PHENO 2020

Prospects for searches for Leptoquarks with large coupling with the top quark

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Based on
PRD 100, 075019 (2019) & arXiv:2004.01096
written in collaboration with
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Background

- **LQs** are color triplet bosons with lepton numbers - **can couple to leptons and quarks**. Currently, they are receiving a lot of attention in the literature as they are one of the leading candidates to resolve the **persistent B-decay anomalies ($R_{K^{(*)}}$ and $R_{D^{(*)}}$)**. The anomalies **hint towards large cross-generational LQ couplings** involving third generation quarks.

- The LHC is searching for LQs that couple with third-generation fermions and has put direct bounds on them. Among the various possible signatures, the $pp \to \ell_q \ell_q \to t\tau\, t\tau$ mode is already extensively searched for by the ATLAS and the CMS collaborations. Assuming 100% branching ratios, the limits stand at about a TeV.

- **LQs can decay to a top quark and a charged (light) lepton giving rise to a resonance system of a boosted top quark and a high-$p_{\rm T}$ lepton at the LHC**. They can be **produced in pairs or singly**. As their mass increases, the pair production cross section falls off faster than the single production cross sections due to the extra phase-space suppression it receives.

- **Large couplings** of LQs **hint towards non-negligible single productions**. However, the common perception is, at the LHC, LQs that couple with third generation quarks exclusively have tiny single production cross sections for perturbative new couplings because of the small b-quark parton density function (PDF) (t-PDF is absent).

Scalar LQ Models

Chandak, Mandal, SM, **PRD 100, 075019 (2019)**

- 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**. From the Buchmüller-Rückl-Wyler models we see that **among the scalar LQs, only S_1, S_3 and R_2 can have the desired decay modes**.

- The relevant Lagrangian terms:

Buchmuller, Ruckl, Wyler, **PLB 191, 442 (1987)**
Doršner, Fajfer, Greljo, Kamenik, Košnik, **PRpt 641, 1 (2016)**

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

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

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

with $j=\{1,2\}$. All neutrinos are denoted by ν_L.

- We assume diagonal CKM & PMNS matrices (a good approximation for LHC direct searches).

Vector LQ Models

Bhaskar, Mandal, SM, **arXiv:2004.01096**

- **Among the possible vector LQ models, the weak singlet $\tilde{U}_1$, doublets V_2 and $\tilde{V}_2$ and the triplet U_3 would qualify.**
- The relevant Lagrangian terms:

Buchmuller, Ruckl, Wyler, **PLB 191, 442 (1987)**
Doršner, Fajfer, Greljo, Kamenik, Košnik, **PRpt 641, 1 (2016)**

$\tilde{U}_1(\mathbf{3},\mathbf{1},5/3)$: $\tilde{x}^{RR}_{1\,3j}\,\bar{t}_R\left(\gamma\cdot\tilde{U}_1\right)\ell^j_R+\text{H.c.}$

$U_1(\mathbf{3},\mathbf{1},2/3)$: $x^{LL}_{1\,3j}\left\{\bar{t}_L\left(\gamma\cdot U_1\right)\nu_L+\bar{b}_L\left(\gamma\cdot U_1\right)\ell^j_L\right\}+x^{RR}_{1\,3j}\,\bar{b}_R\left(\gamma\cdot U_1\right)\ell^j_R+\text{H.c.}$

$V_2(\bar{\mathbf{3}},\mathbf{2},5/6)$: $-x^{RL}_{2\,3j}\bar{b}^C_R\left\{\left(\gamma\cdot V_2^{1/3}\right)\nu_L-\left(\gamma\cdot V_2^{4/3}\right)\ell^j_L\right\}+x^{LR}_{2\,3j}\left\{\bar{t}^C_L\left(\gamma\cdot V_2^{1/3}\right)-\bar{b}^C_L\left(\gamma\cdot V_2^{4/3}\right)\right\}\ell^j_R+\text{H.c.}$

$\tilde{V}_2(\bar{\mathbf{3}},\mathbf{2},-1/6)$: $\tilde{x}^{RL}_{2\,3j}\bar{t}^C_R\left\{-\left(\gamma\cdot\tilde{V}_2^{1/3}\right)\ell^j_L+\left(\gamma\cdot\tilde{V}_2^{-2/3}\right)\nu_L\right\}+\text{H.c.}$

$U_3(\mathbf{3},\mathbf{3},2/3)$: $x^{LL}_{3\,3j}\left\{-\bar{b}_L\left(\gamma\cdot U_3^{2/3}\right)\ell^j_L+\bar{t}_L\left(\gamma\cdot U_3^{2/3}\right)\nu_L+\sqrt{2}\,\bar{b}_L\left(\gamma\cdot U_3^{-1/3}\right)\nu_L+\sqrt{2}\,\bar{t}_L\left(\gamma\cdot U_3^{5/3}\right)\ell^j_L\right\}$

$+$ H.c. with $j=\{1,2\}$. All neutrinos are denoted by ν_L.

Simple Models & Benchmarks

Chandak, Mandal, SM, **PRD 100, 075019 (2019)**

- We can write **a simple phenomenological Lagrangian** for the scalar models,

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

- In this notation, a charge 1/3 (5/3) scalar LQ is generically represented by $\phi_1(\phi_5)$.
- η_L and $\eta_R = 1 - \eta_L$ are the fractions of leptons coming from LQ decays that are left-handed and right-handed respectively.

		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 Models & Benchmarks

Bhaskar, Mandal, SM, **arXiv:2004.01096**

- We can write **a similar simplified phenomenological Lagrangian for the vLQ models**,

$$\mathscr{L} \supset \Lambda_\ell \left\{ \sqrt{\eta_R}\ \bar{t}^C_L \left(\gamma \cdot \chi_1\right) \ell_R + \sqrt{\eta_L}\ \bar{t}^C_R \left(\gamma \cdot \chi_1\right) \ell_L \right\} + \ \Lambda_\nu\ \bar{b}^C_R \left(\gamma \cdot \chi_1\right) \nu_L$$
$$+\bar{\Lambda}_\ell \left\{ \epsilon_R \sqrt{\eta_R}\ \bar{b}_R \left(\gamma \cdot \chi_2\right) \ell_R + \sqrt{\eta_L}\ \bar{b}_L \left(\gamma \cdot \chi_2\right) \ell_L \right\} + \ \bar{\Lambda}_\nu\ \bar{t}_L \left(\gamma \cdot \chi_2\right) \nu_L$$
$$+\tilde{\Lambda}_\ell \left\{ \sqrt{\eta_R}\ \bar{t}_R \left(\gamma \cdot \chi_5\right) \ell_R + \sqrt{\eta_L}\ \bar{t}_L \left(\gamma \cdot \chi_5\right) \ell_L \right\} + \ \mathrm{H.c.}$$

- In this notation, a charge 1/3 (5/3) vLQ is generically represented by $\chi_1 (\chi_5)$.

- **The kinetic terms for a vLQ contains a free parameter, usually denoted as κ**

$$\mathscr{L} \supset -\frac{1}{2} \chi^\dagger_{\mu\nu} \chi^{\mu\nu} + M^2_\chi\ \chi^\dagger_\mu \chi^\mu - i g_s \kappa\, \chi^\dagger_\mu T^a \chi_\nu\ G^{a\,\mu\nu}$$

Simple Models & Benchmarks

Bhaskar, Mandal, SM, **arXiv:2004.01096**

		Simplified models [Eqs. (14) – (16)]			LQ models [Eqs. (1) – (13)]			
Benchmark scenario	Possible charge(s)	Type of LQ	Non-zero couplings equal to λ	Charged lepton chirality fraction	Type of LQ	Non-zero coupling equal to λ	Decay mode(s)	Branching ratios(s) $\{\beta, 1-\beta\}$
LC	1/3	χ_1	Λ_ℓ	$\eta_L = 1$	$\tilde{V}_2^{1/3}$	$\tilde{x}_{2\,3j}^{RL}$	$t\ell$	$\{100\%, 0\}$
	2/3	χ_2	$\bar{\Lambda}_\nu$	—	$\left(\tilde{V}_2^{-2/3}\right)^\dagger$	$\left(\tilde{x}_{2\,3j}^{RL}\right)^*$	$t\nu$	
	5/3	χ_5	$\tilde{\Lambda}_\ell$	$\eta_L = 1$	$U_3^{5/3}$	$\sqrt{2}\, x_{3\,3j}^{LL}$	$t\ell$	
LCSS*	2/3	χ_2	$\bar{\Lambda}_\ell = \bar{\Lambda}_\nu$	$\eta_L = 1$	U_1	$x_{1\,3j}^{LL}$	$\{t\nu, b\ell\}$	$\{50\%, 50\%\}$
LCOS			$\bar{\Lambda}_\ell = -\bar{\Lambda}_\nu$		$U_3^{2/3}$	$-x_{3\,3j}^{LL}$		
RC	1/3	χ_1	Λ_ℓ	$\eta_R = 1$	$V_2^{1/3}$	$x_{2\,3j}^{LR}$	$t\ell$	$\{100\%, 0\}$
	5/3	χ_5	$\tilde{\Lambda}_\ell$		$\tilde{U}_1$	$\tilde{x}_{1\,3j}^{RR}$		
RLCSS*	1/3	χ_1	$\Lambda_\ell = \Lambda_\nu$	$\eta_R = 1$	$V_2^{1/3}$	$x_{2\,3j}^{LR} = -x_{2\,3j}^{RL}$	$\{t\ell, b\nu\}$	$\{50\%, 50\%\}$
RLCOS*			$\Lambda_\ell = -\Lambda_\nu$		$V_2^{1/3}$	$x_{2\,3j}^{LR} = x_{2\,3j}^{RL}$		

Production of LQs

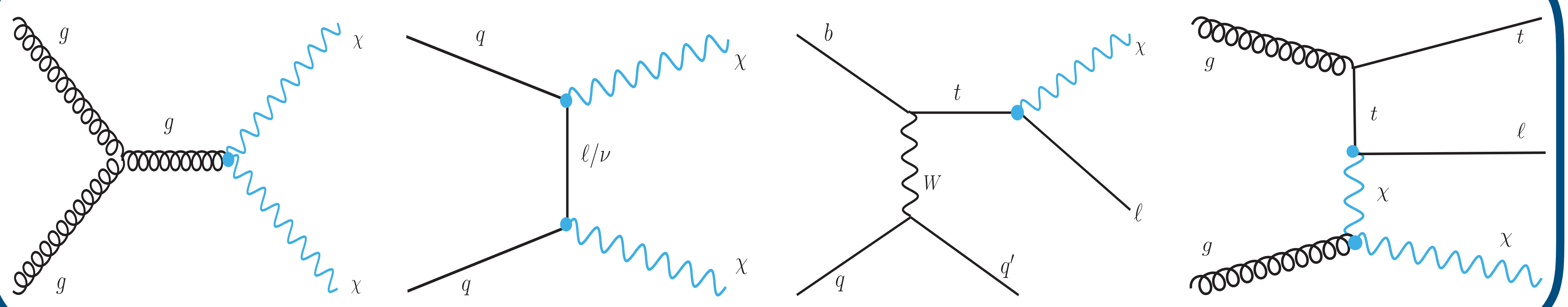
- The **pair production** process leads to the following final state

$$pp \to \phi\phi \,/\, \chi\chi \to (t\ell)(t\ell)$$

where a $\phi(\chi)$ stands for either a $\phi_1(\chi_1)$ or a $\phi_5(\chi_5)$.

- **Single production channels**, where a LQ is produced in association with a lepton and either a jet or a top-quark, lead to

$$pp \to \left\{(\phi \,/\, \chi)t\ell \to (t\ell)t\ell\right\} + \left\{(\phi \,/\, \chi)\ell j \to (t\ell)\ell j\right\}$$



Production of LQs

$\lambda = 1$

Chandak, Mandal, SM, **PRD 100, 075019 (2019)**
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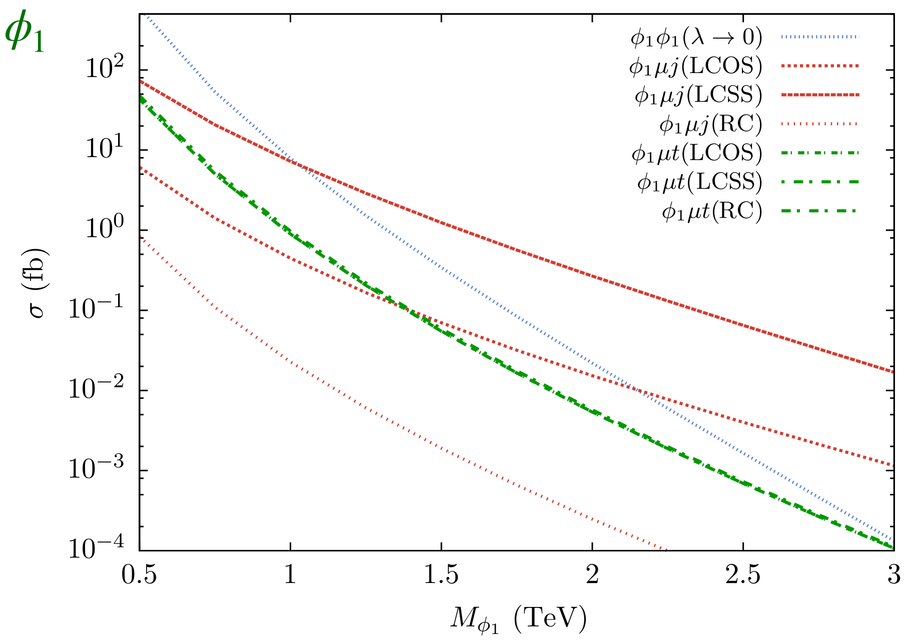
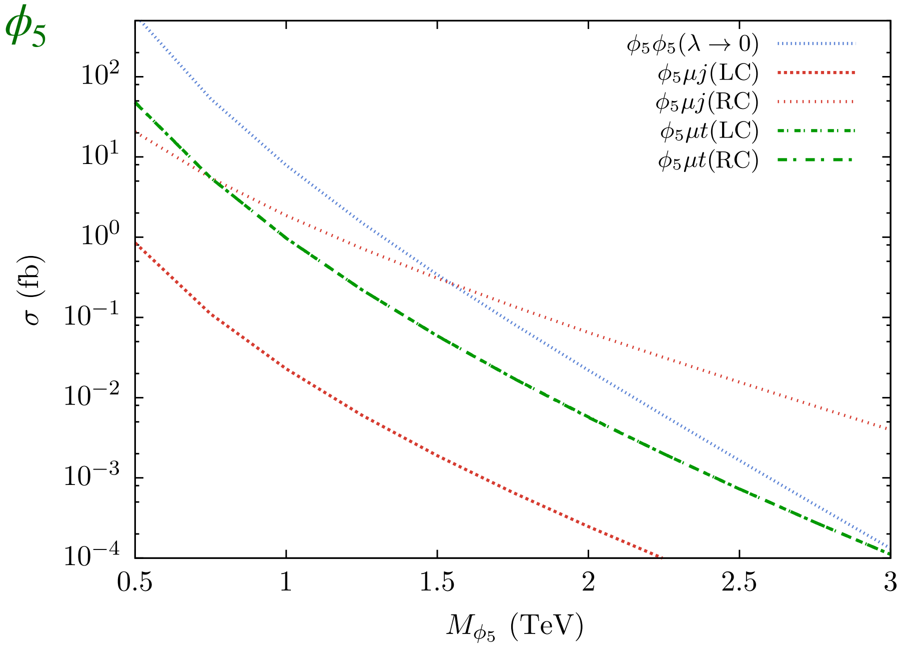
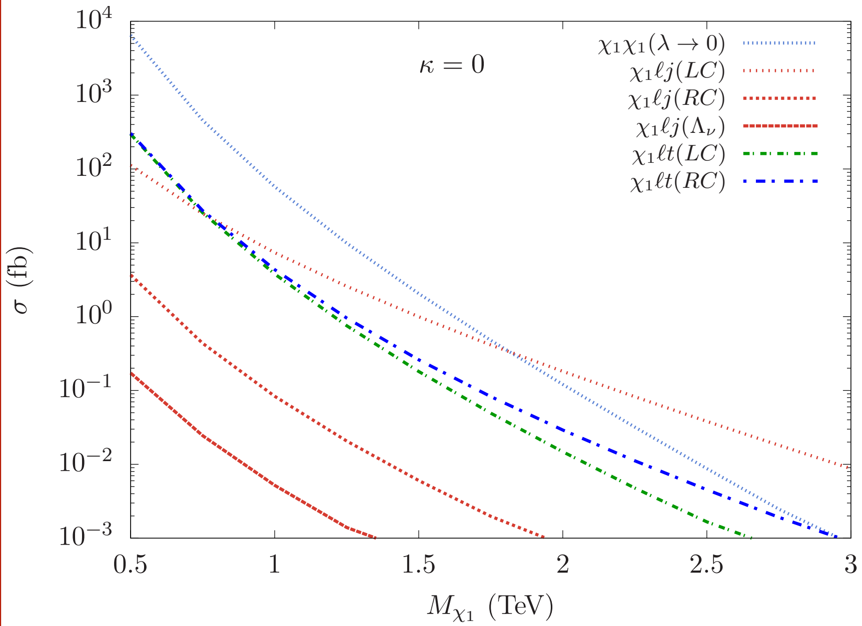
ϕ_1

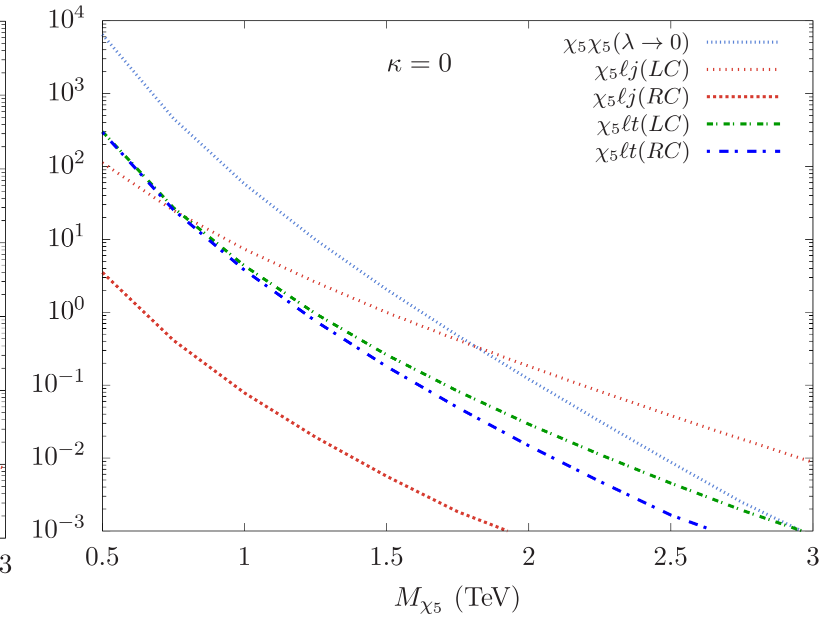


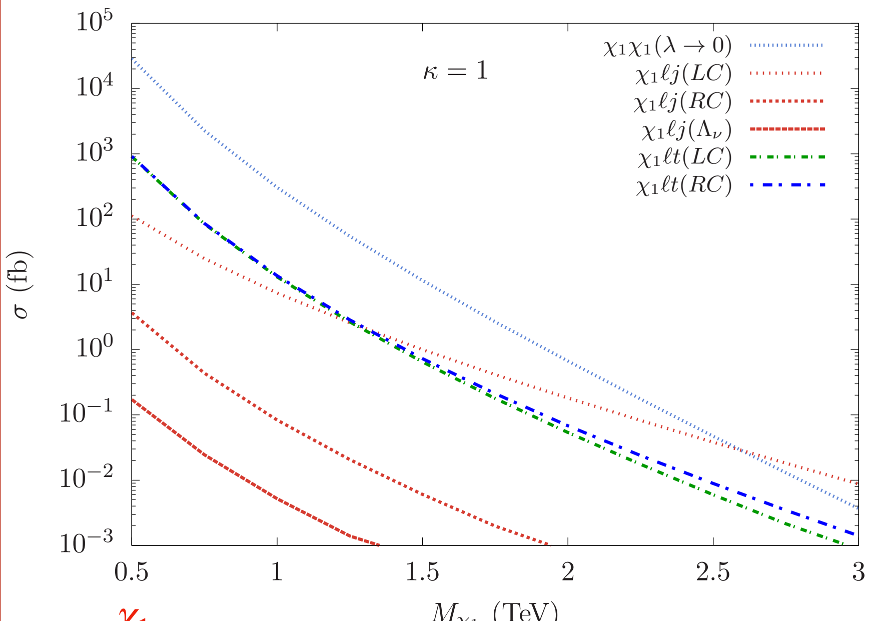
ϕ_5



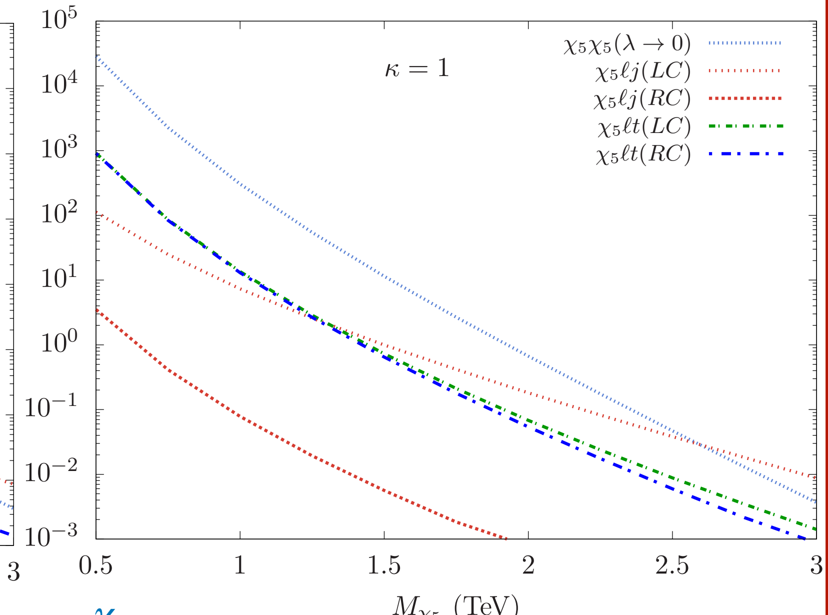
Scalars







χ_1



χ_5

Vectors

Signal Topology

- 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 (SFOS) 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**. For example, at the parton level, a $t\ell\, t\ell$ final state can be produced from both the pair production as well as the $pp \to (\phi \,/\, \chi)t\ell$ processes. Hence, **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.

SM Backgrounds

Bhaskar, Mandal, SM, **arXiv:2004.01096**

- The main SM background processes for this signal topology: **single Z and tt processes**. Processes with a large cross section containing a single lepton can also act as a background if the second lepton appears due to a jet misidentified as a lepton. However, due to very small misidentification rate, this class of processes contribute negligibly to the total background.

- We use **MadGraph5 at LO**. The higher-order effects are considered through K-factors. We use **NNPDF2.3LO PDFs, Pythia6 & Delphes3** (with the default CMS card). Fatjets are reconstructed using the **FastJet** package by clustering Delphes tower objects. To reconstruct hadronic tops from fatjets, we use **HEPTopTagger**.

Background processes		σ (pb)	QCD Order
$V + jets$ [109, 110]	$Z + jets$	6.33×10^4	NNLO
	$W + jets$	1.95×10^5	NLO
$VV + jets$ [111]	$WW + jets$	124.31	NLO
	$WZ + jets$	51.82	NLO
	$ZZ + jets$	17.72	NLO
Single t [112]	tW	83.1	N^2LO
	tb	248.0	N^2LO
	tj	12.35	N^2LO
tt [113]	$tt + jets$	988.57	N^3LO
ttV [114]	ttZ	1.045	NLO+NNLL
	ttW	0.653	NLO+NNLL

Signal Selection

- We apply the following sets of cuts on the signal and background events sequentially.

◉ At least **one top-jet (obtained from HEPTopTagger) with** $p_T(t_h) > 135$ **GeV**. **Two SFOS leptons with** $p_T(\ell_1) > 400$ **GeV and** $p_T(\ell_2) > 200$ **GeV and pseudorapidity** $|\eta(\ell)| < 2.5$. For electron, we consider the barrel-endcap cut on η between 1.37 and 1.52.

◉ Invariant mass of lepton pair $M(\ell_1, \ell_2) > 120$ **GeV** to avoid Z-peak.

◉ The missing energy $MET < 200$ **GeV**.

◉ The scalar sum of the transverse p_T of all visible objects, $S_T > 1.2 \times \mathrm{Min}\left(M_{\ell_q}, 1750\right)$ **GeV**.

◉ $M(\ell_1, t)$ OR $M(\ell_2, t) > 0.8 \times \mathrm{Min}\left(M_{\ell_q}, 1750\right)$ **GeV**.

Significance

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

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

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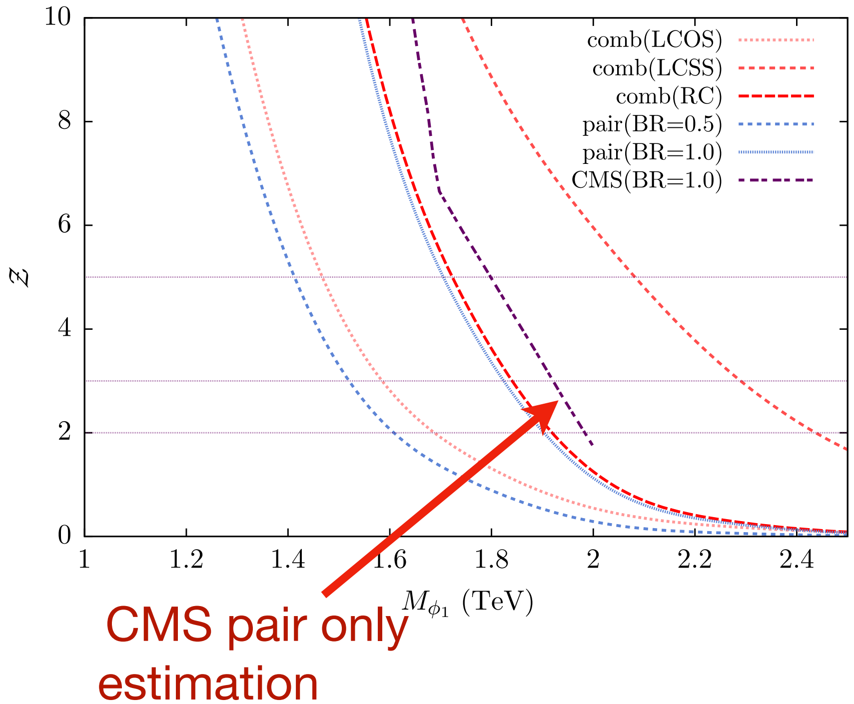
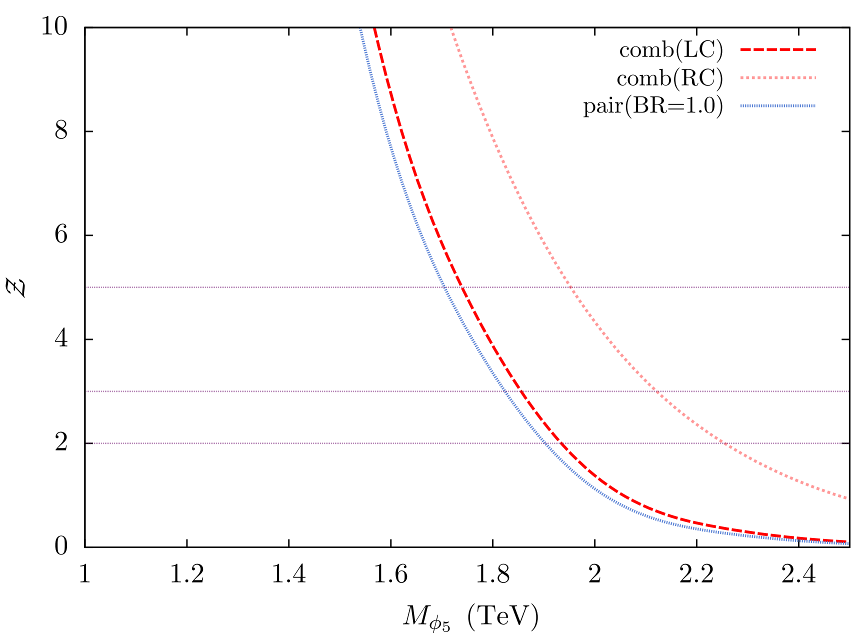
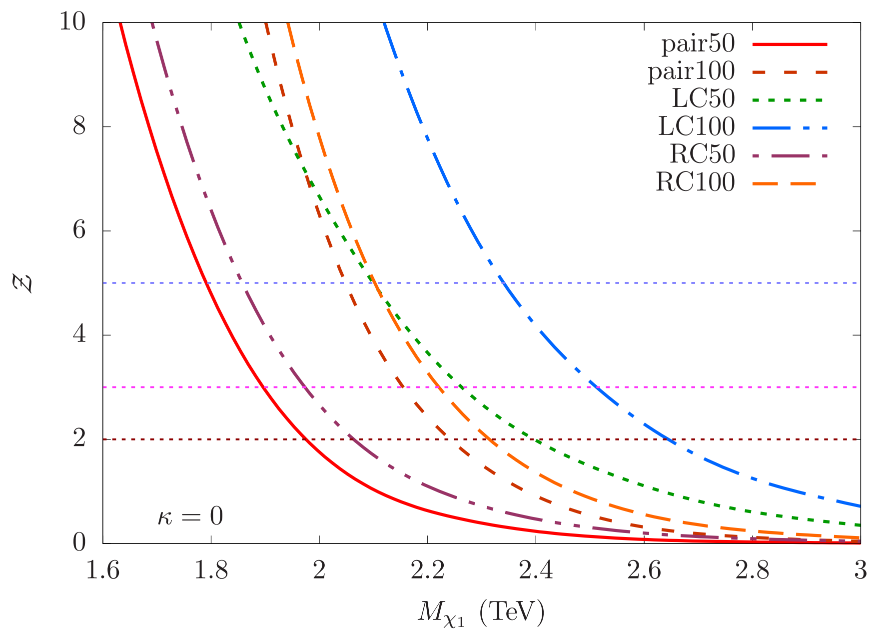
ϕ_1

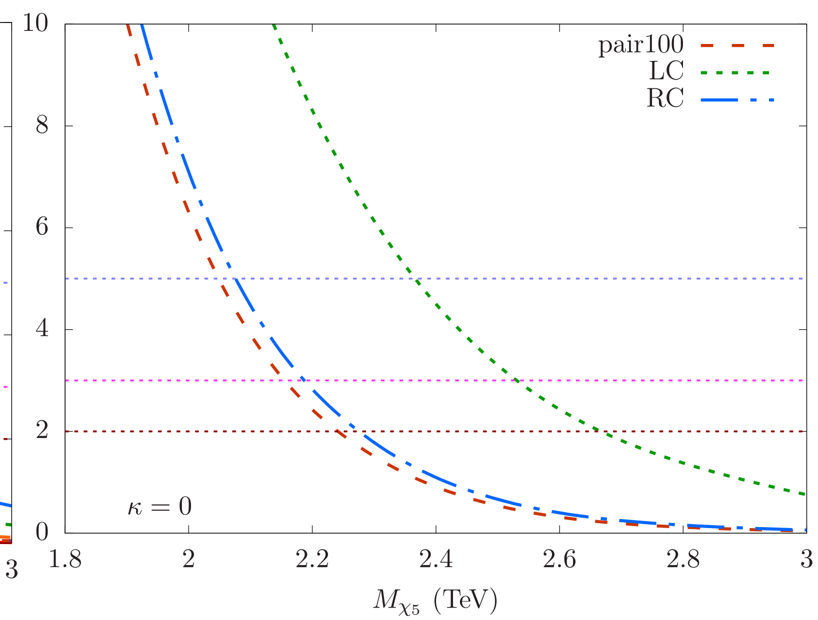


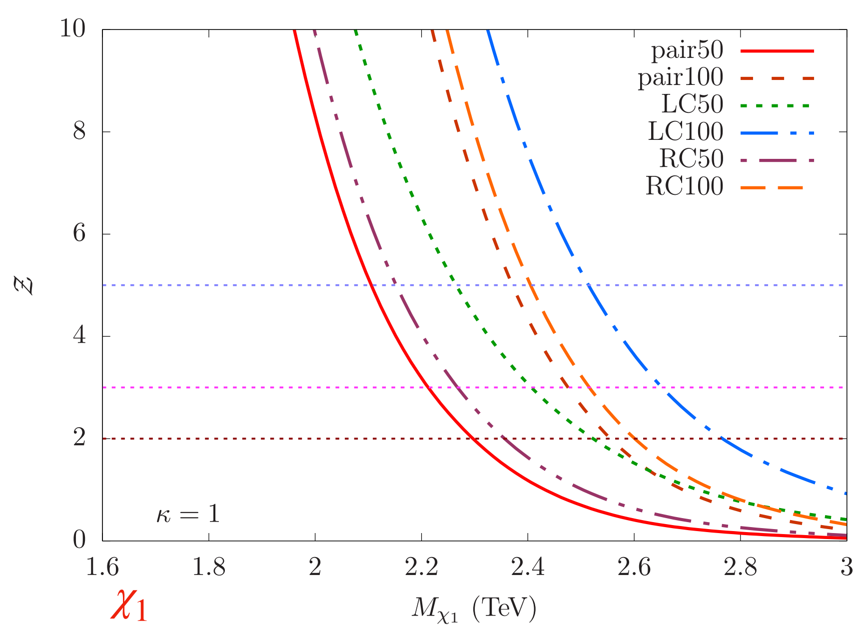
ϕ_5



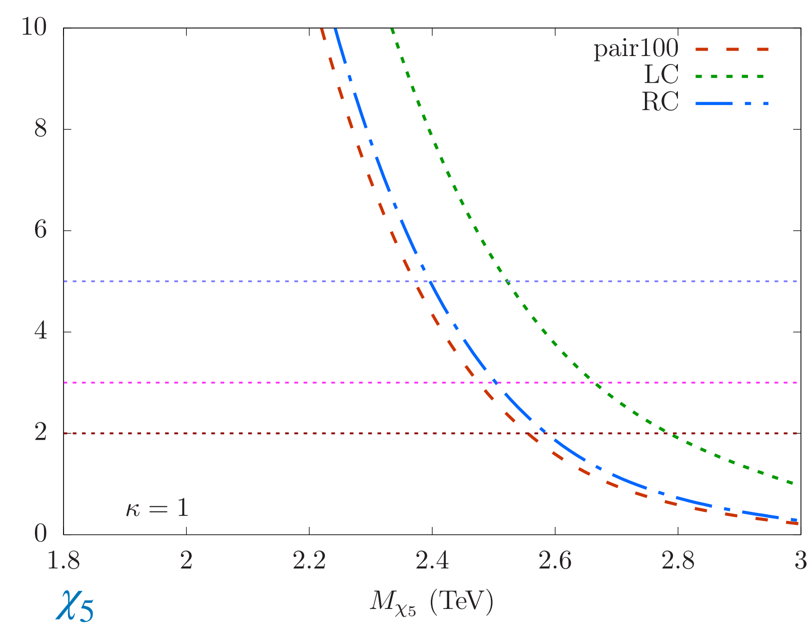
Scalars







χ_1



χ_5

Vectors

Discovery

3 ab^{-1}

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

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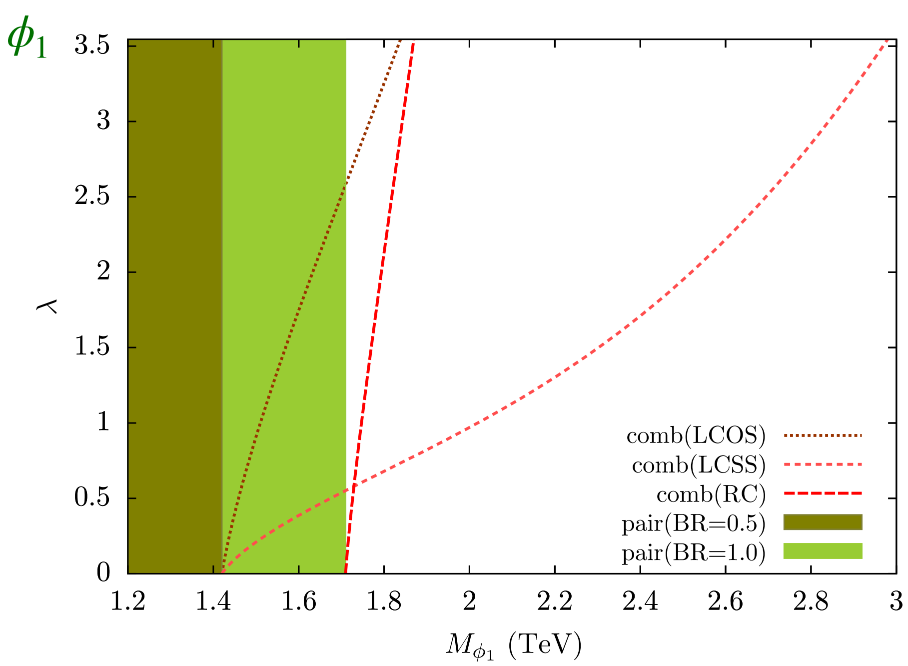

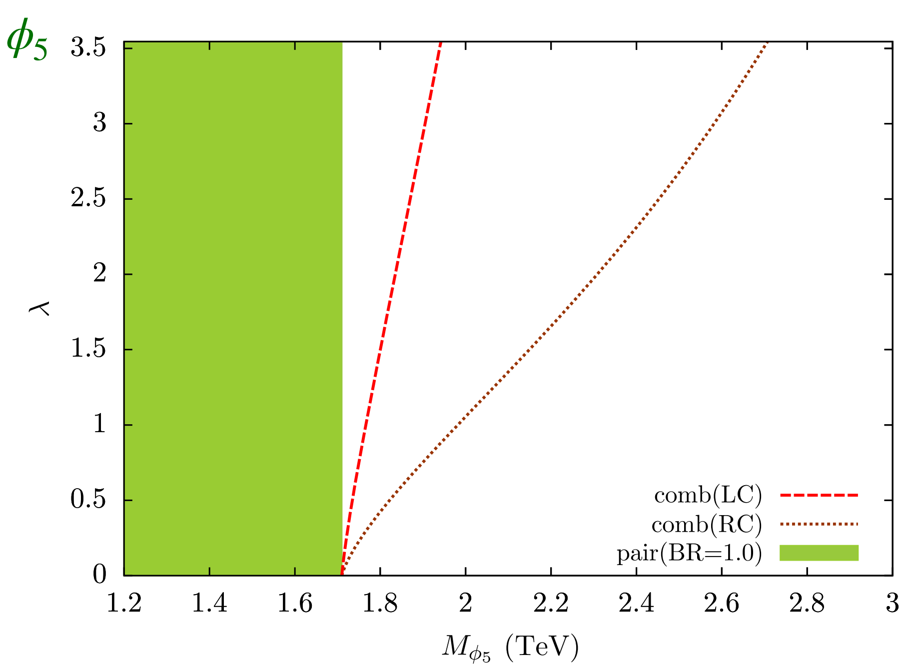

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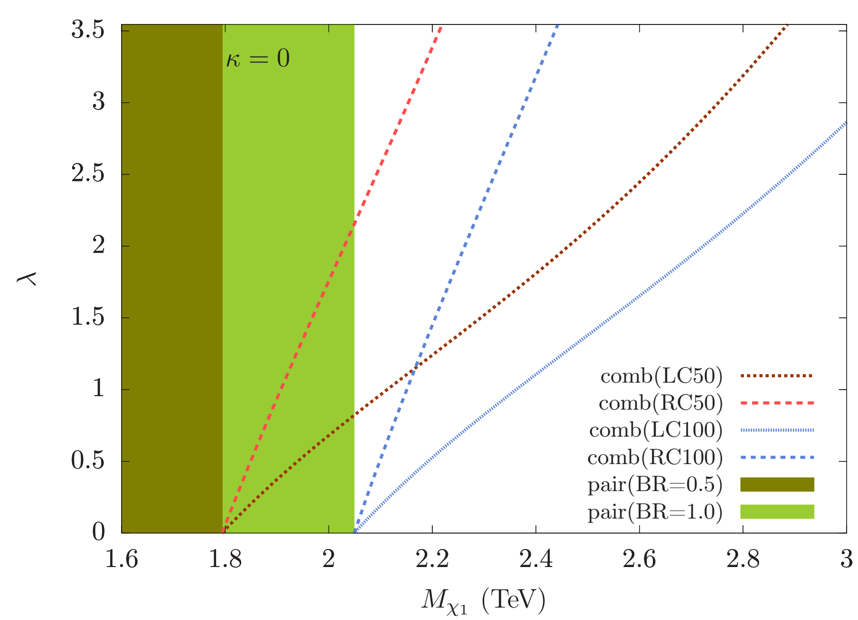

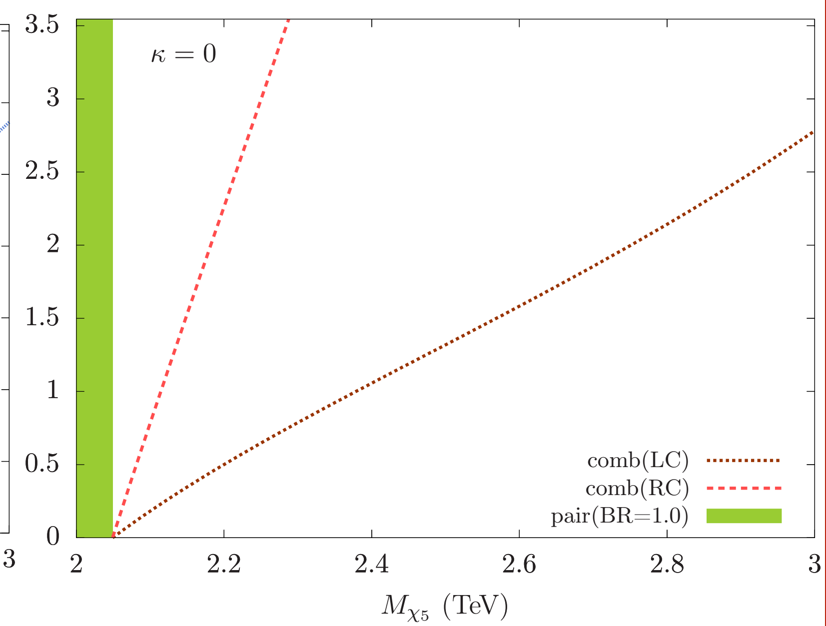

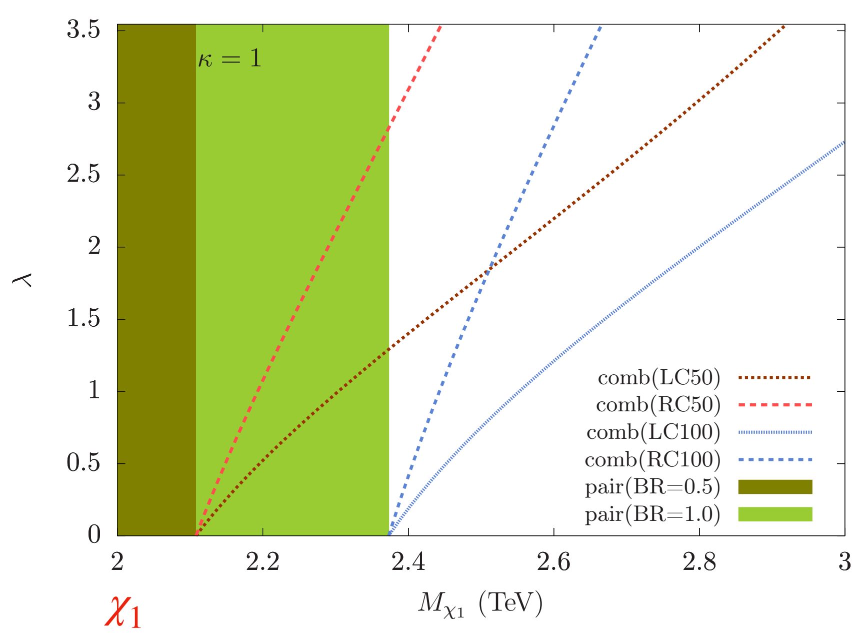

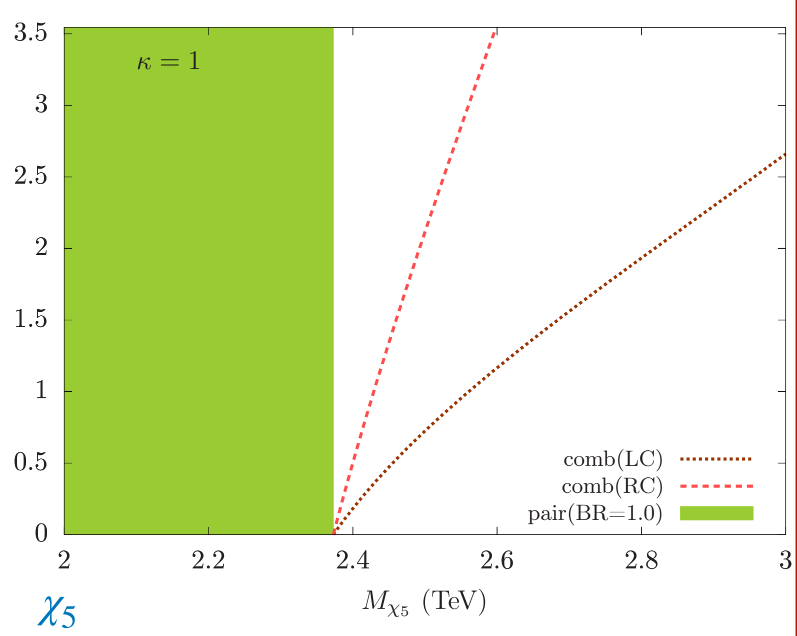

Vectors

Exclusion

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

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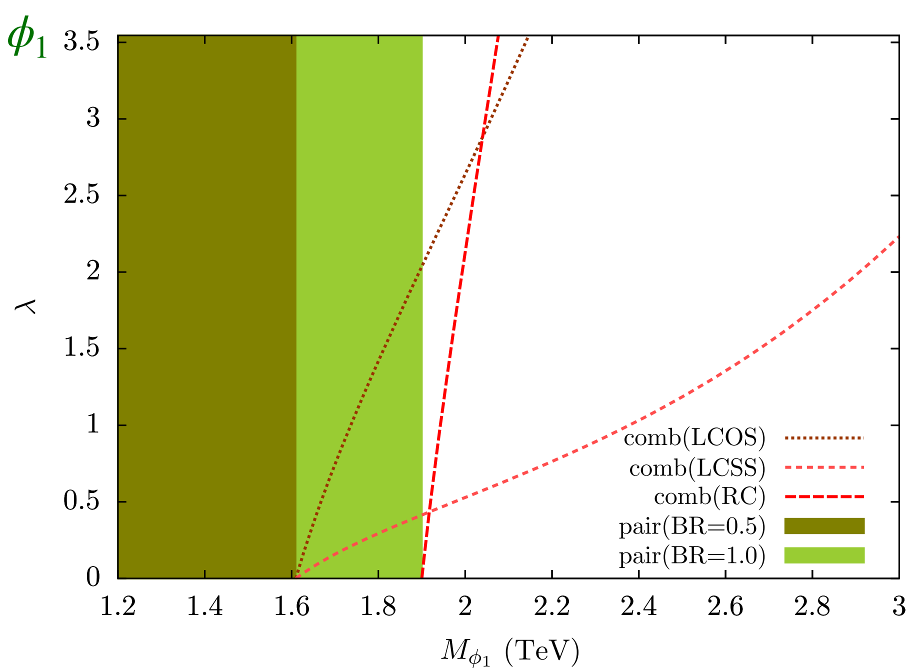
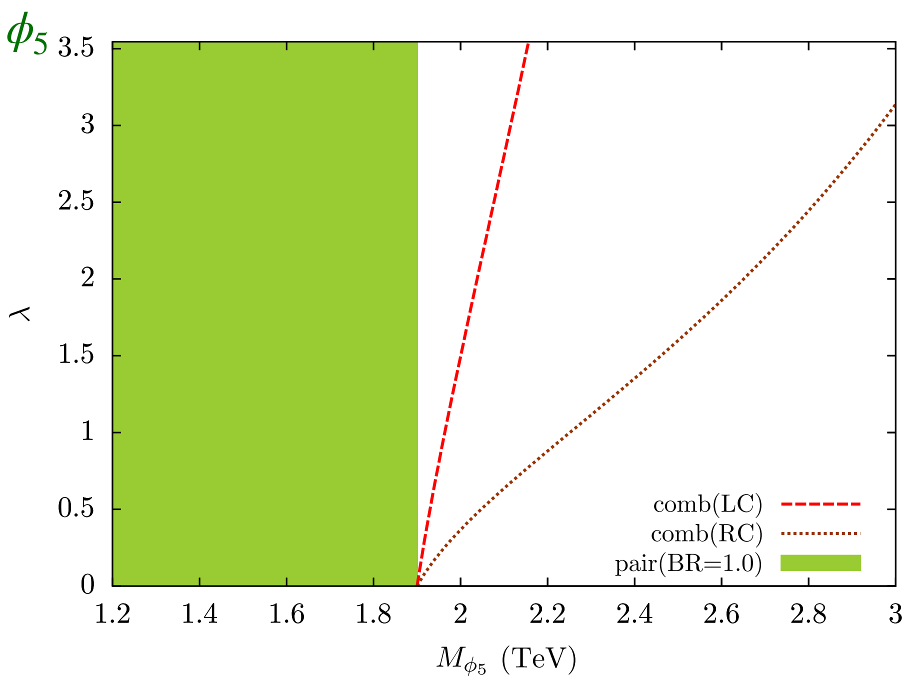
$$\sigma_{\text{signal}} \approx \sigma_{\text{pair}}\left(M_{\ell_q}\right) + \lambda^2 \sigma_{\text{single}}\left(\lambda = 1, M_{\ell_q}\right)$$





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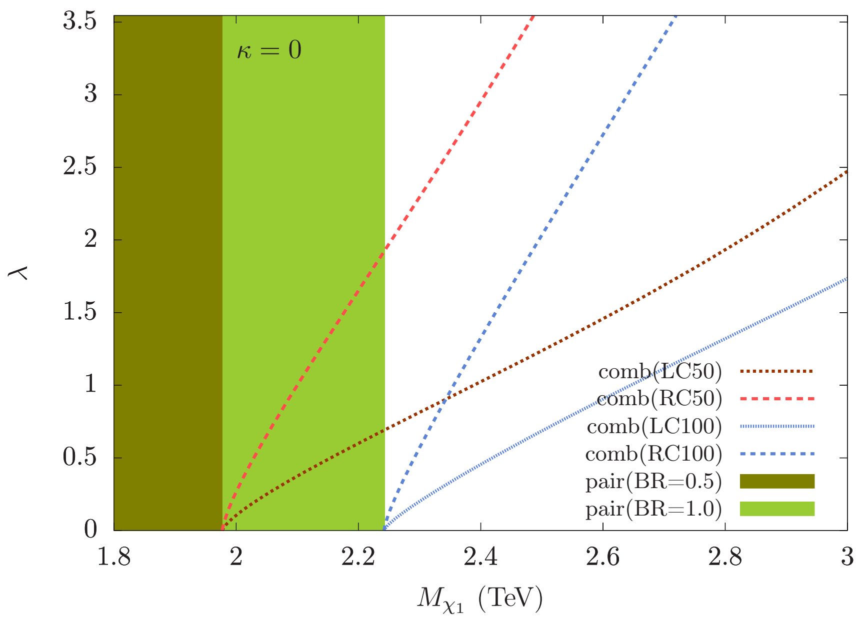

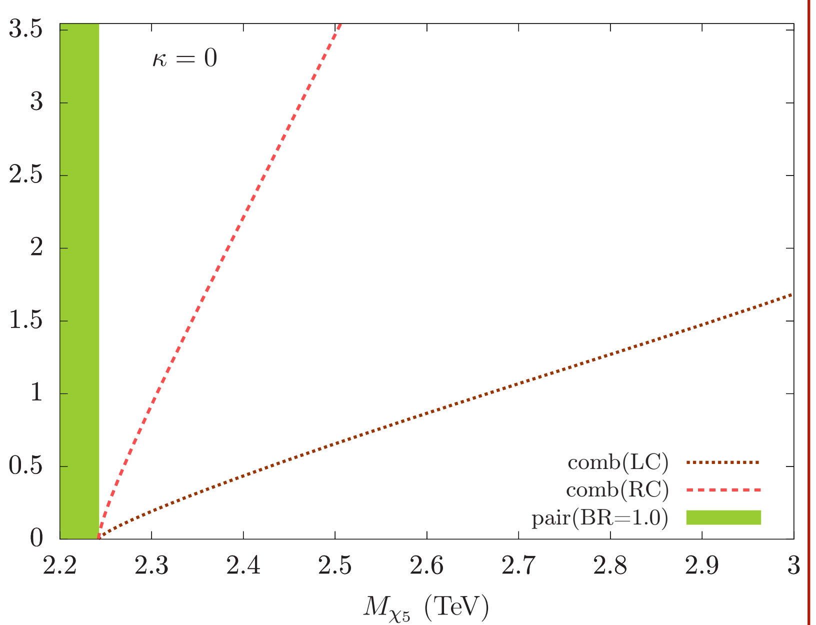

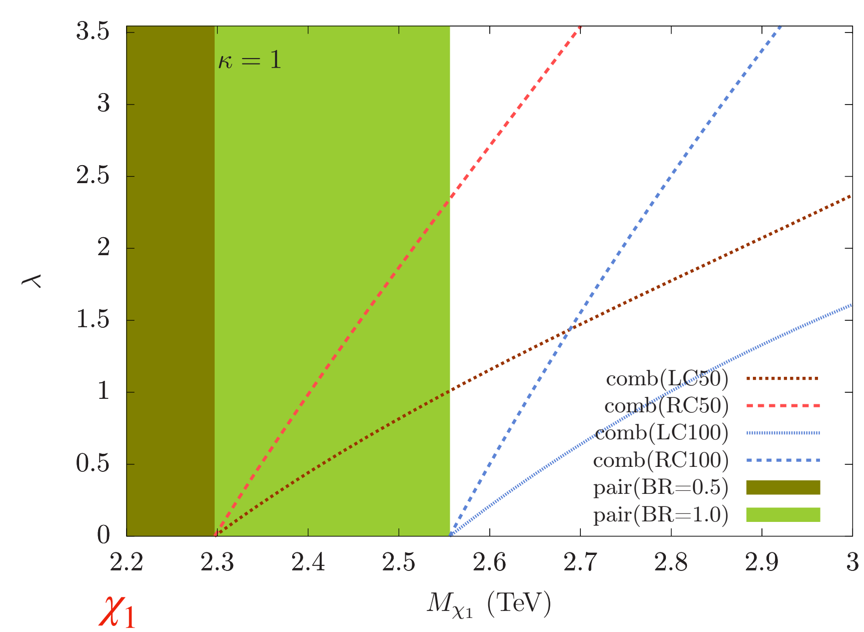

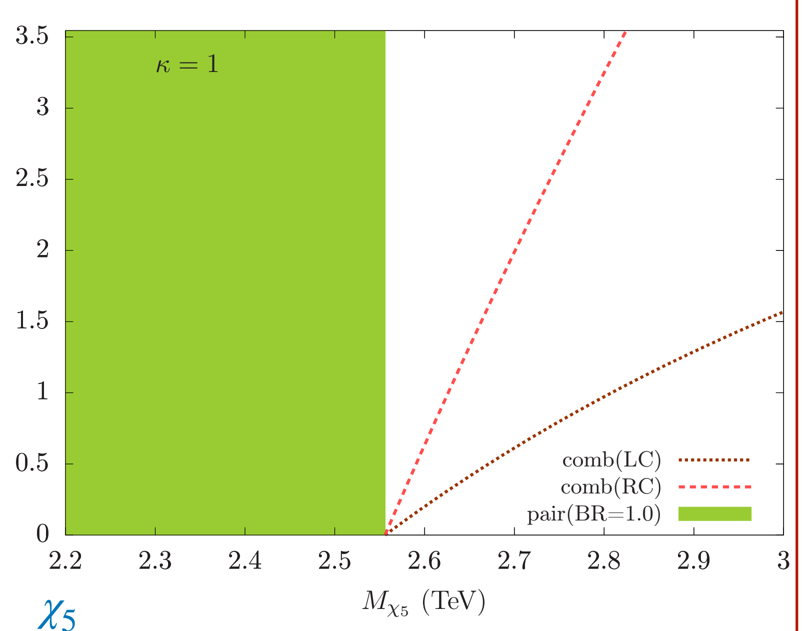

Vectors

Summary

- The HL-LHC may discover/exclude charge 1/3 and 5/3 LQs that decay to a top quark and a charged lepton even if they are significantly heavier than a TeV.
- We have introduced some simple Lagrangians (suitable for bottom-up single production studies) that can cover the relevant parameter spaces of the full models. We have identified some representative benchmark scenarios.
- Despite considering LQ couplings with only third generation quarks, we see that the single production cross sections are not necessarily very small as long as the cross-generational coupling (λ) is not small.
- Discussed a strategy of combining single and pair production events to maximise discovery/exclusion reach. In some scenarios, the single production can significantly enhance the reach.

Thank You