Schwinger mechanism from lattice QCD

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(A.C. Aguilar, M. N. Ferreira, and J.P., in preparation)

Perceiving the Emergence of Hadron Mass through AMBER@CERN (VI)

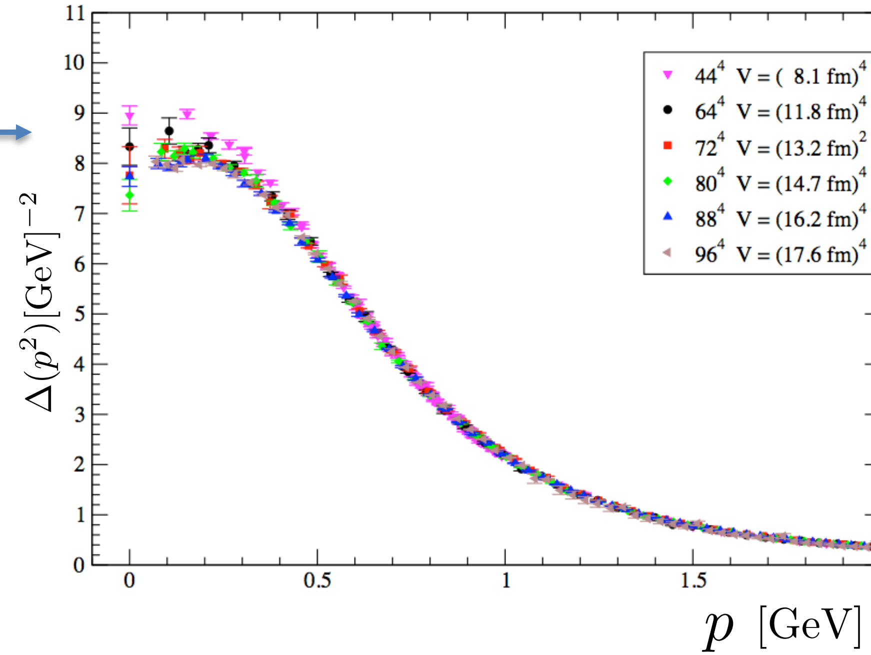
27-29 of September, 2021

Emergence of mass in the gauge sector of QCD

J. M. Cornwall, Phys. Rev. D26, 1453 (1982); A.C.Aguilar, D.Binosi, and J.P, Phys. Rev. D 78, 025010 (2008)

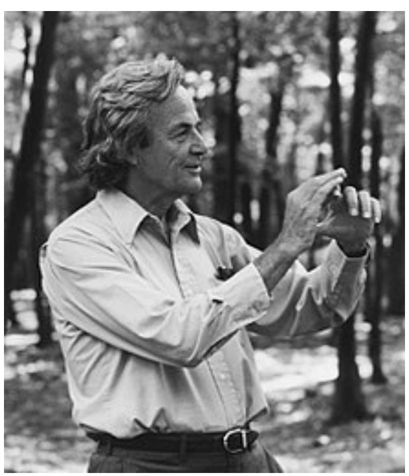
- Lattice QCD: The gluon propagator saturates in the deep infrared

- Unequivocal signal of gluon mass generation



- A mass term $m^2 A^2$ in the Lagrangian is forbidden by gauge invariance

- A dynamical mechanism is needed



All mass is interaction

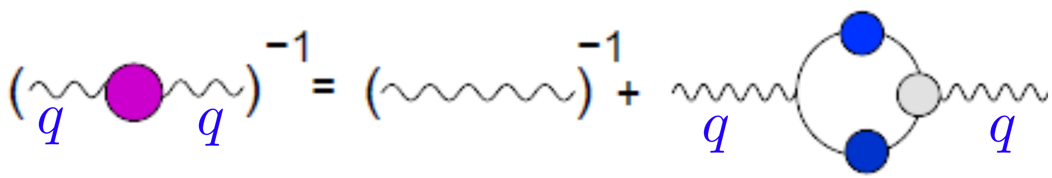
Richard P. Feynman

Schwinger mechanism

J. S. Schwinger, Phys. Rev.125, 397 (1962); Phys.Rev.128, 2425 (1962)

Schwinger dispelled the misconceptions surrounding
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.

Schwinger-Dyson equation for gauge boson propagator



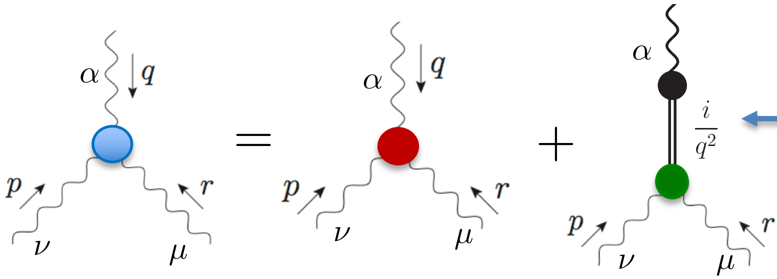
$$\Delta^{-1}(q^2) = q^2[1 + \Pi(q^2)]$$

If, for some reason

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

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

Schwinger mechanism in QCD



massless colored excitations
controlled by Bethe-Salpeter eq.

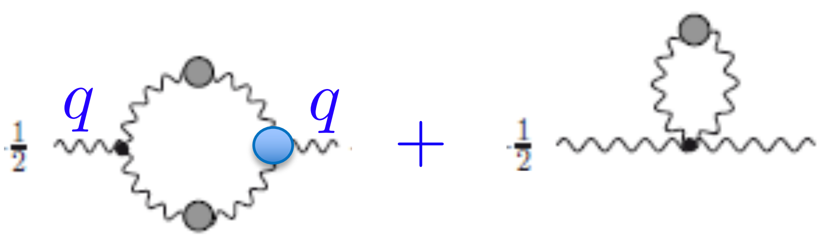
A.C.Aguilar, D. Ibanez, V. Mathieu, and J. P., Phys. Rev. D 85, 014018 (2012)
A.C. Aguilar, D. Binosi, and J.P, Phys. Rev. D 95, no.3, 034017 (2017)

$$\mathrm{I\Gamma}_{\alpha\mu\nu}(q,r,p) = \underbrace{\Gamma_{\alpha\mu\nu}(q,r,p)}_{\text{pole-free}} + \underbrace{V_{\alpha\mu\nu}(q,r,p)}_{\text{poles}}$$

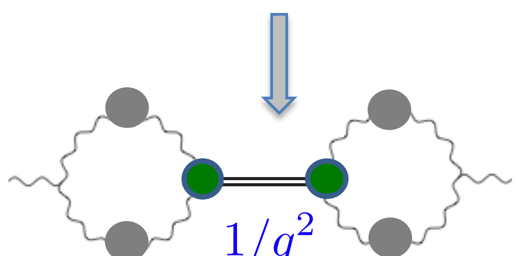
- The poles are "longitudinally coupled": $q^\alpha/q^2,\ r^\mu/r^2,\ p^\nu/p^2$

⇒ Drop out from "on-shell" amplitudes and "lattice observables"

- Provide the necessary pole in the gluon vacuum polarization:

$$\Delta^{-1}(q^2) = q^2 + \tfrac{1}{2}$$ 

$$+\ldots$$



$$\Rightarrow \quad \Delta^{-1}(0) = m^2$$

The Schwinger mechanism has a clear dynamical origin,
and is compatible with all field theoretic principles and requirements,
such as BRST symmetry and renormalizability

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Is there some smoking-gun signal associated with its onset
(other than the infrared finiteness of the gluon propagator) ?

In other words, is the mechanism falsifiable ?

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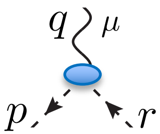
ANSWER: YES

The displacement of the Ward identities satisfied by the vertices,
in conjunction with lattice simulations, may confirm or rule out
the Schwinger mechanism

A toy example: scalar QED

Schwinger mechanism off



Takahashi identity

$$q^\mu \underbrace{\Gamma_\mu(q,r,p)}_{\text{pole-free}} = D^{-1}(p^2) - D^{-1}(r^2)$$

$q \to 0$, $p \to -r$ ⇓ *Taylor expansion*

Ward identity

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

Tensorial decomposition

$$\Gamma_\mu(0,r,-r) = L(r^2) r_\mu$$

⇓

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

Schwinger mechanism on

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

The Takahashi identity does not change

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

$q \to 0$ ⇓ *Taylor expansion*

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

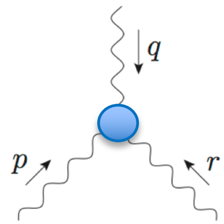
⇒

$$L(r^2) = 2\frac{\partial D^{-1}(r^2)}{\partial r^2} - \underbrace{2\,\mathbb{C}(r^2)}_{\text{displacement}}$$

The real thing: three-gluon vertex

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

$q \to 0$



Ward identity

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

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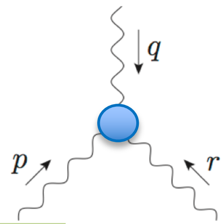

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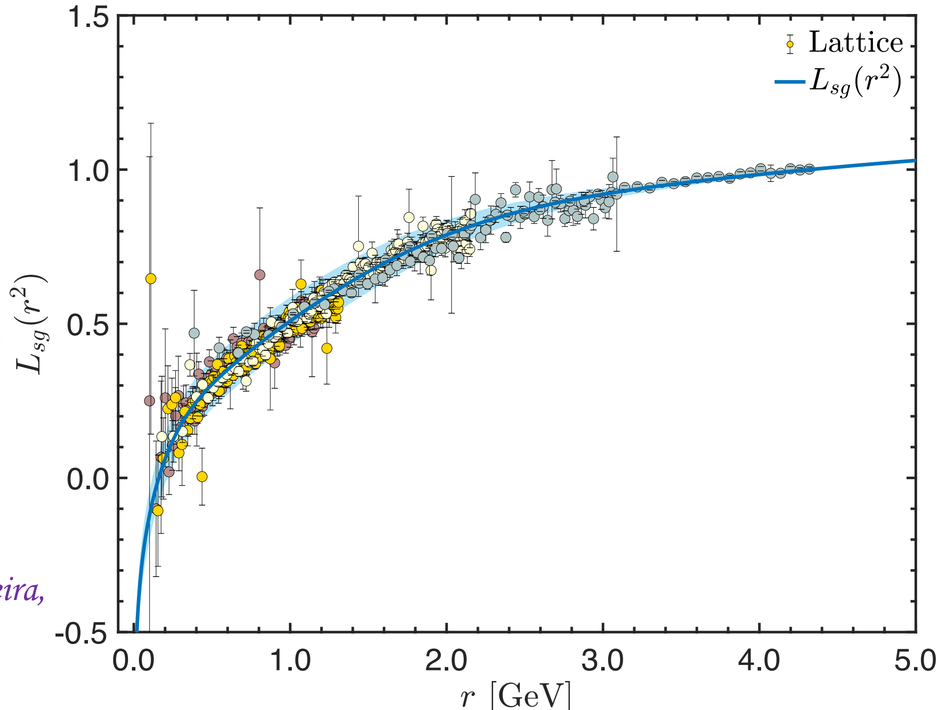
"displacement"

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

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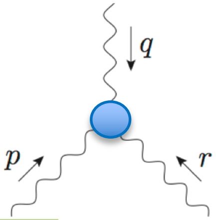

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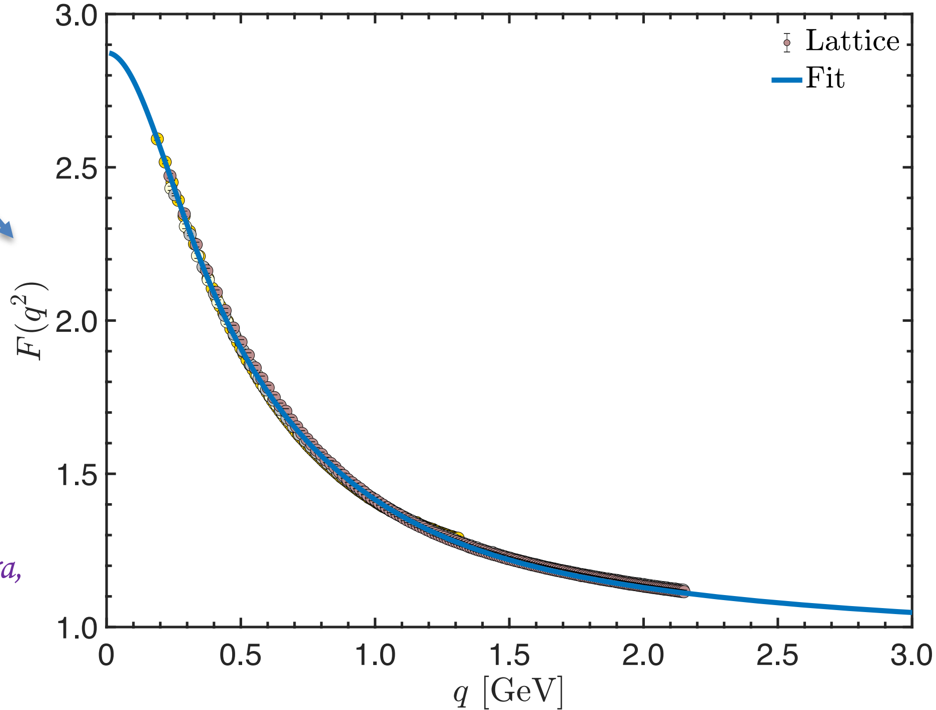
"displacement"

Ghost dressing function

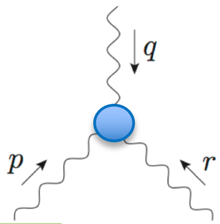


A.C. Aguilar, C.O. Ambrosio, F. De Soto, M.N. Ferreira, B.M. Oliveira, J.P and J. Rodriguez-Quintero, Phys. Rev. D 104 no.5, 054028, (2021)

The real thing: three-gluon vertex

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

$q \to 0$

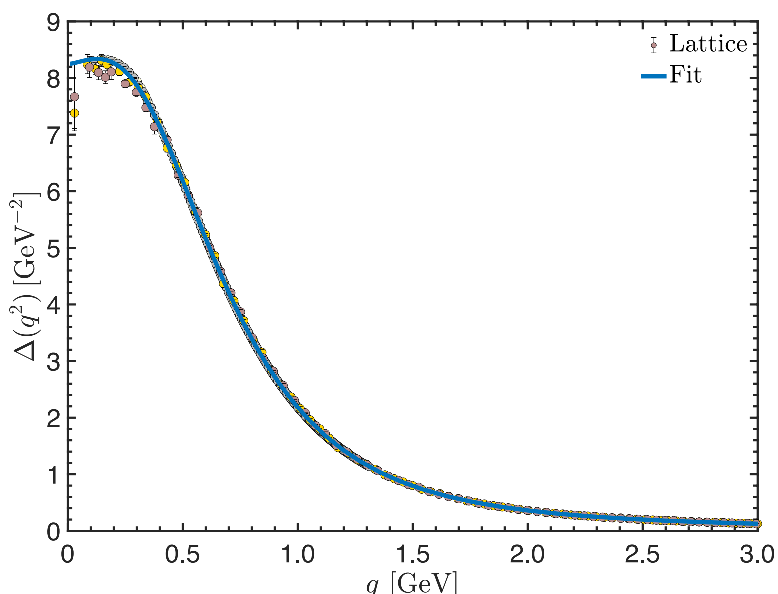


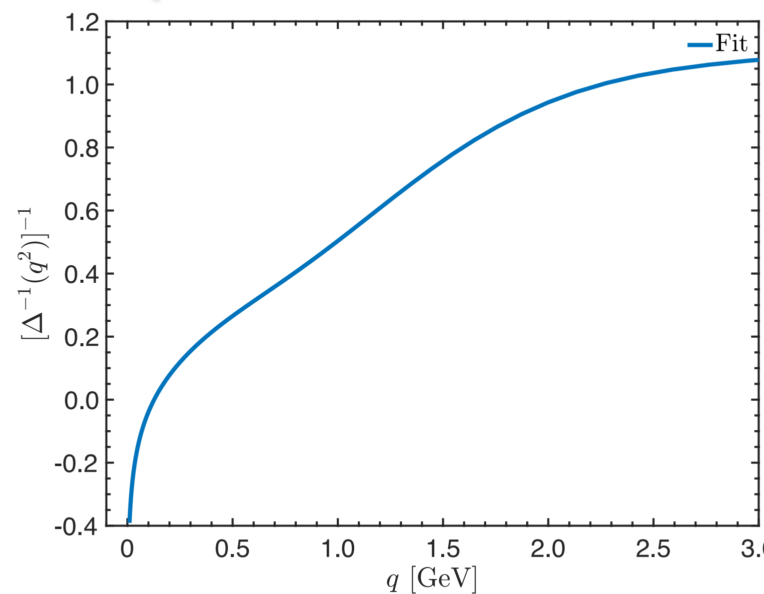
Ward identity

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

"displacement"

inverse gluon propagator





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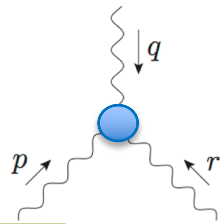

Ward identity

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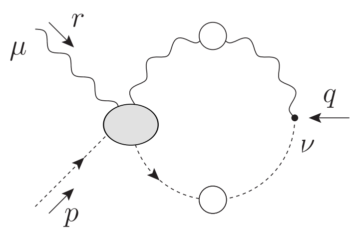
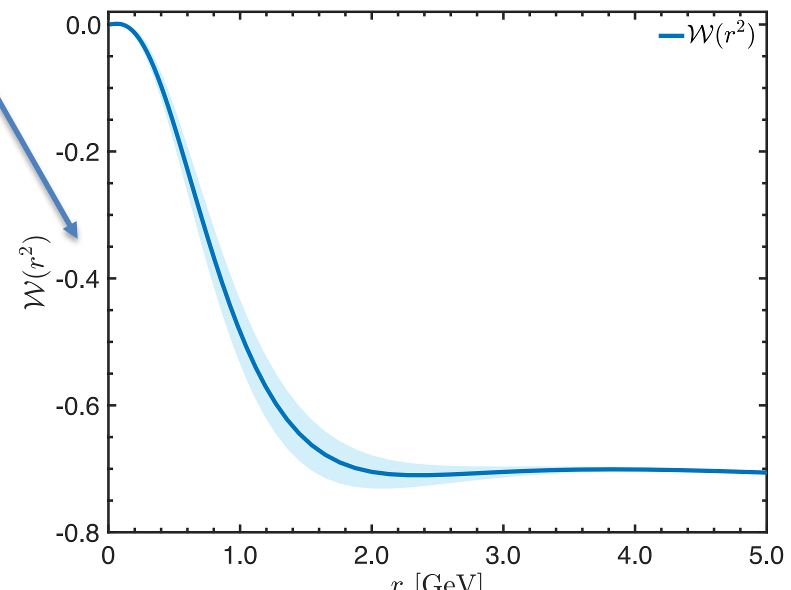
partial derivative of the ghost-gluon kernel



Computated from a Schwinger-Dyson eq.

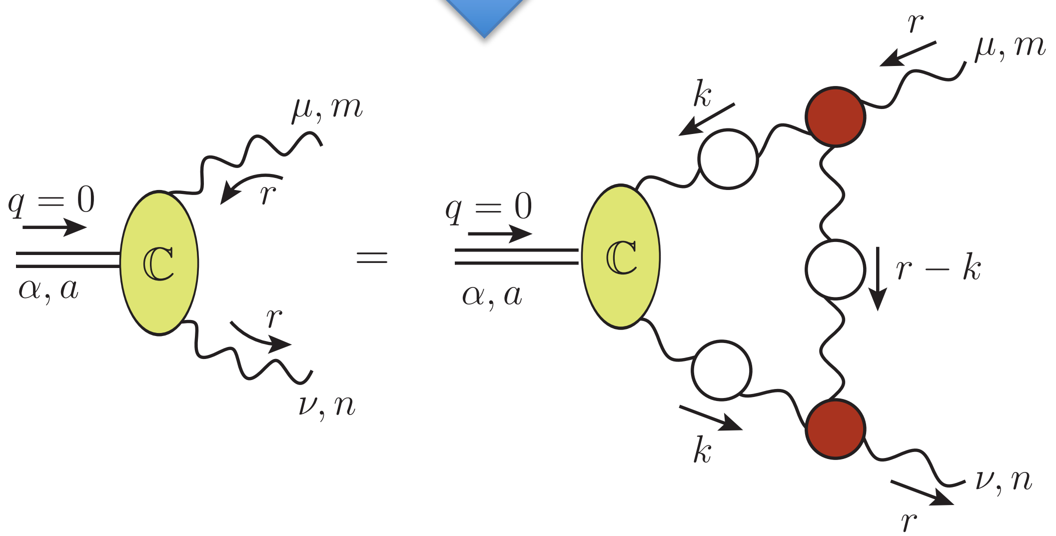


But, remember:

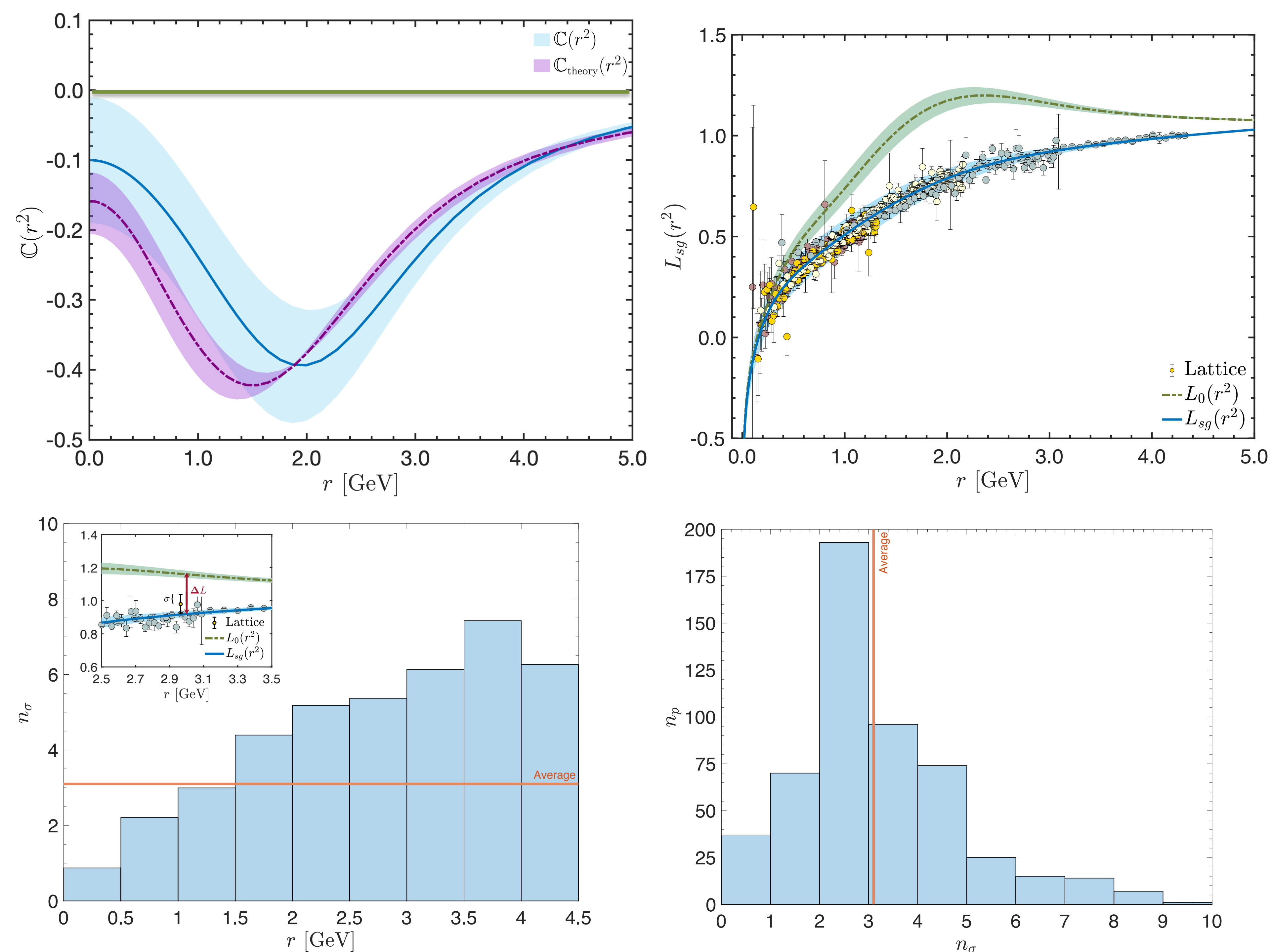
$\mathbb{C}(r^2)$ *is computed from a special Bethe-Salpeter equation*

A.C.Aguilar, D. Ibanez, V. Mathieu, and J. P., Phys. Rev. D 85, 014018 (2012)

A.C.Aguilar, D.Binosi, C.T.Figueiredo and J.P., Eur. Phys. J. C78, no.3, 181 (2018)



The determination from the Ward identity must be compatible with the theoretical prediction



$\mathbb{C}(r^2)$
$\mathbb{C}_{\text{theory}}(r^2)$
r [GeV]
Lattice
$L_0(r^2)$
$L_{sg}(r^2)$
r [GeV]
ΔL
σ
Lattice
$L_0(r^2)$
$L_{sg}(r^2)$
r [GeV]
n_σ
Average
r [GeV]
Average
n_p
n_σ

Conclusions

- The Schwinger mechanism leaves its "imprint" on the Ward identity of the three-gluon vertex, in the form of "mismatches" among its ingredients

- Using lattice inputs, we find a promising signal of about $3\,\sigma$

Future tasks

- Reduce lattice errors in the region below 2 GeV

- Refine the determination of $\mathcal{W}(r^2)$