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Squark Pair Production at NLO matched with Parton Showers

arXiv:1305.4061

in collaboration with R. Gavin, C. Hangst, M. Krämer, M. Mühlleitner, M. Pellen and M. Spira
Eva Popenda | 29.08.2013

Introduction

- Major task at the LHC: Direct Search for supersymmetric particles and determination of their properties
- Main production channels: Coloured sparticles $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$
- In the currently tested mass region: $\tilde{q}\tilde{q}$ production dominant channel

[Falgari, Schwinn & Wever, '12]

- Status: QCD NLO predictions for cross sections of pair produced sparticles by PROSPINO *[Beenakker, Hopker, Spira & Zerwas, '96]*

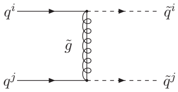
  - Squark masses assumed to be degenerate
  - Various subchannels not treated individually
  - (Differential) K-factors assumed to be flat

- Here: Squark pair production at NLO
  - ➡ Without any assumptions on mass spectrum
  - ➡ Embedded in fully differential partonic Monte Carlo program
  - ➡ Matched with Parton Showers in the POWHEG-BOX

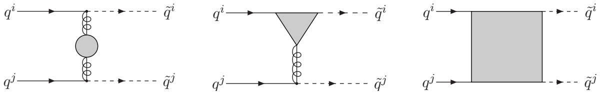
[Frixione, Nason, Oleari & Re, '10]

Elements of the NLO calculation I

Tree level



Virtual corrections



UV divergent

[FeynArts, FormCalc, LoopTools]

Dimensional regularization: $D = 4 - 2\epsilon$

Mismatch between fermionic and bosonic degrees of freedom $\rightarrow$ Breaks SUSY
SUSY restoring counterterm:

$$\hat{g}_s = g_s(1 + \alpha_s/3\pi)$$

Renormalization:

- Mass and field renormalization in on-shell scheme
- Strong coupling constant in $\overline{MS}$ scheme: $\tilde{g}_s^{(0)} = g_s + \delta g_s$

  Decouple heavy particles from running of α_s to match experimental value

$$\delta g_s = \frac{\alpha_s}{8\pi}\left[\beta_0\left(-\Delta + \log\frac{Q^2}{\mu^2}\right) - 2\log\frac{m_{\tilde{g}}^2}{Q^2} - \frac{2}{3}\log\frac{m_t^2}{Q^2} - \sum_{i=1,12}\frac{1}{6}\log\frac{m_{\tilde{q}_i}^2}{Q^2}\right]$$

Elements of the NLO calculation II

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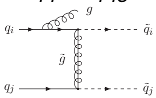
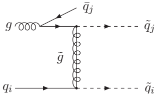
Real corrections $qq \to \tilde{q}\tilde{q}g$ $qg \to \tilde{q}\tilde{q}\bar{q}$



soft + collinear
Divergencies



collinear
Divergencies

[Madgraph]

Catani-Seymour subtraction formalism

$$\sigma_{NLO} = \int d\Phi_3 \, d\sigma^R + \int d\Phi_2 \, d\sigma^V$$

$\rightarrow$ Monte Carlo implementation technically difficult:
Cancellation between integrated phase spaces of different multiplicities

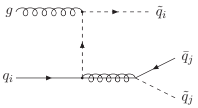
$$\sigma^{NLO} = \int d\Phi_3 \, [d\sigma^R - d\sigma^A] + \int d\Phi_2 \, [d\sigma^V + \int d\Phi_1 d\sigma^A]$$

- $d\sigma^A$ same singular behaviour as $d\sigma^R$
- Integration over one-parton subspace analytically
- Cancel divergencies, carry out remaining integration numerically

[Catani, Seymour '97]
[Catani, Dittmaier, Seymour, Trocsanyi '02]

Elements of the NLO calculation III

For $m_{\tilde{q}_j} < m_{\tilde{g}}$:
Resonant $\tilde{q}\tilde{g}$ production with subsequent decay



$$|M_{qg}|^2 = |M_{nr}|^2 + 2 \cdot \mathrm{Re}(M_r M_{nr}^*) + |M_r|^2$$

On-shell subtraction methods

- Diagram removal - type I (DR): $|M_{qg}|^2 \approx |M_{nr}|^2$
- Diagram removal - type II (DR-II): $|M_{qg}|^2 \approx |M_{nr}|^2 + 2 \cdot \mathrm{Re}(M_r M_{nr}^*)$
- Diagram subtraction (DS):

  Remove resonant contribution for $(p_{\tilde{q}_j} + p_{\bar{q}_j})^2 \to m_{\tilde{g}}^2$ by a local counterterm $d\sigma_{\text{sub}}$

  $\to$ Gauge invariant in the limit $\Gamma_{\tilde{g}} \to 0$
  $\to$ Ideal for MC event generators

$$d\sigma_{\text{sub}} = \Theta(\sqrt{\hat{s}} - m_{\tilde{g}} - m_{\tilde{q}_i}) \cdot \Theta(m_{\tilde{g}} - m_{\tilde{q}_j}) \cdot |M_r(\tilde{\Phi}_3)|^2 \cdot \frac{m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}{(m_{\tilde{q}_j \bar{q}_j}^2 - m_{\tilde{g}}^2)^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2} \cdot d\tilde{\Phi}_3$$

Modified DS scheme for fully gauge invariant result $\to$ arXiv:1305.4061

NLO Results I

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K-factors in individual subchannels

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}}$$

PROSPINO: NLO cross sections of individual subchannels obtained by scaling LO cross sections with global K-factor of the total cross section

$\rightarrow$ Is the K-factor constant in the various subchannels?

$$m_{\tilde{q}} = 1800 \text{ GeV} \qquad m_{\tilde{g}} = 1600 \text{ GeV} \qquad \sqrt{s} = 8 \text{ TeV}$$

Channel	$\tilde{u}_L \tilde{u}_L$	$\tilde{u}_L \tilde{u}_R$	$\tilde{u}_L \tilde{d}_L$	$\tilde{u}_L \tilde{d}_R$	$\tilde{d}_L \tilde{d}_L$	$\tilde{d}_L \tilde{d}_R$	Sum
K-Factor	1,10	1,17	1,21	1,22	1,19	1,30	1,16

- K-factors vary in a range of 20 %
- Independent treatment reasonable: different channels have different kinematic distributions

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Differential *K*-factors on Production Level

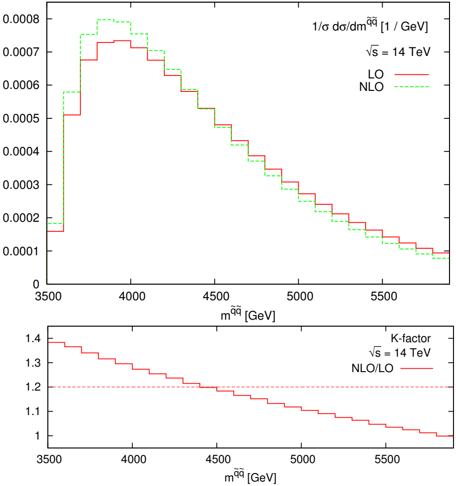
So far:

- NLO corrections have no impact on shape of distributions
- NLO distributions obtained by scaling LO distributions with the global *K*-factor

$$m_{\tilde{q}} \approx 1800 \text{ GeV} \quad m_{\tilde{g}} = 1602 \text{ GeV}$$

$$\sqrt{s} = 14 \text{ TeV}$$

- Differential *K*-factor varies in a range of 40%
- NLO corrections can change shape of distributions
- Full NLO distributions should be taken into account



NLO Results III

Differential K-factors with Decays

- Shortest decay chain: $\tilde{q} \to q + \tilde{\chi}_1^0$

$\mathrm{BR}(\tilde{u}_L \to u\tilde{\chi}_1^0)$	$\mathrm{BR}(\tilde{u}_R \to u\tilde{\chi}_1^0)$
0.001	0.566

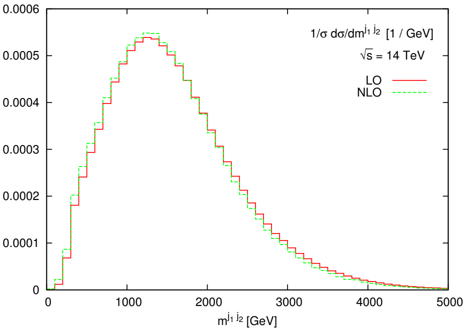
$\mathrm{BR}(\tilde{u}_L \to u\tilde{\chi}_1^0)$	$\mathrm{BR}(\tilde{u}_R \to u\tilde{\chi}_1^0)$
0.012	0.254

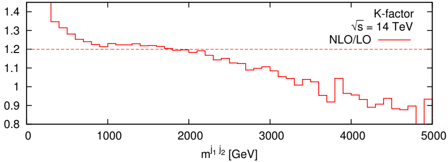
- Partons clustered with anti-k_T algorithm with $R = 0.4$ *[FastJet 3.0.3]*
- Jets required to fulfil

$$p_T^j > 20 \text{ GeV}, \quad |\eta^j| < 2.8$$

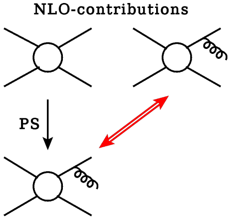
- Distribution inherits strong phase space dependence observed at production level

[Hollik, Lindert & Pagani, '12]





Matching $\tilde{q}\tilde{q}$ Production in the POWHEG-BOX



- Realistic predictions for measurements:
  Combination of NLO parton level results with Parton Showers
- Avoid double-counting:
  Contributions in real parts of NLO result and radiation added by shower
- POWHEG method: *[Nason, '04; Frixione, Nason & Oleari, '07]*
  Generate hardest emission first, maintain full NLO accuracy and add subsequent radiation with p_T-vetoed shower
- Process-independent parts (generation of first emission & subtraction of IR divergencies) automatized in POWHEG-BOX *[Frixione, Nason, Oleari & Re, '10]*
- Process-dependent parts have to be provided (colour flows, flavours structures, Born & colour-correlated Born amplitudes squared, finite part of virtual corrections, real amplitudes squared)

  ➡ Independent check of implementation of NLO calculation

Effects of different Parton Showers

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- LHE files obtained from POWHEG-BOX interfaced with
  - ➡ PYTHIA 6 (version 6.4.26): *[Sjostrand, Mrenna & Skands, '06]*
    I Usage of p_T-ordered shower, Perugia 0 tune
  - ➡ HERWIG++ (version 2.6.1): *[Bahr et al, '08; Arnold et al, '12]*
    IIa p_T-ordered Dipole shower
    IIb Angular-ordered default shower with p_T-veto (w/o soft, wide-angle radiation)

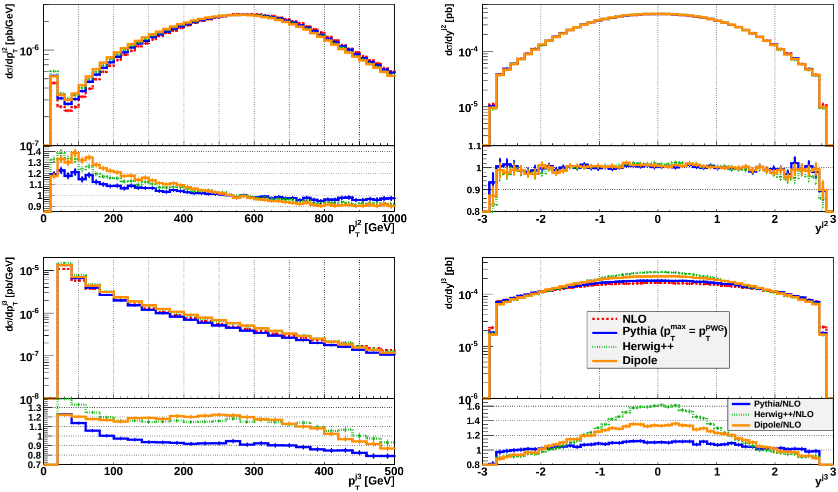
- Decays $\tilde{q} \to q + \tilde{\chi}_1^0$ performed by shower programs directly

  Check of distributions after decay with independent NLO implementation

  - ➡ PYTHIA: Performs decays during showering stage
    Radiation off decay independent from radiation related to production
    Starting scale for shower related to mass of decaying particle
  - ➡ HERWIG++: Performs decays before parton shower
    p_T^{PWG} applied for radiation related to production and decay
    Starting scale for shower much smaller than in PYTHIA

  We have set p_T^{PWG} as starting scale for all types of radiation

Effects of different Parton Showers



Conclusions

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Summary

- Squark pair production at NLO completed
- Treating different subchannels independently reasonable
- Important to take full NLO distributions into account
- Comparison to implementation in POWHEG BOX
- Output interfaced to PYTHIA, Dipole and default shower of HERWIG++
- Sizebale differences for 3rd jet could be traced back to ISR

Outlook

- Combine with decay $\tilde{q} \to q\tilde{\chi}_1^0$ at NLO
- Study phenomenological effects with full NLO accuracy
- Calculate and implement other processes: Keep track of spin information

Gauge invariant on-shell subtraction scheme

- Gauge dependent matrix elements no longer used as building blocks
- Instead: extract poles in $(p_{\tilde{q}_j} + p_{\bar{q}_j})^2 - m_{\tilde{g}}^2 = s_{jg}$ analytically
  Introducing $\Gamma_{\tilde{g}}$ preserves gauge invariance

$$|M_{tot}|^2 = \frac{f_0}{s_{jg}^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2} + \frac{s_{jg}}{s_{jg}^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}\, f_1 + f_2(s_{jg})$$

➡ Measure for gauge dependence

$$\Delta(\Gamma_{\tilde{g}}, s_{jg}) = \tilde{f}_2(s_{jg})\, \frac{m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}{s_{jg}^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}$$

- Subtraction term in both schemes identical

$$d\sigma_{\text{sub}} = \Theta(\sqrt{\hat{s}} - m_{\tilde{g}} - m_{\tilde{q}_i}) \cdot \Theta(m_{\tilde{g}} - m_{\tilde{q}_j}) \cdot \frac{f_0(\tilde{\Phi}_3)}{(m_{\tilde{q}_j\bar{q}_j}^2 - m_{\tilde{g}}^2)^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2} \cdot d\tilde{\Phi}_3$$

$$m_{\tilde{q}_j\bar{q}_j}^2 \to m_{\tilde{g}}^2 : \qquad |M_r(\tilde{\Phi}_3)|^2 \cdot m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2 \to f_0(\tilde{\Phi}_3)$$

Elements of the NLO calculation IV

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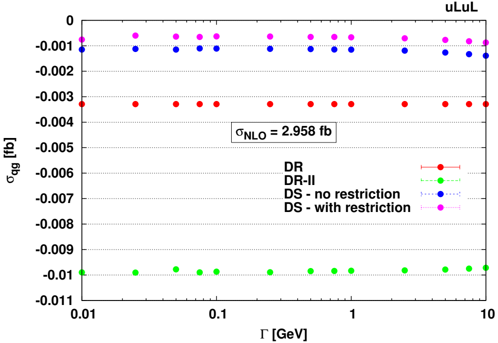
Comparison of different on-shell subtraction methods



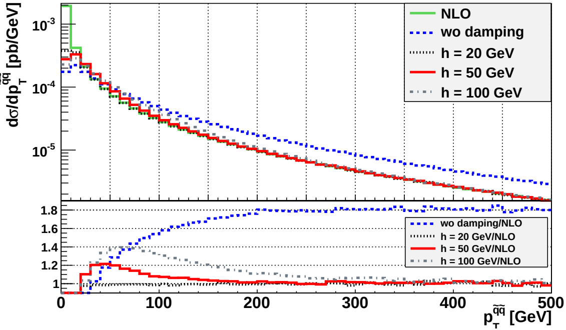
- Magnitude of terms neglected in Diagram Removal (DR) schemes can be sizable
- Influence of jacobian in DS scheme not negligible
- Impact on specific channels (e.g. $\tilde{u}_L \tilde{c}_L$) can be as large as $\mathcal{O}(20\%)$
- Impact on total NLO cross section is a sub percent effect

Damping of $\overline{\mathcal{B}}/\mathcal{B}$ enhancement

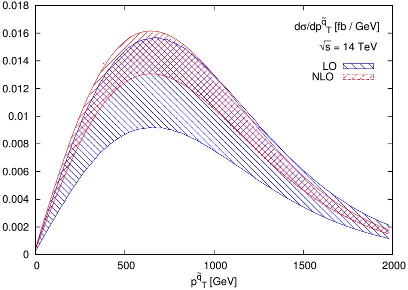
$$d\sigma_{\sigma_{PWG}} \rightarrow \left(\frac{\overline{\mathcal{B}}}{\mathcal{B}}\mathcal{R}_s + (\mathcal{R} - \mathcal{R}_s)\right) d\Phi_{n+1} = \left[(1 + \mathcal{O}(\alpha_s))\mathcal{R}_s + (\mathcal{R} - \mathcal{R}_s)\right] d\Phi_{n+1}$$

$$\mathcal{R}_s = \mathcal{F}\mathcal{R}$$

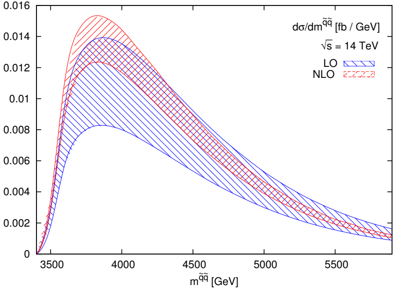
$$\mathcal{F} = \frac{h^2}{p_T^2 + h^2}$$



Errorbands

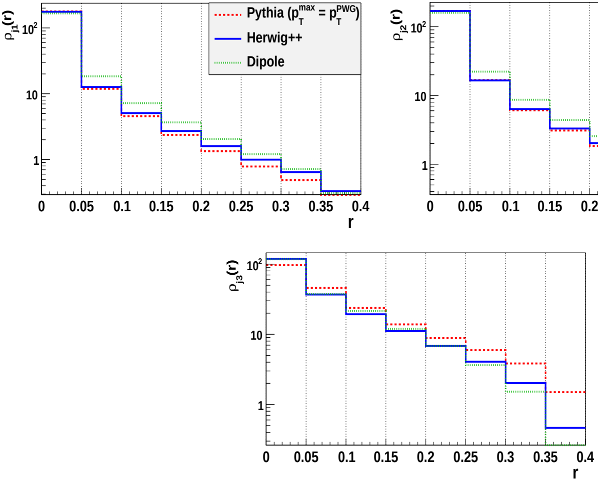


0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
500
1000
1500
2000
$p^{\tilde{q}}_T$ [GeV]
$d\sigma/dp^{\tilde{q}}_T$ [fb / GeV]
$\sqrt{s}$ = 14 TeV
LO
NLO



0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
3500
4000
4500
5000
5500
$m^{\tilde{q}\tilde{q}}$ [GeV]
$d\sigma/dm^{\tilde{q}\tilde{q}}$ [fb / GeV]
$\sqrt{s}$ = 14 TeV
LO
NLO

Jet shapes


Pythia ($p_T^{max} = p_T^{PWG}$)
Herwig++
Dipole
$\rho_{j1}(r)$
$\rho_{j2}(r)$
$\rho_{j3}(r)$
10^2
10
1
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
r