Soft-Gluon Resummation for Leptoquark Pair-Production at the LHC

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Work in progress together with Benjamin Fuks,
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Outline

Scalar leptoquark pair-production at the LHC

Leptoquarks Δ

- Appearing in many BSM models (e.g. RPV SUSY, GUTs)
- Relevant for flavour physics (e.g. LFU violation for B-meson decays)
- Coloured under SU(3) $\Rightarrow$ should be copiously produced at the LHC

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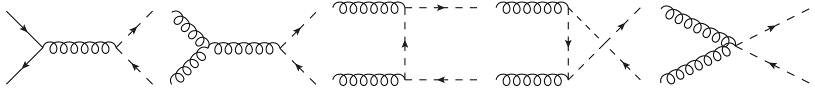

- Same diagrams as for stop-antistop ($\tilde{t}\tilde{t}^*$) production in the MSSM
- Pure QCD couplings: QCD corrections can be sizeable
- No BSM found so far: masses M_Δ in TeV range

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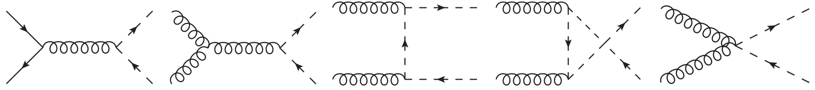

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Threshold region $\sqrt{\hat{s}} \to 2M_\Delta$ increasingly relevant

$\sqrt{\hat{s}}$: partonic centre-of-mass energy

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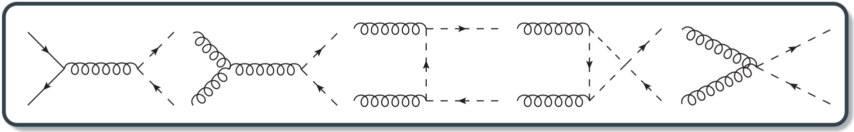

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Threshold logs $\ln \beta^2 \equiv \ln(1 - \hat{\rho})$ with $\hat{\rho} = 4M_\Delta^2/\hat{s}$ endangering perturbativity!

From factorisation to resummation

Rough idea of threshold resummation in direct QCD approach:

- Factorise **matrix element** and **phase space** into **hard**/**soft** part

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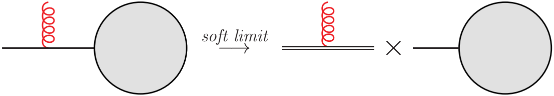

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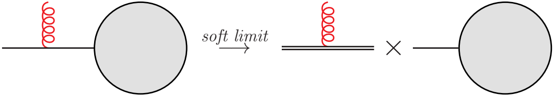

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Phase space: momentum entanglement vanishes in **Mellin space** ✓

$$\boxed{\tilde{\sigma}^{(N)} := \int_0^1 \mathrm{d}\hat{\rho}\, \hat{\rho}^{N-1}\, \sigma(\hat{\rho})}$$

N: Mellin moment

Factorised form of the cross section

Separation of enhanced terms near threshold:

$$\tilde{\sigma}^{(\text{soft+Coul})}_{ij\to kl} = \sum_{\text{colours } I} H^{(N)}_{ij\to kl,I} \times \Delta^{(N)}_i \Delta^{(N)}_j \times S^{(N)}_{ij\to kl,I} \times \mathcal{C}^{(N)}_{ij\to kl,I}$$

with

- $H^{(N)}_{ij\to kl,I}$: hard function (LO + h.o. hard-matching coefficients)
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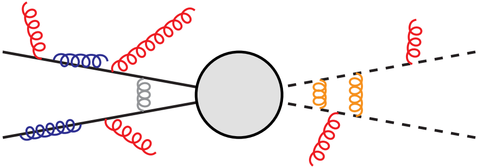

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Hard-matching coefficients (independent of N) include virtual loop corrections to the hard process

Here: approximate by using hard coefficients for $\tilde{t}\tilde{t}^*$ production

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

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$$\ln\beta^2 \xrightarrow{\text{Mellin}} \ln N =: L$$

(neglect subleading terms $\mathcal{O}(1/N)$)

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

[Kodaira, Trentadue '82][Sterman '87][Catani, D'Emilio, Trentadue '88][Catani, Trentadue '89][Kidonakis, Sterman '96]
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Factorises from H close to threshold *[Beneke, Falgari, Schwinn '09-10]*:

$$\tilde{\sigma}^{(0)}_{ij\to kl,I}\mathcal{C}^{(N)}_{ij\to kl,I} = \int_0^1 \mathrm{d}\hat{\rho}\, \hat{\rho}^{N-1} \hat{\sigma}^{(0)}_{ij\to kl,I}(\hat{\rho}) \left\{1 + D\frac{\alpha_s}{\beta} + \mathcal{O}\left(\frac{\alpha_s^2}{\beta^2}\right)\right\}$$

with $\hat{\rho} = 4M_\Delta^2/\hat{s}$, $\hat{\sigma}^{(0)}_{ij\to kl,I}$ and $\tilde{\sigma}^{(0)}_{ij\to kl,I}$ the partonic LO cross sections in physical and Mellin space

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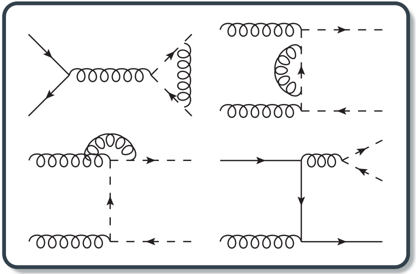
Inverse transform from Mellin-moment to physical space applying the *minimal prescription* [Catani, Mangano, Nason, Trentadue '96] and **match to NLO**:

$$\int_{\text{CT}} \mathrm{d}N\, \rho^{-N}\, \tilde{f}_i^{(N+1)}\, \tilde{f}_j^{(N+1)}\, \tilde{\sigma}^{(\text{soft+Coul})}_{ij\to\Delta\Delta^*} \longrightarrow \sigma^{\text{NLO+NNLL}}_{pp\to\Delta\Delta^*}$$

with $\rho = 4M_\Delta^2/S$, $\sqrt{S}$: hadronic centre-of-mass energy, $\tilde{f}^{(N)}$: PDFs in Mellin space

NLO corrections to scalar leptoquark pair-production



NLO corrections calculated from scratch:

- Virtual amplitudes in OS/$\overline{\text{MS}}$-scheme calculated with `FeynArts/FormCalc` *[Hahn et al. '98-'19]*
- Loop integrals numerically evaluated with `COLLIER` *[Denner, Dittmaier, Hofer '17]*
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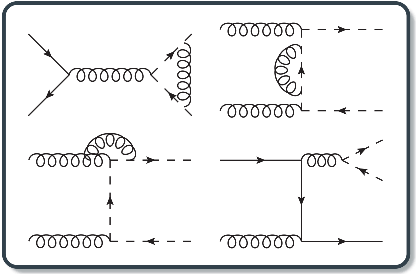

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Decoupling of heavy fields from α_s running:

- Since α_s appears already at LO, heavy fields (top, LQ) affect coefficient $\beta_0 = \frac{41}{24\pi}$ of α_s running
- To restore SM running with 5 light flavours with $\beta_0^{5\text{fl}} = \frac{23}{12\pi}$, heavy logs need to be subtracted
- Modify renormalisation constant of g_s: $\delta Z_{g_s}^{\text{dec}} = \delta Z_{g_s} - \frac{\alpha_s}{8\pi}\left[\frac{1}{6}\ln\frac{M_\Delta^2}{\mu_R^2} + \frac{2}{3}\ln\frac{m_t^2}{\mu_R^2}\right]$
- Resulting in running of α_s of: $\boxed{\mu_R^2 \frac{\mathrm{d}}{\mathrm{d}\mu_R^2}\alpha_s = -\alpha_s\left[\beta_0 - \frac{1}{4\pi}\left(-\frac{1}{6} - \frac{2}{3}\right)\right] = -\alpha_s\beta_0^{5\text{fl}}}$

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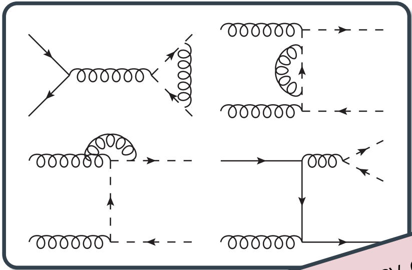

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✓ Consistency check with codes from
[Krämer, Plehn, Spira, Zerwas '05]
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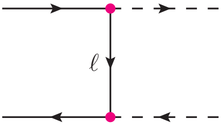
Lepton-exchange contributions

Besides pure QCD contributions, there exists the possibility of LQ pair-production via a lepton-exchange diagram:



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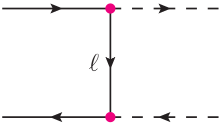

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Properties:

- Yukawa coupling λ (in general: matrix in fermion generation space)

→ Constraints from atomic parity violation for coupling between 1st gen. fermions: $|\lambda_{1st}| \lesssim 0.3$ for $M_\Delta \sim 1$ TeV *[Doršner, Fajfer, Greljo '14]*

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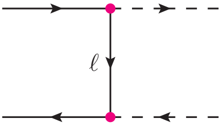

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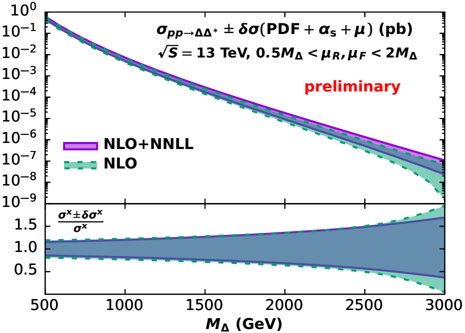
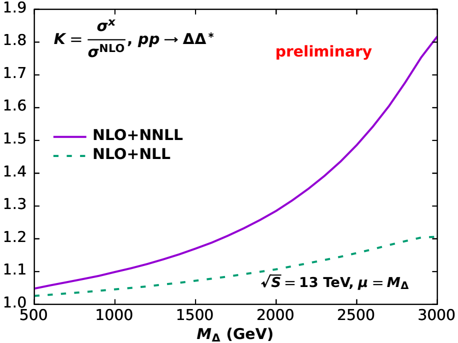
- Subleading to QCD diagrams, but of similar size as resummed corrections
- Toy model: 1 LQ coupling only to one type of quarks and leptons
- NLO QCD corrections taken into account, but no "λ-corrections"; production cross section thus containing terms:
  - ⇒ **LO**: $\mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha_s\lambda^2)$, $\mathcal{O}(\lambda^4)$
  - ⇒ **NLO**: $\mathcal{O}(\alpha_s^3)$, (approx.) $\mathcal{O}(\alpha_s^2\lambda^2)$, (approx.) $\mathcal{O}(\alpha_s\lambda^4)$

Total cross sections at NLO+NNLL accuracy





Mass dependence of cross sections

- Cross section enhanced by resummed corrections

Preliminary results!

PDF sets used: `PDF4LHC15_NLO_MC` for NLO, `PDF4LHC15_NNLO_MC` for NLO+NNLL

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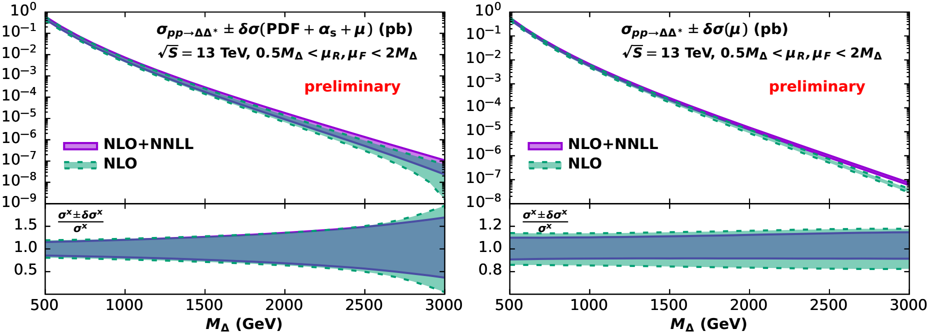

Mass dependence of cross sections

Preliminary results!

- Cross section enhanced by resummed corrections
- PDFs dominant source of uncertainty towards higher masses
- Scale error (7-point method) reduced wrt. NLO, almost independent of M_Δ

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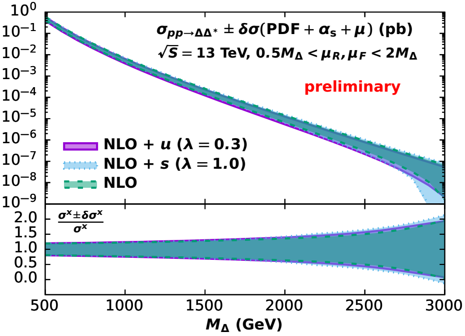
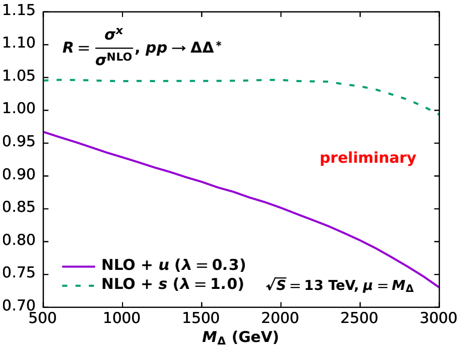
Effect of t-channel contributions on NLO





Lepton-exchange diagram

Preliminary results!

- Lepton mass negligible ($\Rightarrow$ independent of lepton properties)
- Coupling to u-quarks with λ = 0.3 leads to negative contributions of -25% at high M_Δ
- Coupling to s-quarks with λ = 1.0 leads to almost constant positive contributions of 5%

PDF sets used: `PDF4LHC15_NLO_MC` for NLO

Summary and conclusions

Leptoquarks: messengers to a varitety of BSM models

NLO+NNLL threshold resummation in Mellin-moment space

- Soft-gluon corrections become important close to the production threshold, i.e. for high masses (no new particles found so far)
- NNLL, Coulomb, and hard contributions enhance the cross section and stabilise the scale variation wrt. NLO

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