Leptoquarks at the LHC: Beyond the Lepton-Quark Final State

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B-meson anomalies

There are currently several anomalies in B-decays coming from BABAR, BELLE, LHCb. For example the ratio of branching ratios

$$R(D^*) = \frac{Br(B \to D^* \tau \ \nu)}{Br(B \to D^* l \ \nu)}$$

differs from the SM prediction by 3.4 standard deviations.

B-meson anomalies

Name	Definition	Observed value	[ref]	SM prediction	[ref]	Discrepancy
R_K	$\frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	[2]	1	[9, 10]	2.6σ
R_{K^*}	$\frac{Br(B^0 \to K^{0*} \mu^+ \mu^-)}{Br(B^0 \to K^{0*} e^+ e^-)}$	$[0.66, 0.69]^{+0.11}_{-0.07} \pm 0.03$	[7]	$[0.926, 0.9965] \pm 0.0005$	[9, 10]	$[2.2\sigma, 2.5\sigma]$
R_D	$\frac{Br(B \to D^* \tau^- \nu)}{Br(B \to D \ell^- \nu)}$	$0.407 \pm 0.039 \pm 0.024$	[11]	0.299 ± 0.011	[12]	2.3σ
R_{D^*}	$\frac{Br(B \to D^* \tau^- \nu)}{Br(B \to D^* \ell^- \nu)}$	$0.304 \pm 0.013 \pm 0.007$	[11]	0.252 ± 0.003	[13]	3.4σ
$R_{J/\psi}$	$\frac{Br(B_c^+ \to J/\psi \tau^+ \nu)}{Br(B_c^+ \to J/\psi \mu^+ \nu)}$	$0.71 \pm 0.17 \pm 0.18$	[8]	0.29 ± 0.07	[14]	1.7σ

TABLE I: Anomalies in B meson decays. For the experimental values, statistical and systematic uncertainties are shown separately. For R_{K^*}, we report in brackets the two LHCb measurements, in the q^2 bins $[0.045, 1.1]$ GeV^2 and $[1.1, 6]$ GeV^2. For $R_{D^{(*)}}$, we use the 2017 HFLAV world average, which is based on [1, 3–6].

There are other deviations in decays to D-mesons and to kaons.

Many of these appear to violate lepton universality.

B-meson anomalies

Many many authors:
Altmannshofer, Crivellin,Freytsis,
Ligeti….

Can apparently be explained by new physics operators

$$O = \frac{1}{\Lambda^2}\, l\, \gamma^\alpha\, l' \quad q\, \gamma_\alpha\, q'$$

The l and q (and Λ) depend on the anomaly to be explained. For the kaon anomalies, the scale can be as high as ~50 TeV, while for the D-anomalies, the scale is about ~TeV.

Suggests new physics which is a Z' or a leptoquark.

We will look at the leptoquark possibility. We denote this field as Φ.

Problems with Leptoquarks

Leptoquarks have problems: they can lead to proton decay, since we could in principle have couplings $\Phi\, lq$ as well as $\Phi\, qq$. This can however be solved by models in which baryon and/or lepton number is conserved.

They are also quite constrained by direct searches at the LHC. They are strongly produced and decay to a quark and lepton. The signal is therefore two leptons plus jets, and searches for this signal constrain leptoquark masses to be above 750 GeV for the $c\,\tau$ case, and 1.5 TeV for the $b\,\mu$ case.

Also one might not want to have a further naturalness problem for a new light scalar.

One option to address these issues: take the leptoquarks to be composite.
Naturalness is addressed, and as we now see, the LHC bounds can also be significantly reduced.

Composite leptoquarks

Cline, 1710.02140

Take a hidden gauge group G (we take SU(N)) and vectorlike fields Q, S in the fundamental.

Q is further charged under SM color.

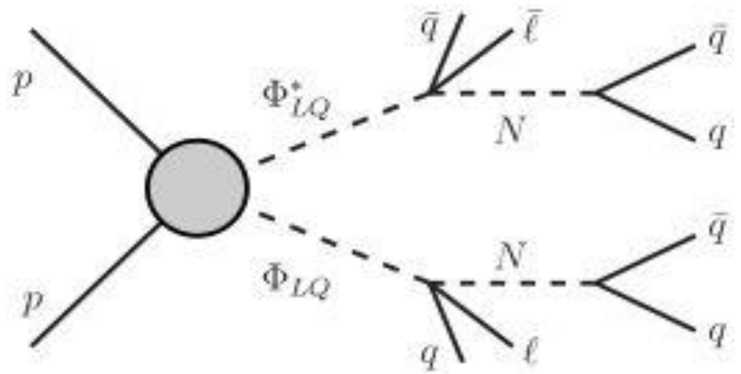
Once G confines, we get composite states (QS), (SS), (QQ).

Φ = (QS) is a leptoquark.

But now we have further states, in particular N = (SS), which is neutral under SM.

This opens up new possibilities for the leptoquark decay.

Composite leptoquarks



We assume there is an interaction

L = QSql

where q, l are SM fields.

This is required to generate the leptoquark interactions.

But it also produces a new leptoquark decay $\Phi \rightarrow$ Nql.

If the new decay dominates, then the leptoquark phenomenology is modified, and also depends on the dominant decay of the neutral state N.

We further consider the case when N decays to a dijet.

The pair produced leptoquarks then produce a signal of 2 leptons and 6 jets.

Composite leptoquarks

Note that we would probably expect the lowest mass leptoquark to be a scalar, rather than the apparently preferred (for the B-anomalies) vector leptoquark.

For the LHC analysis it doesn’t make much difference.

Composite leptoquarks: LHC Constraints

Current bounds on this scenario come from a variety of searches at the LHC:

(a) second generation leptoquark searches

(b) third generation leptoquark searches

(c) R-parity violating searches: can have large number of jets

(d) Dijet resonances: relevant if the lepton is missed, which can happen since the lepton can be soft if the mass differences are small. The two neutral states can then be seen as a paired dijet resonance.

Composite leptoquarks: LHC Constraints

A previous set of authors had set up a system to compare signals from new models to ATLAS and CMS results (Asadi, Buckley, DiFranzo, Monteux, Shih).

This is an application of the maximum likelihood method.

For each bin in the published results, suppose the background is B, the error is e, and the signal contribution is s. The observed number is O.

The likelihood would then be usually $P(O|\ s+B)$, where this is a Poisson distribution.

Instead we take the true background to be B+b, where b is chosen to maximize
$L = P(O|\ s+B+b)\ \exp(-(b/e)^2)$.

Then calculate the -2(log likelihood ratio) for the cases with signal and no signal.

The total log likelihood is then required to be less than 4.

This was used to set bounds on our model.

Composite leptoquarks: New constraints

As expected, leptoquark bounds are weakened.

If the leptoquark and neutral state are quasi-degenerate, the leptons are soft and easily missed.

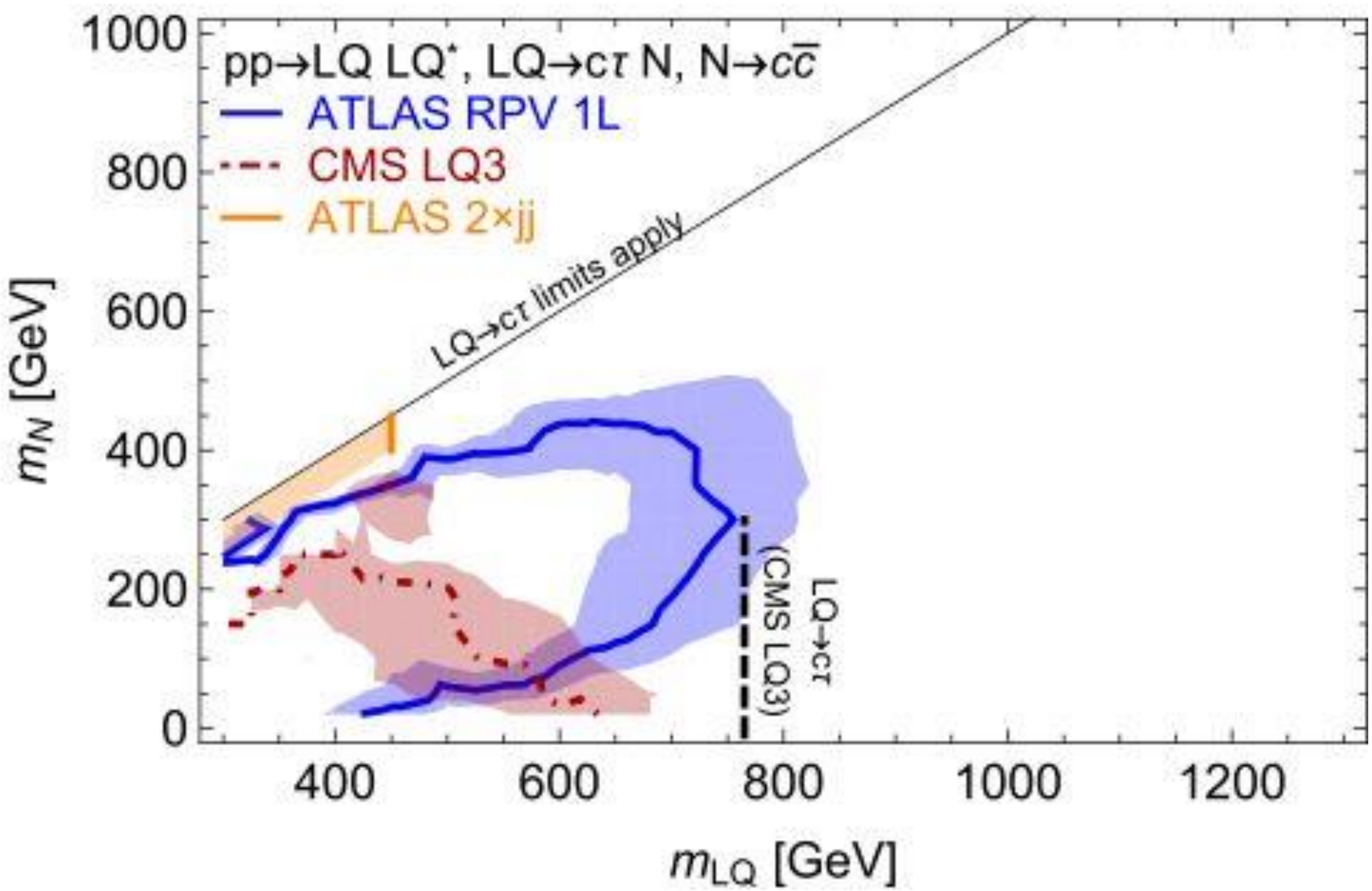
If the leptoquark is much heavier than the neutral state, the decay products are boosted and the isolation cuts can remove the leptons.

The bounds also depend on the branching ratios of the two leptoquark decays $\Phi \to Nql$ and $\Phi \to ql$.

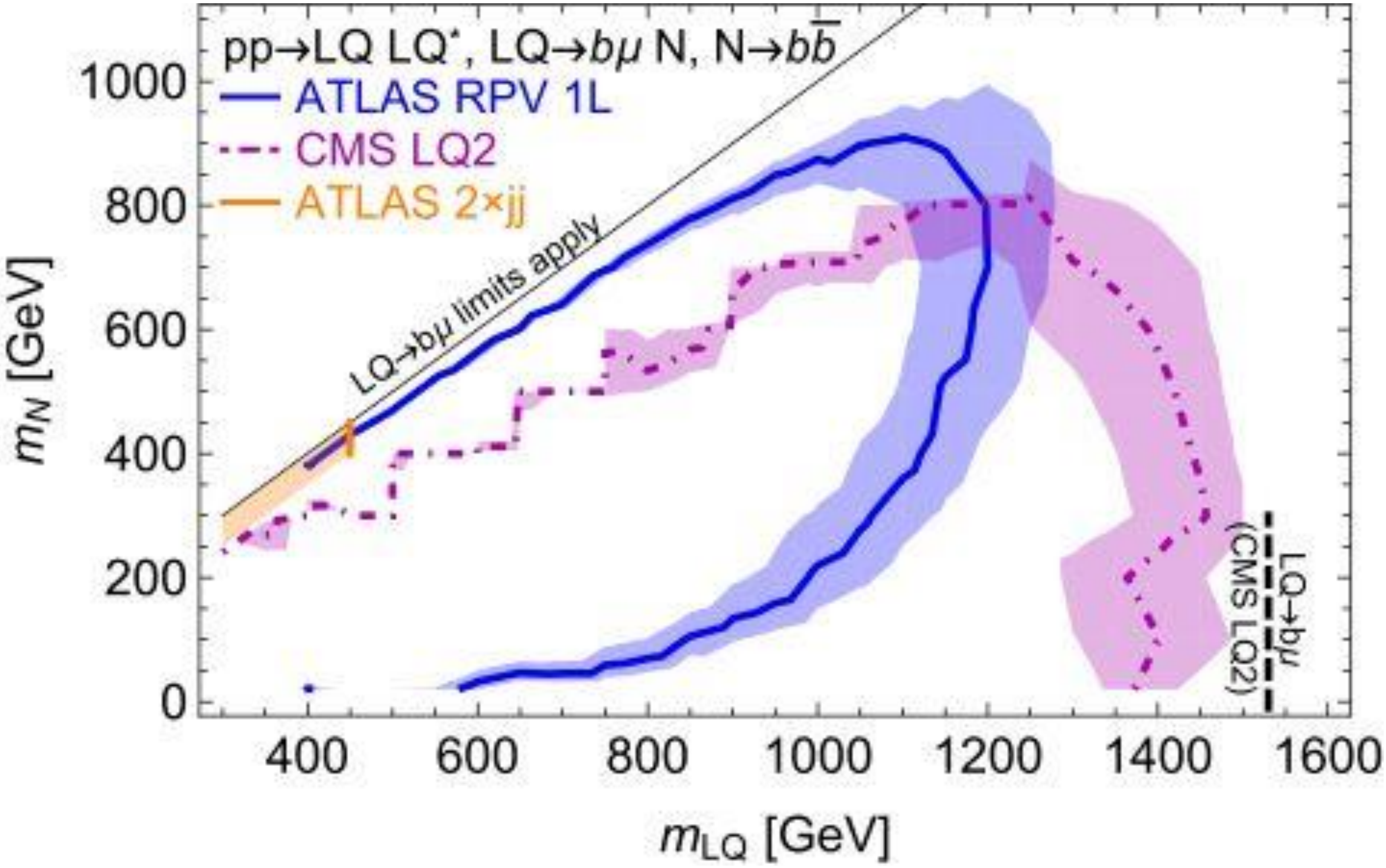
These effects are much more pronounced for the decays involving taus.

In principle, such leptoquarks could be as light as ~500 GeV.

Composite leptoquarks: New constraints

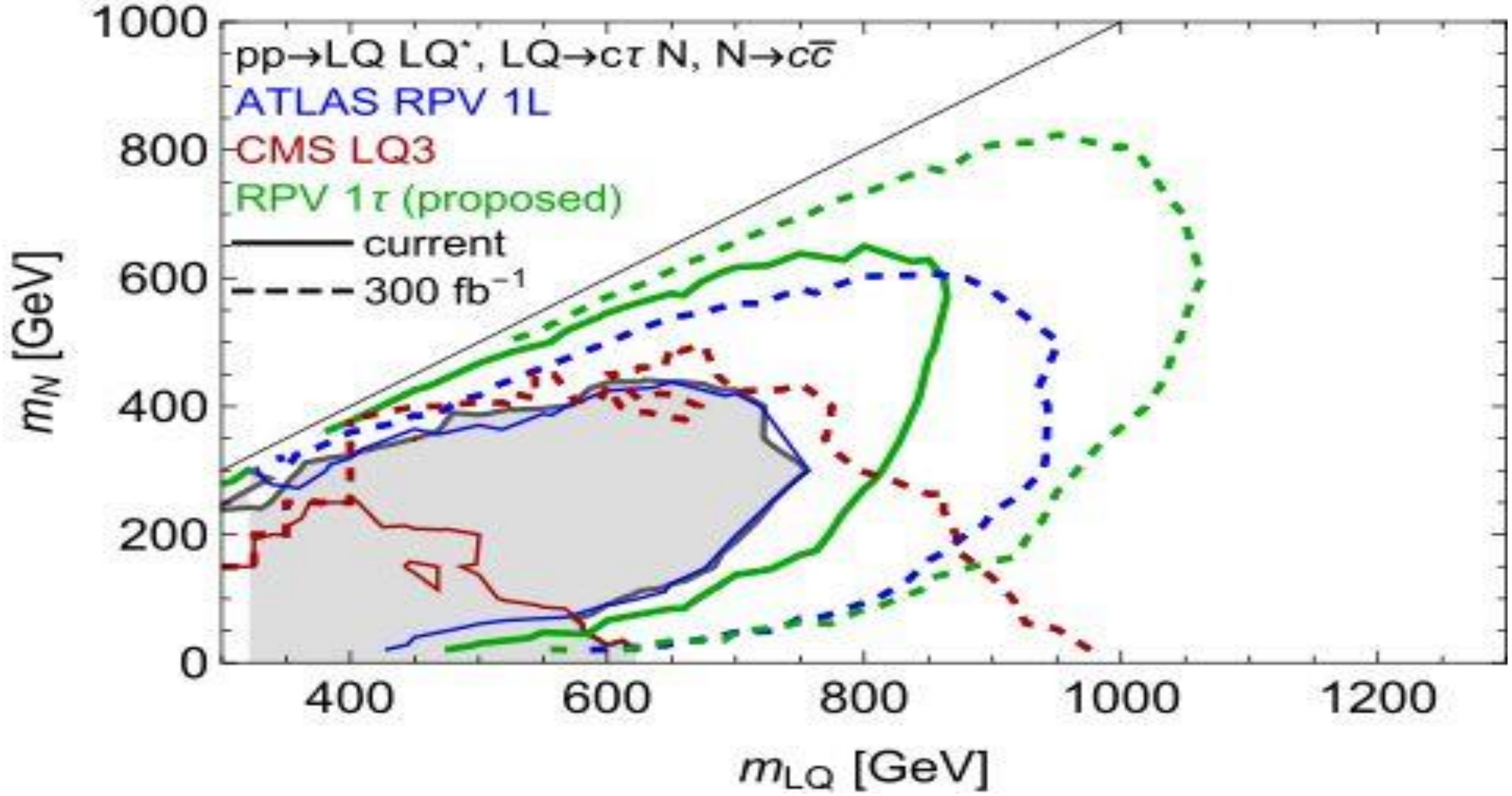


Composite leptoquarks: New constraints



Composite leptoquarks: future constraints

Further searches at the LHC will cut into much of the parameter space



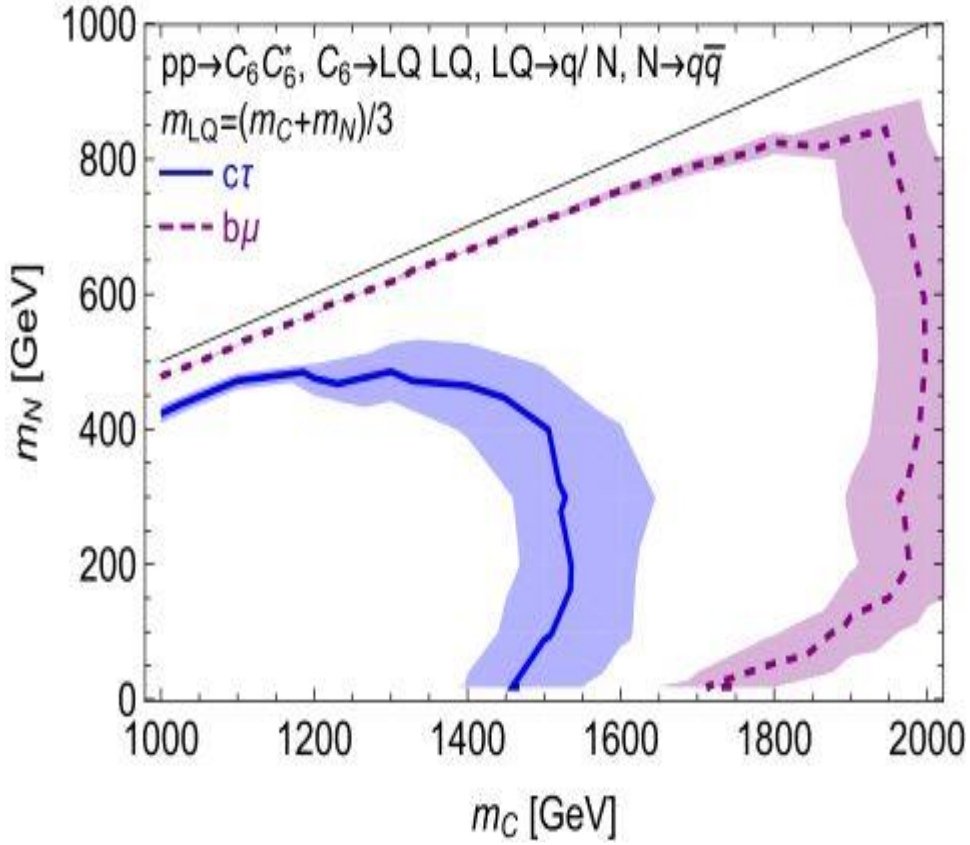
Composite leptoquarks: New signals

There can also be new signals from this sector.

For instance, there are new colored objects, the composite states (QQ). These can be pair produced, and in suitable models, they can each decay to a pair of leptoquarks.

This leads to a signal with 4 leptons and 12 jets.

This striking signal is already constrained (by lepton plus jet searches) but dedicated searches could improve the reach.



Composite leptoquarks: New searches

We could improve bounds on composite leptoquarks even further by a dedicated search. Currently the strongest bounds in a significant part of parameter space comes from the leptoquark search. This only requires two jets. Imposing the requirement of having more jets would improve the reach.

Similarly the RPV search requires only one lepton. Requiring two leptons would again significantly improve the reach.

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Conclusions

The anomalies in B-meson decays motivate leptoquarks.

Naturalness, proton decay, and LHC bounds motivate composite leptoquarks.

These are typically accompanied by new states, which modify the phenomenology of leptoquarks.

Bounds on composite leptoquarks can be significantly weaker; leptoquark masses can be as low as ~500 GeV.

New dedicated searches could constrain or discover these models, even with current data.