Searches for the S_1 Leptoquark

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Work with Manuel Drees

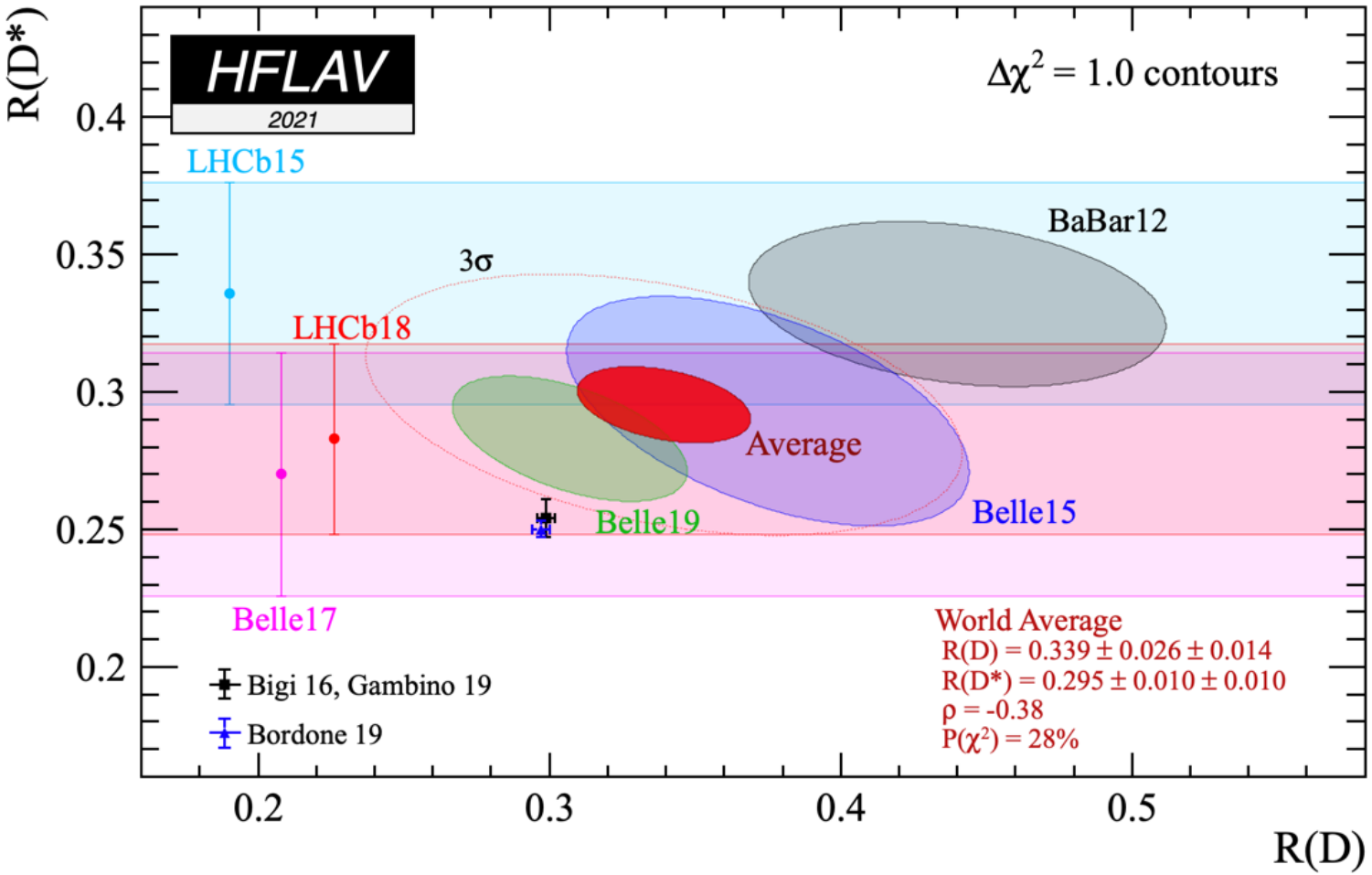
Outline

1. $R_{D^{(*)}}$ anomalies
2. S_1 Leptoquark
3. Existing Constraints
4. Existing Collider Searches
5. Proposed Search

B-anomalies ($R_{D^{(*)}}$)

- Existing experimental anomalies in semi-leptonic decay ($b \to c\ell\nu$):

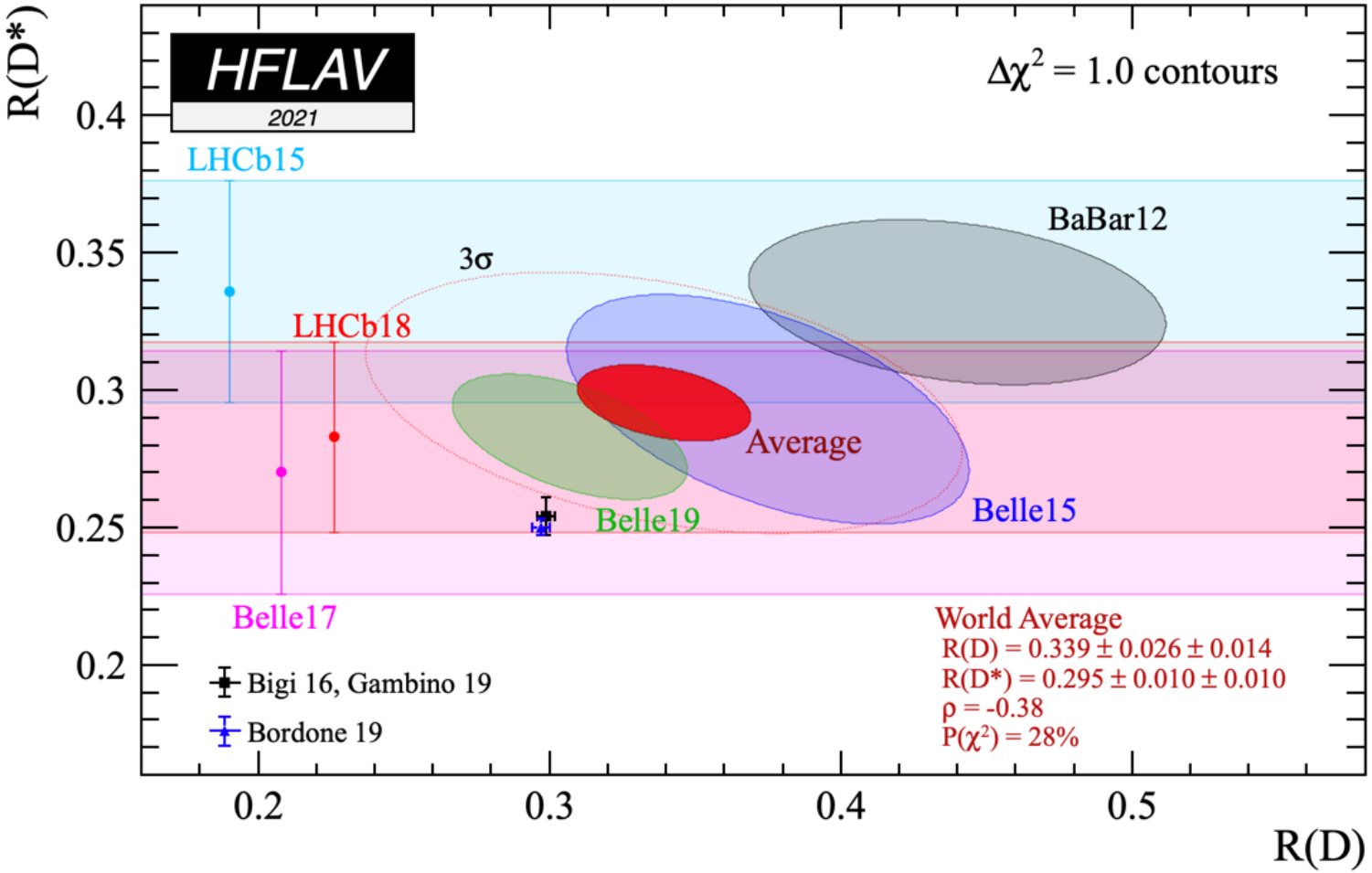
$$R_{D^{(*)}} \equiv \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)} \text{ (with } \ell = e, \mu),$$



B-anomalies ($R_{D^{(*)}}$)

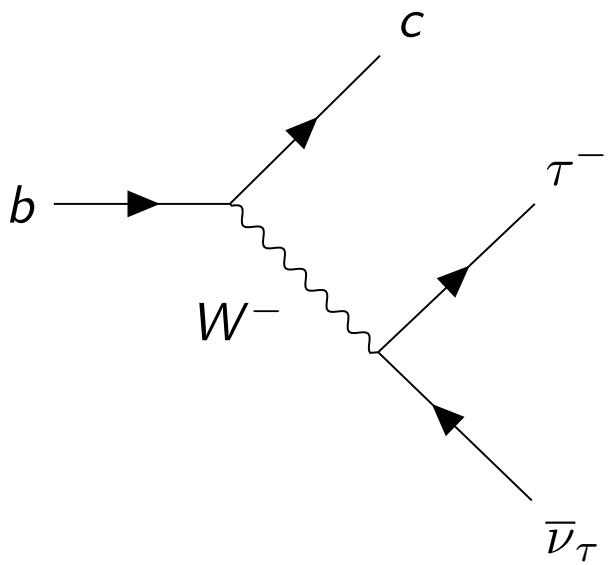
- Current status:

$$R_D : 1.4\sigma, \quad R_{D*} : 2.9\sigma, \quad R_D \text{ and } R_{D*} : 3.4\sigma \tag{1}$$



Lepton Flavor Universality Violation(LFUV)?

- In the SM:



- Lepton Flavor Universality Violation(LFUV) in BSM Physics?

Possible Solution: S_1 Leptoquark

$S_1(\bar{3}, 1, 1/3)$

$$\mathcal{L}_{S_1} = y_L^{ij}\overline{Q_i^C} i\tau_2 L_j S_1 + y_R^{ij}\overline{u_{Ri}^C} e_{Rj} + h.c.$$
$$= S_1[(V^* y_L)_{ij}\overline{u_{Li}^C}\ell_{Lj} - (y_L)_{ij}\overline{d_{Li}^C}\nu_{Lj} + \overline{u_{Ri}^C} e_{Rj}] + h.c.$$

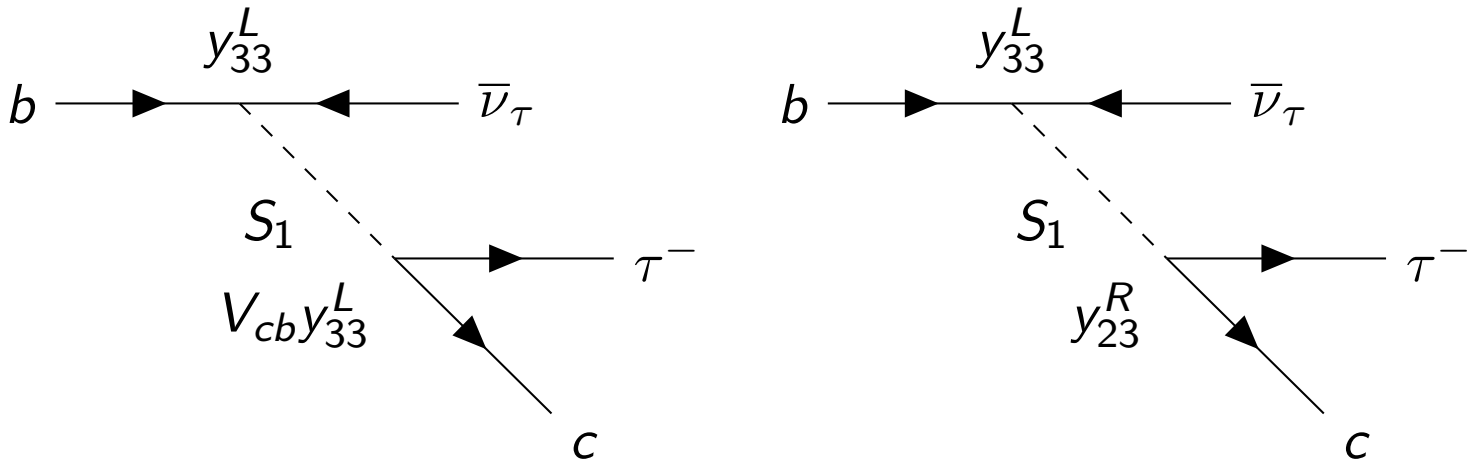


Figure: $b \to c\tau\nu$ via the S_1 leptoquark

We will focus only on the two-coupling case.

Method: Existing Constraints

Low-Energy Flavour Observables

Used DSixTools

- $R_{D^{(*)}}$ anomalies — M.Blanke *et al* [1811.09603]
- $P_\tau(D^*)$: τ polarization of $B \to D^{(*)}\tau^-\overline{\nu}$ — [1811.09603]
- $F_L(D^*)$: D* polarization of $B \to D^{(*)}\tau^-\overline{\nu}$ — [1811.09603]
- $g_V^{Z\overline{\tau}\tau}$, $g_A^{Z\overline{\tau}\tau}$ weak coupling — Y.Cai *et al* [1704.05849]
- $g^{W\overline{\tau}\nu}$ weak coupling — A.Crivellin *et al* [1905.08257]

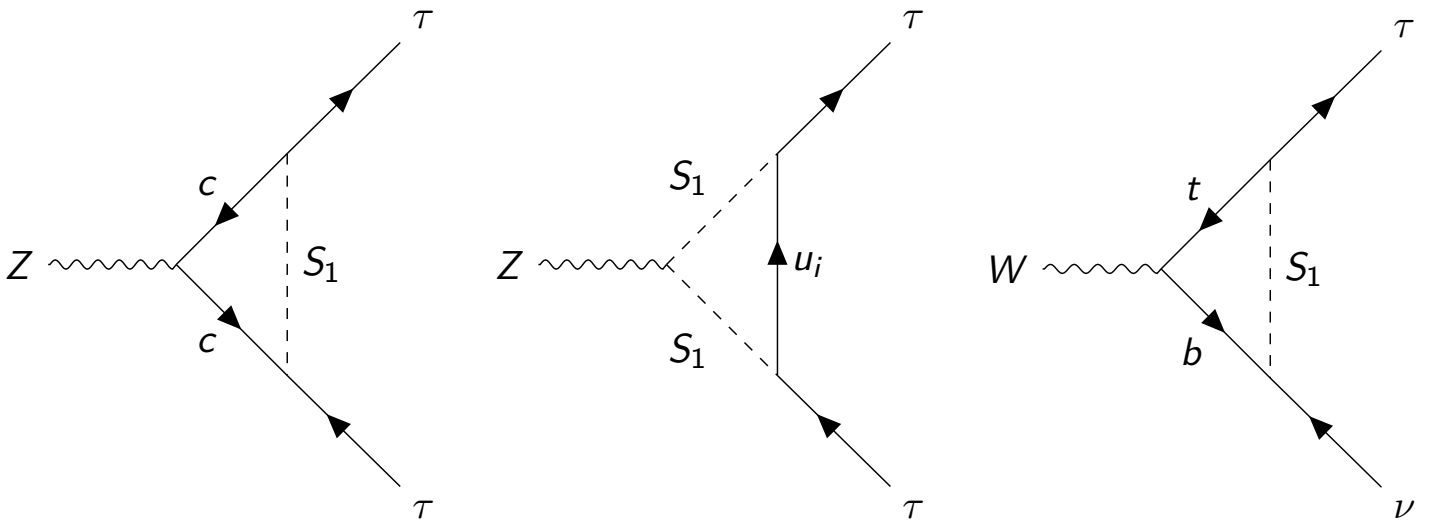


Figure: S_1 leptoquark contribution to W$\tau\nu$ and Z$\tau\tau$ couplings

Best Fit Parameters

- 3-dim parameter space $(M_{S_1}, y^L_{33}, y^R_{23})$
- To reduce it to 2-dim space, we fix our y^R_{23} to its best fitted value considering the relevant observables:

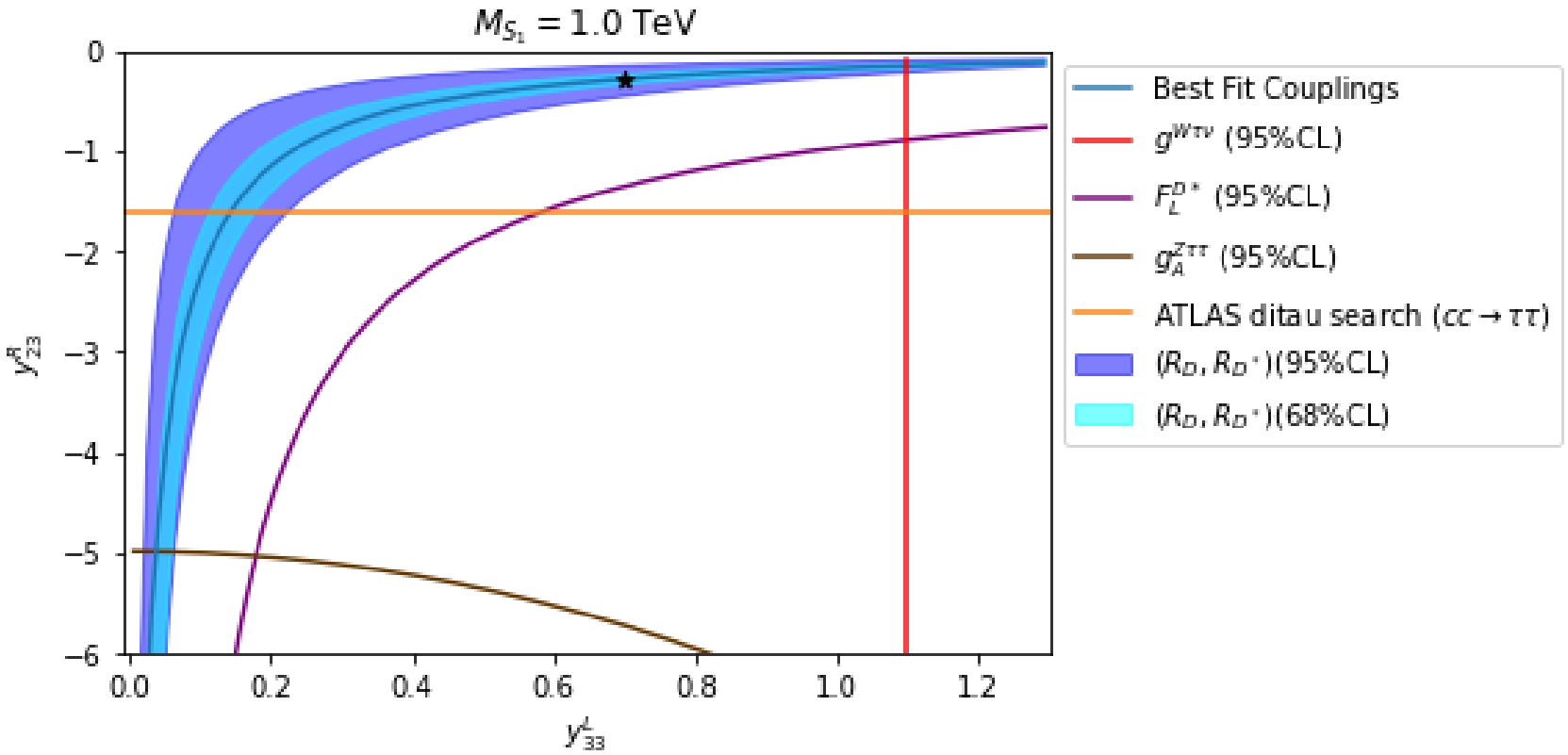


Figure: Couplings of best fit with M_{S_1} =1 TeV

Best Fit Parameters

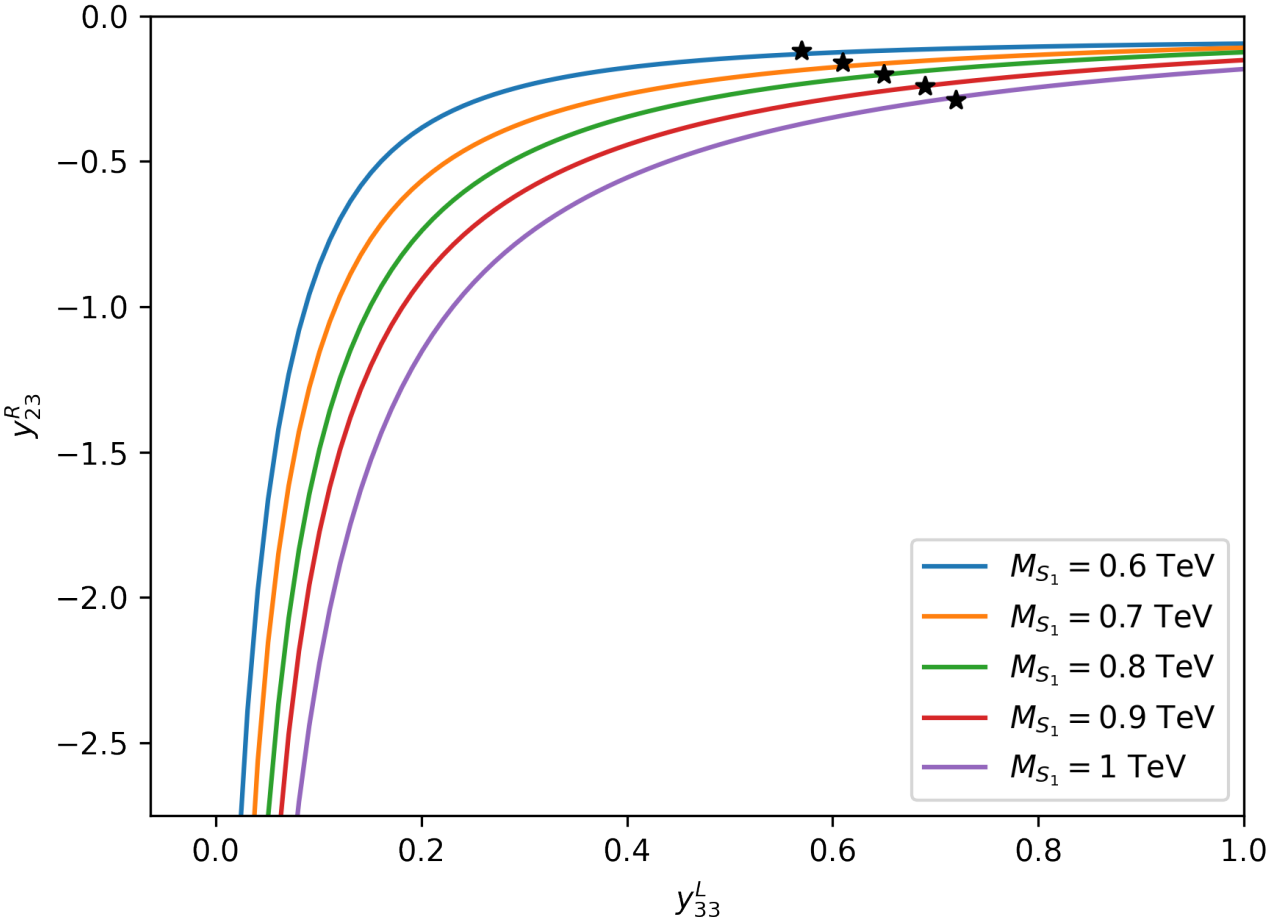


Figure: Couplings of best fit with different M_{S_1}

Method: Existing Constraints

LHC Searches

Used FeynRules, Madgraph, Pythia8, Delphes, Tauola, CheckMATE

- 3rd Gen. LQ Searches $(tt\tau\tau)$ ATLAS @ 13TeV, 139fb^{-1} [2101.11582]
- SUSY Searches $(bb + MET)$ ATLAS @ 13TeV, 36fb^{-1} [1708.09266]
- Z' Searches $(\tau\tau)$ ATLAS @ 13TeV, 36fb^{-1} taken from A. Angelescu *et al* [1808.08179]

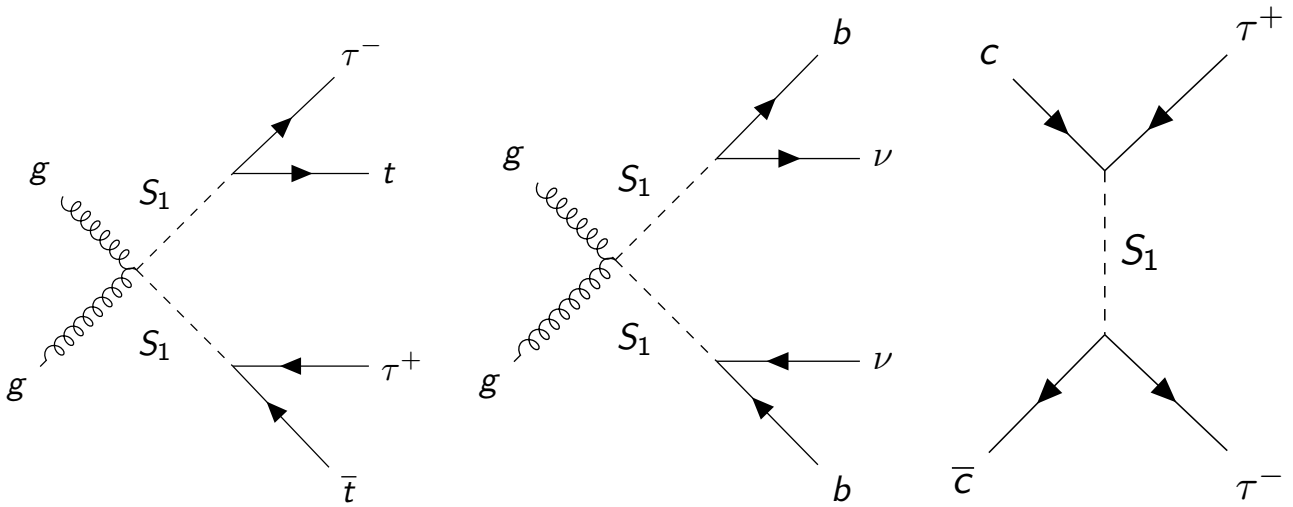
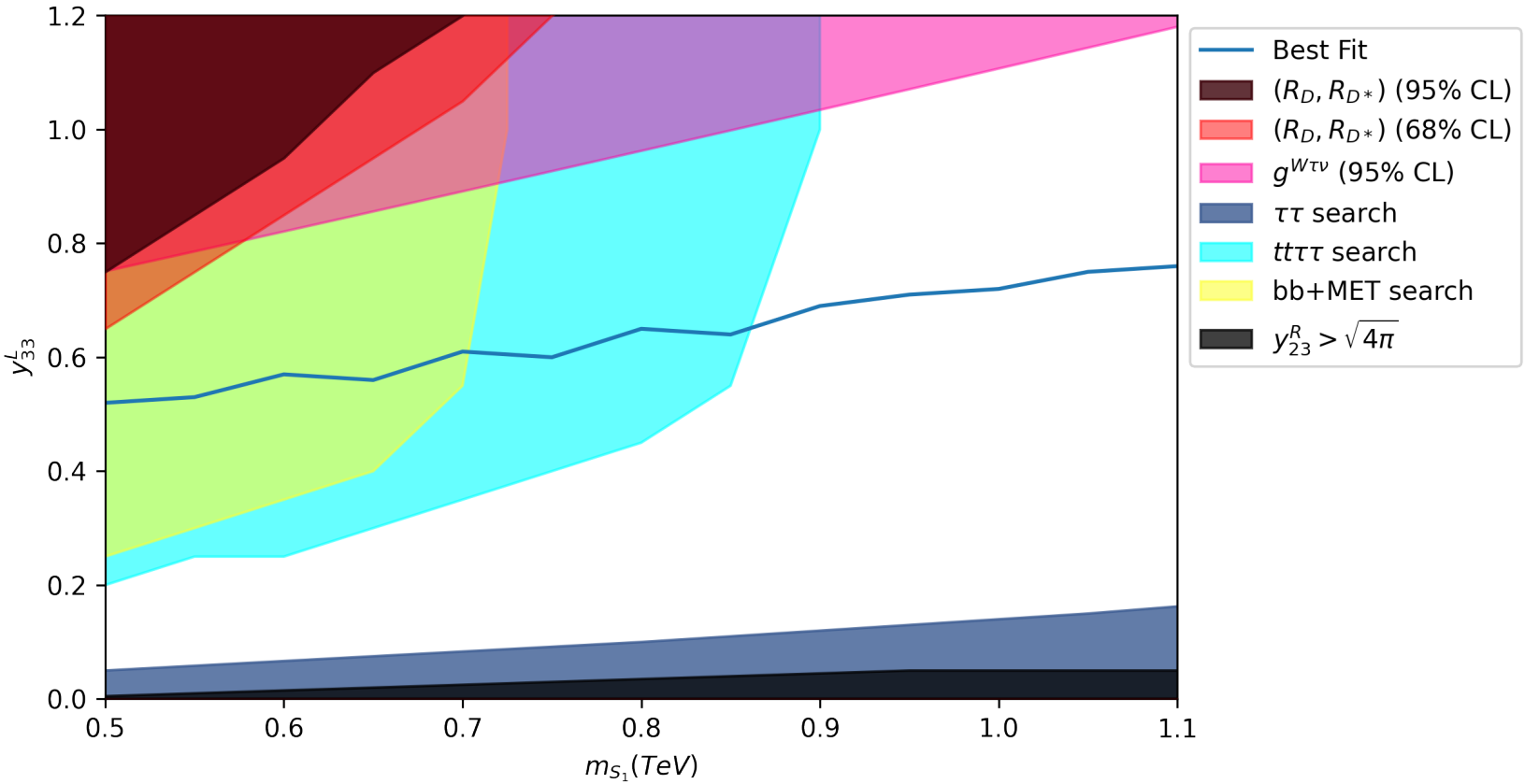


Figure: Examples of processes in LHC searches

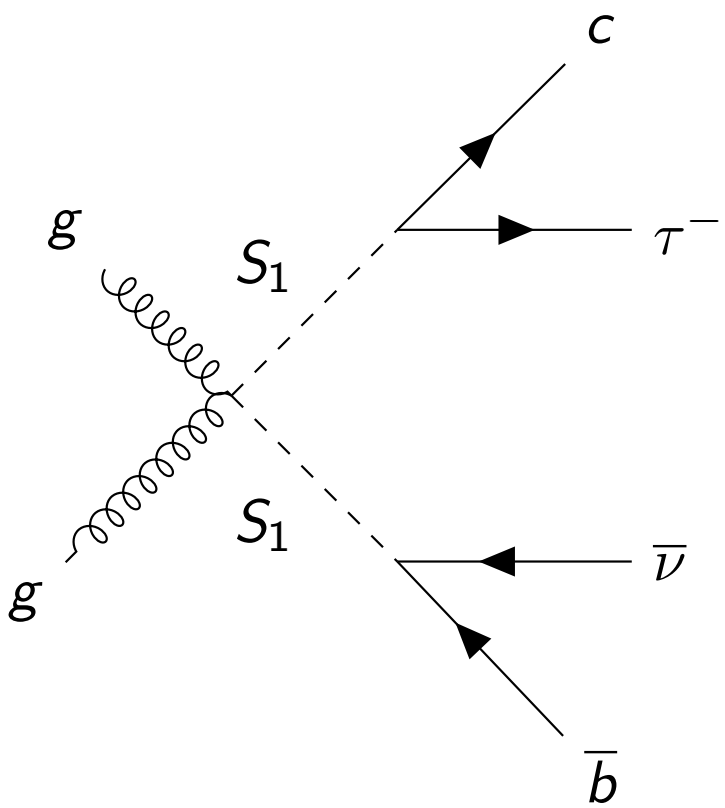
Results



- Still some unconstrained parameter space region left

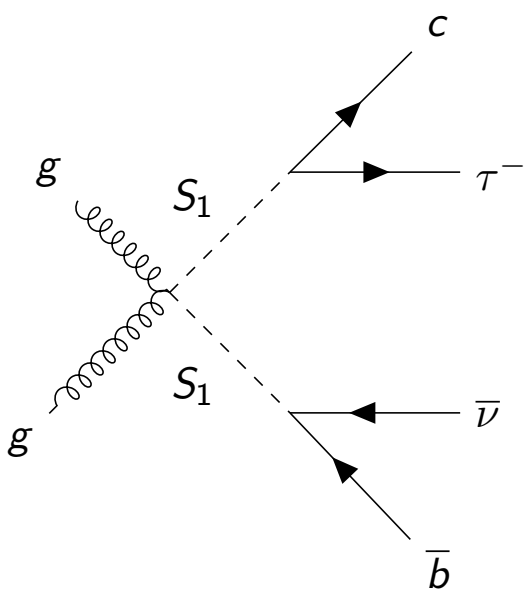
$c\tau b\nu$ Search

- Unconstrained parameter space region can be searched using the b+j+τ_h+MET signature (Recall $b \to c\tau\nu$)



Check current reachable LHC capabilities ($139\,\text{fb}^{-1}$) at 13 TeV

$c\tau b\nu$ Search: Background Processes



Background process

- W+jets :
  $W + jj \to \tau\nu jj$, $W + j \to \tau\nu j$
- $t\bar{t}$:
  $WbWb \to jj\tau\nu\tau\nu$, $WbWb \to jjjj\tau\nu$
- single top :
  $jWb \to jj\tau\nu$
- Z/γ+jets :
  $Z/\gamma + jj \to jj\tau\tau$, $Z/\gamma + j \to j\tau\tau$
- QCD background(multijets)

$c\tau b\nu$ Search: Cutflow

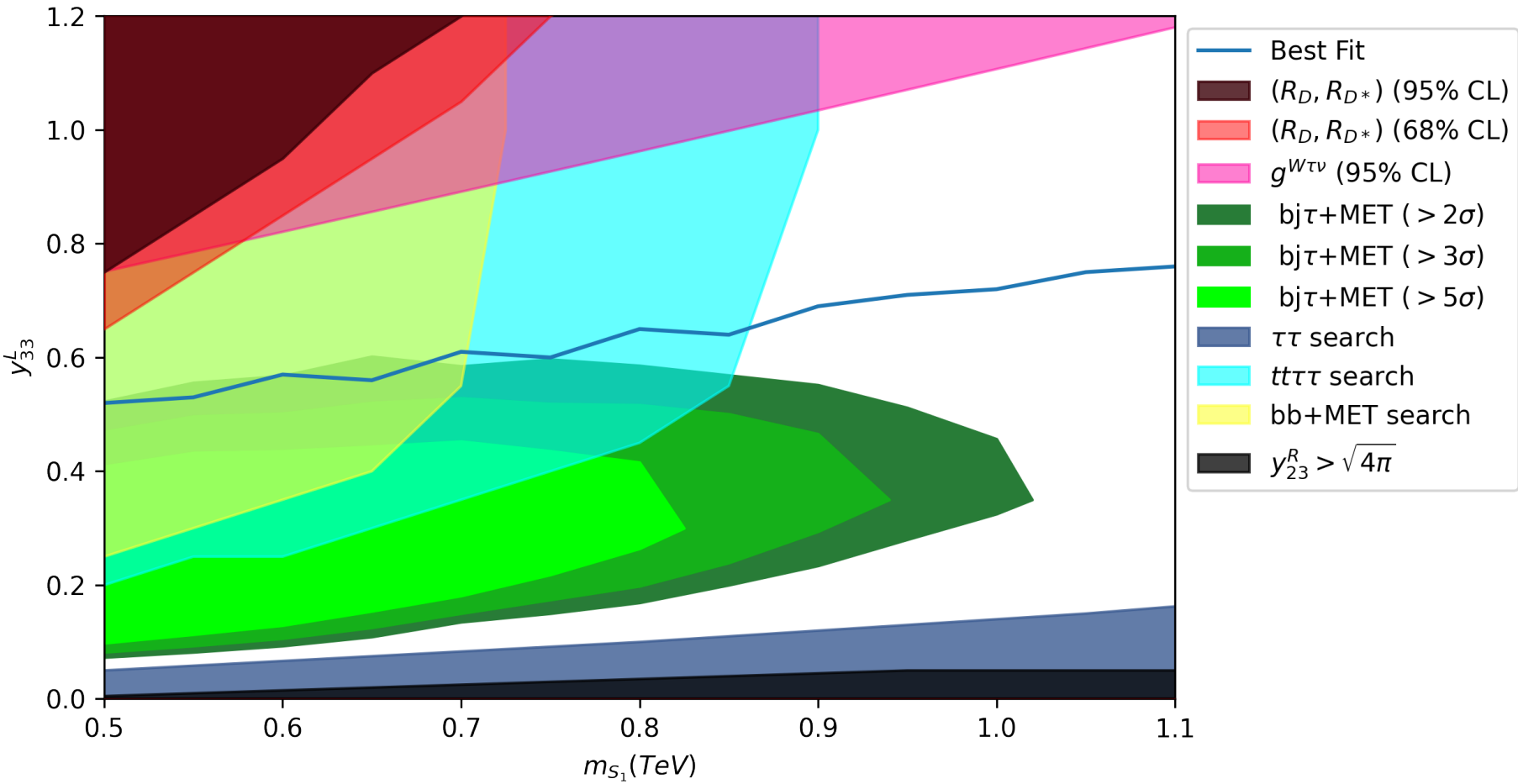
Benchmark:

$$y_L^{33} = 0.2, \quad y_R^{23} = -0.7, \quad m_{S_1} = 800\,\text{GeV}, \tag{2}$$

Cutflow of our event selection process:

Cuts	Total Background,B	Signal,S	Significance, $S/\sqrt{B}$
Basic Cuts	77752.832	88.382	0.316
$p_T^{\text{sum}} > 900\,\text{GeV}$	4210.600	71.340	1.099
$\text{MET} > 200\,\text{GeV}$	3558.907	60.742	1.018
$p_T(\tau) > 200\,\text{GeV}$	673.752	40.198	1.548
$p_T(b) > 150\,\text{GeV}$	377.098	32.821	1.690
$p_T(j) > 50\,\text{GeV}$	360.185	31.479	1.658
$m_{\text{inv}}(b,j) > 100\,\text{GeV}$	357.208	31.398	1.661
$m_T(\tau, \text{MET}) > 350\,\text{GeV}$	14.331	21.650	5.718
$r > 0.6$ or $r < 0.2$	10.650	19.792	6.064

Results: b+j+τ_h+MET signature



- The discovery sensitivity of proposed search is at current LHC capabilities (13TeV at 139fb^{-1})

Conclusion

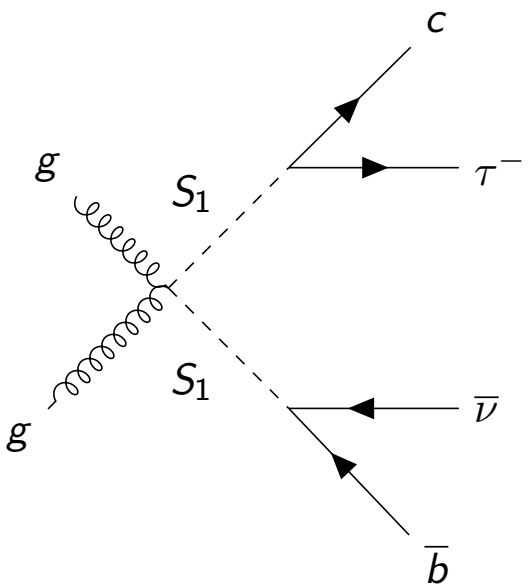
1. $R_{D(*)}$ anomalies have been here for awhile now
2. S_1 LQ is one of the possible single LQ solution
3. There are still possible gap in collider searches
4. Can be patched up with b+j+τ_h+MET search

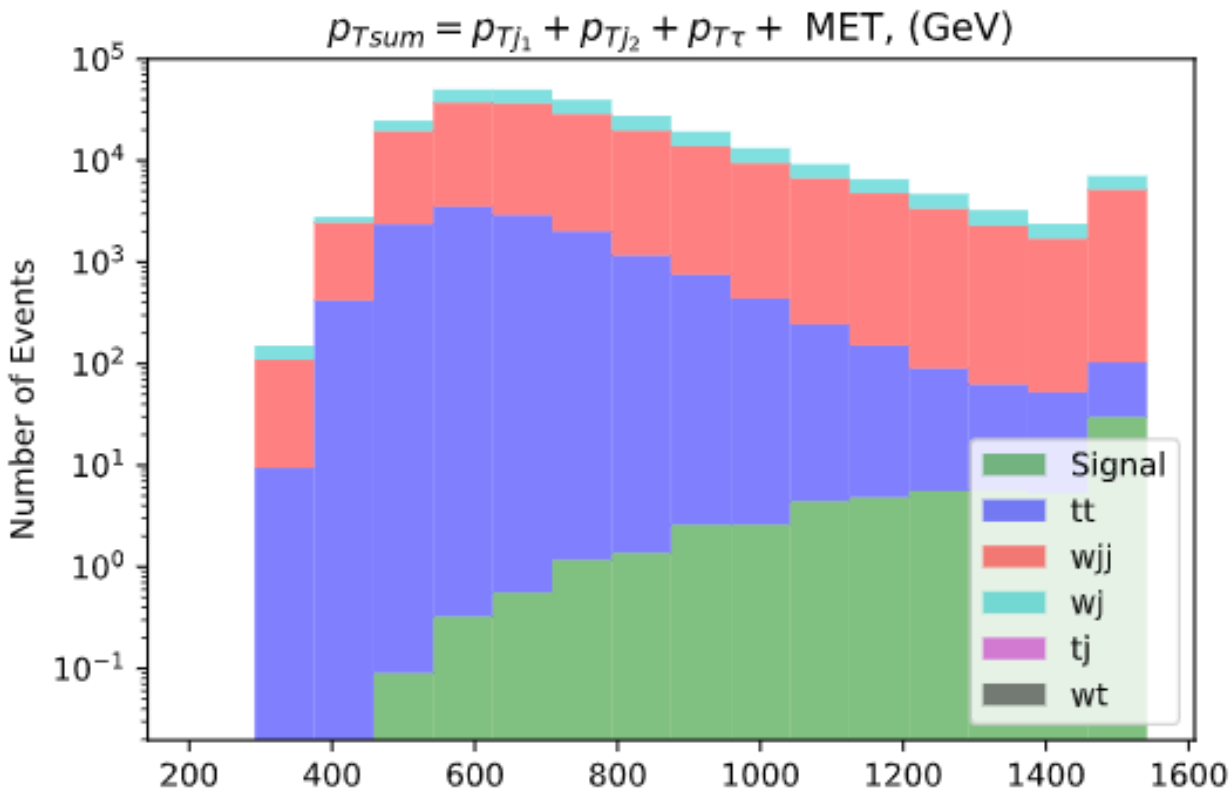
Thanks

Questions?

Backup: $c\tau b\nu$ Search: Developing cuts

The best way to come up with cuts is to have an idea of how the distributions of the variables look like. We want to take away as much back ground while still retaining most of our signal. As an example, looking at p_T sum:





Possible Solution: S_1 Leptoquark

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$$\mathcal{L}_{S_1} = y_L^{ij}\overline{Q_i^C} i\tau_2 L_j S_1 + y_R^{ij}\overline{u_{Ri}^C} e_{Rj} + h.c.$$
$$= S_1[(V^* y_L)_{ij}\overline{u_{Li}^C}\ell_{Lj} - (y_L)_{ij}\overline{d_{Li}^C}\nu_{Lj} + \overline{u_{Ri}^C} e_{Rj}] + h.c.$$

Variations of the model:

- $S_1 + S_3$ leptoquark : $R_{D^{(*)}}$, $R_{K^{(*)}}$, g-2 — V. Gherardi *et al* [2008.09548]
- $S_1 + R_2$ leptoquark : $R_{D^{(*)}}$, $R_{K^{(*)}}$, g-2, m_ν — D. Zhang *et al* [2105.08670]
- $S_1 + \phi^+$ charged singlet : $R_{D^{(*)}}$, $R_{K^{(*)}}$, g-2, $|V_{us}|$ — D. Marzocca *et al* [2104.05730]
- $S_1 + \chi_0, \chi_1$ fermions : $R_{D^{(*)}}$, Dark Matter — G. Bélanger *et al* [2111.08027]

But for our studies, we focus only on single S_1 leptoquark solution to the $R_{D^{(*)}}$ anomalies.