First Principle QCD within fRG approach

Chuang Huang

Heidelberg University, Institute for Theoretical Physics

The QCD Phase Diagram: From Theory to Experimental Signatures, Oct. 7-11, 2025

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Based on:
Wei-jie Fu, CH, Jan M. Pawlowski, Yang-yang Tan, Li-jun Zhou, '*Four-quark scatterings in QCD III*', Phys. Rev. D 112 (2025), 054047;
Wei-jie Fu, CH, Jan M. Pawlowski, Yang-yang Tan, '*Four-quark scatterings in QCD II*', SciPost Phys. 17(2024), 148;
Wei-jie Fu, CH, Jan M. Pawlowski, Yang-yang Tan, '*Four-quark scatterings in QCD I*, SciPost Phys. 14 (2023) 069,;

fQCD collaboration: https://fqcd-collaboration.github.io/

Outline

- Introduction
- Computation setting and scale independence
- Chiral symmetry breaking and quark correlation functions
- Matter sector and chiral relation
- Summary and ***outlook***

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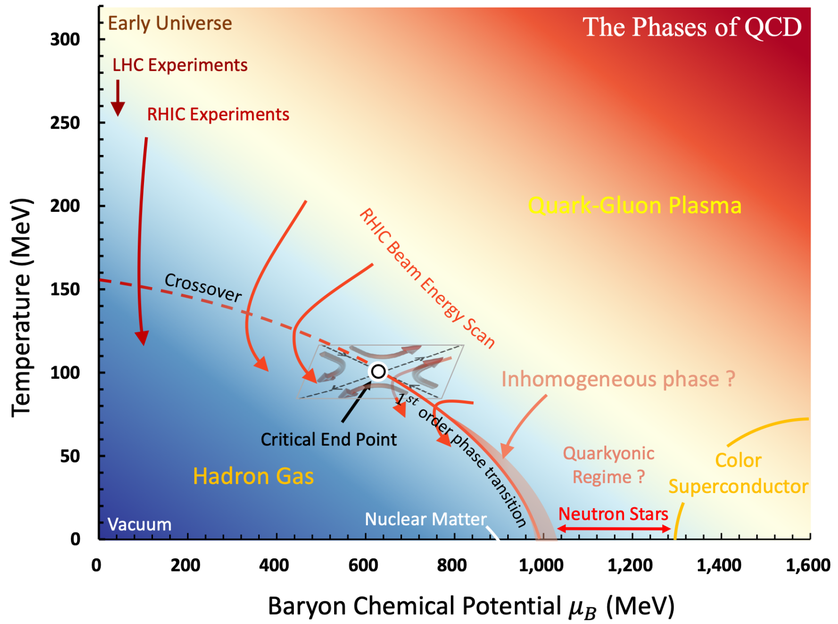
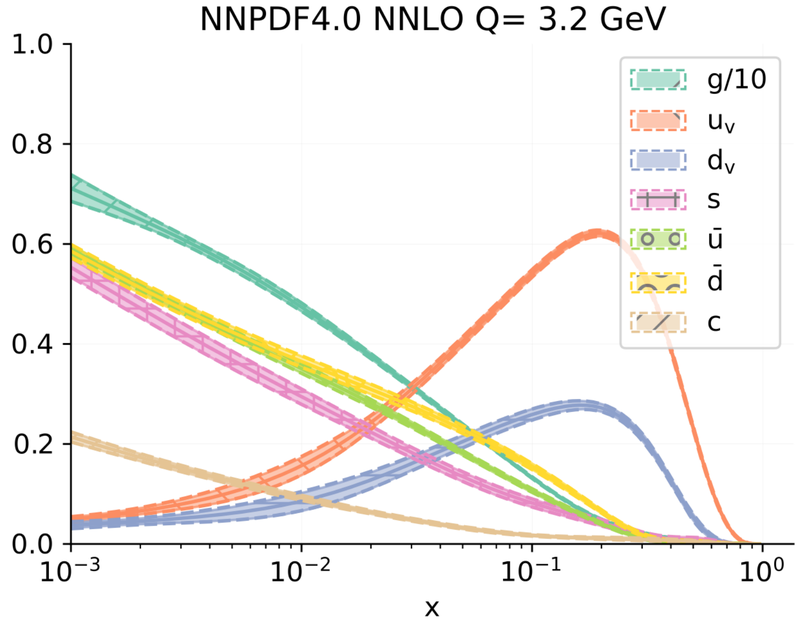
Topics in QCD Study

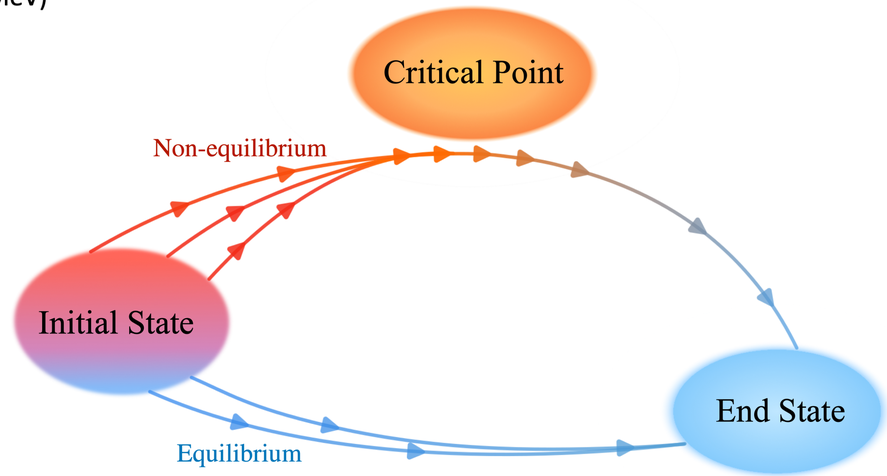
Phase Structure



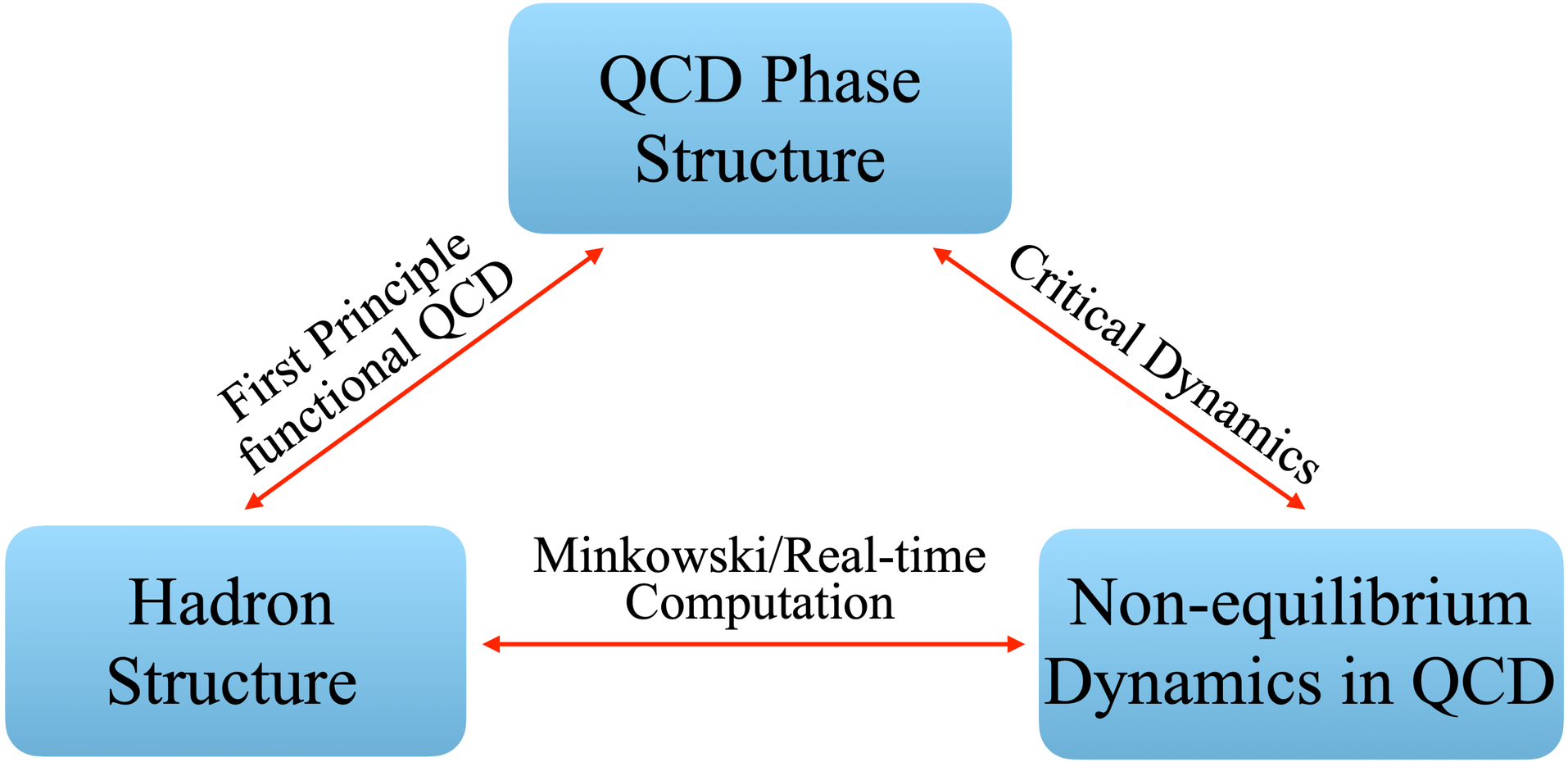
Hadron Structure



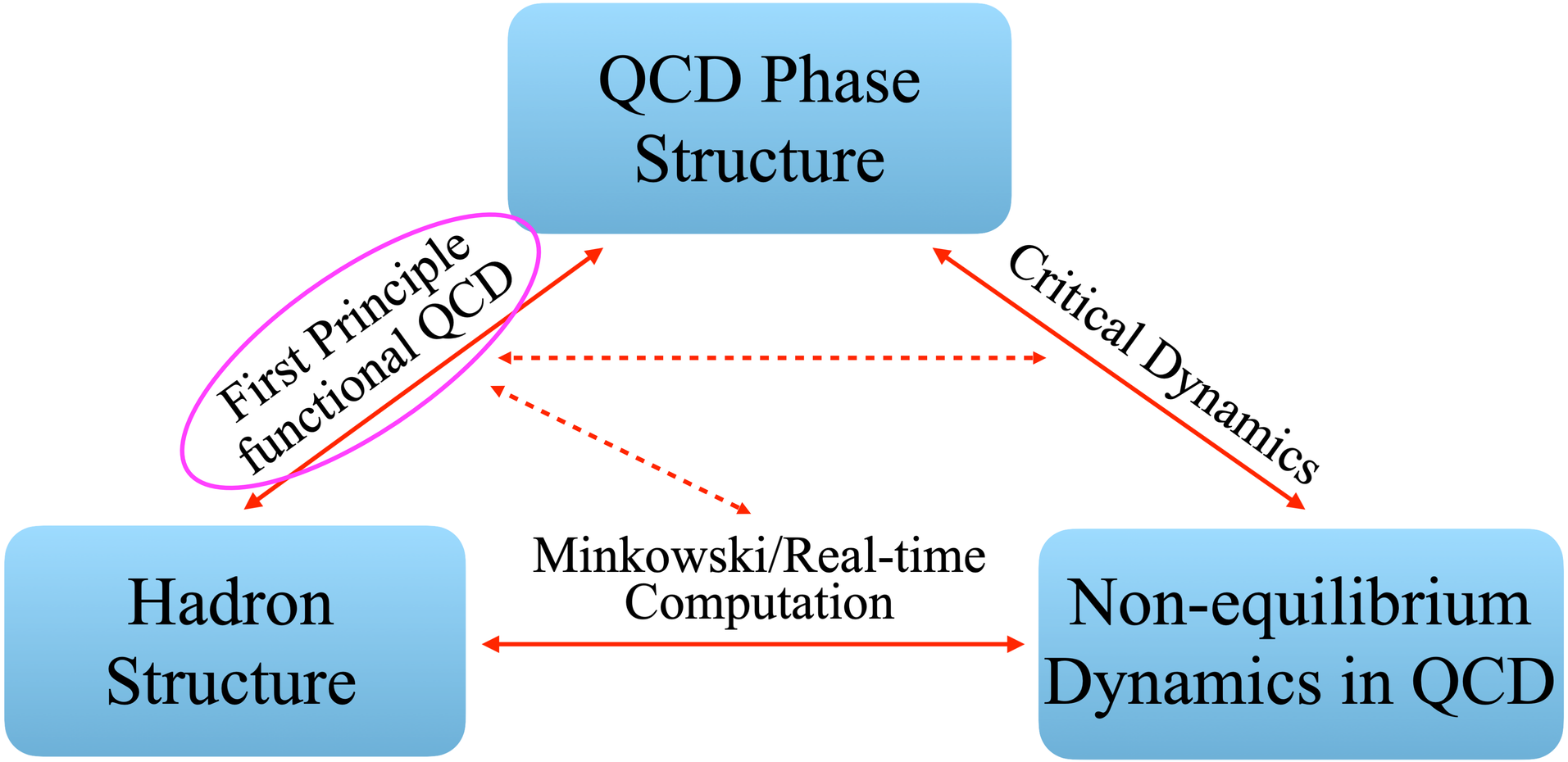
Non-equilibrium Dynamics



Theoretical Studies of Functional QCD



Theoretical Studies of Functional QCD



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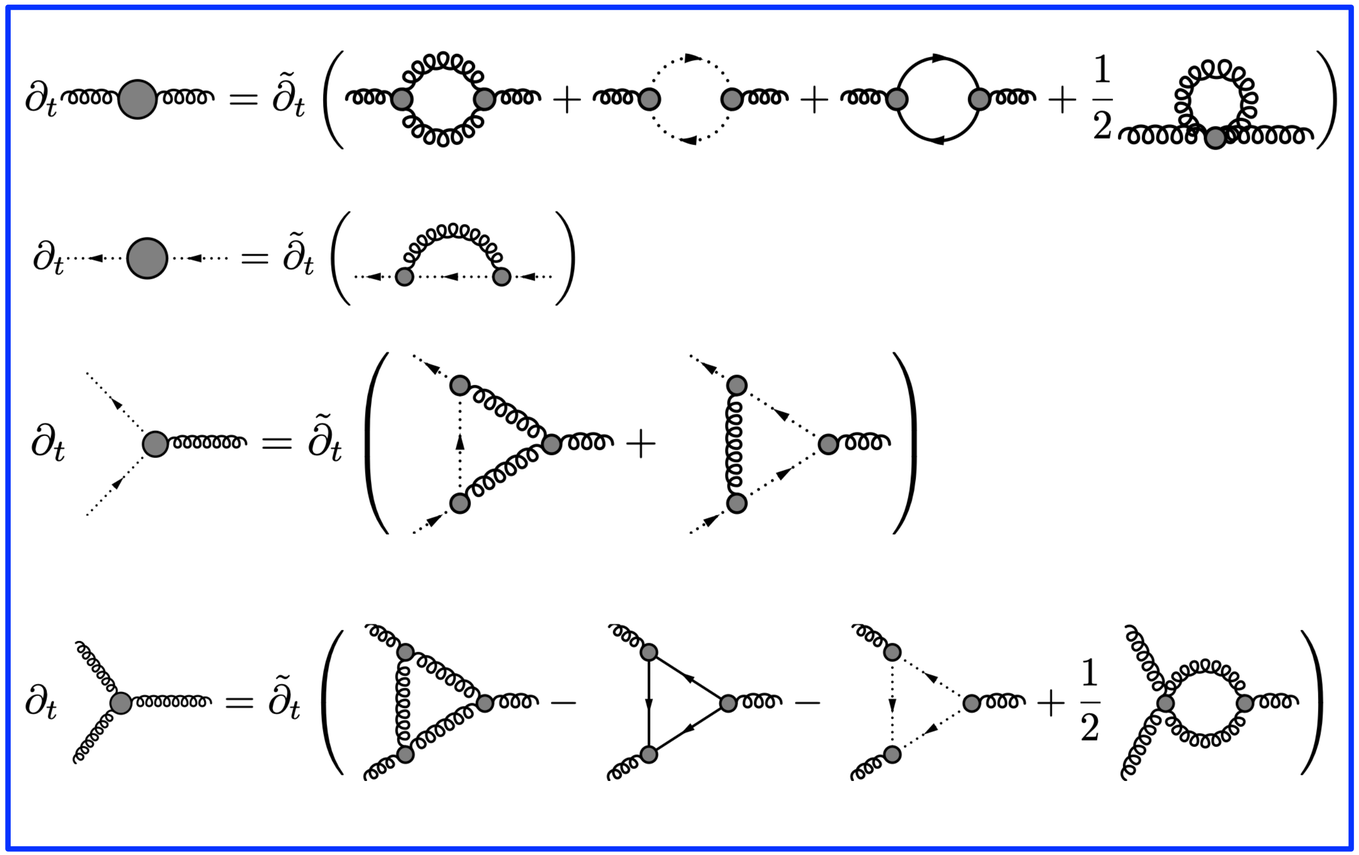
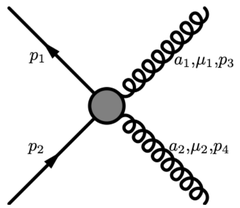
2+1 QCD with fRG

Glue sector

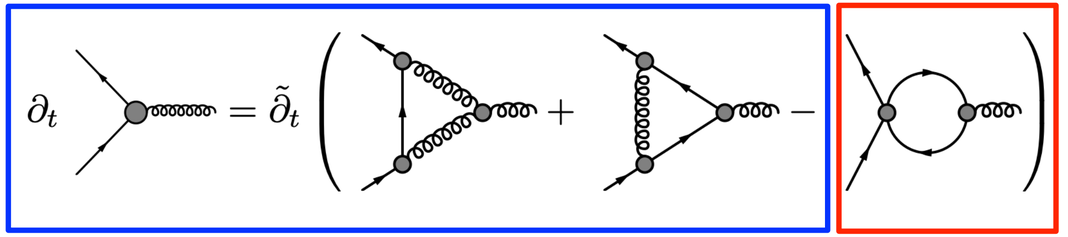


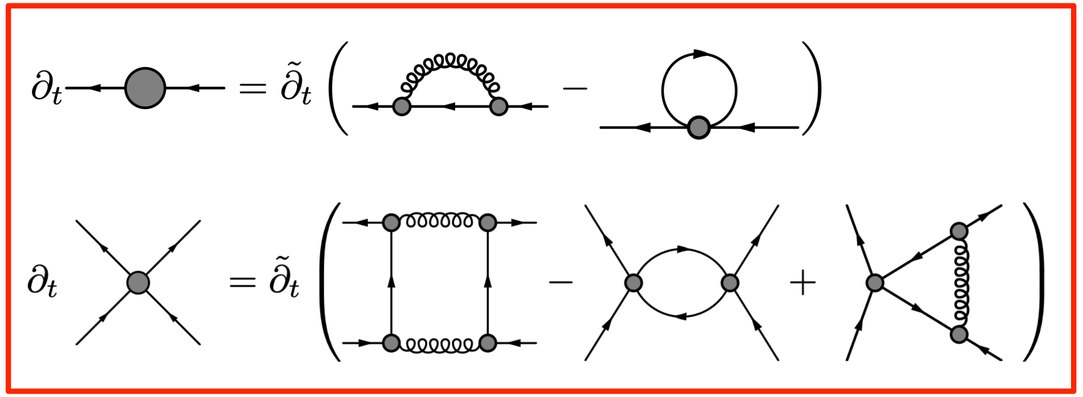
+



terms

Matter sector





Symmetry point truncation

$$\lambda^{(n)}(p_1, p_2, \cdots, p_n) \approx \lambda^{(n)}(\bar{p}) \quad \bar{p} = \sqrt{1/n \sum_i^n p_i^2}$$

s,t,u-channel truncation

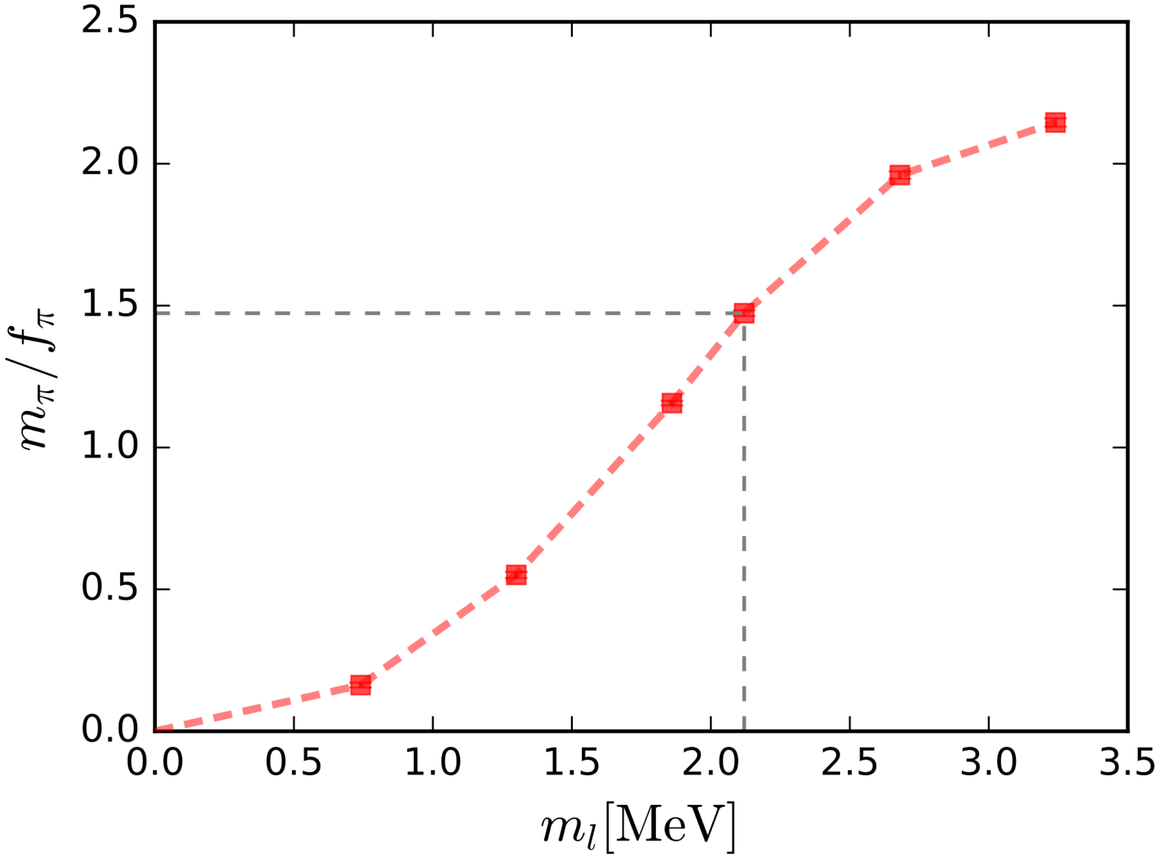
Computation setting

Parameters table

Observables	Value	Parameters	Value
m_π/f_π	137.0/93.0	m_l	2.1 MeV
m_K/f_π	494.0/93.0	m_s	55.9 MeV
M_l	344.5 MeV		
M_s	487.3 MeV		
m_σ	515.2 MeV		
f_K	114.1 MeV		

$\Lambda = 35.7\,\mathrm{GeV}$ $\alpha_{s,\Lambda} = 0.179$

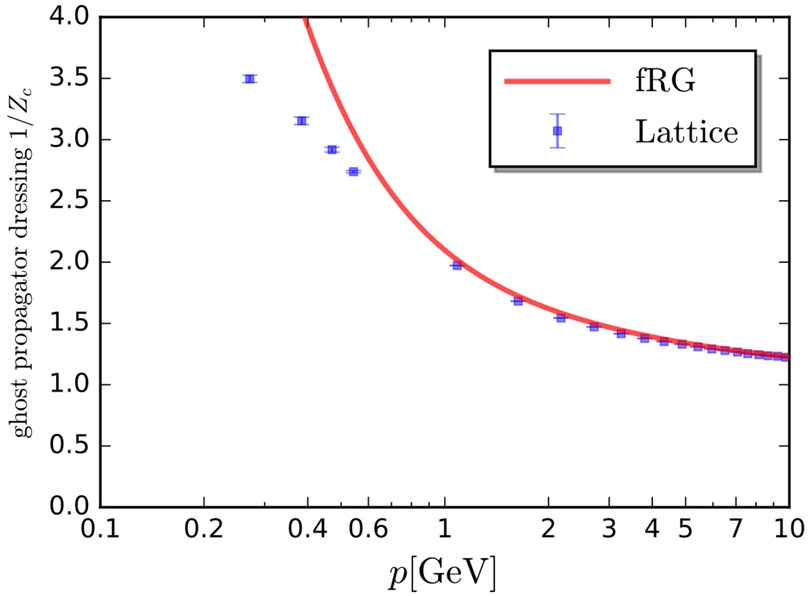
Parameters tuning



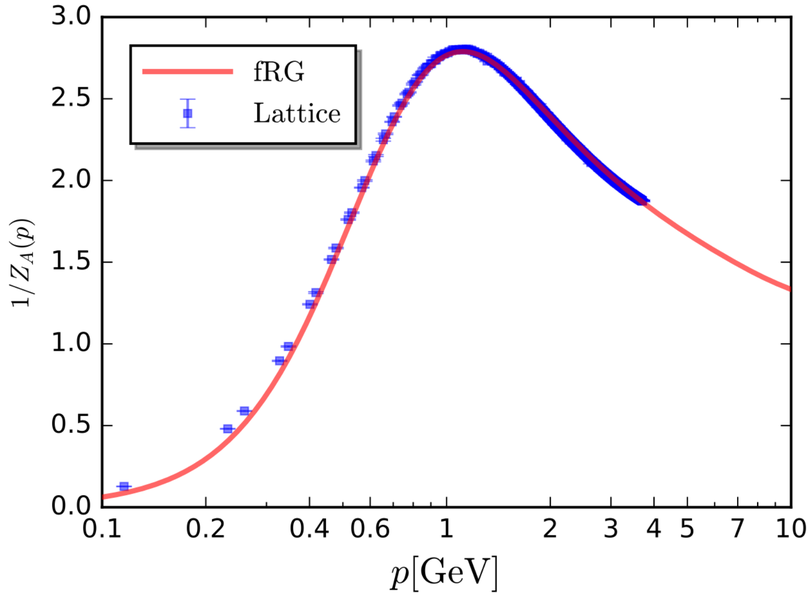
fRG: Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

Glue sector in QCD

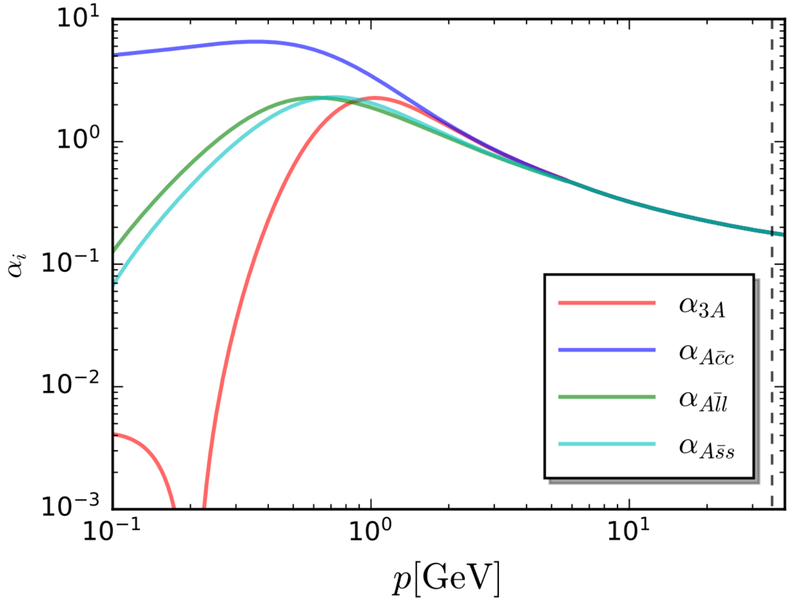
Ghost dressing



Gluon dressing



Couplings

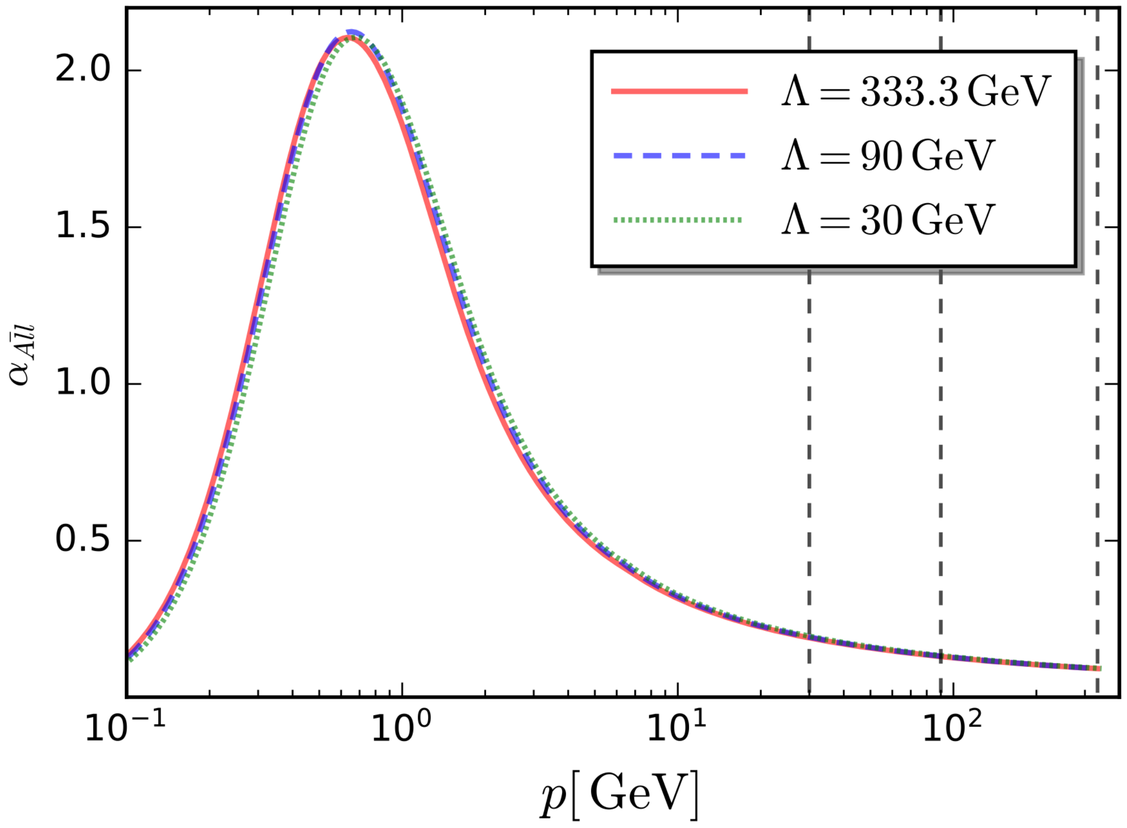


Lattice: Boucaud *et al.*, *PRD* 98 (2018) 114515

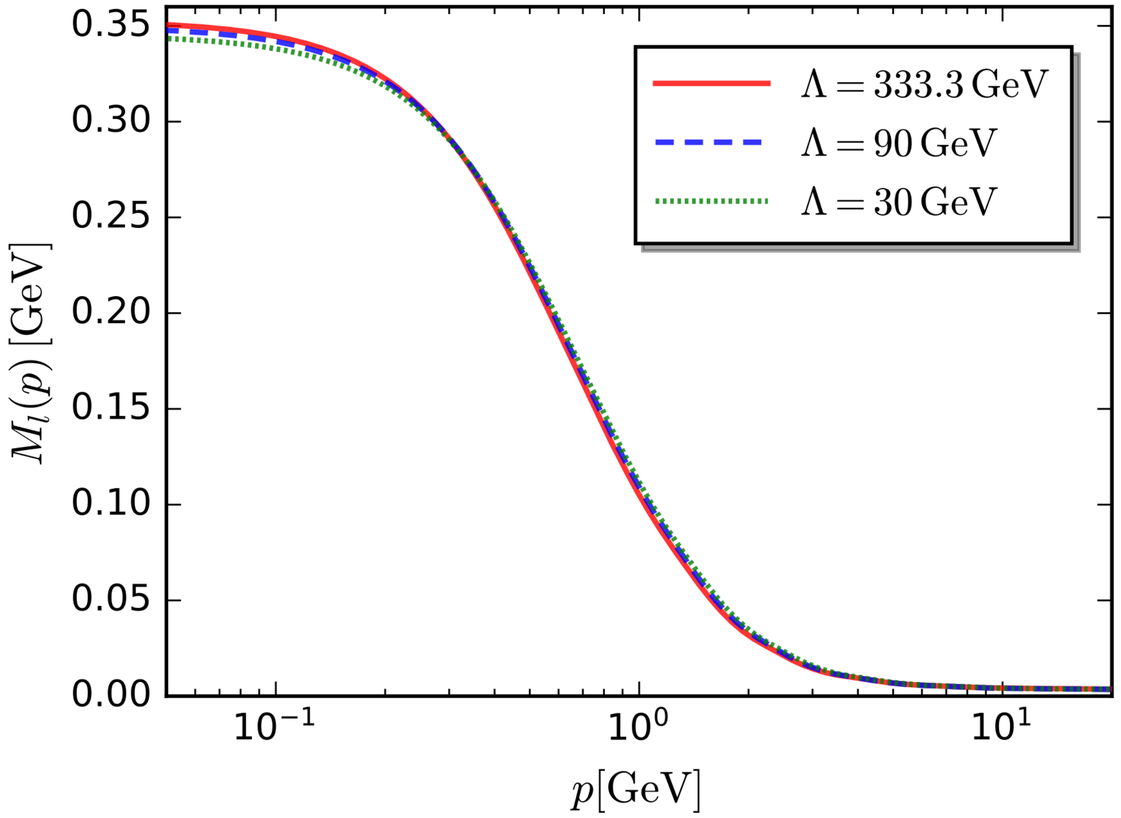
fRG: Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

Scale independence

Couplings



Quark mass



Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

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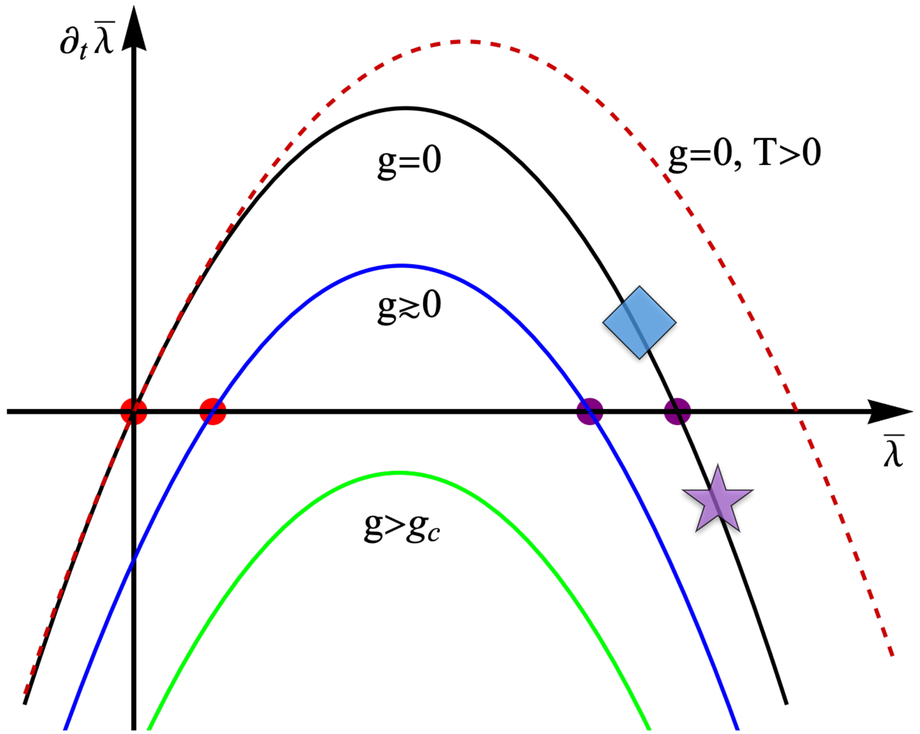
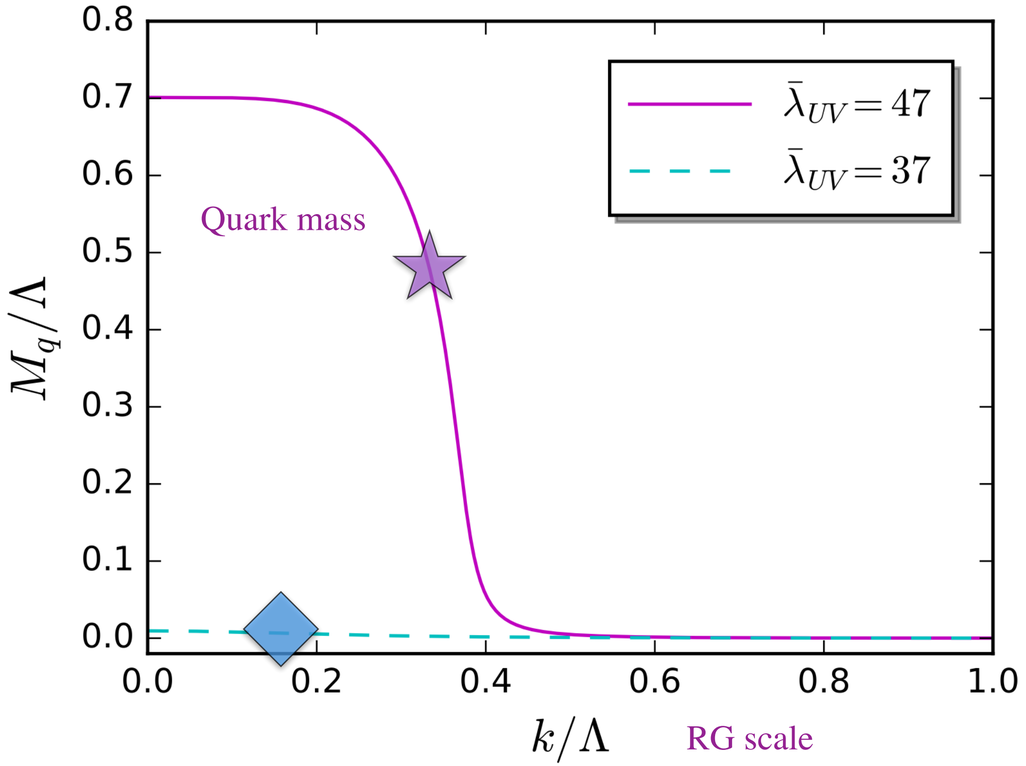
Chiral symmetry breaking

β function of 4-quark coupling

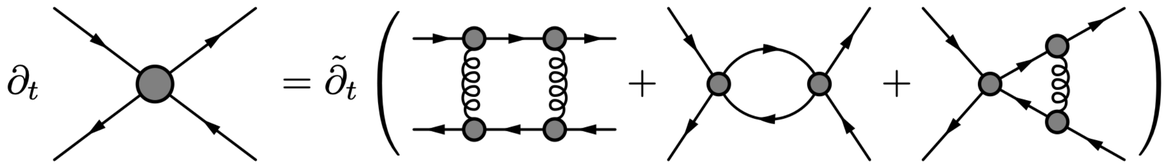


Braun, Gies, *JHEP* 06 (2006) 024.

$$\partial_t \bar{\lambda} = (d-2)\bar{\lambda} - a\bar{\lambda}^2 - b\bar{\lambda}g^2 - cg^4,$$
$$a = C_1,\ b = c = d = 0$$

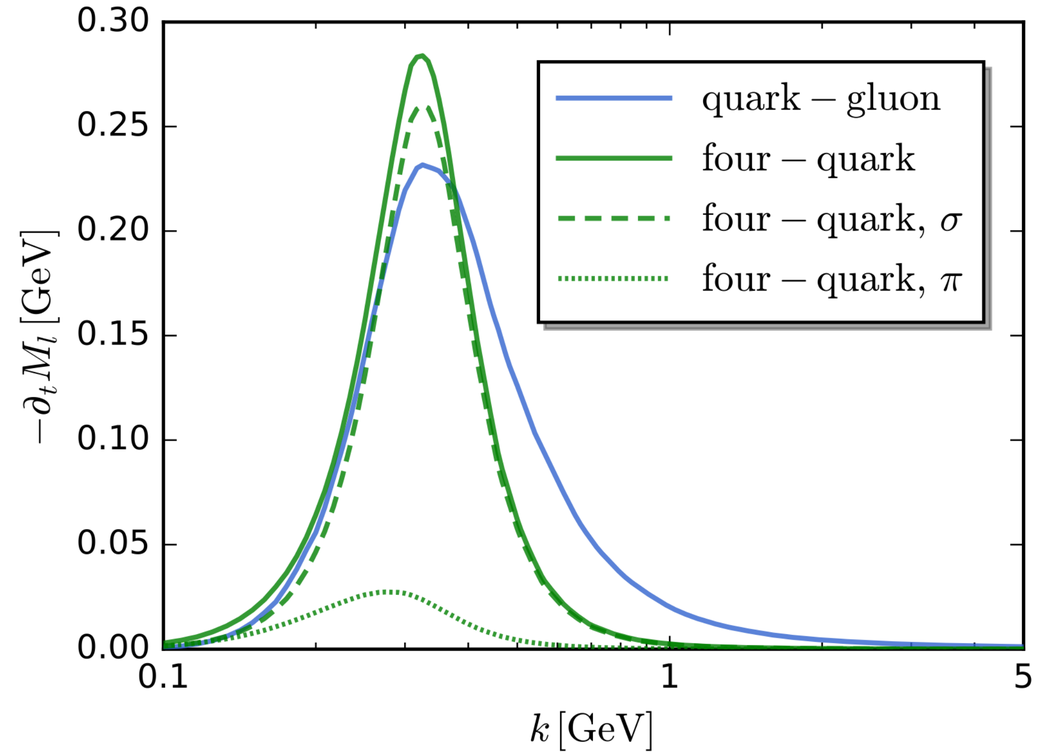


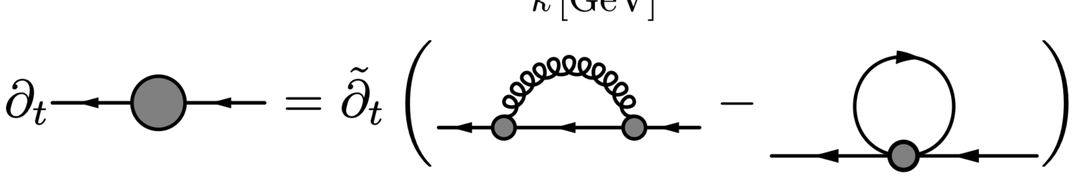
Fu, CH, Pawlowski, Tan, *SciPost Phys.* 14 (2023) 069



Flow analyze

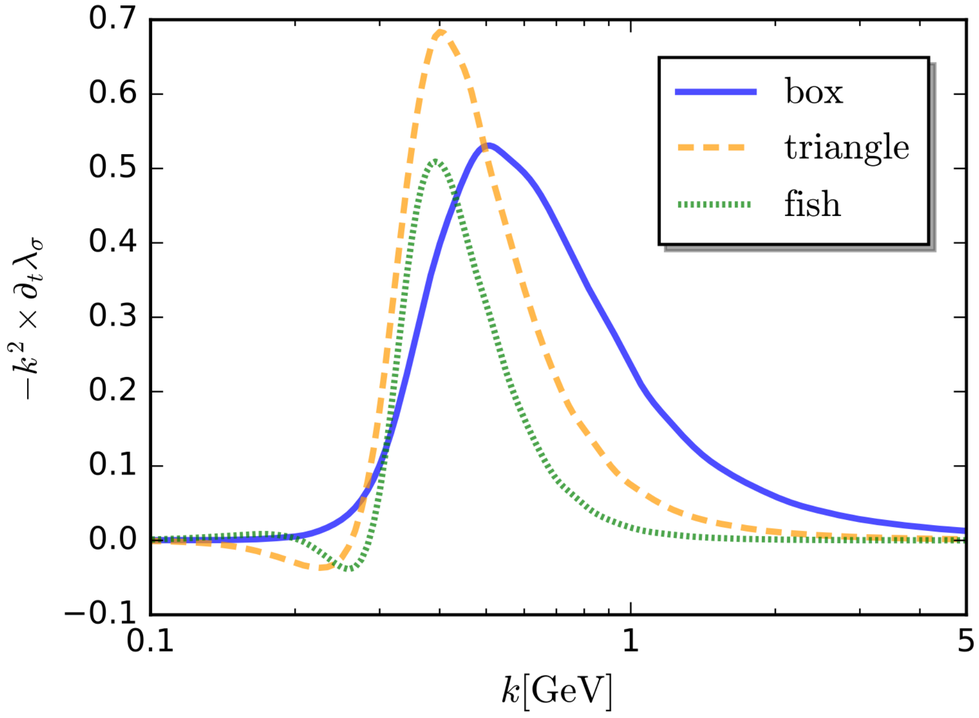
Flow of the light quark mass

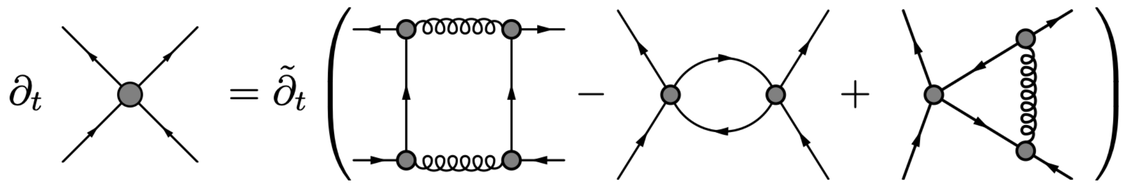




Quark-gluon Four-quark

Flow of the λ_σ



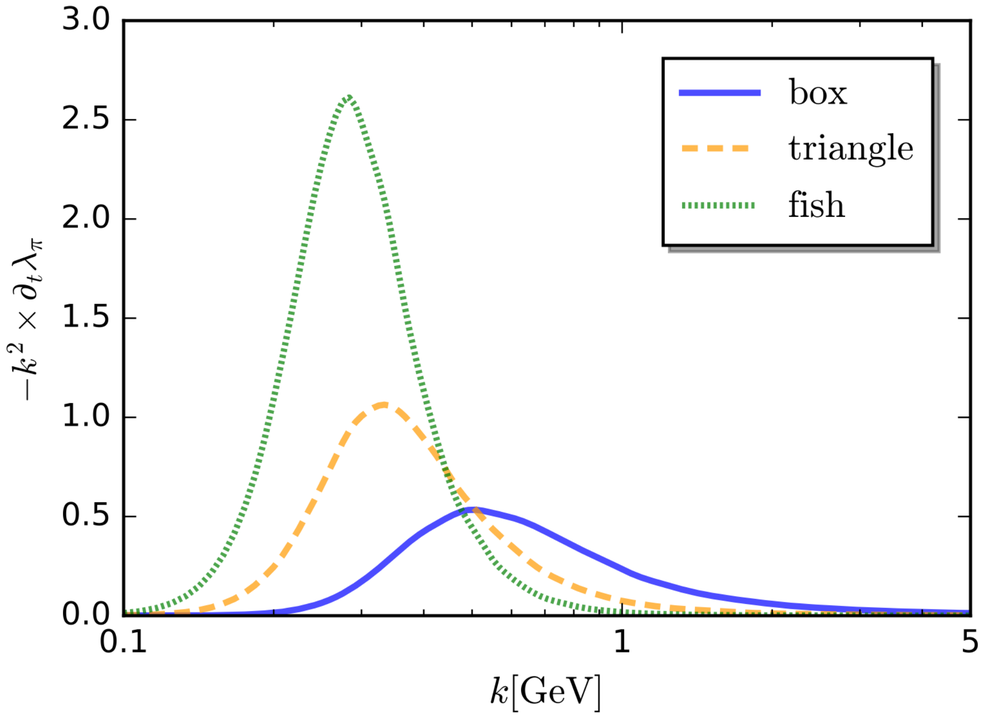


Box Fish Triangle

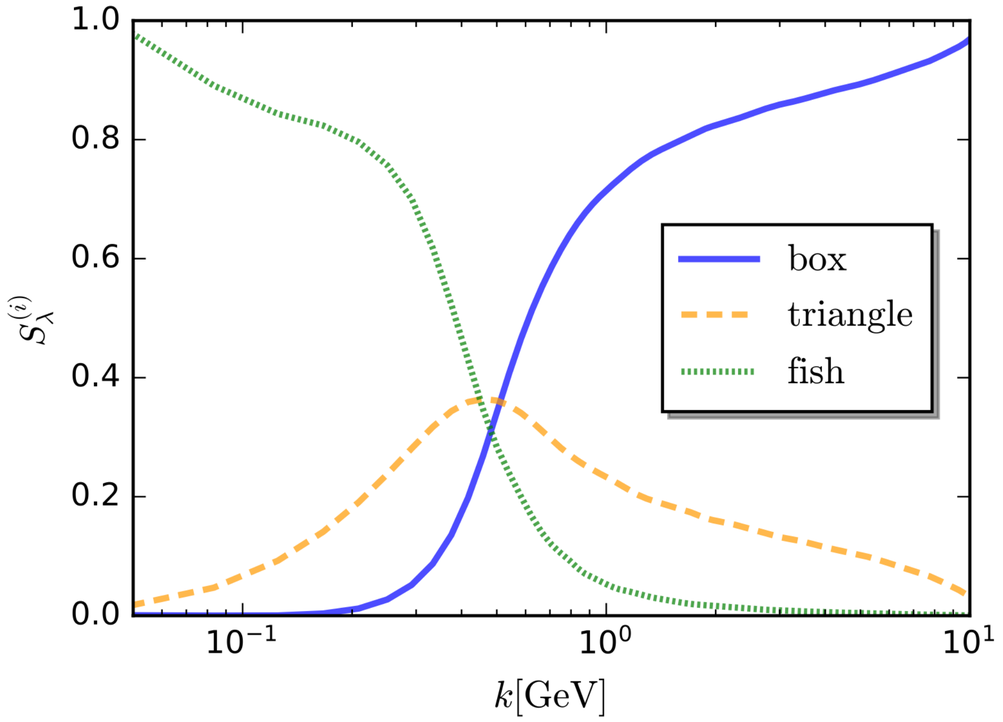
Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

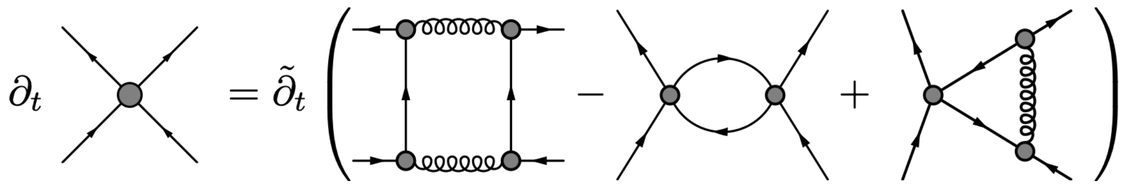
Flow analyze

Flow of the λ_π



Normalised Flow of the λ_π

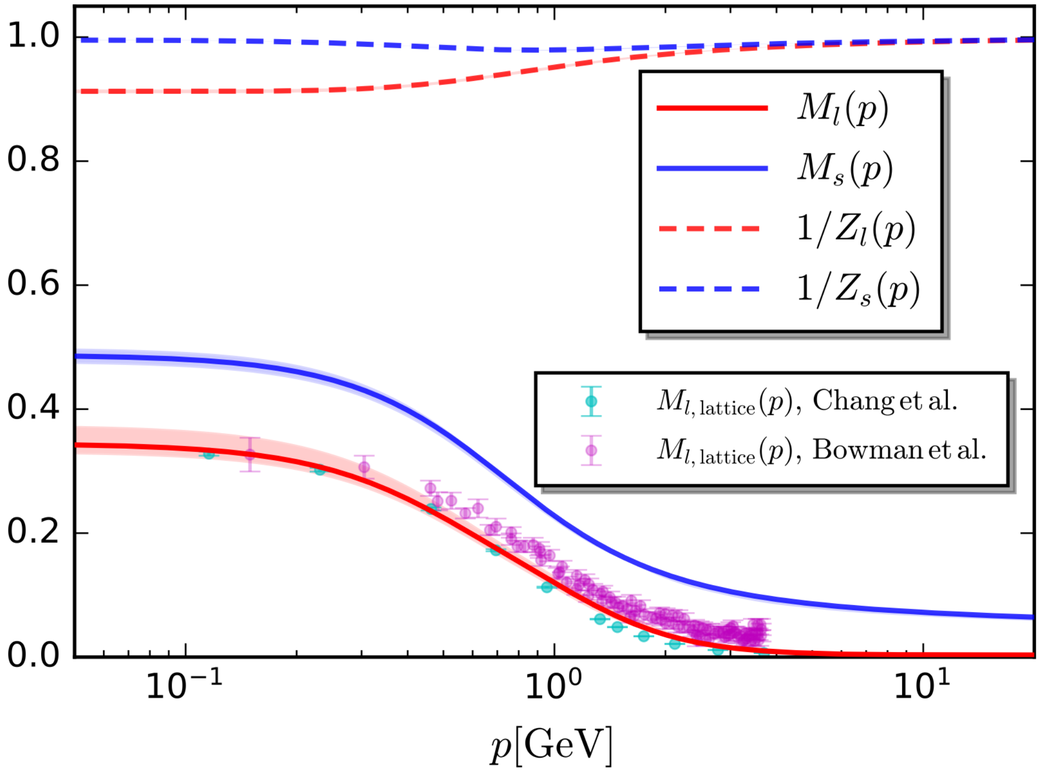




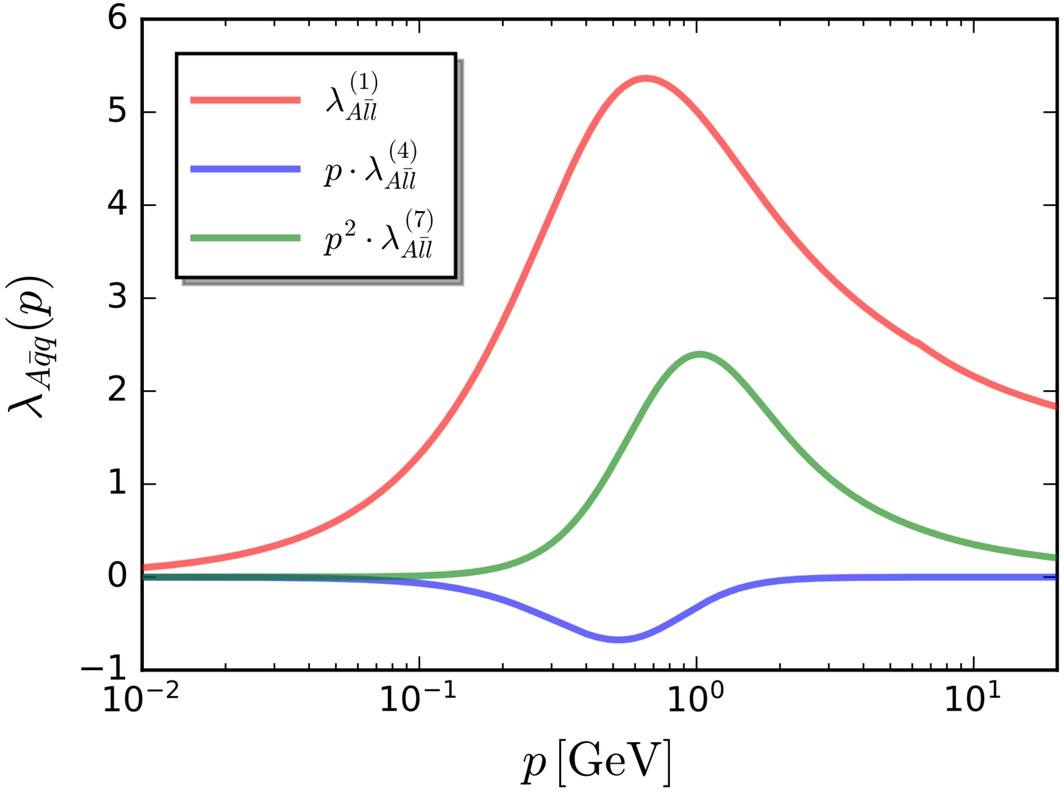
Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

Quark correlation functions

Quark propagators



Quark-gluon vertex



Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

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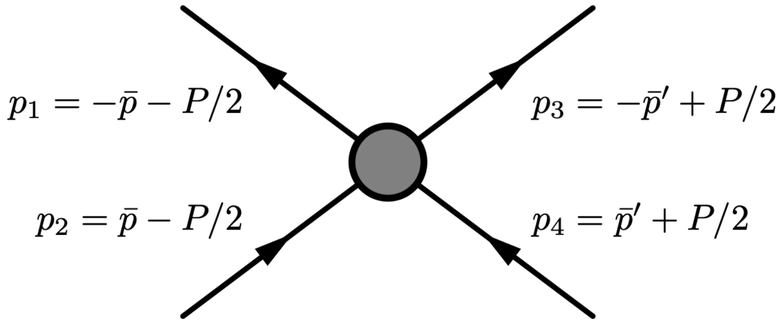
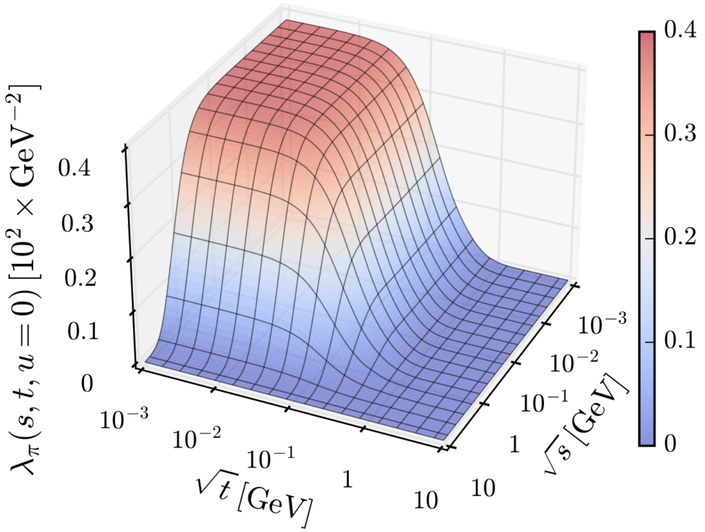
Four-quark vertex in QCD

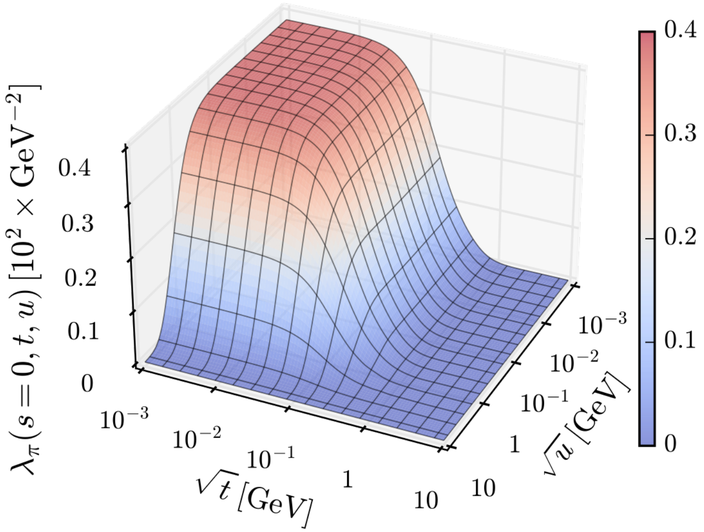
s, t, u-channel truncation



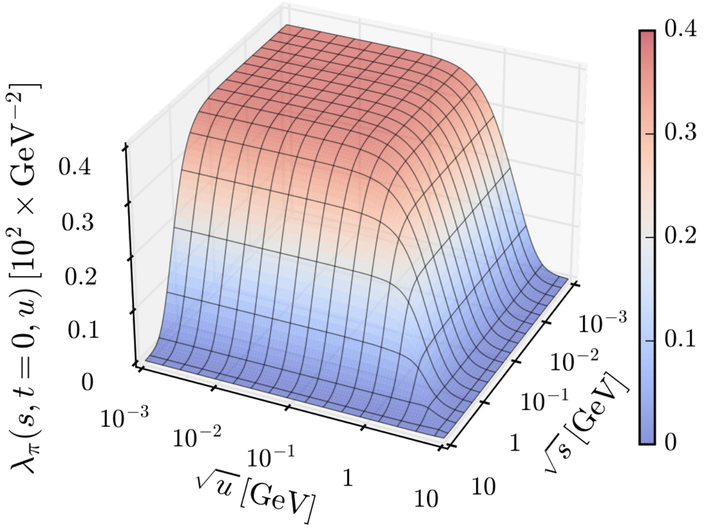
$$\lambda_\alpha(p_1, p_2, p_3, p_4) \approx \lambda_\alpha(s, t, u)$$



s and t channel with u=0



t and u channel with s=0

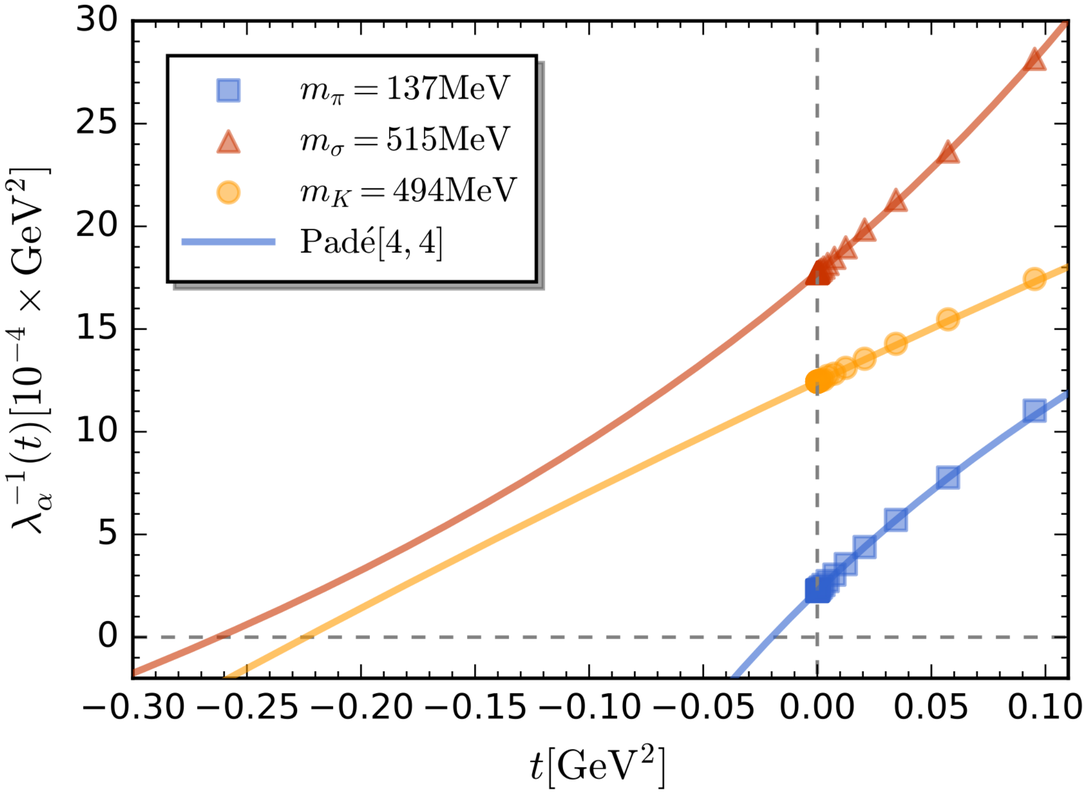


s and u channel with t=0

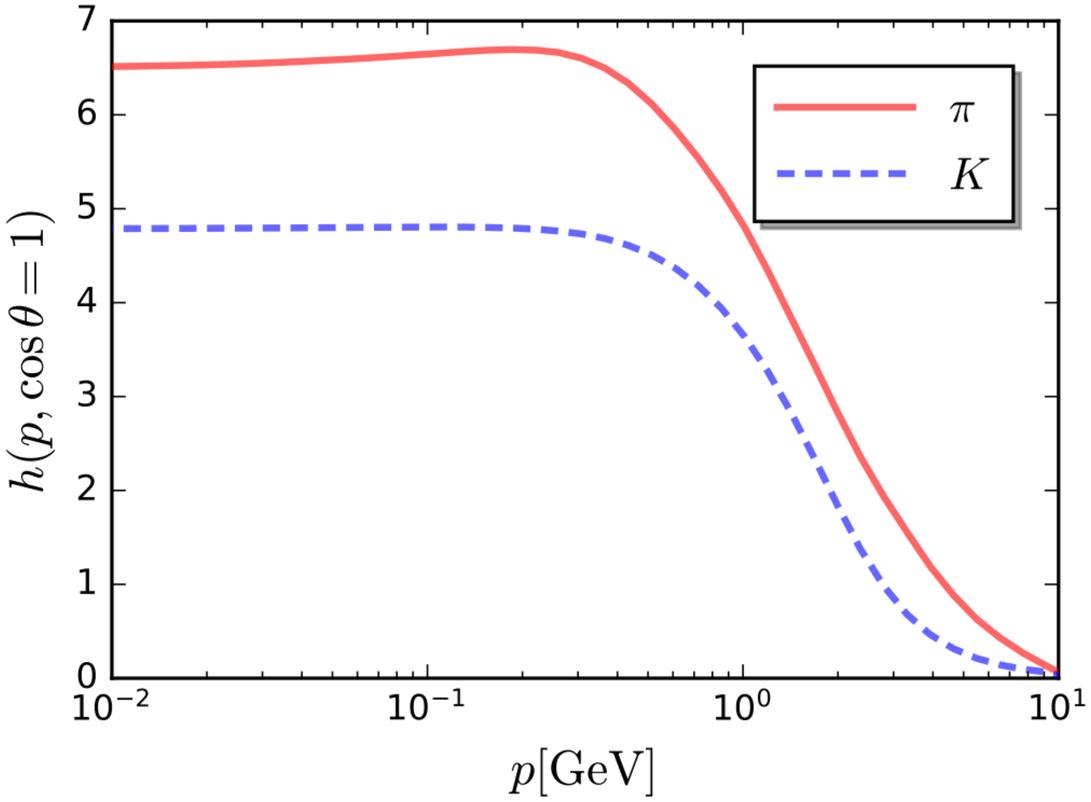
Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

Extraction of meson mass and BS amplitude

Meson mass



BS amplitude

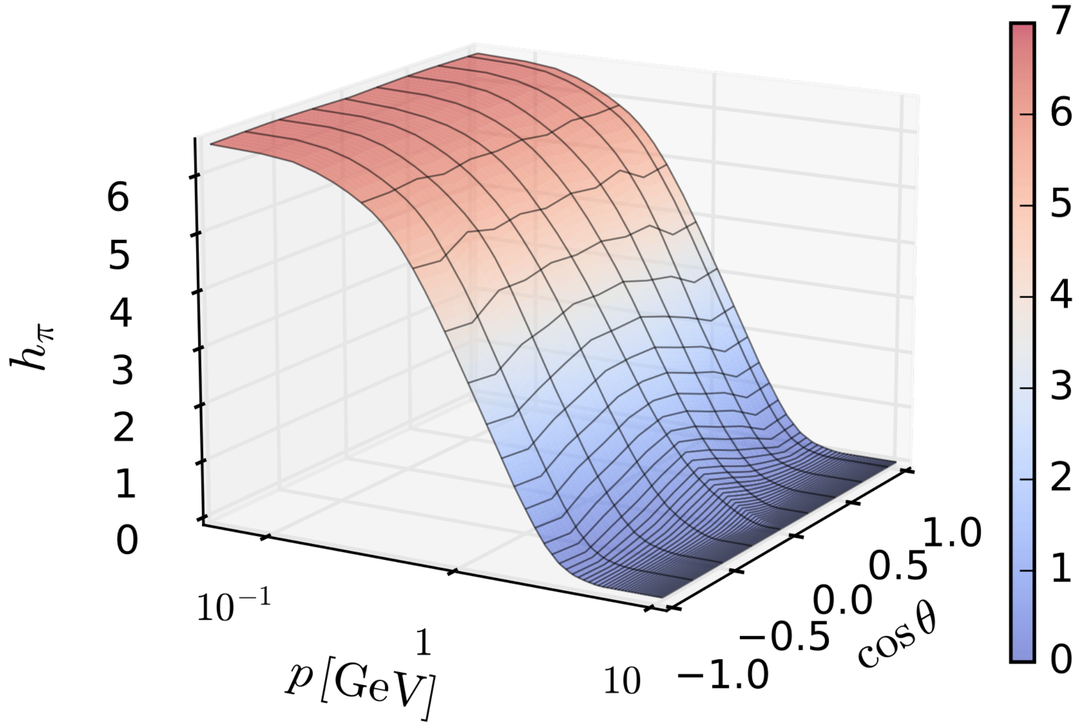


$$\lambda_\pi(P^2, p, \cos\theta) \sim \frac{h_\pi^2(p, \cos\theta)}{P^2 + m_\pi^2}$$

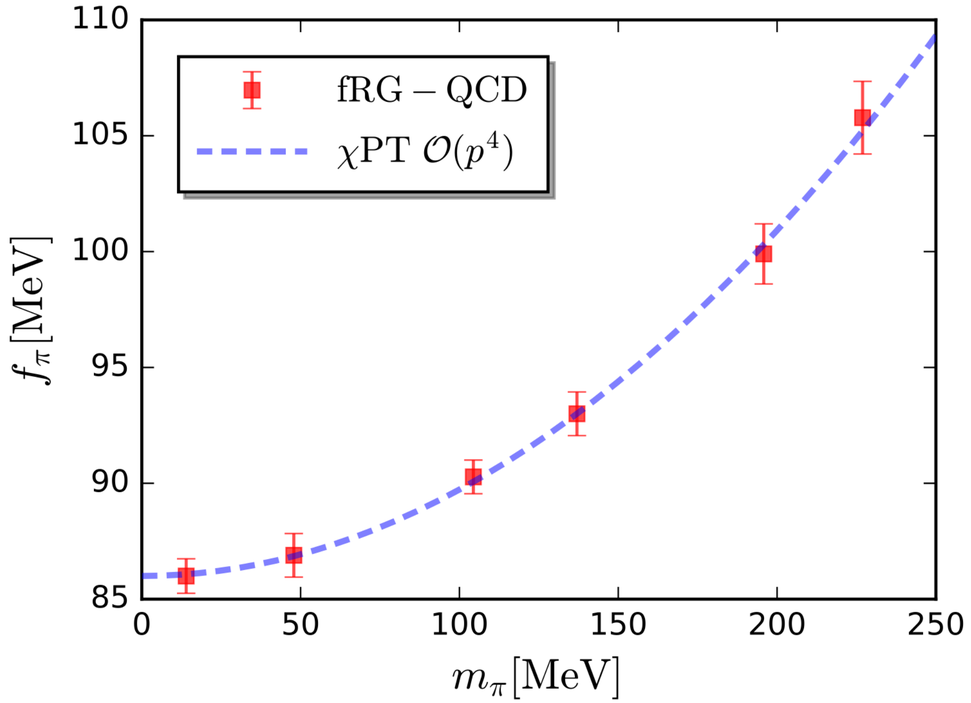
Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

Bethe-Salpeter amplitude and Chiral relation

Pion BS amplitude



Chiral relation



$$\left\langle 0 \left| J^a_{5\mu}(x) \right| \pi^b \right\rangle = iP_\mu f_\pi \delta^{ab}$$

Fu, CH, Pawlowski, Tan, Zhou, Phys. Rev. D 112 (2025), 054047

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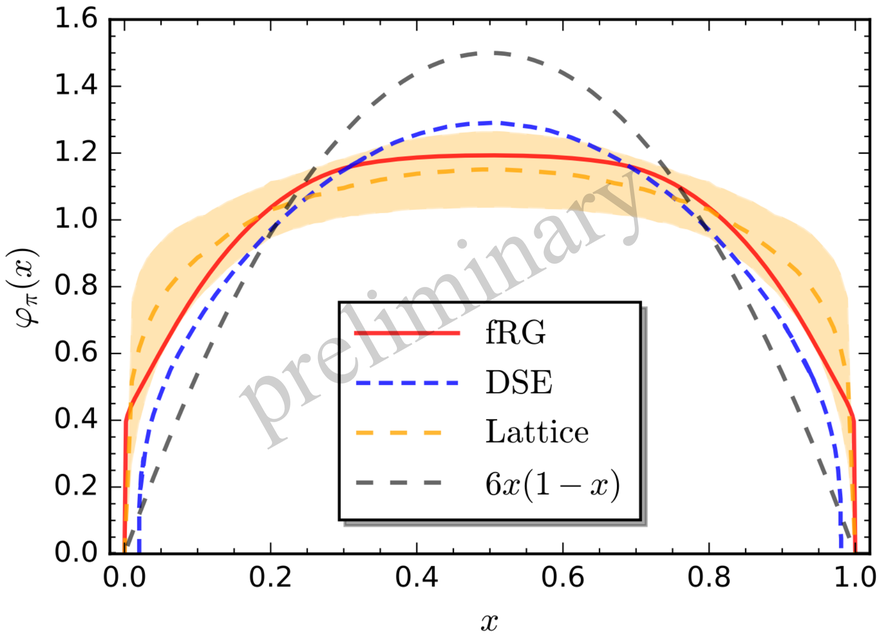
Summary and *Outlook*

★ Chiral symmetry breaking under the QCD four-quark scatterings

★ Quantitative QCD correlation functions in first-principle functional QCD

★ Apply the vacuum first-principle functional QCD calculations to the study of hadron structure

★ Quantitative QCD phase diagram: Finite T&μ + momentum dependence+ global potential. (with Franz Sattler, Konrad Kockler and Gan Min…)



Chang, Fu, CH, Pawlowski, Tan, in preparation

Thanks very much for your attentions!