Searching for Leptoquarks at the High-Luminosity LHC

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Mainly based on arXiv:1808.10309

Laboratori Nazionali di Frascati, 14-9-2018

Motivation

LQs are hypothetical particles carrying both lepton and baryon number

- Appear in a variety of BSM theories

  Pati-Salam, GUT, BSM composite dynamics, R-Parity violating Supersymmetry …..

- LQs coupled to third generation quarks represent the best candidates to explain B-physics anomalies

B-physics anomalies

Indication of lepton flavor universality violation in B meson decays

Observed at Belle, Babar and by LHCb

$\sim 4\sigma$ $$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

$$R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}}$$

$$\ell = e\,,\mu$$

b → c transition
charged current
tree-level in the SM

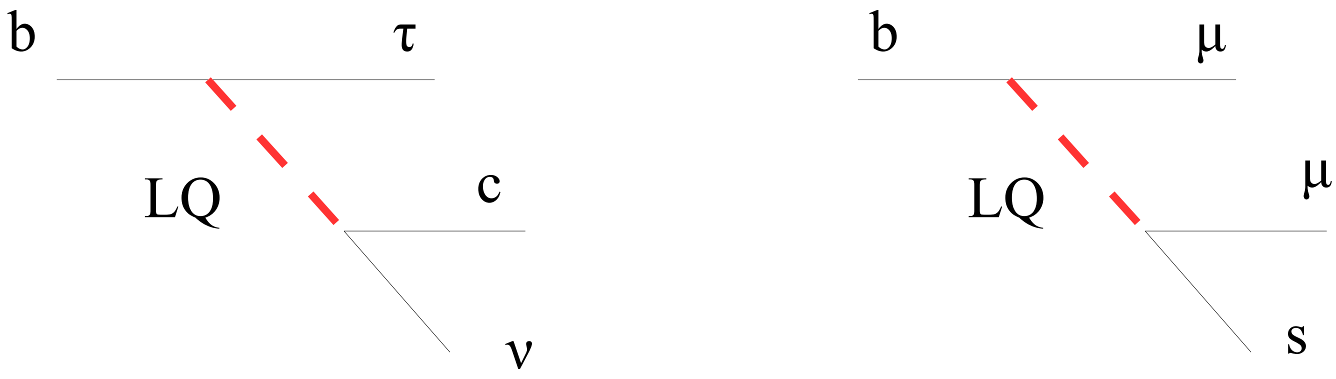
$\sim 4\sigma$ $$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

$$R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}$$

b → s transition
neutral current
loop-level in the SM

Clean observable (hadronic uncertainties cancel to a large extent)

LQs in the TeV range can explain these anomalies



Two different **scalar** LQs can explain the anomalies

A single 2/3-charged **vector** LQ can explain both $R_{K(*)}$ and $R_{D(*)}$

- LQs coupled to third generation quarks represent the best candidates to explain B-physics anomalies:
W'/Z' models are in tension with high-p_T di-tau data and radiative constraints, charged Higgs is in tension with $B_c \to \tau\nu$

Setup

We will consider both scalar and vector LQs

$\underline{S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)}$

Marzocca, JHEP 1907 121
Becirevic et al, 1806.05689
.....

$$\mathcal{L}_{S_3} \supset y_L^{ij} \, \overline{Q_i^C} i\tau_2 (\tau_k S_3^k) L_j + \text{h.c.}$$

↓

$$\mathcal{L}_{S_3} \supset -y_L^{ij} \, \overline{d_{L\,i}^C} \nu_{L\,j} \, S_3^{(1/3)} - \sqrt{2} \, y_L^{ij} \, \overline{d_{L\,i}^C} \ell_{L\,j} \, S_3^{(4/3)}$$
$$+\sqrt{2} \, (V^* y_L)^{ij} \, \overline{u_{L\,i}^C} \nu_{L\,j} \, S_3^{(-2/3)} - (V^* y_L)^{ij} \, \overline{u_{L\,i}^C} \ell_{L\,j} \, S_3^{(1/3)} + \text{h.c.}$$

$S_3 \to t\,\nu$

Considered in models addressing flavor anomalies with two scalar LQs (S_3 for $R_{K(*)}$, S_1 for $R_{D(*)}$)
Motivated in particular in models with a BSM composite dynamics, where they can emerge as pNGBs

Setup

We will consider both scalar and vector LQs

$\underline{U_1 = (\mathbf{3}, \mathbf{1}, 2/3)}$

Buttazzo et al, JHEP 1711 044
Angelescu et al, 1808.08179
…..

$$\mathcal{L}_{U_1} \supset x_L^{ij}\, \bar{Q}_i \gamma_\mu U_1^\mu L_j + x_R^{ij}\, \bar{d}_{R\,i} \gamma_\mu U_1^\mu \ell_{R\,j} + w_R^{ij} \bar{u}_{R\,i} \gamma_\mu U_1^\mu \nu_{R\,j} + \text{h.c.}$$

Considering only the interactions with left-handed fields
(motivated by B-physics anomalies)

$$\mathcal{L}_{U_1}^L = (V^* x_L)^{ij}\, \bar{u}_{L\,i} \gamma_\mu U_1^\mu \nu_{L\,j} + x_L^{ij} \bar{d}_{L\,i} \gamma_\mu U_1^\mu \ell_{L\,j} + \text{h.c.}$$

$U_1 \to t\,\nu$ $U_1 \to b\,\tau$

Particularly interesting for the B anomalies, since a single particle can explain both $R_{K(*)}$ and $R_{D(*)}$

LQs phenomenology at the LHC

Production mechanisms:

- QCD pair production

  Model independent for scalar LQs

  Depends on a parameter for vector LQ (unspecified UV dynamics)

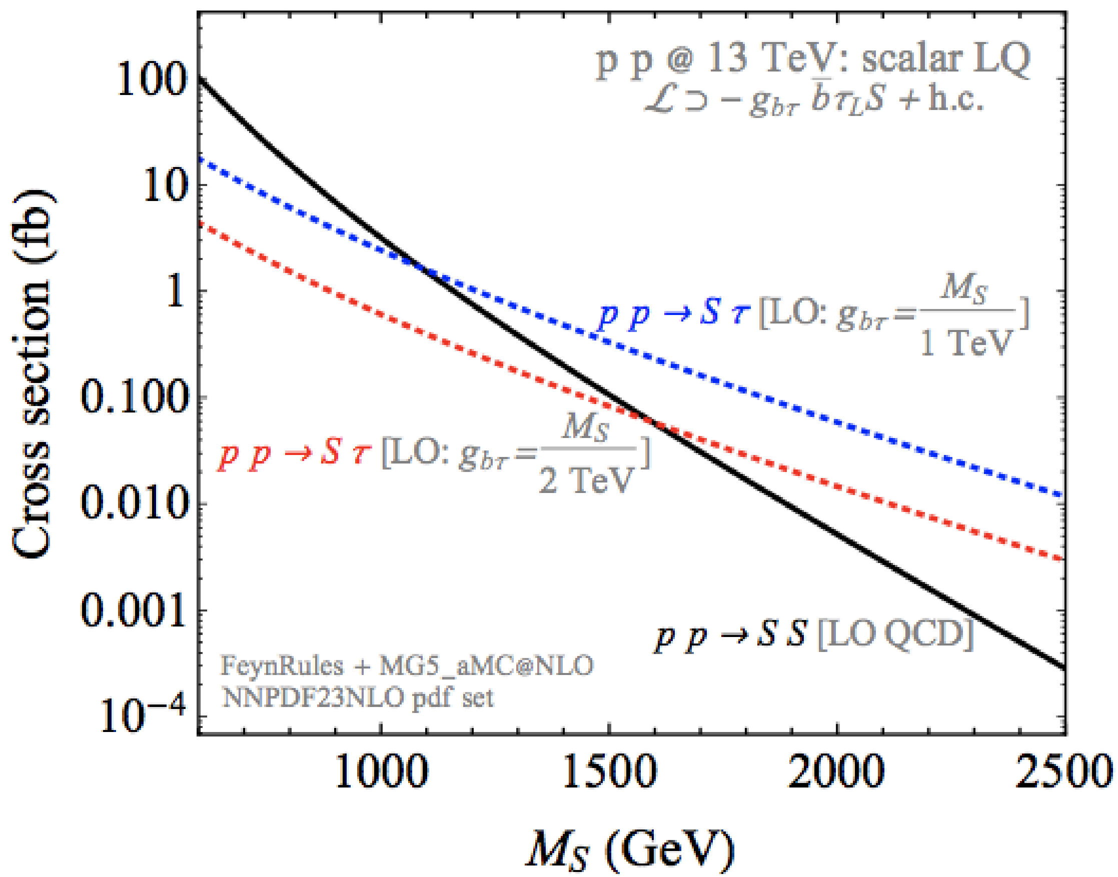
$$\mathcal{L}^{kin} = -\frac{1}{2} U_1^{\dagger\mu\nu} U^1_{\mu\nu} - i\, g_s\, k\, U_1^{\dagger\mu} T^a U_1^{\nu} G^a_{\mu\nu}$$

We can distinguish two main cases:
k=0 (minimal coupling, MC), k=1 (Yang-Mills, YM)

- Single production (model dependent)

One can also search for t-channel exchange of LQs,
which affect the tails of di-lepton pT distributions

LQs phenomenology at the LHC



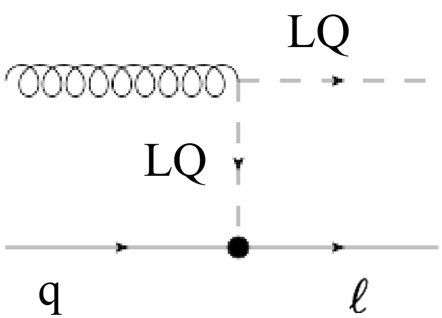
From

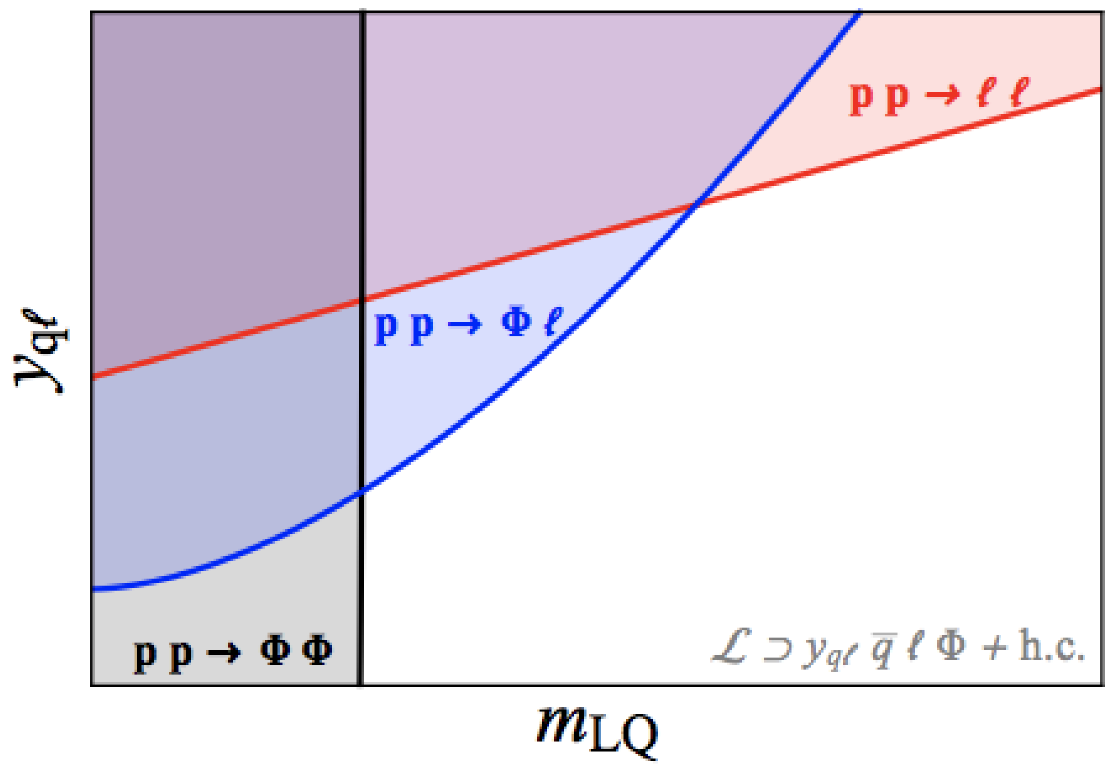
Buttazzo, Greljo, Isidori, Marzocca, JHEP 1711, 044

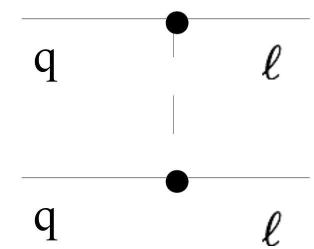
LQs phenomenology at the LHC

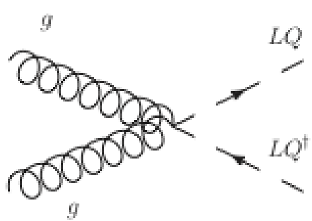
Sketch of the different channel reach

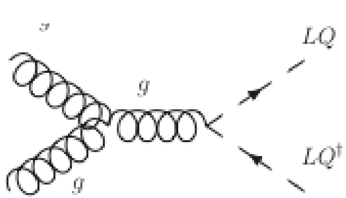
From
Dorsner, Greljo, JHEP 1805 126







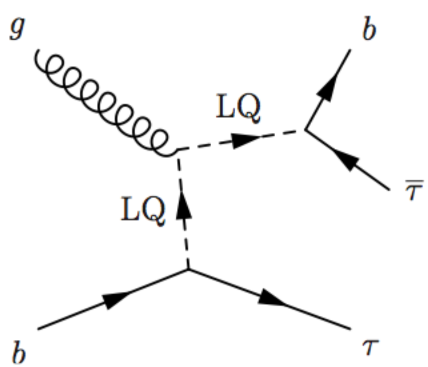


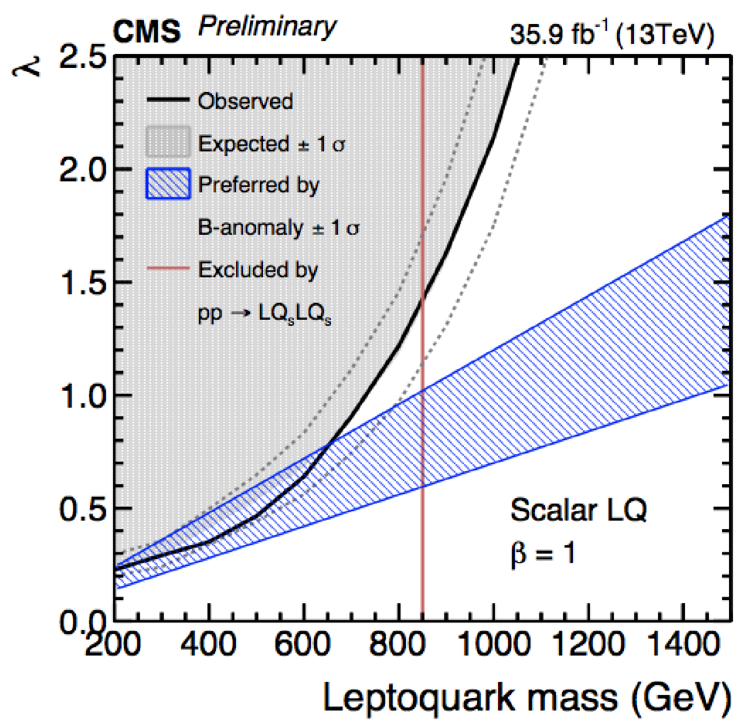


Current LHC Searches

Several ATLAS and CMS searches considered pair production.

CMS also considered recently the single production





CMS-PAS-EXO-17-029

Figure 4: The 95% confidence level expected and observed exclusion limits on the Yukawa coupling λ at the LQ-lepton-quark vertex, as a function of the LQ mass. A branching fraction of the LQ to a τ lepton and a b quark $\beta = 1$ is assumed. The red line corresponds to the limit obtained from a search for pair-produced LQs decaying to $\ell\tau_h$bb [24]. The vertically shaded region is the expected exclusion limit from this analysis. The diagonally shaded blue region shows the parameter space preferred by the anomalies reported by B-factory experiments [23].

Current LHC Searches

Several ATLAS and CMS searches considered pair production.

The strongest constraints on 2/3-charged third-generation LQs are set by the CMS analysis JHEP 1707, 121

Table 1: Summary of the observed (expected) mass limits at the 95% CL, and the cross sections σ that correspond to the excluded mass values. The columns show scalar or vector leptoquarks with the choice of κ, while the rows show the LQ decay channel.

	LQ_S		$LQ_V, \kappa = 1$		$LQ_V, \kappa = 0$	
	mass [GeV]	σ [fb]	mass [GeV]	σ [fb]	mass [GeV]	σ [fb]
$LQ \to q\nu$, q = u, d, s, or c	980 (940)	5.9 (8.0)	1790 (1830)	1.1 (0.9)	1410 (1415)	2.0 (2.0)
$LQ \to b\nu$	1100 (1070)	2.4 (3.0)	1810 (1800)	1.0 (1.1)	1475 (1440)	1.3 (1.7)
$LQ \to t\nu$	1020 (980)	4.3 (5.9)	1780 (1740)	1.2 (1.5)	1460 (1385)	1.5 (2.4)
$LQ \to \begin{cases} t\nu\ (B = 50\%) \\ b\tau\ (B = 50\%) \end{cases}$	—	—	1530 (1460)	1.3 (2.1)	1115 (1095)	3.7 (4.2)

13 TeV, 35.9 fb-1

Current LHC Searches

Several ATLAS and CMS searches considered pair production.

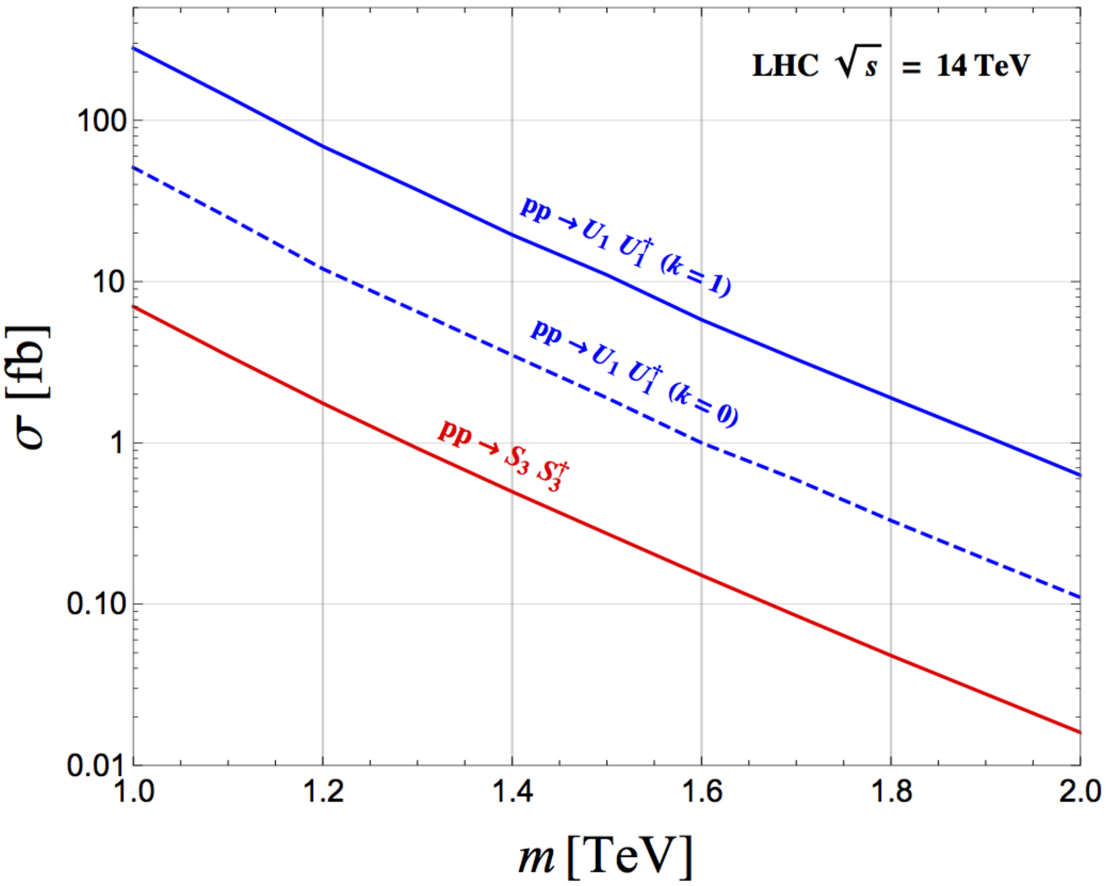
The strongest constraints on 2/3-charged third-generation LQs are set by the CMS analysis JHEP 1707, 121

This analysis reinterprets the results of a search for gluinos and squarks. It applies standard cuts for supersymmetric searches in the multijet + missing energy channel (missing E_T, H_T, ...)

In our study we will try to improve the search strategy in the t-tbar+missing energy channel, making it more tailored for LQs and by using the identification of the t-tbar pair

The t-tbar plus missing energy channel

We consider pair produced LQs each decaying into t+neutrino



QCD
LO for Vector LQ
NLO for scalar LQ
[Dorsner, Greljo,
JHEP 1805, 126]

The t-tbar plus missing energy channel

We consider pair produced LQs each decaying into t+neutrino

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

Field	Spin	Quantum Numbers	Operators	$\mathcal{B}(\mathrm{LQ} \to t\bar{\nu})$
R_2	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{u_R} R_2 i\tau_2 L$	≤ 0.5
$\widetilde{R}_2$	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\overline{Q} \widetilde{R}_2 \nu_R$	≤ 1
$\bar{S}_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	$\overline{u_R^C} \bar{S}_1 \nu_R$	≤ 1
S_3	0	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{Q^C} i\tau_2 \vec{\tau} \cdot \vec{S}_3 L$	≤ 1
U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\overline{Q} \gamma_\mu U_1^\mu L\,,\ \overline{u_R} \gamma_\mu U_1^\mu \nu_R$	$\leq 0.5\,,\ 1$
$\widetilde{V}_2$	1	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	$\overline{u_R^C} \gamma_\mu \widetilde{V}_2^\mu i\tau_2 L\,,\ \overline{Q^C} \gamma_\mu i\tau_2 \widetilde{V}_2^\mu \nu_R$	$\leq 0.5\,,\ 1$
U_3	1	$(\mathbf{3}, \mathbf{3}, 2/3)$	$\overline{Q} \gamma_\mu \vec{\tau} \cdot \vec{U}_3^\mu L$	≤ 0.5

Table 1: Classification of the LQ states that can decay to $t\bar{\nu}$, in terms of the SM quantum numbers, $(SU(3)_c, SU(2)_L, Y)$, with $Q = Y + T_3$. We adopt the same notation of Ref. [24] and we omit color, weak isospin and flavor indices for simplicity. The last column correspond to the maximal value of $\mathcal{B}(\mathrm{LQ} \to t\bar{\nu})$, as allowed by gauge symmetries. In the cases where interactions to lepton doublets (L) and right-handed neutrinos (ν_R) are both allowed, i.e. for the models U_1 and $\widetilde{V}_2$, we give the maximal branching fraction assuming only interactions to L or ν_R, respectively.

The t-tbar plus missing energy channel

We consider pair produced LQs each decaying into t+neutrino

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

Field	Spin	Quantum Numbers	Operators	$\mathcal{B}(\mathrm{LQ} \to t\bar{\nu})$
R_2	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\overline{u_R} R_2 i\tau_2 L$	≤ 0.5
$\widetilde{R}_2$	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	$\overline{Q} \widetilde{R}_2 \nu_R$	≤ 1
$\bar{S}_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	$\overline{u_R^C} \bar{S}_1 \nu_R$	≤ 1
S_3	0	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$\overline{Q^C} i\tau_2 \vec{\tau} \cdot \vec{S}_3 L$	≤ 1
U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\overline{Q} \gamma_\mu U_1^\mu L\,,\ \overline{u_R} \gamma_\mu U_1^\mu \nu_R$	$\leq 0.5\,,\ 1$
$\widetilde{V}_2$	1	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	$\overline{u_R^C} \gamma_\mu \widetilde{V}_2^\mu i\tau_2 L\,,\ \overline{Q^C} \gamma_\mu i\tau_2 \widetilde{V}_2^\mu \nu_R$	$\leq 0.5\,,\ 1$
U_3	1	$(\mathbf{3}, \mathbf{3}, 2/3)$	$\overline{Q} \gamma_\mu \vec{\tau} \cdot \vec{U}_3^\mu L$	≤ 0.5

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The t-tbar plus missing energy channel

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$\widetilde{V}_2$	1	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	$\overline{u_R^C} \gamma_\mu \widetilde{V}_2^\mu i\tau_2 L\,,\ \overline{Q^C} \gamma_\mu i\tau_2 \widetilde{V}_2^\mu \nu_R$	$\leq 0.5\,,\ 1$
U_3	1	$(\mathbf{3}, \mathbf{3}, 2/3)$	$\overline{Q} \gamma_\mu \vec{\tau} \cdot \vec{U}_3^\mu L$	≤ 0.5

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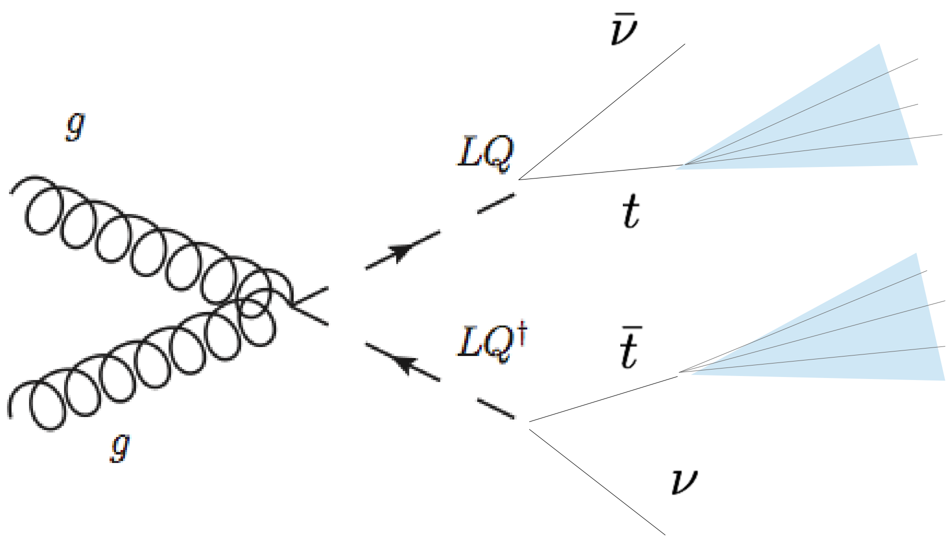
The t-tbar plus missing energy channel



Hadronically decaying tops

Top decay products collected in fat-jets (anti-kt R=1.0)

The Signal:

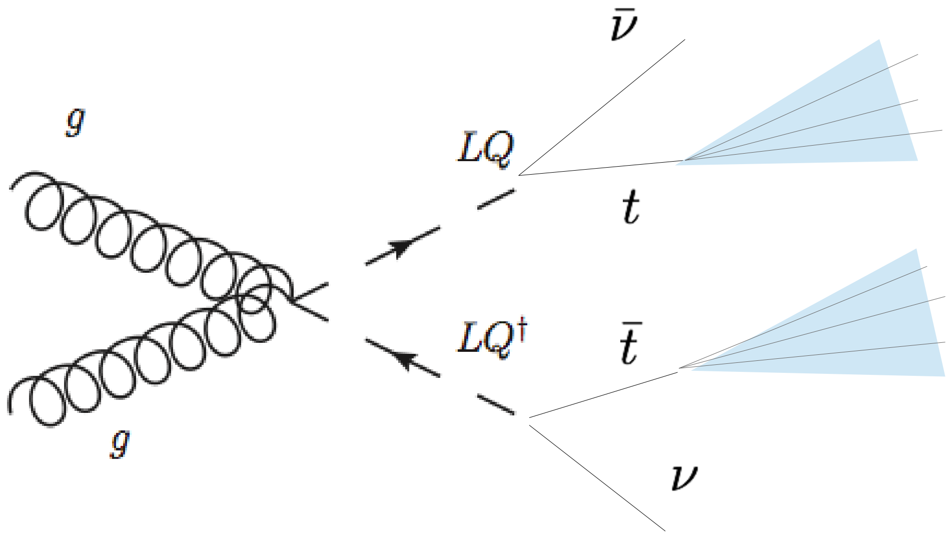
$$\not{E}_T > 250\,\text{GeV}\,, \qquad n_j \geq 2\ \ (p_T\, j > 30\,\text{GeV}\,,\, |\eta_j| < 5)\,, \qquad \text{lep veto}\,,$$

Background:

Z (→ νν) + jets W (→ lν) + jets t-tbar (→ lν + jets)

where the lepton is lost

The t-tbar plus missing energy channel



Hadronically decaying tops

Top decay products collected in fat-jets (anti-kt R=1.0)

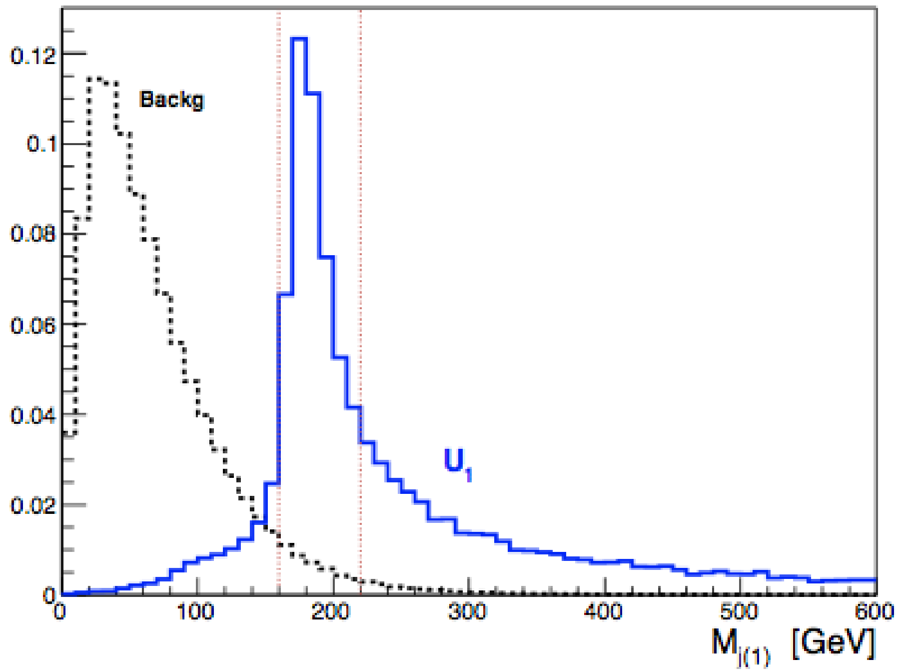
Monte Carlo Simulations:

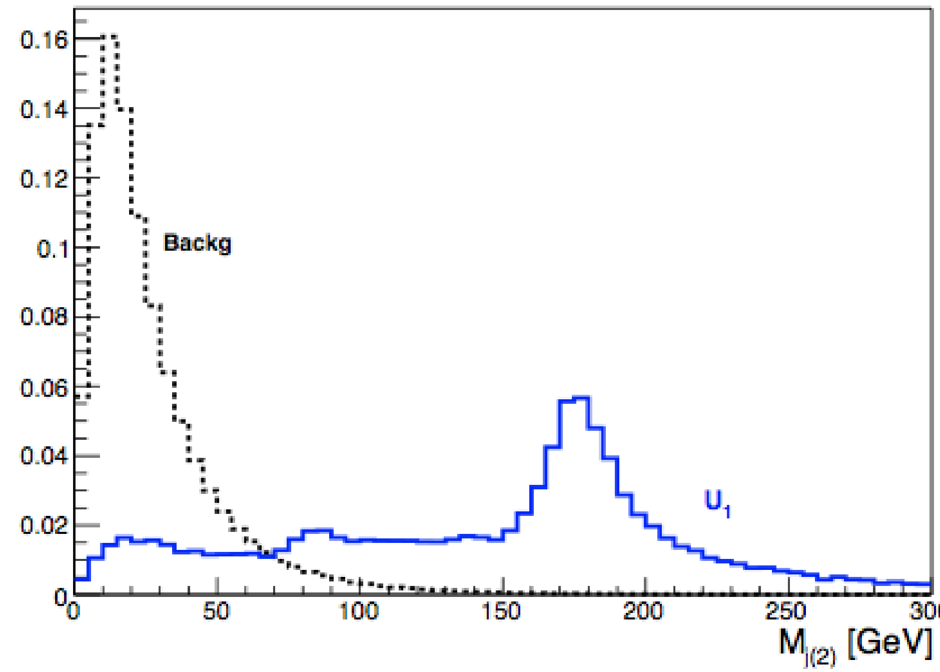
MadGraph5_aMC@NLO + Pythia + smearing to the jet momenta (detector effects)

Signal events generated with UFO models created with FeynRules

Events generated at LO in QCD
K-factors (~1.5) to take into account NLO QCD effects applied to the cross section for Scalar LQs. Calculated by using the code by Dorsner, Greljo, JHEP 1805, 126

The t-tbar tagging





p_T-leading jet

Second leading jet

Jets clustered with anti-kt algorithm, cone size R=1.0

Acceptance				Top Tagging			
U_1 (YM)		S_3		U_1 (YM)		S_3	
m [TeV]	σ [fb]	m [TeV]	σ [fb]	m [TeV]	σ [fb]	m [TeV]	σ [fb]
1.6	0.45	1.1	1.4	1.6	0.097	1.1	0.23
1.7	0.26	1.2	0.71	1.7	0.056	1.2	0.13
1.8	0.15	1.3	0.38	1.8	0.032	1.3	0.073
1.9	0.084	1.4	0.21	1.9	0.019	1.4	0.042
2.0	0.050	1.5	0.11	2.0	0.011	1.5	0.024
2.1	0.030	1.6	0.064	2.1	0.0068	1.6	0.013

	Acceptance σ [fb]	Top Tagging σ [fb]
$Z + jets$	4560	3.02
$W + jets$	1330	0.86
$t\bar{t}$	95	0.36
Tot. Backg	5990	4.24

Top tagging efficiency of ~20% for the signal

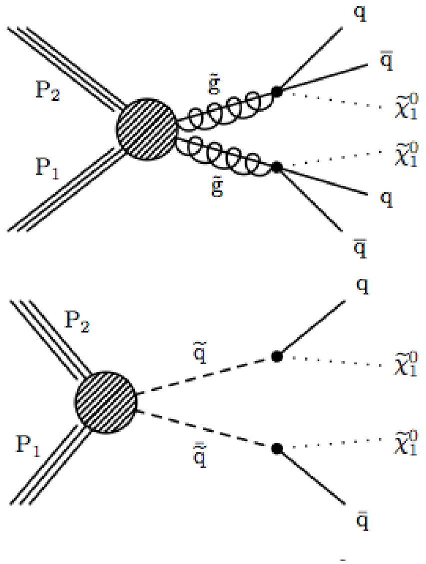
rejection of ~ 1.4 10^3 for the background

“top observables"

Constructed out of the tagged tops, t(1) and t(2)

M_{T2} variable used in experimental searches for Supersymmetry

CMS, Eur.Phys.J. C77 (2017) no.10, 710



$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}\,\mathrm{X}(1)} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}\,\mathrm{X}(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right]$$

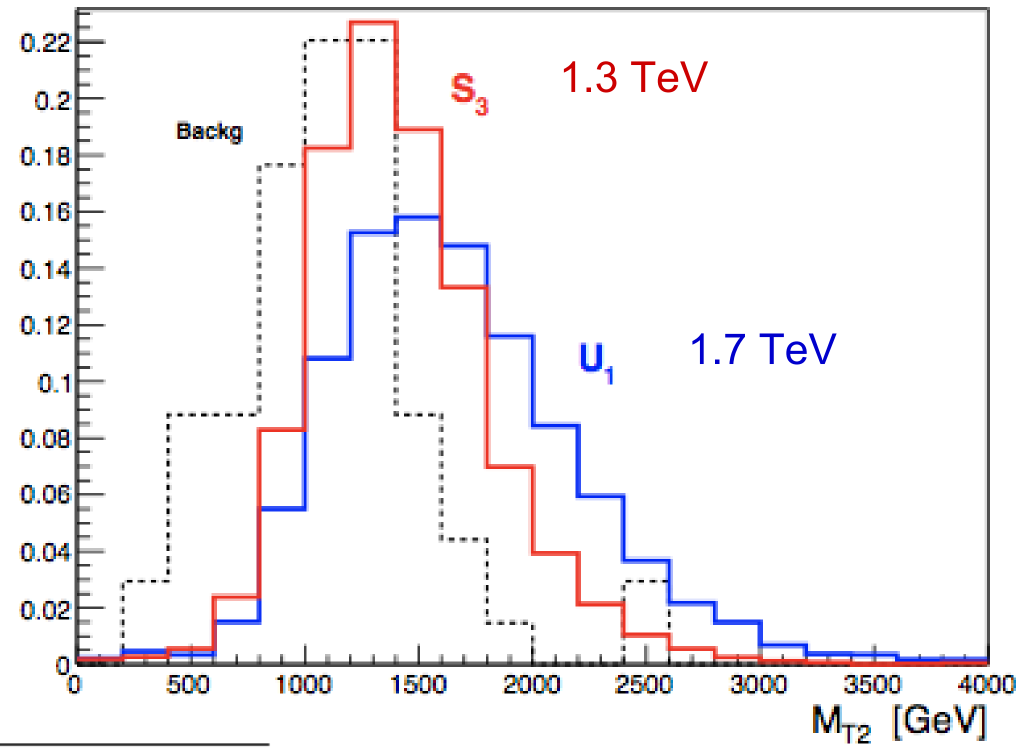
Constructed out of *pseudo-jets* and
trial missing energy vectors

“top observables"

Constructed out of the tagged tops, t(1) and t(2)

Distributions after the cuts: $\not{E}_T > 500\,\mathrm{GeV} \quad M_{tt} > 800\,\mathrm{GeV}$

Variable inspired by the M_{T2} used by experimentalists



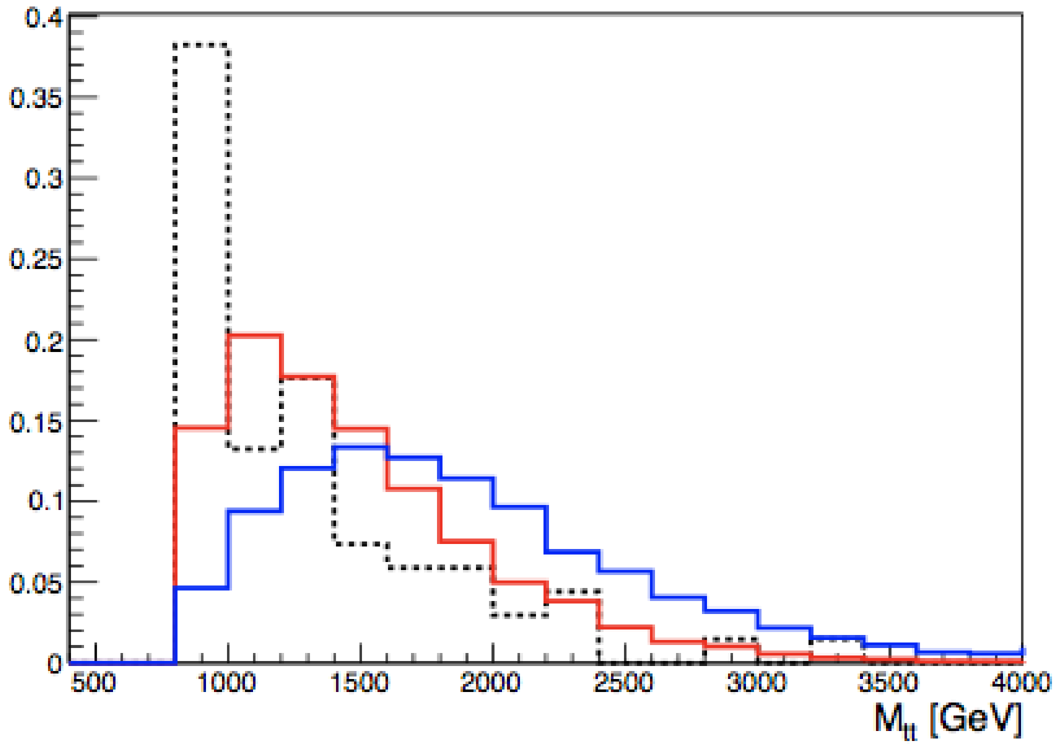
$$M_{T2} \equiv \max\left\{M_{T\,t(1)}, M_{T\,t(2)}\right\}$$

$$M_{T\,t(i)} = \sqrt{2\ \not{E}_T\, p_T\, t(i)\left(1 - \Delta\phi(\not{E}\,, t(i))/\pi\right)}\,, \qquad i = 1, 2$$

“top observables"

Constructed out of the tagged tops, t(1) and t(2)

Distributions after the cuts: $\not{E}_T > 500\,\mathrm{GeV}$ $M_{tt} > 800\,\mathrm{GeV}$



“top observables"

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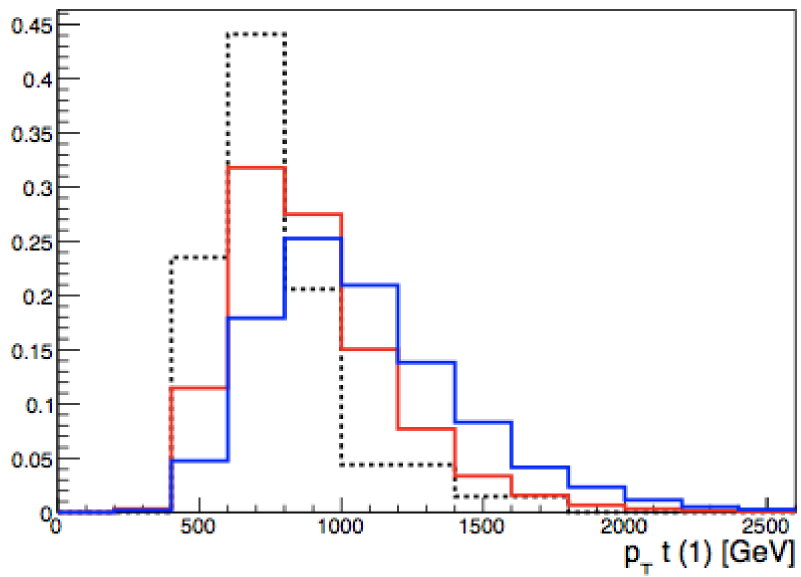
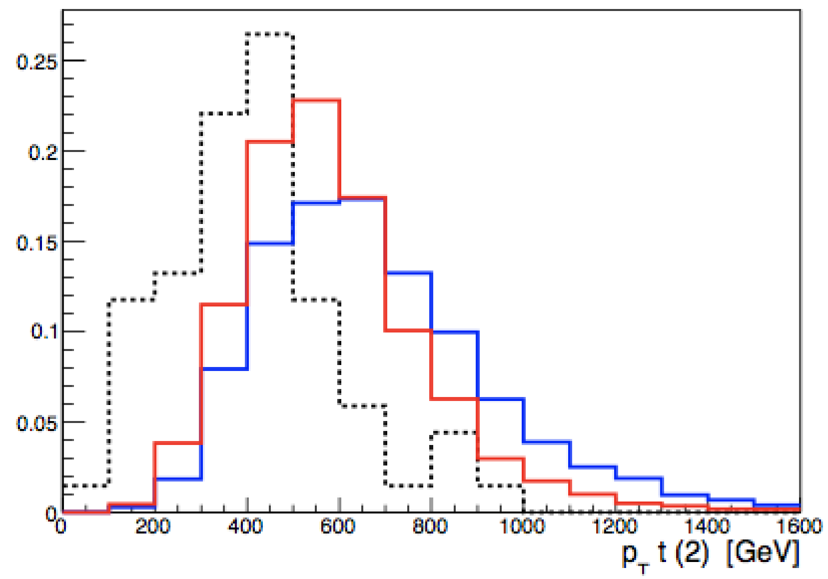
Distributions after the cuts: $\not{E}_T > 500\,\mathrm{GeV} \quad M_{tt} > 800\,\mathrm{GeV}$





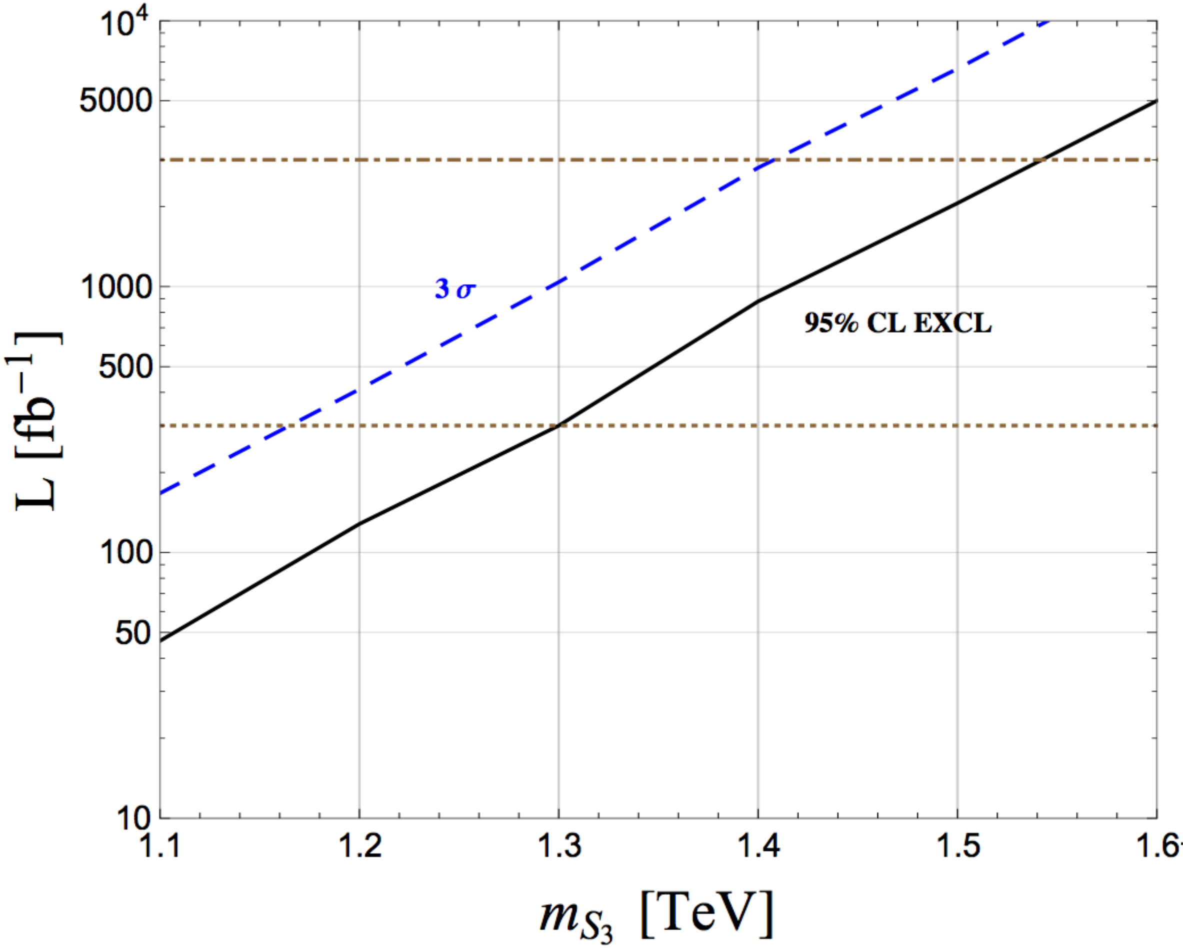
Final selection

$$\not{E}_T > 500\,\mathrm{GeV} \quad M_{tt} > 800\,\mathrm{GeV}$$

$$\begin{array}{llll} \textit{loose}: & M_{T2} > 800\,\mathrm{GeV} & p_T\,t(1) > 500\,\mathrm{GeV} & p_T\,t(2) > 300\,\mathrm{GeV}\,, \\ \textit{tight}: & M_{T2} > 1100\,\mathrm{GeV} & p_T\,t(1) > 700\,\mathrm{GeV} & p_T\,t(2) > 500\,\mathrm{GeV}\,, \end{array}$$

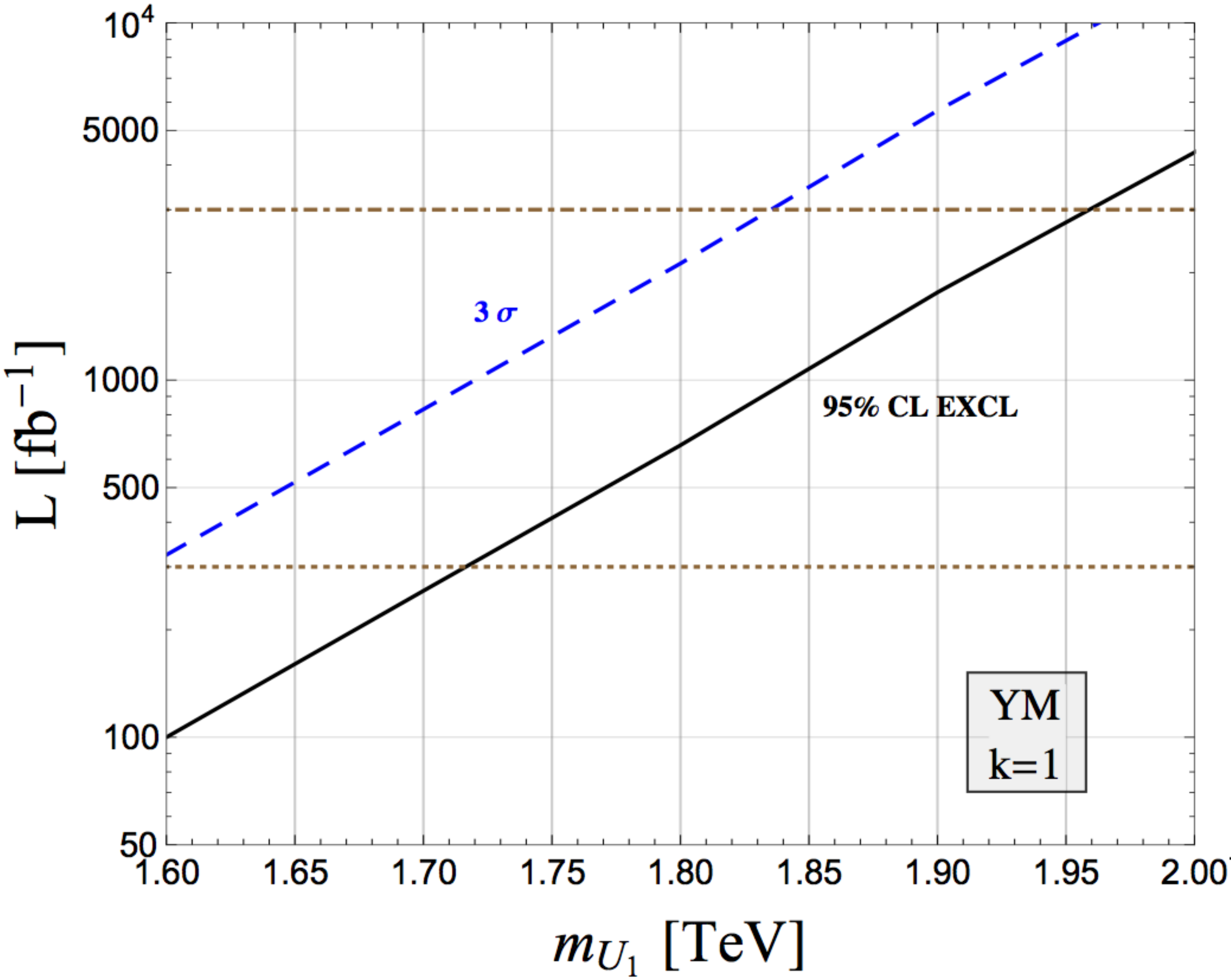
			U_1 (YM)			
m [TeV]	1.6	1.7	1.8	1.9	2.0	2.1
σ [fb]	0.047	0.030	0.019	0.011	0.0072	0.0045
			S_3			
m [TeV]	1.1	1.2	1.3	1.4	1.5	1.6
σ [fb]	0.12	0.074	0.047	0.028	0.011	0.0066
Backg.			*loose*		*tight*	
σ [fb]			0.25		0.080	

HL-LHC Reach



	95% CL EXCL m_{S_3}	3σ obs. m_{S_3}
300 fb^{-1}	1.3 TeV	1.16 TeV
3 ab^{-1}	1.54 TeV	1.41 TeV

HL-LHC Reach

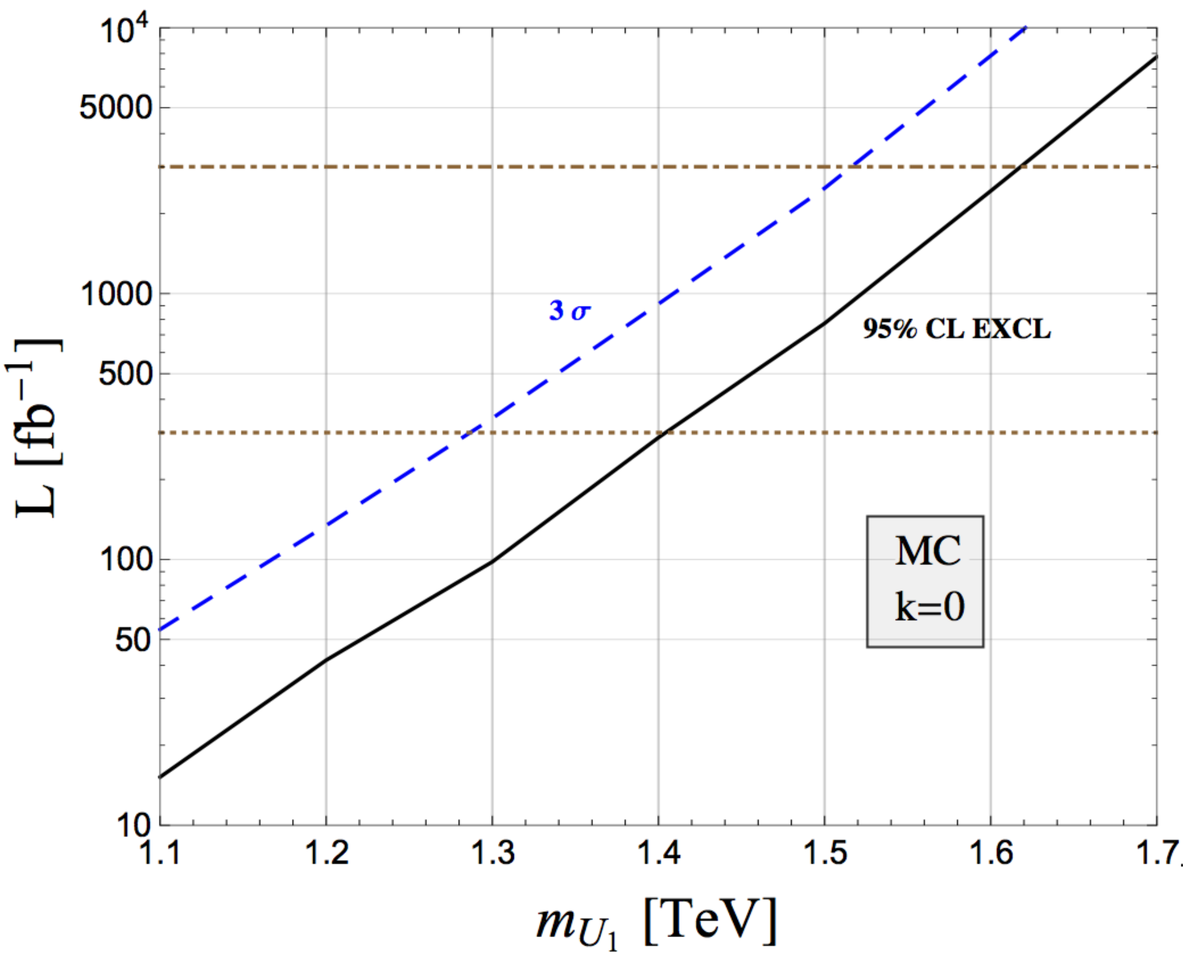


$$\mathcal{L}^{kin} = -\frac{1}{2} U_1^{\dagger\mu\nu} U^1_{\mu\nu} - i\, g_s\, k\, U_1^{\dagger\mu} T^a U_1^{\nu} G^a_{\mu\nu}$$

Yang-Mills case

	95% CL EXCL m_{U_1}	3σ obs. m_{U_1}
300 fb^{-1}	1.72 TeV	1.6 TeV
3 ab^{-1}	1.96 TeV	1.83 TeV

HL-LHC Reach



$$\mathcal{L}^{kin} = -\frac{1}{2} U_1^{\dagger\mu\nu} U^1_{\mu\nu} - i\, g_s\, k\, U_1^{\dagger\mu} T^a U_1^\nu G^a_{\mu\nu}$$

Minimal
Coupling case

	95% CL EXCL m_{U_1}	3σ obs. m_{U_1}
300 fb^{-1}	1.4 TeV	1.28 TeV
3 ab^{-1}	1.62 TeV	1.52 TeV

Distinguishing between Scalar and Vector LQs

In the case of a future discovery in the channel of a signal from a LQ at the HL-LHC, which observables can characterize the signal?

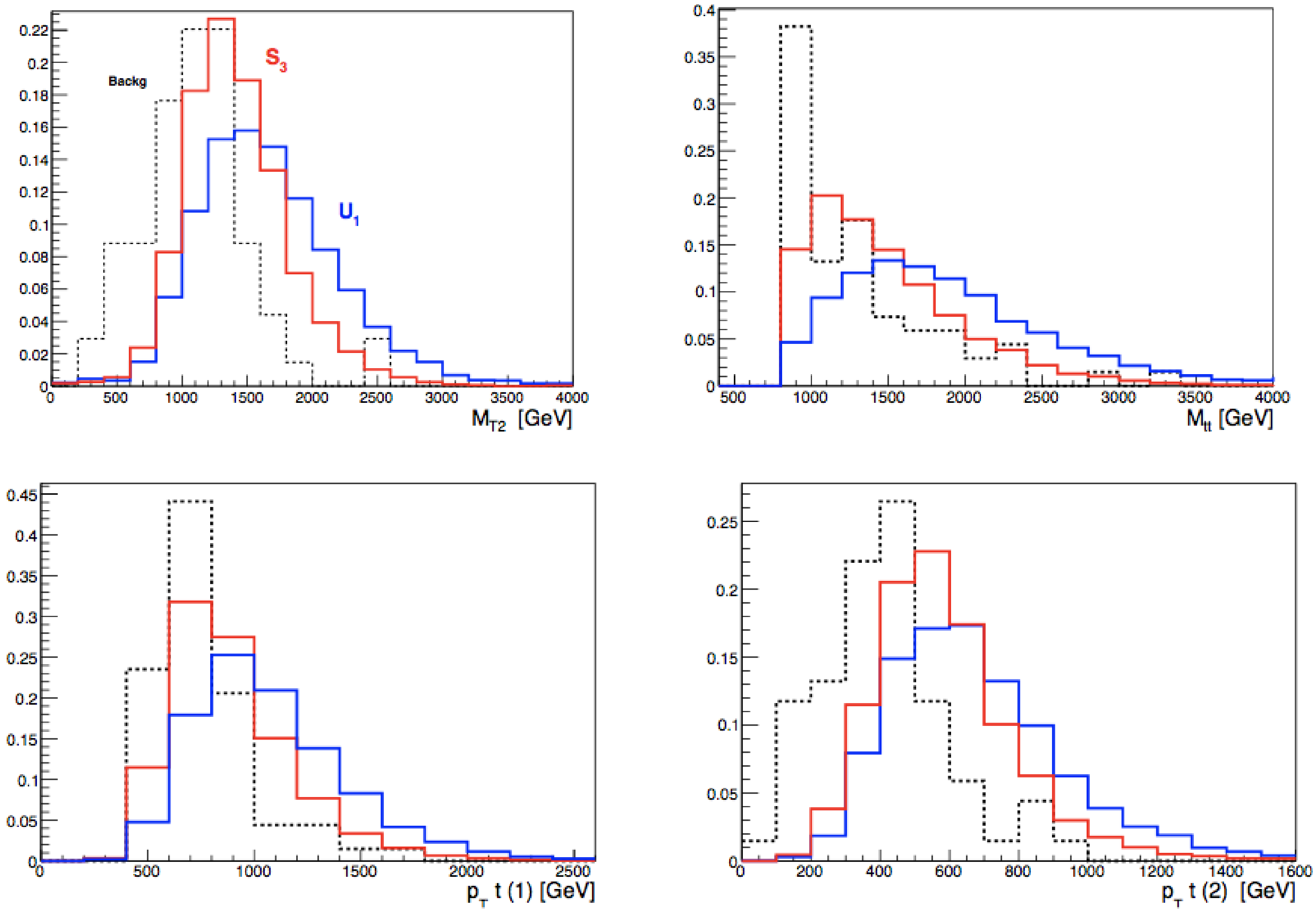
With 3 ab-1 a 5σ discovery could be realized either for a U_1 of ~1.7 TeV, in the YM case, or a lighter S_3 of ~1.3 TeV

↓

A first category of observables use the difference in the energy of the final state to distinguish a Vector LQ from a Scalar LQ. They are the "top observables" already used in the signal-to-background selection

Top observables

$\not{E}_T > 500\,\mathrm{GeV} \quad M_{tt} > 800\,\mathrm{GeV}$



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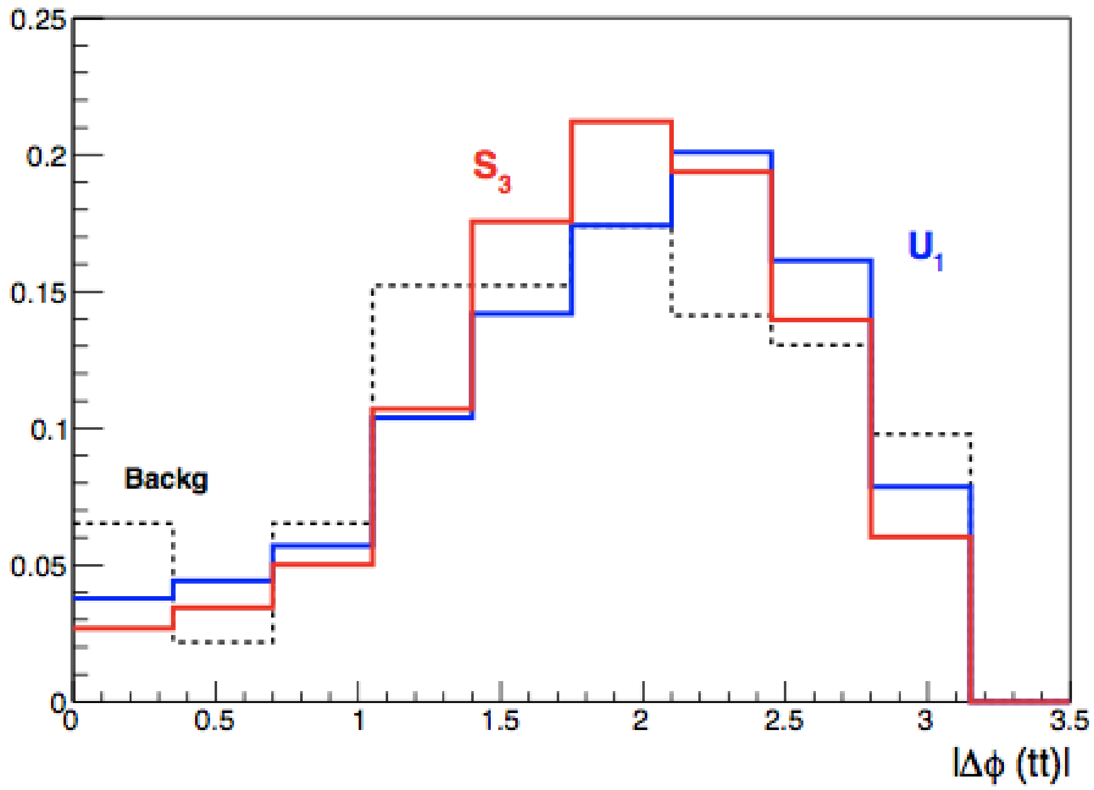
We can even **directly** probe the spin of the LQs by analyzing an angular variable: the azimuthal separation between the two tops.
It is particularly useful to distinguish between the scenarios of scalar LQ and vector LQ in the MC case.

Azimuthal correlation between the tops

$\not{E}_T > 500\,\text{GeV} \quad M_{tt} > 800\,\text{GeV}$



Implications to the flavor anomalies

It accomodates flavor anomalies, which demand for Left-handed couplings of LQs, larger couplings to 3rd generation

The symmetry protects from unwanted flavor-violating effects

Quite natural in “top-triggered” EWSB models (Barbieri et al. '11, '12)

We consider the flavor ansatz

$$U(2)_q \times U(2)_\ell$$

Buttazzo, Greljo, Isidori, Marzocca, JHEP 1711, 044

$$\sqrt{2}\ (V^* y_L)^{ij}\ \overline{u^C_{L\,i}}\nu_{L\,j}\, S_3^{(-2/3)} \qquad y_L^{ij} \equiv g_3\,\beta_{ij}\,, \quad \beta_{ij} = \delta_{3i}\delta_{3\alpha}$$

$$(V^* x_L)^{ij}\,\bar{u}_{L\,i}\gamma_\mu U_1^\mu \nu_{L\,j} + x_L^{ij}\bar{d}_{L\,i}\gamma_\mu U_1^\mu \ell_{L\,j} \qquad x_L^{ij} \equiv g_U\,\beta_{ij}\,, \quad \beta_{ij} = \delta_{3i}\delta_{3\alpha}$$

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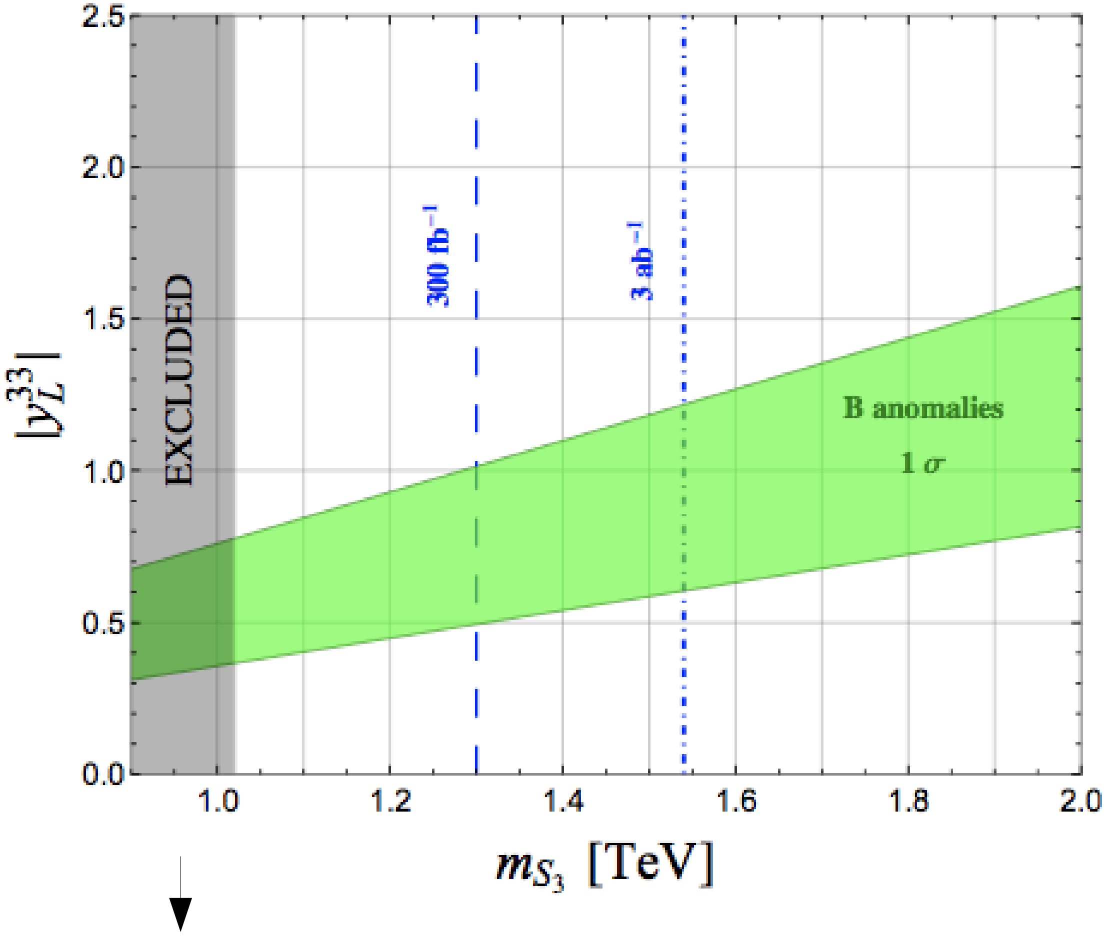

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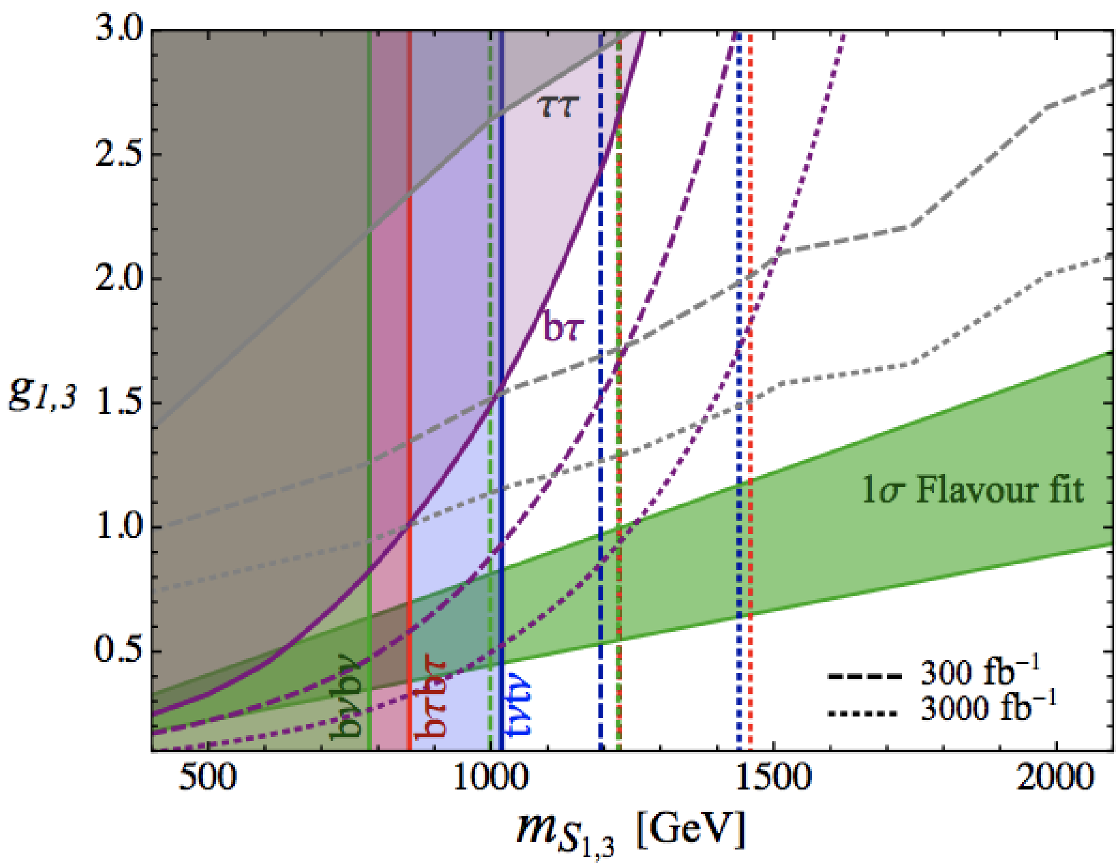
1σ flavor fit from Marzocca, JHEP 1807, 121

From CMS, PRD 89 no 3, 032005
13 TeV, 35.9 fb-1

Implications to the flavor anomalies



We consider the flavor ansatz

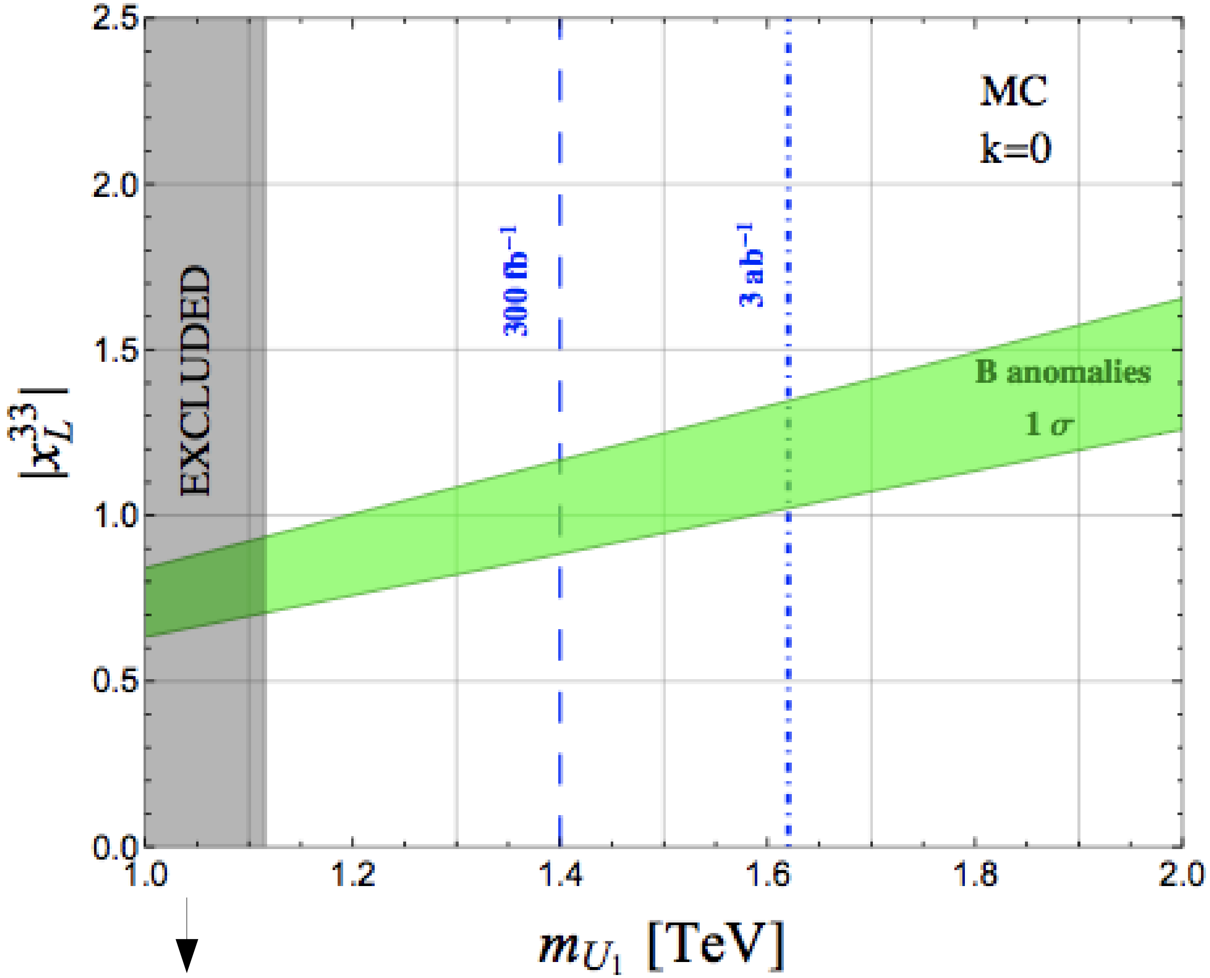
$$U(2)_q \times U(2)_\ell$$

Buttazzo, Greljo, Isidori, Marzocca, JHEP 1711, 044

from Marzocca, JHEP 1807, 121

$$\mathcal{L}_{LQ} = g_1 s^\dagger_{1,-\frac{1}{3}} \left(\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau \right) + g_3 s^\dagger_{3,-\frac{1}{3}} \left(-\bar{t}^c_L \tau_L - \bar{b}^c_L \nu_\tau \right) + h.c.$$
$$+ \sqrt{2} g_3 \left(s^\dagger_{3,\frac{2}{3}} \bar{t}^c_L \nu_\tau - s^\dagger_{3,-\frac{4}{3}} \bar{b}^c_L \tau_L \right) + h.c. \; ,$$

Implications to the flavor anomalies



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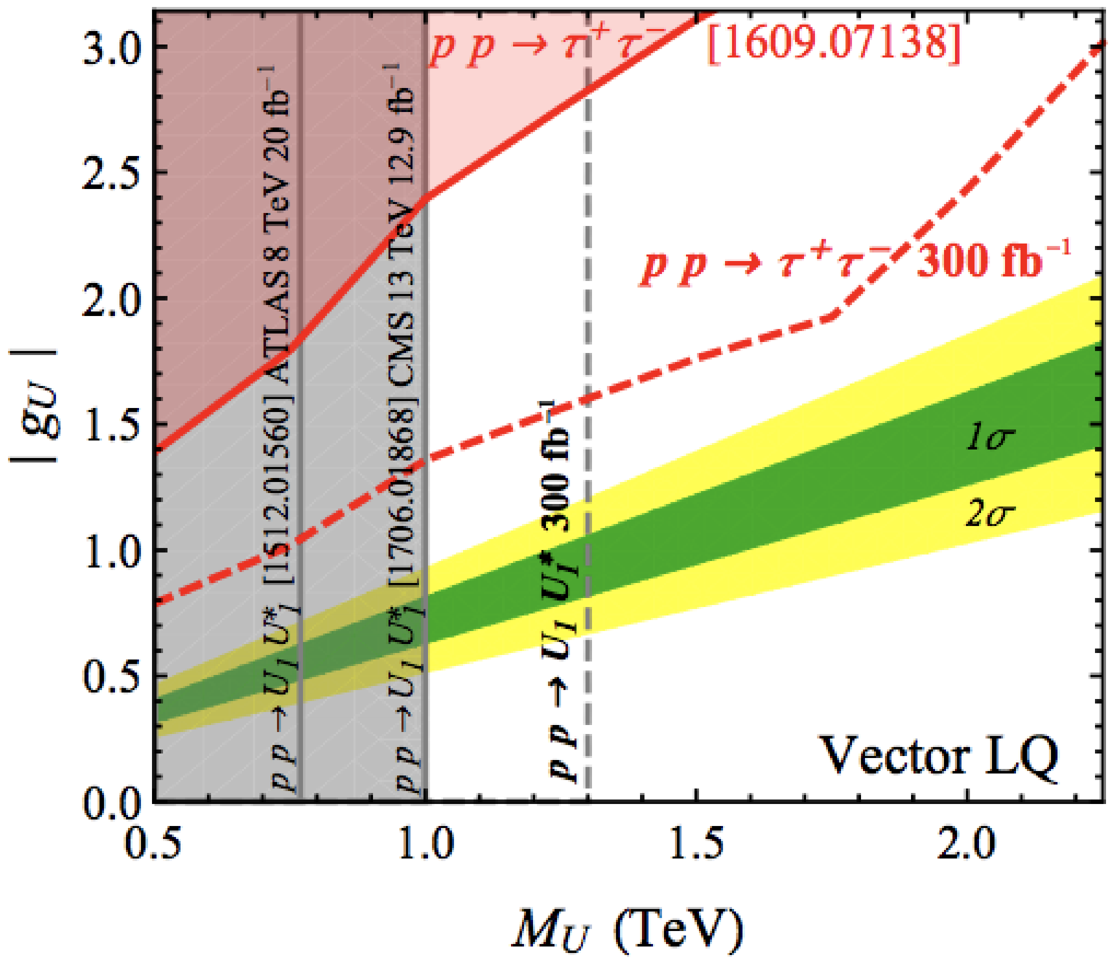
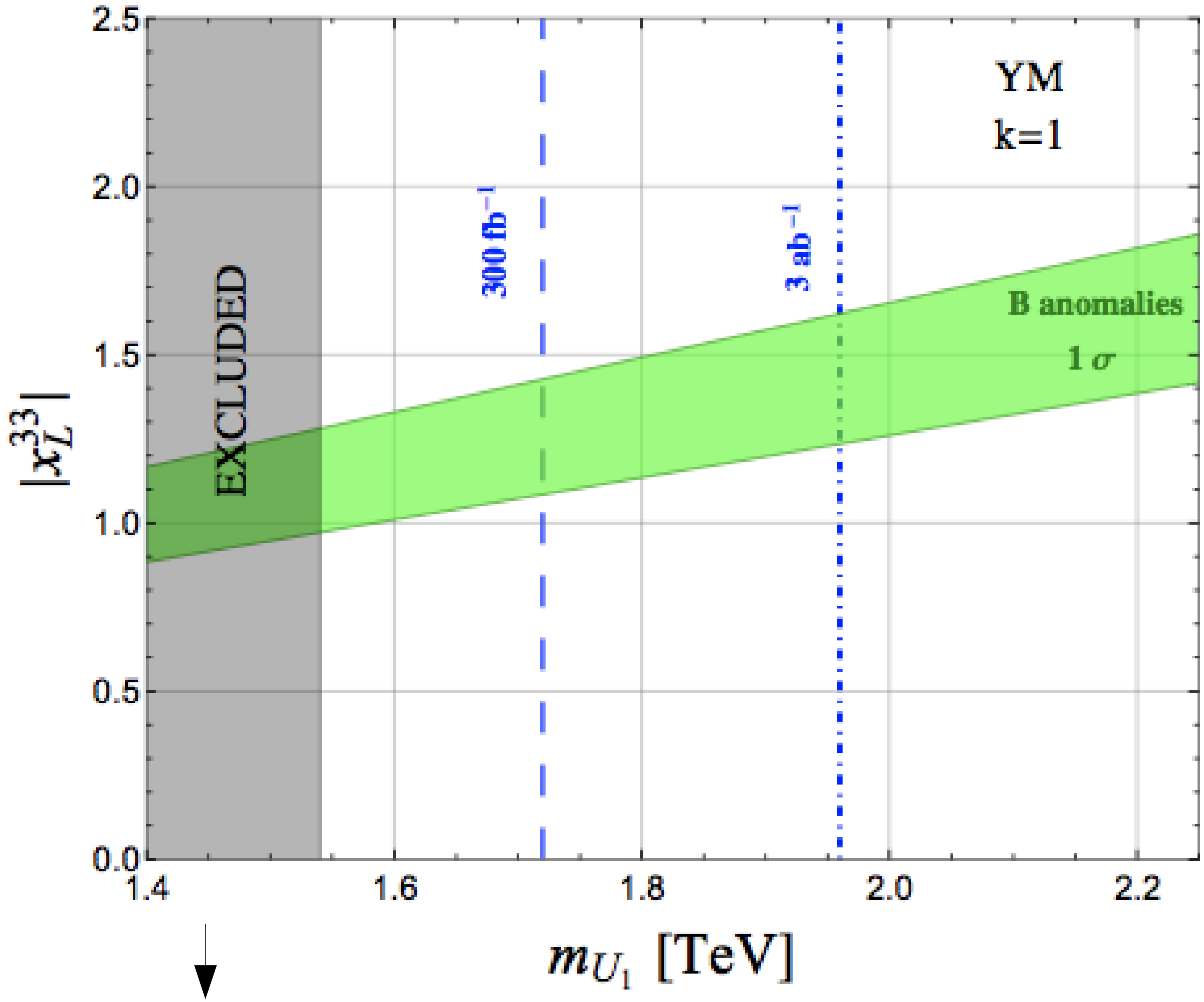


From

Buttazzo, Greljo, Isidori, Marzocca, JHEP 1711, 044

Extrapolation From the CMS analysis in the bτbτ channel

Implications to the flavor anomalies



1σ flavor fit from

Buttazzo, Greljo, Isidori, Marzocca, JHEP 1711, 044

From CMS, PRD 89 no 3, 032005
13 TeV, 35.9 fb-1

Conclusions

- LQs are interesting particles to be searched for at colliders: predicted in appealing BSM models and best candidates to accomodate B-physics anomalies
- t-tbar plus missing energy channel from pair production of third-generation LQs is one of the most efficient to discover LQs
- A dedicated search in the channel at the LHC, relying on the t-tbar tagging, can significantly extend the reach
- “top observables” are useful to both discriminate the signal from the background and to characterize the signal (Distinguishing between scalar and vector LQs)
- Wide HL-LHC reach on the parameter space of interesting models (in particular for the flavor anomalies)