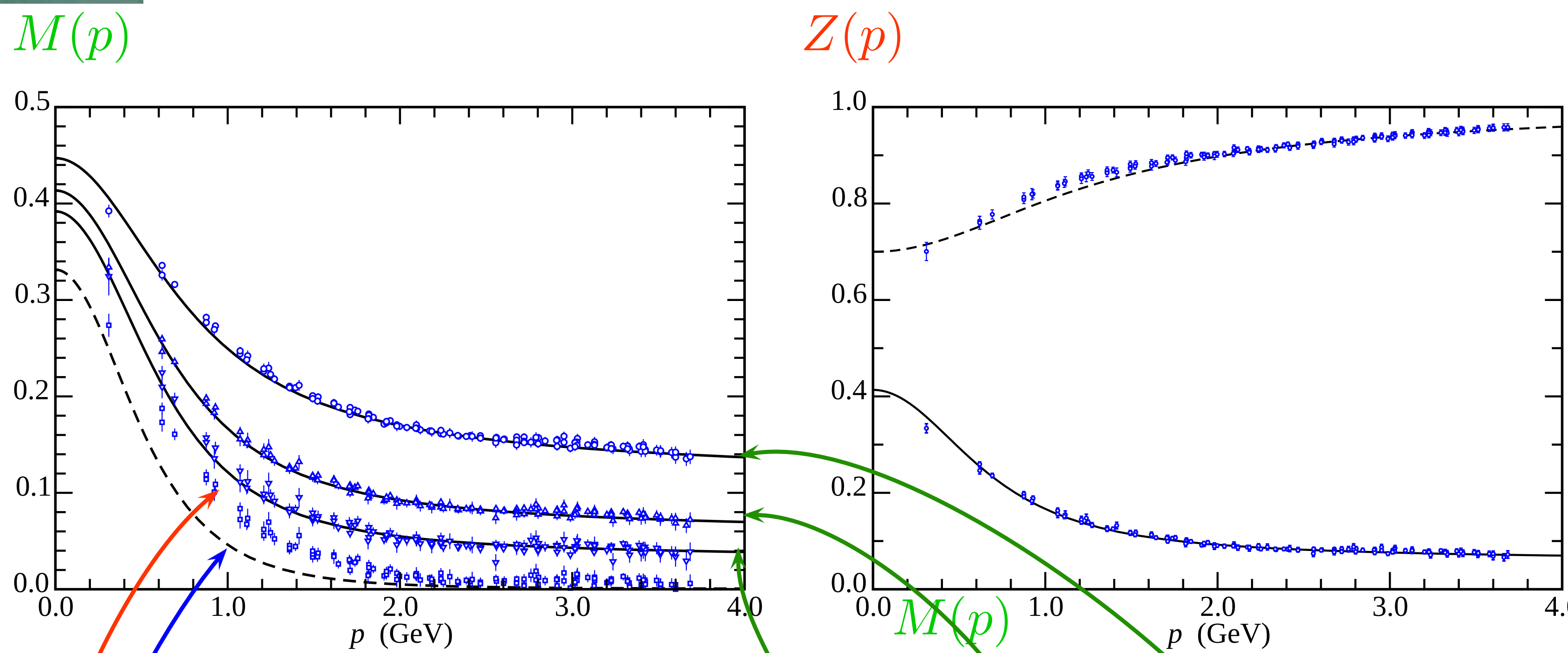

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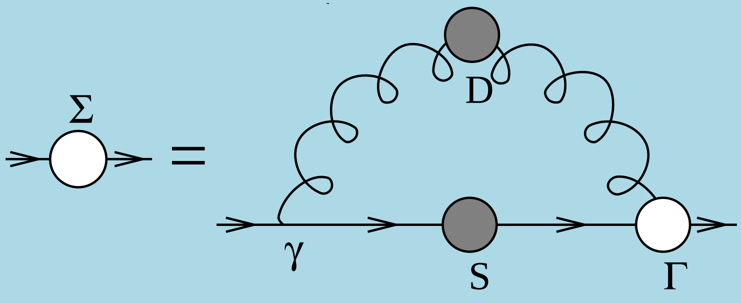
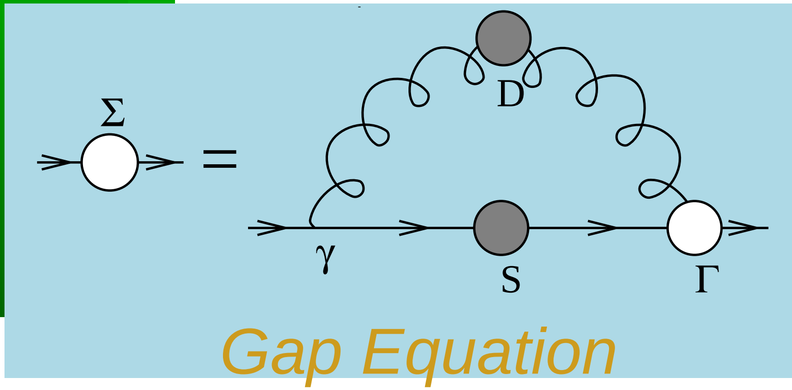
- Linear extrapolation of lattice data to chiral limit is inaccurate

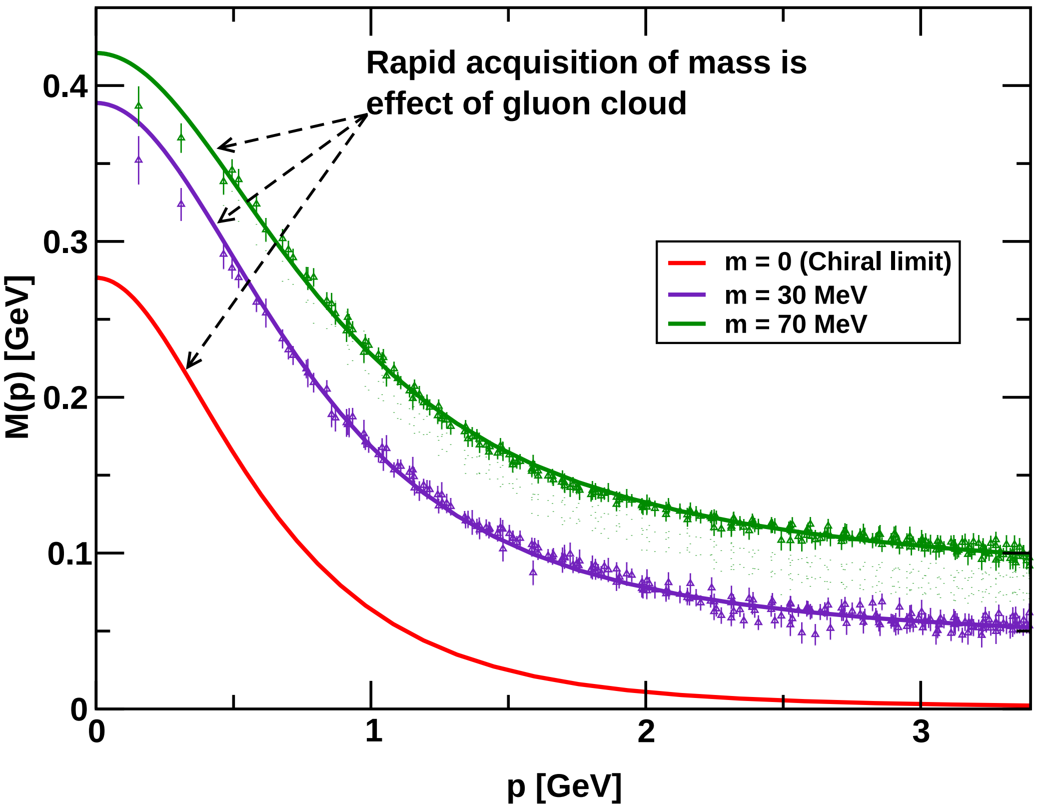
Frontiers of Nuclear Science: A Long Range Plan (2007)



Gap Equation

Frontiers of Nuclear Science: Theoretical Advances





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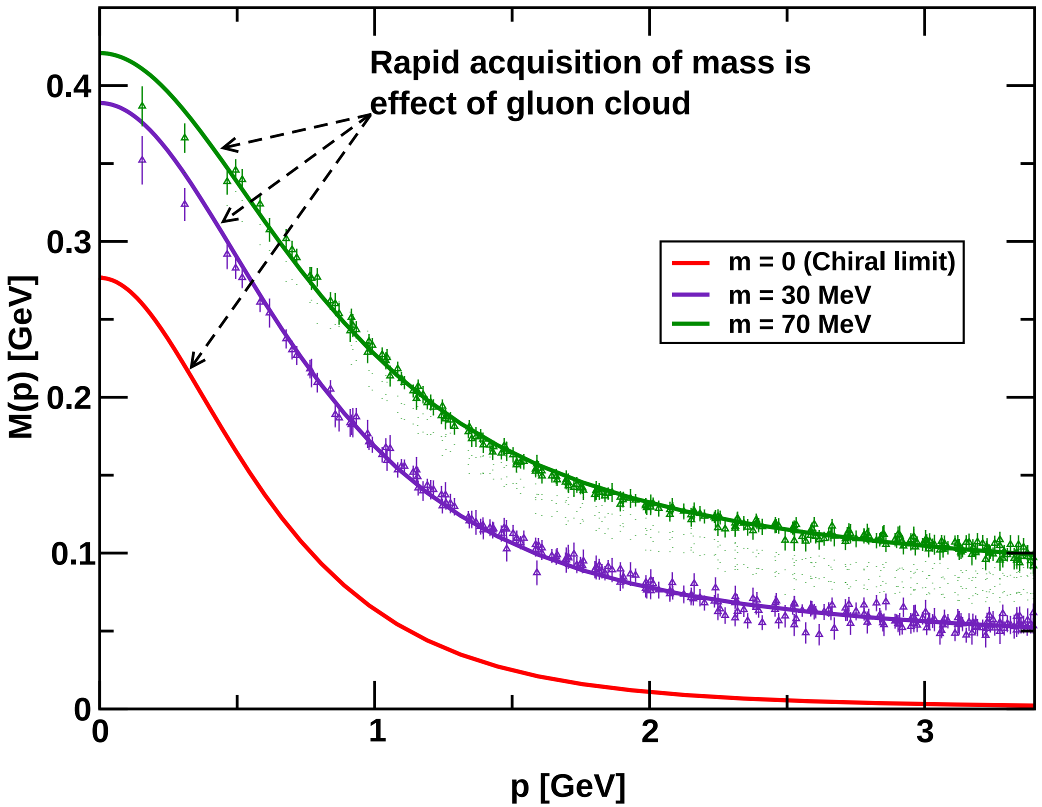
Mass from nothing.

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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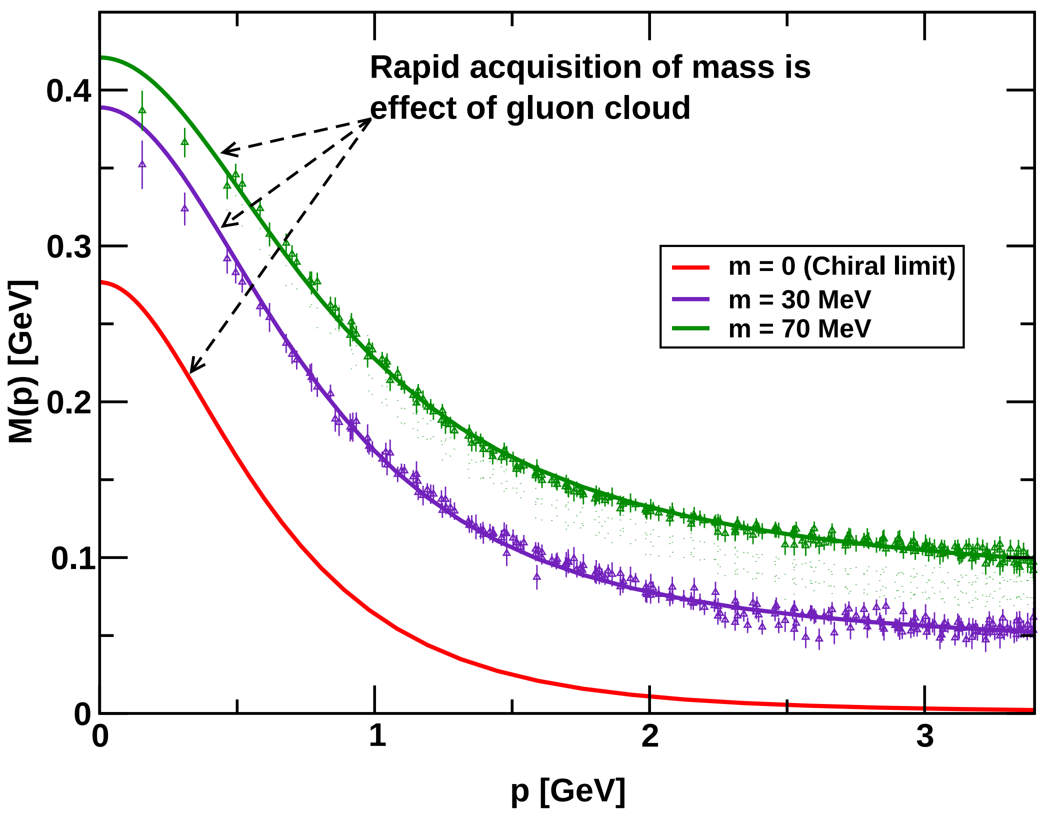

Dimensionless product: $r_\pi \, f_\pi$

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- Great strides towards placing nucleon studies on same footing as mesons

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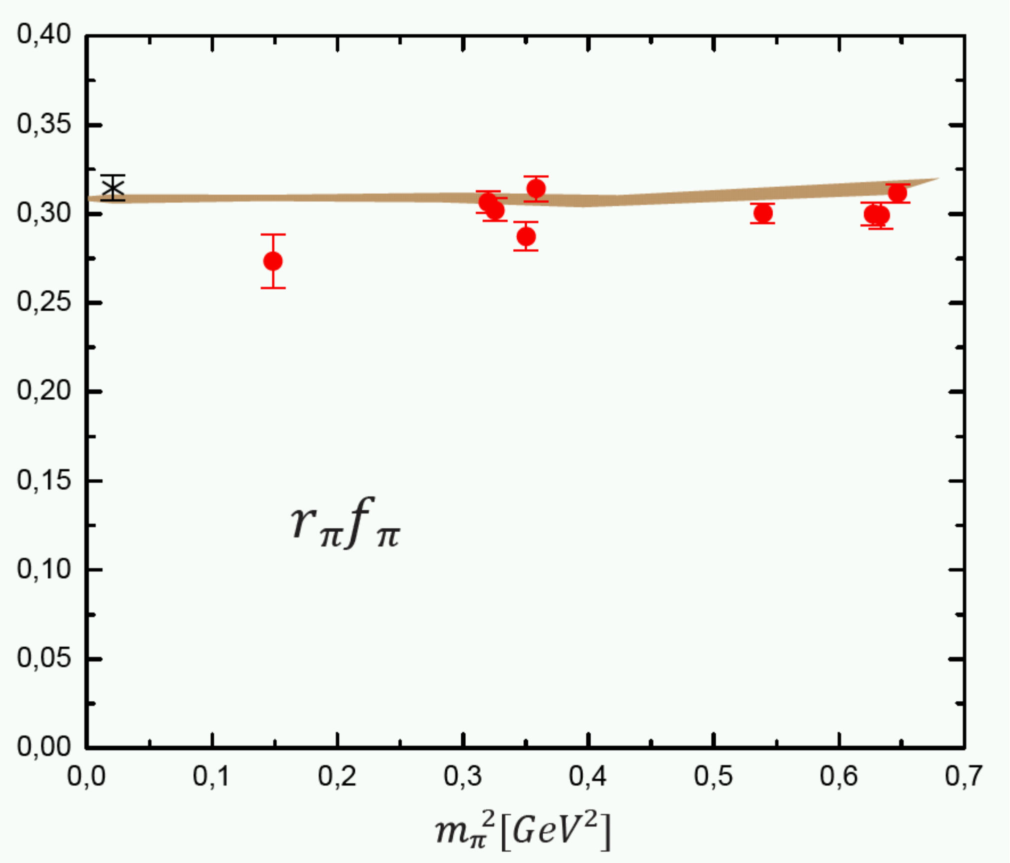
- DSE prediction



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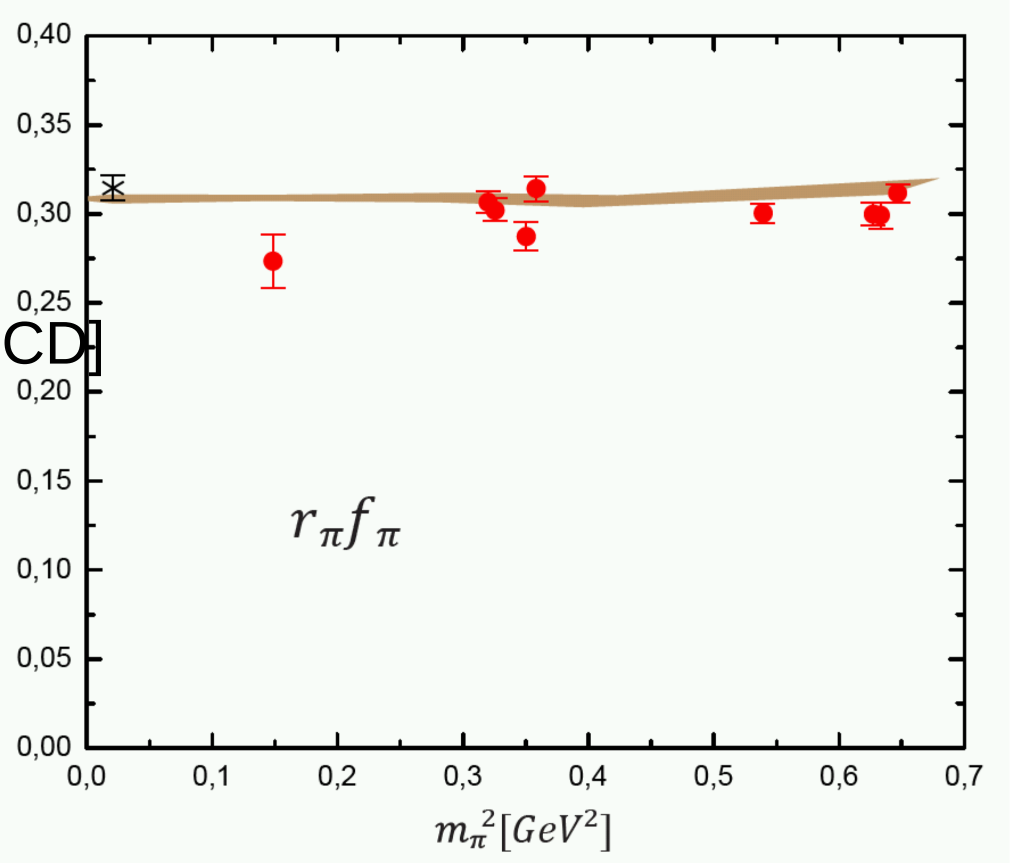

- DSE prediction
- Lattice results
  – James Zanotti [UK QCD]

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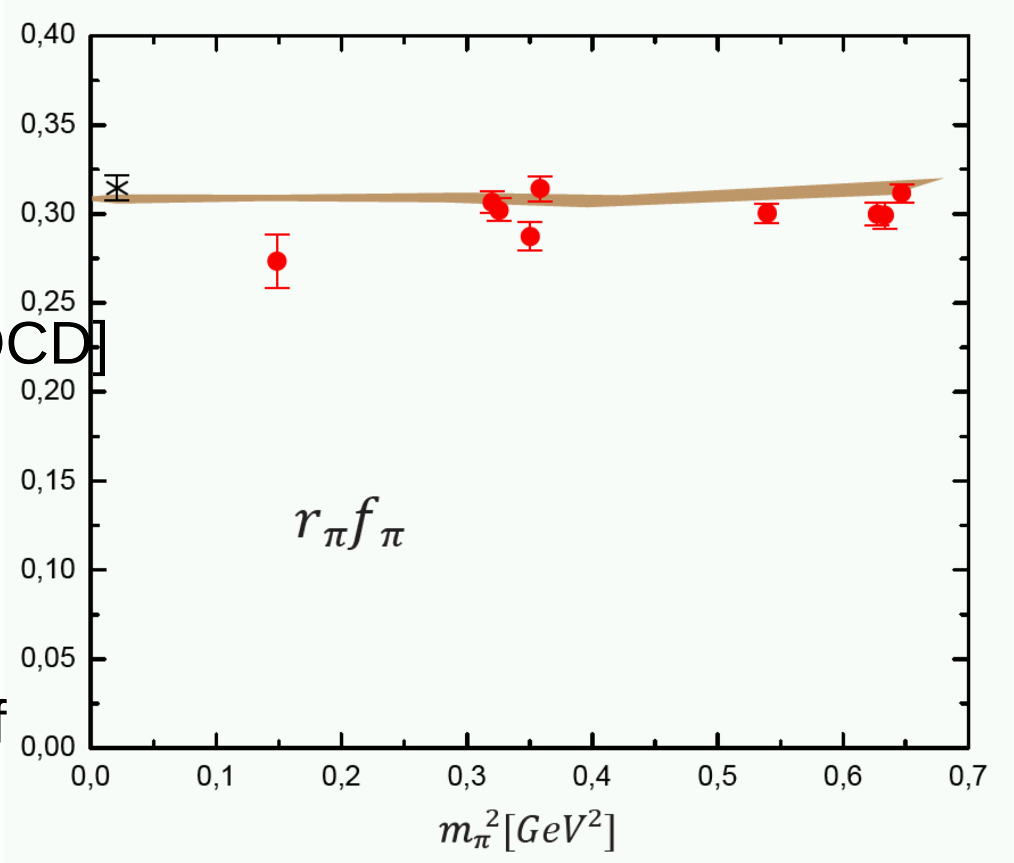

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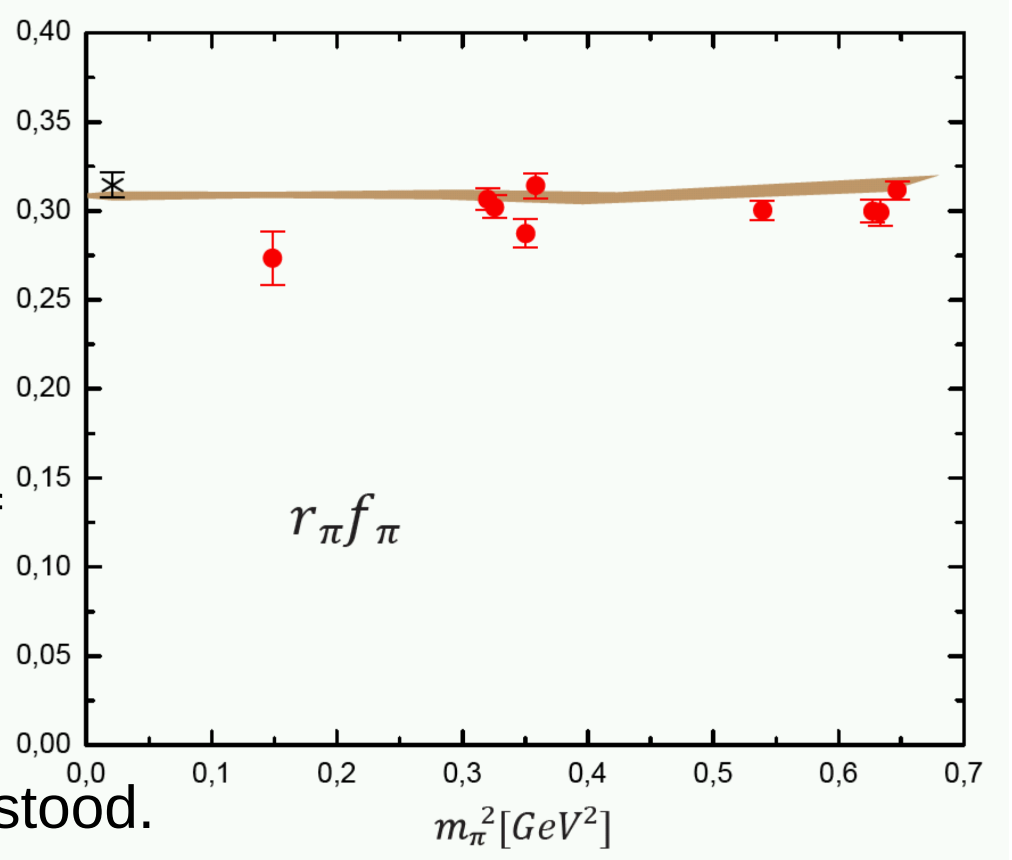
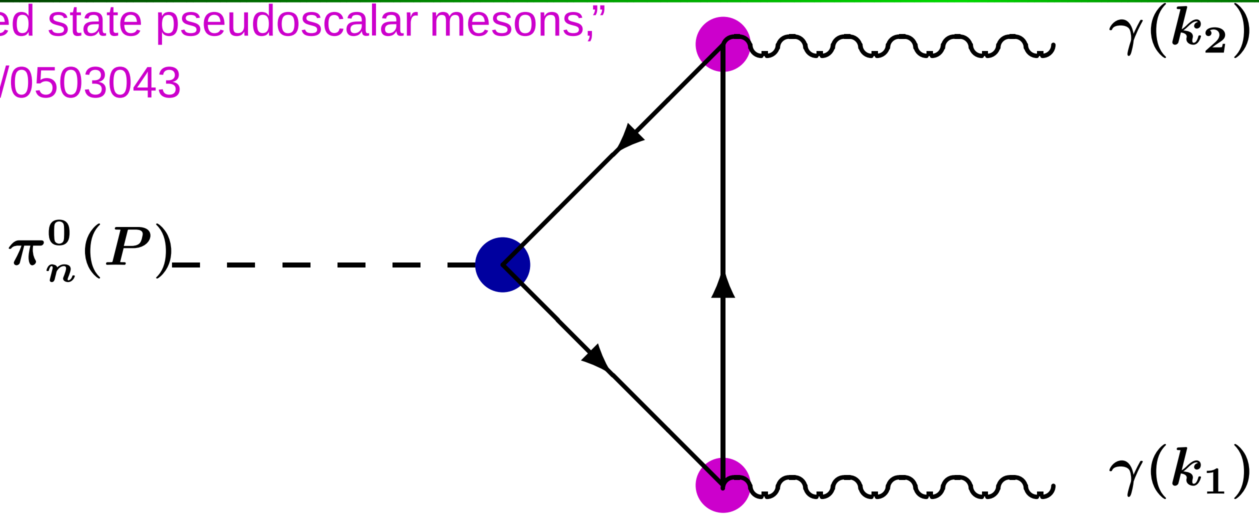


- DSE prediction
- Fascinating result: DSE and Lattice – Experimental value obtains independent of current-quark mass.
- Potentially useful but must first be understood.

Two-photon Couplings of Pseudoscalar Mesons

Höll, Krassnigg, Maris, *et al.*,
"Electromagnetic properties of ground and excited state pseudoscalar mesons,"
nu-th/0503043



$$T^{\pi^0_n}_{\mu\nu}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}\, G^{\pi^0_n}(k_1,k_2)$$

- Define: $\mathcal{T}_{\pi^0_n}(P^2,Q^2) = G^{\pi^0_n}(k_1,k_2)\Big|_{k_1^2=Q^2=k_2^2}$

  This is a transition form factor.

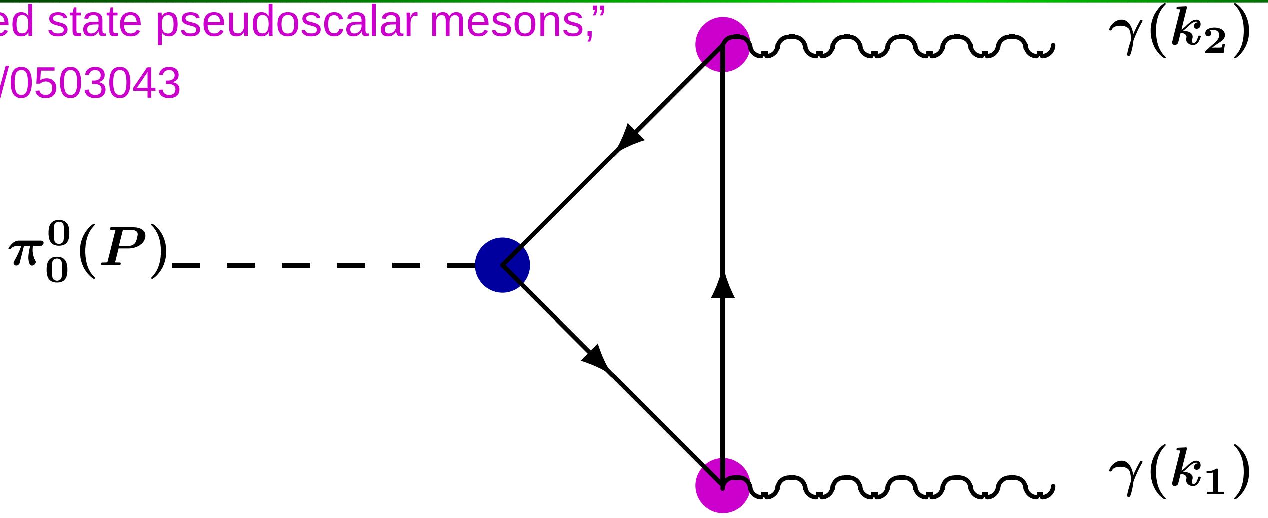
- Physical Processes described by couplings:

  $g_{\pi^0_0\gamma\gamma} := \mathcal{T}_{\pi^0_0}(-m^2_{\pi^0_0}, 0)$

  Width: $\Gamma_{\pi^0_n\gamma\gamma} = \alpha^2_{\rm em}\, \frac{m^3_{\pi_n}}{16\pi^3}\, g^2_{\pi_n\gamma\gamma}$

Two-photon Couplings: Goldstone Mode

Höll, Krassnigg, Maris, *et al.*, "Electromagnetic properties of ground and excited state pseudoscalar mesons," nu-th/0503043



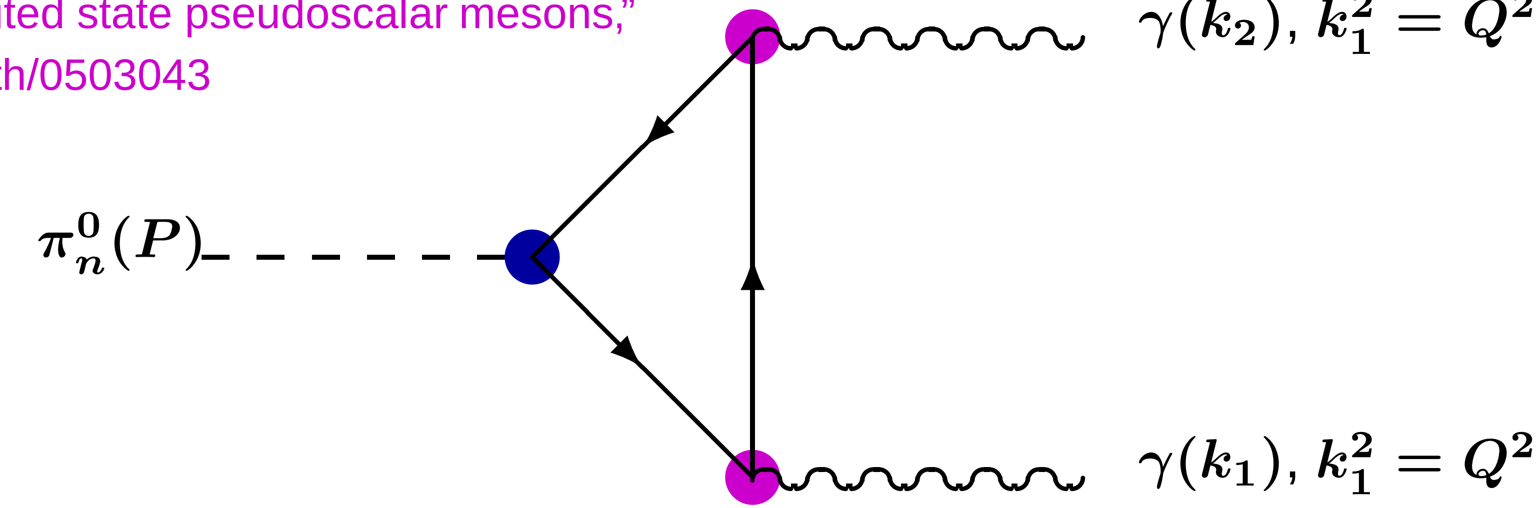
- $$T_{\mu\nu}^{\pi_0^0}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}\, G^{\pi_0^0}(k_1,k_2)$$
  - Chiral limit, model-independent and algebraic result

    $$g_{\pi_0^0\gamma\gamma} := \mathcal{T}_{\pi_0^0}(-m_{\pi_0^0}^2 = 0, 0) = \frac{1}{2}\frac{1}{f_{\pi_0}}$$

    So long as truncation veraciously preserves chiral symmetry and the pattern of its dynamical breakdown
- The most widely known consequence of the Abelian anomaly

Two-photon Couplings: Transition Form Factor

Höll, Krassnigg, Maris, *et al.*,
"Electromagnetic properties of ground and excited state pseudoscalar mesons,"
nu-th/0503043



$$T_{\mu\nu}^{\pi_n^0}(k_1,k_2) = \frac{\alpha}{\pi} i\varepsilon_{\mu\nu\rho\sigma}k_{1\rho}k_{2\sigma}\, G^{\pi_n^0}(k_1,k_2)$$

So long as truncation preserves chiral symmetry and the pattern of its dynamical breakdown, and the one-loop renormalisation group properties of QCD: model-independent result – $\forall n$:

$$\mathcal{T}_{\pi_n^0}(P^2,Q^2) = G^{\pi_n^0}(k_1,k_2)\Big|_{k_1^2=Q^2=k_2^2} \stackrel{Q^2\gg\Lambda^2_{\rm QCD}}{=} \frac{4\pi^2}{3}\frac{f_{\pi_n}}{Q^2}$$

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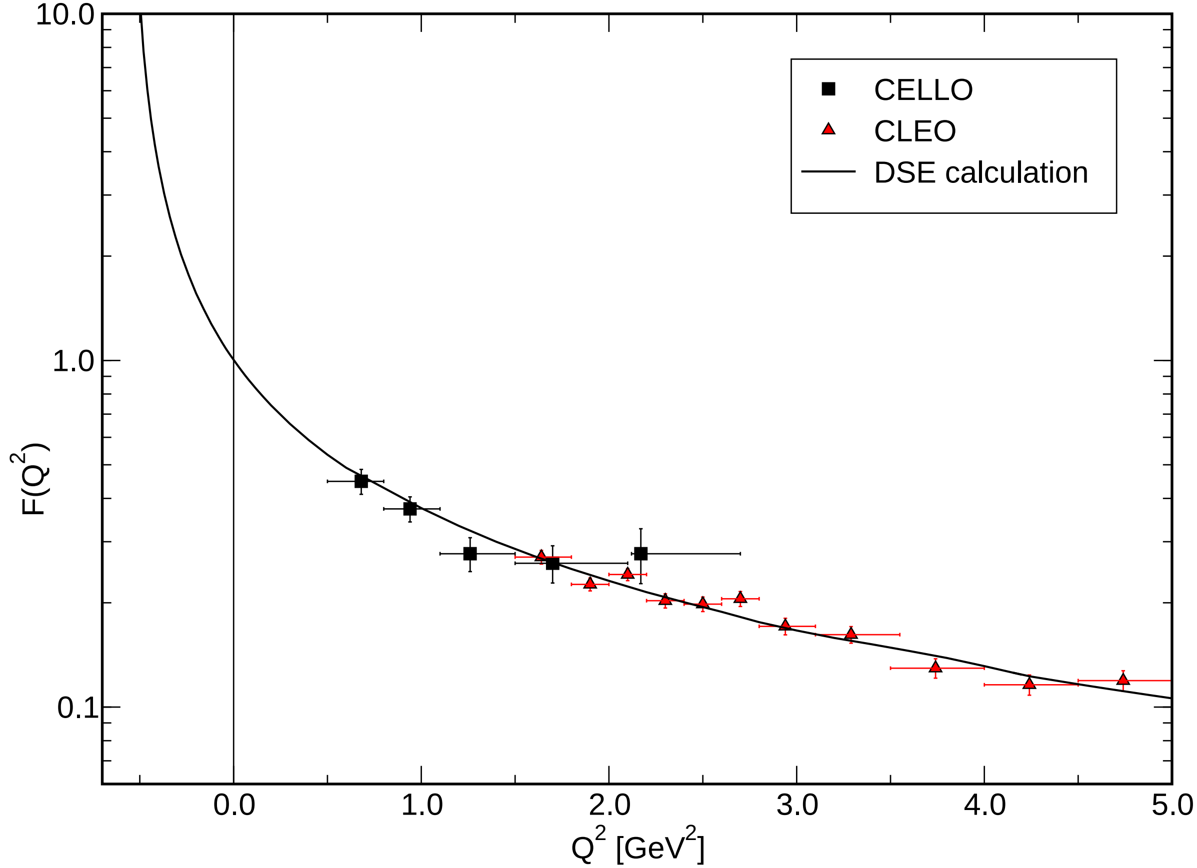
Two-photon Couplings: Transition Form Factor

Maris and Tandy, " Electromagnetic transition form-factors of light mesons," nucl-th/0201017



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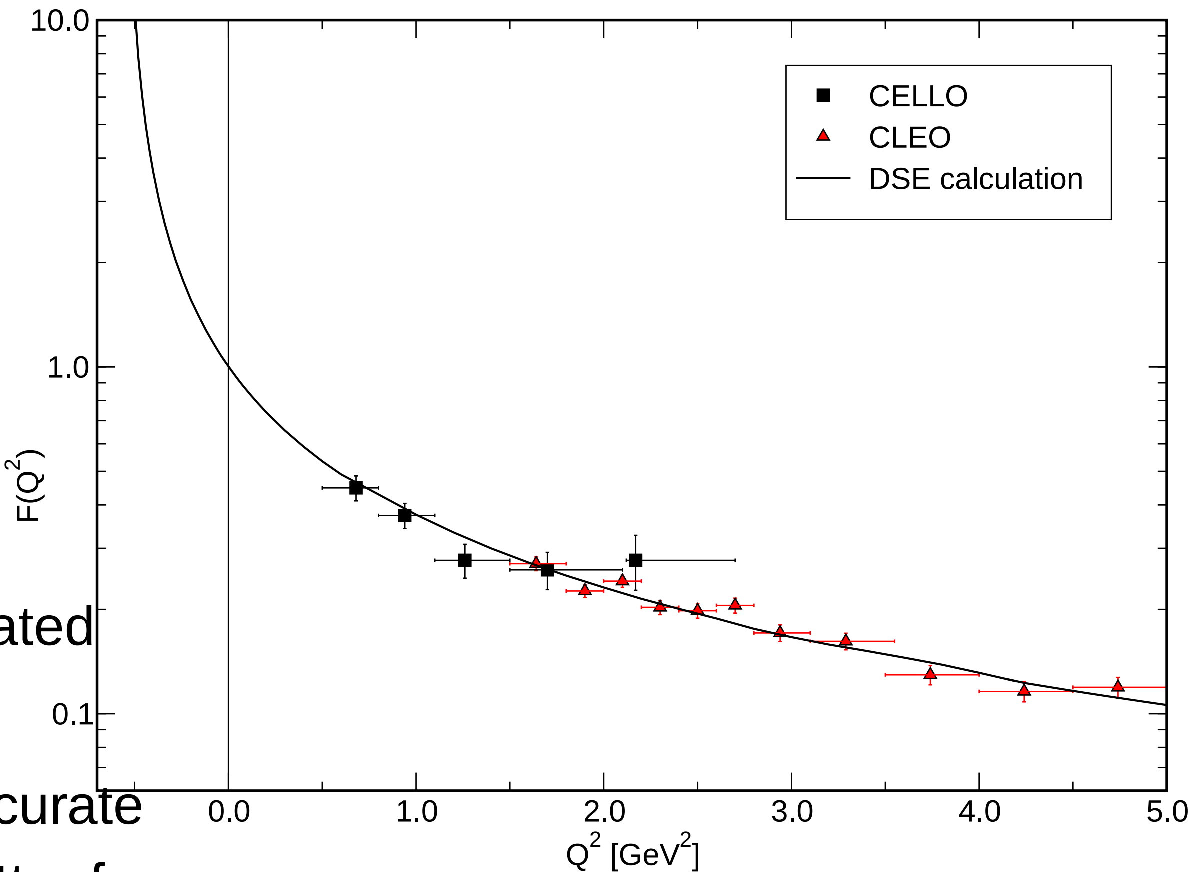

DSE result:

- normalisation calculated
- ρ-meson generated dynamically
- pQCD result accurate to $\sim$ 20% or better for $Q^2 \geq 3$ GeV^2

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Pions and Form Factors

Pions and Form Factors

- Dynamical coupled-channels model ... Analyzed extensive JLab data ... Completed a study of the $\Delta(1236)$
  - *Meson Exchange Model for πN Scattering and $\gamma N \to \pi N$ Reaction*, T. Sato and T.-S. H. Lee, Phys. Rev. C **54**, 2660 (1996)
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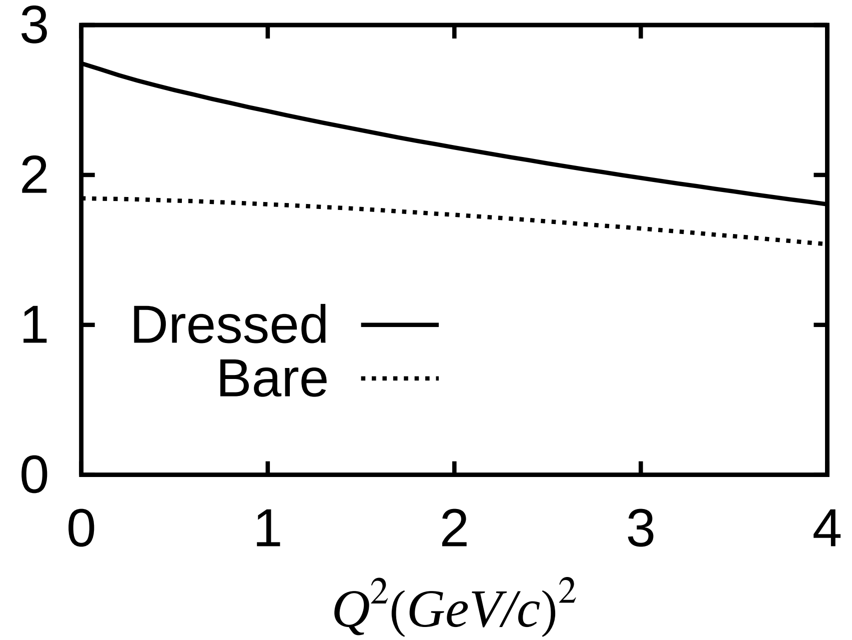
- Pion cloud effects are large in the low Q^2 region.

Ratio of the M1 form factor in $\gamma N \to \Delta$ transition and proton dipole form factor G_D. Solid curve is $G_M^*(Q^2)/G_D(Q^2)$ including pions; Dotted curve is $G_M(Q^2)/G_D(Q^2)$ without pions.



Harry Lee

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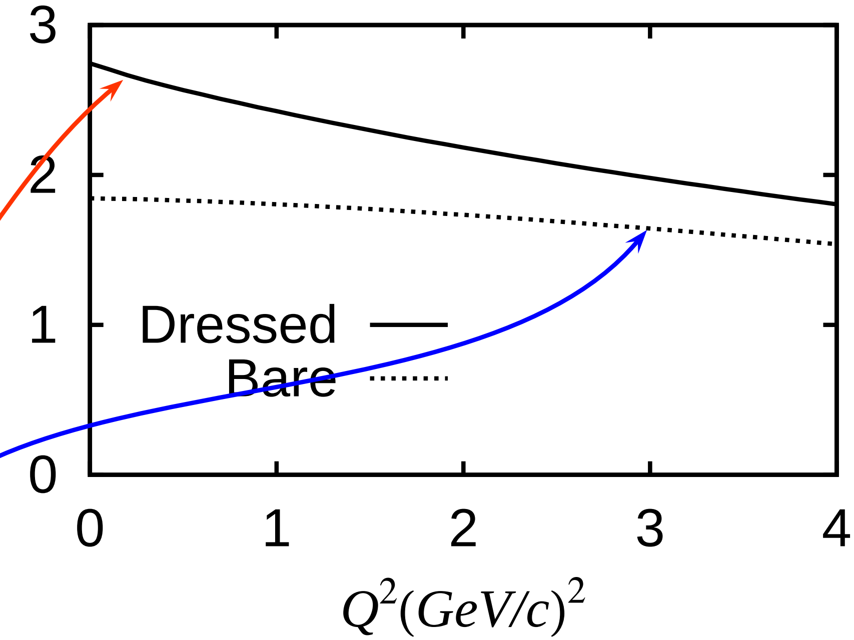
Quark Core



- Responsible for only 2/3 of result at small Q^2
- Dominant for $Q^2 >$ 2 – 3 GeV^2

Results: Nucleon and Δ Masses

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Results: Nucleon and Δ Masses

Mass-scale parameters (in GeV) for the scalar and axial-vector diquark correlations, fixed by fitting nucleon and Δ masses

Set A – fit to the actual masses was required; whereas for
Set B – fitted mass was offset to allow for "π-cloud" contributions

set	M_N	M_Δ	m_{0^+}	m_{1^+}	ω_{0^+}	ω_{1^+}
A	0.94	1.23	0.63	0.84	0.44=1/(0.45 fm)	0.59=1/(0.33 fm)
B	1.18	1.33	0.80	0.89	0.56=1/(0.35 fm)	0.63=1/(0.31 fm)

- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV

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- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV
- Axial-vector diquark provides significant attraction

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Argonne National Laboratory

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Set B – fitted mass was offset to allow for "π-cloud" contributions

set	M_N	M_Δ	m_{0^+}	m_{1^+}	ω_{0^+}	ω_{1^+}
A	0.94	1.23	0.63	0.84	0.44=1/(0.45 fm)	0.59=1/(0.33 fm)
B	1.18	1.33	0.80	0.89	0.56=1/(0.35 fm)	0.63=1/(0.31 fm)

- $m_{1^+} \to \infty$: $M_N^A = 1.15$ GeV; $M_N^B = 1.46$ GeV
- Constructive Interference: 1^{++}-diquark + $\partial_\mu \pi$

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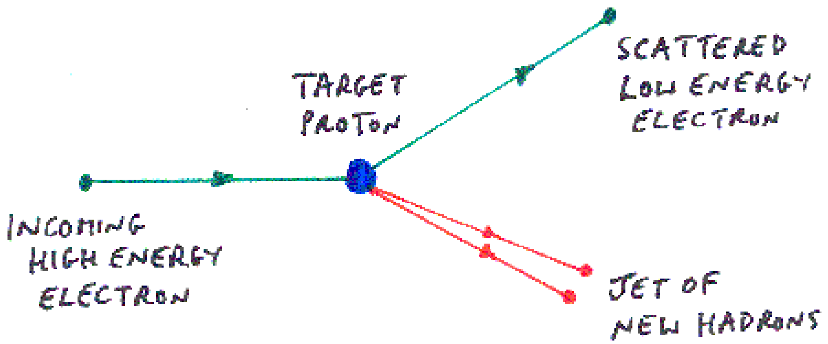
Deep-inelastic scattering

Deep-inelastic scattering

- Looking for Quarks

Deep-inelastic scattering



- Looking for Quarks

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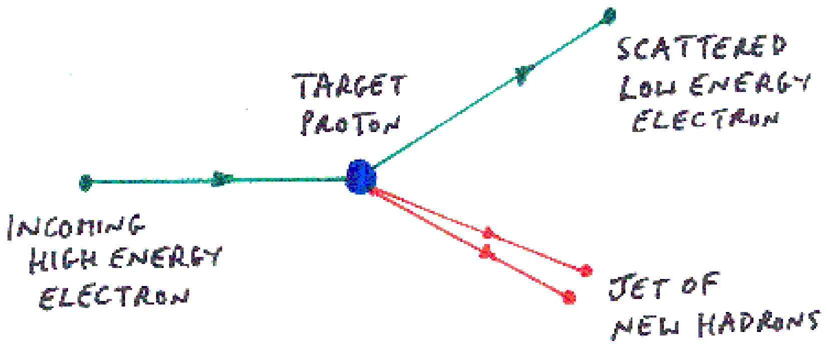
Deep-inelastic scattering

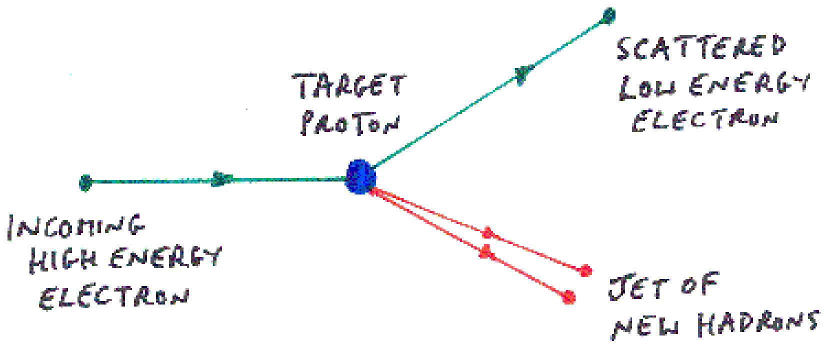


- Looking for Quarks

- Signature Experiment for QCD:

  Discovery of Quarks at SLAC

Deep-inelastic scattering



- Looking for Quarks

- Signature Experiment for QCD:
  Discovery of Quarks at SLAC
- Cross-section: Interpreted as Measurement of Momentum-Fraction Prob. Distribution: $q(x)$, $g(x)$

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Pion's valence quark distn

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Pion's valence quark distn

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- However, NO π Targets!

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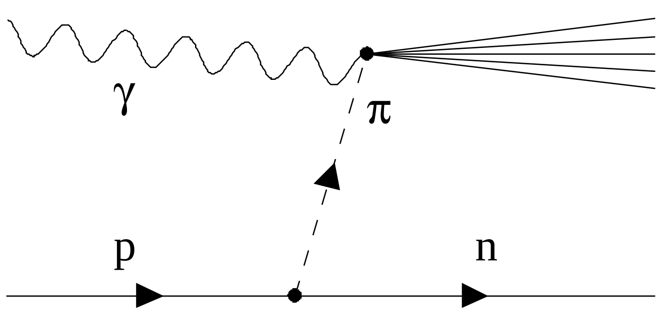
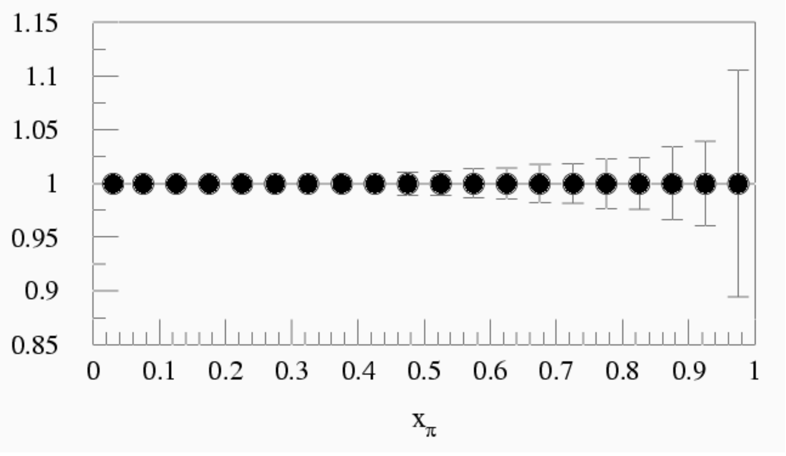
Pion's valence quark distn

- π is Two-Body System: "Easiest" Bound State in QCD
- However, NO π Targets!
- Existing Measurement Inferred from Drell-Yan:
  $\pi N \to \mu^+ \mu^- X$
- Proposal (Holt & Reimer, ANL, nu-ex/0010004)

  $e^-_{5\mathrm{GeV}} - p_{25\,\mathrm{GeV}}$ Collider $\to$ Accurate "Measurement"





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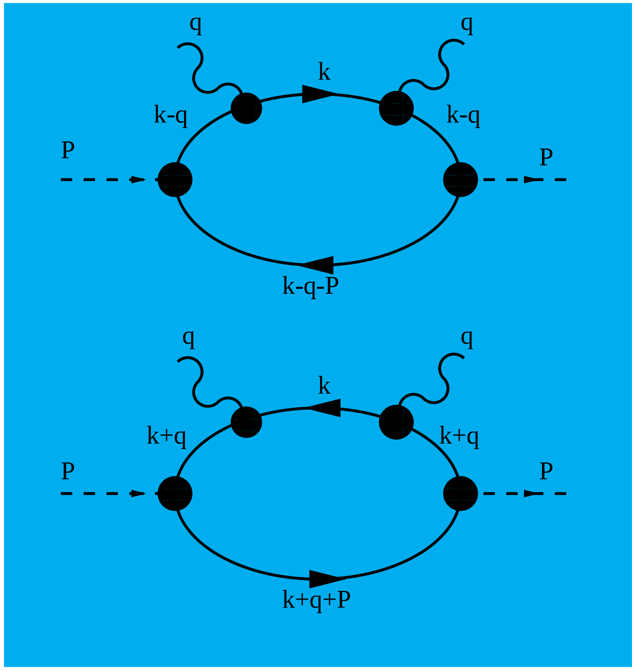
Handbag diagrams



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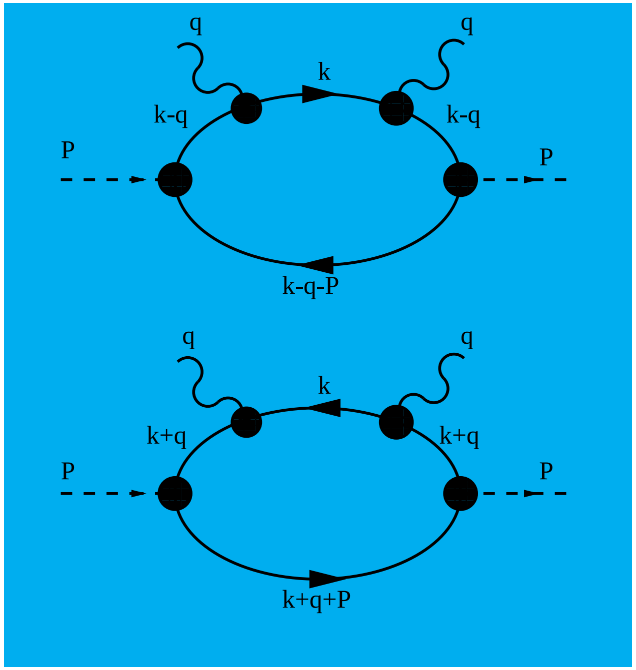
Handbag diagrams



$$W_{\mu\nu}(q;P) = \frac{1}{2\pi}\mathrm{Im}\left[T^{+}_{\mu\nu}(q;P) + T^{-}_{\mu\nu}(q;P)\right]$$

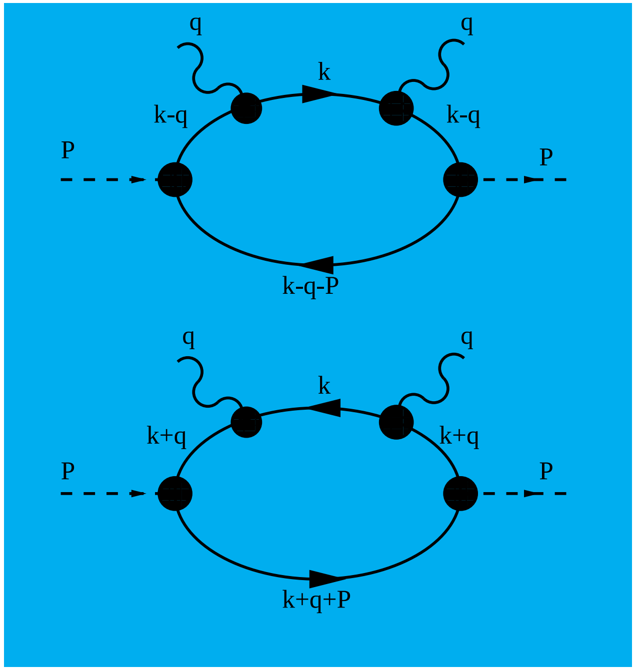
$$T^{+}_{\mu\nu}(q,P) = \mathrm{tr}\int\frac{d^4k}{(2\pi)^4}\,\tau_-\bar{\Gamma}_\pi(k_{-\frac{1}{2}};-P)\,S(k_{-0})\,ieQ\Gamma_\nu(k_{-0},k)$$
$$\times\, S(k)\,ieQ\Gamma_\mu(k,k_{-0})\,S(k_{-0})\tau_+\Gamma_\pi(k_{-\frac{1}{2}};P)\,S(k_{--})$$

Handbag diagrams

Bjorken Limit: $q^2 \to \infty\,, \quad P\cdot q \to -\infty$

but $x := -\dfrac{q^2}{2P\cdot q}$ fixed.

Numerous algebraic simplifications



$$W_{\mu\nu}(q;P) \;=\; \frac{1}{2\pi}\,\mathrm{Im}\left[T^{+}_{\mu\nu}(q;P)+T^{-}_{\mu\nu}(q;P)\right]$$

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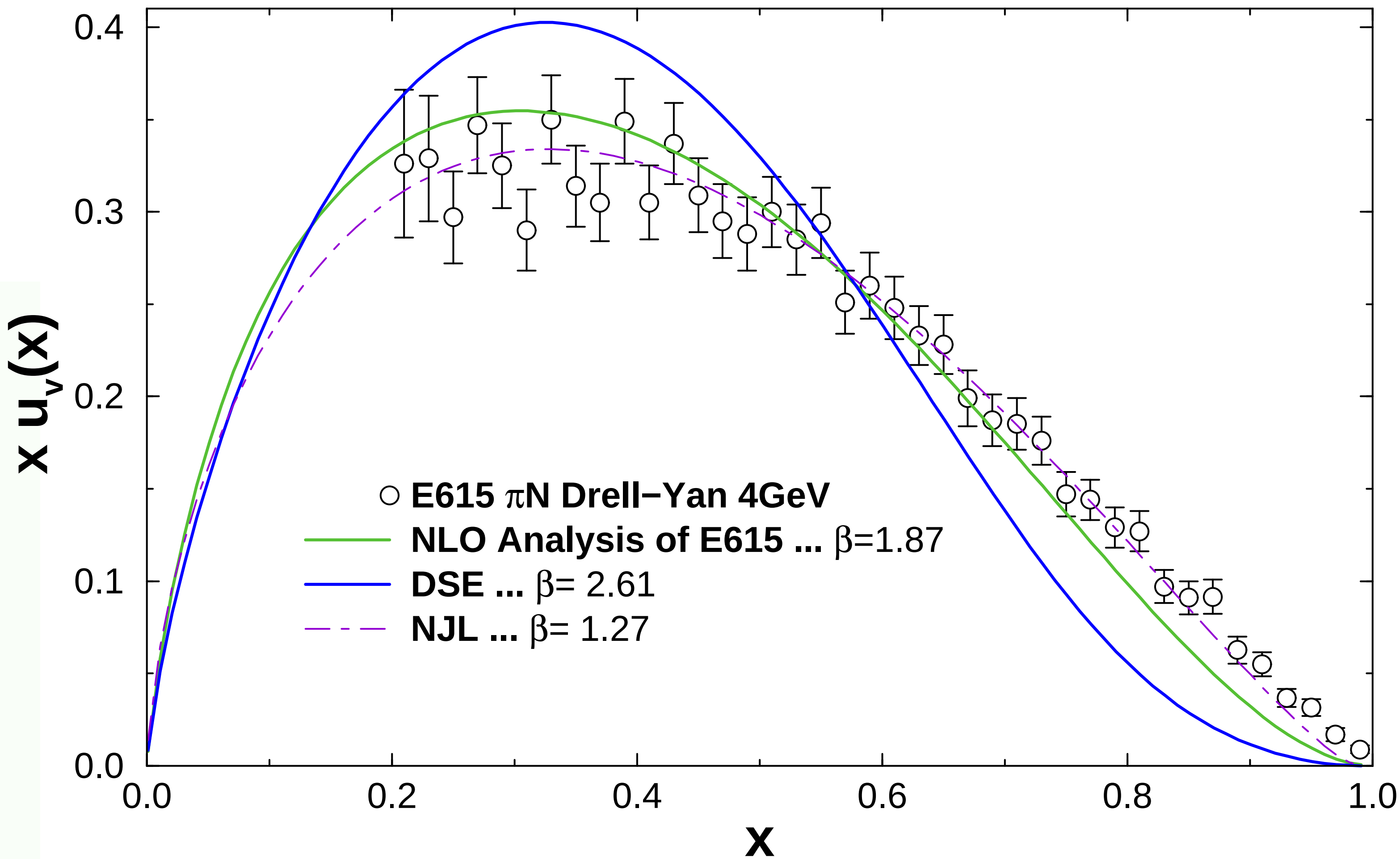
Extant theory vs. experiment

K. Wijersooriya, P. Reimer and R. Holt,
nu-ex/0509012 ... Phys. Rev. C (Rapid)



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