SCHWINGER MECHANISM IN QCD

Joannis Papavassiliou

Department of Theoretical Physics and IFIC

University of Valencia-CSIC

J.P., CHIN. PHYS. C 46 (2022) 11, 112001 [HEP-PH 2207.04977]

M.N.FERREIRA AND J.P., PARTICLES 6, NO.1, 312-363 (2023) [HEP-PH 2301.02314]

L3: FLAVOUR AND QUARK MATTER

JANUARY 8-9, 2024

DYNAMICAL GENERATION OF A GLUON MASS

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

ANTISYMMETRIC FIELD TENSOR $\quad F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$

COVARIANT DERIVATIVE IN THE ADJOINT $\quad D^{ab}_\mu = \partial_\mu \delta^{ac} + g f^{amb} A^m_\mu$

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 $\quad \int \frac{d^d k}{k^2} = 0$

HOWEVER: GLUON SELF-INTERACTIONS GENERATE A NON-PERTURBATIVE MASS

J.M.CORNWALL, PHYS.REV. D26, 1453 (1982)

THE FIRST PLACE WHERE THE EMERGENCE OF A MASS IS FELT IS THE GLUON PROPAGATOR

ACCORDING TO CORNWALL: GLUON PROPAGATOR FINITE AT THE ORIGIN

NON-PERTURBATIVE METHODS (E.G. SCHWINGER-DYSON EQUATIONS) ARE REQUIRED

HISTORICALLY

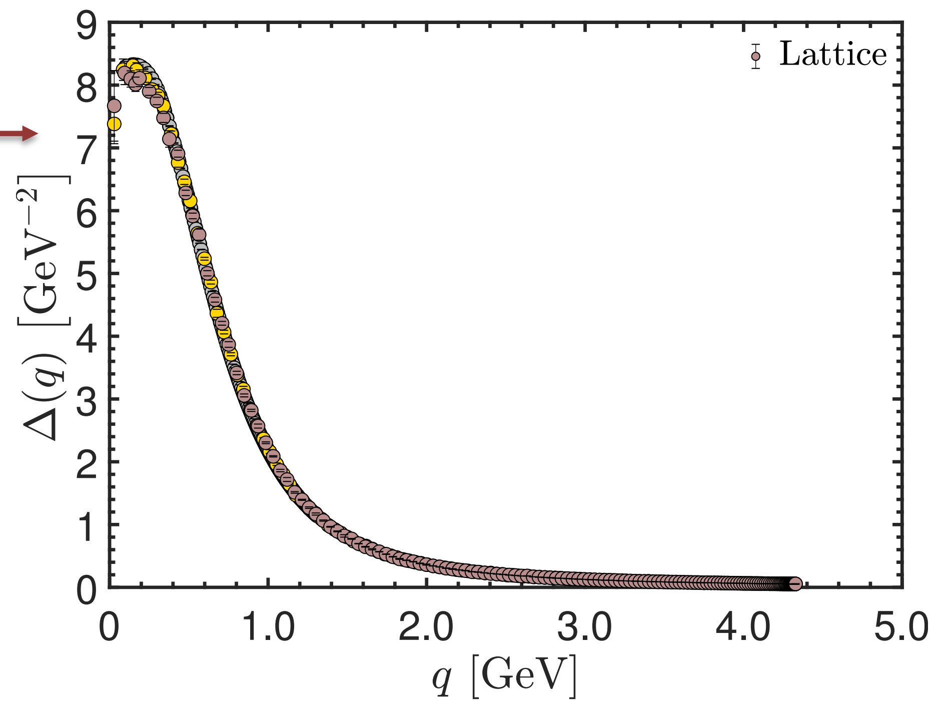
DURING A QUARTER OF A CENTURY MANY DIFFERENT STUDIES PREDICTED A VARIETY OF DISTINCT BEHAVIORS FOR THE GLUON PROPAGATOR

(MANDELSTAM, STINGL, KUGO-OJIMA, GRIBOV-ZWANZIGER, GHOST DOMINANCE …)

TURNING POINT: LARGE-VOLUME LATTICE SIMULATIONS (CIRCA 2007)

I. BOGOLUBSKY ET AL, PROC. SCI., LATTICE2007 (2007) 290

$$\Delta(0) = \frac{1}{m^2}$$



THE SATURATION OF THE GLUON PROPAGATOR IN THE DEEP INFRARED IS THE UNEQUIVOCAL SIGNAL OF GLUON MASS GENERATION

MUST EXPLAIN THIS FROM WITHIN QCD, WITHOUT MODIFYING THE LAGRANGIAN !

SCHWINGER MECHANISM

GAUGE BOSON PROPAGATOR

$$\Delta_{\mu\nu}(q) = -i\Delta(q)P_{\mu\nu}(q)\,, \qquad P_{\mu\nu}(q) = g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}$$

TREE LEVEL :

$$\Delta^{-1}(q^2) = \; q^2 + m^2 = \; q^2\left[1 + \frac{m^2}{q^2}\right]$$

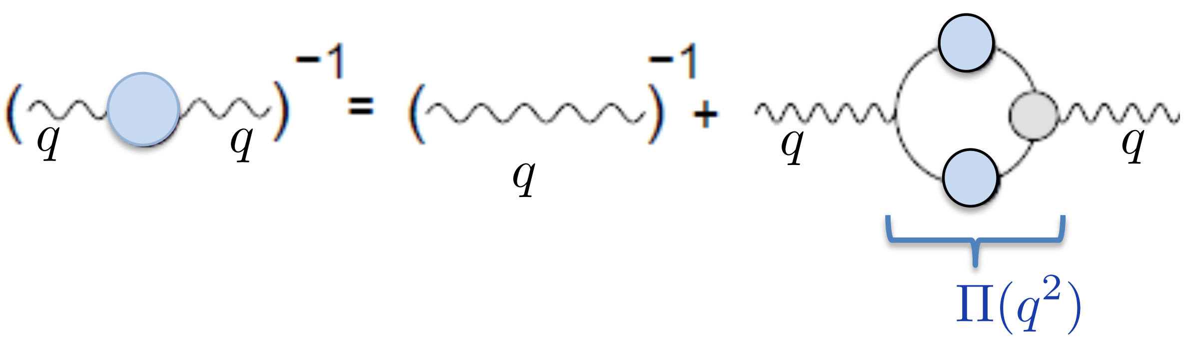
ACTS AS A POLE

IN GENERAL :

$$\Delta^{-1}(q^2) = \; q^2 + m^2 + \Pi(q^2)$$

VACUUM POLARIZATION

SCHWINGER-DYSON EQUATION FOR GAUGE BOSON PROPAGATOR



WHEN THE SYMMETRY PROHIBITS A TREE-LEVEL MASS: $\Longrightarrow$ $m^2 = 0$

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

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

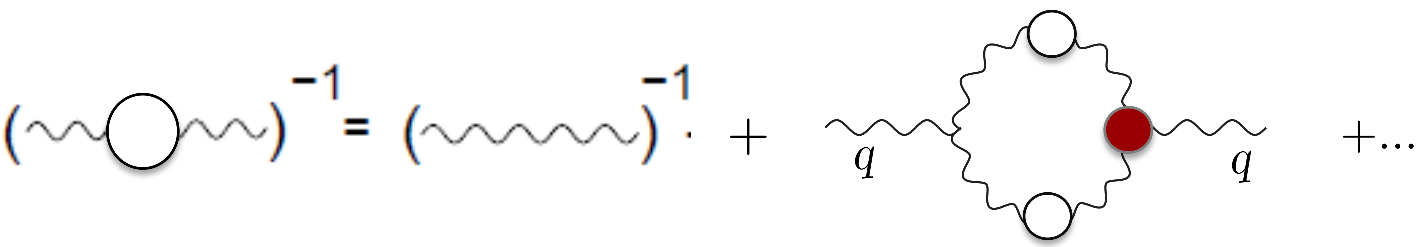
$$\Longrightarrow \quad \Delta^{-1}(0) = c > 0$$

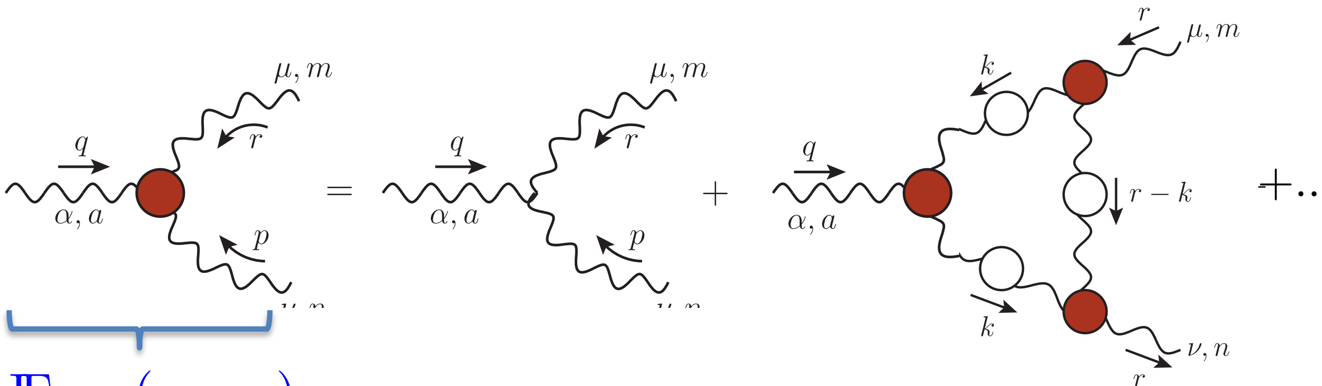
GAUGE INVARIANCE AND MASS

A GAUGE BOSON 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)

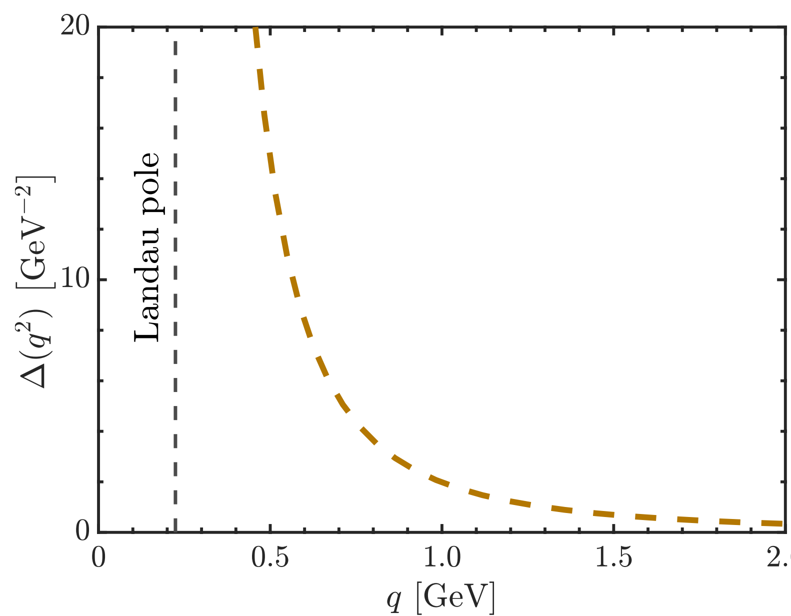
SYSTEM OF SCHWINGER-DYSON EQUATIONS (SDEs)





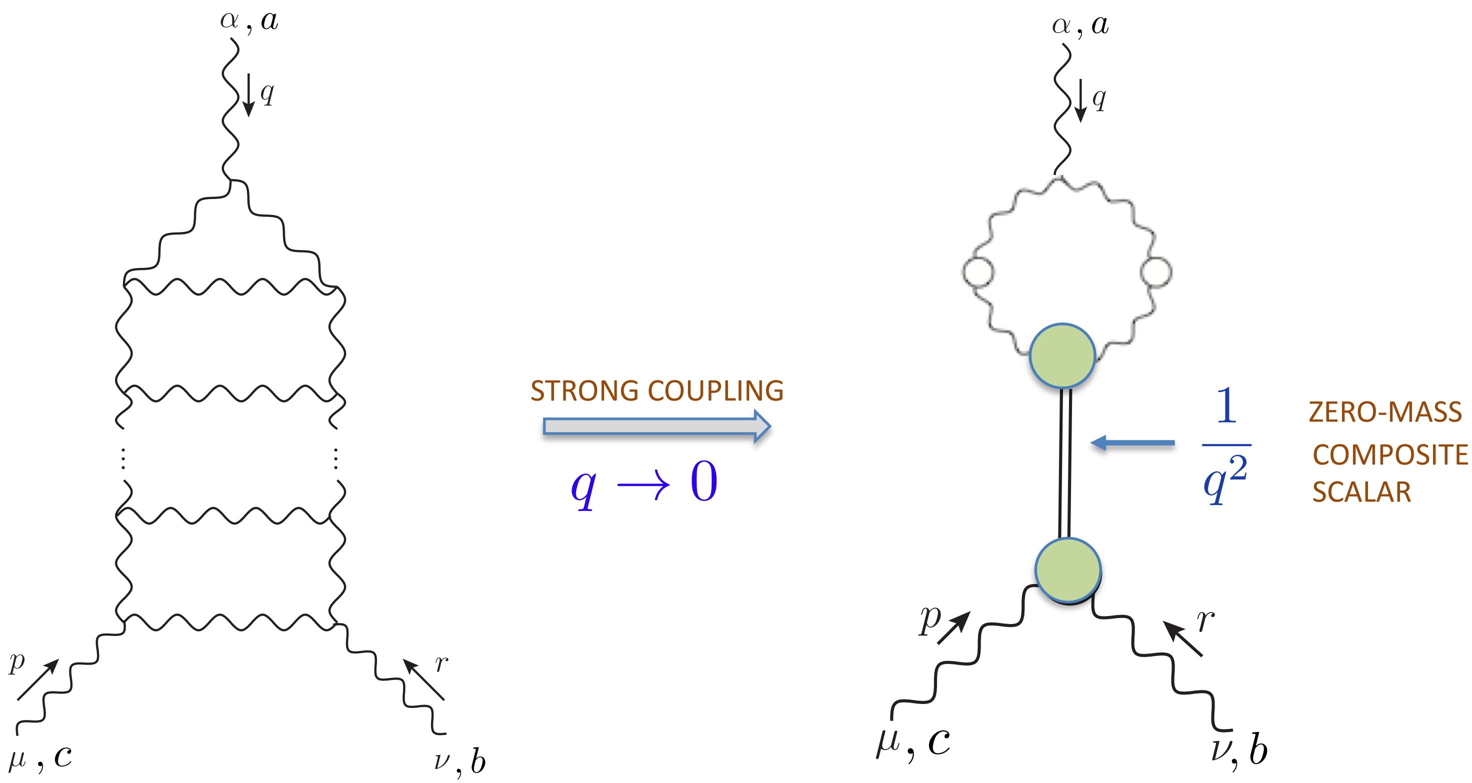
$\mathbb{I}\Gamma_{\alpha\mu\nu}(q, r, p)$

IN THE ABSENCE OF A MASS, THE SYSTEM HAS NO INFRARED STABLE SOLUTIONS



BUT THE THEORY FINDS THE WAY TO STABILIZE ITSELF :

DYNAMICAL FORMATION OF COLOR-CARRYING MASSLESS SCALAR EXCITATIONS



THE MASSLESS POLE REQUIRED FOR TRIGGERING THE SCHWINGER MECHANISM
IN QCD IS PRODUCED FROM THE INTERACTIONS

GENERAL STRUCTURE OF THE THREE-GLUON VERTEX

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

REMEMBER

$$V_{\alpha\mu\nu}(q,r,p) = \frac{q_\alpha}{q^2} g_{\mu\nu} C_1(q,r,p)$$

BOSE SYMMETRY IMPOSES

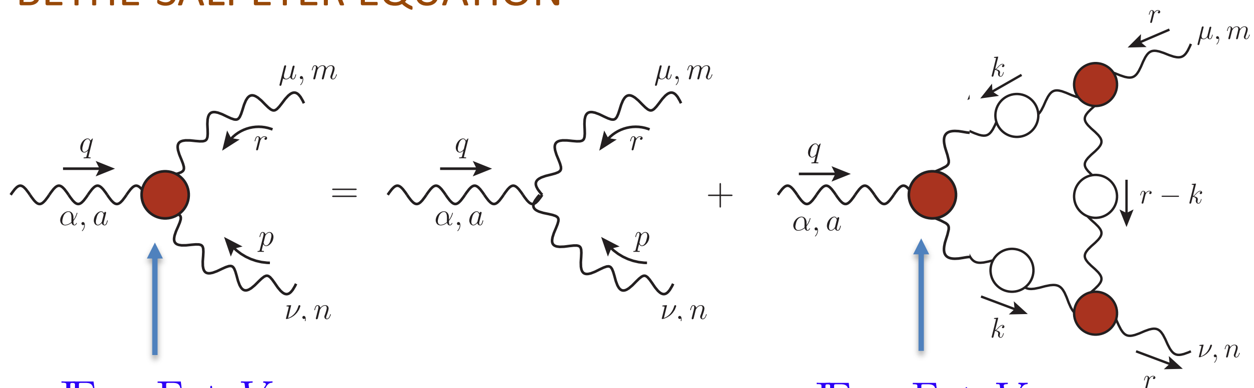
$$C_1(q,r,p) = -C_1(q,p,r) \quad \Longrightarrow \quad C_1(0,r,-r) = 0$$

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

RESIDUE FUNCTION

BETHE-SALPETER EQUATION

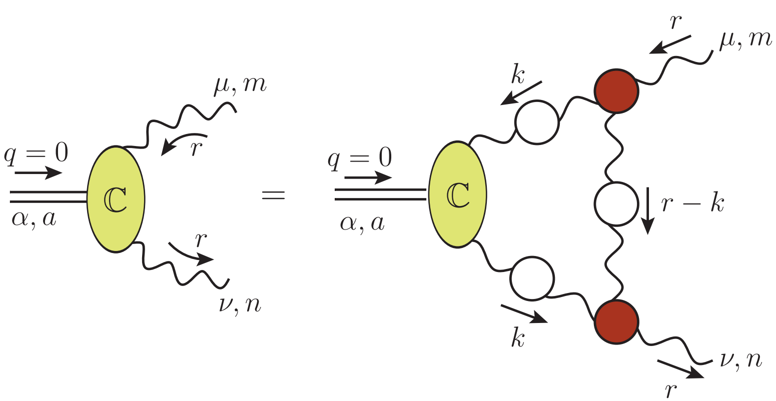
START WITH VERTEX SDE:



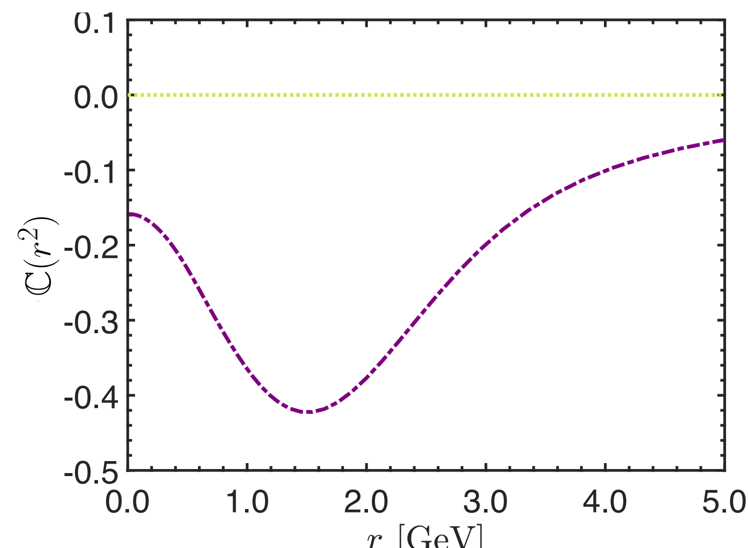
SUBSTITUTE: $\quad \mathbb{I}\Gamma = \Gamma + V \qquad \mathbb{I}\Gamma = \Gamma + V$

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

BSE



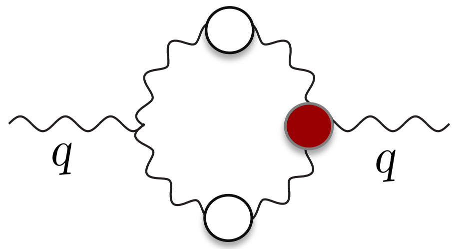
NON-TRIVIAL SOLUTION



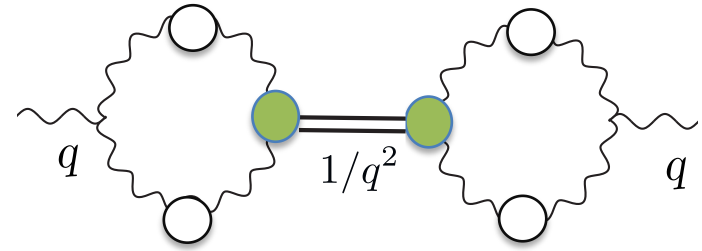
$\mathbb{C}(r^2)$ ACTS AS BETHE-SALPETER AMPLITUDE

EMERGENCE OF A GLUON MASS

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

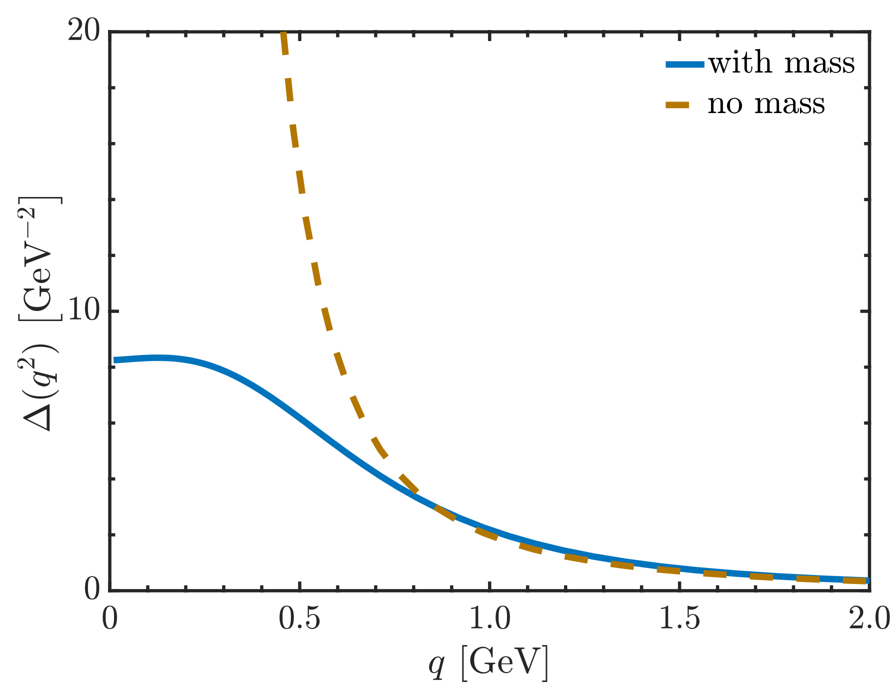


$$= \lim_{q\to 0}$$



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

$$= m^2$$



THE 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

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

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

HOWEVER

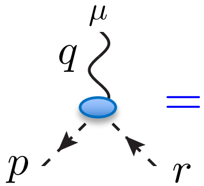
THERE IS A CHARACTERISTIC FEATURE, UNIQUE TO THIS MECHANISM,
WHICH ALLOWS THE UNEQUIVOCAL CONFIRMATION OF THIS SCENARIO

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

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

$$\begin{array}{c} q \to 0 \\ p \to -r \end{array} \Big\Downarrow \text{ TAYLOR EXPANSION}$$

WARD IDENTITY

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

TENSORIAL DECOMPOSITION

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

$$\Big\Downarrow$$

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

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

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

$$q \to 0 \ \Big\Downarrow \text{ TAYLOR EXPANSION}$$

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

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

$$\Big\Downarrow$$

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

DISPLACEMENT FROM LATTICE QCD : APPLY THIS IDEA ON THE THREE-GLUON VERTEX

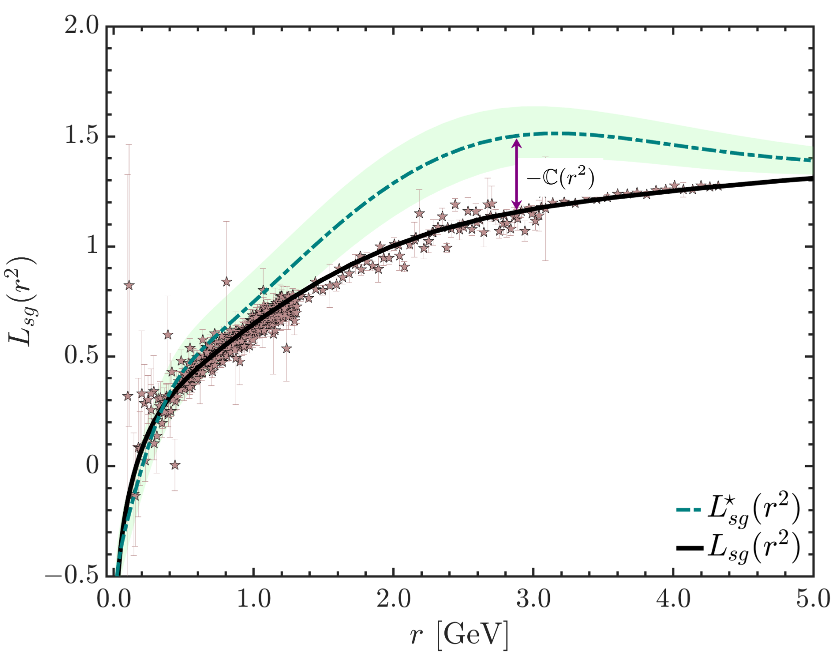
A.C.AGUILAR, F. DE SOTO, M.N.FERREIRA, J.P., F. PINTO-GOMEZ, C.D. ROBERTS, J. RODRIGUEZ-QUINTERO, PHYS.LETT. B 841 (2023) 137906

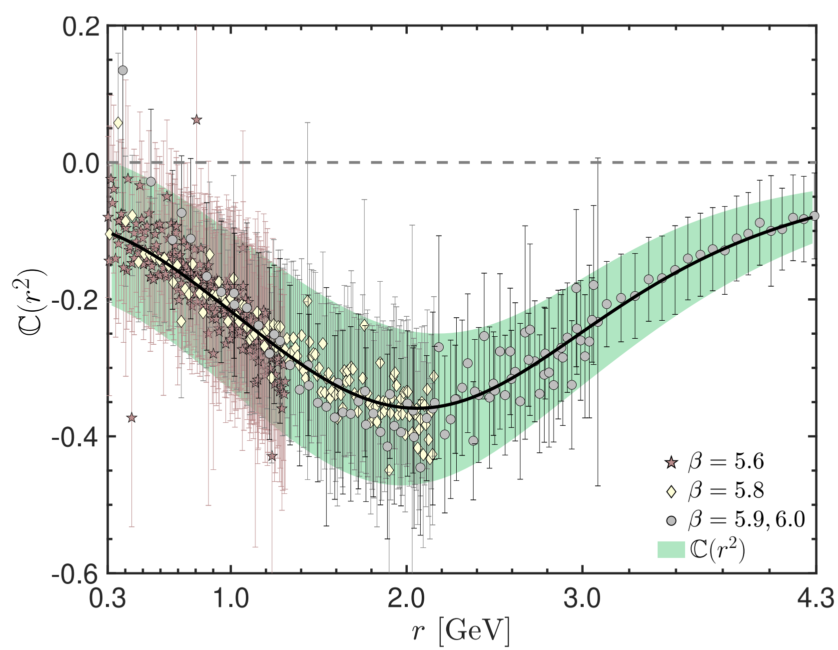
SLAVNOV-TAYLOR IDENTITY:

$$q^\alpha \Gamma_{\alpha\mu\nu}(q,r,p) + C_1(q,r,p) g_{\mu\nu} = F(q^2)\left[\Delta^{-1}(p^2) P_\nu^\sigma(p) H_{\sigma\mu}(p,q,r) - \Delta^{-1}(r^2) P_\mu^\sigma(r) H_{\sigma\nu}(r,q,p)\right]$$

TAYLOR EXPANSION → WARD IDENTITY

$$\underbrace{L_{sg}(r^2)}_{\text{LATTICE QCD}} = \underbrace{L^\star_{sg}(r^2)}_{\text{COMPUTE WITH INPUTS FROM LATTICE QCD}} + \underbrace{\mathbb{C}(r^2)}_{\text{DISPLACEMENT FUNCTION}}$$





35.7 σ AWAY FROM THE NULL HYPOTHESIS!

CONCLUSIONS

GLUON SELF-INTERACTIONS GENERATE A DYNAMICAL MASS SCALE IN THE GAUGE SECTOR OF QCD

DYNAMICS AND SYMMETRY ARE TIGHTLY INTERTWINED

FULL CONFIRMATION OF THE ACTION OF THE SCHWINGER MECHANISM FROM LATTICE QCD

TRULY MASS FROM NOTHING