Charm physics: f_D and f_{D_s} status and outlook

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Outline

1 Motivation

2 Decay Constant Analysis

3 Current Projects

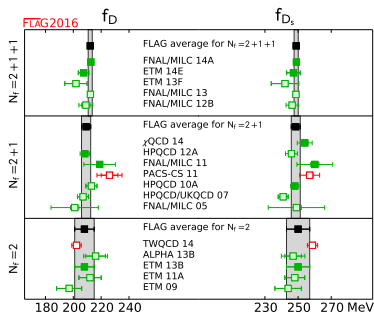# Motivation - Flavour Physics
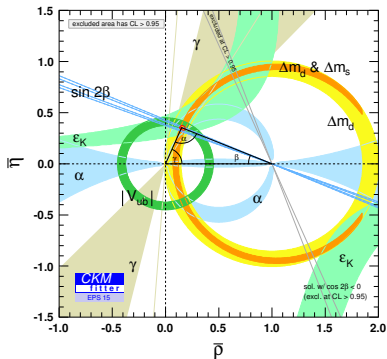
Experiment

- Belle, BaBar, CLEO-c
- LHCb, Belle II

Theory

- K, D and B physics to test unitarity of the CKM matrix.

$\Rightarrow$ Place tight bounds on SM predictions

D and B physics

FLAG 2016 (*arXiv:1607.00299*)

Goal: $D_{(s)}$ and $B_{(s)}$ phenomenology

- masses
- decay constants
- semi-leptonics

Outcome:

- Test of SM
- Reduce systematic errors by direct computation

Charm physics in the RBC/UKQCD program

- **Charm phenomenology (f_D, f_{D_s}, Bag, ξ, semi-leptonics)**

- 2+1+1f ensemble generation
- GIM mechanism
  (see Rare Kaon talk by **A. Lawson Thurs 17^{50}**)
- Charm contribution to the HVP
  (see talk by **M. Spraggs Tue 17^{10}**)
- Semi-leptonic B decays in RHQ e.g. $B \to D$
  (see talks by **E. Lizarazo Fri 17^{10}** & **O. Witzel Wed 10^{20}**)
- Ratio Method to push from c to b (*arXiv:0909.3187*)

Our Action: Domain Wall Fermions

- Chiral fermions
- Automatically $\mathcal{O}(a)$-improved

- **Physical Pion Mass ensembles**: Moebius Domain Wall Fermions (*arXiv:0409118*)
- Tiny Chiral extrapolation is done with Shamir DWFs (*arXiv:9303005*)

- Tested with quenched **PILOT STUDY**.
  $\Rightarrow$ **Quenched study as proof of concept:**
  JHEP **05** (2015) 072 (arXiv:1504.01630 [hep-lat])
  JHEP **04** (2016) 037 (arXiv:1602.04118 [hep-lat])

Dynamical Ensembles

2 ensembles with physical pion masses
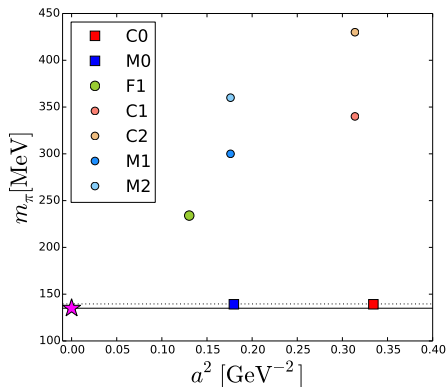
$L^3 \times T/a^4$	a^{-1}/GeV	m_π/MeV
$48^3 \times 96$	**1.73**	**139**
$24^3 \times 64$	1.78	340
$24^3 \times 64$	1.78	430
$64^3 \times 128$	**2.36**	**139**
$32^3 \times 64$	2.38	300
$32^3 \times 64$	2.38	360
$48^3 \times 96$	2.77	230

(C0 + M0: **arXiv:1411.7017**)

Set up of Simulation

Valence Quarks:

- light and strange: unitary ($M_5 = 1.8$)
- heavy from quenched study: (*arXiv:1602.04118*)
  $am_h \leq 0.4$, $M_5 = 1.6$, $L_s = 12$
- Expect same qualitative features in $N_f = 2 + 1$

$\Rightarrow$ **Mixed action** between the (light+strange) and the heavy quark sector.

Computational Details:

- Volume averaging by using $\mathbb{Z}_2$-Wall sources.
- HDCG (*arXiv:1402.2585*) for light and strange. CG for heavy
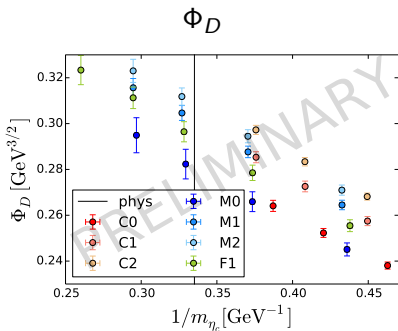- Monitored time-slice residual (*arXiv:0508023*):
  $r_t = \max_t \frac{|D\psi - \eta|_t}{|\psi|_t}$
- Many source position per configuration

Decay Constant Data

Masses and MEs from combined fit to $\langle AP \rangle$ and $\langle PP \rangle$ including 1st excited states: $\mathcal{O}(a, m_l, m_s, m_h)$.[1]
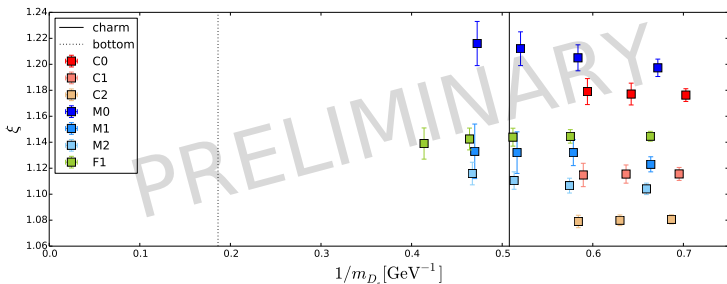
$$\Phi_P = f_P \sqrt{m_P}$$

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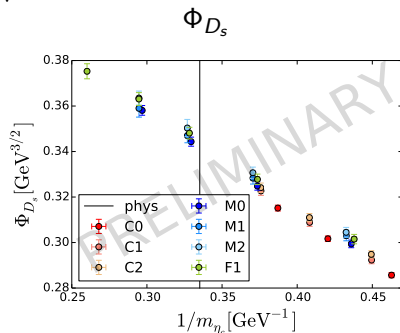
[1]so far: Z_A from conserved light-light current

Ratio of Bag parameters ξ

$$B_P = \frac{\langle P^0 | O_{VV+AA} | \bar{P}^0 \rangle}{\frac{8}{3} f_P^2 m_P^2}, \qquad \xi = \frac{f_{hs}\sqrt{B_{hs}}}{f_{hl}\sqrt{B_{hl}}}$$

PLAN:

- Renormalisation of mixed action for Bag parameters. (**A. Khamseh Wed 10[20]**)

- Extrapolate to B via ratio method. arXiv:0909.3187

Analysis

$$\mathcal{O}(a, m_l, m_s, m_h) \rightarrow \mathcal{O}(a = 0, m_l^{\mathrm{phys}}, m_s^{\mathrm{phys}}, m_c^{\mathrm{phys}})$$

- Extrapolate to m_s^{phys} (from global fit arXiv:1411.7017).
- Global fit: CL+heavy quark mass + light quark mass

$$
\begin{aligned}
\mathcal{O}(a, m_l, m_h) = \ & \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) \\
& + C_{CL}^0 \, a^2 \\
& + C_\chi^0 \left(m_\pi^2 - m_\pi^{2\,\mathrm{phys}} \right) \\
& + C_{P_h}^0 \, \Delta m_{P_h}^{-1}
\end{aligned}
\tag{1}
$$

where $\Delta m_{P_h}^{-1} = m_{P_h}^{-1} - m_{P_h}^{\mathrm{phys}\,-1}$ with $P_h = D, D_s, \eta_c$

Analysis

$$\mathcal{O}(a, m_l, m_s, m_h) \to \mathcal{O}(a = 0, m_l^{\mathrm{phys}}, m_s^{\mathrm{phys}}, m_c^{\mathrm{phys}})$$

- Extrapolate to m_s^{phys} (from global fit arXiv:1411.7017).
- Global fit: CL+heavy quark mass + light quark mass

$$
\begin{aligned}
\mathcal{O}(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) \\
+ \left[C_{CL}^0 + C_{CL}^1 \, \Delta m_{P_h}^{-1} \right] a^2 \\
+ \left[C_{\chi}^0 + C_{\chi}^1 \, \Delta m_{P_h}^{-1} \right] \left(m_\pi^2 - m_\pi^{2\,\mathrm{phys}} \right) \\
+ \left[C_{P_h}^0 \right] \Delta m_{P_h}^{-1}
\end{aligned}
\tag{1}
$$

where $\Delta m_{P_h}^{-1} = m_{P_h}^{-1} - m_{P_h}^{\mathrm{phys}\,-1}$ with $P_h = D, D_s, \eta_c$

Strange Quark Mass Correction

- Slight mistuning between unitary and physical strange quark mass.

ensemble	am_s^{unitary}	am_s^{physical}	mismatch
coarse	0.03620	0.03580(16)	-1.1%
medium	0.02661	0.02539(17)	-4.8%
fine	0.02144	0.02132(17)	-0.6%

- Parameterise mistuning in terms of dimensionless α:

$$\mathcal{O}^{\mathrm{phys}} = \mathcal{O}^{\mathrm{uni}} \left(1 + \alpha_{\mathcal{O}} \frac{m_s^{\mathrm{phys}} - m_s^{\mathrm{uni}}}{m_s^{\mathrm{phys}}} \right)$$

- Find $\alpha_{\mathcal{O}}$ from subset of ensembles and apply to others.

Strange Quark Mass Correction

$$\mathcal{O}^{\mathrm{phys}} = \mathcal{O}^{\mathrm{uni}} \left(1 + \alpha_{\mathcal{O}} \frac{m_s^{\mathrm{phys}} - m_s^{\mathrm{uni}}}{m_s^{\mathrm{phys}}} \right)$$

- Calculate 2 values of m_s on C1 and M1
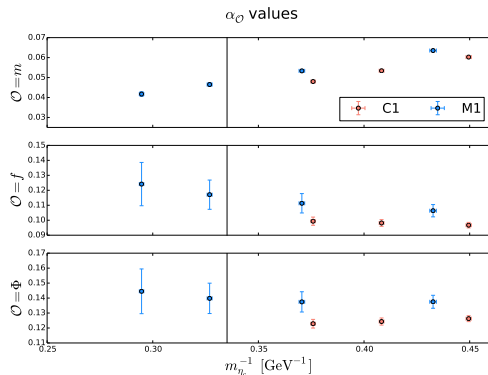
Strange Quark Mass Correction

$$\mathcal{O}^{\text{phys}} = \mathcal{O}^{\text{uni}} \left(1 + \alpha_{\mathcal{O}} \frac{m_s^{\text{phys}} - m_s^{\text{uni}}}{m_s^{\text{phys}}} \right)$$
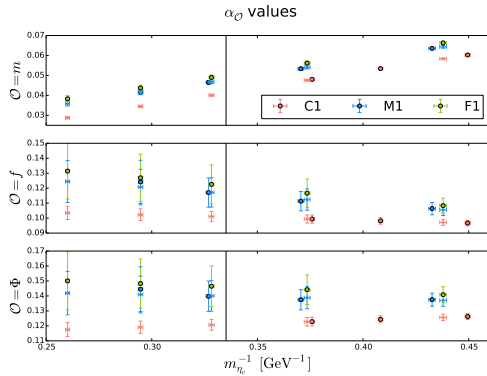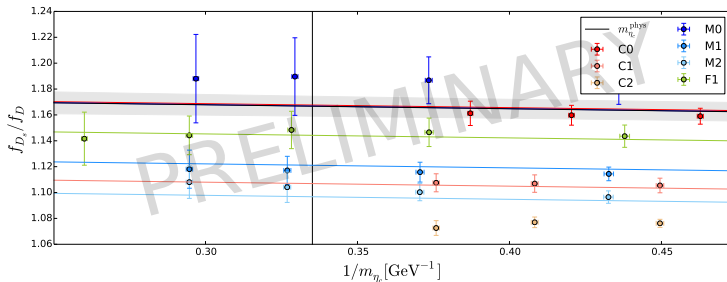
- Calculate 2 values of m_s on C1 and M1
- Extrapolate to F1 masses
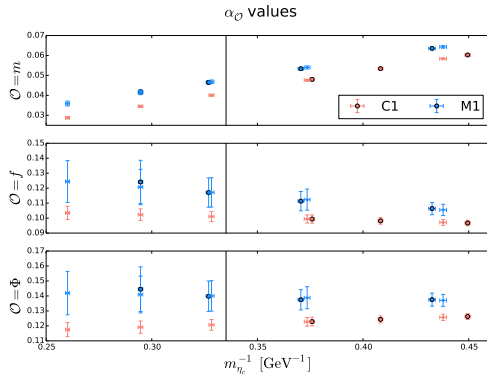
$\alpha_{\mathcal{O}}$ values

Strange Quark Mass Correction

$$\mathcal{O}^{\mathrm{phys}} = \mathcal{O}^{\mathrm{uni}}\left(1 + \alpha_{\mathcal{O}}\frac{m_s^{\mathrm{phys}} - m_s^{\mathrm{uni}}}{m_s^{\mathrm{phys}}}\right)$$

- Calculate 2 values of m_s on C1 and M1
- Extrapolate to F1 masses
- Extrapolate to F1 lattice spacing

$\alpha_{\mathcal{O}}$ values

f_{D_s}/f_D Global Fit

$$\mathcal{O}(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) + C_{CL}^0 \, a^2 + C_\chi^0 \, \Delta m_\pi^2 + C_{P_h}^0 \, \Delta m_{P_h}^{-1}$$

$$f_{D_s}/f_D = 1.167(8)_{\mathrm{stat}}$$

f_{D_s}/f_D Systematics

m_π and m_h, dependence
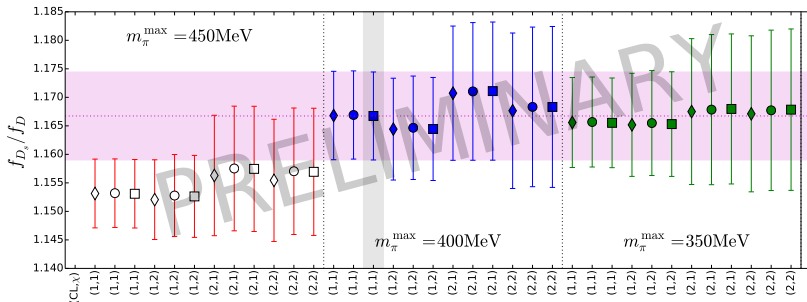
$$f_{D_s}/f_D = 1.167(8)_{\text{stat}} \binom{+4}{-2}_{\text{fit}}$$

To Do: FV, Isospin, fully correlated fits, m_{η_c}-disconnected and sea-charm

Φ_D

$$\mathcal{O}(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) + C_{CL}^0 \, a^2$$
$$+ \left(C_\chi^0 + C_\chi^1 \Delta m_{P_h}^{-1} \right) \Delta m_\pi^2 + C_{P_h}^0 \Delta m_{P_h}^{-1} \quad (2)$$
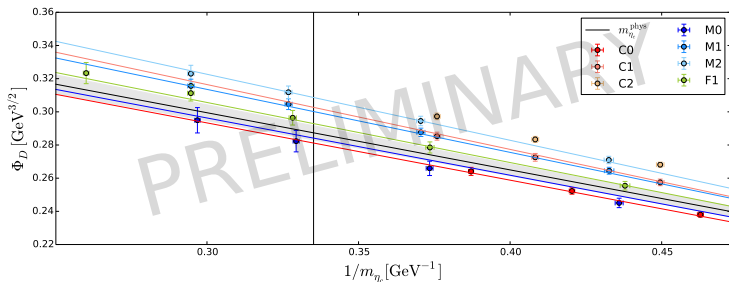
$$\Phi_D = 0.2857(44)_{\mathrm{stat}} \, \mathrm{GeV}^{3/2}$$

Φ_{D_s}

$$\mathcal{O}(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) + \left(C_{CL}^0 + C_{CL}^1 \, \Delta m_{P_h}^{-1} \right) \, a^2$$
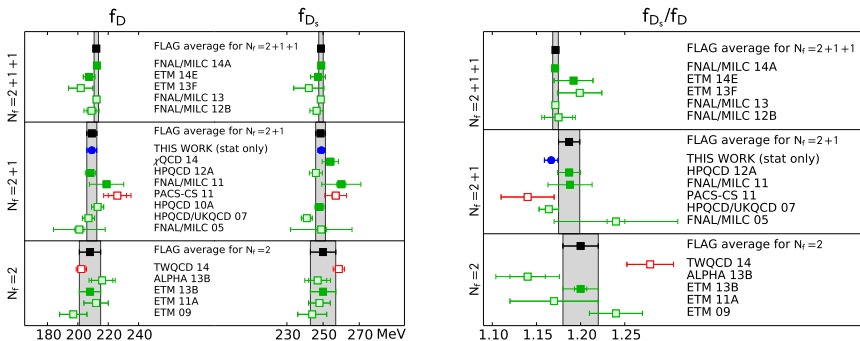$$+ \, C_\chi^0 \, \Delta m_\pi^2 + C_{P_h}^0 \, \Delta m_{P_h}^{-1} \tag{3}$$
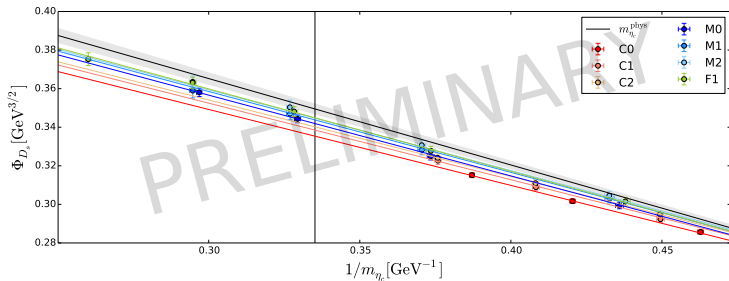
$$\Phi_{D_s} = 0.3495(26)_{\mathrm{stat}} \mathrm{GeV}^{3/2}$$

comparison with FLAG (decay constants)

adapted from FLAG 2016 (arXiv:1607.00299)

PRELIMINARY and **STATISTICAL ERROR ONLY**

V_{cd} and V_{cs} comparison with literature

adapted from FLAG 2016
(arXiv:1607.00299)
using data from arXiv:1509.02220
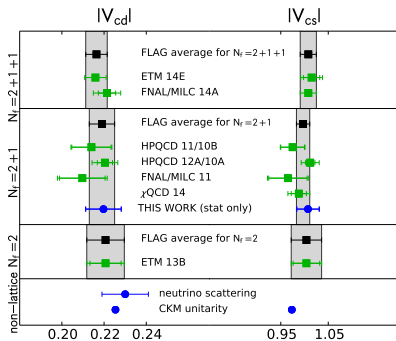
PRELIM, STAT ERROR ONLY

Fit systematics:

- m_π^{cuts}
- ways to set m_c
- mass-dependent chiral and CL coeffs.

Not finalised yet

- Take all correlation into account
- FV
- Isospin
- sea-charm effects
- renormalisation

New set-up

Problems

- $am_h^{\max} < am_h^{\mathrm{phys}}$ on Coarse
- Poor Signal-to-noise for
  $m_\pi = 139\mathrm{MeV}$ and
  $m_h \gtrsim m_c^{\mathrm{phys}}$

Solutions?

- Stout Smeared charm
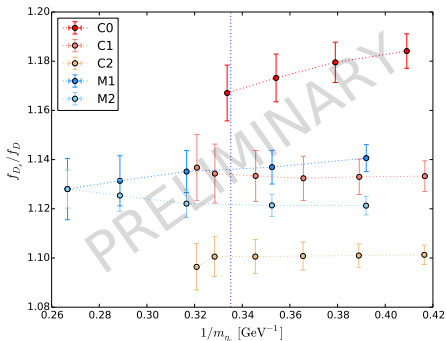- Gaussian Smearing for
  source + sink

Noise growth

D mesons on M0
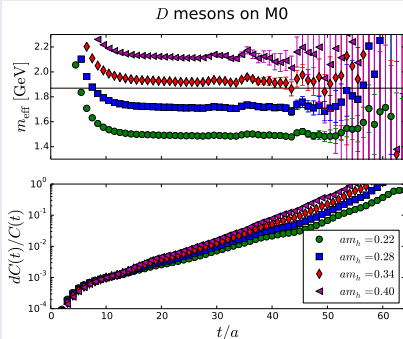
"Smeared Runs"

WORK IN PROGRESS:

First Data (Limited statistic)

am_h reach

- Sweetspot: $M_5 = 1.0$
  3 hits of stout smearing
  ($\rho = 0.1$)
  $\Rightarrow \mathbf{am_h \lesssim 0.7}$
- **Can reach charm** on all ensembles
- **Physical program:**
  f_D, f_{D_s}, semi-leptonics, bag parameters, ξ, HVP
- Ratio Method to reach b.

Summary

What we have done:

- D and D_s decay constants
- at **Physical Pion Masses** $(2+1f$ simulation) in an automatically $\mathcal{O}(a)$-improved setting.
- Continuum Limit with 3 lattice spacings.
- Global fit with full control of systematics

Current work:

- Finalising systematic error budget
- Produce smeared data on other ensembles
- semi-leptonics, ratio method, combined analysis of all data

ADDITIONAL SLIDES

Justus Tobias Tsang

Definition of the Residual Mass

From the axial Ward identity we define the **residual mass** am_{res} as

$$am_{\text{res}} = \frac{\sum\limits_{\mathbf{x}}\langle J_{5q}(x)P(0)\rangle}{\sum\limits_{\mathbf{x}}\langle P(x)P(0)\rangle}$$

where J_{5q} is the pseudoscalar density in the centre of the 5th dimension.

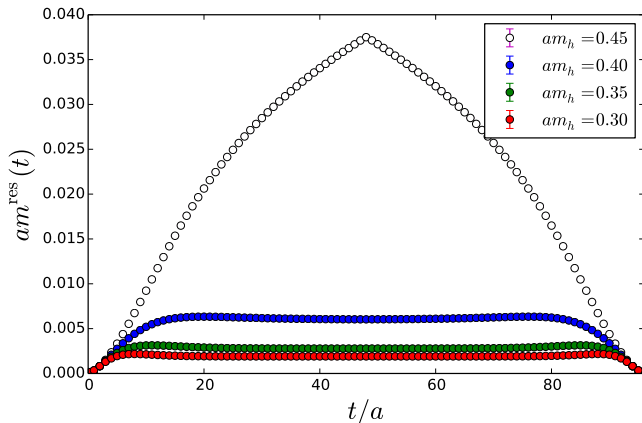$\Rightarrow$ measure of the residual chiral symmetry breaking

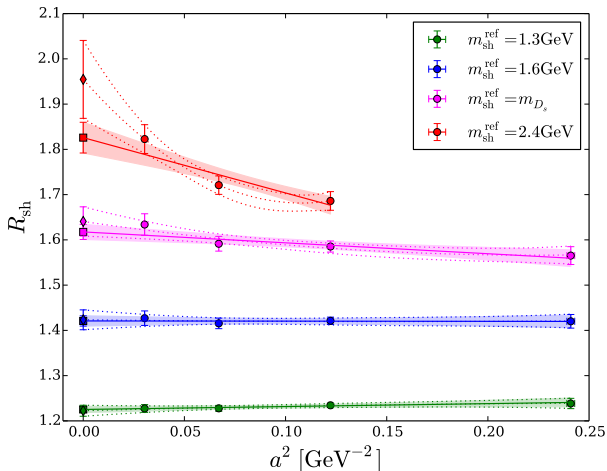# Quenched Study: M_5 and bound on am_h - quenched
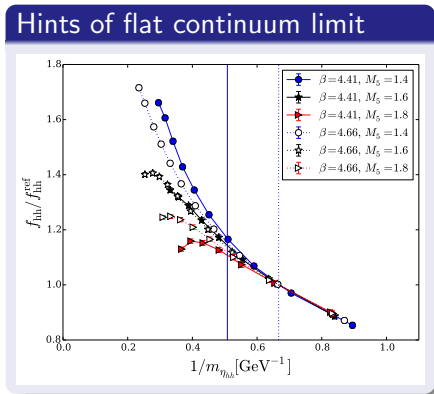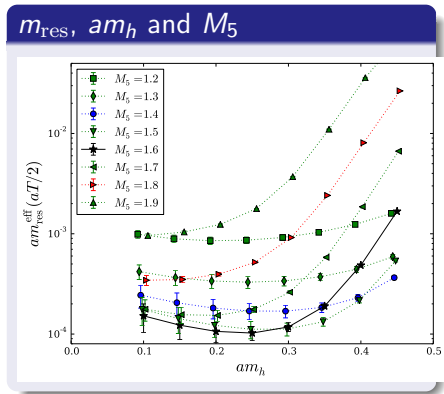
JHEP **04** (2016) 037 (arXiv:1602.04118 [hep-lat])

$am_h \lesssim 0.4$ bound in 2+1f tested on C0

$am_h \lesssim 0.4$ bound still applies

$\Rightarrow$

Quenched Study: Flat continuum limit scaling

JHEP **04** (2016) 037 (arXiv:1602.04118 [hep-lat])

Definitions

- Decay constants: $\langle 0 | A_{cq}^{\mu} | D_q(p) \rangle = f_{D_q} p_{D_q}^{\mu}$

  $\Rightarrow$ Extraction of $|V_{cd}|$ and $|V_{cs}|$

- Bag Parameters: $B_P = \frac{\langle P^0 | O_{VV+AA} | \overline{P}^0 \rangle}{8/3 f_P^2 m_P^2}$ where
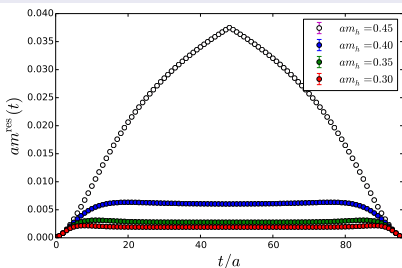 $O_{VV+AA} = (\bar{h}\gamma_{\mu}q)(\bar{h}\gamma_{\mu}q) + (\bar{h}\gamma_5\gamma_{\mu}q)(\bar{h}\gamma_5\gamma_{\mu}q)$

- ξ:

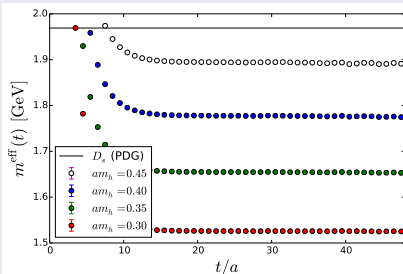$$\xi = \frac{f_{hs}\sqrt{B_{hs}}}{f_{hl}\sqrt{B_{hl}}}$$

  $\Rightarrow$ Extraction of $|V_{td}/V_{ts}|$

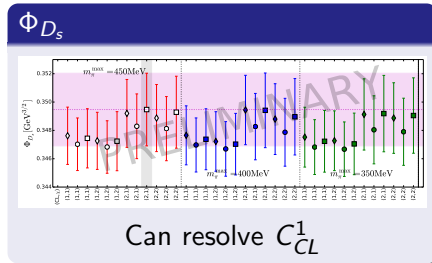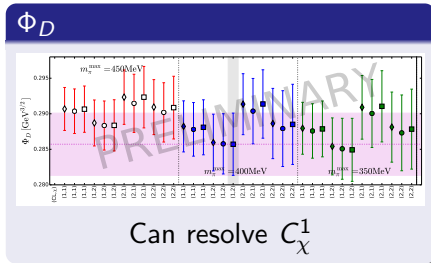# Limitations of current formalism

Residual mass

reach in m_h

Restriction $am_h \lesssim 0.4$ in agreement with quenched
$\Rightarrow$ **Cannot reach physical charm on the coarsest ensembles**

f_{D_s} and f_D Systematics

Φ_D

Can resolve C_χ^1

Φ_{D_s}

Can resolve C_{CL}^1

To Do:

- Renormalisation
- FV
- Isospin

- Fully correlated fits
- m_{η_c}-disconnected
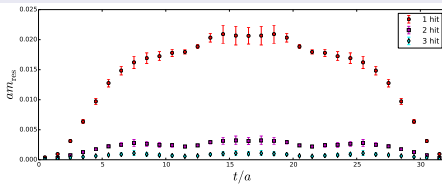- sea-charm

Smeared Kernel: Set-up

Smearing

Found sweetspot for

- $M_5 = 1.0$
- 3 hits of stout smearing
- Standard Stout parameter $\rho = 0.1$

hit comparison

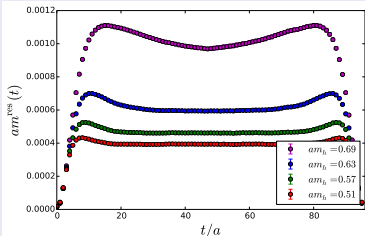- Gaussian smearing of light and strange
- Kernel smearing of heavy quarks

$\Rightarrow$ Now test the reach of am_h

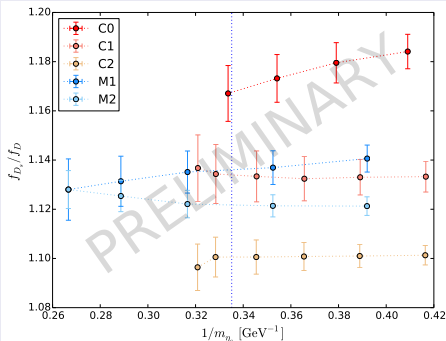# Smeared Kernel

Residual Mass

am_h reach

- **Can reach charm**
- Limited statistic
- $am_h \lesssim 0.7$