Theory develoments in $B_{(s)}$ mixing

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for the RBC-UKQCD Collaborations

Based on arXiv:1812.08791

Durham, IPPP
Towards the Ultimate Precision in Flavour Physics

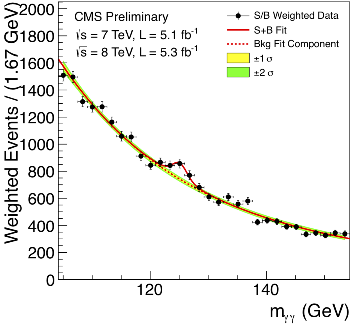
04 April 2019

THE UNIVERSITY of EDINBURGH

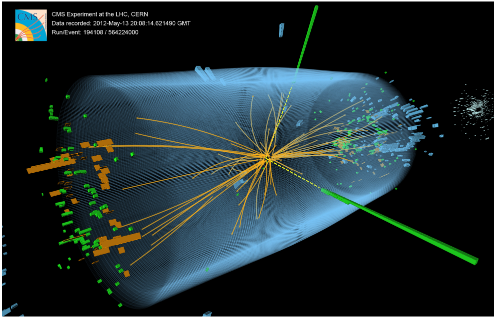
Outline

Where to find New Physics?

1. Direct searches:
   ⇒ *Bump in the spectrum*



source:CERN

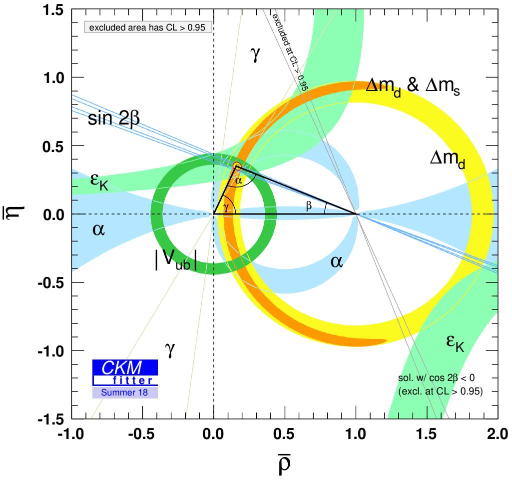


e.g. Higgs discovery in 2012

Where to find New Physics?

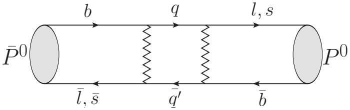
1. Direct searches:
   ⇒ *Bump in the spectrum*
2. Indirect searches:
   Precision tests of SM:
   → Quantum corrections due to new particles modify SM predictions
   → NP shows as discrepancy between experiment and theory

⇒ **Over-constrain SM**



Neutral meson mixing

Neutral mesons oscillate with their antiparticles



$$\mathcal{A} \propto \left| \sum_{q=u,c,t} \frac{m_q^2}{M_W^2} V_{qb} V_{ql}^* \right|^2 \approx \frac{m_t^4}{M_W^4} \left| V_{tb} V_{tl}^* \right|^2$$

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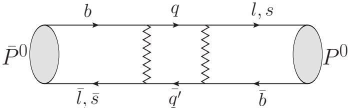

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Difference between mass eigenstates: $\Delta m \Rightarrow \Delta m^{\mathrm{exp}}$ measured to $< 1\%$!

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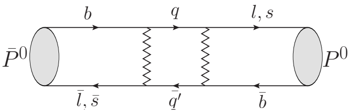

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Difference between mass eigenstates: $\Delta m \Rightarrow \Delta m^{\mathrm{exp}}$ measured to $< 1\%$!

$$\Delta m \propto \underbrace{\left\langle B^0_{(s)} \middle| \mathcal{H}^{\Delta b=2} \middle| \bar{B}^0_{(s)} \right\rangle}_{\text{Short distance}} + \underbrace{\sum_n \frac{\left\langle B^0_{(s)} \middle| \mathcal{H}^{\Delta b=1} \middle| n \right\rangle \left\langle n \middle| \mathcal{H}^{\Delta b=1} \middle| \bar{B}^0_{(s)} \right\rangle}{E_n - M_{B_{(s)}}}}_{\text{Long distance}}$$

$E_n \sim m_W, m_t \Rightarrow$ **Short distance dominated**.

Operator Product Expansion

Two scale problem: $\Lambda_{\mathrm{QCD}} \sim 1\,\mathrm{GeV} \ll m_{EW} \sim 100\,\mathrm{GeV}$:

$\Rightarrow$ Factorise via OPE

$$\Delta m \propto \sum_i C_i(\mu) \left\langle B^0_{(s)} \middle| \mathcal{O}_i^{\Delta b=2}(\mu) \middle| \bar{B}^0_{(s)} \right\rangle$$

- Perturbative model-dependent Wilson coefficients $C_i(\mu)$
- Non-perturbative model-independent matrix elements of $\mathcal{O}_i^{\Delta b=2}(\mu)$

Operator Product Expansion

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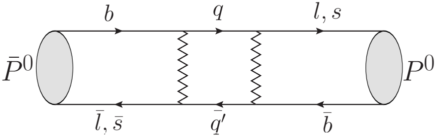
- Perturbative model-dependent Wilson coefficients $C_i(\mu)$
- Non-perturbative model-independent matrix elements of $\mathcal{O}_i^{\Delta b=2}(\mu)$
- 5 independent (parity even) operators $\mathcal{O}_i$.
- SM: $\mathcal{O}_1 = \left(\bar{b}_a \gamma_\mu \left(\mathbb{1} - \gamma_5\right) q_a\right) \left(\bar{b}_b \gamma_\mu \left(\mathbb{1} - \gamma_5\right) q_b\right) = \mathcal{O}_{VV+AA}$

Flavour Physics and CKM - neutral meson mixing

Experiment $\approx$ *CKM* $\times$ non-perturbative $\times$ (PT+kinematics)



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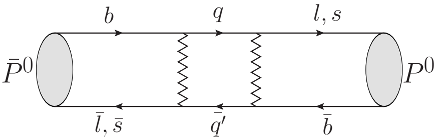
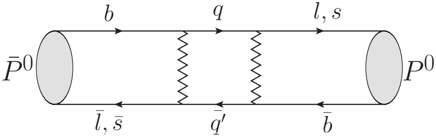


$$\Delta m_P = \left| V^*_{tq_2} V_{tq_1} \right| \times f_P^2 m_P \hat{B}_P \times \frac{G_F^2 m_W^2}{6\pi^2} \mathcal{K}$$

Flavour Physics and CKM - neutral meson mixing

$$\text{Experiment} \approx CKM \times \text{non-perturbative} \times (\text{PT+kinematics})$$



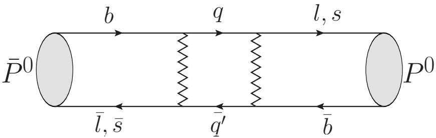
$$\Delta m_P = \left| V_{tq_2}^* V_{tq_1} \right| \times f_P^2 m_P \hat{B}_P \times \frac{G_F^2 m_W^2}{6\pi^2} \mathcal{K}$$

[HFLAV]

$$\Delta m_d = 0.5064 \pm 0.0019 \, \mathrm{ps}^{-1}$$
$$\Delta m_s = 17.757 \pm 0.021 \, \mathrm{ps}^{-1}$$

Flavour Physics and CKM - neutral meson mixing

Experiment ≈ *CKM* × non-perturbative × (PT+kinematics)



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Computing ξ gives access to

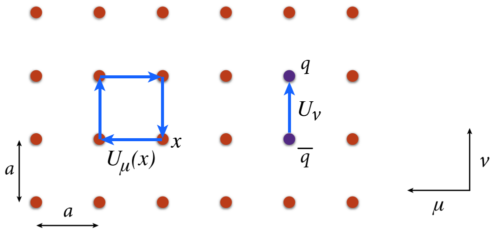
$$\xi^2 = \frac{f_{B_s}^2 \hat{B}_{B_s}}{f_B^2 \hat{B}_B} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\Delta m_s}{\Delta m_d} \frac{m_B}{m_{B_s}}$$

Lattice QCD methodology

Wick rotate ($t \to i\tau$) Path Integral to Euclidean space:

$$\langle \mathcal{O} \rangle_E = \frac{1}{Z} \int \mathcal{D}[\psi, \overline{\psi}]\, \mathcal{D}[U]\, \mathcal{O}[\psi, \overline{\psi}, U]\, e^{-S_E[\psi, \overline{\psi}, U]}$$

Introducing lattice renders PI large **but finite** dimensional.



PDG

- Finite lattice spacing a
  $\Rightarrow$ UV regulator
- Finite Box of length L
  $\Rightarrow$ IR regulator

$\Rightarrow$ Calculate PI **explicitly** via Monte Carlo sampling:

Multiple scale problem: back of the envelope

Control IR (Finite Size Effects) and UV (discretisation) effects

$$m_\pi L \gtrsim 4$$
$$a^{-1} \gg \text{Mass scale of interest}$$

For $m_\pi = m_\pi^{\rm phys} \sim 140\,\mathrm{MeV}$ and $m_b \approx 4.2\,\mathrm{GeV}$:

$$L \gtrsim 5.6\,\mathrm{fm}$$
$$a^{-1} \sim 4.2\,\mathrm{GeV} \approx (0.05\,\mathrm{fm})^{-1}$$

Requires $N \equiv L/a \gtrsim 120 \Rightarrow N^3 \times (2N) \gtrsim 4 \times 10^8$ lattice sites.

VERY EXPENSIVE to satisfy both constraints simultaneously.

A Lattice Computation

Lattice vs Continuum

We simulate:

- at finite lattice spacing a
- in finite volume L^3
- lattice regularised
- Some bare input quark masses am_l, am_s, am_h
  In general: $m_\pi \neq m_\pi^{\mathrm{phys}}$

We want:

- $a = 0$
- $L = \infty$
- some continuum scheme
- $m_l = m_l^{\mathrm{phys}}$
- $m_s = m_s^{\mathrm{phys}}$
- $m_h = m_c^{\mathrm{phys}}, m_b^{\mathrm{phys}}$

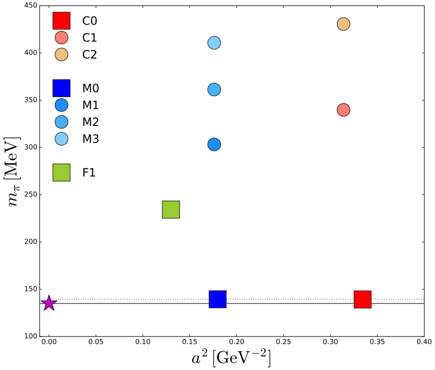
$\Rightarrow$ Need to control all limits!

$\rightarrow$ particularly simultaneously control FV and discretisation

$\Rightarrow$ Decide on a fermion action:

Wilson, Staggered, Twisted Mass, **Domain Wall fermions**, $\cdots$

RBC/UKQCD $N_f = 2+1$ ensembles



- Iwasaki gauge action
- Domain Wall Fermion action
  $\Rightarrow N_f = 2+1$ flavours in the sea
  $\Rightarrow M_5 = 1.8$ for light and strange
- **2 ensembles with physical pion masses** [PRD **93** (2016) 074505]
- 3 Lattice spacings [JHEP **12** (2017) 008]
- Heavier m_π ensembles guide small chiral extrapolation of F1

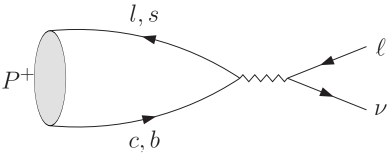
Chiral Fermions:

$\Rightarrow$ $O(a)$ improved

$\Rightarrow$ Multiplicative renormalisation

Lattice setup [arXiv:1812.08791]

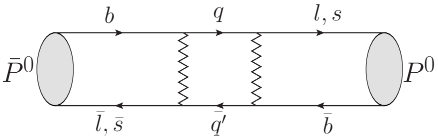
Leptonic decays:



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

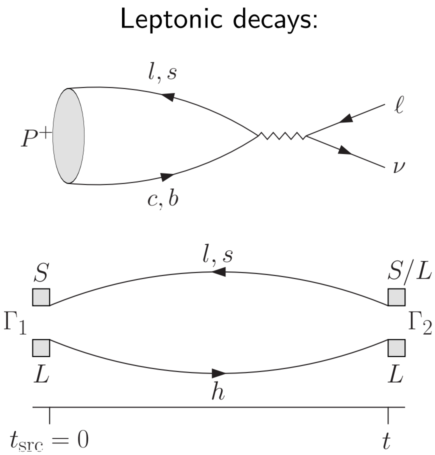
- Details of DWF heavy quark discretisation differs from l/s $\Rightarrow$ mixed-action
- Range of charm (and heavier) quark masses

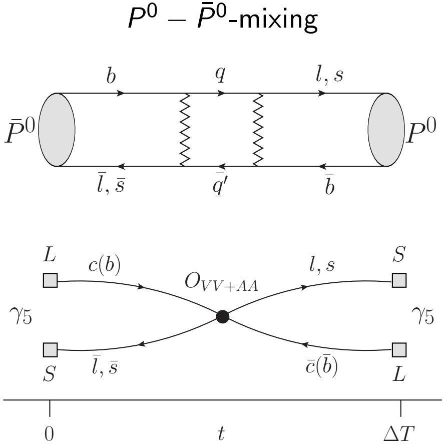
$P^0 - \bar{P}^0$-mixing



$$B_P = \frac{\langle \bar{P}^0 | O_{VV+AA} | P^0 \rangle}{8/3 f_P^2 m_P^2}$$

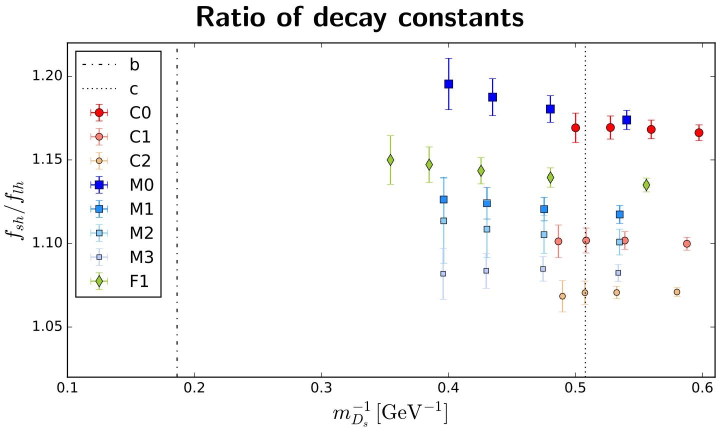
- Volume average via (Gaussian smeared) $\mathbb{Z}_2$-Wall sources
- Sources placed on many time planes, binned





Many source-sink separations ΔT for 4-quark operator

Results of correlator fits



⇒ Renormalisation constants cancel

⇒ Mild linear behaviour with $1/m_H$ and a^2

⇒ Stat precision: 0.4 - 1.0 %

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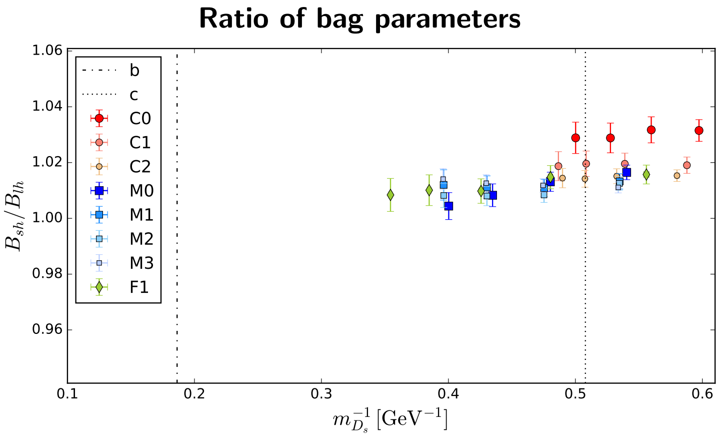

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Global fit form

Base fit

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

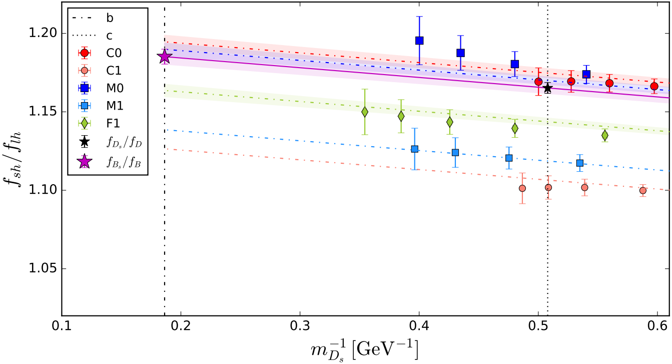
Assess systematic errors by

- varying cuts on pion mass
- using $m_H = m_D$, m_{D_s} and m_{η_c}
- varying inclusion/exclusion of heaviest data points
- varying inclusion/exclusion of fit parameters
- including/estimating higher order terms (a^4, $\left(\Delta m_\pi^2\right)^2$, $\left(\Delta m_H^{-1}\right)^2$)

$\Rightarrow$ All fits are fully correlated.

Global fit results - ratio of decay constants

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



Ratio of decay constants for $m_\pi \leq 350\,\mathrm{MeV}$

Global fit results - ratio of decay constants

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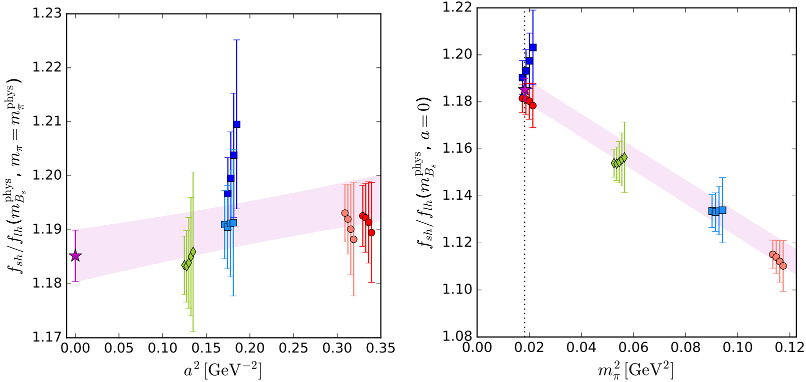
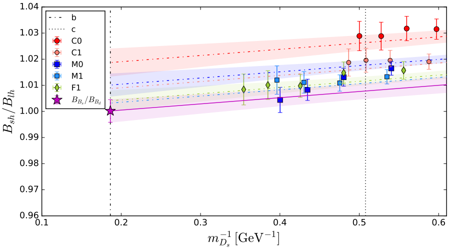


Ratio of decay constants for $m_\pi \leq 350\,\mathrm{MeV}$

Global fit results - ratio of bag parameters and ξ

$B_{B_s}/B_B(a, m_\pi, m_H)$

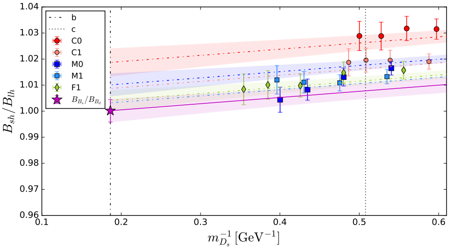


Recall: $\xi \equiv f_{B_s}/f_B \times \sqrt{B_{B_s}/B_B}$

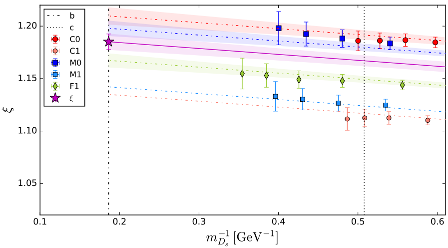
1. chiral-CL of product of ratios
2. product of chiral-CL of ratios.

Global fit results - ratio of bag parameters and ξ

$B_{B_s}/B_B(a, m_\pi, m_H)$



$\xi(a, m_\pi, m_H)$



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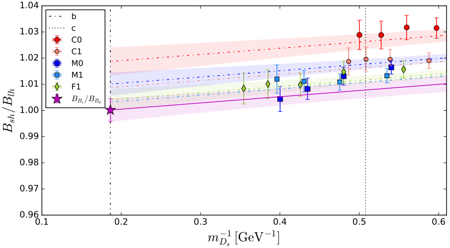
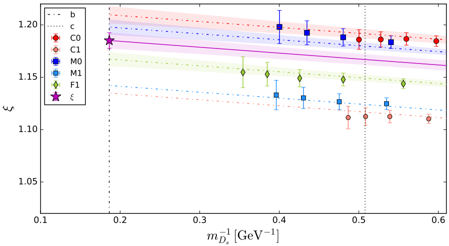


$\xi(a, m_\pi, m_H)$



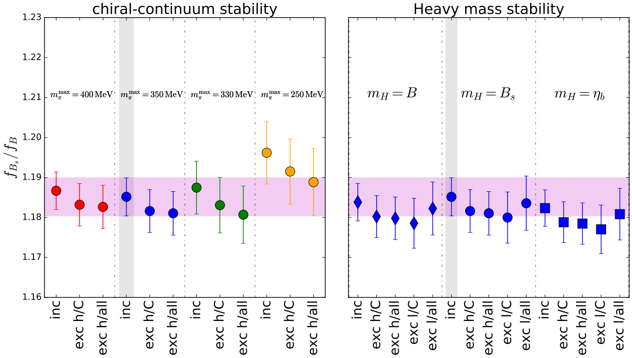
$$\lim_{a\to 0; m_q \to \mathrm{phys}} \left[f_{hs}/f_{hl} \sqrt{B_{hs}/B_{hl}} \right] (a, m_\pi, m_H) = 1.1851(74)_{\mathrm{stat}}$$

$$[f_{B_s}/f_B]_{\mathrm{phys}} \times \sqrt{[B_{B_s}/B_B]_{\mathrm{phys}}} = 1.1853(54)_{\mathrm{stat}}$$

chiral continuum limit of individual ratios gives better signal

Systematic Errors - variations of cuts to data for f_{B_s}/f_B

- Global fits all correlated with satisfying p-values.
- sys error: includes chiral-CL (left), heavy mass (right), H.O. terms, $m_u \neq m_d$ and FV.



$$f_{B_s}/f_B = 1.1852(48)_{\rm stat} \binom{+134}{-145}_{\rm sys}$$

Systematic Errors - variations of cuts to data for B_{B_s}/B_B

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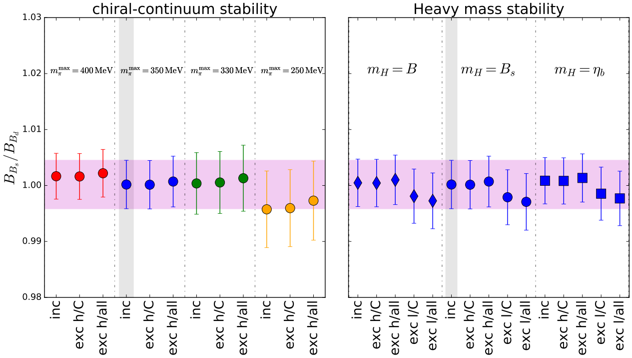

$$B_{B_s}/B_B = 1.0002(43)_{\mathrm{stat}} \left({}^{+60}_{-82}\right)_{\mathrm{sys}}$$

Systematic Errors - variations of cuts to data for ξ

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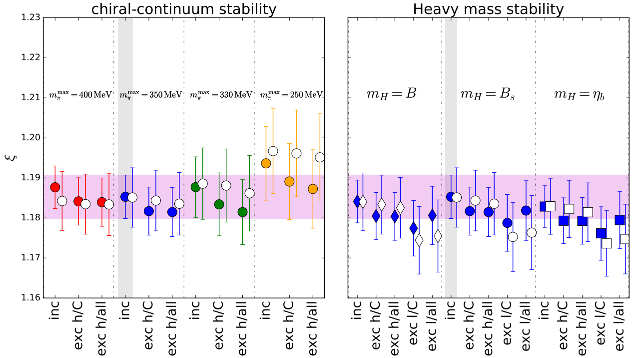
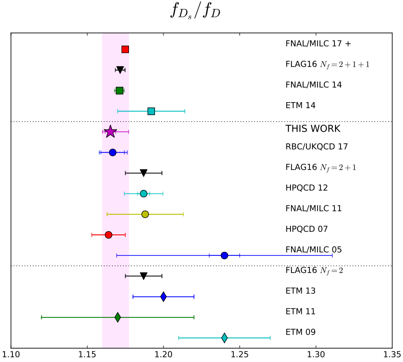
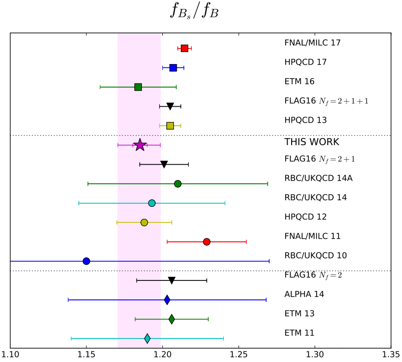


$$\xi = 1.1853(54)_{\mathrm{stat}} \left({}^{+116}_{-156} \right)_{\mathrm{sys}}$$

Comparison to literature - ratio of decay constants

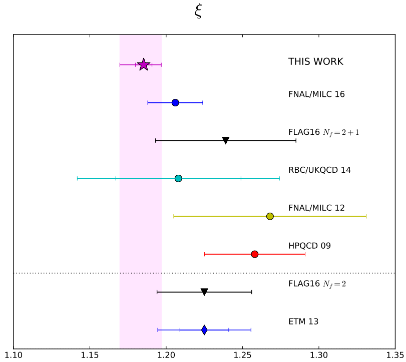


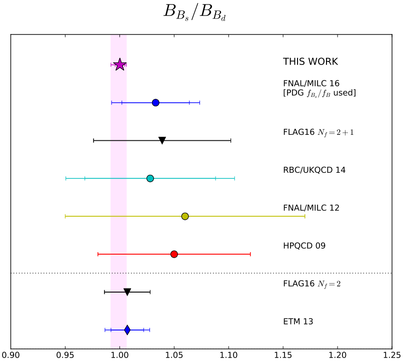


- Self consistent with RBC/UKQCD17: JHEP **12** (2017) 008
- Complimentary to (most) literature - no effective action for b.
- One of few results with physical pion masses.

$$|V_{cd}/V_{cs}| = 0.2148(56)_{\mathrm{exp}} \left({}^{+22}_{-10}\right)_{\mathrm{lat}}$$

Comparison to literature



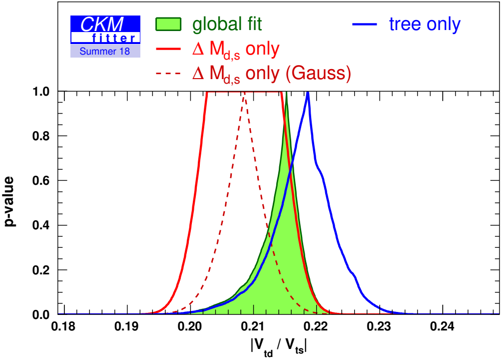


- Complimentary - no effective action needed for b
- Complimentary - **no operator mixing**!
- **First time with physical pion masses**

$$|V_{td}/V_{ts}| = 0.2018(\ 4)_{\mathrm{exp}} \left({}^{+20}_{-27}\right)_{\mathrm{lat}}$$

Results for $|V_{td}/V_{ts}|$

$$|V_{td}/V_{ts}| = \begin{cases} 0.2088(^{+16}_{-30}) & \text{CKMfitter (Summer '18)} \\ 0.211(3) & \text{UTfit (Summer '18)} \end{cases}$$



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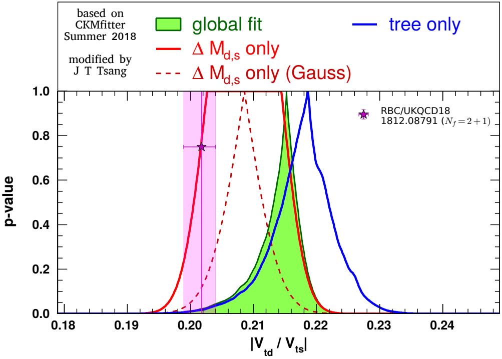

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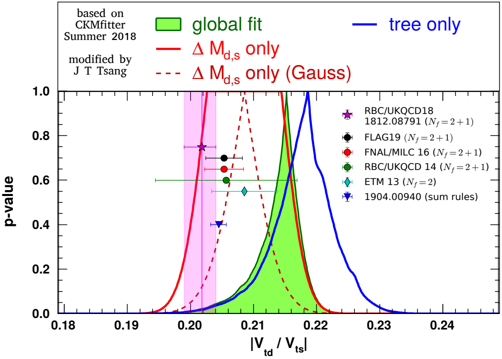


Neutral meson mixing - Beyond the Standard Model

RBC/UKQCD's $K-\bar{K}$ BSM mixing calculation

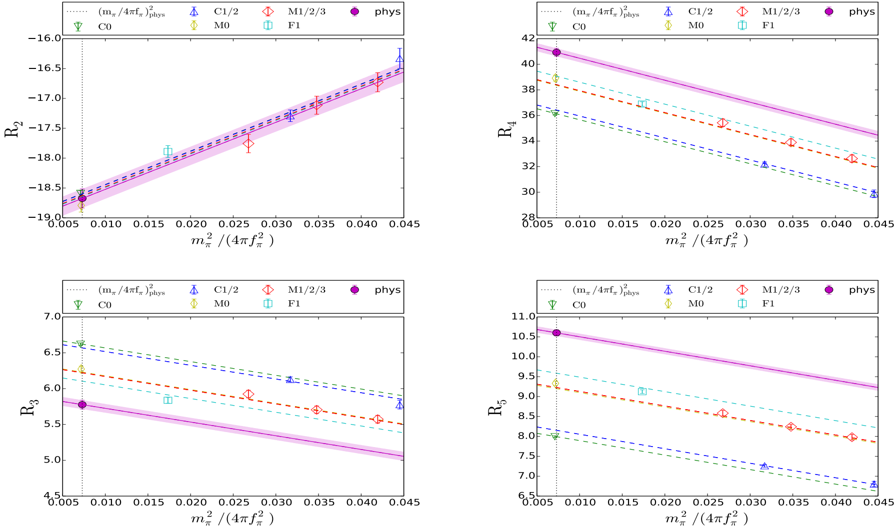
Peter Boyle, Nicolas Garron, Jamie Hudspith, Andreas Jüttner, **Julia Kettle**, Ava Khamseh, Christoph Lehner, Amarjit Soni, JTT

[1710.09176, 1812.04981, in preparation]

- OPE separates (model dep) short distance contributions (Wilson coeff's) from (model indep.) long distance matrix elements
- In SM only $\mathcal{O}_1 = VV + AA$ contributes to mixing
- Beyond SM get further 4 (parity even) operators: $VV - AA$, $SS - PP$, $SS + PP$, TT
- Consider ratios

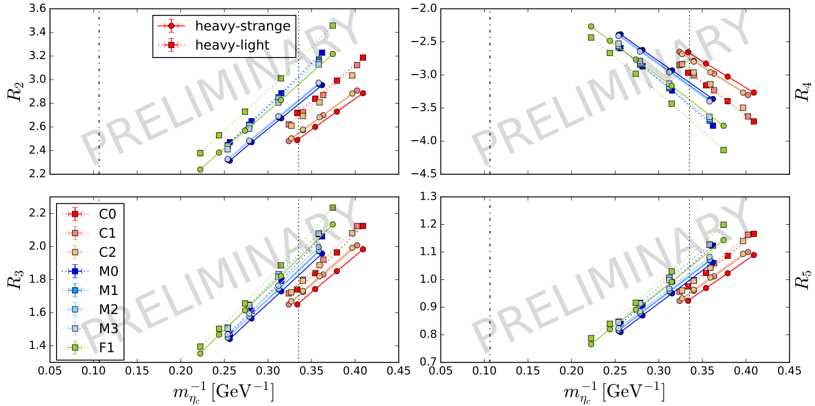
$$R_i \equiv \frac{\langle \bar{P}^0 | \mathcal{O}_i | P^0 \rangle}{\langle \bar{P}^0 | \mathcal{O}_1 | P^0 \rangle} \qquad i = 2, 3, 4, 5$$

preliminary $K^0 - \bar{K}^0$ results [1812.04981,in preparation]

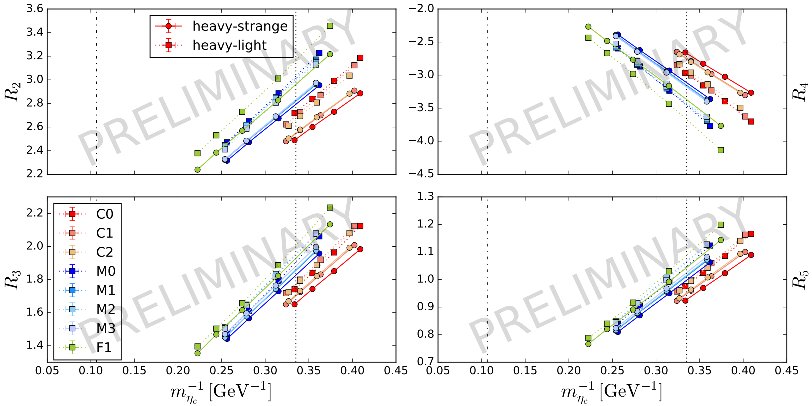


PRELIMINARY RESULTS in $\overline{MS}$ at $3\,\mathrm{GeV}$

$B^0_{(s)} - \bar{B}^0_{(s)}$ and $D^0 - \bar{D}^0$ PRELIMINARY and BARE



$B^0_{(s)} - \bar{B}^0_{(s)}$ and $D^0 - \bar{D}^0$ **PRELIMINARY and BARE**



- "quite linear" in m_H^{-1}
- similar slopes for h-l and h-s $\Rightarrow SU(3)$ breaking rat's?
- renormalisation to be done (mixed action + op mixing)
- analogous analysis to $K - \bar{K}$ paper + m_H dependence

Limitations and “ultimate precision”

Experimental precision on $\Delta m_s \sim 0.1\%$ and $\Delta m_d \sim 0.4\%$.
Theoretical precision on $\xi \sim 1.3\%$

	f_{D_s}/f_D		f_{B_s}/f_B		ξ		B_{B_s}/B_{B_d}	
	absolute	relative	absolute	relative	absolute	relative	absolute	relative
central	1.1652		1.1852		1.1853		1.0002	
stat	0.0035	0.30%	0.0048	0.40%	0.0054	0.46%	0.0043	0.43%
fit chiral-CL	$^{+0.0112}_{-0.0031}$	$^{+0.96}_{-0.26}\%$	$^{+0.0110}_{-0.0045}$	$^{+0.93}_{-0.38}\%$	$^{+0.0084}_{-0.0038}$	$^{+0.71}_{-0.32}\%$	$^{+0.0020}_{-0.0044}$	$^{+0.20}_{-0.44}\%$
fit heavy mass	$^{+0.0003}_{-0.0000}$	$^{+0.02}_{-0.00}\%$	$^{+0.0000}_{-0.0081}$	$^{+0.00}_{-0.69}\%$	$^{+0.0000}_{-0.0091}$	$^{+0.00}_{-0.77}\%$	$^{+0.0012}_{-0.0031}$	$^{+0.12}_{-0.31}\%$
H.O. heavy	0.0000	0.00%	0.0054	0.45%	0.0049	0.41%	0.0021	0.21%
H.O. disc.	0.0009	0.07%	0.0009	0.07%	0.0021	0.18%	0.0016	0.16%
$m_u \neq m_d$	0.0009	0.08%	0.0009	0.07%	0.0010	0.08%	0.0001	0.01%
finite size	0.0021	0.18%	0.0021	0.18%	0.0021	0.18%	0.0018	0.18%
total systematic	$^{+0.0114}_{-0.0039}$	$^{+0.98}_{-0.34}\%$	$^{+0.0125}_{-0.0137}$	$^{+1.06}_{-1.16}\%$	$^{+0.0102}_{-0.0146}$	$^{+0.86}_{-1.24}\%$	$^{+0.0041}_{-0.0070}$	$^{+0.41}_{-0.70}\%$
total sys+stat	$^{+0.0120}_{-0.0052}$	$^{+1.03}_{-0.45}\%$	$^{+0.0134}_{-0.0145}$	$^{+1.13}_{-1.22}\%$	$^{+0.0116}_{-0.0156}$	$^{+0.97}_{-1.32}\%$	$^{+0.0060}_{-0.0082}$	$^{+0.60}_{-0.82}\%$

$\Rightarrow$ **Systematically Improvable** with finer lattices at (near) physical m_π.

Conclusions and Outlook

$SU(3)$ breaking ratios

- **arXiv:1812.08791**
- f_{D_s}/f_D, f_{B_s}/f_B, B_{B_s}/B_B and ξ
- $|V_{cd}/V_{cs}|$, $|V_{td}/V_{ts}|$
- 3 lattice spacings, 2 m_π^{phys}
- First result for ξ and B_{B_s}/B_B with m_π^{phys}
- m_h from below m_c to $\sim m_b/2$
  $\Rightarrow$ extrapolation to b for ratios
  $\Rightarrow$ fully relativistic
- Good continuum scaling and self-consistent
- Competitive precision

Outlook

- Mixed action NPR
- f_D, f_{D_s}, f_B, f_{B_s}
- physical pion mass ensemble at the finest lattice spacing
- $\hat{B}_B$, $\hat{B}_{B_s}$
- BSM mixing operators:
  - $K-\bar{K}$ (✓)
  - $D-\bar{D}$ (short distance (✓))
  - $B_{(s)}-\bar{B}_{(s)}$
    $\Rightarrow$ SU(3) breaking ratios?
    $\Rightarrow$ other smart ratios?
    Error likely dominated by heavy quark reach

ADDITIONAL SLIDES

Parameters of QCD

$$S_{\mathrm{QCD}}[\psi,\overline{\psi},U] = S_G[U] + S_F[\psi,\overline{\psi},U]$$
$$= \int \mathrm{d}^4x \frac{1}{2g^2}\mathrm{Tr}\left[F_{\mu\nu}F_{\mu\nu}\right] + \sum_{N_f}\overline{\psi}_f\left(\gamma_\mu D_\mu + m_f\right)\psi_f$$

Coupling constant g + **quark masses** m_f $\Rightarrow$ defines QCD.

$$Z = \int \mathcal{D}[\psi,\overline{\psi}]\mathcal{D}[U]e^{-S[\psi,\overline{\psi},U]} = \int \mathcal{D}[U]\prod_{N_f}\det\left(D + m_f\right)e^{-S_G[U]}$$

Typical current simulations: $N_f = 2+1$. $\Rightarrow$ 3 parameters $(1 + 2)$

Lattice action choices

Light and strange

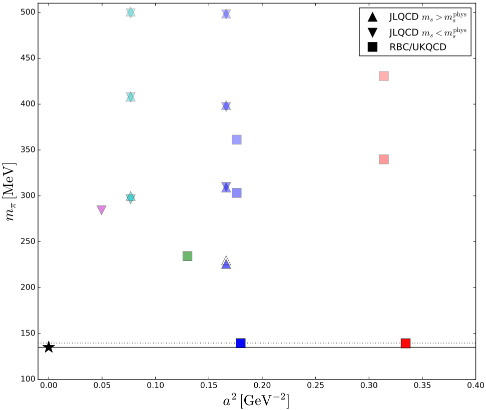
- Unitary light quark mass
- Physical strange quark mass
- DWF parameters same between sea and valence
- Gaussian source (sink) smearing for better overlap with ground state

Heavy (charm and beyond)

- Möbius DWF
- $M_5 = 1.0,\ L_s = 12$
- Stout smeared (3 hits, $\rho = 0.1$)
- Range of quark masses from below charm to $\sim m_b/2$ on finest ensemble

$\Rightarrow$ $\mathbb{Z}_2$-noise sources on every 2nd time slice
$\Rightarrow$ **All DWF** mixed action set-up
$\Rightarrow$ Increased heavy quark reach compared to [JHEP **04** (2016) 037,JHEP **12** (2017) 008]
$\rightarrow$ extrapolation towards b

Increased set of ensembles?



JLQCD: (triangles)

Fine lattices:

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

UKQCD: (squares)

Physical Pion masses

Both: $N_f = 2+1$ DWF

3+3 Lattice Spacings

$\Rightarrow$ Further heavy quark reach on JLQCD ensembles

$\Rightarrow$ Chiral extrapolation stabilised by $m_\pi^{\rm phys}$ ensembles

$\Rightarrow$ **Combined physics analysis?**