HUMBOLDT-UNIVERSITÄT ZU BERLIN

First QCD+QED simulations with C* boundary conditions

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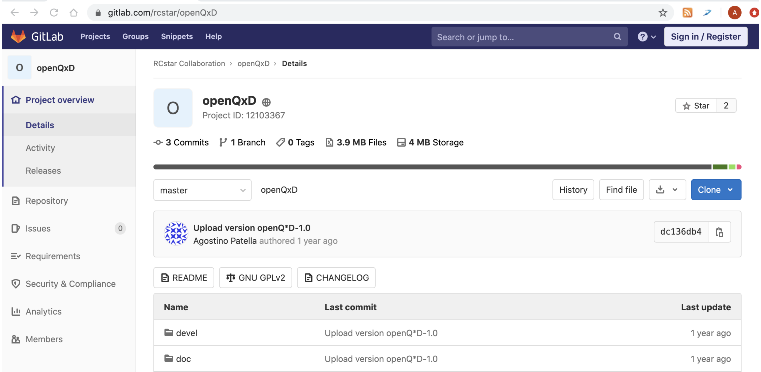
Technical setup

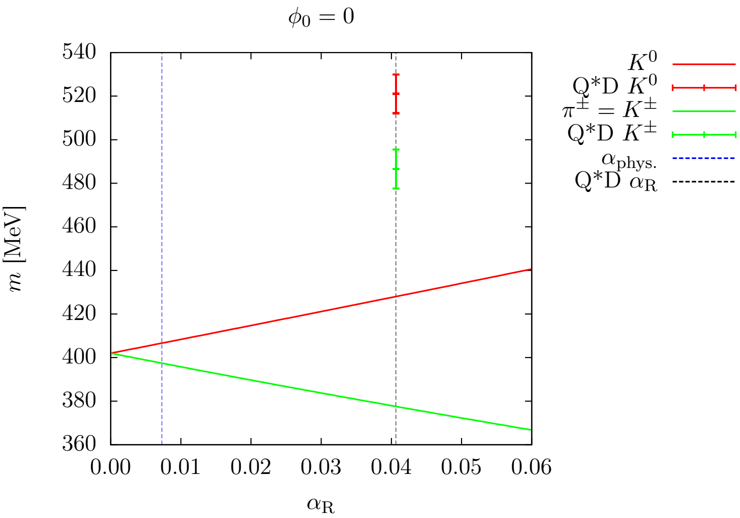
- First serious simulations with the openQ*D code[a]



Available at `https://gitlab.com/rcstar/openQxD`

[a] Campos et al., ‘openQ*D code: a versatile tool for QCD+QED simulations’.

Overview



$\phi_0 = 8t_0 \left(m^2_{K^\pm} - m^2_{\pi^\pm}\right)$

$\phi_1 = 8t_0 \left(m^2_{K^0} + m^2_{K^\pm} + m^2_{\pi^\pm}\right) \simeq \phi_1^{\mathrm{phys.}}$

$\phi_2 = \frac{8t_0}{\alpha_{\mathrm{R}}} \left(m^2_{K^0} - m^2_{K^\pm}\right) \simeq \phi_2^{\mathrm{phys.}}$

$\phi_3 = \sqrt{8t_0} \left(m_{D_s^\pm} + m_{D^\pm} + m_{D^0}\right) \simeq \phi_3^{\mathrm{phys.}}$

Setup

- C* boundary conditions in all three spatial dimensions[b]
- All ensembles at $\beta = 3.24$[c]
- Lattice spacing is determined using $N_f = 2 + 1$ value of $\sqrt{8t_0^\star} = 0.413(5)(2)$ fm[d]

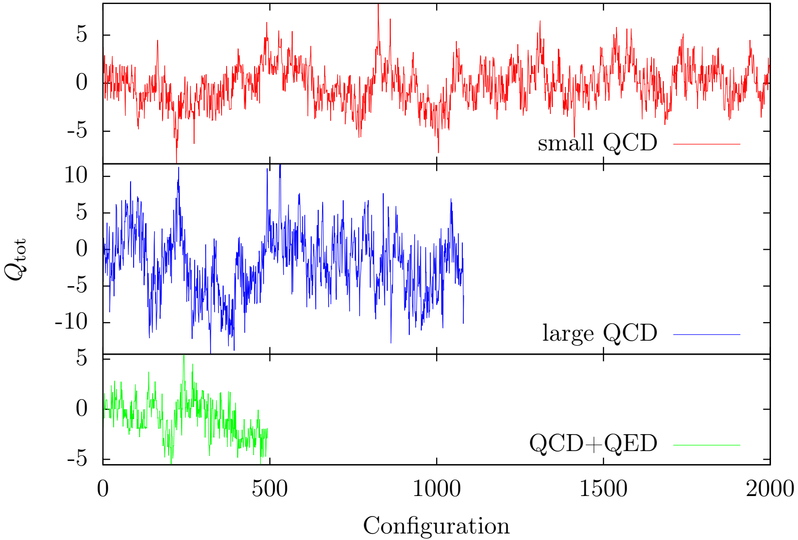
Ens.	small QCD	large QCD	QCD+QED
N_{cfg}	2000	1082	494
Volume	64×32^3	80×48^3	64×32^3
α	0.0	0.0	0.05
α_R	0.0	0.0	0.04
a [fm]	0.0537	0.0537	0.0523
$m_{\pi^\pm}$ [MeV]	402(3)	402(2)	487(8)
$Lm_{\pi^\pm}$	3.50	5.26	4.13

[b] Lucini et al., 'Charged hadrons in local finite-volume QED+QCD with C* boundary conditions'.

[c] Höllwieser, Knechtli and Korzec, 'Scale setting for $N_f = 3 + 1$ QCD'.

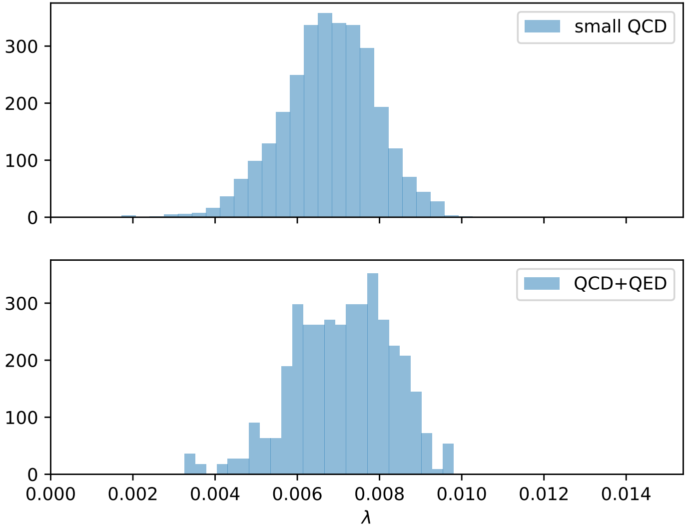
[d] Bruno, Korzec and Schaefer, 'Setting the scale for the CLS 2+1 flavor ensembles'.

Results - Diagnostic observables



Results - Diagnostic observables

Eigenvalue of $\sqrt{D^\dagger D}$ for up quark



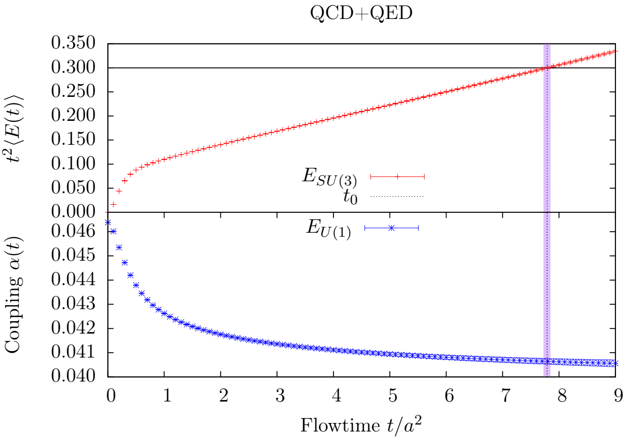
Results - Wilson Flow

- t_0 is obtained by solving the equation

$$t^2 \left\langle E_{SU(3)}(t) \right\rangle \Big|_{t_0} = 0.3$$

- α_R is extracted via[e]

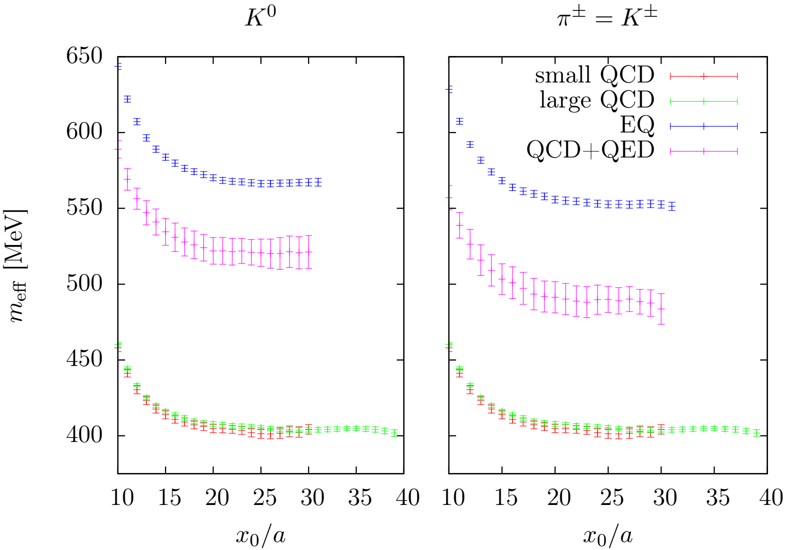
$$\alpha_R = \frac{t^2 \left\langle E_{U(1)}(t) \right\rangle}{4\pi\mathcal{N}} \Bigg|_{t_0}$$



[e] Borsanyi et al., 'Ab initio calculation of the neutron-proton mass difference'.

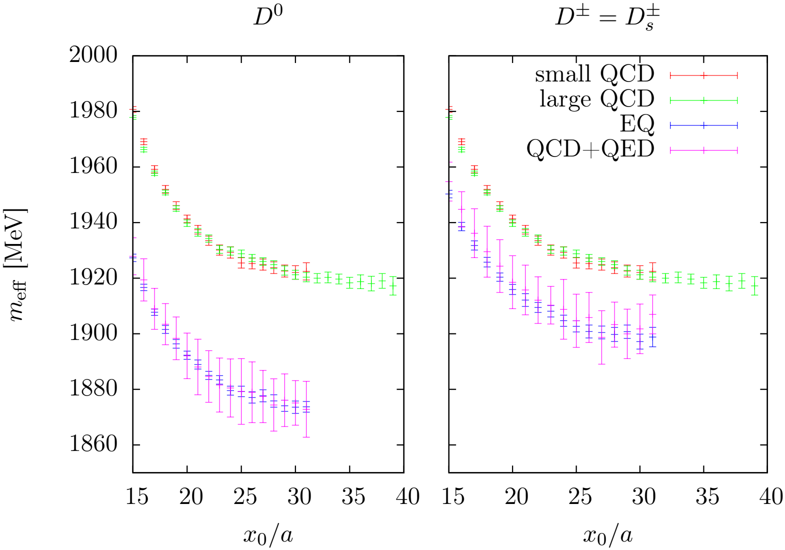
Results - Masses

Charged masses are extracted from gauge invariant interpolating operators[f]



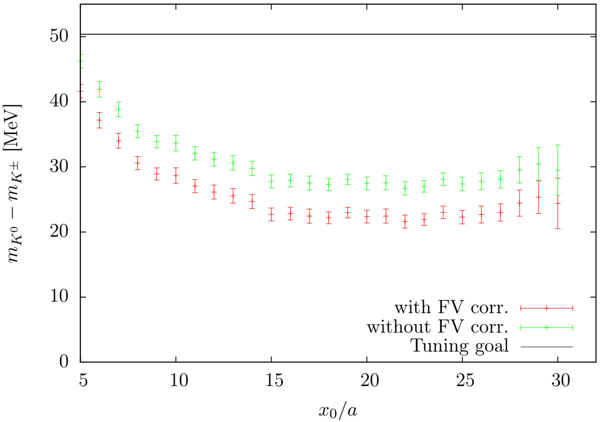
[f] Hansen et al., 'Gauge invariant determination of charged hadron masses'.

Results - Masses



Results - QCD+QED Kaon splitting

$m_{K^0} = 521(11)\,\text{MeV}$ $m_{K^\pm} = 487(8)\,\text{MeV}$



QED FV corrections[g] : $\frac{\Delta m(L)}{m} = \alpha_R \left\{ \frac{q^2 \xi(1)}{2mL} + \frac{q^2 \xi(2)}{2(mL)^2} + \mathcal{O}\left(\frac{1}{L^4}\right) \right\}$

[g] Lucini et al., 'Charged hadrons in local finite-volume QED+QCD with C* boundary conditions'.

Summary and Outlook

✓ Production of $N_f = 1 + 2 + 1$ fully dynamical QCD+QED configurations

- Using openQ*D with C* boundary conditions
- $\alpha_{\mathrm{R}} \approx 0.04$

✓ Demonstration that the openQ*D framework is functional and the used algorithm is stable

- No topological freezing
- Dirac operator has clear gap

✓ Measurement of charged mesons and Wilson flow observables

- Charged meson masses were extracted in a gauge invariant setup
- Wilson flow observables were used to fix the scale and extract α_{R}

✓ Extraction of the Kaon mass splitting with good precision

- Reduction of the statistical error through taking correlation between Kaons into account

➤ Tuning of the parameters for the QCD+QED ensemble

- Currently: Light mesons are too heavy
- Goal: Light meson masses close to the $SU(3)$ symmetric point with the correct splitting

➤ Reevaluation of the tuning strategy

Thank you!

References I

Sz. Borsanyi et al. ‘Ab initio calculation of the neutron-proton mass difference’. In: *Science* 347 (2015), pp. 1452–1455. DOI: 10.1126/science.1257050. arXiv: 1406.4088 [hep-lat].

Mattia Bruno, Tomasz Korzec and Stefan Schaefer. ‘Setting the scale for the CLS 2+1 flavor ensembles’. In: *Physical Review D* 95.7 (2017). ISSN: 24700029. DOI: 10.1103/PhysRevD.95.074504. arXiv: 1608.08900.

Isabel Campos et al. ‘openQ*D code: a versatile tool for QCD+QED simulations’. In: (Aug. 2019). arXiv: 1908.11673. URL: http://arxiv.org/abs/1908.11673.

Martin Hansen et al. ‘Gauge invariant determination of charged hadron masses’. In: *JHEP* 05 (2018), p. 146. DOI: 10.1007/JHEP05(2018)146. arXiv: 1802.05474 [hep-lat].

Roman Höllwieser, Francesco Knechtli and Tomasz Korzec. ‘Scale setting for $N_f = 3 + 1$ QCD’. In: (2020). arXiv: 2002.02866.

Biagio Lucini et al. ‘Charged hadrons in local finite-volume QED+QCD with C* boundary conditions’. In: 2016 (2015). DOI: 10.1007/JHEP02(2016)076. arXiv: 1509.01636.

Backup - Setup

- Lüscher-Weisz $SU(3)$ gauge action
- Compact $U(1)$ with Fourier acceleration
- Non-perturbatively $\mathcal{O}(a)$ improved Wilson fermions for the QCD ensembles
- For QCD+QED ensemble same value of c_{SW} as for the QCD ones
- Periodic boundary conditions in time
- C* boundary conditions in all spatial directions
- RHMC with rational approximation for all quarks
- Deflation solvers for up and down/strange quarks

Backup - Results - Stability of the Algorithm

Ens.	N_{cfg}	Acceptance	$\langle e^{-\Delta H} \rangle$	$\tau_{\langle E(t_0) \rangle}$	Cost per MDU [ch]
small QCD	2000	95%	0.998(5)	57(29)	228(4)
large QCD	1082	98%	0.995(2)	29(14)	1924(44)
QCD+QED	494	97%	0.998(3)	7.2(8)	826(24)