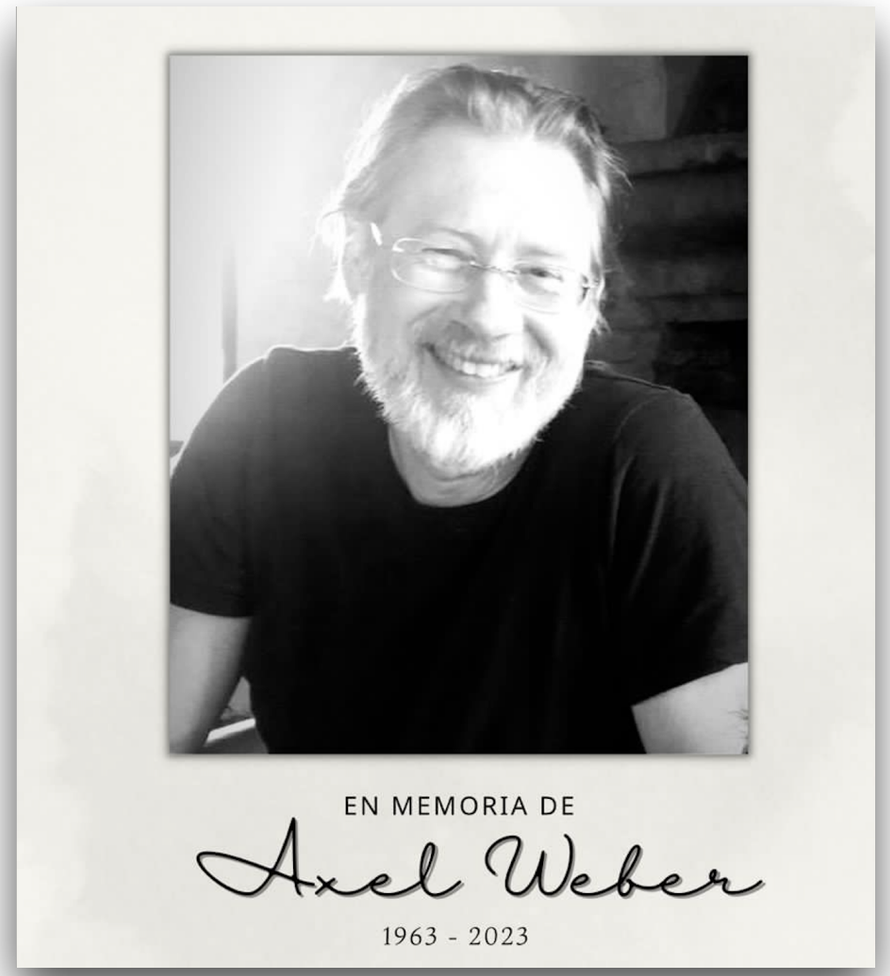
Confinement & the gluon mass gap

Jan M. Pawlowski

Universität Heidelberg

Morelia, November 22th 2023

In memoriam Axel Weber

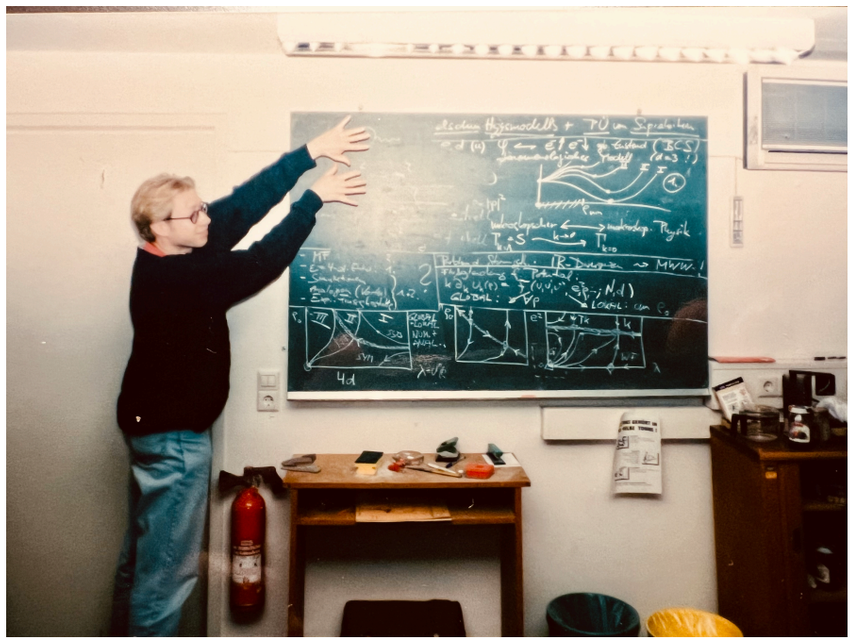


Scientific childhood memories

Axel Weber ‘95

Heidelberg/Paris 1990-95

PhD office ITP Heidelberg



Cross-blackboard physics

Training for the next 1/4-final loss

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Axel Weber ‘95

Thanks, Axel and Manfred,

for convincing me of flow equations

being a cool approach for doing exciting physics!

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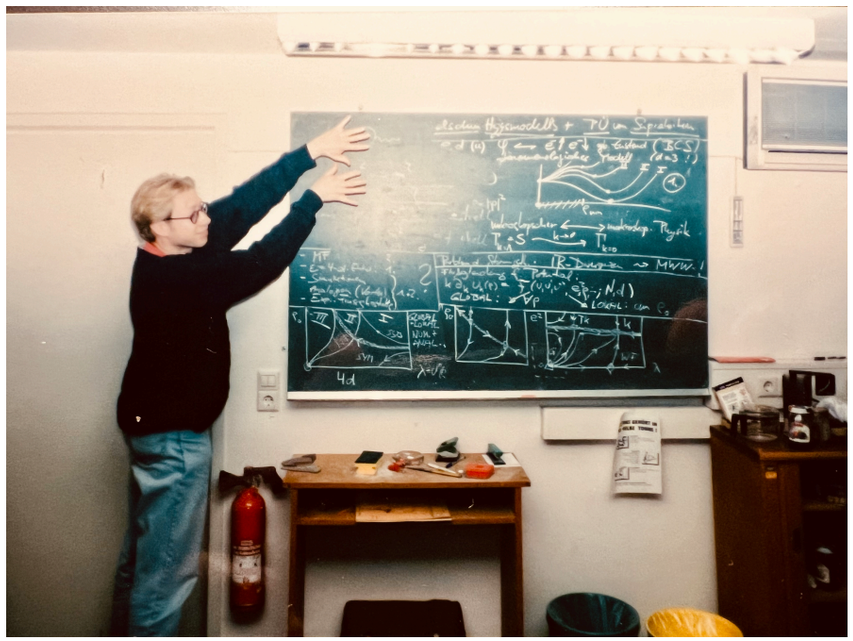


Cross-blackboard physics

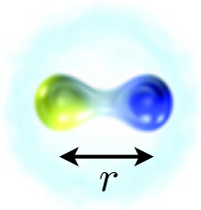
Training for the next 1/4-final loss

Outline

- Confinement and the QCD mass gap
- Gluon mass gap, confinement and QCD mass gap
- Gluon condensates & the gluon mass gap

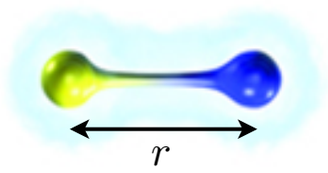
Confinement & the QCD mass gap

Confinement



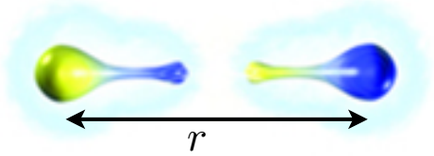
Free energy

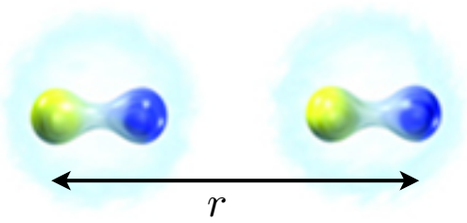
$$F_{q\bar{q}} \simeq -\frac{1}{r}$$



$$F_{q\bar{q}} \simeq \sigma r$$

string breaking at $\mathrm{r} \approx 1\mathrm{fm}$



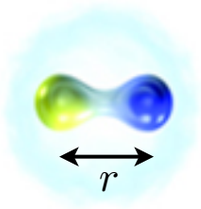


$$F_{q\bar{q}} \simeq \text{const.}$$

QCD mass gap

Confinement & the QCD mass gap

Confinement



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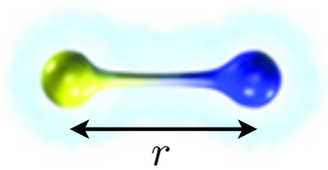

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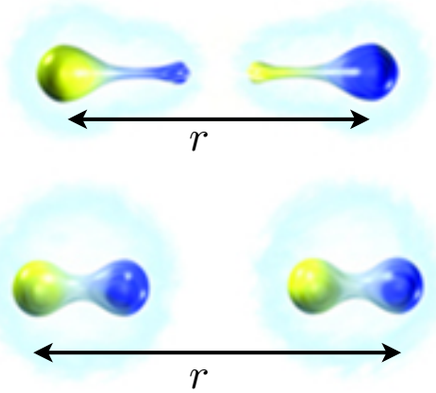

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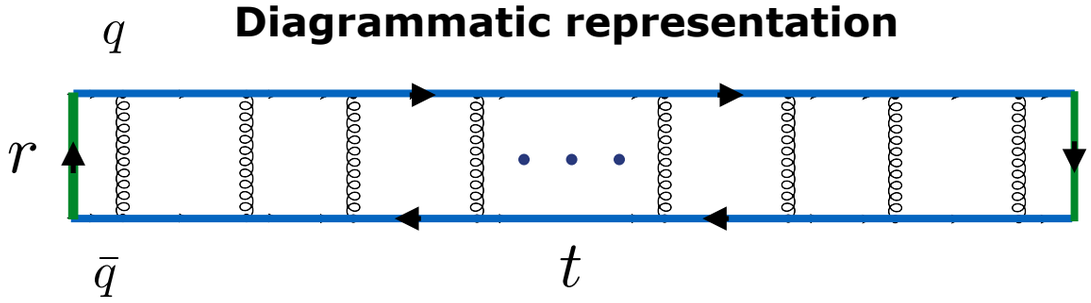
Diagrammatic representation



Wilson loop — Polyakov loop correlation

QCD mass gap

Confinement & the QCD mass gap

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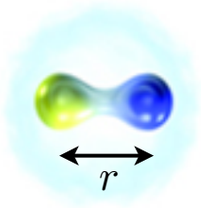

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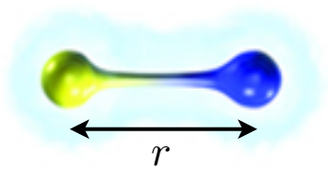

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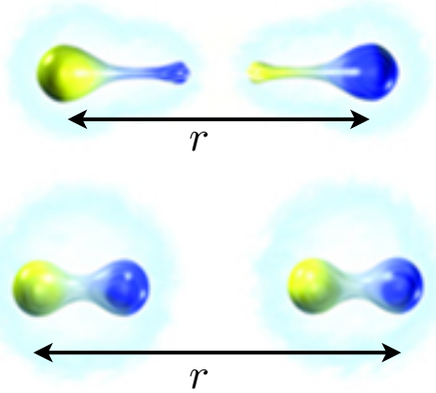

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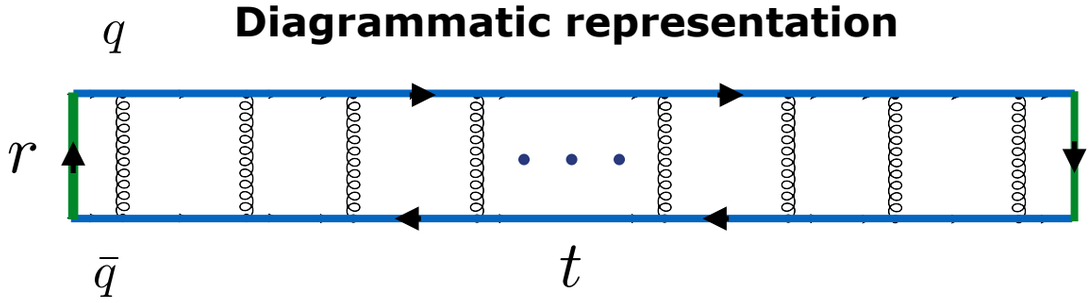

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QCD mass gap

Millenium prize problem

'Show that Yang-Mills theory exists
and has a (spectral) mass gap'

Confinement & the QCD mass gap

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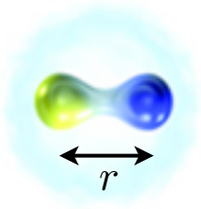

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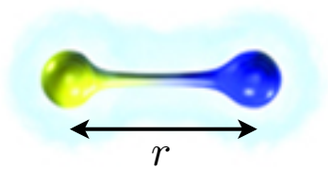

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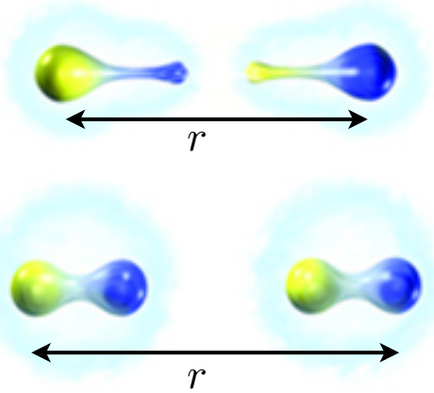

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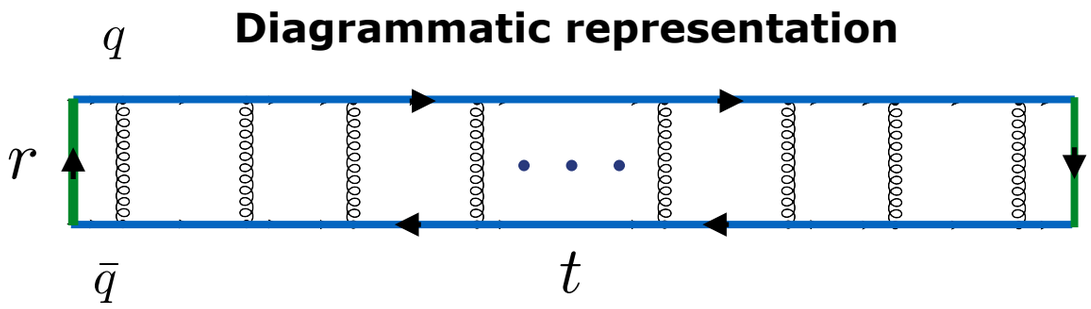

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Glueball masses in Yang-Mills theory

Glueball		Mass
J^{PC}	0^{++}	$\sim 1800\,\mathrm{MeV}$
scalar		
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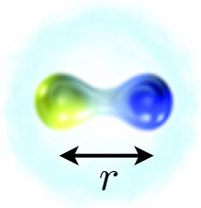

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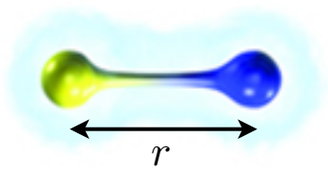

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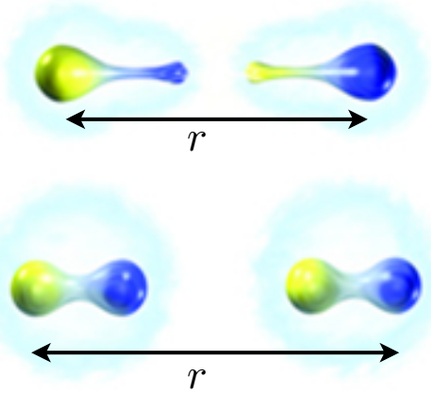

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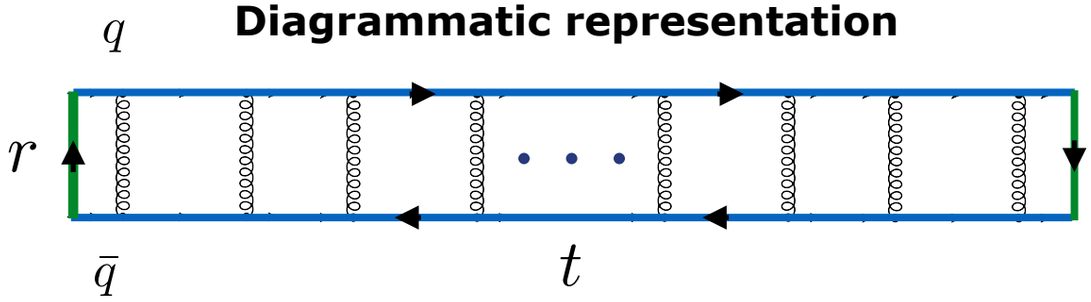

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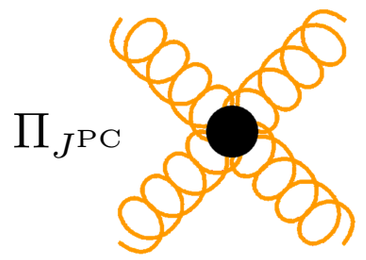

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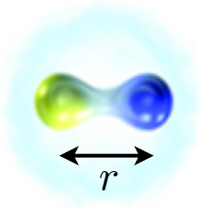

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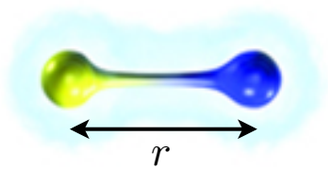

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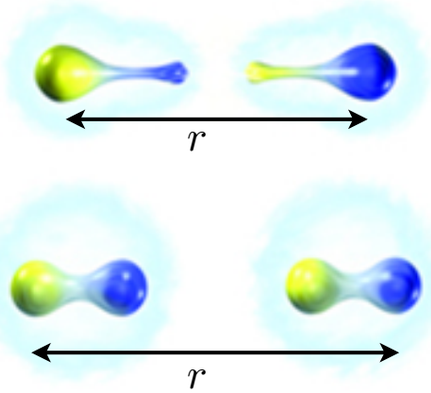

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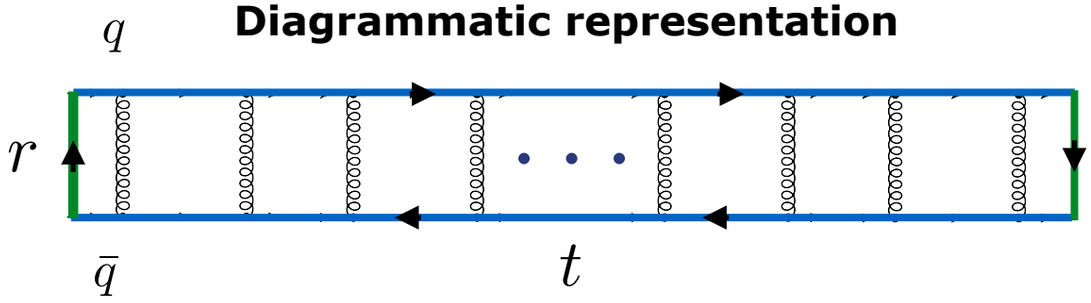

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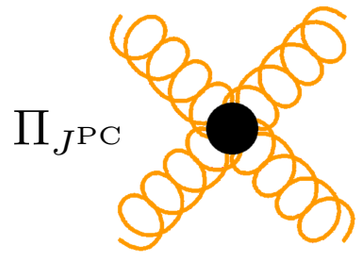

Both properties stem from the gluon mass gap

Gluon mass gap with the functional renormalisation group

Landau gauge QCD

Founding fRG papers

Ellwanger, Hirsch, Weber, *Z.Phys.C* 69 (1996) 687-698

***Eur.Phys.J.C* 1 (1998) 563-578**

Axel Weber ‘95

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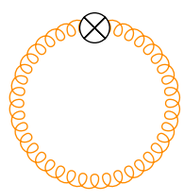
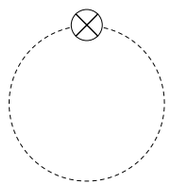
Flow equation for effective action

$$\partial_t \Gamma[A] = \frac{1}{2}$$  $$-$$ 

$$t = \log k/k_{\mathrm{ref}}$$

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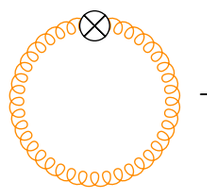
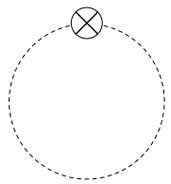
$$\partial_t \Gamma[A] = \frac{1}{2}$$  $$-$$ 

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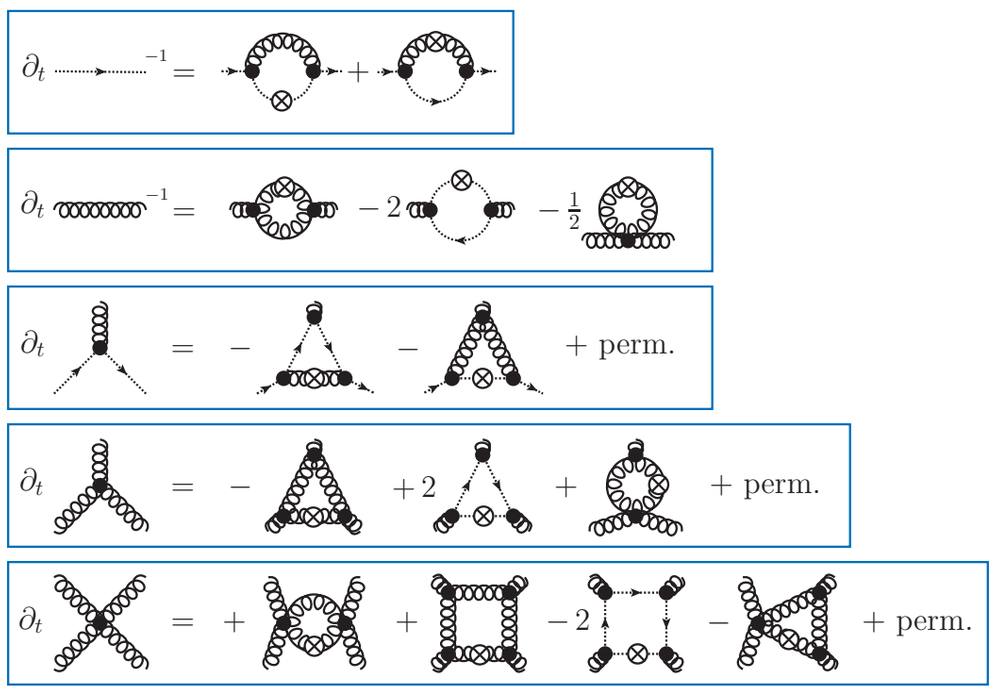

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Papavassiliou et al

'Most serious (advanced) contender'

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BRST-quartet

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Gluon condensates

Topic here

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Gluon condensates

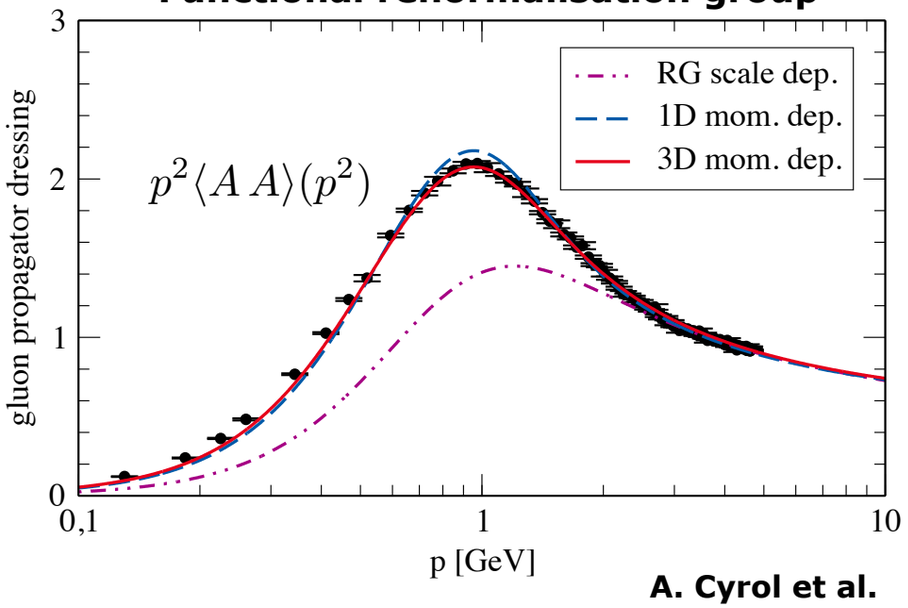
Topic here

Facets of the same confinement dynamics?

Gluon propagators ‘off the shelf’

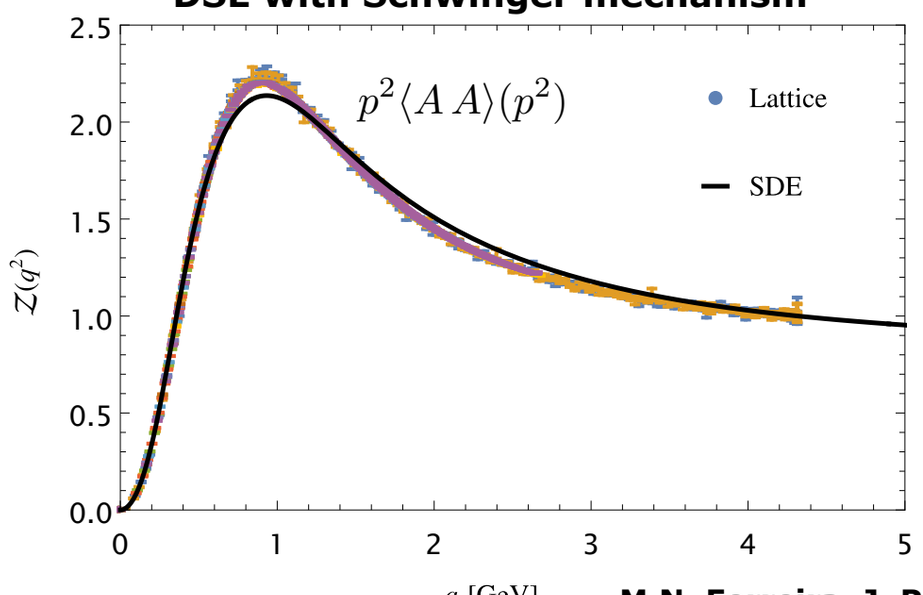
Gluon dressing function in the Landau gauge

Functional renormalisation group



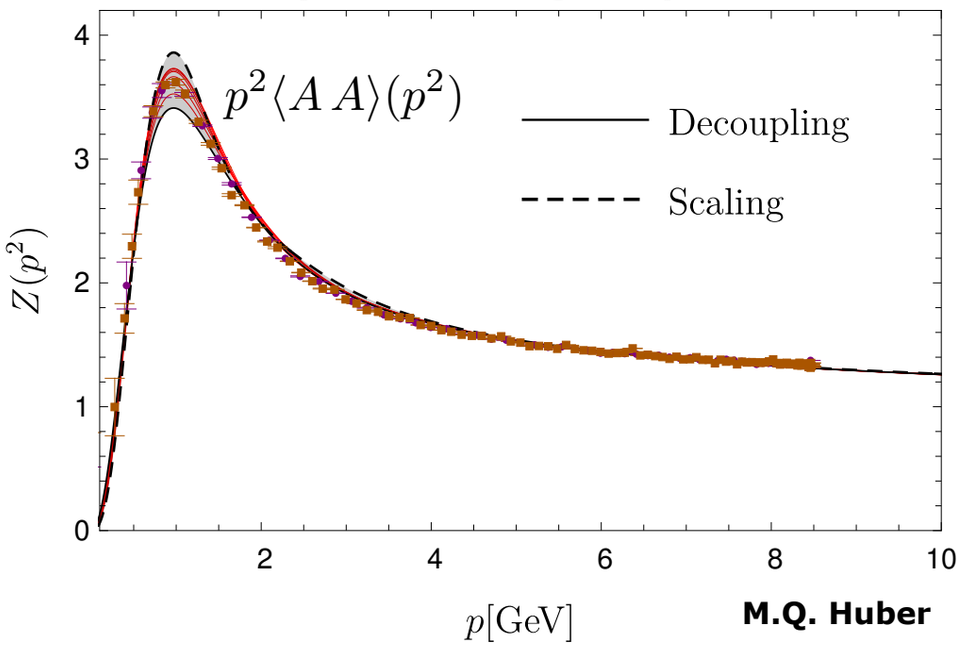
A. Cyrol et al.

DSE with Schwinger mechanism



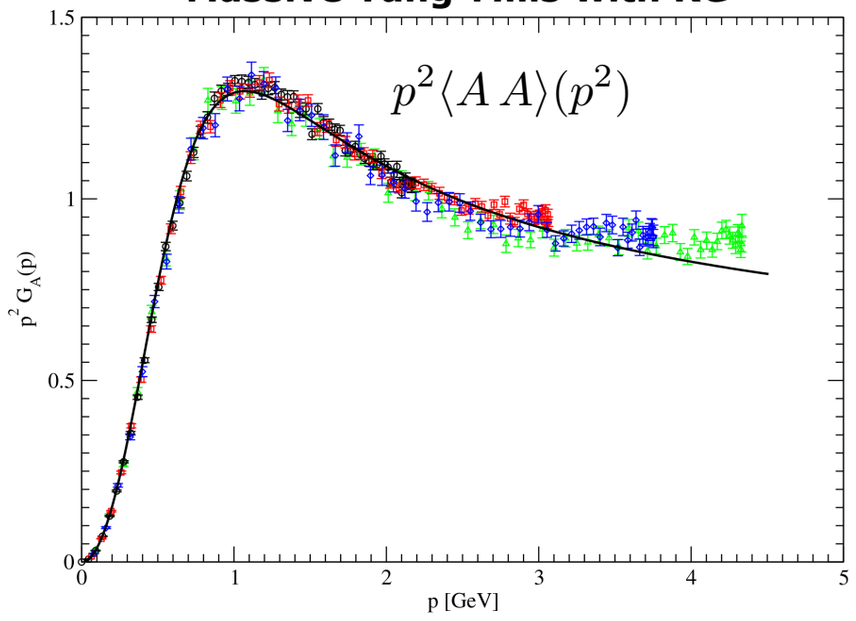
M.N. Ferreira, J. Papavassiliou

Dyson-Schwinger equation



M.Q. Huber

Massive Yang-Mills with RG

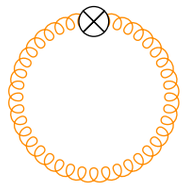
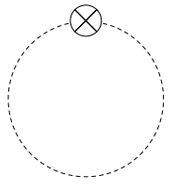


P. Dall’Olio, A. Weber

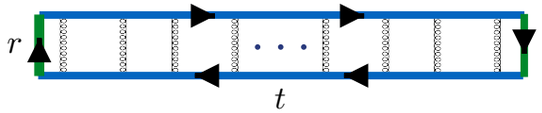
Gluon mass gap & Confinement

Screening-mass induced confinement

Polyakov loop potential

$$\partial_t V(A_0) = \frac{1}{2}$$  $$-$$ 

Deconfining Confining



$$\langle L[A_0](\boldsymbol{x})\, L^\dagger[A_0](\boldsymbol{x}+\hat{\boldsymbol{r}})\rangle$$

Gluon mass gap & Confinement

Screening-mass induced confinement

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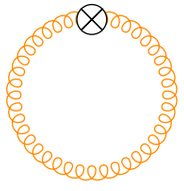
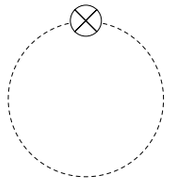
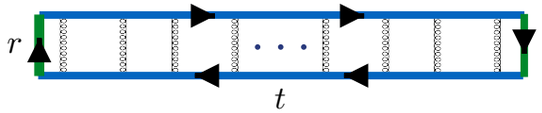
$$\partial_t V(A_0) = \frac{1}{2}$$  $$-$$ 

Deconfining Confining



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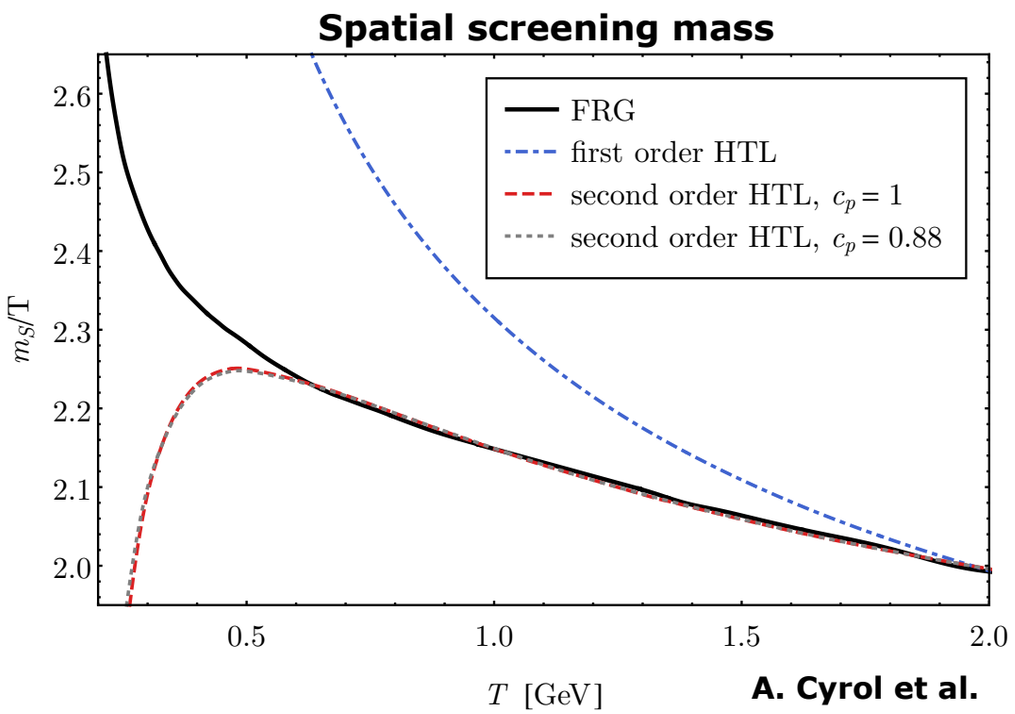

$$\int_{-\infty}^{\infty} \frac{dp}{2\pi} \left\langle A_0(\boldsymbol{p})\, A_0(-\boldsymbol{p})\right\rangle e^{\mathrm{i}\, p\, x} \quad \overset{x\to\infty}{\longrightarrow} \quad c_e\, e^{-m_s x}$$

$$p_0 = 0 \qquad\qquad p = \|\boldsymbol{p}\|$$

Gluon mass gap & Confinement

Screening-mass induced confinement

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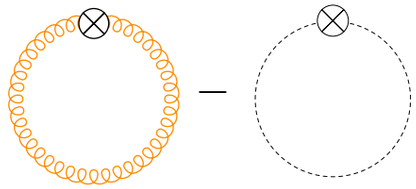
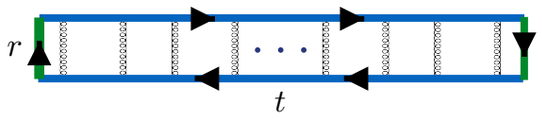
$$\partial_t V(A_0) = \frac{1}{2}$$  $$-$$

Deconfining **Confining**



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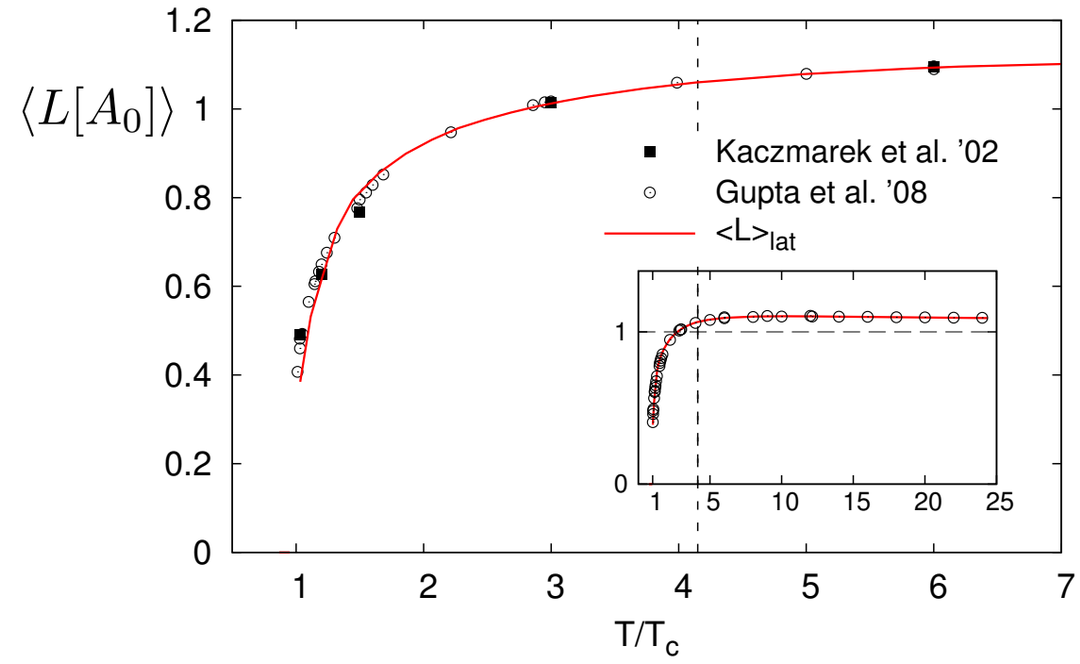
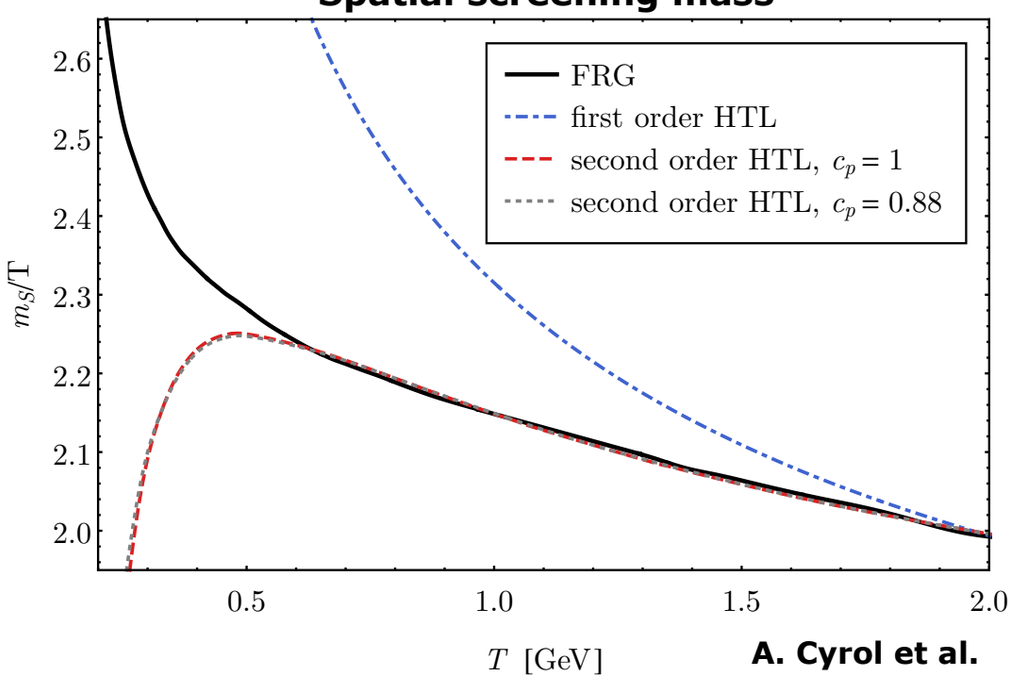


T. Herbst et al.

Spatial screening mass



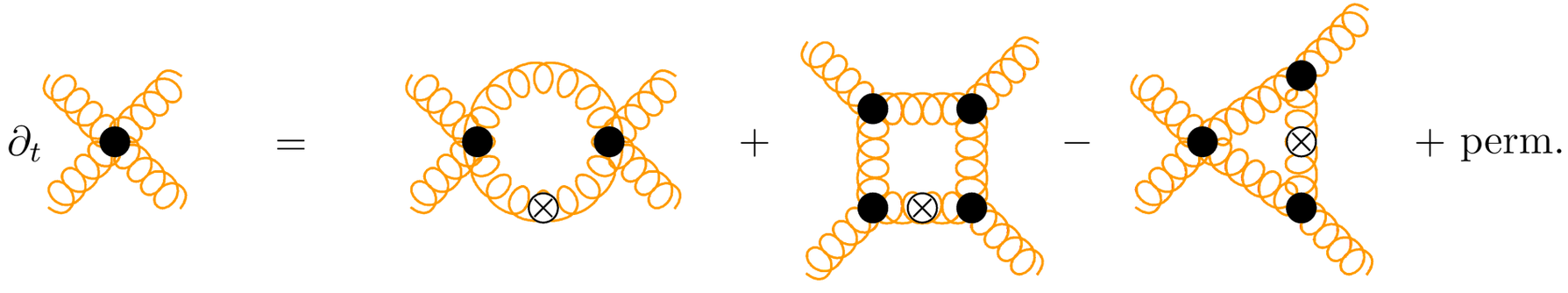
A. Cyrol et al.

$$\int_{-\infty}^{\infty} \frac{dp}{2\pi} \left\langle A_0(\boldsymbol{p})\, A_0(-\boldsymbol{p})\right\rangle e^{\mathrm{i}\, p\, x} \quad \overset{x\to\infty}{\longrightarrow} \quad c_e\, e^{-m_s x}$$

$$p_0 = 0 \qquad\qquad p = \|\boldsymbol{p}\|$$

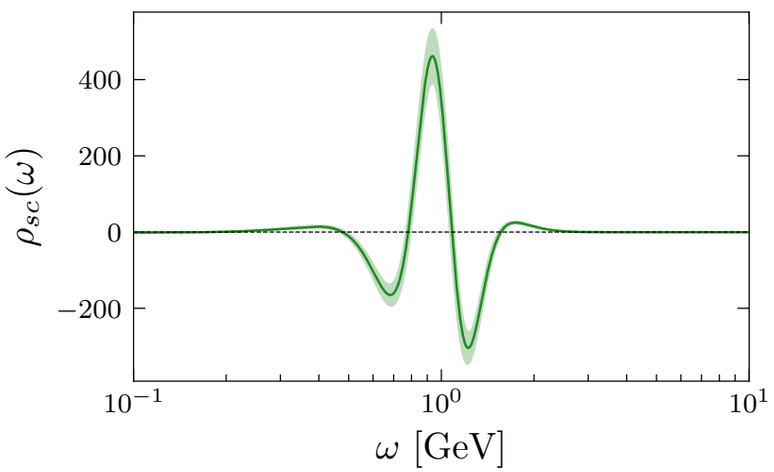
Gluon mass gap & spectral mass gap in Yang-Mills

Bound state masses from screening masses

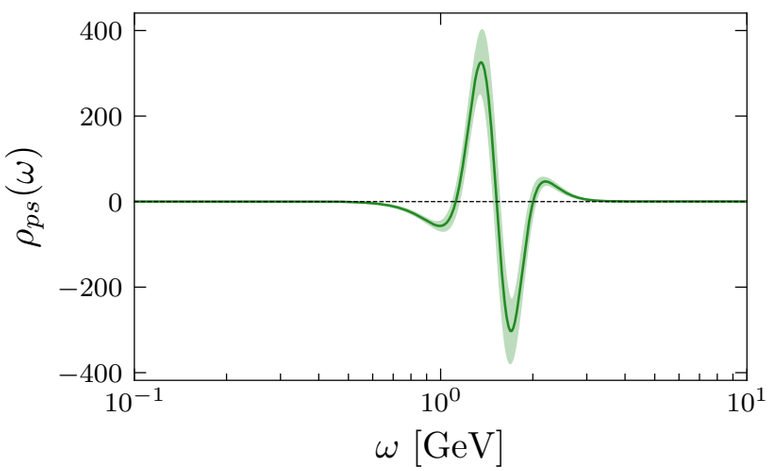


Spectral functions of 4-gluon vertex

Scalar channel



Pseudoscalar channel



Schneider, Turnwald et al.

$m_{0^{++}} = 1840\,\mathrm{MeV}$

$m_{0^{-+}} = 2700\,\mathrm{MeV}$

Gluon condensate

Worked out during Axel's stay 20/21 as a guest professor /EMMI visiting professor at the Institute for Theoretical Physics, U Heidelberg

Color condensate operator

$$\chi^{AB} = \frac{1}{2} F^a_{\mu\nu} F^b_{\mu\nu} \left(\{t^a \, , \, t^b\}^{AB} - \frac{1}{N_c} \delta^{ab} \delta^{AB} \right)$$

Horak, Ihssen, Papavassiliou, JMP, Weber, Wetterich, *SciPost Phys.* 13 (2022) 2, 042

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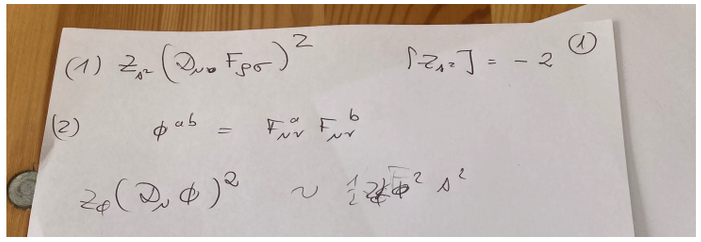
During Axel's stay in Heidelberg, summer 2021



Notes from 22th October 2020

Horak, Ihssen, Papavassiliou, JMP, Weber, Wetterich, *SciPost Phys.* 13 (2022) 2, 042

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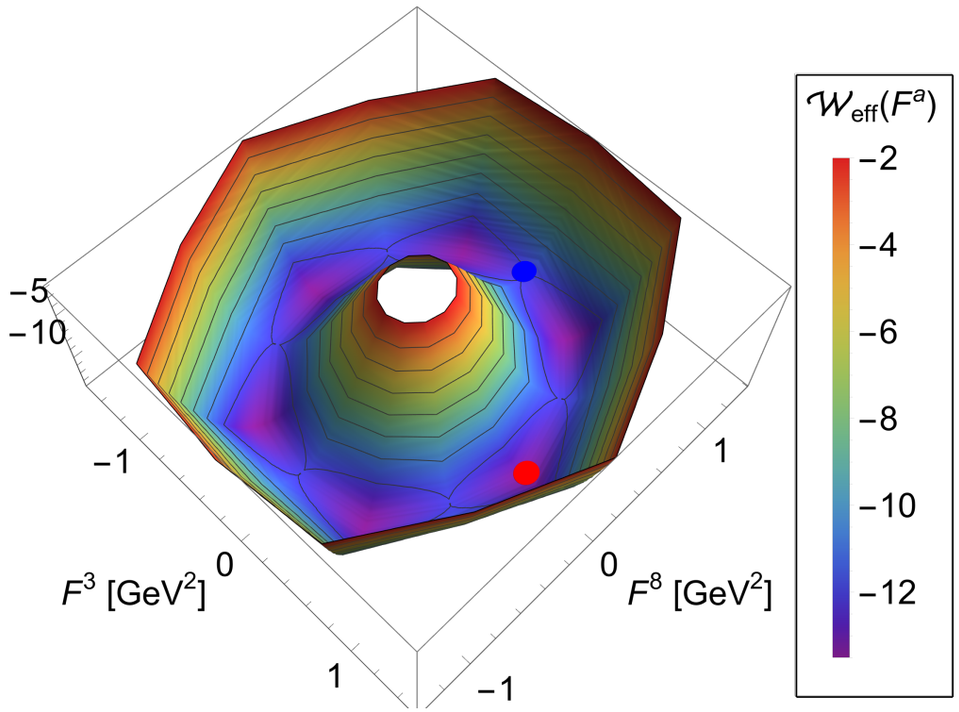
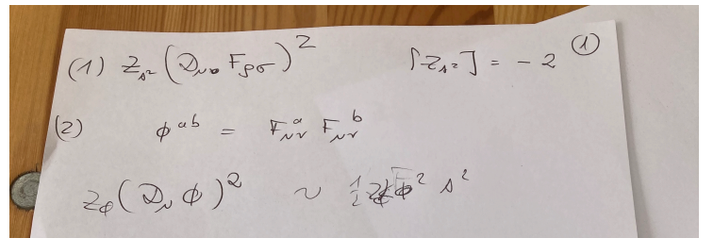
Effective potential $\mathcal{W}_{\rm eff}(F^a)$





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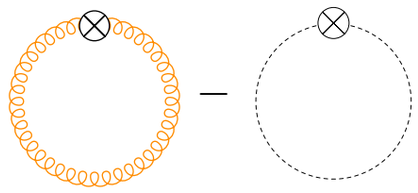
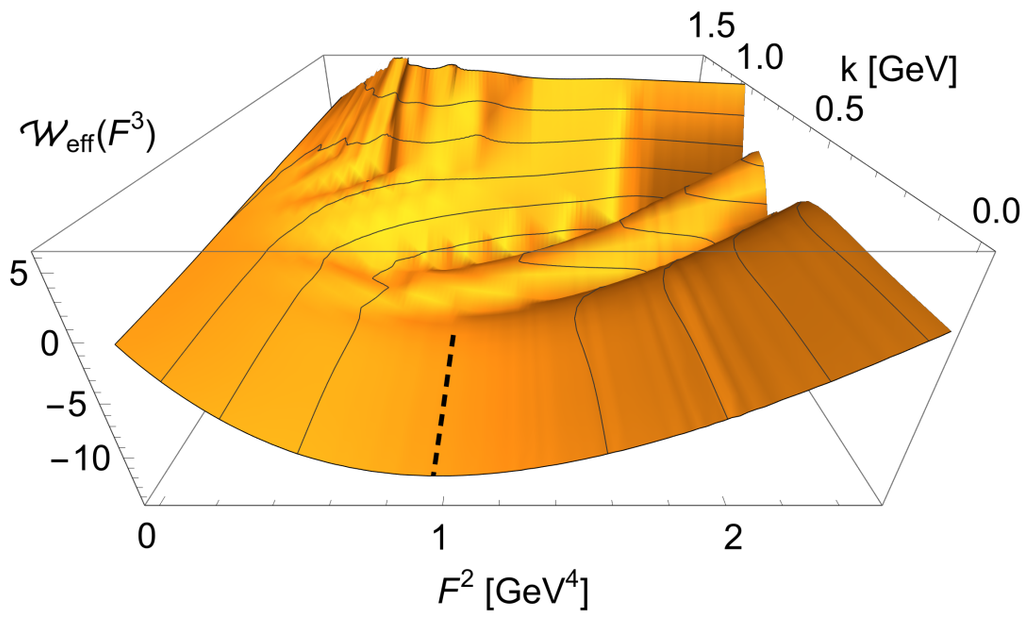
Horak, Ihssen, Papavassiliou, JMP, Weber, Wetterich, *SciPost Phys.* 13 (2022) 2, 042

Gluon condensate

Flow of effective potential

$$\partial_t \mathcal{W}_{\rm eff}(F) = \frac{1}{2}$$  $$-$$

Scale-dependence of $\mathcal{W}_{\rm eff}(F^a)$



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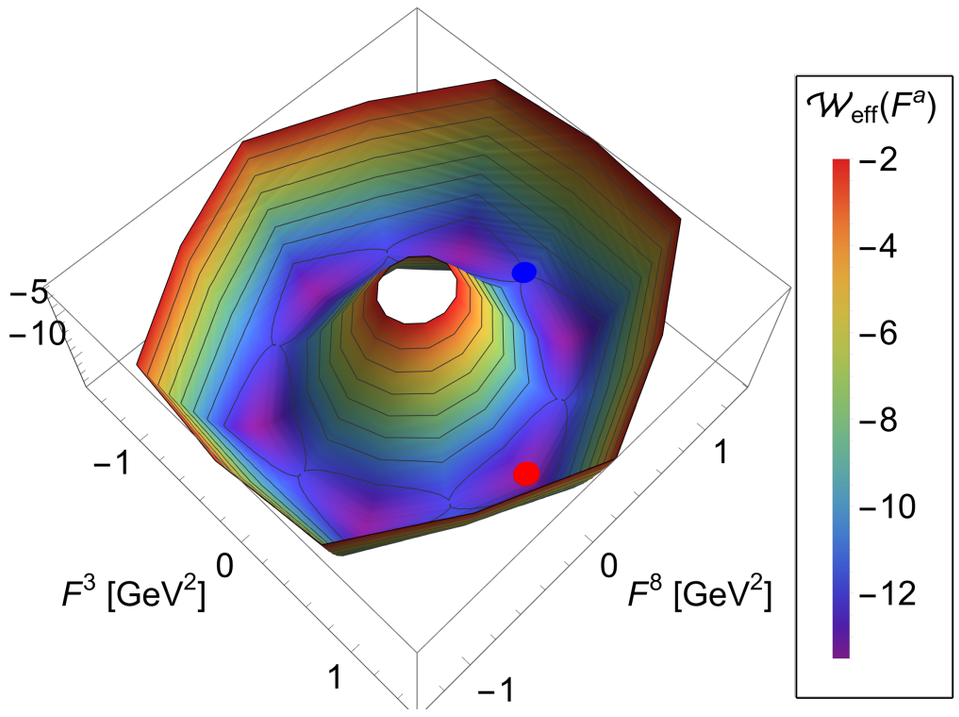

Fieldstrength at minimum

$$\langle F \rangle^2_{\lambda_3} = 0.98(11)\,\mathrm{GeV}^4$$

Horak, Ihssen, Papavassiliou, JMP, Weber, Wetterich, *SciPost Phys.* 13 (2022) 2, 042

Gluon mass gap

Expansion of effective action about the color condensate

$$\Gamma_F[A] = \frac{Z_F}{4}\int_x (D_\mu F_{\nu\rho})^a (D_\mu F_{\nu\rho})^a \quad \rightarrow \quad \Gamma_F[A] \simeq \frac{1}{2} m_3^2 \int_x A_\mu^a A_\mu^a + \cdots$$

$$m_3^2 = \frac{Z_F}{8}\langle F \rangle^2$$

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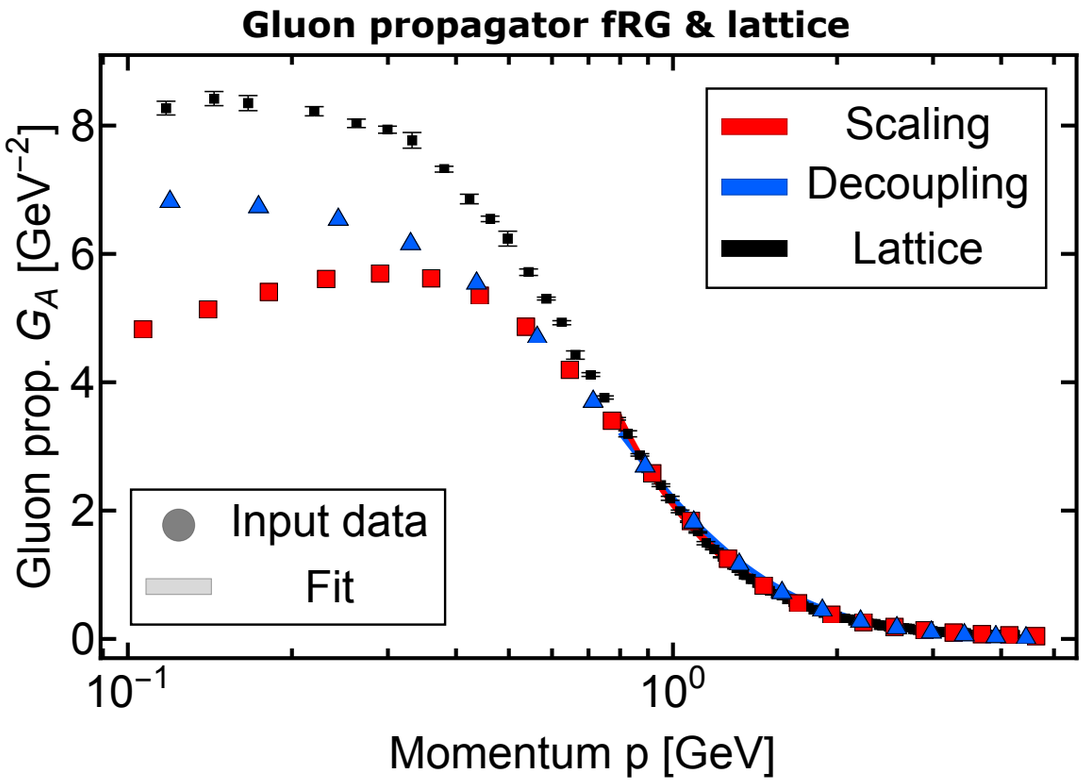

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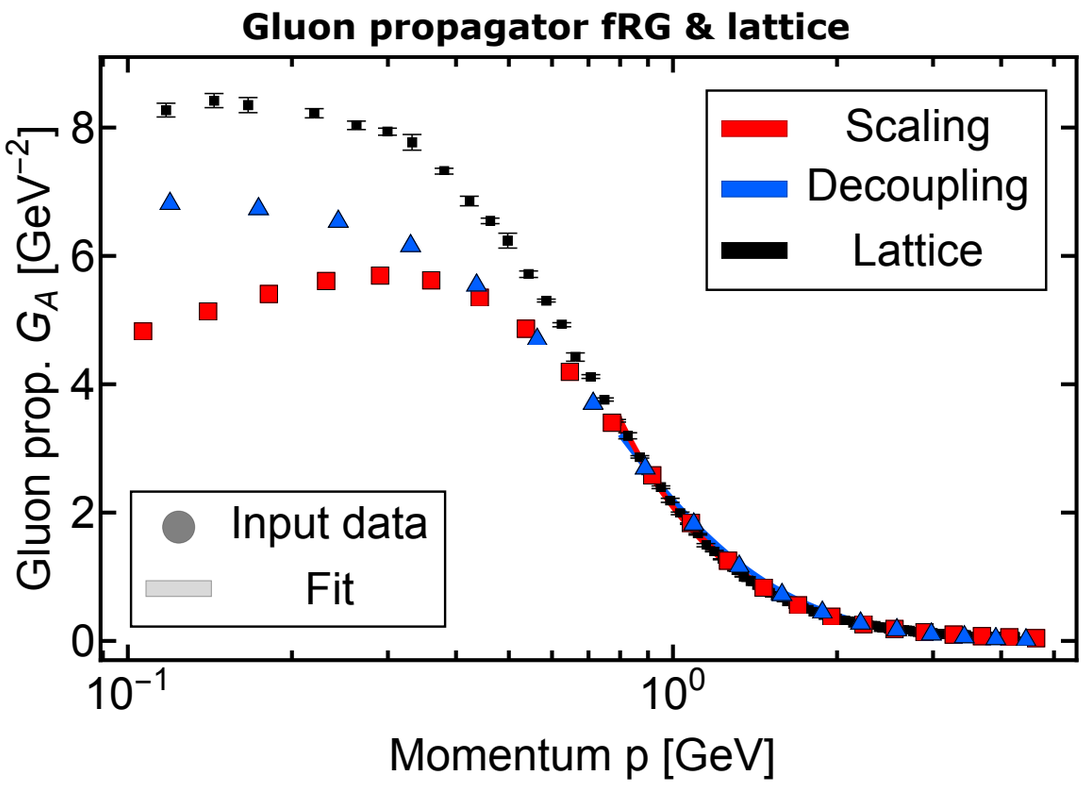

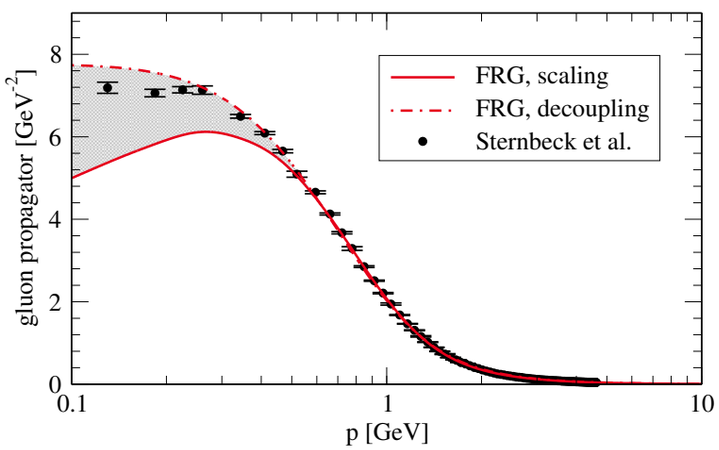

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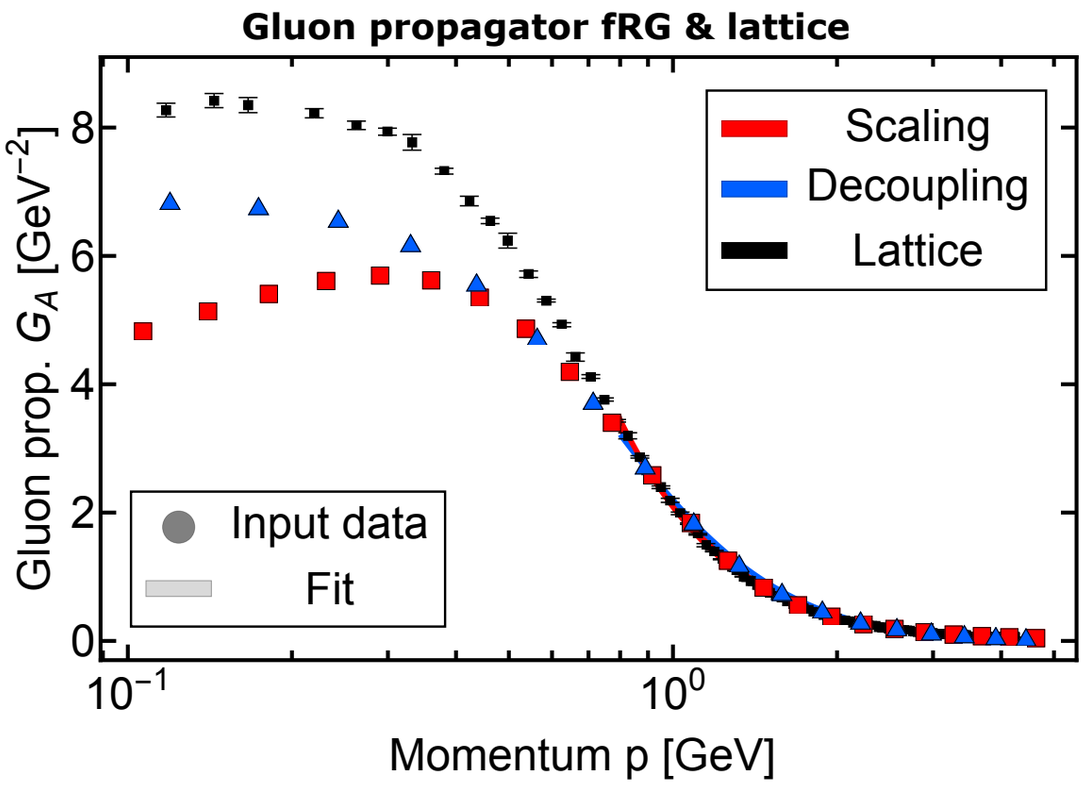
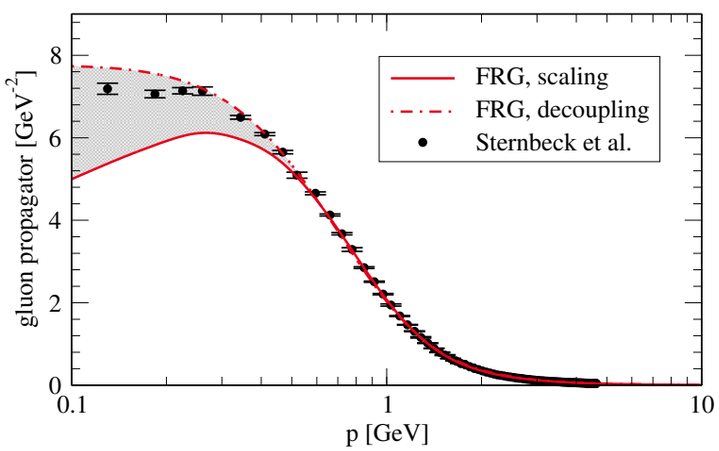




Condensate-induced mass gap

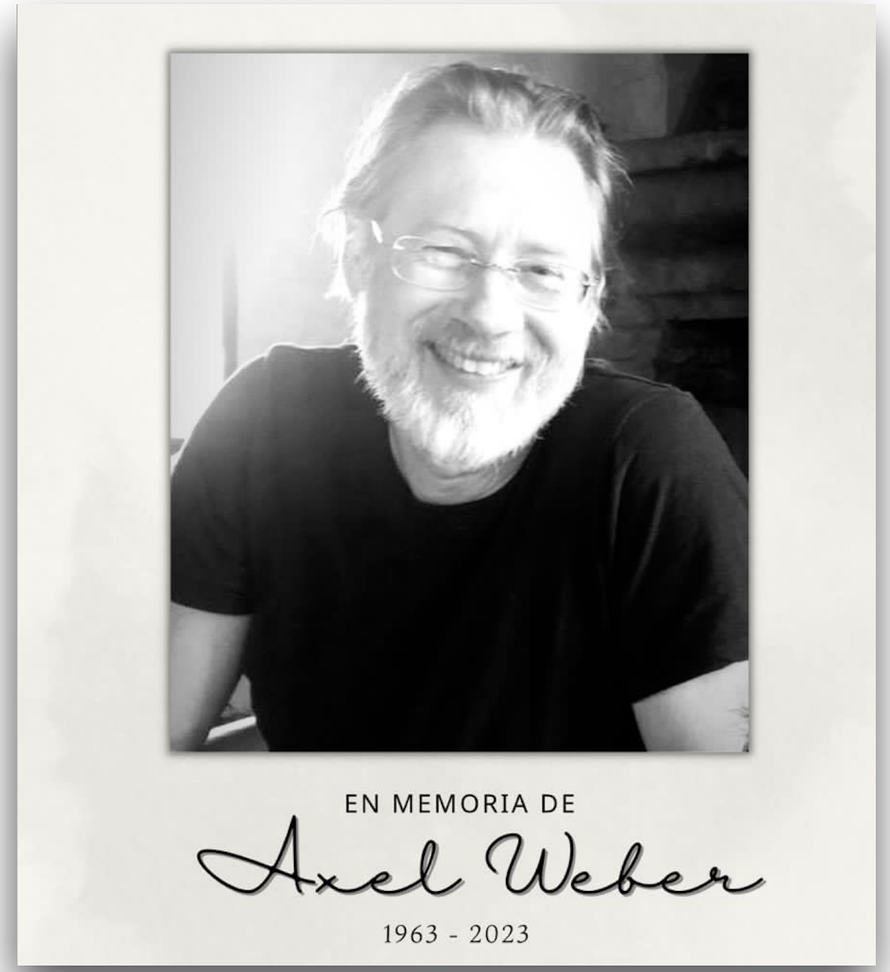
$$m_{\rm gap} = 0.312(27)\,{\rm GeV}$$

$$m_{\rm gap}^{\rm (lattice)} = 0.3536(11)\,{\rm GeV}$$

$$m_{\rm gap}^{\rm (Schwinger)} = 0.320(35)\,{\rm GeV}$$

Horak, Ihssen, Papavassiliou, JMP, Weber, Wetterich, *SciPost Phys.* 13 (2022) 2, 042

In fond memory of



You are dearly missed