Scalar leptoquarks and flavor anomalies: a comparison of pair production modes at NLO-QCD

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Introduction

- There are strong hints for the breakdown of the lepton flavour universality in the heavy meson decays

$$R_{K^{(*)}} \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \qquad \bigg| \qquad R_{D^{(*)}} \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\ell\nu_\ell)}$$

- To address both the anomalies two species of Leptoquarks are usually introduced

  R_2 models — $(\mathbf{3}, \mathbf{2})_{7/6}$ with couplings to taus and electrons (O. Popov, M. Schmidt, G. White, 1905.06339)

  Two-leptoquark model inspired by GUT: R_2 and S_3. The two Leptoquarks couple to muons and taus (D. Becerivic et al. 1806.05689)

  The singlet-triplet model: S_1 and S_3. Can also addresses the muon anomalous magnetic moment (A. Crivellin, D. Muller, F. Saturnino, 1912.04224)

Leptoquarks are also natural predictions of Grand-unified theories

The theoretical setup

- We consider minimal simplified leptoquark models that involve different leptoquark species: S_1, R_2, S_3

$$S_1 : \ (\mathbf{3}, \mathbf{1})_{-1/3}, \quad R_2 : (\mathbf{3}, \mathbf{2})_{+7/6}, \quad S_3 : \ (\mathbf{3}, \mathbf{3})_{-1/3}$$

- The most general Lagrangian is thus given by

$$\begin{aligned} \mathscr{L}_{\rm LQ} \supset \quad & y_1^{\rm RR} \bar{u}_R^c \ell_R S_1^\dagger + y_1^{\rm LL} (Q_L^c \cdot \ell_L) \ S_1^\dagger \\ + \quad & y_2^{\rm LR} \bar{\ell}_R Q_L R_2^\dagger + y_2^{\rm RL} \bar{u}_R (\ell_L \cdot R_2) \\ + \quad & y_3^{\rm LL} (\bar{Q}_L^c \cdot \sigma_k \ell_L) \ (S_3^k)^\dagger + {\rm H.c.} \end{aligned}$$

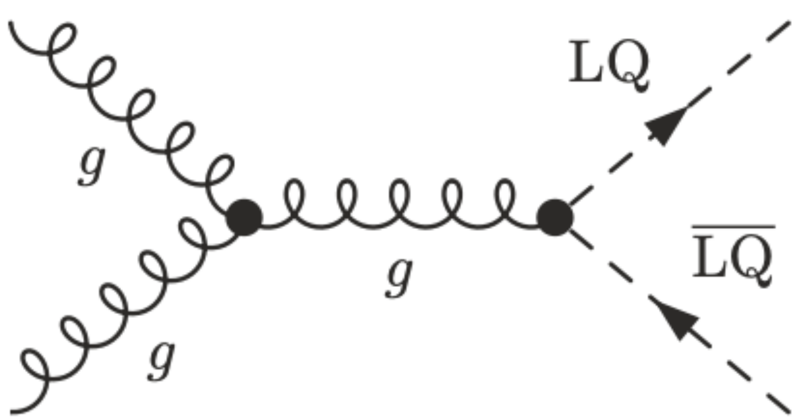
Flavour indices are not shown here: $y_1^{\rm RR} \equiv y_{1,ij}^{\rm RR}$

First index is for quark generation while second is for lepton generation

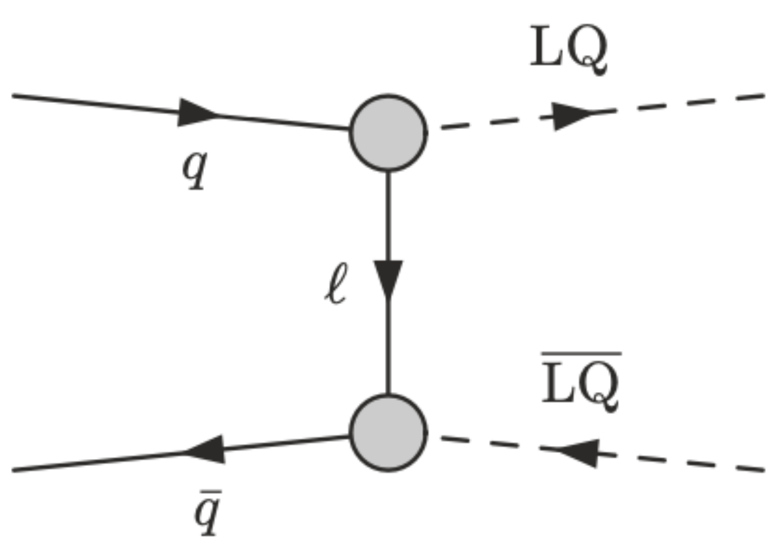
$$S_1 \equiv S_1^{(-1/3)}, \quad R_2 = \begin{pmatrix} R_2^{(+5/3)} \\ R_2^{(+2/3)} \end{pmatrix}, \quad S_3 = \begin{pmatrix} \frac{1}{\sqrt{2}} S_3^{(-1/3)} & S_3^{(+2/3)} \\ S_3^{(+4/3)} & -\frac{1}{\sqrt{2}} S_3^{(-1/3)} \end{pmatrix}$$

Anatomy of leptoquark pair production at the LHC

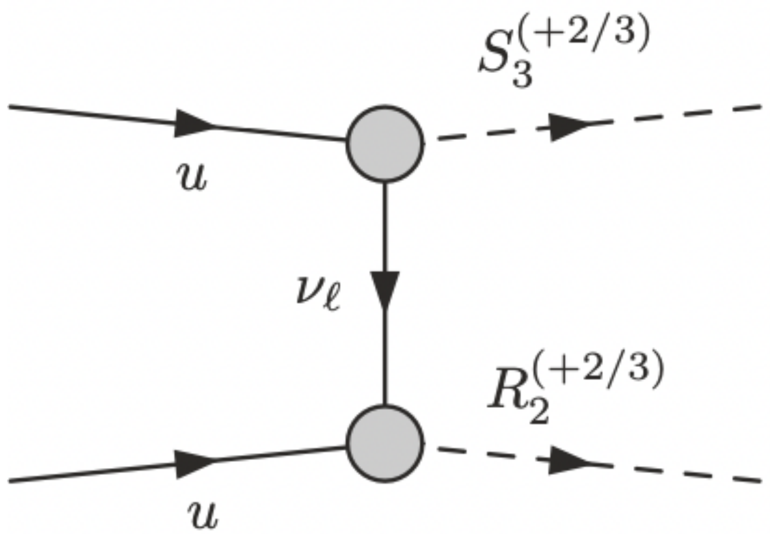
- Leptoquarks are produced at the LHC through ggF and $q\bar{q}$ annihilation (since they have color charge).
- It was pointed recently that there are novel leptoquark pair production channels through the exchange of charged leptons involving two different leptoquark mass eigenstates (Dorsner, Fajfer and Lejlic; 2103.11702).
- These channels can have large rates if the Yukawa-type couplings (y_{ij}) have moderate or large values. Depends also on the PDF…etc.



QCD-driven LQ pair production



T-channel contribution



Off-diagonal pair production

Anatomy of leptoquark pair production at the LHC

- There are three categories of off-diagonal leptoquark channels depending on the total electric charge of the final state.
- Assume $y^{\rm LL}_{3,12}$, $y^{\rm LR}_{2,12}$ and $y^{\rm RL}_{2,12}$ are non-zero and $m_{S_3} = m_{R_2}$; we expect the following proportions

- Charge $\pm 4/3$

$uu \to R_2^{(+2/3)} S_3^{(+2/3)}; uu \to R_2^{(+5/3)} S_3^{(-1/3)}$

$$\frac{\sigma[R_2^{(+5/3)} S_3^{(-1/3)}]}{\sigma[R_2^{(+2/3)} S_3^{(+2/3)}]} \approx \frac{1}{2}\left(\frac{y^{\rm LR}_{2,12}}{y^{\rm RL}_{2,12}}\right)^2$$

- Charge $\pm 1/3$

$ud \to R_2^{(+2/3)} S_3^{(-1/3)}; ud \to R_2^{(+5/3)} S_3^{(-4/3)}$

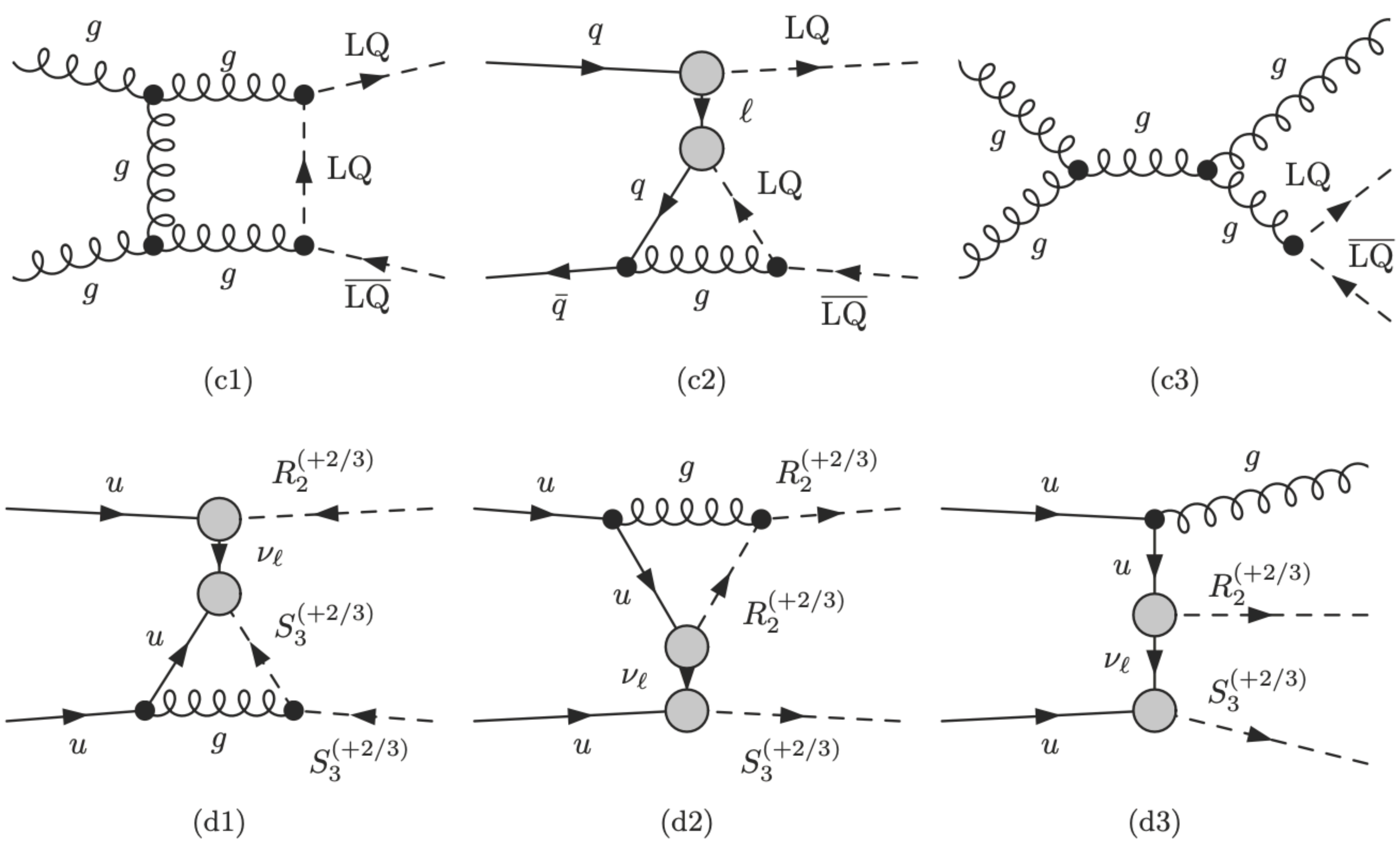
$$\frac{\sigma[R_2^{(+2/3)} S_3^{(-1/3)}]}{\sigma[R_2^{(+5/3)} S_3^{(-4/3)}]} \approx \frac{1}{2}$$

- Charge ± 1

$u\bar{d} \to R_2^{(+5/3)} R_2^{(-2/3)}; u\bar{d} \to S_3^{(+1/3)} S_3^{(+2/3)}$

$$\frac{\sigma[R_2^{(+5/3)} R_2^{(-2/3)}]}{\sigma[S_3^{(+1/3)} S_3^{(+2/3)}]} \approx \frac{1}{2}\left(\frac{y^{\rm RL}_{2,12}}{y^{\rm LL}_{3,12}}\right)^4$$

$$\sigma[pp \to X]_{Q=\pm 4/3} > \sigma[pp \to X]_{Q=\pm 1/3} > \sigma[pp \to X]_{Q=\pm 1}$$



Pur QCD corrections plus corrections involving leptons in t-channel

No box diagrams in off-diagonal channels

$$
\begin{array}{llll}
 & \sigma^{\mathrm{NLO\ w}/t\text{-channel}} = & \sigma^{(0)} & + \quad \sigma^{(1)} \\
(1): & & \mathcal{O}(\alpha_s^2) & \mathcal{O}(\alpha_s^3); \\
(2): & & \boxed{\mathcal{O}(y^4) \quad \mathcal{O}(y^4\alpha_s);} & \\
(3): & & \mathcal{O}(y^2\alpha_s) & \mathcal{O}(y^2\alpha_s^2).
\end{array}
$$

(taken from 2108.11404)

R_2 and S_3 coupling to first- and second-generation quarks

We consider first scenarios involving R_2 and S_3 leptoquarks coupling to first- and second-generation quarks

- Contribution of R_2 leptoquarks only

$$m_{R_2} = 1600 \text{ GeV} \qquad \begin{array}{l} (i)\ y = y^{\text{LR}}_{2,12} \in [0.1, 1.5]; \quad y^{\text{LR}}_{2,22} = 0 \\ (ii)\ y = y^{\text{LR}}_{2,22} \in [0.1, 1.5]; \quad y^{\text{LR}}_{2,12} = 0 \end{array}$$

Two on-diagonal channels: $R_2^{(+2/3)}R_2^{(-2/3)}; R_2^{(+5/3)}R_2^{(-5/3)}$
One off-diagonal channel: $R_2^{(\pm 5/3)}R_2^{(\mp 2/3)}$

- Models involving both R_2 and S_3 leptoquarks

$$m_{R_2} = m_{S_3} = 1600 \text{ GeV}$$

$$y^{\text{LR}}_{2,12} = y^{\text{RL}}_{2,12} = y^{\text{LL}}_{3,12} \in [0.1, 1.5]$$

Five on-diagonal channels: $R_2^{(+2/3)}R_2^{(-2/3)}, R_2^{(+5/3)}R_2^{(-5/3)}, S_3^{(+2/3)}S_3^{(-2/3)}, S_3^{(+1/3)}S_3^{(-1/3)}, S_3^{(+4/3)}R_2^{(-4/3)}$

Seven off-diagonal channel: $R_2^{(\pm 5/3)}R_2^{(\mp 2/3)}, S_3^{(\pm 1/3)}S_3^{(\pm 4/3)}, S_3^{(\pm 2/3)}S_3^{(\pm 1/3)}$
$R_2^{(\pm 2/3)}S_3^{(\mp 1/3)}, R_2^{(\pm 2/3)}S_3^{(\pm 2/3)}, R_2^{(\pm 5/3)}S_3^{(\mp 1/3)}, R_2^{(\pm 5/3)}S_3^{(\mp 4/3)}$

Benchmark scenarios addressing the flavour anomalies

Phenomenologically viable scenarios with only R_2 leptoquarks (1905.06339) addresses both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies

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

$$m_{\rm LQ} = 1000 \text{ GeV}$$

A model with R_2 and S_3 leptoquarks motivated by SU(5) GUT (1806.05869) addresses both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies and consistent with all the other measurements

	$y^{\rm LR}_{2,33}$	$y^{\rm RL}_{2,22}$	$y^{\rm RL}_{2,23}$	$y^{\rm LL}_{3,22}$	$y^{\rm LL}_{3,23}$	$y^{\rm LL}_{3,32}$	$y^{\rm LL}_{3,33}$
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

$$m_{R_2} = 1300 \text{ GeV}$$
$$m_{S_3} = 2000 \text{ GeV}$$

A model with S_1 and S_3 leptoquarks (2009.01771) addresses both $R_{K^{(*)}}$ and $R_{D^{(*)}}$ as well as muon (g-2)

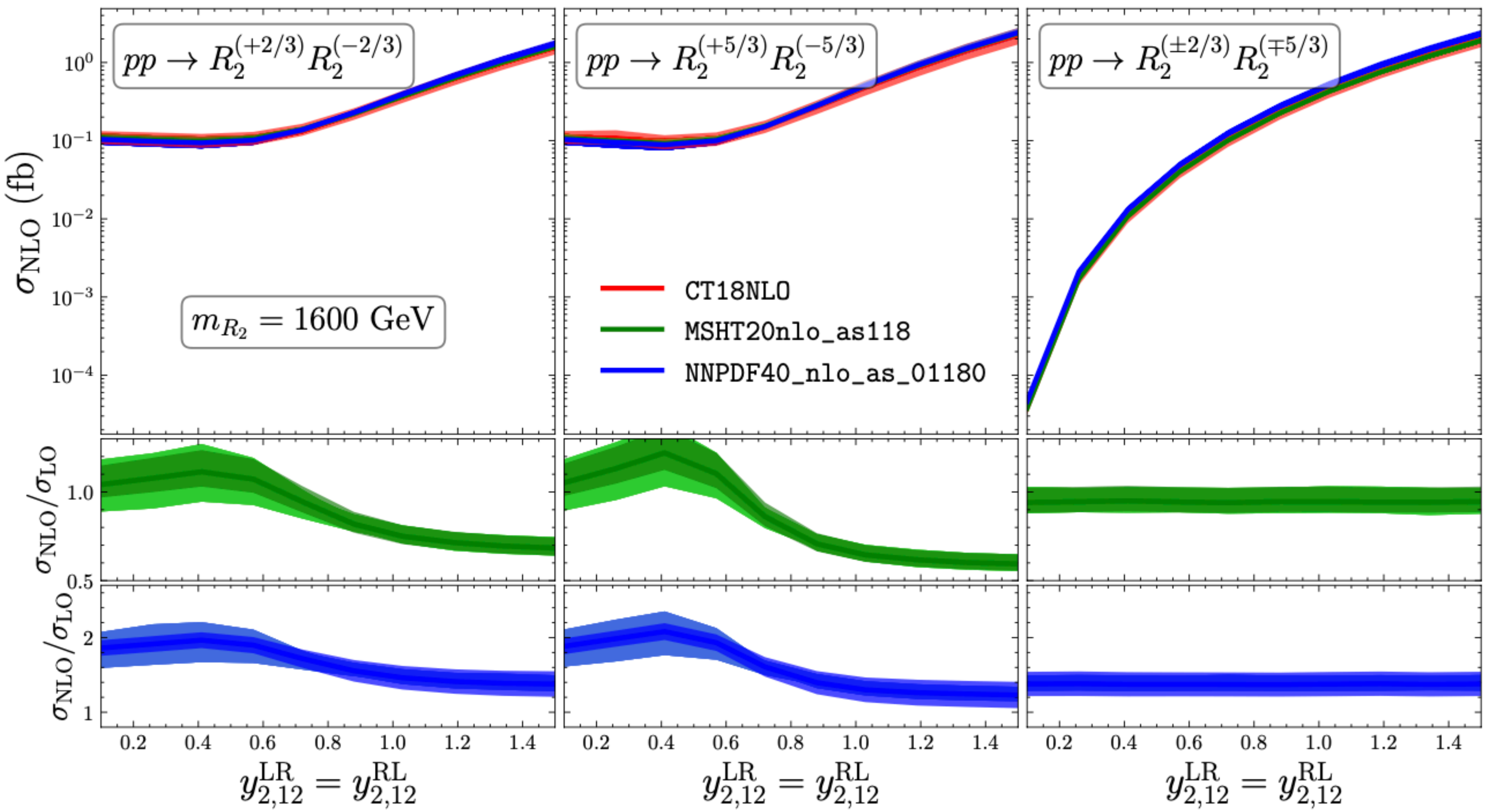
	$y^{\rm LL}_{1,22}$	$y^{\rm LL}_{1,23}$	$y^{\rm LL}_{1,32}$	$y^{\rm LL}_{1,33}$	$y^{\rm RR}_{1,23}$	$y^{\rm RR}_{1,32}$	$y^{\rm LL}_{3,22}$	$y^{\rm LL}_{3,23}$	$y^{\rm LL}_{3,32}$	$y^{\rm LL}_{3,33}$
c_1	-0.0082	-1.46	-0.016	-0.064	1.34	-0.19	-0.019	0.58	-0.059	-0.11
c_2	0.0078	1.36	-0.055	0.052	-1.47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

$$m_{S_1} = m_{S_3} = 1200 \text{ GeV}$$

Technical setup

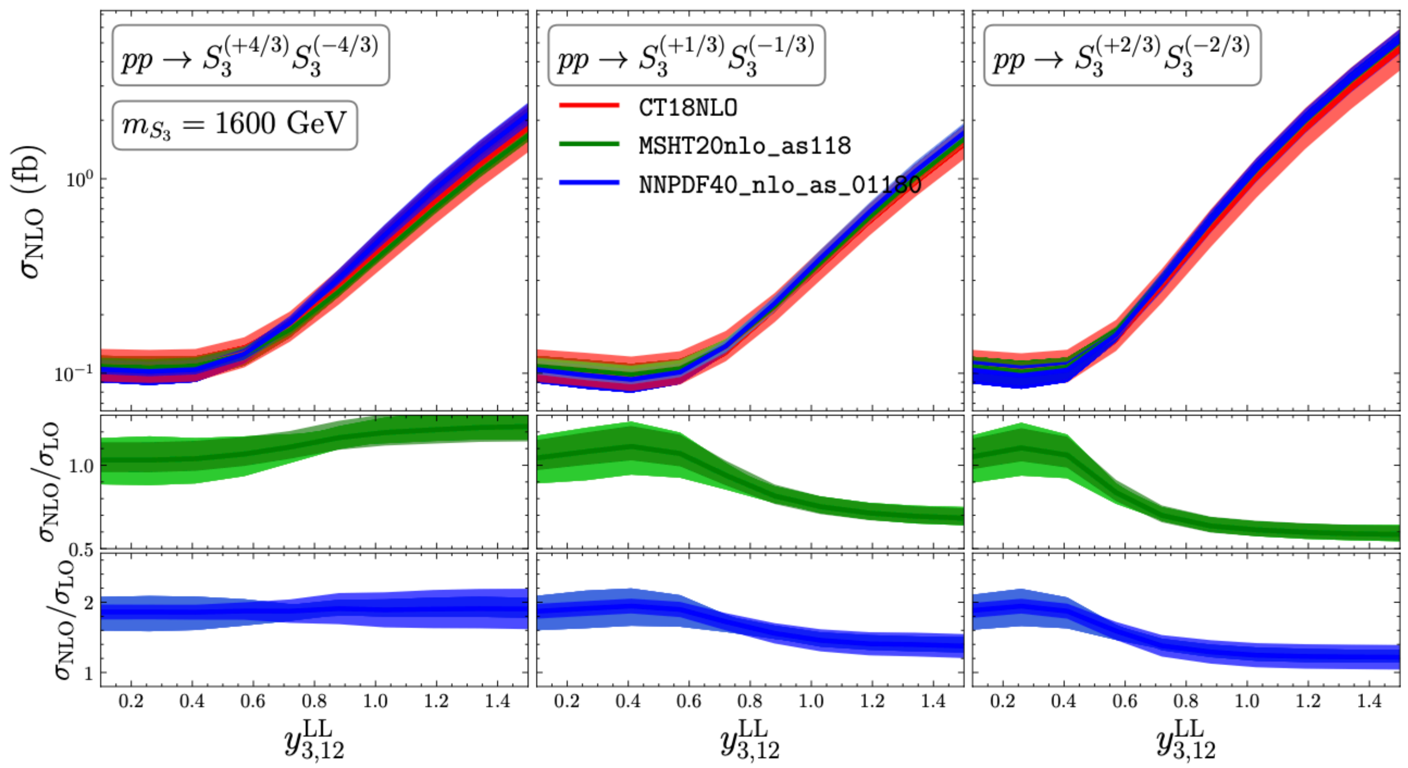
- We calculate the fixed-order cross section at LO and NLO with Madgraph5_aMC@NLO
- The model file with instructions on how to add t-channel diagrams at NLO can be found in (https://www.uni-muenster.de/Physik.TP/research/kulesza/leptoquarks.html)
- To assess the dependence on the PDF we use three NLO PDF sets (MSHT20nlo_as_0118, CT18NLO and NNPDF4.0_nlo_as_01180) and two LO PDF sets (MSHT20lo_as_0130 and NNPDF4.0_lo_as_01180)
- The calculations were done for the scale choice of $\mu_R = \mu_F = m_{\mathrm{LQ}}$
- Scale uncertainties are computed the seven-point method where variations where we vary the factorization and renormalisation by a factor 2 in the two directions while keeping their ratio to a factor of two at most.
- All the results were cross-checked by comparing with the results of POWHEG-BOX.

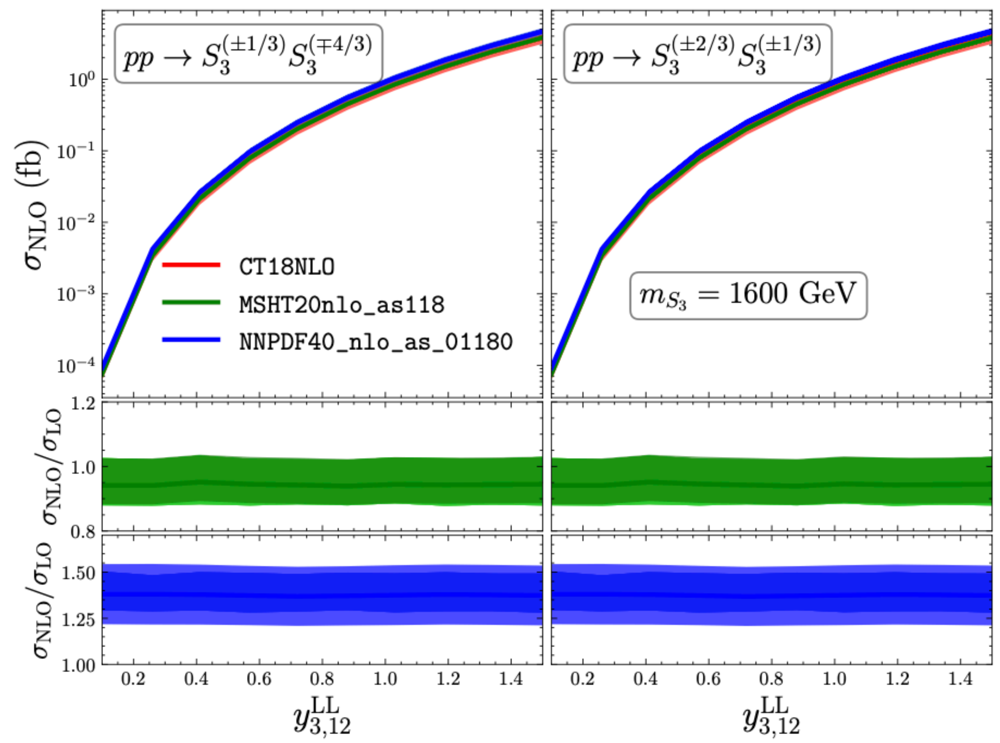
Production cross section at NLO-QCD



- K-factors are not generic and depend on the PDF set and the process.
- On-diagonal channels have a K-factor that depend on the value of y
- The K-factor of off-diagonal channel is flat.
- The rates of both on diagonal and off-diagonal channels become similar for moderate to large values of y

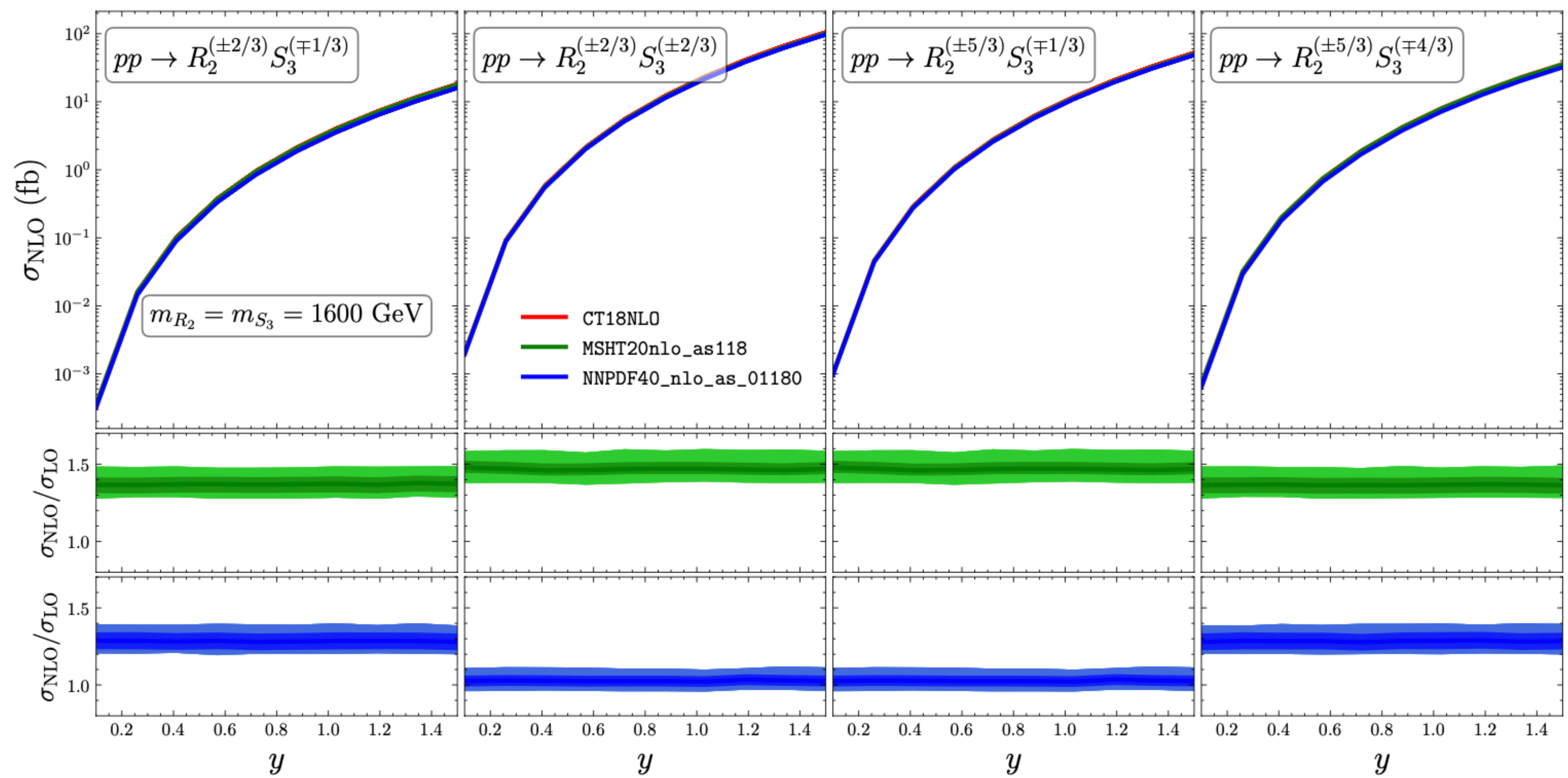
Production cross section at NLO-QCD





Same observation applies for processes involving S_3 leptoquarks only

Production cross section at NLO-QCD



- Mixed channels have a flat K-factors that range from 0.9 to 1.6.
- The rates become very large for e.g. $R_2^{(\pm 2/3)} S_3^{(\pm 2/3)} \approx 100$ fb for $y \approx 1.5$.

The role of t-channel diagrams at NLO-QCD

(i) case of models involving R_2 leptoquarks only with $y = y^{\rm LR}_{2,12} \in [0.1, 1.5]$; $\quad y^{\rm LR}_{2,22} = 0$

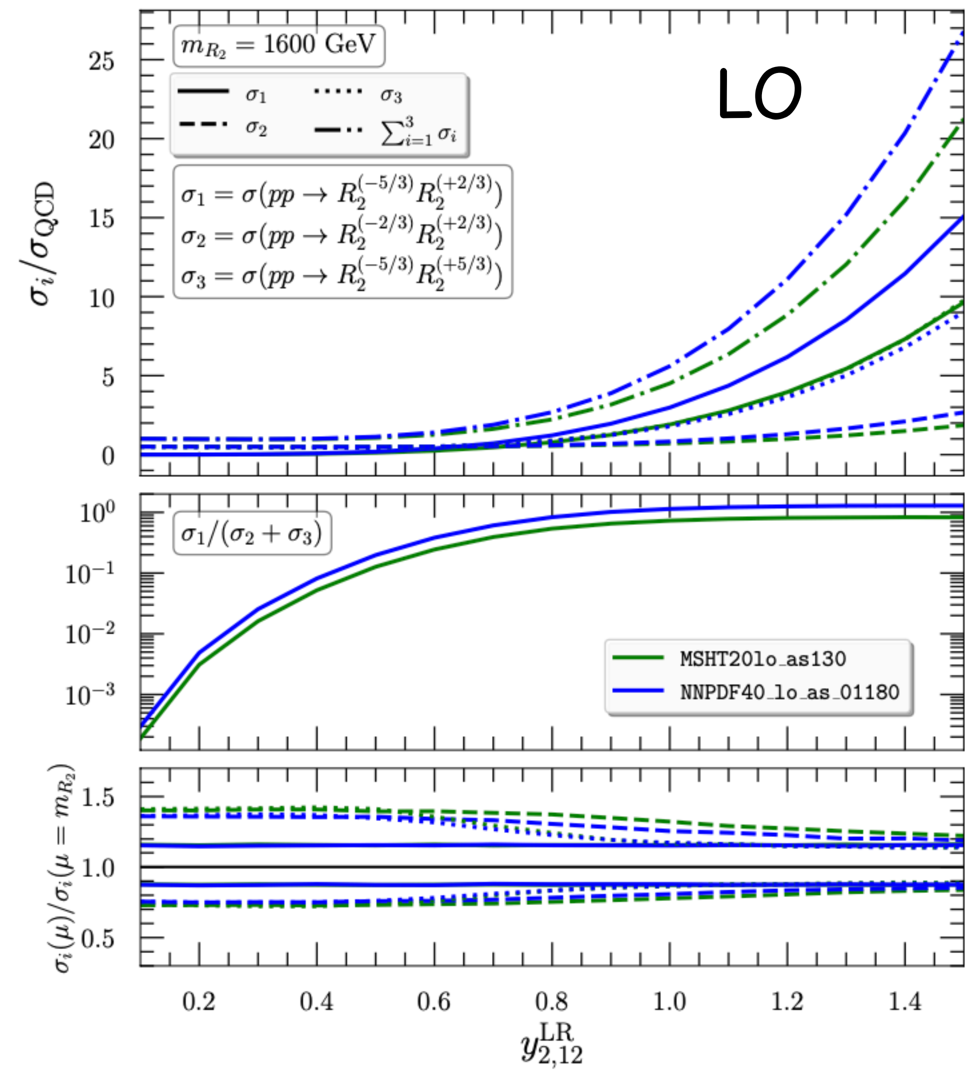
$$\sigma_1 \equiv \sigma\left[pp \to R_2^{(\pm 5/3)} R_2^{(\mp 2/3)}\right]$$

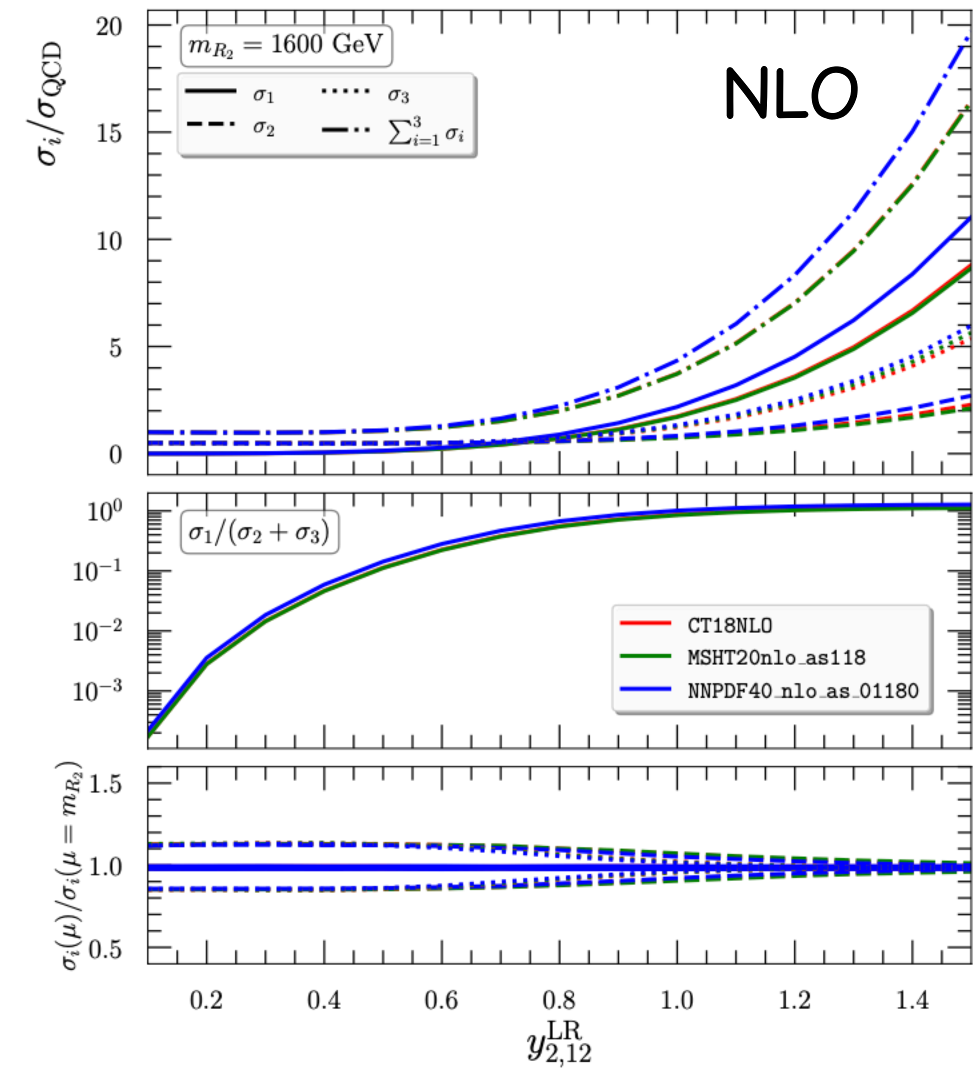
$$\sigma_2 \equiv \sigma\left[pp \to R_2^{(-2/3)} R_2^{(+2/3)}\right]$$

$$\sigma_3 \equiv \sigma\left[pp \to R_2^{(-5/3)} R_2^{(+5/3)}\right]$$

$$\sigma_{\rm QCD} \equiv \sum_i \sigma[pp \to R_2^i \bar{R}_2^i]$$

$$y^{\rm LR}_{2,ij} = y^{\rm RL}_{2,ij} = 0$$

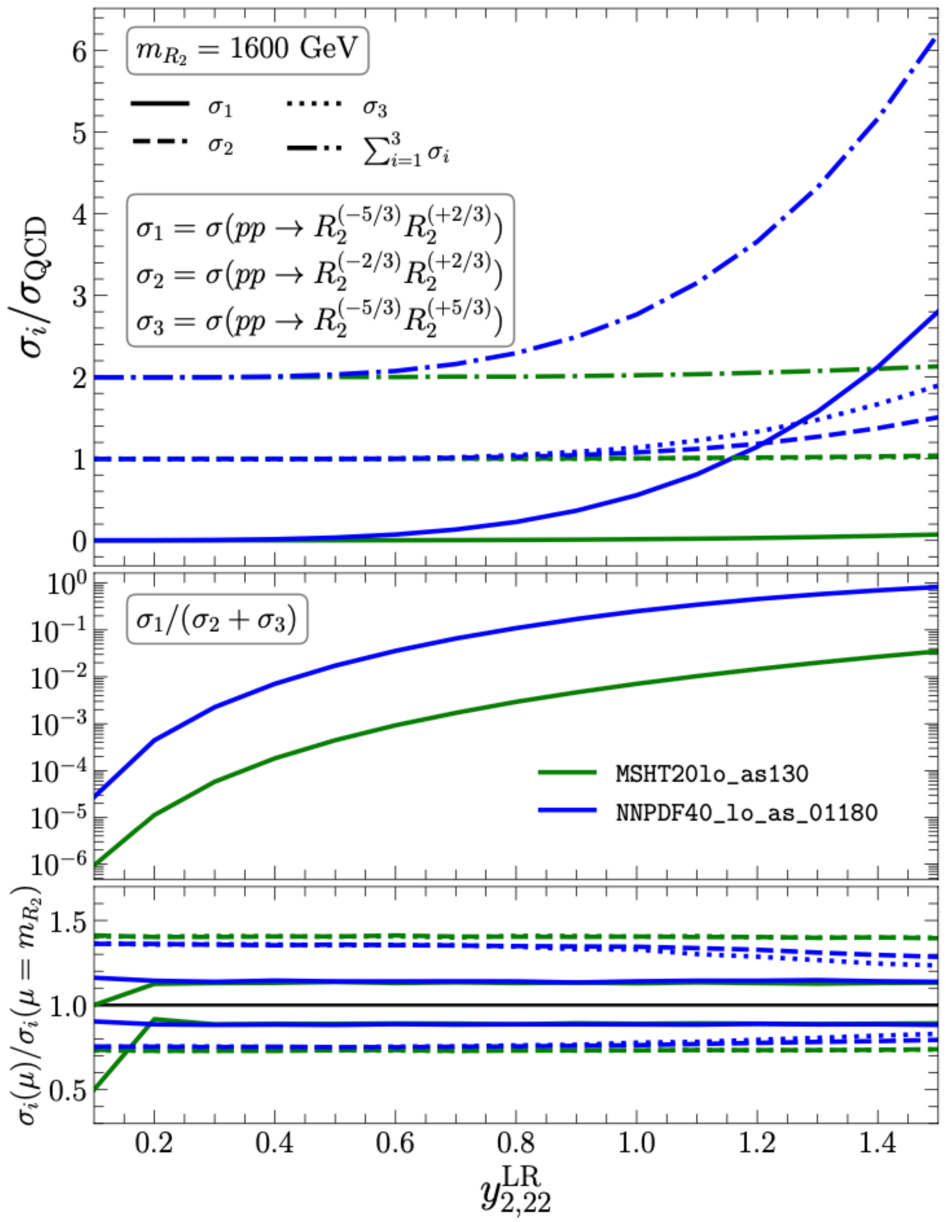


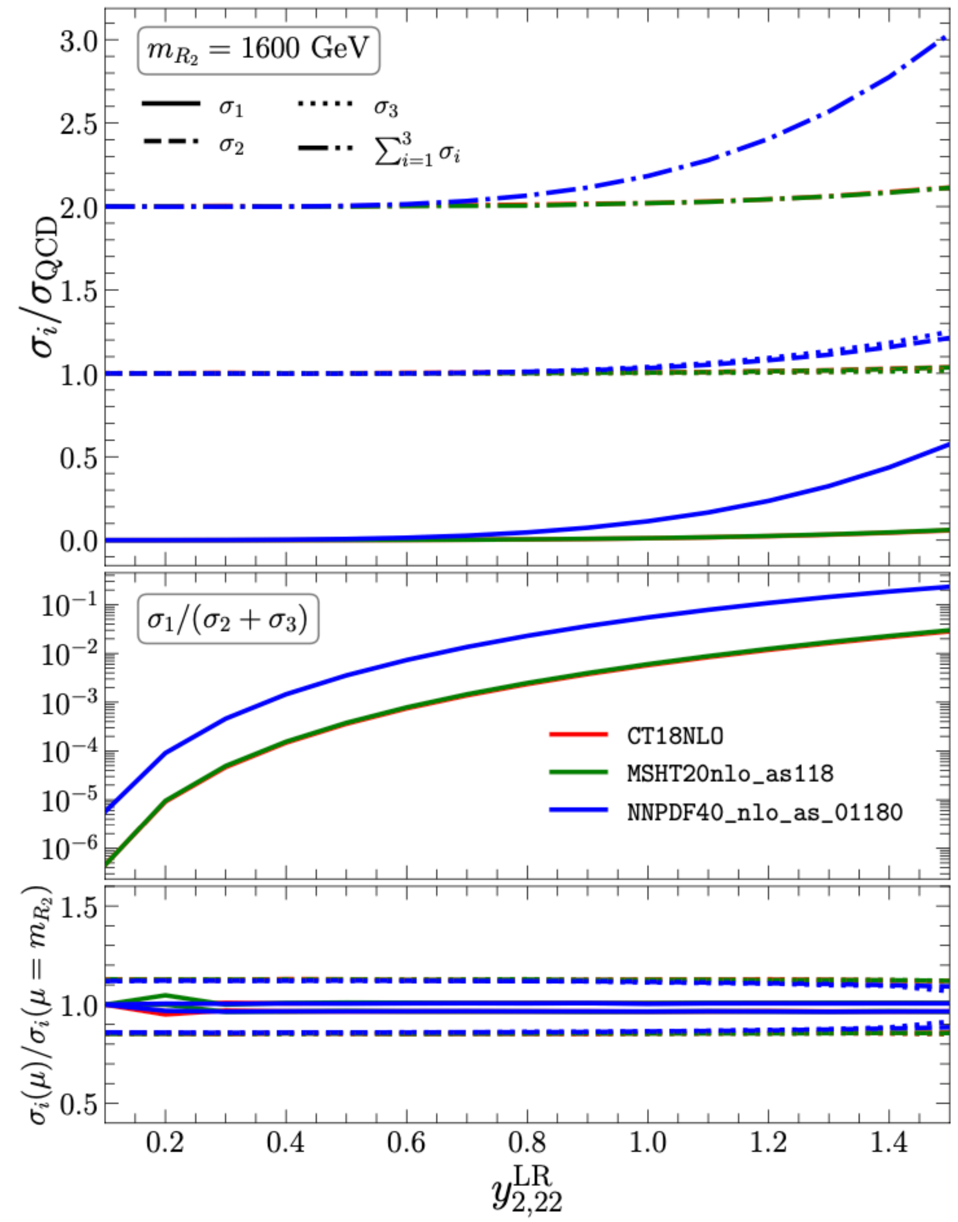


- The contribution of the t-channel, and off-diagonal channels become very large for moderate to large y
- Scale uncertainties become smaller when we go from LO to NLO.
- Agreement between PDF sets improve when we go from LO to NLO.

The role of t-channel diagrams at NLO-QCD

(ii) case of models involving R_2 leptoquarks only with $y = y_{2,22}^{\mathrm{LR}} \in [0.1, 1.5]$; $\quad y_{2,12}^{\mathrm{LR}} = 0$

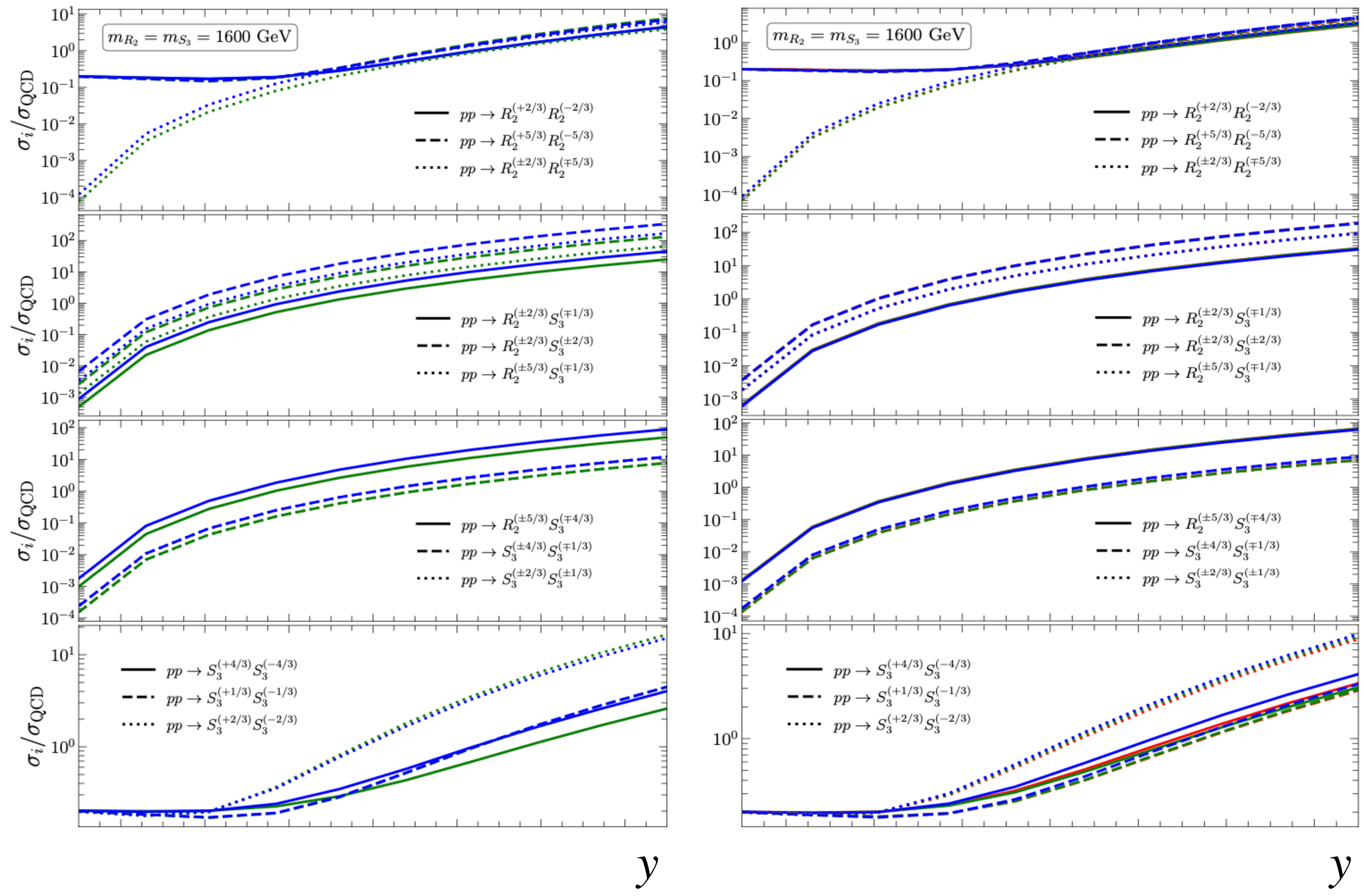




- Some disagreement between NNPDF4.0 and the two other PDF sets is observed: treatment of charm PDF?

The role of t-channel diagrams at NLO-QCD

(iii) case of models involving R_2 and S_3 leptoquarks with $y \in [0.1, 1.5]$

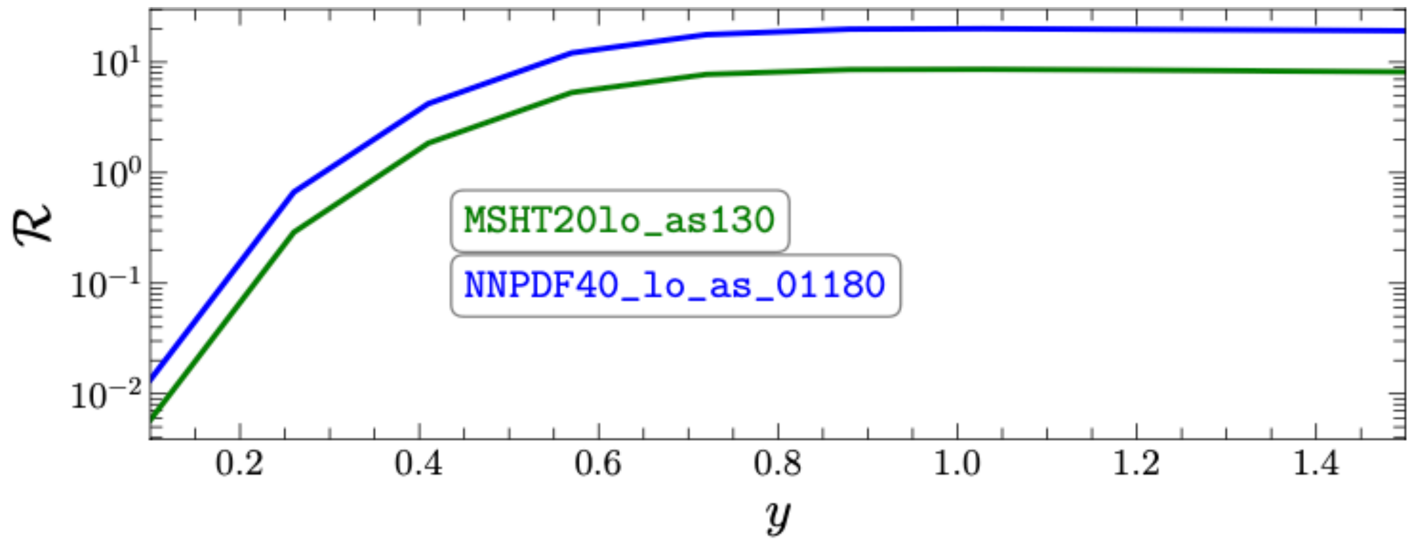


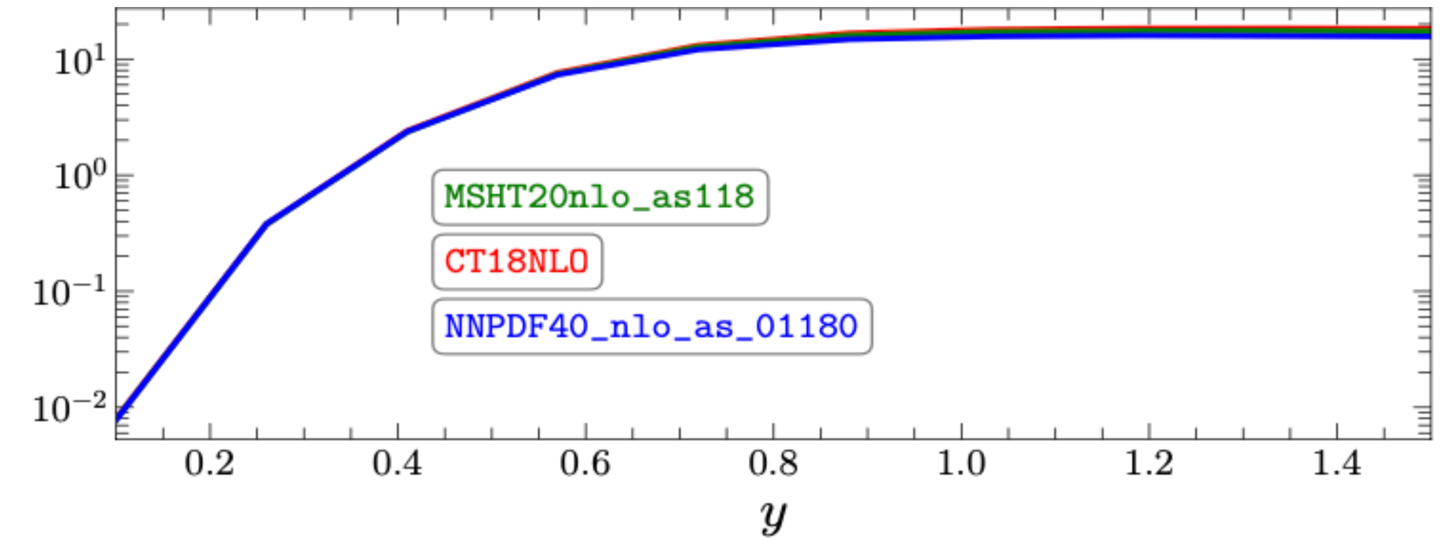
$$\sigma_{\rm QCD} = \sum_i R_2^i \bar{R}_2^i + \sum_i S_3^i \bar{S}_3^i \quad \text{for} \quad y_{2,12}^{\rm LR} = y_{2,12}^{\rm RL} = y_{3,12}^{\rm LL} = 0$$

The role of t-channel diagrams at NLO-QCD

(iii) case of models involving R_2 and S_3 leptoquarks with $y \in [0.1, 1.5]$

What about the importance of off-diagonal channels in this case?





$$\mathcal{R} = \frac{\sum_{i\neq j} \sigma\left[pp \to \mathrm{LQ}_i\,\mathrm{LQ}_j\right]}{\sum_i \sigma\left[pp \to \mathrm{LQ}_i\,\mathrm{LQ}_i\right]},$$

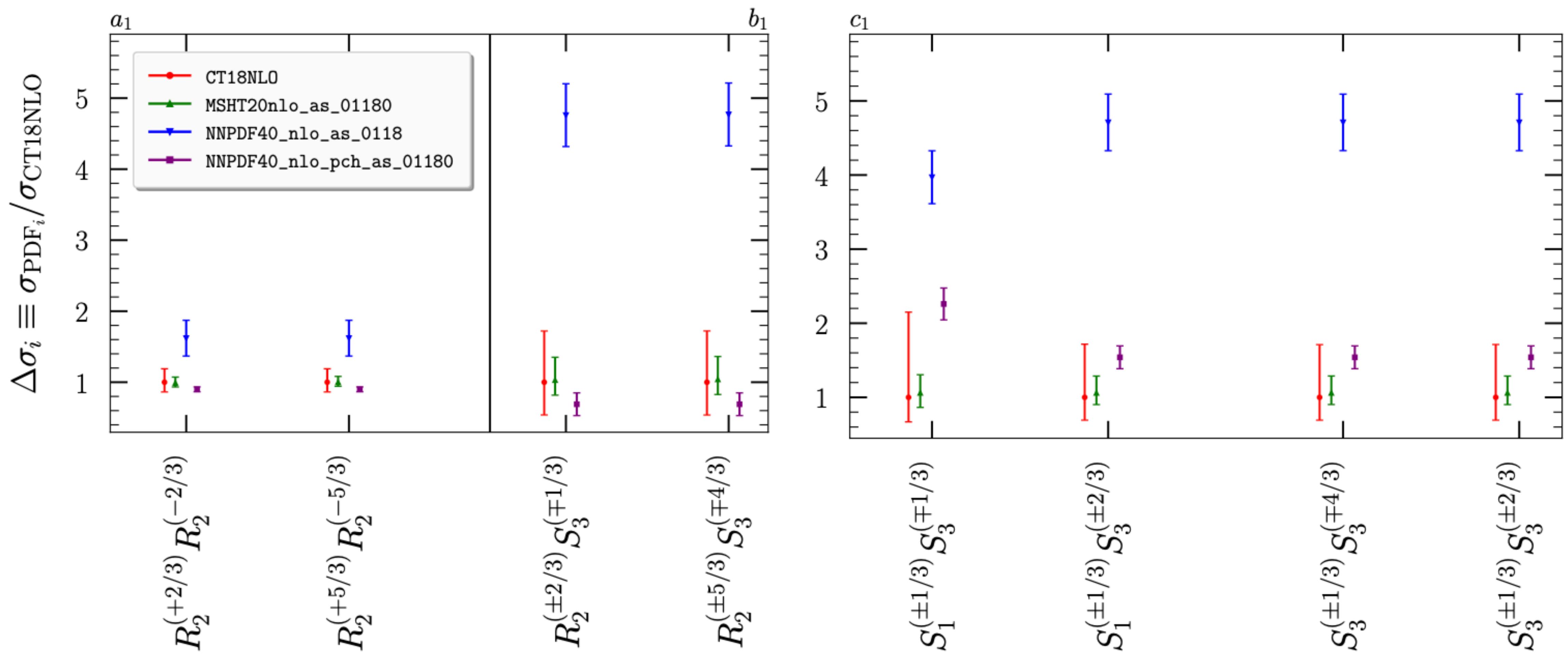
- The contribution off-diagonal channels become of order 10-20 for moderate to large y and is flat for y > 0.7.
- The agreement between the PDF sets improves at NLO.

Results for phenomenologically viable models addressing the anomalies

		CT18NLO	MSHT20_nlo_as_0118	NNPDF40_nlo_as_01180
c_1	$S_1^{(+1/3)}S_1^{(-1/3)}$	$1.45^{+10.4\%+18.7\%}_{-12.8\%-13.0\%}$	$1.47^{+12.3\%+7.8\%}_{-10.9\%-5.4\%}$	$1.78^{+6.6\%+10.8\%}_{-8.9\%-10.8\%}$
	$S_3^{(+2/3)}S_3^{(-2/3)}$	$1.35^{+11.3\%+16.3\%}_{-14.3\%-12.2\%}$	$1.36^{+12.9\%+7.1\%}_{-12.8\%-4.9\%}$	$1.30^{+10.9\%+3.5\%}_{-13.2\%-3.5\%}$
	$S_3^{(+1/3)}S_3^{(-1/3)}$	$1.35^{+11.9\%+16.3\%}_{-13.9\%-12.2\%}$	$1.36^{+13.4\%+7.1\%}_{-13.0\%-4.9\%}$	$1.29^{+10.7\%+3.5\%}_{-14.3\%-3.5\%}$
	$S_3^{(+4/3)}S_3^{(-4/3)}$	$1.35^{+11.9\%+16.4\%}_{-13.6\%-12.2\%}$	$1.37^{+12.6\%+7.1\%}_{-12.8\%-4.9\%}$	$1.30^{+10.8\%+3.5\%}_{-13.1\%-3.5\%}$
	$S_1^{(\pm1/3)}S_3^{(\mp1/3)}$	$0.036^{+4.3\%+115.0\%}_{-5.4\%-33.1\%}$	$0.038^{+10.2\%+24.5\%}_{-0.1\%-19.6\%}$	$0.14^{+4.1\%+35.7\%}_{-5.8\%-35.7\%}$
	$S_1^{(\pm1/3)}S_3^{(\pm2/3)}$	$0.032^{+4.4\%+71.7\%}_{-5.2\%-30.8\%}$	$0.034^{+9.9\%+22.7\%}_{-0.2\%-15.8\%}$	$0.15^{+4.6\%+38.2\%}_{-5.2\%-38.2\%}$
	$S_3^{(\pm2/3)}S_3^{(\pm1/3)}$	$0.0051^{+4.9\%+71.3\%}_{-4.4\%-30.8\%}$	$0.0054^{+10.7\%+22.7\%}_{-0.1\%-15.8\%}$	$0.0239^{+4.3\%+38.2\%}_{-5.7\%-38.2\%}$
	$S_3^{(\pm1/3)}S_3^{(\mp4/3)}$	$0.0051^{+4.9\%+71.1\%}_{-4.4\%-30.8\%}$	$0.0054^{+10.8\%+22.8\%}_{-0.2\%-15.7\%}$	$0.0239^{+4.5\%+38.1\%}_{-5.8\%-38.1\%}$
c_2	$S_1^{(+1/3)}S_1^{(-1/3)}$	$1.44^{+10.4\%+18.2\%}_{-12.9\%-13.0\%}$	$1.46^{+12.0\%+7.7\%}_{-11.8\%-5.3\%}$	$1.73^{+7.2\%+10.8\%}_{-9.1\%-10.8\%}$
	$S_3^{(+2/3)}S_3^{(-2/3)}$	$1.41^{+10.6\%+17.5\%}_{-13.4\%-13.0\%}$	$1.41^{+12.1\%+7.6\%}_{-12.1\%-5.3\%}$	$1.64^{+6.9\%+12.1\%}_{-10.1\%-12.1\%}$
	$S_3^{(+1/3)}S_3^{(-1/3)}$	$1.39^{+11.1\%+17.0\%}_{-13.3\%-12.5\%}$	$1.40^{+12.9\%+7.3\%}_{-11.9\%-5.0\%}$	$1.47^{+9.4\%+5.1\%}_{-11.9\%-5.1\%}$
	$S_3^{(+4/3)}S_3^{(-4/3)}$	$1.48^{+10.9\%+22.1\%}_{-12.2\%-13.0\%}$	$1.52^{+13.0\%+7.9\%}_{-9.7\%-5.5\%}$	$1.74^{+7.2\%+10.0\%}_{-9.4\%-10.0\%}$
	$S_1^{(\pm1/3)}S_3^{(\mp1/3)}$	$0.138^{+4.7\%+115.0\%}_{-5.1\%-33.1\%}$	$0.146^{+9.7\%+24.6\%}_{-0.2\%-19.7\%}$	$0.553^{+4.1\%+35.8\%}_{-5.8\%-35.8\%}$
	$S_1^{(\pm1/3)}S_3^{(\pm2/3)}$	$0.125^{+4.4\%+71.6\%}_{-6.7\%-30.9\%}$	$0.132^{+9.8\%+22.7\%}_{-0.1\%-15.8\%}$	$0.588^{+4.6\%+38.2\%}_{-5.3\%-38.2\%}$
	$S_3^{(\pm2/3)}S_3^{(\pm1/3)}$	$0.102^{+5.0\%+71.9\%}_{-4.8\%-30.8\%}$	$0.108^{+11.0\%+23.0\%}_{-0.2\%-15.8\%}$	$0.481^{+4.3\%+38.1\%}_{-5.7\%-38.1\%}$
	$S_3^{(\pm1/3)}S_3^{(\mp4/3)}$	$0.102^{+5.1\%+71.7\%}_{-4.2\%-30.9\%}$	$0.108^{+10.9\%+22.8\%}_{-0.5\%-15.8\%}$	$0.481^{+4.5\%+38.1\%}_{-5.8\%-38.1\%}$

Treatment of charm PDF

For some channels, the difference between the NNPDF4.0 and the other PDFs can be of order 2-5. Possibly treatment of charm PDF?



Using the NNPDF40_nlo_pch_as_01180 we found that we can reach very good agreement with respect to the other PDFs within the PDF errors.

Conclusions and Outlook

- We have studied scalar leptoquark pair production modes at the LHC at NLO-QCD including t-channel contributions with lepton exchange.
- New channels dubbed as off-diagonal can become competitive with on-diagonal channels for moderate to large values of the Yukawa-type couplings.
- QCD corrections at NLO result in smaller uncertainty bands and better agreement between the different PDF sets.
- Small contributions of the off-diagonal channels for scenarios addressing flavor anomalies.
- Steps are now to be made to have full NLO+PS predictions for future LHC analyses.