PHENO 2021

LHC LIMITS ON THE B-ANOMALIES MOTIVATED U_1 LEPTOQUARK MODELS

SUBHADIP MITRA (IIIT HYDERABAD)

Based on 2101.12069

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In collaboration with Arvind Bhaskar, Diganta Das, Tanumoy Mandal, & Cyrin Neeraj

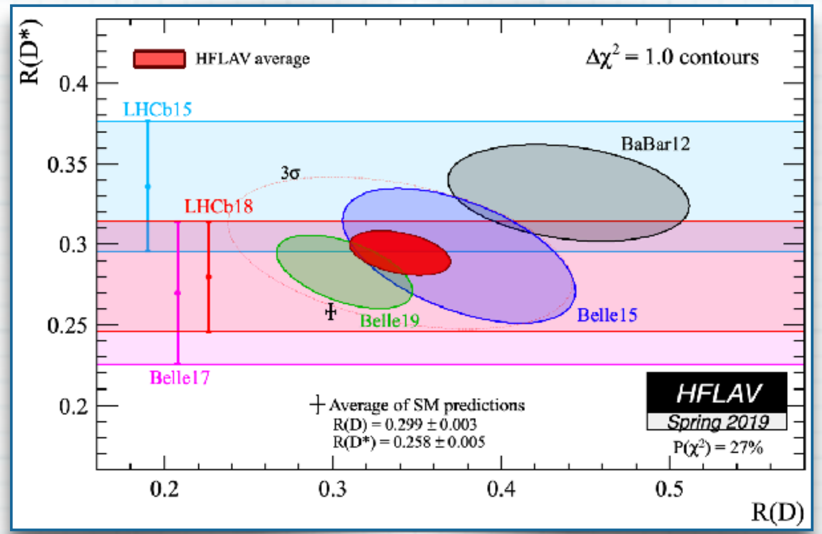
Violation of Lepton Flavour Universality! New Physics?

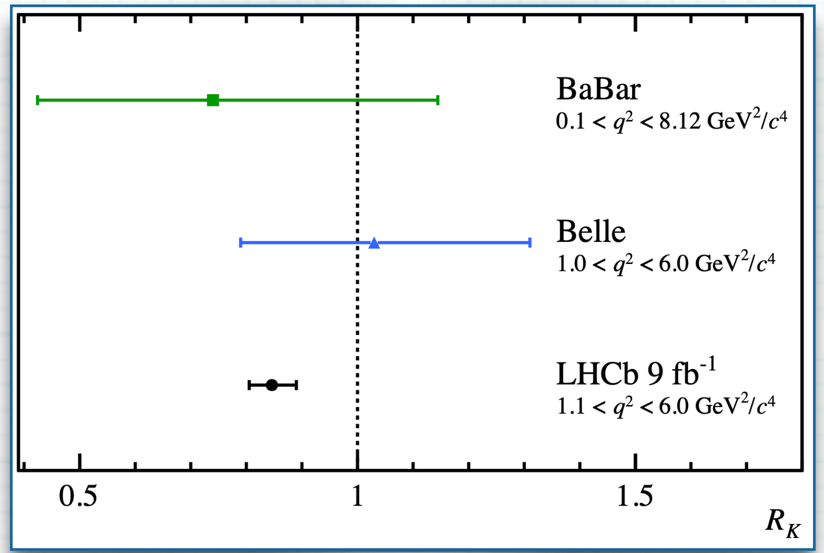
- LFU is in tension with recent experimental measurements of semileptonic B-meson decays.

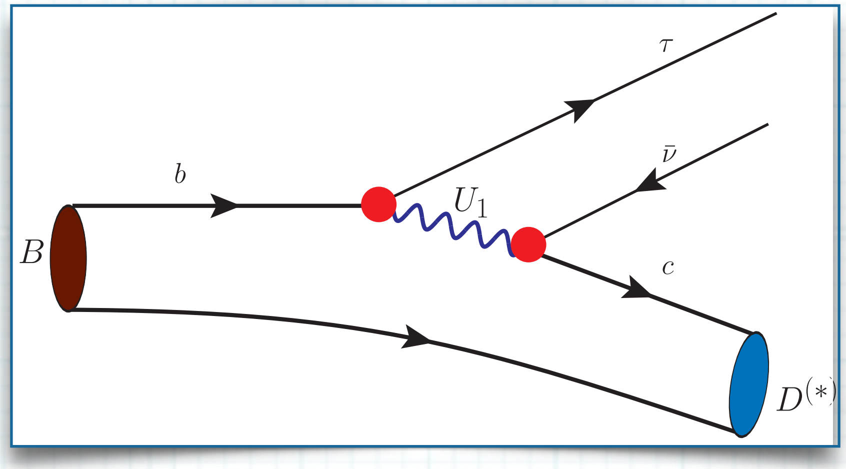
✓

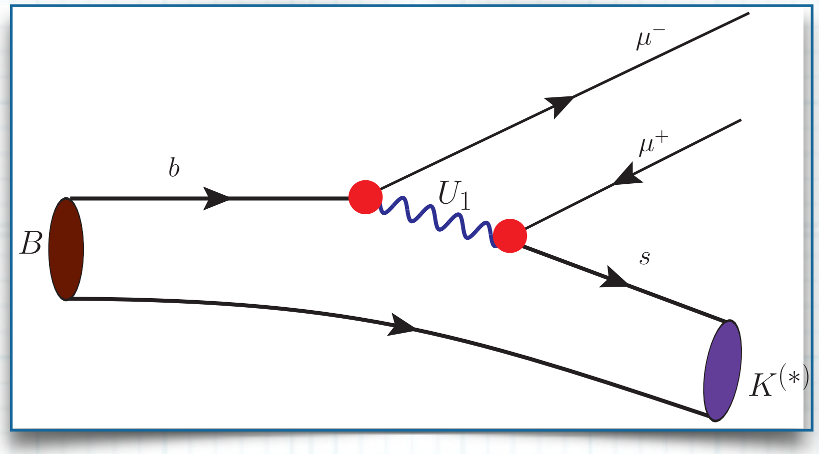
$$R_{D^{(*)}} = \frac{\mathscr{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathscr{B}(B \to D^{(*)}\hat{\ell}\bar{\nu})}$$

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









- A TeV-scale charge-2/3 weak-singlet vLQ $U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$ can resolve both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies simultaneously. It is a color-triplet vector boson with nonzero lepton and baryon numbers.

Bottom-Up Scenarios

- The interaction Lagrangian

$$\mathscr{L} \supset x_{1\,ij}^{LL}\, \bar{Q}^i \gamma_\mu U_1^\mu P_L L^j + x_{1\,ij}^{RR}\, \bar{d}_R^i \gamma_\mu U_1^\mu P_R \ell_R^j + \text{H.c.}$$

- $x_{1\,ij}^{LL}$ and $x_{1\,ij}^{RR}$ are 3×3 matrices in flavour space. We assume them to be real. Since we are interested in the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies, we set all components that do not participate directly in these decays to zero.

$R_{D^{(*)}}$ Operators

- U_1 contribution to the $b \to c\tau\bar{\nu}$ transition

$$\mathscr{L} \supset -\frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + \mathscr{C}_{V_L}\right) \mathscr{O}_{V_L} + \mathscr{C}_{S_L} \mathscr{O}_{S_L} \right]$$

$$\mathscr{C}_{V_L}^{U_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{\lambda_{c\nu}^L \left(\lambda_{b\tau}^L\right)^*}{M_{U_1}^2}, \quad \mathscr{C}_{S_L}^{U_1} = -\frac{1}{2\sqrt{2}G_F V_{cb}} \frac{2\lambda_{c\nu}^L \left(\lambda_{b\tau}^R\right)^*}{M_{U_1}^2}$$

Flavour Ansatz

$$x_1^{LL} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda_{23}^L \\ 0 & 0 & \lambda_{33}^L \end{pmatrix}$$

$$x_1^{RR} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33}^R \end{pmatrix}$$

- Nonzero $\mathscr{C}_{V_L}$ and $\mathscr{C}_{S_L}$ would also contribute to other observables like $F_L(D^*)$, $P_\tau(D^*)$, etc.

$R_{D^{(*)}}$ Scenarios

- We construct scenarios with one and two nonzero couplings.

$R_{D^{(*)}}$ scenarios	$\lambda^L_{c\nu}$	$\lambda^L_{b\tau}$	$\lambda^R_{b\tau}$
RD1A	λ^L_{23}	$V^*_{cb}\lambda^L_{23}$	–
RD1B	$V_{cb}\lambda^L_{33}$	λ^L_{33}	–
RD2A	$V_{cs}\lambda^L_{23}+V_{cb}\lambda^L_{33}$	λ^L_{33}	–
RD2B	$V_{cs}\lambda^L_{23}$	–	λ^R_{33}

$R_{K^{(*)}}$ Operators

- A general Lagrangian for $b \to s\mu^+\mu^-$ transition

$$\mathscr{L} \supset \frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts} \sum_{i=9,10,S,P} \left(\mathscr{C}_i\mathscr{O}_i + \mathscr{C}'_i\mathscr{O}'_i\right)$$

$$x_1^{LL} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda^L_{22} & 0 \\ 0 & \lambda^L_{32} & 0 \end{pmatrix}$$

$$x_1^{RR} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda^R_{22} & 0 \\ 0 & \lambda^R_{32} & 0 \end{pmatrix}$$

Flavour Ansatz

$$\mathscr{C}_9^{U_1} = -\mathscr{C}_{10}^{U_1} = \frac{\pi}{\sqrt{2}G_F V_{tb}V^*_{ts}\alpha} \frac{\lambda^L_{s\mu}(\lambda^L_{b\mu})^*}{M^2_{U_1}}$$

$$\mathscr{C}_S^{U_1} = -\mathscr{C}_P^{U_1} = \frac{\sqrt{2}\pi}{G_F V_{tb}V^*_{ts}\alpha} \frac{\lambda^L_{s\mu}(\lambda^R_{b\mu})^*}{M^2_{U_1}}$$

$$\mathscr{C}_9'^{\,U_1} = \mathscr{C}_{10}'^{\,U_1} = \frac{\pi}{\sqrt{2}G_F V_{tb}V^*_{ts}\alpha} \frac{\lambda^R_{s\mu}(\lambda^{R*}_{b\mu})}{M^2_{U_1}}$$

$$\mathscr{C}_S'^{\,U_1} = \mathscr{C}_P'^{\,U_1} = \frac{\sqrt{2}\pi}{G_F V_{tb}V^*_{ts}\alpha} \frac{\lambda^R_{s\mu}(\lambda^{L*}_{b\mu})}{M^2_{U_1}}$$

$R_{K^{(*)}}$ Scenarios

- We construct scenarios with one and two nonzero couplings.

$R_{K^{(*)}}$ scenarios	$\lambda^L_{s\mu}$	$\lambda^L_{b\mu}$	$\lambda^R_{s\mu}$	$\lambda^R_{b\mu}$
RK1A	$V^*_{cs}\lambda^L_{22}$	$V^*_{cb}\lambda^L_{22}$	–	–
RK1B	$V^*_{ts}\lambda^L_{32}$	$V^*_{tb}\lambda^L_{32}$	–	–
RK1C	–	–	$V_{cs}\lambda^R_{22}$	$V_{cb}\lambda^R_{22}$
RK1D	–	–	$V_{ts}\lambda^R_{32}$	$V_{tb}\lambda^R_{32}$
RK2A	λ^L_{22}	λ^L_{32}	–	–
RK2B	λ^L_{22}	–	–	λ^R_{32}
RK2C	–	λ^L_{32}	λ^R_{22}	–
RK2D	–	–	λ^R_{22}	λ^R_{32}

Different Scenarios, Different Signatures

- In these scenarios, the production modes and the dominant decay modes of U_1 would vary. Hence, an U_1 might lead to different signatures in different scenarios.

$$pp \to \left\{ \begin{array}{lclcl} U_1U_1 & \to & s\mu\, s\mu & \equiv & \mu\mu + 2j \\ U_1U_1 & \to & s\mu\, c\nu & \equiv & \mu + \not{E}_T + 2j \\ U_1U_1 & \to & c\nu\, c\nu & \equiv & \not{E}_T + 2j \end{array} \right\}$$

λ^L_{22} (RK1A)

$$pp \to \left\{ \begin{array}{lclcl} U_1U_1 & \to & b\mu\, b\mu & \equiv & \mu\mu + 2j \\ U_1U_1 & \to & b\mu\, t\nu & \equiv & \mu + \not{E}_T + j_t + j \\ U_1U_1 & \to & t\nu\, t\nu & \equiv & \not{E}_T + 2j_t \end{array} \right\}$$

λ^L_{32} (RK1B)

Pair Production

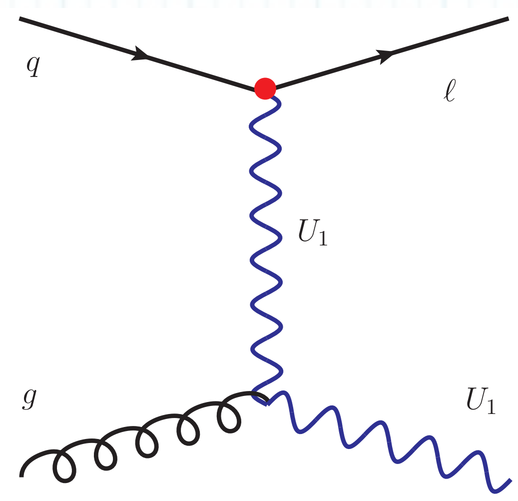
- Possible final states. A simple parametrisation to show the relative strengths.

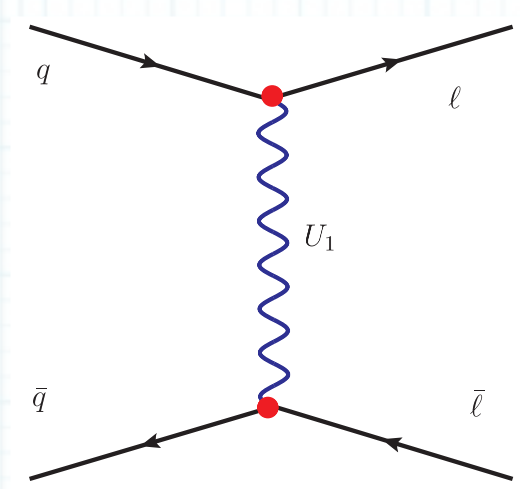
Nonzero couplings	Signatures					
	$\tau\tau+2j$	$\tau+\not{E}_T+2j$	$\not{E}_T+2j$	$\tau+\not{E}_T+j_t+j$	$\not{E}_T+2j_t$	$\not{E}_T+j_t+j$
λ^L_{23} (Scenario RD1A)	0.25	0.50	0.25	–	–	–
λ^L_{33} (Scenario RD1B)	0.25	–	–	0.50	0.25	–
λ^R_{33}	1.00	–	–	–	–	–
$\lambda^L_{23}, \lambda^L_{33}$ (Scenario RD2A)	0.25	ξ	ξ^2	$\frac{1}{2}-\xi$	$\left(\frac{1}{2}-\xi\right)^2$	$2\xi\left(\frac{1}{2}-\xi\right)$
$\lambda^L_{23}, \lambda^R_{33}$ (Scenario RD2B)	$\left(\frac{1}{2}+\xi\right)^2$	$2\left(\frac{1}{4}-\xi^2\right)$	$\left(\frac{1}{2}-\xi\right)^2$	–	–	–
	$\mu\mu+2j$	$\mu+\not{E}_T+2j$	$\not{E}_T+2j$	$\mu+\not{E}_T+j_t+j$	$\not{E}_T+2j_t$	$\not{E}_T+j_t+j$
λ^L_{22} (Scenario RK1A)	0.25	0.50	0.25	–	–	–
λ^L_{32} (Scenario RK1B)	0.25	–	–	0.50	0.25	–
λ^R_{22} (Scenario RK1C)	1.00	–	–	–	–	–
λ^R_{32} (Scenario RK1D)	1.00	–	–	–	–	–
$\lambda^L_{22}, \lambda^L_{32}$ (Scenario RK2A)	0.25	ξ	ξ^2	$\frac{1}{2}-\xi$	$\left(\frac{1}{2}-\xi\right)^2$	$2\xi\left(\frac{1}{2}-\xi\right)$
$\lambda^L_{22}, \lambda^R_{32}$ (Scenario RK2B)	$\left(\frac{1}{2}+\xi\right)^2$	$2\left(\frac{1}{4}-\xi^2\right)$	$\left(\frac{1}{2}-\xi\right)^2$	–	–	–
$\lambda^R_{22}, \lambda^L_{32}$ (Scenario RK2C)	$\left(\frac{1}{2}+\xi\right)^2$	–	–	$2\left(\frac{1}{4}-\xi^2\right)$	$\left(\frac{1}{2}-\xi\right)^2$	–
$\lambda^R_{22}, \lambda^R_{32}$ (Scenario RK2D)	1.00	–	–	–	–	–

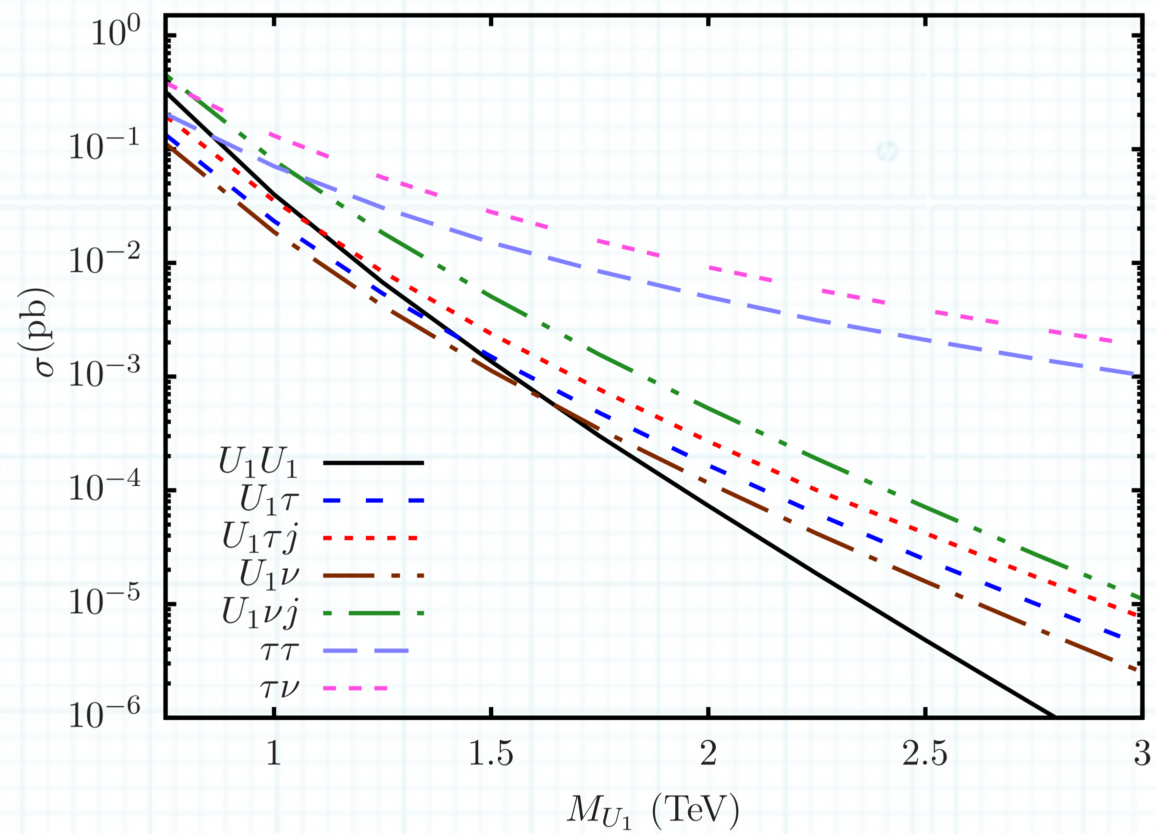
ξ is a free parameter

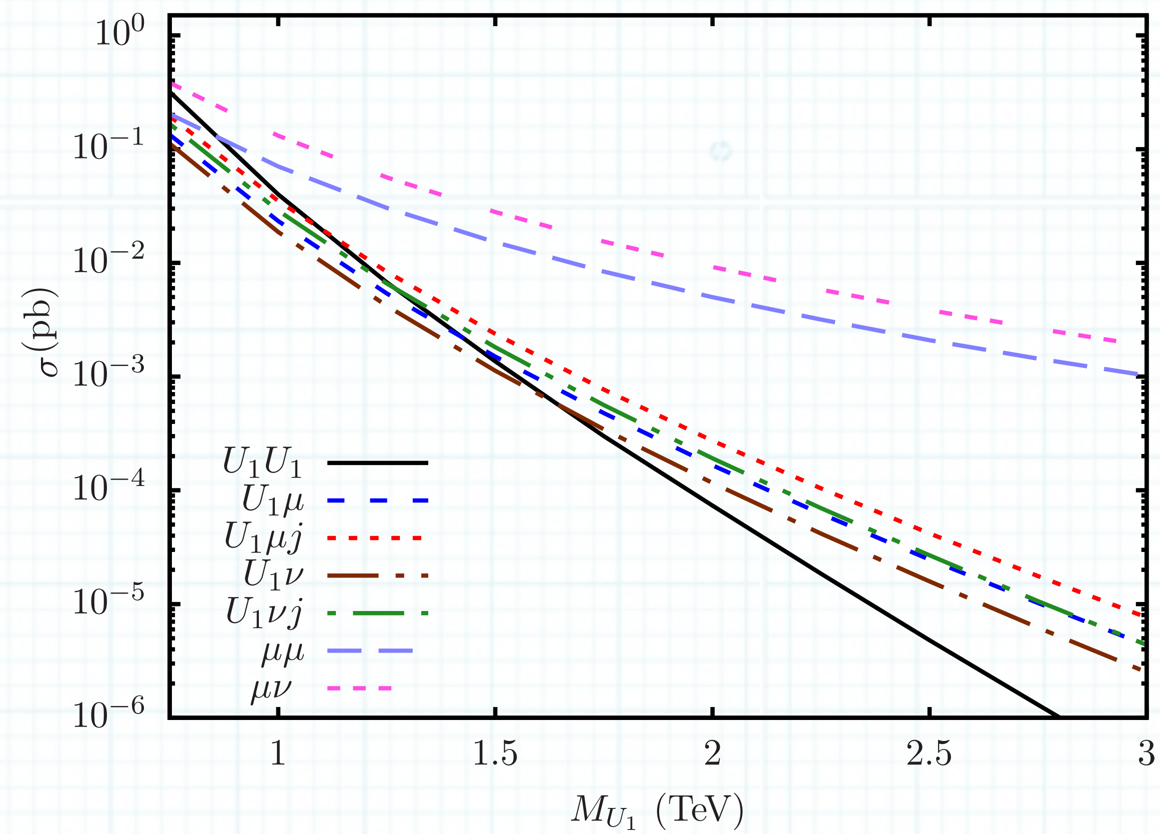
Single and Non-Resonant Productions

- λ-dependent single productions and t-channel LQ exchange.
- If λ is not small and/or the U_1 is heavy, they are the dominant processes.
- Non-resonant production does not depend on branching ratios.





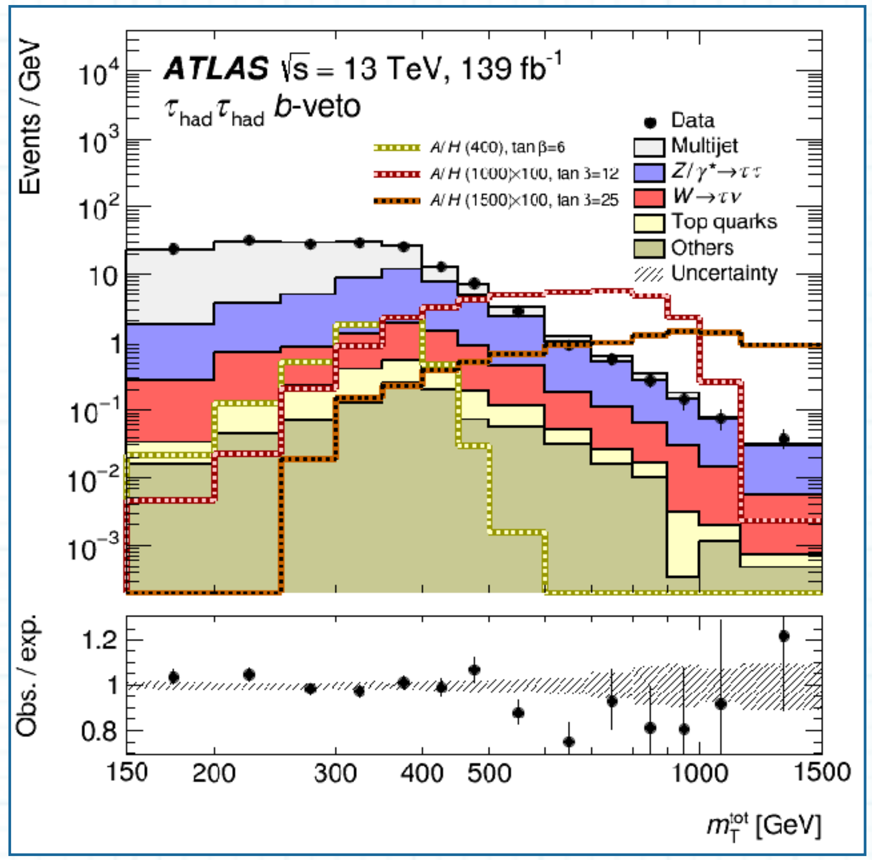




ATLAS $\tau\tau$ (139 fb^{-1}) and CMS $\mu\mu$ (140 fb^{-1}) Resonance Searches

- All three production modes would lead to $\ell\ell + jets$ final states.
- The signal to the dilepton searches would be a combination of these three processes + the interference of t-channel process with the SM $pp \to Z/\gamma \to \ell\ell$ process.
- The interference is destructive, leading to a reduction of events.

2002.12223



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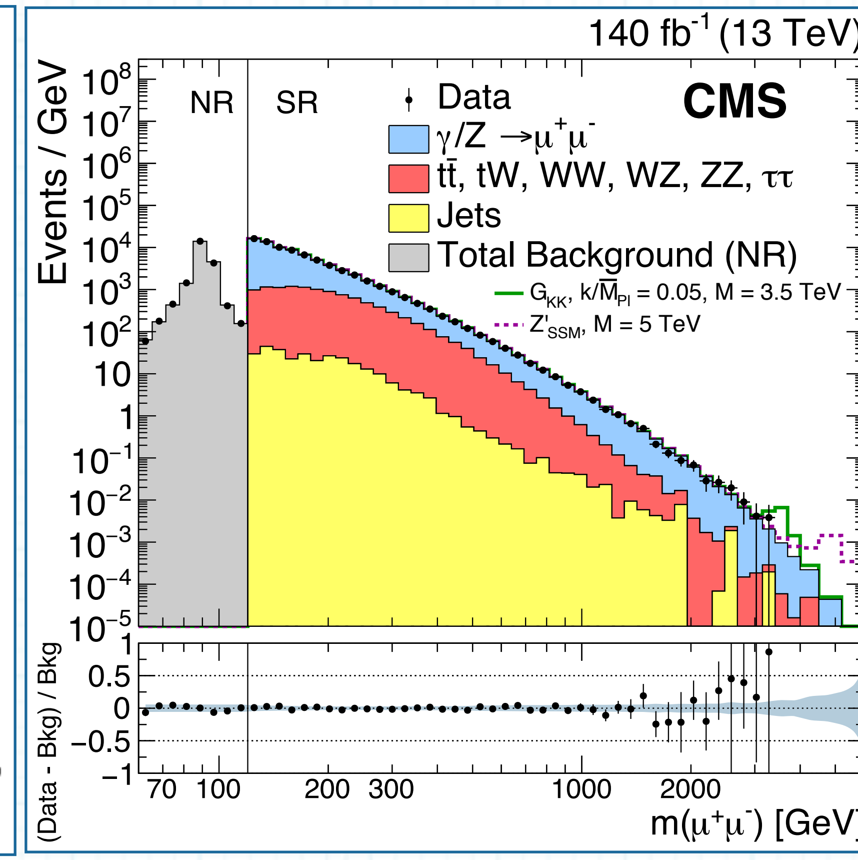


Mass (Tev)	Pair production σ^p	ε^p	$\mathcal{N}^p$	Single production σ^s	ε^s	$\mathcal{N}^s$	t-channel LQ σ^{nr4}	ε^{nr4}	$\mathcal{N}^{nr4}$	Interference σ^{nr2}	ε^{nr2}	$\mathcal{N}^{nr2}$
Contribution to $\tau\tau$ signal [82]												
$\lambda^L_{23} = 1$ (Scenario RD1A)												
1.0	40.87	2.33	8.59	58.80	3.30	35.07	70.57	7.22	183.33	-232.63	3.17	-266.21
1.5	1.39	1.50	0.19	3.91	2.74	1.93	14.94	7.00	37.77	-104.31	3.34	-125.62
2.0	0.08	1.01	0.01	0.44	2.50	0.20	5.04	7.25	13.19	-58.79	3.28	-69.57
$\lambda^L_{33} = 1$ (Scenario RD1B)												
1.0	35.67	1.69	5.43	29.00	2.57	13.46	20.20	6.21	45.26	-75.02	3.08	-83.41
1.5	1.17	1.09	0.11	1.72	2.16	0.67	4.31	6.22	9.68	-33.62	2.88	-33.01
2.0	0.06	0.81	0.00	0.17	1.98	0.06	1.39	6.27	3.15	-18.97	2.88	-19.71

A χ^2 Test

- For each distribution, we define the test statistic as

$$\chi^2 = \sum_i^{bins} \left(\frac{\mathcal{N}^i_{\rm T}(M_{U_1}, \lambda) - \mathcal{N}^i_{\rm D}}{\Delta \mathcal{N}^i} \right)^2$$

- $\mathcal{N}^i_{\rm T}(M_{U_1}, \lambda)$ = theory events and $\mathcal{N}^i_{\rm D}$ = the number of observed events in the i^{th} bin.

$$\mathcal{N}^i_{\rm T}(M_{U_1}, \lambda) = \left[\mathcal{N}^p(M_{U_1}, \lambda) + \mathcal{N}^s(M_{U_1}, \lambda) + \mathcal{N}^{nr}(M_{U_1}, \lambda)\right] + \mathcal{N}^i_{\rm SM}\,.$$

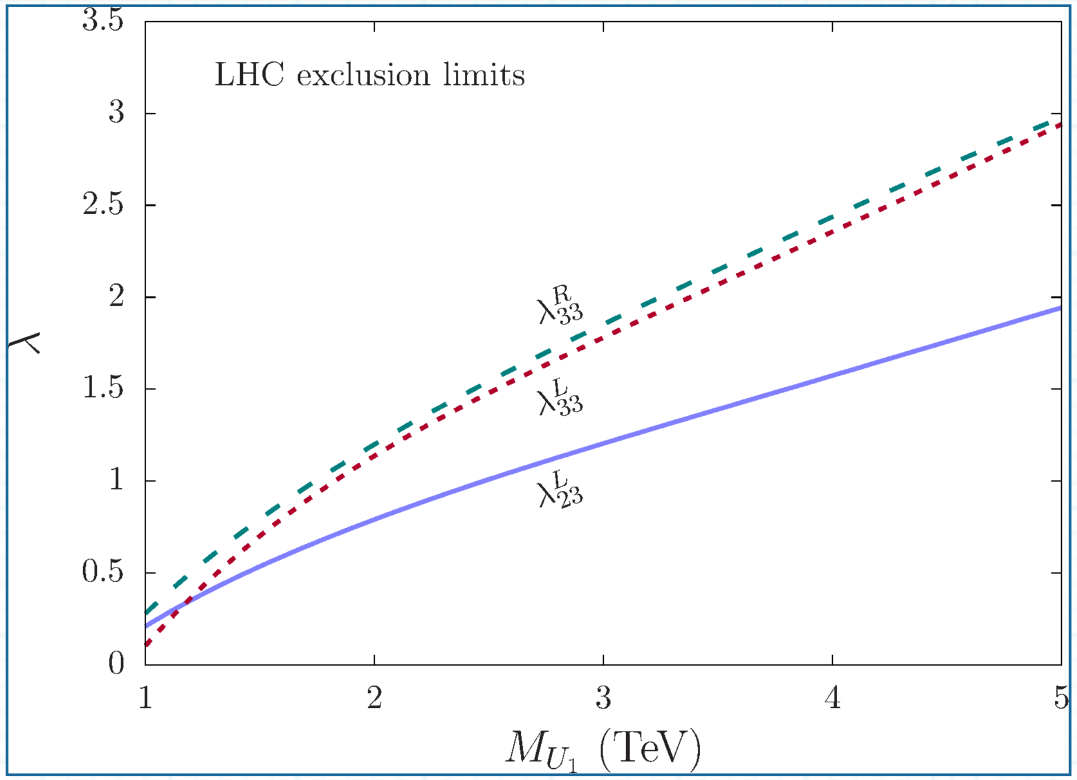
- For the error $\Delta\mathcal{N}^i$, we use

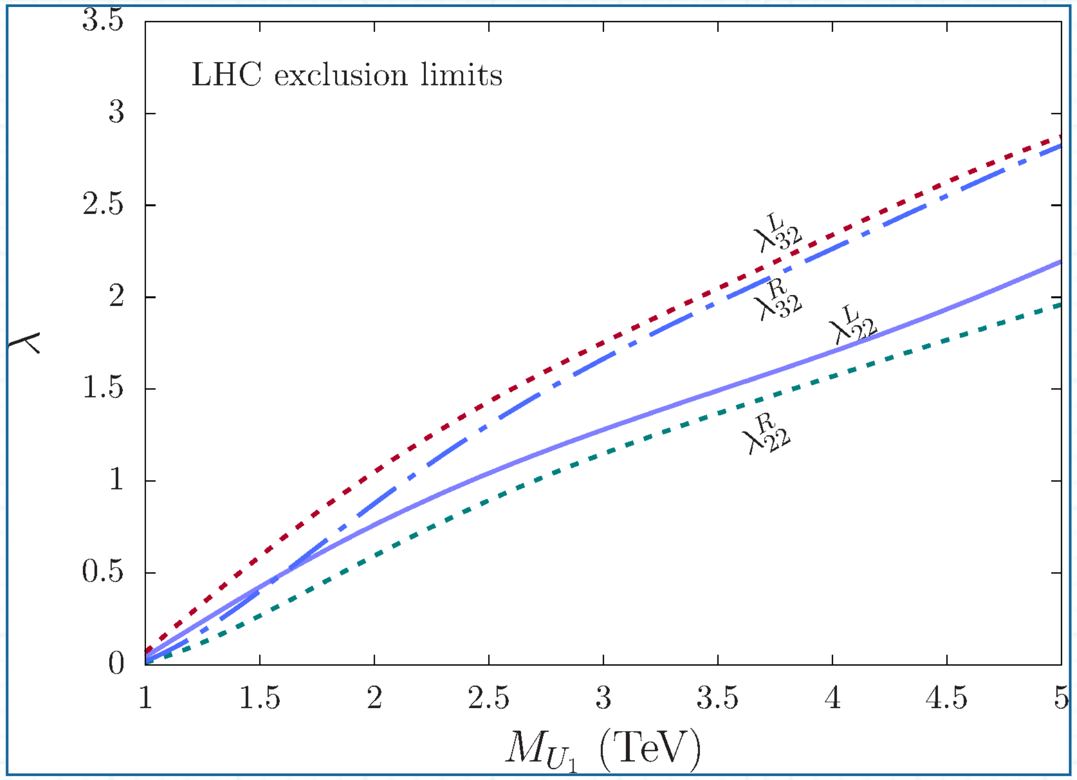
$$\Delta\mathcal{N}^i = \sqrt{\left(\Delta\mathcal{N}^i_{stat}\right)^2 + \left(\Delta\mathcal{N}^i_{syst}\right)^2}$$

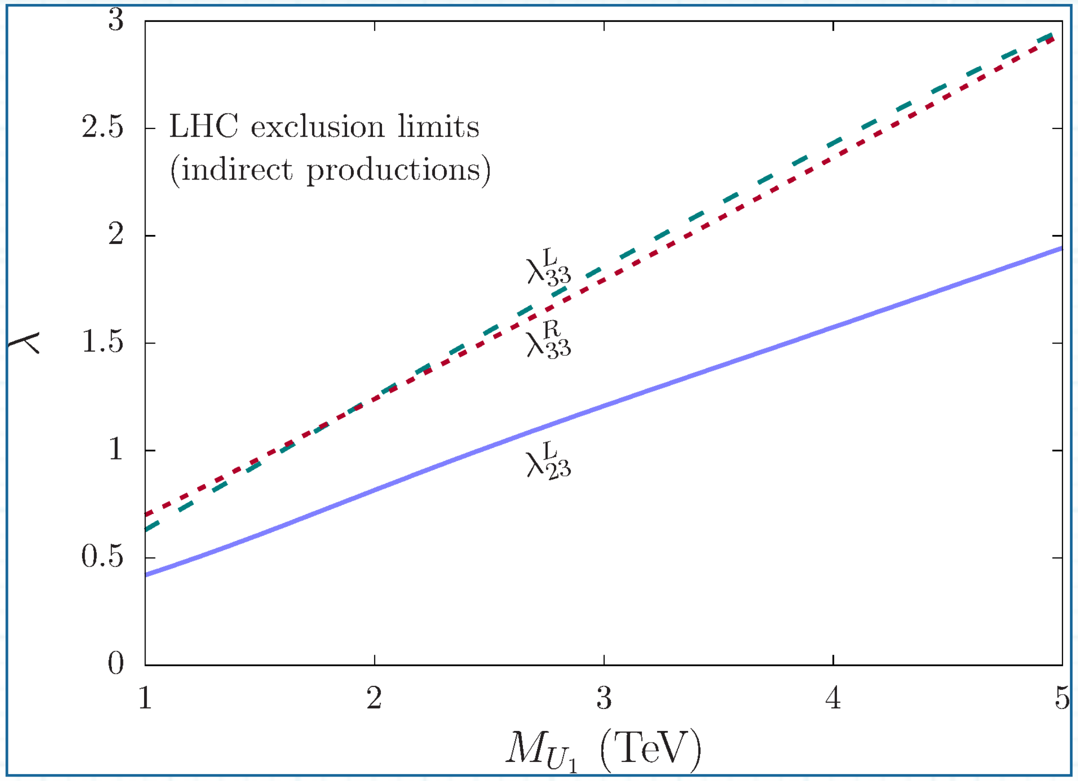
  where $\Delta\mathcal{N}^i_{stat} = \sqrt{\mathcal{N}^i_D}$ and we assume a uniform 10% systematic error

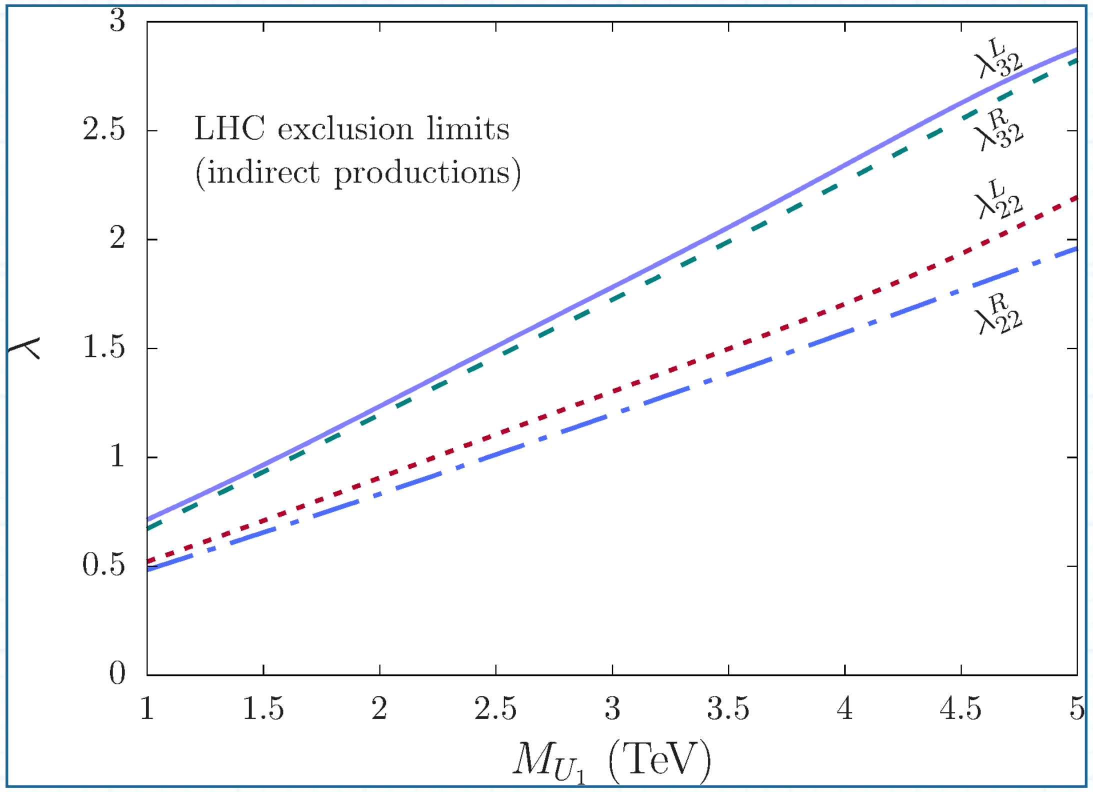
- In every scenario, for some benchmark masses $M_{U_1} = M^b_{U_1}$, we compute the minimum of χ^2 by varying the couplings. In one-coupling scenarios, we obtain the 1σ and 2σ CL upper limit on the coupling at $M^b_{U_1}$ from the values of λ for which $\Delta\chi^2(M^b_{U_1}, \lambda) = \chi^2(M^b_{U_1}, \lambda) - \chi^2_{min}(M^b_{U_1})$ equals 1 and 4, respectively.

- The limits on multi-coupling scenarios can be obtained similarly.


LHC exclusion limits
λ^R_{33}
λ^L_{33}
λ^L_{23}
λ
M_{U_1} (TeV)

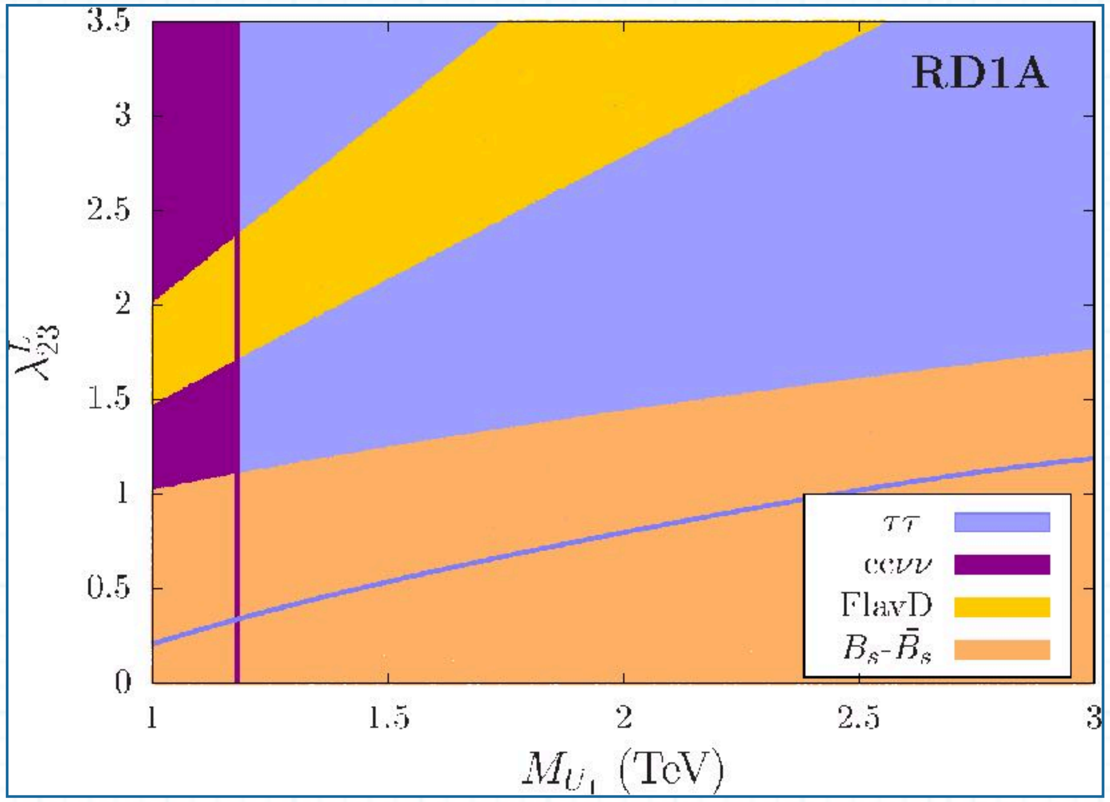

LHC exclusion limits
λ^L_{32}
λ^R_{32}
λ^L_{22}
λ^R_{22}
λ
M_{U_1} (TeV)


LHC exclusion limits
(indirect productions)
λ^L_{33}
λ^R_{33}
λ^L_{23}
λ
M_{U_1} (TeV)

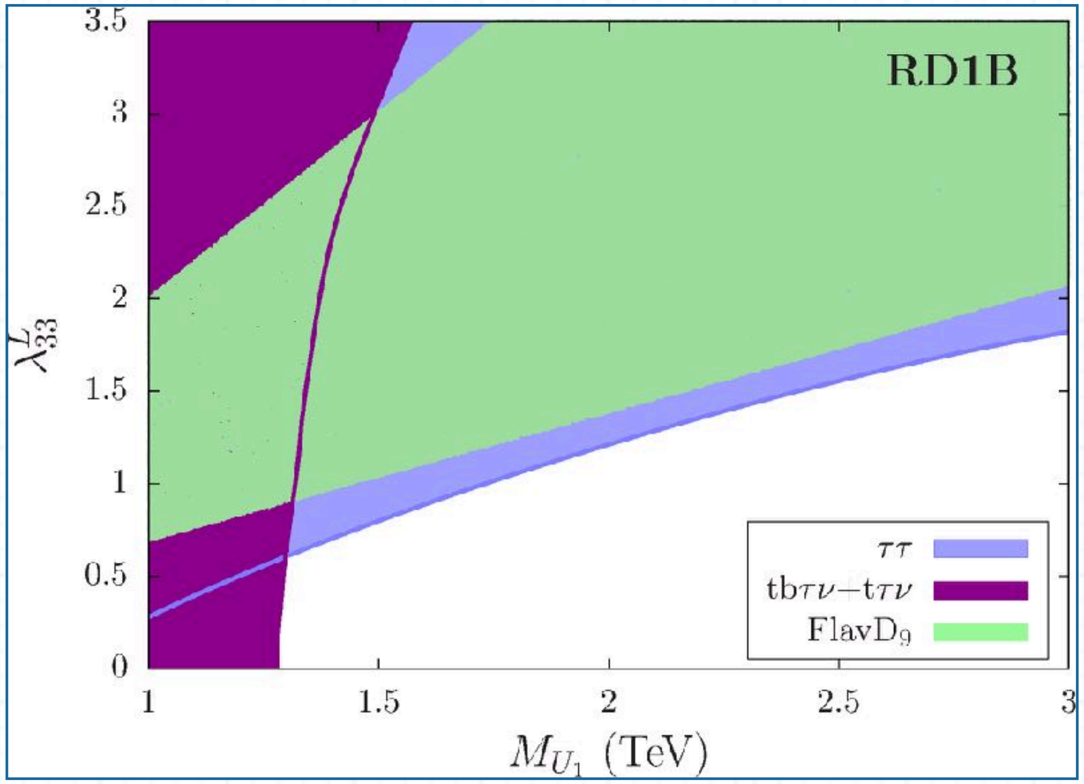

LHC exclusion limits
(indirect productions)
λ^L_{32}
λ^R_{32}
λ^L_{22}
λ^R_{22}
λ
M_{U_1} (TeV)

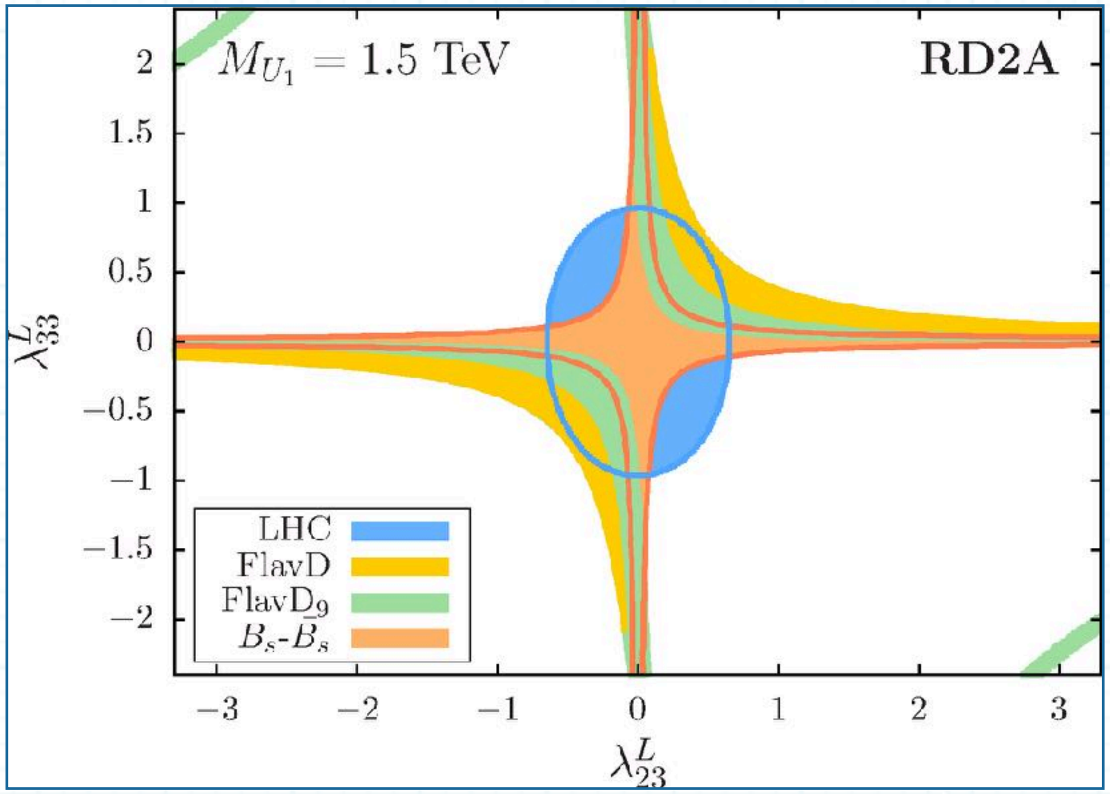
The $R_{D^{(*)}}$ Scenarios Are Severely Constrained

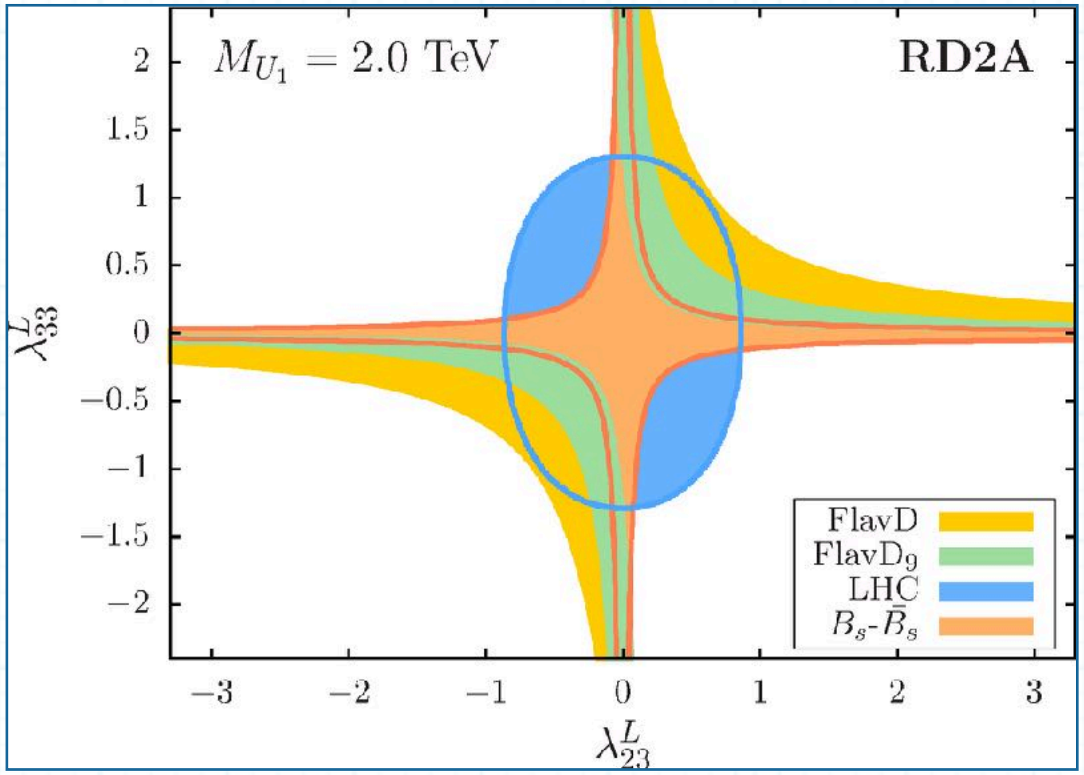
CMS 1805.10228



CMS 2012.04178

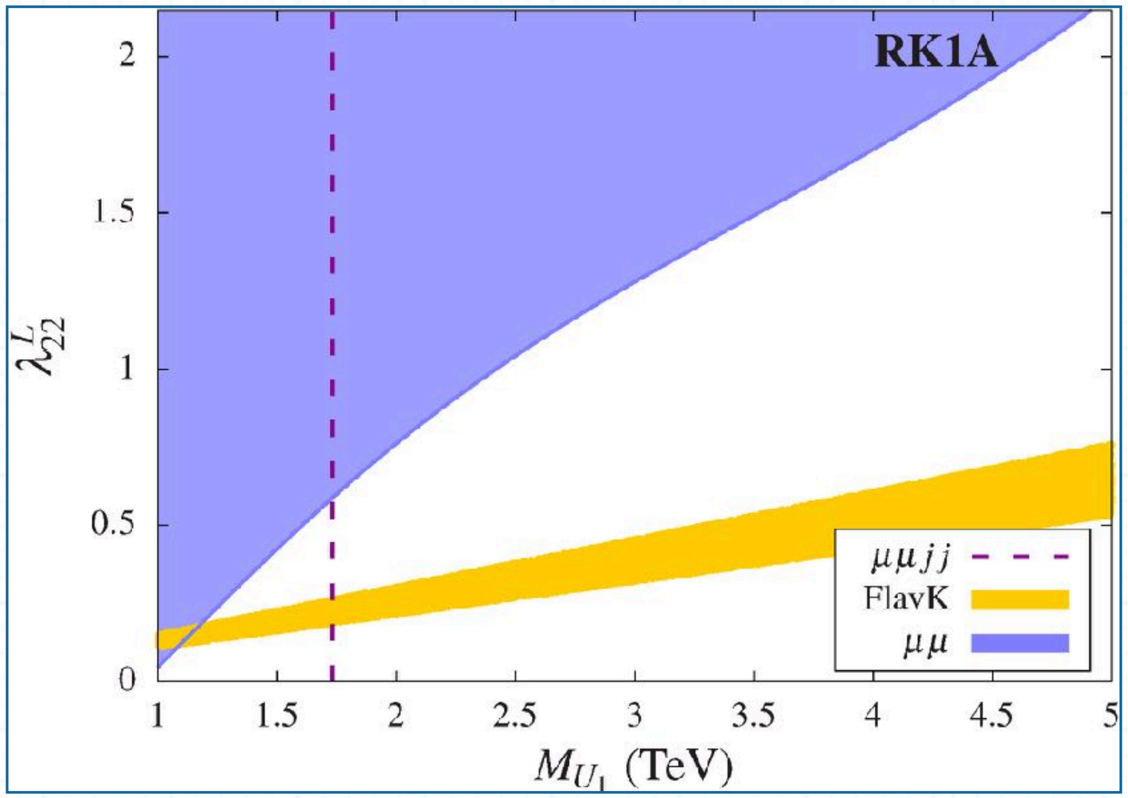




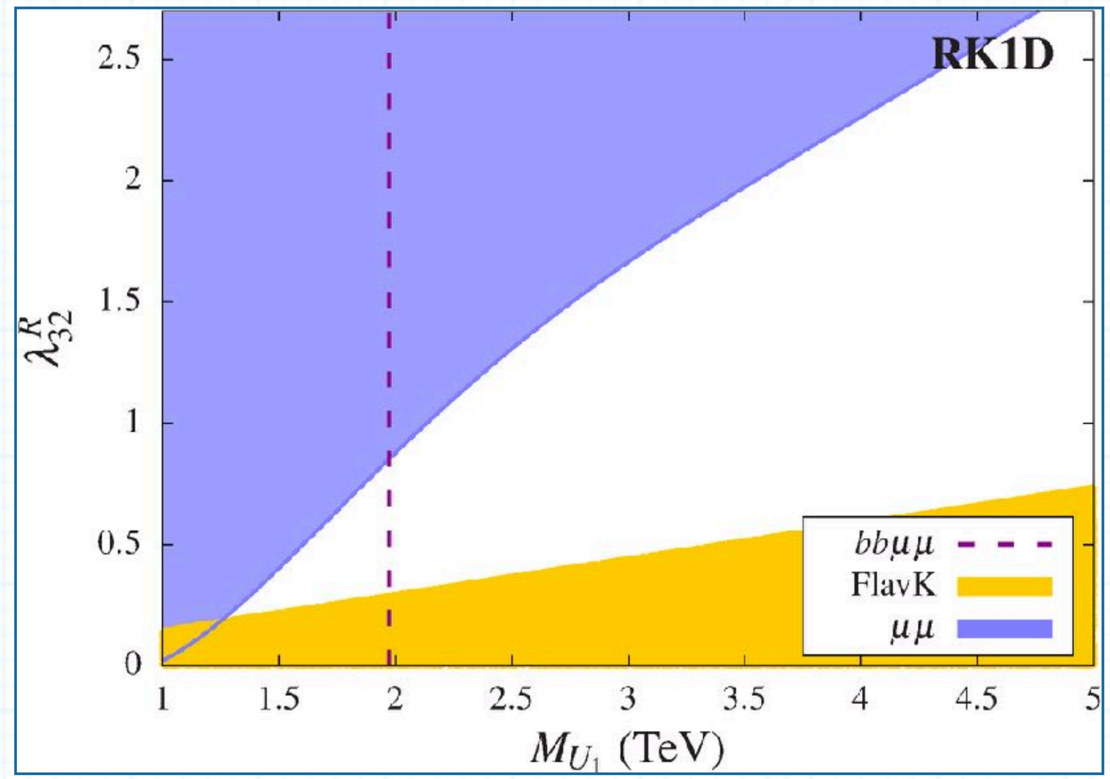


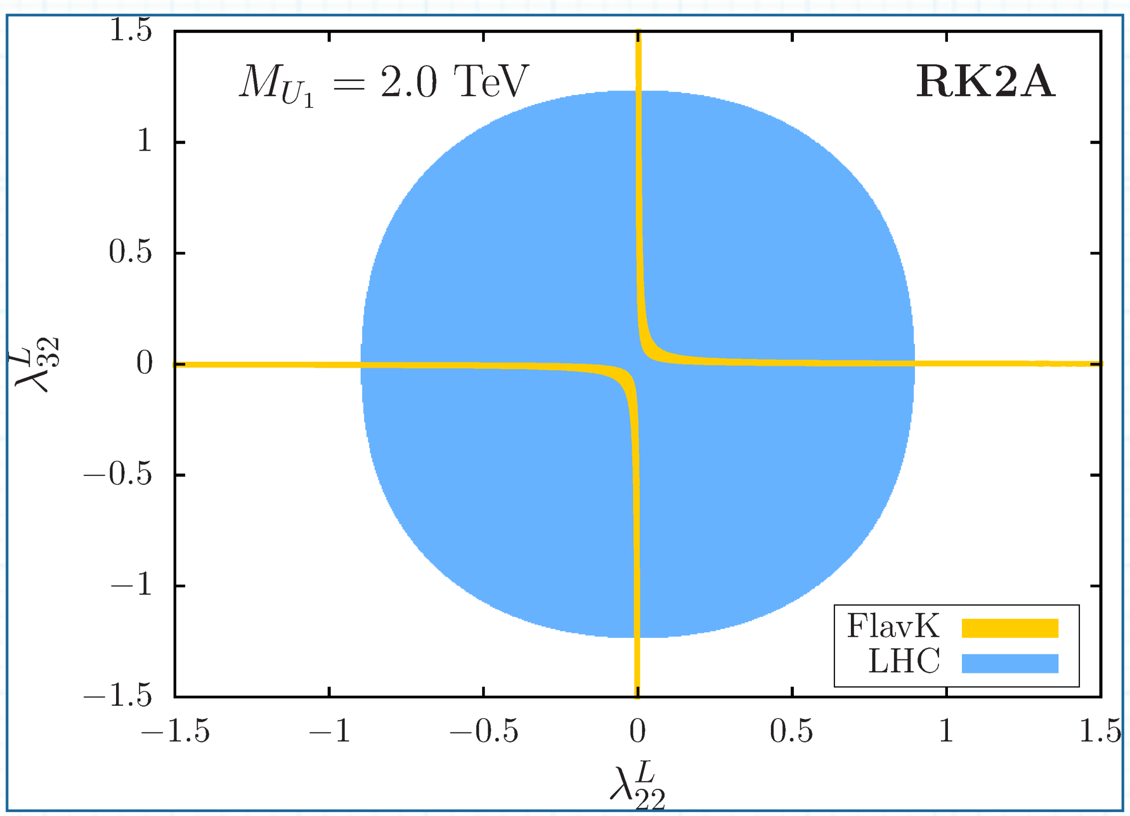
Recast of ATLAS Scalar LQ Search Data Rules out U_1 Below ~2 TeV

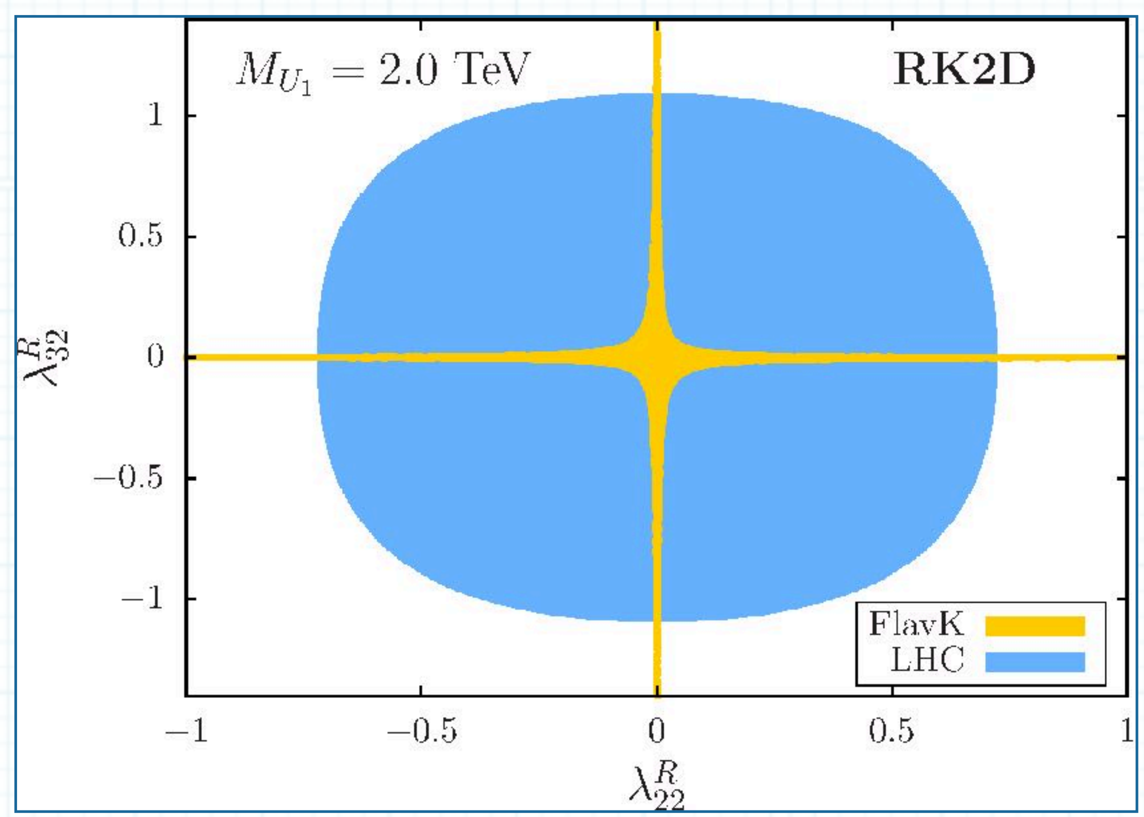
ATLAS 2006.05872 Recast



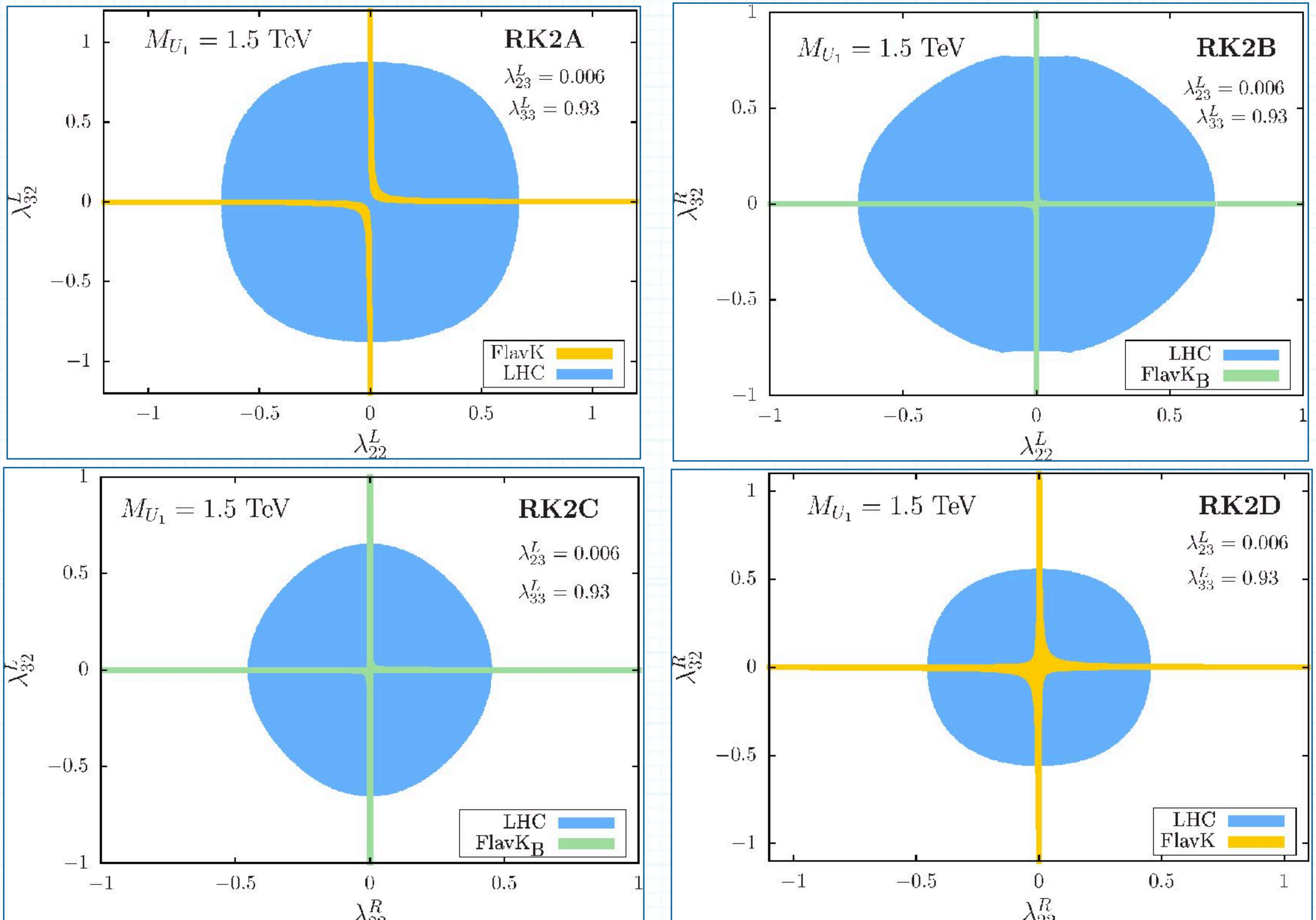
ATLAS 2006.05872 Recast







A 1.5 TeV U_1 Can Explain Both the Anomalies



Thank you

PHENO 2021

LHC LIMITS ON THE B-ANOMALIES MOTIVATED U_1 LEPTOQUARK MODELS

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