Precision Predictions for Scalar Leptoquark Pair Production at the LHC

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Outline

1 Motivation & Leptoquark Scenarios

2 Precision calculations

3 Numerical results for the LHC @ 13 TeV
Scalar leptoquarks

Scalar leptoquarks: coupling to both leptons and quarks
- Appearing in many BSM models (e.g. RPV SUSY, SU(5) GUTs)
- Relevant for B-physics flavour anomalies (e.g. LFUV for $B \rightarrow D^{(*)}\ell\bar{\nu}$)
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Leptoquark pair-production $pp \to LQ LQ' + X$ at a hadron collider

- Coloured and therefore copiously produced at the LHC, QCD corrections can be sizeable
- Similar to $\tilde{t}\tilde{t}^*$ production
- Increasingly relevant contributions from Yukawa couplings due to flavour anomalies
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No LQs found: $m_{LQ}$ limits in TeV range
Scalar leptoquarks: coupling to both leptons and quarks

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Leptoquark pair-production $pp \to LQ LQ^{(\dagger)} + X$ at a hadron collider

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Theoretical status of pair production:

- NLO-QCD [Krämer, Plehn, Spira, Zerwas '97, '05]
- NLO-QCD+PS [Mandal, Mitra, Seth '16][Doršner, Greljo '18]
- NLO+NNLL [CB, Fuks, Kulesza, Schwartländer '20-'22]
- LO “off-diagonal” [Doršner, Fajfer, Lejlić '21]
- NLO “(off-)diagonal” [CB, Fuks, Jueid, Kulesza '22]
Simplified model with different species of LQs:

\[ L_{\text{int}} = \text{scalar QCD interactions} \]

\[ + y_{1}^{RR} \bar{u}_{R}^{c} \ell_{R} S_{1}^{\dagger} + y_{1}^{LL} \left( \tilde{Q}_{L}^{c} \cdot L_{L} \right) S_{1}^{\dagger} + \tilde{y}_{1}^{RR} \bar{d}_{R}^{c} \ell_{R} \tilde{S}_{1}^{\dagger} \]

\[ + y_{2}^{LR} \bar{e}_{R} Q_{L} R_{2}^{\dagger} + y_{2}^{RL} \bar{u}_{R} \left( L_{L} \cdot R_{2} \right) + \tilde{y}_{2}^{RL} \bar{d}_{R} \left( L_{L} \cdot \tilde{R}_{2} \right) \]

\[ + y_{3}^{LL} \left( \tilde{Q}_{L}^{c} \cdot \sigma_{k} L_{L} \right) \left( S_{3}^{k} \right)^{\dagger} + h.c. \]

with the 3 Pauli matrices \( \sigma_{k} \), the component fields (mass eigenstates) with a specific electric charge:

\[ S_{1} = S_{1}^{(-1/3)}, \quad \tilde{S}_{1} = \tilde{S}_{1}^{(-4/3)}, \quad R_{2} = \begin{pmatrix} R_{2}^{(+5/3)} \\ R_{2}^{(+2/3)} \end{pmatrix}, \quad \tilde{R}_{2} = \begin{pmatrix} R_{2}^{(+2/3)} \\ R_{2}^{(-1/3)} \end{pmatrix}, \quad S_{3} = \frac{1}{\sqrt{2}} \sigma_{k} S_{3}^{k} = \begin{pmatrix} 1/\sqrt{2} S_{3}^{(-1/3)} \quad S_{3}^{(2/3)} \\ S_{3}^{(-4/3)} \quad -1/\sqrt{2} S_{3}^{(-1/3)} \end{pmatrix} \]

and the 3 \( \times \) 3 Yukawa matrices in flavour space \( y_{1}^{RR}, y_{1}^{LL}, y_{2}^{LR}, y_{2}^{RL}, \tilde{y}_{2}^{RL}, y_{3}^{LL} \) (\( y_{AB}^{n,ij} ; i: \text{quark}, j: \text{lepton gen. index} \))
Leptoquark species and lepton-exchange contributions

**Simplified model** with different species of LQs:

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

with the 3 Pauli matrices \( \sigma_k \), the component fields (mass eigenstates) with a specific electric charge:

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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} R_2^{(-1/3)} \\ R_2^{(-2/3)} \end{pmatrix}, \quad S_3 = \frac{1}{\sqrt{2}} \sigma_k S_3^k = \begin{pmatrix} S_3^{(-1/3)} \\ S_3^{(-4/3)} \end{pmatrix}
\]

and the \( 3 \times 3 \) Yukawa matrices in flavour space \( y_1^{RR}, y_1^{LL}, y_2^{LR}, y_2^{RL}, \tilde{y}_2^{RL}, y_3^{LL} \) (\( y_{AB}^{n,ij}; i: \text{quark}, j: \text{lepton gen. index} \))

**Coupling orders of cross section at tree level:** \( \mathcal{O}(\alpha_s^2) \)
Leptoquark species and lepton-exchange contributions

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\[ + y_2^{\text{LR}} \bar{e}_R Q_L R_2^+ + y_2^{\text{RL}} \bar{u}_R (L_L \cdot R_2) + \tilde{y}_2^{\text{RL}} \bar{d}_R (L_L \cdot \tilde{R}_2) \]

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and the 3 × 3 Yukawa matrices in flavour space \(y_1^{\text{RR}}, y_1^{\text{LL}}, y_2^{\text{LR}}, y_2^{\text{RL}}, y_3^{\text{LL}}\) (\(y_{nij}^{AB}: i: \text{quark}, j: \text{lepton gen. index}\))

Coupling orders of cross section at tree level: \(\mathcal{O}(\alpha_s^2), \mathcal{O}(\alpha_s y^2), \mathcal{O}(y^4)\)
Motivation & Leptoquark Scenarios

**Leptoquark species and lepton-exchange contributions**

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\mathcal{L}_{\text{int}} = \text{scalar QCD interactions} + y_{1}^{RR}\bar{u}cL_{R}S_{1}^{\dagger} + y_{1}^{LL}Q_{cL}\sigma_{k}L_{L}(S_{3}^{k})^{\dagger} + \ldots
\]

with the 3 Pauli matrices \(\sigma_{k}\), the component fields (mass eigenstates) with a specific electric charge:

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**Coupling orders of cross section at tree level:**

\[\mathcal{O}(\alpha_{s}^{2}), \mathcal{O}(\alpha_{s}y^{2}), \mathcal{O}(y^{4})\] interference terms

**Strong constraints from atomic parity violation** for 1st gen. couplings \([\text{Doršner, Fajfer, Greljo '14}]\)
**Benchmark scenarios**

**Simple scenarios:**

1. $S_1$ model with $m_{S_1} \in [1, 2] \text{ TeV}$, $y_{1,22}^{LL} = -0.15$, $y_{1,32}^{LL} = 3$

2. $R_2$ model with $m_{R_2} \in [1, 2] \text{ TeV}$, $y_{2,22}^{RL} = 1.5$

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

   ▶ Can only give an explanation to flavour anomaly $R_K(\ast)$, but not $R_D(\ast)$

   ▶ Yukawa couplings other than the mentioned ones set to zero
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   ▶ Can only give an explanation to flavour anomaly $R_K(\ast)$, but not $R_D(\ast)$

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**Phenomenologically viable scenarios:**

(a) $R_2$ model with $m_{R_2} = 1$ TeV [Popov, Schmidt, White ’19]

(b) $R_2 – S_3$ model with $m_{S_1} = 1.3$ TeV, $m_{S_3} = 2$ TeV [Bečirević, Doršner, Fajfer, Košnik, Faroughy, Sumensari ’18]

(c) $S_1 – S_3$ model with $m_{S_1} = m_{S_3} = 1.2$ TeV [Crivellin, Müller, Saturnino ’20]

   ▶ Points in allowed range of $y_{ij}$ values to simultaneously describe $R_D(\ast)$ and $R_K(\ast)$
Diagonal 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
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- $t$-channel contributions & interferences with QCD diagrams included consistently

MadGraph5_aMC@NLO

Model implemented into FEYNRULES

Renormalisation with NLOCT & FEYNARTS

Generation of UFO model file for evaluation of fixed-order predictions

POWHEG-BOX

Virtual corrections calculated with FEYNARTS, FORMCALC, COLLIER

Real corrections generated with MG4

Modifications for coloured BSM particles

Consistency checks $\checkmark$, very good agreement between the two codes

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

[Alioli, Nason, Oleari, Re '10]

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

[Alloul, Christensen, Degrande, Duhr, Fuks '15]

[Hahn, Perez-Victoria '98-'00][Denner, Dittmaier, Hofer '17]

[Murayama et al., Stelzer et al., Alwall et al. '92-'07]

[Alloul, Christensen, Degrande, Duhr, Fuks '15]
Soft-gluon resummation

**Threshold region** $\sqrt{\hat{s}} \rightarrow 2m_{LQ}$ increasingly relevant

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

($\sqrt{\hat{s}}$: partonic centre-of-mass energy)
Soft-gluon resummation

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

- Enhanced logs $\ln \beta^2$ with $\beta^2 \equiv 1 - 4m_{LQ}^2/\hat{s} \to 0$ stemming from soft-gluon emission
- Factorisation of cross section in **Mellin space** $\ln \beta^2 \to \ln N$ near threshold ($N \to \infty$):

$$\tilde{\sigma}_{ij \to LQ \bar{LQ}}^{(\text{resum})} = \sum_{\text{colours} \ l} H_{ij \to LQ \bar{LQ},l}^{(N)} \times \Delta_i^{(N)} \Delta_j^{(N)} \times S_{ij \to LQ \bar{LQ},l}^{(N)},$$

$i, j$: partons
Soft-gluon resummation

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- Factorisation of cross section in *Mellin space* $\ln \beta^2 \to \ln N$ near threshold ($N \to \infty$):

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

$i, j$: partons

- $H^{(N)}_{ij \to LQ LQ^*, I}$: matching coefficient (hard & Coulomb-gluon contributions)
- $\Delta_i^{(N)}$, $S^{(N)}_{ij \to LQ LQ^*, I}$: 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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Threshold region $\sqrt{s} \rightarrow 2m_{LQ}$ increasingly relevant

- Enhanced logs $\ln \beta^2$ with $\beta^2 \equiv 1 - 4m_{LQ}^2/\sqrt{s} \rightarrow 0$ stemming from soft-gluon emission
- Factorisation of cross section in Mellin space $\ln \beta^2 \rightarrow \ln N$ near threshold ($N \rightarrow \infty$):

$$\tilde{\sigma}_{ij \rightarrow LQ LQ^*}^{(\text{resum})} = \sum_{\text{colours } I} H_{ij \rightarrow LQ LQ^* I}^{(N)} \times \Delta_i^{(N)} \Delta_j^{(N)} \times S_{ij \rightarrow LQ LQ^* I}^{(N)}$$

$i, j$: partons

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

Factorisation leads to exponentiation and thus all-order resummation of threshold logs
Motivation & Leptoquark Scenarios

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**Threshold region** $\sqrt{s} \rightarrow 2m_{LQ}$ increasingly relevant

- Enhanced logs $\ln \beta^2$ with $\beta^2 \equiv 1 - 4m_{LQ}^2 / \sqrt{s} \rightarrow 0$ stemming from soft-gluon emission
- Factorisation of cross section in **Mellin space** $\ln \beta^2 \rightarrow \ln N$ near threshold ($N \rightarrow \infty$):

$$\tilde{\sigma}^{(\text{resum})}_{ij \rightarrow LQ LQ^*} = \sum_{\text{colours } l} H^{(N)}_{ij \rightarrow LQ LQ^*} \times \Delta^{(N)}_i \times \Delta^{(N)}_j \times S^{(N)}_{ij \rightarrow LQ LQ^*,l}$$

$i, j$: partons

- $H^{(N)}_{ij \rightarrow LQ LQ^*}$: matching coefficient (hard & **Coulomb-gluon** contributions)
- $\Delta^{(N)}_i, S^{(N)}_{ij \rightarrow LQ LQ^*}$: resummed logs from **soft-collinear** and **soft wide-angle** radiation

$$\Delta^{(N)}_i \times \Delta^{(N)}_j \times S^{(N)}_{ij \rightarrow kl,l} = \exp \left[ L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + ... \right]$$

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[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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**Threshold region** $\sqrt{s} \rightarrow 2m_{\text{LQ}}$ increasingly relevant

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- Factorisation of cross section in Mellin space $\ln \beta^2 \rightarrow \ln N$ near threshold ($N \rightarrow \infty$):

$$\tilde{\sigma}_{ij \rightarrow \text{LQ LQ}^*}^{(\text{resum})} = \sum_{\text{colours } I} H_{ij \rightarrow \text{LQ LQ}^*,I}^{(N)} \times \Delta_{i}^{(N)} \Delta_{j}^{(N)} \times S_{ij \rightarrow \text{LQ LQ}^*,I}^{(N)}$$

with

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

$$\Delta_{i}^{(N)} \Delta_{j}^{(N)} S_{ij \rightarrow kl,I}^{(N)} = \exp \left[ L g_{1}(\alpha_s L) + g_{2}(\alpha_s L) + \alpha_s g_{3}(\alpha_s L) + \ldots \right]$$

[Kodaira, Trentadue '82][Sterman '87][Catani, D'Emilio, Trentadue '88][Catani, Trentadue '89][Kidonakis, Sterman '96]
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with

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

Inverse Mellin transform, matching to NLO to avoid double counting:

$$\sigma_{pp \rightarrow LQ LQ^*}^{NLO+NNLL} = \sigma_{pp \rightarrow LQ LQ^*}^{NLO} + \int_{CT} dN (...) \left[ \tilde{\sigma}_{ij \rightarrow LQ LQ^*}^{(\text{resum})} - \tilde{\sigma}_{ij \rightarrow LQ LQ^*}^{(\text{resum})} \bigg|_{NLO} \right]$$

[Catani, Mangano, Nason, Trentadue '96]
Relative importance of the different effects

**Analysis**

- **Top-left:** $t$-channel effects
- **Top-right:** soft-gluon effects
- **Bottom-left:** PDF effects
- **Bottom-right:** combined effects

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Motivation & Leptoquark Scenarios

Relative importance of the different effects

Analysis

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- **Top-right:** soft-gluon effects
- **Bottom-left:** PDF effects
- **Bottom-right:** combined effects

→ Effects strongly dependent on LQ final state and PDF set
→ All contributions equally important, influence the results in often constrasting ways
Results for different benchmark points (1)

- **Dark-coloured bars**: scale uncertainties; **light-coloured bars**: combined scale + PDF uncertainties
Results for different benchmark points (1)

- **Dark-coloured bars**: scale uncertainties; **light-coloured bars**: combined scale + PDF uncertainties

  → Reduction of scale uncertainties wrt. NLO-QCD due to NNLL corrections

  → From very mild to moderately strong effects
### Benchmark scenarios
- First scale, then PDF uncertainty
- NLO-wt = NLO-QCD + t-channel effects
- NNLL-wt = NLO-wt + NNLL
- $K_{\text{wt}} = \frac{\text{NLO-wt}}{\text{NLO-QCD}}$
- $K_{\text{NNLL}} = \frac{\text{NNLL-wt}}{\text{NLO-QCD}}$
- From very mild to moderately strong effects

| BP | LQ | PDF   | NLO-QCD (fb) | NLO-wt (fb) | NNLL-wt (fb) | $K_{\text{wt}}$ | $K_{\text{NNLL}}$ |
|----|----|-------|--------------|-------------|--------------|---------------|------------------|
| $a_1$ | $R_2$ | CT18   | 5.49±11.4%+11.4% | 6.91±7.7%+15.5% | 8.71±6.6%+2.5% | 1.26 | 1.59 |
|     |     | NNPDF31 | 5.24±11.6%+3.8% | 8.92±4.2%+28.0% | 8.40±3.0%+2.3% | 1.70 | 1.60 |
|     |     | MSHT20 | 5.55±11.4%+4.7% | 6.88±8.0%+6.6% | 8.26±4.8%+7.9% | 1.24 | 1.49 |
| $a_2$ | $R_2$ | CT18   | 5.49±11.4%+11.4% | 5.51±11.5%+15.5% | 6.40±6.7%+15.3% | 1.00 | 1.17 |
|     |     | NNPDF31 | 5.24±11.6%+3.8% | 5.30±11.4%+4.0% | 5.48±7.3%+3.9% | 1.01 | 1.05 |
|     |     | MSHT20 | 5.55±11.4%+4.7% | 5.58±11.2%+4.8% | 6.29±6.7%+5.3% | 1.01 | 1.13 |
| $b_1$ | $R_2$ | CT18   | 0.700±12.0%+14.8% | 0.705±11.7%+15.0% | 0.846±7.0%+21.0% | 1.01 | 1.21 |
|     |     | NNPDF31 | 0.641±12.1%+7.6% | 0.664±11.4%+8.2% | 0.683±7.8%+8.9% | 1.04 | 1.07 |
|     |     | MSHT20 | 0.707±11.9%+6.3% | 0.713±11.7%+6.4% | 0.835±7.0%+7.2% | 1.01 | 1.18 |
| $b_2$ | $R_2$ | CT18   | 0.700±12.0%+14.8% | 0.720±11.5%+15.6% | 0.877±6.6%+22.5% | 1.03 | 1.25 |
|     |     | NNPDF31 | 0.641±12.1%+7.6% | 0.733±11.7%+12.9% | 0.730±7.3%+13.5% | 1.14 | 1.14 |
|     |     | MSHT20 | 0.707±11.9%+6.3% | 0.728±11.1%+6.7% | 0.862±6.7%+7.7% | 1.03 | 1.22 |
| $c_1$ | $S_3^{(-4/3)}$ | CT18   | 1.35±11.8%+13.6% | 1.35±11.7%+13.6% | 1.59±6.9%+18.6% | 1.00 | 1.18 |
|     |     | NNPDF31 | 1.26±12.0%+5.9% | 1.26±11.7%+5.7% | 1.30±7.6%+6.1% | 1.00 | 1.03 |
|     |     | MSHT20 | 1.36±11.8%+5.7% | 1.37±11.7%+5.7% | 1.58±7.0%+6.4% | 1.01 | 1.16 |
| $c_2$ | $S_3^{(-4/3)}$ | CT18   | 1.35±11.8%+13.6% | 1.49±9.9%+16.2% | 1.75±6.3%+21.0% | 1.10 | 1.30 |
|     |     | NNPDF31 | 1.26±12.0%+5.9% | 1.57±8.3%+11.7% | 1.71±5.3%+12.8% | 1.25 | 1.36 |
|     |     | MSHT20 | 1.36±11.8%+5.7% | 1.52±12.1%+6.4% | 1.77±5.9%+7.4% | 1.12 | 1.30 |
## Results for different benchmark points (2)

### Benchmark scenarios

- **First scale, then PDF uncertainty**
- **NLO-wt = NLO-QCD + t-channel effects**
- **NNLL-wt = NLO-wt + NNLL**
- **$K_{\text{wt}} = \text{NLO-wt}/\text{NLO-QCD}$**
- **$K_{\text{NNLL}} = \text{NNLL-wt}/\text{NLO-QCD}$**
- From very mild to moderately strong effects

### Table

| BP | LQ | PDF    | NLO-QCD (fb) | NLO-wt (fb) | NNLL-wt (fb) | $K_{\text{wt}}$ | $K_{\text{NNLL}}$ |
|----|----|--------|-------------|-------------|-------------|----------------|----------------|
| $a_1$ | $R_2$ | CT18 | 5.49 | 6.91 | 8.71 | 1.26 | 1.59 |
|     |     | NNPDF3.1 | 5.24 | 8.92 | 8.40 | 1.70 | 1.60 |
|     |     | MSHT20 | 5.55 | 6.88 | 8.26 | 1.24 | 1.49 |

| $a_2$ | $R_2$ | CT18 | 5.49 | 5.51 | 6.40 | 1.00 | 1.17 |
|     |     | NNPDF3.1 | 5.24 | 5.30 | 5.48 | 1.01 | 1.05 |
|     |     | MSHT20 | 5.55 | 5.58 | 6.29 | 1.01 | 1.13 |

| $b_1$ | $R_2$ | CT18 | 0.70 | 0.705 | 0.846 | 1.01 | 1.21 |
|     |     | NNPDF3.1 | 0.64 | 0.664 | 0.835 | 1.04 | 1.07 |
|     |     | MSHT20 | 0.707 | 0.713 | 0.835 | 1.01 | 1.18 |

| $b_2$ | $R_2$ | CT18 | 0.70 | 0.720 | 0.877 | 1.03 | 1.25 |
|     |     | NNPDF3.1 | 0.64 | 0.733 | 0.730 | 1.14 | 1.14 |
|     |     | MSHT20 | 0.707 | 0.728 | 0.862 | 1.03 | 1.22 |

| $c_1$ | $S_3^{(−4/3)}$ | CT18 | 1.35 | 1.35 | 1.59 | 1.00 | 1.18 |
|     |     | NNPDF3.1 | 1.26 | 1.26 | 1.30 | 1.00 | 1.03 |
|     |     | MSHT20 | 1.36 | 1.37 | 1.58 | 1.01 | 1.16 |

| $c_2$ | $S_3^{(−4/3)}$ | CT18 | 1.35 | 1.35 | 1.75 | 1.10 | 1.30 |
|     |     | NNPDF3.1 | 1.26 | 1.57 | 1.71 | 1.25 | 1.36 |
|     |     | MSHT20 | 1.36 | 1.52 | 1.77 | 1.12 | 1.30 |
### Benchmark scenarios

- First scale, then PDF uncertainty
- NLO-wt = NLO-QCD + t-channel effects
- NNLL -wt = NLO-wt + NNLL
- $K_{\text{wt}} = \frac{\text{NLO-wt}}{\text{NLO-QCD}}$
- $K_{\text{NNLL}} = \frac{\text{NNLL-wt}}{\text{NLO-QCD}}$
- From very mild to moderately strong effects

### Results for different benchmark points (2)

| BP | LQ | PDF     | NLO-QCD (fb) | NLO-wt (fb) | NNLL-wt (fb) | $K_{\text{wt}}$ | $K_{\text{NNLL}}$ |
|----|----|---------|--------------|-------------|--------------|----------------|-----------------|
| $a_1$ | $R_2$ | CT18    | 5.49 ±11.4%| 6.91 ±7.7%| 8.71 ±4.6%| 1.26 | 1.59 |
|      |     | NNPDF3.1| 5.24 ±11.6%| 8.92 ±4.2%| 8.40 ±4.2%| 1.70 | 1.60 |
|      |     | MSHT20  | 5.55 ±11.4%| 6.88 ±8.0%| 8.26 ±4.8%| 1.24 | 1.49 |
| $a_2$ | $R_2$ | CT18    | 5.49 ±11.4%| 5.51 ±11.5%| 6.40 ±6.7%| 1.01 | 1.17 |
|      |     | NNPDF3.1| 5.24 ±11.6%| 5.30 ±11.4%| 5.48 ±7.3%| 1.01 | 1.05 |
|      |     | MSHT20  | 5.55 ±11.4%| 5.58 ±11.2%| 6.29 ±6.7%| 1.01 | 1.13 |
| $b_1$ | $R_2$ | CT18    | 0.700 ±12.0%| 0.705 ±11.7%| 0.846 ±7.0%| 1.01 | 1.21 |
|      |     | NNPDF3.1| 0.641 ±12.1%| 0.664 ±11.4%| 0.683 ±7.8%| 1.04 | 1.07 |
|      |     | MSHT20  | 0.707 ±11.9%| 0.713 ±11.7%| 0.835 ±7.0%| 1.01 | 1.18 |
| $b_2$ | $R_2$ | CT18    | 0.700 ±12.0%| 0.720 ±11.5%| 0.877 ±7.6%| 1.03 | 1.25 |
|      |     | NNPDF3.1| 0.641 ±12.1%| 0.733 ±11.7%| 0.730 ±7.3%| 1.14 | 1.14 |
|      |     | MSHT20  | 0.707 ±11.9%| 0.728 ±11.1%| 0.862 ±6.7%| 1.03 | 1.22 |
| $c_1$ | $S_3^{(-4/3)}$ | CT18    | 1.35 ±11.8%| 1.35 ±11.7%| 1.59 ±6.9%| 1.00 | 1.18 |
|      |     | NNPDF3.1| 1.26 ±12.0%| 1.26 ±11.7%| 1.30 ±7.6%| 1.00 | 1.03 |
|      |     | MSHT20  | 1.36 ±12.0%| 1.37 ±11.7%| 1.58 ±7.0%| 1.01 | 1.16 |
| $c_2$ | $S_3^{(-4/3)}$ | CT18    | 1.35 ±11.8%| 1.49 ±9.9%| 1.75 ±4.3%| 1.10 | 1.30 |
|      |     | NNPDF3.1| 1.26 ±12.0%| 1.57 ±8.3%| 1.71 ±5.3%| 1.25 | 1.36 |
|      |     | MSHT20  | 1.36 ±12.0%| 1.52 ±12.1%| 1.77 ±5.9%| 1.12 | 1.30 |
## Results for different benchmark points (2)

### Benchmark scenarios

- First scale, then PDF uncertainty
- NLO-wt = NLO-QCD + t-channel effects
- NNLL-wt = NLO-wt + NNLL
- $K_{\text{wt}} = \frac{\text{NLO-wt}}{\text{NLO-QCD}}$
- $K_{\text{NNLL}} = \frac{\text{NNLL-wt}}{\text{NLO-QCD}}$

- From very mild to moderately strong effects

| BP | LQ  | PDF    | NLO-QCD (fb) | NLO-wt (fb) | NNLL-wt (fb) | $K_{\text{wt}}$ | $K_{\text{NNLL}}$ |
|----|-----|--------|--------------|-------------|--------------|----------------|------------------|
| $a_1$ | $R_2$ | CT18   | 5.49 $^{+11.4\%}_{-13.5\%}$ | 6.91 $^{+7.7\%}_{-9.8\%}$ | 8.71 $^{+4.6\%}_{-3.1\%}$ | 1.26 | 1.59 |
|     |     | NNPDF3.1 | 5.24 $^{+11.6\%}_{-13.6\%}$ | 8.92 $^{+4.2\%}_{-6.1\%}$ | 8.40 $^{+4.2\%}_{-2.5\%}$ | 1.70 | 1.60 |
|     |     | MSHT20 | 5.55 $^{+11.4\%}_{-13.4\%}$ | 6.88 $^{+8.0\%}_{-10.1\%}$ | 8.26 $^{+8.8\%}_{-3.3\%}$ | 1.24 | 1.49 |

| $a_2$ | $R_2$ | CT18   | 5.49 $^{+11.4\%}_{-13.5\%}$ | 5.51 $^{+11.5\%}_{-13.2\%}$ | 6.40 $^{+6.7\%}_{-6.1\%}$ | 1.00 | 1.17 |
|     |     | NNPDF3.1 | 5.24 $^{+11.6\%}_{-13.6\%}$ | 5.30 $^{+11.4\%}_{-13.3\%}$ | 5.48 $^{+7.3\%}_{-5.9\%}$ | 1.01 | 1.05 |
|     |     | MSHT20 | 5.55 $^{+11.4\%}_{-13.4\%}$ | 5.58 $^{+11.2\%}_{-13.4\%}$ | 6.29 $^{+6.7\%}_{-6.1\%}$ | 1.01 | 1.13 |

| $b_1$ | $R_2$ | CT18   | 0.700 $^{+12.0\%}_{-14.0\%}$ | 0.705 $^{+11.7\%}_{-14.0\%}$ | 0.846 $^{+7.0\%}_{-5.8\%}$ | 1.01 | 1.21 |
|     |     | NNPDF3.1 | 0.641 $^{+12.1\%}_{-14.1\%}$ | 0.664 $^{+11.4\%}_{-13.5\%}$ | 0.835 $^{+7.0\%}_{-5.7\%}$ | 1.01 | 1.18 |
|     |     | MSHT20 | 0.707 $^{+11.9\%}_{-14.0\%}$ | 0.713 $^{+11.7\%}_{-13.8\%}$ | 0.835 $^{+7.0\%}_{-5.7\%}$ | 1.01 | 1.18 |

| $b_2$ | $R_2$ | CT18   | 0.700 $^{+12.0\%}_{-14.0\%}$ | 0.720 $^{+11.5\%}_{-13.5\%}$ | 0.877 $^{+6.6\%}_{-5.6\%}$ | 1.03 | 1.25 |
|     |     | NNPDF3.1 | 0.641 $^{+12.1\%}_{-14.1\%}$ | 0.733 $^{+11.7\%}_{-12.9\%}$ | 0.730 $^{+7.3\%}_{-7.3\%}$ | 1.14 | 1.14 |
|     |     | MSHT20 | 0.707 $^{+11.9\%}_{-14.0\%}$ | 0.728 $^{+11.1\%}_{-13.6\%}$ | 0.862 $^{+6.7\%}_{-5.5\%}$ | 1.03 | 1.22 |

| $c_1$ | $S_3^{(-4/3)}$ | CT18   | 1.35 $^{+11.8\%}_{-13.8\%}$ | 1.35 $^{+11.7\%}_{-13.9\%}$ | 1.59 $^{+6.9\%}_{-6.0\%}$ | 1.00 | 1.18 |
|     |     | NNPDF3.1 | 1.26 $^{+12.0\%}_{-14.0\%}$ | 1.26 $^{+11.7\%}_{-14.2\%}$ | 1.30 $^{+7.6\%}_{-5.9\%}$ | 1.00 | 1.03 |
|     |     | MSHT20 | 1.36 $^{+11.7\%}_{-13.8\%}$ | 1.37 $^{+11.7\%}_{-13.7\%}$ | 1.58 $^{+7.0\%}_{-5.8\%}$ | 1.01 | 1.16 |

| $c_2$ | $S_3^{(-4/3)}$ | CT18   | 1.35 $^{+11.8\%}_{-13.8\%}$ | 1.49 $^{+9.9\%}_{-12.4\%}$ | 1.75 $^{+6.3\%}_{-4.9\%}$ | 1.10 | 1.30 |
|     |     | NNPDF3.1 | 1.26 $^{+12.0\%}_{-14.0\%}$ | 1.57 $^{+8.3\%}_{-10.9\%}$ | 1.71 $^{+5.3\%}_{-3.3\%}$ | 1.25 | 1.36 |
|     |     | MSHT20 | 1.36 $^{+11.7\%}_{-13.8\%}$ | 1.52 $^{+10.1\%}_{-12.1\%}$ | 1.77 $^{+5.9\%}_{-4.7\%}$ | 1.12 | 1.30 |
**Results for different benchmark points (2)**

| BP  | LQ | PDF          | NLO-QCD (fb)               | NLO-wt (fb)           | NNLL-wt (fb)          | $K_{\text{wt}}$ | $K_{\text{NNLL}}$ |
|-----|----|--------------|----------------------------|-----------------------|-----------------------|----------------|-----------------|
| $a_1$ | $R_2$ | CT18         | 5.49 *11.4%+11.4% -13.5%+11.4% | 6.91 *7.7%+15.5% -9.8%+15.5% | 8.71 *4.6%+2.5% -3.1%+2.5% | 1.26 | 1.59 |
|     |     | NNPDFS31     | 5.24 *11.6%+3.8% -13.6%+3.8% | 8.92 *4.2%+28.0% -6.1%+28.0% | 8.40 *4.2%+30.2% -2.5%+30.2% | 1.70 | 1.60 |
|     |     | MSHT20       | 5.55 *11.4%+4.7% -13.4%+4.7% | 6.88 *8.0%+6.6% -10.1%+6.6% | 8.26 *4.8%+7.9% -3.3%+7.9% | 1.24 | 1.49 |
| $a_2$ | $R_2$ | CT18         | 5.49 *11.4%+11.4% -13.5%+11.4% | 5.51 *11.5%+11.5% -13.2%+11.5% | 6.40 *6.7%+15.3% -6.1%+15.3% | 1.00 | 1.17 |
|     |     | NNPDFS31     | 5.24 *11.6%+3.8% -13.6%+3.8% | 5.30 *11.4%+4.0% -13.3%+4.0% | 5.48 *7.3%+3.9% -5.9%+3.9% | 1.01 | 1.05 |
|     |     | MSHT20       | 5.55 *11.4%+4.7% -13.4%+4.7% | 5.58 *11.2%+4.8% -13.4%+4.8% | 6.29 *6.7%+5.3% -6.1%+5.3% | 1.01 | 1.13 |
| $b_1$ | $R_2$ | 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 |
|     |     | NNPDFS31     | 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 |
|     |     | MSHT20       | 0.707 *11.9%+6.3% -14.0%+6.3% | 0.713 *11.7%+6.4% -13.8%+6.4% | 0.835 *7.0%+7.2% -5.7%+7.2% | 1.01 | 1.18 |
| $b_2$ | $R_2$ | 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 |
|     |     | NNPDFS31     | 0.641 *12.1%+7.6% -14.1%+7.6% | 0.733 *11.7%+12.9% -13.6%+12.9% | 0.730 *7.3%+13.5% -6.9%+13.5% | 1.14 | 1.14 |
|     |     | MSHT20       | 0.707 *11.9%+6.3% -14.0%+6.3% | 0.728 *11.1%+6.7% -13.6%+6.7% | 0.862 *6.7%+7.7% -5.5%+7.7% | 1.03 | 1.22 |
| $c_1$ | $S_3$ | CT18         | 1.35 *11.8%+13.6% -13.8%+13.6% | 1.35 *11.7%+13.6% -13.9%+13.6% | 1.59 *6.9%+18.6% -6.0%+18.6% | 1.00 | 1.18 |
|     |     | NNPDFS31     | 1.26 *12.0%+5.9% -14.0%+5.9% | 1.26 *11.7%+5.9% -14.2%+5.9% | 1.30 *7.6%+6.1% -5.9%+6.1% | 1.00 | 1.03 |
|     |     | MSHT20       | 1.36 *11.7%+5.7% -13.8%+5.7% | 1.37 *11.7%+5.7% -13.7%+5.7% | 1.58 *7.0%+6.4% -5.8%+6.4% | 1.01 | 1.16 |
| $c_2$ | $S_3$ | CT18         | 1.35 *11.8%+13.6% -13.8%+13.6% | 1.49 *9.9%+16.2% -12.4%+16.2% | 1.75 *4.3%+21.0% -4.9%+21.0% | 1.10 | 1.30 |
|     |     | NNPDFS31     | 1.26 *12.0%+5.9% -14.0%+5.9% | 1.57 *8.3%+11.7% -10.9%+11.7% | 1.71 *5.3%+12.8% -3.3%+12.8% | 1.25 | 1.36 |
|     |     | MSHT20       | 1.36 *11.7%+5.7% -13.8%+5.7% | 1.52 *12.1%+6.4% | 1.77 *5.9%+7.4% -4.7%+7.4% | 1.12 | 1.30 |

### Benchmark scenarios

- **First scale**, then PDF uncertainty
- **NLO-wt** = **NLO-QCD** + t-channel effects
- **NNLL-wt** = **NLO-wt** + NNLL
- $K_{\text{wt}}$ = **NLO-wt** / **NLO-QCD**
- $K_{\text{NNLL}}$ = **NNLL-wt** / **NLO-QCD**

From very mild to moderately strong effects
Summary and conclusions

Predictions at NLO with t-channel + NNLL
Full NLO-QCD corrections including lepton-exchange contributions as well as soft-gluon resummation at NNLL calculated and available publicly:
https://www.uni-muenster.de/Physik.TP/research/kulesza/leptoquarks.html
Summary and conclusions

Predictions at NLO with $t$-channel + NNLL
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Impact of $t$-channel, soft-gluon, PDF contributions

- Effects of similar size, sometimes contrasting behaviour

⇒ All contributions have to be taken into account for consistent results
Summary and conclusions

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Impact of $t$-channel, soft-gluon, PDF contributions
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Phenomenologically viable benchmark scenarios in light of the flavour anomalies
- Very mild to moderately strong enhancements on the cross sections and uncertainties
- Effects strongly dependent on the size of the Yukawa couplings
- Treatment of charm densities in the PDFs affecting scenarios with large charm couplings
Motivation & Leptoquark Scenarios

Summary and conclusions

Predictions at NLO with t-channel + NNLL
Full NLO-QCD corrections including lepton-exchange contributions as well as soft-gluon resummation at NNLL calculated and available publicly:
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Impact of t-channel, soft-gluon, PDF contributions

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Phenomenologically viable benchmark scenarios in light of the flavour anomalies

- Very mild to moderately strong enhancements on the cross sections and uncertainties
- Effects strongly dependent on the size of the Yukawa couplings
- Treatment of charm densities in the PDFs affecting scenarios with large charm couplings

Thank you for your attention! 😊
Backup
Benchmark values for the leptoquark couplings

Model containing the $R_2$ leptoquark

| $B$ | $y_{2,23}^{RL}$ | $y_{2,23}^{LR}$ | $y_{2,21}^{LR}$ | $y_{2,31}^{LR}$ |
|-----|----------------|----------------|----------------|----------------|
| $a_1$ | $1.84 + 1.84i$ | $0.354 + 0.354i$ | $-0.015i$ | $0.262 + 0.262i$ |
| $a_2$ | $0.309 + 0.951i$ | $0.951 + 0.309i$ | $0.011 - 0.011i$ | $0.37i$ |

[Popov, Schmidt, White; 1905.06339]

Model containing the $R_2$ and $S_3$ leptoquarks

| $B$ | $y_{2,33}^{LR}$ | $y_{2,22}^{RL}$ | $y_{2,23}^{RL}$ | $y_{3,22}^{LL}$ | $y_{3,23}^{LL}$ | $y_{3,32}^{LL}$ | $y_{3,33}^{LL}$ |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $b_1$ | $-0.18734 + 1.12287i$ | $0.265001$ | $1.17382$ | $-0.010$ | $-0.045$ | $-0.265$ | $-1.173$ |
| $b_2$ | $-0.18734 + 1.12287i$ | $0.37353$ | $1.59511$ | $-0.014$ | $-0.061$ | $-0.373$ | $-1.594$ |

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

Model containing the $S_1$ and $S_3$ leptoquarks

| $B$ | $y_{1,22}^{LL}$ | $y_{1,23}^{LL}$ | $y_{1,32}^{LL}$ | $y_{1,33}^{LL}$ | $y_{1,23}^{RR}$ | $y_{1,32}^{RR}$ | $y_{3,22}^{LL}$ | $y_{3,23}^{LL}$ | $y_{3,32}^{LL}$ | $y_{3,33}^{LL}$ |
|-----|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $c_1$ | $-0.0082$ | $-1.46$ | $-0.016$ | $-0.064$ | $1.34$ | $-0.19$ | $-0.019$ | $0.58$ | $-0.059$ | $-0.11$ |
| $c_2$ | $0.0078$ | $1.36$ | $-0.055$ | $0.052$ | $-1.47$ | $-0.053$ | $-0.017$ | $-1.23$ | $-0.070$ | $0.066$ |

[Crivellin, Müller, Saturnino; 1912.04224]
Impact on experimental mass limits

Example study from [ATLAS '20] featuring a single LQ species $S_1^{(-1/3)}$

- Exclusion limits can be lowered by more than 50 GeV
- Largely dependent on PDF set