Electroweakino pair production at the LHC in NLO+NLL with resummation-improved PDFs

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Work done with J. Fiaschi
• J. Fiaschi, MK
  
  Slepton pair production at the LHC in NLO+NLL with resummation-improved parton densities
  
  JHEP 1803 (2018) 094 [1801.10357]
References

- J. Fiaschi, MK
  Slepton pair production at the LHC in NLO+NLL with resummation-improved parton densities
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- J. Fiaschi, MK
  Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II
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- J. Fiaschi, MK
  Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II

- J. Fiaschi, MK, M. Sunder
  Beyond the SM Physics at the HL-LHC and HE-LHC
  WG3 of the CERN Workshop, 1812.07831
Motivation

Supersymmetry:

- High scale: Poincaré symmetry, supergravity, string theory
- Weak scale: Hierarchy problem, unification, dark matter
- Simplified: Prototype for many more minimal BSM theories
- Actively searched for by ATLAS and CMS → Runs 3 and 4
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Theoretical calculations:

- NLO+(N)NLL for squarks, gluinos; sleptons, gauginos
- Public code RESUMMINO
- Total cross sections increased, scale dependence reduced
- PDF uncertainty still NLO, not reduced
Resummation-improved parton densities (NNPDF3.0)

M. Bonvini et al., JHEP 1509 (2015) 191

NLO+NLL calculations not available for all processes.
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Analysis with reduced data set:
- Deep-inelastic scattering
- Drell-Yan production
- Top-pair production
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Also NLO analysis with identical data set.
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Also NLO analysis with identical data set.

Particularities:
- Replica method problematic in Mellin space (need all $x$)
- Outliers produce unphysical (e.g. negative) cross sections
- Larger, not smaller uncertainty than in global analysis
NLO+NLL cross sections with global NLO+NLL PDFs


\[ K = \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO global}}}{\sigma(\text{NLO})_{\text{NLO global}}} \cdot \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO+NLL reduced}}}{\sigma(\text{NLO} + \text{NLL})_{\text{NLO reduced}}} \]
NLO+NLL cross sections with global NLO+NLL PDFs


K-factor:

\[ K = \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO} \text{ global}}}{\sigma(\text{NLO})_{\text{NLO} \text{ global}}} \cdot \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO} + \text{NLL} \text{ reduced}}}{\sigma(\text{NLO} + \text{NLL})_{\text{NLO} \text{ reduced}}} \]

(Approximate) NLO+NLL cross sections with NLO+NLL PDFs:

\[ \sigma(\text{NLO} + \text{NLL})_{\text{NLL} + \text{NLO} \text{ global}} = K \cdot \sigma(\text{NLO})_{\text{NLO} \text{ global}} \]
NLO+NLL cross sections with global NLO+NLL PDFs


K-factor:

\[ K = \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO global}}}{\sigma(\text{NLO})_{\text{NLO global}}} \cdot \frac{\sigma(\text{NLO} + \text{NLL})_{\text{NLO+NLL reduced}}}{\sigma(\text{NLO} + \text{NLL})_{\text{NLO reduced}}} \]

(Approximate) NLO+NLL cross sections with NLO+NLL PDFs:

\[ \sigma(\text{NLO} + \text{NLL})_{\text{NLL+NLO global}} = K \cdot \sigma(\text{NLO})_{\text{NLO global}} \]

(Approximate) NLO+NLL global PDF error:

- Vary NLO global PDFs in \( \sigma(\text{NLO})_{\text{NLO global}} \)
- Eliminate replicas with unphysical behaviour
- Vary scales with 7-point method directly in \( \sigma(\text{NLO} + \text{NLL}) \)
- Add in quadrature for total uncertainty
NLO+NLL cross sections with global NLO+NLL PDFs


K-factor:

\[ K = \frac{\sigma(NLO + NLL)_{NLO \ \text{global}}}{\sigma(NLO)_{NLO \ \text{global}}} \cdot \frac{\sigma(NLO + NLL)_{NLO+NLL \ \text{reduced}}}{\sigma(NLO + NLL)_{NLO \ \text{reduced}}} \]

(Approximate) NLO+NLL cross sections with NLO+NLL PDFs:

\[ \sigma(NLO + NLL)_{NLL+NLO \ \text{global}} = K \cdot \sigma(NLO)_{NLO \ \text{global}} \]

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Similar definition for \( d\sigma/dM_{\ell\ell} \).
Application to electroweak SUSY searches at the LHC

Minimal Supersymmetric Standard Model:

- Universality of soft SUSY-breaking masses (pMSSM)
- Natural SUSY spectrum $\rightarrow$ Higgsino masses below 1 TeV
- Compressed spectrum $\left( m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_0^2} \simeq m_{\tilde{\chi}_1^0} \right)$
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Processes in RESUMMINO:

- $pp \rightarrow \tilde{\ell}\tilde{\ell}^*$ ($\ell = e, \mu$), $\tilde{\tau}_R\tilde{\tau}_R^*$, $\tilde{\tau}_1\tilde{\tau}_1^*$
- $pp \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp$, $\tilde{\chi}_i^\pm \tilde{\chi}_j^0$, $\tilde{\chi}_i^0 \tilde{\chi}_j^0$ ($i, j = 1, 2$)
- Also $pp \rightarrow \tilde{g}\tilde{\chi}_j^{\pm,0}$, $\tilde{q}_i\tilde{\chi}_j^{\pm,0}$ (in progress), $pp \rightarrow Z' \rightarrow \ell\ell$
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Minimal Supersymmetric Standard Model:

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Processes in RESUMMINO:

- \( pp \rightarrow \tilde{\ell}\tilde{\ell}^* \) (\( \ell = e, \mu \)), \( \tilde{\tau}_R\tilde{\tau}_R^*, \tilde{\tau}_1\tilde{\tau}_1^* \)
- \( pp \rightarrow \tilde{\chi}_i^\pm\tilde{\chi}_j^\mp, \tilde{\chi}_i^\pm\tilde{\chi}_j^0, \tilde{\chi}_i^0\tilde{\chi}_j^0 \) (\( i, j = 1, 2 \))
- Also \( pp \rightarrow \tilde{g}\tilde{\chi}_j^{\pm,0}, \tilde{q}_i\tilde{\chi}_j^{\pm,0} \) (in progress), \( pp \rightarrow Z' \rightarrow \ell\ell \)

Experimental signatures:

- \( \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow W^{\pm}\tilde{\chi}_1^0 \rightarrow \ell\bar{\nu}\tilde{\chi}_1^0, \tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0 \rightarrow \ell\ell\tilde{\chi}_1^0 \)
- Soft leptons, moderate \( E_T \)
- Branching ratios, efficiencies to be added by ATLAS, CMS
Invariant mass distribution for left-handed slepton pairs


At the peak, NLO increases LO by 16%, NLL in addition by 2-3%.

Red: Full K-factor. Blue: PDFs only, partially compensated by MEs.
Total cross section for left-handed slepton pairs


ATLAS/CMS limits ($\mathcal{L} = 35 - 50 \text{ fb}^{-1}$): $m_{\tilde{\ell}^{L(R)}} > 400$ (290) GeV. NLO+NLL cross sections with NLO+NLL PDFs smaller by $\sim 4\%$. 

$pp \rightarrow \tilde{\ell}^+ \tilde{\ell}^- @ \sqrt{s} = 13 \text{ TeV}$
Total cross sections for right-handed and max. mixed staus


Right-handed staus: Smaller by almost a factor 3.
Maximally mixed staus: Smaller by about a factor 2.
Similar behaviour of higher-order corrections.
$$\mu = 200 \text{ GeV} < M_{1,2} = 1 \text{ TeV}, \ m_{\tilde{\chi}^0_2 - \tilde{\chi}^\pm_1} \approx m_{\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1} \approx 5 \text{ GeV}.$$  
At low $M_{\tilde{\chi} \tilde{\chi}}$, NLO increases LO by 20%, NLL in addition by 1-4%.
Total cross sections for positive and negative higgsinos

J. Fiaschi, MK, PRD 98 (2018) 055014

Positive charginos have larger $\sigma$, increased by NLO+NLL PDFs. Negative charginos have smaller $\sigma$, reduced by NLO+NLL PDFs.
Invariant mass distribution for heavier gauginos

J. Fiaschi, MK, PRD 98 (2018) 055014

\[ pp \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^+_1 \ @ \ \sqrt{s} = 13 \text{ TeV} \ (m_{\tilde{\chi}^0_2} = 784 \text{ GeV}) \]

NLO increases LO by 30-80%, NLL in addition by 6-10%.
Winos considerably heavier than higgsinos \(\rightarrow\) closer to threshold.
Total cross section for heavier gauginos

J. Fiaschi, MK, PRD 98 (2018) 055014

Small effect from resummation in PDFs.
Summary

- RESUMMINO with new NLO+NLL PDFs \[1507.01006\]
- Should lead to smaller PDF uncertainties
- Reduced data set leads to larger (!) PDF uncertainties
- Best of both worlds using $K$-factor prescription \[1510.00375\]
Summary

• RESUMMINO with new NLO+NLL PDFs [1507.01006]
• Should lead to smaller PDF uncertainties
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• Best of both worlds using $K$-factor prescription [1510.00375]

• Cross sections increase from 7 (8) TeV to 13 (27) TeV [1812.07831]
• Large cross sections for left-handed sleptons/light higgsinos
• Large NLL corrections in particular for heavy winos
• NLL in MEs partially compensated by NLL in PDFs