Anomalies vs Mixing and CPV

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Beyond the Flavour Anomalies – 2 Apr 2020
(based on 1909.11087 with L. Di Luzio, A. Lenz, T. Rauh)

Flavour anomalies

- Lots of signs:
  - R_K, R_{K^*}
  - P_5'
  - ...

Flavour anomalies

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  - R_K, R_{K^*}
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BEYOND

Why talk about mixing?

- Anomalies require coupling to $(\bar{s}b)(\bar{\mu}\mu)$
- Therefore some quark flavour changing coupling
- Meson mixing is a great probe of quark flavour changing effects

Why talk about mixing?

- Why though?
- Several reasons:
- In the SM, B_s mixing is:
  - Loop supressed (No FCNC in the SM at tree level)
  - GIM supressed ($m_u \approx m_c \approx 0$ – relative to m_t)

Why talk about mixing?

- In the SM, B_s mixing is:
  - Loop supressed (No FCNC in the SM at tree)
  - GIM supressed ($m_u \approx m_c \approx 0$, relative to m_t)
- So plenty of ways for NP to show up competitively with the SM

Precision precision precision

- No use looking for NP if you can't say how big the SM background is
- For a long time, mixing plagued by low precision from hadronic matrix elements

Precision precision precision

- $\Delta M_s^{\rm SM}$:
  - 2006: $(19.3 \pm 6.7)\,{\rm ps}^{-1}$ (35% unc)
  - 2011: $(17.3 \pm 2.4)\,{\rm ps}^{-1}$ (14% unc)
  - 2015: $(18.3 \pm 2.7)\,{\rm ps}^{-1}$ (15% unc) (V_{cb} problems)

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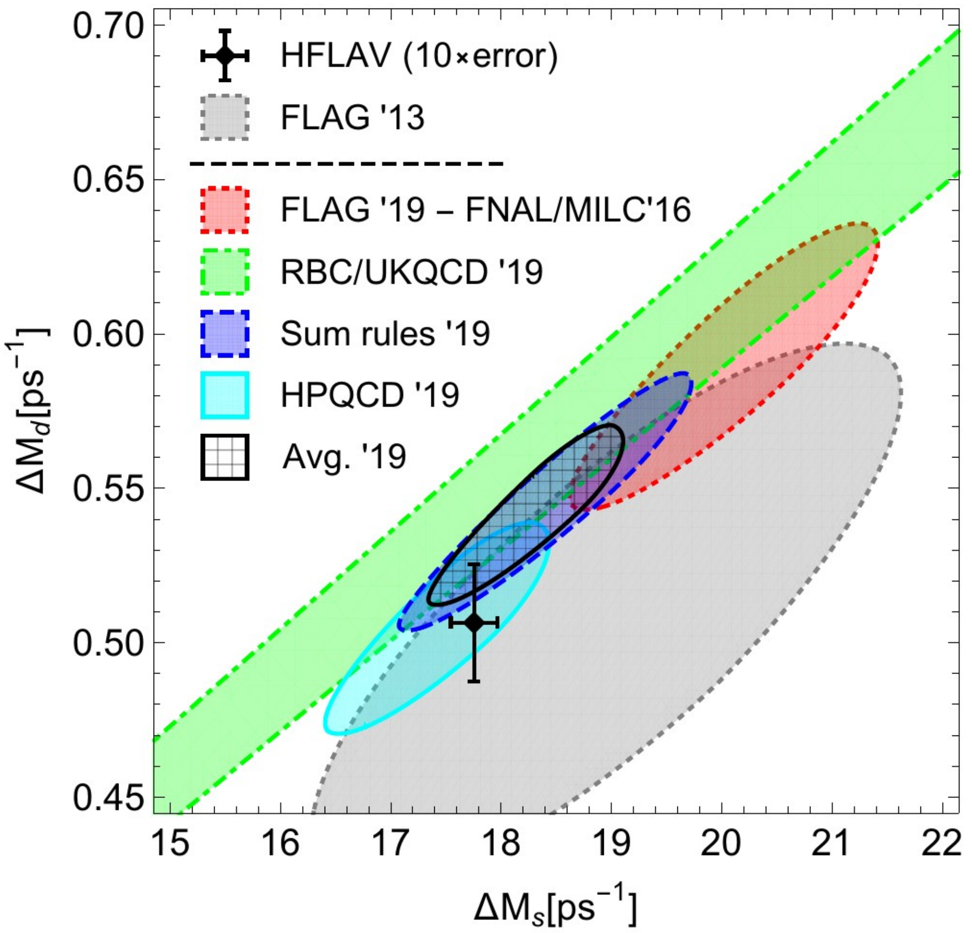
  - 2015: $(18.3 \pm 2.7)\,\mathrm{ps}^{-1}$ (15% unc) (V_{cb} problems)
  - 2019: $\left(18.4^{+0.7}_{-1.2}\right)\,\mathrm{ps}^{-1}$ (4-6% unc) (again, V_{cb})
  - 2025?: $(? \pm 0.5)\,\mathrm{ps}^{-1}$ (<3% unc)

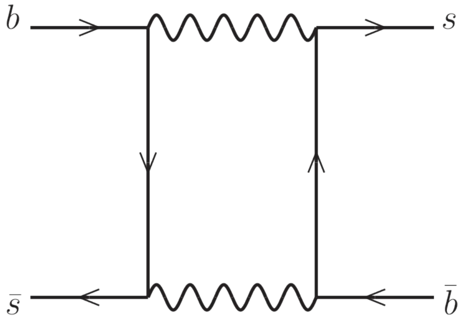
Precision precision precision

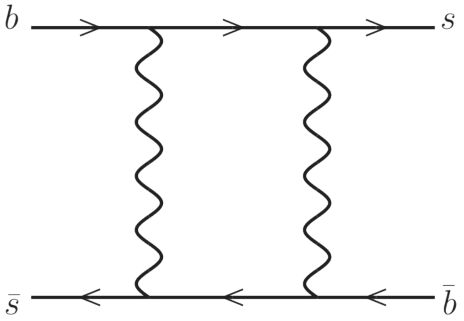


What happened?

- Quick introduction to mixing

Overview of ΔM_s





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

Overview of ΔM_s

- $\Delta M_s = M_{B_H} - M_{B_L}$
- Calculated as $\Delta M_s = 2|M_{12}|$
- $M_{12} = \frac{G_F^2}{16\pi^2} \lambda_t^2 M_W^2 S_0(x_t) \hat{\eta}_B \frac{\langle \bar{B}_s | Q_1 | B_s \rangle}{2M_{B_s}}$

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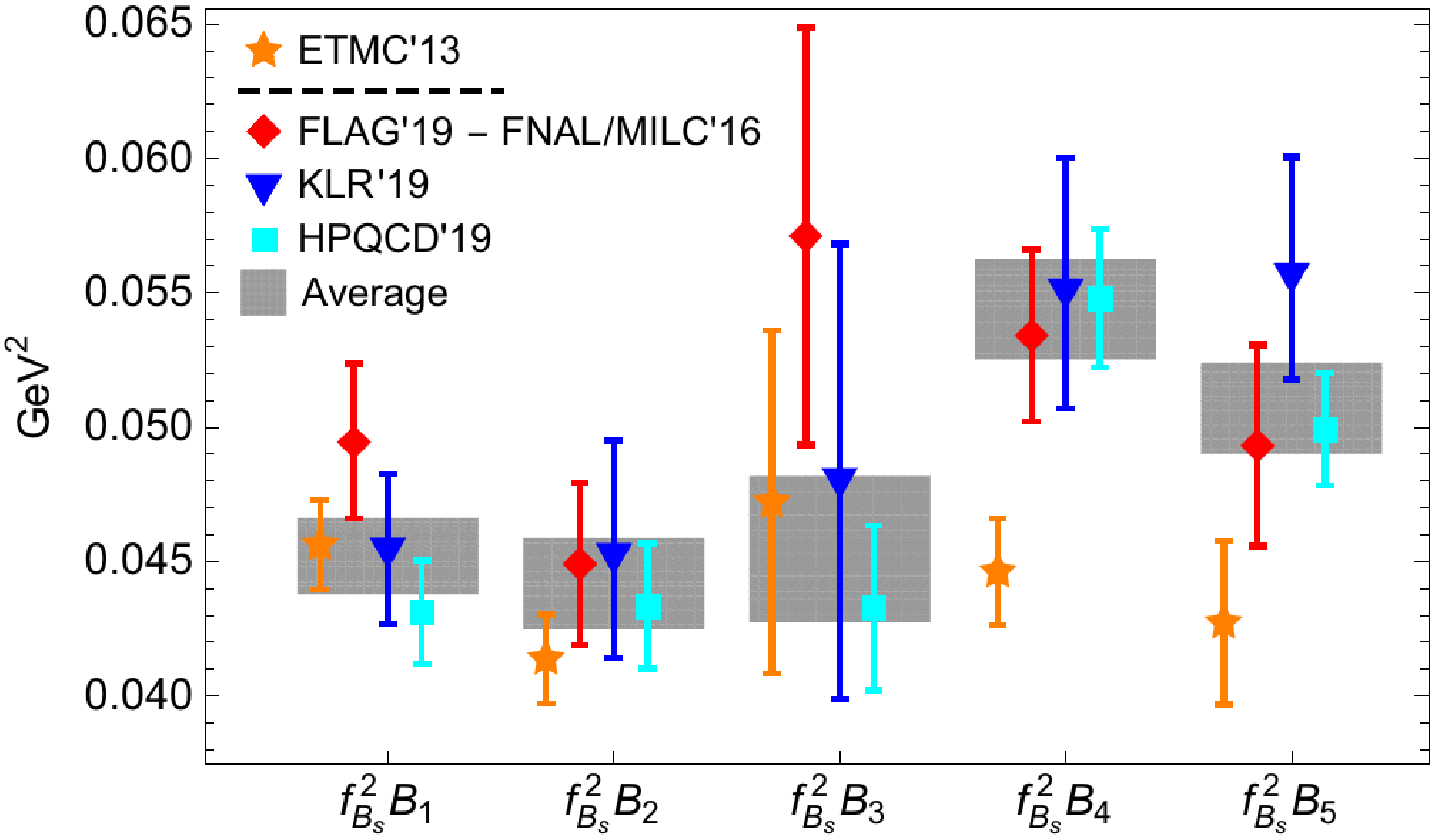
- The matrix element $\langle \bar{B}_s | Q_1 | B_s \rangle$ is generally parameterised as $f_{B_s}^2 B_1$, and this is the largest uncertainty.

What happened?

- New lattice QCD results 1602.03560, 1907.01025
- New HQET sum rules results 1606.06054, 1711.02100, 1904.00940

What happened?



Relating mixing to the anomalies

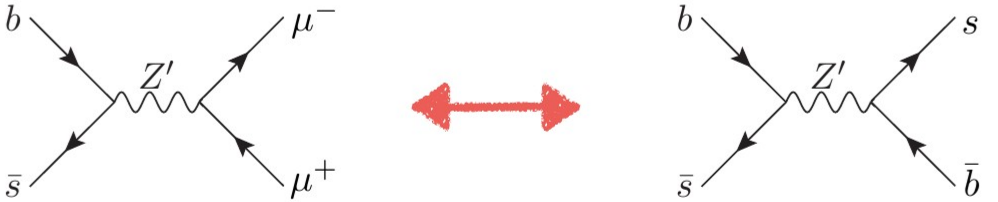
- EFT for mixing:
  - Four quark operators
  - $(\bar{s}\Gamma b)(\bar{s}\Gamma' b)$
- EFT for anomalies:
  - Two quark two lepton operators
  - $(\bar{s}\Gamma b)(\bar{\ell}\Gamma' \ell)$

Relating mixing to the anomalies

- In general, these are unrelated
- So we have to look at more specific models

Relating mixing to the anomalies

- Z' gives tree contribution to both



- LQs give tree for anomalies, loop for mixing

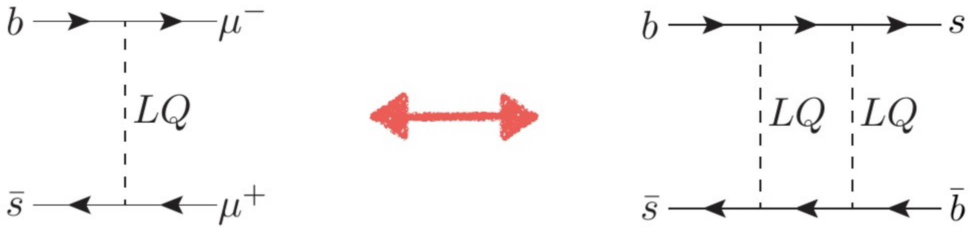
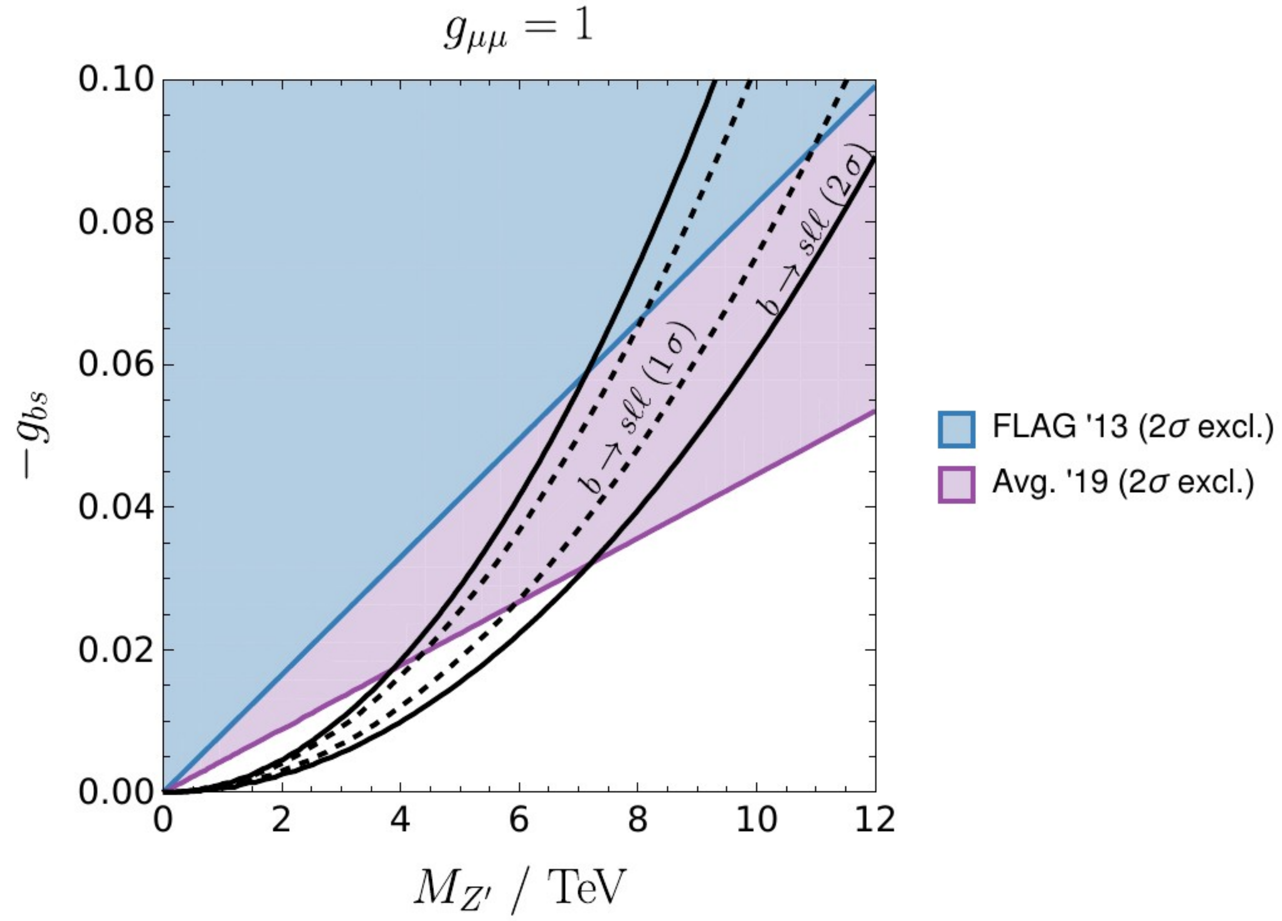


Image: Luca Di Luzio, CKM 2018

Z'

- With a Z' :
  - $C_9 \sim g_{bs} g_{\mu\mu} / M_{Z'}^2$
  - $\Delta M_s \sim g_{bs}^2 / M_{Z'}^2$
- Different dependence on the $\bar{s}b$ coupling gives nice interplay
- Means mixing imposes an upper bound

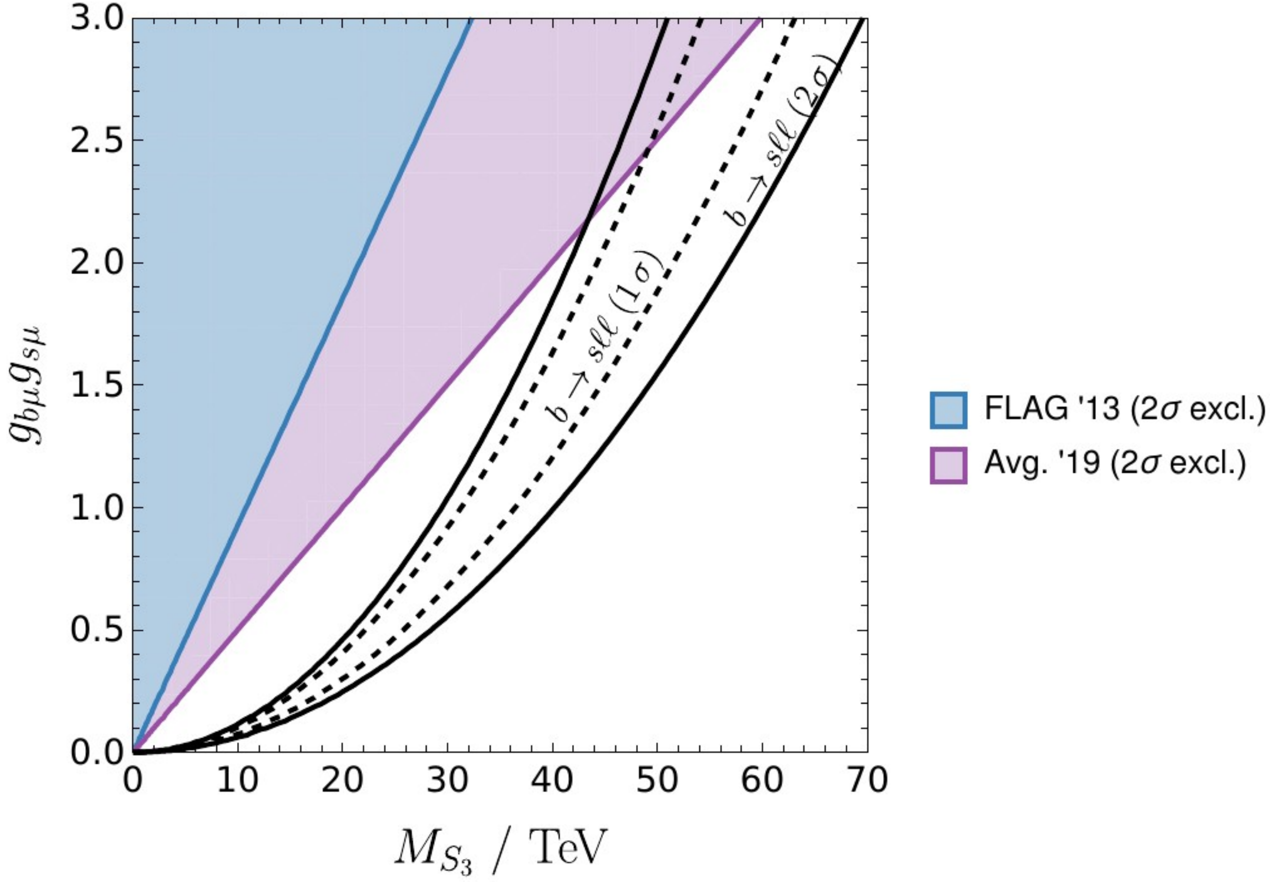
Z'


$g_{\mu\mu} = 1$
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
$-g_{bs}$
$M_{Z'}$ / TeV
$b \to s\ell\ell$ (1σ)
$b \to s\ell\ell$ (2σ)
FLAG '13 (2σ excl.)
Avg. '19 (2σ excl.)

LQ

- With a LQ:
  - $C_9 \sim g_{b\mu} g_{s\mu} / M_{LQ}^2$
  - $\Delta M_s \sim (\Sigma g_{b\ell} g_{s\ell})^2 / M_{LQ}^2$
- Different dependence on the coupling gives nice interplay (subject to assumptions on $g_{b\ell}$)
- Means mixing imposes an upper bound

LQ



3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
$g_{b\mu} g_{s\mu}$
M_{S_3} / TeV
$b \to s\ell\ell$ (1σ)
$b \to s\ell\ell$ (2σ)
FLAG '13 (2σ excl.)
Avg. '19 (2σ excl.)

What about CPV BSM?

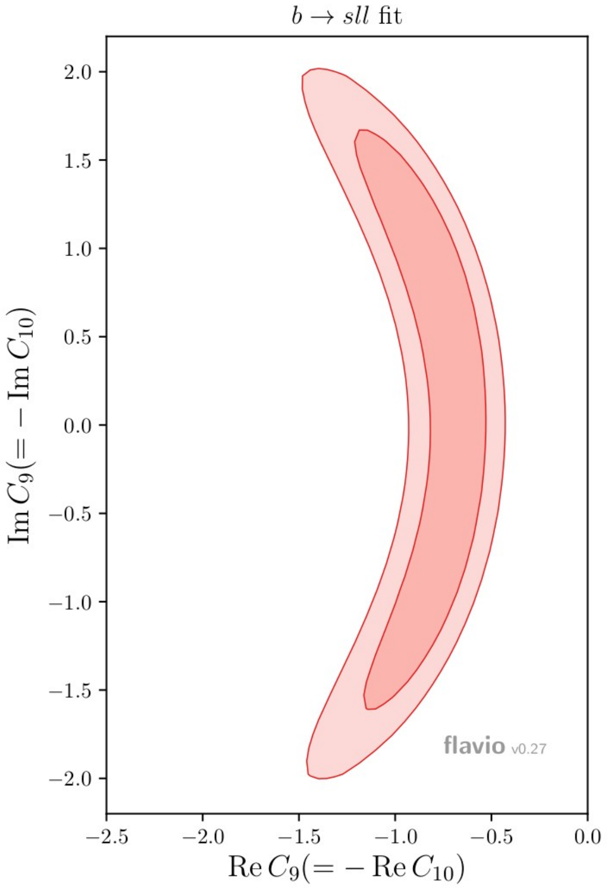
- So far have assumed real BSM giving the anomalies
- Do the anomalies allow new phases to contribute?

What about CPV BSM?

- Leading contribution to anomalies involves interference with SM
- So real BSM
- Imaginary BSM doesn't contribute until next order => poorly constrained

What about CPV BSM?

- (Note – old fit from ~ summer 2018 but conclusion stands)



Mixing constraints

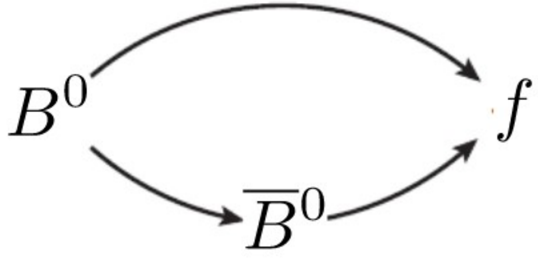
- Mixing can constrain the new phases
- Many CPV observables from mixing
- CPV in mixing – weak phase $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$
- CPV in interference – $B_s \to f$ vs $B_s \to \bar{B}_s \to f$

$a_{\rm sl}^s$

- Weak phase ϕ_{12} observable directly in $a_{\rm sl}^s$
- $a_{\rm sl}^s = |\Gamma_{12}/M_{12}| \sin\phi_{12} = (\Delta\Gamma_s/\Delta M_s)\tan\phi_{12}$
- But hard to measure
- Exp = $(-60 \pm 280) \times 10^{-5}$ HFLAV 2018
- While SM = $(2.06 \pm 0.18) \times 10^{-5}$ 1912.07621

A_{CP}^{mix}

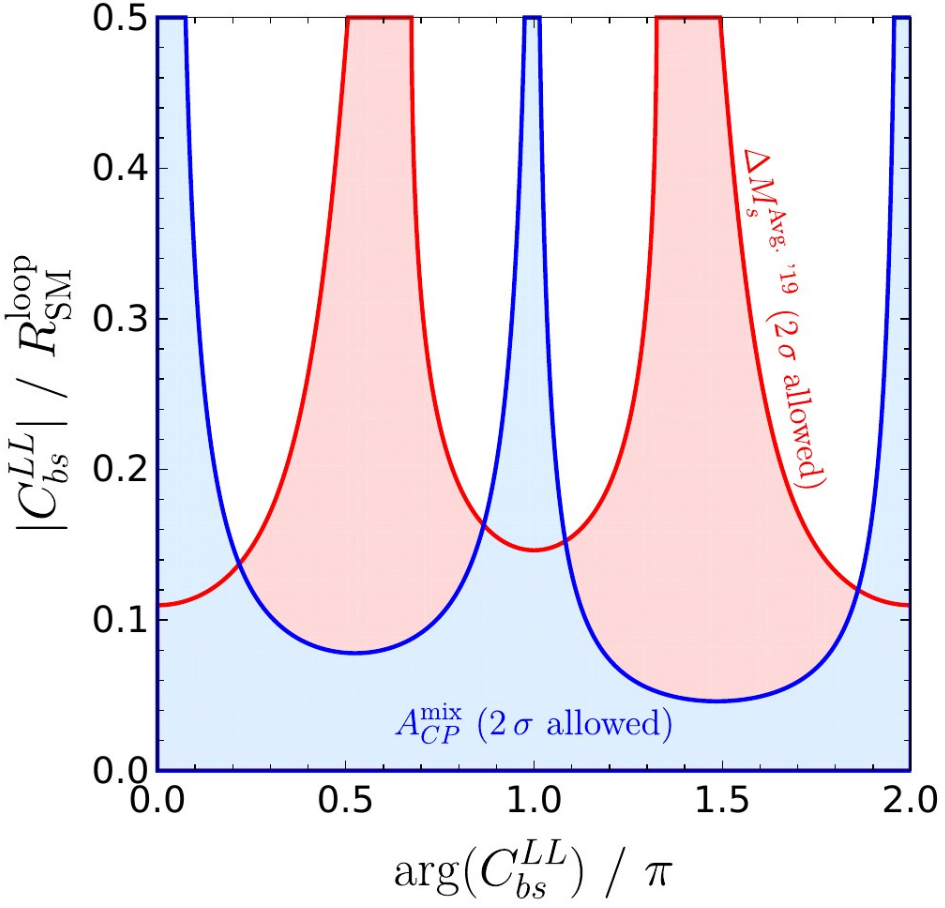
- Interference in decay where both B_s and $\bar{B}_s$ can contribute
- In SM, $B_s \to J/\psi\phi$ gives $\sin 2\beta_s$



A_{CP}^{mix}

- Better than a_{sl}^{s} as is more well measured
  - Exp = 0.021 ± 0.031 HFLAV 2018
- And from theory, known by fitting β_s from other CKM inputs
- Despite large exp error, still pretty constraining

$A_{CP}^{\rm mix}$

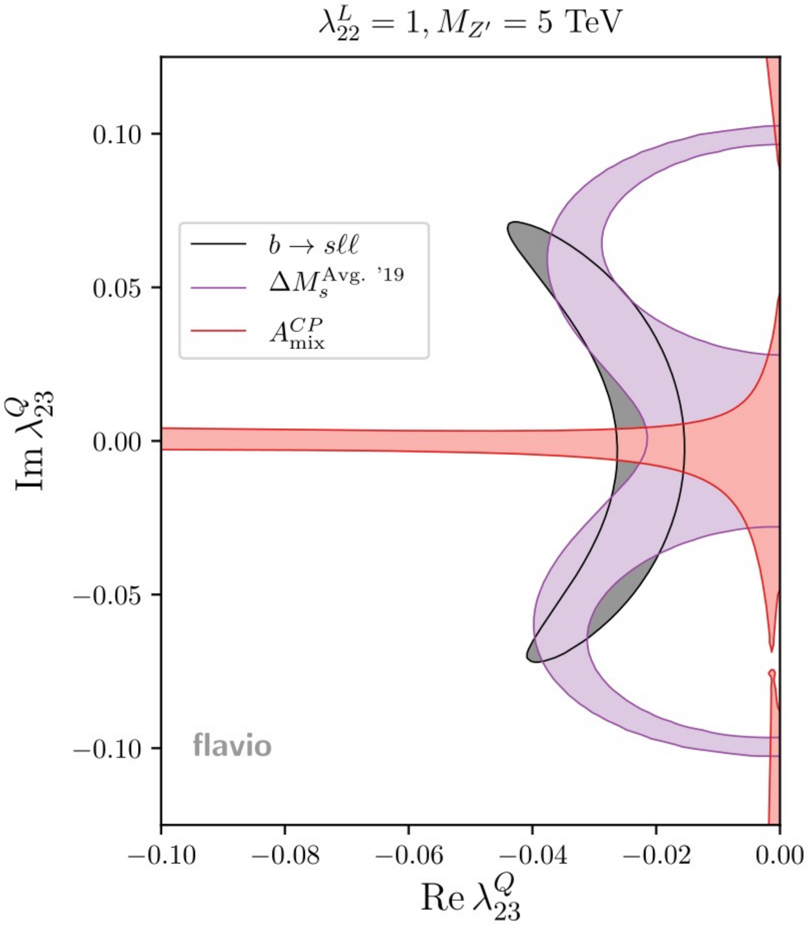


0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
$|C_{bs}^{LL}|$ / $R_{\rm SM}^{\rm loop}$
$\arg(C_{bs}^{LL})$ / π
$\Delta M_s^{\rm Avg.\ '19}$ ($2\,\sigma$ allowed)
$A_{CP}^{\rm mix}$ ($2\,\sigma$ allowed)

Opening the Z' parameter space

- Does adding a new CPV phase weaken the upper bound from mixing?
- Look at more specific point
  - $M_{Z'} = 5\,\mathrm{TeV}, \lambda_{\mu\mu} = 1$
  - Central value of $R_{K^{(*)}}$ gives $\approx 1.5\,\sigma$ tension with ΔM_s

Opening the Z' parameter space



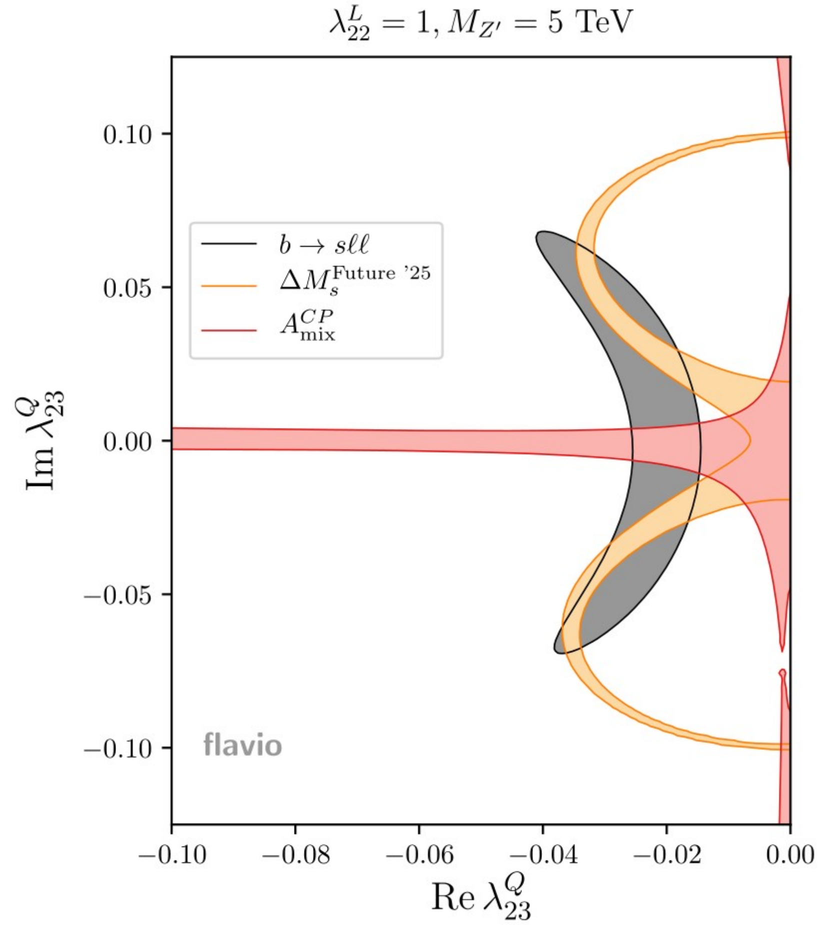
Future precision

- Assuming future increased precision on V_{cb} and $f_B^2 B$
- 1% on V_{cb} from Belle II and LHCb
- 2% on $f_B^2 B$ from lattice and sum rules results
- Get ΔM_s error of $\pm 0.5 \mathrm{ps}^{-1}$

Opening the Z' parameter space

- Look at more specific point
  - $M_{Z'} = 5\,\mathrm{TeV}, \lambda_{\mu\mu} = 1$
  - Central value of $R_{K^{(*)}}$ gives $\approx 4\,\sigma$ tension with ΔM_s

Opening the Z' parameter space



LFU contribution

- Can fit the data with a mix of LFUV and LFU
- $C_L^\mu \approx C_9^{\text{univ}} \approx -0.5$

1704.05446, 1809.08447, 1903.09578

- Large LFU easy to generate through charm loops – exactly as in the SM

1701.09183, 1910.12924

- $C_9^{\text{SM, charm loop}} \approx 0.5 C_9^{\text{SM}}$

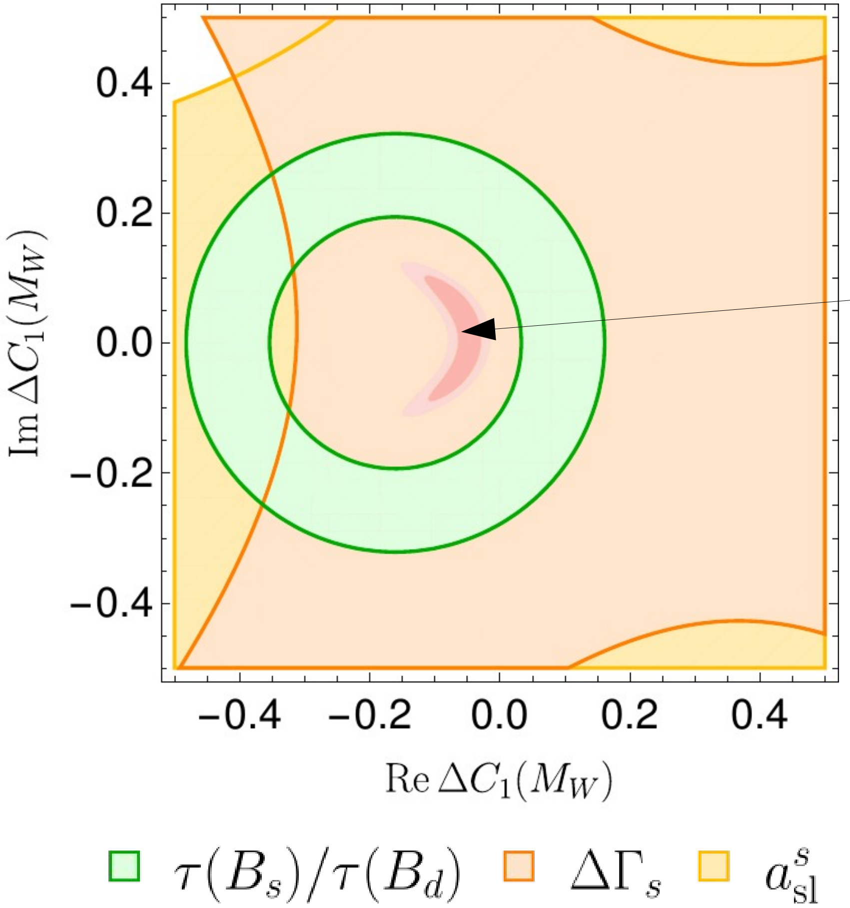
LFU contribution from $(\bar{s}b)(\bar{c}c)$

- With a $(\bar{s}b)(\bar{c}c)$ BSM operator, also get large contribution to $\Delta\Gamma_s$

1701.09183, 1910.12924

- Quick idea: Z′ with $(\bar{s}b)$ and $(\bar{c}c)$
- Possible complex phases

LFU contribution from $(\bar{s}b)(\bar{c}c)$



This C9 region I added by hand – a **very** rough estimate

1701.09183, 1910.12924

Summary

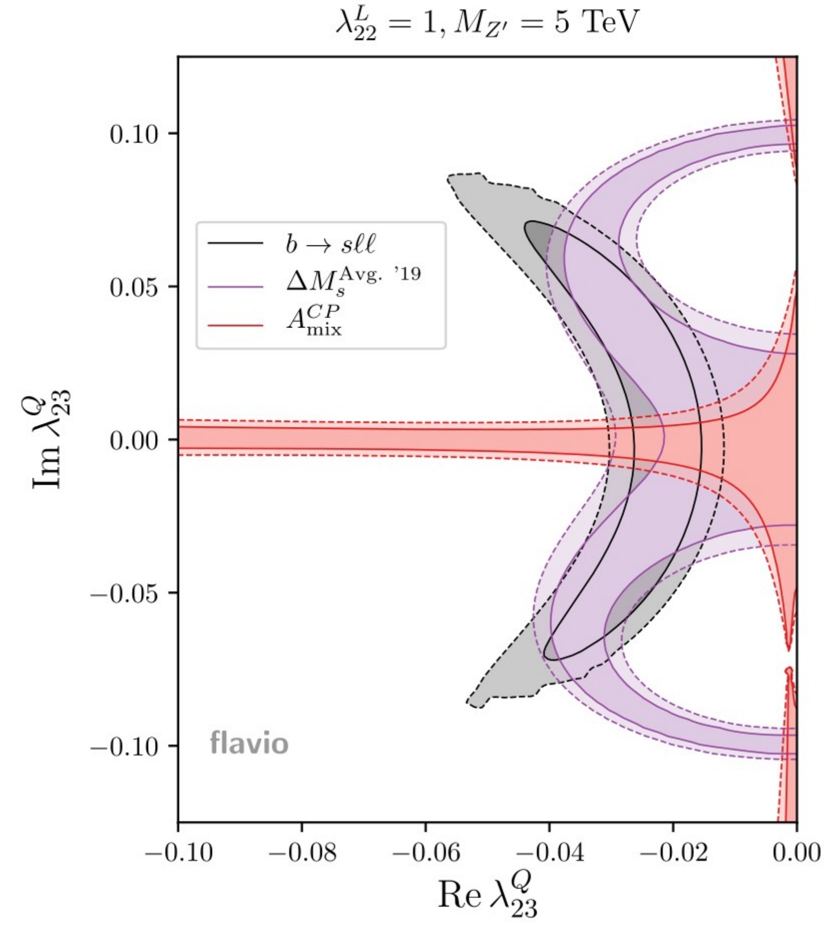
- New determinations of B_s mixing matrix elements bring us towards precision era of mixing
- CP violating couplings don't loosen the bounds
- By 2025 precision will be even better

Discussion points

- What are the current/future values/uncertainties of B mixing matrix elements?
- Are there hidden assumptions in the determination of β_s?
- Is there a LFU effect in C9 – which could be generated by 4 quark operators?

Backup slides

Opening the Z' parameter space



Opening the Z' parameter space