Anomalies in Flavour Physics (and how (not) to solve them)

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IPPP Internal Seminar
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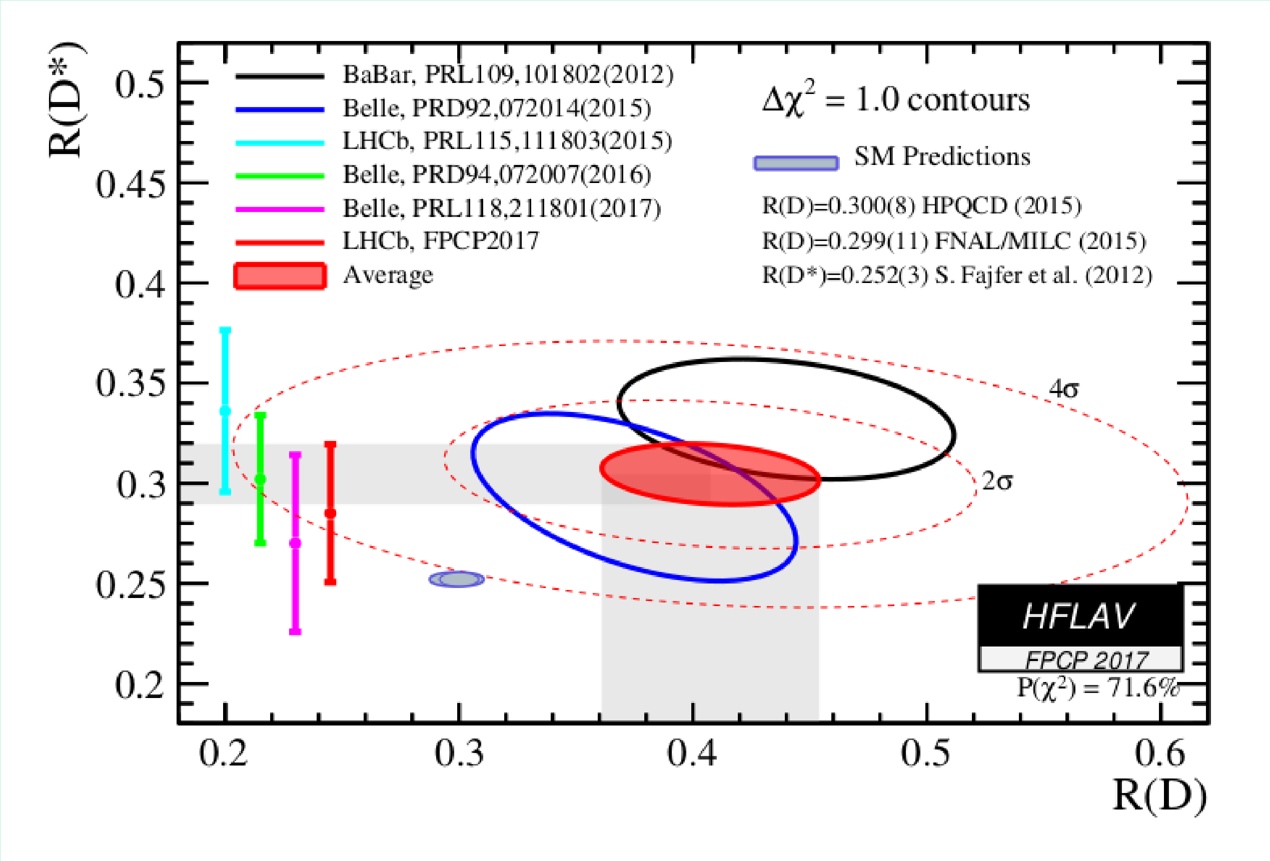
What anomalies have we got?

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

R_D, R_{D^*}



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
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%

$R_K\,, R_{K^*}$

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

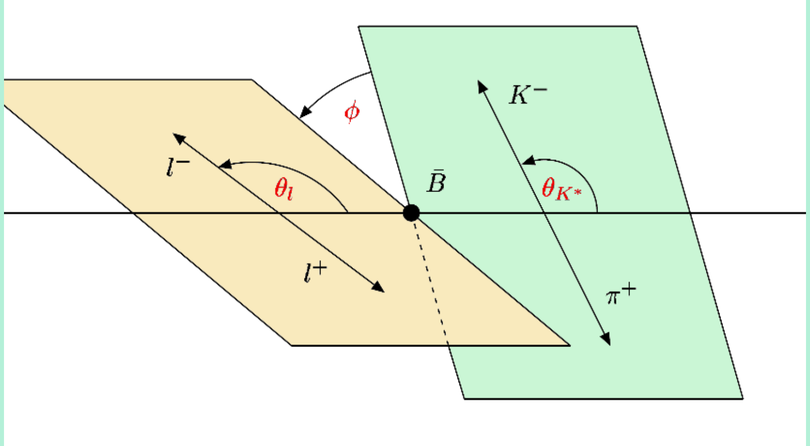
Observable	SM prediction		Measurement	
$R_K : q^2 = [1, 6]\,\text{GeV}^2$	1.00 ± 0.01	[1, 2]	$0.745^{+0.090}_{-0.074} \pm 0.036$	[3]
$R_{K^*}^{\text{low}} : q^2 = [0.045, 1.1]\,\text{GeV}^2$	0.92 ± 0.02	[4]	$0.660^{+0.110}_{-0.070} \pm 0.024$	[5]
$R_{K^*}^{\text{central}} : q^2 = [1.1, 6]\,\text{GeV}^2$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

1704.06240

$P_5^{'}$

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

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



$b \rightarrow s\mu\mu$

- 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

$b \to s \mu \mu$

New physics in the muon sector (Vector Axial basis)									
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
$C_{9,\mu}^{\rm BSM}$	−1.51	−1.15	−1.19	−1.05 −2.08	−0.98 −1.31	−1.04 −1.35	3.9	5.5	6.7
$C_{10,\mu}^{\rm BSM}$	1.13	0.48	0.69	1.49 0.81	0.69 0.28	0.86 0.52	4.0	2.4	4.3
$C_{9,\mu}^{\prime\rm BSM}$	−0.08	−0.24	−0.22	0.20 −0.37	0.44 −0.15	−0.14 −0.33	0.3	1.7	1.6
$C_{10,\mu}^{\prime\rm BSM}$	−0.09	0.10	0.08	0.14 −0.33	0.19 0.01	0.16 0.00	0.4	1.2	1.0

1704.05438

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

$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b\right) F^{\alpha\beta} , \qquad C_7^{SM} = -0.319,$$

$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha \ell\right) , \qquad C_9^{SM} = 4.23,$$

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

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 in any UV model, obviously generate other operators
- Couplings to b and s $\Rightarrow B_s$ mixing can (strongly) constrain

Current status of B_s mixing

- Theory
  - 2015 (1511.09466)
    - $18.3 \pm 2.7\, ps^{-1}$
  - 2017 (1712.06572)
    - $20.01 \pm 1.25\, ps^{-1}$
- Experiment
  - LHCb (2012-15), CDF (2006)
    - $17.757 \pm 0.021\, ps^{-1}$

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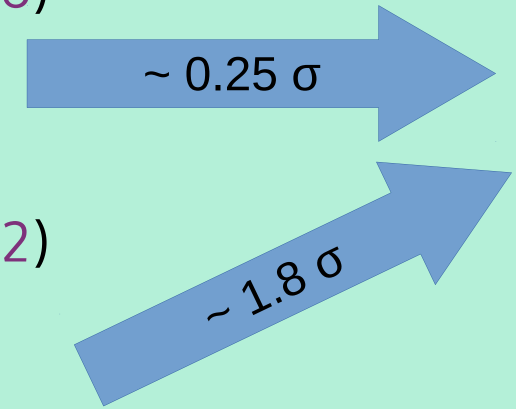

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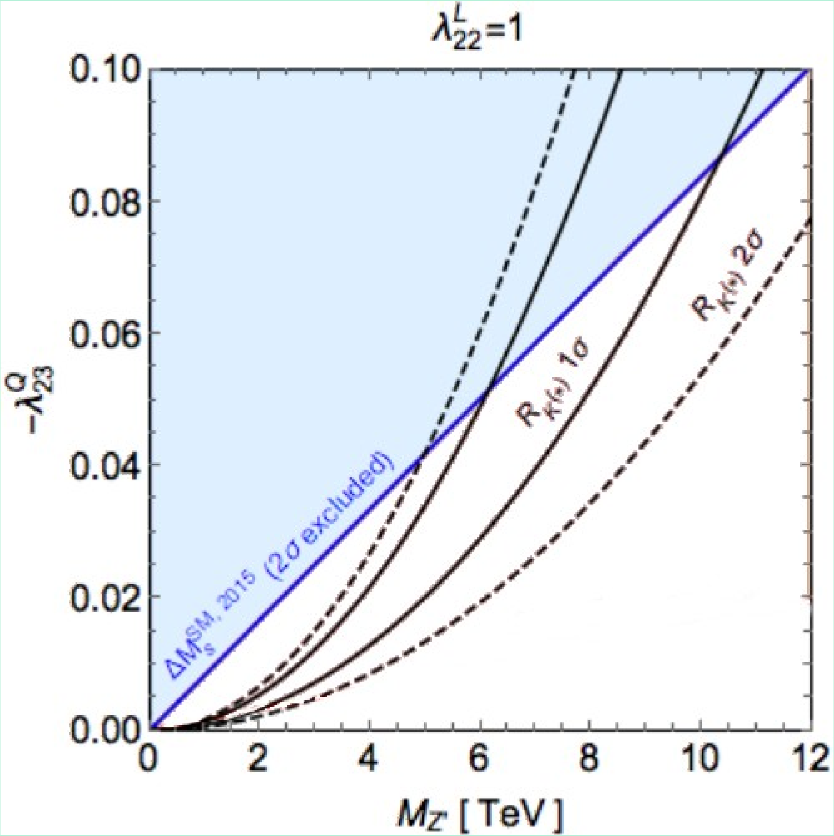
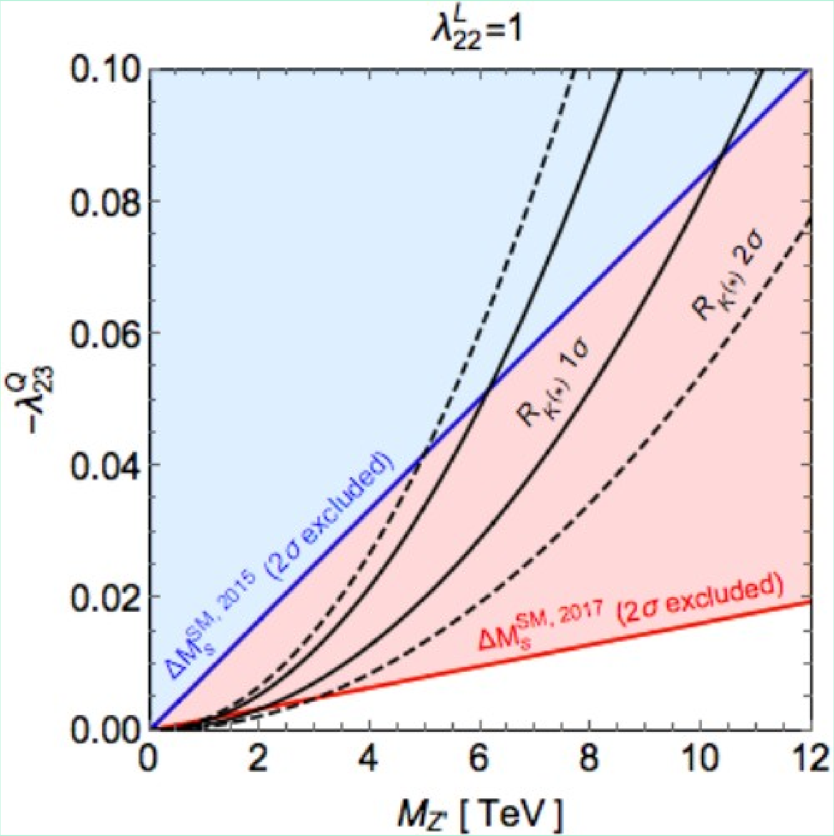
Why big change in SM?

- 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 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

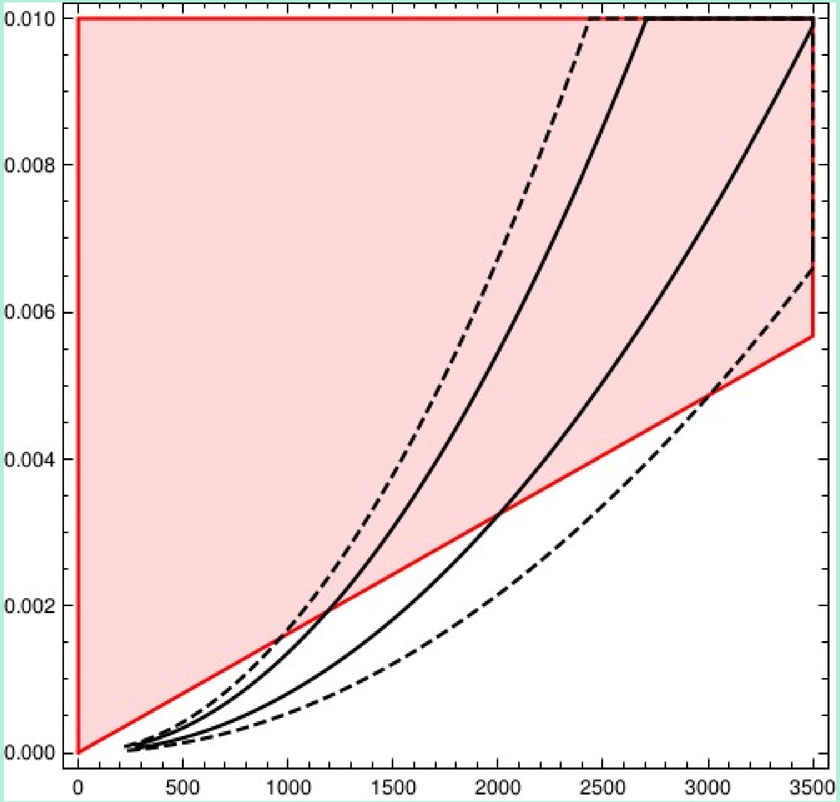
Limits on Z' model (2015)



Limits on Z' model (2017)



Limits on Z' model (2017)



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

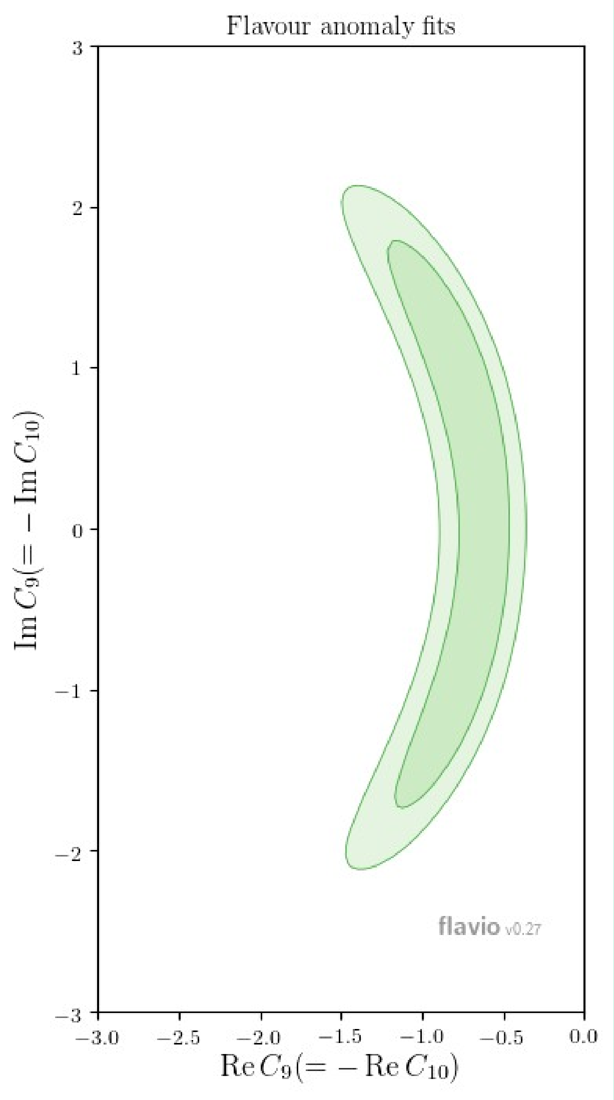
- Most global fits done assuming real couplings – 1703.09247 a notable exception
- How does the best fit region change?

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.

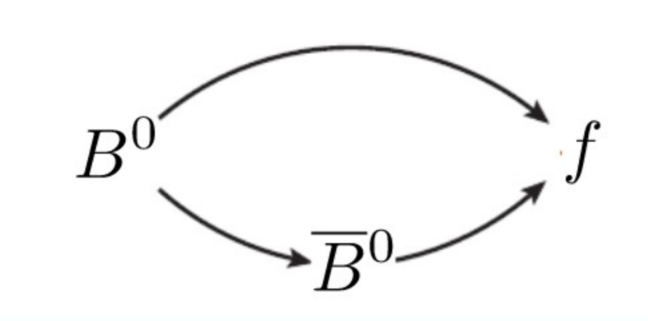
$$R_K \approx 1 + \Re\left(\frac{C_{\text{LL}}^{NP}}{C_{\text{LL}}^{SM}}\right)$$

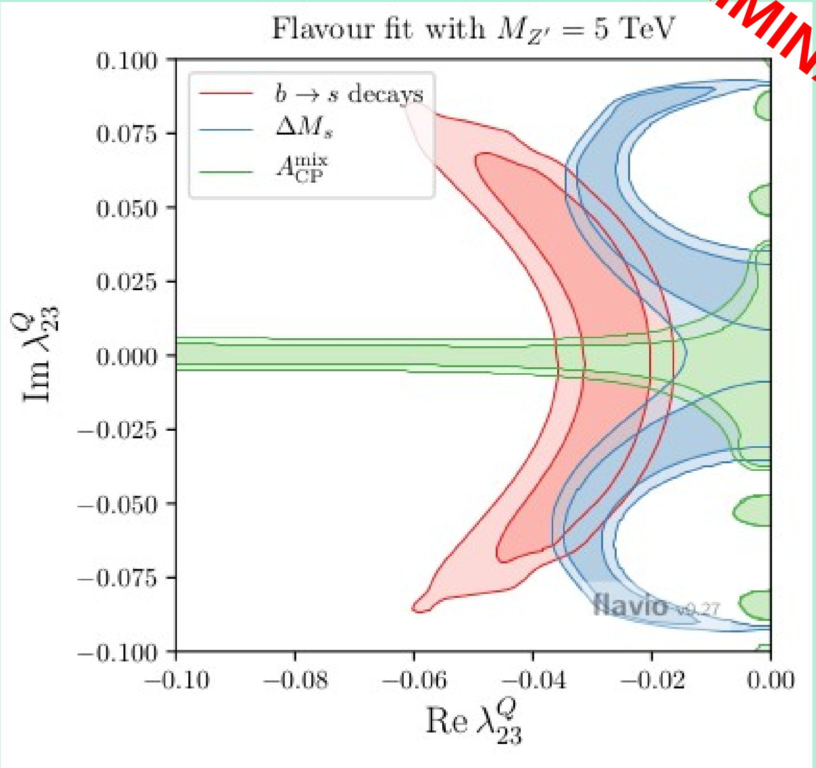


Complex Coupling

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

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

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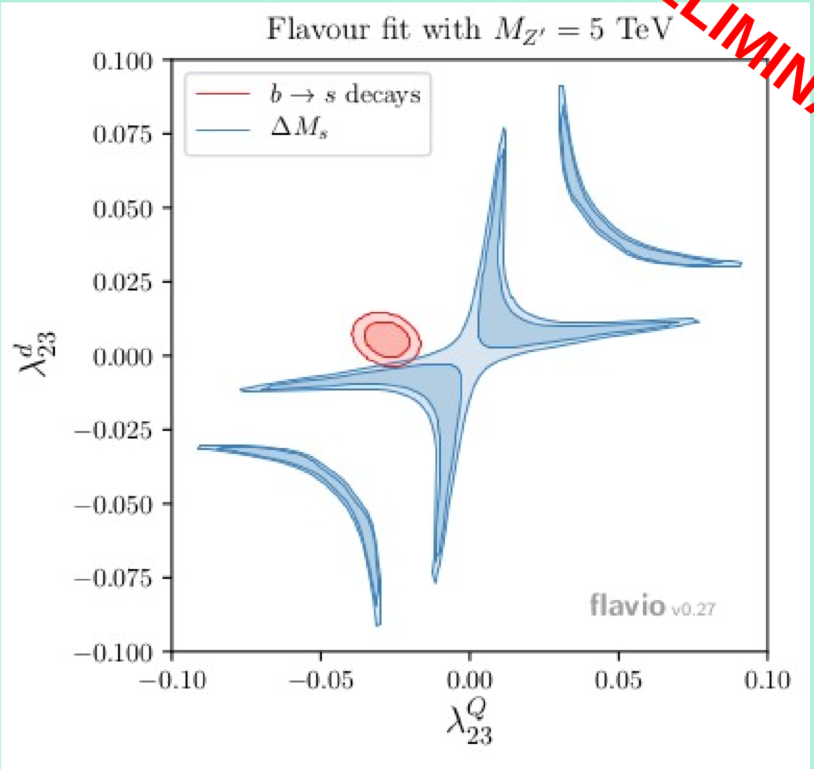

PRELIMINARY

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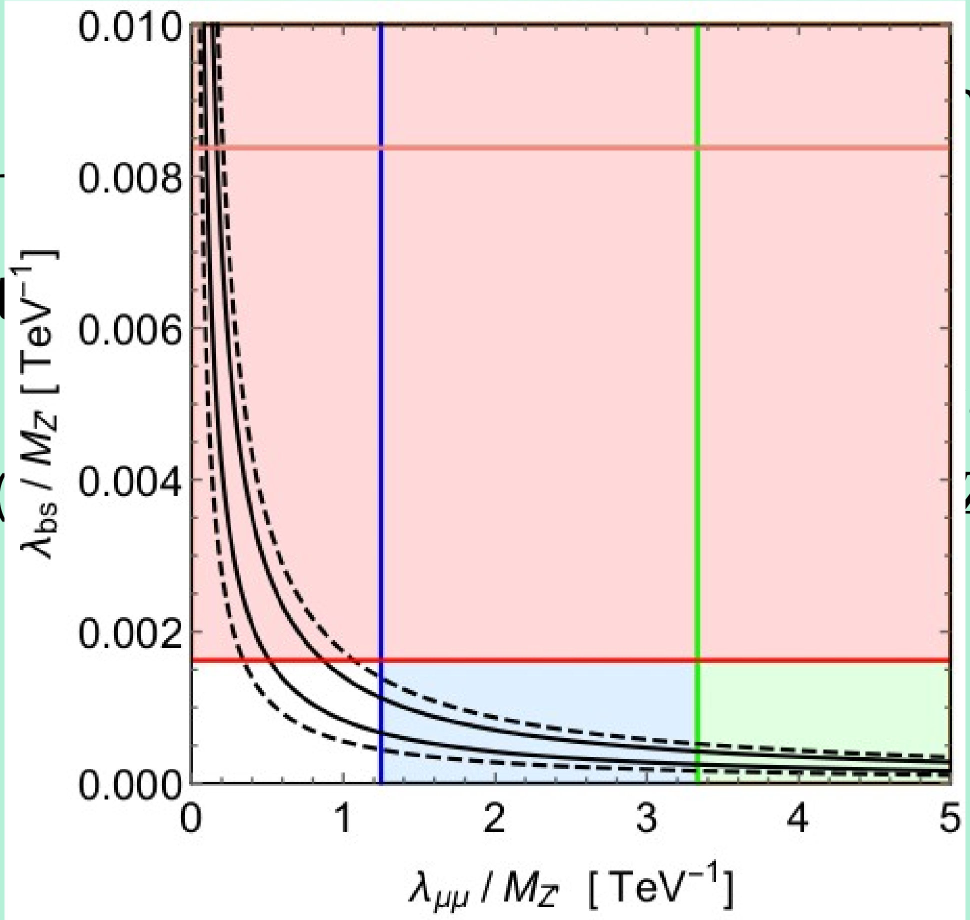
- What constraints are there on low masses?
  - Neutrino trident production (assumes $SU(2)_L$ invariance of NP)
  - $Z \to 4\mu$ (well measured as background for $H \to ZZ^* \to 4\mu$)

How light can we go?

- If complex … n't work, are we okay to jus…
- What const…
  - Neutrino … ariance of NP)
  - $Z \rightarrow 4\mu$ (… $ZZ^* \rightarrow 4\mu$)



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