Charming New Physics in Beautiful Processes?

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Quark Hadron Duality Violation

- 1603.07770
- With Tom Jubb, Alex Lenz, Gilberto Tetlalmatzi-Xolocotzi

Quark Hadron Duality Violation

- Quark Hadron duality basically means that if we sum over enough quark level processes (perturbative), we can approximate the hadronic processes (non-perturbative)
- Duality violation says something is missing

Heavy Quark Expansion

- HQE is method of calculating b quark processes
- Taylor expansion in $\Lambda_{\mathrm{QCD}}/m_b$
  - Really more like O(1 GeV) / energy release
- We use HQE wrong → duality violation

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \ldots$$

Heavy Quark Expansion

- Expect duality to be violated differently in different decay channels

- Look at e.g. mixing expression – GIM and CKM suppressed.

$$-\frac{\Gamma_{12}^s}{M_{12}^s} = \frac{\Gamma_{12}^{s,cc}}{\tilde{M}_{12}^s} + 2\frac{\lambda_u}{\lambda_t}\frac{\Gamma_{12}^{s,cc} - \Gamma_{12}^{s,uc}}{\tilde{M}_{12}^s} + \left(\frac{\lambda_u}{\lambda_t}\right)^2 \frac{\Gamma_{12}^{s,cc} - 2\Gamma_{12}^{s,uc} + \Gamma_{12}^{s,uu}}{\tilde{M}_{12}^s}$$

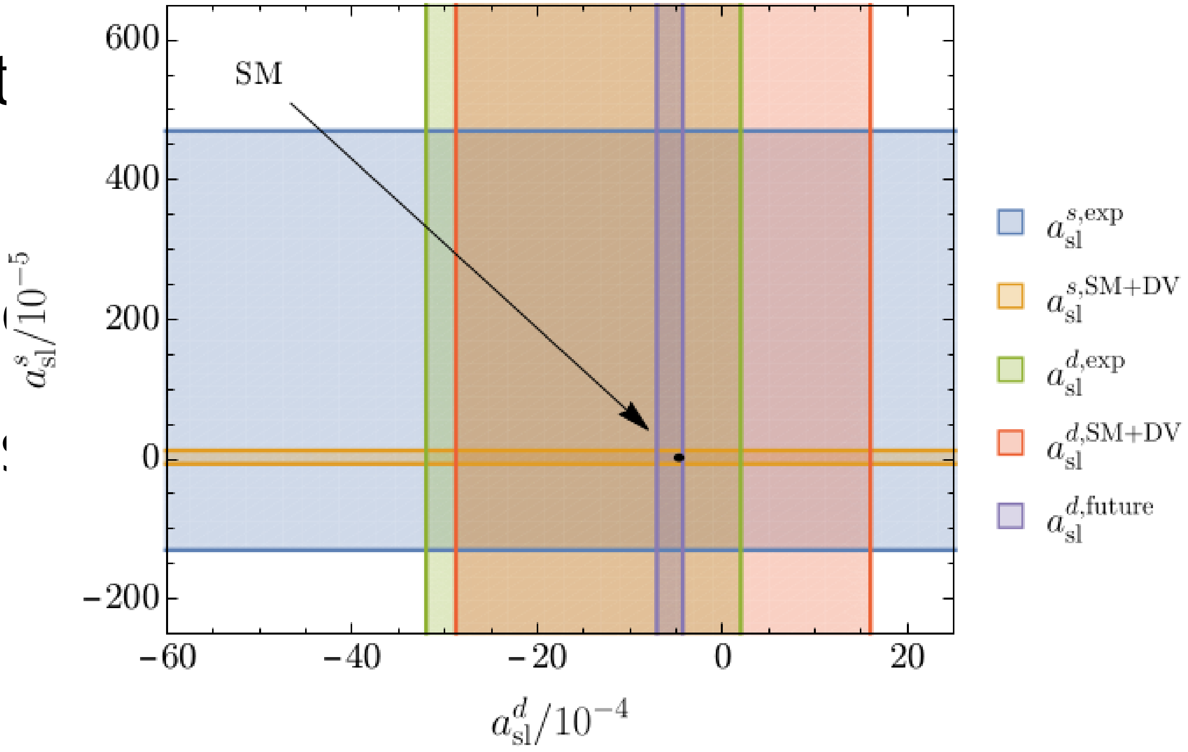
- Duality violation breaks this → potentially large effects

Limits on SM prediction

- Use "best" quantities to constraint duality violation
- Then flip around and see how big the effect can be in poorly measured observables
- Distinguish breakdown of tools to breakdown of SM

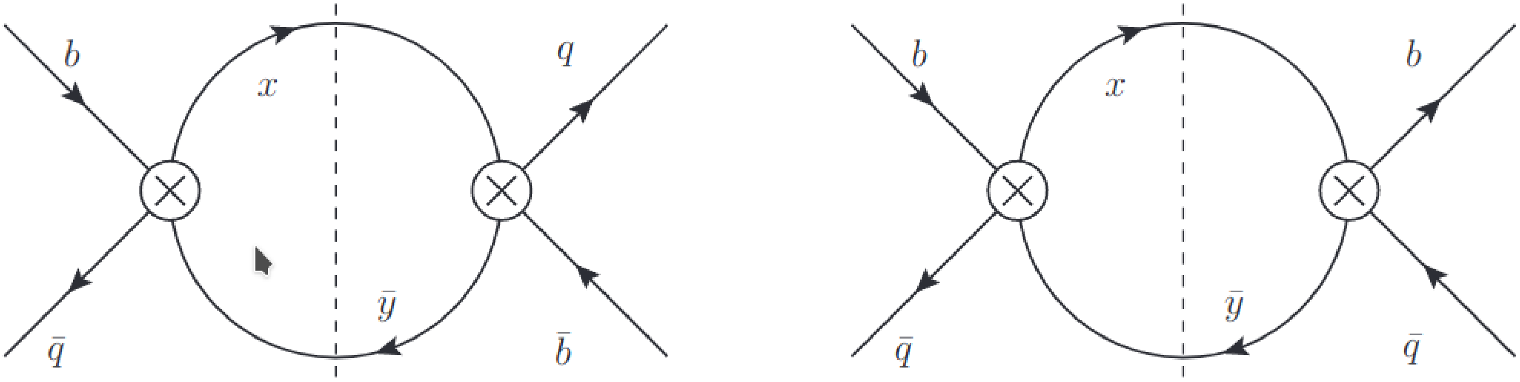
Limits on SM prediction

- Use "best ... ation
- Then flip ... n be in poorly m...
- Distingui... of SM



Meson lifetimes

- Same structure in lifetimes, can constraint duality here as well
- Look for consistency with mixing limits



Future of precision

- Best way to test HQE/QHD is better theory to compare to experiment.
- Examine how far we can go in the near future
- Make reasonable assumptions about progress
- Dim7 matrix elements main issue
  - See sum rules / future lattice

D mixing from duality violation?

- HQE calculation gives result too small (by factor 1000)
- HQE convergence too slow?
- NP at work?
- Or duality violation?

D mixing from duality violation?

- Extreme GIM cancellation at work
  - Terms in sum are of right size, but cancel to several decimal places

$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right) - \lambda_b^2\Gamma_{12}^{dd} \,.$$

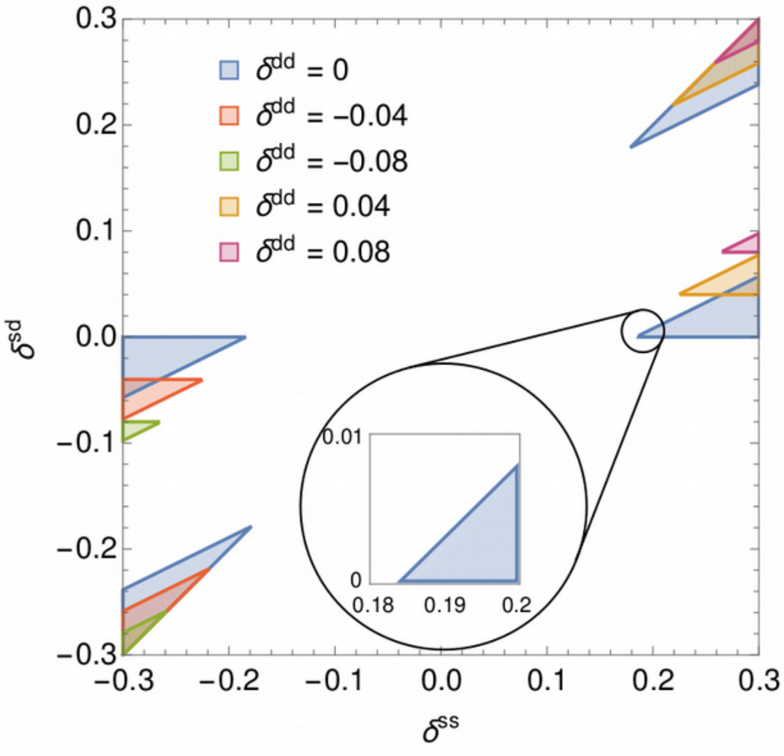
$$\Gamma_{12}^{ss} = 1.8696 - 5.5231\bar{z}_s - 13.8143\bar{z}^2 + \ldots\bar{z}^3 + \ldots \,,$$

$$\Gamma_{12}^{sd} = 1.8696 - 2.7616\bar{z}_s - 7.4906\bar{z}^3 + \ldots\bar{z}^3 + \ldots \,,$$

$$\Gamma_{12}^{dd} = 1.8696 \,.$$

D mixing from duality violation?

- 20% violation causes huge increase



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

- 1701.09183
- With Sebastian Jäger, Alex Lenz, Kirsten Leslie

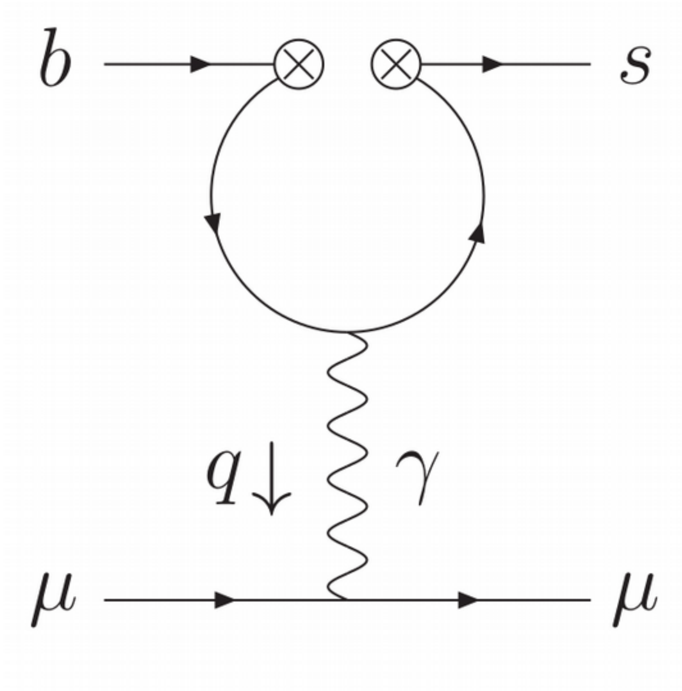
NP in $(\bar{b}s)(\bar{c}c)$?

- Why $(\bar{b}s)(\bar{c}c)$?
- SM contribution to $(\bar{b}s)(\bar{c}c)$ (from integrating out W) gives around half the SM contribution to the $b \to s\mu\mu$ transition

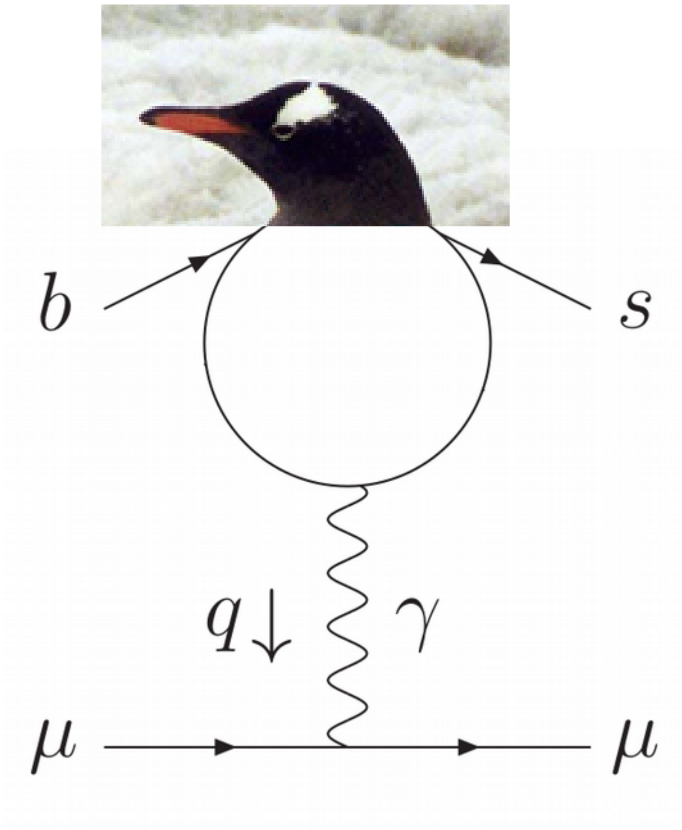
NP in $(\bar{b}s)(\bar{c}c)$?

- Contribution is flavour universal, but can still be partial explanation of $b \to s\bar{l}l$ anomalies
- But these operators also contribute to Bs mixing, Bs lifetimes, and $B_s \to X_s\gamma$
  - So any NP gives rise to a correllated effect

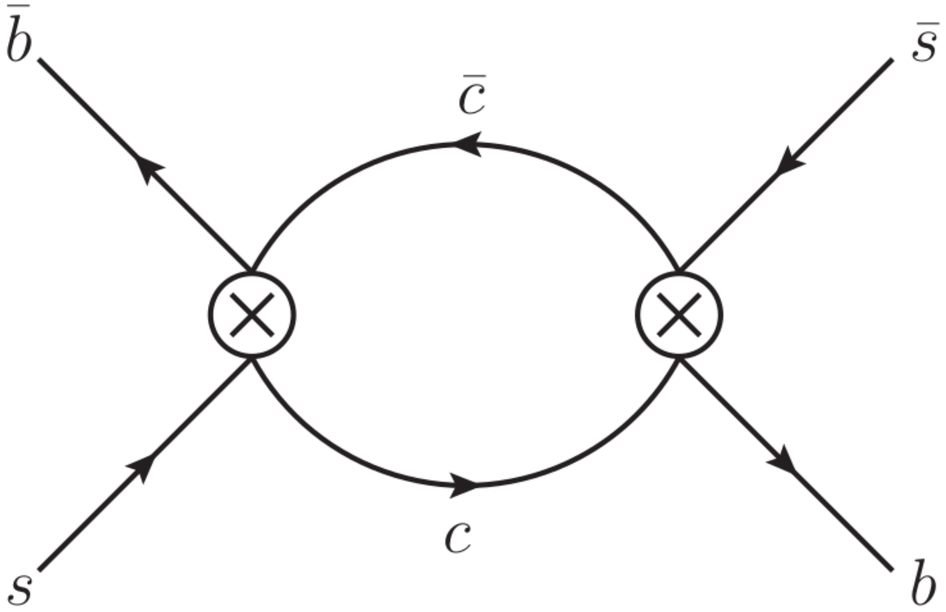
Contribution to rare decays



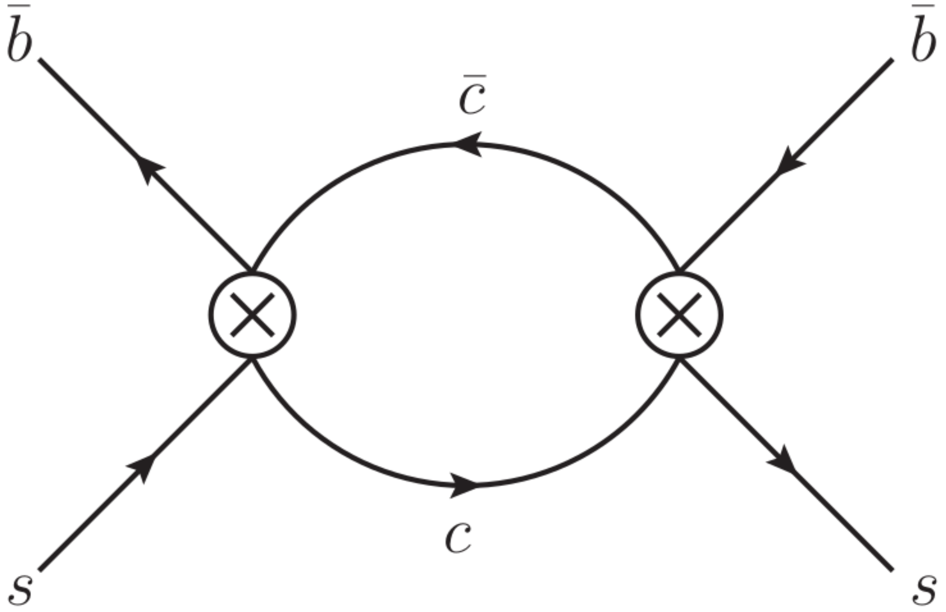
Contribution to rare decays



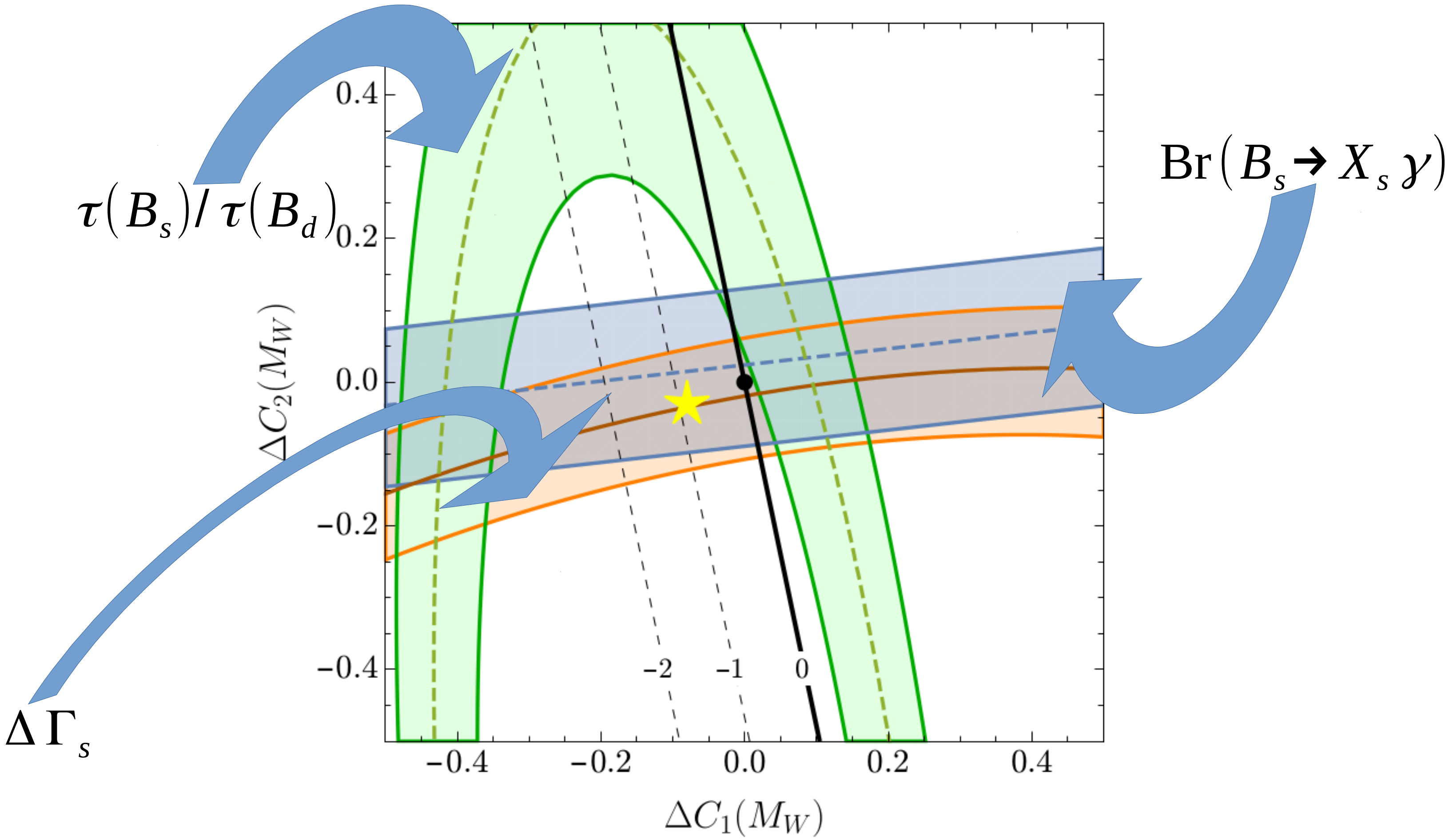
Contribution to mixing and lifetimes



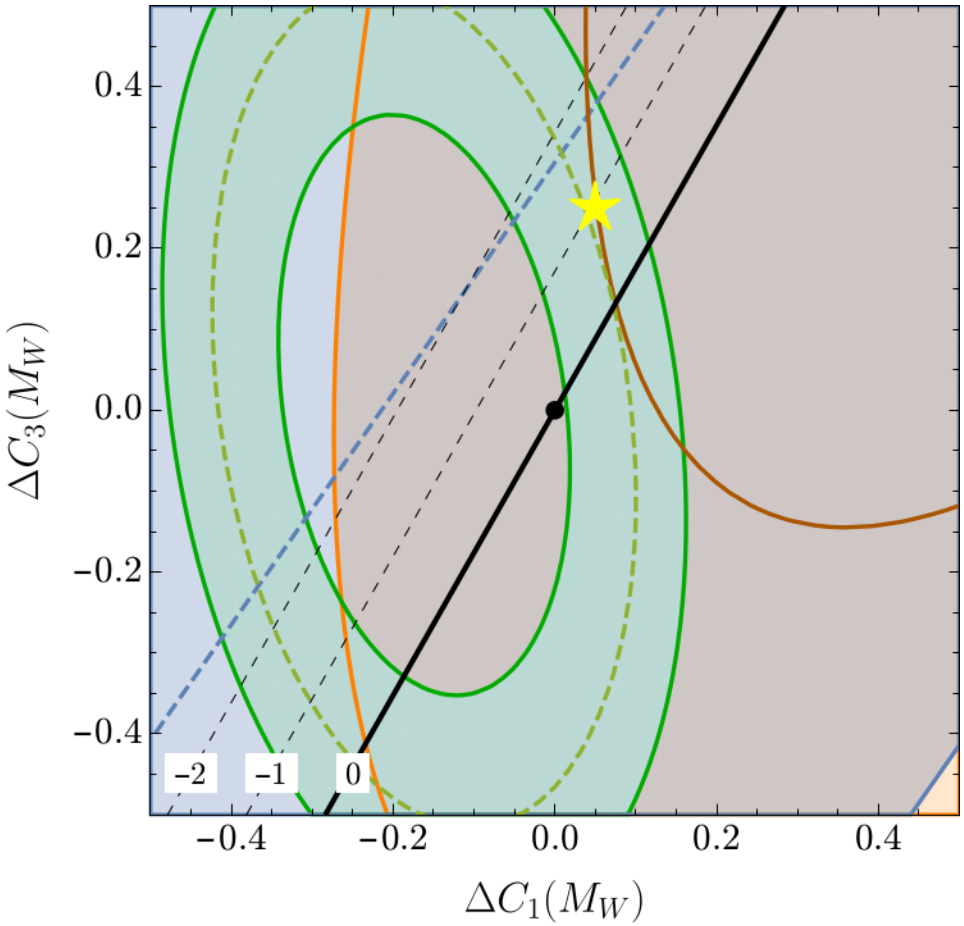
Contribution to mixing and lifetimes



How do the constraints look?

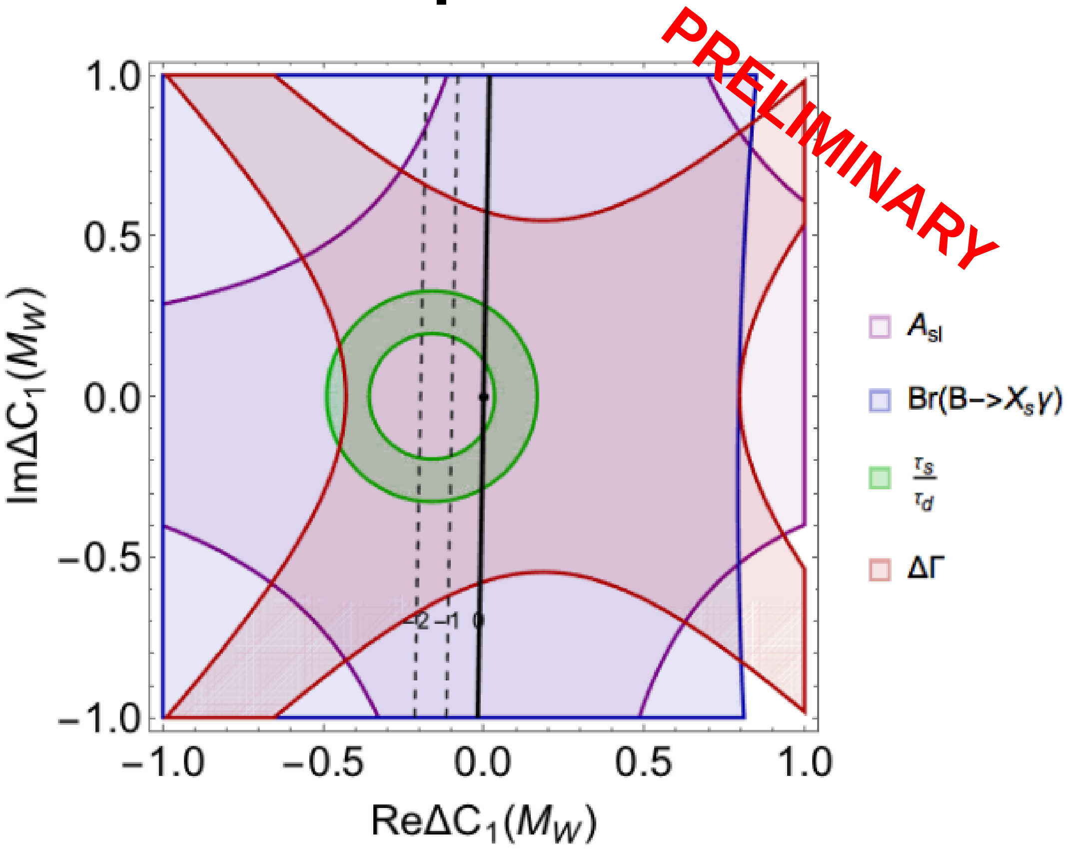


How do the constraints look?

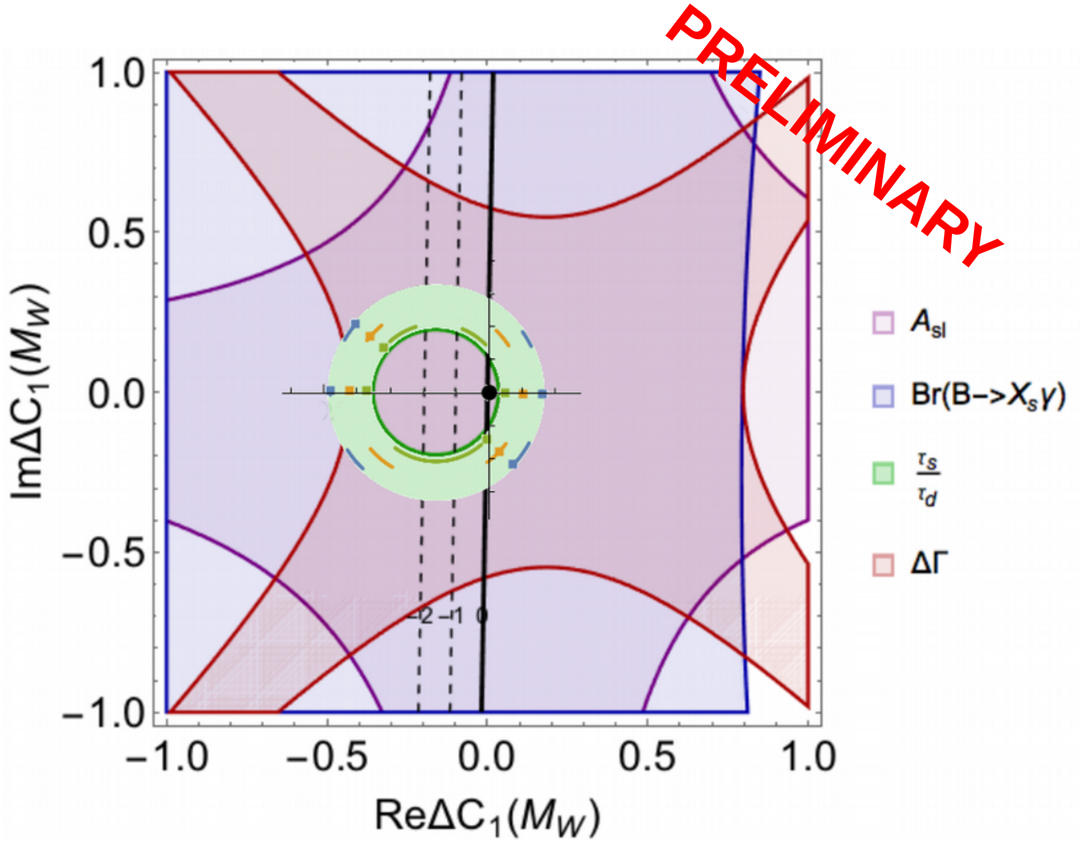


Ongoing work with $(\bar{b}\,s)(\bar{c}\,c)$

Complex NP


PRELIMINARY
1.0
0.5
0.0
−0.5
−1.0
ImΔC$_1$(M_W)
−1.0
−0.5
0.0
0.5
1.0
ReΔC$_1$(M_W)
−2 −1 0
A_{sl}
Br(B−>$X_s\gamma$)
$\frac{\tau_s}{\tau_d}$
ΔΓ

$B \to J/\psi K$ Constraints on Complex ΔC_1 and ΔC_2



Charming Dark Matter

- 1709.01930
- With Tom Jubb, Alex Lenz

DM and flavour

- Consider a DM candidate with new flavour quantum number
- Interesting as opens up non trivial interactions
- But puts you at risk of violating large number of flavour bounds

DM and flavour

- Many models invoke MFV – CKM only source of flavour changing effects
- We go beyond MFV – CKM + new matrix
- As previously mentioned, D mixing not explained by current short distance calculations
- Maybe DM is part of the NP to explain it?

Bounds from DM

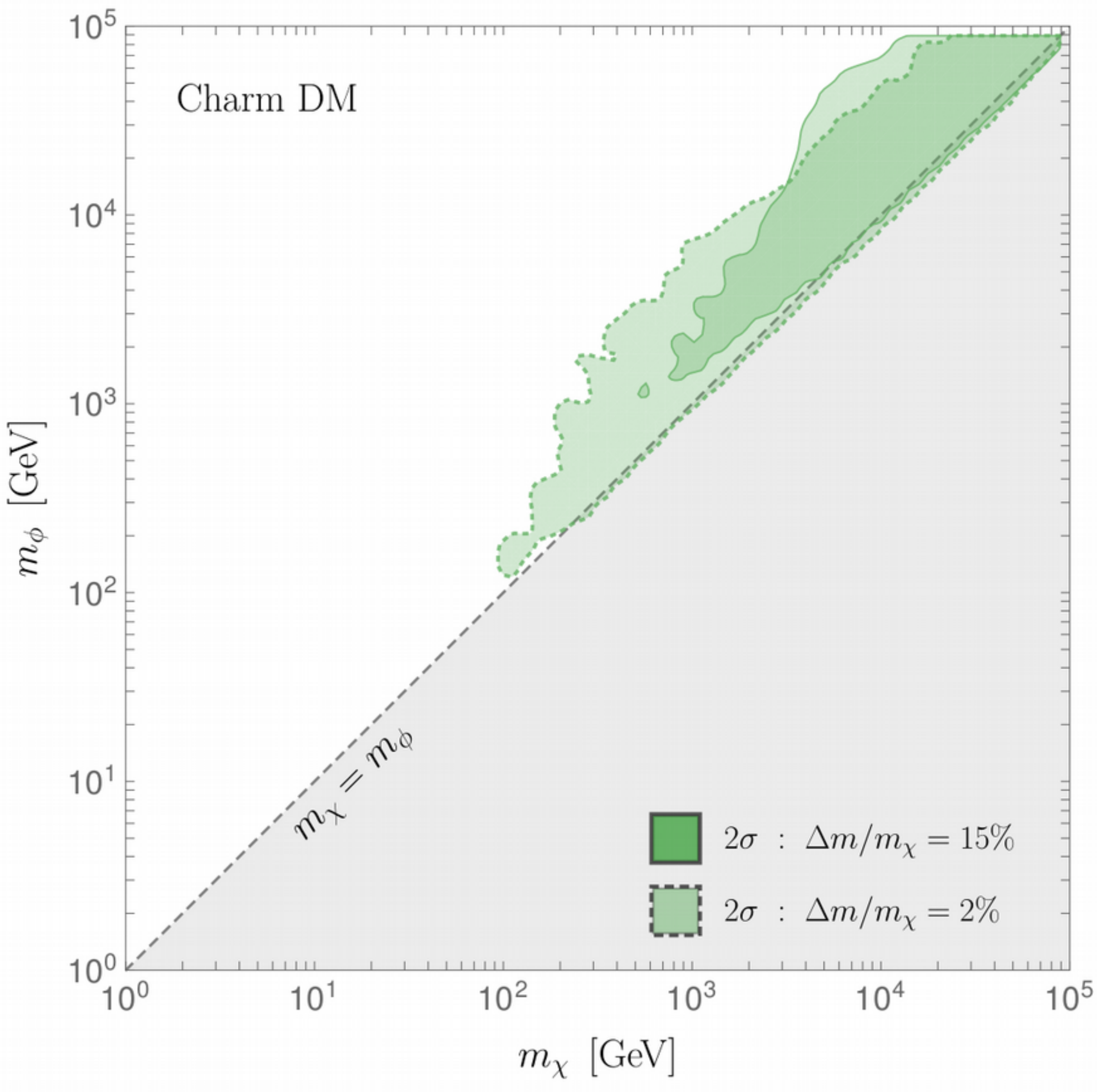
- Direct detection – DM scattering from nuclei
- Indirect detection – DM decay in space alters cosmic ray proportions
- Collider searches for DM production – invisible at LHC

Bounds from flavour

- D mixing
- Rare D decay – $D^0 \to \mu\mu, D^0 \to \pi\mu\mu$

Finding allowed parameter space

- We had many constraints, and large parameter space
  - 3 DM particles, 1 mediator, 3x3 coupling matrix.
- Use Multinest – Bayesian inference tool, Monte Carlo Markov Chain
- Produces 1,2 sigma allowed regions



Charm DM
m_ϕ [GeV]
m_χ [GeV]
$m_\chi = m_\phi$
2σ : $\Delta m/m_\chi = 15\%$
2σ : $\Delta m/m_\chi = 2\%$
10^0
10^1
10^2
10^3
10^4
10^5

Charm is a possibility

- Takeaway message is that with a large coupling to charm (dominant over top, up) there are relatively light DM and mediator masses still allowed.
- Possibility of D mixing ruling out or in these extended models

Sum rules for mixing and lifetime matrix elements

- 1711.02100
- With Alex Lenz, Thomas Rauh

Sum rules for mixing and lifetime matrix elements

- Matrix elements of effective operators are vital to predictions of meson mixing and meson lifetimes
- Both in the SM, and for possible BSM effects
- Standard way of determing them – lattice QCD

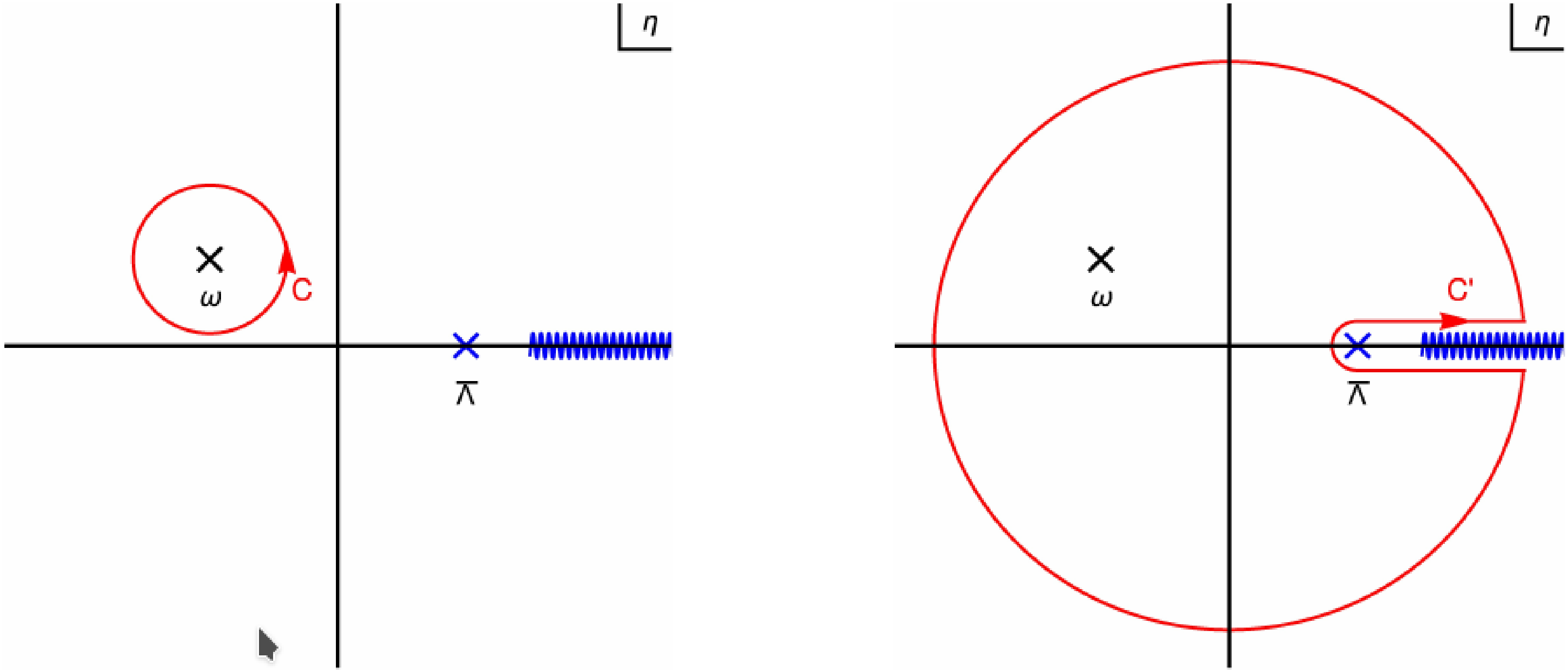
Sum rules

- Different technique to lattice – can provide an independent determination
- Based on quark hadron duality, and analyticity of correlation functions

Sum rules

- Use quark hadron duality + Cauchy residue theorem

Deform the contour:



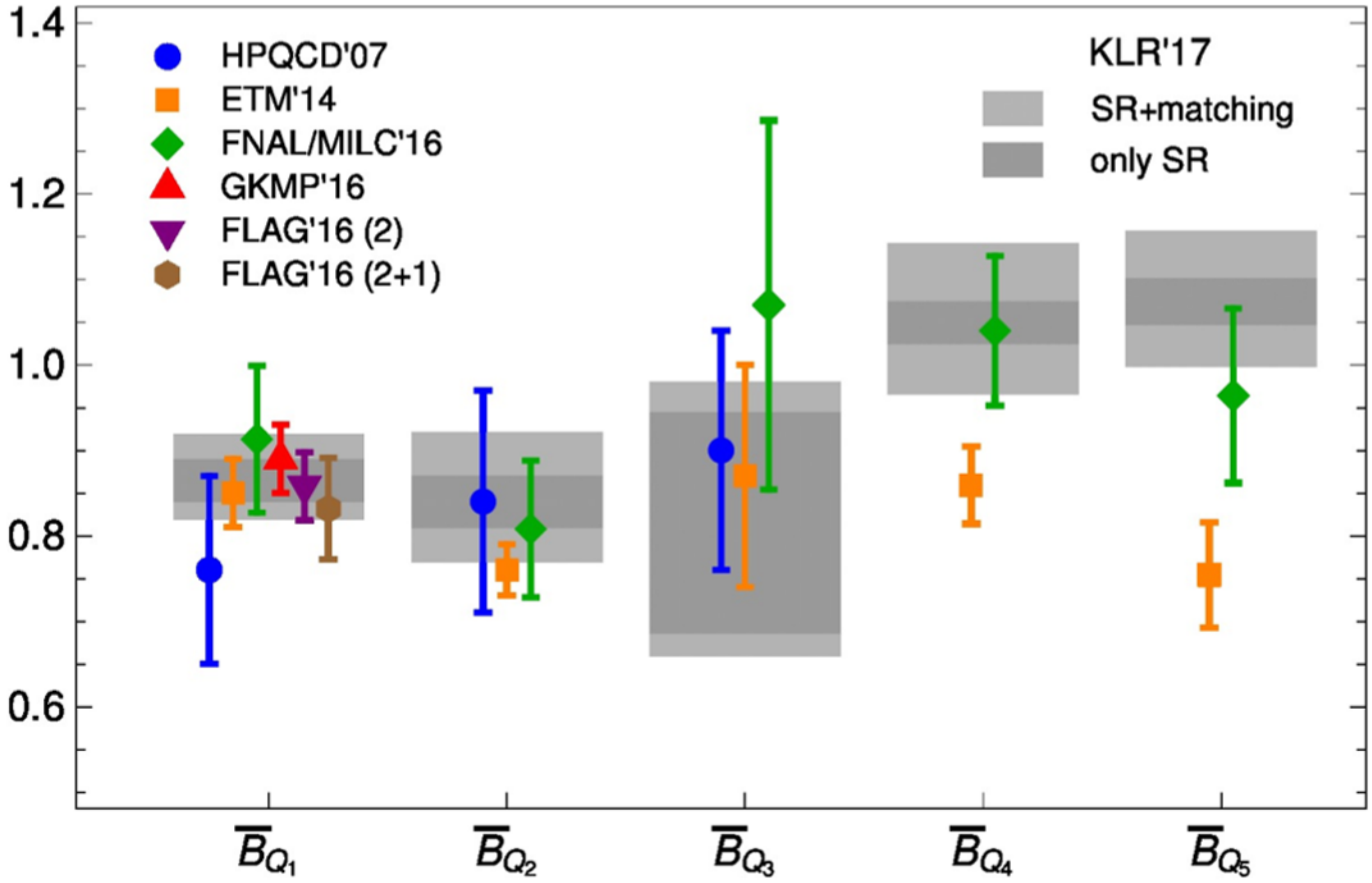
$$\Pi(\omega) = \int_0^\infty d\eta \, \frac{\rho_\Pi(\eta)}{\eta - \omega} + \oint d\eta \, \frac{\Pi(\eta)}{\eta - \omega}$$

Can be computed with an OPE when ω is far away from the physical cut

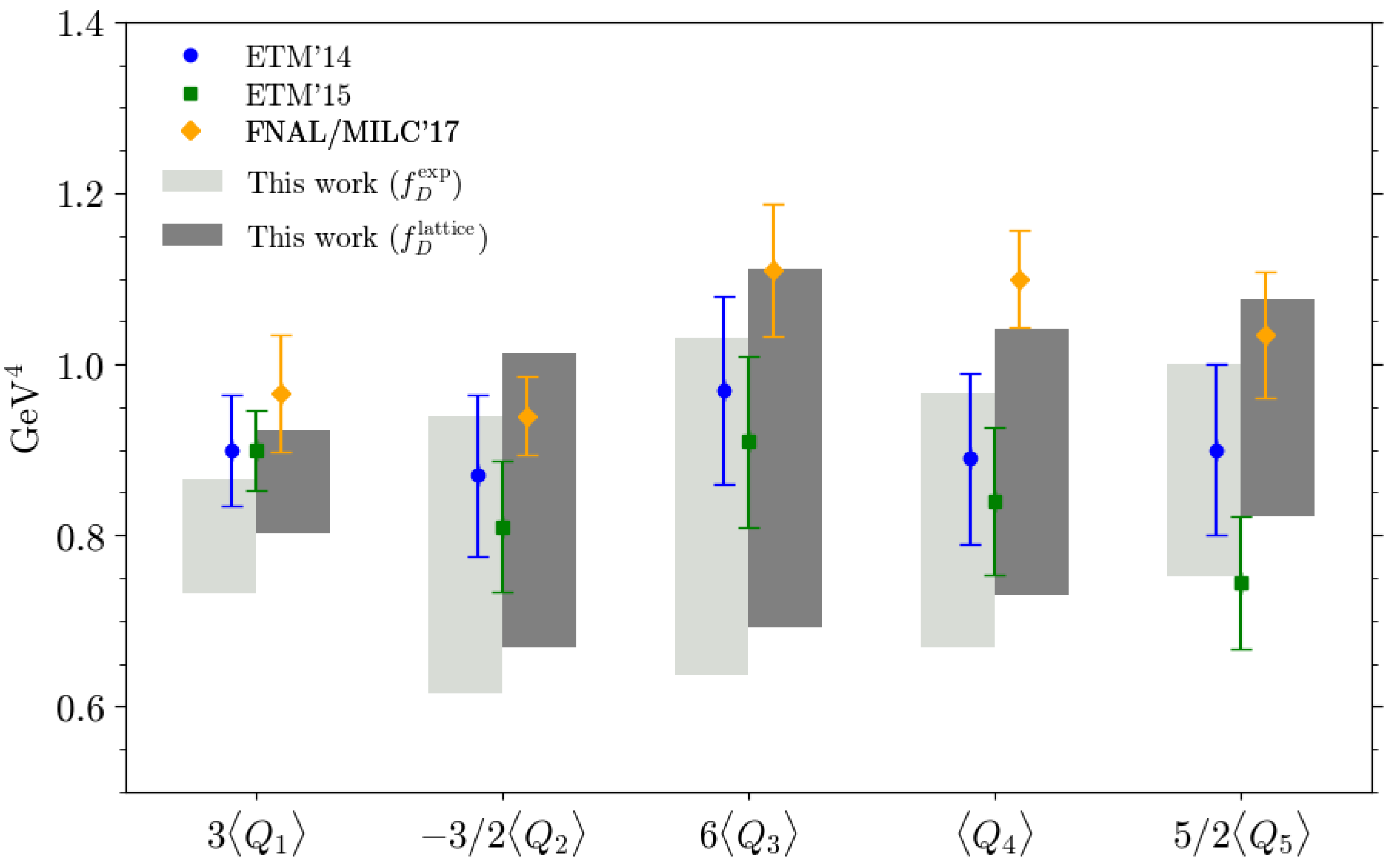
Sum rules

- We can formulate the sum rule to calculate just deviation from VSA, i.e. $\Delta B = B - 1$
- Allows for better precision in results
  - $\Delta B = O(0.1)$ with O(10%) error
  - $B = O(1)$ with O(1%) error

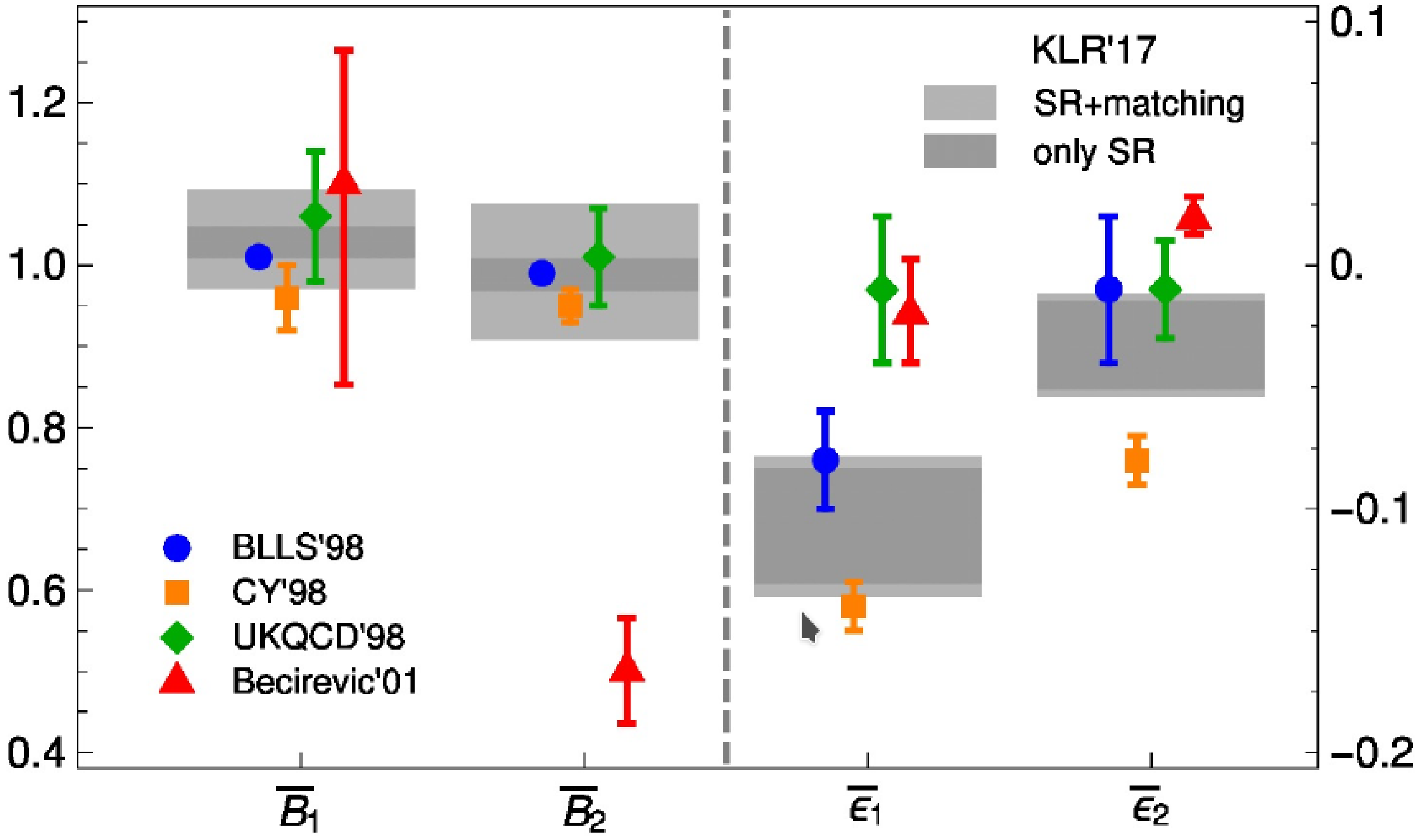
B Mixing results



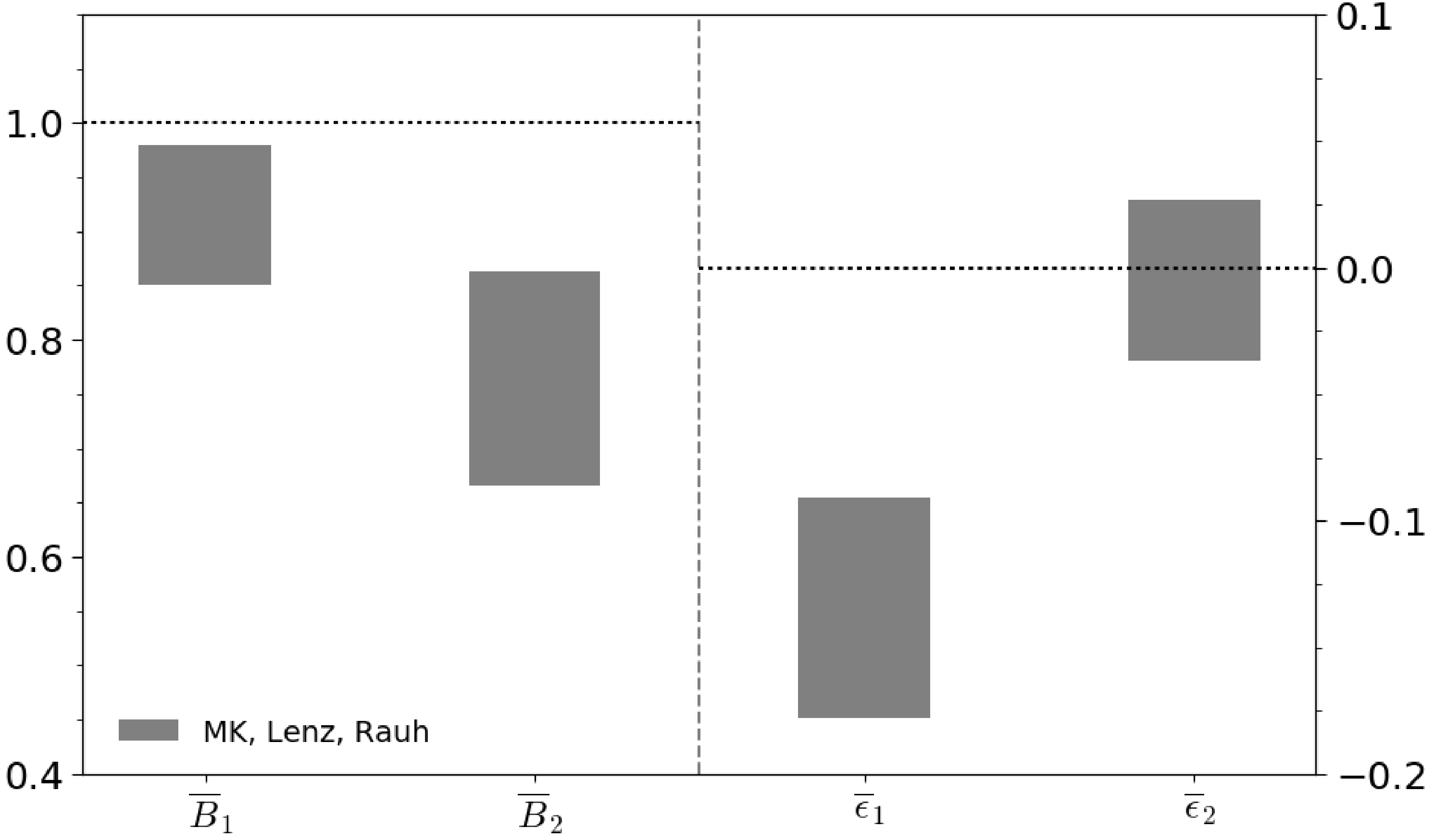
D Mixing results



B lifetimes results



D Lifetimes results



Sum rules vs lattice

- For B sector, our results are comparable in precision to lattice
  - Nice to have independent check
- For D mixing we are again comparable
- For D lifetimes, we are the only calculation available

$$\tau\left(D^{+}\right)/\,\tau\left(D^{0}\right): \mathrm{exp} = 2.536 \pm 0.019 \qquad \mathrm{theory} = 2.2^{+1.7}_{-1.8}$$

Sum rules vs lattice

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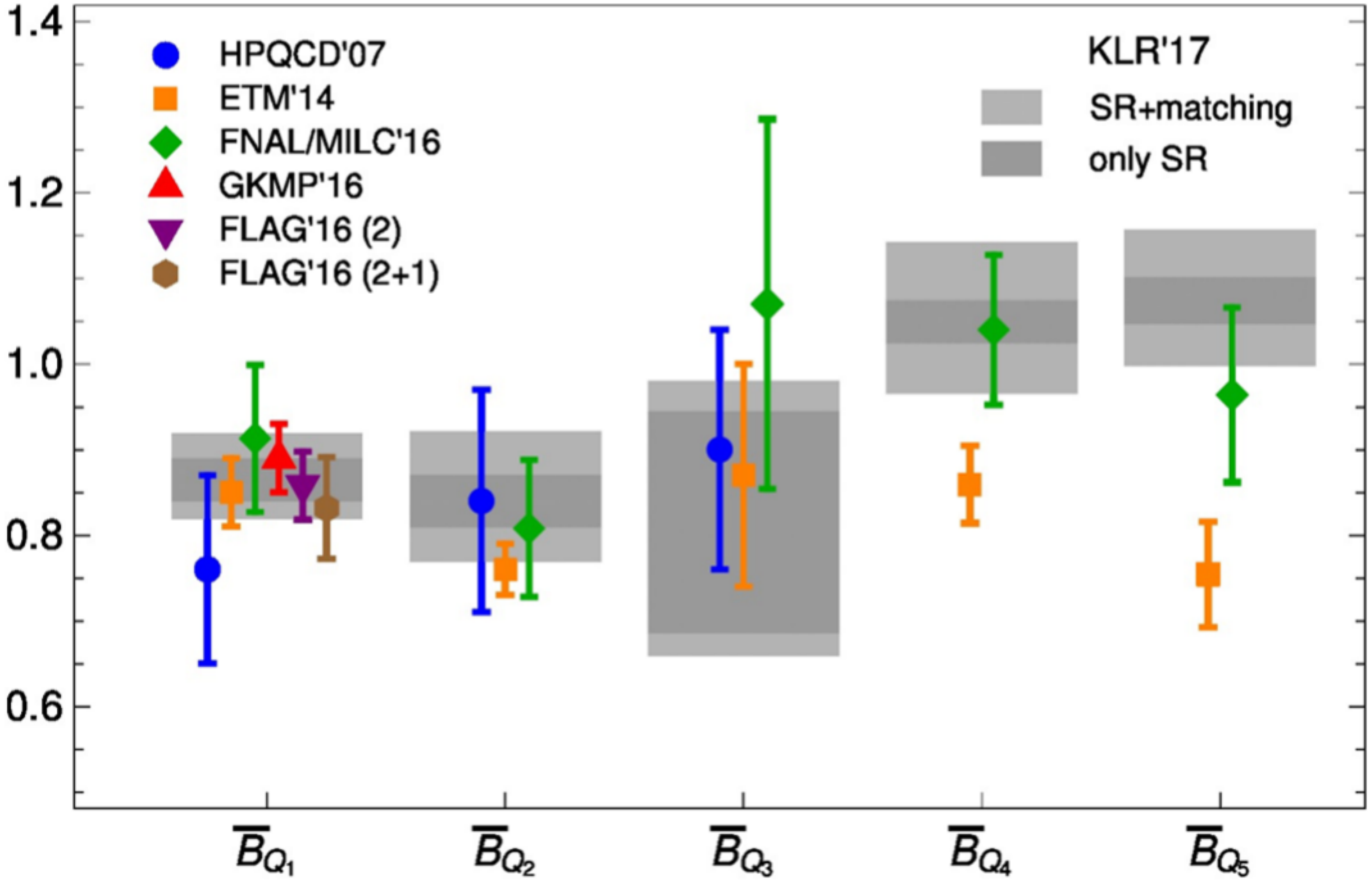
$\tau(D^+)/\tau(D^0): \mathrm{exp} = 2.536 \pm 0.019$ $\quad$ $\mathrm{theory} = 2.7^{+0.74}_{-0.82}$

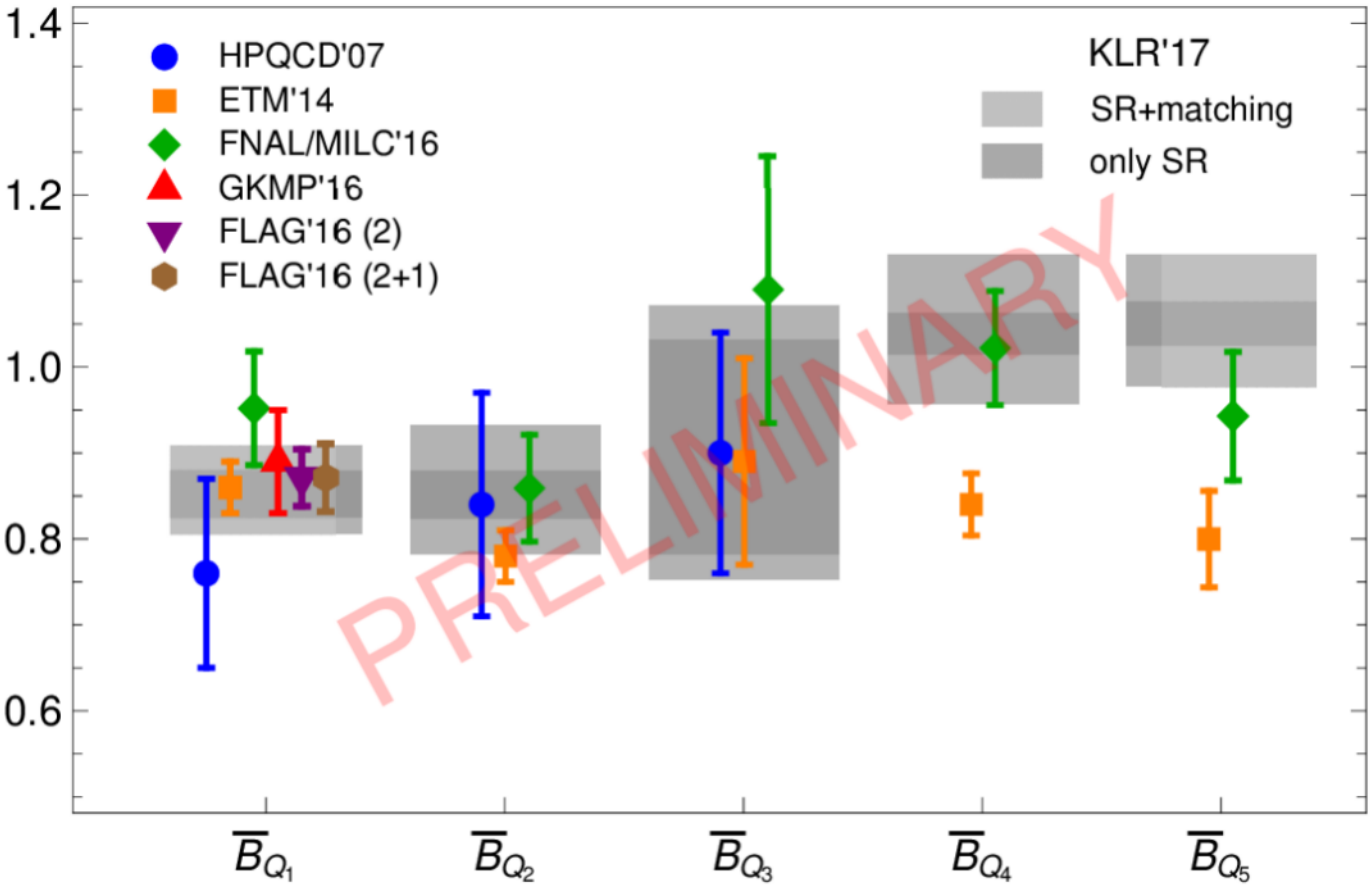
Ongoing work with sum rules

- Strange mass corrections
- Dim7 operators

B_d bag parameters



B_s bag parameters



Dimension 7 operators

$$R_2 = \frac{1}{m_b^2}\bar{b}_i \overleftarrow{D}_\lambda \gamma_\mu (1-\gamma^5) D^\lambda q_i \; \bar{b}_j \gamma^\mu (1-\gamma^5) q_j,$$
$$R_3 = \frac{1}{m_b^2}\bar{b}_i \overleftarrow{D}_\lambda (1-\gamma^5) D^\lambda q_i \; \bar{b}_j (1-\gamma^5) q_j,$$

- Leading errors in $\Delta\Gamma$
- From our duality violation paper – can give 1/3 improvement in precison
- Also in progress by HPQCD lattice group

One Constraint to Kill Them All?

- 1712.06572
- With Luca Di Luzio, Alex Lenz

B_s mixing as $R_{K^{(*)}}$ constraint

- Generally, any R_K explanation must be constrained by B_s mixing
  - $(\bar{b}\,s)(\bar{l}\,l)$ operator → $(\bar{b}\,s)(\bar{b}\,s)$ operator at 1 loop
- But e.g. Z′ gives tree level contribution, so even more so

Bs mixing in the SM

- SM prediction for B_s mixing strongly depends on hadronic matrix element of effective operator
- $\Delta M_s^{\mathrm{SM}} \sim |\langle O \rangle|^2$
- Fermilab-MILC produce new calculation in 2016, now dominates the FLAG average

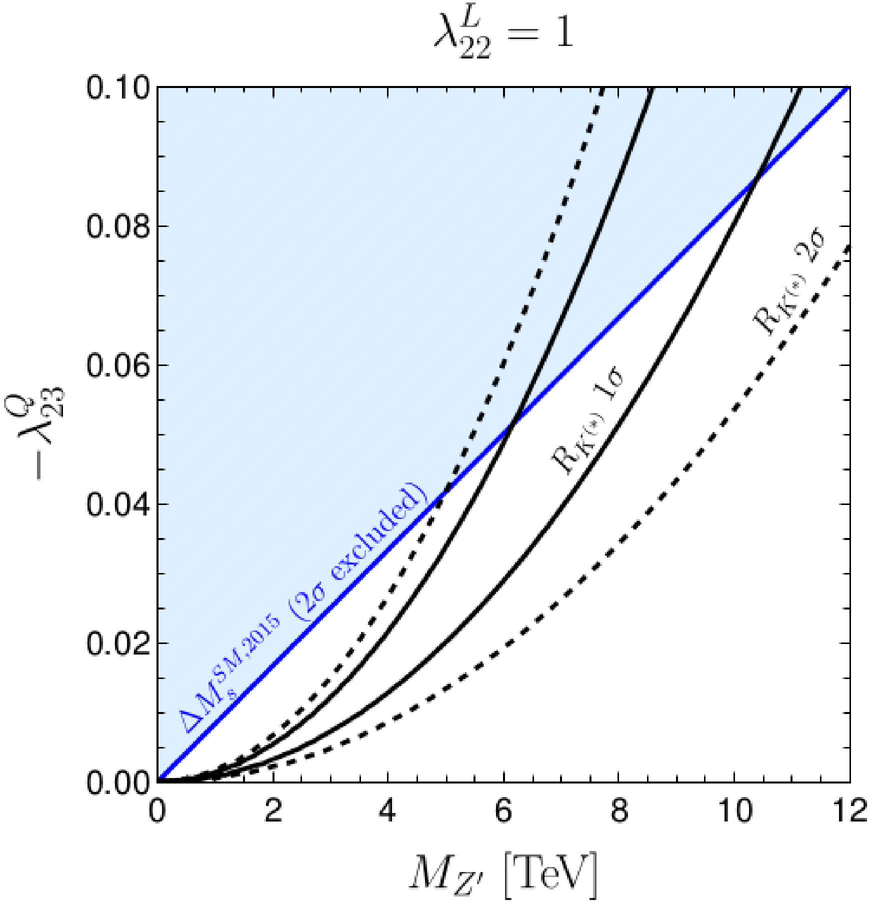
Bs mixing in the SM

- Using previous FLAG average, get $\Delta M_s^{\mathrm{SM}} = 18.3 \pm 2.7\,\mathrm{ps}^{-1}$
- Using new one, get $\Delta M_s^{\mathrm{SM}} = 20.01 \pm 1.25\,\mathrm{ps}^{-1}$
- For comparison, $\Delta M_s^{\mathrm{exp}} = 17.757 \pm 0.021\,\mathrm{ps}^{-1}$
- Gone from agreement to $1.8\,\sigma$ discrepancy

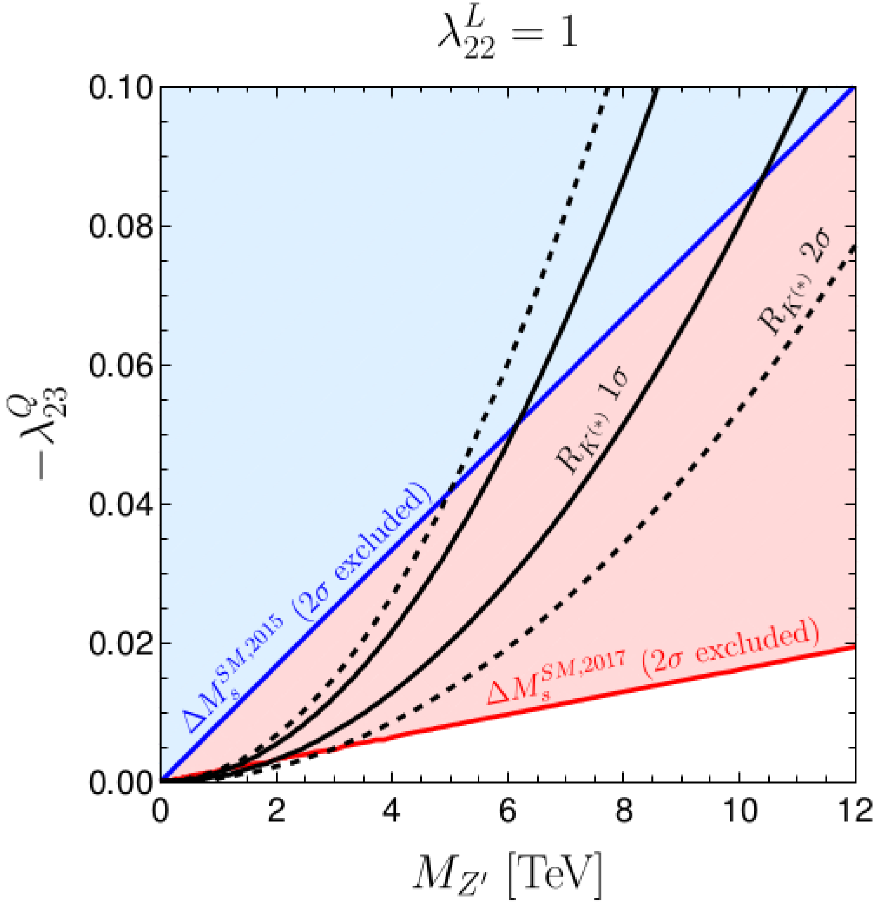
Limits on NP

- Many NP models predict a positive contribution to ΔM_s
- So if SM already above exp, NP increase much more tightly constrained

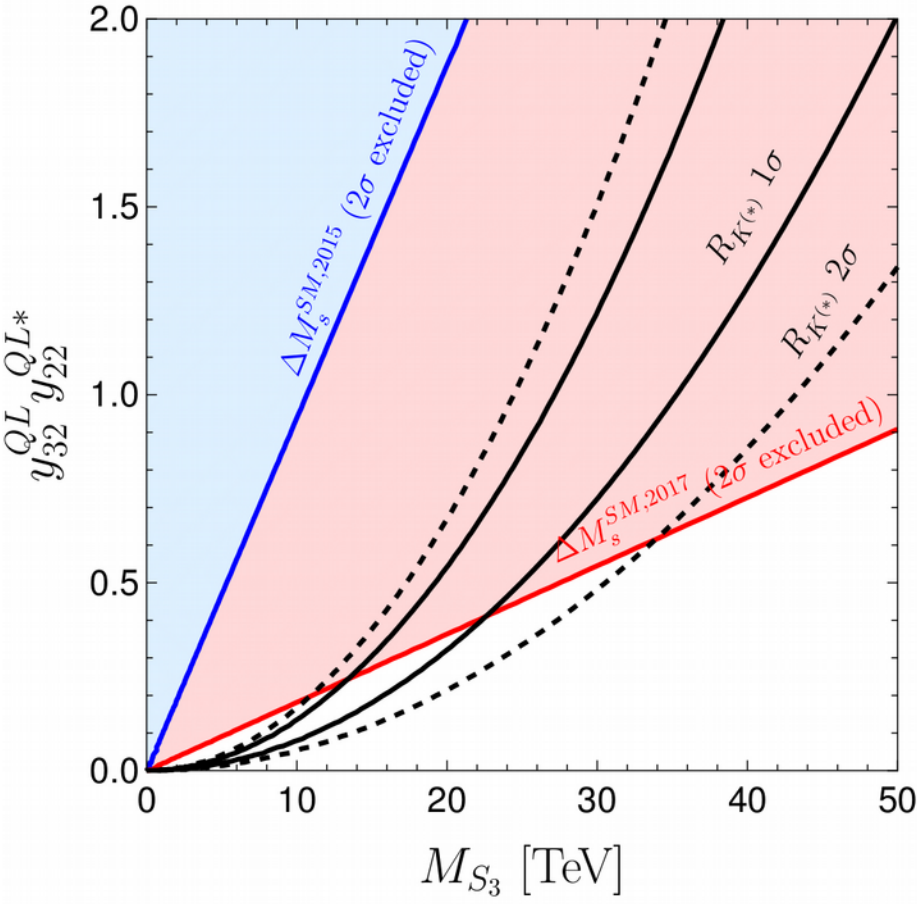
Limits on NP – Z′ (tree contribution)



Limits on NP – Z′ (tree contribution)



Limits on NP – leptoquark (1-loop contribution)

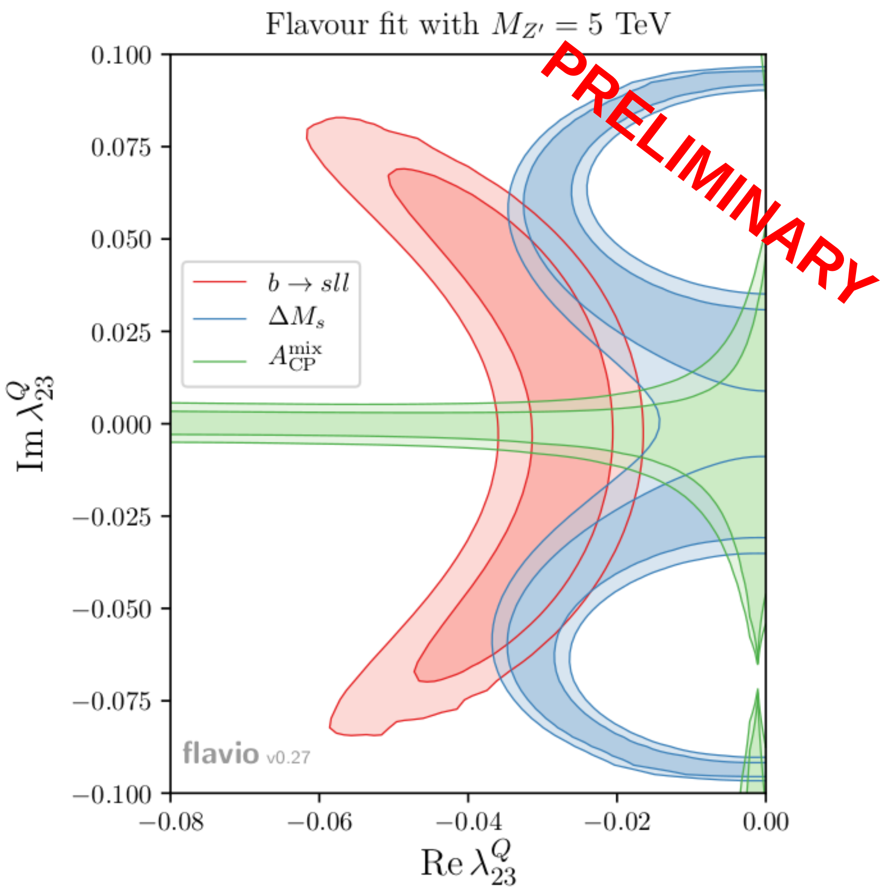


Ongoing work with mixing consraints on NP

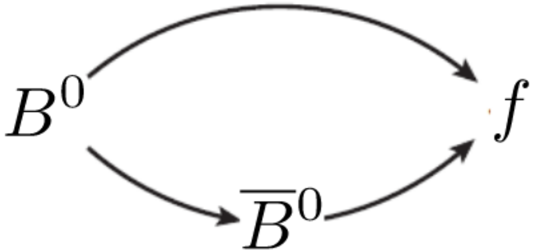
Loopholes

1) F/MILC results will be high compared to other lattice groups → back to old situation
2) Complex coupling → allows negative contribution to ΔM_s
3) Multiple chirality operators → interference allows negative contribution

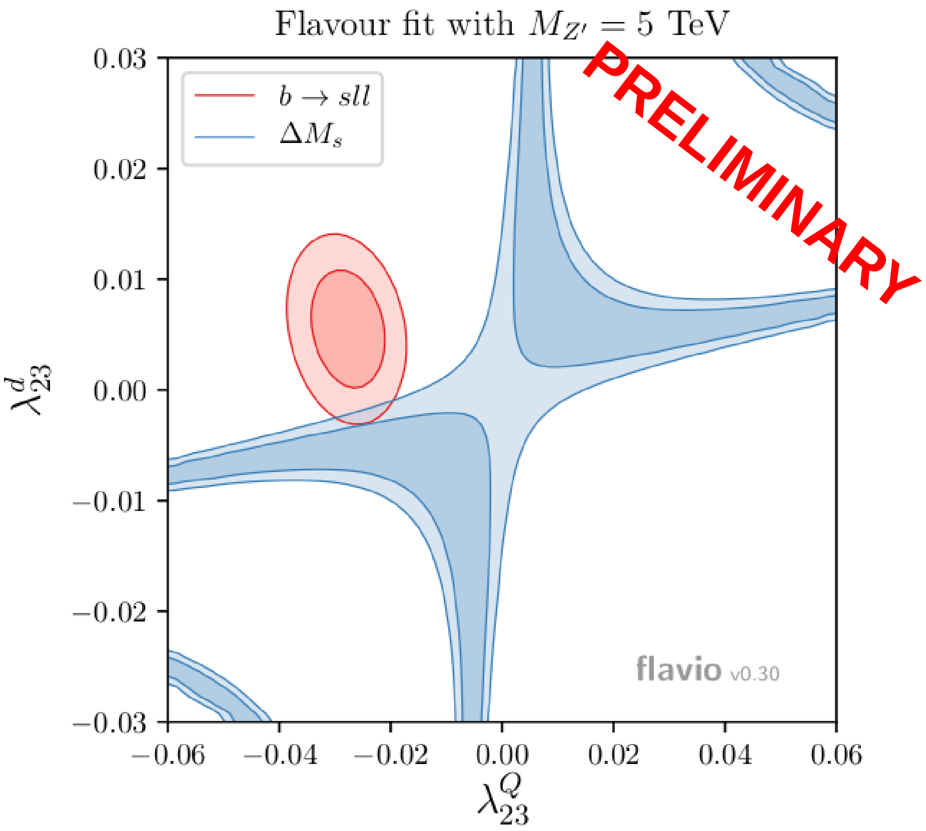
Loopholes – complex coupling



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



Loopholes – different chiralities



- Adding RH coupling allows negative contribution to ΔM_s

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