Meson mixing and lifetimes

Matthew Kirk

LHCb-UK 2018

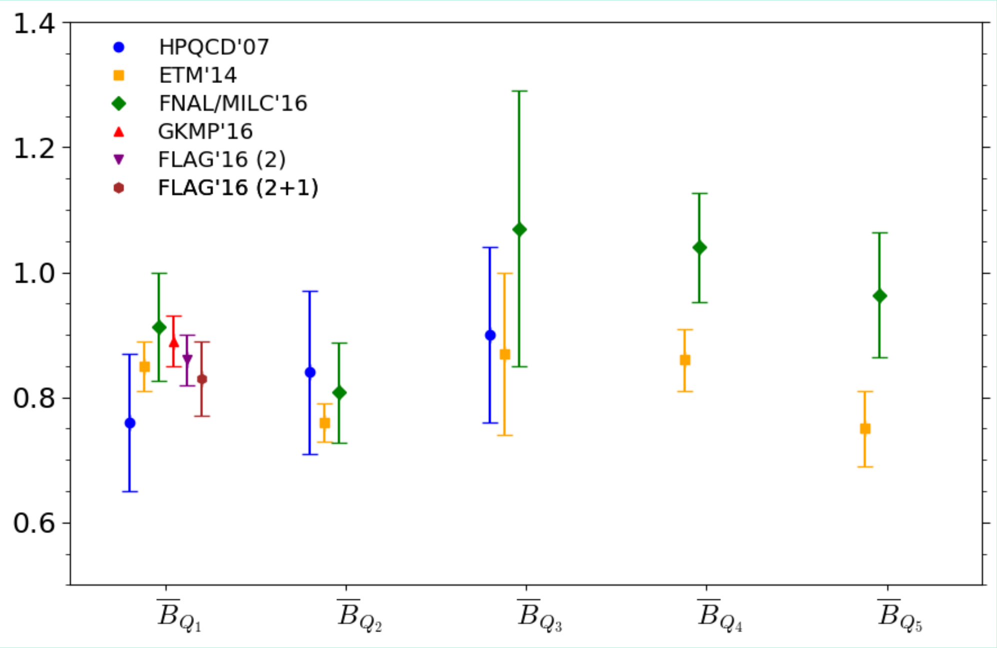
based on **1711.02100 (MK, Rauh, Lenz)**
1712.06572 (Di Luzio, MK, Lenz)

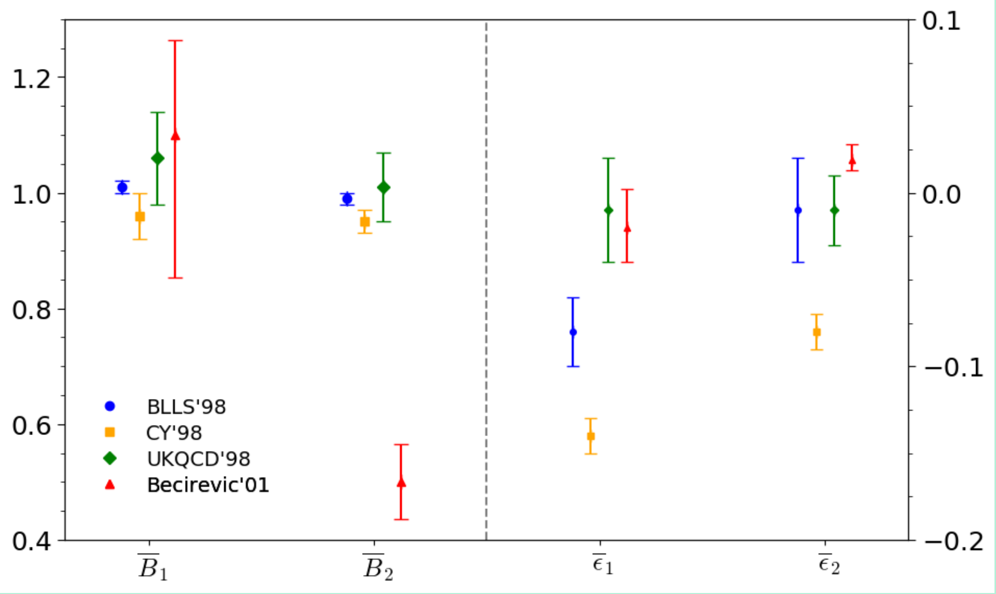
Status before 2017 – experiment

- B_s Mixing
  - ΔM_s is extremely well measured (0.1% uncertainty)
  - $\Delta \Gamma_s$ known with sub 10% uncertainty
- B lifetime ratios
  - $\tau(B_s)/\tau(B_d)$ known with < 0.25% uncertainty
- D Mixing
  - First > 5 sigma measurement from LHCb in 2012
  - $O(10\%)$ accuracy
- D lifetime ratios
  - $\tau(D^+)/\tau(D^0)$ known with <1% uncertainty

Status before 2017 – lattice

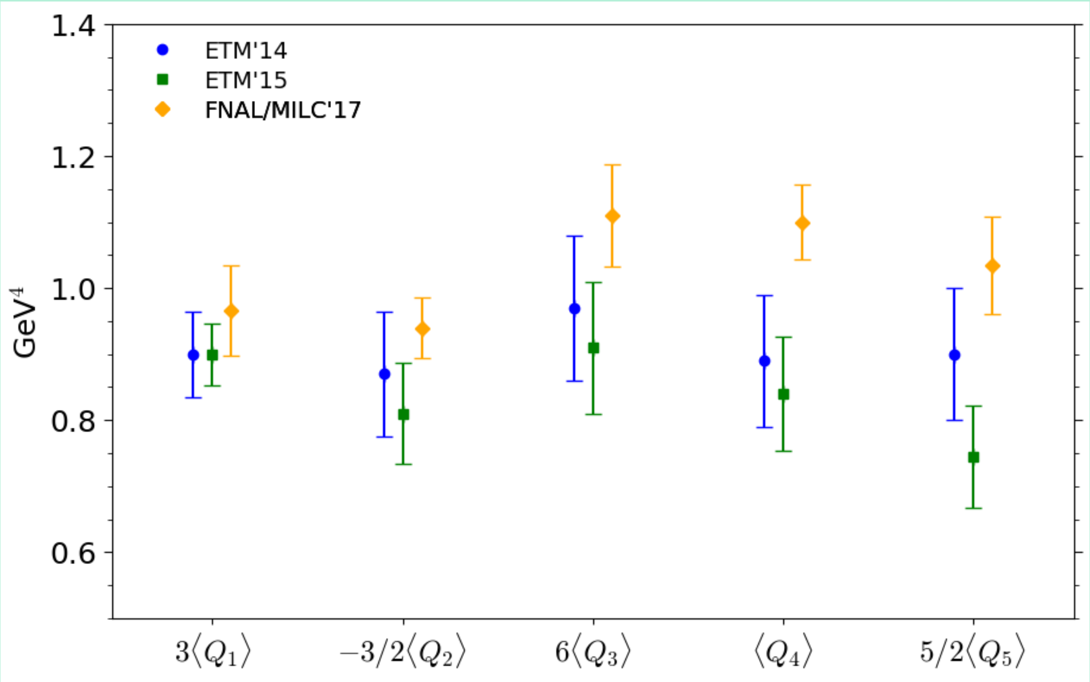
- B_s Mixing
  - Selection of lattice results, all in agreement
- B Lifetimes
  - only old ('98 / '01) lattice results





Status before 2017 – lattice

- D mixing
  - a handful of lattice results



- D lifetimes

Status before 2017 – theory

- B Mixing – $\Delta M_s = 18.3 \pm 2.7\,\text{ps}^{-1}$

  $\Delta \Gamma_s = 0.088 \pm 0.020\,\text{ps}^{-1}$

- B Lifetimes – $\tau(B_s)/\tau(B_d) = 1.0005 \pm 0.0011$

  – $\tau(B^+)/\tau(B_d) = 1.04^{+0.05}_{-0.02}$

- D mixing – ?
- D lifetimes – $\tau(D^+)/\tau(D^0) = 2.2 \pm 1.7$

What has happened since?

- New lattice result from Fermilab-MILC included in FLAG average
  - $f_{B_s}\sqrt{B}$: 270 ± 16 MeV → 274 ± 8 MeV
- HQET sum rule calculation
  - Independent determination of non-perturbative matrix elements for all dimension-6 operators
- V_{cb} discrepancy between inclusive / exclusive is perhaps starting to be resolved?
  - (**1703.08170**, **1707.09509**, **1708.07134**, talk by **Stefan Schacht** at **LHCb Implications**)

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HQET sum rules

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$$
\begin{aligned}
M_3(\omega_1,\omega_2) = {} & (-2\omega_1)^{3d/2-5}(-2\omega_2)^{3d/2-5}\Gamma^3(d/2-1) \\
& \times\Bigg[\frac{\Gamma\left(\frac{3}{2}d-4\right)\Gamma^2\left(5-\frac{3}{2}d\right)\Gamma\left(2-\frac{d}{2}\right)}{(d-3)\Gamma(d-2)} \\
& + 2\frac{\Gamma(8-3d)}{d-3}x^{4-3d/2}\,{}_3F_2\left(\left.\begin{matrix}1, d-2, \frac{3}{2}d-4\\ \frac{3}{2}d-3, 3d-8\end{matrix}\right|\frac{1}{x}\right) \\
& + \frac{4\pi\Gamma(6-2d)x^{3d/2-5}}{(3d-10)\Gamma(d-2)\sin(3\pi d)}\,{}_2F_1\left(\left.\begin{matrix}5-\frac{3}{2}d, 7-2d\\ 6-\frac{3}{2}d\end{matrix}\right|\frac{1}{x}\right) \\
& + 2\frac{\Gamma(8-3d)}{d-3}x^{3d/2-4}\,{}_3F_2\left(\left.\begin{matrix}1, d-2, \frac{3}{2}d-4\\ \frac{3}{2}d-3, 3d-8\end{matrix}\right|x\right) \\
& + \frac{4\pi\Gamma(6-2d)x^{5-3d/2}}{(3d-10)\Gamma(d-2)\sin(3\pi d)}\,{}_2F_1\left(\left.\begin{matrix}5-\frac{3}{2}d, 7-2d\\ 6-\frac{3}{2}d\end{matrix}\right|x\right)\Bigg].
\end{aligned}
$$

HQET sum rules

- Made possible by 3-loop calculations done in 2008 by Grozin, Lee (0812.4522)
- First steps made by Grozin, Klein, Mannel, Pivovarov in mid 2016 (1606.06054)
- Late last year, full set of dim-6 operators done by MK, Lenz, Rauh (1711.02100)

HQET sum rules

- Do all dim 6 operators for mixing AND lifetimes
- How?
  - 3 loop diagrams (with 2 external momenta), reduced using FIRE to those known by Grozin, Lee

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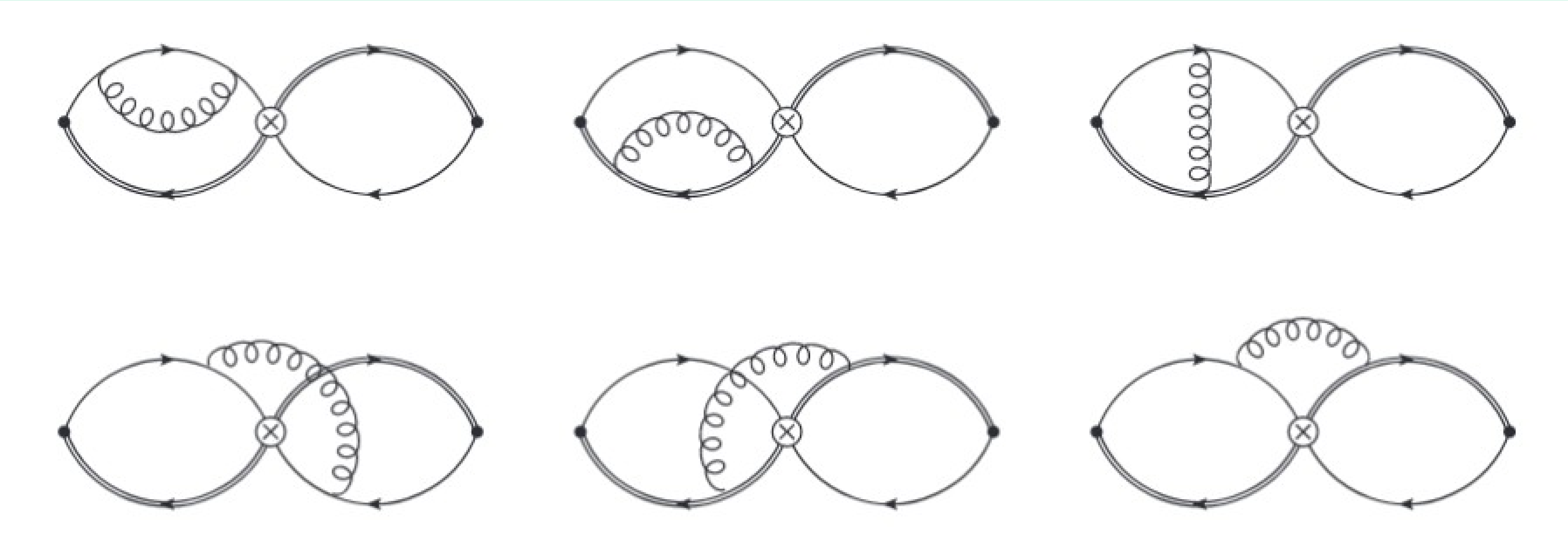


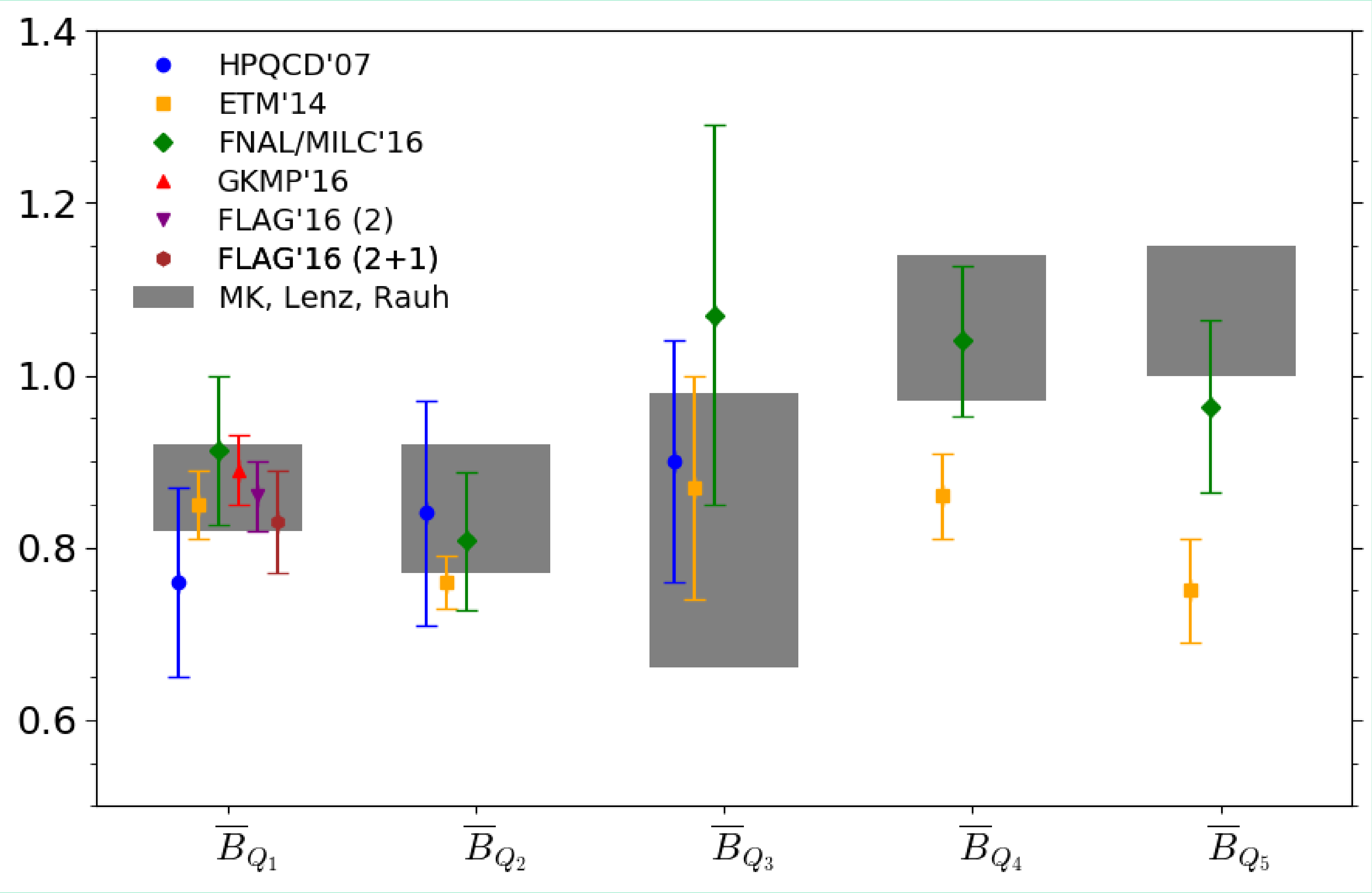
HQET sum rules

- Do all dim 6 operators for mixing AND lifetimes
- How?
  - 3 loop diagrams (with 2 external momenta), reduced using FIRE to those known by Grozin, Lee
  - HQET running to scale m_b
  - HQET-QCD matching (1-loop) at scale m_b

HQET sum rules – results

HQET sum rules – results

B mixing



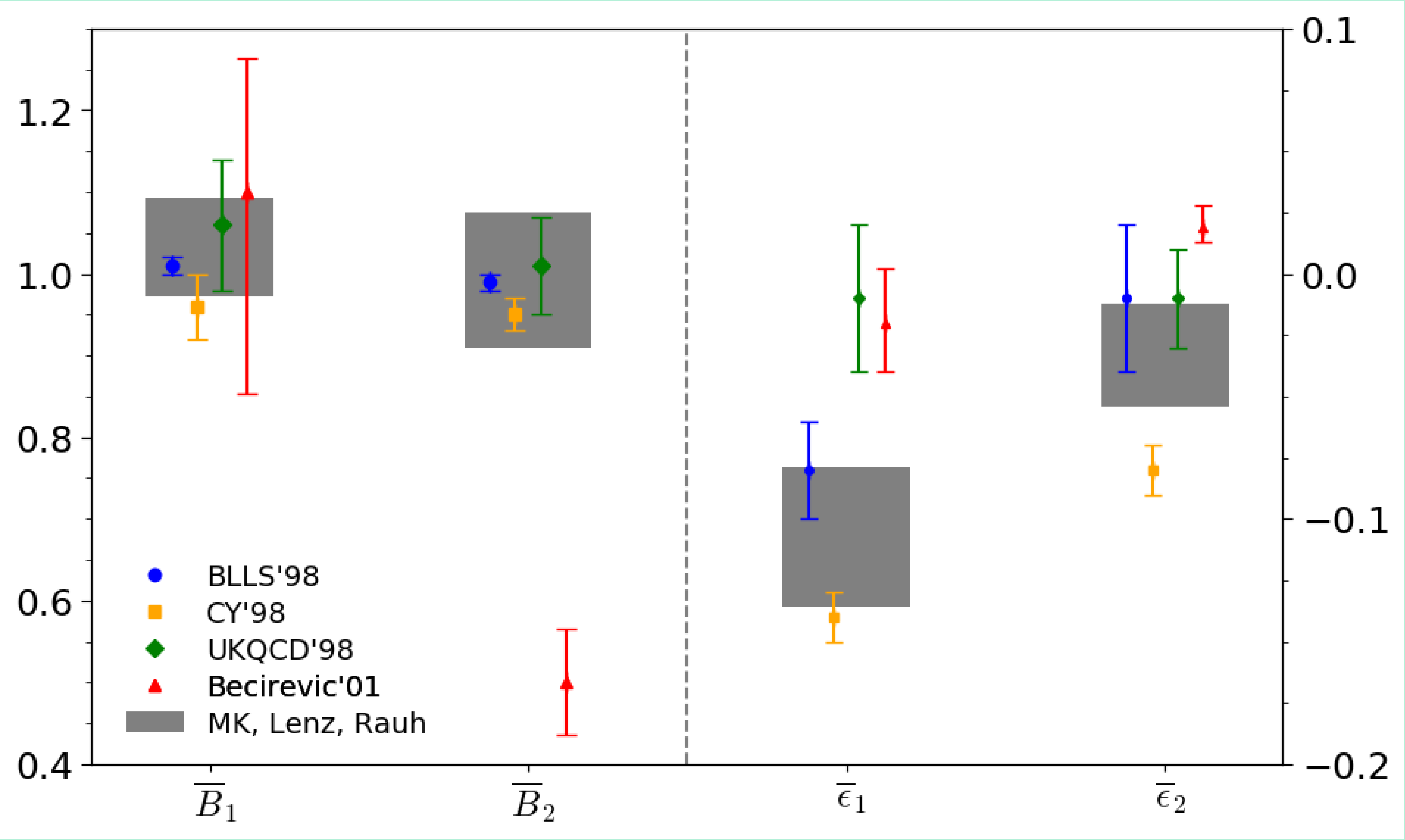
Effect on observables

- $\Delta M_s = 18.1 \pm 1.9\,\mathrm{ps}^{-1}$
- $\Delta \Gamma_s = 0.079 \pm 0.023\,\mathrm{ps}^{-1}$
- $a_{sl}^{s} = 2.0 \pm 0.3 \times 10^{-5}$

- Gives errors that are comparable ($\pm 15\,\%$) with lattice data → lattice not the only game in town

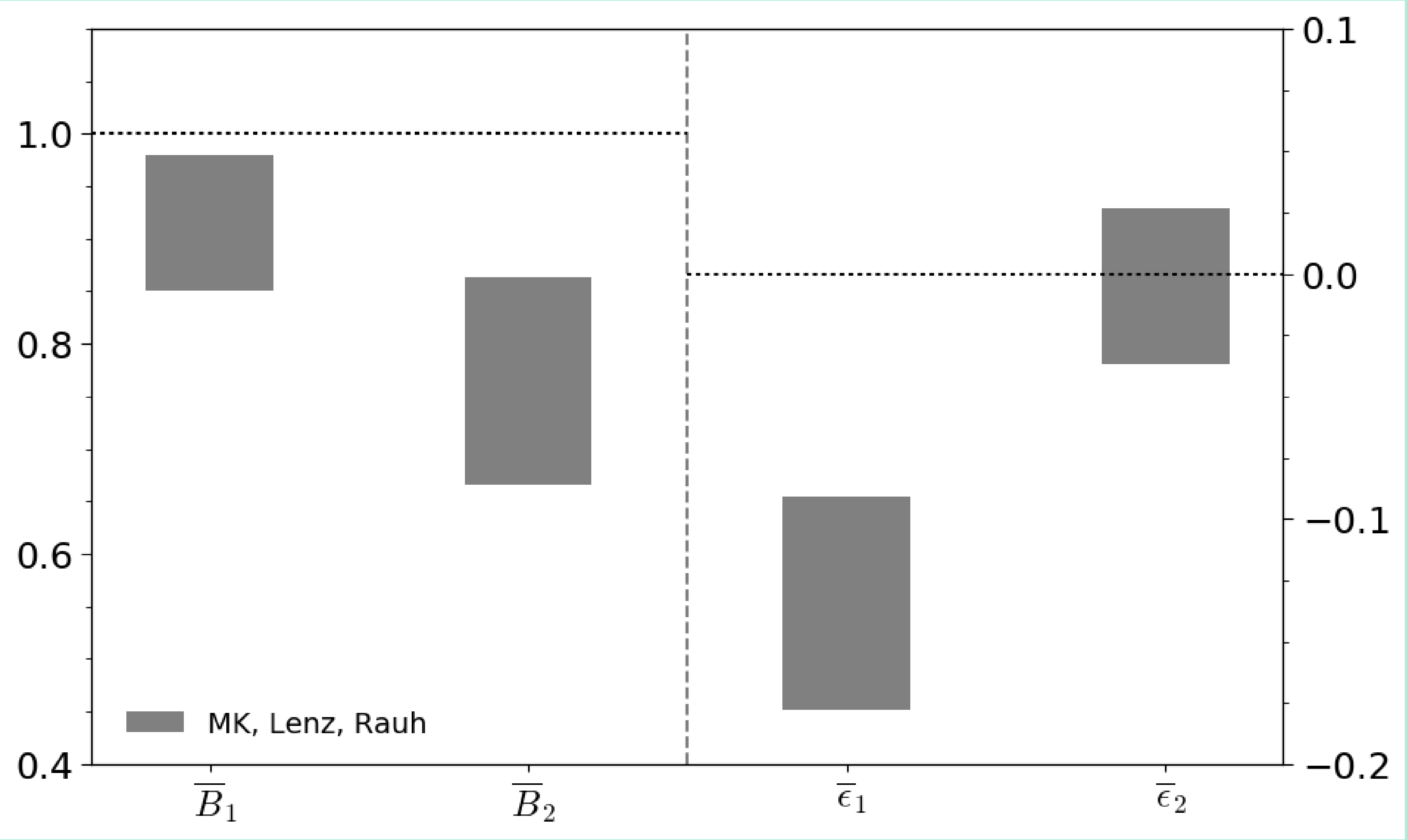
HQET sum rules – results

B lifetimes



HQET sum rules – results

D lifetimes



Effect on observables

- $\tau(B_s)/\tau(B_d) = 0.9994 \pm 0.0025$
- $\tau(B^+)/\tau(B_d) = 1.082^{+0.022}_{-0.026}$
- $\tau(D^+)/\tau(D^0) = 2.7^{+0.7}_{-0.8}$

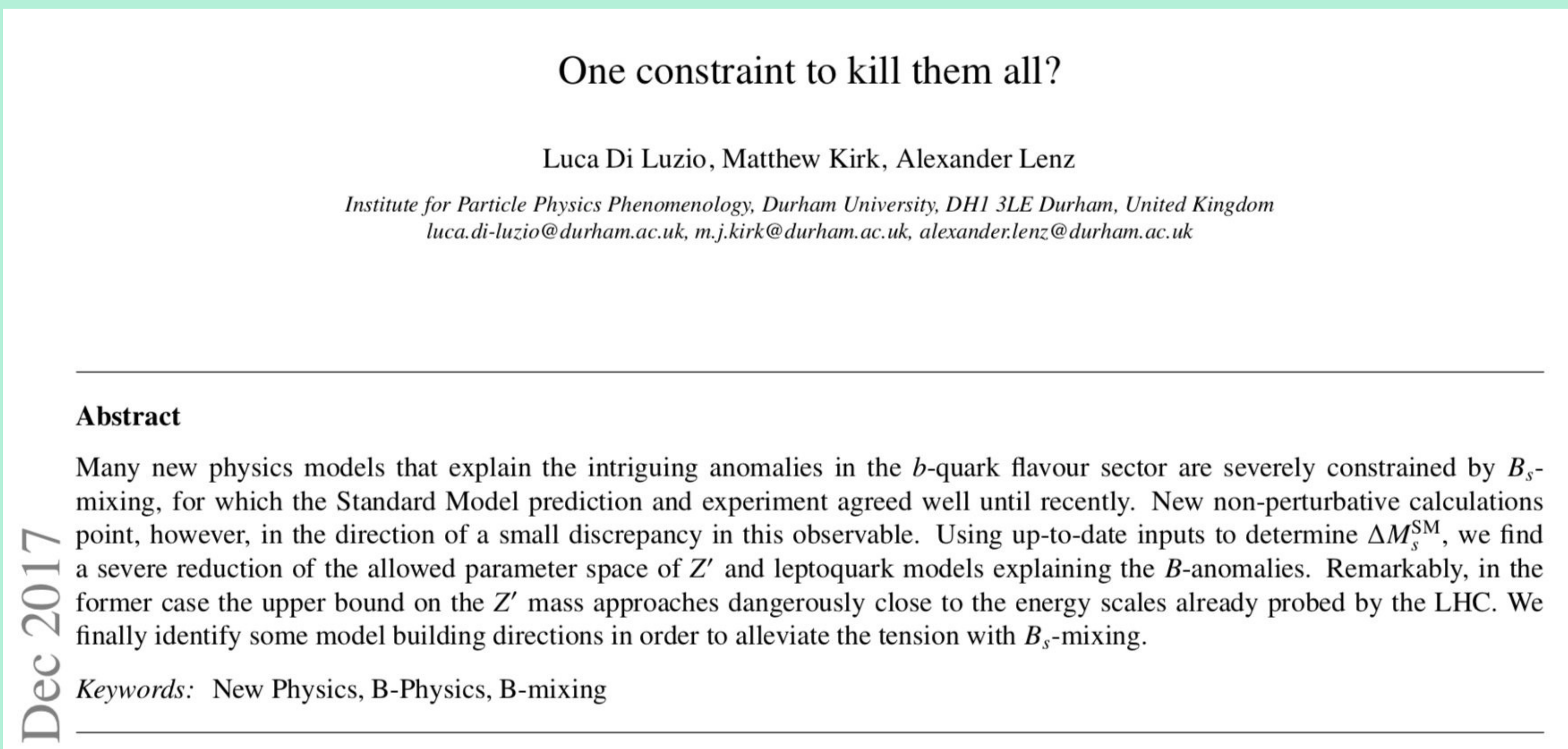
- For lifetimes, lattice hasn't yet arrived → sum rules the only game in town

Effects on NP models

- Non-perturbative parameters very important
- Constraints from B mixing depend sensitively on values

Effects on NP models

- Using the latest FLAG average → much less space for e.g. Z' model
- See 1712.06572 (Di Luzio, MK, Lenz)



One constraint to kill them all?

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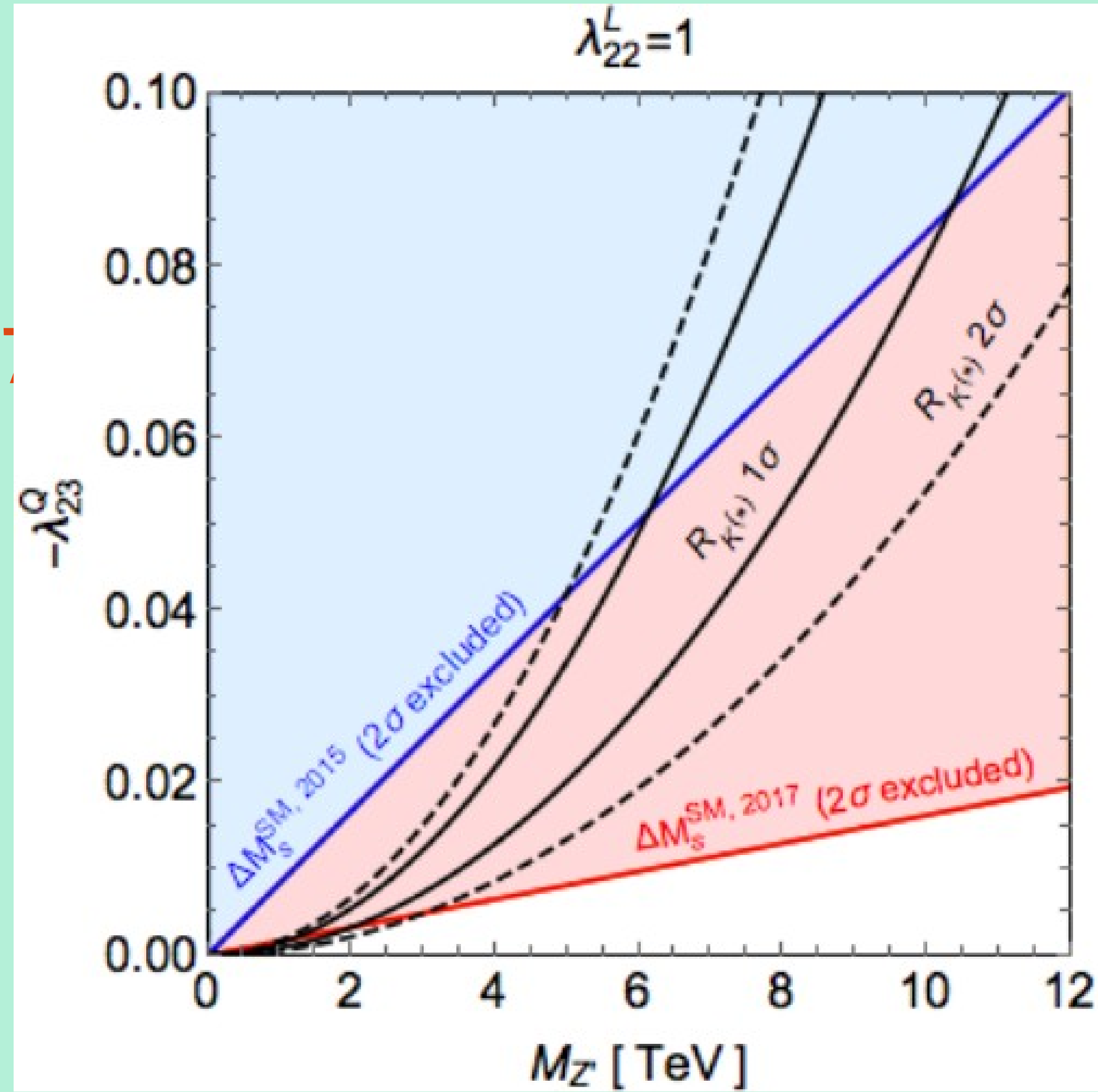
Abstract

Many new physics models that explain the intriguing anomalies in the *b*-quark flavour sector are severely constrained by B_s-mixing, for which the Standard Model prediction and experiment agreed well until recently. New non-perturbative calculations point, however, in the direction of a small discrepancy in this observable. Using up-to-date inputs to determine $\Delta M_s^{\rm SM}$, we find a severe reduction of the allowed parameter space of Z' and leptoquark models explaining the *B*-anomalies. Remarkably, in the former case the upper bound on the Z' mass approaches dangerously close to the energy scales already probed by the LHC. We finally identify some model building directions in order to alleviate the tension with B_s-mixing.

Keywords: New Physics, B-Physics, B-mixing

Effects on NP models

- Using … n less space …
- See 17…



Effects on NP models

- Good example of why independent determinations necessary
- From different lattice groups AND other methods

What next?

- Determination of dimension-7 operators

$$R_2 = \frac{1}{m_b^2} \bar{b}_i \overleftarrow{D}_\lambda \gamma_\mu (1-\gamma^5) D^\lambda q_i \; \bar{b}_j \gamma^\mu (1-\gamma^5) q_j$$

  from lattice / sum rules – reduce error in $\Delta\Gamma_s$

- Lattice confirmation of dimension-6

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- Lattice confirmation of dimension-6

- HPQCD working on both
- MK, Rauh, Lenz working on dim-7 now

What next?

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- Lattice confirmation of dimension-6

- Know $\tau(B_s)/\tau(B_d)$ better from experiment – while already doing very well, theory is currently ahead

Thanks!

Backup

Mixing operators

$$Q_1 = \bar{b}_i \gamma_\mu (1-\gamma^5) q_i \; \bar{b}_j \gamma^\mu (1-\gamma^5) q_j,$$

$$Q_2 = \bar{b}_i (1-\gamma^5) q_i \; \bar{b}_j (1-\gamma^5) q_j, \qquad Q_3 = \bar{b}_i (1-\gamma^5) q_j \; \bar{b}_j (1-\gamma^5) q_i,$$

$$Q_4 = \bar{b}_i (1-\gamma^5) q_i \; \bar{b}_j (1+\gamma^5) q_j, \qquad Q_5 = \bar{b}_i (1-\gamma^5) q_j \; \bar{b}_j (1+\gamma^5) q_i,$$

Lifetime operators

$$Q_1^q = \bar{b}\gamma_\mu(1-\gamma^5)q\ \bar{q}\gamma^\mu(1-\gamma^5)b, \qquad T_1^q = \bar{b}\gamma_\mu(1-\gamma^5)T^A q\ \bar{q}\gamma^\mu(1-\gamma^5)T^A b,$$

$$Q_2^q = \bar{b}(1-\gamma^5)q\ \bar{q}(1+\gamma^5)b, \qquad T_2^q = \bar{b}(1-\gamma^5)T^A q\ \bar{q}(1+\gamma^5)T^A b.$$

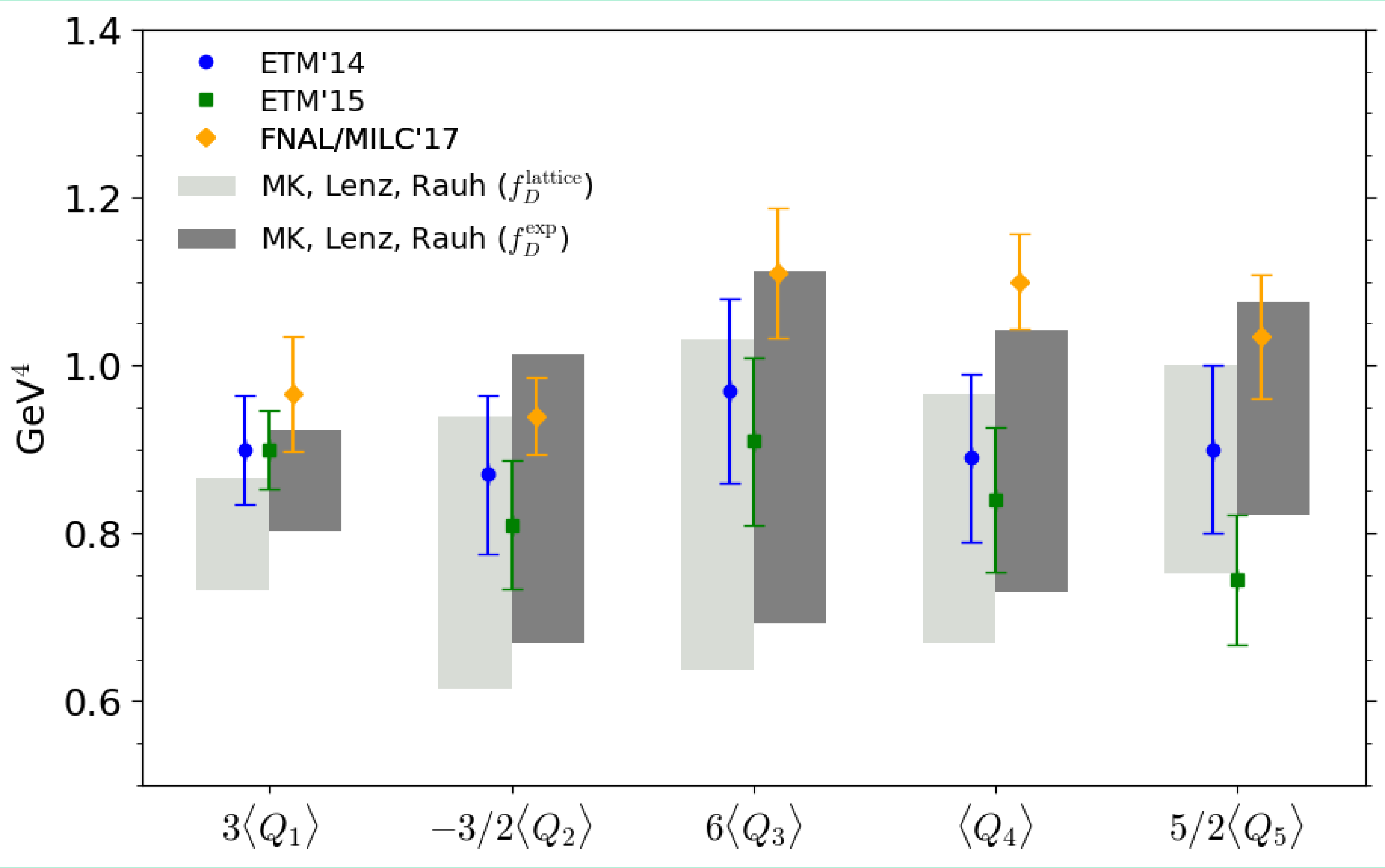
Effects on NP models

- Non-perturbative parameters very important
- Constraints from B mixing depend sensitively on values

Source	$f_{B_s}\sqrt{\hat{B}}$	ΔM_s^{SM}
HPQCD14 [116]	(247 ± 12) MeV	$(16.2 \pm 1.7)\,\mathrm{ps}^{-1}$
HQET-SR [71]	(261 ± 8) MeV	$(18.1 \pm 1.1)\,\mathrm{ps}^{-1}$
ETMC13 [117]	(262 ± 10) MeV	$(18.3 \pm 1.5)\,\mathrm{ps}^{-1}$
HPQCD09 [118] = FLAG13 [119]	(266 ± 18) MeV	$(18.9 \pm 2.6)\,\mathrm{ps}^{-1}$
FLAG17 [65]	$\mathbf{(274 \pm 8)}$ **MeV**	$\mathbf{(20.01 \pm 1.25)\,ps^{-1}}$
Fermilab16 [67]	(274.6 ± 4) MeV	$(20.1 \pm 0.7)\,\mathrm{ps}^{-1}$
HPQCD06 [120]	(281 ± 20) MeV	$(21.0 \pm 3.0)\,\mathrm{ps}^{-1}$
RBC/UKQCD14 [121]	(290 ± 20) MeV	$(22.4 \pm 3.4)\,\mathrm{ps}^{-1}$
Fermilab11 [122]	(291 ± 18) MeV	$(22.6 \pm 2.8)\,\mathrm{ps}^{-1}$

HQET sum rules – results

D mixing



SINCE YEARS OF BEGGING DID NOT HELP - IT'S TIME TO PROVOKE

Lifetimes are too heavy for lattice physicists!

The strongest lattice researcher alive

Arbitrary sum rule researcher

Matrix elements for lifetimes of HEAVY mesons