EMERGENCE OF MASS IN THE GAUGE SECTOR OF QCD

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

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Excelencia Severo Ochoa

DYNAMICAL GENERATION OF A GLUON MASS

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \underbrace{\frac{1}{2\xi}(\partial^\mu A^a_\mu)^2}_{\text{GAUGE-FIXING}} - \underbrace{\overline{c}^a\partial^\mu D^{ab}_\mu c^b}_{\text{GHOSTS}} + \mathcal{L}_{\rm quarks}$$

$$\boxed{F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + gf^{abc}A^b_\mu A^c_\nu} \qquad D^{ab}_\mu = \partial_\mu \delta^{ac} + gf^{amb}A^m_\mu$$

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

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

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

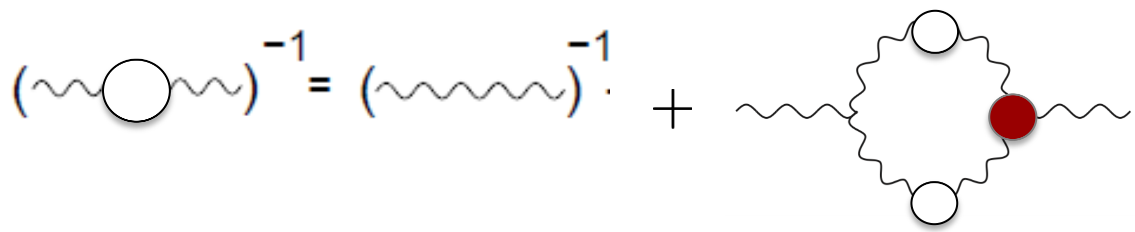
J.HORAK, F.IHSSEN, J.P., J.M.PAWLOWSKI, A.WEBER AND C.WETTERICH, SCIPOST PHYS. 13, NO.2, 042 (2022)

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



$q^2\Pi(q^2)$

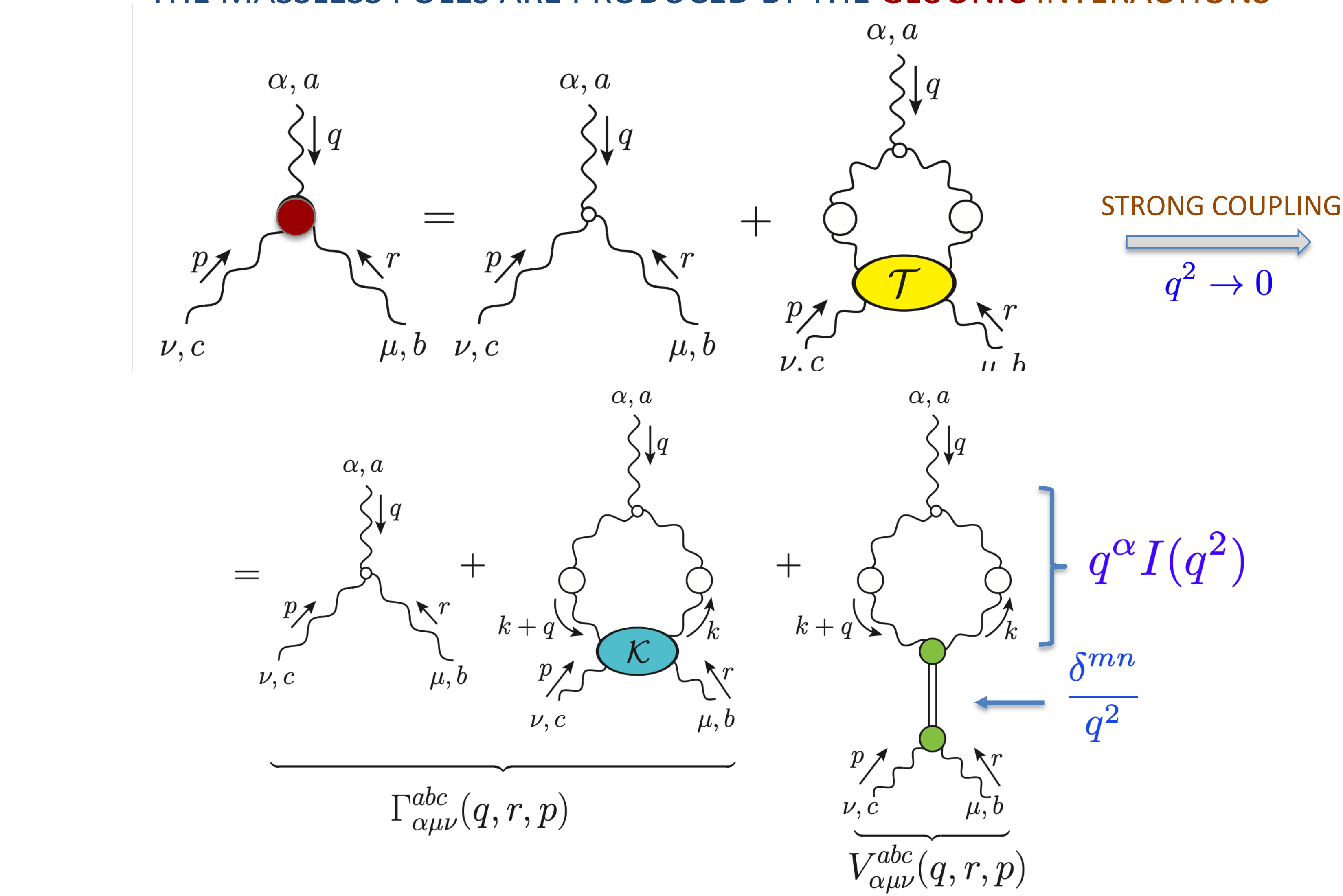
$$\Delta^{-1}(q^2) = q^2[1+\Pi(q^2)]$$

IF, FOR SOME REASON

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

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

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

G. COMITINI, arXiv:2603.22181

GENERAL STRUCTURE OF THE THREE-GLUON VERTEX

$$\mathrm{I\Gamma}^{abc}_{\alpha\mu\nu}(q,r,p) = \underbrace{\Gamma^{abc}_{\alpha\mu\nu}(q,r,p)}_{\text{POLE-FREE}} + \underbrace{V^{abc}_{\alpha\mu\nu}(q,r,p)}_{\text{POLE}}$$

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

BOSE SYMMETRY IMPOSES

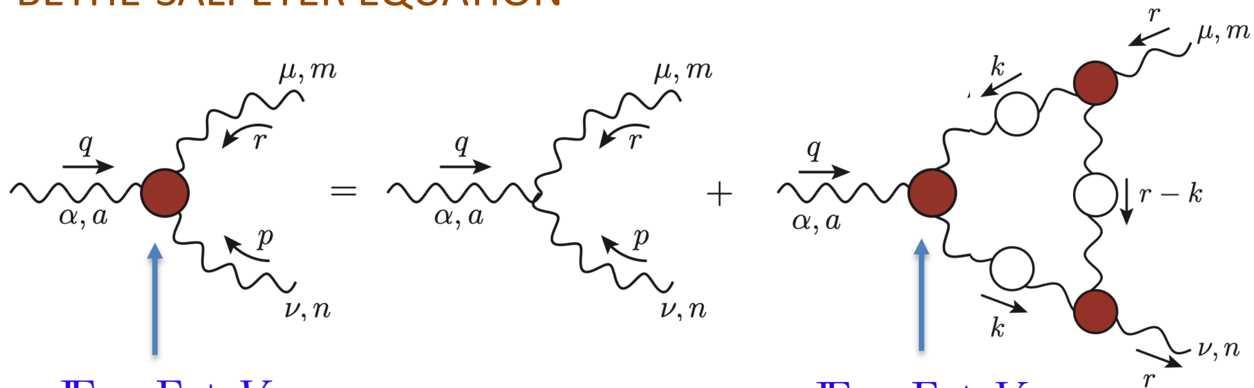
$$C_1(q,r,p) = -C_1(q,p,r) \Longrightarrow C_1(0,r,-r) = 0$$

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

RESIDUE FUNCTION

BETHE-SALPETER EQUATION

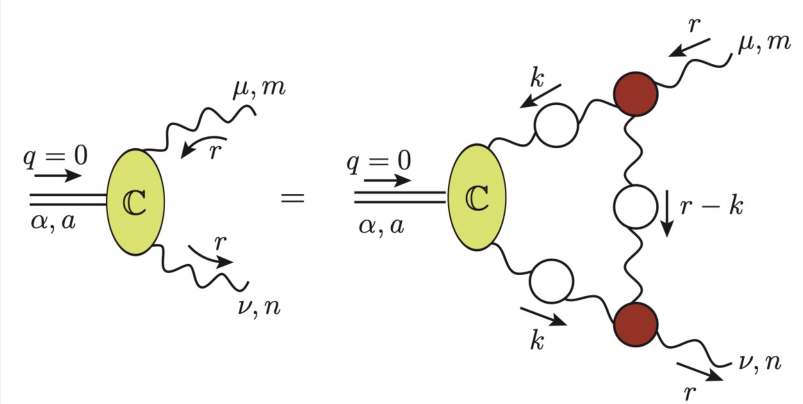
START WITH VERTEX SDE:



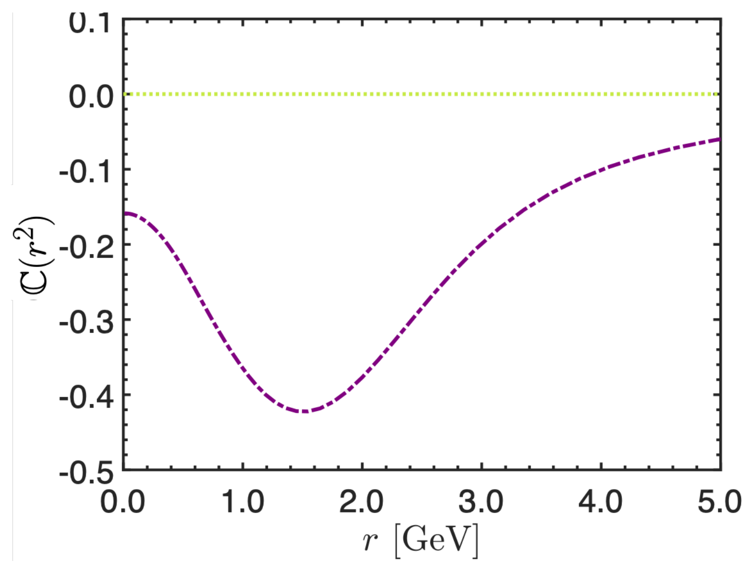
SUBSTITUTE: $\mathrm{I\!\Gamma} = \Gamma + V$ $\qquad$ $\mathrm{I\!\Gamma} = \Gamma + V$

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

BSE



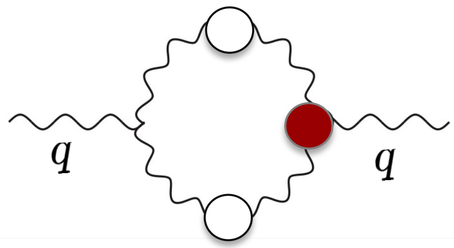
NON-TRIVIAL SOLUTION



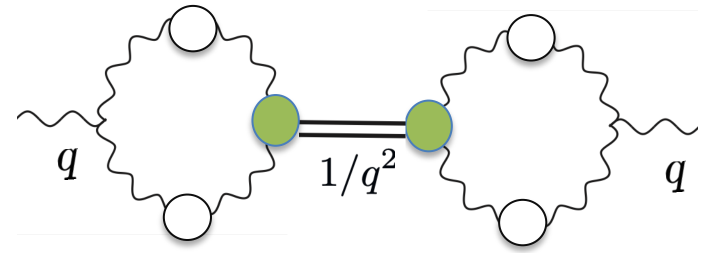
$\mathbb{C}(r^2)$ ACTS AS BETHE-SALPETER AMPLITUDE

EMERGENCE OF A GLUON MASS

$$\Delta^{-1}(0) = \lim_{q\to 0}$$



$$= \lim_{q\to 0}$$



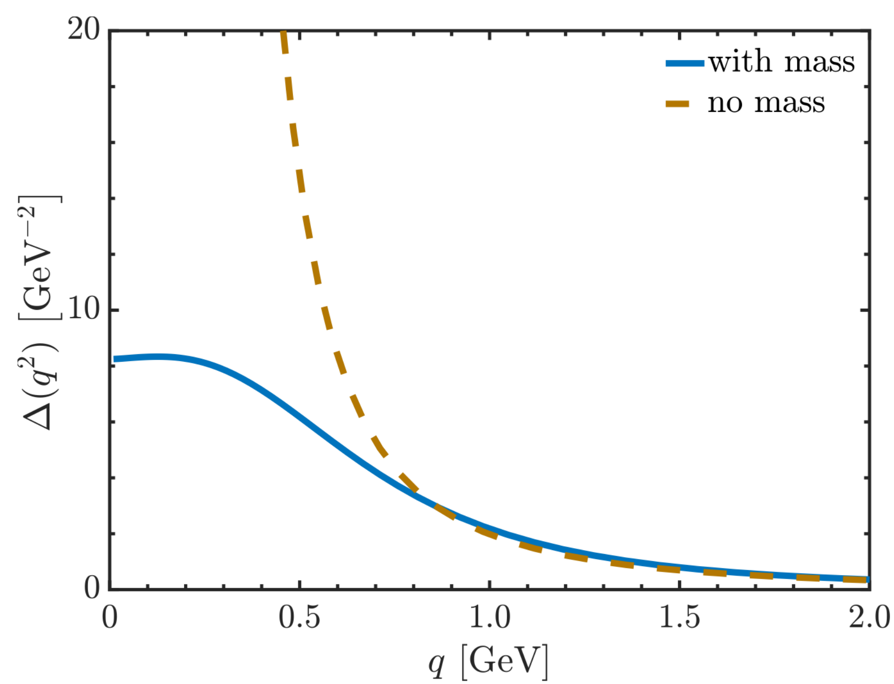
$$= -\frac{3C_{\rm A}\alpha_s}{8\pi}\int_0^\infty dy y^2\,\Delta^2(y)\mathbb{C}(y) \quad = \quad m^2$$

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

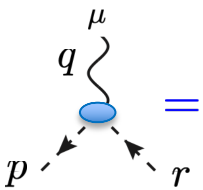
THERE IS A CHARACTERISTIC FEATURE, UNIQUE TO THIS MECHANISM,
WHICH ALLOWS THE UNEQUIVOCAL CONFIRMATION OF THIS SCENARIO

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

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

$q \to 0$
$p \to -r$

TAYLOR EXPANSION

WARD IDENTITY

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

TENSORIAL DECOMPOSITION

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

$$L^\star_{sg}(r^2) = 2\,\frac{\partial D^{-1}(r^2)}{\partial r^2}$$

SCHWINGER MECHANISM ON

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

THE TAKAHASHI IDENTITY DOES NOT CHANGE

$$\begin{aligned} q^\mu \mathrm{I\!\Gamma}_\mu(q,r,p) &= q^\mu \Gamma_\mu(q,r,p) + C(q,r,p) \\ &= D^{-1}(p^2) - D^{-1}(r^2) \end{aligned}$$

$q \to 0$ TAYLOR EXPANSION

WARD IDENTITY

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

TENSORIAL DECOMPOSITION

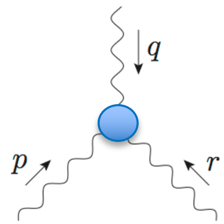
$$\Gamma_\mu(0,r,-r) = L_{sg}(r^2)\, r_\mu$$

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

The real thing: three-gluon vertex

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

$q \to 0$



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

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

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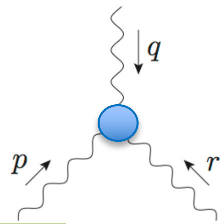
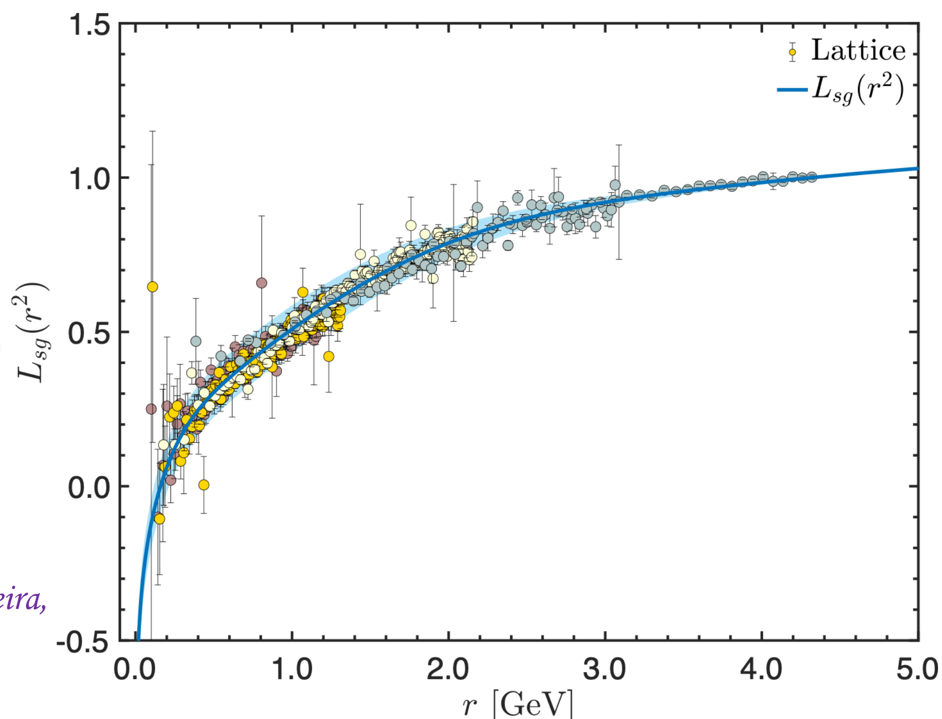


Ward identity

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

Form factor of the three-gluon vertex

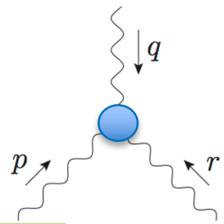


A.C. Aguilar, F. De Soto, M.N.Ferreira, J.P. , J.Rodriguez-Quintero, Phys. Lett. B818 (2021) 136352

The real thing: three-gluon vertex

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

$q \to 0$



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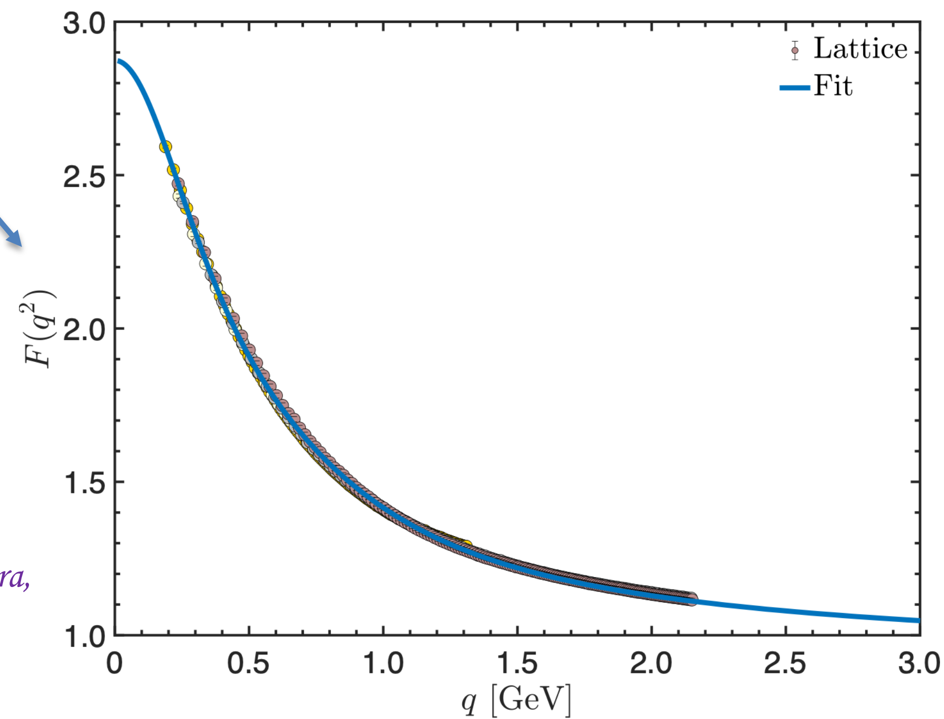
Ghost dressing function

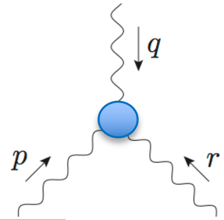


A.C. Aguilar, C.O. Ambrosio, F. De Soto, M.N. Ferreira, B.M. Oliveira, J.P and J. Rodriguez-Quintero,
Phys. Rev. D 104 no.5, 054028, (2021)

The real thing: three-gluon vertex

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

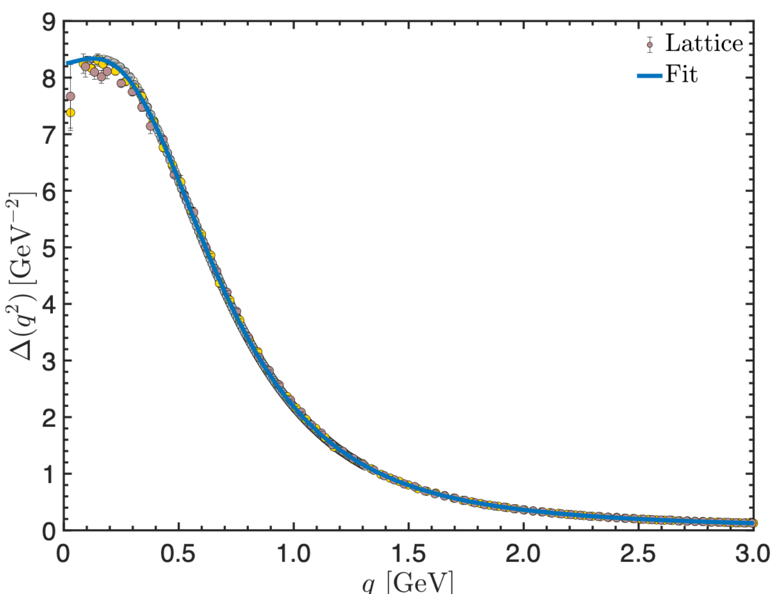
$q \to 0$

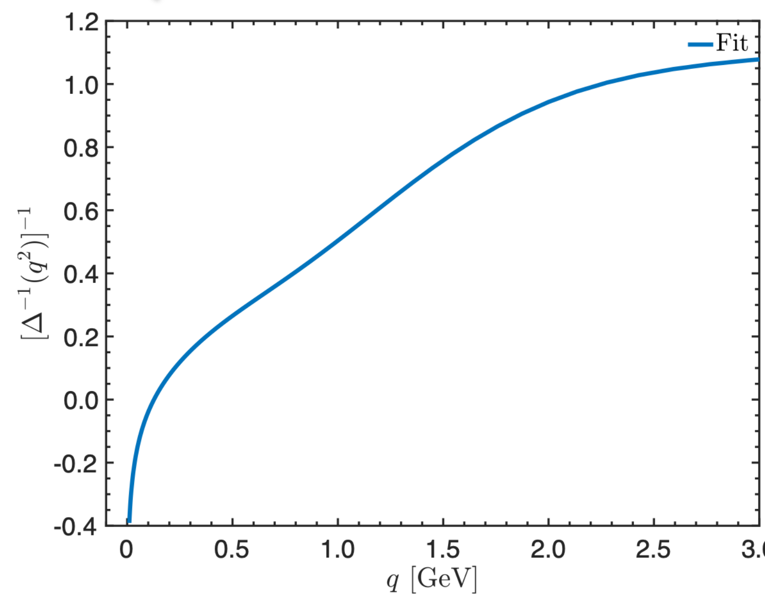


Ward identity

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

inverse gluon propagator





The real thing: three-gluon vertex

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

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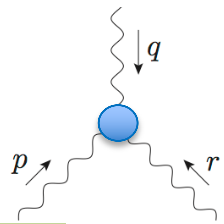
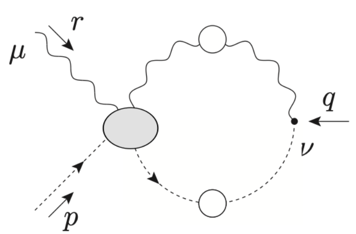


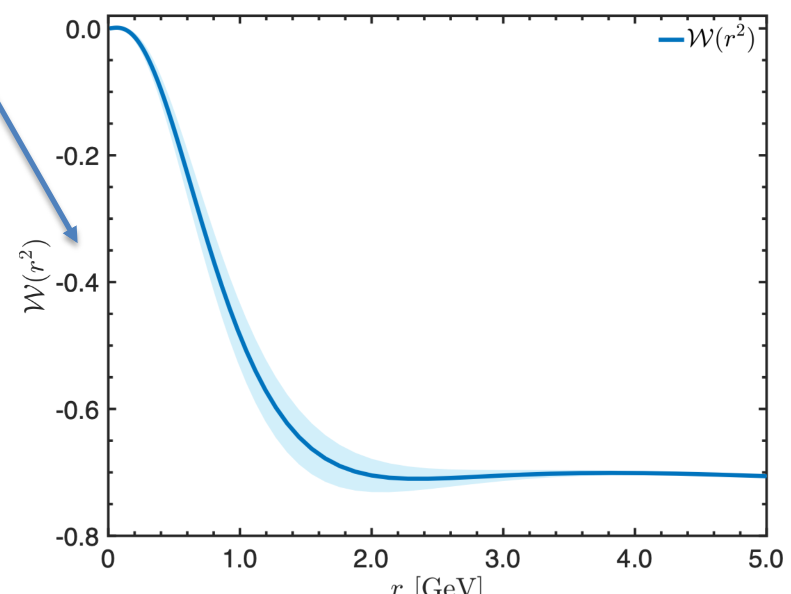
Ward identity

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

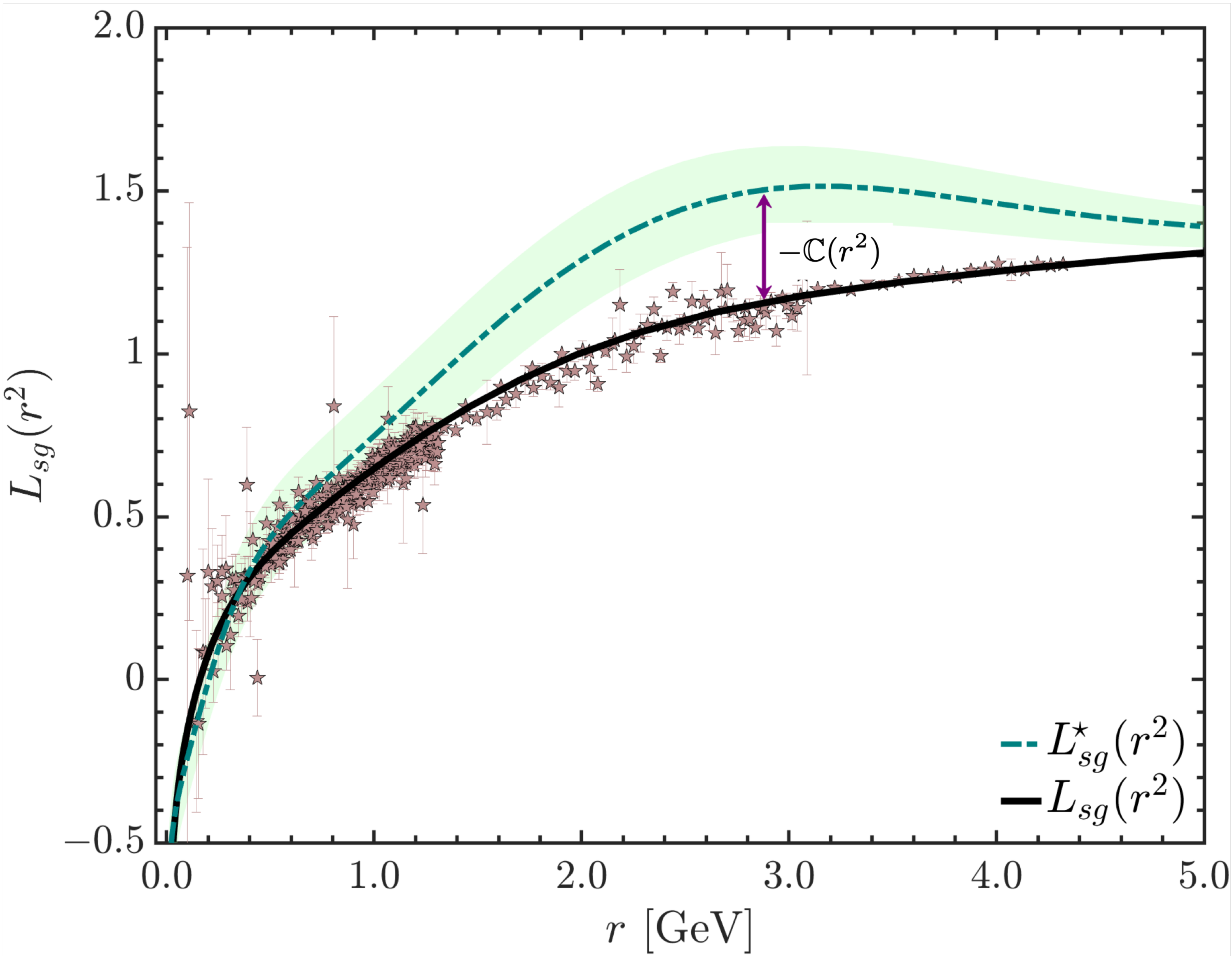
partial derivative of the ghost-gluon kernel

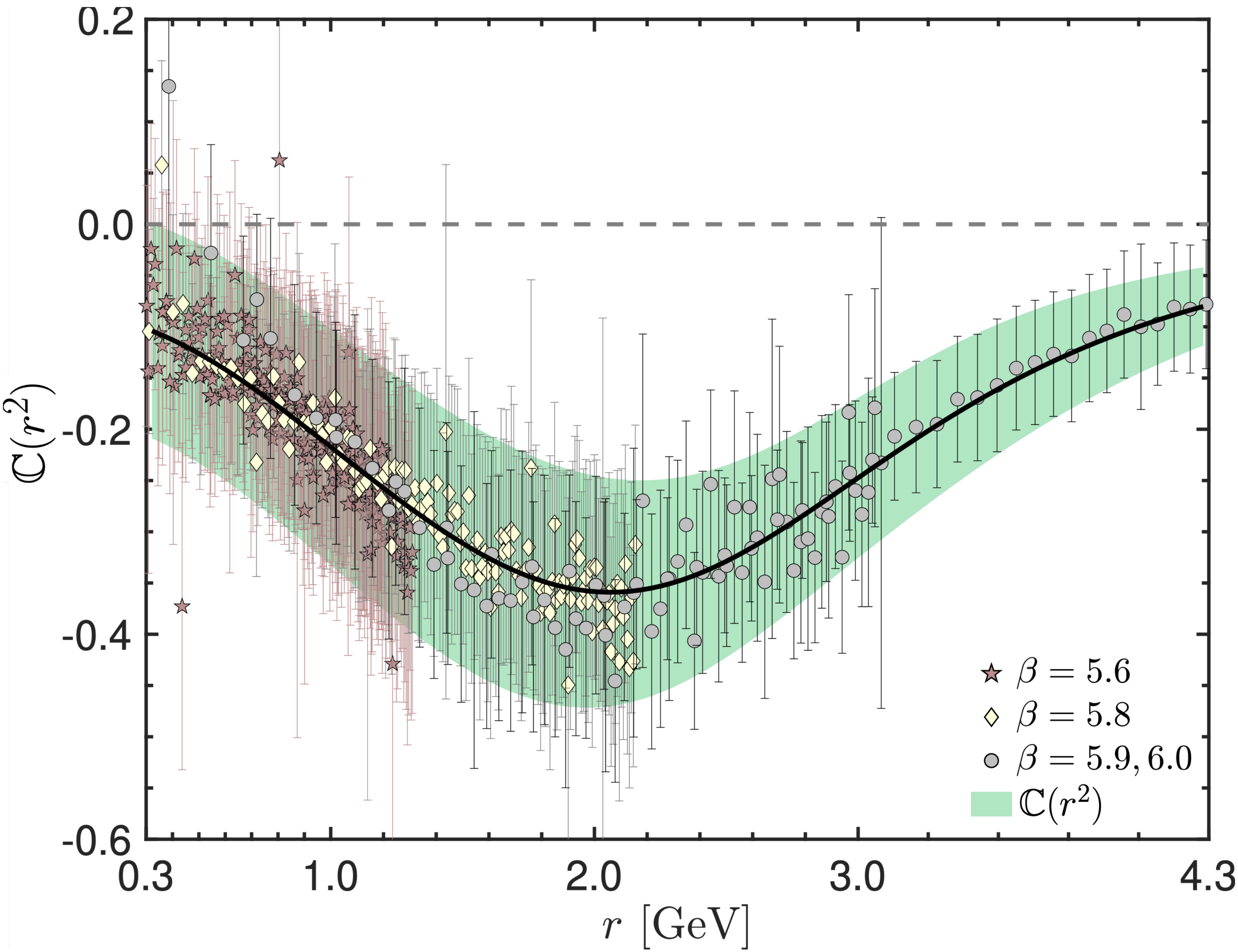


Computated from a Schwinger-Dyson eq.



A.C.AGUILAR, F. DE SOTO, M.N.FERREIRA, J.P., F. PINTO-GOMEZ, C.D. ROBERTS, J. RODRIGUEZ-QUINTERO, PHYS.LETT. B 841 (2023) 137906





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

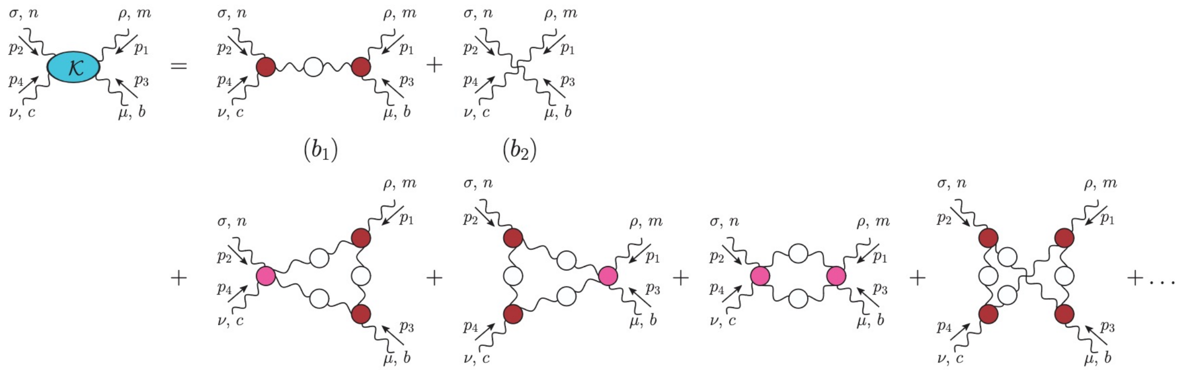
DYNAMICS AND SYMMETRY ARE TIGHTLY INTERTWINED

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)



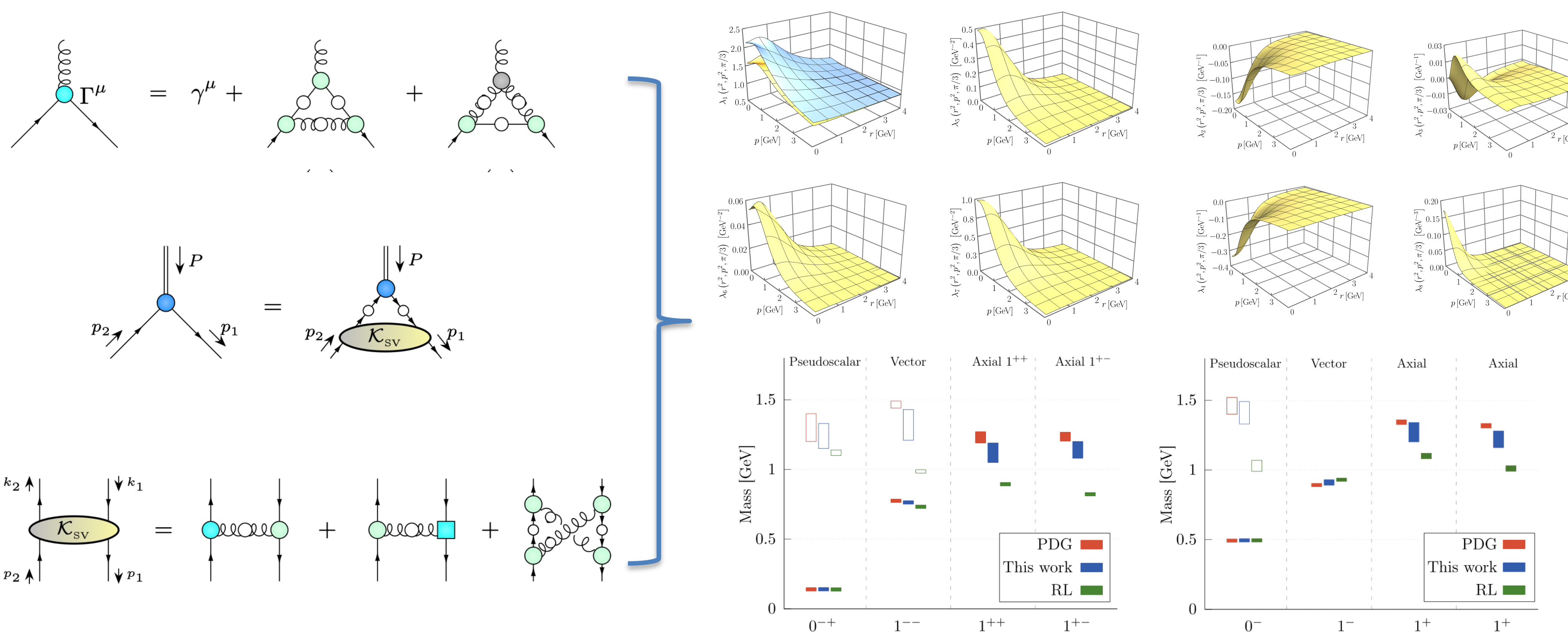
THE EMERGENCE OF THE GLUON MASS PROVIDES THE EXACT FIELD-THEORETIC STABILITY REQUIRED TO DEVELOP NEW, QCD-ROOTED, SYMMETRY-PRESERVING TRUNCATION SCHEMES

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 $\Rightarrow$ 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