Westfälische Wilhelms-Universität Münster

institut für theoretische physik

GRK 2149

ALPHA Collaboration

Charm(ing) meson physics from lattice QCD

RTG *Strong and Weak Interactions — from Hadrons to Dark Matter*

Inauguration Retreat @ Heidehotel Waldhütte, Telgte, November 24 – 26, 2015

Jochen Heitger

November 24, 2015

RG Heitger: Particle Physics Theory & Lattice QCD

Group members

- Ph.D. students:
  Christian Wittemeier, Kevin Eckert ($\in$ GRK 2149)
- M.Sc. students:
  Carl Chr. Köster, Fabian Joswig, Alexander Hock, Matthias Post

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Main research topics $\rightarrow$ ALPHA Collaboration, CLS based

- Determinations of QCD/SM parameters via LQCD: $\alpha_s(\mu)$, m_{quark}
- Non-perturbative renormalization and O(a) improvement
- Lattice hadron and (heavy) flavour physics phenomenology:
  (semi-)leptonic D- & B-meson decays, spectroscopy, HQET, ...

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Planned projects/activities within GRK 2149 $\rightarrow$ RG Khoukaz

- Computation of decay constants $f_{\text{D}}, f_{\text{D}_s}$ in 3–flavour LQCD
- Decoupling of charm (sea) quarks and its physical effects
- $\text{D}_{(s)}$-meson spectroscopy, exotics, hybrids, ... through LQCD

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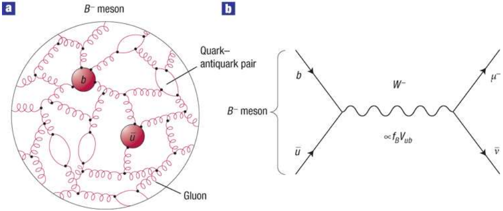
Motivation: Precision heavy flavour physics

New Physics effects expected in the quark flavour sector, because most extensions of the Standard Model (SM) contain ...

- ... new CP-violating phases
- ... new quark flavour-changing interactions



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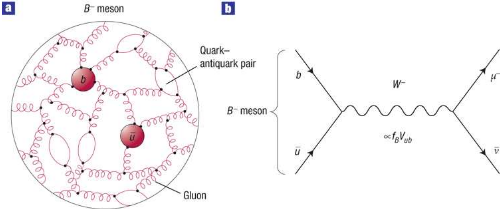

- Quark flavour change in hadrons = weak interaction process
- Associated decays exploited in accelerator experiments, however, always involve hadrons as initial states
  $\Rightarrow$ QCD corrections enter the decay rates & can be significant

In the Standard Model, the couplings of these flavour-changing (weak) interactions are encoded by elements of the CKM matrix / Unitarity Triangle (UT)

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak int.}} = V_{\text{CKM}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{strong int.}} , \quad V_{\text{CKM}} = \begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \pi \to \ell\nu & K \to \ell & B \to \ell\nu \\ & K \to \pi\ell\nu & B \to \pi\ell\nu \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ B_d \leftrightarrow \overline{B}_d & B_s \leftrightarrow \overline{B}_s & \end{pmatrix}$$

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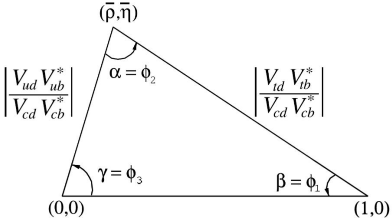
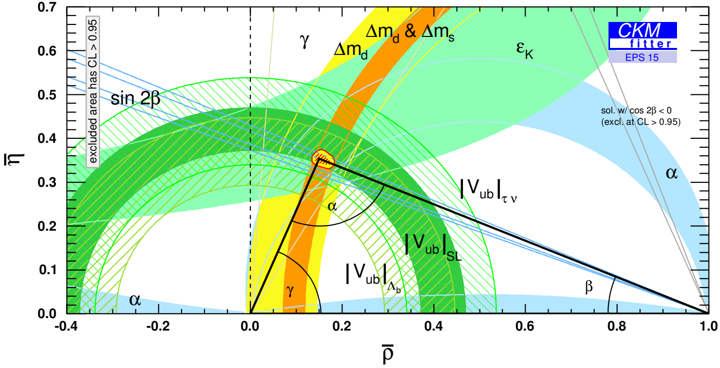
Unitarity of V_{CKM} implies a useful *triangle representation:*

$$V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = \mathbf{1} \qquad \Rightarrow$$



→ SM quark flavour dynamics neatly encoded in the CKM matrix

→ CKM analyses relevant for phenomenology involve crucial inputs both from *experiment and theory*



Impact of weak decays of hadrons on CKM analyses is generically based (via the *OPE*) on schematic relations such as

$$\underbrace{\begin{pmatrix}\text{measured}\\\text{quantity}\end{pmatrix}}_{\text{experiment}} = \begin{pmatrix}\text{kinematic}\\\text{factor}\end{pmatrix} \underbrace{\begin{pmatrix}\text{short-distance}\\\text{factor}\end{pmatrix}}_{\ni\ \text{pert. theory}} \times \underbrace{\begin{pmatrix}\text{QCD}\\\text{factor}\end{pmatrix}}_{\text{LQCD}:\ f^2_{PS},\, f^2_{+},\, \ldots} \times F(V_{q_1 q_2})$$

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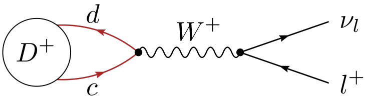
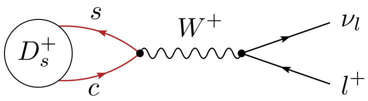
E.g. for the leptonic decay of $D_{(s)}$-mesons of interest here:





Corresponding SM expression for the partial width:

$$\Gamma\left(D_{(s)} \to \ell\,\nu_\ell\right) \;\widehat{=}\; \mathcal{B}\left(D_{(s)} \to \ell\,\nu_\ell\right)/\tau_{D_{(s)}}$$

$$= \frac{G_F^2}{8\pi}\, m_{D_{(s)}}\, m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_{(s)}}^2}\right) f_{D_{(s)}}^2\, |V_{cq}|^2\ ,\quad q = d, s$$

⇒ Required inputs from ...

... Experiment

- Measurement of the decay rate Γ

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(note: due to confinement, significant QCD corrections to Γ)

- Computation of the decay constant $f_{D_{(s)}}$, which is a hadronic matrix element absorbing the low-energy, *non-perturbative* QCD effects

  $\rightarrow$ a task for lattice QCD (LQCD)

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... Theory

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  $\rightarrow$ a task for lattice QCD (LQCD)

CKM analysis of $\mathrm{D}_{(\mathrm{s})}$-meson decays allows:

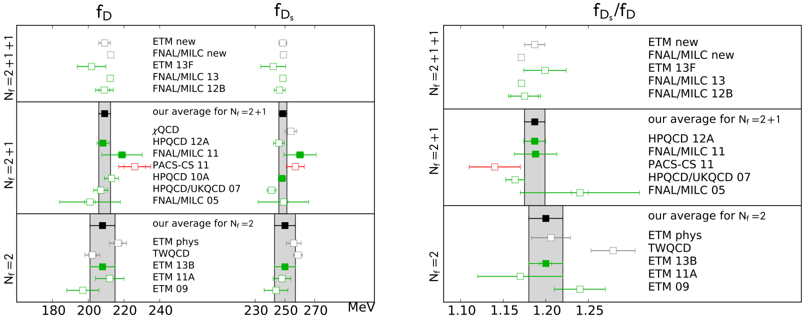
1.) determining the CKM matrix element $|V_{\mathrm{cq}}|$ to (over)constrain the UT

2.) comparing $f_{\mathrm{D}_{(\mathrm{s})}}|V_{\mathrm{cq}}|$ from experiment with LQCD results of $f_{\mathrm{D}_{(\mathrm{s})}}$, if $|V_{\mathrm{cq}}|$ is known (e.g. via CKM unitarity, semi-leptonic decays)

Status of results

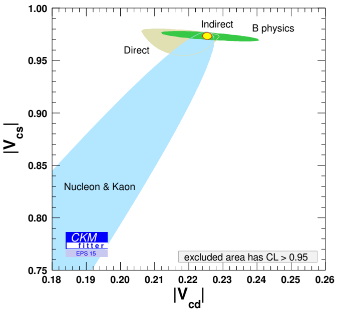
Compilation of lattice results by the ...

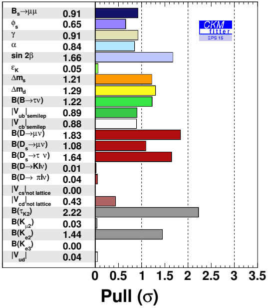
- ... *FLAG Working Group* (FLAG-2 2013: Aoki et al., arXiv:1310.8555)
- ... super-imposed with new lattice results



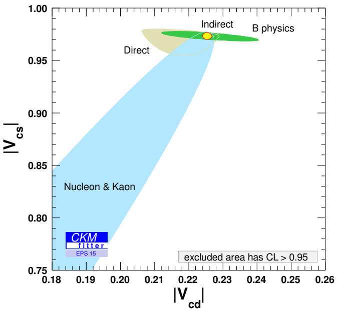
[C. Pena @ Lattice 2015]

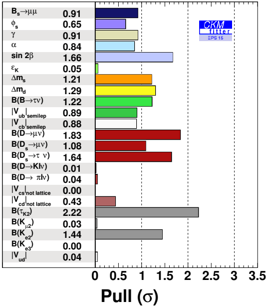
- Towards 1% accuracy: "raw" potential of lattice methods
- Experiments: BES-III, CLEO-c, BaBar, Belle; ... PANDA @ FAIR





- Stringent tests of self-consistency of the SM & extensions
- Deviation between experimental and lattice results for $f_{D_{(s)}}$ could hint at New Physics in the quark flavour sector, complementing direct searches





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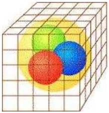
- Current “tensions”: [Rosner & Stone for PDG 2016, arXiv:1509.02220]
  - ▶ f_{D_s} from lattice QCD $\sim 2\sigma$ below estimate with experim. inputs
  - ▶ 2nd row of V_{CKM} conflicts 3–generation unitarity at 2σ level

Lattice QCD — ‘Ab initio’ tool based on FIs & MC

$$\mathcal{L}_{\mathrm{QCD}}\left[g_0, m_f\right] = -\frac{1}{2g_0^2}\,\mathrm{Tr}\left\{F_{\mu\nu}F_{\mu\nu}\right\} + \sum_{f=\mathrm{u,d,s},\ldots} \overline{\psi}_f \left\{\gamma_\mu\left(\partial_\mu + g_0 A_\mu\right) + m_f\right\}\psi_f$$

$$\underbrace{\begin{bmatrix} f_{\mathrm{K}} \\ m_\pi \\ m_{\mathrm{K}} \\ m_{\mathrm{D}} \\ m_{\mathrm{B}} \end{bmatrix}}_{\text{Experiment}} \quad \overset{\mathcal{L}_{\mathrm{QCD}}[g_0, m_f]}{\Longrightarrow} \quad \underbrace{\begin{bmatrix} \Lambda_{\mathrm{QCD}} \\ M_{\mathrm{u}}, M_{\mathrm{d}} \\ M_{\mathrm{s}} \\ M_{\mathrm{c}} \\ M_{\mathrm{b}} \end{bmatrix}}_{\text{QCD parameters (RGIs)}} \quad + \quad \underbrace{\begin{bmatrix} f_{\mathrm{D}} \\ f_{\mathrm{B}} \\ B_{\mathrm{K}}, B_{\mathrm{B}} \\ \xi \\ \ldots \end{bmatrix}}_{\text{Predictions}}$$



Main sources of systematic uncertainties in LQCD computations:

- Part of the vacuum polarization effects is missed, as long as u, d, s (and ideally also c) sea quarks are not incorporated
  $\rightarrow$ today’s LQCD computations use $N_{\mathrm{f}} = 2,\, 2+1$ and even $2+1+1$

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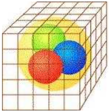


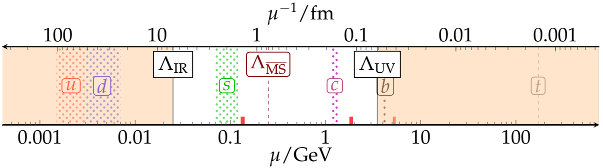
Main sources of systematic uncertainties in LQCD computations:

- Extrapolations to $m_{\mathrm{u,d}}$ guided by χPT to connect to physical world
- Discretization errors, notably from heavy quarks: $\mathrm{O}\left[(am_{\mathrm{Q}})^n\right]$ effects
  $\rightarrow \# \gtrsim 3$ lattice spacings needed to take continuum limit, $a \rightarrow 0$
- Perturbative vs. non-perturbative renormalization

Challenges of treating heavy quarks on the lattice

Predictivity in a quantum field theory relies upon a large scale ratio

interaction range	$\ll$	physical length scales
momentum cutoff	$\gg$	physical mass scales : $\Lambda_{\text{cut}} \sim a^{-1} \gg E_i, m_j$



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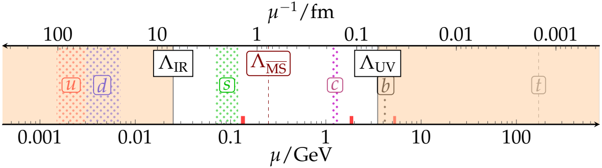

Hierarchy of disparate physical scales difficult to cover simultaneously:

$$\Lambda_{\mathrm{IR}} = L^{-1} \ll m_\pi , \ldots , m_{\mathrm{D}} , m_{\mathrm{B}} \ll a^{-1} = \Lambda_{\mathrm{UV}}$$

$$\downarrow \qquad\qquad \downarrow$$

$$\left\{ \mathrm{O}(\mathrm{e}^{-Lm_\pi}) \Rightarrow L \gtrsim \frac{4}{m_\pi} \sim 6\,\mathrm{fm} \right\} \curvearrowright \; L/a \gtrsim 120 \; \curvearrowleft \left\{ am_{\mathrm{D}} \lesssim \frac{1}{2} \Rightarrow a \approx 0.05\,\mathrm{fm} \right\}$$

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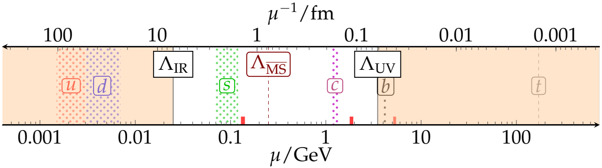
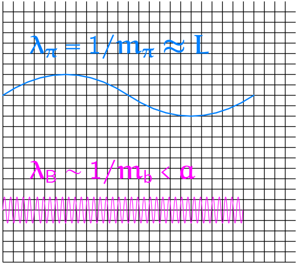
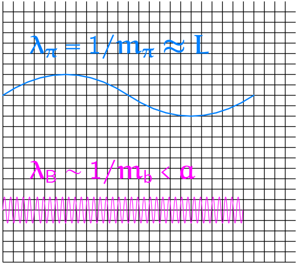


As a consequence of this *multi-scale problem*, heavy quarks are challenging to simulate

$\Rightarrow$ a proper treatment of the heavy quark with a competitive control on the systematic uncertainties involved is difficult



- Light quarks: too light
  - Widely spread objects
  - Finite-volume errors via light π's
- b-quark: too heavy
  - Extremely localized object
  - B-mesons with a propagating b need fine resolutions ($am_b \ll 1$):
    - large discretization errors
    - "they fall through the lattice"



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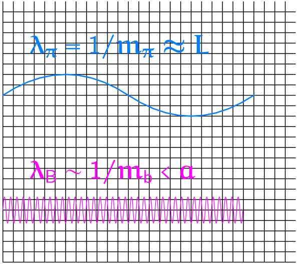
- Bottom physics (dominated by scales $\sim m_b$):
  - including b-quarks in LQCD computations requires $am_b \ll 1$
  - a fully relativistic b not yet feasible with today's CPU resources $\rightarrow$ adopt effective field theories: NRQCD, *HQET*



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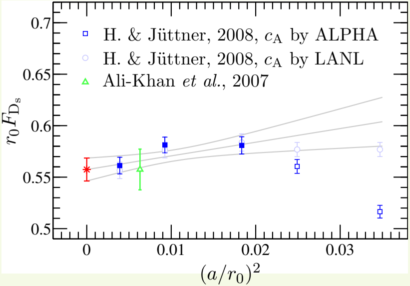
    $\rightarrow$ adopt effective field theories: NRQCD, *HQET*
- Charm physics (dominated by $\sim m_c$) directly accessible, but ...
  - ... needs $am_c < 1$ to keep discretization effects under control
  - ... sufficiently large # of sites to minimize finite-volume effects

Illustration: Cutoff effects in the charm sector

High-precision computation of F_{D_s} in quenched QCD ($N_f = 0$)

- Scaling study down to very fine lattices: $a \approx (0.09 - 0.03)$ fm
- $O(a, am_{q,c})$ cutoff effects relevant & removed NP'ly [ALPHA Collaboration]

Warning: Large lattice artefacts [H. & Jüttner, JHEP0905(2009)101]



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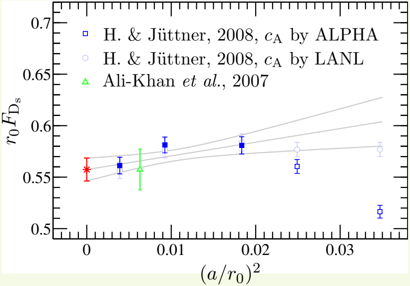

⇒ Small lattice spacings $a \lesssim 0.08$ fm seem mandatory to control the continuum limit for charm (note: challenging for $N_\mathrm{f} > 0$!)

Leptonic $D_{(s)}$-meson decay constants from LQCD

Starting point of the lattice QCD computation:

Low-energy $D_{(s)}$-meson-to-vacuum QCD matrix elements

$$\langle 0 \,|\, A_\mu \,|\, D_q(p) \,\rangle \quad = \quad i\, f_{D_q}\, p_\mu$$

$$A_\mu(x) = \overline{q}(x)\gamma_\mu\gamma_5 c(x) \quad : \quad \text{axial vector current } (q = d, s)$$

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Goal:
Precise computation of $f_{D_{(s)}}$ from $N_f = 2 + 1$ flavour lattice QCD simulations with controlled statistical and systematic errors

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Ingredients of the lattice calculation:

1.) Extraction of $f_{D_{(s)}}$ from asymptotics of correlation functions in the pseudoscalar channel at large Euclidean times & PCAC:

$$C(x_0) = a^3 \sum_{\vec{x}} \langle P(x)P(0) \rangle \overset{x_0 \to \infty}{\sim} p \times e^{-m_{D_{(s)}} x_0} \,, \quad P(x) = \bar{q}\,\gamma_5 c$$

$$f_{D_{(s)}} \propto Z_A \sqrt{p}\, m_{PCAC}\, m_{D_{(s)}}^{-3/2}$$

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Ingredients of the lattice calculation:

2.) Amongst others, prior determination of ...

- ... renormalization factors, such as Z_A
- ... improvement coefficients, such as c_A, to remove the leading discretization errors in the lattice axial current (entering m_{PCAC})

Prerequisites

Computing strategies developed and successfully applied in ...

- ... the quenched approximation ($N_f = 0$)
- ... two-flavour QCD ($N_f = 2$)

ALPHA Collaboration

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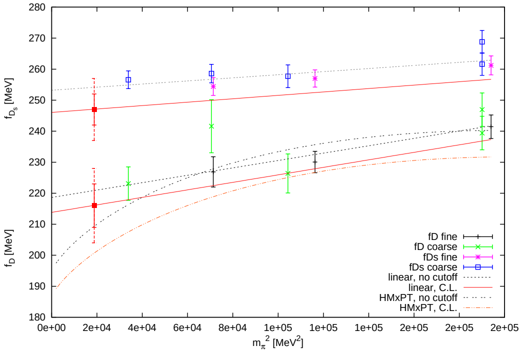
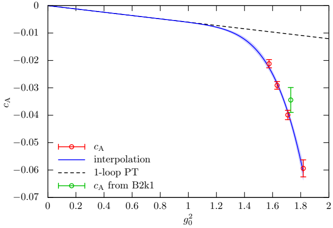
ALPHA Collaboration

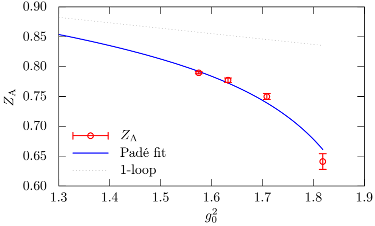
Joint chiral and continuum extrapolations to the physical point of f_D and f_{D_s} in $N_f = 2$ QCD: [H., von Hippel, Schaefer & Virotta, arXiv:1312.7693]



Preliminary work & Configuration ensemble basis

Non-perturbative determination of c_A and Z_A in $N_f = 3$ QCD:





[Bulava, Della Morte, H. & Wittemeier, NPB896 (2015) 555, arXiv:1502.04999; in progress]

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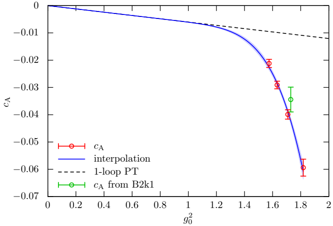

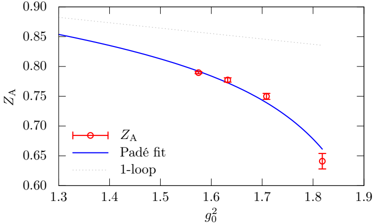

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- A reliable, accurate evaluation of $f_{D_{(s)}}$ requires to generate (computationally demanding) large-volume $N_f = 2 + 1$ QCD configurations at small lattice resolutions and close-to-physical sea quark masses

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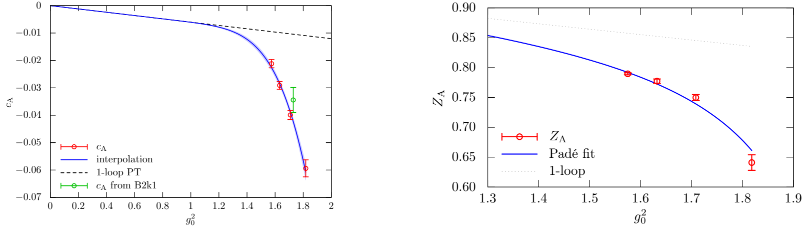

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- A reliable, accurate evaluation of $f_{D_{(s)}}$ requires to generate (computationally demanding) large-volume $N_f = 2 + 1$ QCD configurations at small lattice resolutions and close-to-physical sea quark masses
- *Coordinated Lattice Simulations (CLS)* team effort: $(0.05 \lesssim a \lesssim 0.09)$ fm, m_π's $\gtrsim 140$ MeV

CLS based

→ talk by Stefan Schaefer

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