ANOMALIES 2021

LEPTOQUARK MODELS: LHC BOUNDS AND PROSPECTS

SUBHADIP MITRA (IIIT HYDERABAD)

November 12, 2021

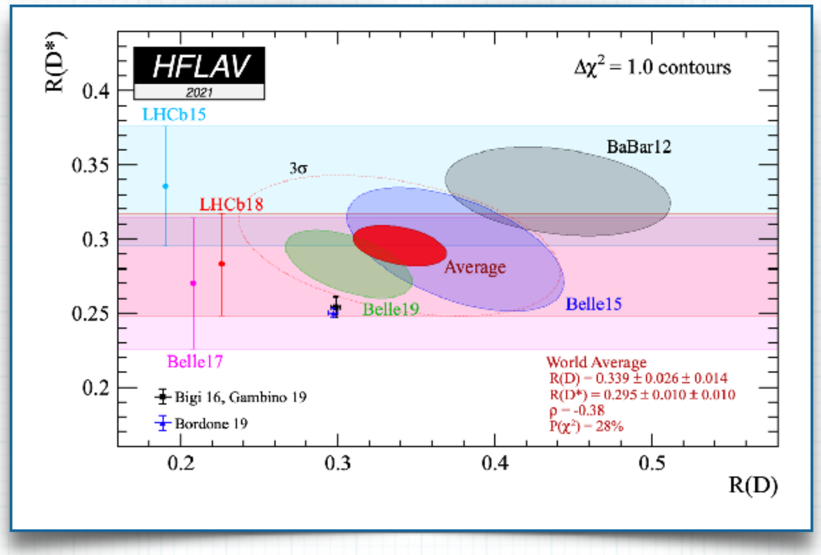
With Arvind, Cyrin, Diganta, Kushagra, Mohit, Tanumoy, Swapnil

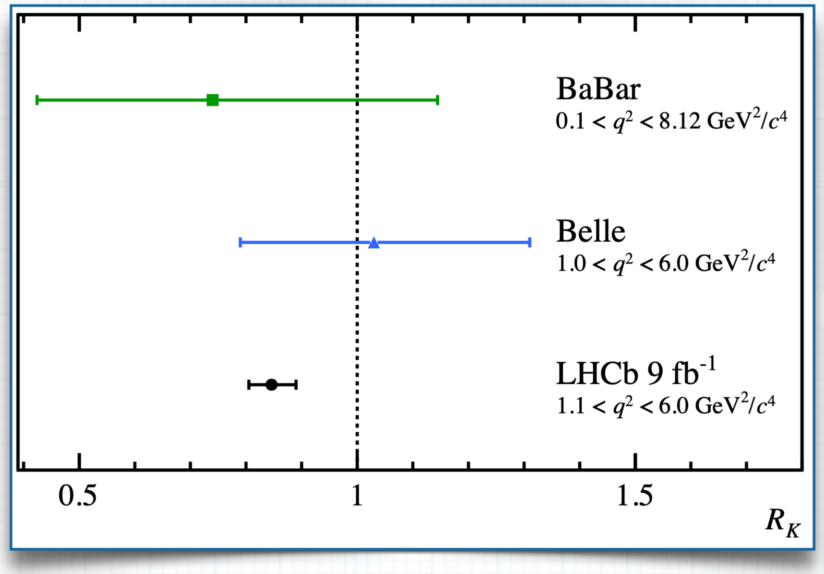
Lepton Flavour Universality Violation

- LFU is in tension with recent measurements of semi-leptonic B-meson decays.

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

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

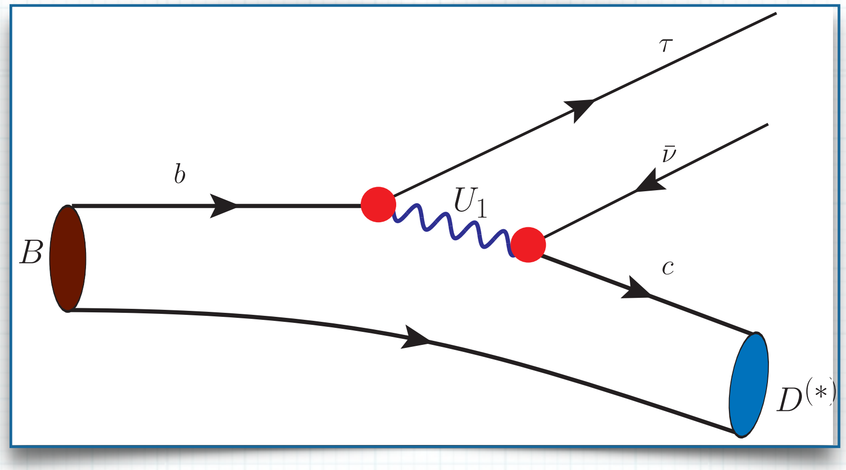


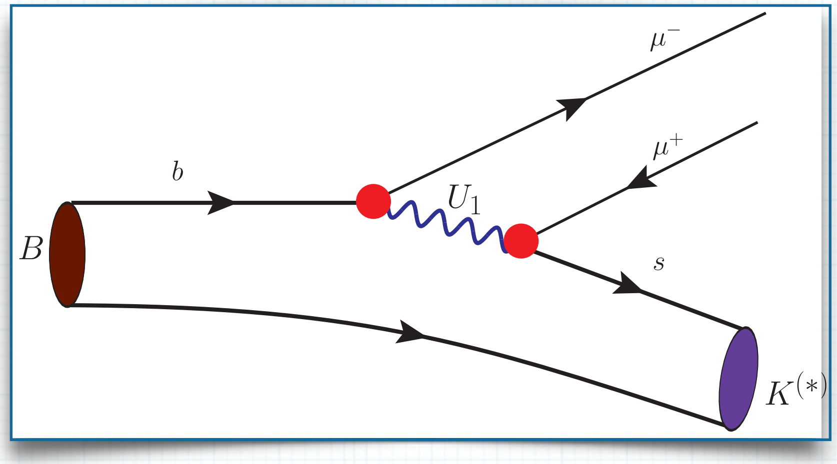


- LQs are colour-triplet bosons with nonzero lepton and baryon numbers. They are promising candidates.

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗

Angelescu et al 2103.12504





- A TeV-scale $S_1 \equiv (\mathbf{3}, \mathbf{1}, 1/3)$ (scalar) or $U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$ (vector) can resolve the anomalies.

Bottom-Up Scenarios

- The interaction Lagrangians

$$\mathscr{L} \supset y^L_{ij}\ \bar{Q}^i \gamma_\mu U_1^\mu L^j + y^R_{ij}\ \bar{d}^i_R \gamma_\mu U_1^\mu \ell^j_R + \text{H.c.}$$ U_1

$$\mathscr{L} \supset y^L_{ij}\, \bar{Q}^c_i \left(i\tau_2\right) L_j S_1^\dagger + y^R_{ij}\, \bar{u}^c_i \ell_{R\,j} S_1^\dagger + \text{H.c.}$$ S_1

- y^L_{ij} and y^R_{ij} 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 contribute directly to these observables to zero**.

- We want to obtain bounds on these models from the existing LHC data. There are **direct search mass exclusion bounds** on scalar and vector LQs (relatively **straightforward**). We will use the **high-p_T di-lepton and lepton+MET data** to put additional bounds on parameters like couplings and masses (**not** straightforward).

	Integrated Luminosity [fb^{-1}]	Scalar LQ Mass [GeV]	Vector LQ, $\kappa = 0$ Mass [GeV]	Vector LQ, $\kappa = 1$ Mass [GeV]
LQ $\to t\nu$ ($\mathscr{B} = 1.0$) [85, 87]	35.9 (36.1)	1020 (992)	1460	1780
LQ $\to q\nu$ ($\mathscr{B} = 1.0$) [85]	35.9	980	1410	1790
LQ $\to b\nu$ ($\mathscr{B} = 1.0$) [85, 87]	35.9 (36.1)	1100 (968)	1475	1810
LQ $\to b\tau\ / t\nu (\mathscr{B} = 0.5)$ [88]	137	950	1290	1650
LQ $\to b\tau$ ($\mathscr{B} = 1.0$) [87] $*$	(36.1)	(1000)	–	–
LQ $\to \mu j$ ($\mathscr{B} = 1.0$) [86] $*$	(139)	(1733)	–	–
LQ $\to \mu c$ ($\mathscr{B} = 1.0$) [86]	(139)	(1680)	–	–
LQ $\to \mu b$ ($\mathscr{B} = 1.0$) [86] $*$	(139)	(1721)	–	–

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

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

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

$$\mathscr{C}_{V_L}^{S_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{\left(\lambda^L_{c\tau}\right)^* \lambda^L_{b\nu}}{2M^2_{S_1}}, \quad \mathscr{C}_{S_L}^{S_1} = -\frac{1}{2\sqrt{2}G_F V_{cb}} \frac{\left(\lambda^R_{c\tau}\right)^* \lambda^L_{b\nu}}{2M^2_{S_1}}, \quad \mathscr{C}_{T_L}^{S_1} = -\frac{1}{4}\mathscr{C}_{S_L}^{S_1}$$

$$\mathscr{C}_{V_L}^{U_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \frac{\lambda^L_{c\nu} \left(\lambda^L_{b\tau}\right)^*}{M^2_{U_1}}, \quad \mathscr{C}_{S_L}^{U_1} = -\frac{1}{2\sqrt{2}G_F V_{cb}} \frac{2\lambda^L_{c\nu} \left(\lambda^R_{b\tau}\right)^*}{M^2_{U_1}}$$

Flavour Ansatz

$$y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda^L_{23} \\ 0 & 0 & \lambda^L_{33} \end{pmatrix}$$

$$y^R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda^R_{23} \\ 0 & 0 & \lambda^R_{33} \end{pmatrix} \begin{matrix} \\ \leftarrow S_1 \\ \leftarrow U_1 \end{matrix}$$

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

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

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

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

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

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

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

- Nonzero Wilson coefficients would also contribute to other observables like $F_L(D^*)$, $P_\tau(D^*)$, etc.

- We construct scenarios with one and two nonzero couplings.

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

U_1

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

The S_1 scenarios will have $\lambda^L_{c\tau}$, $\lambda^L_{b\nu}$, and $\lambda^R_{c\tau}$

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

U_1

$R_{K^{(*)}}$ 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 LQs would vary. Hence, a LQ has different LHC signatures in different scenarios.

- In the U_1 scenarios RD1A and RD1B the coefficient $\mathscr{C}_{V_L}$ receives nonzero contribution proportional to the square of an unknown new coupling (either λ^L_{23} or λ^L_{33}). Hence, from an effective theory perspective, these two look almost the same.

- However, the dominant decay modes of U_1 in these two scenarios are different

RD1A	$U_1 \to c\nu/s\tau$	$(\text{jet} + \text{MET} \ / \ \tau + \text{jet})$	Can be produced via c and s-initiated processes
RD1B	$U_1 \to t\nu/b\tau$	$(t + \text{MET} \ / \ \tau + \text{jet}_{(b)})$	Can be produced via b-initiated processes

- Hence, one needs to analyse the LHC bounds for the scenarios differently.

U_1

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

λ^L_{22}

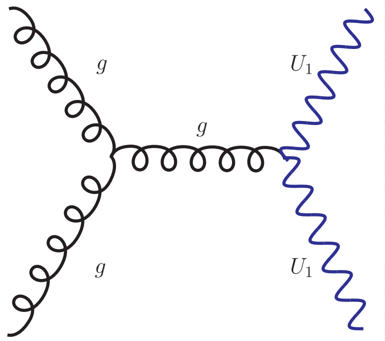
$$pp \to \left\{ \begin{array}{llll} U_1U_1 & \to & b\mu\, b\mu & \equiv & \mu\mu + 2j \\ U_1U_1 & \to & b\mu\, t\nu & \equiv & \mu + \not{E}_T + j_t + j \\ U_1U_1 & \to & t\nu\, t\nu & \equiv & \not{E}_T + 2j_t \end{array} \right\}$$

λ^L_{32}

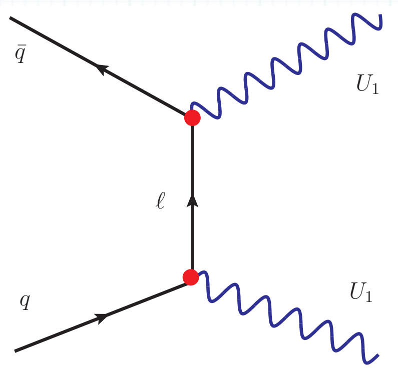
Pair Production

- 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	–	–	–	–	–



U_1

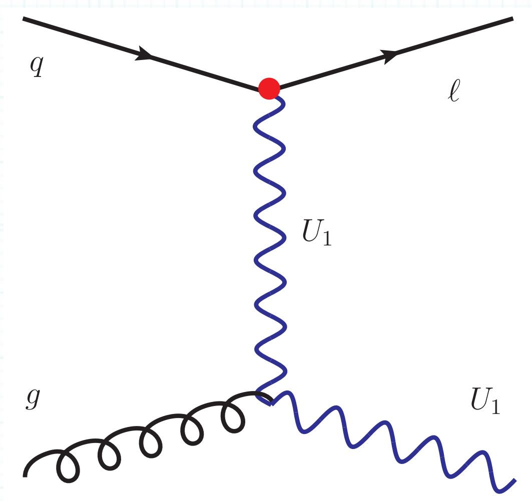


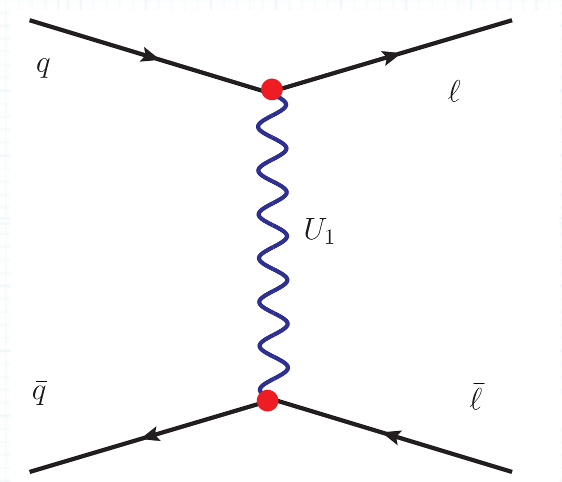
ξ is a free parameter

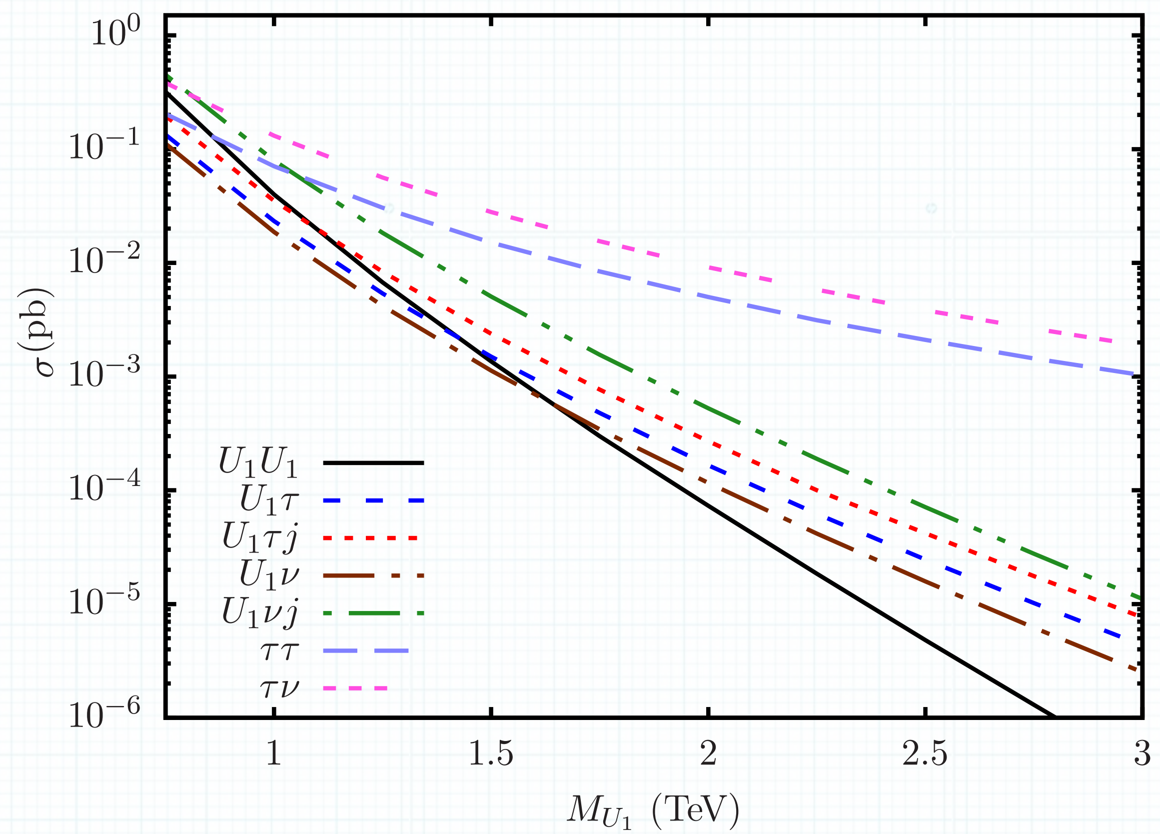
Single and Non-Resonant Productions

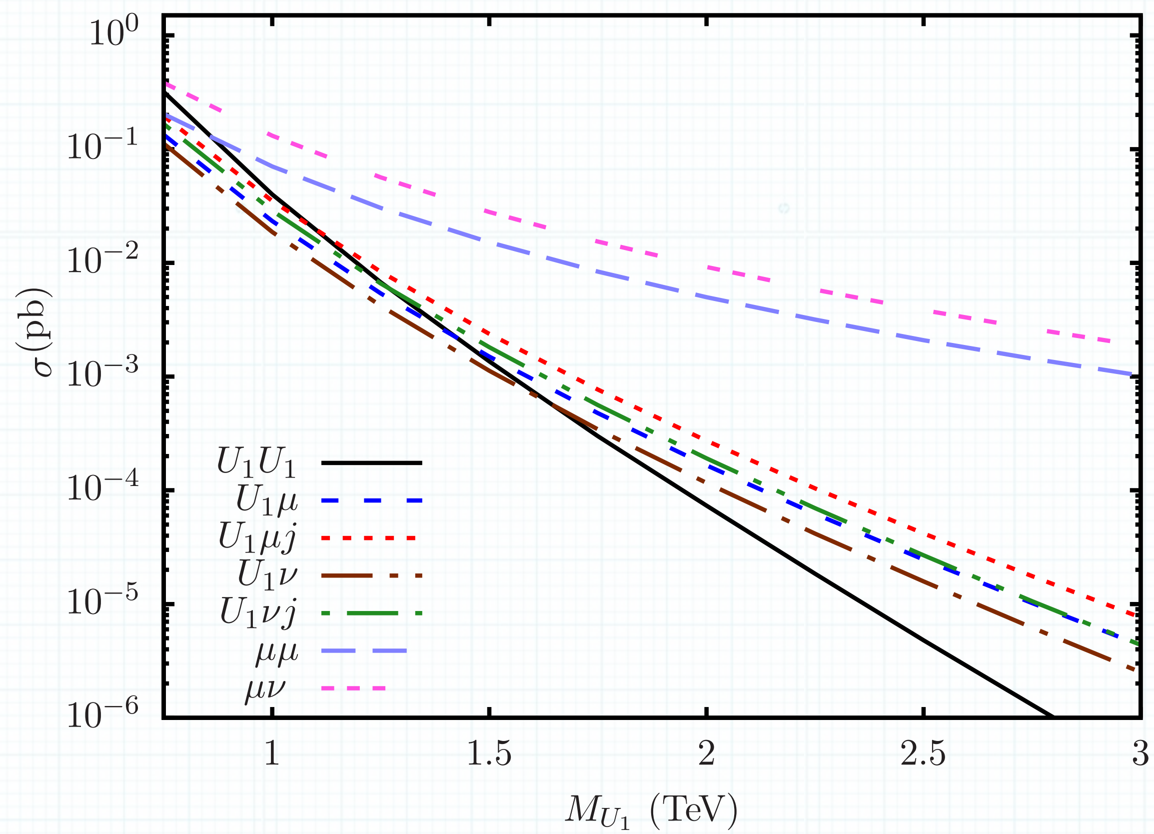
U_1

- 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.





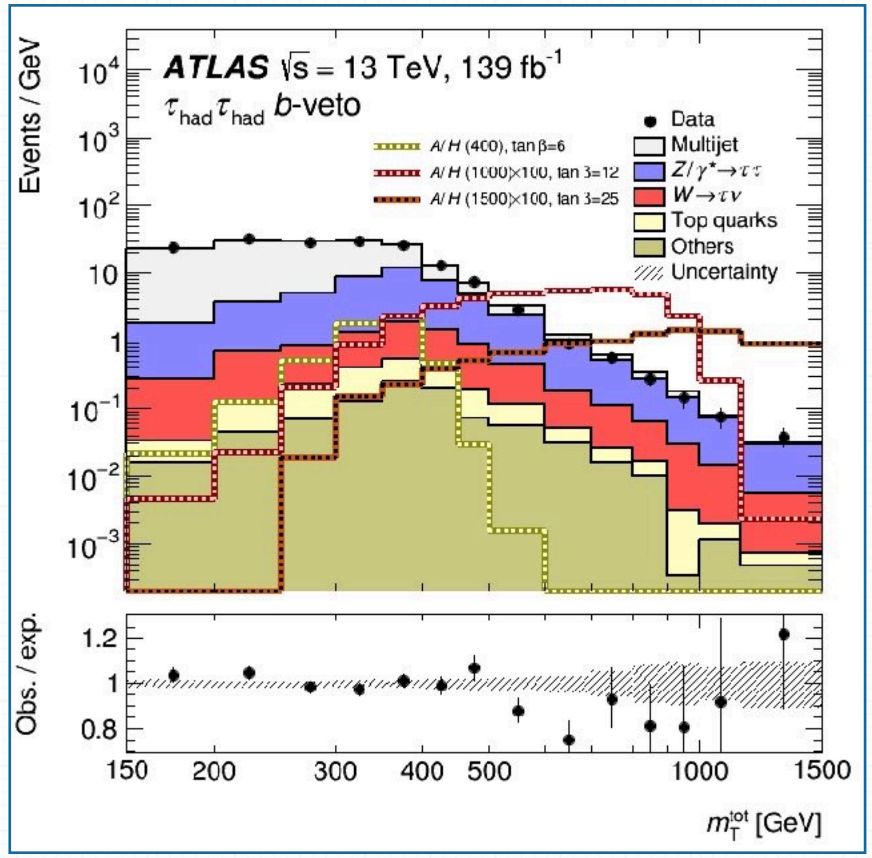




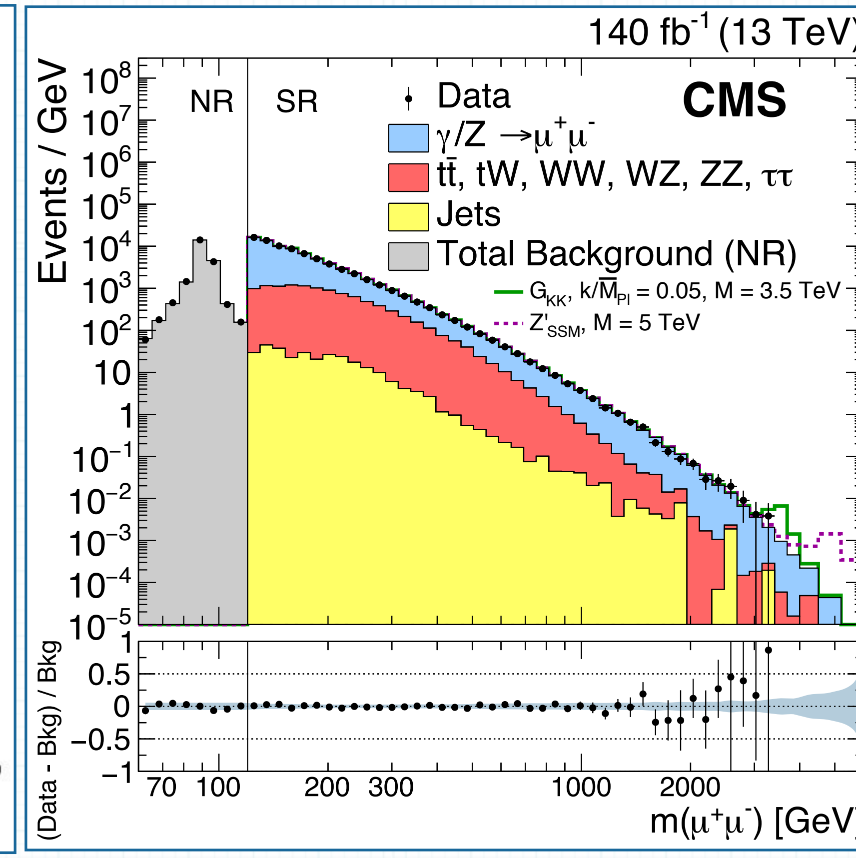
ATLAS $\tau\tau$ (139 fb^{-1}) and CMS $\mu\mu$ (140 fb^{-1}) Resonance Searches

- 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



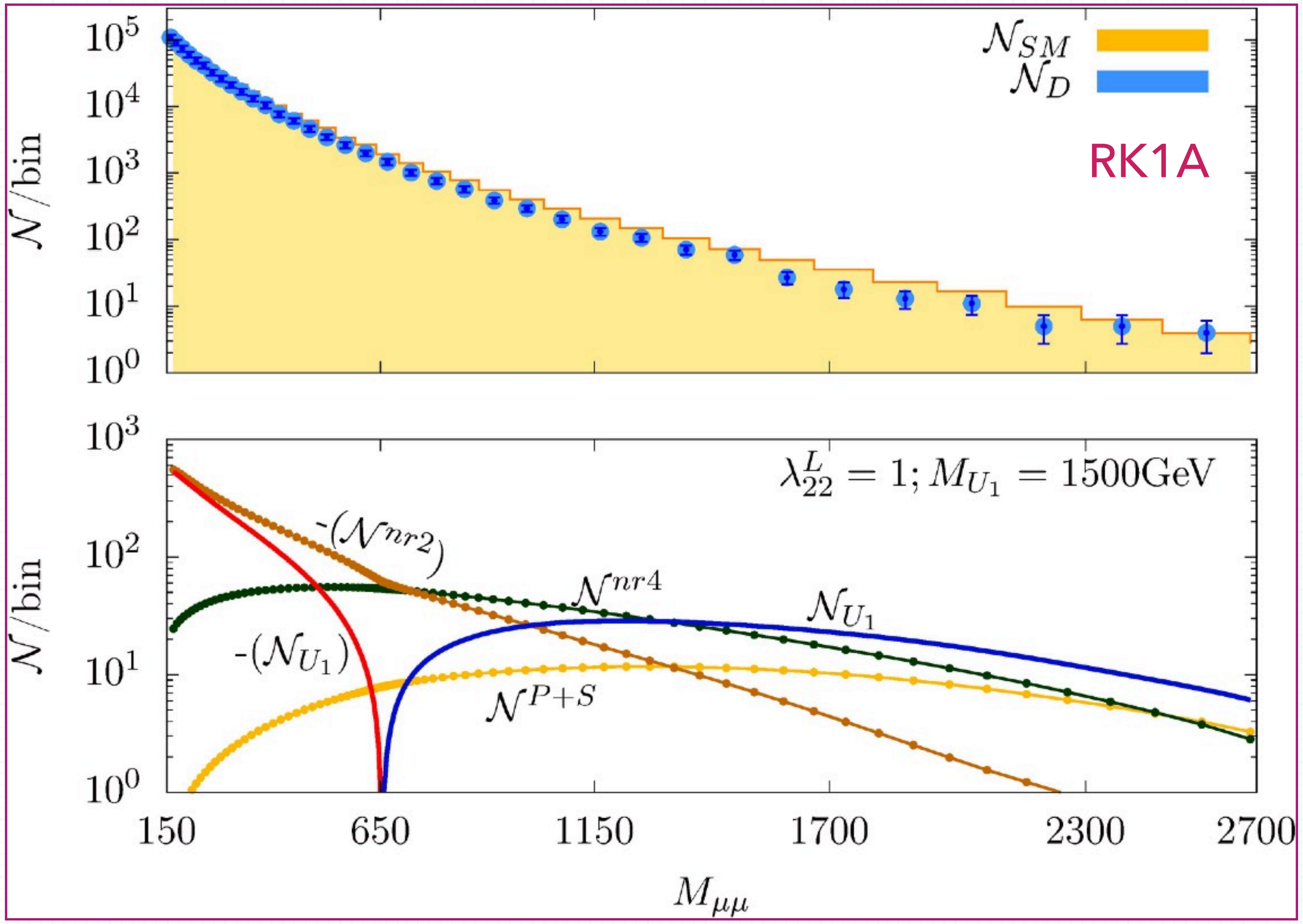
2103.02708



Mass	Pair production			Single production			t-channel LQ			Interference		
(Tev)	σ^p	ε^p	$\mathcal{N}^p$	σ^s	ε^s	$\mathcal{N}^s$	σ^{nr4}	ε^{nr4}	$\mathcal{N}^{nr4}$	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

Illustration

U_1



- The limits on multi-coupling scenarios can be obtained with cross-section parametrisation.

$$\sigma^p(M_{U_1}, \lambda) = \sigma^{p_0}(M_{U_1}) + \sum_i^n \lambda_i^2 \sigma_i^{p_2}(M_{U_1}) + \sum_{i \geq j}^n \lambda_i^2 \lambda_j^2 \sigma_{ij}^{p_4}(M_{U_1})$$

$$\mathcal{N}^p = \left\{ \sigma^{p_0} \times \epsilon^{p_0} + \sum_i^n \lambda_i^2 \sigma_i^{p_2} \times \epsilon_i^{p_2} + \sum_{i \geq j}^n \lambda_i^2 \lambda_j^2 \sigma_{ij}^{p_4} \times \epsilon_{ij}^{p_4} \right\} \times \mathcal{B}^2(M_{U_1}, \lambda) \times L$$

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.

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

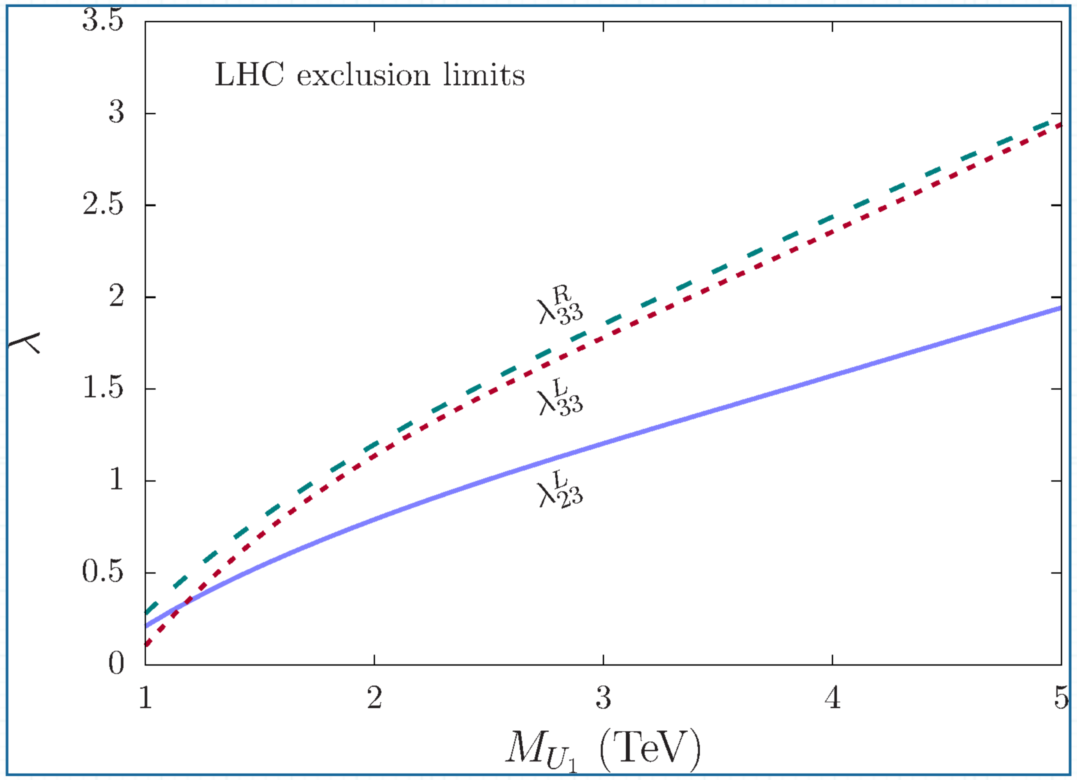
- For the error $\Delta\mathcal{N}^i$, we use $$\Delta\mathcal{N}^i = \sqrt{\left(\Delta\mathcal{N}^i_{stat}\right)^2 + \left(\Delta\mathcal{N}^i_{syst}\right)^2}$$

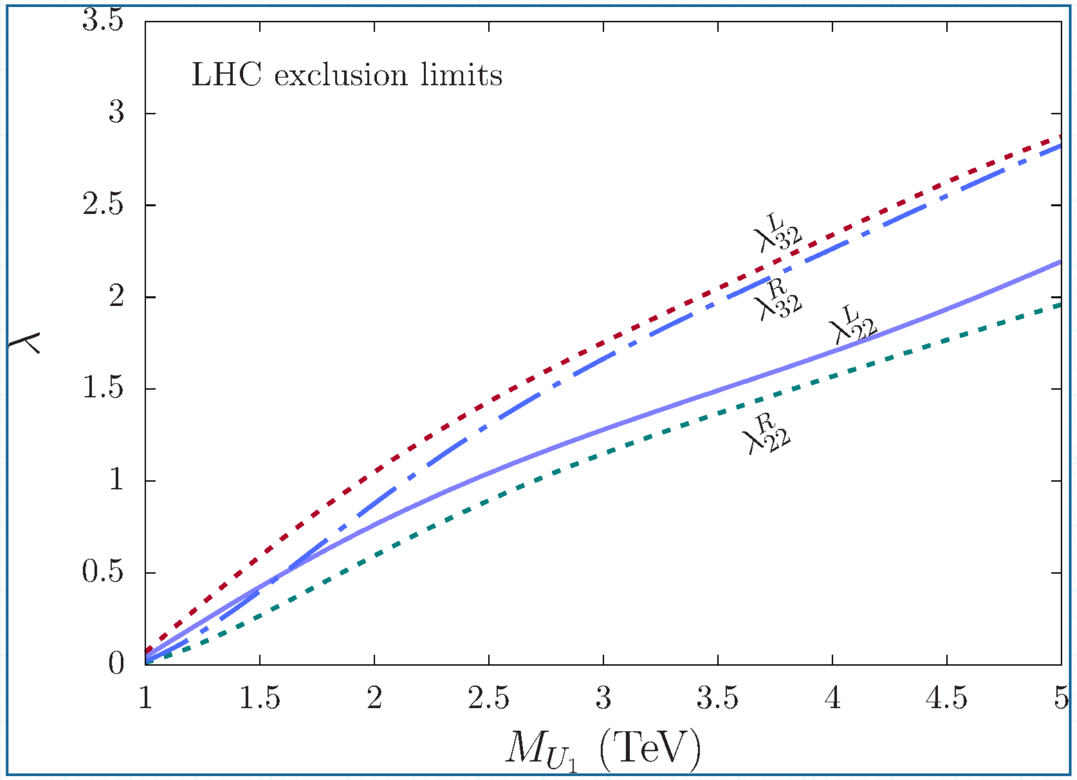
  where $\Delta\mathcal{N}^i_{stat} = \sqrt{\mathcal{N}^i_D}$ and we assume a uniform 10% systematic error

- 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.

U_1

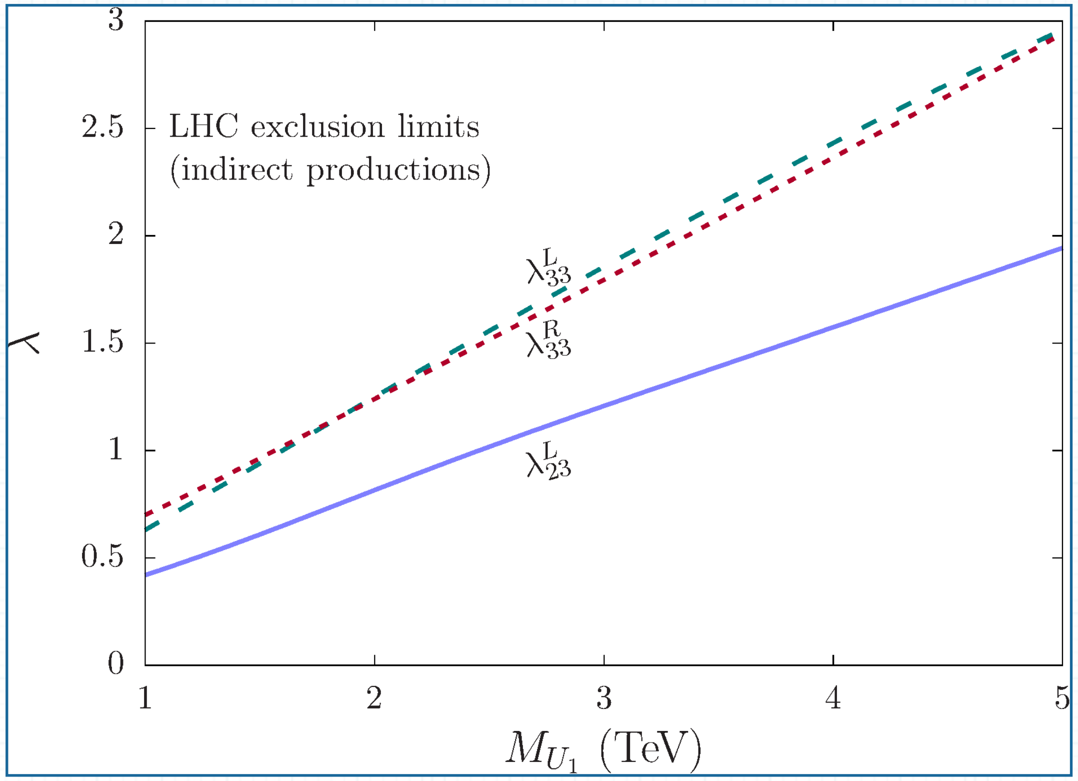
2101.12069

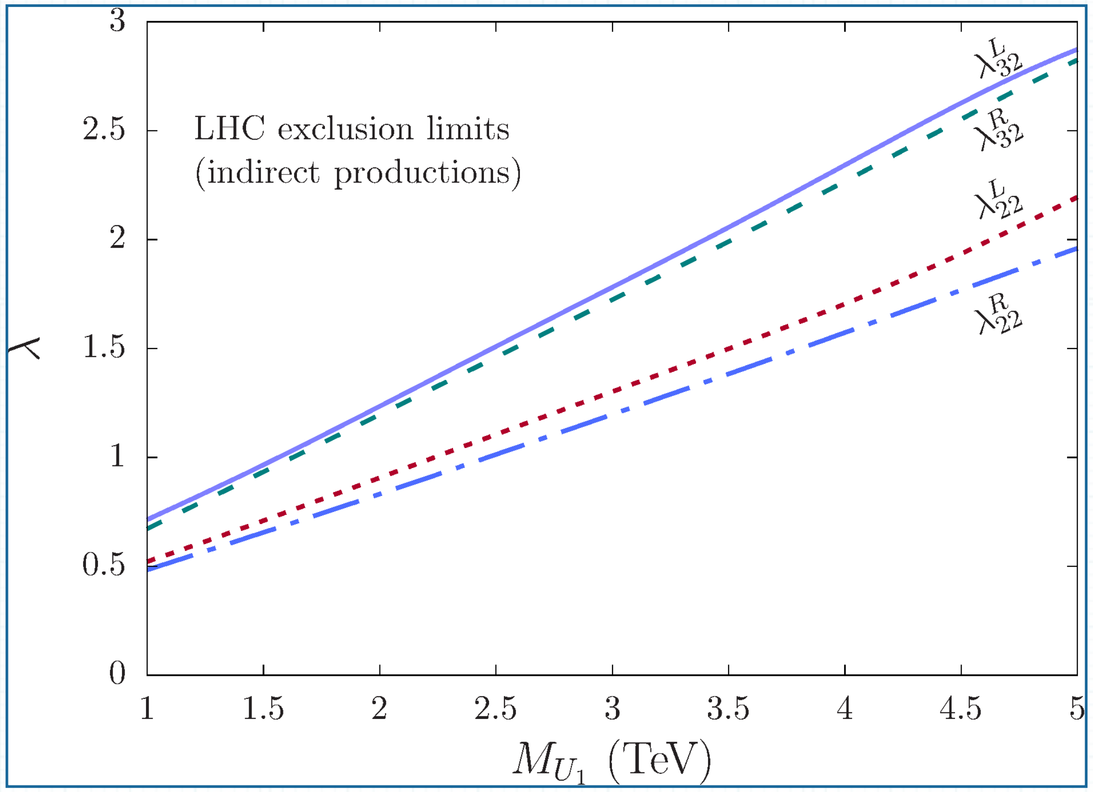




2002.12223

2103.02708





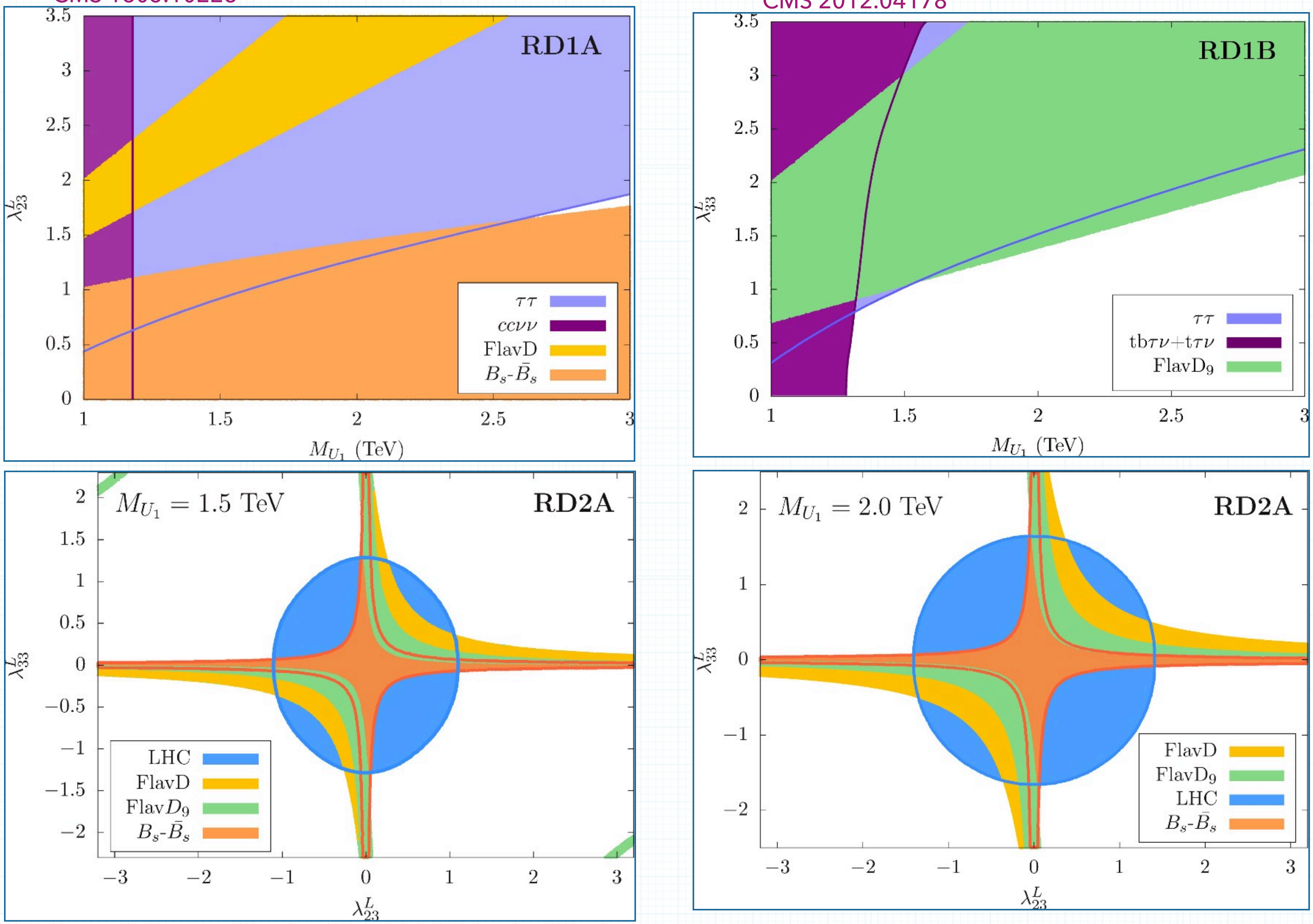
The Simple $R_{D^{(*)}}$ Scenarios Are Severely Constrained

U_1

2101.12069

CMS 1805.10228

CMS 2012.04178

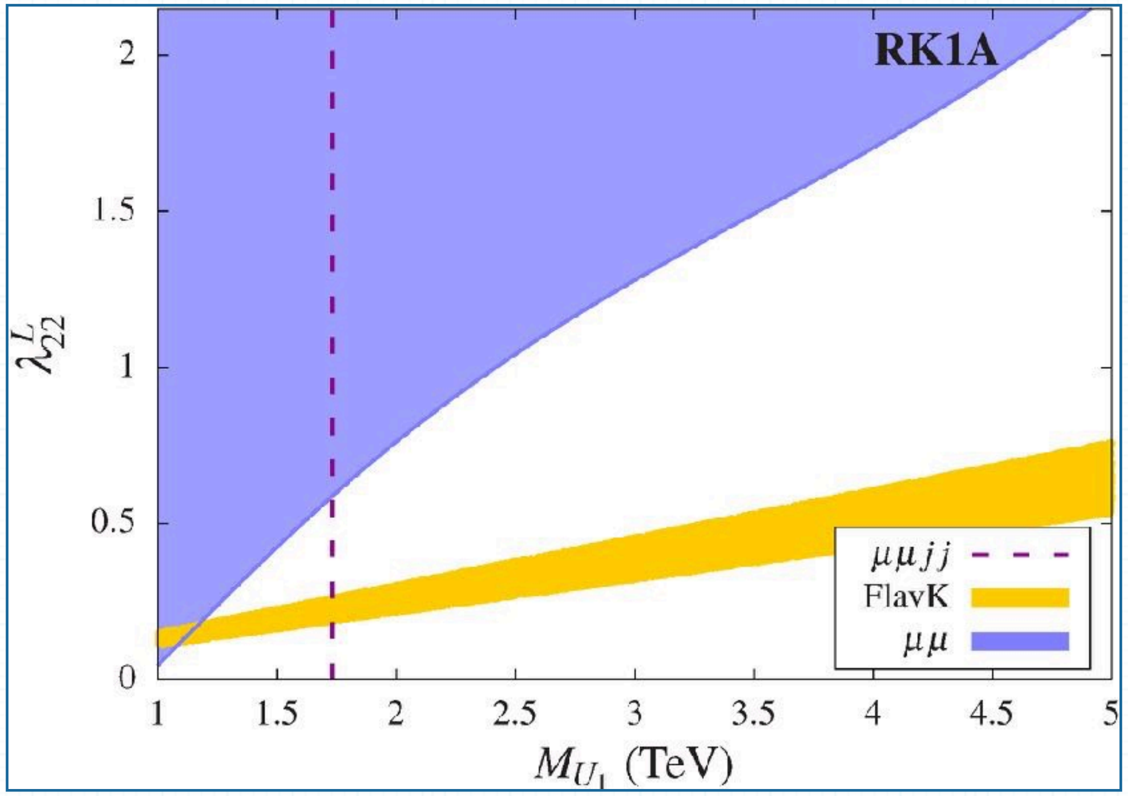


Recast of ATLAS Scalar LQ Search Data Rules out U_1 Below ~2 TeV

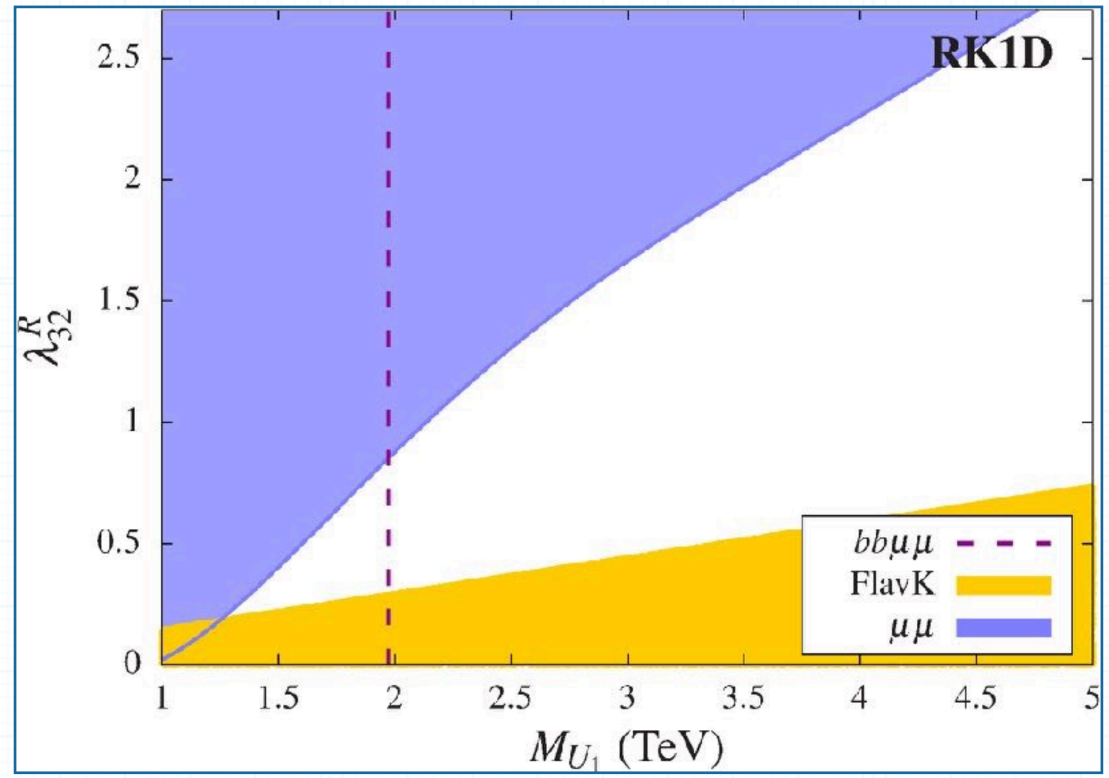
U_1

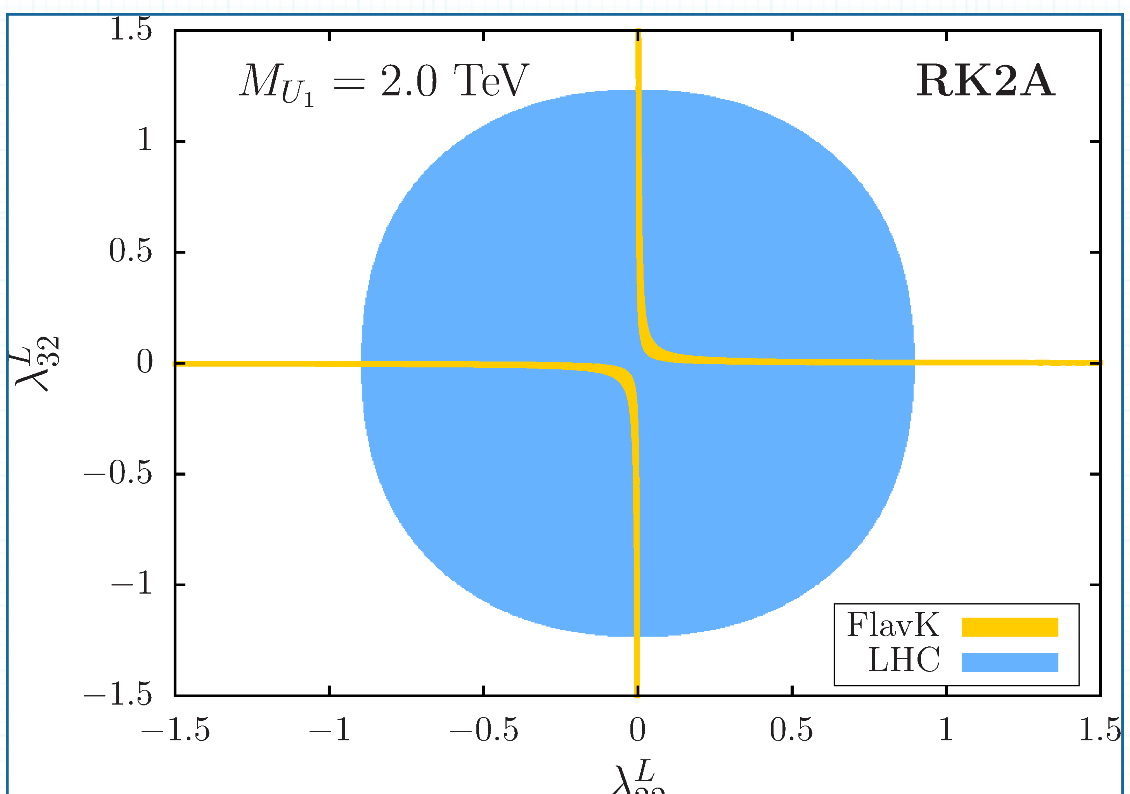
2101.12069

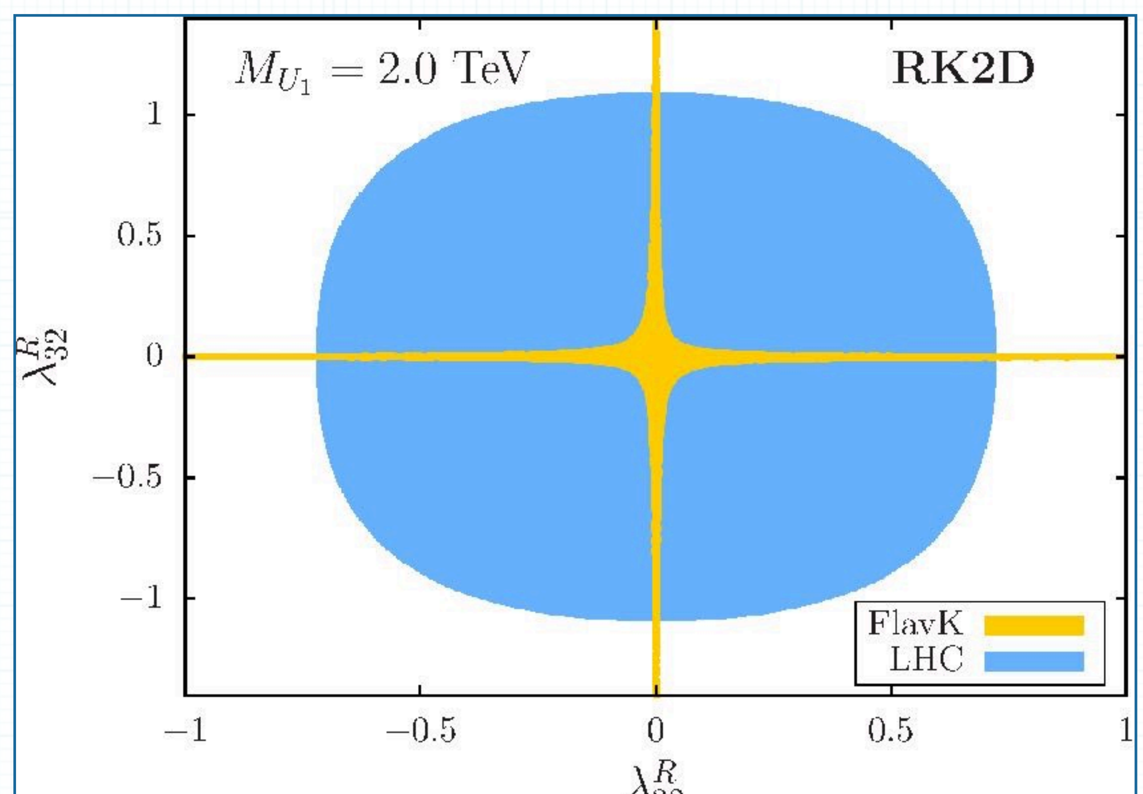
ATLAS 2006.05872 Recast



ATLAS 2006.05872 Recast



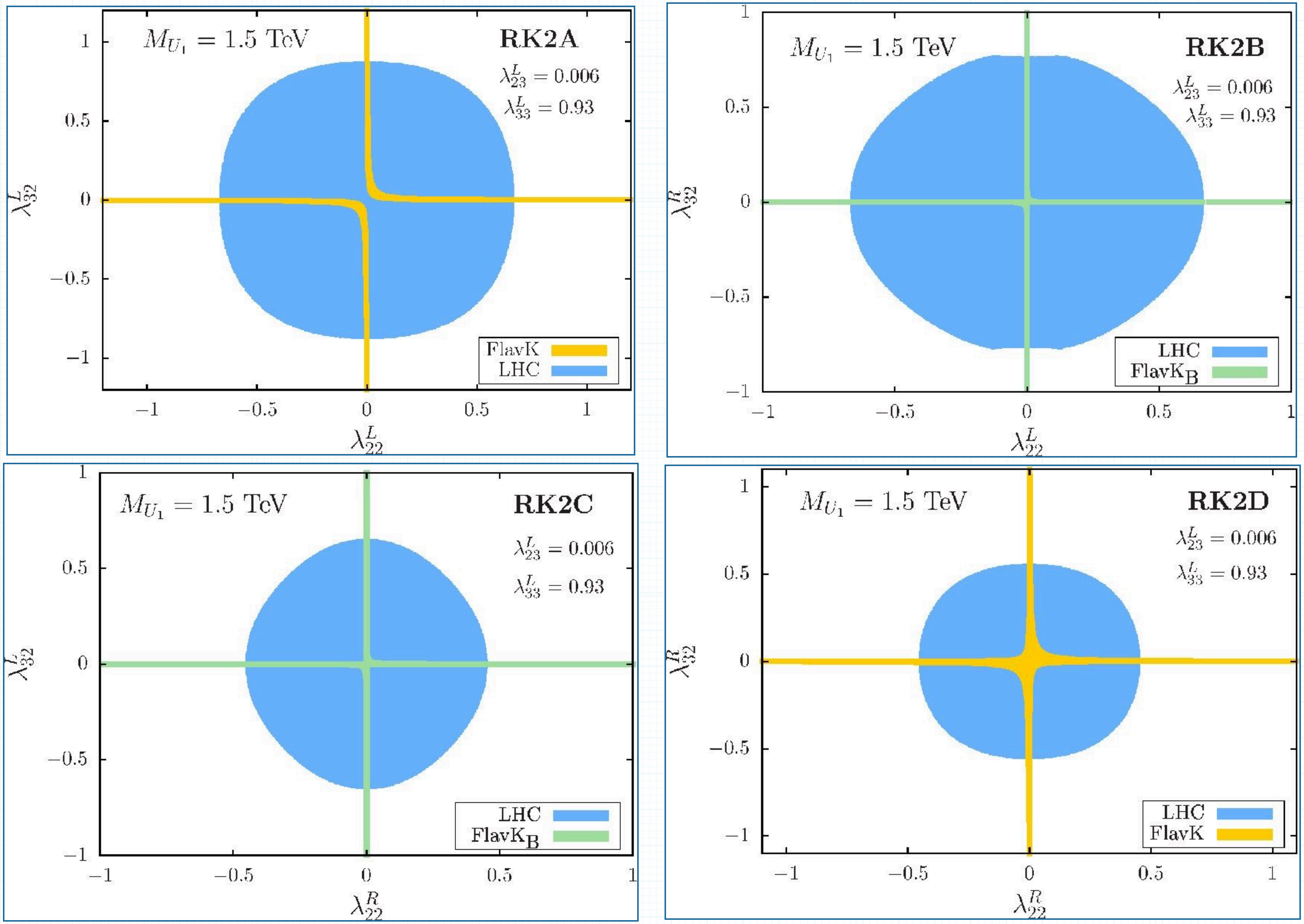




A 1.5 TeV U_1 Can Explain Both the Anomalies

U_1

2101.12069

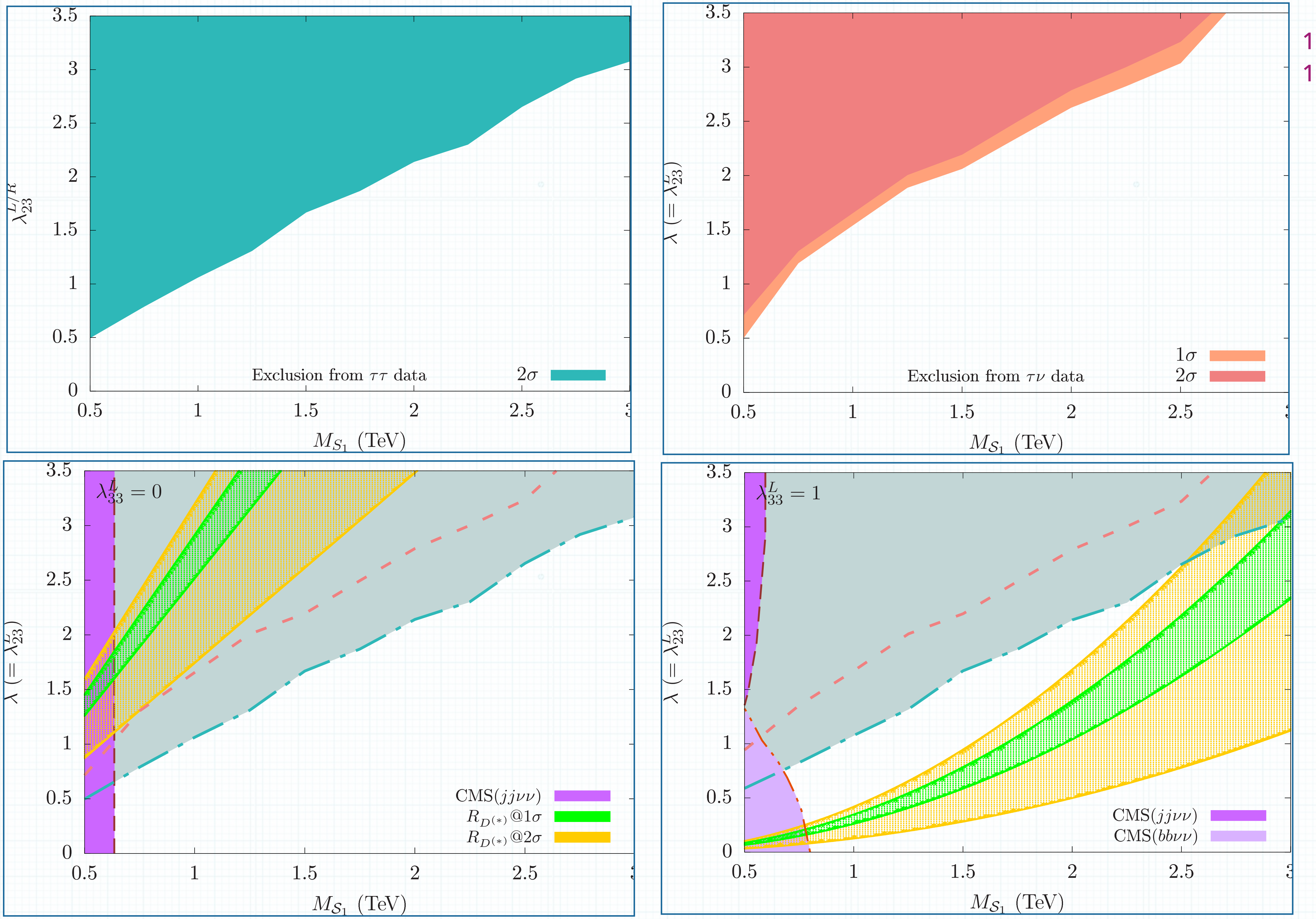


Bounds on S_1

1709.07242

1801.06992

1811.03561
1902.08108



Prospects at the HL-LHC

- The anomalies hint towards **large cross-generational LQ couplings involving third-generation quarks.** The $pp \to \ell_q \ell_q \to (t/b)(\tau/\nu) + (t/b)(\tau/\nu)$ modes are already searched for by the ATLAS and the CMS collaborations. **Assuming 100% branching ratios, the limits roughly stand at about a TeV or more**.

- LQs can be produced in pairs or singly. **Large couplings of LQs hint towards non-negligible single productions.** Hence, **current limits will improve further** if large cross-generational couplings are considered.

- The single productions of LQs that exclusively couple with third-generation quarks have tiny single-production cross-sections for perturbative new couplings because of the small b-quark PDF. But, the HL-LHC can help.

- **Interesting signature:** LQs can decay to **a top quark and a charged lepton** giving rise to a resonance system of a boosted top quark and a high-p_{T} lepton at the LHC.

Simple Parametrisation

- Electromagnetic charge conservation forces the LQs that decay to a top quark and a charged lepton to have electromagnetic charge 1/3 or 5/3.

$$S_1(\bar{\mathbf{3}},\mathbf{1},1/3): \quad y^{LL}_{1\,3j}\left(-\bar{b}^C_L\nu_L + \bar{t}^C_L\ell^j_L\right)S_1 + y^{RR}_{1\,3j}\;\bar{t}^C_R\ell^j_R S_1 + \text{H.c.}$$

$$S_3(\bar{\mathbf{3}},\mathbf{3},1/3): \quad -y^{LL}_{3\,3j}\left[\left(\bar{b}^C_L\nu_L + \bar{t}^C_L\ell^j_L\right)S^{1/3} + \sqrt{2}\left(\bar{b}^C_L\ell^j_L S^{4/3}_3 - \bar{t}^C_L\nu_L S^{-2/3}\right)\right] + \text{H.c.}$$

$$R_2(\mathbf{3},\mathbf{2},7/6): \quad -y^{RL}_{2\,3j}\;\bar{t}_R\ell^j_L R^{5/3}_2 + y^{RL}_{2\,3j}\;\bar{t}_R\nu_L R^{2/3}_2 + y^{LR}_{2\,j3}\;\bar{\ell}^j_R t_L R^{5/3\,*}_2 + y^{LR}_{2\,j3}\;\bar{\ell}^j_R b_L R^{2/3\,*}_2 + \text{H.c.}$$

$$\mathscr{L} \supset \lambda_\ell\left(\sqrt{\eta_L}\,\bar{t}^C_L\ell_L + \sqrt{\eta_R}\,\bar{t}^C_R\ell_R\right)\phi_1 + \lambda_\nu\bar{b}^C_L\nu_L\phi_1 + \tilde{\lambda}_\ell\left(\sqrt{\eta_L}\,\bar{t}_R\ell_L + \sqrt{\eta_R}\,\bar{t}_L\ell_R\right)\phi_5 + \text{H.c.}$$

		Simplified model [Eqs. (9)–(10)]			LQ models [Eqs. (3)–(8)]			
Benchmark scenario	Possible charge(s)	Type of LQ	Nonzero couplings equal to λ	Lepton chirality fraction	Type of LQ	Nonzero coupling equal to λ	Decay mode(s)	Branching ratio(s)
LCSS	1/3	ϕ_1	$\lambda_\ell = \lambda_\nu$	$\eta_L = 1,\ \eta_R = 0$	$S_3^{1/3}$	$-y^{LL}_{33j}$	$\{t\ell, b\nu\}$	$\{50\%, 50\%\}$
LCOS	1/3	ϕ_1	$\lambda_\ell = -\lambda_\nu$	$\eta_L = 1,\ \eta_R = 0$	S_1	y^{LL}_{13j}	$\{t\ell, b\nu\}$	$\{50\%, 50\%\}$
RC	$\{1/3, 5/3\}$	$\{\phi_1, \phi_5\}$	$\{\tilde{\lambda}_\ell, \lambda_\ell\}$	$\eta_L = 0,\ \eta_R = 1$	$\{S_1, R_2^{5/3}\}$	$\{y^{RR}_{13j}, y^{LR}_{2j3}\}$	$t\ell$	100%
LC	5/3	ϕ_5	$\tilde{\lambda}_\ell$	$\eta_L = 1,\ \eta_R = 0$	$R_2^{5/3}$	$-y^{RL}_{23j}$	$t\ell$	100%

Simple Parametrisation

Similar for vLQs, but the kinetic terms for vLQs contain another free parameter, κ

- Electromagnetic charge conservation forces the LQs that decay to a top quark and a charged lepton to have electromagnetic charge 1/3 or 5/3.

$$S_1(\bar{\mathbf{3}},\mathbf{1},1/3): \quad y^{LL}_{1\,3j}\left(-\bar{b}^C_L\nu_L + \bar{t}^C_L\ell^j_L\right)S_1 + y^{RR}_{1\,3j}\,\bar{t}^C_R\ell^j_R S_1 + \text{H.c.}$$

$$S_3(\bar{\mathbf{3}},\mathbf{3},1/3): \quad -y^{LL}_{3\,3j}\left[\left(\bar{b}^C_L\nu_L + \bar{t}^C_L\ell^j_L\right)S^{1/3} + \sqrt{2}\left(\bar{b}^C_L\ell^j_L S^{4/3}_3 - \bar{t}^C_L\nu_L S^{-2/3}\right)\right] + \text{H.c.}$$

$$R_2(\mathbf{3},\mathbf{2},7/6): \quad -y^{RL}_{2\,3j}\,\bar{t}_R\ell^j_L R^{5/3}_2 + y^{RL}_{2\,3j}\,\bar{t}_R\nu_L R^{2/3}_2 + y^{LR}_{2\,j3}\,\bar{\ell}^j_R t_L R^{5/3\,*}_2 + y^{LR}_{2\,j3}\,\bar{\ell}^j_R b_L R^{2/3\,*}_2 + \text{H.c.}$$

$$\mathscr{L} \supset \lambda_\ell\left(\sqrt{\eta_L}\,\bar{t}^C_L\ell_L + \sqrt{\eta_R}\,\bar{t}^C_R\ell_R\right)\phi_1 + \lambda_\nu\bar{b}^C_L\nu_L\phi_1 + \tilde{\lambda}_\ell\left(\sqrt{\eta_L}\,\bar{t}_R\ell_L + \sqrt{\eta_R}\,\bar{t}_L\ell_R\right)\phi_5 + \text{H.c.}$$

		Simplified model [Eqs. (9)–(10)]			LQ models [Eqs. (3)–(8)]			
Benchmark scenario	Possible charge(s)	Type of LQ	Nonzero couplings equal to λ	Lepton chirality fraction	Type of LQ	Nonzero coupling equal to λ	Decay mode(s)	Branching ratio(s)
LCSS	1/3	ϕ_1	$\lambda_\ell = \lambda_\nu$	$\eta_L = 1,\ \eta_R = 0$	$S_3^{1/3}$	$-y^{LL}_{33j}$	$\{t\ell, b\nu\}$	$\{50\%, 50\%\}$
LCOS	1/3	ϕ_1	$\lambda_\ell = -\lambda_\nu$	$\eta_L = 1,\ \eta_R = 0$	S_1	y^{LL}_{13j}	$\{t\ell, b\nu\}$	$\{50\%, 50\%\}$
RC	$\{1/3, 5/3\}$	$\{\phi_1, \phi_5\}$	$\{\tilde{\lambda}_\ell, \lambda_\ell\}$	$\eta_L = 0,\ \eta_R = 1$	$\{S_1, R_2^{5/3}\}$	$\{y^{RR}_{13j}, y^{LR}_{2j3}\}$	$t\ell$	100%
LC	5/3	ϕ_5	$\tilde{\lambda}_\ell$	$\eta_L = 1,\ \eta_R = 0$	$R_2^{5/3}$	$-y^{RL}_{23j}$	$t\ell$	100%

Combined Signal

- We consider hadronic decays of tops. **The characteristic of our signal is the presence of one or two boosted top quarks forming one/two top-like fatjets and two high-p_T leptons.**

- If we define our signal as events containing **exactly two high-p_T same flavor opposite sign leptons and at least one hadronic top-like fatjet** in the final state then it would include both single and pair productions and enhance the sensitivity.

- There is **some overlap between the pair and the single production processes. One has to be careful to avoid double-counting** while computing single productions. We ensure that for any single production process both $\phi(\chi)$ and $\phi^\dagger(\bar{\chi})$ are never on-shell simultaneously.

Background processes		σ (pb)	QCD order
$V+$ jets [56, 57]	$Z+$ jets	6.33×10^4	NNLO
	$W+$ jets	1.95×10^5	NLO
$VV+$ jets [58]	$WW+$ jets	124.31	NLO
	$WZ+$ jets	51.82	NLO
	$ZZ+$ jets	17.72	NLO
Single t [59]	tW	83.10	N^2LO
	tb	248.00	N^2LO
	tj	12.35	N^2LO
tt [60]	$tt+$ jets	988.57	N^3LO
ttV [61]	ttZ	1.05	NLO+NNLL
	ttW	0.65	NLO+NNLL

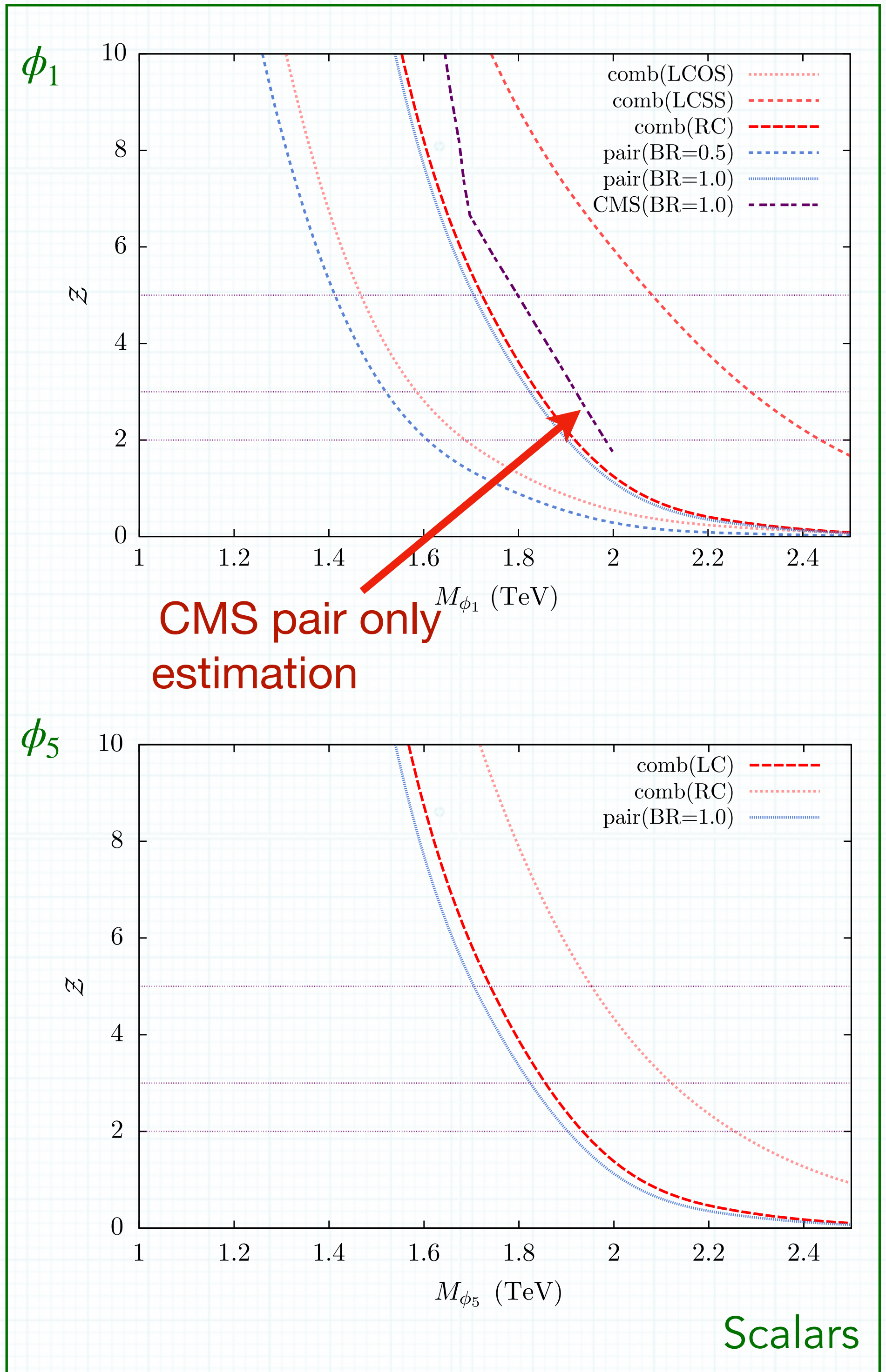
Significance

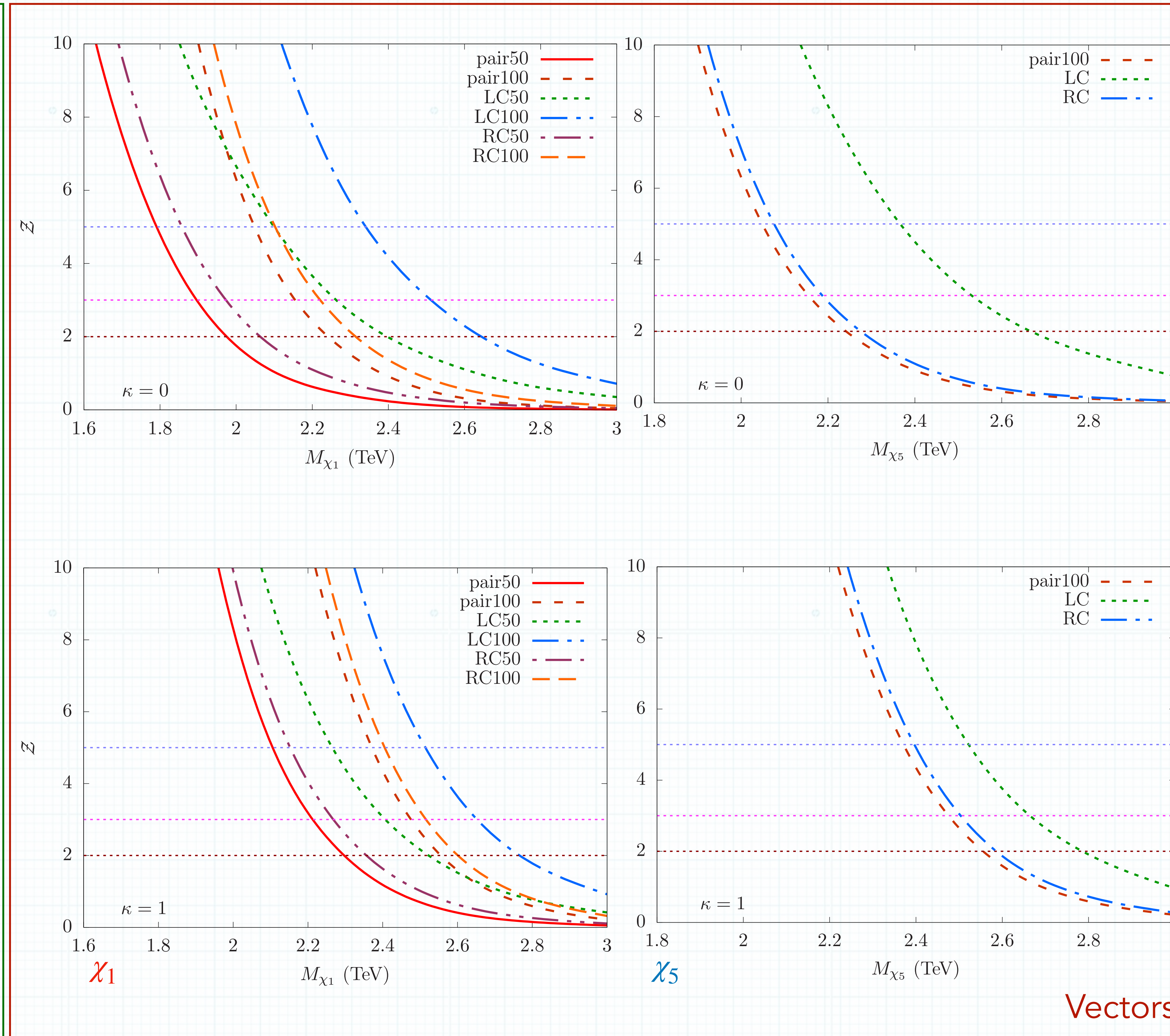
1907.11194

$3\ \mathrm{ab}^{-1}$ $\lambda = 1$

$$\mathcal{Z} = \sqrt{2\left(N_S + N_B\right)\ln\left(\frac{N_S + N_B}{N_B}\right) - 2N_S}$$

2004.01096





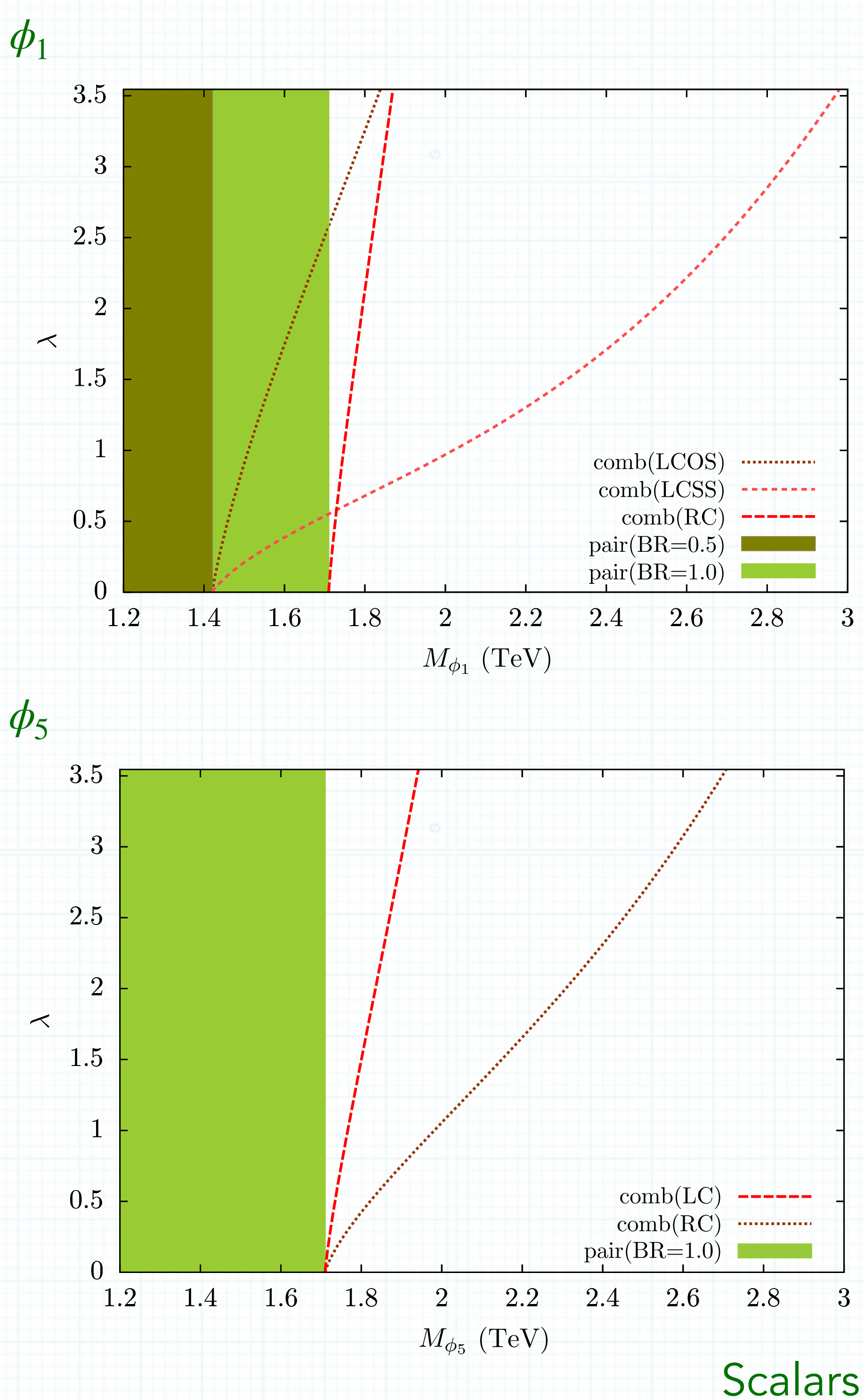
Discovery

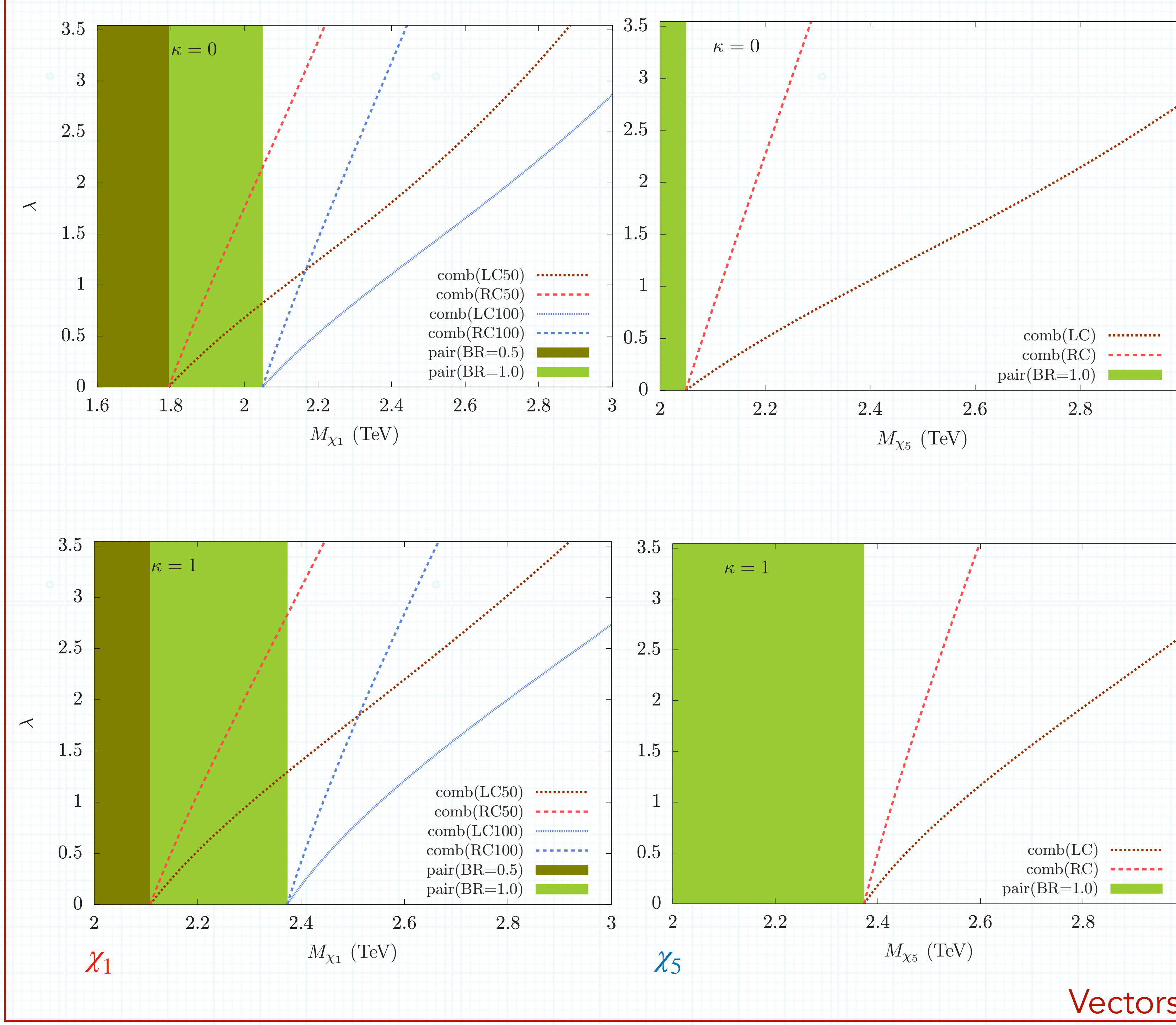
$3\ \mathrm{ab}^{-1}$

$$\sigma_{\text{signal}} \approx \sigma_{\text{pair}}\left(M_{\ell_q}\right) + \lambda^2 \sigma_{\text{single}}\left(\lambda = 1, M_{\ell_q}\right)$$

1907.11194

2004.01096





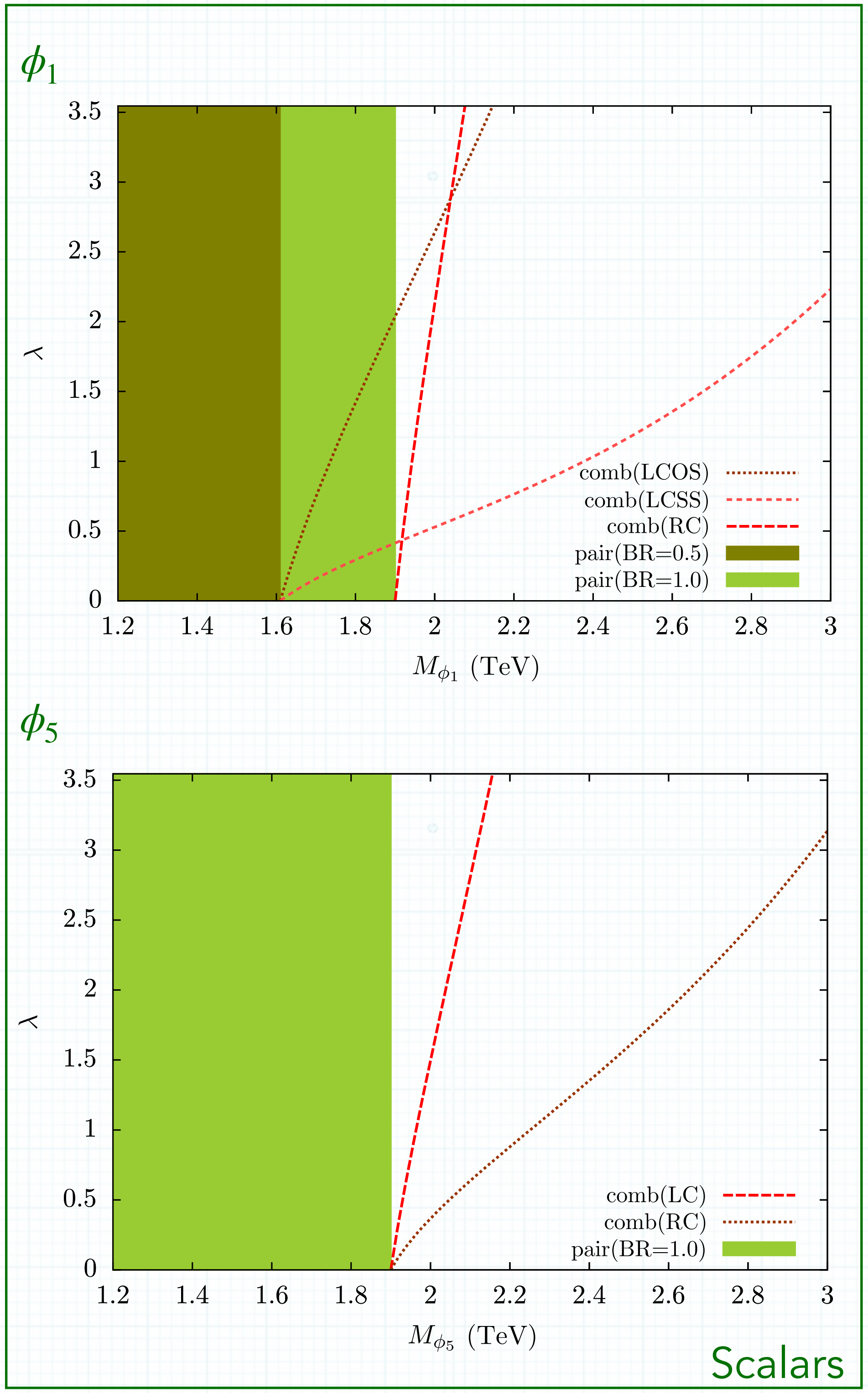
Exclusion

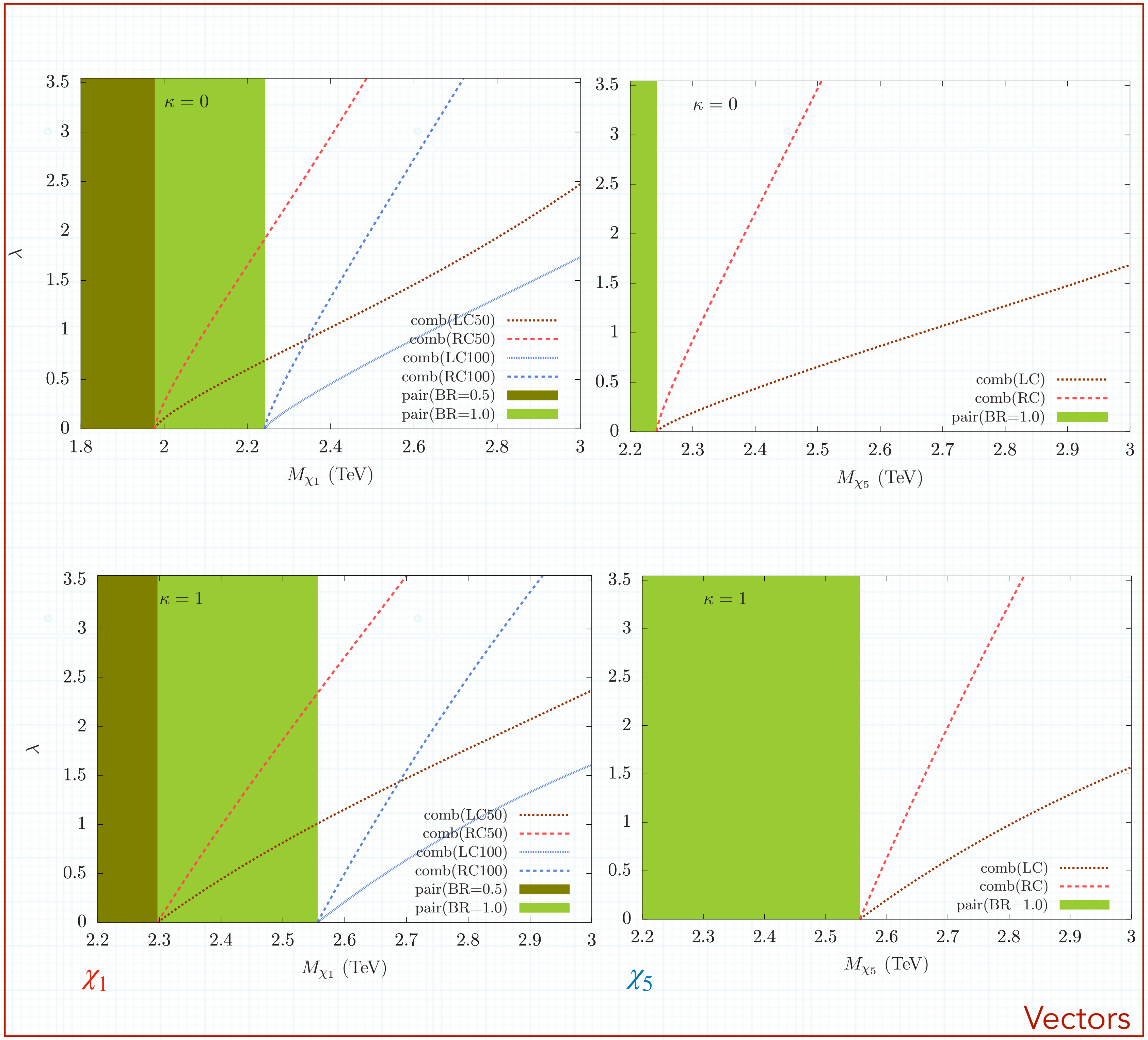
1907.11194

$3\ \text{ab}^{-1}$

$$\sigma_{\text{signal}} \approx \sigma_{\text{pair}}\left(M_{\ell_q}\right) + \lambda^2 \sigma_{\text{single}}\left(\lambda = 1, M_{\ell_q}\right)$$

2004.01096





Discovery

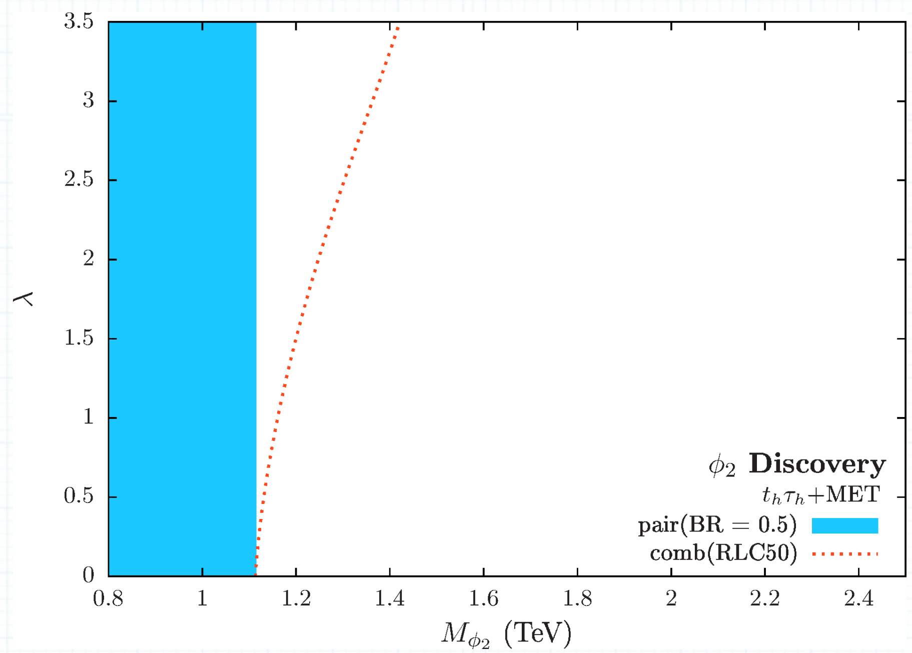
$3\ \mathrm{ab}^{-1}$

$$\sigma_{\rm signal} \approx \sigma_{\rm pair}\left(M_{\ell_q}\right) + \lambda^2 \sigma_{\rm single}\left(\lambda = 1, M_{\ell_q}\right)$$

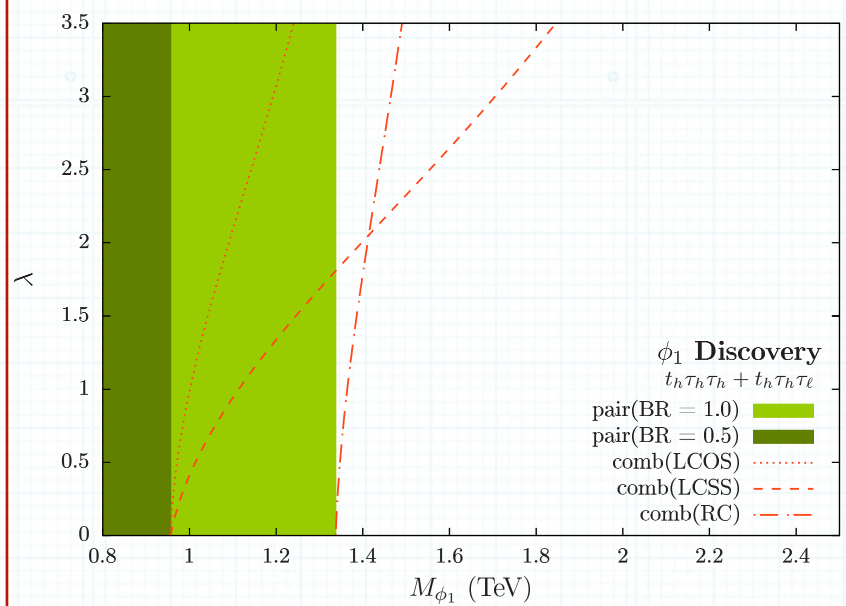
2106.07605

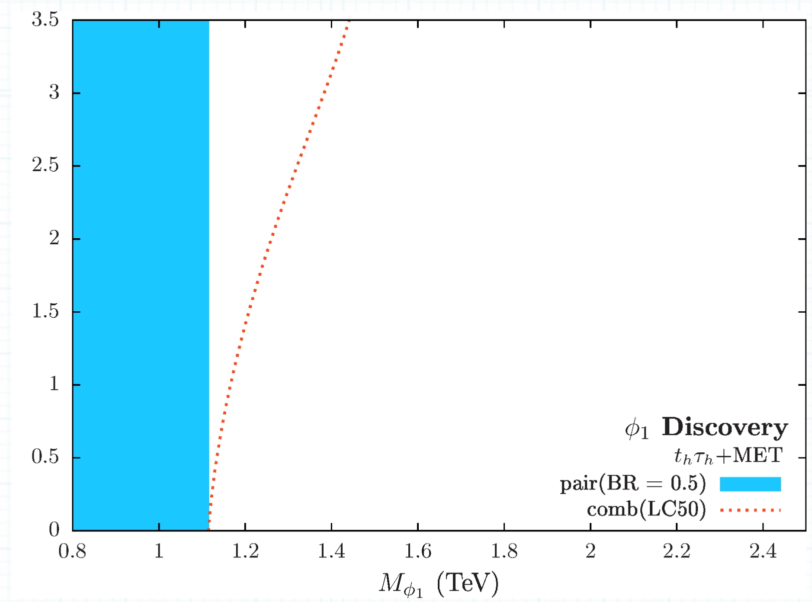
Scalar

ϕ_2

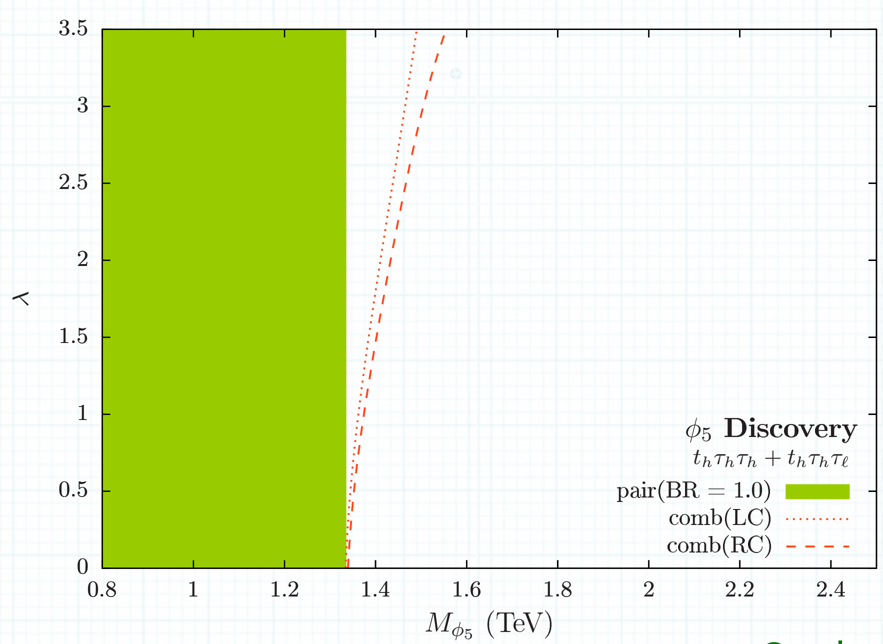


ϕ_1

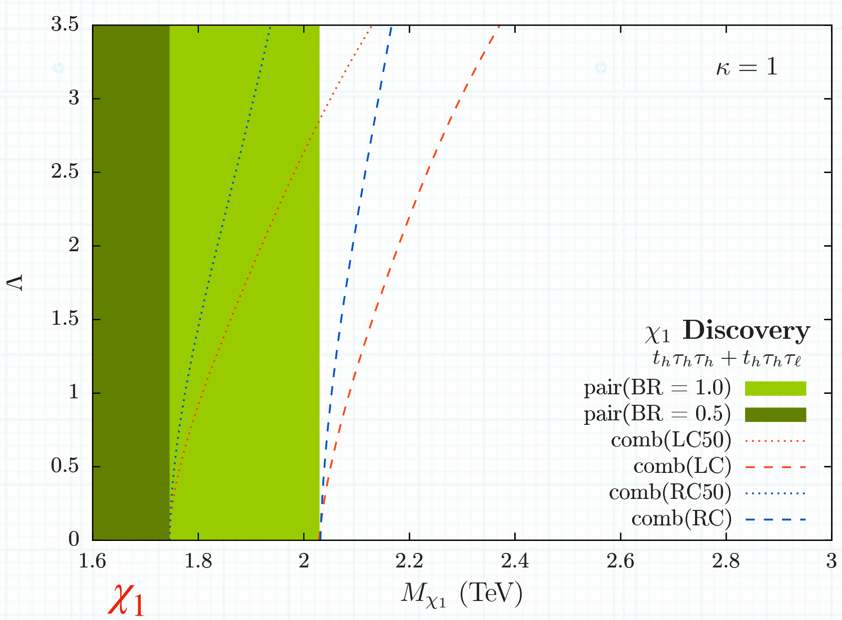




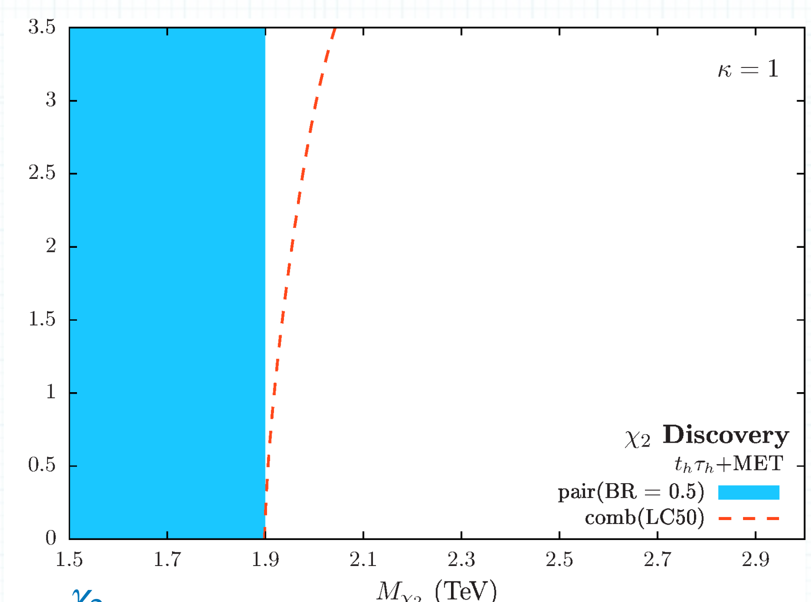
ϕ_5



Scalars



χ_1



χ_2

Vectors

Exclusion

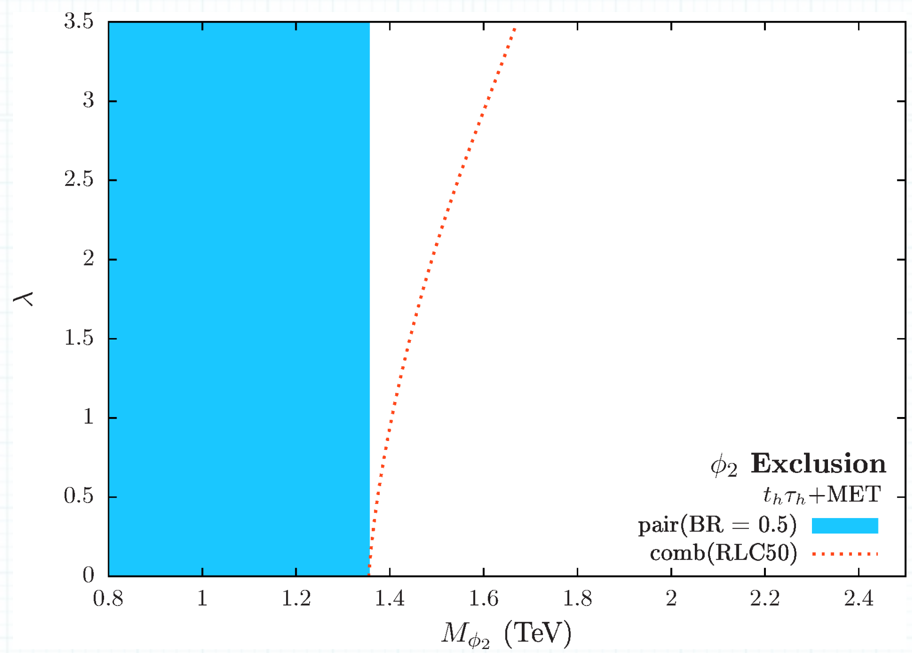
$3\ \mathrm{ab}^{-1}$

$$\sigma_{\text{signal}} \approx \sigma_{\text{pair}}\left(M_{\ell_q}\right) + \lambda^2 \sigma_{\text{single}}\left(\lambda = 1, M_{\ell_q}\right)$$

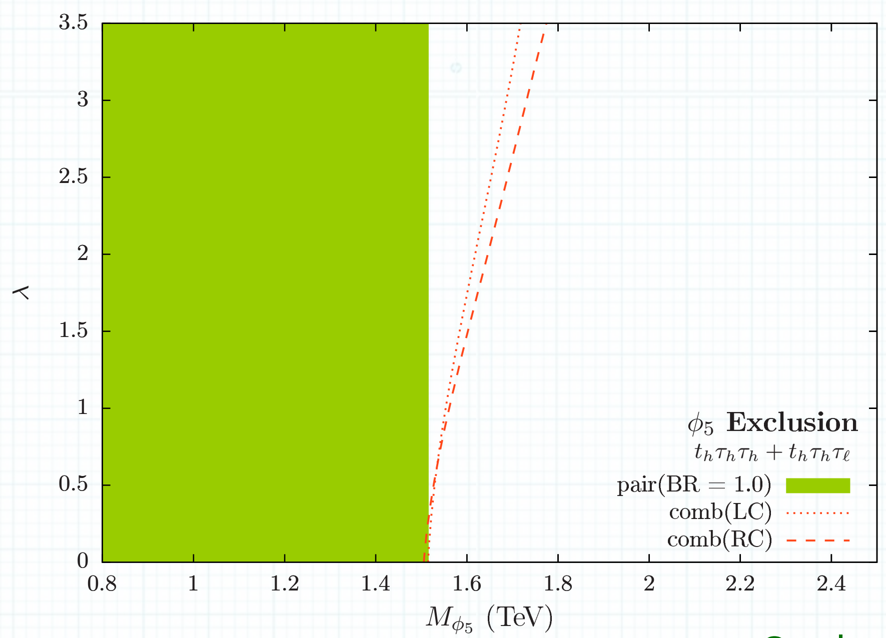
2106.07605

Scalars

ϕ_2

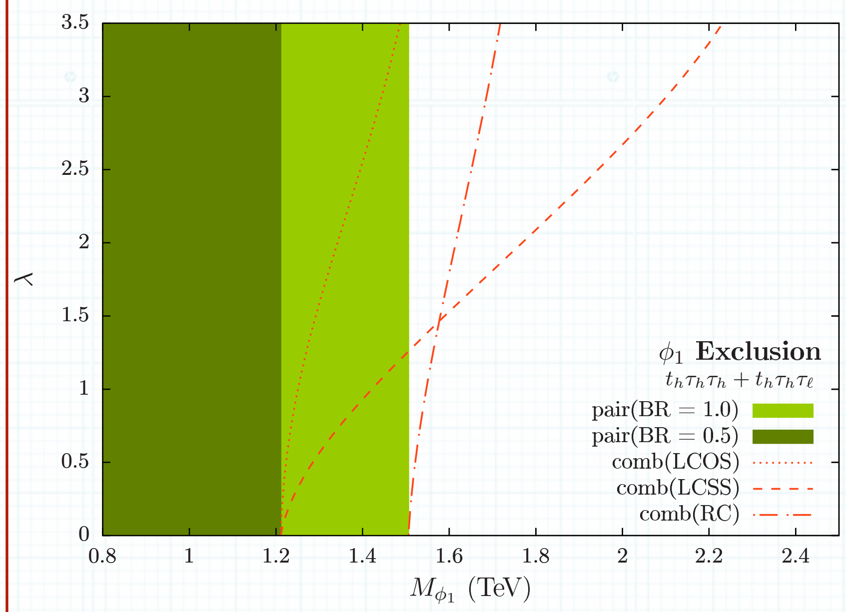


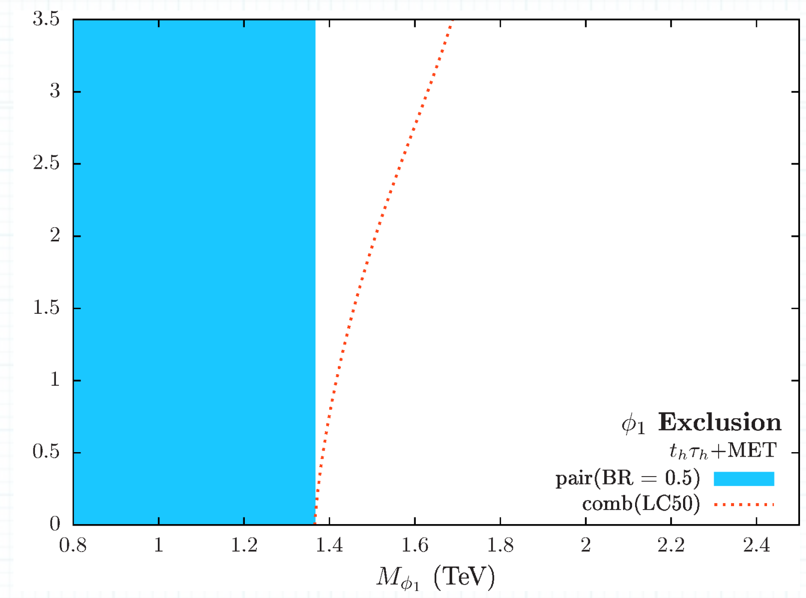
ϕ_5

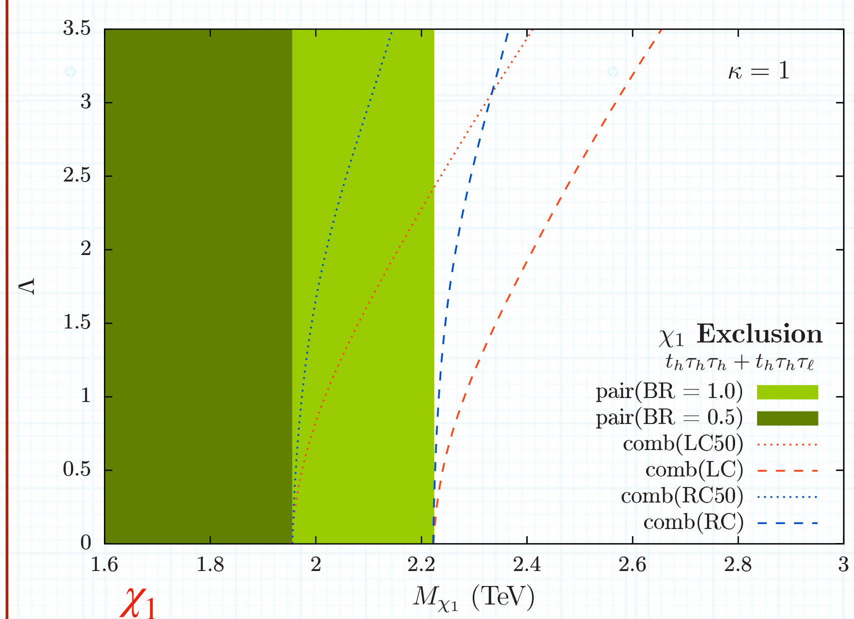


Scalar

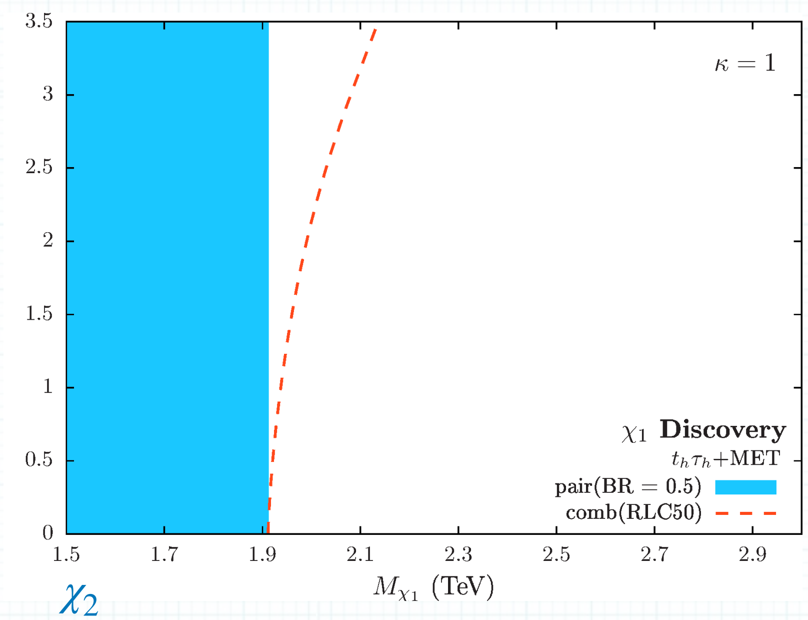
ϕ_1







χ_1



χ_2

Vectors

- The LHC dilepton data can constrain the LQ parameters needed to accommodate the anomalies. The method is generic and, with a suitable parametrisation of the cross-sections, can be used to put bounds on single-coupling and multi-coupling scenarios.

- The single-coupling U_1 scenarios are ruled out or under stress. Multi-coupling scenarios are better. A 1.5 TeV U_1 can explain both$R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies.

- The anomalies hint towards **large cross-generational LQ couplings involving third-generation quarks hinting towards non-negligible single productions.** Hence, **current limits will improve further** if large cross-generational couplings are considered.

- **Interesting signature:** LQs can decay to **a top quark and a charged lepton** giving rise to a resonance system of a boosted top quark and a high-$p_{\rm T}$ lepton at the LHC.

Thank you

ANOMALIES 2021

LEPTOQUARK MODELS: LHC BOUNDS AND PROSPECTS

SUBHADIP MITRA (IIIT HYDERABAD)

Based on
PRD 104 (2021) 7, 075037 [2106.07605]
PRD 104 (2021) 3, 035016 [2101.12069]
PRD 101 (2020) 11, 115015 [2004.01096]
PRD 101 (2020) 1, 015011 [1902.08108]
PRD 100 (2019) 7, 075019 [1907.11194]
PRD 99 (2019) 5, 055028 [1811.03561]

With
Arvind Bhaskar
Kushagra Chandak
Diganta Das
Tanumoy Mandal
Cyrin Neeraj
Swapnil Raz
Mohit Sharma

November 12, 2021