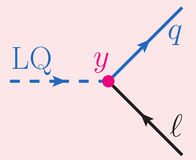
Scalar Leptoquark Pair Production at Hadron Colliders

Christoph Borschensky *in collaboration with Benjamin Fuks, Anna Kulesza, Daniel Schwartländer*

Eberhard Karls Universität Tübingen

Motivation

Scalar leptoquarks at the LHC



- Scalar leptoquarks (LQs) are hypothetical bosonic particles coupling to both leptons and quarks; they appear in Grand Unified Theories (e.g. SU(5)) as well as many Standard Model extensions (e.g. RPV SUSY).
- Recently, flavour anomalies have led to renewed interest in scalar LQs, as they can reduce or even remove tension between theory and experiment.
- Current exclusion limits for LQ masses are in between 1.2 – 1.8 TeV (depending on the generation).
- Scalar LQs are colour-charged and lie in the fundamental representation of $SU(3)_C$.
- They can therefore be copiously produced at hadron colliders such as the LHC (similar to $\tilde{t}\tilde{t}^*$ production in the MSSM) and QCD corrections can be sizeable.

Models and benchmarks

- The Lagrangian for scalar LQ interactions consists of the following terms:

$$\mathcal{L}_{\text{LQ}} = \text{scalar QCD interactions} + y_1^{RR}\,\bar{u}_R^c\,\ell_R\,S_1^\dagger + y_1^{LL}\,(\bar{Q}_L^c\cdot L_L)\,S_1^\dagger + \tilde{y}_1^{RR}\,\bar{d}_R^c\,\ell_R\,\tilde{S}_1^\dagger + y_2^{LR}\,\bar{e}_R\,Q_L\,R_2^\dagger + y_2^{RL}\,\bar{u}_R\,(L_L\cdot R_2) + \tilde{y}_2^{RL}\,\bar{d}_R\,(L_L\cdot\tilde{R}_2) + y_3^{LL}\,(\bar{Q}_L^c\cdot\sigma_k\,L_L)\,(S_3^k)^\dagger + \text{h.c.}$$

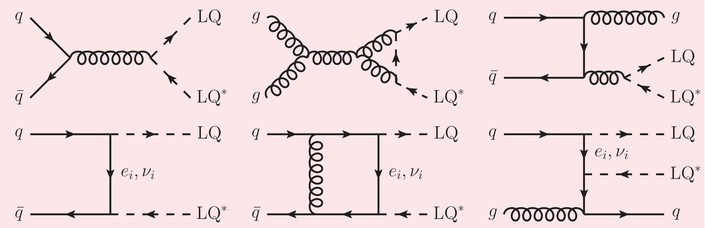
with the different LQ fields

$$S_1 = S_1^{(-1/3)},\ \tilde{S}_1 = \tilde{S}_1^{(-4/3)},\ R_2 = \begin{pmatrix} R_2^{(+5/3)} \\ R_2^{(+2/3)} \end{pmatrix},\ \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{(+2/3)} \\ \tilde{R}_2^{(-1/3)} \end{pmatrix},\ S_3 = \frac{1}{\sqrt{2}}\sigma_k S_3^k = \begin{pmatrix} \frac{1}{\sqrt{2}}S_3^{(-1/3)} & S_3^{(+2/3)} \\ S_3^{(-4/3)} & -\frac{1}{\sqrt{2}}S_3^{(-1/3)} \end{pmatrix}.$$

- We consider benchmark scenarios with one or more types of these fields, as required by a simultaneous solution of the flavour anomalies $R_{K^{(*)}}$ and $R_{D^{(*)}}$: R_2 only (***a***), $R_2 + S_3$ (***b***), $S_1 + S_3$ (***c***).
- For these benchmarks, only certain Yukawa couplings are set to values other than zero.

Theoretical calculations

NLO & *t*-channel contributions



- Real and virtual α_s corrections have been calculated. With large y, t-channel lepton exchange contributions become relevant.
- A power counting of the coupling orders up to NLO-QCD leads to:

$\sigma^{\text{NLO w/ } t\text{-channel}} =$	$\sigma^{(0)}$	+	$\sigma^{(1)}$
(*QCD*):	$\mathcal{O}(\alpha_s^2)$		$\mathcal{O}(\alpha_s^3)$;
(*t-channel*):	$\mathcal{O}(y^4)$		$\mathcal{O}(y^4\alpha_s)$;
(*interference*):	$\mathcal{O}(y^2\alpha_s)$		$\mathcal{O}(y^2\alpha_s^2)$

Soft-gluon resummation

- Heavy LQs with mass m_{LQ} are often produced close to their production threshold $S \sim 4m_{\text{LQ}}^2$; the partonic threshold region $\hat{s} \sim 4m_{\text{LQ}}^2$ then defines the major contribution. The threshold limit is thus:

$$\beta \equiv \sqrt{1 - \frac{4m_{\text{LQ}}^2}{\hat{s}}} \to 0$$

- In this limit, phase space is heavily constrained, forcing higher-order gluon radiation to be soft, which leads to logs $\ln\beta$ to become large.
- Then, soft terms factorise and can be resummed to all orders:

$$\tilde{\sigma}_{ij\to \text{LQ}\,\text{LQ}^*}^{\text{res,NNLL}} = \sum_{\text{colours } I} \tilde{\sigma}_{ij\to \text{LQ}\,\text{LQ}^*,I}^{(0)}(N) \times \Delta_i\Delta_j\Delta_I^S(N+1) \times \mathcal{C}_{ij\to \text{LQ}\,\text{LQ}^*,I}(N)$$

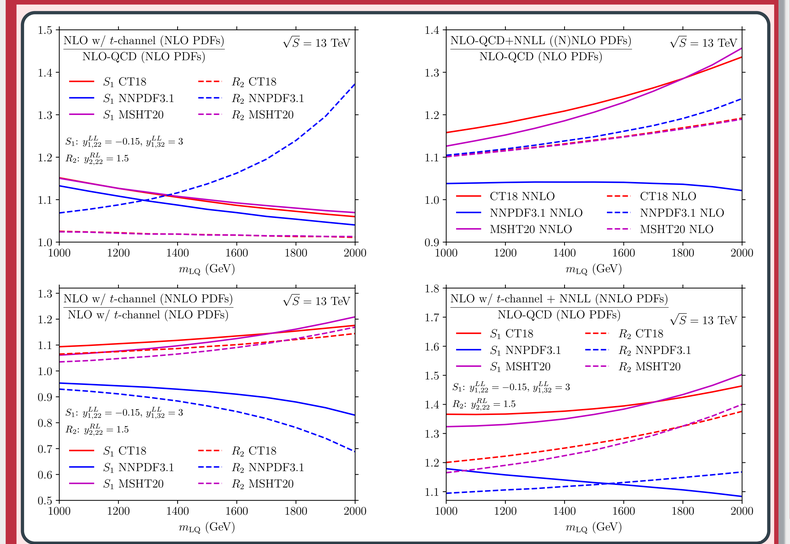
- The functions given in Mellin space, $\tilde{f}(N) := \int_0^1 \mathrm{d}x\, x^{N-1} f(x)$, are:
  - $\tilde{\sigma}_{ij\to \text{LQ}\,\text{LQ}^*,I}^{(0)}(N)$: Born cross section for partons i, j,
  - $\Delta_i\Delta_j\Delta_I^S(N+1)$: resummed soft-collinear & soft wide-angle terms,
  - $\mathcal{C}_{ij\to \text{LQ}\,\text{LQ}^*,I}(N)$: hard-matching coefficient.
- The NNLL cross section is then matched to the NLO result.

Numerical setup

- The numerical evaluation is done with two independent implementations in MadGraph5_aMC@NLO and the POWHEG-BOX.
- Three PDF sets are employed: CT18, NNPDF3.1, MSHT20; using NLO (NNLO) sets for NLO (NLO + NNLL) predictions.
- The central renormalisation and factorisation scale is set to $\mu_R = \mu_F = m_{\text{LQ}}$. The uncertainty is determined via the 7-point method.

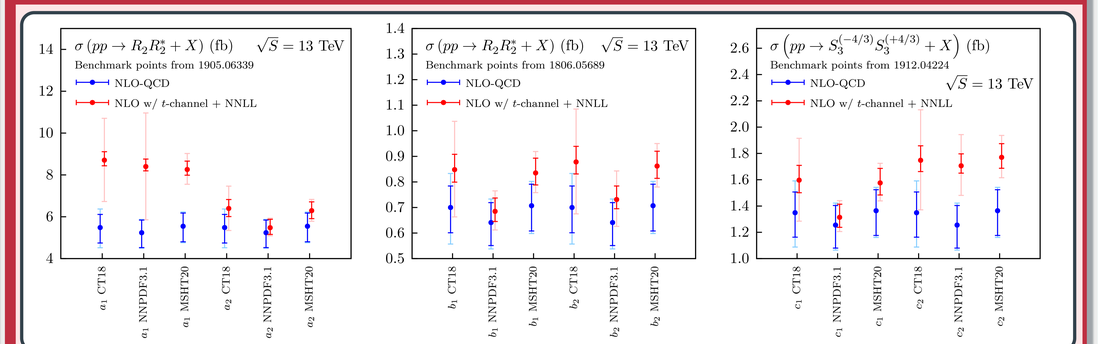
Results: precision predictions

Individual contributions



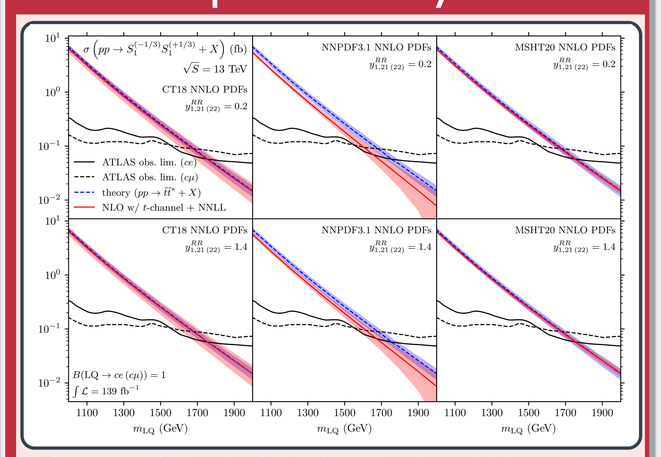
- t-channel, soft-gluon, and PDF effects are of similar size, $\mathcal{O}(10\%)$.
- The best prediction can be influenced in contrasting ways; thus, for a reliable prediction, *all terms need to be taken into account*.

Predictions for benchmark scenarios



- For a selection of points from the benchmark scenarios (***a***), (***b***), (***c***), NLO-QCD and NLO w/ t-channel + NNLL predictions are shown. Dark (light) error bars correspond to scale (scale and PDF) uncertainties.
- NNLL contributions greatly improve the scale uncertainty, while PDF uncertainties grow when switching to NNLO PDFs, except for the most recent MSHT20 set.
- For some points, the NLO-QCD and NLO w/ t-channel + NNLL results do not agree within their errors.

Impact on analysis



- Shown are the ATLAS limits from arXiv:2006.05872, where a simple S_1 model with only one decay mode is studied.
- Our best predictions with a small ($y_{1,2k}^{RR} = 0.2$) and larger ($y_{1,2k}^{RR} = 1.4$) Yukawa coupling are overlayed.
- The exclusion limits can be lowered by more than 50 GeV. Additional non-zero couplings could lead to bigger effects.

References

- C. Borschensky, B. Fuks, A. Kulesza, D. Schwartländer, arXiv:210x.xxxxx (*in preparation to be submitted*)
- C. Borschensky, B. Fuks, A. Kulesza, D. Schwartländer, PRD 101 (2020) 11, 115017