Heavy Domain Wall Fermions:
The RBC and UKQCD charm physics program

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RBC-UKQCD Collaborations

Granada

20 June 2017

THE UNIVERSITY *of* EDINBURGH

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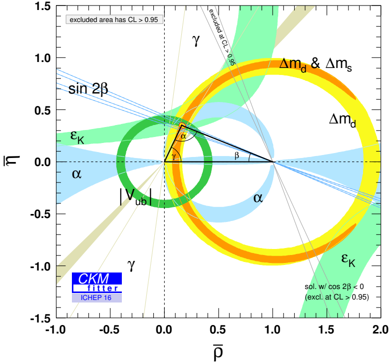
Outline

1. Motivation
2. Set-Up 1 - charm
   - f_D, f_{D_s} and f_{D_s}/f_D
   - ξ
   - m_c
3. Set-Up 2 - pushing further
   - First results
4. Aside: Combined Analysis of JLQCD + RBC/UKQCD data
5. Summary and Outlook

Motivation - Flavour Physics



CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

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

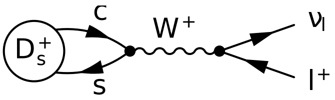
Experimental decay rate

$$\Gamma_{\text{exp.}} = V_{CKM} \times (weak + em) \times (strong) \quad [+\mathcal{O}(\alpha_{EM})]$$

Motivation - Charm (and b) Observables

Large number of processes of interest:

- Decay constants f_D, f_{D_s}
  - $\Rightarrow$ Access $|V_{cd}|$, $|V_{cs}|$
  - $\Rightarrow$ First test for Heavy-DWF



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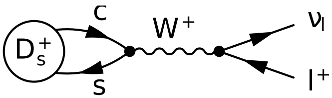
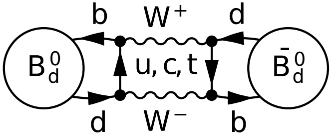
  Bag parameters and ξ
  - $\Rightarrow$ Access $|V_{td}/V_{ts}|$





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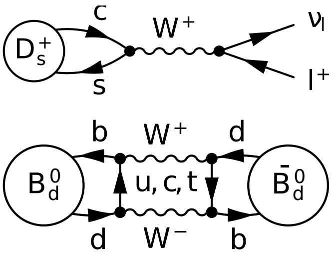
  - $\Rightarrow$ Input for further simulations



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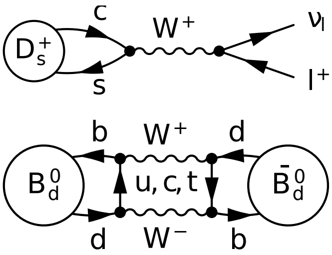
- charm contribution to HVP



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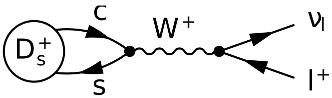

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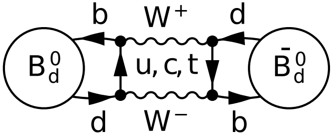
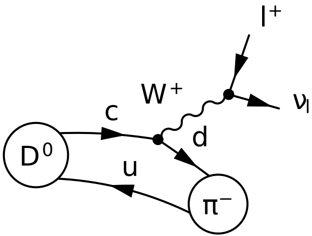


- charm quark mass m_c
  - $\Rightarrow$ Input for further simulations
- charm contribution to HVP
- Semi-leptonic decays
  - $\Rightarrow$ Access $|V_{cd}|$, $|V_{cs}|$



Motivation: Domain Wall Fermions

DWFs provide a method to simulate (approximately) chiral fermions on the lattice at the expense of a fifth dimension

$\Rightarrow$ Automatic $\mathcal{O}(a)$ improvement

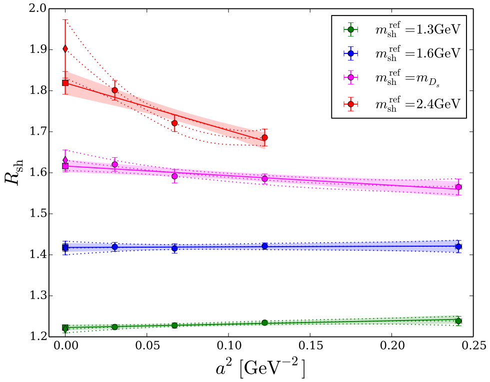
$\Rightarrow$ No operator mixing:
$\Rightarrow$ easier renormalisation

$\Rightarrow$ Additional parameters L_s and M_5:
M_5 only affects UV behaviour:
$\Rightarrow$ use to reduce discretisation effects?

BUT:

- More expensive due to fifth dimension

- Scan parameter space for good action for heavy quarks.
- Keep light and strange unitary ($M_5 = 1.8$)

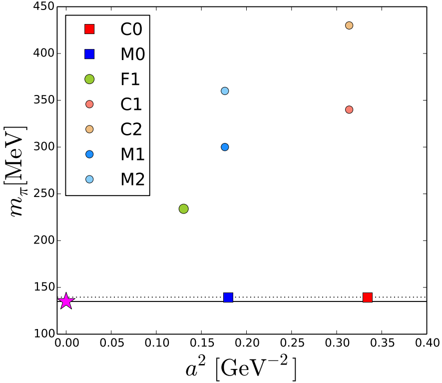


Quenched Pilot Study:
JHEP **05** (2015) 072
JHEP **04** (2016) 037

- Good chiral properties and $O(a)$-improvement
- Find flat CL for modification of DW param's for charm: $M_5 = 1.6$ and $am_h \lesssim 0.4$

$\Rightarrow$ **Mixed action**

RBC/UKQCD Ensembles



	$L^3 \times T/a^4$	a^{-1}/GeV	m_π/MeV
C0	$48^3 \times 96$	**1.73**	**139**
C1	$24^3 \times 64$	1.78	340
C2	$24^3 \times 64$	1.78	430
M0	$64^3 \times 128$	**2.36**	**139**
M1	$32^3 \times 64$	2.38	300
M2	$32^3 \times 64$	2.38	360
F1	$48^3 \times 96$	**2.77**	230

(C0 + M0: arXiv:1411.7017)
(F1: arXiv:1701.02644)

- $N_f = 2 + 1$ Domain Wall Fermions
- **2 ensembles with physical pion masses**
- 3 Lattice spacings

Technical slide - Sources and Statistics

- $\mathbb{Z}_2$-Wall sources
- placed on many source planes
- binned into one effective measurements per config

Name	hits/conf	confs	total
C0	48	88	4224
C1	32	100	3200
C2	32	101	3232
M0	32	80	2560
M1	32	83	2656
M2	16	77	1232
F1	48	82	3936

Technical slide - Sources and Statistics

- $\mathbb{Z}_2$-Wall sources
- placed on many source planes
- binned into one effective measurements per config
- strange quark mass slightly mistuned on some ensembles

Name	am_s^{phys}	am_s^{sim}
C0	0.03580(16)	0.0362
C1	0.03224(18)	
C2	0.03224(18)	
M0	0.02539(17)	0.02661
M1	0.02477(18)	
M2	0.02477(18)	
F1	0.02132(17)	0.02144

Decay constants

Experimental decay rate

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Leptonic decays

$$\mathcal{B}(D_{(s)} \to l\bar{\nu}_l) = |V_{cq}|^2 \mathcal{K}(m_l, m_{D_q}) f_{D_q}^2, \qquad q = d, s$$

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If we can determine the strong contribution independently we can make predictions for $|V_{CKM}|$.

Experimental decay rate

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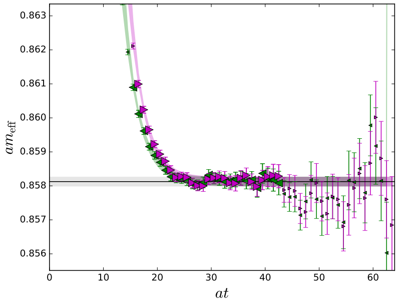
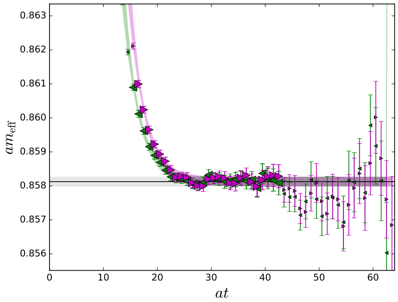
Lattice calculation

$$\mathcal{Z}_A \langle 0| \bar{c}\gamma_4\gamma_5 q \,|D_q(0)\rangle = f_{D_q} m_{D_q}, \qquad q = d, s$$



Uncorrelated simultaneous two-exponential fit to $\langle PP \rangle$ and $\langle AP \rangle$ channels for D_s at $am_h = 0.34$ on M0.



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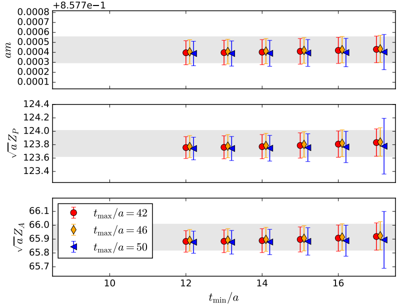
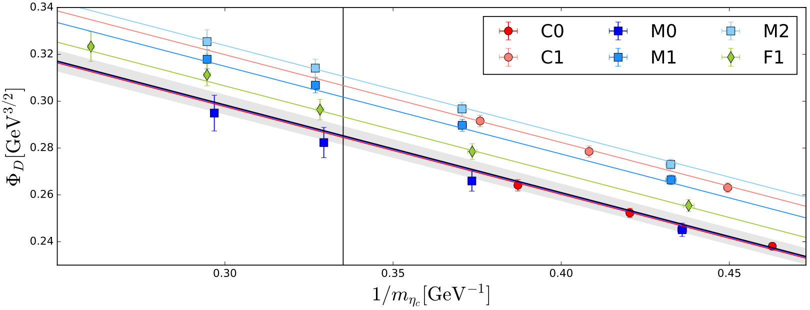
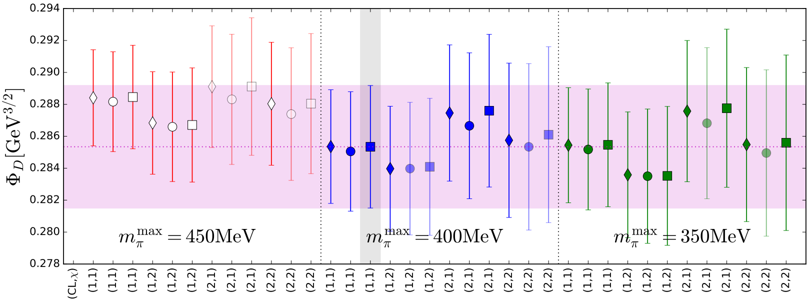


Variation of $t_{\rm min}$ and $t_{\rm max}$.

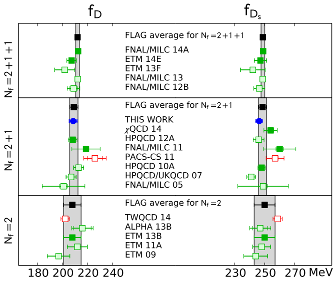
$$\mathcal{O}(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) + \left(C_{CL}^0 + C_{CL}^1 \, \Delta m_{P_h}^{-1} \right) a^2 + C_\chi^0 \, \Delta m_\pi^2 + C_{P_h}^0 \, \Delta m_{P_h}^{-1}$$

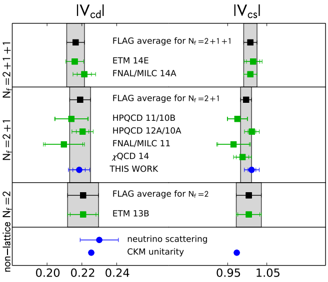


$$\Phi_P = f_P \sqrt{m_P}$$



- Mixed action renormalisation: $\left|1 - \frac{\mathcal{Z}_A(M_5{=}1.8)}{\mathcal{Z}_A(M_5{=}1.6)}\right| < 0.5\%$
- Variations of fit ansatz and pion cuts to determine systematics
- Different ways to fix charm ($D(\diamond)$, $D_s(\bigcirc)$, and $\eta_c(\square)$)



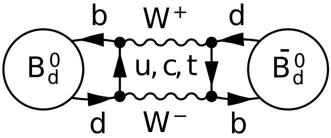


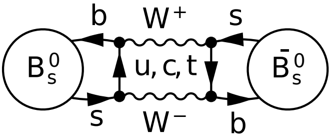
Plots inspired by FLAG III [arXiv:1607.00299]

$$f_D = 208.7(2.8)_{\rm stat}\left({}^{+2.1}_{-1.8}\right)_{\rm sys}\,\mathrm{MeV} \qquad |V_{cd}| = 0.2185(50)_{\rm exp}\left({}^{+35}_{-37}\right)_{\rm lat}$$

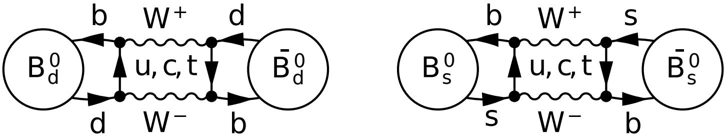
$$f_{D_s} = 246.4(1.3)_{\rm stat}\left({}^{+1.3}_{-1.9}\right)_{\rm sys}\,\mathrm{MeV} \qquad |V_{cs}| = 1.011(16)_{\rm exp}\left({}^{+4}_{-9}\right)_{\rm lat}$$

Neutral Meson Mixing





$$\Delta m_q = |V_{tq}^* V_{tb}|^2 \times \mathcal{K} \times \mathcal{M}_q$$



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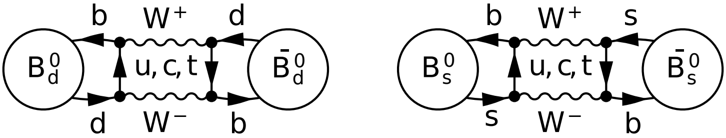

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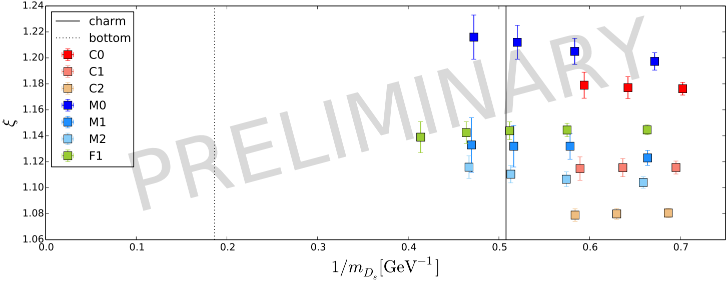
$$= \langle \bar{B}_q^0 | O_{VV+AA} | B_q^0 \rangle$$

Ratio of Bag parameters ξ (1511.09328)

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



Fits by A. Khamseh

STATUS:

- Data at charm: percent level precision
- Mild heavy mass dependence
- More data on disk + many src/snk separations

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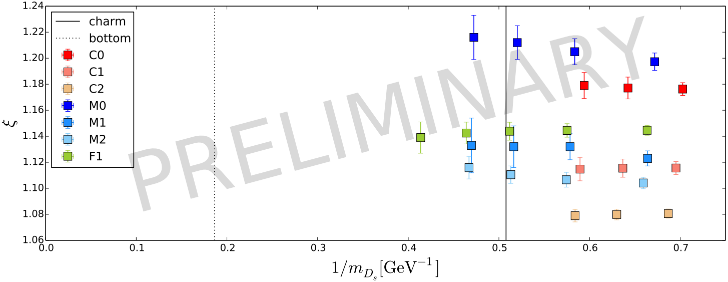

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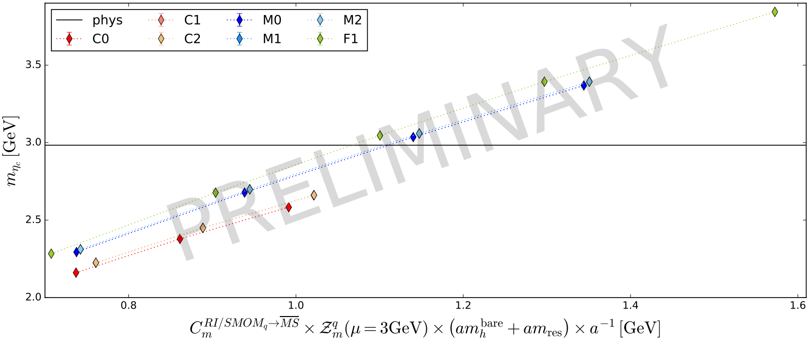
PLAN:

- Renormalisation of mixed action for Bag parameters.
- Analyse further data and add to global fit
- Extrapolate to B

Charm quark mass

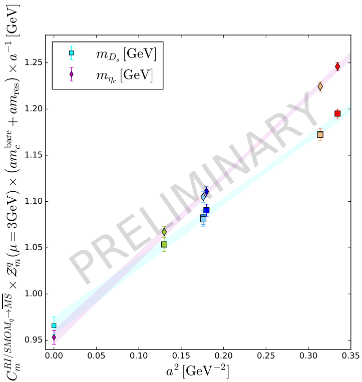


Definitions and coefficients from 1208.4412 and 1411.7017

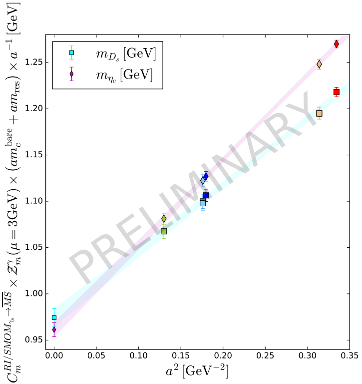
- $\Rightarrow$ Determine $m_c(a)$ from m_{η_c} (or m_{D_s})
- $\Rightarrow$ Renormalisation of mixed action still ongoing
  - $\Rightarrow$ Currently use $Z_m(M_5 = 1.8)$

Charm quark mass

$\not{q}$ − scheme



γ_μ − scheme



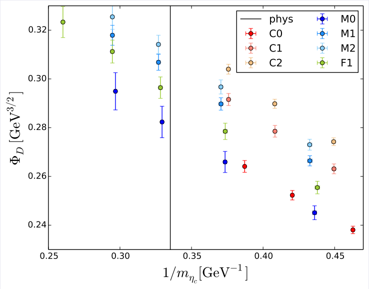
⇒ Renormalisation of mixed action still ongoing
⇒ No chiral extrapolation done yet
⇒ Good agreement between two schemes

Current Limitations

Problems

- $am_h^{\max} < am_c^{\text{phys}}$ on Coarse

heavy quark reach



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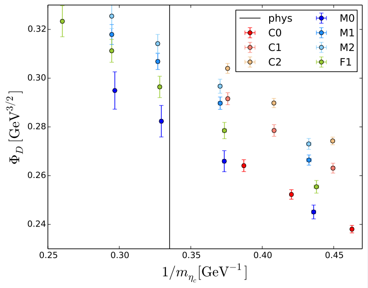
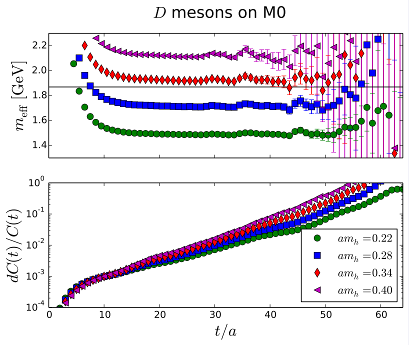


Noise growth



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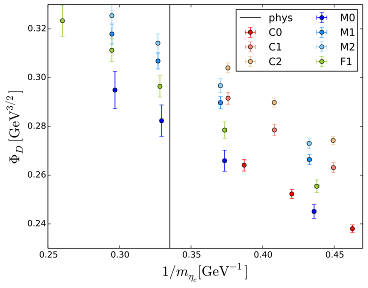

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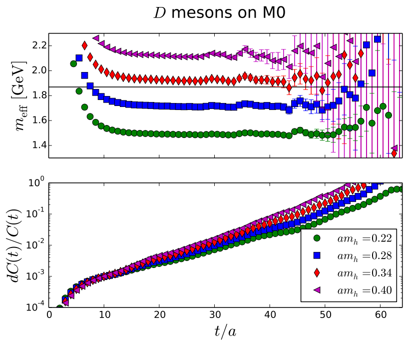


Solutions?

- Stout Smeared charm
- Gaussian Smearing for source + sink

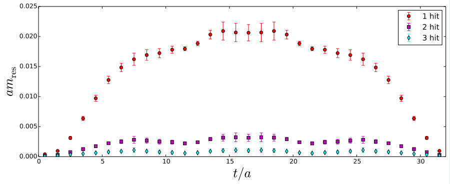
Stout smeared runs

Stout Smearing

Found sweet-spot for

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

hit comparison



Fits by A. Khamseh

Conclusion

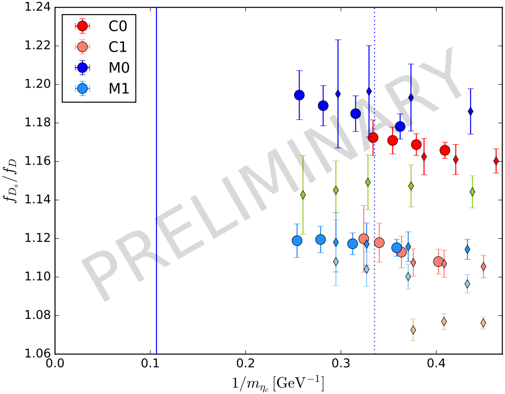
$\Rightarrow$ Gaussian smearing of light and strange

$\Rightarrow$ Stout smearing of heavy quarks

$\Rightarrow$ $am_h \lesssim 0.7$

First results with smeared action

First Data (Limited statistic)

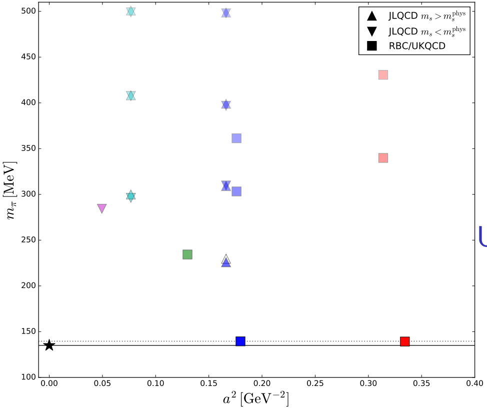


Comments

- **Reach physical charm quark mass** on **all** ensembles
- More data soon
- Renormalisation in progress
- **Physics program:** decay constants, semi-leptonics, bag parameters, ξ, HVP
- Push towards b.

Combined Data from JLQCD and RBC/UKQCD

in collaboration with Guido Cossu, Brendan Fahy, Shoji Hashimoto



Both: $N_f = 2+1$ DWF

3+3 Lattice Spacings

JLQCD: (triangles)

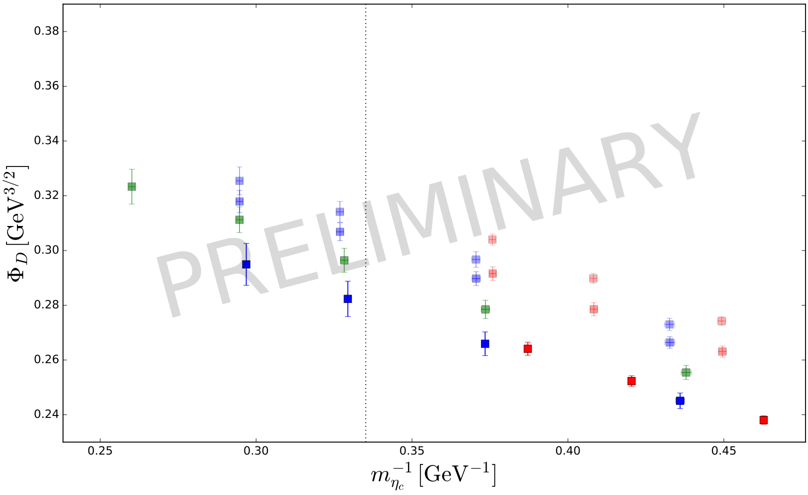
Fine lattices: $a^{-1} = 2.4 - 4.5\,\mathrm{GeV}$

UKQCD: (squares)

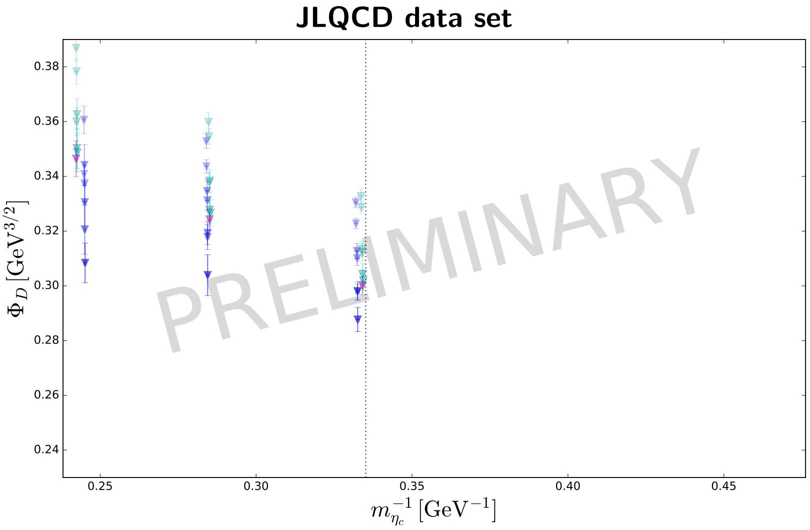
Physical Pion masses

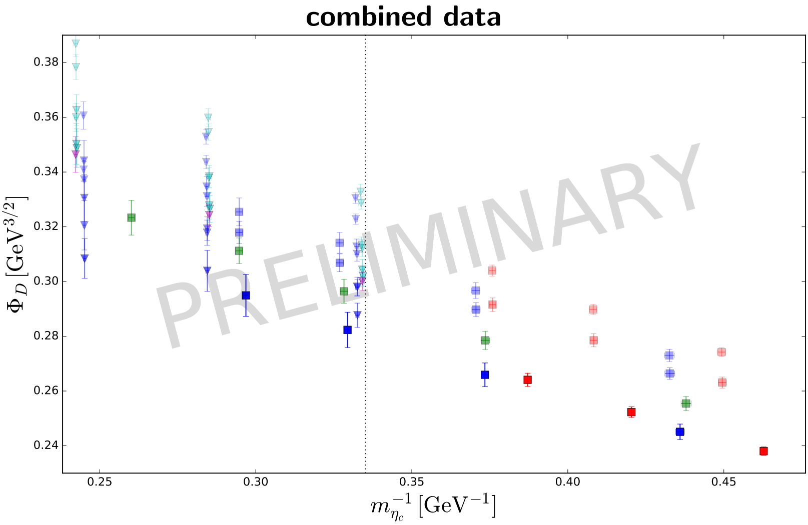
Combine data sets for well controlled chiral and continuum limit.

RBC/UKQCD data set



Ongoing Work: JLQCD + UKQCD - data




combined data
PRELIMINARY
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
$\Phi_D\,[\mathrm{GeV}^{3/2}]$
0.25
0.30
0.35
0.40
0.45
$m_{\eta_c}^{-1}\,[\mathrm{GeV}^{-1}]$

Ongoing Work: JLQCD + UKQCD - plans

- Data on both sides of charm
- Global fit with universality constraint is ongoing.
  First try:

$$
\begin{aligned}
\mathcal{O}_i(a, m_l, m_h) = \mathcal{O}(0, m_l^{\mathrm{phys}}, m_h^{\mathrm{phys}}) \\
+ C_\chi \, \Delta m_\pi^2 + C_H \, \Delta m_H^{-1} \\
+ \left(C_{CL}^{UK} \, \delta_{UK,i} + C_{CL}^{KEK} \, \delta_{KEK,i} \right) \, a^2 \\
+ C_K \Delta(2\, m_K^2 - m_\pi^2)
\end{aligned}
$$

- Can include data with $am_s \neq am_s^{\mathrm{phys}}$ without corrections
- Include new smeared RBC/UKQCD data

DONE

Established HDWF

- DWF as heavy quark discretisation: $M_5 = 1.6$, $am_h \lesssim 0.4$
- JHEP **05** (2015) 072
  JHEP **04** (2016) 037
- Good Continuum Scaling
- $N_f = 2+1$: f_D, f_{D_s} with competitive precision (arXiv:1701.02644)
- 3 lattice spacings, 2 physical pion mass ensembles.

Conclusions and Outlook

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ONGOING

Analysis underway

- Determination of m_c
- Bag parameters, ξ
- JLQCD+UKQCD
- reach beyond c with Kernel Smearing
- charm contribution to HVP

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Data in Production

- beyond c
- semi-leptonics
- NPR for smeared kernel

ADDITIONAL SLIDES

Systematic errors

obs	val	stat ($\times 10^4$)	sys ($\times 10^4$)	fit ($\times 10^4$)	FV ($\times 10^4$)	h.o. CL ($\times 10^4$)	$m_u \neq m_d$ ($\times 10^4$)	ren ($\times 10^4$)	m_s ($\times 10^4$)
Φ_D $[\mathrm{GeV}^{3/2}]$	0.2853	38	$^{+29}_{-24}$	$^{+24}_{-18}$	10	-	4.7	11	-
Φ_{D_s} $[\mathrm{GeV}^{3/2}]$	0.3457	26	$^{+18}_{-26}$	$^{+\ 3}_{-19}$	6	7	4.4	14	0.9
f_{D_s}/f_D	1.1667	77	$^{+57}_{-43}$	$^{+44}_{-23}$	35	-	8	-	3

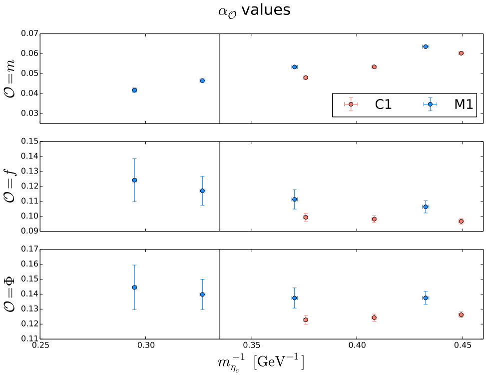
Systematic error budget for decay constants (arXiv:1701.02644)

Strange Quark Mass Correction

⇒ Parameterise mistuning in terms of dimensionless α:

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

- Calculate 2 values of m_s on C1 and M1



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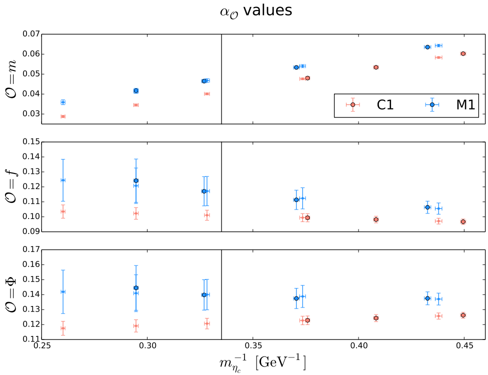
- Extrapolate to F1 masses



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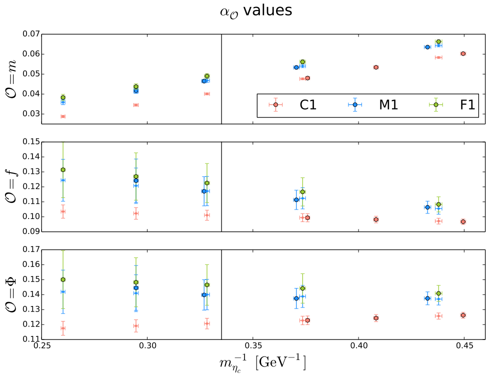
- Extrapolate to F1 lattice spacing



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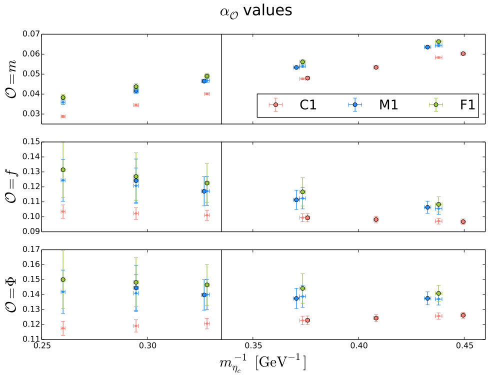
- Extrapolate to F1 lattice spacing

⇒ Small correction

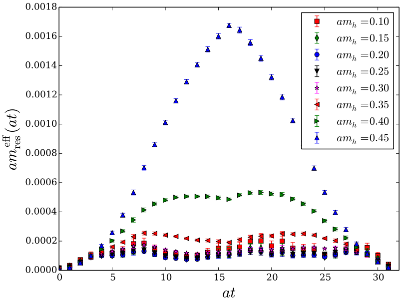


Residual Mass

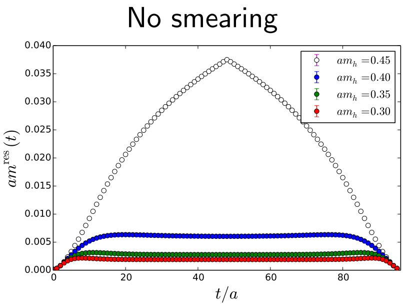
What happens at large input quark masses? Check residual mass

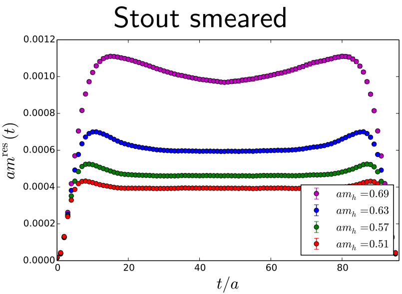
$$C_{m_{\rm res}}(t) = \frac{\left\langle \sum_{\mathbf{x}} J_{5q}^{a}(x) P(0) \right\rangle}{\left\langle \sum_{\mathbf{x}} P(x) P(0) \right\rangle}$$

- Expect plateau
- For $M_5 = 1.6$ mechanism seems to break down for $am_h \gtrsim 0.4$
- No longer simulating (approx.) chiral QCD



$N_f = 2 + 1$: Residual Mass





$am_h^{\rm bare} \lesssim 0.4$

$am_h^{\rm bare} \lesssim 0.7$