What Mixing and Lifetimes can tell us about NP

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(based on work with L. Di Luzio, D. King, A. Lenz, T. Rauh)

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What NP?

- Various $b \to s l l$ anomalies
- Suggests NP that generates effective operator $(\bar{b} s)(\bar{l} l)$
- What else does this lead to?

General approach

- $(\bar{b}\, s)(\bar{l}\, l)$ effective operator
  - Rare decays (why we are using it)
  - Mixing – double insertion allows $(\bar{b}\, s)(\bar{b}\, s)$ operator at one loop in EFT

Specific Model – Z′

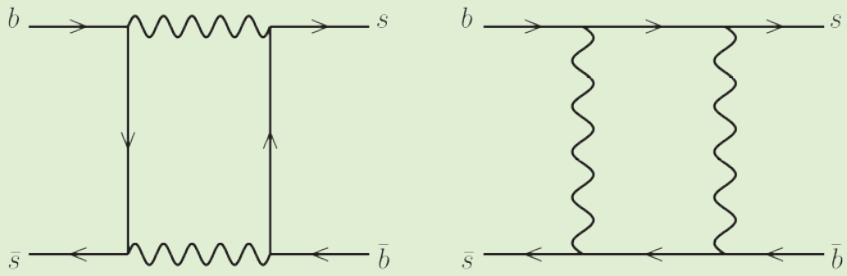
- $(\bar{b}s)(\bar{l}l)$ effective operator from $\bar{b}s$ and $\bar{l}l$ coupling
  - Rare decays (why we are using it)
  - Mixing – $\bar{b}s$ double insertion allows $(\bar{b}s)(\bar{b}s)$ operator at tree level

Meson mixing introduction

- Quantum effects allow the transition meson ↔ antimeson
- So flavour eigenstate not mass eigenstate
- Diagonalise Hamiltonian to find two mass states, with different mass and width

Mixing in the SM

$$\frac{\partial}{\partial t}\begin{pmatrix} B_s \\ \overline{B}_s \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} B_s \\ \overline{B}_s \end{pmatrix}$$



$$M_{12}^q = \frac{G_F^2}{16\pi^2}\lambda_t^2 M_W^2 S_0(x_t)\hat{\eta}_B \frac{\langle \overline{B}_q | Q_1 | B_q \rangle}{2M_{B_q}}$$

$$\Gamma_{12}^q = -\frac{G_F^2 m_b^2}{24\pi M_{B_q}} \sum_{x=u,c}\sum_{y=u,c}\left[G_1^{q,xy}\langle \overline{B}_q | Q_1 | B_q \rangle - G_2^{q,xy}\langle \overline{B}_q | Q_2 | B_q \rangle\right] + \mathcal{O}(1/m_b)$$

Status ~ 2015

- HFLAV (LHCb, CDF) exp average = $17.757 \pm 0.021\,\mathrm{ps}^{-1}$
- SM (1511.09466) prediction = $18.3 \pm 2.7\,\mathrm{ps}^{-1}$

New lattice

- Fermilab / MILC (1602.03560) produce new lattice calculation of $f_{B_s}\sqrt{B}$
  - Essentially calculation of $\langle Q \rangle$ where Q is SM mixing operator
- Much higher precision than previous lattice → dominates FLAG average

$$f_{B_s}\sqrt{B}\ :\ 270\pm16\ \text{MeV} \rightarrow 274\pm8\ \text{MeV}$$

New SM

- $f_{B_s}\sqrt{B}$ contributes ~90% uncertainty in SM prediction
  - So more precision here very welcome
- With FNAL/MILC results, get new SM prediction

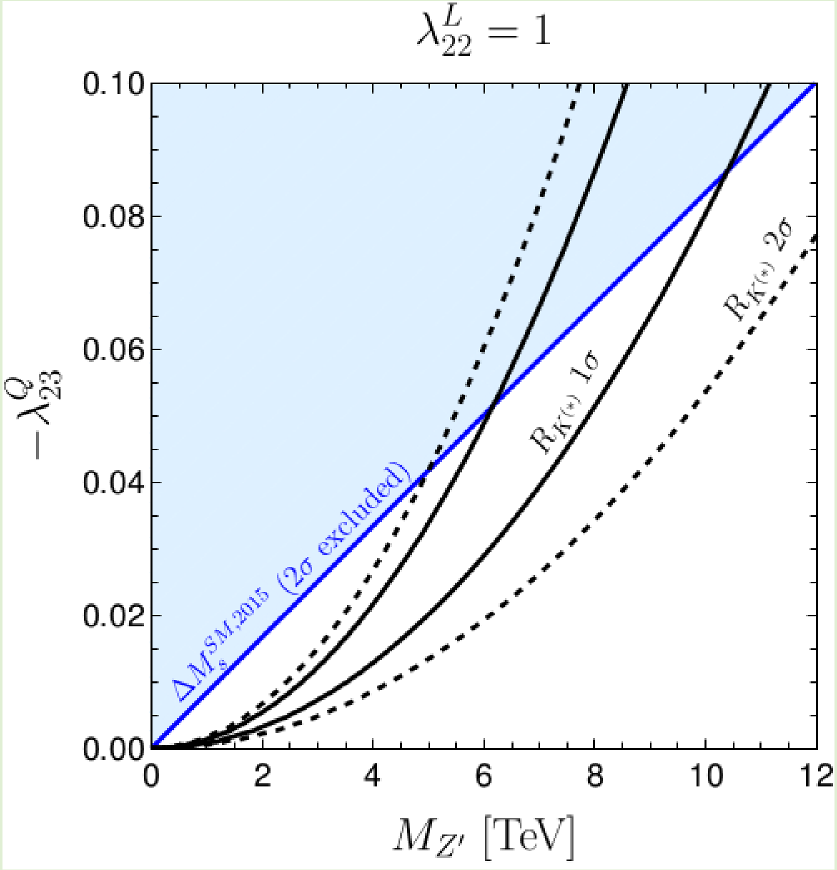
  (1712.06572) = $20.01 \pm 1.25\,\mathrm{ps}^{-1}$

  → 1.8 sigma discrepancy

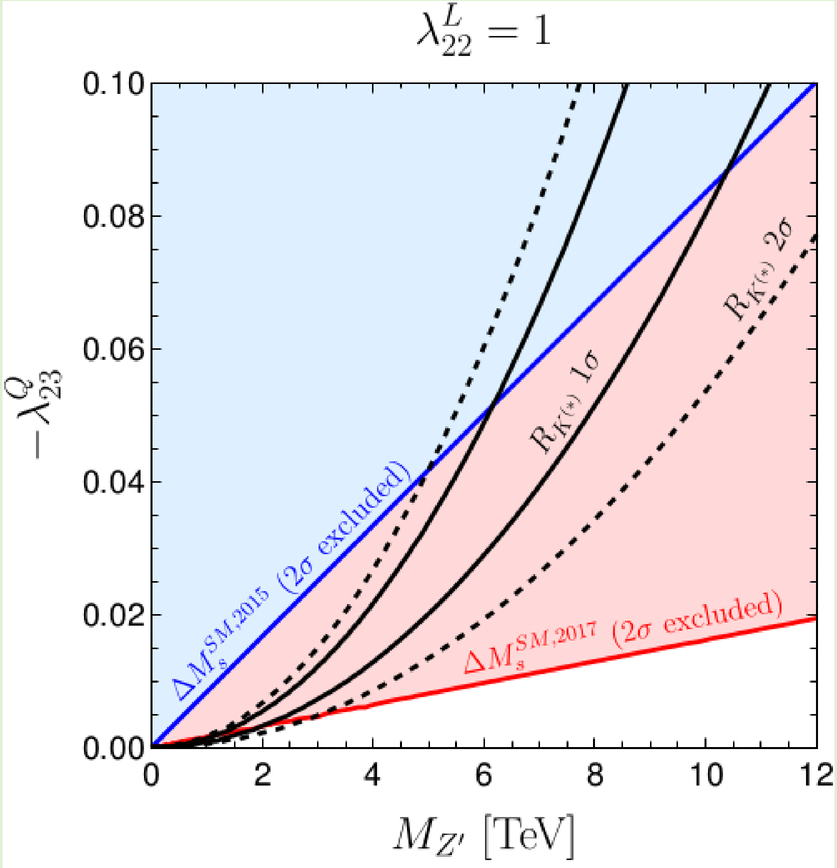
What does this tell us about NP?

- Taking the new FLAG average (i.e. basically the FNAL/MILC result), we find $\Delta M_s^{\mathrm{SM}} > \Delta M_s^{\mathrm{exp}}$
- Problem for many NP models, which have $\Delta M_s^{\mathrm{NP}} > \Delta M_s^{\mathrm{SM}}$

Limits on Z' model (2015)



Limits on Z' model (2017)



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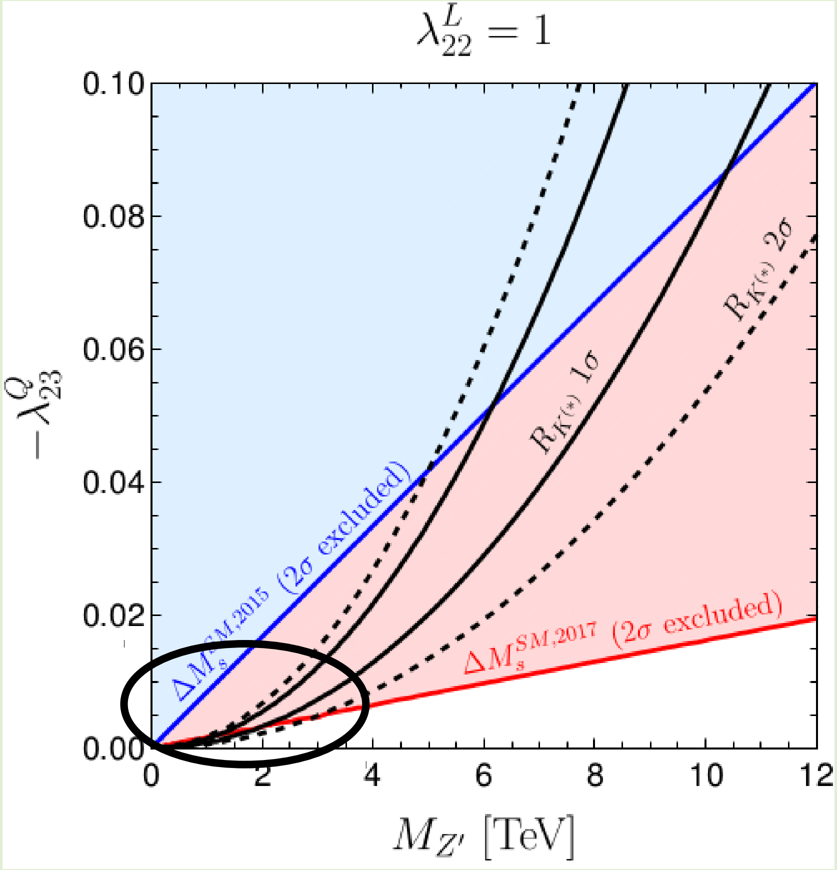

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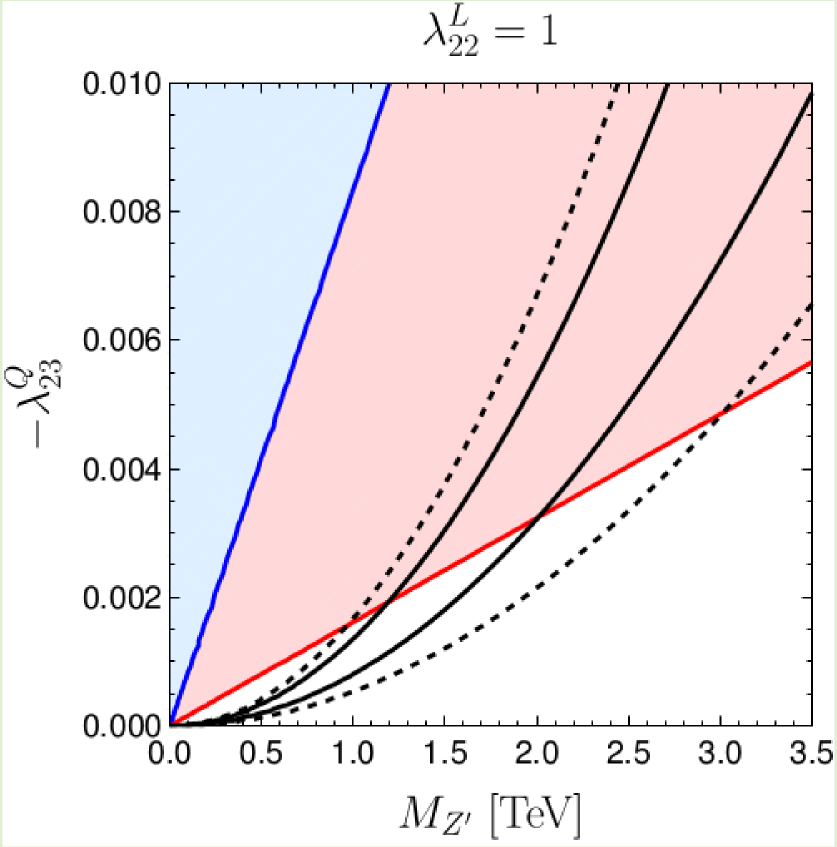


Stronger B_s mixing constraints

- Roughly a factor 5 in mass limits
- Actually a generic feature of the new result (if $\kappa > 0$)

$$\frac{\Delta M_s^{\text{Exp}}}{\Delta M_s^{\text{SM}}} = \left| 1 + \frac{\kappa}{\Lambda_{\text{NP}}^2} \right| \Rightarrow \frac{\Lambda_{\text{NP}}^{2017}}{\Lambda_{\text{NP}}^{2015}} = \sqrt{\frac{\frac{\Delta M_s^{\text{Exp}}}{\left(\Delta M_s^{\text{SM}} - 2\delta\Delta M_s^{\text{SM}}\right)^{2015}} - 1}{\frac{\Delta M_s^{\text{Exp}}}{\left(\Delta M_s^{\text{SM}} - 2\delta\Delta M_s^{\text{SM}}\right)^{2017}} - 1}} \simeq 5.2$$

Loopholes…

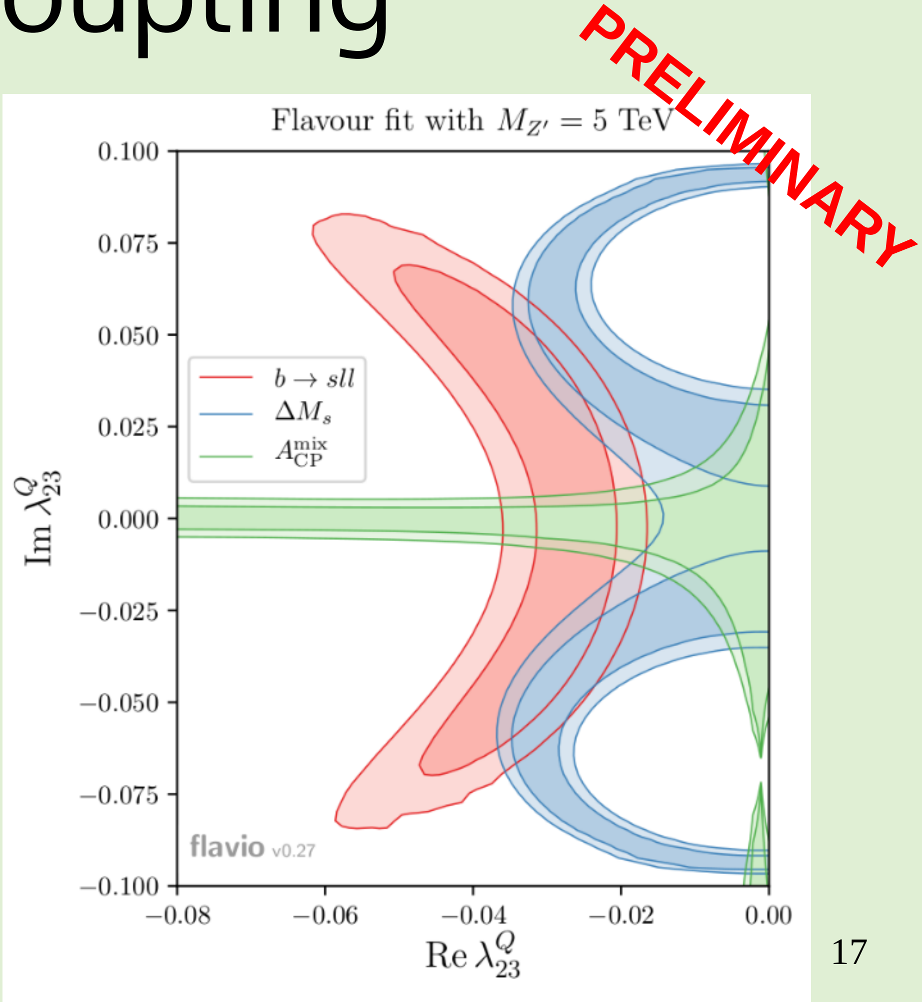
Complex Coupling

- As soon as we have complex couplings

  → new sources of CP violation

  → new constraints

- For B_s mixing, mixing induced CP asymmetry



Complex Coupling

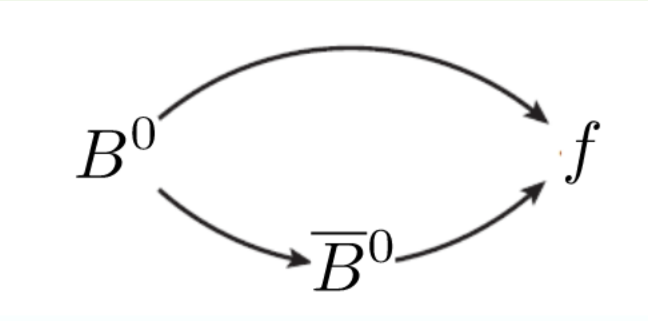
PRELIMINARY

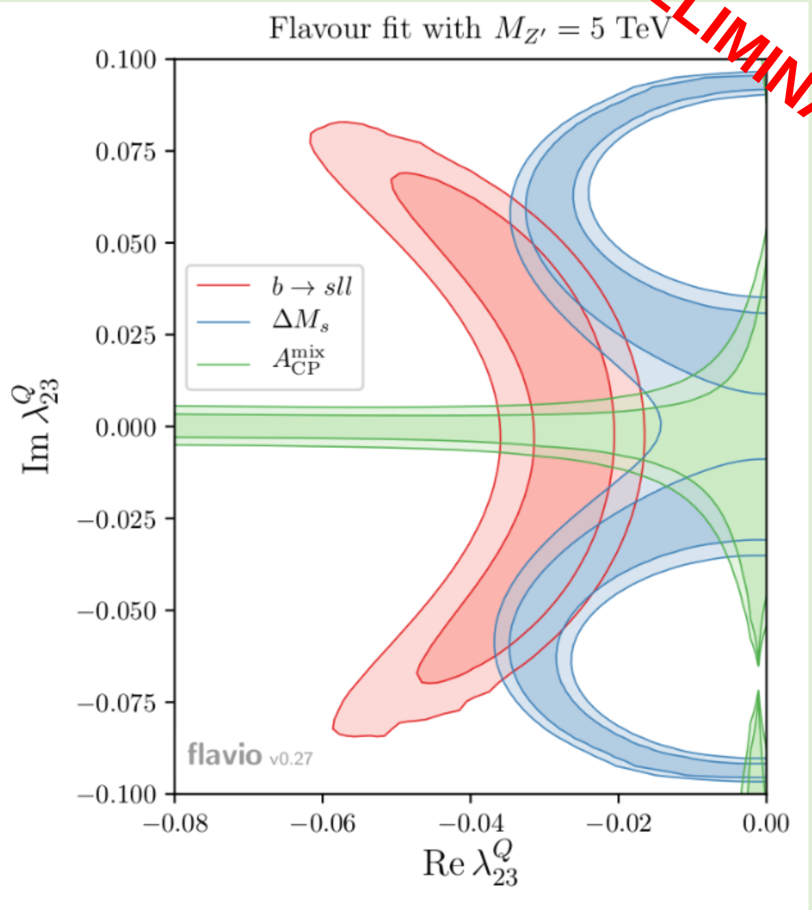
- As soon as we have complex couplings

  → new sources of CP violation

  → new constraints

- For B_s ... induce

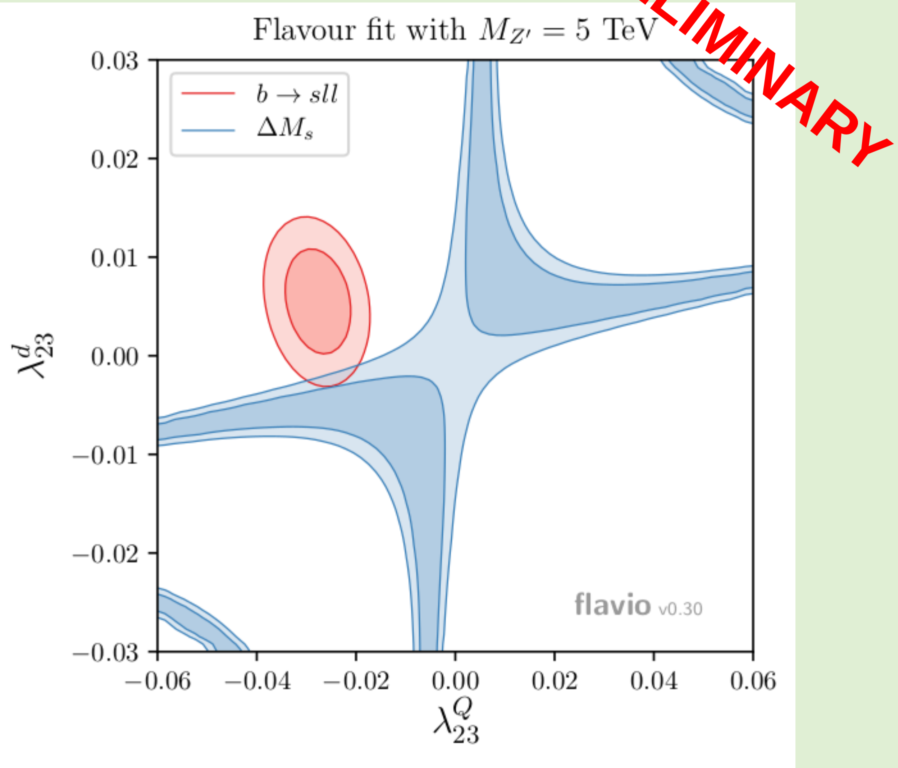




RH quark coupling

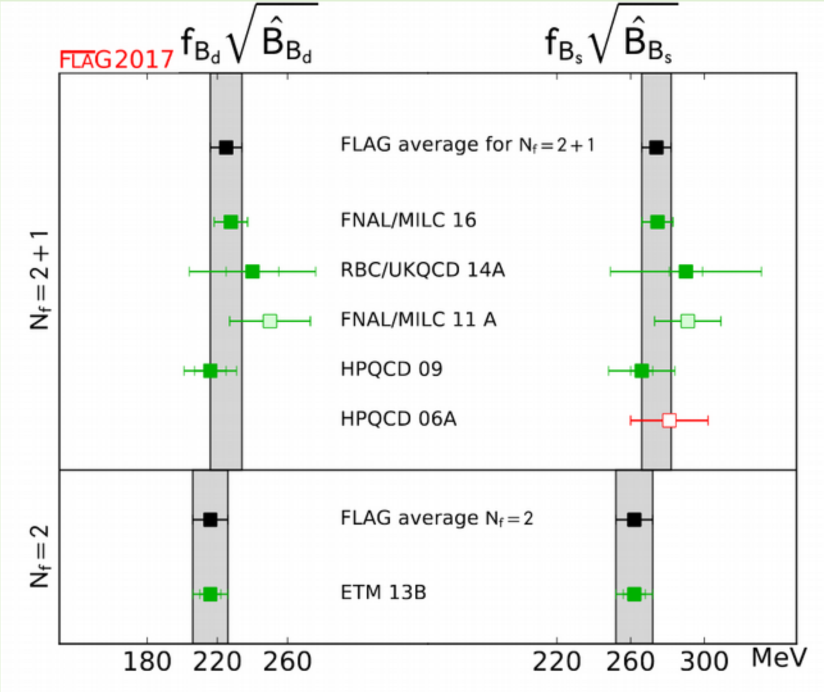
- Adding RH coupling allows negative contribution to ΔM_s

$$\mathcal{L}_{Z'}^{\text{eff}} \supset -\frac{1}{2M_{Z'}^2}\left[(\lambda_{23}^Q)^2\left(\bar{s}_L\gamma_\mu b_L\right)^2 + (\lambda_{23}^d)^2\left(\bar{s}_R\gamma_\mu b_R\right)^2 + 2\lambda_{23}^Q\lambda_{23}^d(\bar{s}_L\gamma_\mu b_L)(\bar{s}_R\gamma_\mu b_R) + \text{h.c.}\right].$$



Cross check of lattice result

- Since $f_{B_s}\sqrt{B}$ so important, and lattice average currently dominated by FNAL/MILC, what cross checks can be done?
- Use QCD/HQET sum rules to compute B
- Independent determination



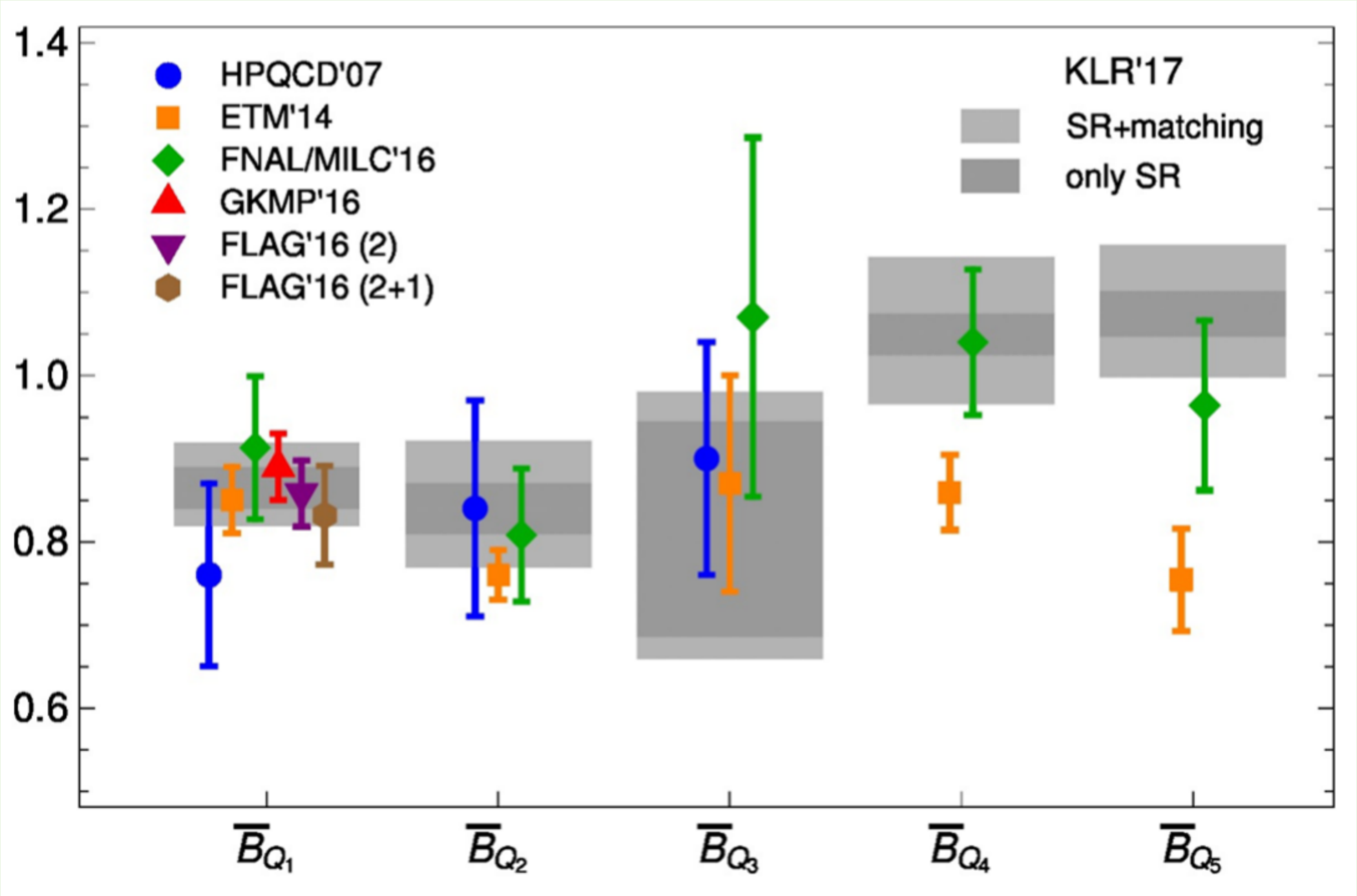
Sum rule calculation

- Have done all operators that contribute to ΔM and $\Delta \Gamma$ at dim6 (4 quark, no derivatives)
- Also ongoing now, include m_s effects with expansion up to m_s^2
- Just bag parameter, not decay constant
  - Have to use another source for that

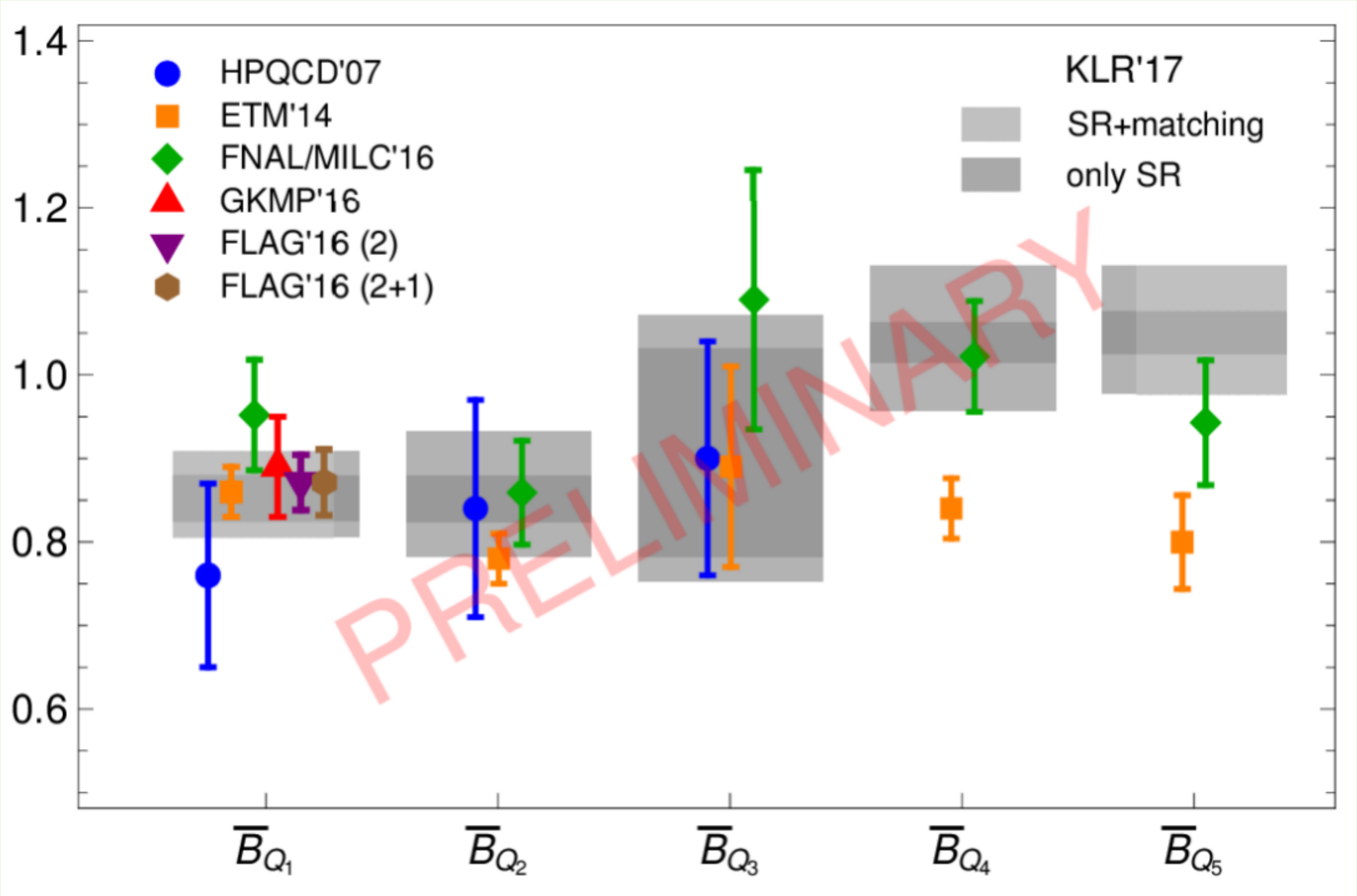
Sum rule calculation

- 0812.4522 (Grozin, Lee) – master 3 loop integrals
- 1606.06054 (Grozin, Klein, Mannel, Pivovarov) – calculation of SM operator (ΔM only)
- 1711.02100 (MK, Lenz, Rauh) – all dim6 operators (lifetime and mixing)

B_d bag parameters



B_s bag parameters



Sum rule precision

- Comparable to lattice
  - And major contribution coming from the matching
    - Improvable (go to NNLO) with current technology
  - Possibility to beat them at their own game ;-)

Meson lifetimes for NP

- While not directly applicable in the minimal explanation for R_{K}, meson lifetimes can be strong bounds on NP as well.
- E.g. allow some NP in $(\bar{b}\,s)(\bar{c}\,c)$ gives LFU contribution to ΔC_9 (1701.09183)
- Strong bound from $\tau(B_s)/\tau(B_d)$

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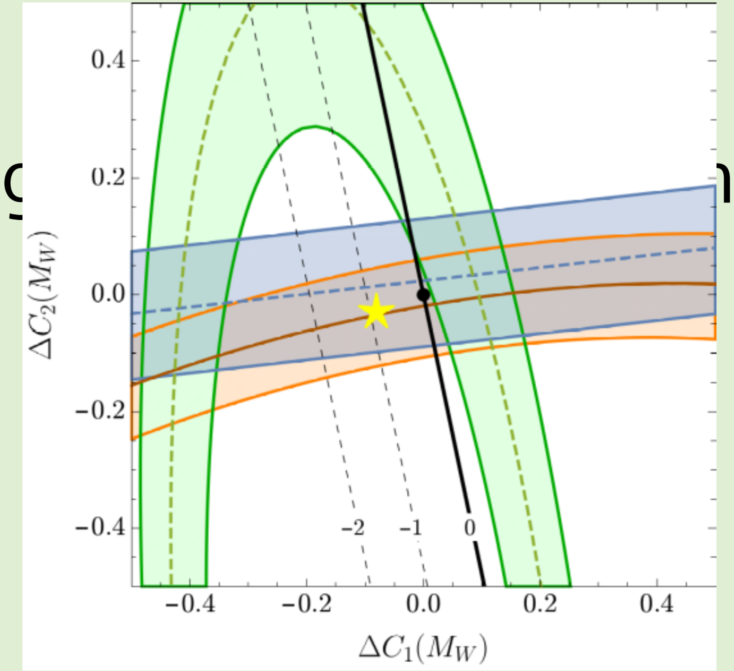


Meson lifetimes for NP

- LFU contribution to ΔC_9 worth further consideration (see

Towards the discovery of new physics with lepton-universality ratios of $b \to s\ell\ell$ decays

Li-Sheng Geng, Benjamín Grinstein, Sebastian Jäger, Jorge Martin Camalich, Xiu-Lei Ren, Rui-Xiang Shi

(Submitted on 18 Apr 2017 (v1), last revised 20 Apr 2017 (this version, v2))

Are we overlooking Lepton Flavour Universal New Physics in $b \to s\ell\ell$?

Marcel Algueró, Bernat Capdevila, Sébastien Descotes-Genon, Pere Masjuan, Joaquim Matias

(Submitted on 22 Sep 2018)

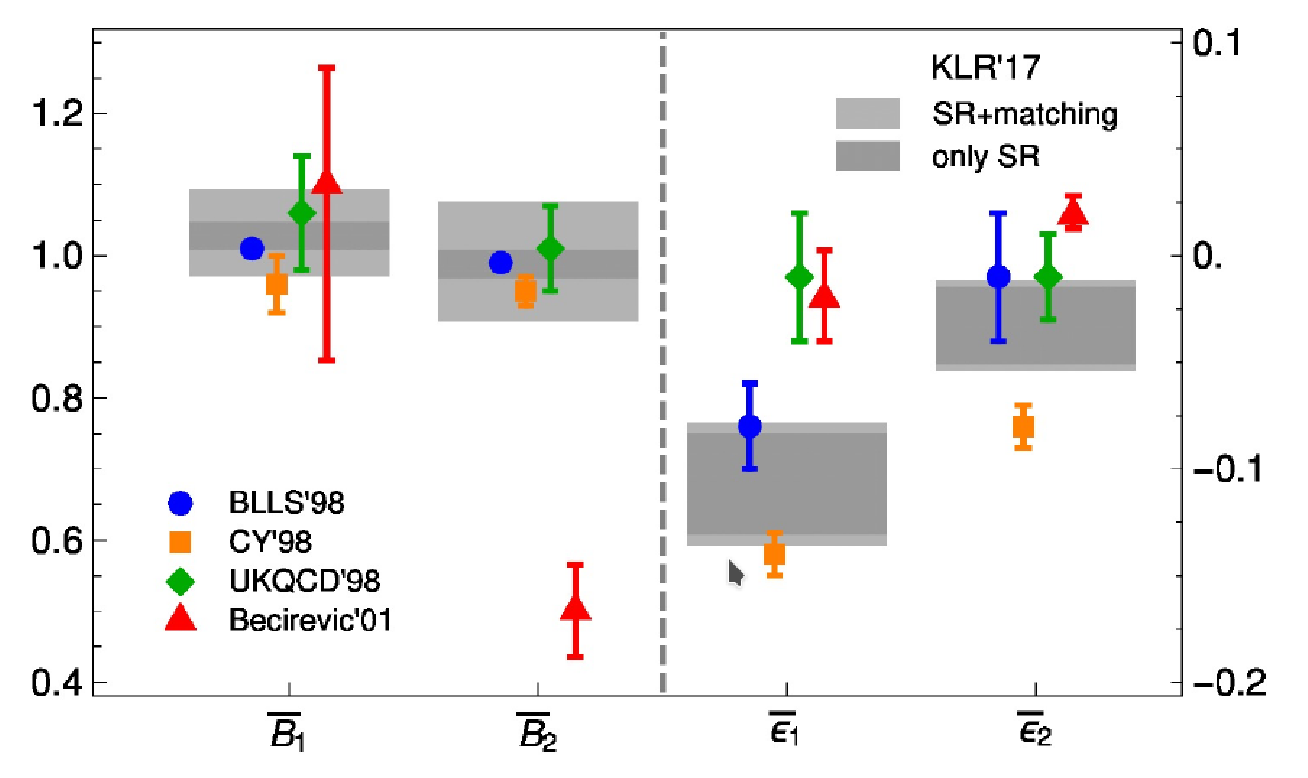
Meson lifetimes for NP

- LFU contribution to ΔC_9 worth further consideration (see e.g. 1704.05446, 1809.08447)
- Follow up to 1701.09183 coming soon
- Looking at complex couplings and constraints from $B \to J/\psi K$
- Also examining full basis of $(\bar{b}s)(\bar{c}c)$ operators

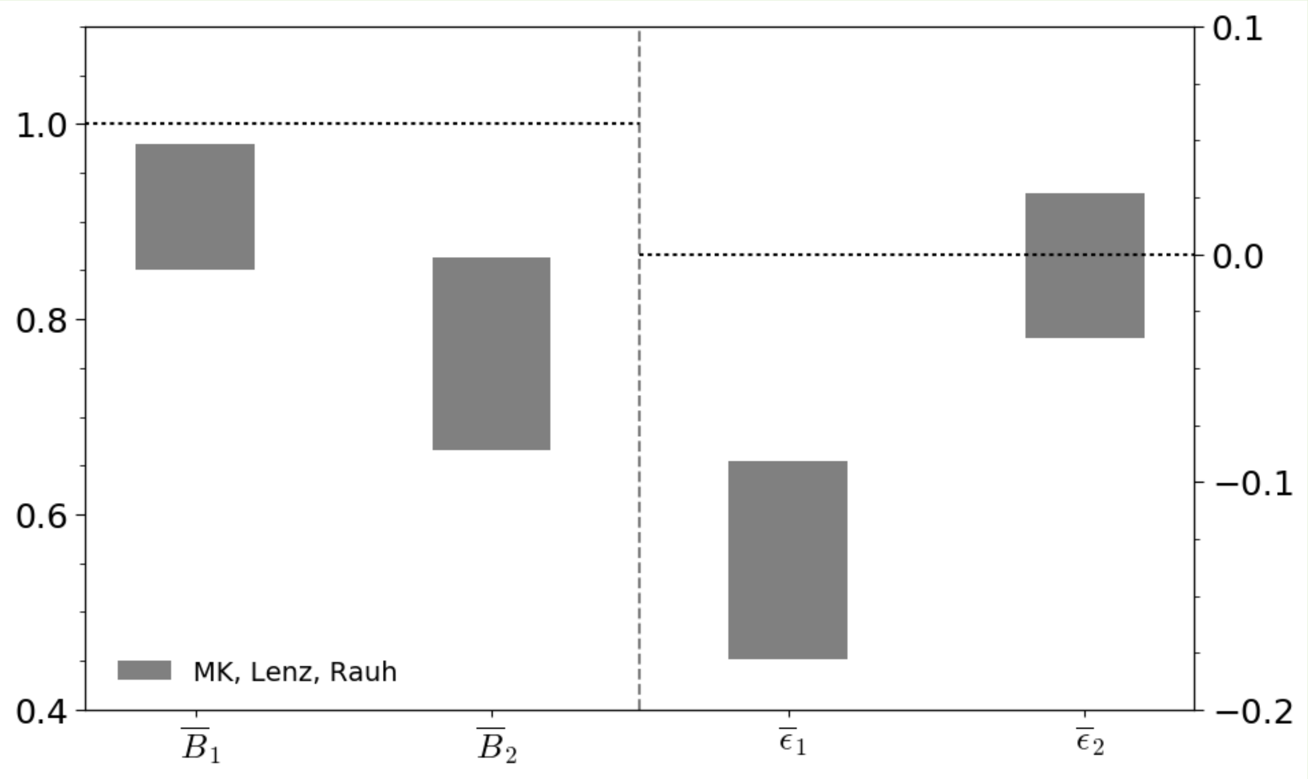
Lifetime matrix elements

- Need matrix elements of contributing operators.
- In SM, there are 4 operators at dim6 (four quark, no derivatives)
- No lattice results since 2001 (hep-ph/0110124)

B lifetime bag parameters



D lifetime bag parameters



D lifetimes to test the HQE

- Experiment measures $\tau(D^+)/\tau(D^0) = 2.536 \pm 0.019$
- Old SM prediction (1305.3588) was 2.2 ± 1.7
  - They (Lenz, Rauh) used $B = 1 \pm 1/3, \epsilon = 0 \pm 1/10$
- New prediction with sum rule calculation is $2.7^{+0.7}_{-0.8}$
  - Good agreement

D lifetimes to test the HQE

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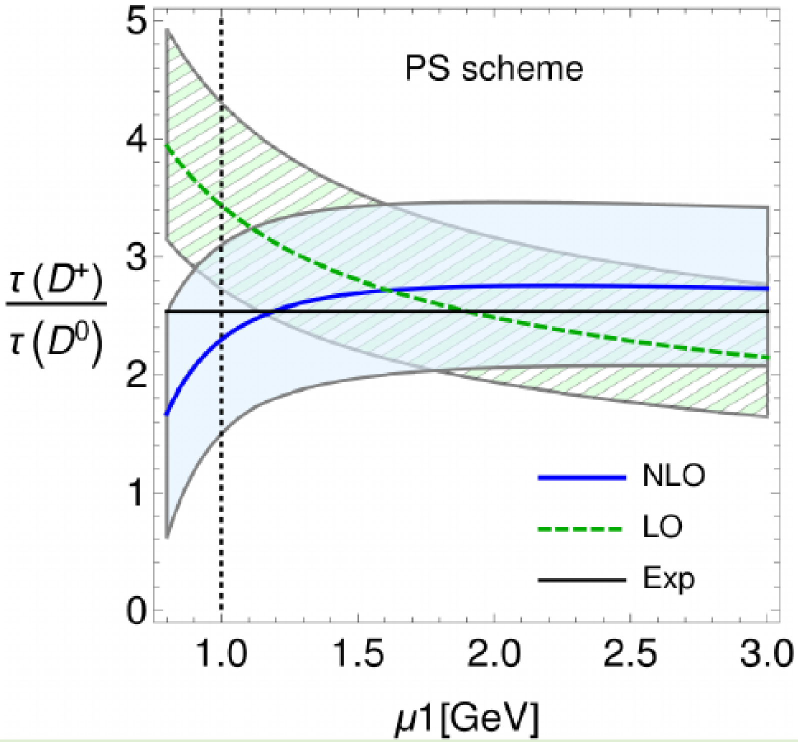
- O
  - –
- N
  - –



Good convergence:

NLO QCD +28%, 1/mc -34%.

Good behaviour under scale variation above about 1 GeV.

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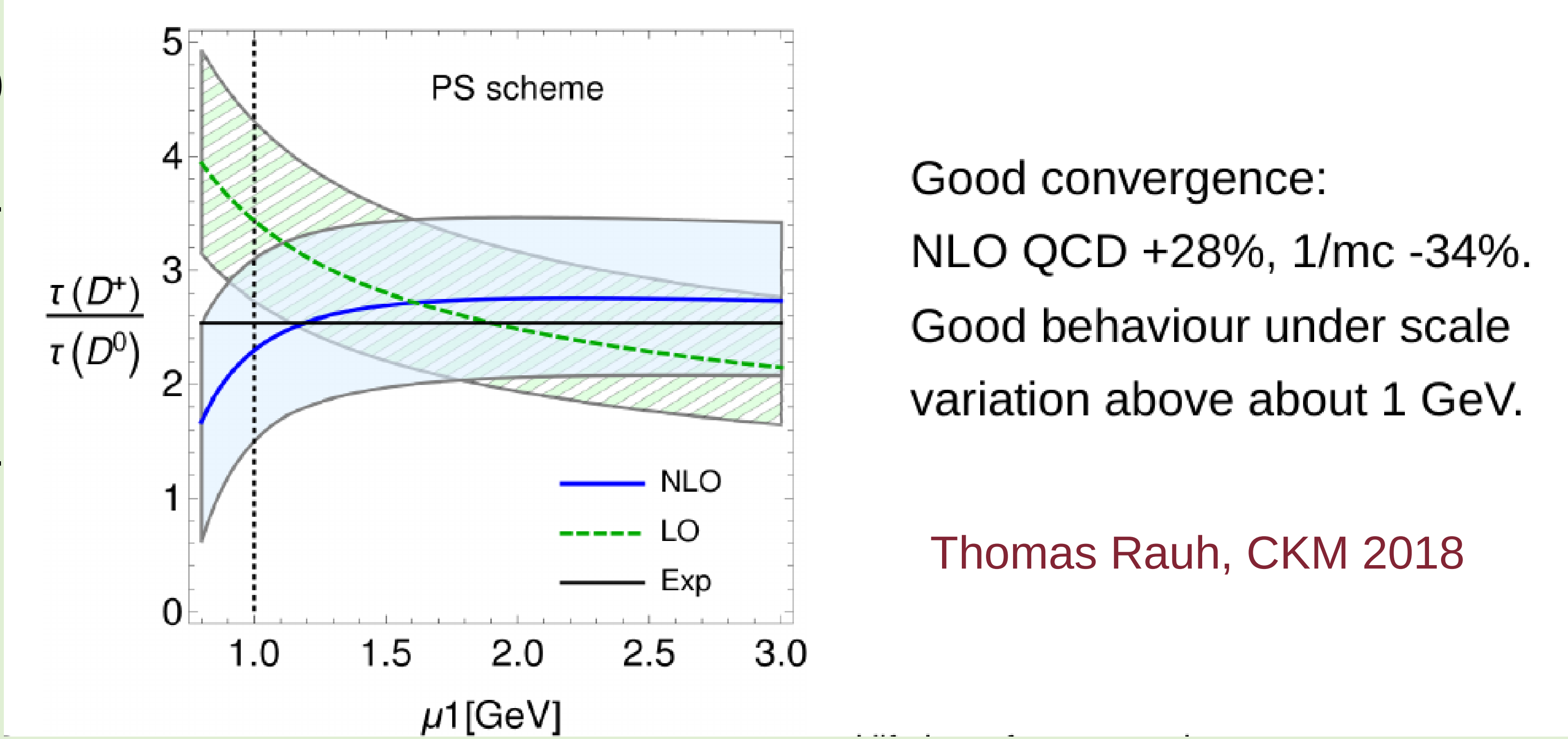

Sum rules conquer lifetimes

- Only game in town
  - Only state of the art for B mesons
  - Only alternative to vacuum saturation approximation for D mesons

Conclusions

- B mixing is and will be a very important constraint on any NP altering the $b \to s$ transition.
- If Fermilab-MILC result is confirmed, many NP models must be lighter than previously thought.
- For more general NP models, lifetimes can also be constraining → important to get lattice confirmation of lifetime matrix elements

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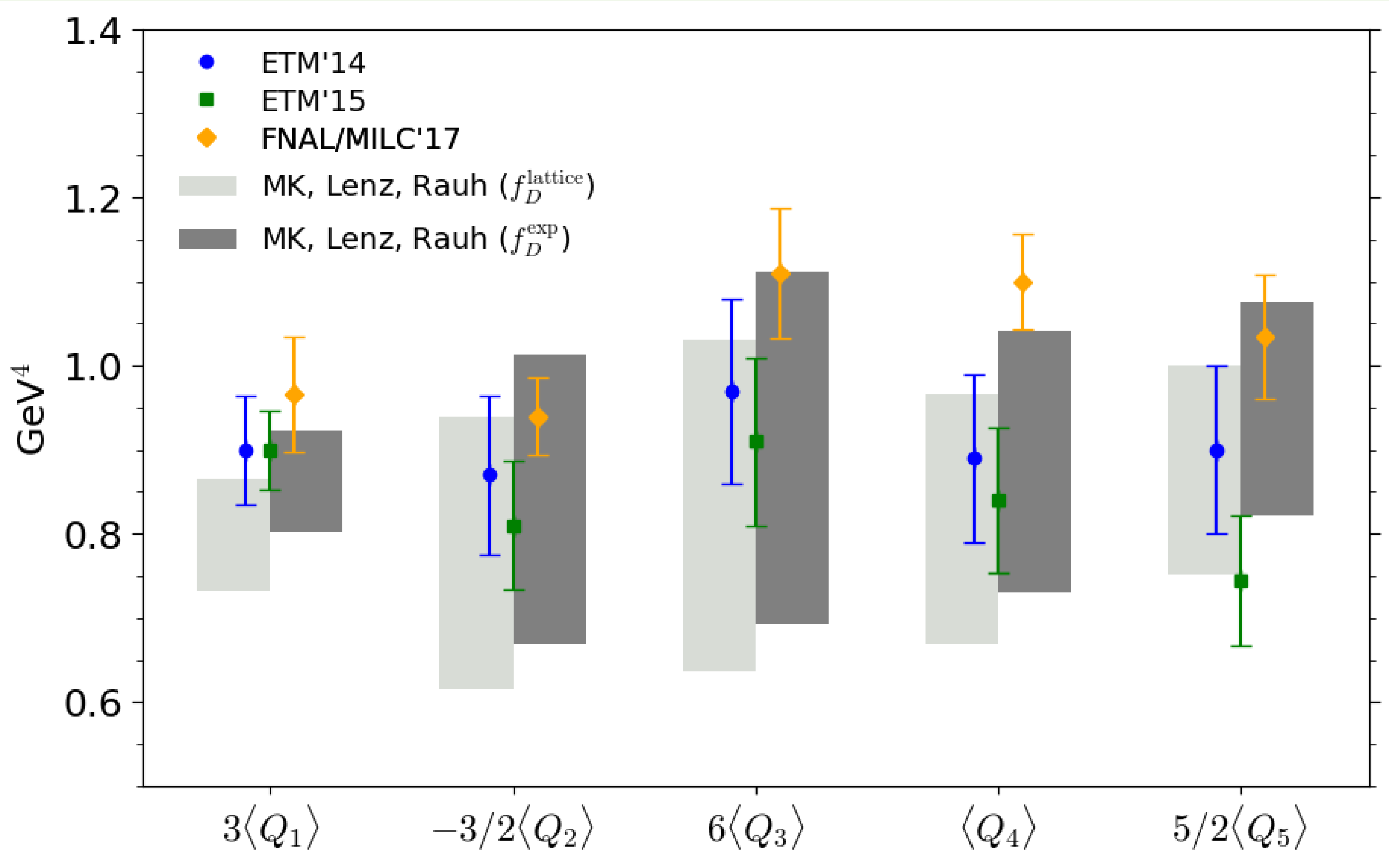
Extras

Effect of non-perturbative parameters on NP models

Source	$f_{B_s}\sqrt{\hat{B}}$	$\Delta M_s^{\rm SM}$
HPQCD14 [132]	(247 ± 12) MeV	$(16.2 \pm 1.7)\,\mathrm{ps}^{-1}$
ETMC13 [133]	(262 ± 10) MeV	$(18.3 \pm 1.5)\,\mathrm{ps}^{-1}$
HPQCD09 [134] = FLAG13 [135]	(266 ± 18) MeV	$(18.9 \pm 2.6)\,\mathrm{ps}^{-1}$
FLAG17 [70]	$\mathbf{(274 \pm 8)}$ **MeV**	$\mathbf{(20.01 \pm 1.25)\,ps^{-1}}$
Fermilab16 [72]	(274.6 ± 8.8) MeV	$(20.1 \pm 1.5)\,\mathrm{ps}^{-1}$
HQET-SR [77, 136]	(278^{+28}_{-24}) MeV	$(20.6^{+4.4}_{-3.4})\,\mathrm{ps}^{-1}$
HPQCD06 [137]	(281 ± 20) MeV	$(21.0 \pm 3.0)\,\mathrm{ps}^{-1}$
RBC/UKQCD14 [138]	(290 ± 20) MeV	$(22.4 \pm 3.4)\,\mathrm{ps}^{-1}$
Fermilab11 [139]	(291 ± 18) MeV	$(22.6 \pm 2.8)\,\mathrm{ps}^{-1}$

HQET sum rules – D mixing



Vacuum saturation approximation

$$\langle B_s|(\bar{q}\,\Gamma\, b)(\bar{q}\,\Gamma\, b)|\overline{B_s}\rangle = \sum_{\text{all states}} \langle B_s|(\bar{q}\,\Gamma\, b)|X\rangle\langle X|(\bar{q}\,\Gamma\, b)|\overline{B_s}\rangle$$

$$\approx \langle B_s|(\bar{q}\,\Gamma\, b)|0\rangle\langle 0|(\bar{q}\,\Gamma\, b)|\overline{B_s}\rangle$$

These then look like decay constants for meson to vacuum – extracted from experimental decay width

$$\langle B_s|(\bar{q}\,\Gamma\, b)(\bar{q}\,\Gamma\, b)|\overline{B_s}\rangle = B_\Gamma \langle B_s|(\bar{q}\,\Gamma\, b)|0\rangle\langle 0|(\bar{q}\,\Gamma\, b)|\overline{B_s}\rangle$$

Bag parameter