

Squark Pair Production at NLO matched with Parton Showers

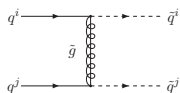
arXiv:1305.4061

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Eva Popeno | 29.08.2013

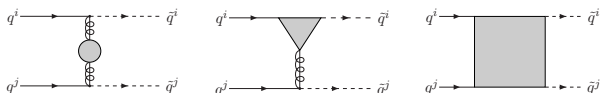


- **Major task at the LHC:** Direct Search for supersymmetric particles and determination of their properties
- **Main production channels:** Coloured sparticles $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$
- **In the currently tested mass region:** $\tilde{q}\tilde{q}$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

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:

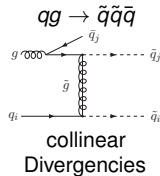
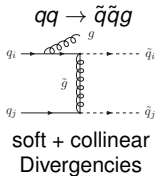
- Mass and field renormalization in on-shell scheme

- 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

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

Real corrections



[Madgraph]

Catani-Seymour subtraction formalism

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

→ Monte Carlo implementation technically difficult:

Cancellation between integrated phase spaces of different multiplicities

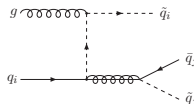
$$\sigma^{NLO} = \int d\Phi_3 [d\sigma^R - d\sigma^A] + \int d\Phi_2 [d\sigma^V + \int d\Phi_1 d\sigma^A]$$

- $d\sigma^A$ 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]

For $m_{\tilde{q}_j} < m_{\tilde{g}}$:

Resonant $\tilde{q}\tilde{g}$ production with subsequent decay



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

On-shell subtraction methods

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

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

→ Gauge invariant in the limit $\Gamma_{\tilde{g}} \rightarrow 0$

→ Ideal for MC event generators

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

Modified DS scheme for fully gauge invariant result → arXiv:1305.4061

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

→ Is the K -factor constant in the various subchannels?

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

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

Differential K -factors on Production Level

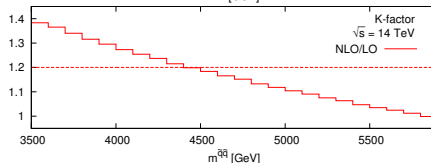
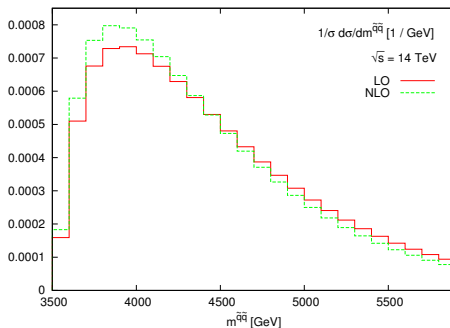
So far:

- 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



Differential K -factors with Decays

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

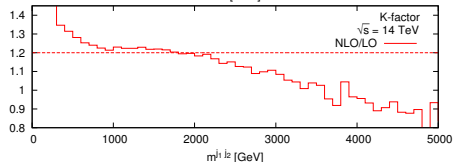
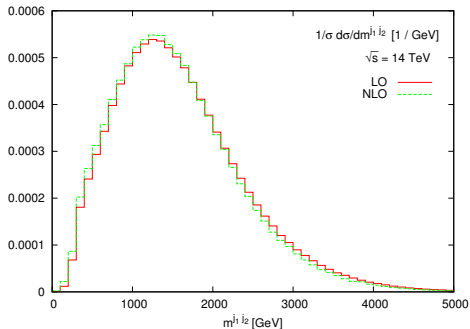
$\text{BR}(\tilde{u}_L \rightarrow u\tilde{\chi}_1^0)$	$\text{BR}(\tilde{u}_R \rightarrow u\tilde{\chi}_1^0)$
0.001	0.566
$\text{BR}(\tilde{d}_L \rightarrow d\tilde{\chi}_1^0)$	$\text{BR}(\tilde{d}_R \rightarrow d\tilde{\chi}_1^0)$
0.012	0.254

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

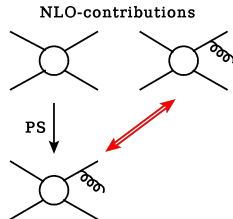
$$p_T^j > 20 \text{ GeV}, \quad |\eta^j| < 2.8$$

- Distribution inherits strong phase space dependence observed at production level

[Hollik, Lindert & Pagani, '12]



- **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

- LHE files obtained from POWHEG-BOX interfaced with
 - ➔ PYTHIA 6 (version 6.4.26): *[Sjostrand, Mrenna & Skands, '06]*
 - | 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)

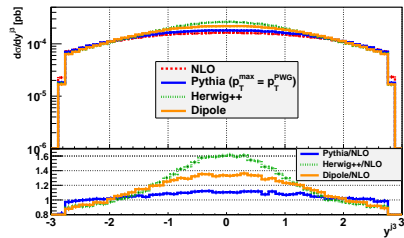
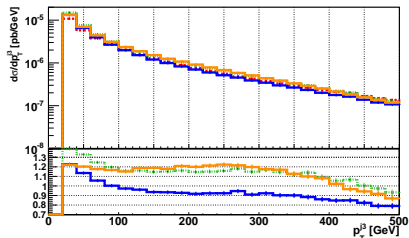
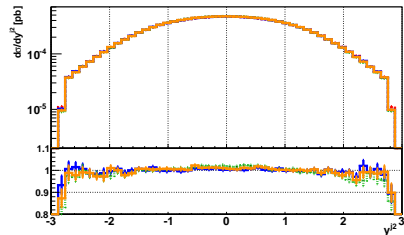
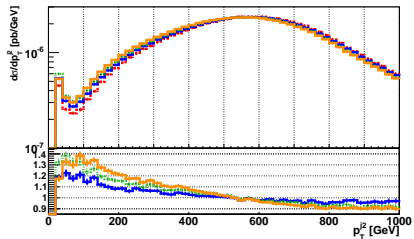
- Decays $\tilde{q} \rightarrow q + \tilde{\chi}_1^0$ performed by shower programs directly

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



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++
- Sizeable differences for 3rd jet could be traced back to ISR

Outlook

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

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

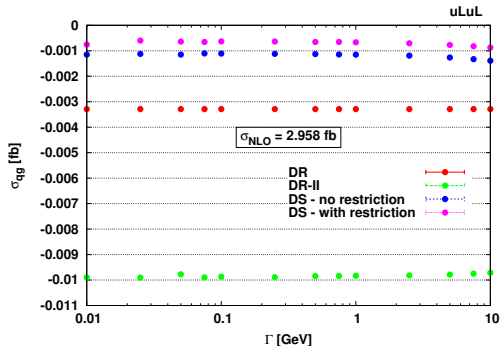
$$\Delta(\Gamma_{\tilde{g}}, s_{jg}) = \tilde{f}_2(s_{jg}) \frac{m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}{s_{jg}^2 + m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2}$$

- Subtraction term in both schemes identical

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

$$m_{\tilde{q}_j \tilde{q}_i}^2 \rightarrow m_{\tilde{g}}^2 : \quad |M_r(\tilde{\Phi}_3)|^2 \cdot m_{\tilde{g}}^2 \Gamma_{\tilde{g}}^2 \rightarrow f_0(\tilde{\Phi}_3)$$

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

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

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

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

