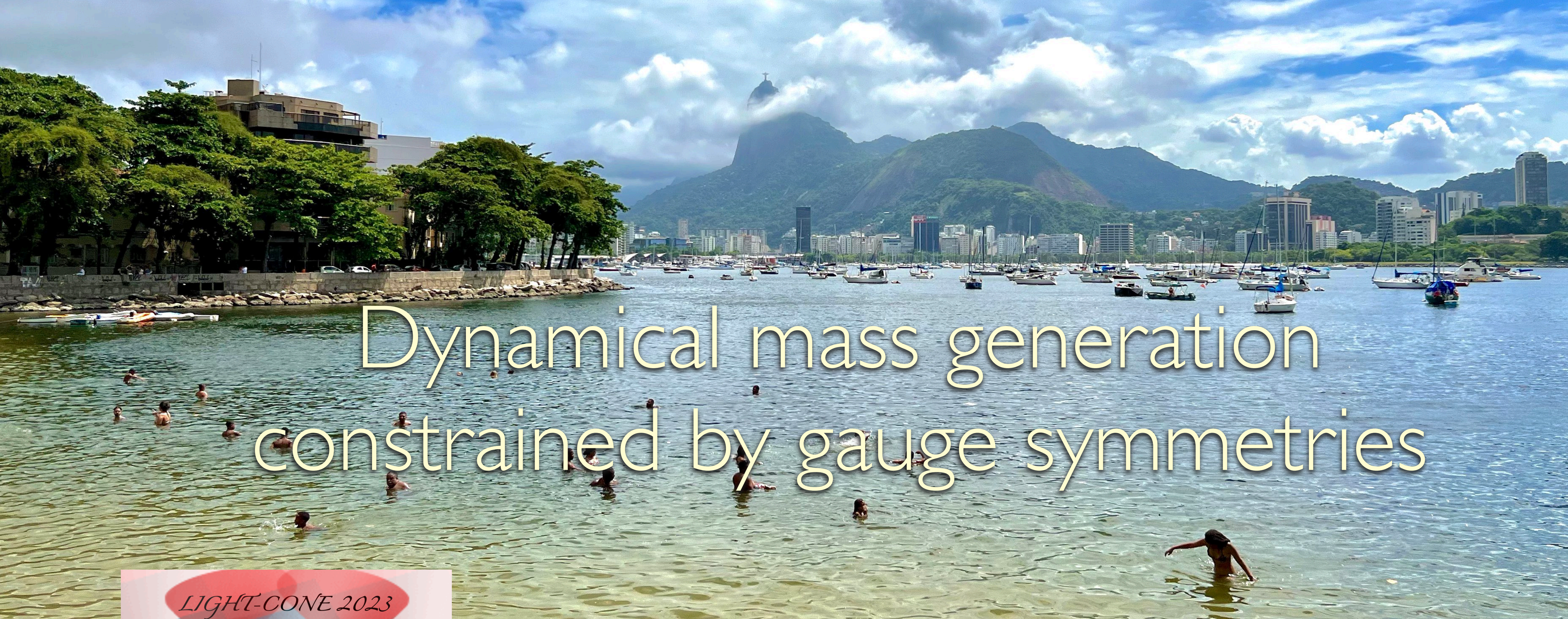

# Dynamical mass generation constrained by gauge symmetries

LIGHT-CONE 2023
CBPF September 18-22, 2023
Vermelha Beach

*Light-Cone 2023: Hadrons and Symmetries*

Centro Brasileiro de Pesquisas Físicas
Rio de Janeiro, 18–22 September 2023


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1933

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INCT-FNA
Instituto Nacional de Ciência e Tecnologia Física Nuclear e Aplicações

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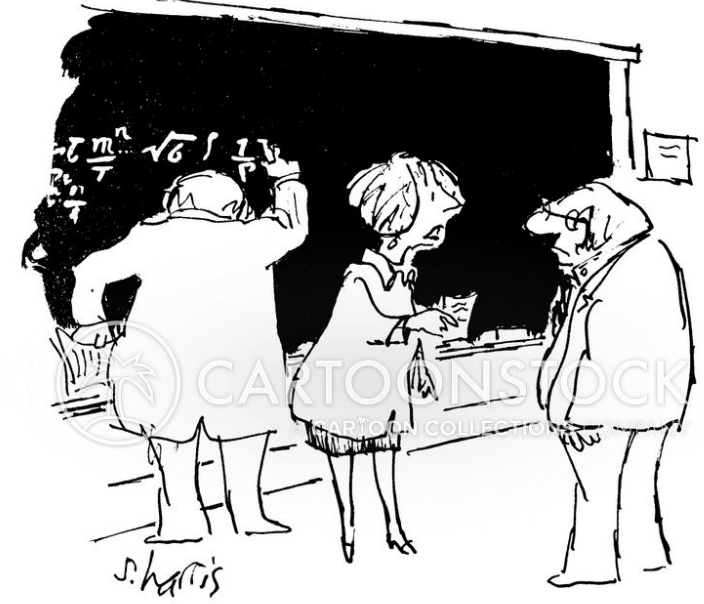
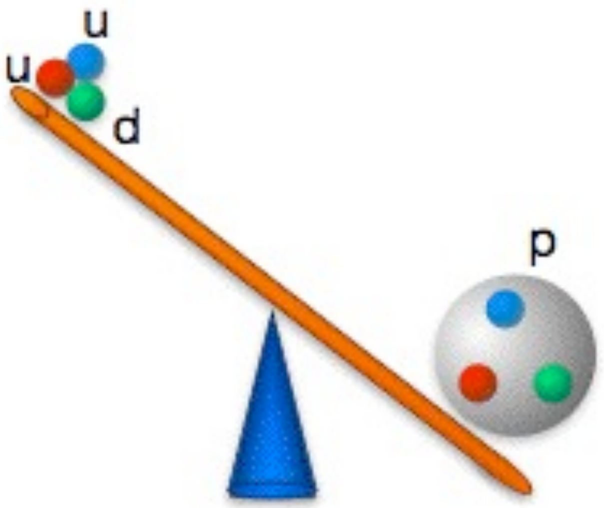


"WE COLLABORATE. I'M AN EXPERT, BUT NOT AN AUTHORITY, AND DR. GELBIS IS AN AUTHORITY, BUT NOT AN EXPERT."

# *Work in collaboration with*

- Luis Albino, Universidad de Michoacán, Mexico
- Adnan Bashir, Jefferson Lab, USA & Universidad de Michoacán, Mexico
- José Roberto Lessa, Universidade Cidade de São Paulo, Brazil
- Orlando Oliveira, Universidade de Coimbra, Portugal
- Eduardo Rojas, Universidad de Nariño, Colombia
- Fernando Serna, Universidade de Sucre, Colombia
- Roberto Correa da Silveira, Universidade Cidade de São Paulo, Brazil

# Quantum ChromoDynamics

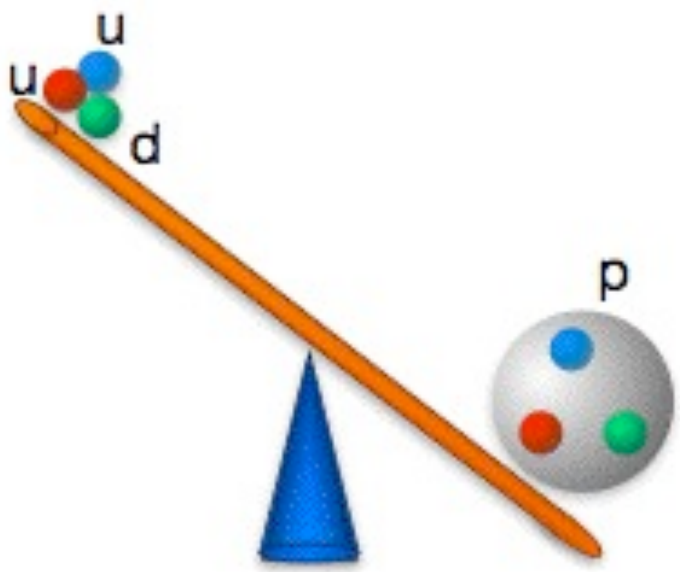



- We strive for a description of interactions between quarks and gluons which form hadrons as observed in *Nature*.

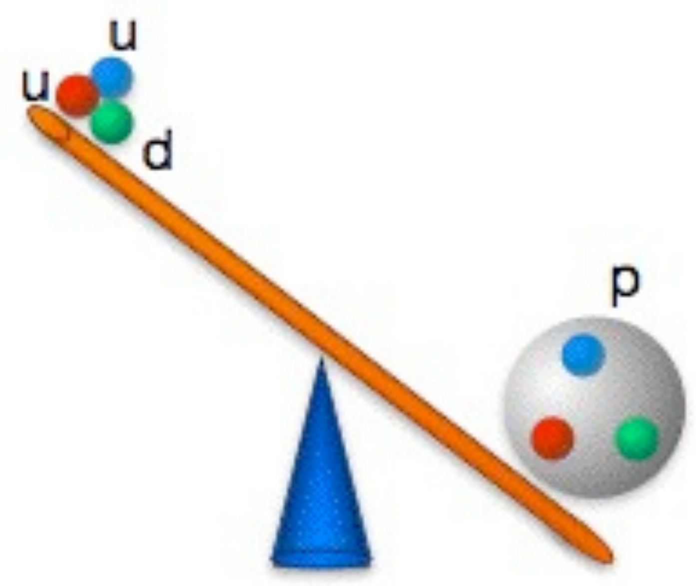
- The key issue is: while the Brout-Englert-Higgs mechanism has been established as the essential explicit source of elementary particle's masses, the same cannot be said of the atoms and their nuclei.

- The lightest Nambu-Goldstone mode of QCD, the pion, is more than an order of magnitude heavier than the sum of two light current quarks

- The formation of hadronic and nuclear bound states via its fundamental constituents is an inherently *nonperturbative* problem.



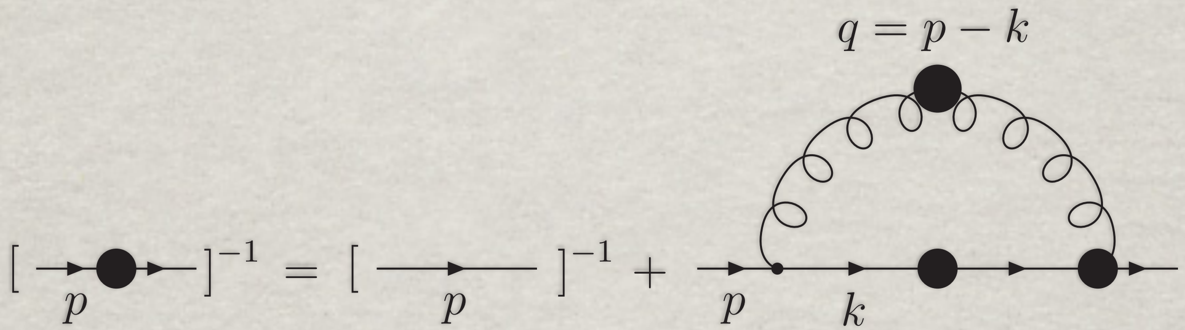

So where do the Hadron's masses come from after all?! The Higgs boson isn't doing the job alone!




Hint: the gluons interact with each other and have infinite ways to interact with the quark and “dress it”.

# Dyson-Schwinger equation in QCD

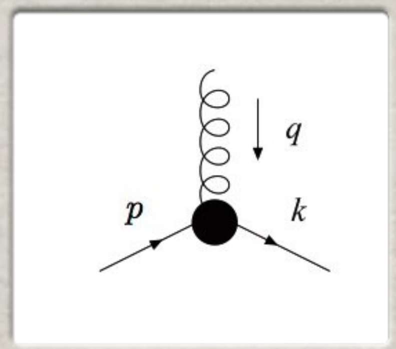
The propagator can be obtained from QCD's gap equation: the Dyson-Schwinger equation (DSE) for the dressed-fermion self-energy, which involves the set of infinitely many coupled equations.




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

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

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




| | | |
|---|---|---|
| $D_{\mu\nu}$ | : | 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 |

Each satisfies it's own DSE !

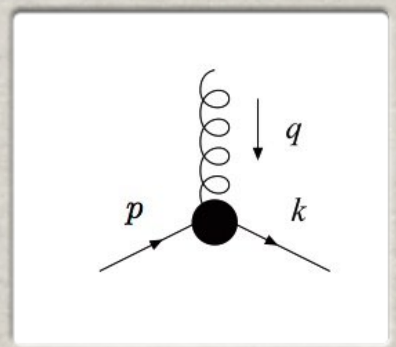
# Dyson-Schwinger equation in QCD

The propagator can be obtained from QCD's gap equation: the Dyson-Schwinger equation (DSE) for the dressed-fe... ...coupled equations.

## Running Quark Mass

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

$$\begin{aligned} S^{-1}(p) &= Z_2(i\gamma\cdot p + m^{\rm bm}) + \Sigma(p) := i\gamma\cdot p\,A(p^2) + B(p^2) \\ \Sigma(p) &= Z_1 \int^{\Lambda} \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S(q)\,\Gamma^a_\nu(q,p) \end{aligned}$$

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Each satisfies it's own DSE !

# Rainbow Truncation

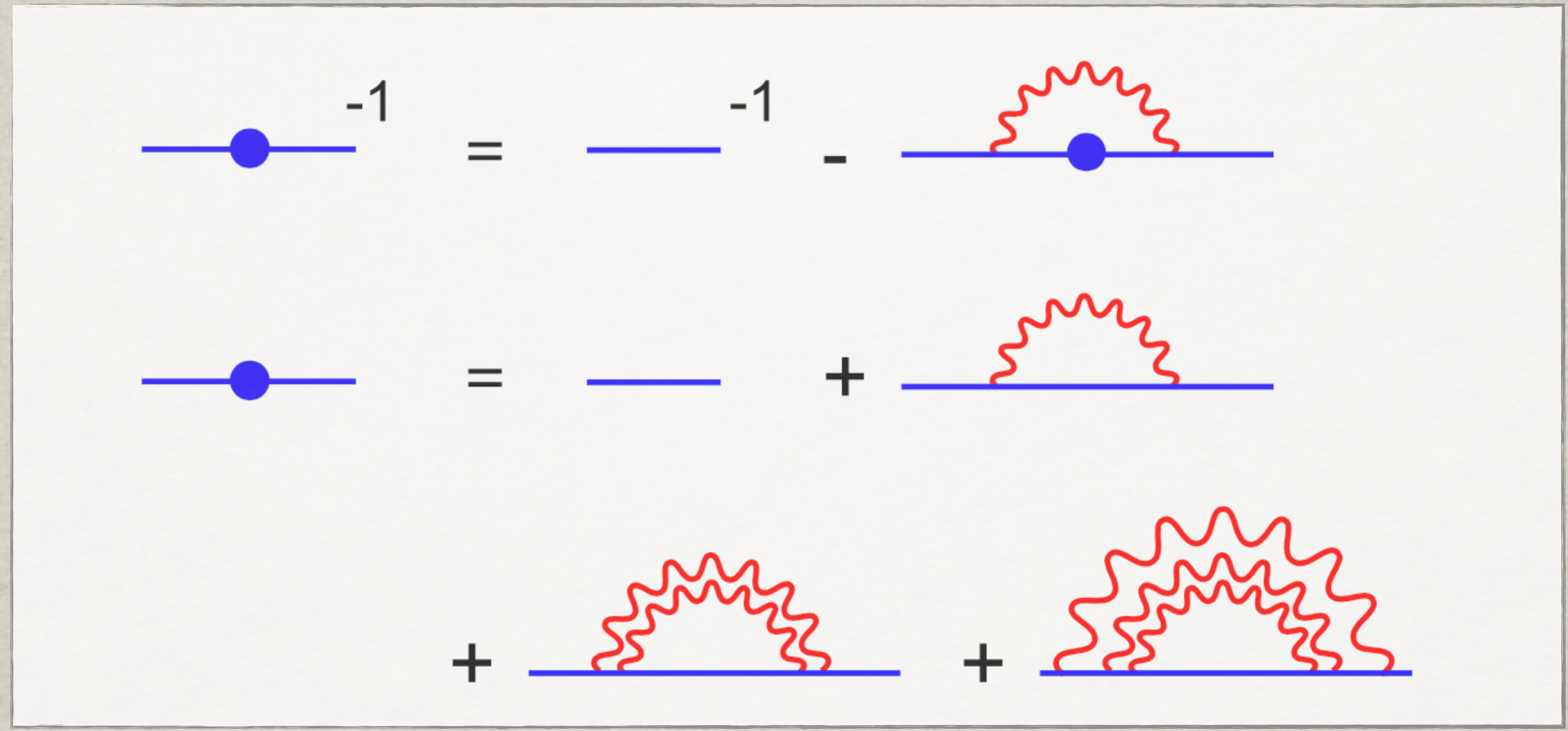
Since the Dyson-Schwinger Equation for QCD imply an infinite tower of non-linear integral equations, a symmetry preserving truncation scheme must be employed. The leading term in such a scheme is the Rainbow-Ladder (RL) truncation (Abelian approach).

$$\Gamma_\nu \;\to\; \gamma_\nu$$

RL truncation satisfies flavor non-singlet axial-vector Ward-Takahashi identities (chiral symmetry!) but has bad gauge dependence.

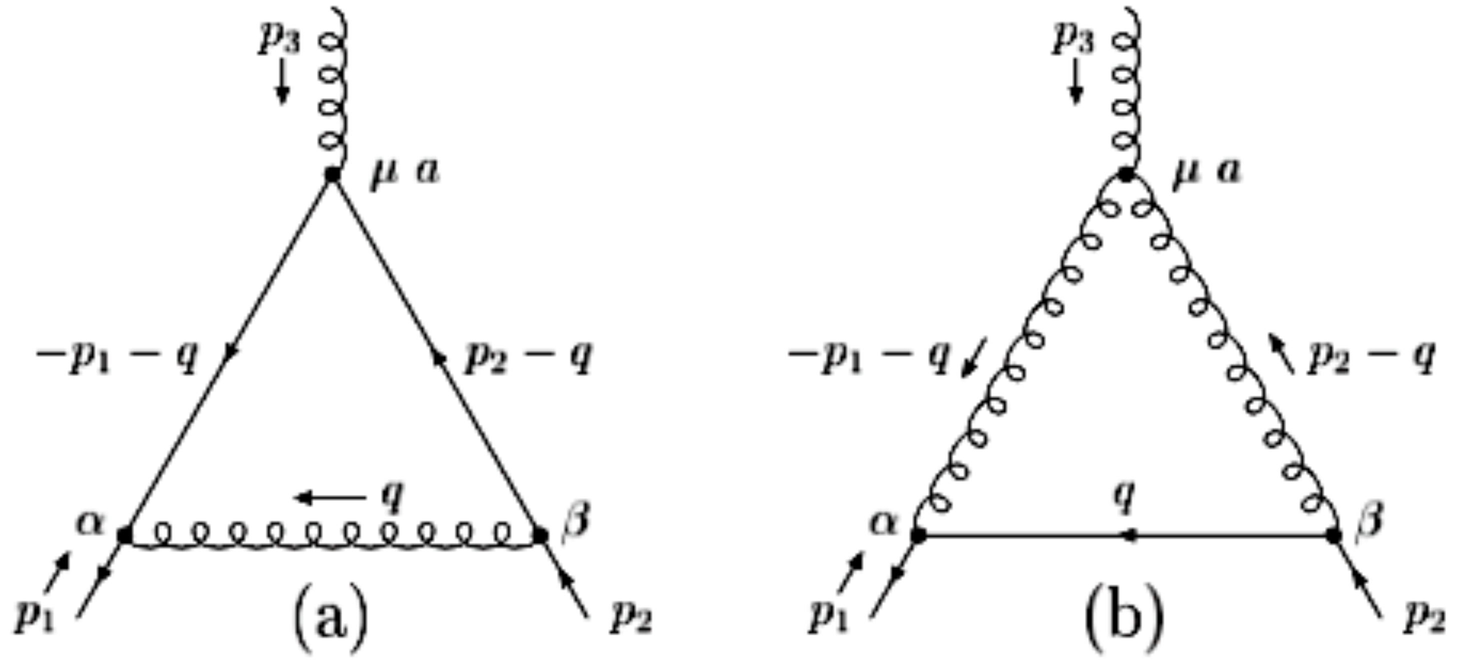
$\Rightarrow$ Landau gauge!

# Rainbow Truncation




Here the bare gauge-boson propagator is used, can also be dressed.

# The Quark-Gluon Vertex in QCD




(a) *Abelian* correction at one loop
(b) *Non-Abelian* correction at one loop

- The quark-gluon vertex in a tree-order is just $i\,\frac{\lambda_i}{2}\gamma_\mu$ .
- However, already at one loop the Dirac-tensor structure is very complex.

*Davydychev*, *Osland and Saks* (2000)

# Nonperturbative quark-gluon vertex: tensor structure

The fermion-gauge-boson vertex can be decomposed into "longitudinal" and transverse components: $\Gamma_\mu(k,p) = \Gamma_\mu^L(k,p) + \Gamma_\mu^T(k,p)$

$$\Gamma_\mu^L(k,p) = \sum_{i=1}^{4} \lambda_i(k^2,p^2)\, L_\mu^i(k,p)$$

$$\Gamma_\mu^T(k,p) = \sum_{i=1}^{8} \tau_i(k^2,p^2)\, T_\mu^i(k,p)$$

$$\Gamma_\mu(k,p)\Big|_{k^2=p^2=q^2=\mu^2} = \gamma_\mu$$

$$q \cdot \Gamma_\mu^T(k,p) = 0$$

# Nonperturbative quark-gluon vertex: tensor structure

Which independent tensor structures to specify the longitudinal and transverse vertex?
Following Ball and Chiu (1980), one can write:

RL approximation

$$
\begin{aligned}
L^1_\mu(k,p) &= \gamma_\mu \\
L^2_\mu(k,p) &= \tfrac{1}{2}(k+p)_\mu\,\gamma\cdot(k+p) \\
L^3_\mu(k,p) &= -i\,(k+p)_\mu \\
L^4_\mu(k,p) &= -\sigma_{\mu\nu}\,(k+p)_\mu \\
\\
T^1_\mu(k,p) &= i\,[p_\mu(k\cdot q) - k_\mu(p\cdot q)] \\
T^2_\mu(k,p) &= [p_\mu(k\cdot q) - k_\mu(p\cdot q)]\,\gamma\cdot t \\
T^3_\mu(k,p) &= q^2\gamma_\mu - q_\mu\,\gamma\cdot q \\
T^4_\mu(k,p) &= -\,[p_\mu(k\cdot q) - k_\mu(p\cdot q)]\,p^\nu k^\rho \sigma_{\nu\,\rho} \\
T^5_\mu(k,p) &= \sigma^{\mu\,\nu} q_\nu \\
T^6_\mu(k,p) &= -\gamma_\mu\left(k^2 - p^2\right) + t_\mu\,\gamma\cdot q \\
T^7_\mu(k,p) &= \tfrac{i}{2}(k^2-p^2)\,[\gamma_\mu\gamma\cdot t - t_\mu] + t_\mu\,p^\nu k^\rho \sigma_{\nu\rho} \\
T^8_\mu(k,p) &= -i\gamma_\mu\,p^\nu k^\rho \sigma_{\nu\,\rho} - p_\mu\,\gamma\cdot k + k_\mu\,\gamma\cdot p
\end{aligned}
$$

# Nonperturbative quark-gluon vertex: symmetries

Which steps to remedy a gauge dependence? Clearly must be beyond rainbow truncation as bare vertex violates gauge variance:

$$q_\mu i\Gamma_\mu(k,p) \quad = \quad S^{-1}(k) - S^{-1}(p)$$

Best "prepared" with Landau gauge to minimize dependence.

First step is the proposal for the longitudinal vertex by Ball and Chiu:

$$\Gamma^L_\mu(k,p) = \sum_{i=1}^{4} \lambda_i(k^2,p^2)\, L^i_\mu(k,p)$$

$$\lambda_1(k^2,p^2) = \frac{1}{2}\left[A(k^2)+A(p^2)\right] \qquad \lambda_2(k^2,p^2) = \frac{A(k^2)-A(p^2)}{k^2-p^2}$$

$$\lambda_3(k^2,p^2) = \frac{B(k^2)-B(p^2)}{k^2-p^2} \qquad \lambda_4(k^2,p^2) = 0$$

Widely employed in phenomenology though transverse part remains undetermined.

What about gauge covariance, does it satisfy Landau-Khalatnikov-Fradkin transformations?

What about multiplicative renormalizability?

# Nonperturbative quark-gluon vertex: symmetries

Which steps to remedy a gauge dependence? Clearly must be beyond rainbow truncation as bare vertex violates gauge variance:

$$iq^\mu \gamma_\mu \neq i\gamma\cdot k\, A(k^2) + B(k^2) - i\gamma\cdot p\, A(p^2) - B(p^2)$$

Best "prepared" with Landau gauge to minimize dependence.

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$$\lambda_1(k^2,p^2) = \tfrac{1}{2}\left[A(k^2) + A(p^2)\right] \qquad \lambda_2(k^2,p^2) = \frac{A(k^2) - A(p^2)}{k^2 - p^2}$$

$$\lambda_3(k^2,p^2) = \frac{B(k^2) - B(p^2)}{k^2 - p^2} \qquad \lambda_4(k^2,p^2) = 0$$

Widely employed in phenomenology though transverse part remains undetermined.

What about gauge covariance, does it satisfy Landau-Khalatnikov-Fradkin transformations?

What about multiplicative renormalizability?

# What about the transverse vertex?

Not constrained by Ward-Takahashi or Slavnov-Taylor identities (BRST symmetries).

What about invariance of generating functional under transverse symmetry transformations?

## Infinitesimal Lorentz transformation

$$\delta_T\psi(x) = \frac{1}{4}g\alpha(x)\epsilon^{\mu\nu}\sigma_{\mu\nu}\psi(x), \quad \delta_T\bar{\psi}(x) = \frac{1}{4}g\alpha(x)\epsilon^{\mu\nu}\bar{\psi}(x)\sigma_{\mu\nu},$$

Kei-Ichi Kondo, Int. J. Mod. Phys. A12(1996)

**Infenitissimal Lorentz transformantion transforms the original gauge symmetry transformation into its transverse direction.**

What is the origin of these transverse identities?

# What is the origin of these transverse identities?

$$\psi(x) \longrightarrow \psi'(x) = \psi(x) + ig\alpha(x)\psi(x),\ \bar{\psi}(x) \longrightarrow \bar{\psi}'(x) = \bar{\psi}(x) - ig\alpha(x)\bar{\psi}(x),$$

$$q_\mu \Gamma_V^\mu(p_1, p_2) = S_F^{-1}(p_1) - S_F^{-1}(p_2),$$

## What is the origin of these transverse identities?

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↓

$$q_\mu \Gamma^\mu_V(p_1, p_2) = S_F^{-1}(p_1) - S_F^{-1}(p_2),$$

$$\delta_T \psi(x) = \frac{1}{4} g\alpha(x)\epsilon^{\mu\nu}\sigma_{\mu\nu}\psi(x), \quad \delta_T \bar{\psi}(x) = \frac{1}{4} g\alpha(x)\epsilon^{\mu\nu}\bar{\psi}(x)\sigma_{\mu\nu},$$

Infinitesimal Lorentz transformation

Kei-Ichi Kondo,Int.J.Mod.Phys.A12(1996)

↓

$$\int D[\psi, \bar{\psi}, A] e^{i\int d^4x L_{\rm QED}[\psi, \bar{\psi}, A]} \psi(x_1)\bar{\psi}(x_2)$$
$$= \int D[\psi', \bar{\psi}', A'] e^{i\int d^4x L_{\rm QED}[\psi', \bar{\psi}', A']} \psi'(x_1)\bar{\psi}'(x_2).$$

# What is the origin of these transverse identities?

$$\psi(x) \longrightarrow \psi'(x) = \psi(x) + ig\alpha(x)\psi(x), \;\; \bar{\psi}(x) \longrightarrow \bar{\psi}'(x) = \bar{\psi}(x) - ig\alpha(x)\bar{\psi}(x),$$

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Infinitesimal Lorentz transformation

Kei-Ichi Kondo,Int.J.Mod.Phys.A12(1996)

$$\int D[\psi, \bar{\psi}, A] e^{i\int d^4x L_{\rm QED}[\psi,\bar{\psi},A]} \psi(x_1)\bar{\psi}(x_2) = \int D[\psi', \bar{\psi}', A'] e^{i\int d^4x L_{\rm QED}[\psi',\bar{\psi}',A']} \psi'(x_1)\bar{\psi}'(x_2).$$

$$\begin{aligned} & iq^\mu \Gamma_V^\nu(p_1, p_2) - iq^\nu \Gamma_V^\mu(p_1, p_2) \\ = \; & S_F^{-1}(p_1)\sigma^{\mu\nu} + \sigma^{\mu\nu} S_F^{-1}(p_2) + 2m\Gamma_T^{\mu\nu}(p_1, p_2) \\ & + (p_{1\lambda} + p_{2\lambda})\varepsilon^{\lambda\mu\nu\rho}\Gamma_{A\rho}(p_1, p_2) - \int \frac{d^4k}{(2\pi)^4} 2k_\lambda \varepsilon^{\lambda\mu\nu\rho}\Gamma_{A\rho}(p_1, p_2; k), \end{aligned}$$

# Abelian Ward-Takahashi identities: divergence and curl

Ward-Takahashi identity:

$$q_\mu i\Gamma_\mu(k,p) = S^{-1}(k) - S^{-1}(p)$$

Transverse Ward-Takahashi identities:

$$\begin{aligned} q_\mu\Gamma_\nu(k,p) - q_\nu\Gamma_\mu(k,p) &= S^{-1}(p)\sigma_{\mu\nu} + \sigma_{\mu\nu}S^{-1}(k) \\ &+ 2im\Gamma_{\mu\nu}(k,p) + t_\lambda\varepsilon_{\lambda\mu\nu\rho}\Gamma^A_\rho(k,p) + A^V_{\mu\nu}(k,p) \end{aligned}$$

$$\begin{aligned} q_\mu\Gamma^A_\nu(k,p) - q_\nu\Gamma^A_\mu(k,p) &= S^{-1}(p)\sigma^5_{\mu\nu} - \sigma^5_{\mu\nu}S^{-1}(k) \\ &+ t_\lambda\varepsilon_{\lambda\mu\nu\rho}\Gamma_\rho(k,p) + V^A_{\mu\nu}(k,p) \end{aligned}$$

# Slavnov-Taylor Identity

One can relate the longitudinal form factors $\lambda_i$ to the quark propagator's scalar and vector pieces, $B(p^2)$ and $A(p^2)$ via an STI:

$$i\,q\cdot\Gamma^a(k,p) = G(q^2)\left[S^{-1}(-k)\,H^a(k,p) - \bar{H}^a(p,k)\,S^{-1}(p)\right]$$

Ghost dressing function

Quark-ghost scattering kernel

Decomposition of $H(k,p)$ and its conjugate in terms of Lorentz covariants:

$$H(p_1,p_2,p_3) \;=\; X_0\,\mathbb{I}_D + i\,X_1\,\gamma\cdot p_1 + i\,X_2\,\gamma\cdot p_2 + i\,X_3\,\sigma_{\alpha\beta}\,p_1^\alpha p_2^\beta$$

$$\overline{H}(p_2,p_1,p_3) \;=\; \overline{X}_0\,\mathbb{I}_D - i\,\overline{X}_2\,\gamma\cdot p_1 - i\,\overline{X}_1\,\gamma\cdot p_2 + i\,\overline{X}_3\,\sigma_{\alpha\beta}\,p_1^\alpha p_2^\beta$$

$$X_i \equiv X_i(p_1,p_2,p_3) \qquad\qquad X_i(p,k,q) = \bar{X}_i(k,p,q)$$


Davydychev, Osland & Saks (2001)
A .C. Aguilar and J. Papavassiliou (2011)
A. C. Aguilar, J.  C. Cardona, M. N. Ferreira and J.~Papavassiliou (2016, 2018)

# Decoupling the transverse STIs

$$q_\mu \Gamma^a_\nu(k,p) - q_\nu \Gamma^a_\mu(k,p) = G(q^2)\left[S^{-1}(p)\sigma_{\mu\nu} H^a(k,p) + \bar{H}^a(p,k)\,\sigma_{\mu\nu} S^{-1}(k)\right] + 2im\,\Gamma^a_{\mu\nu}(k,p) + t_\alpha \epsilon_{\alpha\mu\nu\beta}\Gamma^{5a}_\beta(k,p) + A^a_{\mu\nu}(k,p)$$

$$q_\mu \Gamma^{5a}_\nu(k,p) - q_\nu \Gamma^{5a}_\mu(k,p) = G(q^2)\left[S^{-1}(p)\sigma^5_{\mu\nu} H^a(k,p) - \bar{H}^a(p,k)\,\sigma^5_{\mu\nu} S^{-1}(k)\right] + t_\alpha \epsilon_{\alpha\mu\nu\beta}\Gamma^a_\beta(k,p) + V^a_{\mu\nu}(k,p)$$

- The decoupling of the vector and axialvector vertices can be achieved by appropriate projections with two tensors which lead to two independent equations for each vertex ! S.-x. Qin, L. Chang, Y.-x. Liu, C.D. Roberts & S. Schmidt (2013)

- Using the two identities for the vector vertex, we can use another set of projections to isolate the 8 tensor structures of the transverse vertex as functions of the *quark propagator, the ghost dressing function, the quark-ghost scattering form factors and an hitherto undetermined nonlocal tensor structure.*

# Gluon and ghost dressing functions

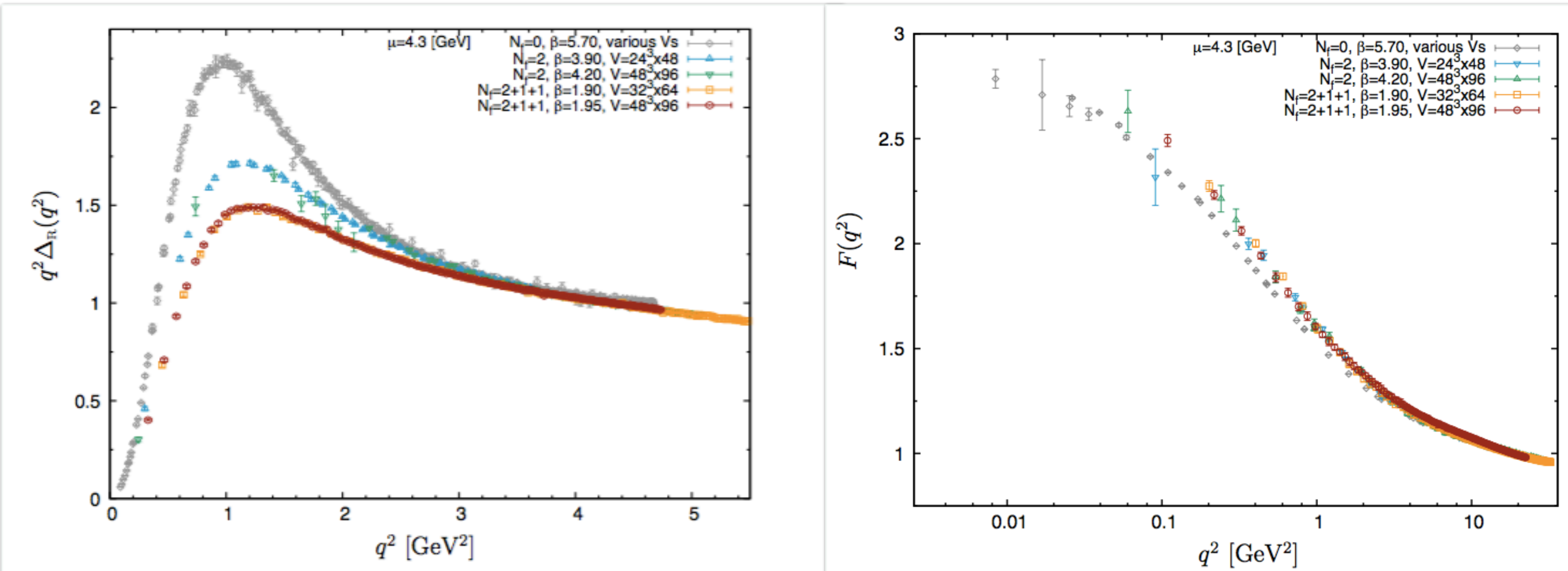
The gluon propagator in Landau gauge is:

$$\Delta^{ab}_{\mu\nu}(q) = \delta^{ab}\left(\delta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Delta(q^2) \qquad\qquad \Delta(q^2) \stackrel{q^2\to\infty}{\longrightarrow} \frac{1}{q^2}$$

The ghost propagator is:

$$D^{ab}(q^2) = -\,\delta^{ab}\,\frac{G(q^2)}{q^2} \qquad\qquad G(q^2) \stackrel{q^2\to\infty}{\longrightarrow} 1$$

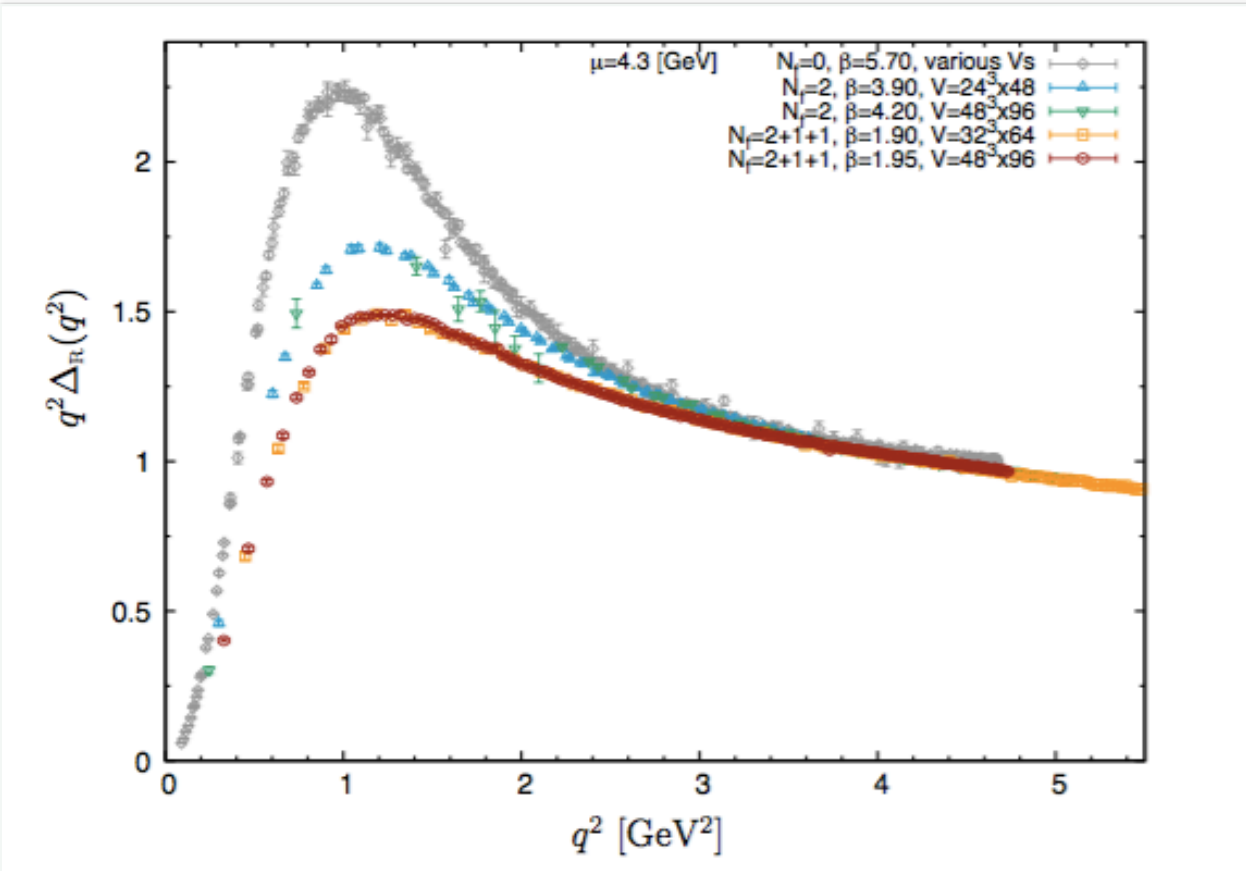
# Gluon and ghost dressing functions

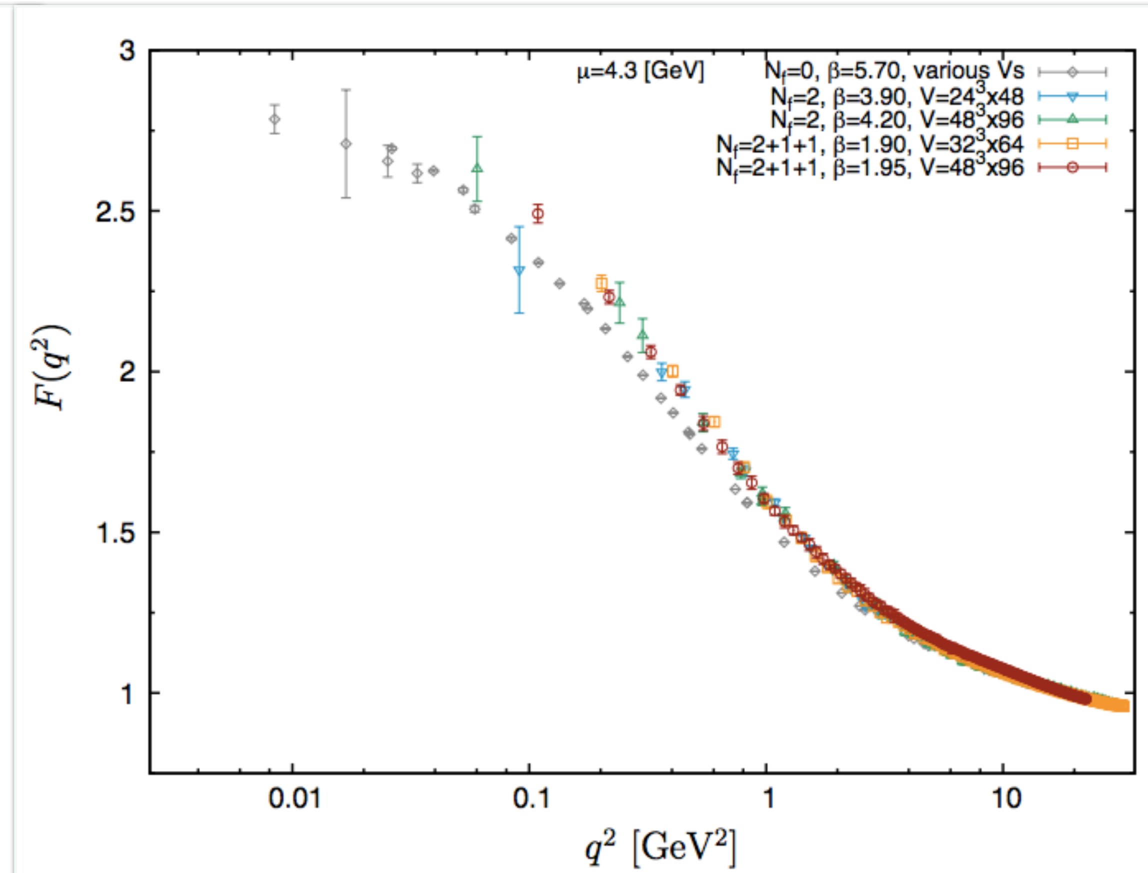



DSE solutions with three sets of propagators from different collaborations:

- Set I: Bogolubsky *et al.*, Phys. Lett. B 676, 69 (2009)
- Set II: Dudal *et al.*, Annals Phys. 397, 351-364 (2018)
  Duarte *et al.*, Phys. Rev. D 94 (2016)
- Set III: A. Ayala et al., Phys. Rev. D 86, 074512 (2012)

# Gluon and ghost dressing functions



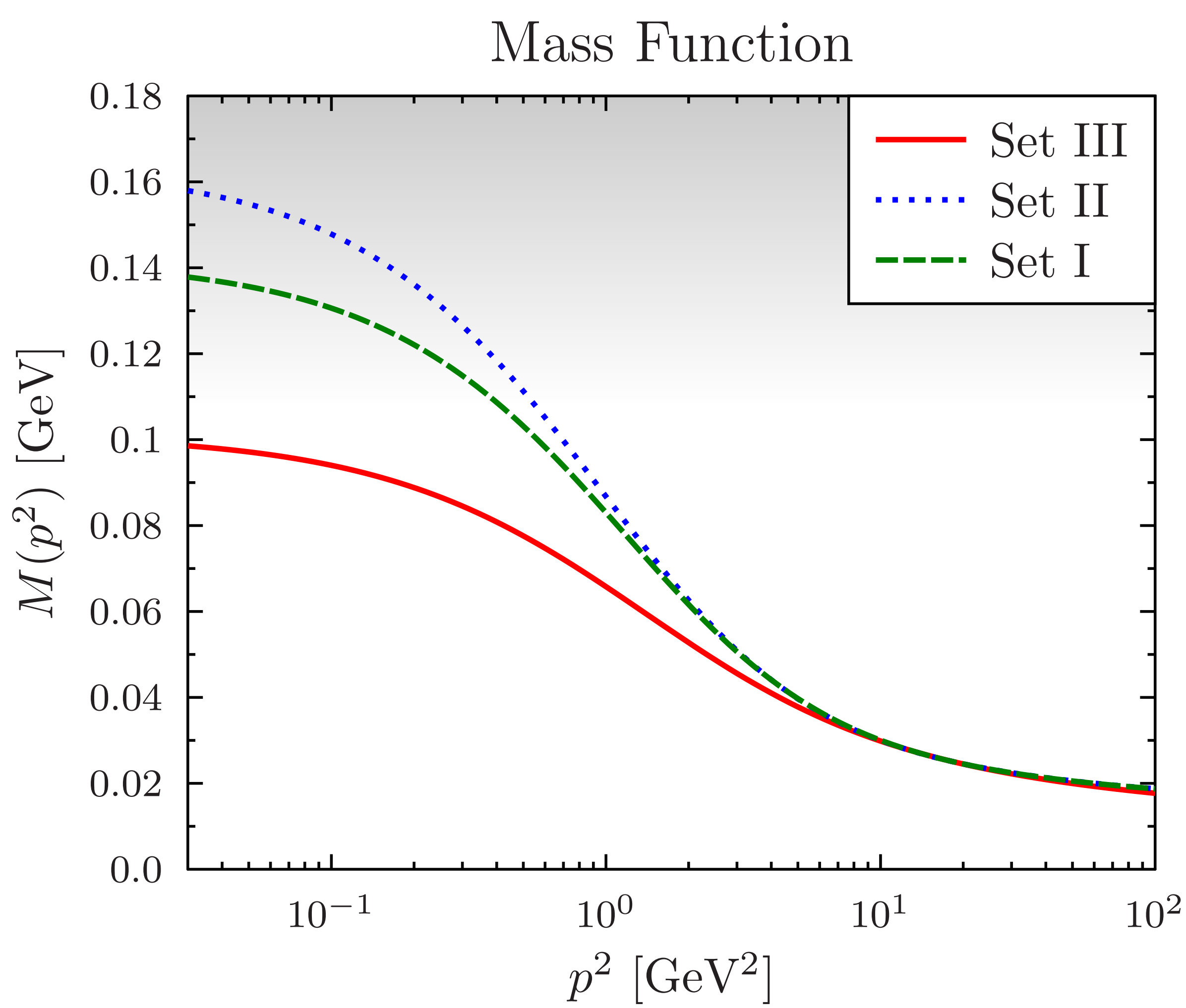

$$\Delta(q^2) = Z\,\frac{q^2+M_1^2}{q^4+M_2^2q^2+M_3^4}\left[1+\omega\ln\left(\frac{q^2+M_0^2}{\Lambda_{\rm QCD}^2}\right)\right]^{\gamma_{\rm gl}}$$

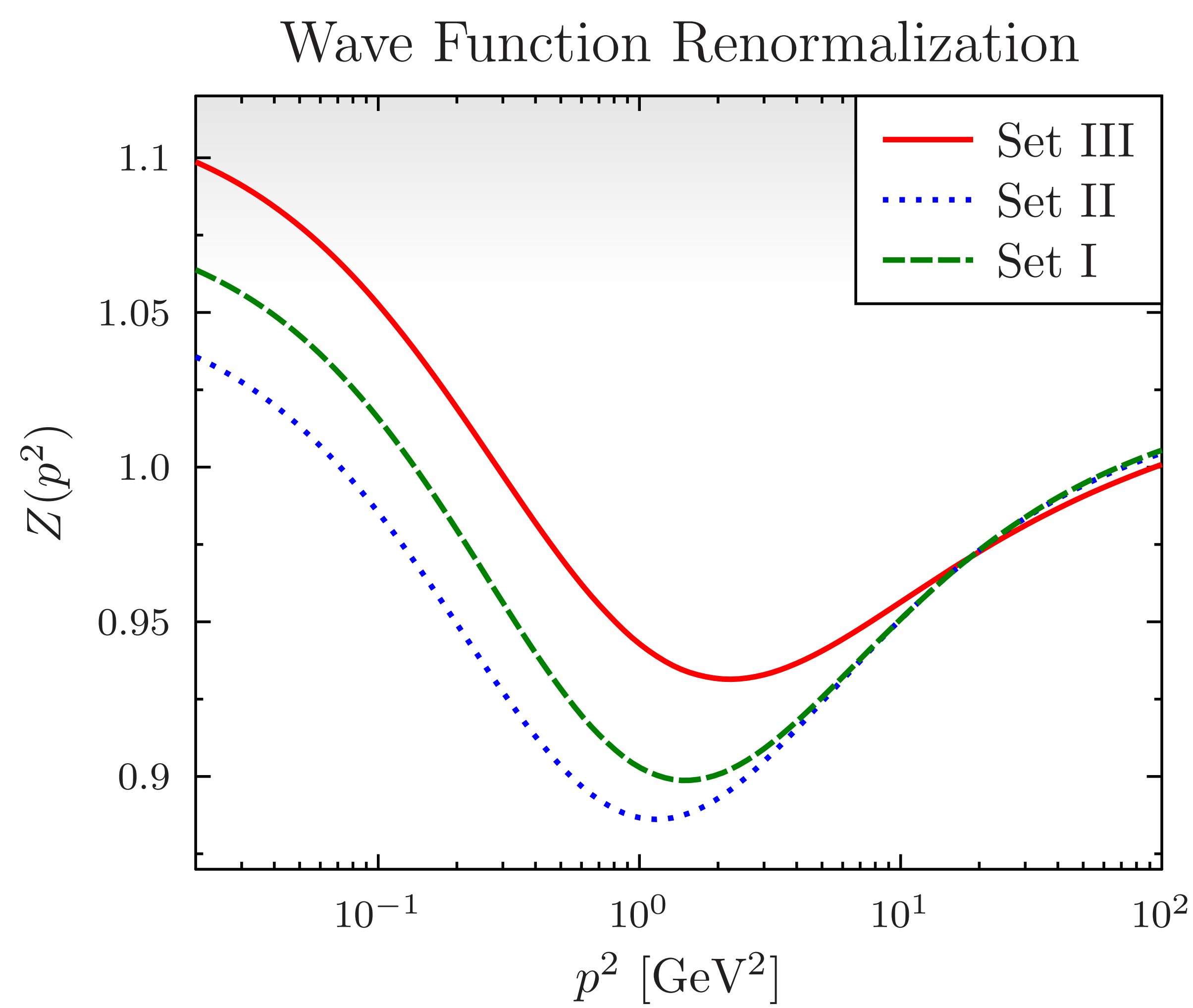
$$G(q^2) = Z\,\frac{q^4+M_2^2q^2+M_1^4}{q^4+M_4^2q^2+M_3^4}\left[1+\omega\ln\left(\frac{q^2+\frac{m_1^4}{q^2+m_0^2}}{\Lambda_{\rm QCD}^2}\right)\right]^{\gamma_{\rm gh}}$$

D. Dudal, O. Oliveira and P. J. Silva, Annals Phys. **397** (2018)

# Mass function with non-transverse vertex

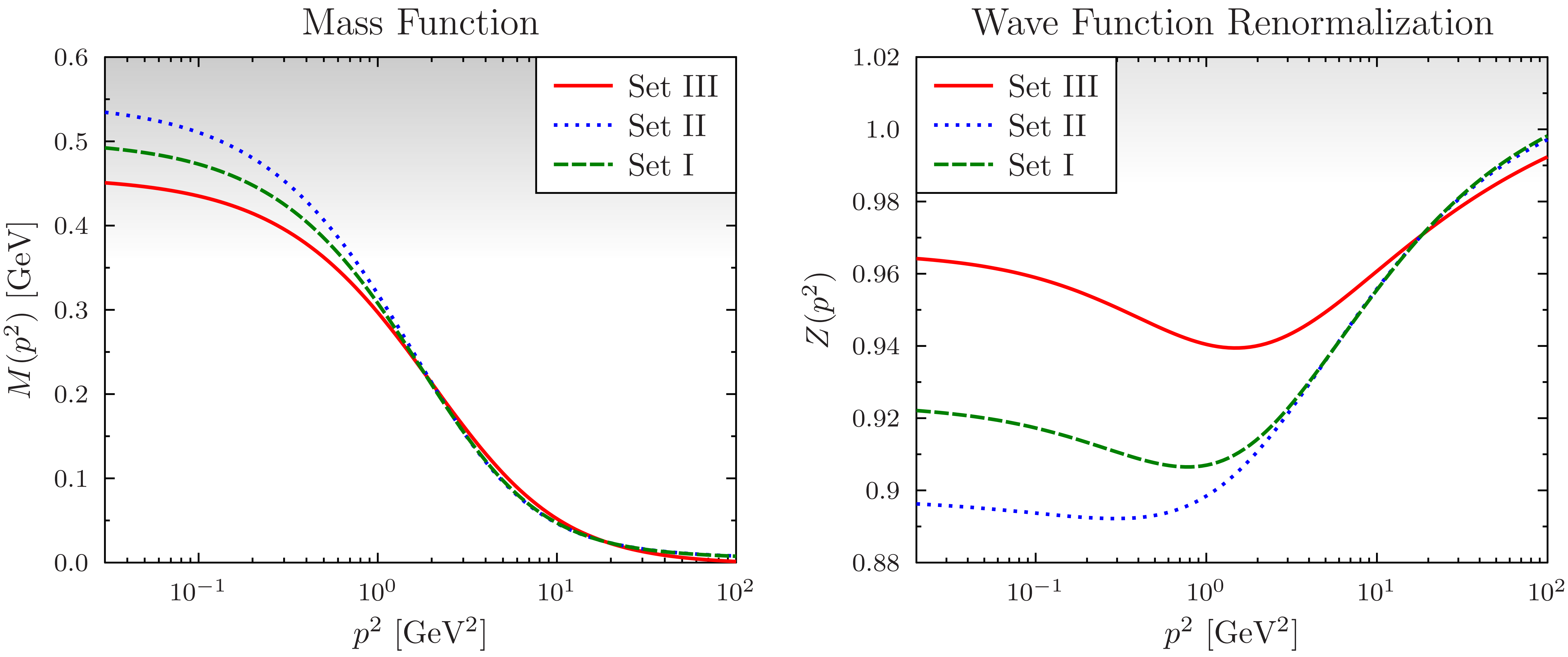
$$\Gamma^L_\mu(k,p) = \sum_{i=1}^{4} \lambda_i(k^2,p^2)\, L^i_\mu(k,p)$$



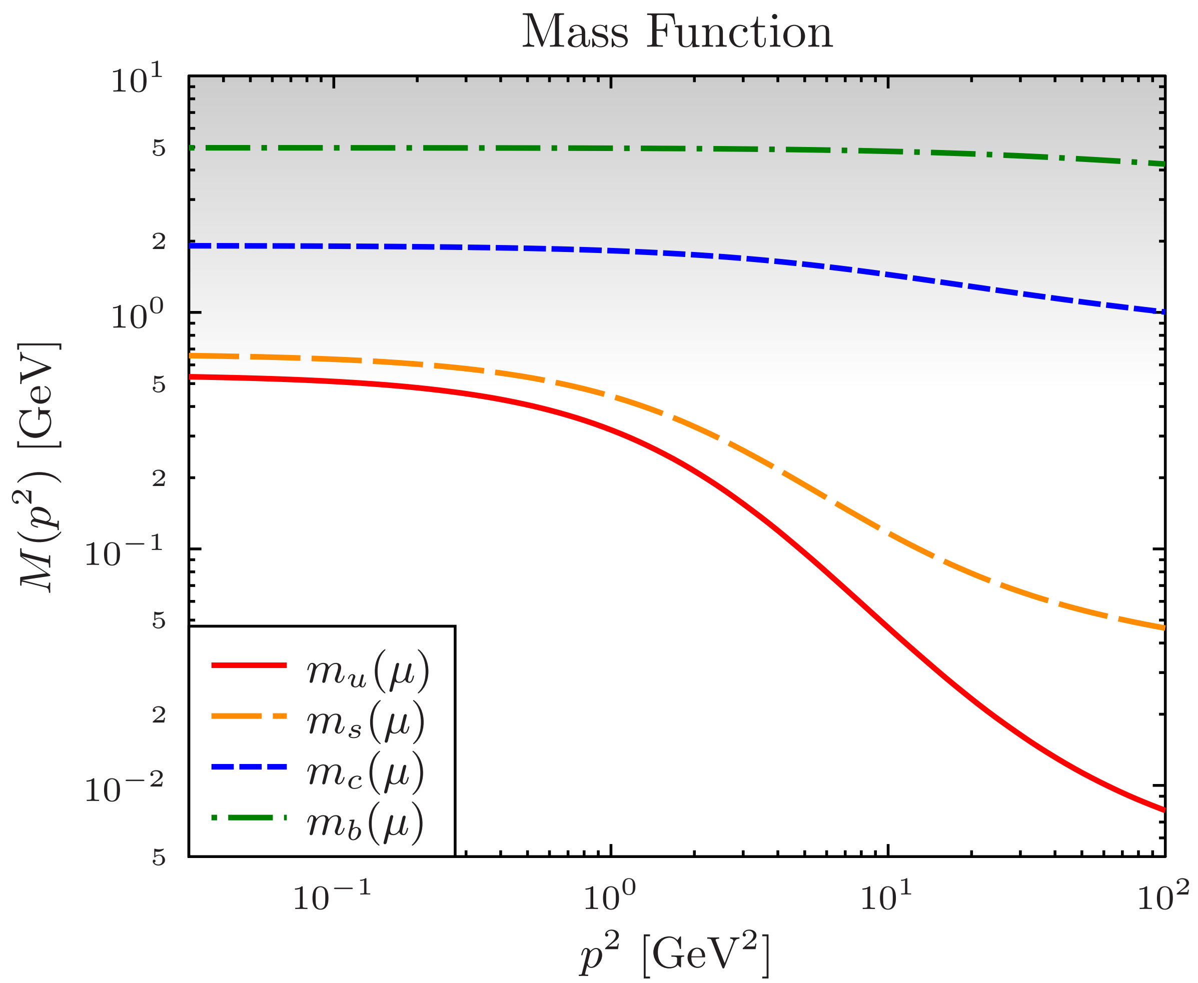



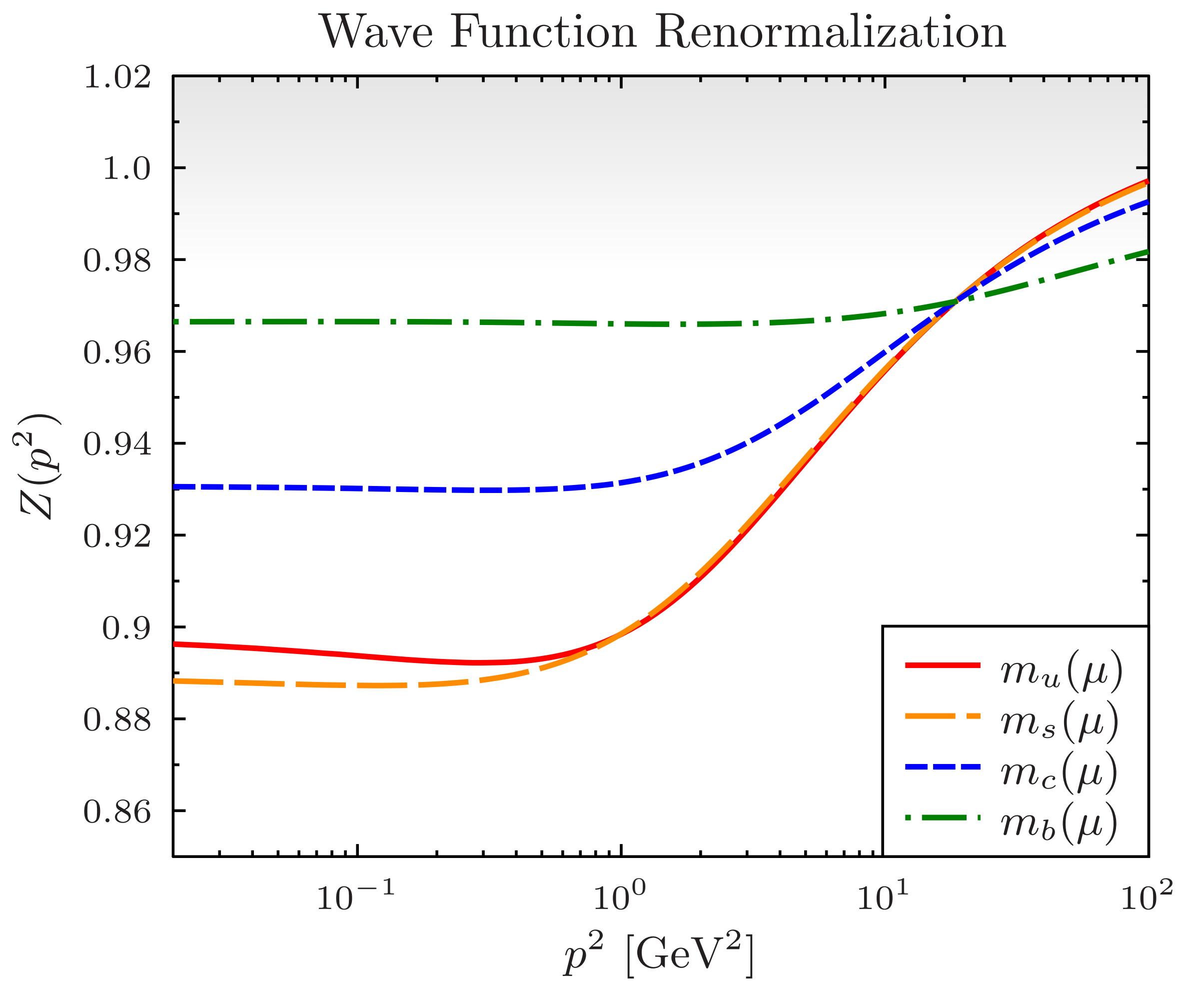
# Mass functions with full quark-gluon vertex

$$\Gamma_\mu(k,p) = \Gamma^L_\mu(k,p) + \Gamma^T_\mu(k,p)$$

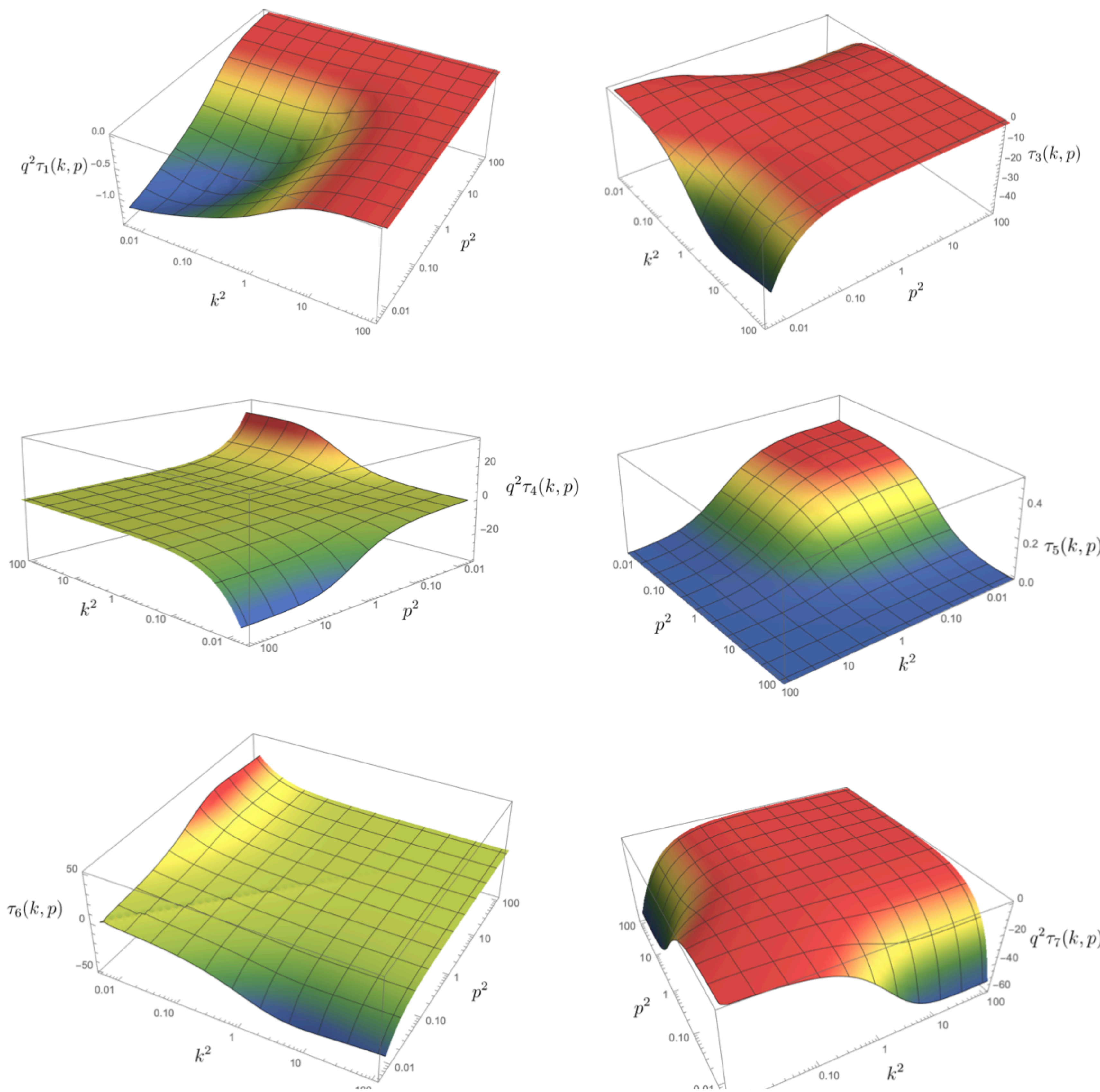


# Flavor dependence of DSE solutions



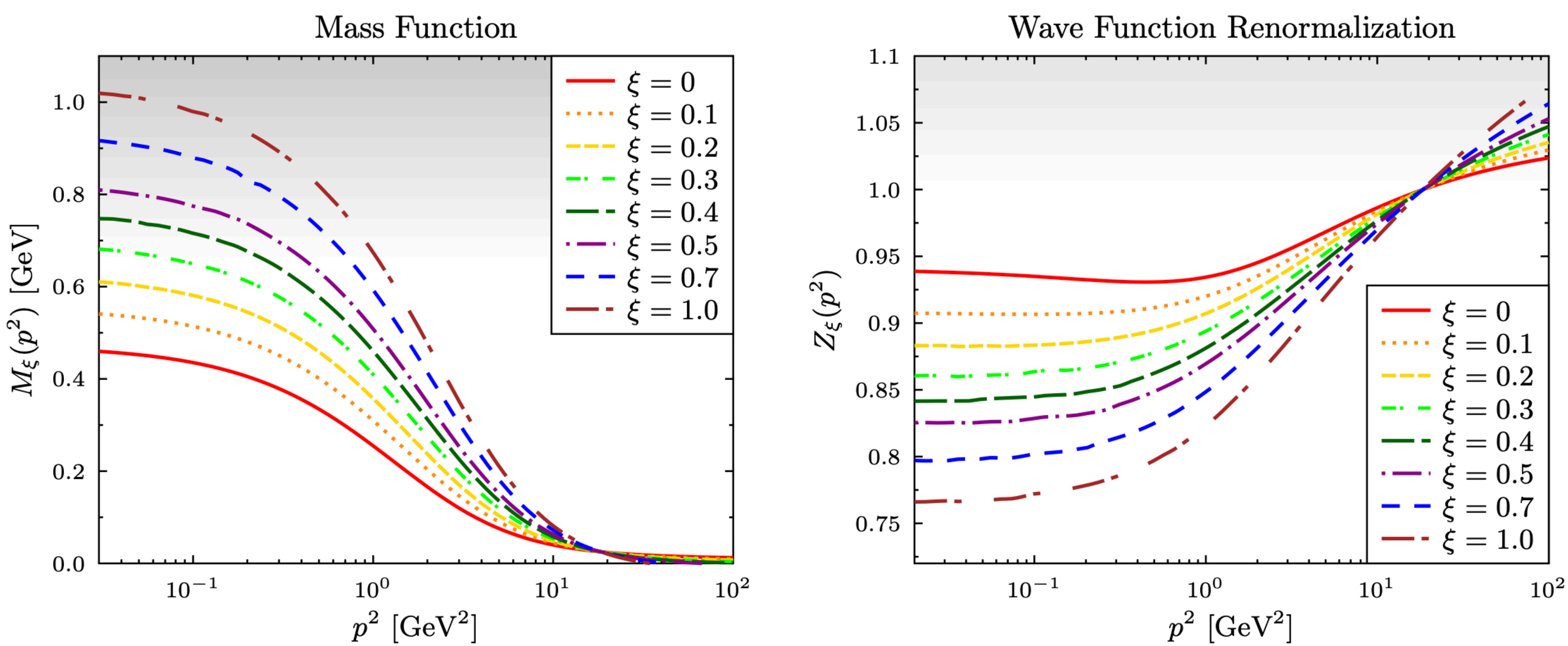



# Quark-gluon transverse vertex



# DSE with gluon propagators in $R_\xi$ gauge

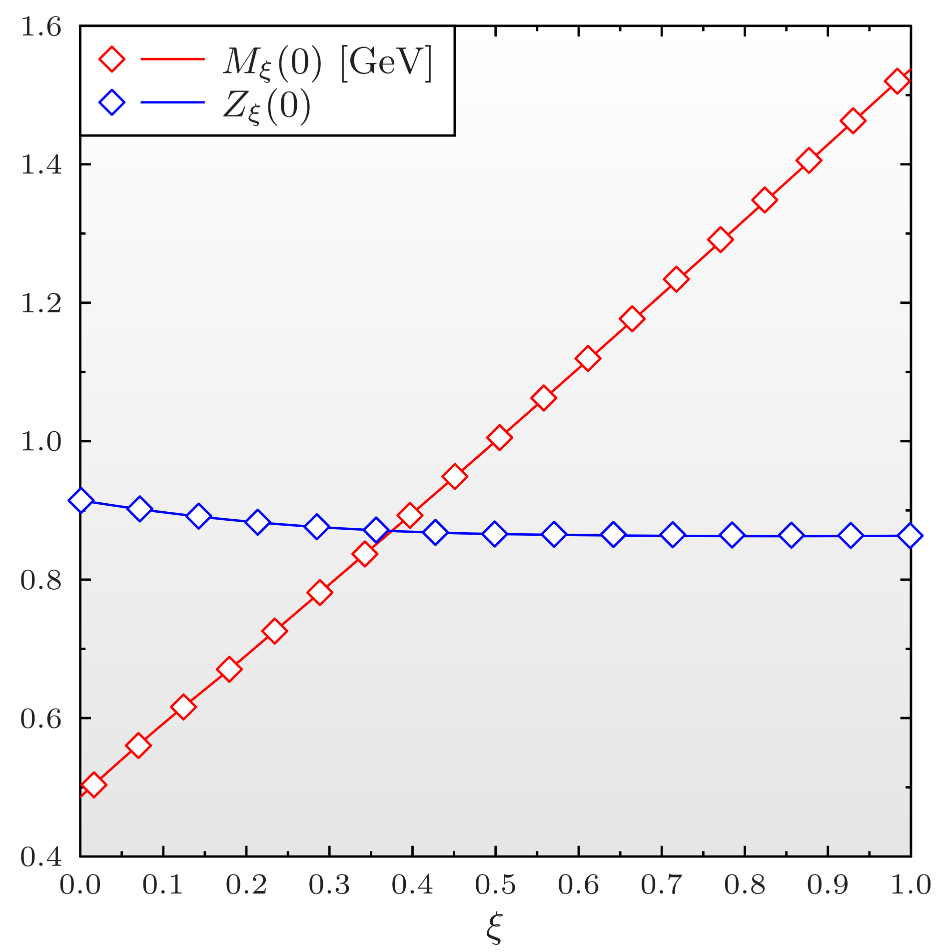
Lattice QCD input for gluon: P. Bicudo, D. Binosi, N. Cardoso, O. Oliveira and P. J. Silva, Phys. Rev. D 92, 114514 (2015)

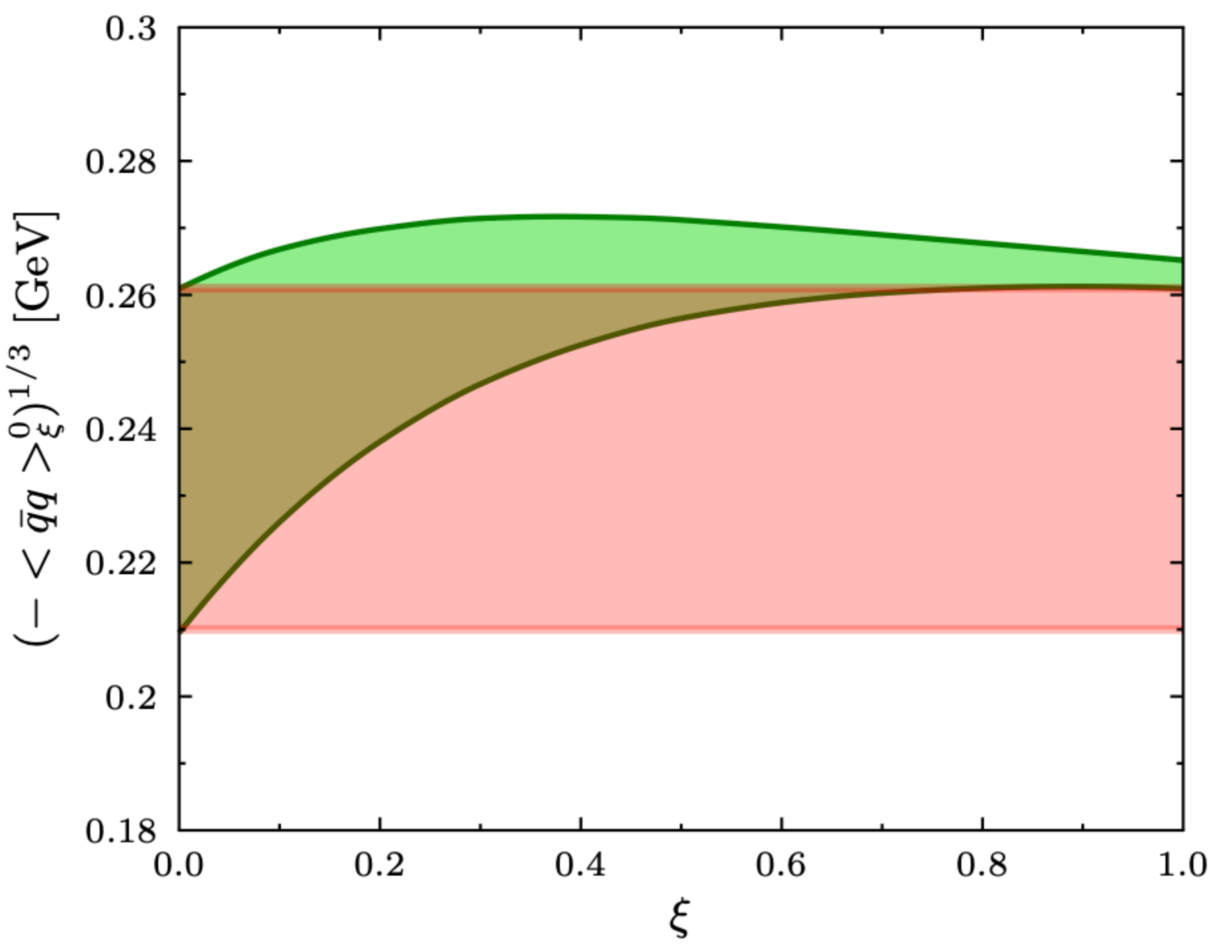



$$\alpha_s^\xi = 0.29 + 0.098\xi - 0.064\xi^2$$

A. C. Aguilar, D. Binosi and J. Papavassiliou, Phys. Rev. D95, 034017 (2017)

# DSE with gluon propagators in $R_\xi$ gauge: constituent mass and quark condensate




Lattice QCD input for gluon: P. Bicudo, D. Binosi, N. Cardoso, O. Oliveira and P. J. Silva, Phys. Rev. D 92, 114514 (2015)

# Quark Propagator in Light Cone Gauge

Wilson lines in definitions of Parton Distributions Functions

$$q(x) = \int \frac{d\lambda}{4\pi} e^{-ixP\cdot n\lambda} \left\langle P \left| \bar{\psi}_q(\lambda n) \not{n} W(\lambda, n\cdot A) \psi_q(0) \right| P \right\rangle$$

In light-cone gauge: $n \cdot A = 0 \quad \Longrightarrow \quad W(0, n\lambda) = \mathcal{P} e^{-ig \int_\lambda^0 n\cdot A(n\xi)\, d\xi} \equiv 1$

# Quark Propagator in Light Cone Gauge

$$S^{-1}(p) = Z_2(i\gamma \cdot p + m^{\rm bm}) + \Sigma(p)$$
$$\Sigma(p) = Z_1 \int^\Lambda \frac{d^4q}{(2\pi)^4}\, g^2 D_{\mu\nu}(p-q)\frac{\lambda^a}{2}\gamma_\mu S(q)\Gamma^a_\nu(q,p)$$

The general form of the quark propagator in light-cone gauge:

$$S_f^{-1}(p) = iA(p^2)\not{p} + B(p^2) + iC(p^2)\not{n}$$

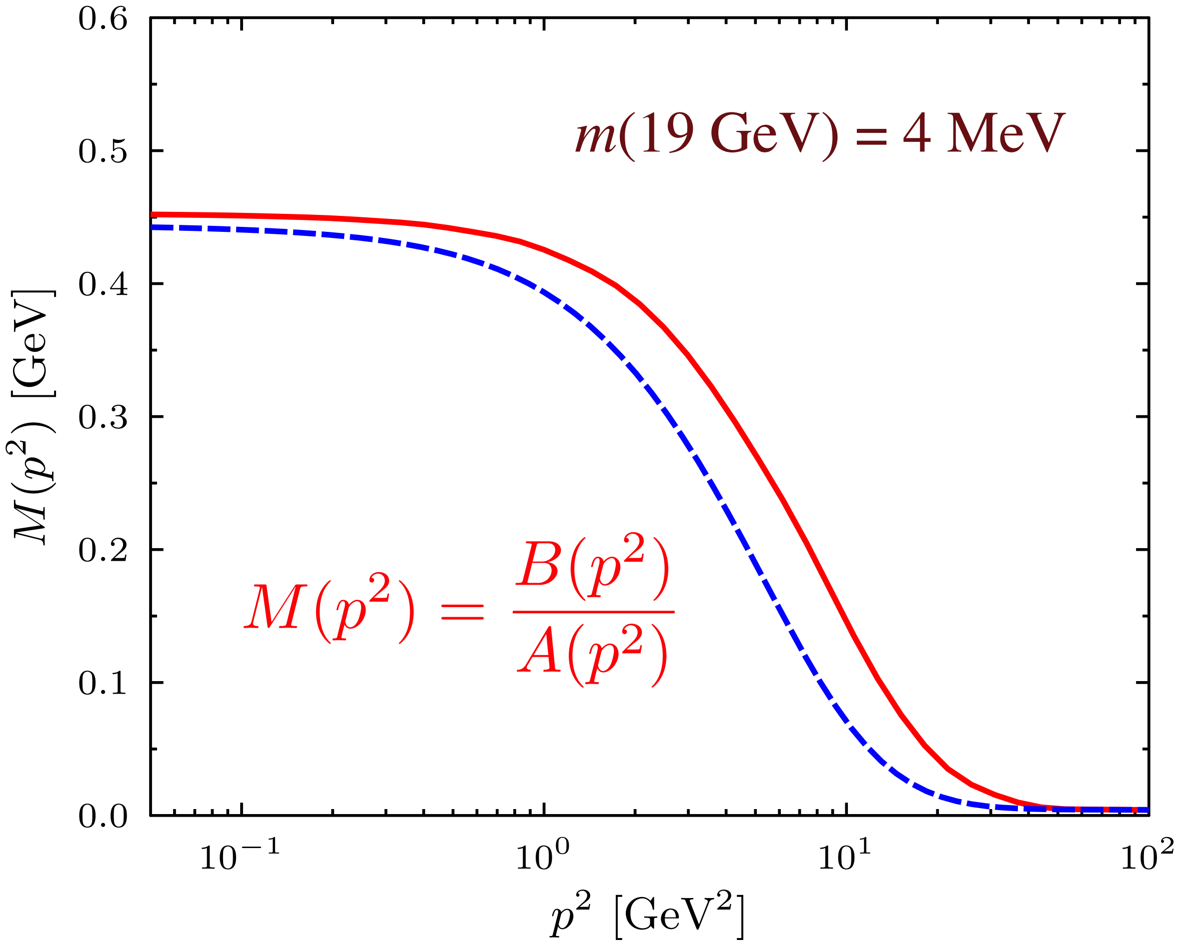
$n$ is a light-like vector with $n^2 = 0$ and introduces a preferred direction, in particular in the momentum integral of the gap equation.

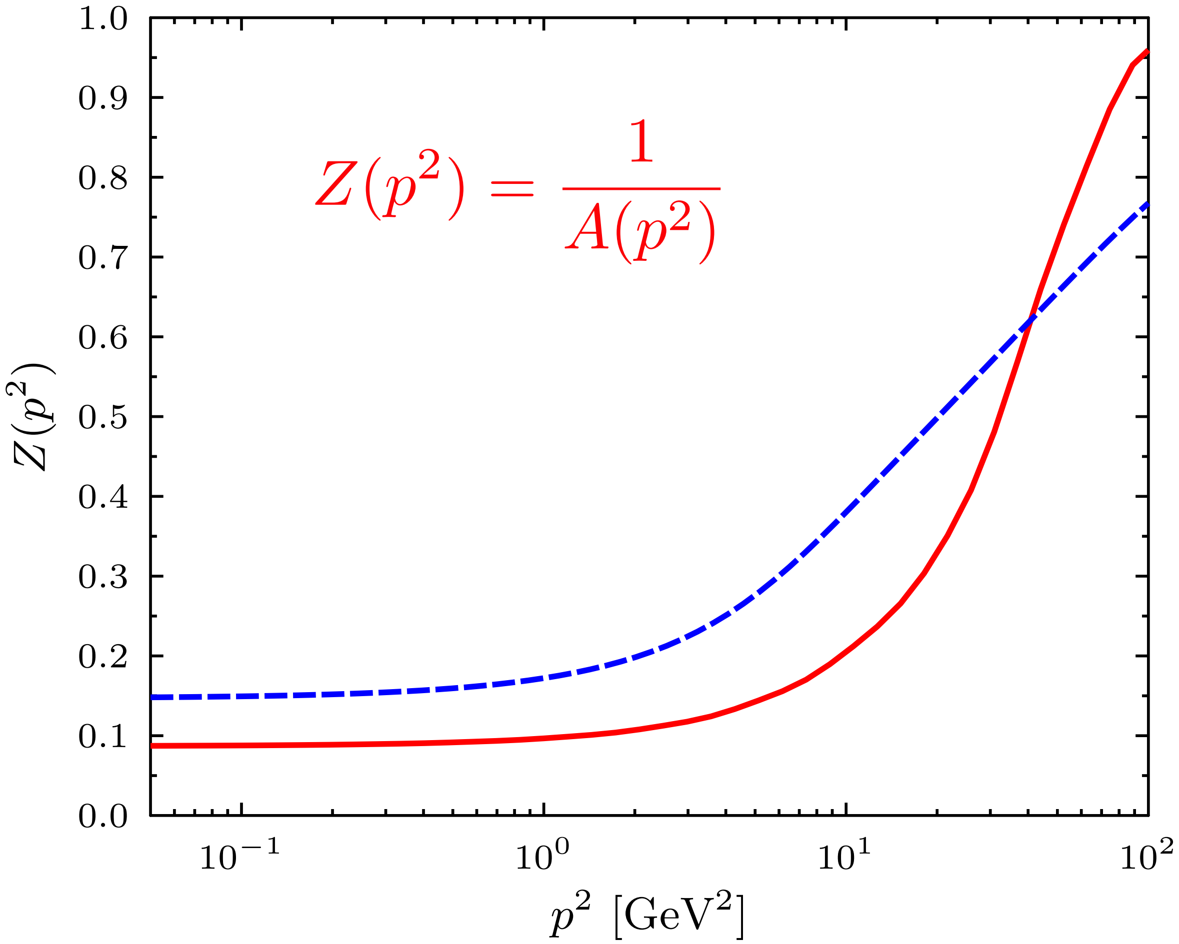
In light-cone gauge the gluon propagator is:

$$D_{\mu\nu}(q) = \frac{\Delta(q^2)}{q^2}\left[\delta_{\mu\nu} - \frac{q_\mu n_\nu + n_\mu q_\nu}{n \cdot q}\right] \quad \Leftarrow \quad n_\mu D_{\mu\nu}(q) = 0$$

# Quark Propagator in Light Cone Gauge

$$S_f^{-1}(p) = iA(p^2)\not{p} + B(p^2) + iC(p^2)\not{n}$$




Angular dependence between $n_\mu$ and $p_\mu$ of $M(p^2)$and $Z(p^2)$ represents the *gauge dependence* of quark propagator.

$$S_f^{-1}(p) = iA(p^2)\not{p} + B(p^2) + iC(p^2)\not{n} \quad \Rightarrow \quad C(p^2) \text{ is complex valued}$$

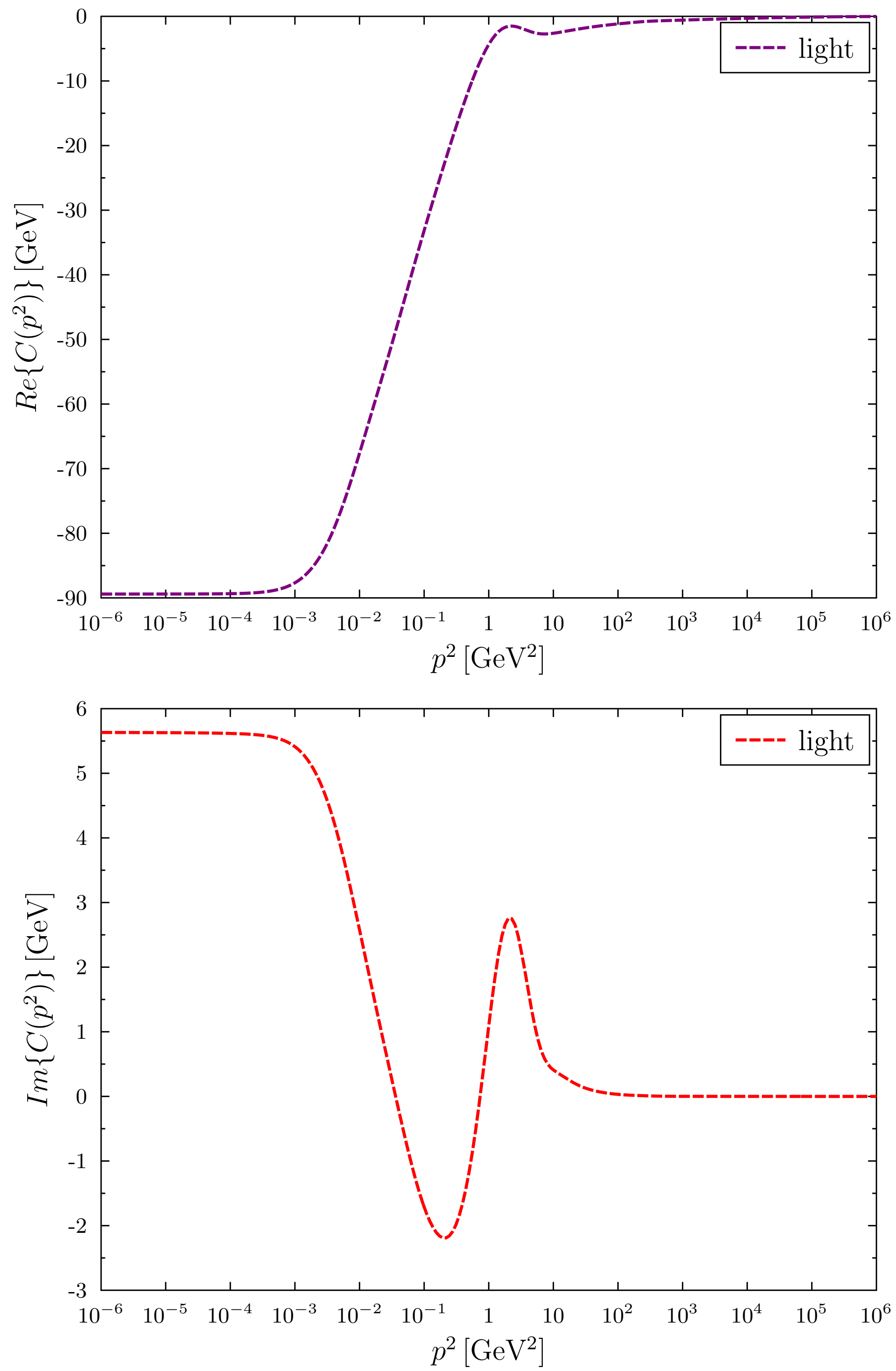



Figure. On the top real part and in the bottom imaginary part of C($p^2$) with $p = |p|(0,0,0,1)$.

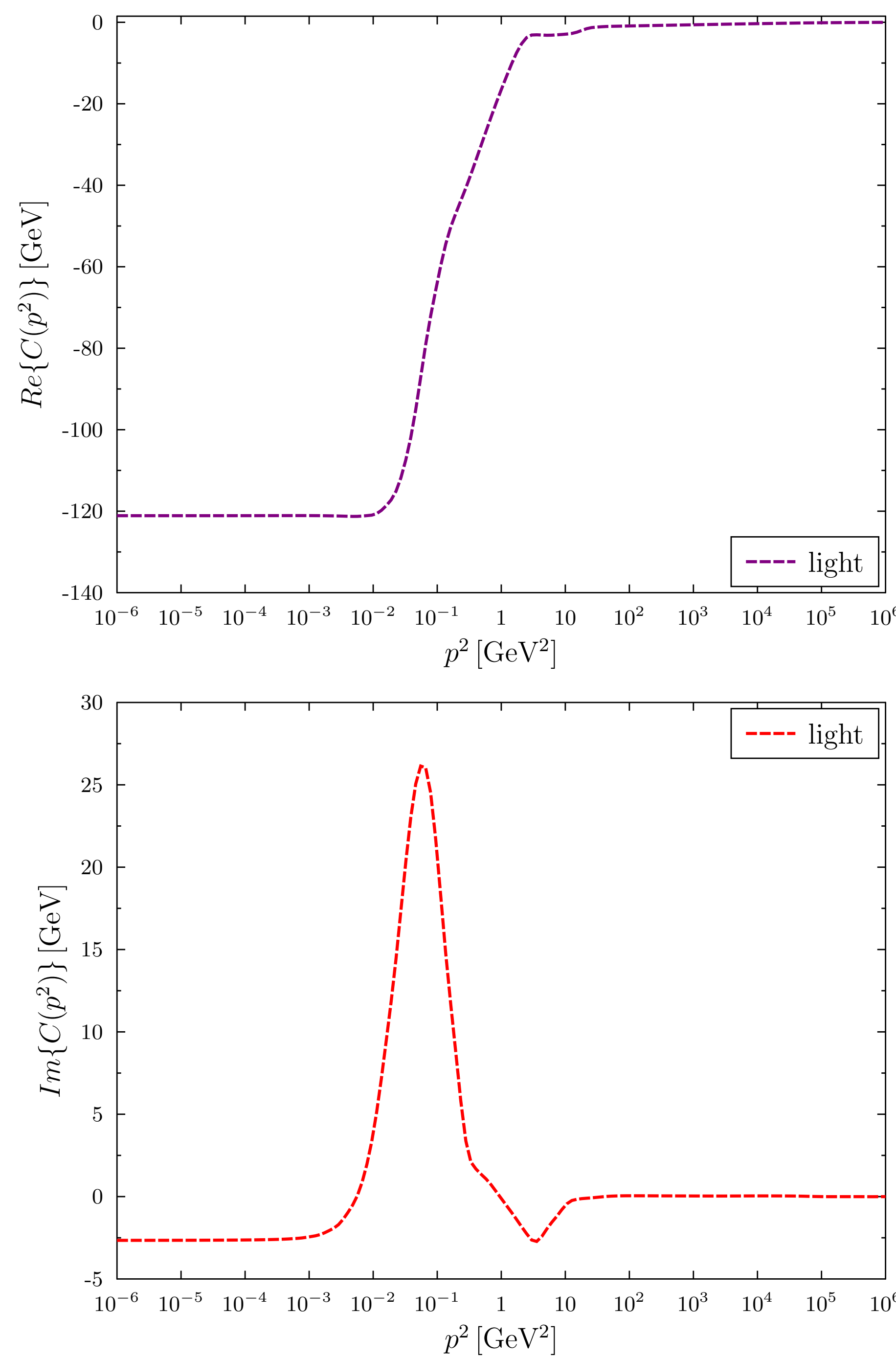



Figure. On the top real part and in the bottom imaginary part of C($p^2$) with $p = |p|(0, 0, y_p\sqrt{1-z_p^2}, z_p)$.

# Conclusions & Progress

- We derived a quark-gluon vertex from symmetries (gauge + Lorentz), that is we don't solve the inhomogeneous BSE for the quark-gluon vertex.

- The self-consistent solutions employ as ingredients gluon and ghost propagators from lattice QCD.

- The transverse vertex is necessary to ensure multiplicative renormalizability and contributes significantly to DCSB and therefore to a *constituent quark mass scale*.

- Underway: deriving the Bethe-Salpeter kernel consistent with this quark-gluon vertex (STIs) that *also satisfies the axialvector Ward identity and thus guarantees a zero pion mass in the chiral limit and the correct DCSB pattern for the meson spectrum.*

- First steps of calculating nonperturbative quark propagators in light-cone gauge.