High-energy implications of flavour anomalies

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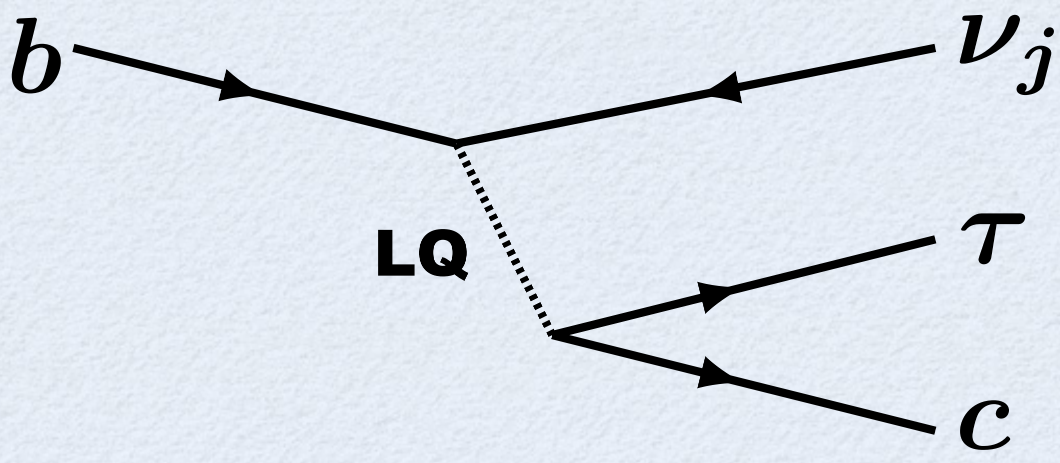
LQ search in relation with $R_{D^{(*)}}$

Ryoutaro Watanabe (INFN Roma Tre)

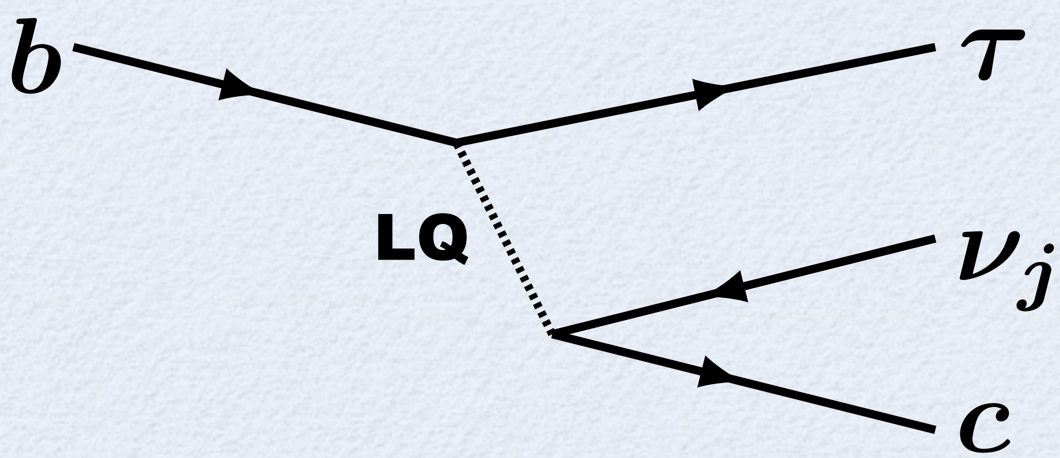
[1603.05248] in collaboration with

Kenji Nishiwaki, Dumont Beranger

LQ contributions



S_1

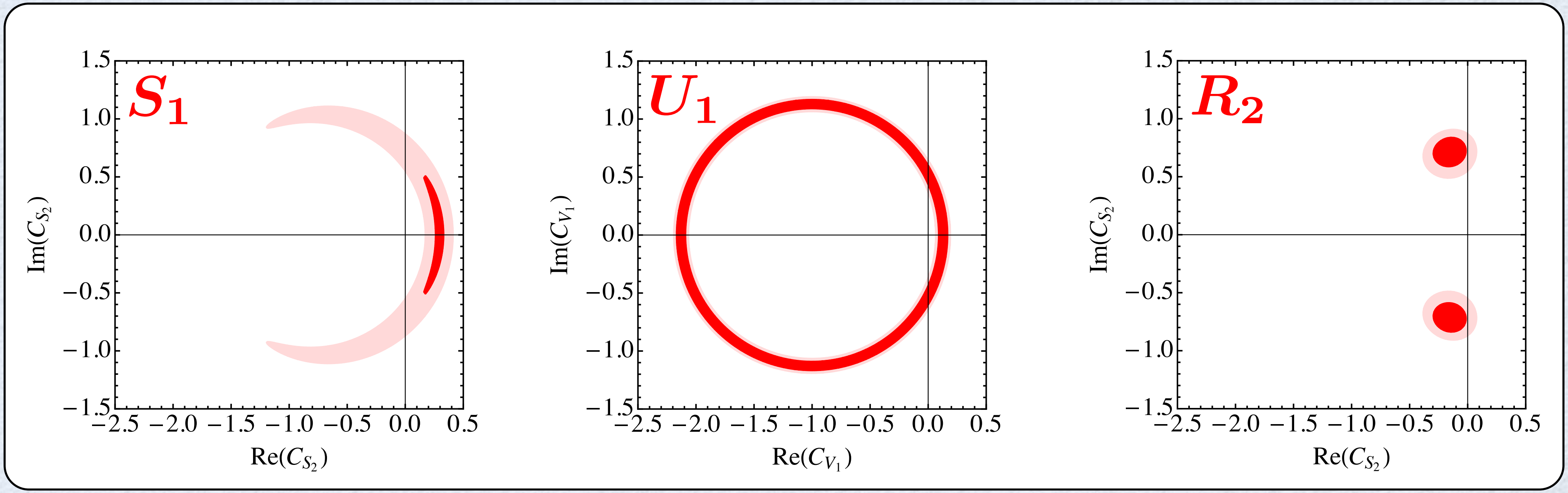


$U_1,\ R_2$

LQ solutions to the $R_{D^{(*)}}$ anomaly

$S_1 : [SU(3)_c, SU(2)_L, U(1)_Y] = [\bar{3}, 1, 1/3]$

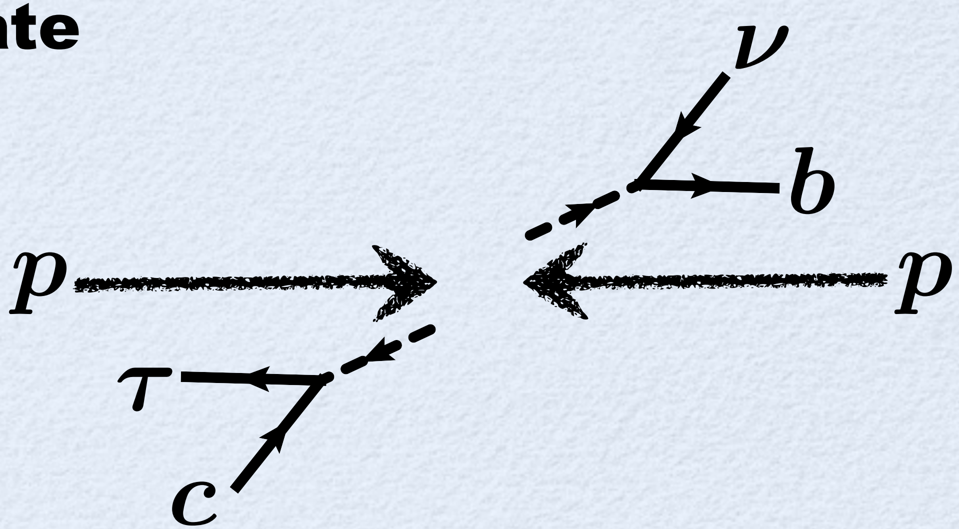
$U_1 : [3, 1, 2/3]$ $R_2 : [3, 2, 7/6]$



$$C = \frac{(\text{LQ coupling})^2}{M_{\text{LQ}}^2} \times C_{\text{SM}}^{-1} \quad \left(C_{\text{SM}} = 2\sqrt{2} G_F V_{cb} \right)$$

This talk

- ✔ **Singlet scalar leptoquark**
- ✔ **Collider signals**
  - **— 8TeV bound translated**
  - **— 14TeV expected in 2016**
  - **— Development up to date**

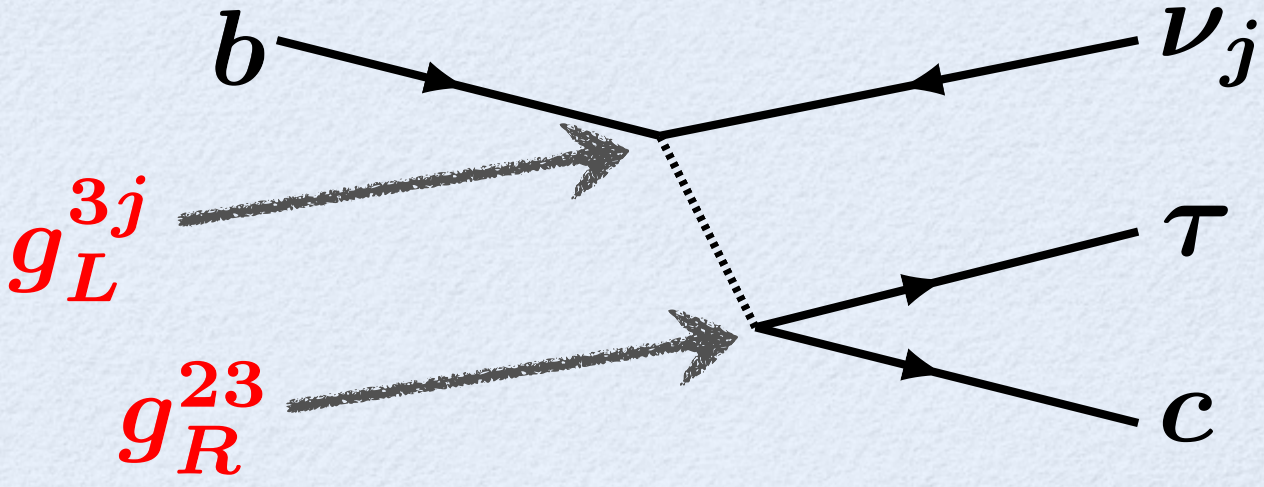


8TeV bounds

Properties of S_1

✔ **Interaction**

$$\mathcal{L}_{\rm LQ} = \left(g_L^{ij}\, \overline{Q}_L^{c,i} (i\sigma_2) L_L^j + g_R^{ij}\, \overline{u}^{c,i} \ell_R^j \right) S_1$$



Many possible decays : $S_1 \to (u^i\, \ell^j),\ (d^i\, \nu^j)$

Solution

✔ **Condition explaining $\bar{B} \to D^{(*)} \tau \bar{\nu}$ anomaly**

$$\frac{g_L^{3j}\; g_R^{23*}}{2M_{S_1}^2} = \begin{cases} -0.25\, C_{\rm SM} & (j = 3) \\ \pm 0.66\, C_{\rm SM} & (j \neq 3) \end{cases}$$

$C_{\rm SM} = 2\sqrt{2} G_F V_{cb}$: SM contribution

✔ **Assumption in this talk**

Keep this condition, namely for g_R^{23*},

$$g_R^{23*} = -0.25 C_{\rm SM} \times 2M_{S_1}^2 \Big/ g_L^{33}$$

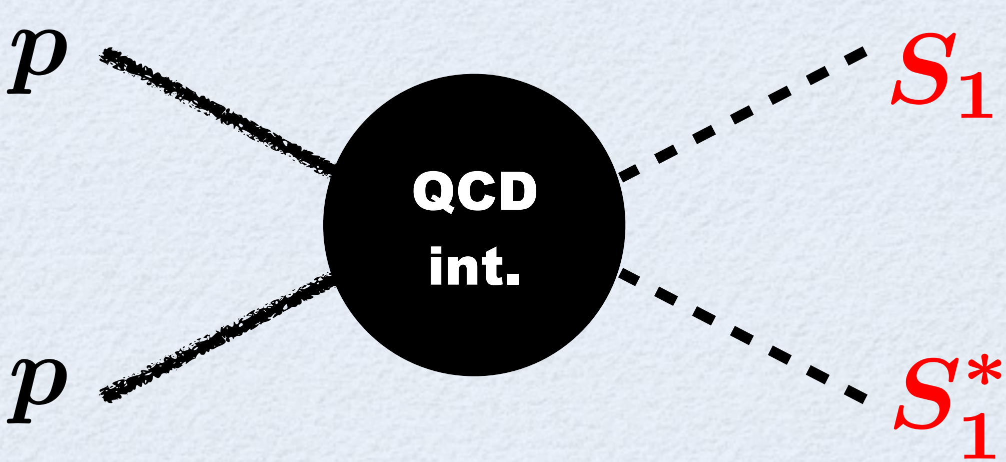
Collider signals

✔ **Decay at collider**

$$g_L^{33} \ : \ S_1 \to b\nu_\tau ,\ t\tau \qquad\qquad g_R^{23} \ : \ S_1 \to c\tau$$

(Production at LHC)

Pair production by QCD, independent on $g_{L,R}$



Collider signals

✔ **Dominant process**

$$pp \to S_1 S_1^* \to \begin{cases} (t\tau)(t\tau) \\ (b\nu)(b\nu) \\ (c\tau)(c\tau) \\ \vdots \end{cases}$$

1. **What is the current bound ?**
2. **Potential at high luminosity?**

Framework

✔ **Setup motivated by the $\bar{B} \to D^{(*)}\tau\bar{\nu}$ anomaly**

$$g_L^{33} \neq 0,$$

$$g_R^{23} = \text{fixed to explain } R(D^{(*)}),$$

$$\text{others} = 0$$

Possible decay : $S_1 \to (t\tau),\ (b\nu_\tau),\ (c\tau)$

Production : **Pair production by QCD**

Framework

✔ **Setup motivated by the $\bar{B} \to D^{(*)}\tau\bar{\nu}$ anomaly**

$$g_L^{33} \neq 0,$$

$$g_R^{23} = \text{fixed to explain } R(D^{(*)}),$$

$$\text{others} = 0$$

Process :

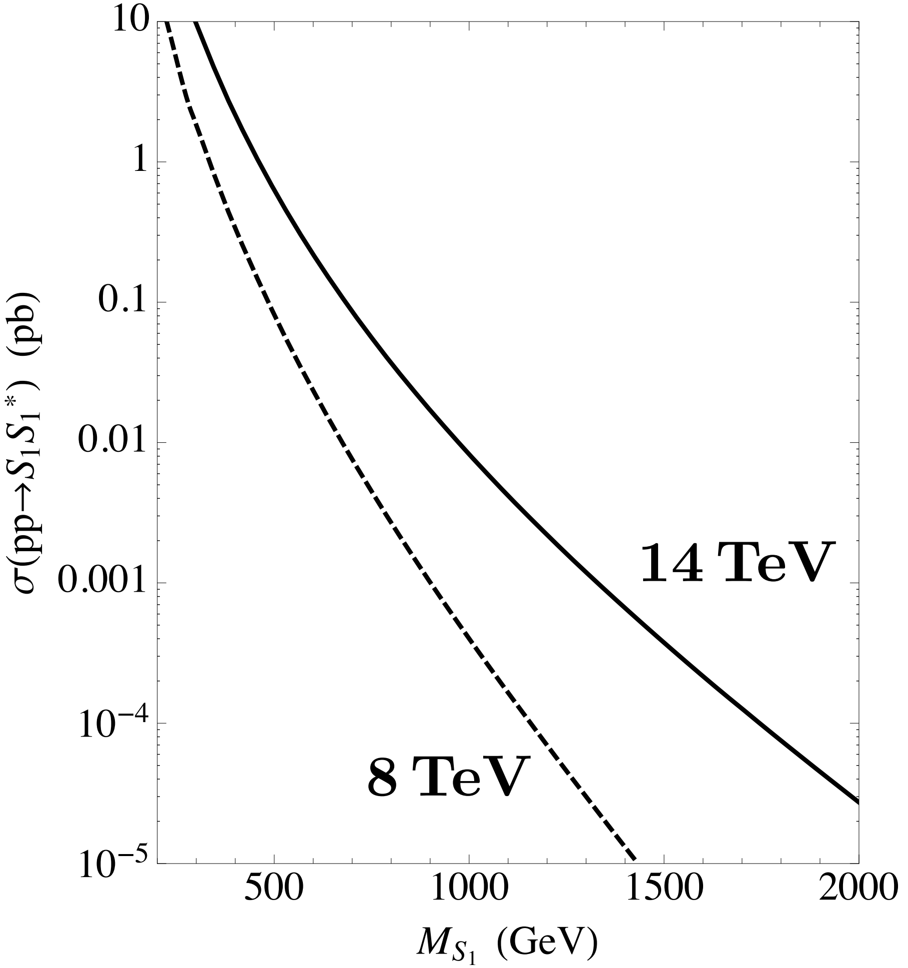
$$pp \to S_1 S_1^* \to \begin{cases} (t\tau)(t\tau) \\ (b\nu)(b\nu) \\ (c\tau)(c\tau) \\ \vdots \end{cases}$$

Framework

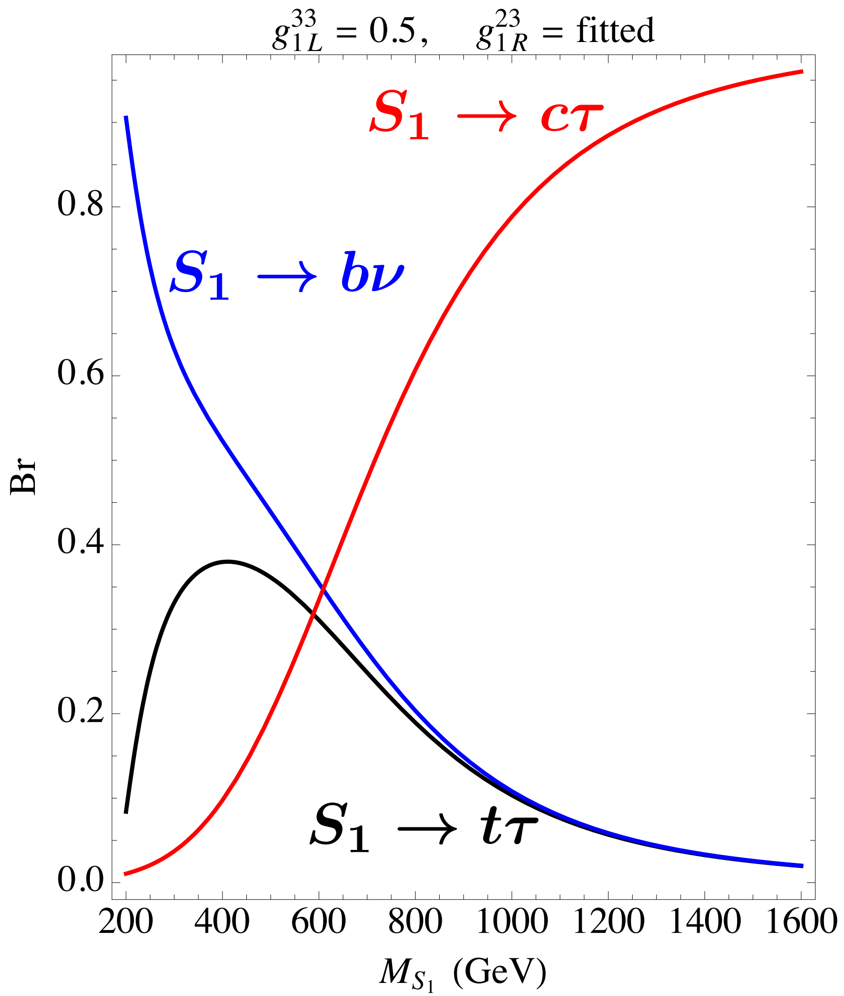
e.g. $\sigma \sim 8\,\mathrm{fb}^{-1}$ for $M = 1$ TeV, at 14 TeV

✔ **Check on property**

Cross section (NLO)



Branching ratios

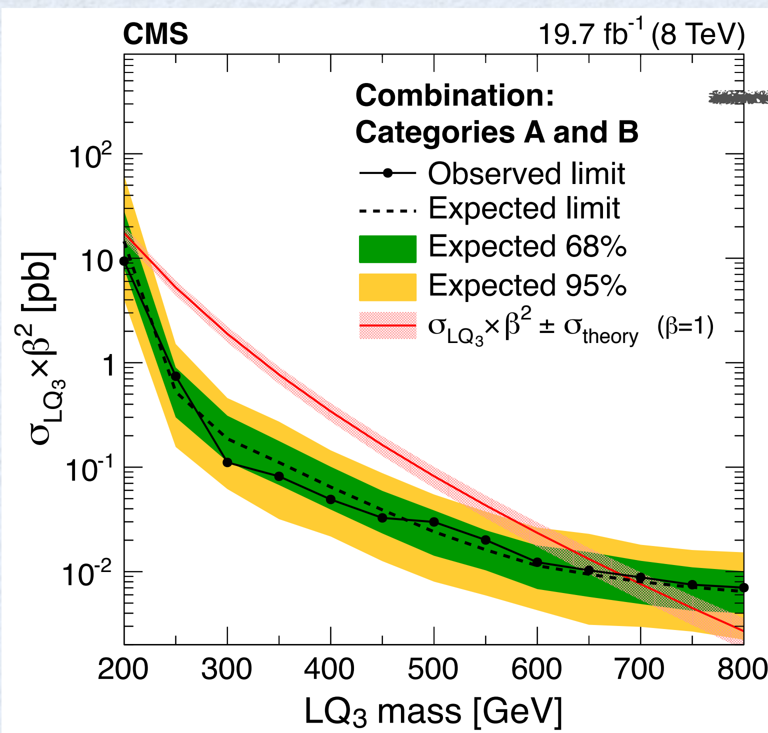


Present search for $(t\tau)(t\tau)$

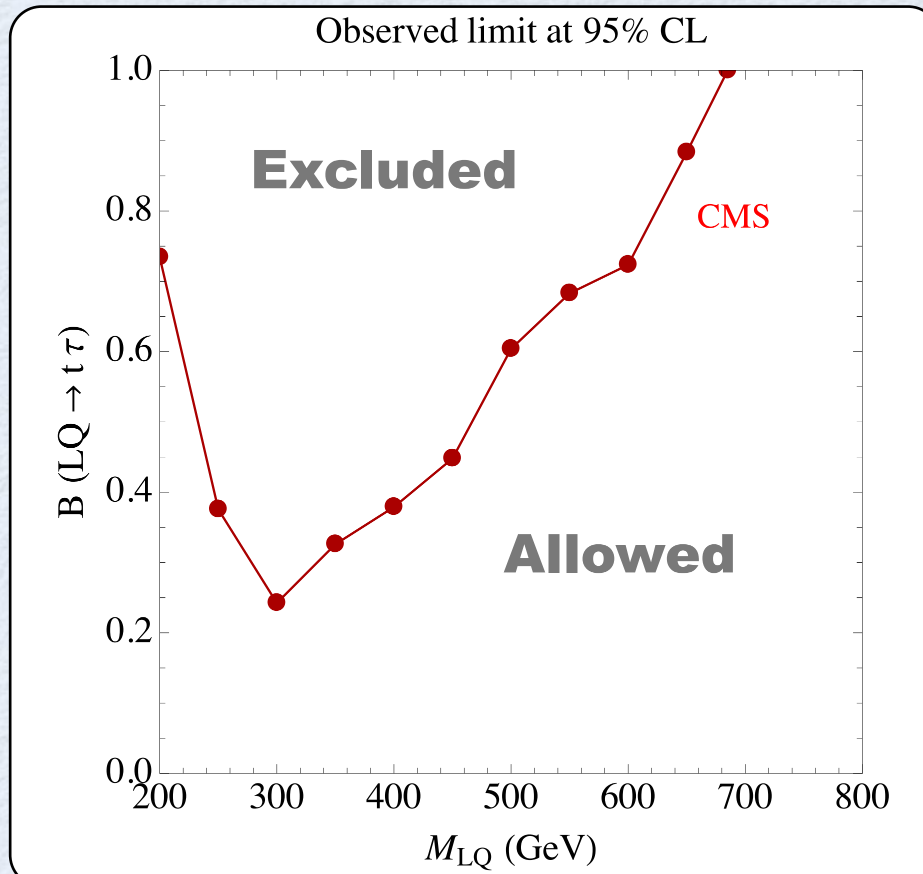
✔ Direct search at CMS

Observed limit on $\sigma(pp \to \mathrm{LQ}\,\overline{\mathrm{LQ}}) \times \mathcal{B}(\mathrm{LQ} \to t\tau)^2$

Constraint on Br is obtained



arXiv:1503.09049 (CMS)

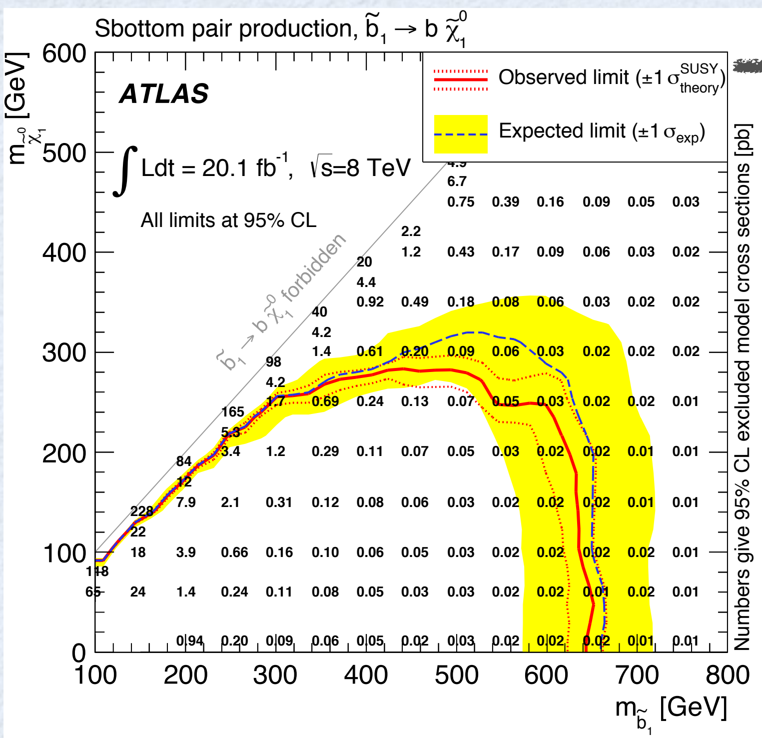


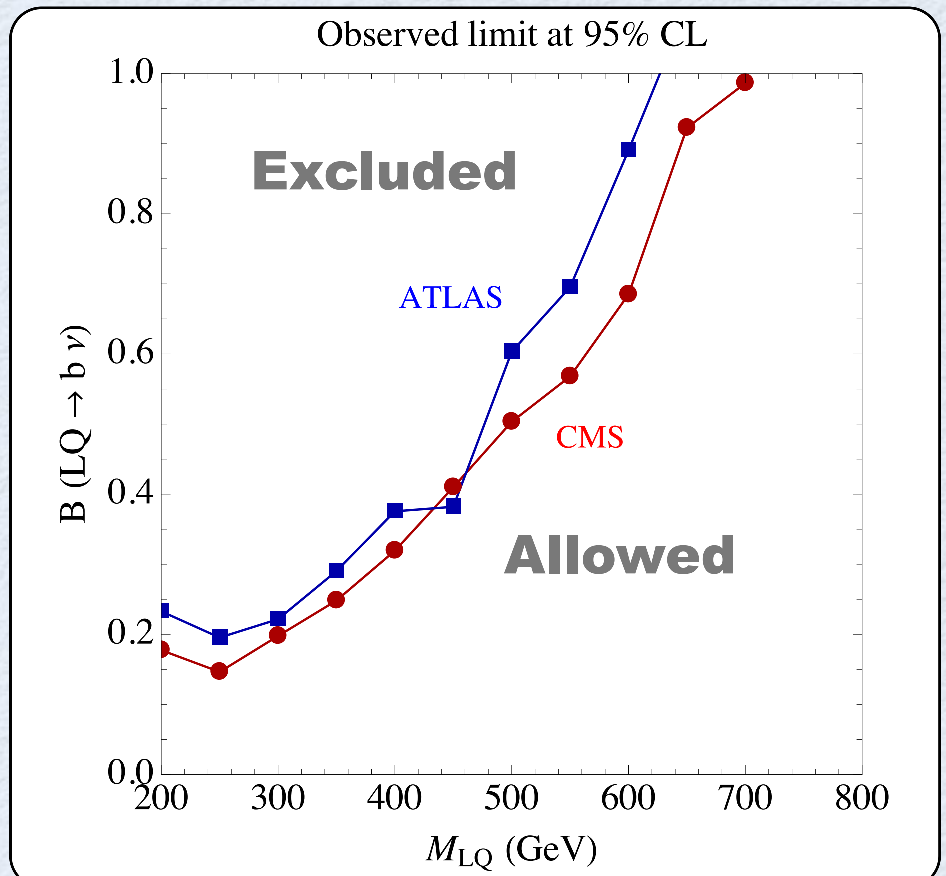
Present search for $(b\nu)(b\nu)$

✔ SUSY (sbottom) searches at CMS & ATLAS

The final state : $(b\tilde{\chi}_1^0)(b\tilde{\chi}_1^0)$

Straightforward translation to $(b\nu)(b\nu)$ is possible





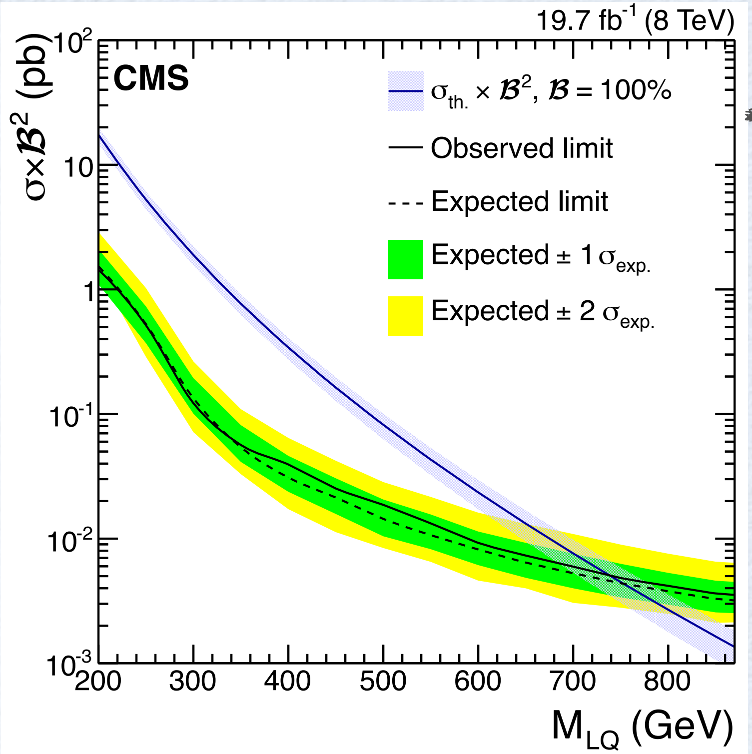
arXiV:1308.2631 (ATLAS)
arXiv:1503.08037 (CMS)

Present search for $(c\tau)(c\tau)$

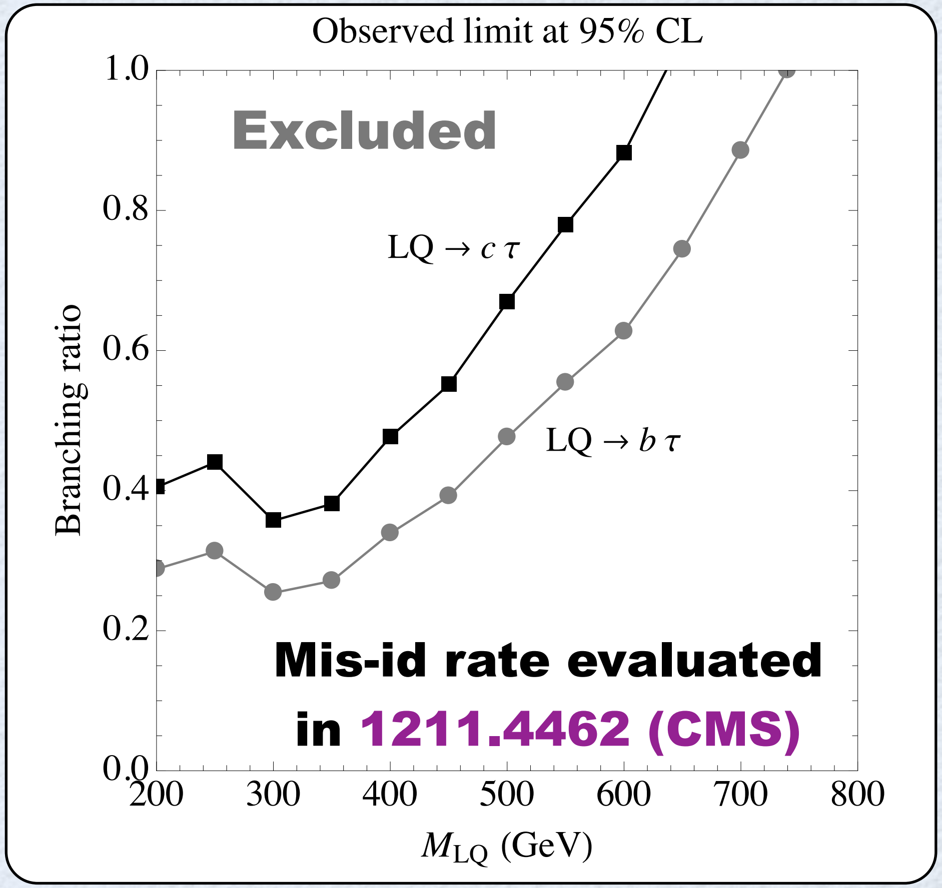
✔ $(b\tau)(b\tau)$ search at CMS

We can reinterpret the result of $(b\tau)(b\tau)$ to that of $(c\tau)(c\tau)$

by taking a probability of mis-identifying c-jets as b-jets

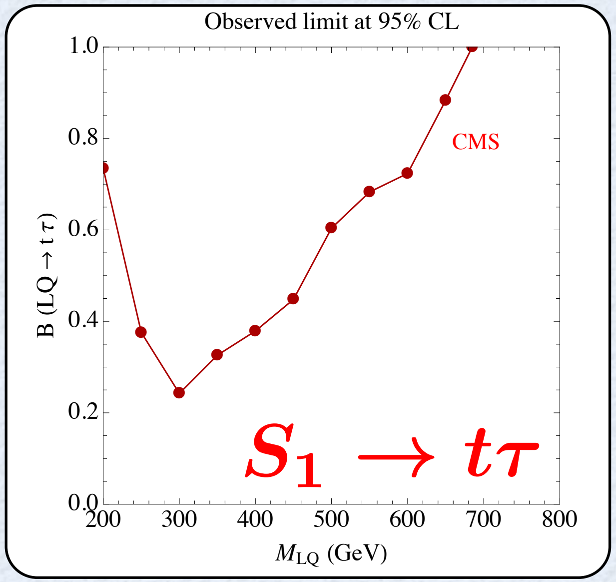


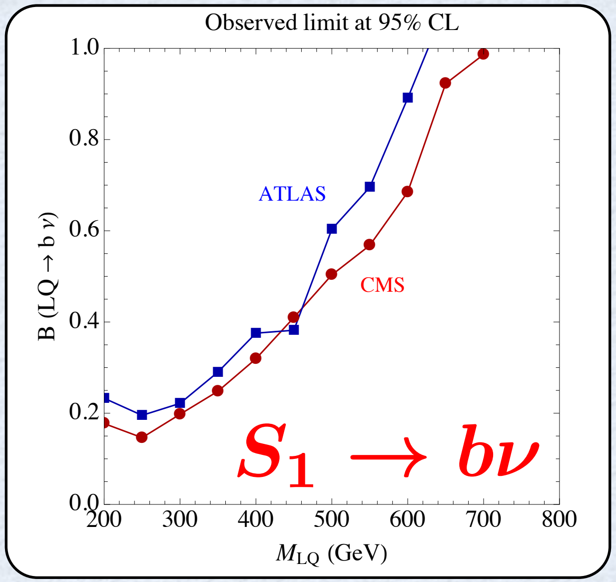
arXiv:1408.0806 (CMS)

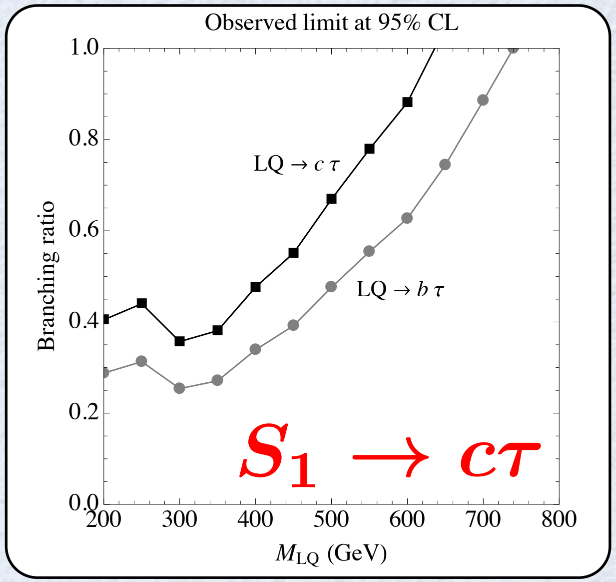


8TeV bound

Present searches provide upper limit of Br's







To model specific case

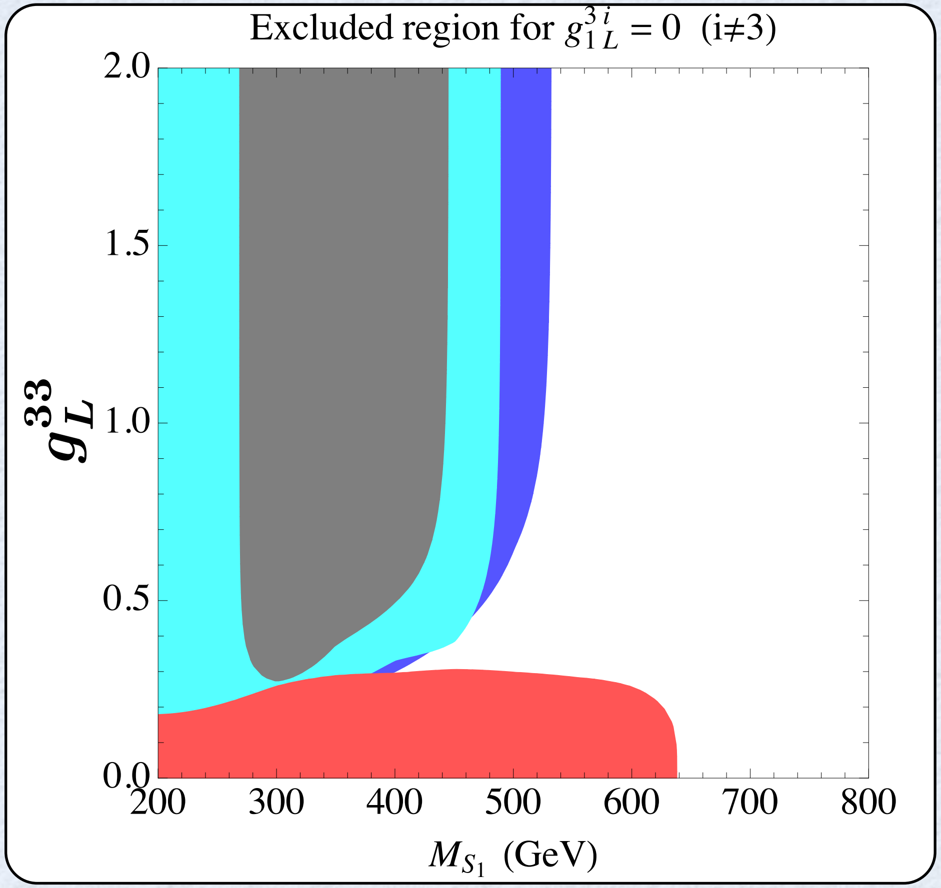
Constraint on (Mass, Branching ratio)

↓

Constraint on (Mass, Coupling)

8TeV bound

Combination for (g_L^{33}, M_{S_1})



Gray : $S_1 \to t\tau$ **(CMS)**

Blue : $S_1 \to b\nu$ **(CMS)**

Cyan : $S_1 \to b\nu$ **(ATLAS)**

Red : $S_1 \to c\tau$ **(CMS)**

For large g_L^{33}, $M_{S_1} < 530\,\mathrm{GeV}$

For small g_L^{33}, $M_{S_1} < 640\,\mathrm{GeV}$

For any region, $M_{S_1} < 400\,\mathrm{GeV}$

"Allowed region" also explains the RD anomaly

14TeV expectation

Target / Availability

$(b\nu)(b\nu)$ $(c\tau)(c\tau)$

Necessary to probe source of the anomaly

SUSY sbottom search can be applied

(ATLAS-COM-PHYS-2014-555)

- can follow the same cut analysis
- adopt ATLAS official b-tag rate

LQ search by $(b\tau)(b\tau)$ can be referred

(CMS, arXiv:1408.0806)

- follow same tau-tag algorithm
- must consider c-tag/mistag rate
- must implement c-tag module in cut analysis (madanalysis5)

Analysis for $(b\nu)(b\nu)$

(Skip)

Cut analysis :

✔ We can follow the same cut analysis with SUSY sbottom search

✔ Signal region cut is (mainly) based on M_{CT} variable

ATLAS-COM-PHYS-2014-555

SM background event :

✔ Relevant processes: (t-tbar), (single top), (z/w+jets), ...etc.

✔ Cut analysis at 14 TeV is already obtained by ATLAS

Signal event :

✔ [FyenRules]	Model file for S1 leptoquark
→ [Madgraph5／Pythia6]	Event generation
→ [DelphesMA5tune]	Detector simulation
→ [Madanalysis]	Cut analysis

Analysis for $(c\tau)(c\tau)$

c jet tagging / mis-tagging rate

✔ **No conclusive & reliable value**

✔ **Three choices by some studies**

Case-1 (Theorist, arXiv:1505.06689)

$$\epsilon_{c\to c} = 50\%\,, \quad \epsilon_{b\to c} = 20\%\,, \quad \epsilon_{\text{light}\to c} = 0.5\%$$

Case-2 (ATLAS, arXiv:1501.01325)

$$\epsilon_{c\to c} = 19\%\,, \quad \epsilon_{b\to c} = 13\%\,, \quad \epsilon_{\text{light}\to c} = 0.5\%$$

Case-3 (ATLAS-PHYS-PUB-2015-001)

$$\epsilon_{c\to c} = 40\%\,, \quad \epsilon_{b\to c} = 25\%\,, \quad \epsilon_{\text{light}\to c} = 10\%$$

Analysis for $(c\tau)(c\tau)$

(Skip)

Cut analysis :

- ✔ We follow the analysis method for $(b\tau)(b\tau)$ given by CMS
- ✔ Tau-tagging algorithm (HPS) is implemented (CMS, arXiv:1109.6034)
- ✔ c-jets tagging module is implemented in madanalysis5
- ✔ Signal regions cut is based on S_T variable (CMS, arXiv:1408.0806)

SM background event :

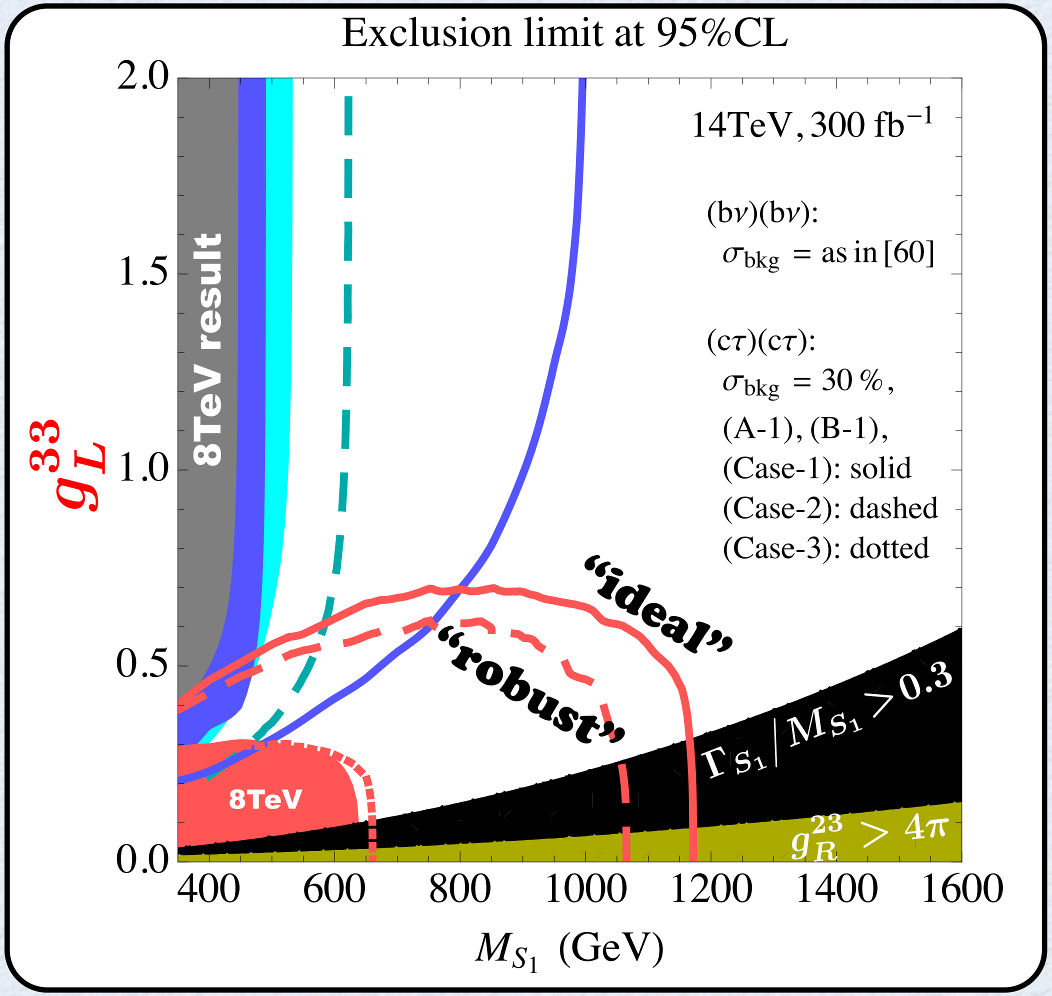
- ✔ We consider (t-tbar; dominant), (w+jets; sub.), (z+jets; less.)
- ✔ We generated 10^7 events for t-tbar, 5*10^6 for w/z+jets

Signal event :

- ✔ We utilize the same procedure with the case for $(b\nu)(b\nu)$

14TeV, expected in 2016

Condition : $g_R^{23*} \simeq -0.5\, C_{\rm SM} M_{S_1}^2 / g_L^{33}$



Blue : $pp \to S_1 S_1^* \to (b\nu)(\bar{b}\bar{\nu})$

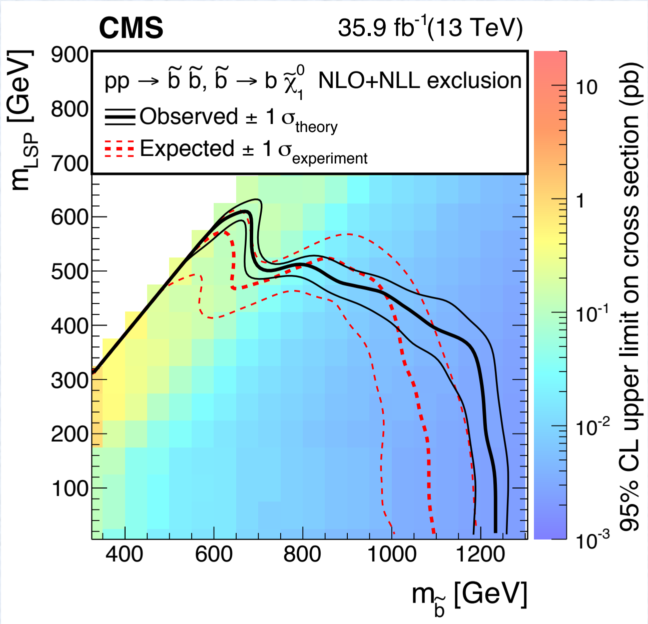
Red : $pp \to S_1 S_1^* \to (c\tau)(\bar{c}\bar{\tau})$

✔ **c-jet tagging is significant to search S1 leptoquark motivated by R(D(*))**

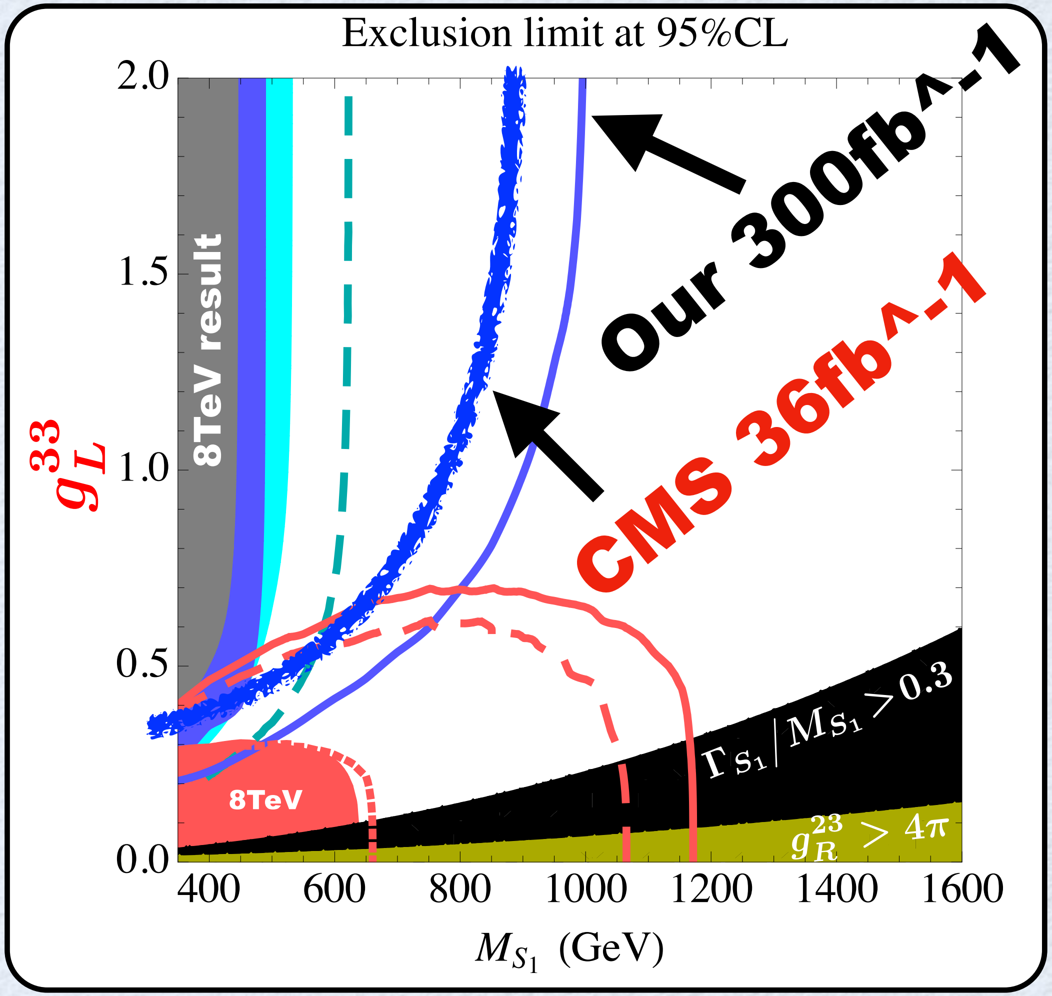
$\lesssim 800$ GeV **Scalar-LQ**
(explaining the anomaly)
can be probed at the LHC

Development up to date

$(b\nu)(b\nu)$ **search :**



Sbottom search at 13TeV
(CMS 1707.07274)
(CMS 1809.05558)



✔ **Efficiency improved more than our simulation**

Development up to date

$c\text{-jet tag}:$

Stop/Scharm search (ATLAS 1805.01649)

"Direct searches at LHC are becoming more and more useful to test the LQ solutions to the RD anomaly"

"For Scalar LQ, please try to look at $(c\tau)(c\tau)$ **"**

$(b\tau)(b\tau)\ \text{search}:$

LQ search (CMS 1806.03472)

$(c\nu)(c\nu)\ \text{search}:$

?

$\Bigg\}\ U_1,\ R_2$

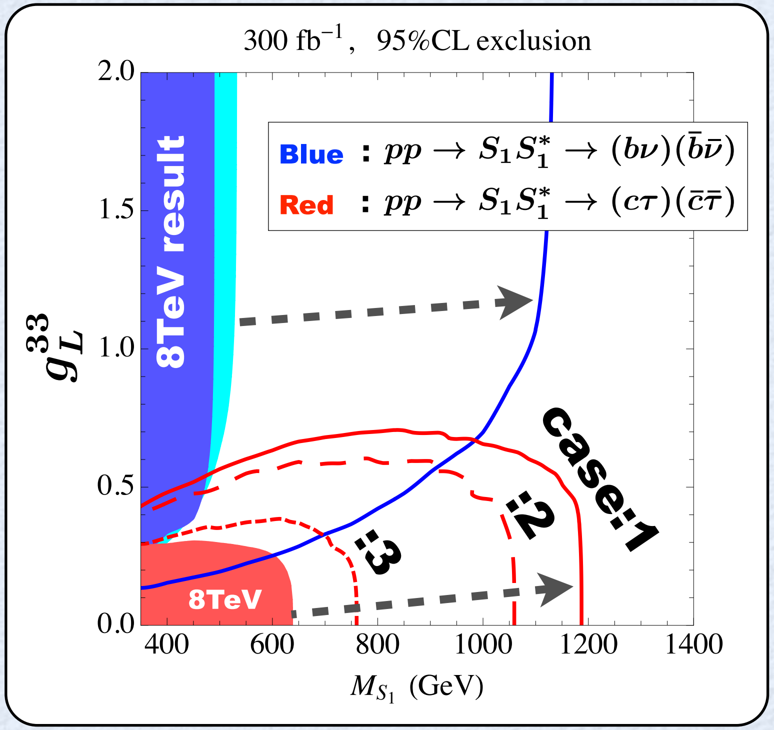
Back up

Summary

S1 Leptoquark can explain $\bar{B} \to D^{(*)}\tau\bar{\nu}$ anomaly

$$\frac{g_L^{33} g_R^{23*}}{2M_{S_1}^2} = -0.25 \times 2\sqrt{2} G_F V_{cb} \qquad \mathcal{L}_{\rm LQ} = \left(g_L^{ij}\, \overline{Q}_L^{c,i} (i\sigma_2) L_L^j + g_R^{ij}\, \overline{u}^{c,i} \ell_R^j \right) S_1$$

Present search / prospect at the LHC



$M_{S_1} < 400\,\text{GeV}$ is already excluded

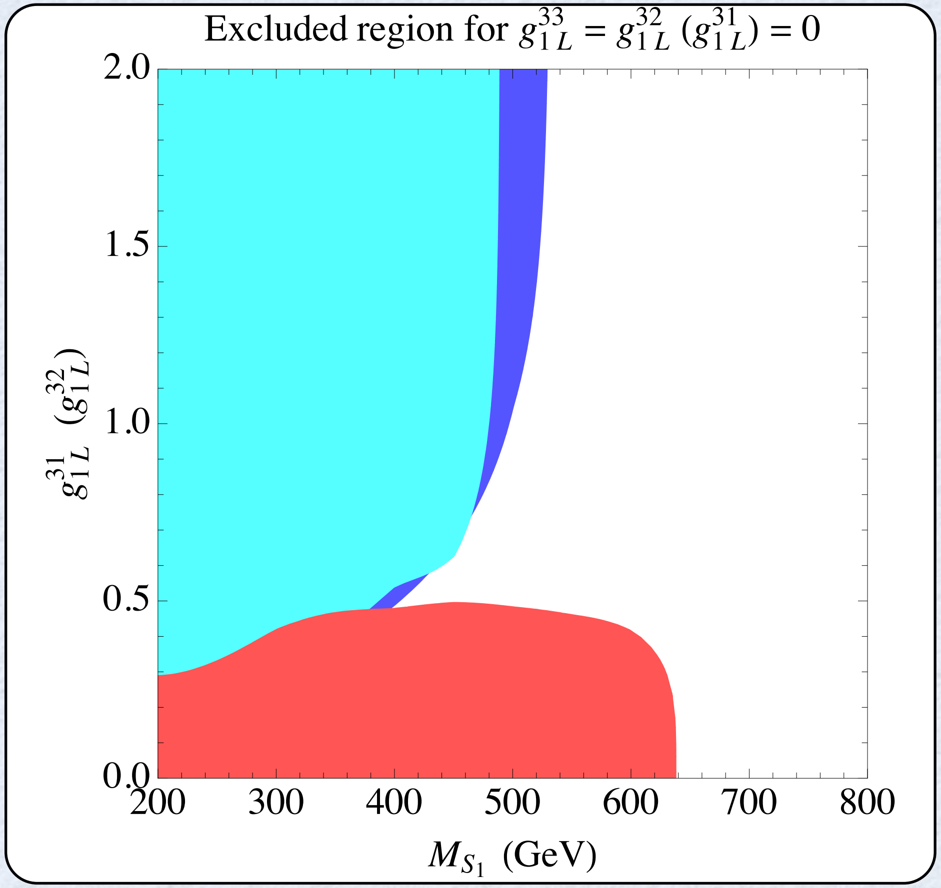
$M_{S_1} < (0.7 - 1)$ TeV can be excluded

(14 TeV, 300 fb^{-1})

We can confirm the flavor anomaly by the search at the LHC

Bound on S1 leptoquark

Result for $(g_{1L}^{3i}\,,\ M_{S_1})\quad i \neq 3$



- g_{1R}^{23} **is fixed as well**
- $S_1 \to t\tau$ **is not relevant**
- g_{1R}^{23} **is fixed**

  so that the condition is satisfied
- **all of the other couplings**

  are set to be zero

$M_{S_1} \sim 400\,\mathrm{GeV}$ **is still allowed !**

Cut details

(b nu)(b nu)

Category	Cut condition (in SRA)
Lepton veto	no e/μ after the isolation
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 150\,\mathrm{GeV}$
Leading jet $p_{\mathrm{T}}\,(j_1)$	$> 130\,\mathrm{GeV}$
Second jet $p_{\mathrm{T}}\,(j_2)$	$> 50\,\mathrm{GeV}$
Third jet $p_{\mathrm{T}}\,(j_3)$	veto if $> 50\,\mathrm{GeV}$
b-tagging	for leading two jets, $n_{b\text{-jets}} = 2$ $(p_{\mathrm{T}} > 20\,\mathrm{GeV},\ \lvert\eta\rvert < 2.5)$
$\Delta\phi_{\mathrm{min}}$	> 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(k)$	> 0.25 for $k = 2$
m_{bb}	$> 200\,\mathrm{GeV}$
m_{CT}	$> 300,\ 350,\ 450,\ 550,\ 650,\ 750\,\mathrm{GeV}$

(c tau)(c tau)

Category	Cut and selection rule
Leptons	(A-1) one τ_{h} and one $\ell = \mu$ (A-2) one τ_{h} and one $\ell = \mu$ or e
Electric charge	opposite sign between τ_{h} and $\ell^{\pm}$
Jet objects	more than three (including τ_{h})
c-tagged jet	(B-1) at least two [redacted]
$M(\tau_{\mathrm{h}}\text{-jet}, c\text{-jet})$	$> 250\,\mathrm{GeV}$
S_{T}	> 100 - $1000\,\mathrm{GeV}$ for each $100\,\mathrm{GeV}$ bin

Discovery potential at 3000fb^-1