Scalar Leptoquark Pair Production at Hadron Colliders

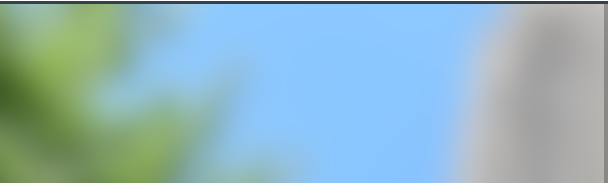
Christoph Borschensky

christoph.borschensky at uni-tuebingen dot de

Eberhard Karls Universität Tübingen

Based on **Phys. Rev. D 101, 115017** and work in progress

in collaboration with **Benjamin Fuks**, **Anna Kulesza**, and **Daniel Schwartländer**



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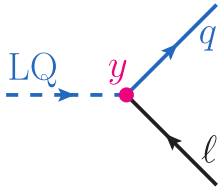
Motivation

Scalar leptoquarks: coupling to both leptons and quarks

- Appearing in many BSM models (e.g. RPV SUSY, SU(5) GUTs)
- Relevant for B-physics anomalies (e.g. LFU violation for $B \to D l \bar{\nu}$)



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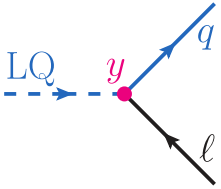
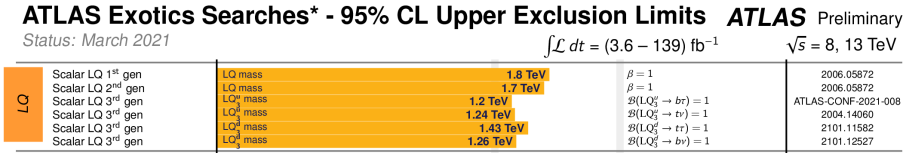


Leptoquark pair-production $pp \to \mathrm{LQ}\,\mathrm{LQ}^* + X$ at a hadron collider



- Coloured under SU(3) and therefore copiously produced at the LHC, QCD corrections can be sizeable
- Similar to stop-antistop production in the MSSM

Theoretical status:

- NLO-QCD *[Krämer, Plehn, Spira, Zerwas '97, '05]*
- NLO-QCD + PS (MG5_aMC@NLO) *[Mandal, Mitra, Seth '16][Doršner, Greljo '18]*
- Only pure QCD effects so far

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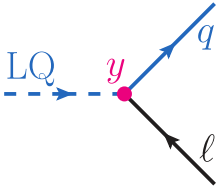

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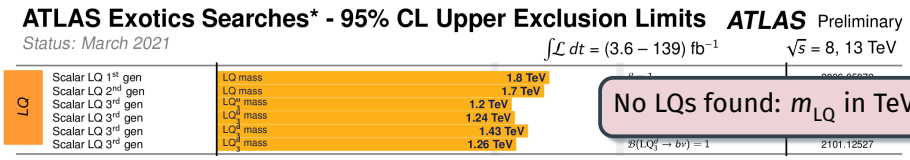

No LQs found: m_{LQ} in TeV range

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Leptoquark species and lepton-exchange contributions

Simplified model with different species of LQs:

$$
\begin{aligned}
\mathcal{L}_{\text{int}} \;=\;& \text{scalar QCD interactions} \\
&+\; y_1^{RR}\,\bar{u}_R^c\,\ell_R\,S_1^\dagger \;+\; y_1^{LL}\left(\bar{Q}_L^c\cdot L_L\right)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\left(L_L\cdot R_2\right) \;+\; \tilde{y}_2^{RL}\,\bar{d}_R\left(L_L\cdot \tilde{R}_2\right) \\
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with the 3 Pauli matrices σ_k and the components of the fields given as mass eigenstates:

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S_1 = S_1^{(-1/3)},\quad \tilde{S}_1 = \tilde{S}_1^{(-4/3)},\quad R_2 = \begin{pmatrix} R_2^{(+5/3)} \\ R_2^{(+2/3)} \end{pmatrix},\quad \tilde{R}_2 = \begin{pmatrix} \tilde{R}_2^{(+2/3)} \\ \tilde{R}_2^{(-1/3)} \end{pmatrix},\quad 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}
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and the 3 × 3 Yukawa matrices in flavour space y_1^{RR}, y_1^{LL}, y_2^{LR}, y_2^{RL}, $\tilde{y}_2^{RL}$, y_3^{LL} ($y_{n,ij}^{AB}$: i: quark, j: lepton gen. index)

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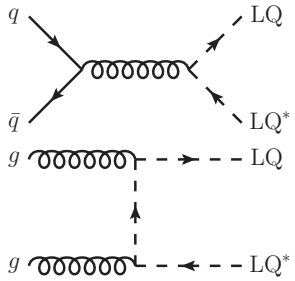

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Coupling orders of cross section at tree level: $\mathcal{O}(\alpha_s^2)$

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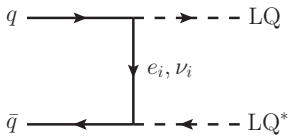

“t-channel contributions”

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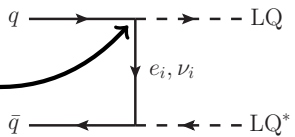
+ $y_1^{RR}\,\bar{u}$ [illegible]

+ $y_2^{LR}\,\bar{e}_R Q_L R_2 + y_2 \cdots u_R (\bar{L}_L \cdots R_2) + y_2 \cdots u_R (\bar{L}_L \cdots R_2)$

+ $y_3^{LL}\left(\bar{Q}_L^c \cdot \sigma_k L_L\right)(S_3^k)^\dagger$ + h.c.

Strong constraints from atomic parity violation for 1st gen. couplings *[Doršner, Fajfer, Greljo '14]*



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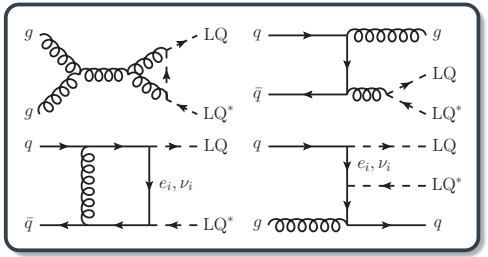
Leptoquark pair production at NLO-QCD

NLO-QCD corrections calculated from scratch

- Full NLO-QCD corrections $\mathcal{O}(\alpha_s^3, \alpha_s^2 y^2, \alpha_s y^4)$
- t-channel contributions & interferences with QCD diagrams included consistently
- $\overline{\text{MS}}$ scheme used for masses and couplings
- UV & IR finiteness ✓
- No parton showers for now



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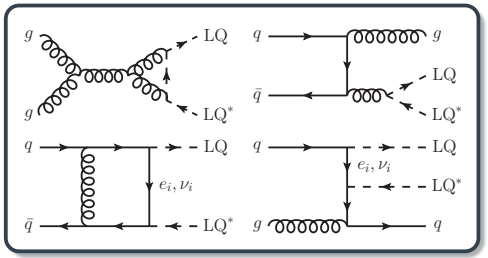


MadGraph5_aMC@NLO
[Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14]

- Model implemented into FeynRules [Alloul, Christensen, Degrande, Duhr, Fuks '14]
- Renormalisation with NLOCT & FeynArts [Degrande '15]
- Generation of UFO model file for evaluation of fixed-order predictions

POWHEG-BOX
[Alioli, Nason, Oleari, Re '10]

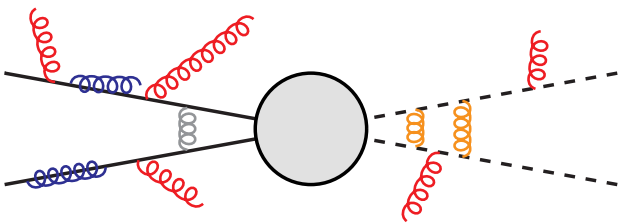
- Virtual corrections calculated with FeynArts, FormCalc, Collier [Hahn, Perez-Victoria '98-'00][Denner, Dittmaier, Hofer '17]
- Real corrections generated with MG4 [Murayama et al., Stelzer et al., Alwall et al. '92-'07]
- Modded to add coloured BSM particles

Independent implementations: very good agreement between the two codes

Soft-gluon resummation

Threshold region $\sqrt{\hat{s}} \to 2m_{\mathrm{LQ}}$ increasingly relevant ($\sqrt{\hat{s}}$: partonic centre-of-mass energy)

- Enhanced logs $\ln \beta^2$ with $\beta^2 \equiv 1 - 4m_{\mathrm{LQ}}^2/\hat{s} \to 0$ stemming from soft-gluon emission



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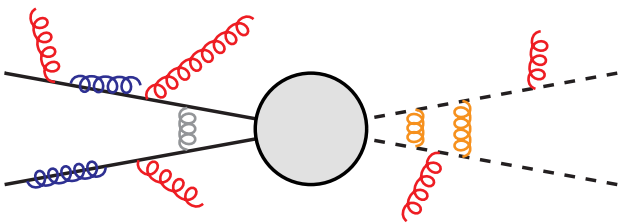
$$\tilde{\sigma}^{(\mathrm{resum})}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*} = \sum_{\text{colours } I} H^{(N)}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*,I} \times \Delta_i^{(N)} \Delta_j^{(N)} \times S^{(N)}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*,I}$$

i, j: partons



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with

- $H_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*,I}^{(N)}$: matching coefficient (hard & Coulomb-gluon contributions)
- $\Delta_i^{(N)}$, $S_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*,I}^{(N)}$: resummed logs from soft-collinear and soft wide-angle radiation

Approximate non-enhanced hard contributions by corresponding $\tilde{t}\tilde{t}^*$ terms

[Broggio, Ferroglia, Neubert, Vernazza, Yang '13][Beenakker, CB, Heger, Krämer, Kulesza, Laenen '16]

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Factorisation leads to exponentiation and thus all-order resummation of threshold logs

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$$\Delta_i^{(N)} \Delta_j^{(N)} S_{ij\to kl,I}^{(N)} = \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

[Kodaira, Trentadue '82][Sterman '87][Catani, D'Emilio, Trentadue '88][Catani, Trentadue '89][Kidonakis, Sterman '96]
[Kidonakis, Oderda, Sterman '98][Contopanagos, Laenen, Sterman '96][Catani, de Florian, Grazzini '01]
[Moch, Vermaseren, Vogt '04][Beneke, Falgari, Schwinn '09][Czakon, Mitov, Sterman '09][Ferroglia, Neubert, Pecjak, Yang '09] ...

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NLL

NNLL

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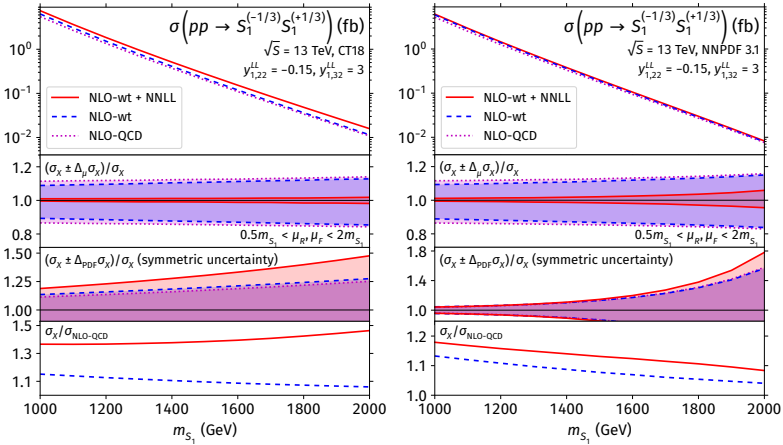
Inverse Mellin transform applying the minimal prescription, matching to NLO:
[Catani, Mangano, Nason, Trentadue '96]

$$\sigma^{\mathrm{NLO}}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*} + \int_{\mathrm{CT}} dN\,(\ldots)\,\tilde{\sigma}^{(\mathrm{resum})}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*}\Big|_{>\mathrm{NLO}} \longrightarrow \sigma^{\mathrm{NLO+NNLL}}_{ij\to \mathrm{LQ}\,\mathrm{LQ}^*}$$

Total cross sections at NLO with t-channel + NNLL

Setup

- CT18 & NNPDF3.1 PDF sets
- "NLO-wt": NLO-QCD with t-channel contributions
- "+ NNLL": with soft-gluon resummation (NNLO PDFs)
- Scale choice $\mu_R = \mu_F$, $\mu_0 = m_{\mathrm{LQ}}$



Benchmarks motivated by *[Angelescu, Bečirević, Faroughy, Sumensari '18]*

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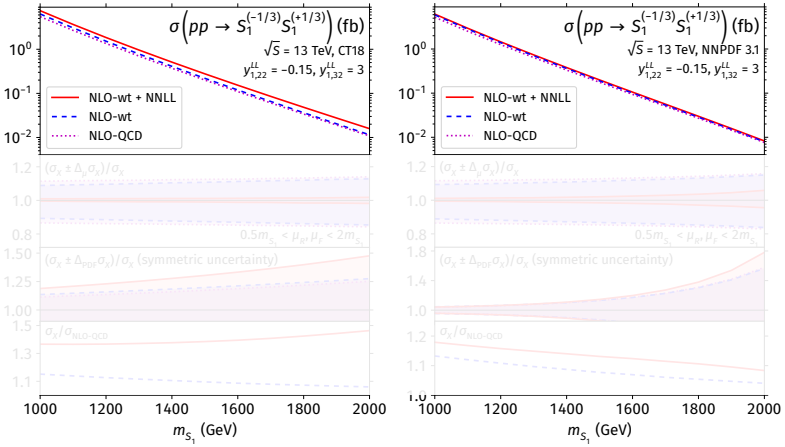
- "NLO-wt": NLO-QCD with t-channel contributions
- "+ NNLL": with soft-gluon resummation (NNLO PDFs)
- Scale choice $\mu_R = \mu_F$, $\mu_0 = m_{\mathrm{LQ}}$

Results

- Positive effects and decreased scale uncertainty for NNLL
- Mild effects for "wt"
- Large m_{LQ}: PDF error dominates
- K-factor strongly dependent on PDF set



Benchmarks motivated by *[Angelescu, Bečirević, Faroughy, Sumensari '18]*

Total cross sections at NLO with t-channel + NNLL

Setup

- CT18 & NNPDF3.1 PDF sets
- "NLO-wt": NLO-QCD with t-channel contributions
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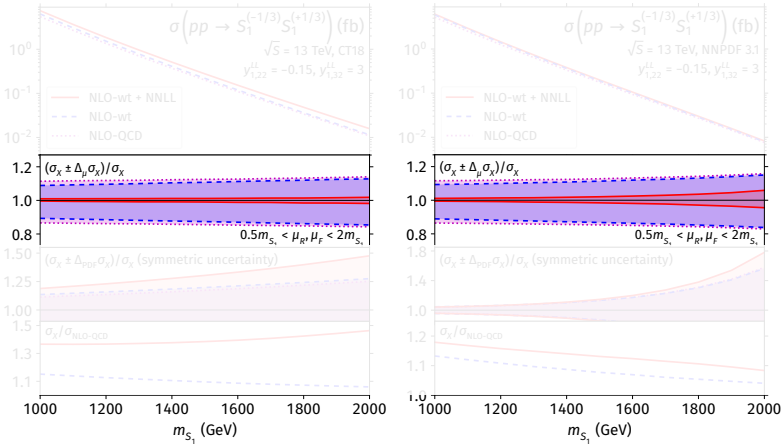

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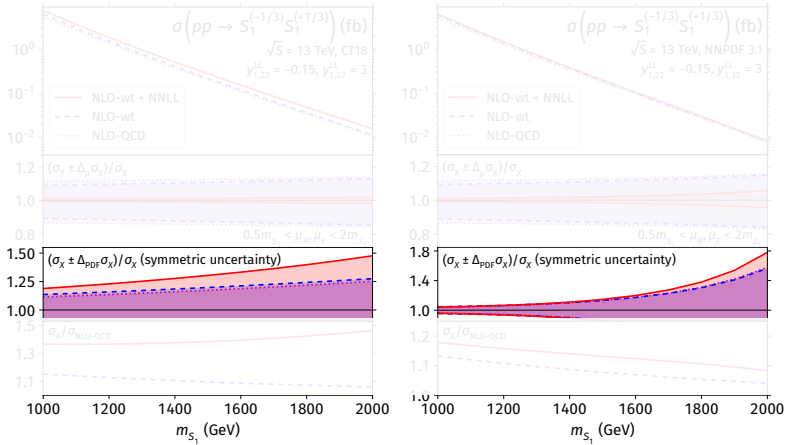

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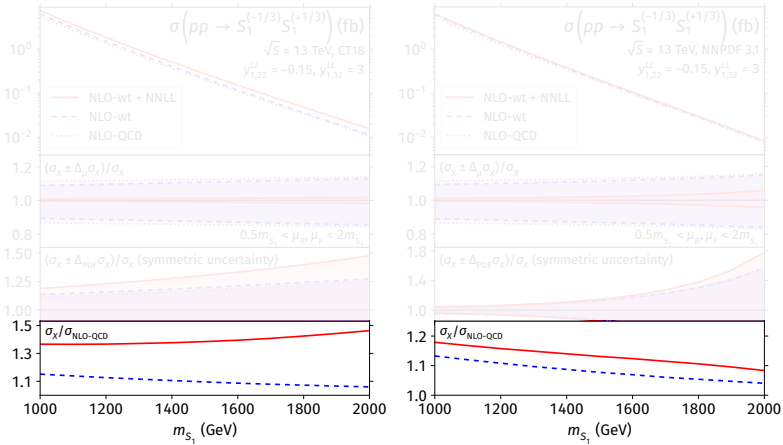
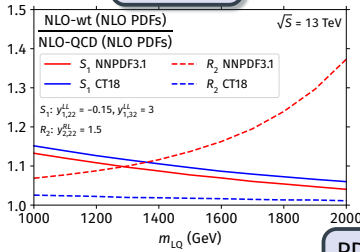


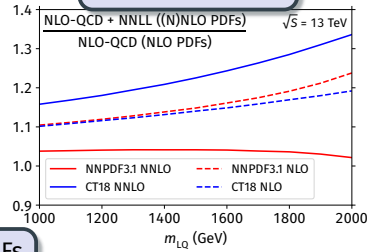
Benchmarks motivated by *[Angelescu, Bečirević, Faroughy, Sumensari '18]*

Relative importance of the different effects

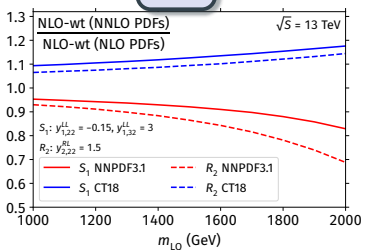
t-channel



Soft-gluon effects



PDFs



Analysis

- S_1 & R_2 production

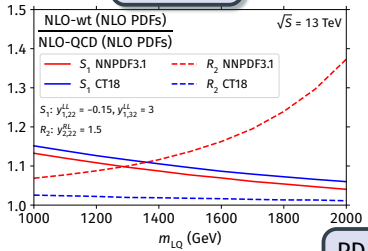
Benchmarks motivated by

[Angelescu, Bečirević, Faroughy, Sumensari '18]

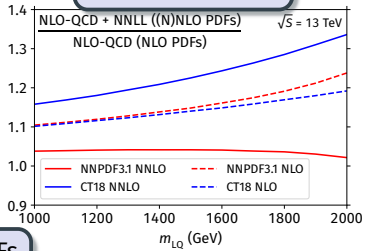
PRELIMINARY

Relative importance of the different effects

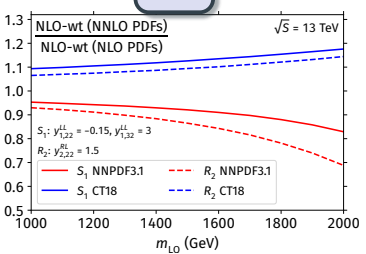
t-channel



Soft-gluon effects



PDFs



Benchmarks motivated by

[Angelescu, Bečirević, Faroughy, Sumensari '18]

PRELIMINARY

Analysis

- S_1 & R_2 production
- Effects strongly dependent on LQ final state and PDF set
- Corrections of similar size
- Influence the results in often constrasting ways

Results for different benchmark points

Benchmark scenarios

a_i: R_2 model with m_{R_2} = 1 TeV
[Popov, Schmidt, White '19]

b_i: S_1 & S_3 model with $m_{S_1} = m_{S_3}$ = 1.2 TeV
[Crivellin, Müller, Saturnino '20]

c_i: R_2 & S_3 model with m_{S_1} = 1.3 TeV and m_{S_3} = 2 TeV
[Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari '18]

- Points in allowed range to simultaneously describe flavour anomalies like $R_{D^{(*)}}$ and $R_{K^{(*)}}$
- From very mild to moderately strong effects

B	LQ	PDF	NLO-QCD (fb)	NLO-wt (fb)	NNLL-wt (fb)	K_{wt}	K_{NNLL}
a_1	$R_2^{(+5/3)}$	CT18	$5.485^{+11.4\%+11.4\%}_{-13.5\%-11.4\%}$	$6.909^{+7.7\%+15.5\%}_{-9.8\%-15.5\%}$	$8.704^{+4.7\%+22.5\%}_{-3.1\%-22.5\%}$	1.26	1.59
		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$8.921^{+4.3\%+28.0\%}_{-6.3\%-28.0\%}$	$8.401^{+4.3\%+30.2\%}_{-2.5\%-30.2\%}$	1.70	1.60
a_2	$R_2^{(+5/3)}$	CT18	$5.485^{+11.4\%+11.4\%}_{-13.5\%-11.4\%}$	$5.498^{+11.5\%+11.5\%}_{-13.4\%-11.5\%}$	$6.391^{+6.6\%+15.3\%}_{-6.0\%-15.3\%}$	1.00	1.17
		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$5.283^{+11.5\%+4.0\%}_{-13.2\%-4.0\%}$	$5.475^{+7.1\%+3.9\%}_{-6.0\%-3.9\%}$	1.01	1.05
b_1	$S_3^{(-4/3)}$	CT18	$1.351^{+11.8\%+13.6\%}_{-13.8\%-13.6\%}$	$1.349^{+11.7\%+13.6\%}_{-13.9\%-13.6\%}$	$1.593^{+6.9\%+18.6\%}_{-6.0\%-18.6\%}$	1.00	1.18
		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.255^{+11.7\%+5.9\%}_{-14.2\%-5.9\%}$	$1.304^{+7.6\%+6.1\%}_{-5.9\%-6.1\%}$	1.00	1.04
b_2	$S_3^{(-4/3)}$	CT18	$1.351^{+11.8\%+13.6\%}_{-13.8\%-13.6\%}$	$1.494^{+9.9\%\ +16.2\%}_{-12.4\%-16.2\%}$	$1.748^{+6.3\%+21.0\%}_{-4.9\%-21.0\%}$	1.11	1.29
		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.570^{+8.3\%\ +11.7\%}_{-10.9\%-11.7\%}$	$1.706^{+5.3\%+12.8\%}_{-3.3\%-12.8\%}$	1.25	1.36
c_1	R_2	CT18	$0.700^{+12.0\%+14.8\%}_{-14.0\%-14.8\%}$	$0.705^{+11.7\%+15.0\%}_{-14.0\%-15.0\%}$	$0.846^{+7.0\%+21.0\%}_{-5.8\%-21.0\%}$	1.01	1.21
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c_2	R_2	CT18	$0.700^{+12.0\%+14.8\%}_{-14.0\%-14.8\%}$	$0.720^{+11.5\%+15.6\%}_{-13.5\%-15.6\%}$	$0.877^{+6.6\%+22.5\%}_{-5.6\%-22.5\%}$	1.03	1.25
		NNPDF3.1	$0.641^{+12.1\%+7.6\%}_{-14.1\%-7.6\%}$	$0.733^{+9.9\%\ +12.9\%}_{-11.7\%-12.9\%}$	$0.730^{+7.3\%+13.5\%}_{-4.9\%-13.5\%}$	1.14	1.14

- First scale, then PDF uncertainty
- NNLL-wt = NLO-wt + NNLL
- K_{wt} = NLO-wt/NLO-QCD
- K_{NNLL} = NNLL-wt/NLO-QCD

PRELIMINARY

Results for different benchmark points

Benchmark scenarios

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[Popov, Schmidt, White '19]

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c_i: R_2 & S_3 model with m_{S_1} = 1.3 TeV and m_{S_3} = 2 TeV
[Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari '18]

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		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$8.921^{+4.3\%+28.0\%}_{-6.3\%-28.0\%}$	$8.401^{+4.3\%+30.2\%}_{-2.5\%-30.2\%}$	1.70	1.60
a_2	$R_2^{(+5/3)}$	CT18	$5.485^{+11.4\%+11.4\%}_{-13.5\%-11.4\%}$	$5.498^{+11.5\%+11.5\%}_{-13.4\%-11.5\%}$	$6.391^{+6.6\%+15.3\%}_{-6.0\%-15.3\%}$	1.00	1.17
		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$5.283^{+11.5\%+4.0\%}_{-13.2\%-4.0\%}$	$5.475^{+7.1\%+3.9\%}_{-6.0\%-3.9\%}$	1.01	1.05
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		NNPDF3.1	$0.641^{+12.1\%+7.6\%}_{-14.1\%-7.6\%}$	$0.664^{+11.4\%+8.2\%}_{-13.5\%-8.2\%}$	$0.683^{+7.8\%+8.9\%}_{-5.6\%-8.9\%}$	1.04	1.07
c_2	R_2	CT18	$0.700^{+12.0\%+14.8\%}_{-14.0\%-14.8\%}$	$0.720^{+11.5\%+15.6\%}_{-13.5\%-15.6\%}$	$0.877^{+6.6\%+22.5\%}_{-5.6\%-22.5\%}$	1.03	1.25
		NNPDF3.1	$0.641^{+12.1\%+7.6\%}_{-14.1\%-7.6\%}$	$0.733^{+9.9\%\ +12.9\%}_{-11.7\%-12.9\%}$	$0.730^{+7.3\%+13.5\%}_{-4.9\%-13.5\%}$	1.14	1.14

- First scale, then PDF uncertainty
- NNLL-wt = NLO-wt + NNLL
- K_{wt} = NLO-wt/NLO-QCD
- K_{NNLL} = NNLL-wt/NLO-QCD

PRELIMINARY

Results for different benchmark points

Benchmark scenarios

a_i: R_2 model with m_{R_2} = 1 TeV
[Popov, Schmidt, White '19]

b_i: S_1 & S_3 model with $m_{S_1} = m_{S_3}$ = 1.2 TeV
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- First scale, then PDF uncertainty
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- K_{NNLL} = NNLL-wt/NLO-QCD

PRELIMINARY

Results for different benchmark points

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[Popov, Schmidt, White '19]

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		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.255^{+11.7\%+5.9\%}_{-14.2\%-5.9\%}$	$1.304^{+7.6\%+6.1\%}_{-5.9\%-6.1\%}$	1.00	1.04
b_2	$S_3^{(-4/3)}$	CT18	$1.351^{+11.8\%+13.6\%}_{-13.8\%-13.6\%}$	$1.494^{+9.9\%\ +16.2\%}_{-12.4\%-16.2\%}$	$1.748^{+6.3\%+21.0\%}_{-4.9\%-21.0\%}$	1.11	1.29
		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.570^{+8.3\%\ +11.7\%}_{-10.9\%-11.7\%}$	$1.706^{+5.3\%+12.8\%}_{-3.3\%-12.8\%}$	1.25	1.36
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- First scale, then PDF uncertainty
- NNLL-wt = NLO-wt + NNLL
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PRELIMINARY

Results for different benchmark points

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a_i: R_2 model with m_{R_2} = 1 TeV
[Popov, Schmidt, White '19]

b_i: S_1 & S_3 model with $m_{S_1} = m_{S_3}$ = 1.2 TeV
[Crivellin, Müller, Saturnino '20]

c_i: R_2 & S_3 model with m_{S_1} = 1.3 TeV and m_{S_3} = 2 TeV
[Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari '18]

- Points in allowed range to simultaneously describe flavour anomalies like $R_{D^{(*)}}$ and $R_{K^{(*)}}$
- From very mild to moderately strong effects

B	LQ	PDF	NLO-QCD (fb)	NLO-wt (fb)	NNLL-wt (fb)	K_{wt}	K_{NNLL}
a_1	$R_2^{(+5/3)}$	CT18	$5.485^{+11.4\%+11.4\%}_{-13.5\%-11.4\%}$	$6.909^{+7.7\%+15.5\%}_{-9.8\%-15.5\%}$	$8.704^{+4.7\%+22.5\%}_{-3.1\%-22.5\%}$	1.26	1.59
		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$8.921^{+4.3\%+28.0\%}_{-6.3\%-28.0\%}$	$8.401^{+4.3\%+30.2\%}_{-2.5\%-30.2\%}$	1.70	1.60
a_2	$R_2^{(+5/3)}$	CT18	$5.485^{+11.4\%+11.4\%}_{-13.5\%-11.4\%}$	$5.498^{+11.5\%+11.5\%}_{-13.4\%-11.5\%}$	$6.391^{+6.6\%+15.3\%}_{-6.0\%-15.3\%}$	1.00	1.17
		NNPDF3.1	$5.237^{+11.6\%+3.8\%}_{-13.6\%-3.8\%}$	$5.283^{+11.5\%+4.0\%}_{-13.2\%-4.0\%}$	$5.475^{+7.1\%+3.9\%}_{-6.0\%-3.9\%}$	1.01	1.05
b_1	$S_3^{(-4/3)}$	CT18	$1.351^{+11.8\%+13.6\%}_{-13.8\%-13.6\%}$	$1.349^{+11.7\%+13.6\%}_{-13.9\%-13.6\%}$	$1.593^{+6.9\%+18.6\%}_{-6.0\%-18.6\%}$	1.00	1.18
		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.255^{+11.7\%+5.9\%}_{-14.2\%-5.9\%}$	$1.304^{+7.6\%+6.1\%}_{-5.9\%-6.1\%}$	1.00	1.04
b_2	$S_3^{(-4/3)}$	CT18	$1.351^{+11.8\%+13.6\%}_{-13.8\%-13.6\%}$	$1.494^{+9.9\%\ +16.2\%}_{-12.4\%-16.2\%}$	$1.748^{+6.3\%+21.0\%}_{-4.9\%-21.0\%}$	1.11	1.29
		NNPDF3.1	$1.255^{+12.0\%+5.9\%}_{-14.0\%-5.9\%}$	$1.570^{+8.3\%\ +11.7\%}_{-10.9\%-11.7\%}$	$1.706^{+5.3\%+12.8\%}_{-3.3\%-12.8\%}$	1.25	1.36
c_1	R_2	CT18	$0.700^{+12.0\%+14.8\%}_{-14.0\%-14.8\%}$	$0.705^{+11.7\%+15.0\%}_{-14.0\%-15.0\%}$	$0.846^{+7.0\%+21.0\%}_{-5.8\%-21.0\%}$	1.01	1.21
		NNPDF3.1	$0.641^{+12.1\%+7.6\%}_{-14.1\%-7.6\%}$	$0.664^{+11.4\%+8.2\%}_{-13.5\%-8.2\%}$	$0.683^{+7.8\%+8.9\%}_{-5.6\%-8.9\%}$	1.04	1.07
c_2	R_2	CT18	$0.700^{+12.0\%+14.8\%}_{-14.0\%-14.8\%}$	$0.720^{+11.5\%+15.6\%}_{-13.5\%-15.6\%}$	$0.877^{+6.6\%+22.5\%}_{-5.6\%-22.5\%}$	1.03	1.25
		NNPDF3.1	$0.641^{+12.1\%+7.6\%}_{-14.1\%-7.6\%}$	$0.733^{+9.9\%\ +12.9\%}_{-11.7\%-12.9\%}$	$0.730^{+7.3\%+13.5\%}_{-4.9\%-13.5\%}$	1.14	1.14

- First scale, then PDF uncertainty
- NNLL-wt = NLO-wt + NNLL
- K_{wt} = NLO-wt/NLO-QCD
- K_{NNLL} = NNLL-wt/NLO-QCD

PRELIMINARY

Summary and conclusions

Precision calculations for scalar leptoquark pair production

Predictions at NLO with *t*-channel + NNLL

- Full NLO-QCD corrections including lepton-exchange contributions as well as soft-gluon resummation at NNLL calculated
- NLO-QCD + NNLL results already publicly available in **NNLL-fast** (link)

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- All effects of similar size, sometimes with opposite sign
- Cross sections moderately to strongly enhanced by these corrections wrt. NLO-QCD

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- ✍ Making the MG5_aMC@NLO models and POWHEG-BOX processes publicly available
- ✍ Impact on leptoquark mass exclusion limits

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Thank you for your Attention! ☺

Backup

Benchmark values for the leptoquark couplings

Model containing the R_2 leptoquark

B	$y^{RL}_{2,23}$	$y^{LR}_{2,33}$	$y^{LR}_{2,21}$	$y^{LR}_{2,31}$
a_1	1.84 + 1.84i	0.354 + 0.354i	−0.015i	0.262 + 0.262i
a_2	0.309 + 0.951i	0.951 + 0.309i	0.011 − 0.011i	0.37i

[Popov, Schmidt, White; 1905.06339]

Model containing the S_1 and S_3 leptoquarks

B	$y^{LL}_{1,22}$	$y^{LL}_{1,23}$	$y^{LL}_{1,32}$	$y^{LL}_{1,33}$	$y^{RR}_{1,23}$	$y^{RR}_{1,32}$	$y^{LL}_{3,22}$	$y^{LL}_{3,23}$	$y^{LL}_{3,32}$	$y^{LL}_{3,33}$
b_1	−0.0082	−1.46	−0.016	−0.064	1.34	−0.19	−0.019	0.58	−0.059	−0.11
b_2	0.0078	1.36	−0.055	0.052	−1.47	−0.053	−0.017	−1.23	−0.070	0.066

[Crivellin, Müller, Saturnino; 1912.04224]

Model containing the R_2 and S_3 leptoquarks

B	$y^{LR}_{2,33}$	$y^{RL}_{2,22}$	$y^{RL}_{2,23}$	$y^{LL}_{3,22}$	$y^{LL}_{3,23}$	$y^{LL}_{3,32}$	$y^{LL}_{3,33}$
c_1	−0.18734 + 1.12287i	0.265001	1.17382	−0.010	−0.045	−0.265	−1.173
c_2	−0.18734 + 1.12287i	0.37353	1.59511	−0.014	−0.061	−0.373	−1.594

[Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari; 1806.05689]