The Roper Excitement

Nucleon Resonances: From Photoproduction to High Photon Virtualities

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Much Excitement About Nothing?

adapted freely from William Shakespeare

- *Observation of the hadron mass spectrum as well as of elastic and transition form factors can be used to study the long-range behavior of QCD's interaction.*
- *Properties of excited hadron states are more sensitive to the long-range behavior of the strong interaction than those of ground states.*

Quantum Chromodynamics

- QCD is the gauge theory that describes strong interactions.
- Description of interactions between quarks and gluons which form hadrons we observe in Nature.
- The formation of hadronic bound states via constituents is an inherently nonperturbative problem.
- It involves precise knowledge of the infrared (long distance) regime of QCD and the dynamical generation of a constituent quark mass.

The Lagrangian of QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - gG^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

The Lagrangian of QCD

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- The key to complexity in QCD lies the gluon field strength tensor.

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g f^{abc} G^b_\mu G^c_\nu$$

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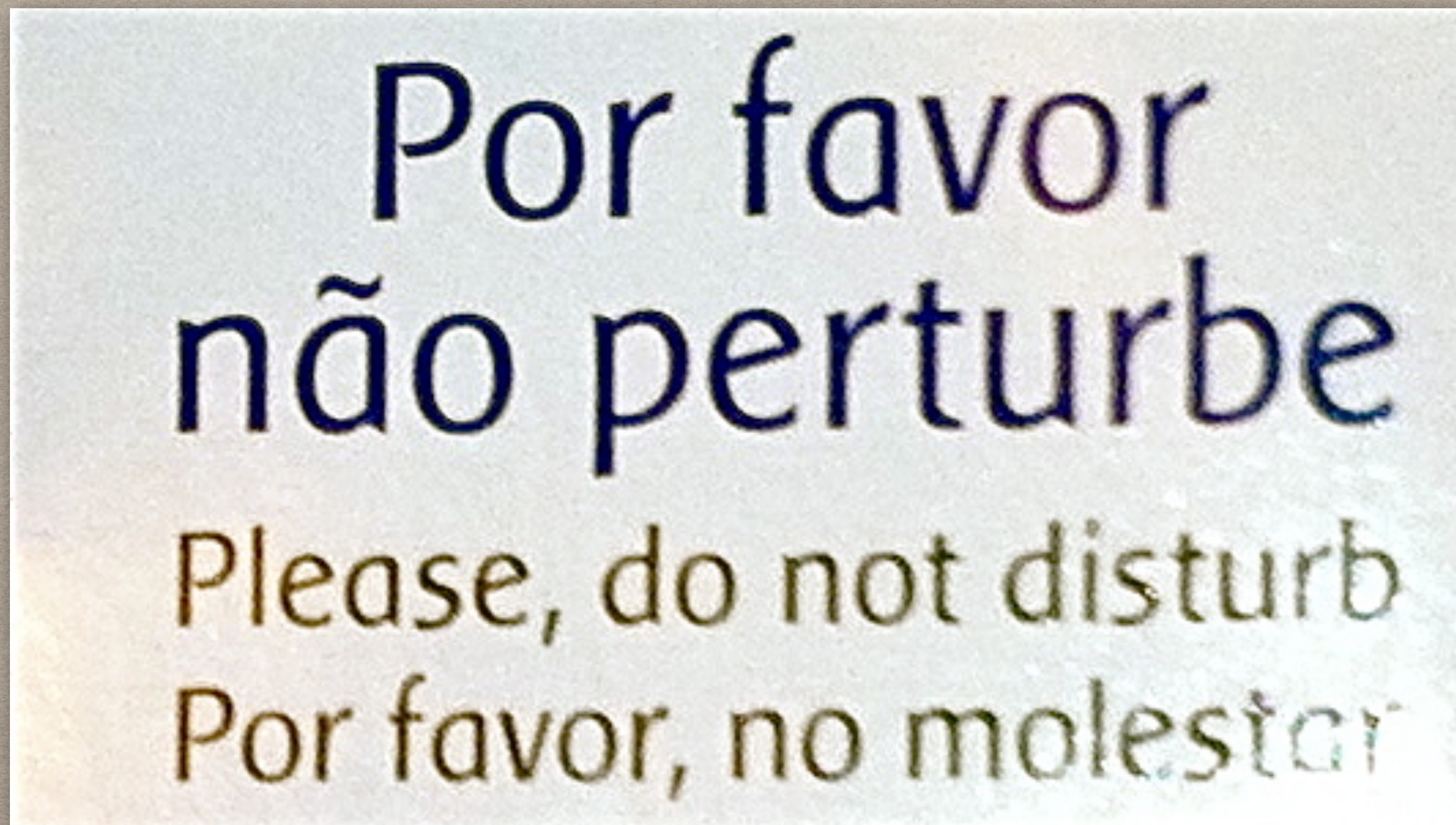
- It generates self-interactions with far-reaching consequences for hadron phenomenology.

This complexity also affects the bare quark-gluon vertex in a nonperturbative manner!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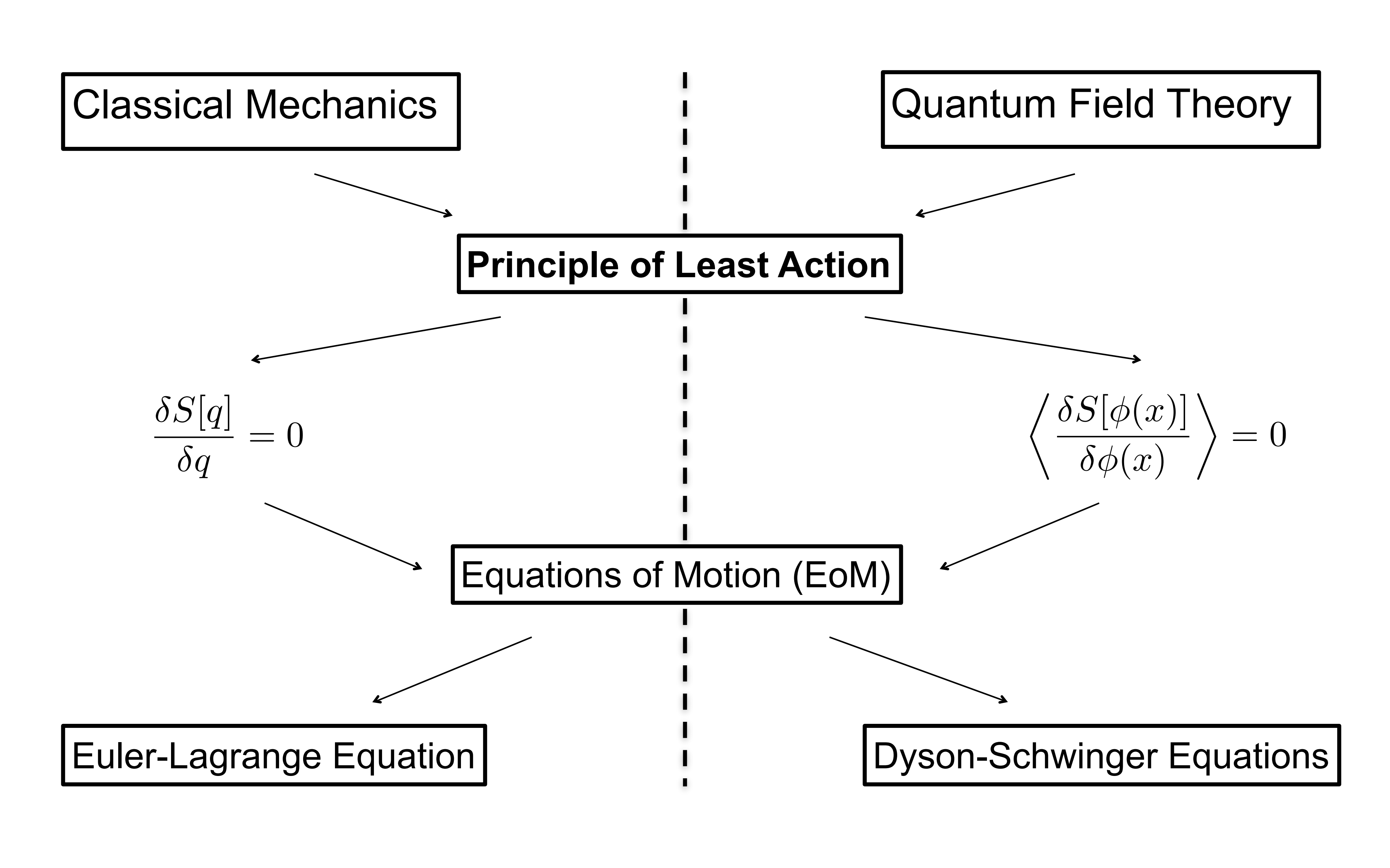
Nonperturbative Continuum Tools for QCD



courtesy of Sishue Qin

QCD's Dyson-Schwinger Equations

The propagator can be obtained from QCD's gap equation: the Dyson-Schwinger equation (DSE) for the dressed-fermion self-energy, which involves the set of infinitely many coupled equations:

$$S^{-1}(p) = Z_2(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p) := i\gamma\cdot p\, A(p^2) + B(p^2)$$

$$\Sigma(p) = Z_1 \int^{\Lambda} \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S(q)\Gamma^a_\nu(q,p)$$

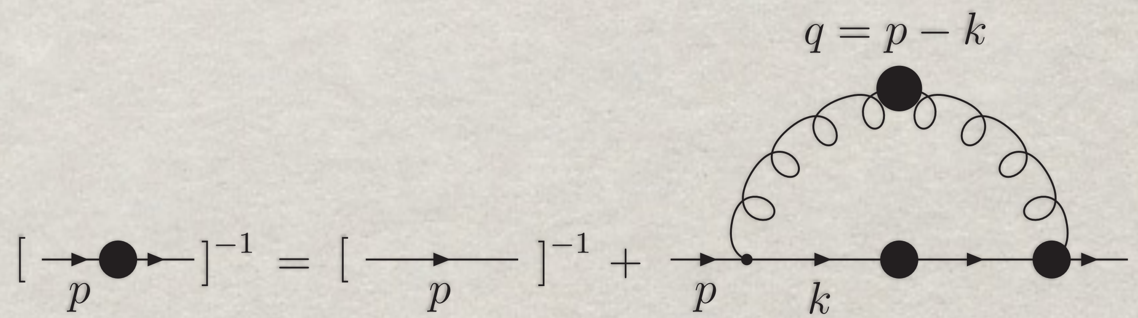
with the *running* mass function $M(p^2) = B(p^2)/A(p^2)$.

each satisfies it's own DSE

$D_{\mu\nu}$	:	dressed-gluon propagator
$\Gamma^a_\nu(q,p)$	:	dressed quark-gluon vertex
Z_2	:	quark wave function renormalization constant
Z_1	:	quark-gluon vertex renormalization constant

$$S^{-1}(p)|_{p^2=\zeta^2} = i\gamma\cdot p + m(\zeta)$$

where ζ is the renormalization point.



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$$\Gamma^a_\nu(q,p)$$

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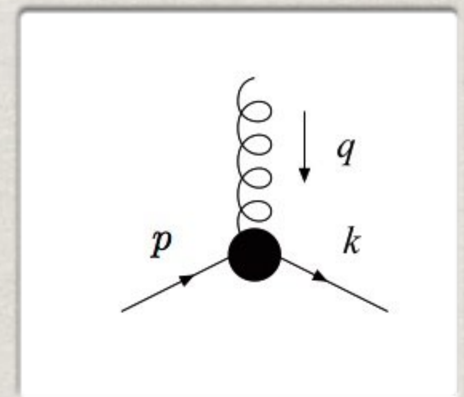

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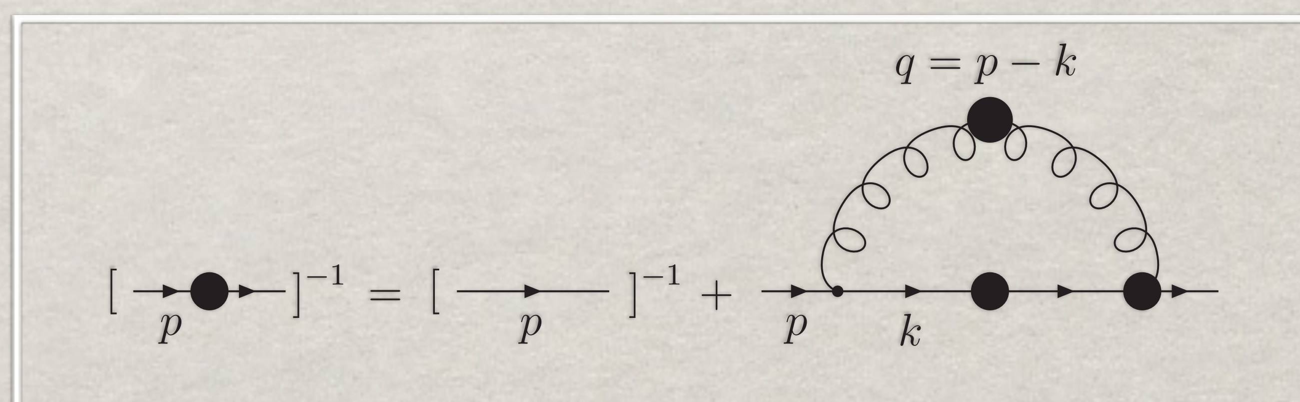
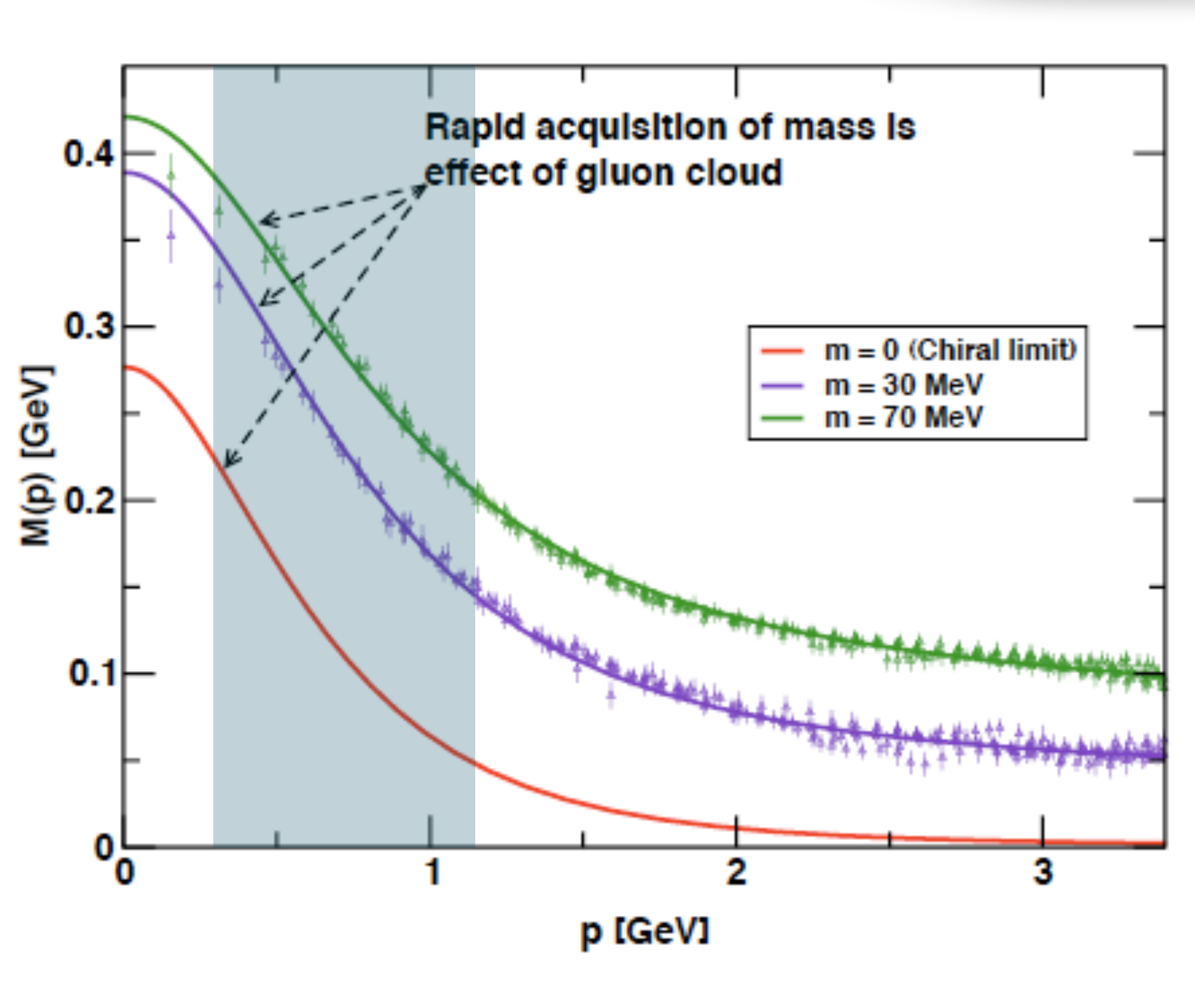


$$S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)}$$



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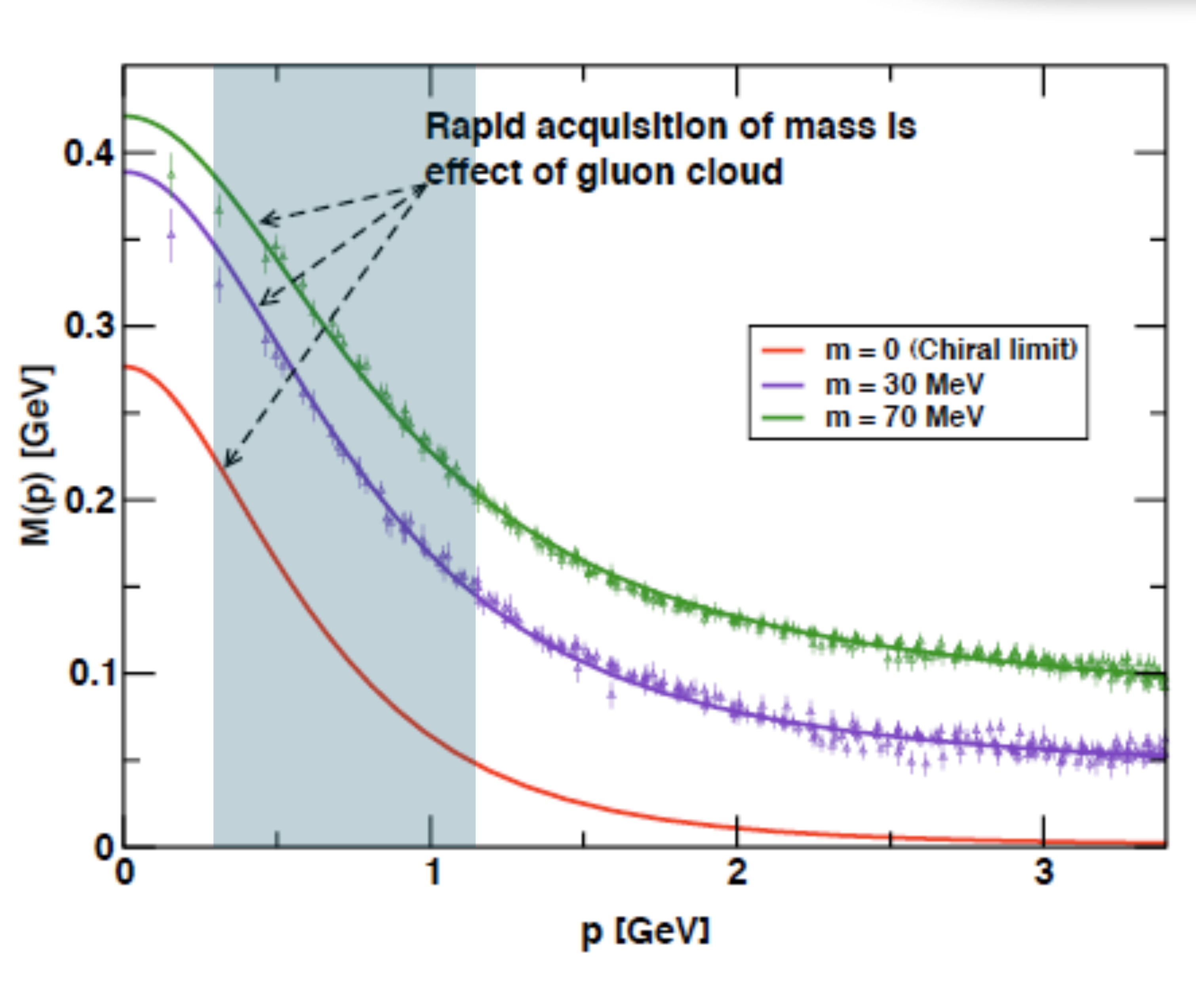


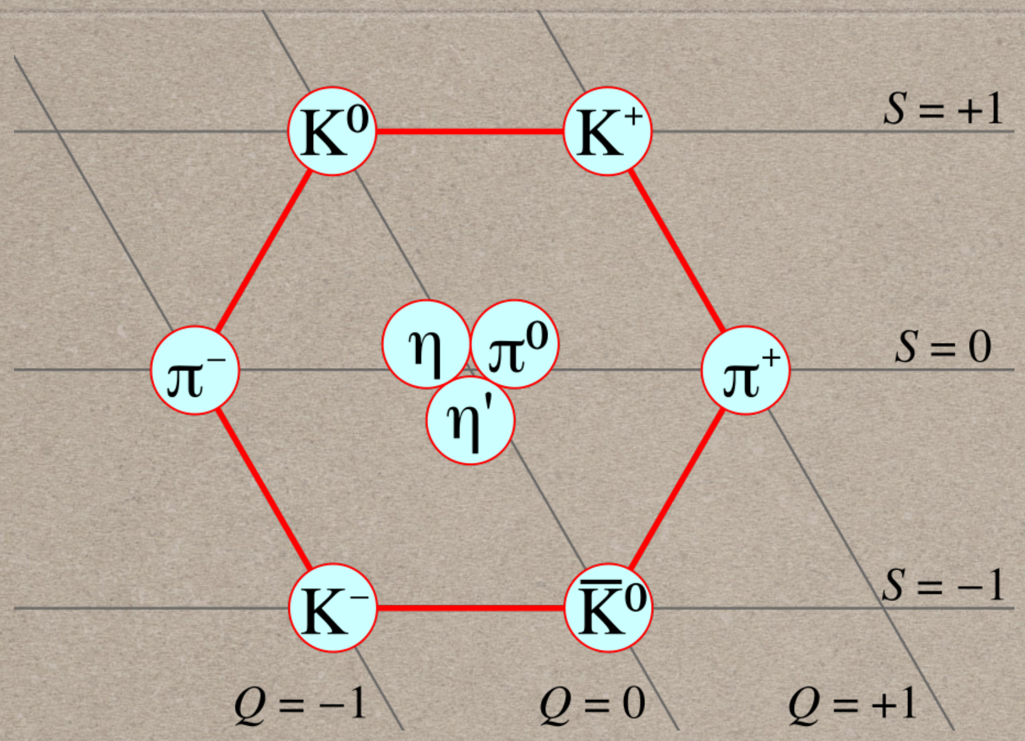
➩ For light quarks the Higgs mechanism is almost irrelevant!

Motivation: Connection with Real World

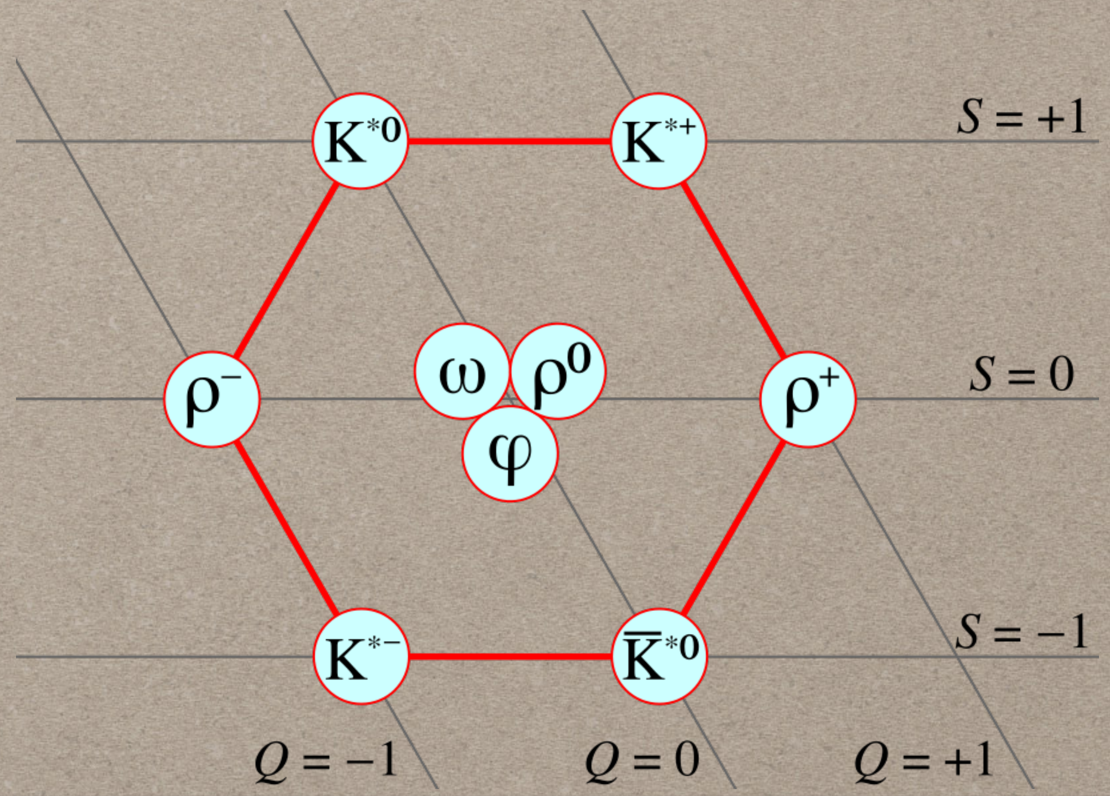
Motivation: Connection with Real World

- How does one incorporate the dressed-quark mass function $M(p^2)$ in study of mesons and baryons? Behavior of $M(p^2)$ is essentially a quantum field theoretical effect.
- In quantum field theory a meson(nucleon) appears as a pole in the four(six)-point quark Green functions amplitude.
- Residue is proportional to meson's Bethe-Salpeter or nucleon's Faddeev amplitude.
- Poincaré covariant Bethe-Salpeter/Faddeev equation sum all possible exchanges and interactions that can take place between dressed-quarks ($Q^2 \gg M^2$).

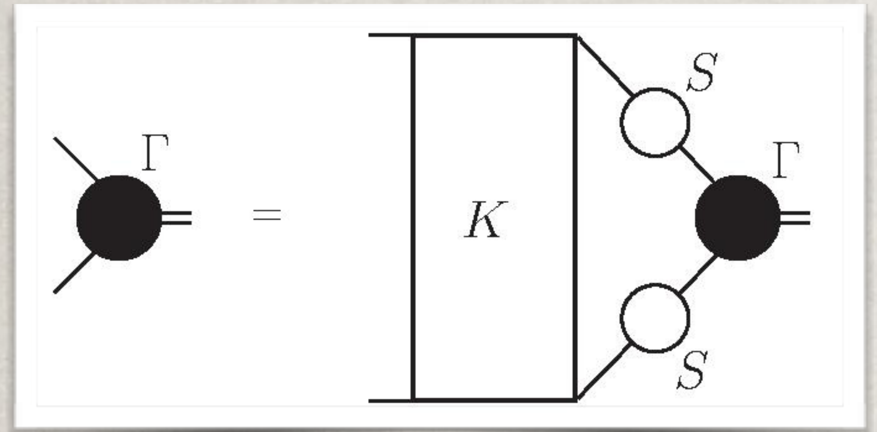
Meson and Baryon Structure and Confinement Properties



Mesons



Bethe-Salpeter Equations for QCD Bound States



$$\Gamma(P,p) = \int \frac{d^4k}{(2\pi)^4}\, K(P,p,k)\, S(k-\tfrac{P}{2})\, \Gamma(P,k)\, S(k+\tfrac{P}{2})$$

Rainbow-Ladder truncation:

$$K(P,p,k) = -\frac{Z_2^2\, \mathcal{G}(q^2)}{q^2} \left(\frac{\lambda^a}{2}\gamma_\mu\right) T_{\mu\nu}(q) \left(\frac{\lambda^a}{2}\gamma_\nu\right)$$

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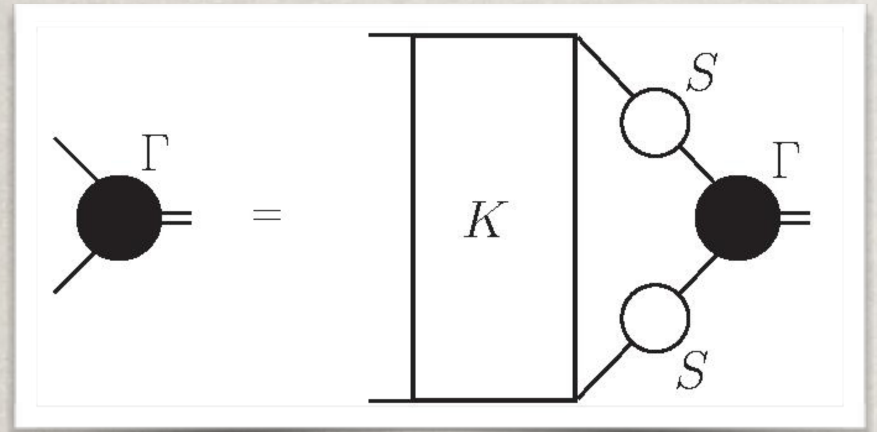

Tough part: how to model nonpertubative QCD interaction beyond rainbow-ladder truncation?

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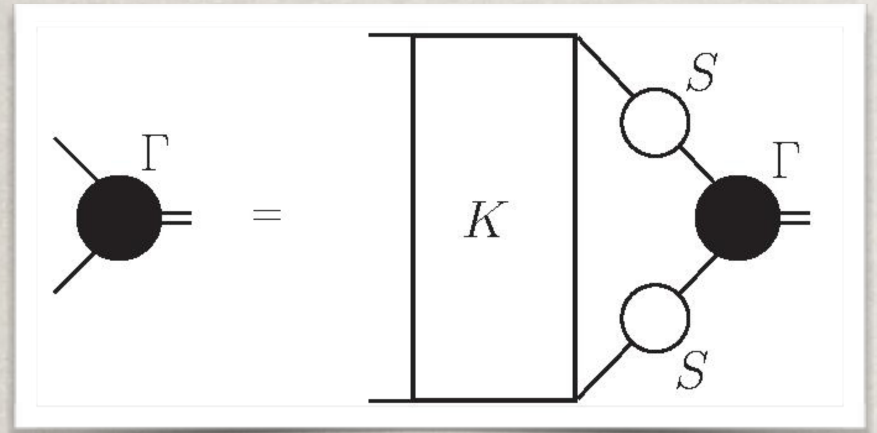

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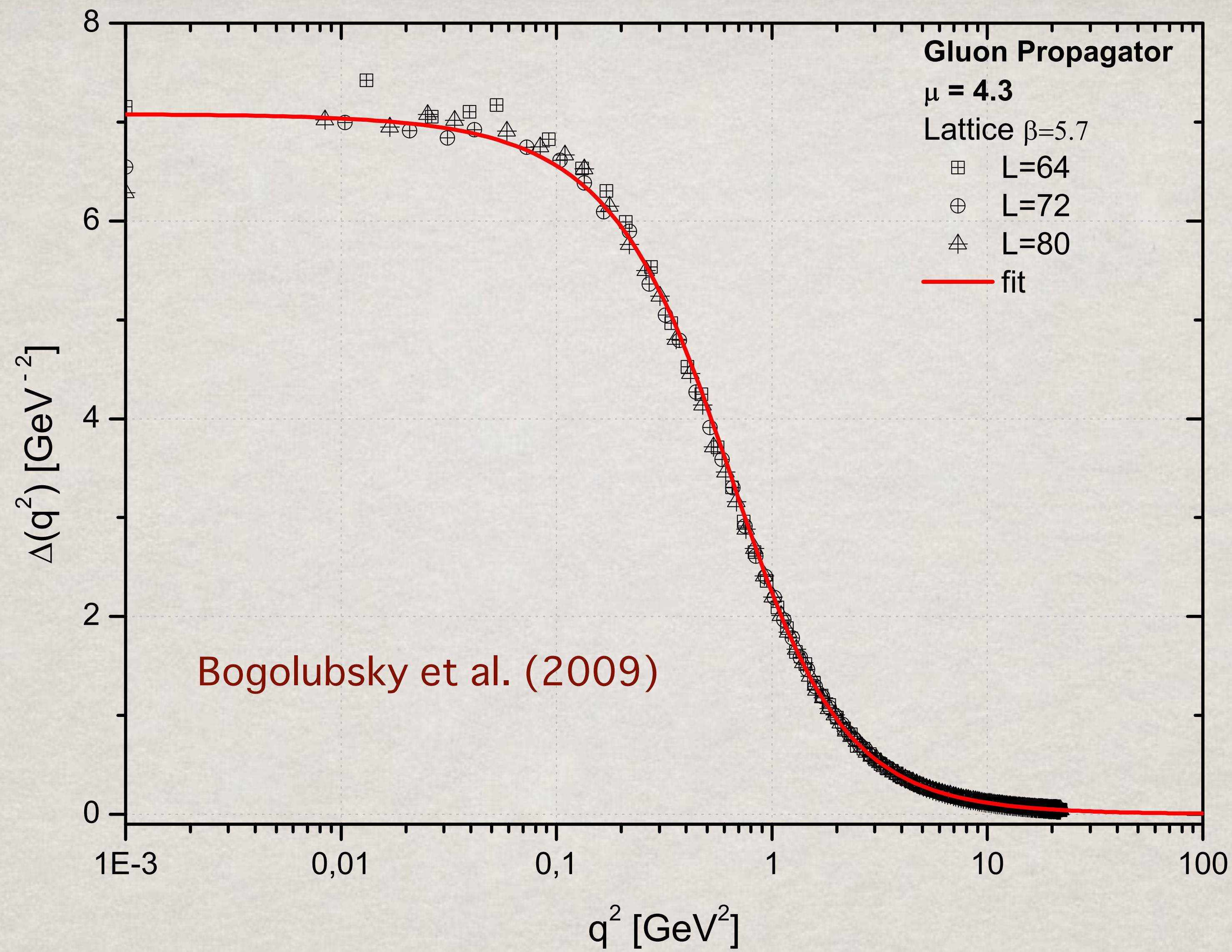
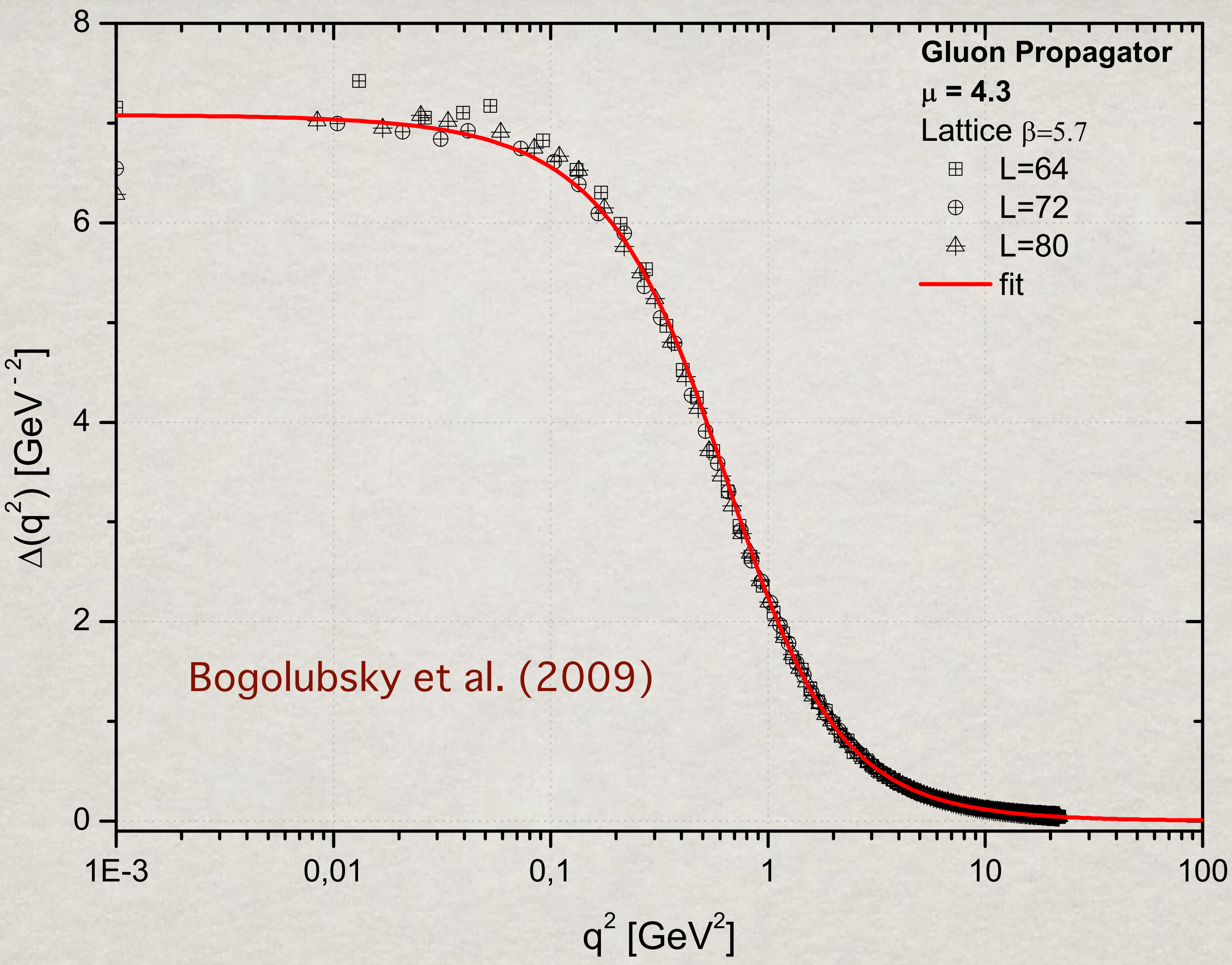
General solution for Poincaré invariant ground- and excited-state amplitudes

$$\Gamma_{P_n}(p,P) = \gamma_5\big[\, i\,\mathbb{I}_D E_{P_n}(p,P) + \gamma\cdot P\, F_{P_n}(p,P) + \gamma\cdot p\,(p\cdot P) G_{P_n}(p,P) + \sigma_{\mu\nu}p_\mu P_\nu\, H_{P_n}(p,P)\big]$$



Use effective interaction which reproduces Lattice QCD and DSE results for gluon-dressing function: infrared massive fixed point; ultraviolet massless propagator.



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Qin, Chang, Liu, Roberts and Wilson 2011

$$\mathcal{G}(s) = \frac{8\pi^2}{\omega^4} D e^{-s/\omega^2} + \frac{8\pi^2 \gamma_m}{\ln\left[\tau + (1 + s/\Lambda^2_{QCD})\right]} \mathcal{F}(s)$$

The Bethe-Salpeter equation is an eigenvalue problem:

$$\lambda(P^2)\,\Gamma_{P_n}(P,p) = \int \frac{d^4k}{(2\pi)^4}\, K(P,p,k)\,\chi_{P_n}(k,P)$$

$\chi_{P_n}(k,P) = S(k-\frac{P}{2})\,\Gamma(P,k)\,S(k+\frac{P}{2})$: Bethe-Salpeter wave function

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The kernel $\mathcal{K}(P^2)$ has a complete set of real eigenvectors ϕ_i with eigenvalues $\lambda_i(P^2)$ which are ordered as $\lambda_0(P^2) > \lambda_1(P^2) > \lambda_2(P^2) > .... > \lambda_i(P^2)$.

$$\lambda(P^2)\,|\Phi\rangle = \mathcal{K}(P^2)\,|\Phi\rangle \quad \longrightarrow \quad |\Phi\rangle = \sum_{i=1}^{\infty} a_i\,|\,\phi_i\rangle$$

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$$|\,\phi_n\rangle := \mathcal{K}^n(P^2)\,|\Phi\rangle = \sum_{i=1}^{\infty} \lambda_i^n a_i\,|\,\phi_i\rangle = \lambda_0^n\left[a_0\,|\,\phi_0\rangle + \sum_{i=1}^{\infty}\left(\frac{\lambda_i}{\lambda_0}\right)^n a_i\,|\,\phi_i\rangle\right]$$

$$|\,\phi_n\rangle \overset{n\to\infty}{=} \lambda_0^n\, a_0\,|\,\phi_0\rangle \simeq \lambda_0\,\mathcal{K}^{n-1}(P^2)\,|\Phi\rangle$$

- Eigenvalue spectrum is not limited to the ground state.
- Excited states with smaller eigenvalues can be determined with the same iterative methods.
- Usage of Gram-Schmidt orthogonalization process:

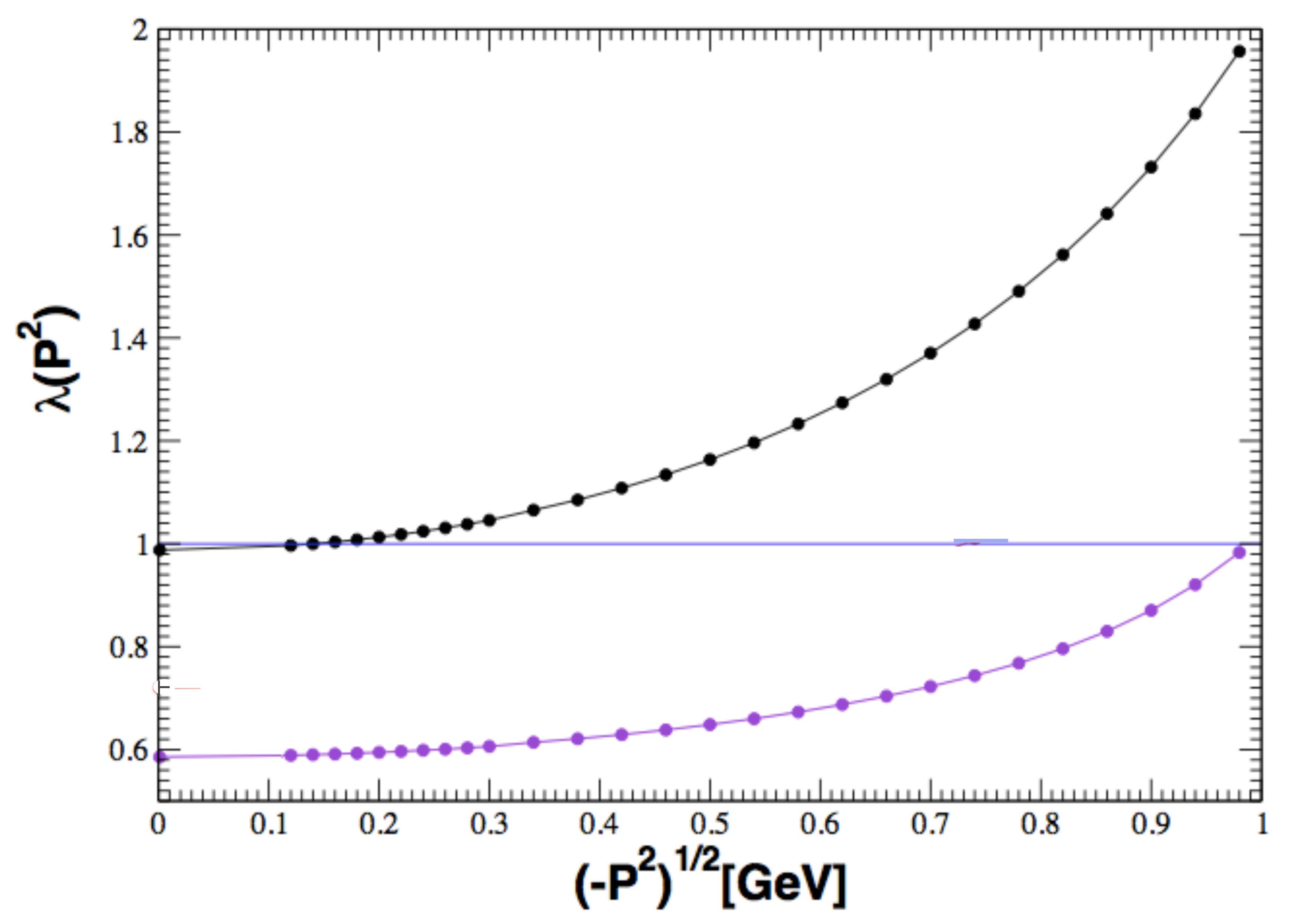
$$|\tilde{\Phi}\rangle = |\Phi\rangle - \frac{\langle \phi_0 \,|\, \Phi \rangle}{\langle \phi_0 \,|\, \phi_0 \rangle} \, |\phi_0\rangle$$

- Modern and more efficient approach is the implicitly restarted Arnoldi method (IRAM).
- Based on the stabilized Gram-Schmidt orthogonalization in the Krylov subspace obtained by iteration:

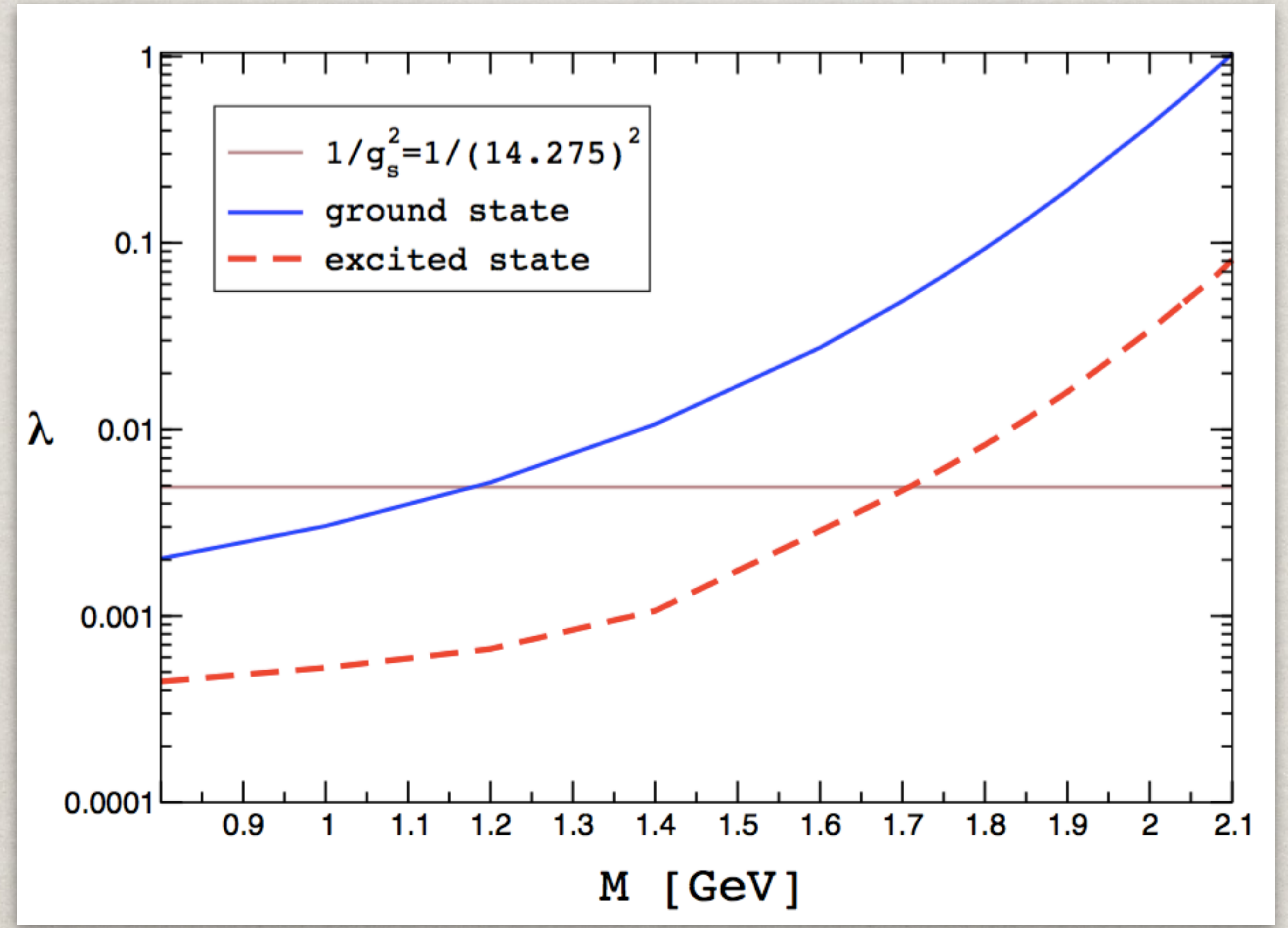
$$\mathcal{S}_r := \left\{ \Phi, K\Phi, K^2\Phi, K^3\Phi, ..., K^{r-1}\Phi \right\}$$

- The Arnoldi method generalizes the Gram-Schmidt process by computing the eigenvalues of the orthogonal projection of K onto the Krylov subspace $\Rightarrow$ yields smaller eigenvalues.

Examples of eigenvalue spectrum — Pion



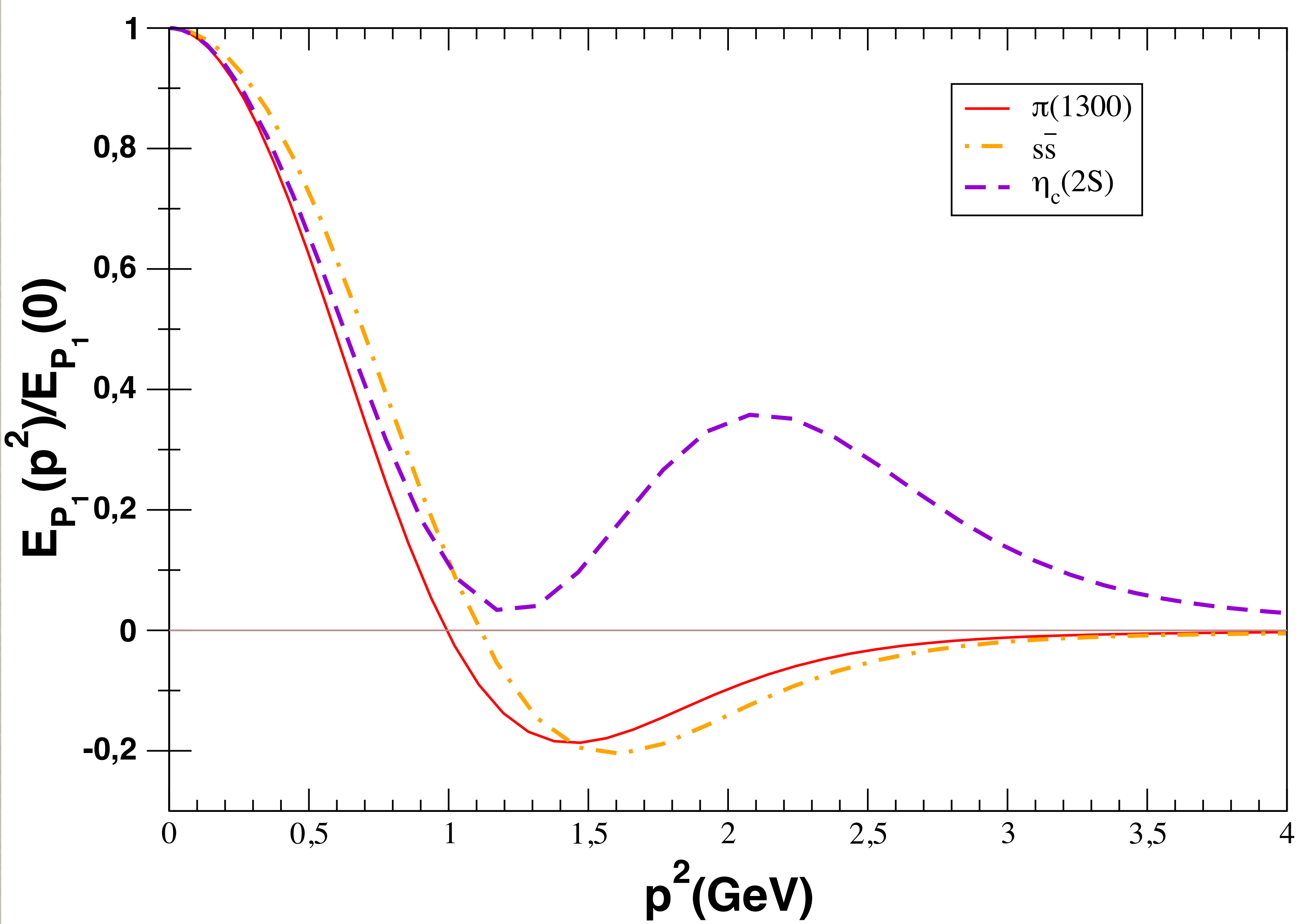
Examples of eigenvalue spectrum — Nucleon



Chebyshev expansion of 1st excited state: $E_{P_1}(p,P) = \sum_{m=0}^{\infty} E_{P_1}^m(p,P)\, U_m(\cos\theta)$

$$\Gamma_{P_n}(p,P) = \gamma_5 \big[i\,\mathbb{I}_D E_{P_n}(p,P) + \gamma\cdot P\, F_{P_n}(p,P) + \gamma\cdot p\,(p\cdot P) G_{P_n}(p,P) + \sigma_{\mu\nu} p_\mu P_\nu\, H_{P_n}(p,P) \big]$$

Lowest Chebyshev moment $E_{P_1}^0(p^2, P^2)$



Qin, Chang, Liu, Roberts and Wilson 2011

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E. Rojas, B. El-Bennich & J.P.B.C. de Melo (2014)

	Model 1 [GeV]	Model 2 [GeV]	Reference
m_π	0.138	0.153	0.139 [36]
f_π	0.139	0.189	0.1304 [36]
$m_{\pi(1300)}$	0.990	1.414	1.30 ± 0.10 [36]
$f_{\pi(1300)}$	-1.1×10^{-3}	-8.3×10^{-4}	
m_K	0.493	0.541	0.493 [36]
f_K	0.164	0.214	0.156 [36]
$m_{K(1460)}$	1.158	1.580	1.460 [36]
$f_{K(1460)}$	−0.018	−0.017	
$m_{\bar{s}s}$	1.287	1.702	
$f_{\bar{s}s}$	−0.0214	−0.0216	
$m_{\eta_c(1S)}$	3.065	3.210	2.984 [36]
$f_{\eta_c(1S)}$	0.389	0.464	0.395 [37]
$m_{\eta_c(2S)}$	3.402	3.784	3.639 [36]
$f_{\eta_c(2S)}$	0.089	0.105	

$$f^0_{P_n}(\mu) \equiv 0 \; , \; n \geq 1$$

The two models correspond to different parametrizations of the gluon-dressing function neither model reproduces equally well ground and excited states.

➪ Must go beyond rainbow-ladder truncation in DSE and BSE !

Open-Charm Mesons

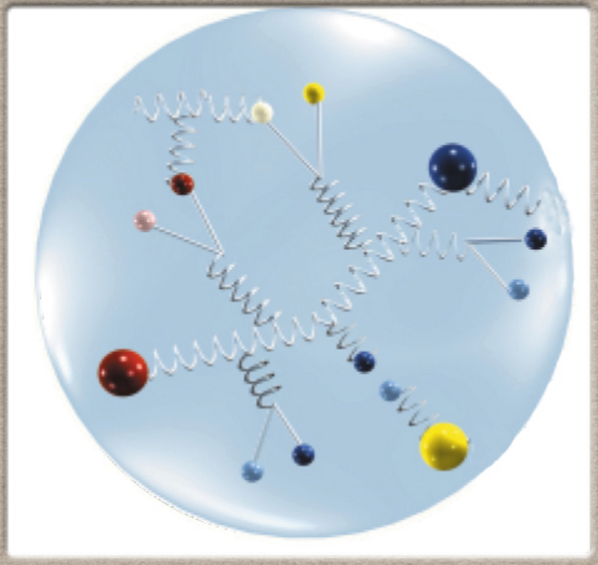
- So far, we have first results for the heavy-light systems: *D* mesons

	Model	Experiment [63]
m_D	2.115	1.869
f_D	0.204	$0.2067 \pm 0.0085 \pm 0.0025$
m_{D_s}	2.130	1.968
f_{D_s}	0.249	0.260 ± 0.004

E. Rojas, B. El-Bennich & J.P.B.C. de Melo (2014)

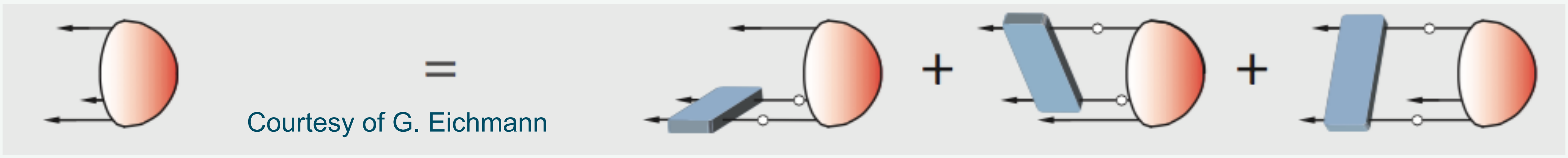
However, masses too large and mass difference too small.

- This was expected, strong mass asymmetry doesn't allow for simple quark-gluon vertex and rainbow-ladder truncation.



Nucleons

Covariant Fadeev Equation



Courtesy of G. Eichmann

R.T. Cahill, C.D. Roberts, J. Praschifka (1989)

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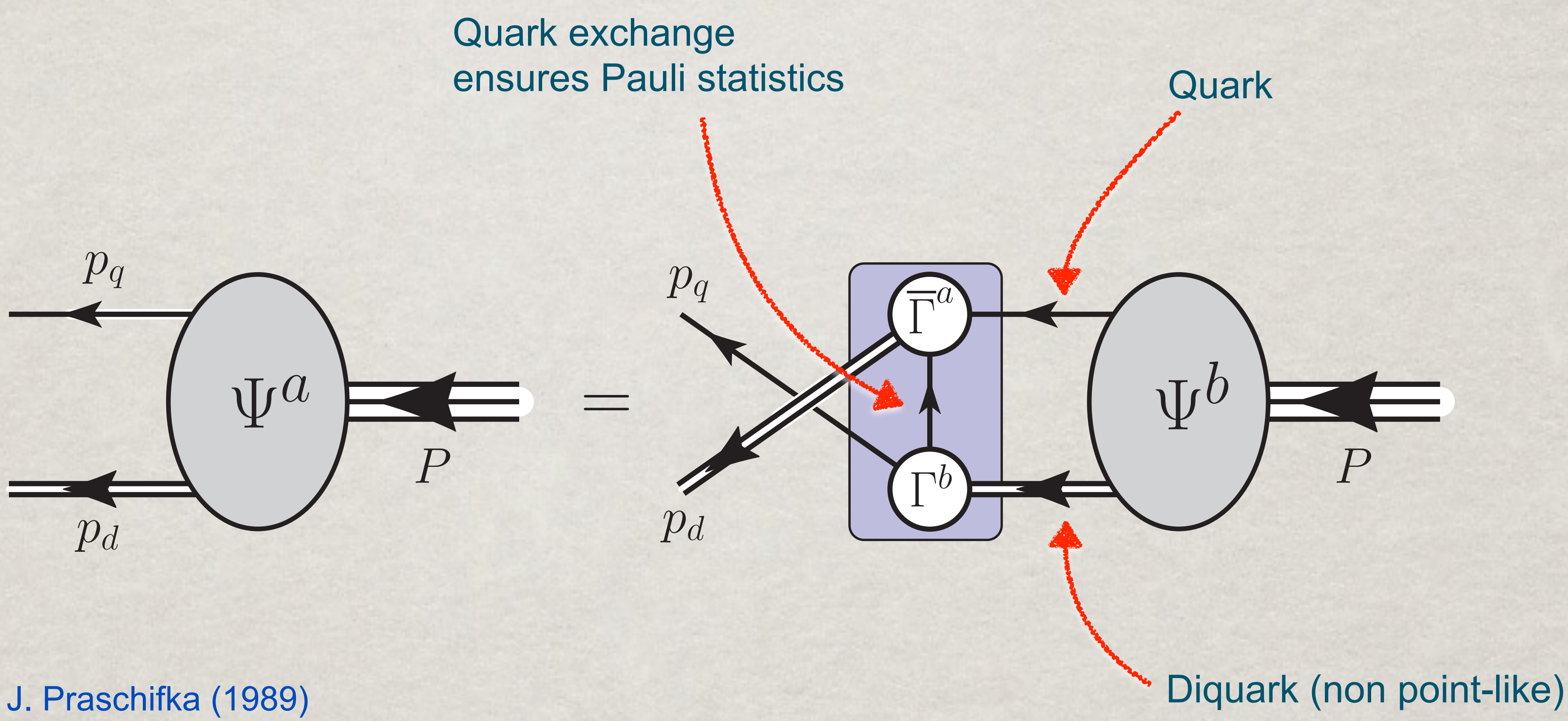
Covariant Fadeev Equation



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Linear homogeneous matrix equation yields Poincaré covariant Faddeev amplitude (wave function) that describes relative motion of quark-diquark within nucleon.

Diquark-Quark Description

- Tractable Faddeev equation is based on the observation that an interaction which describes color-singlet mesons also generates non point-like quark-quark (diquark) correlations in the color anti-triplet channel.

SU(3): $3 \otimes 3 = \bar{3} \oplus 6$

- Diquark correlations are a dynamical consequence of strong-coupling in QCD: scalar & axial-vector diquarks.

- The same mechanism that produces an almost massless pion from two dynamically-massive quarks (DCSB) forces a strong correlation between two quarks in color anti-triplet channels within a baryon.

- Diquark correlations employed in Faddeev equation are ***not*** point-like.

- Typically, $r_{0+} \sim r_{\pi}$ & $r_{1+} \sim r_{\rho}$ (actually 10% larger).

- They have soft form factors.

Nucleon Electromagnetic Form Factors

Composite nucleon must interact with photon via nontrivial current constrained by Ward-Takahashi identities!

$$J_\mu(P',P) = ie\,\bar{u}(P')\,\Lambda_\mu(q,P)\,u(P)\,,$$
$$= ie\,\bar{u}(P')\left(\gamma_\mu F_1(Q^2) + \frac{1}{2M}\,\sigma_{\mu\nu}\,Q_\nu\,F_2(Q^2)\right)u(P)$$

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2}F_2(Q^2)\,,\; G_M(Q^2) = F_1(Q^2) + F_2(Q^2)\,.$$

$$\mu_n = \kappa_n = G_M^n(0)\,,\; \mu_p = 1 + \kappa_p = G_M^p(0)$$

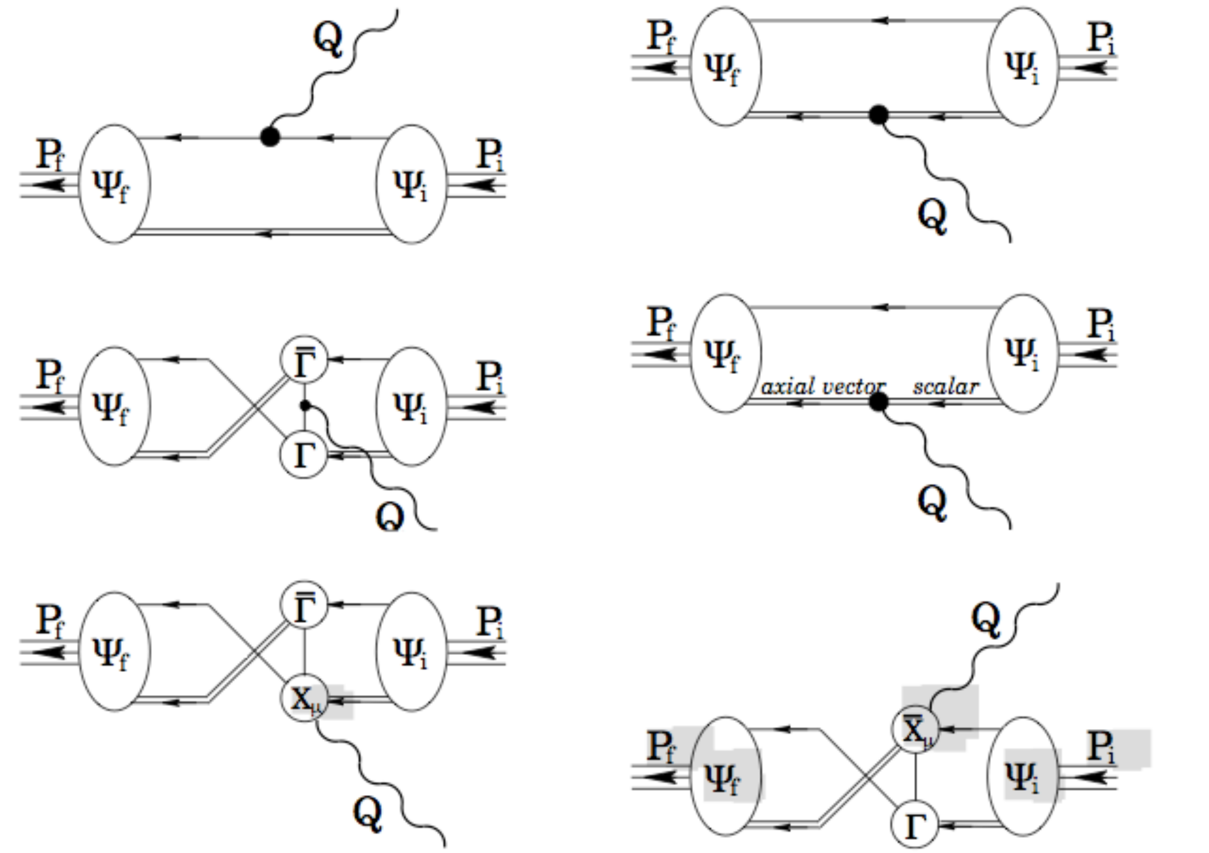

Figure 2. Vertex which ensures a conserved current for on-shell nucleons described by the Faddeev amplitudes, $\Psi_{i,f}$, described in Sect. 2 and Appendix A: *Faddeev Equation*. The single line represents $S(p)$, the dressed-quark propagator, Sec. A.2.1, and the double line, the diquark propagator, Sec. A.2.3; Γ is the diquark Bethe-Salpeter amplitude, Sec. A.2.2; and the remaining vertices are described in Appendix C: the top-left image is Diagram 1; the top-right, Diagram 2; and so on, with the bottom-right image, Diagram 6.

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\begin{aligned}
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\end{aligned}
$$

$$
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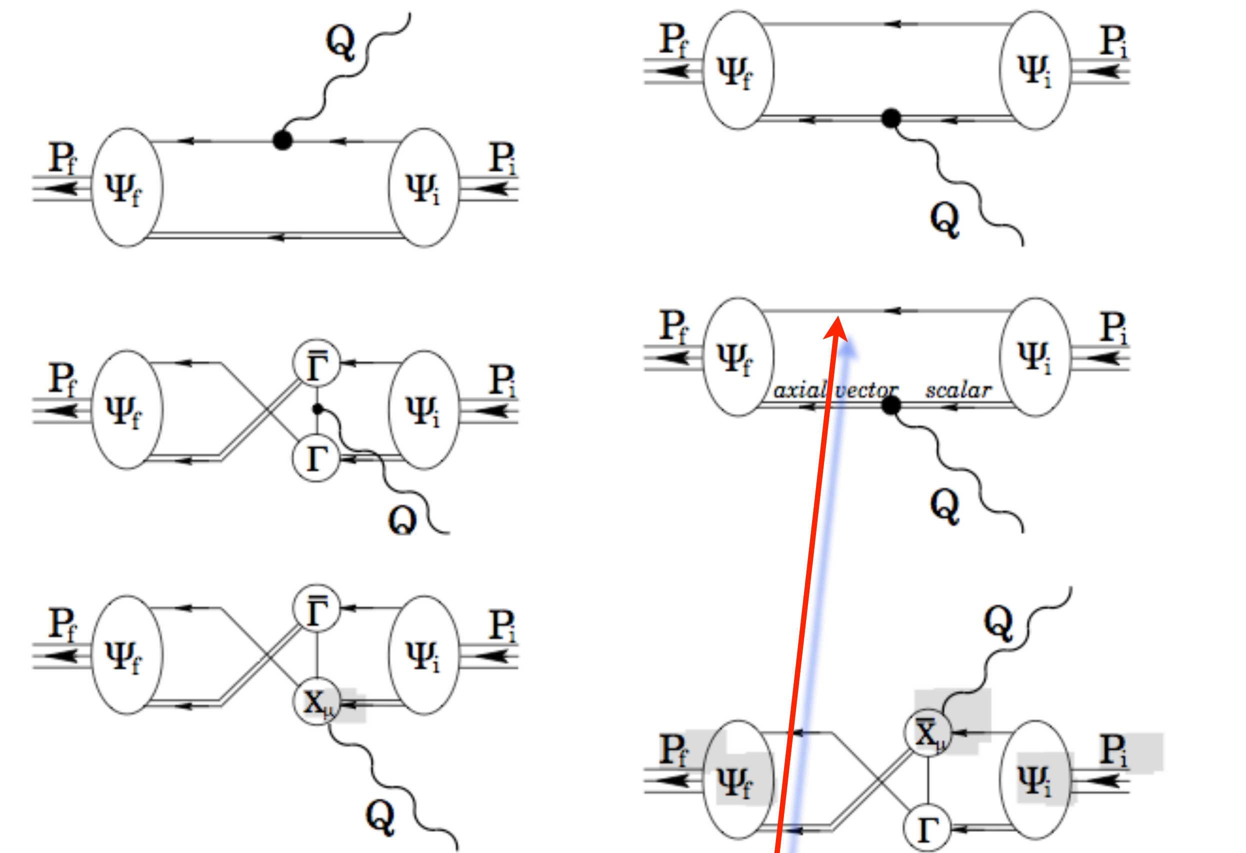

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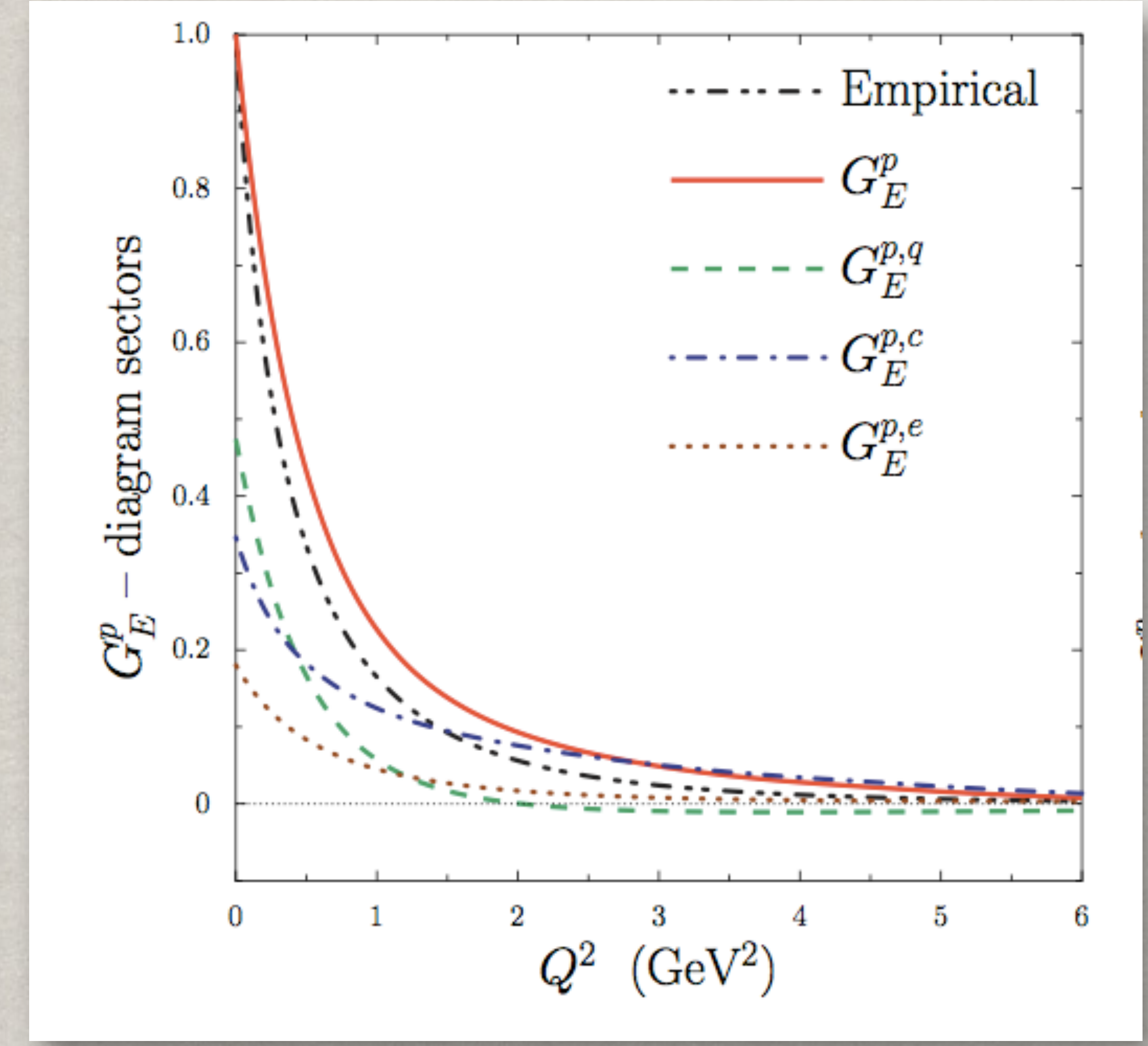
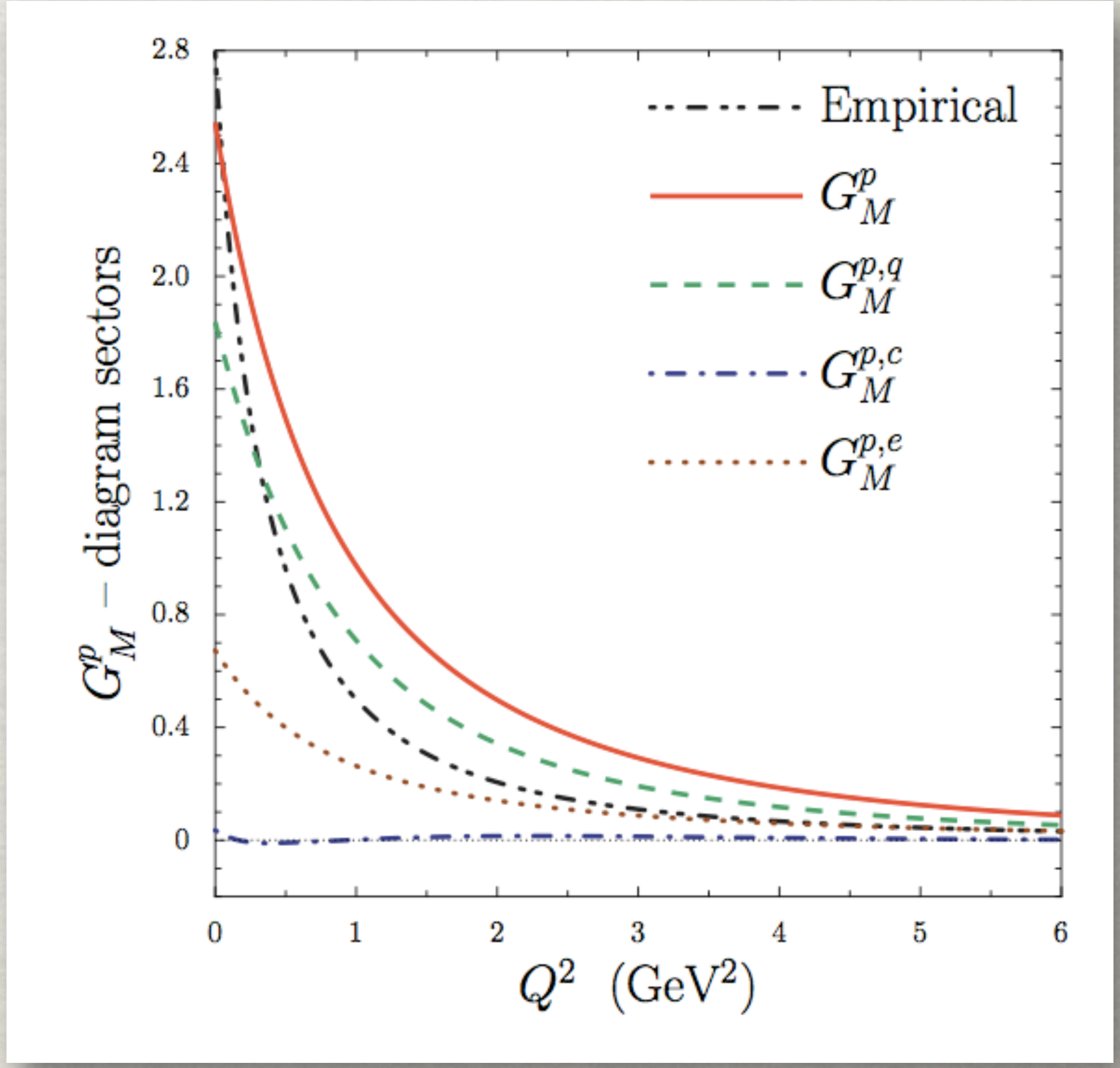
Dressed quark propagator solutions of QCD's Dyson-Schwinger equations.

$$
S(p) = -i\gamma\cdot p\,\sigma_V(p^2,\zeta^2) + \sigma_S(p^2,\zeta^2) = \frac{1}{i\gamma\cdot p\,A(p^2,\zeta^2) + B(p^2,\zeta^2)} = \frac{Z(p^2,\zeta^2)}{i\gamma\cdot p + M(p^2)}
$$

⇒ momentum dependence !

Proton's Sachs Electric and Magnetic Form Factors





I.C. Cloët, G. Eichmann, B. El-Bennich, T. Klähn and C.D. Roberts, Few Body Syst. 46 (2009)

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2} F_2(Q^2)\,,\; G_M(Q^2) = F_1(Q^2) + F_2(Q^2)\,.$$

$$\mu_n = \kappa_n = G_M^n(0)\,,\; \mu_p = 1 + \kappa_p = G_M^p(0)$$

Exposing the dressed mass function

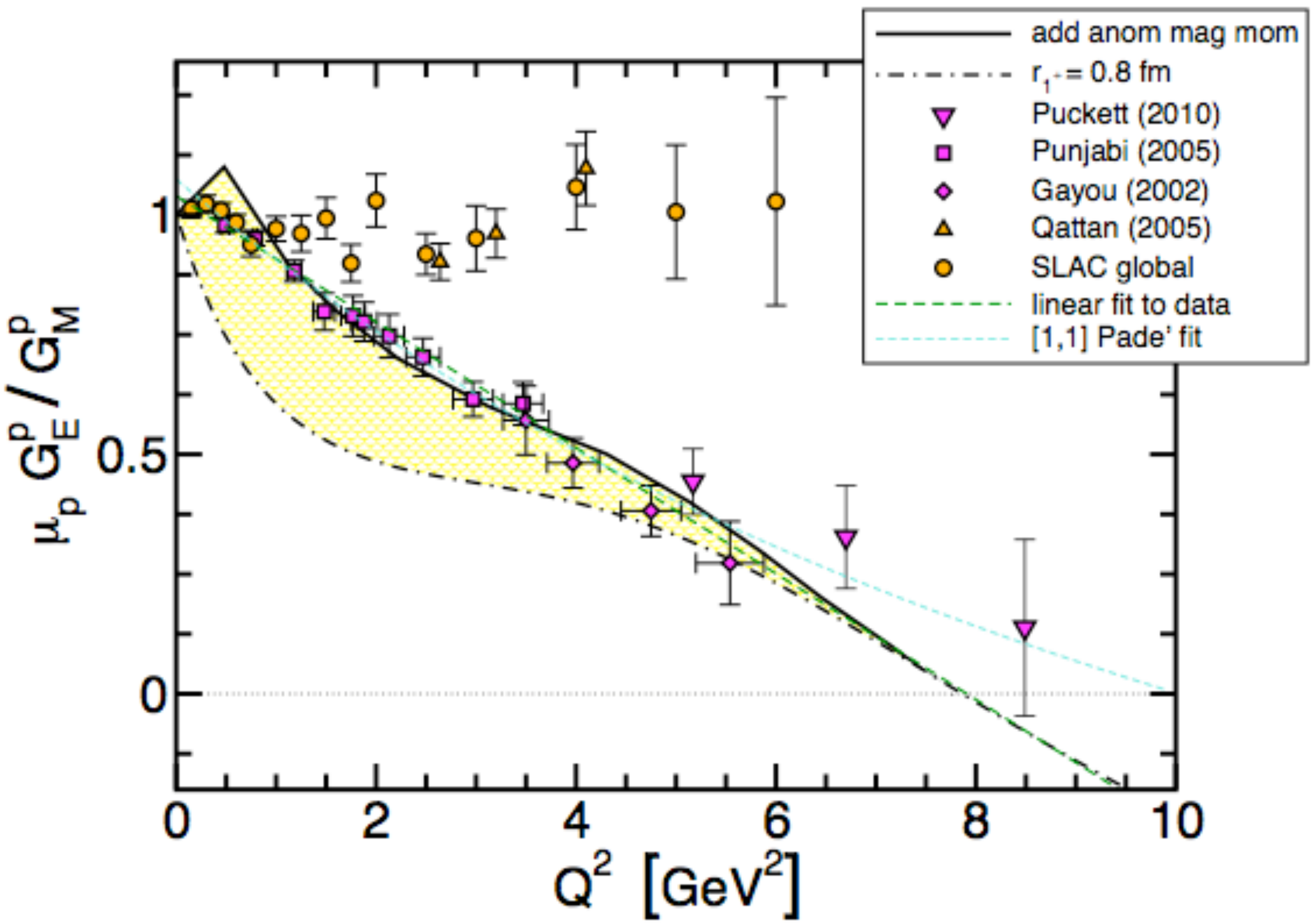
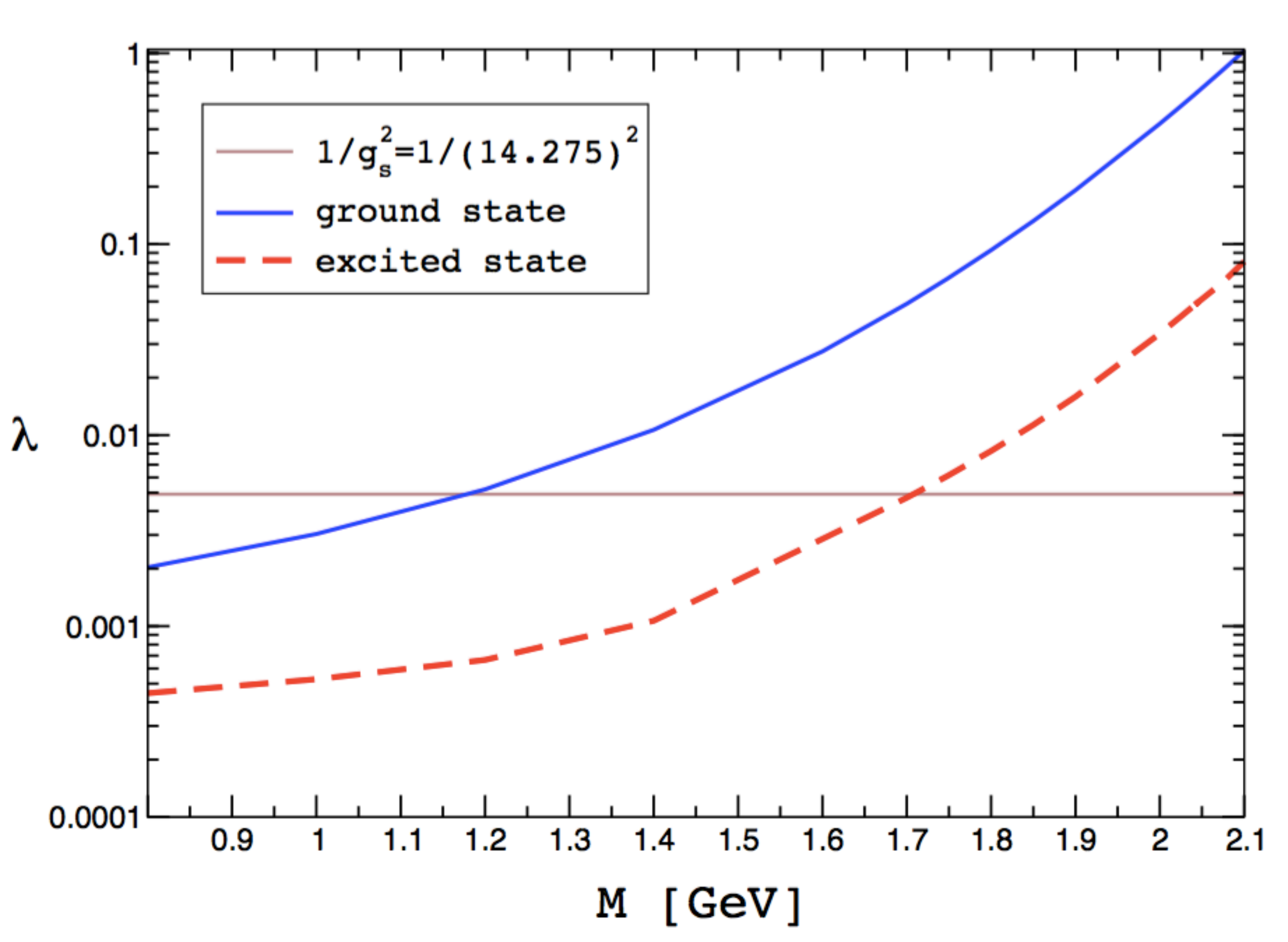


FIGURE 1. Proton electric-to-magnetic form factor ratio. The *dot-dashed curve* is the result in Ref. [12], whereas the *solid curve* is obtained by repeating that calculation with inclusion of a momentum-dependent dressed-quark anomalous magnetic moment that is characterised by a $Q^2 = 0$ strength $\eta_{cm} = 0.4$. Data: diamonds – [27]; squares – [28]; up-triangles – [29]; circles [30]; and down-triangles [31]. *Dashed curve*: [1,1]-Padé fit to available JLab data; and *dotted curve*, a linear fit.

Ground and Radially Excited States of the Nucleon



Roper Quark-Core Mass

	R_{core}^{DSE}	$R_{core}^{Contact}$	R_{bare}^{DCCM}
Mass	1.73	1.72	1.76

DSE : Faddeev amplitude of 1st excited state with dressed quark propagators

J. Segovia, B. El-Bennich, E. Rojas, I.C. Cloët, C.D. Roberts, S.-S. Xu, H.-S. Zhong, Phys. Rev. Lett. (2015)

Contact : Faddeev amplitude of 1st excited state with contact interaction gap equation

D.J. Wilson, I. C. Cloët, L. Chang, C.D. Roberts, Phys. Rev. C (2012)

DCCM : Dynamical Coupled Channel Model

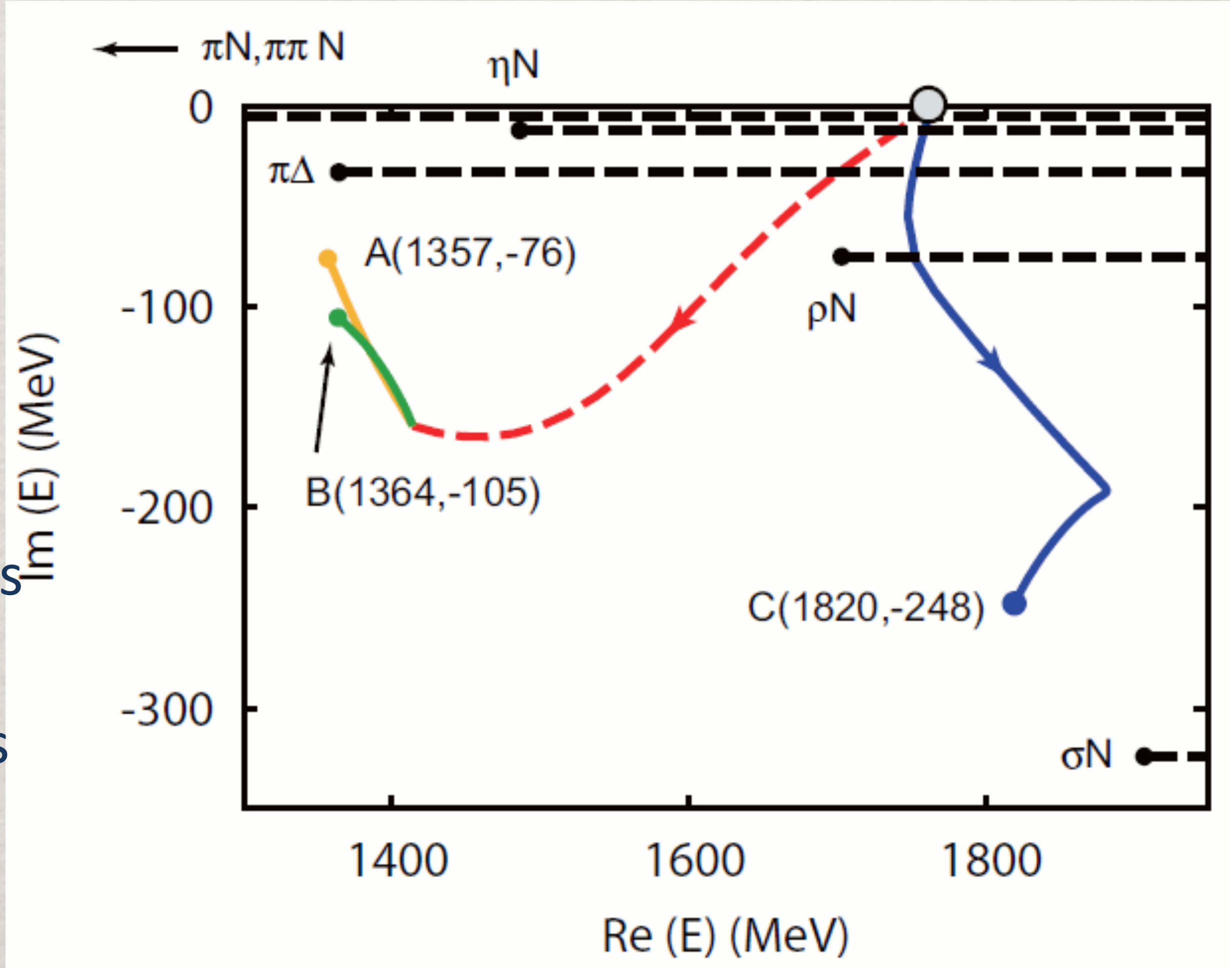
N. Suzuki, B. Julio-Díaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, Phys. Rev. Lett. (2010)

Roper Quark-Core Mass

N. Suzuki et al., *Phys.Rev.Lett. 104 (2010) 042302*

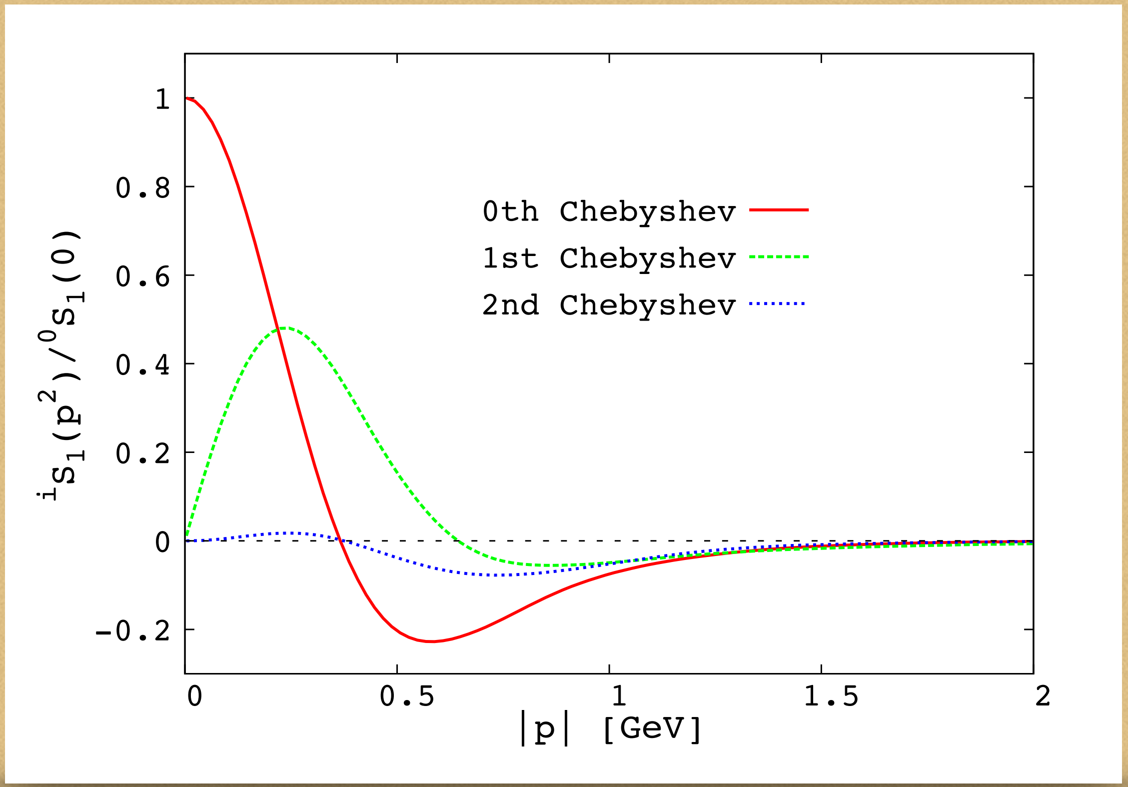
EBAC & the Roper resonance

- EBAC examined the dynamical origins of the two poles associated with the Roper resonance
- Both of them, together with the next higher resonance in the P_{11} partial wave were found to have the same originating bare state
- Coupling to the meson-baryon continuum induces multiple observed resonances from the same bare state.
- All PDG identified resonances consist of a core state and meson-baryon components.



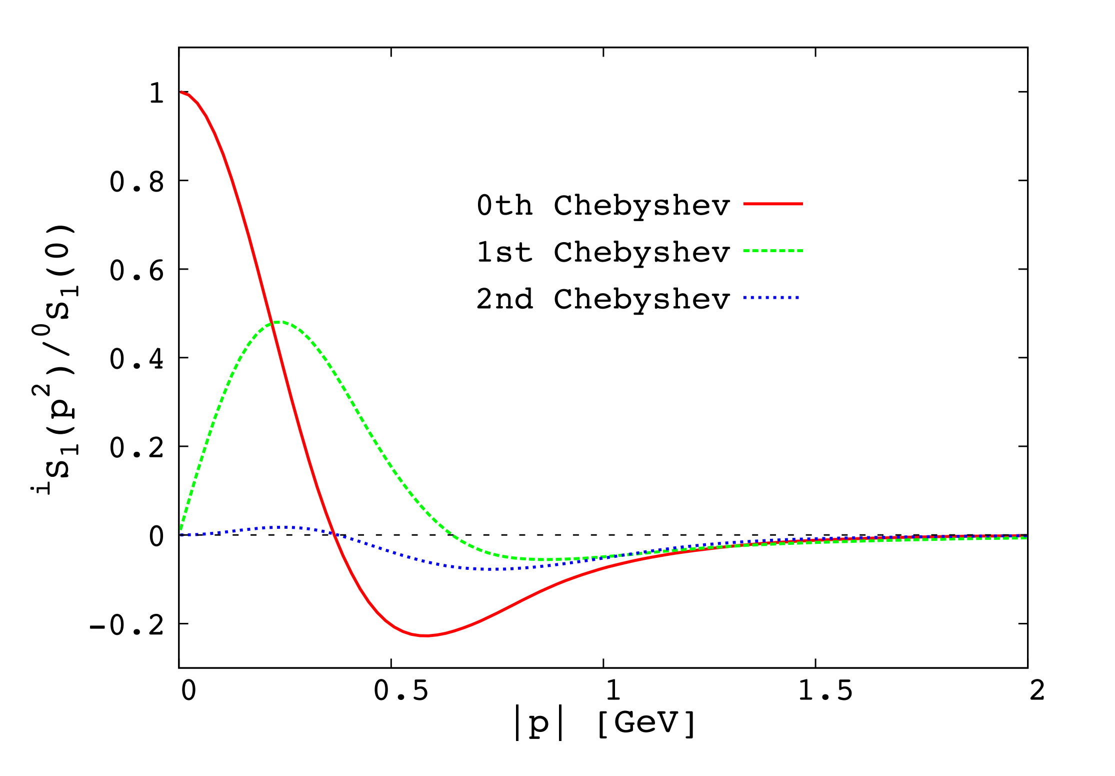
Chebyshev Moments

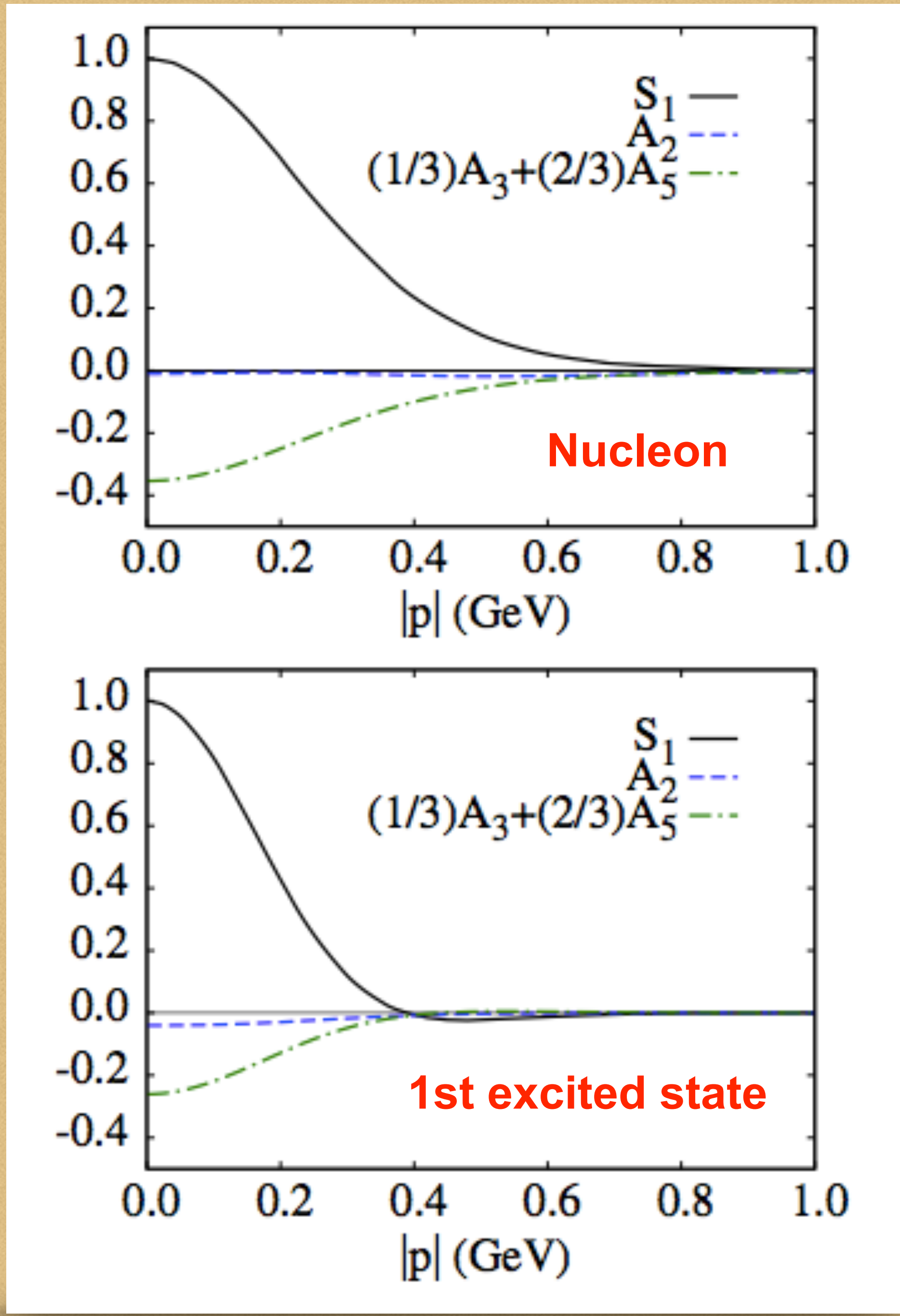
First three Chebyshev moments of leading S_1 component of 1st excited state's Faddeev amplitude



Chebyshev Moments

First three Chebyshev moments of leading S_1 component of 1st excited state's Faddeev amplitude





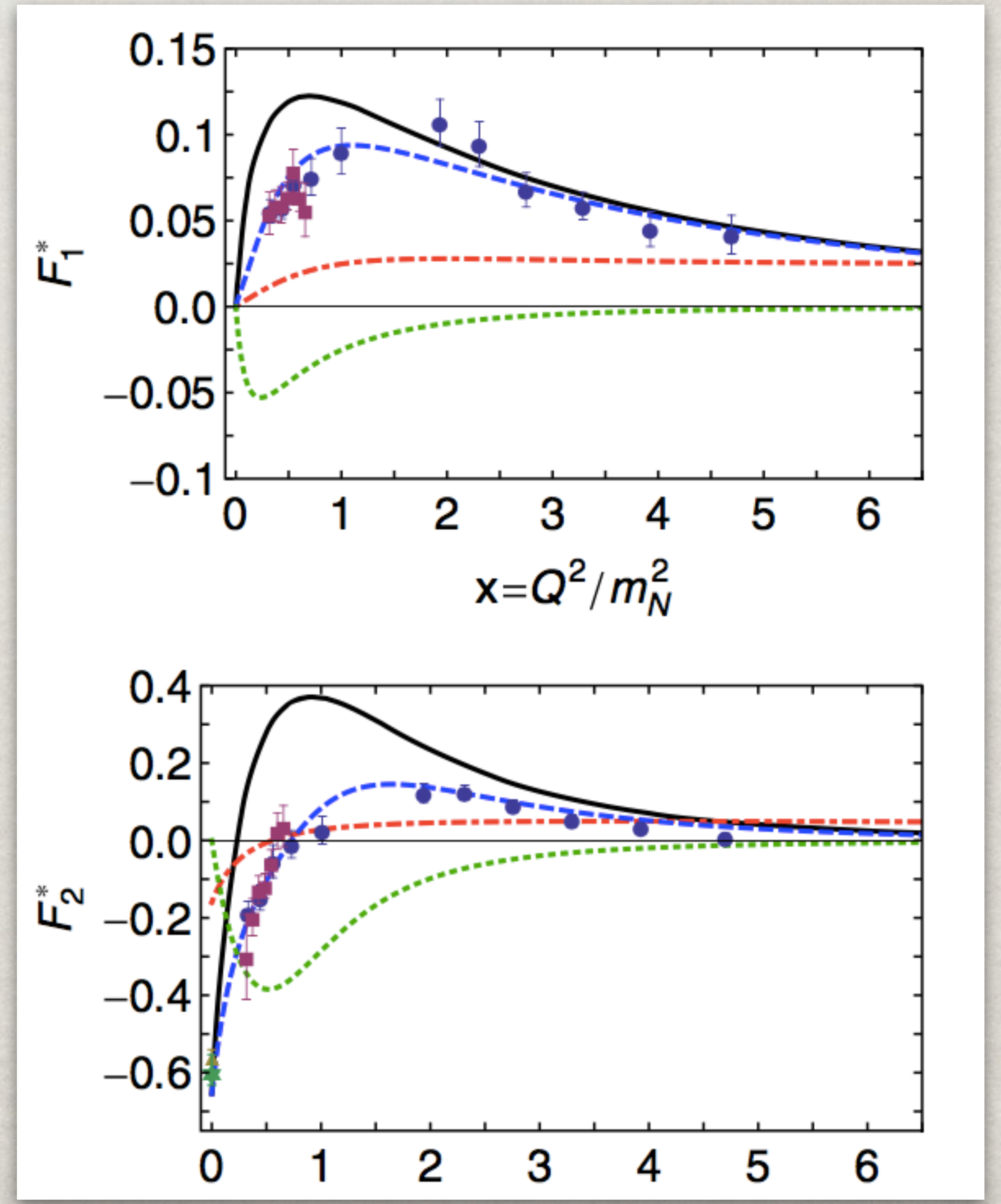
Zeroth Chebyshev moments of all *S*-wave components in the Faddeev wave function.
S_1 is associated with the baryon's scalar diquark; A_2, A_3, A_5 associated with axialvector correlation.

Dirac and Pauli Transition Form Factors

DSE-Faddeev solution

Contact interaction

Meson Cloud Correction



Conclusive Remarks

- Computed spectrum of 1st radial excitations for pseudoscalar (un)flavored mesons based on a rainbow-ladder kernel.
- The meson spectrum obtained clearly indicates that the ladder approximation is neither appropriate for radial excitations of light mesons nor for heavy-light (charmed) mesons.
- Along similar lines we show that the first radial excitation of the 3-quark nucleon core using a quark-diquark Faddeev kernel.
- The mass found for this excited nucleon agrees very well with that of the bare unclothed quark core.