

EMERGENCE OF MASS IN THE GAUGE SECTOR OF QCD

Joannis Papavassiliou

Department of Theoretical Physics and IFIC
University of Valencia-CSIC

M.N. FERREIRA AND J.P., PROG. PART. NUCL. PHYS. 144, 104186 (2025)



DYNAMICAL GENERATION OF A GLUON MASS

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \underbrace{\frac{1}{2\xi}(\partial^\mu A_\mu^a)^2}_{\text{GAUGE-FIXING}} - \underbrace{\bar{c}^a \partial^\mu D_\mu^{ab} c^b}_{\text{GHOSTS}} + \mathcal{L}_{\text{quarks}}$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + gf^{abc} A_\mu^b A_\nu^c$$

$$D_\mu^{ab} = \partial_\mu \delta^{ac} + gf^{amb} A_\mu^m$$

- GAUGE SYMMETRY FIRST, AND, AFTER THE GAUGE-FIXING, BRST SYMMERTY PROHIBIT A MASS TERM $m^2 A_\mu^a A^{a\mu}$ FOR THE GLUON

- PROPERLY REGULARIZED PERTURBATION THEORY CANNOT GENERATE A GLUON MASS AT ANY FINITE ORDER $\int \frac{d^d k}{k^2} = 0$

HOWEVER: GLUON SELF-INTERACTIONS GENERATE A NON-PERTURBATIVE MASS
THROUGH THE ACTION OF THE SCHWINGER MECHANISM J.M.CORNWALL, PHYS.REV. D26, 1453 (1982)

THIS MASS SCALE AFFECTS BOTH CORRELATION FUNCTIONS AND PHYSICAL OBSERVABLES



SCHWINGER MECHANISM

A VECTOR MESON MAY ACQUIRE A MASS, EVEN IF THE GAUGE SYMMETRY FORBIDS A MASS TERM AT THE LEVEL OF THE FUNDAMENTAL LAGRANGIAN, PROVIDED THAT ITS VACUUM POLARIZATION FUNCTION DEVELOPS A POLE AT ZERO MOMENTUM TRANSFER

J. S. SCHWINGER, PHYS. REV.125, 397 (1962); PHYS.REV.128, 2425 (1962)

SCHWINGER-DYSON EQUATION FOR
GAUGE BOSON PROPAGATOR

$$(\text{wavy line with circle})^{-1} = (\text{wavy line})^{-1} + \underbrace{\text{loop diagram}}_{q^2 \Pi(q^2)}$$



$$\Delta^{-1}(q^2) = q^2 [1 + \Pi(q^2)]$$

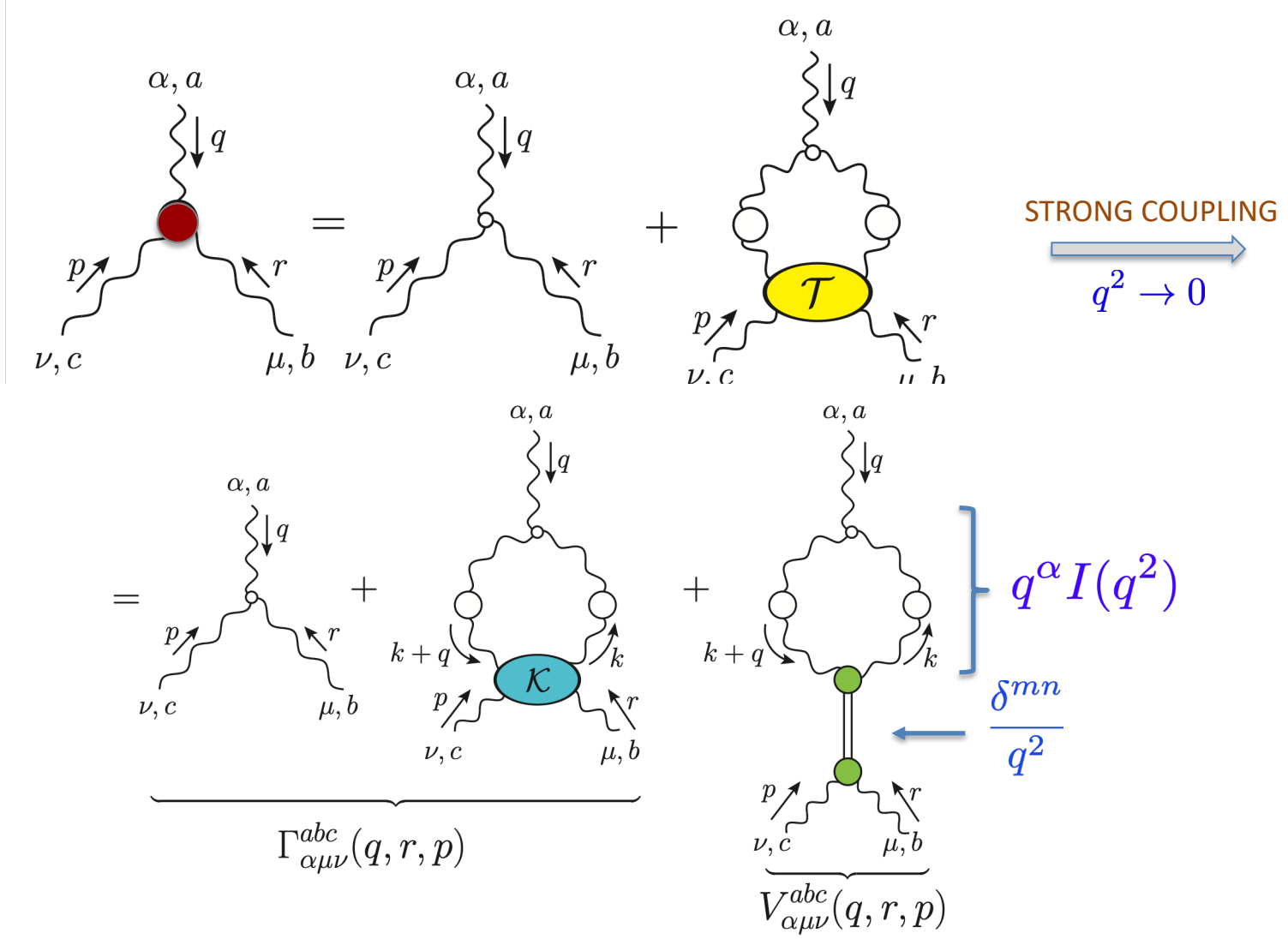
IF, FOR SOME REASON

$$\lim_{q^2 \rightarrow 0} \Pi(q^2) = \frac{c}{q^2}, \quad c > 0$$



$$\Delta^{-1}(0) = c > 0$$

THE MASSLESS POLES ARE PRODUCED BY THE **GLUONIC** INTERACTIONS



- DYNAMICAL FORMATION OF MASSLESS COLORED EXCITATIONS
- MASSLESS POLES ARE LONGITUDINALLY COUPLED: THEY DROP OUT FROM ON-SHELL AMPLITUDES AND LATTICE OBSERVABLES
- ACT AS COMPOSITE WOULD-BE GOLDSTONE BOSONS

GENERAL STRUCTURE OF THE THREE-GLUON VERTEX

$$\Pi_{\alpha\mu\nu}^{abc}(q, r, p) = \underbrace{\Gamma_{\alpha\mu\nu}^{abc}(q, r, p)}_{\text{POLE-FREE}} + \underbrace{V_{\alpha\mu\nu}^{abc}(q, r, p)}_{\text{POLE}}$$

$$V_{\alpha\mu\nu}^{abc}(q, r, p) = f^{abc} \frac{q_\alpha}{q^2} \left[g_{\mu\nu} C_1(q, r, p) + \cdots \right]$$

BOSE SYMMETRY IMPOSES

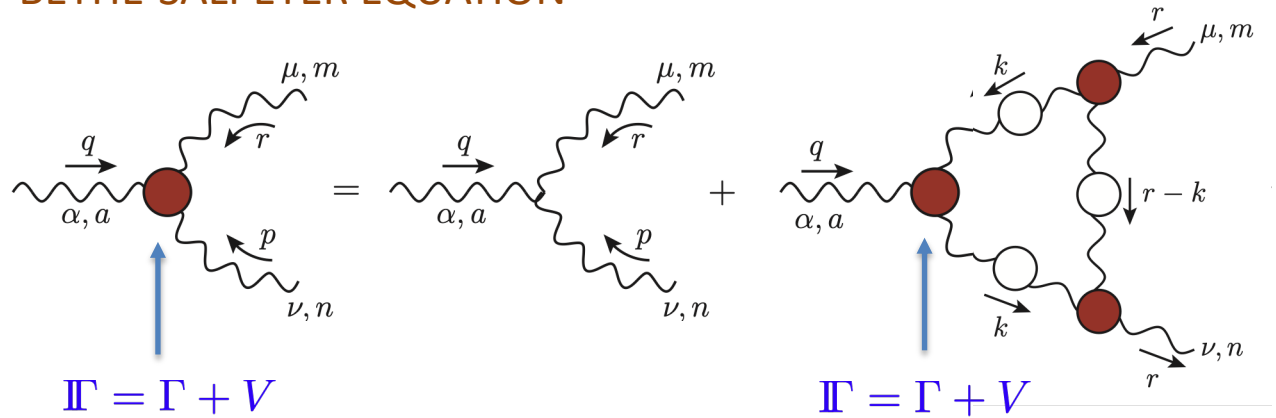
$$C_1(q, r, p) = -C_1(q, p, r) \quad \Longrightarrow \quad C_1(0, r, -r) = 0$$

$$\Longrightarrow \quad \lim_{q \rightarrow 0} C_1(q, r, p) = 2(q \cdot r) \underbrace{\left[\frac{\partial C_1(q, r, p)}{\partial p^2} \right]_{q=0}}_{\mathbb{C}(r^2)} + \mathcal{O}(q^2)$$

RESIDUE FUNCTION

BETHE-SALPETER EQUATION

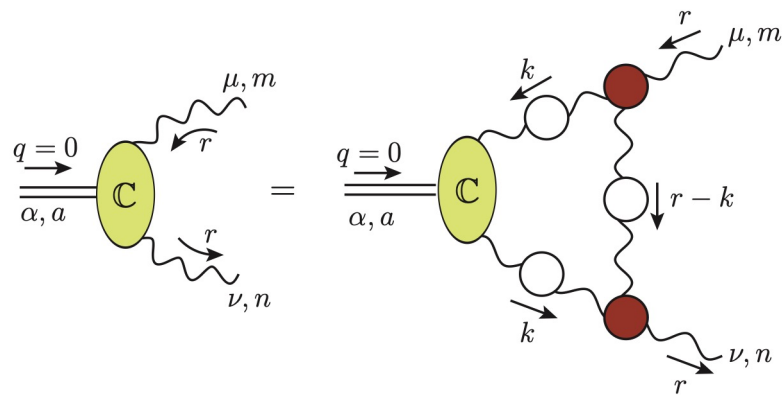
START WITH VERTEX SDE:



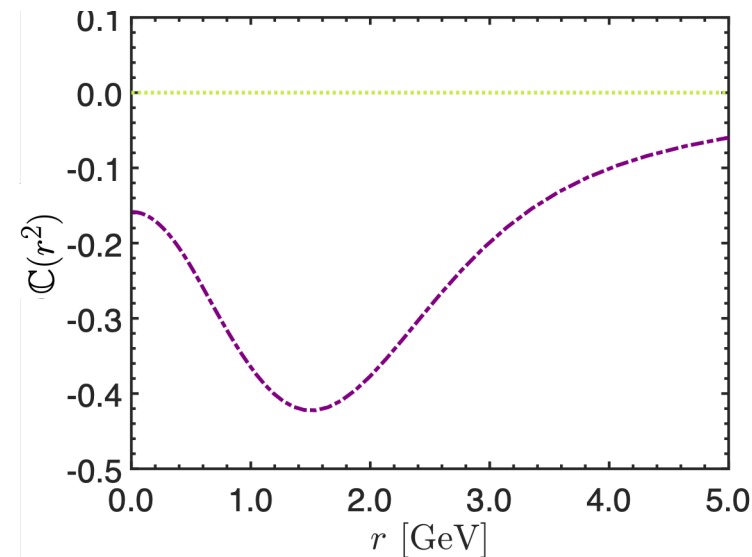
SUBSTITUTE:

TAKE THE LIMIT $q \rightarrow 0$ AND USE $\lim_{q \rightarrow 0} V(q, r, p) = 2(q \cdot r)\mathbb{C}(r^2)$

↓ BSE



→ NON-TRIVIAL SOLUTION



→ $\mathbb{C}(r^2)$ ACTS AS BETHE-SALPETER AMPLITUDE

EMERGENCE OF A GLUON MASS

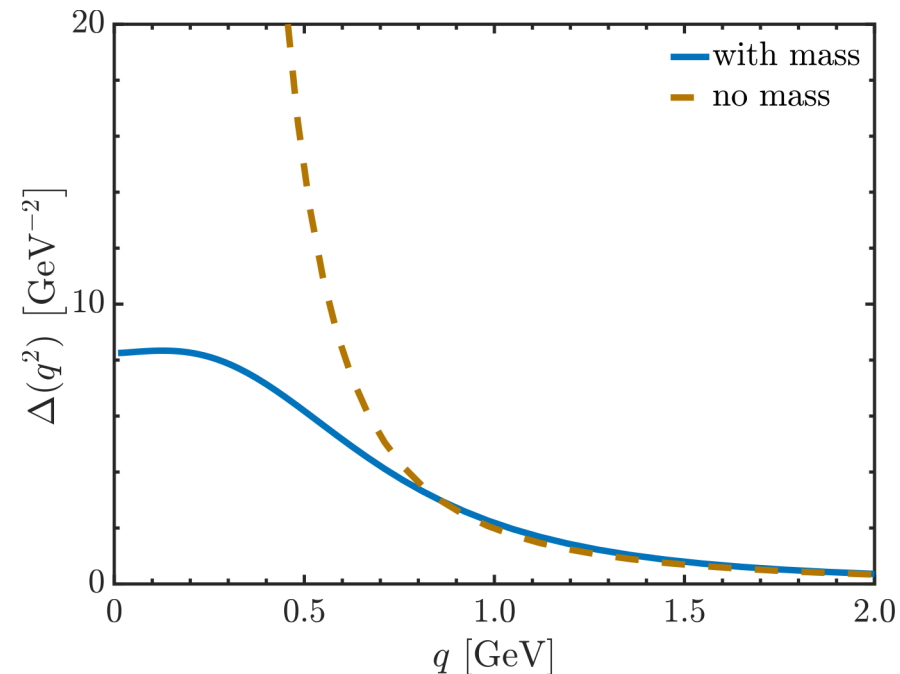
$$\Delta^{-1}(0) = \lim_{q \rightarrow 0} \text{diagram} = \lim_{q \rightarrow 0} \text{diagram} = -\frac{3C_A \alpha_s}{8\pi} \int_0^\infty dy y^2 \Delta^2(y) \mathbb{C}(y) = m^2$$

The first diagram shows a wavy line with momentum q entering a loop with two white vertices and a red vertex. The second diagram shows the same loop with two green vertices connected by a double line labeled $1/q^2$.

SIMPLE PHYSICALLY-MOTIVATED MODEL
OF THE GLUON PROPAGATOR

$$\Delta^{-1}(q^2) \sim q^2 \left[a \ln \left(\frac{q^2 + m^2}{\Lambda^2} \right) + b \ln \left(\frac{q^2}{\Lambda^2} \right) \right] + m^2$$

THE EXACT SOLUTION REQUIRES
A FULLY COUPLED ANALYSIS, TAKING
ALL VERTICES INTO ACCOUNT



A DECISIVE FEATURE: WARD IDENTITY DISPLACEMENT

A.C.AGUILAR, D. BINOSI, C.T. FIGUEIREDO, AND JP, PHYS.REV.D 94 (2016) 045002

THE LONGITUDINAL NATURE OF THE POLES MAKES THEIR DIRECT DETECTION IMPOSSIBLE

$$V_{\alpha\mu\nu}^{abc}(q, r, p) = f^{abc} \frac{q_\alpha}{q^2} \left[g_{\mu\nu} C_1(q, r, p) + \cdots \right]$$

PHYSICAL QUANTITIES AND (LANDAU-GAUGE) LATTICE OBSERVABLES ARE ALWAYS FINITE:
THE SCHWINGER POLES DO NOT INTRODUCE ANY DIVERGENCES

HOWEVER

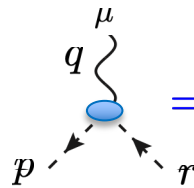
THERE IS A CHARACTERISTIC FEATURE, UNIQUE TO THIS MECHANISM,
WHICH ALLOWS THE UNEQUIVOCAL CONFIRMATION OF THIS SCENARIO

THE WARD IDENTITIES UNDERGO A FINITE DISPLACEMENT WITH RESPECT
TO THE RESULT FOUND IN THE ABSENCE OF THE SCHWINGER MECHANISM

QUITE REMARKABLY, THE QUANTITY THAT DETERMINES THIS EFFECT IS NONE OTHER THAN

$$\mathbb{C}(r^2)$$

SCHWINGER MECHANISM OFF



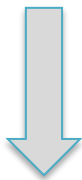
$$= \Gamma_\mu(q, r, p)$$

TAKAHASHI IDENTITY

$$q^\mu \Gamma_\mu(q, r, p) = D^{-1}(p^2) - D^{-1}(r^2)$$

$q \rightarrow 0$
 $p \rightarrow -r$

TAYLOR EXPANSION



WARD IDENTITY

$$\Gamma_\mu(0, r, -r) = \frac{\partial D^{-1}(r^2)}{\partial r^\mu}$$

TENSORIAL DECOMPOSITION

$$\Gamma_\mu(0, r, -r) = L_{sg}^*(r^2) r_\mu$$



$$L_{sg}^*(r^2) = 2 \frac{\partial D^{-1}(r^2)}{\partial r^2}$$

SCHWINGER MECHANISM ON

$$\mathbb{I}_\mu(q, r, p) = \underbrace{\Gamma_\mu(q, r, p)}_{\text{POLE-FREE}} + \frac{q_\mu}{q^2} C(q, r, p)$$

THE TAKAHASHI IDENTITY DOES NOT CHANGE

$$q^\mu \mathbb{I}_\mu(q, r, p) = q^\mu \Gamma_\mu(q, r, p) + C(q, r, p) = D^{-1}(p^2) - D^{-1}(r^2)$$

$q \rightarrow 0$

TAYLOR EXPANSION



WARD IDENTITY

$$\Gamma_\mu(0, r, -r) = \frac{\partial D^{-1}(r^2)}{\partial r^\mu} - 2r_\mu \underbrace{\left[\frac{\partial C(q, r, p)}{\partial p^2} \right]_{q=0}}_{\mathbb{C}(r^2)}$$

TENSORIAL DECOMPOSITION

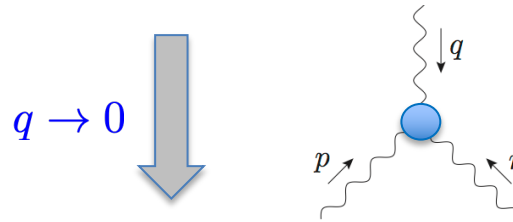
$$\Gamma_\mu(0, r, -r) = L_{sg}(r^2) r_\mu$$



$$L_{sg}(r^2) = L_{sg}^*(r^2) - \underbrace{2 \mathbb{C}(r^2)}_{\text{DISPLACEMENT}}$$

The real thing: three-gluon vertex

Non-Abelian Slavnov-Taylor identity: same idea, but more structure

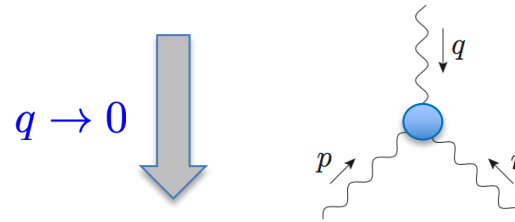


Ward identity

$$\underbrace{\mathbb{C}(r^2)}_{\text{"displacement"}} = L_{sg}(r^2) - F(0) \left\{ \frac{\mathcal{W}(r^2)}{r^2} \Delta^{-1}(r^2) + \frac{d\Delta^{-1}(r^2)}{dr^2} \right\}$$

The real thing: three-gluon vertex

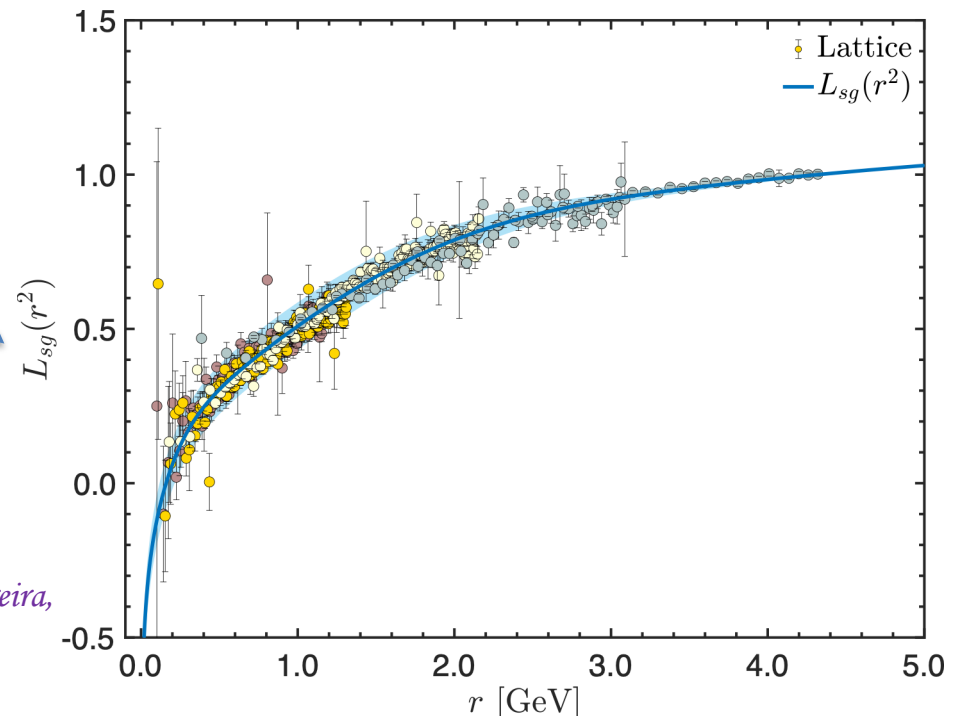
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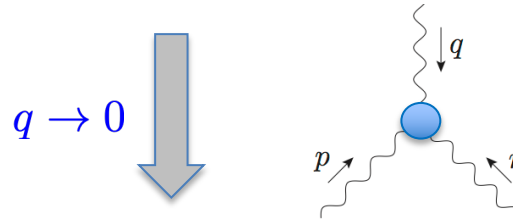
Form factor of the
three-gluon vertex



A.C. Aguilar, F. De Soto, M.N.Ferreira,
J.P. , J.Rodríguez-Quintero,
Phys. Lett. B818 (2021) 136352

The real thing: three-gluon vertex

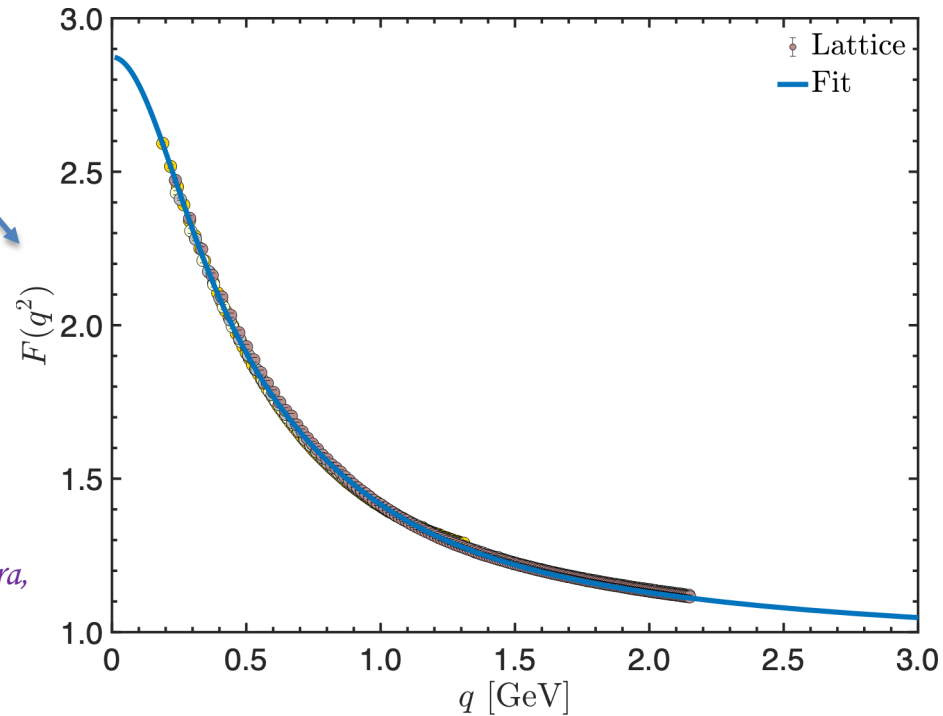
Non-Abelian Slavnov-Taylor identity: same idea, but more structure



Ward identity

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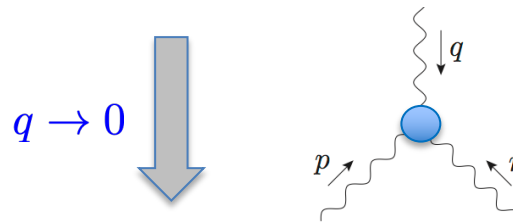
Ghost dressing
function



*A.C. Aguilar, C.O. Ambrosio, F. De Soto, M.N. Ferreira,
B.M. Oliveira, J.P. and J. Rodriguez-Quintero,
Phys. Rev. D 104 no.5, 054028, (2021)*

The real thing: three-gluon vertex

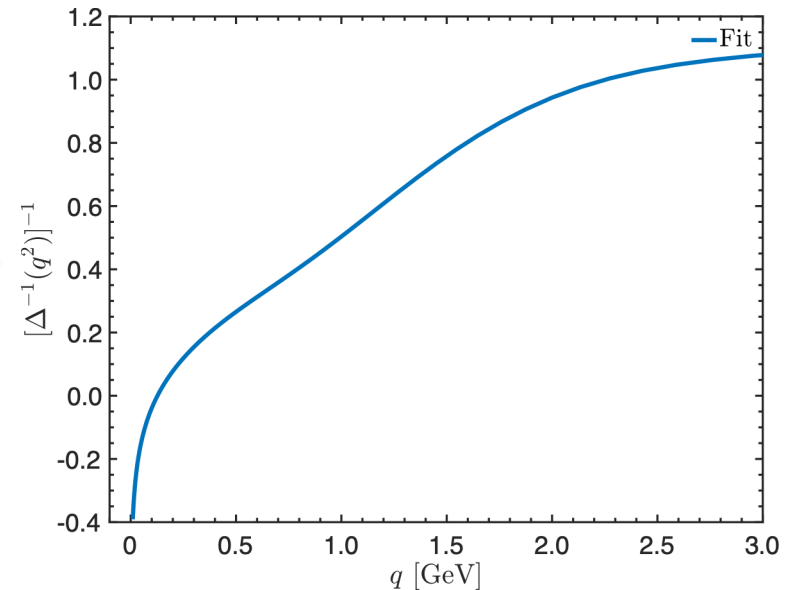
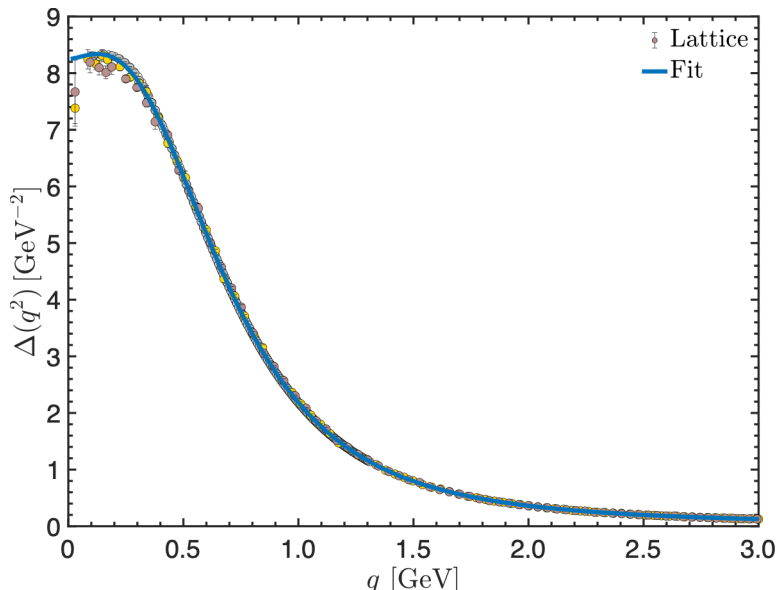
Non-Abelian Slavnov-Taylor identity: same idea, but more structure



Ward identity

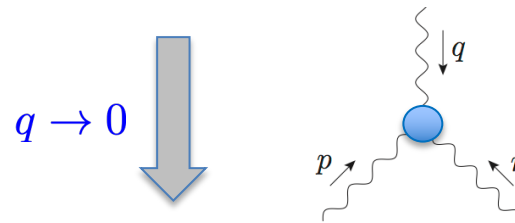
$$\underbrace{\mathbb{C}(r^2)}_{\text{"displacement"}} = L_{sg}(r^2) - F(0) \left\{ \frac{\mathcal{W}(r^2)}{r^2} \Delta^{-1}(r^2) + \frac{d\Delta^{-1}(r^2)}{dr^2} \right\}$$

inverse gluon propagator



The real thing: three-gluon vertex

Non-Abelian Slavnov-Taylor identity: same idea, but more structure

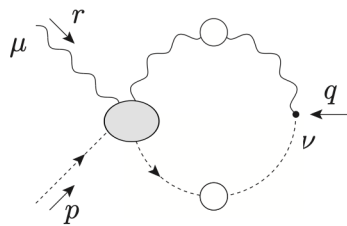


$q \rightarrow 0$

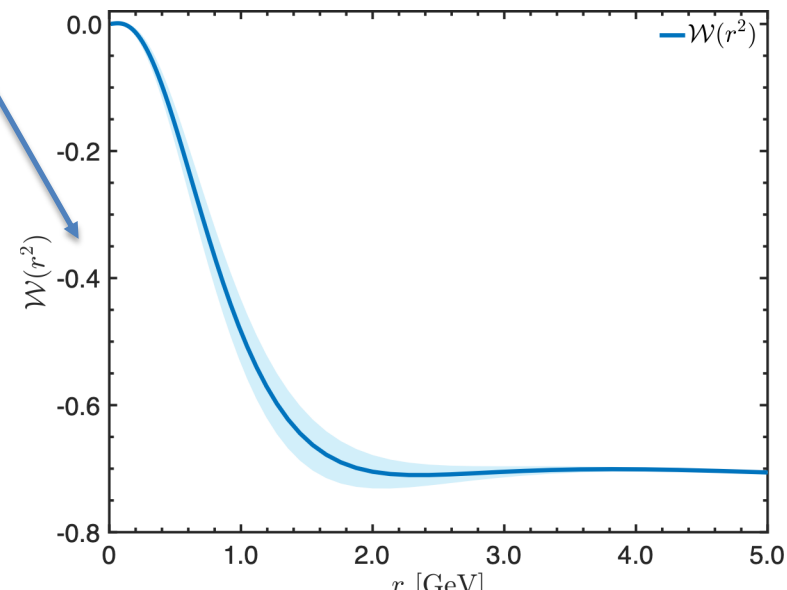
Ward identity

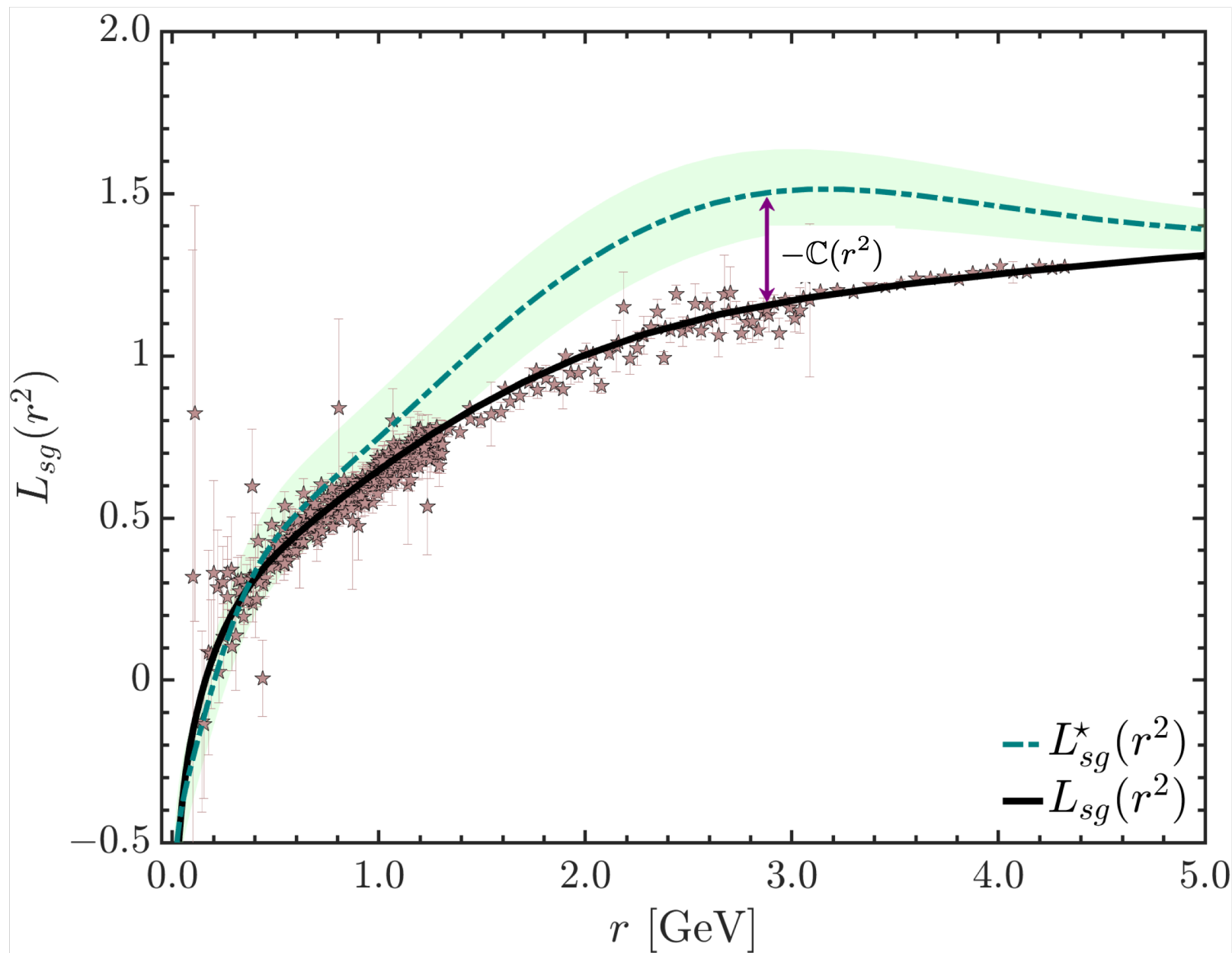
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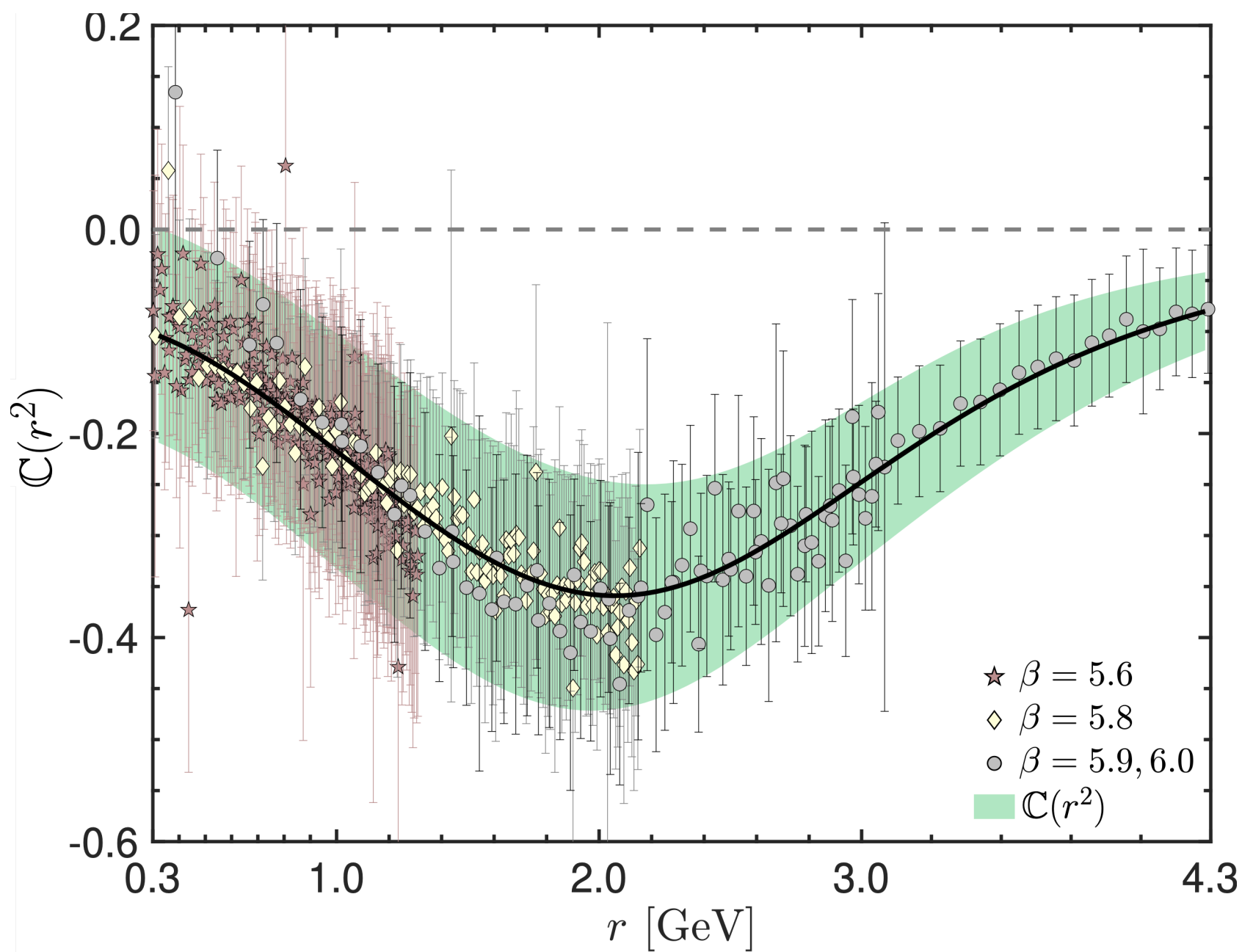
partial derivative of the
ghost-gluon kernel



Computed from a
Schwinger-Dyson eq.







35 σ AWAY FROM THE NULL HYPOTHESIS!

CONCLUSIONS

THE ACTION OF THE SCHWINGER MECHANISM GENERATES
A DYNAMICAL MASS SCALE IN THE GAUGE SECTOR OF QCD

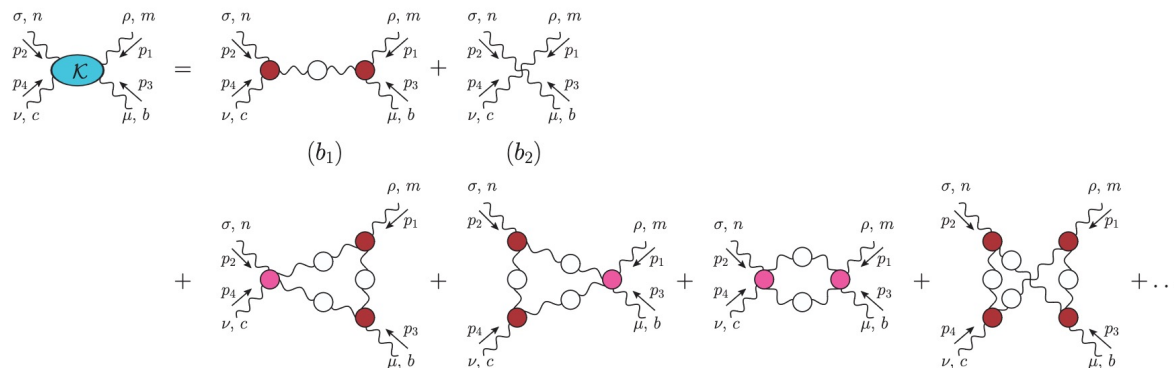
DYNAMICS AND SYMMETRY ARE TIGHTLY INTERTWINED

POLE RESIDUE = BS AMPLITUDE FOR POLE FORMATION = DISPLACEMENT FUNCTION

THE EMERGENCE OF THE GLUON MASS TAMES THE LANDAU POLE
AND STABILIZES THE DYNAMICAL EQUATIONS

IN FUNCTIONAL APPROACHES, THIS MASS REACHES THE OBSERVABLES (LIGHTEST GLUBALL MASS)

M.Q.HUBER, C.S.FISCHER AND H.SANCHIS-ALEPUZ, EUR. PHYS. J. C 80, NO.11, 1077 (2020)



THE EMERGENCE OF THE GLUON MASS PROVIDES THE EXACT FIELD-THEORETIC STABILITY REQUIRED TO DEVELOP **NEW, QCD-ROOTED, SYMMETRY-PRESERVING TRUNCATION SCHEMES**

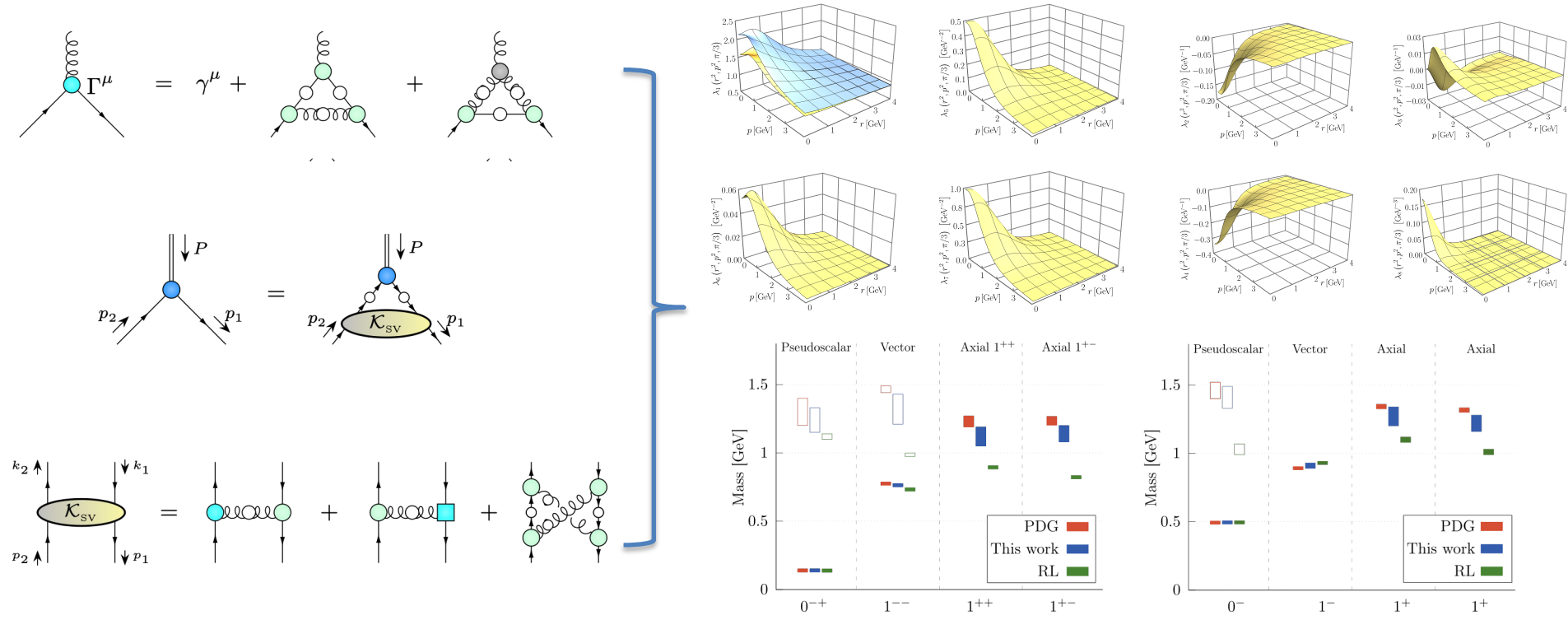
A.S. Miramontes, J.M. Morgado, J.P., and J.M.Pawlowski,
 ``A comprehensive approach to the physics of mesons,``
 Eur. Phys. J. C 85, no.9, 1055 (2025)

M.N. Ferreira, A.S. Miramontes, J.M. Morgado, J.P., and J.M. Pawlowski,
 ``Pion physics with dressed quark-gluon vertices,``
 Eur. Phys. J. C 86, no.4, 325 (2026)

M.N. Ferreira, A.S. Miramontes, J.M. Morgado and J.P.,
 ``Light mesons in the symmetric-vertex approximation,``
 Eur. Phys. J. C 86, no.7, 858 (2026)



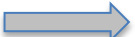
SYMMETRIC-VERTEX APPROXIMATION



PROFOUND RELATION BETWEEN GLUON MASS AND CONFINEMENT

THE GLUON MASS **STABILIZES** CLASSICAL GAUGE CONFIGURATIONS

STABLE MACROSCOPIC SOLUTIONS : **THICK CENTER VORTICES**

CONDENSATION OF CENTER VORTICES  **WILSON LOOP AREA LAW**



WHAT IS THE RELATION TO THE **KUGO-OJIMA** FORMALISM ?

IS THERE A **QUARTET-MECHANISM** INTERPRETATION OF THIS?

TALK BY G. COMITINI