Constraints on new physics from the latest results in meson mixing

Matthew Kirk
(based on work with L. Di Luzio, A. Lenz)

Durham University

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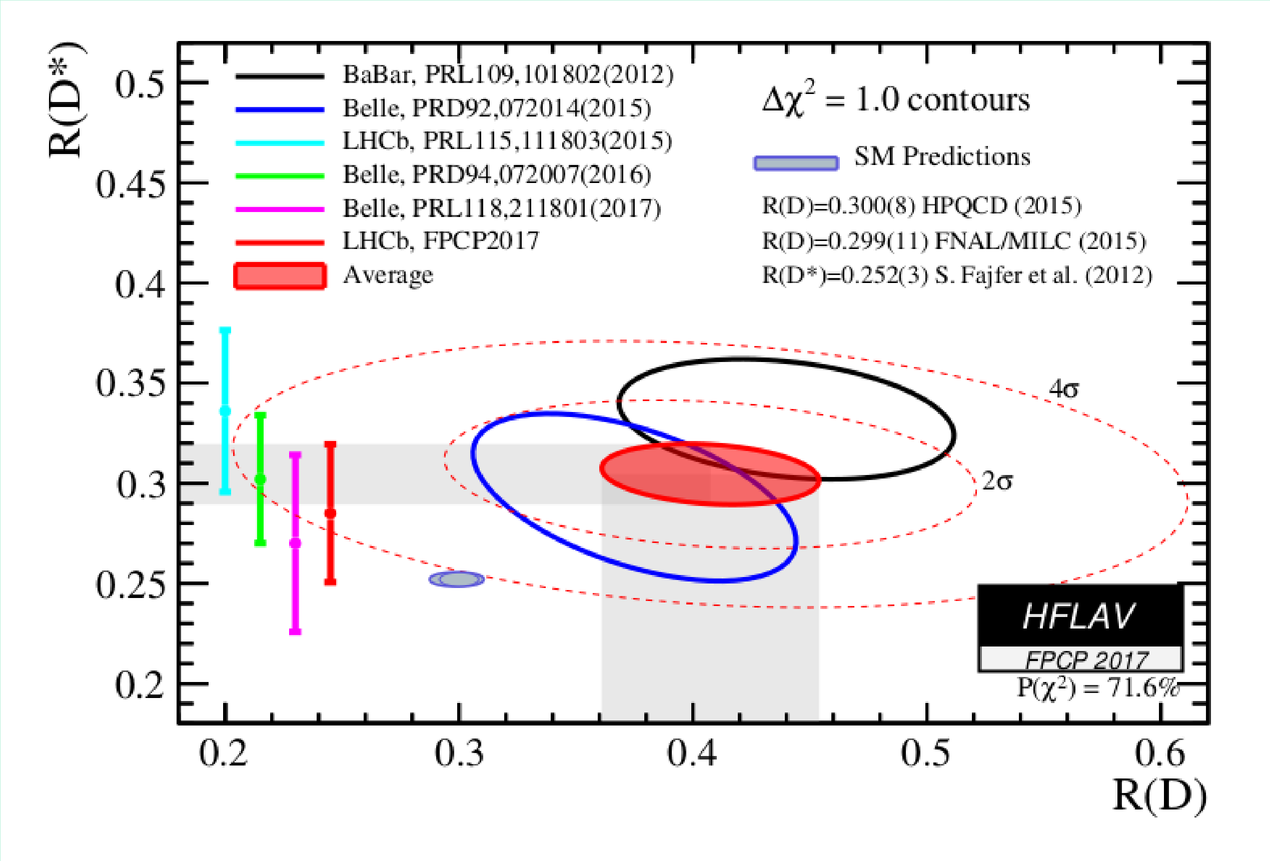
What anomalies have we got?

- Lepton flavour universality violation
  - $R_K, R_{K*} : b \to s l l$
  - $R_D, R_{D*} : b \to c l \nu$
- Angular observables
  - $P_5^{'} : \frac{d^4\Gamma}{dq^2 \, d\cos\theta_l \, d\cos\theta_K \, d\phi}$
- Branching ratios
  - $B^- \to K^- \mu\mu, B^0 \to K^0 \mu\mu, B_s \to \phi\mu\mu$

R_D, R_{D*}



R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ²) = 71.6%
0.2
0.3
0.4
0.5
0.6
R(D)

R_K, R_{K*}

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

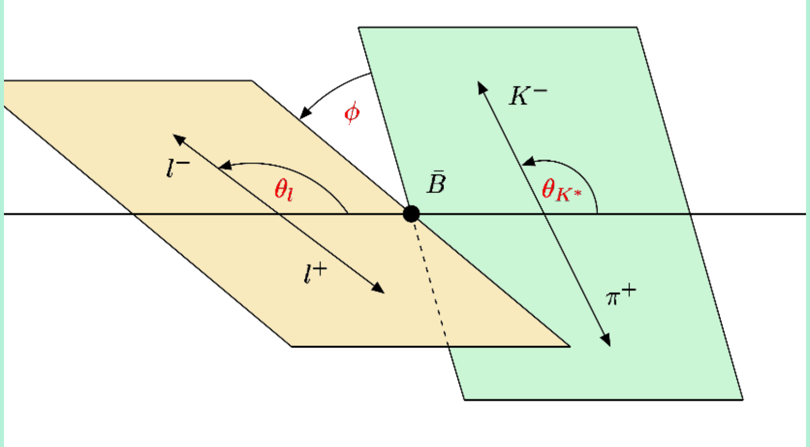
Observable	SM prediction		Measurement	
$R_K : q^2 = [1, 6]\,\mathrm{GeV}^2$	1.00 ± 0.01	[1, 2]	$0.745^{+0.090}_{-0.074} \pm 0.036$	[3]
$R_{K^*}^{\mathrm{low}} : q^2 = [0.045, 1.1]\,\mathrm{GeV}^2$	0.92 ± 0.02	[4]	$0.660^{+0.110}_{-0.070} \pm 0.024$	[5]
$R_{K^*}^{\mathrm{central}} : q^2 = [1.1, 6]\,\mathrm{GeV}^2$	1.00 ± 0.01	[1, 2]	$0.685^{+0.113}_{-0.069} \pm 0.047$	[5]

1704.06240

$P_5^{'}$

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

$$
P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}
$$



$b \to s\mu\mu$

- Do global fits to relevant processes

New physics in the muon sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	all
$C^{\rm BSM}_{b_L\mu_L}$	-1.33	-1.33	-1.33	-0.99 -1.70	-1.01 -1.68	-1.10 -1.58	4.1	4.6	6.2
$C^{\rm BSM}_{b_L\mu_R}$	0.68	-0.73	-0.35	1.27 0.10	-0.40 -1.03	-0.03 -0.65	1.2	2.1	1.1
$C^{\rm BSM}_{b_R\mu_L}$	0.03	-0.20	-0.15	0.32 -0.26	-0.04 -0.29	-0.01 -0.25	0.1	1.3	1.1
$C^{\rm BSM}_{b_R\mu_R}$	-0.44	0.41	0.29	0.14 -1.00	0.61 0.18	0.50 0.07	0.8	1.7	1.3

New physics in the electron sector									
Wilson coeff.	Best-fit			1-σ range			$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$		
	'clean'	'dirty'	all	'clean'	'dirty'	all	'clean'	'dirty'	all
$C^{\rm BSM}_{b_Le_L}$	1.72	0.15	0.99	2.31 1.21	0.69 -0.39	1.30 0.70	4.1	0.3	3.5
$C^{\rm BSM}_{b_Le_R}$	-5.15	-1.70	-3.46	-4.23 -6.10	0.33 -2.83	-2.81 -4.05	4.3	0.9	3.6
$C^{\rm BSM}_{b_Re_L}$	0.085	-0.51	0.02	0.39 -0.21	0.29 -1.55	0.30 -0.25	0.3	0.7	0.1
$C^{\rm BSM}_{b_Re_R}$	-5.60	2.10	-3.63	-4.66 -6.56	3.52 -2.70	-2.65 -4.43	4.2	0.5	2.5

1704.05438

- "Clean" observables favour NP in LH quarks & electrons or muons
- Including "dirty" favours muons over electrons

$b \to s\mu\mu$

Wilson coeff.	Best-fit 'clean'	Best-fit 'dirty'	Best-fit all	1-σ range 'clean'	1-σ range 'dirty'	1-σ range all	$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$ 'clean'	$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$ 'dirty'	$\sqrt{\chi^2_{\rm SM} - \chi^2_{\rm best}}$ all
$C^{\rm BSM}_{9,\mu}$	−1.51	−1.15	−1.19	−1.05 −2.08	−0.98 −1.31	−1.04 −1.35	3.9	5.5	6.7
$C^{\rm BSM}_{10,\mu}$	1.13	0.48	0.69	1.49 0.81	0.69 0.28	0.86 0.52	4.0	2.4	4.3
$C'^{\rm BSM}_{9,\mu}$	−0.08	−0.24	−0.22	0.20 −0.37	0.44 −0.15	−0.14 −0.33	0.3	1.7	1.6
$C'^{\rm BSM}_{10,\mu}$	−0.09	0.10	0.08	0.14 −0.33	0.19 0.01	0.16 0.00	0.4	1.2	1.0

New physics in the muon sector (Vector Axial basis)

1704.05438

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} (V^*_{ts} V_{tb}) \sum_i C^\ell_i(\mu)\, \mathcal{O}^\ell_i(\mu)$$

$$\mathcal{O}^{(\prime)}_7 = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_{R(L)} b\right) F^{\alpha\beta}\,, \qquad C^{SM}_7 = -0.319,$$

$$\mathcal{O}^{\ell(\prime)}_9 = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \ell\right)\,, \qquad C^{SM}_9 = 4.23,$$

$$\mathcal{O}^{\ell(\prime)}_{10} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)} b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right). \qquad C^{SM}_{10} = -4.41.$$

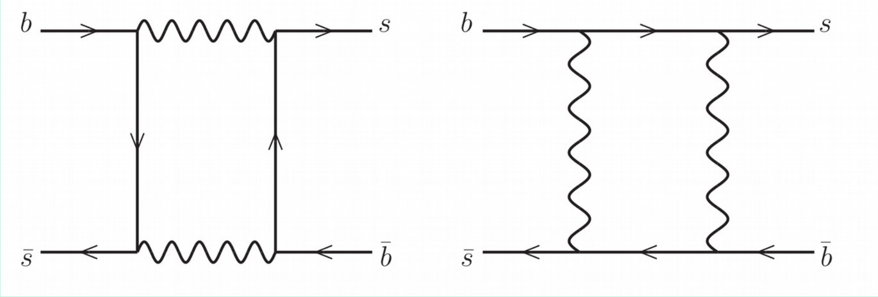
Models to explain the anomalies

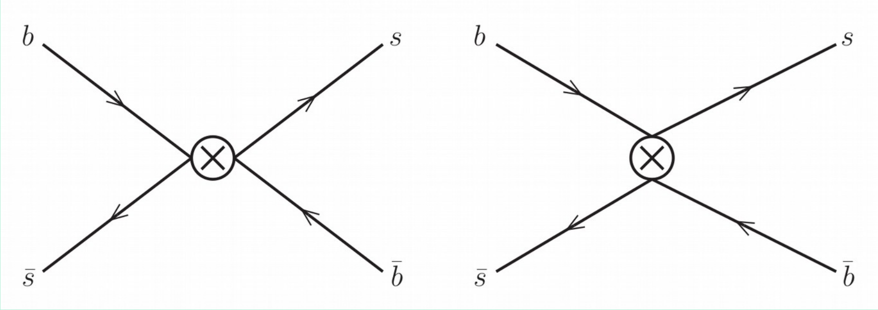
- We want to generate coupling to LH b/s and LH muons
- Z' , leptoquarks, composite Higgs, SUSY, ...

- Quite a few possibilities – but all bring with them extra constraints (and more in any UV complete model)
- Couplings to b and s $\Rightarrow B_s$ mixing can (strongly) constrain

B_s Mixing

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





Current status of B_s mixing

- Theory
  - 2015 (1511.09466)
    - $18.3 \pm 2.7\, ps^{-1}$
- Experiment
  - LHCb (2012-15), CDF (2006)
    - $17.757 \pm 0.021\, ps^{-1}$

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One constraint to kill them all?

Luca Di Luzio, Matthew Kirk, Alexander Lenz

Institute for Particle Physics Phenomenology, Durham University, DH1 3LE Durham, United Kingdom
luca.di-luzio@durham.ac.uk, m.j.kirk@durham.ac.uk, alexander.lenz@durham.ac.uk

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

Current status of B_s mixing

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~ 0.25 σ

~ 1.8 σ

- Experiment
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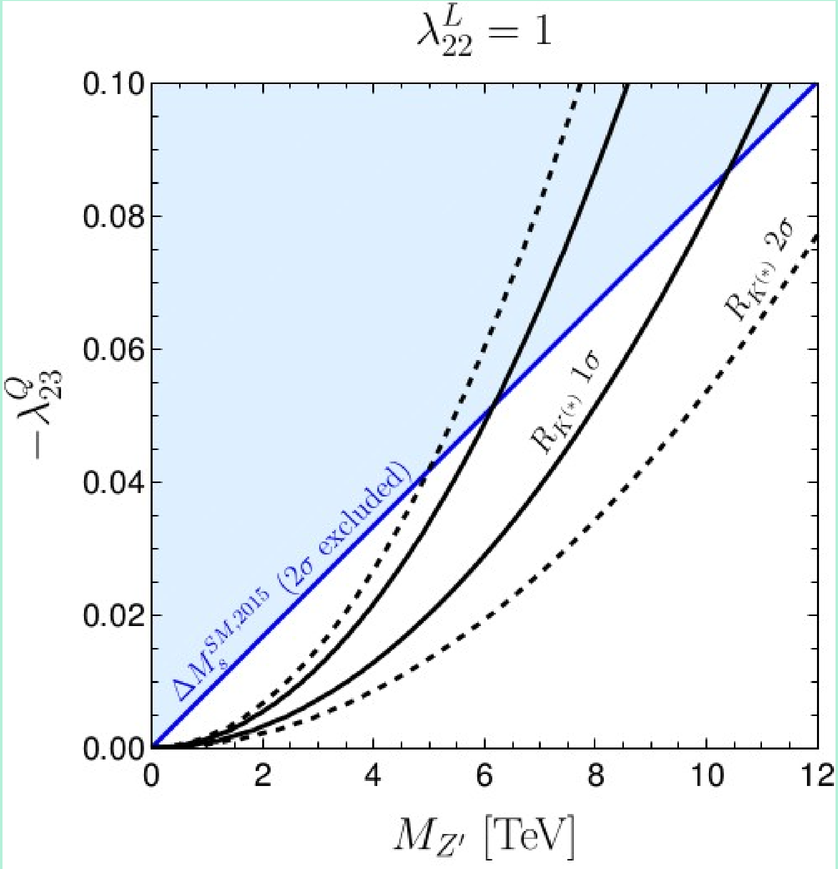
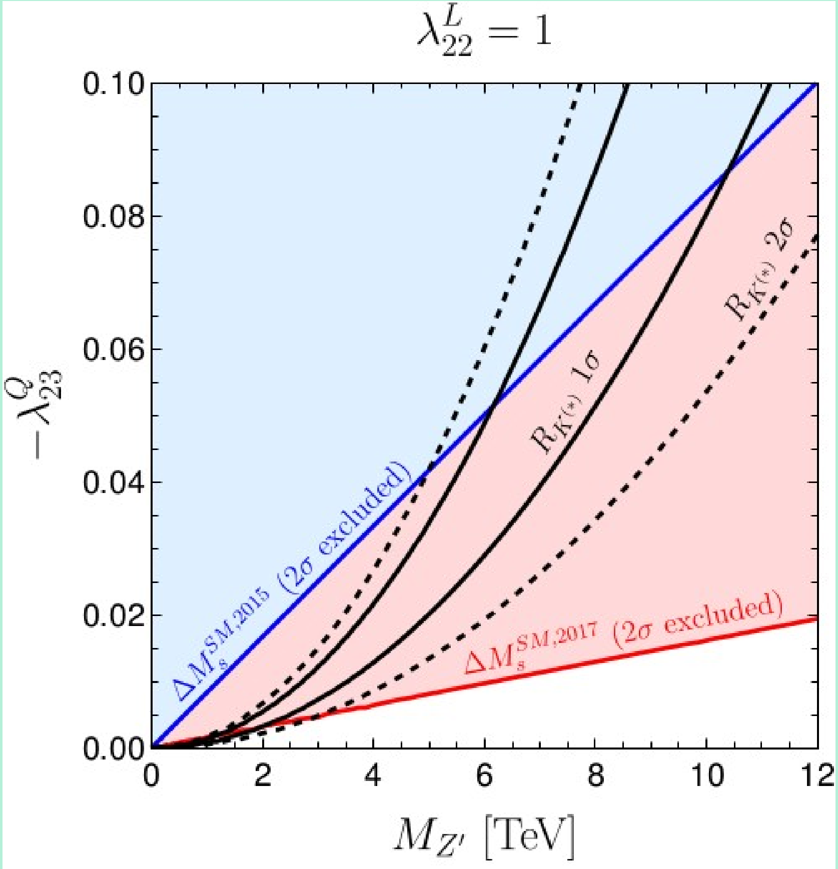
Why big change in SM?

- Important input parameter: $f_{B_s}\sqrt{B}$
  - $\Delta M_s \propto f_{B_s}^2 B$, contributes > 90% of uncertainty
- Non-perturbative – generally determined by lattice
  - Other approaches available, e.g. sum rules (see talk by T. Rauh, 1711.02100)
- Fermilab-MILC collaboration produced new result
  - Incorporated by FLAG (lattice averaging group)
  - $f_{B_s}\sqrt{B}$: 270 ± 16 MeV → 274 ± 8 MeV

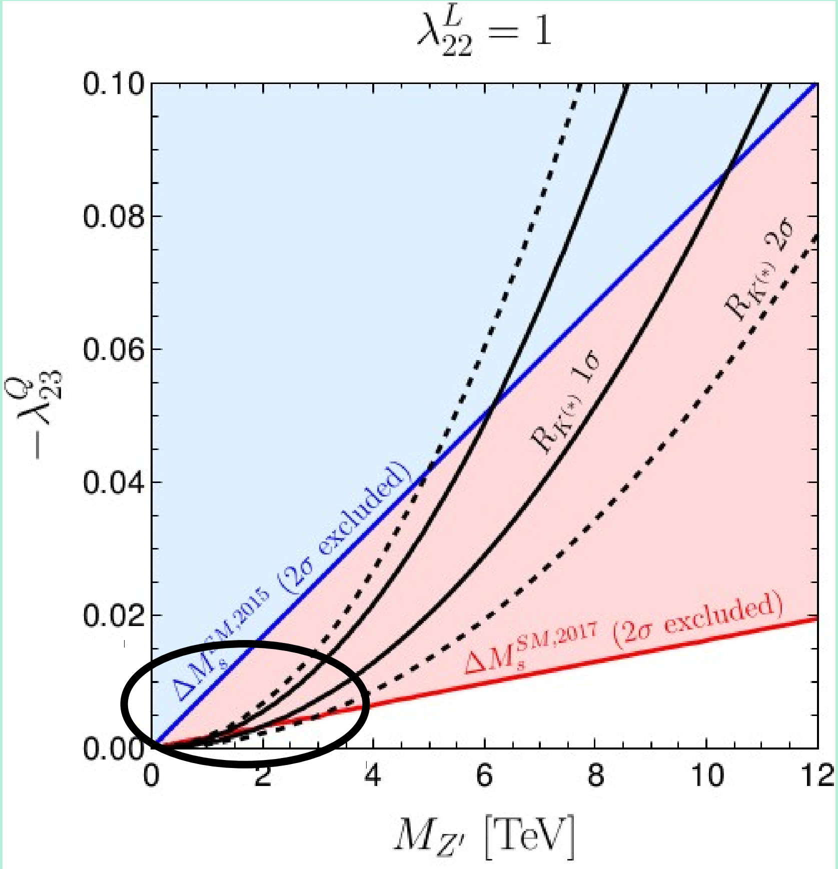
Limits on Z' model (2015)



Limits on Z' model (2017)



Limits on Z' model (2017)



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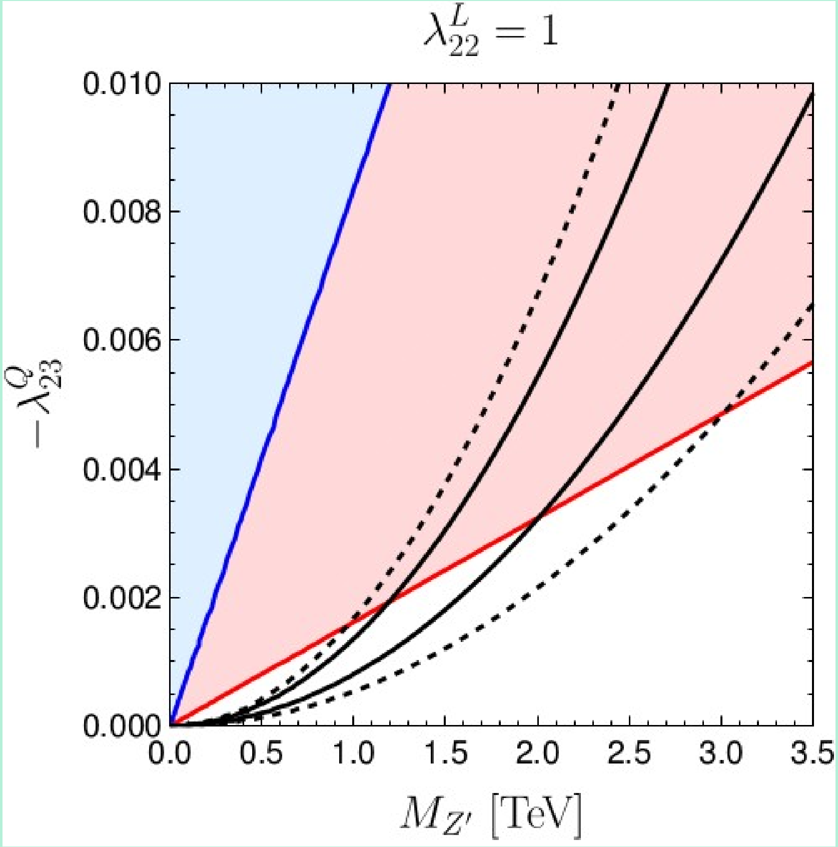


Stronger B_s mixing constraints

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

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

Avoiding constraint

- Simple Z' model → Z' mass must be below ~ 3 TeV
- Rather than minimising the effect, how can we use our NP to improve the fit with B_s mixing result?
- Need to get a negative contribution to ΔM_s

“Solving” ΔM_s discrepancy

- Complex couplings
  - What other constraints come in?
- LH and RH quark couplings
  - Any interesting RG effects?

- Does this affect the fit to the b→s mu mu anomalies?

Complex Coupling

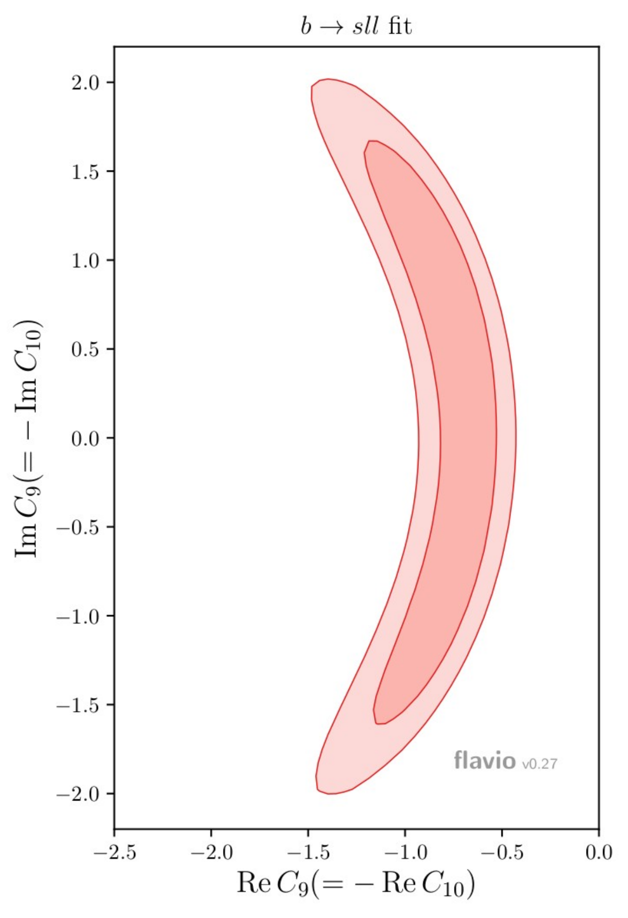
- Most global fits done assuming real couplings – 1703.09247 a notable exception
- How does the best fit region change?

Complex Coupling

- Not much dependence on the imaginary part

- Can see this by expanding in $\frac{C^{NP}}{C^{SM}}$, which we assume to be small.

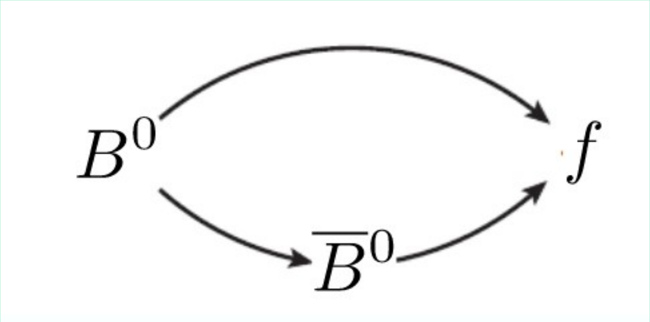
$$R_K \approx 1 + \Re\left(\frac{C_{\mathrm{LL}}^{NP}}{C_{\mathrm{LL}}^{SM}}\right)$$

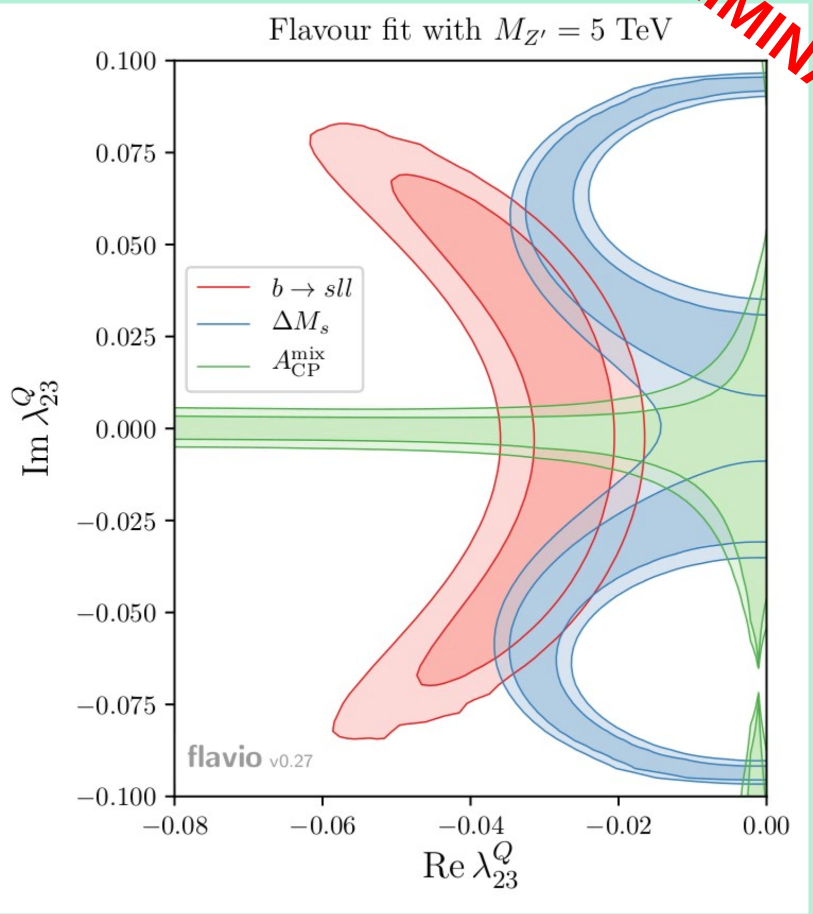


Complex Coupling

PRELIMINARY

- As soon as we have complex couplings
  - → new sources of CP violation
  - → new constraints
- For B_s mixing, mixing induced CP asymmetry





LH and RH quark couplings

- Extra operators mean we can get different sign from interference term
- Also get RG running effects which slightly enhance the LR term relative to LL or RR

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

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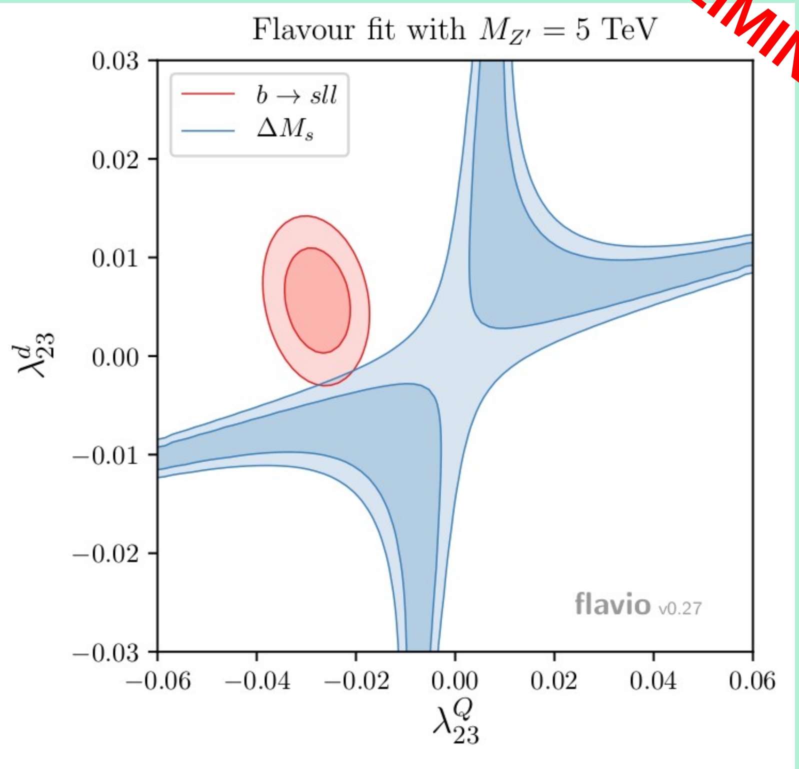

How light can we go?

- If complex or different chirality couplings don't work, are we okay to just have a light Z'?
- What constraints are there on low masses?

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- What constraints are there on low masses?
  - Neutrino trident production (assumes $SU(2)_L$ invariance of NP)
  - $Z \to 4\mu$ (well measured as background for $H \to Z Z^* \to 4\mu$)

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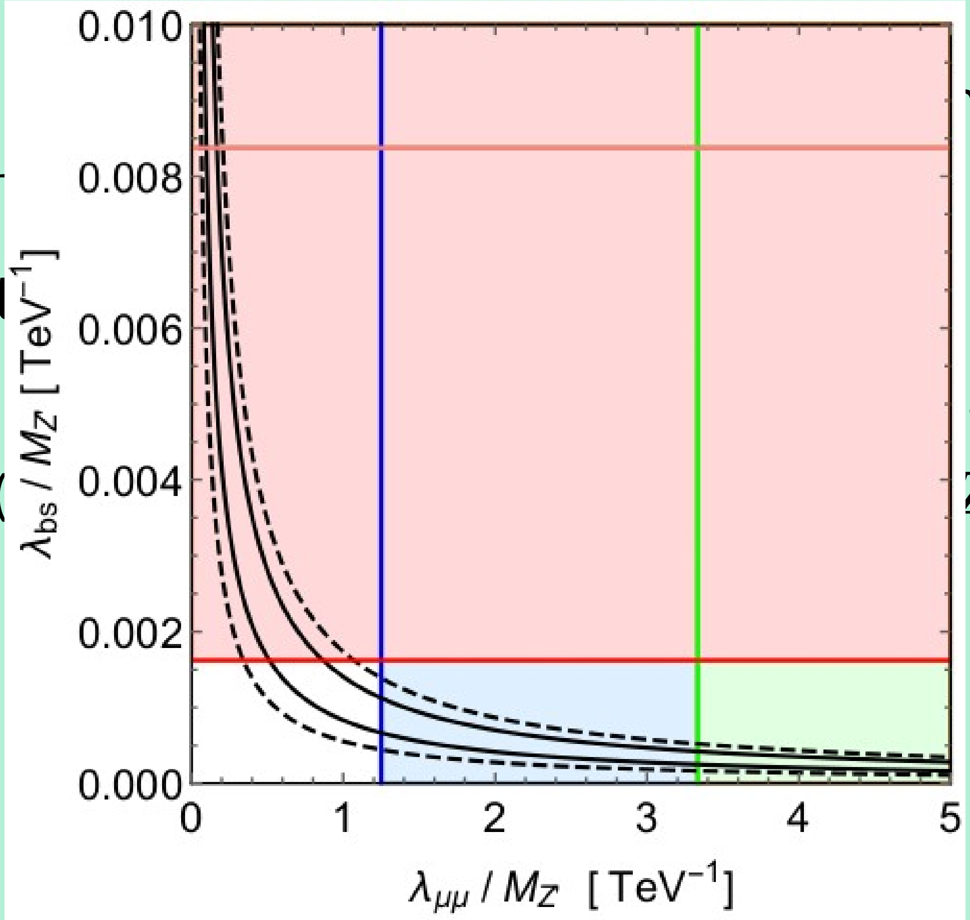
- What const
  - Neutrino ariance of NP)
  - $Z \rightarrow 4\mu$ ($Z Z^* \rightarrow 4\mu$)



Summary

- B_s mixing provides a strong constraint on any NP coupling to b and s
- Using the latest inputs gives 2 sigma tension
- Want to solve $b \to s\mu\mu$ anomalies and improve B_s mixing fit?
  - Complex coupling? Ruled out by A_{CP}^{mix}
  - Coupling to left and right handed quarks? Doesn't work with R_K, R_{K*}
  - Light Z'? Neutrino trident production and $Z \to 4\mu$ on your tail

BACKUP

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 [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	$(22.6 \pm 2.8)\ \mathrm{ps}^{-1}$

Vacuum saturation approximation

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

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

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

$$= B_\Gamma f_{B_s}^2 M_{B_s}^2$$