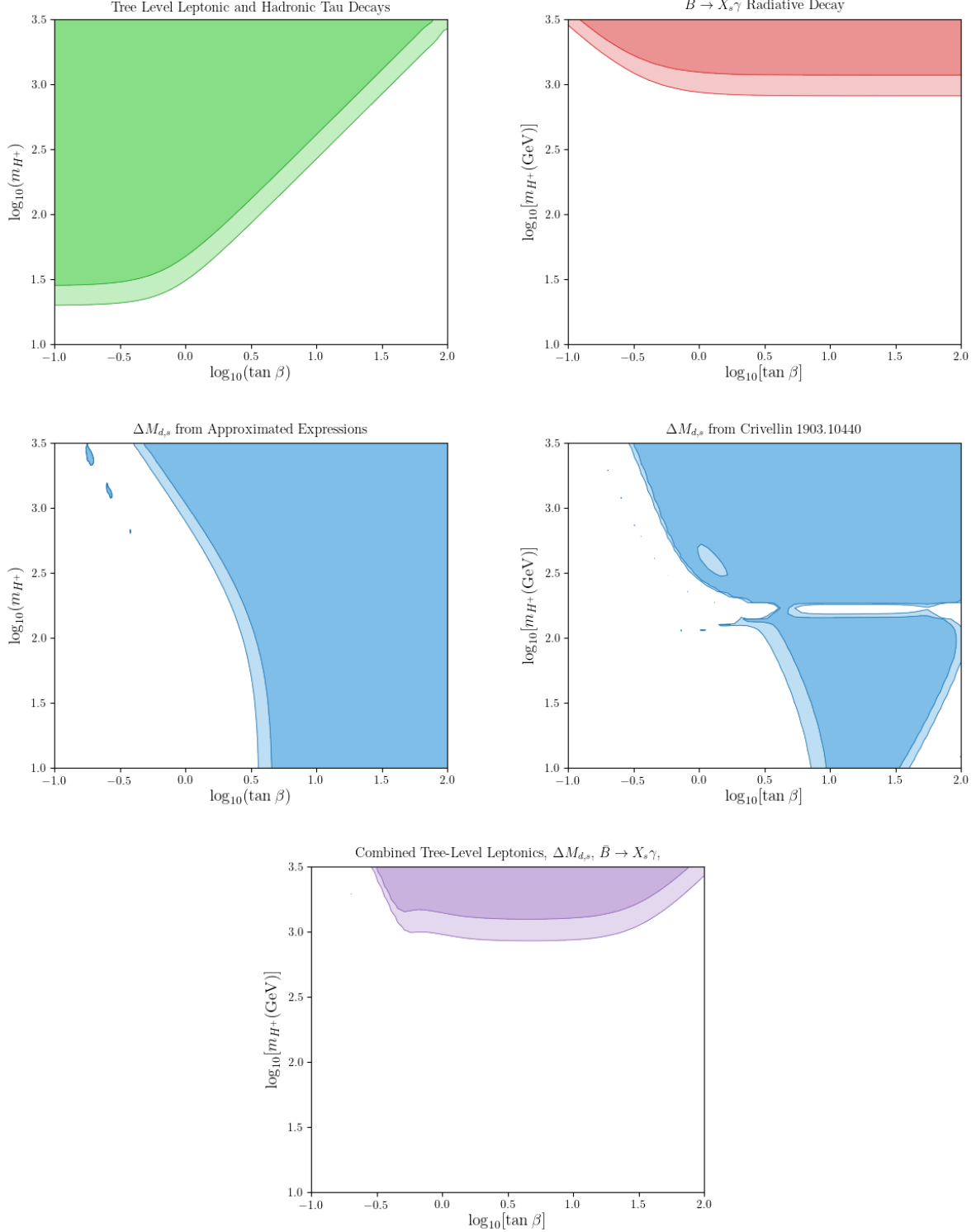


# Project Notes

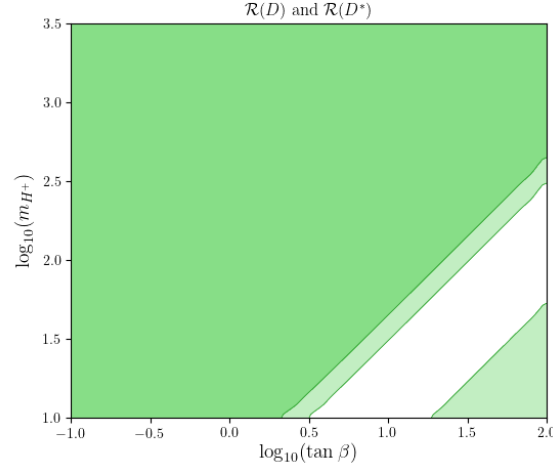
## 1 Replicating results

- Here are my plots for replicating what we did in first term:

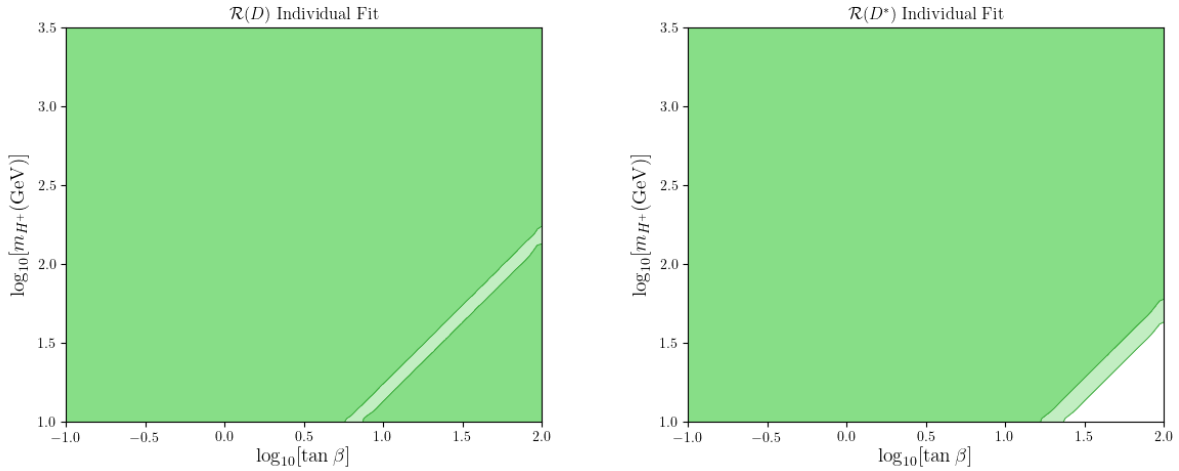


- Like Oliver, the main difference seems to be with  $b \rightarrow s \gamma$  where it fits higher than before – **the combined fit yields  $m_{H^+} \gtrsim 890 \text{ GeV}$  at  $2\sigma$  compared to  $m_{H^+} \gtrsim 500 \text{ GeV}$  in my previous fits**
- *Note: all the plots here are showing contours for  $1, 2\sigma$*
- This is using the higher order  $b \rightarrow s \gamma$  expressions from [Crivellin 1903.10440](#)

- I have modified the SM value in flavio for  $b \rightarrow s\gamma$  to fit the current result of  $(3.40 \pm 0.17)e^{-4}$
- It seems like it could be down to how flavio fits, but we would need to confirm this
- I have also included the fit for B mixing from higher-order expressions in [Crivellin 1903.10440](#) to show the difference – the gap we find around  $m_{H^+} \sim m_t(m_t)$  is due to divergences in the loop functions for this value
- Adding in  $B_{s,d} \rightarrow \mu\mu$  and  $\mathcal{R}(D^{(*)})$  yields similar results to what I had before



- $\mathcal{R}(D)$  and  $\mathcal{R}(D^*)$  are fitting simultaneously it seems right now, which wasn't what we had before, so looking at individual plots:

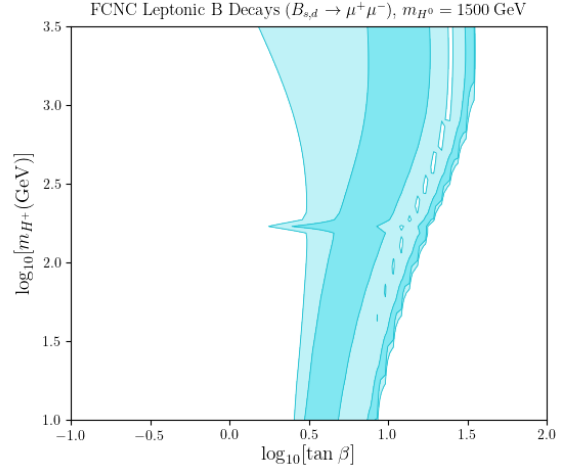
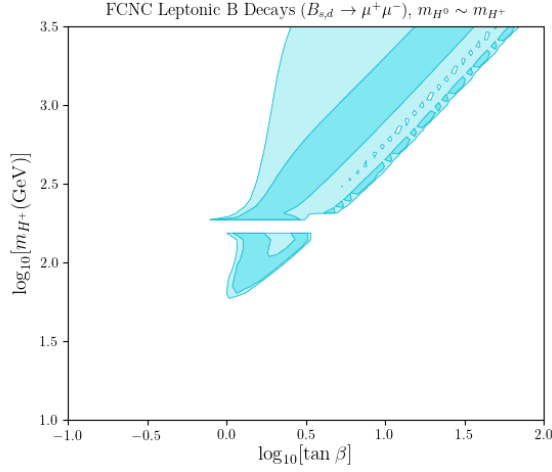


- It appears that both of them do fit individually which is not what we had before – I'm not quite sure why this is the case currently
- For  $B_{s,d} \rightarrow \mu\mu$ , the left diagram is approximating  $m_{H^+} \sim m_{H^0}$  which is the rough limit James has from the obliques, and the right diagram is fixing  $m_{H^0} = 1500$  GeV
- Using the convention from 1903.10440 for the trilinear couplings means that instead of using  $M = m_{12}/(\sin \beta \cos \beta)$  as I did previously, you use  $\lambda_3$  from the 2HDM potential
- The two trilinear couplings we have to consider are

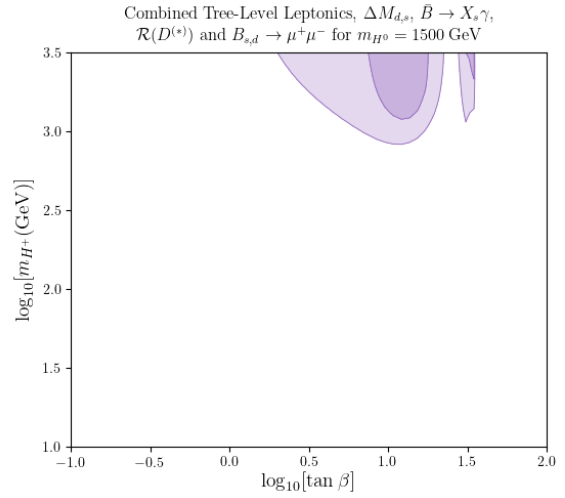
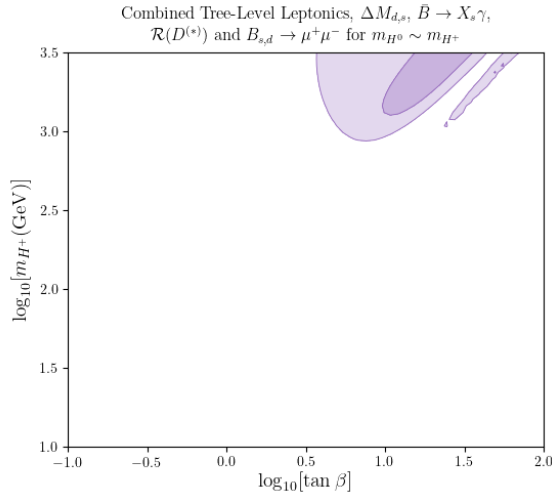
$$\lambda_{h^0 H^+ H^-} = v \sin(\beta - \alpha) \lambda_3,$$

$$\lambda_{H^0 H^+ H^-} = v \cos(\beta - \alpha) \lambda_3$$

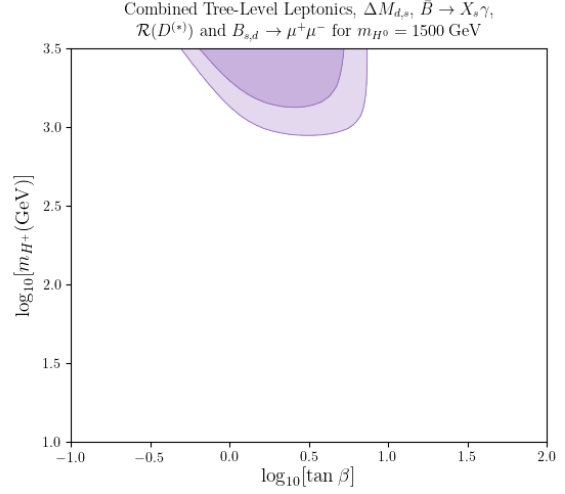
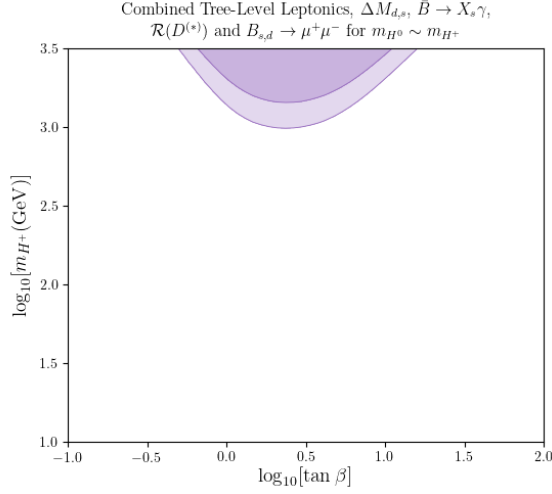
- In the alignment limit which I have been using so far for these,  $\sin(\beta - \alpha) = 1$ , so we only have to consider  $\lambda_{h^0 H^+ H^-}$
- Using the updated values from Y Amhis at ICHEP 2020 and some code updates:



- These seem to preserve the overall shapes of the plots, but shifts constraints towards higher  $\tan \beta$
- Updated global fits incoming to see the change there
- The contributions from the trilinear coupling seems to be minimal anyway, varying  $\lambda_3$  from  $0.01 \rightarrow 2$  doesn't change the results to any noticeable level, so for now I have set  $\lambda_3 = 0.1$
- The coupling only contributes to  $C_S$  and  $C_P$  operators so far which only impact  $B \rightarrow \mu\mu$
- Checking the combined fit for all these observables to compare to my overall project work (bar the inclusion of James' obliques):



- Left is approximating  $m_{H^+} \sim m_{H^0}$  as above for  $B \rightarrow \mu\mu$  (can't compare to project directly as didn't use this limit); right is fixing  $m_{H^0} = 1500$  GeV
- For the left, we have  $m_{H^+} \gtrsim 890$  GeV,  $\tan \beta \gtrsim 3.4$
- For the right, we have  $m_{H^+} \gtrsim 890$  GeV,  $\tan \beta \lesssim 35$ ; in my project for this, I had  $m_{H^+} \gtrsim 500$  GeV and  $\tan \beta \lesssim 21$
- Interestingly, these new plots are beginning to look more similar to my very early work using  $B \rightarrow \mu\mu$  in the large  $\tan \beta$  limit
- Below are the old plots for comparison to the above
- The constraints on  $m_{H^+}$  have not changed at all since this primarily comes from  $b \rightarrow s\gamma$ , but the constraints on  $\tan \beta$  have been significantly shifted to the right



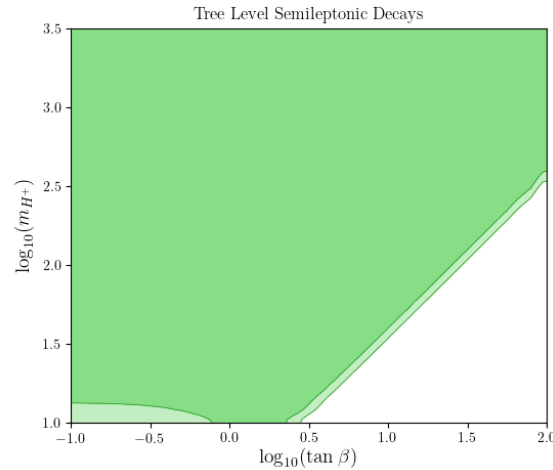
## 2 New Observables and To Do

- Also started looking at the tree-level semileptonic decays
- For semileptonics and leptonics, I think the WC contributions work out the same, e.g. for  $b \rightarrow u \mu \nu_\mu$  (using the subscript convention from [flavio's WET basis](#))

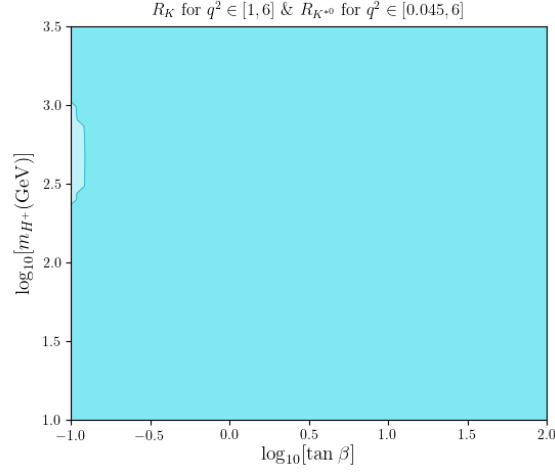
$$\mathcal{O}_{SR} = -\frac{4G_F}{\sqrt{2}} V_{ub} (\bar{u}_L b_R) (\bar{\mu}_R \nu_{\mu L}) \rightarrow C_{SR} = \frac{m_u}{m_{H^+}^2}$$

$$\mathcal{O}_{SL} = -\frac{4G_F}{\sqrt{2}} V_{ub} (\bar{u}_R b_L) (\bar{\mu}_L \nu_{\mu R}) \rightarrow C_{SL} = \frac{m_b \tan^2 \beta}{m_{H^+}^2}$$

- For the tree-level leptonics, this transforms to  $r_H$  from [0907.5135](#), and looks to give the right results for semileptonics (including being used for the  $\mathcal{R}(D)$ s above)
- So providing the SM calculations for the semileptonics are fine, it's quite simple to fit these too:



- The next thing is to look at  $R_K$  and  $R_{K^{*0}}$
- From [1704.05340](#), the operators needed for the  $R_K$ 's are  $C_7, C_7', C_9, C_9', C_{10}, C_{10}'$  for both  $bs\mu\mu$  and  $bsee$  – I think we also need to consider  $C_8, C_8'$  so these are also calculated and included in my fits
- All these can be taken from [1903.10440](#) – the only new WCs are  $C_9, C_9'$  as the others are included in  $b \rightarrow s \gamma$  and  $B \rightarrow \mu\mu$
- So far, we get essentially no constraint in our parameter space from  $R_K$  and  $R_{K^{*0}}$ :



- There still needs to be more checks in case I've missed something, but so far we see a small region excluded at  $1\sigma$  in the left of the plot and that's it
- I want to check in literature for the  $R_K$ s in 2HDM Type II to see if there's any fits that include these to see what results have been found historically to give some at least a rough idea of what should be expected
- I have looked at the fit for the  $R_K$ s in [2007.11942](#) and it's not the easiest to compare to, but it looks like they've found only a small constraint from  $R_K$ s near what would be along the left axis of our plots, which is roughly similar to where we're beginning to see a constraint here
- I need to do the fits including  $B \rightarrow \mu\mu$  in the wrong sign limit too and compare to my previous results