Hints of new physics in flavour anomalies

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Outline

- Basics of flavour physics
- History of flavour anomalies
- Introduction to meson mixing
  - How mixing and anomalies interact
- Introduction to meson lifetimes
  - How lifetimes and anomalies interact
- Future of anomalies

The What and Why of Flavour Physics

The What and Why of Flavour Physics

- What is flavour?
  - The different generations of quarks and leptons
- In the SM
  - Only difference is non universal Yukawa coupling to Higgs – generates different mass and flavour basis
- Means quarks couple with CKM, leptons with PMNS

The What and Why of Flavour Physics

- Why? To study these differences – why different masses, why CKM / PMNS look the way they do, why different generations at all?
- Almost easy answer to why 3 generations:
  - Need at least 3 to generate CP violation
- But SM prediction for CP violation off by 10 orders of magnitude from observed baryon asymmetry

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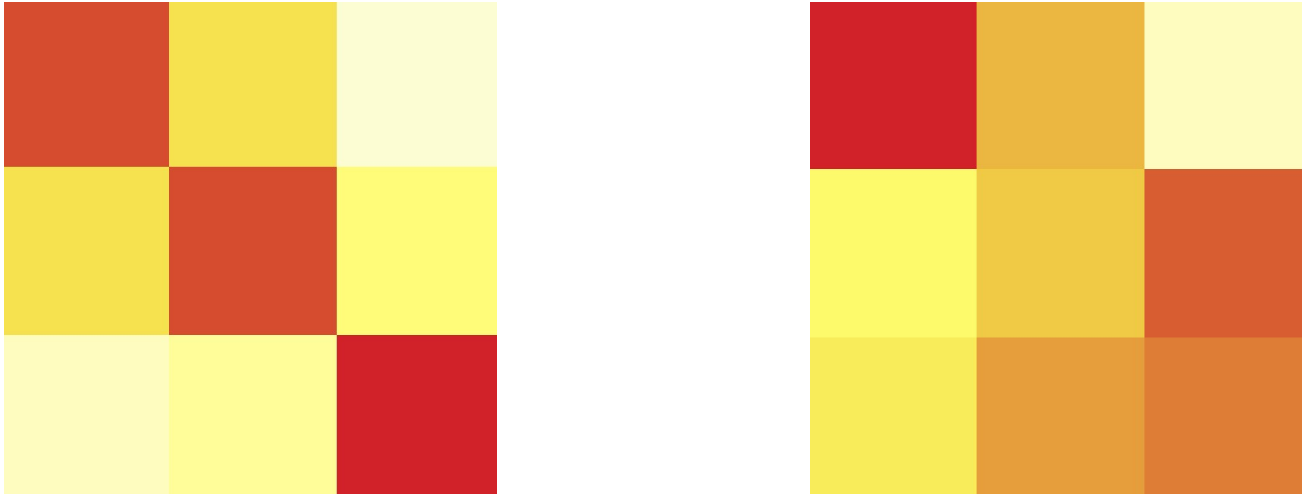

The What and Why of Flavour Physics

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The What and Why of Flavour Physics

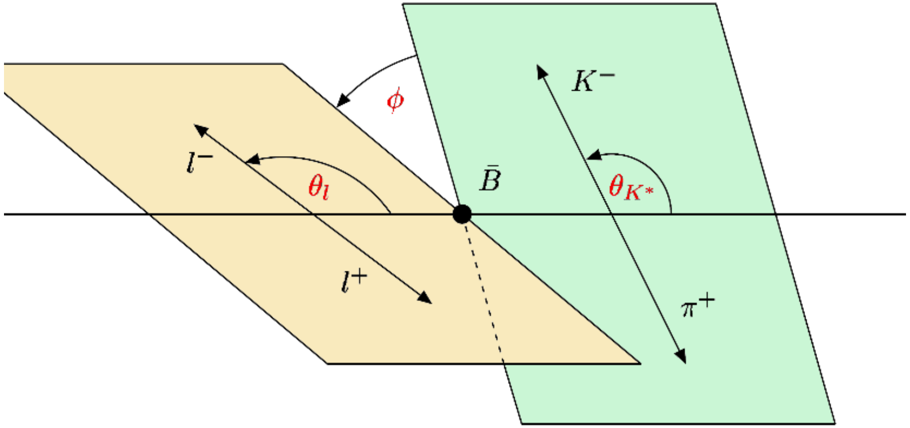
- Why 1: CP violation (big picture)
- Why 2: Lots of flavour changing processes are rare in the SM
  - Easy to enhance, even with high scale NP
- Why 3: Study the SM and our tools
  - Flavour physics is paradigm of EFT – Fermi theory

Flavour anomalies

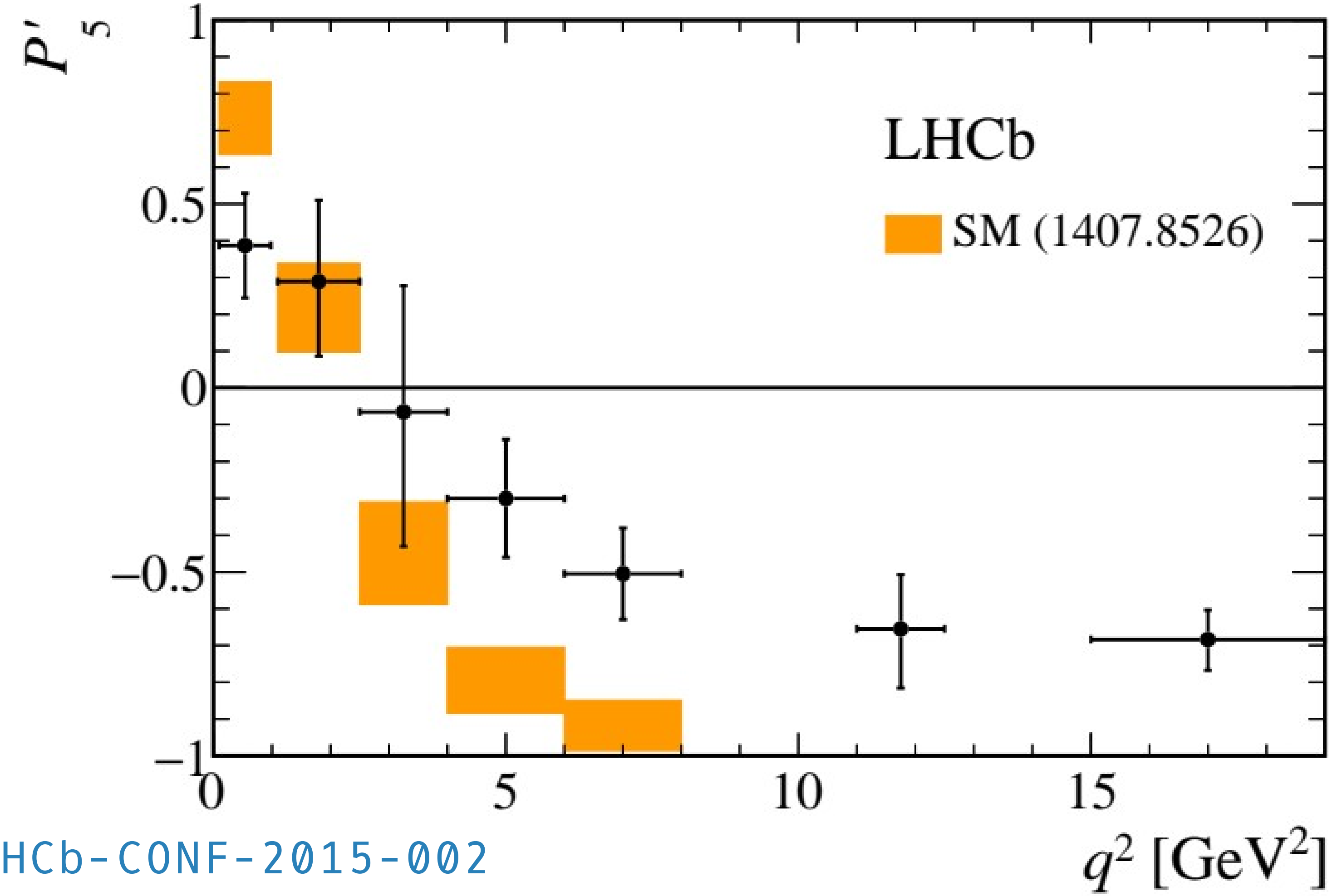
Flavour anomalies: a history

- $P_5^{'}$ in 2013, $3.7\,\sigma$ local deviation
- R_K in 2014, $2.6\,\sigma$ local deviation
- R_{K^*} in 2017, $2{-}2.5\,\sigma$ local deviation

$P_5^{'}$



$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$



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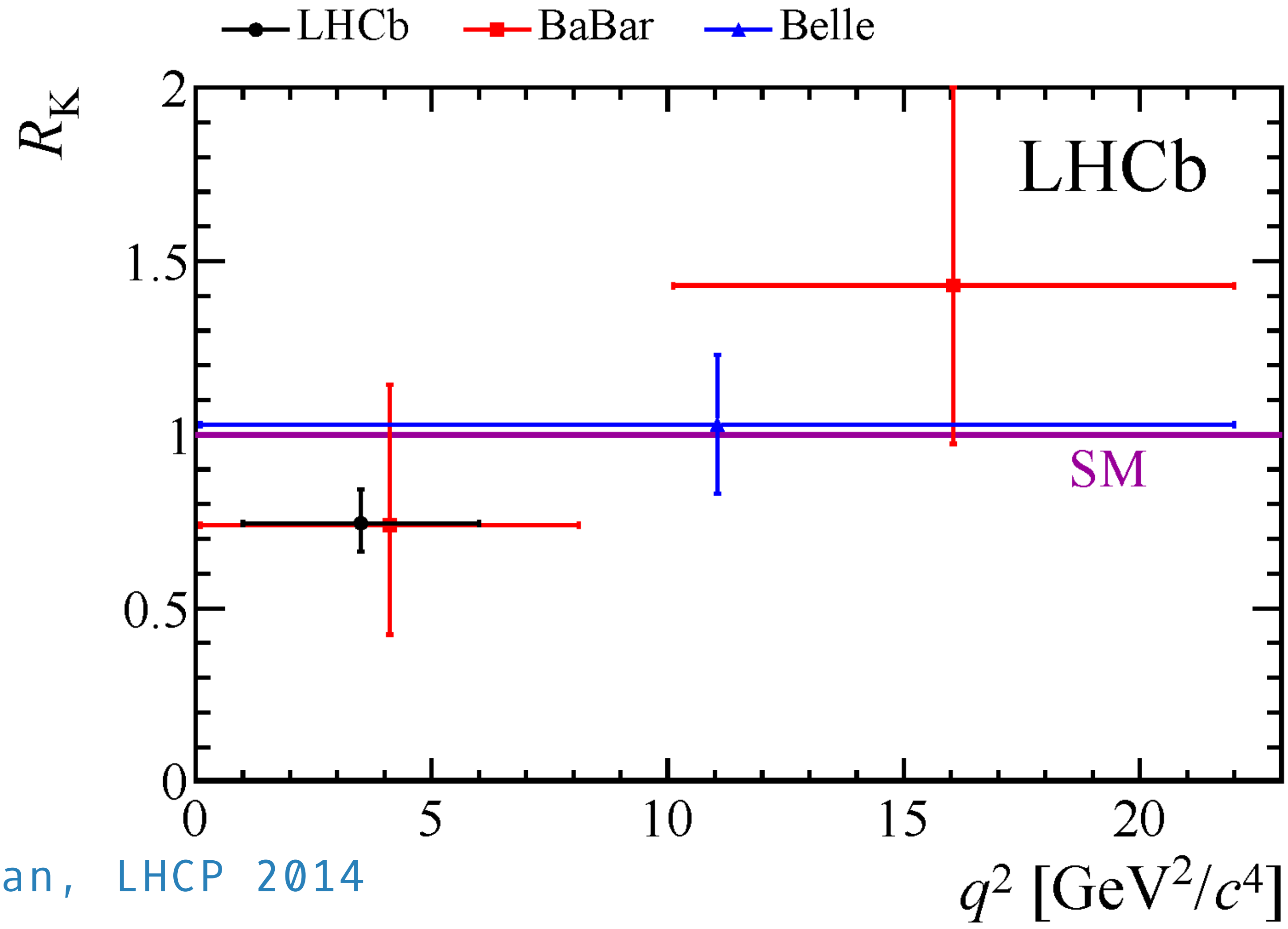
Flavour anomalies: a history

- $P_5^{'}$ in 2013, $3.7\,\sigma$ local deviation
- R_K in 2014, $2.6\,\sigma$ local deviation
- R_{K^*} in 2017, $2-2.5\,\sigma$ local deviation

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}$$



De Cian, LHCP 2014

Flavour anomalies: a history

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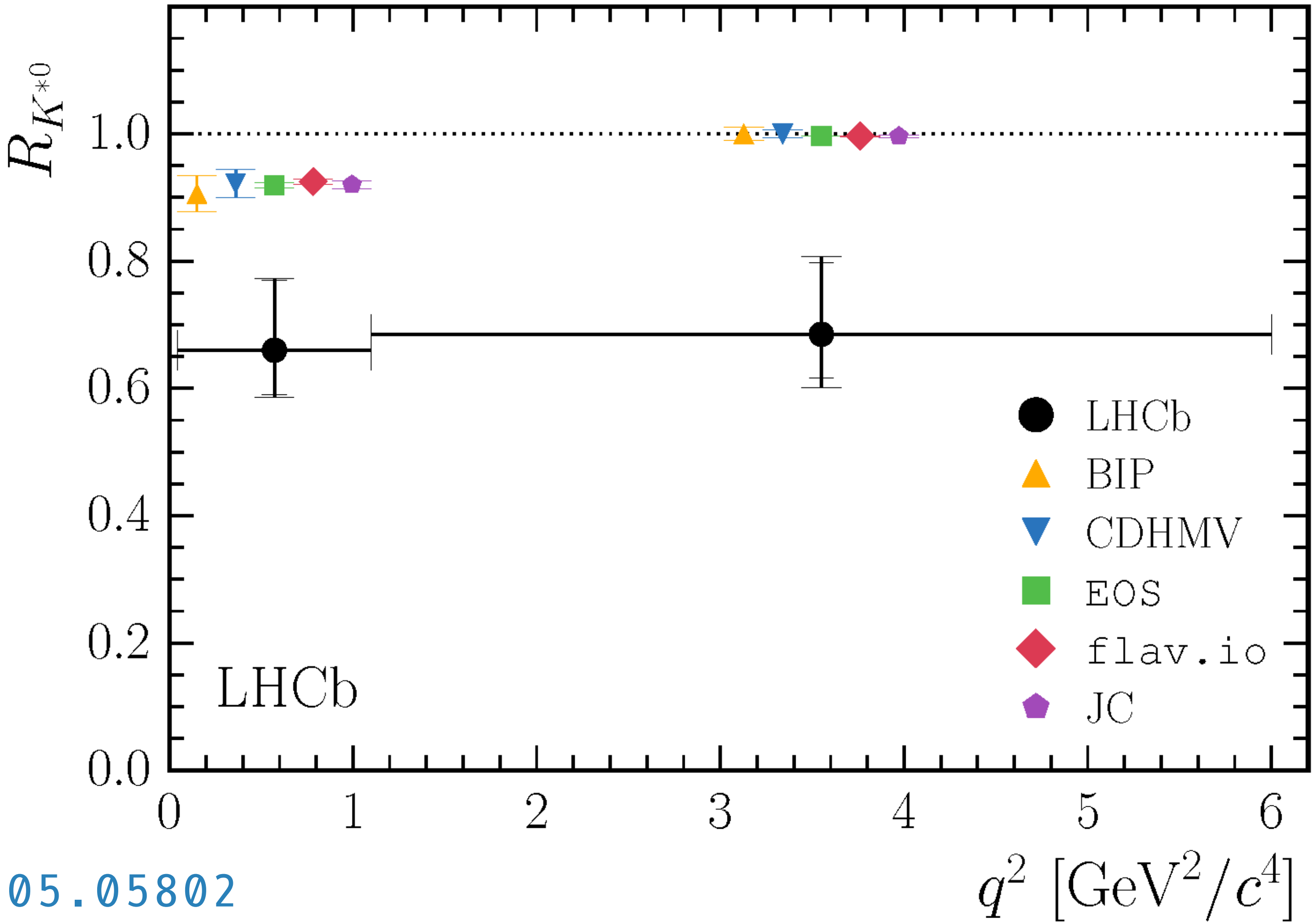

$R_{K^{*0}}$
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
q^2 [GeV$^2/c^4$]
LHCb
● LHCb
▲ BIP
▼ CDHMV
■ EOS
◆ flav.io
⬟ JC

1705.05802

$R_{K^{(*)}}$

- Very nice as SM predictions are very precise – O(1%)
  - Hadronic uncertainties cancel
    - Note: only in SM – most NP predictions have large uncertanties
- $R_K(1 < q^2 < 6) = 1 \pm 0.01$
- $R_{K^*}(0.045 < q^2 < 1.1) = 0.92 \pm 0.02$
- $R_{K^*}(1.1 < q^2 < 6) = 1 \pm 0.01$

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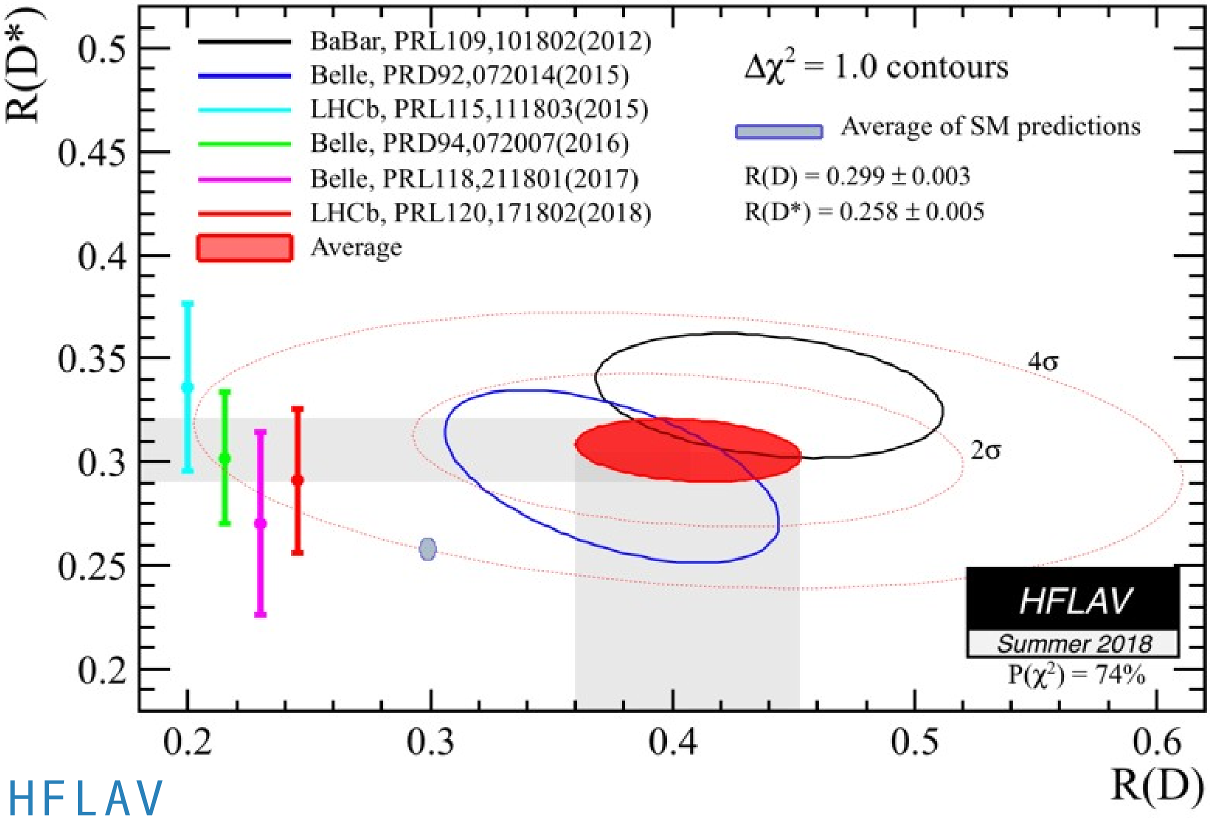
$R_{D^{(*)}}$

- $B \rightarrow D \ell \nu$ decays
- $R_{D^{(*)}} = \mathrm{Br}\left(B \rightarrow D^{(*)} \tau \nu\right) / \mathrm{Br}\left(B \rightarrow D^{(*)} \mu \nu\right)$
- Tree level, charged current decay
- Overall $4.1\,\sigma$

$R_{D^{(*)}}$


R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, PRL120,171802(2018)
Average
$\Delta\chi^2 = 1.0$ contours
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
4σ
2σ
HFLAV
Summer 2018
$P(\chi^2) = 74\%$

HFLAV

$R_{D^{(*)}}$

- $B \rightarrow D \ell \nu$ decays
- $R_{D^{(*)}} = \mathrm{Br}\left(B \rightarrow D^{(*)} \tau \nu\right) / \mathrm{Br}\left(B \rightarrow D^{(*)} \mu \nu\right)$
- Tree level, charged current decay
- Overall $4.1\,\sigma$
- Not going to talk about this more

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Coherent anomalies

- All in b→$s\mu\mu$
- EFT that describes these decays has 6 operators
- Can do global fits to all data, with one or more NP operator in play

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, & \mathcal{O}_{7'} &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}, \\
\mathcal{O}_{9\ell} &= \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), & \mathcal{O}_{9'\ell} &= \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{10\ell} &= \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), & \mathcal{O}_{10'\ell} &= \frac{e}{16\pi^2} m_b (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell).
\end{aligned}$$

Coherent anomalies

- Coherent in the sense that a single NP contribution – $C_{9\mu}$ – can provide a large improvement in the fit to the data
- With just $C_{9\mu}$, 5.8 σ (or 3.9 with only LFUV)

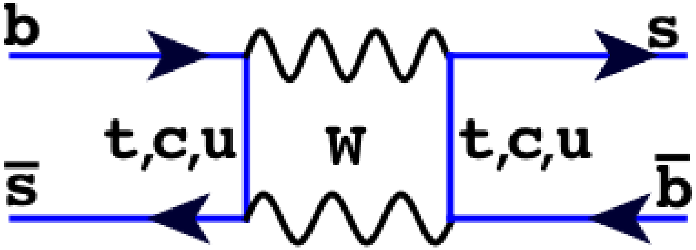
1704.05340

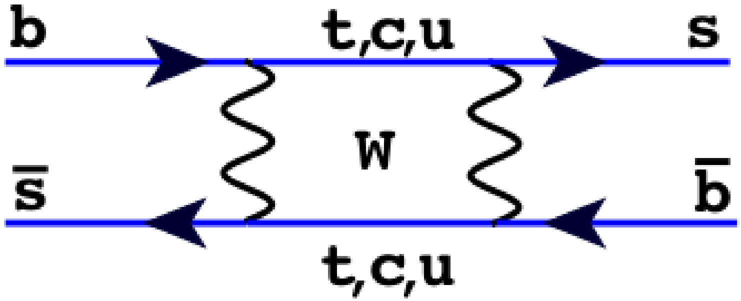
Meson Mixing

Short introduction to meson mixing

- Consider $B, \overline{B}$ meson
- Definied by their quark content – $\overline{b}d, b\overline{d}$
  - So they are flavour eigenstates
- But they can oscillate into one another

Short introduction to meson mixing

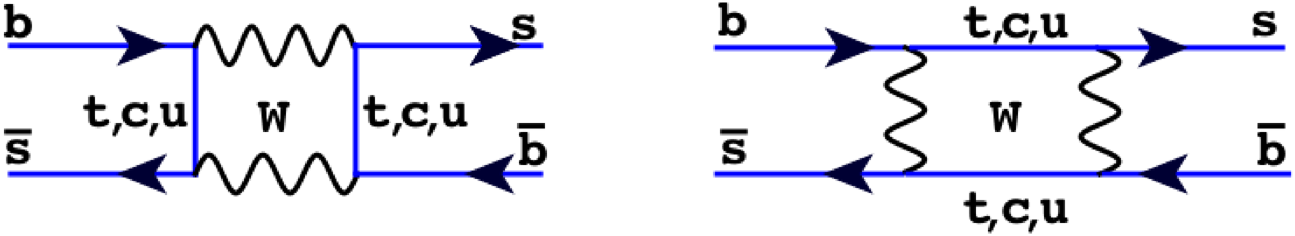




Short introduction to meson mixing

- Can imagine this mixing giving off-diagonal terms in a Schrödinger like equation

- To find mass eigenstates, have to diagonalise



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

Short introduction to meson mixing

- Get two new observables – mass difference and width difference between the two mass eigenstates B_H, B_L (heavy and light)
- $\Delta M = M_{B_H} - M_{B_L}$
- $\Delta \Gamma = \Gamma_{B_H} - \Gamma_{B_L}$

Calculating ΔM and $\Delta\Gamma$

- ΔM comes from $\Delta F{=}2$ operators
- $\Delta\Gamma$ from loop diagrams involving $\Delta F{=}1$ operators
  - Because $\Delta\Gamma$ comes from lifetimes
  - Optical theorem $\langle B|Q|B\rangle = \mathrm{Im}\sum_X \langle B|Q|X\rangle\langle X|Q|B\rangle$

Calculating ΔM and $\Delta\Gamma$

- In the SM, just one operator contributes to ΔM
  - $(\bar{b}^{\alpha}\gamma^{\mu}P_L s^{\alpha})(\bar{b}^{\beta}\gamma_{\mu}P_L s^{\beta})\,,$
- $\Delta\Gamma$ has many contributing operators

$$
\begin{aligned}
&(\bar{b}^{\alpha}\gamma^{\mu}P_L s^{\alpha})(\bar{b}^{\beta}\gamma_{\mu}P_L s^{\beta})\,,\\
&(\bar{b}^{\alpha}P_L s^{\alpha})(\bar{b}^{\beta}P_L s^{\beta})\,,\\
&(\bar{b}^{\alpha}P_L s^{\beta})(\bar{b}^{\beta}P_L s^{\alpha})\,,\\
&(\bar{b}^{\alpha}P_L s^{\alpha})(\bar{b}^{\beta}P_R s^{\beta})\,,\\
&(\bar{b}^{\alpha}P_L s^{\beta})(\bar{b}^{\beta}P_R s^{\alpha})\,,
\end{aligned}
$$

Calculating ΔM and $\Delta\Gamma$

- $\Delta M \sim C_i \langle Q_i \rangle$, where $\langle Q \rangle = \langle B | Q | B \rangle$
- C_i calculated in perturbation theory
- $\langle Q_i \rangle$ need non perturbative technique
  - Lattice QCD
  - Sum rules

$\langle Q \rangle$

- Note for later
- For historical reasons, $\langle Q \rangle$ generally parameterised as $\langle Q_i \rangle = f_B^2 M_B^2 B_i$
- B_i is bag parameter, contains all the "interesting" physics (assuming you know f_B alrady)

Why anomalies → mixing

Anomalies → mixing

- As said earlier, flavour anomalies strongly suggests NP in $\bar{s}\,b\,\bar{\ell}\,\ell$ operator
- Easy to see that two insertions of NP give $\bar{s}\,b\,\bar{s}\,b$
- So there is always a link: NP in $b \rightarrow s\,\bar{\ell}\,\ell$ always give NP in B_s mixing

Mixing → anomalies

- Reverse is also true
- If we know about mixing, limits what can happen with anomalies
- So what do we know?

Status of B_s mixing

ΔM_s circa 2016

- Experiment: $17.757 \pm 0.021\,\mathrm{ps}^{-1}$

  HFLAV

- SM: $18.3 \pm 2.7\,\mathrm{ps}^{-1}$ 1511.09466
  - Relies on FLAG 2013 for $f_B^2 B$

- SM and experiment in agreement

ΔM_s circa 2018

- Experiment: $17.757 \pm 0.021\,\mathrm{ps}^{-1}$ HFLAV
- SM: $20.01 \pm 1.25\,\mathrm{ps}^{-1}$ 1712.06572
  - Relies on FLAG 2017 for $f_B^2 B$
  - Which is dominated by Fermilab/MILC results from 2016
- SM and experiment disagree at $\sim 1.8\,\sigma$

ΔM_s circa 2018

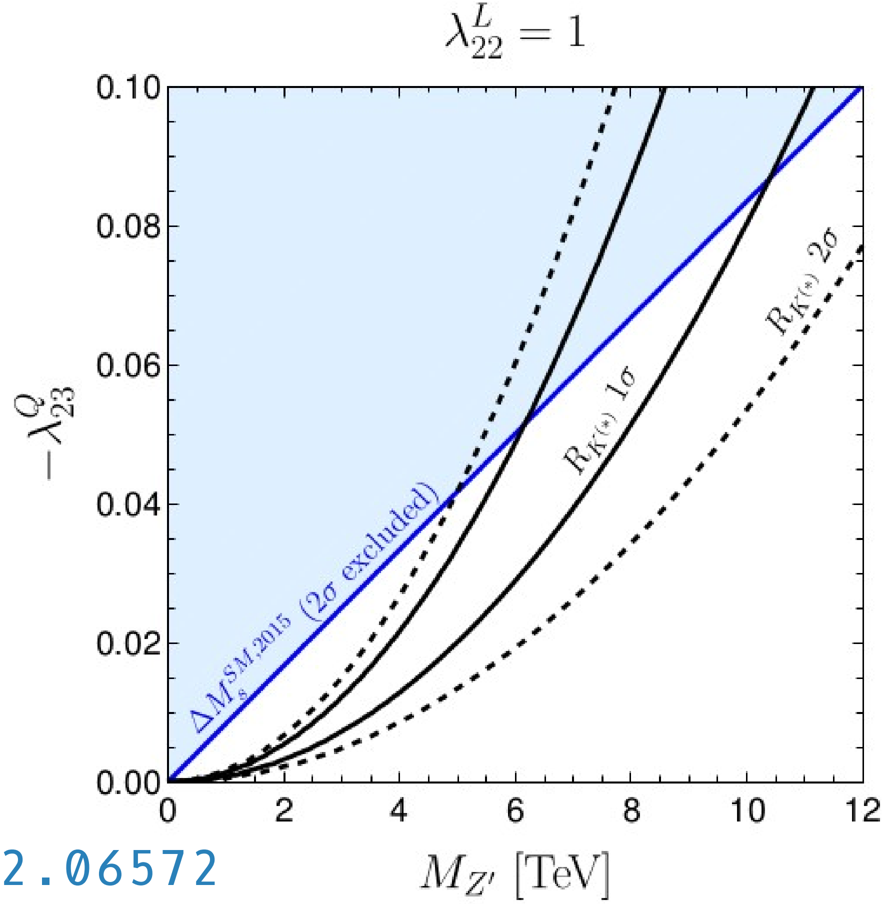
- SM and experiment disagree at ~1.8σ
- On its own, not very interesting
- But large class of NP models give positive contribution to ΔM_s
  - i.e. $\Delta M_s^{\mathrm{th}} \geq \Delta M_s^{\mathrm{SM}}$
  - So 1.8σ discrepancy only gets worse

- (see e.g. `1602.04020` for example – CMFV)

Concrete example

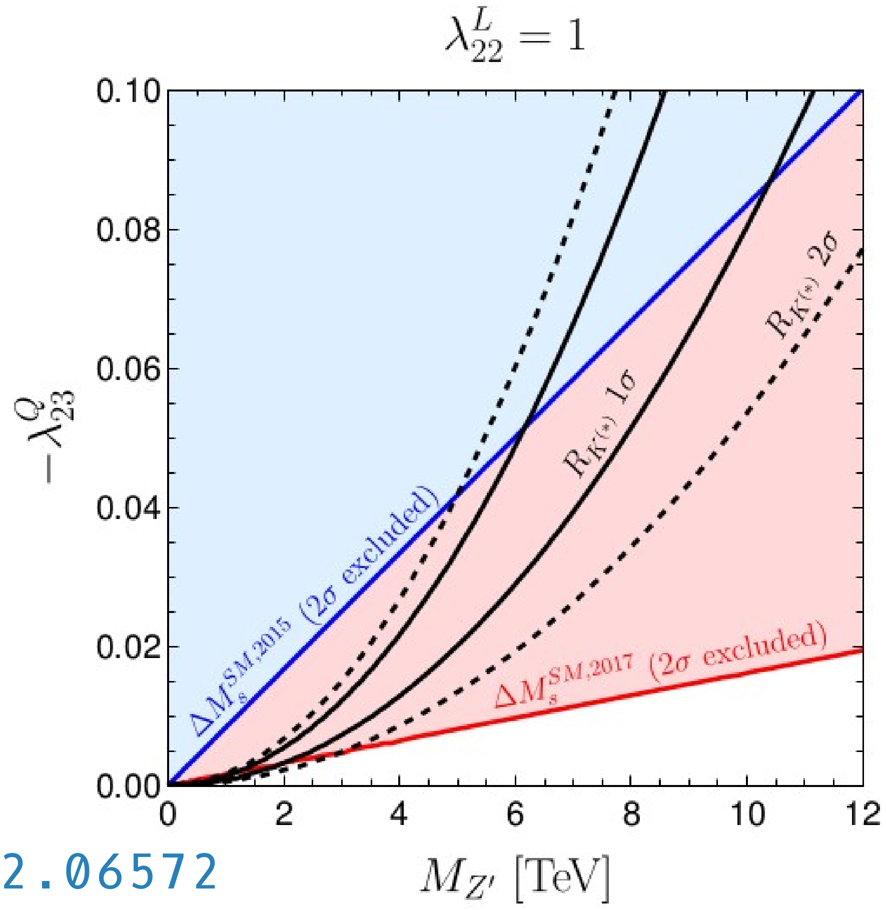
- Look at how only $R_{K^{(*)}}$ and B_s mixing restrict parameter space
- Imagine a new vector boson - Z'
- $Z'_\mu\left(\lambda_{23}^{Q}\,\bar{s}\,\gamma^\mu P_L\, b+\lambda_{22}^{L}\bar{\mu}\,\gamma^\mu P_L\mu\right)$

Concrete example



1712.06572

Concrete example



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Strength of bounds

- Can show that factor of 5 change is generic – applies to any NP model with positive contribution

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

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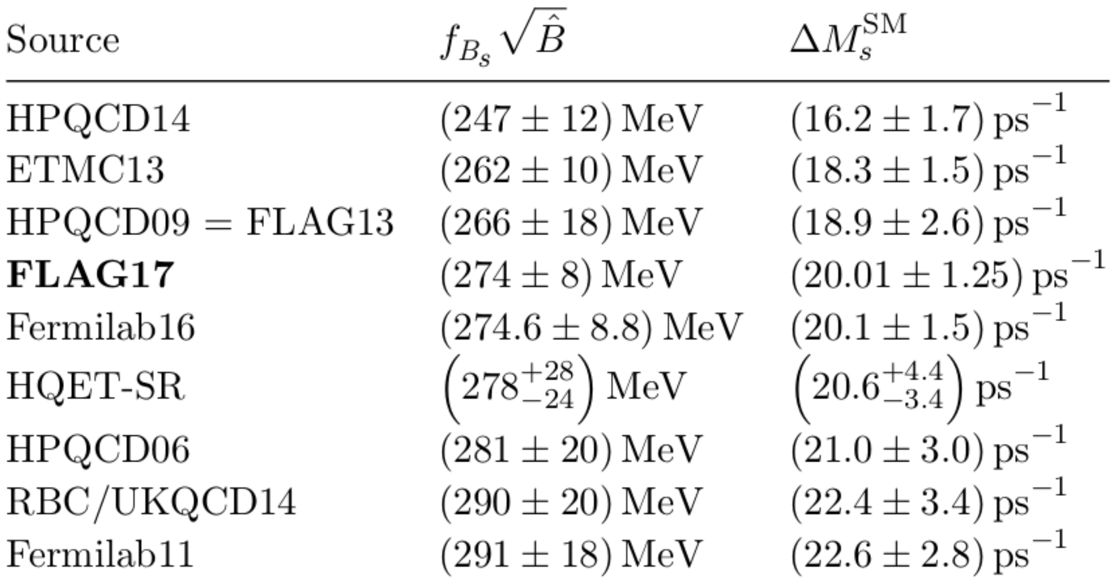
- Should we believe the new result for $f_B^2 B$?

- Range of different individual numbers
  - This is why we average
  - In this case, FLAG is the lattice averaging group



Source	$f_{B_s}\sqrt{\hat{B}}$	ΔM_s^{SM}
HPQCD14	(247 ± 12) MeV	$(16.2 \pm 1.7)\,\mathrm{ps}^{-1}$
ETMC13	(262 ± 10) MeV	$(18.3 \pm 1.5)\,\mathrm{ps}^{-1}$
HPQCD09 = FLAG13	(266 ± 18) MeV	$(18.9 \pm 2.6)\,\mathrm{ps}^{-1}$
FLAG17	(274 ± 8) MeV	$(20.01 \pm 1.25)\,\mathrm{ps}^{-1}$
Fermilab16	(274.6 ± 8.8) MeV	$(20.1 \pm 1.5)\,\mathrm{ps}^{-1}$
HQET-SR	$\left(278^{+28}_{-24}\right)$ MeV	$\left(20.6^{+4.4}_{-3.4}\right)\,\mathrm{ps}^{-1}$
HPQCD06	(281 ± 20) MeV	$(21.0 \pm 3.0)\,\mathrm{ps}^{-1}$
RBC/UKQCD14	(290 ± 20) MeV	$(22.4 \pm 3.4)\,\mathrm{ps}^{-1}$
Fermilab11	(291 ± 18) MeV	$(22.6 \pm 2.8)\,\mathrm{ps}^{-1}$

1712.06572

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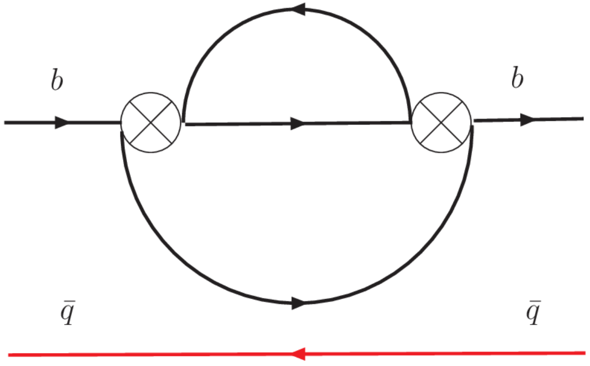
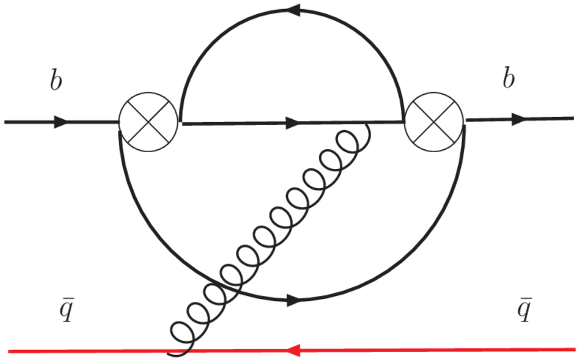
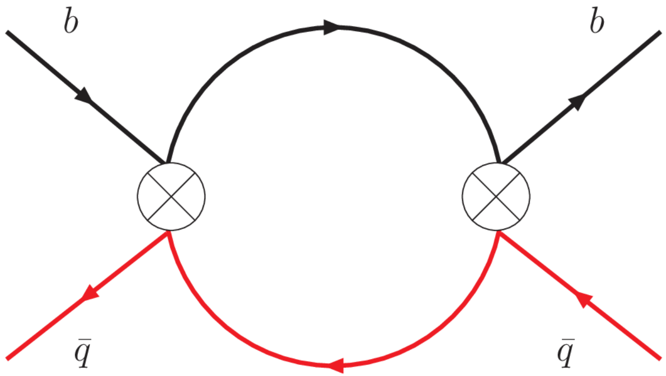
Meson lifetimes

Quick recap on lifetimes

- Use optical theorem to calculate
  - Imaginary parts of B → B processes



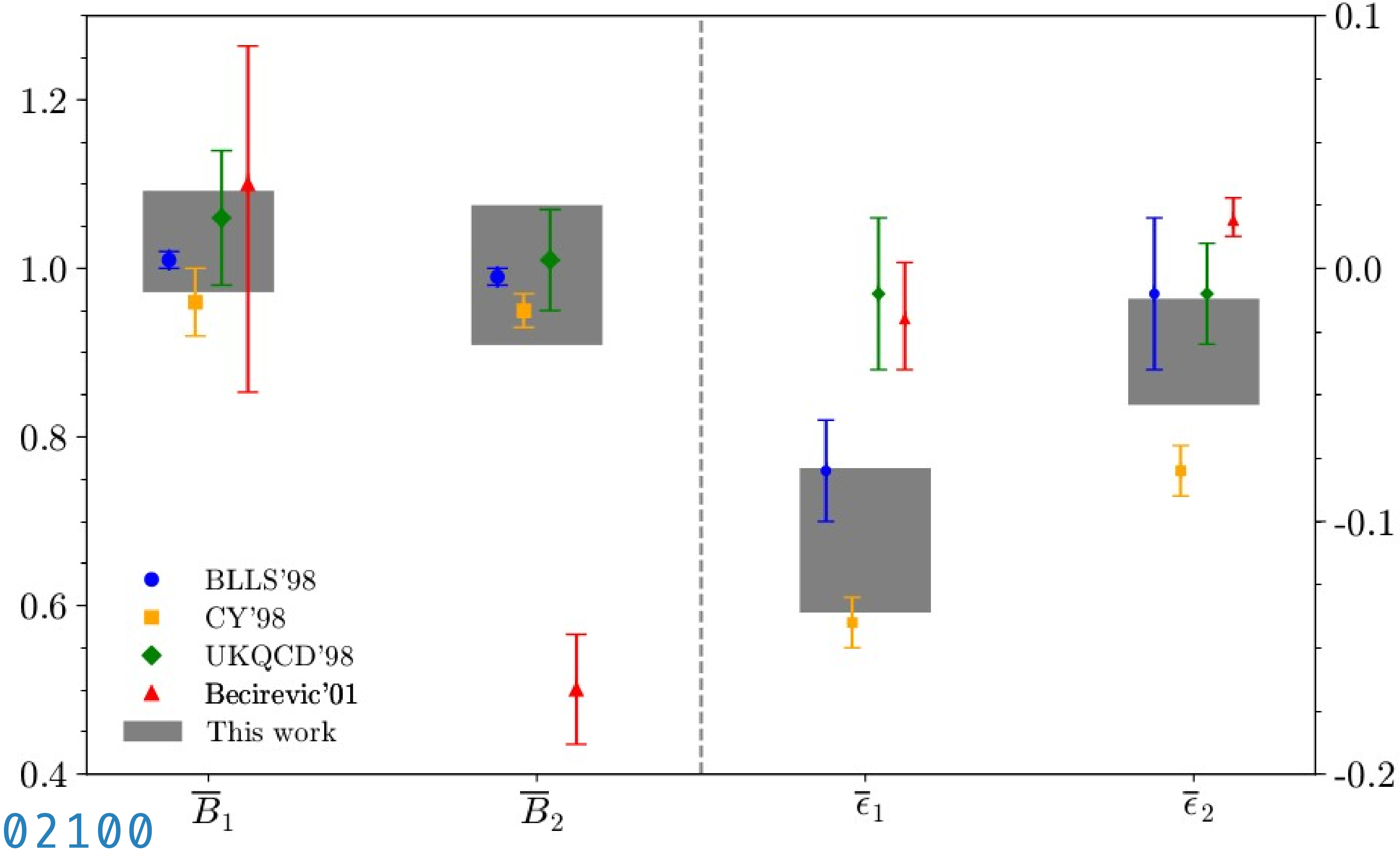




Theory status

- Like mixing, requires hadronic matrix elements to make predictions
- Less well studied by lattice community
- Most recent results from 2001 proceedings
- But recent sum rule calculation also

Sum rules for bag parameters



1711.02100

Theory status

- Taking a ratio cancels off various uncertain parameters
- Best theory prediction: $\frac{\tau(B_s)}{\tau(B_d)} = 1.0005 \pm 0.0011$

  1603.07770

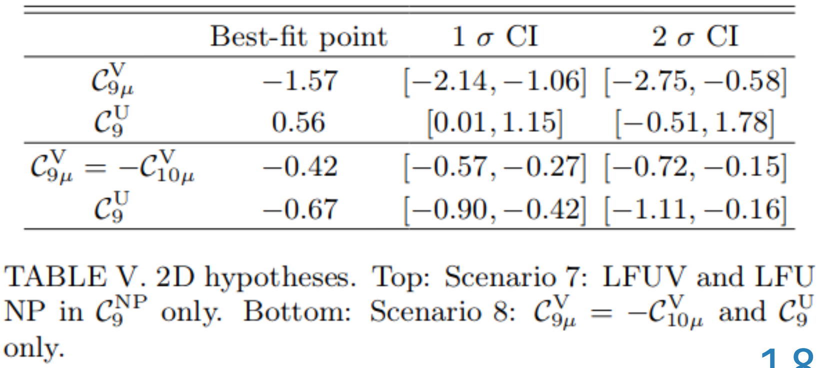
  (uncertainty of 0.1%!)

Lifetime ratio $\boldsymbol{\tau}(B_s)/\boldsymbol{\tau}(B_d)$

- What use is this for the flavour anomalies?
- Most obvious: $(\bar{s}\,b)(\bar{\ell}\,\ell)$ operator contributes to $B_s \to \ell\,\ell$ decay rate → alters lifetime ratio
- However supressed by $(m_\mu/m_b)^2 \simeq 10^{-4}$
- But what about more general NP?

Lifetime ratio $\tau(B_s)/\tau(B_d)$

- While LFUV NP is most interesting, seems likely (and fits also support) that there is also contribution that is LFU
  - See e.g. 1704.05446, 1809.08447



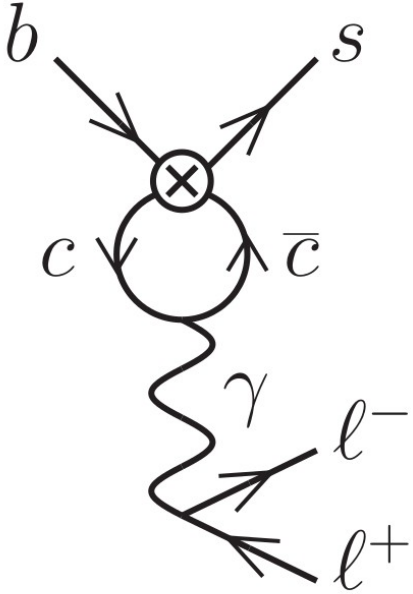
	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}^{\rm V}_{9\mu}$	-1.57	$[-2.14,-1.06]$	$[-2.75,-0.58]$
$\mathcal{C}^{\rm U}_{9}$	0.56	$[0.01,1.15]$	$[-0.51,1.78]$
$\mathcal{C}^{\rm V}_{9\mu}=-\mathcal{C}^{\rm V}_{10\mu}$	-0.42	$[-0.57,-0.27]$	$[-0.72,-0.15]$
$\mathcal{C}^{\rm U}_{9}$	-0.67	$[-0.90,-0.42]$	$[-1.11,-0.16]$

TABLE V. 2D hypotheses. Top: Scenario 7: LFUV and LFU NP in $\mathcal{C}^{\rm NP}_9$ only. Bottom: Scenario 8: $\mathcal{C}^{\rm V}_{9\mu}=-\mathcal{C}^{\rm V}_{10\mu}$ and $\mathcal{C}^{\rm U}_9$ only.

1809.08447

Lifetime ratio $\tau(B_s)/\tau(B_d)$

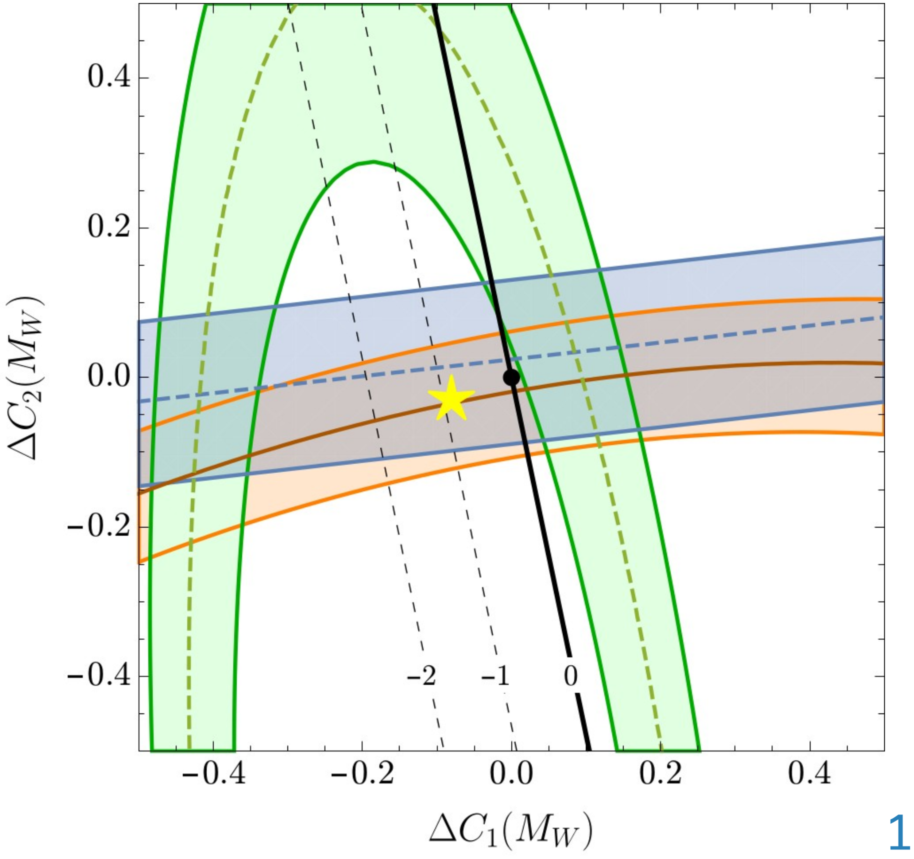
- In SM, about half of (LFU) contribution to C_9 comes from charm loops
- So what if NP appears in $(\bar{s}\,b)(\bar{c}\,c)$?
- Now lifetime contribution only suppressed by $(m_c/m_b)^2 \simeq 0.15$

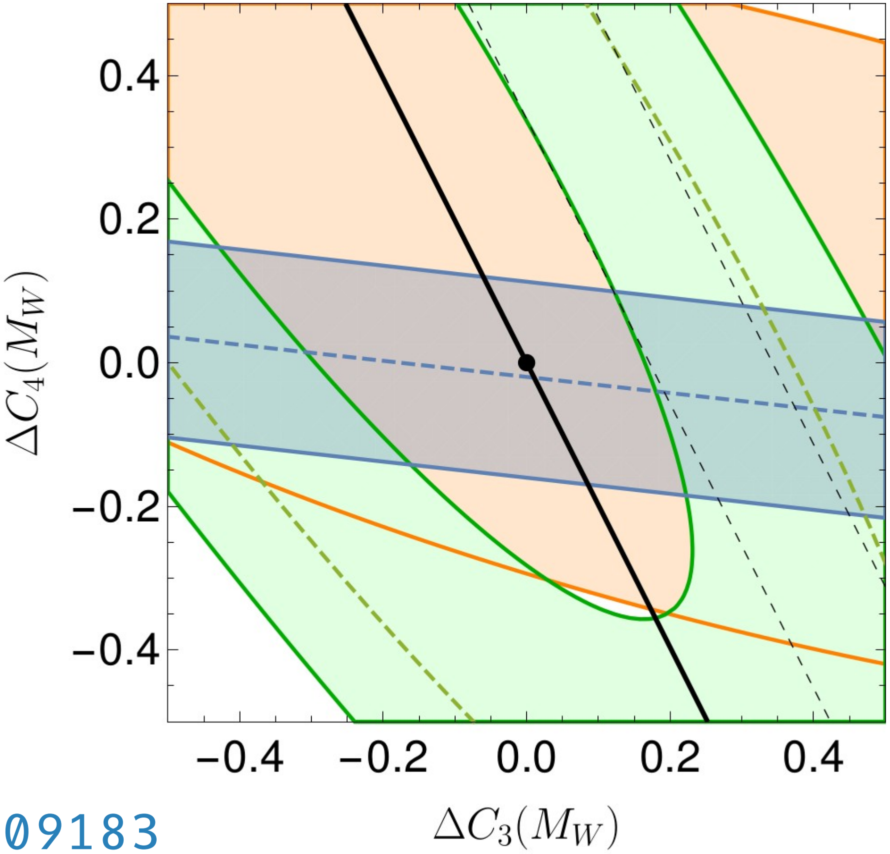


NP in $(\bar{s}\,b)(\bar{c}\,c)$

- Gives rise to correlated effects in several observables
  - Nice way to test, and allows to discriminate between various Dirac structures
- Study in `1701.09183` (+ upcoming $\lesssim$ 1 month)

NP in $(\bar{s}\,b)(\bar{c}\,c)$





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Future of flavour anomalies

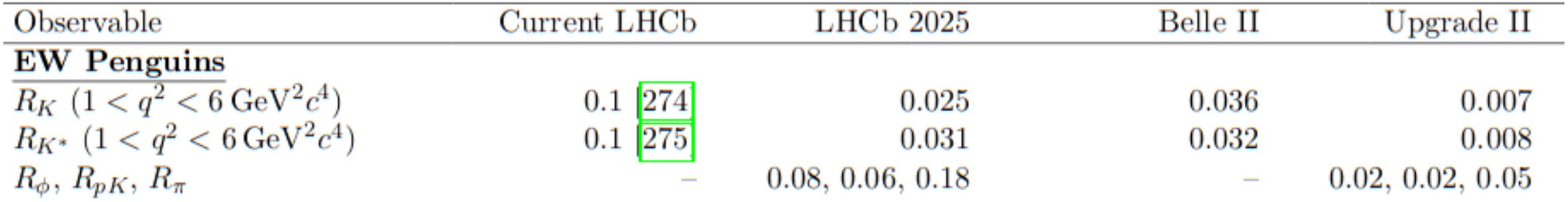
When will we know?

- Currently, no single measurement has a $5\,\sigma$ deviation from SM
  - i.e. no "discovery"
- When might we expect this to happen?
- (Disclaimer – not an experimentalist, numbers taken blindly from their talks)

LFUV – $R_{K^{(*)}}$

- Now: uncertainty on $R_{K^{(*)}}$ ~ 12% (run 1 data)
- In progress, update to R_K with run 2 data
  - If central value remains the same, 7% uncertainty
- LHCb 2025: Uncertainty 3-4%
  - If same central value → $10\,\sigma$ deviation
- Belle II should be able to confirm

LFUV – $R_{K^{(*)}}$



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05

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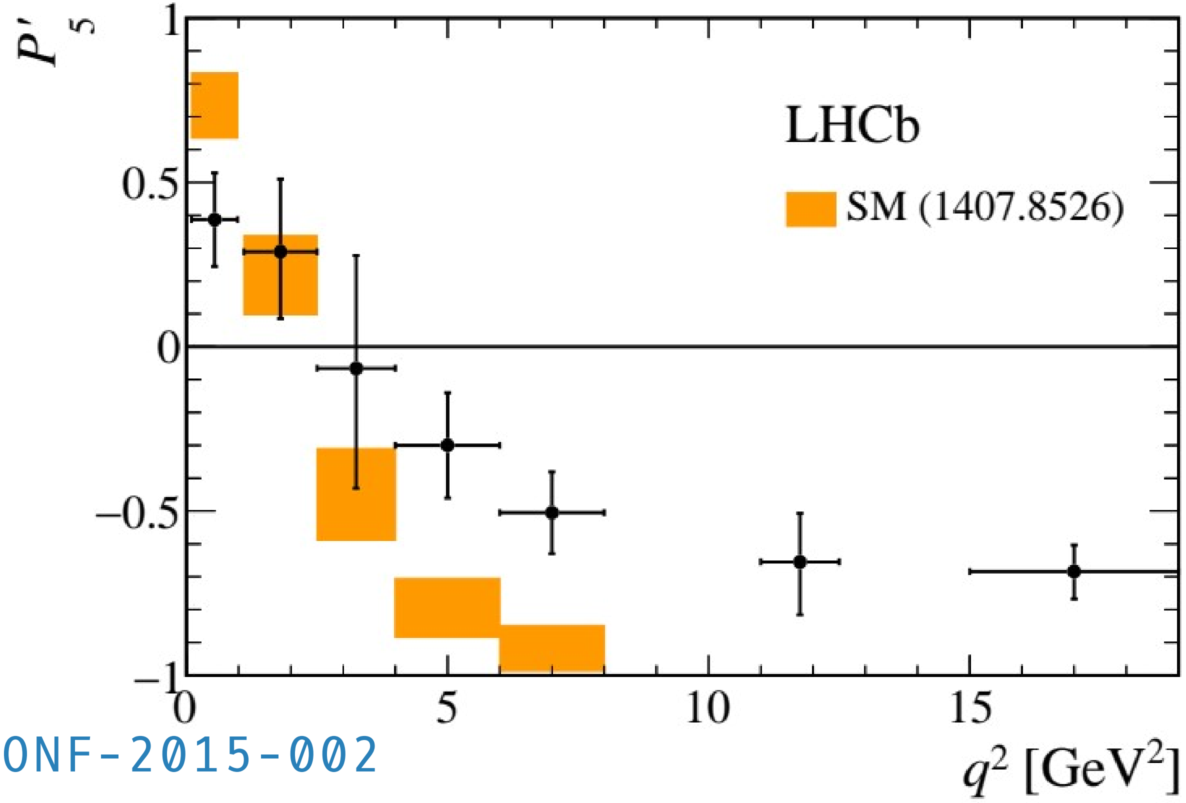
Angular observables - $P_5^{'}$



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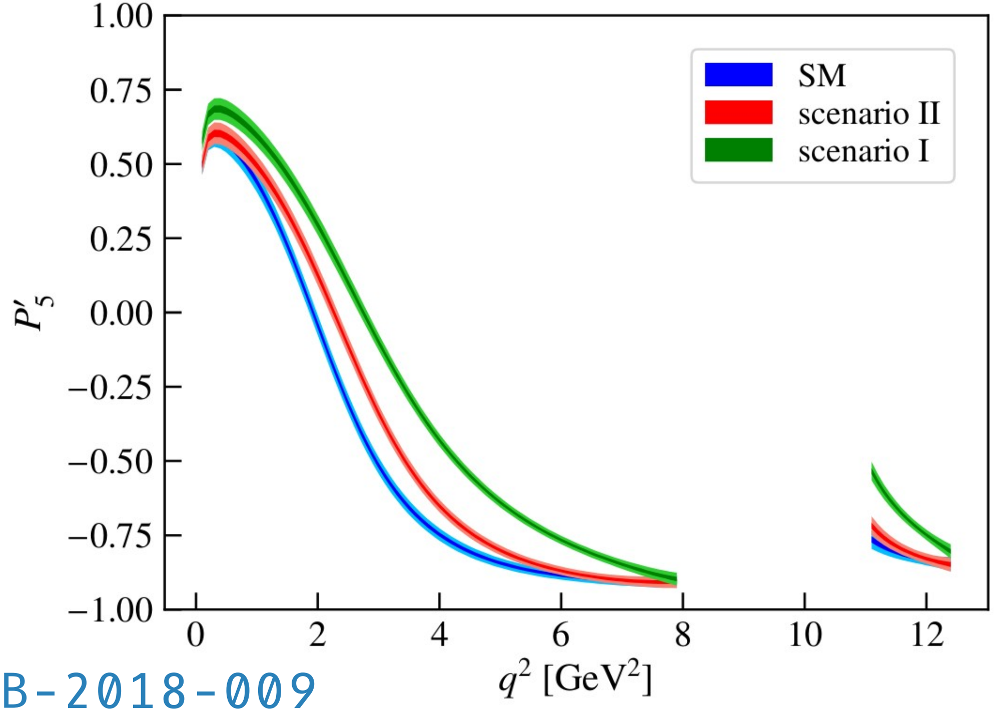
Angular observables - $P_5^{'}$

- By ~2035 (LHCb upgrade 2), can use $P_5^{'}$ to easily distinguish between various NP scenarios.

Angular observables - $P_5^{'}$

- Red is $C_9^\mu = -C_{10}^\mu = -0.7$
- Green is $C_9^\mu = -1.4$
- Blue is SM
- 3σ contours



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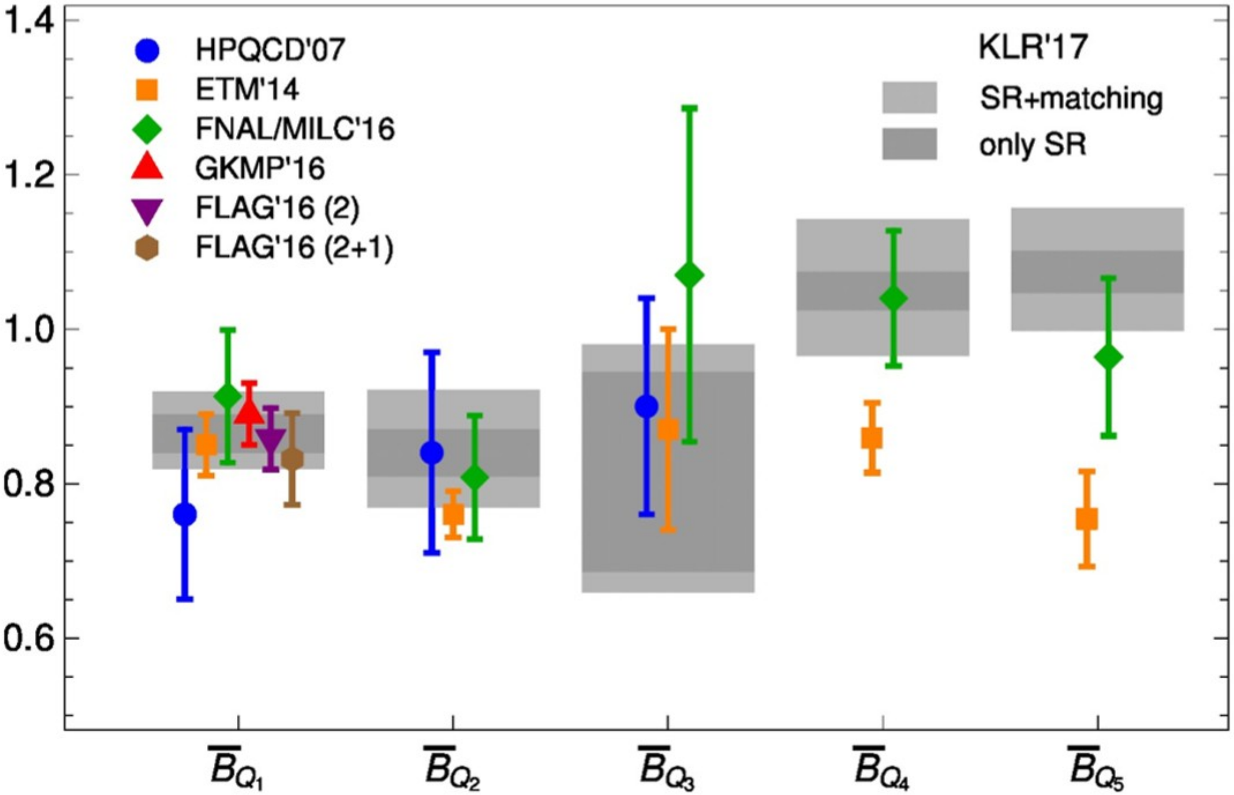
Summary

- Flavour anomalies possibly most exciting signs of NP at the moment
  - Unexpected area: LFUV
- Meson mixing very important in constraining BSM models
  - Lattice results the key
- But soon we will know for sure
  - Then a variety of other flavour observables (e.g. lifetimes) will play their part

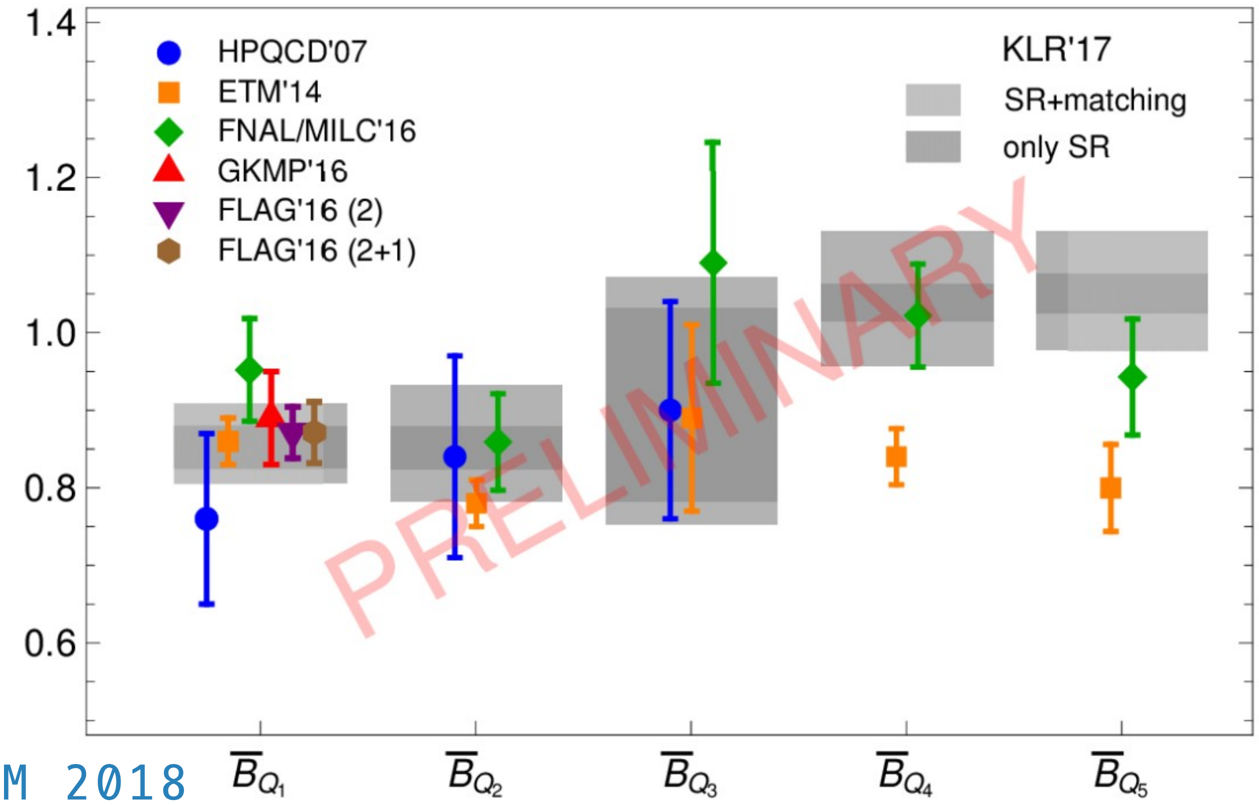
Backup

Sum rules



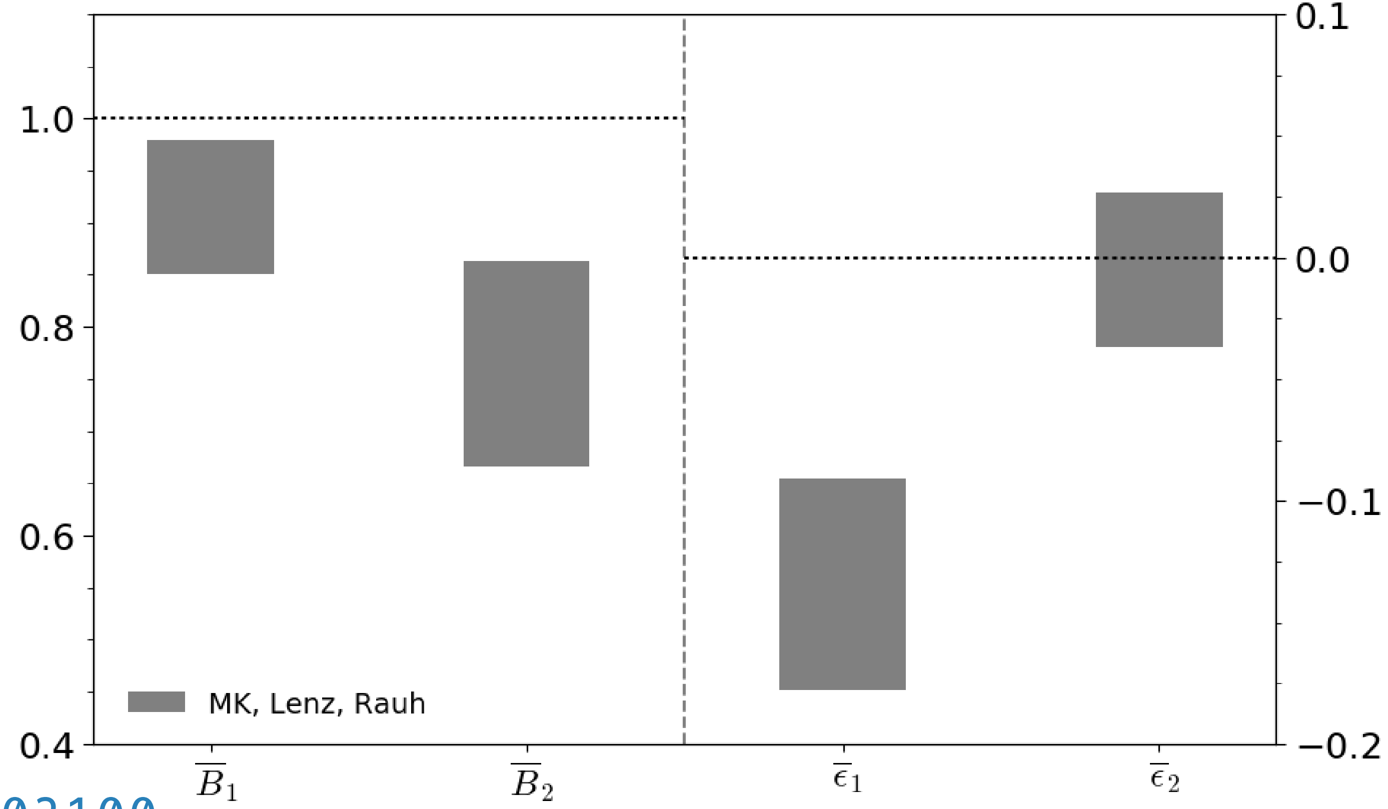
1711.02100

Sum rules



Rauh, CKM 2018

Sum rules

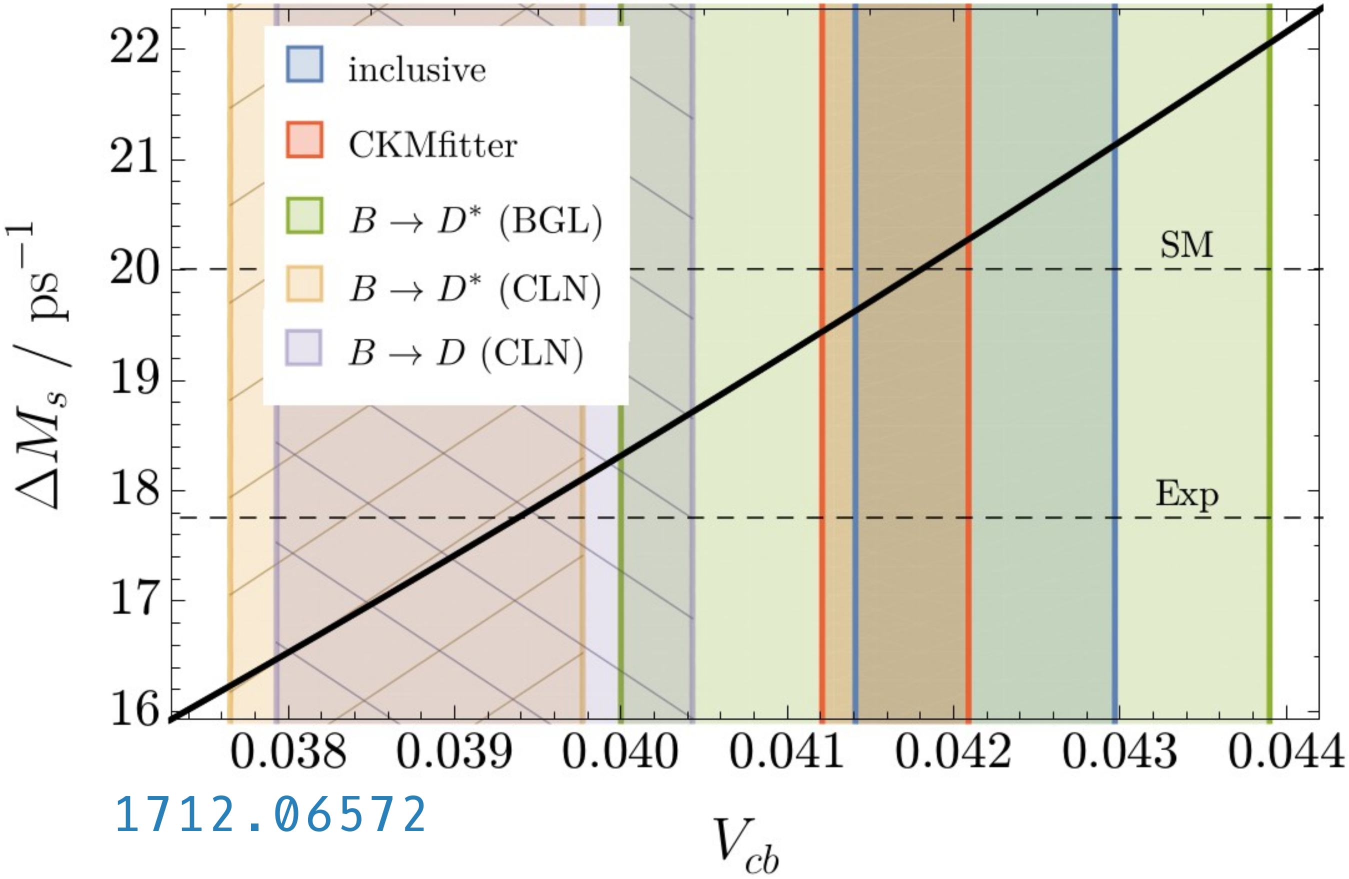


1711.02100

FLAG discrepancy

- FLAG 2017 average: $f_{B_s}\sqrt{\hat{B}} = 274 \pm 8\,\mathrm{MeV}$
- But they also give
  - $f_{B_s} = 228.4 \pm 3.7\,\mathrm{MeV}$
  - $\hat{B} = 1.35 \pm 0.06$
- Naive combination: $f_{B_s}\sqrt{\hat{B}} = 265 \pm 7\,\mathrm{MeV}$

V_{cb} dependence



1712.06572