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Squark Production and Decay at NLO matched with Parton Showers

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in collaboration with R. Gavin, C. Hangst, M. Krämer, M. Mühlleitner, M. Pellen and M. Spira
Eva Popenda | 30.4.2014

Introduction

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- 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

  NLO + NLL (soft gluon resummation) by NLL-fast *[Kulesza, Motyka; Beenakker et al, '09-'11]*

- Here: Squark pair production at NLO

  ➡ Without any assumptions on mass spectrum

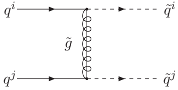
  ➡ Decay $\tilde{q} \to q + \tilde{\chi}_1^0$ at NLO added

  ➡ Matched with Parton Showers in the POWHEG-BOX

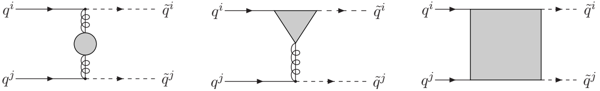
  [Frixione, Nason, Oleari & Re, '10]

Elements of the NLO calculation

Tree level



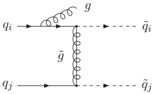
Virtual corrections



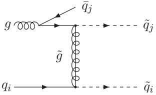
[FeynArts, FormCalc, LoopTools]

Real corrections:

$qq \to \tilde{q}\tilde{q}g$



$qg \to \tilde{q}\tilde{q}\bar{q}$



[Madgraph]

Catani-Seymour subtraction formalism

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

- $d\sigma^A$ 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]

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

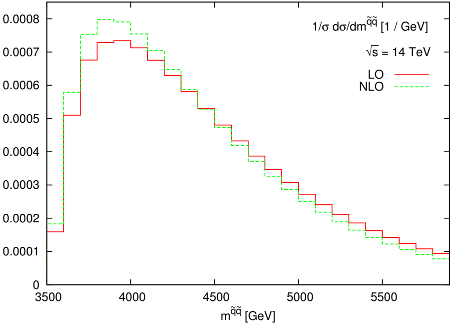
Differential K-factors on Production Level

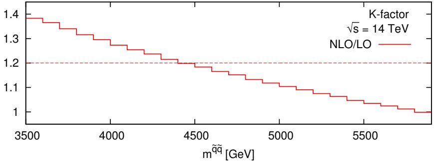
So far:

- 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 at LO

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

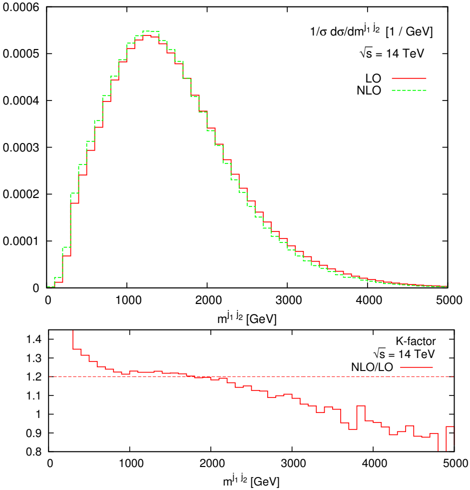
$$d\sigma = (d\sigma_0 + d\sigma_1) \cdot \frac{d\Gamma_0^i}{\Gamma_{tot,0}^i} \cdot \frac{d\Gamma_0^j}{\Gamma_{tot,0}^j}$$

$$\sigma_{\mathrm{LO}} = 1.271 \text{ fb}$$
$$\sigma_{\mathrm{NLO}} = 1.498 \text{ fb}$$

- 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



Combining production and decays at NLO

Narrow-width approximation:

$$(d\sigma_0 + d\sigma_1) \cdot \frac{d\Gamma^i_0 + d\Gamma^i_1}{\Gamma^i_{tot,0} + \Gamma^i_{tot,1}} \cdot \frac{d\Gamma^j_0 + d\Gamma^j_1}{\Gamma^j_{tot,0} + \Gamma^j_{tot,1}}$$

[SDECAY: Muhlleitner et al., '03]

1. Taylor expansion in α_s of numerator & denominator to NLO

$$d\sigma^{NLO} = \frac{1}{\Gamma^i_{tot,0}\,\Gamma^j_{tot,0}} \Big[d\sigma_0 d\Gamma^i_0 d\Gamma^j_0 \big(1 - \frac{\Gamma^i_{tot,1}}{\Gamma^i_{tot,0}} - \frac{\Gamma^j_{tot,1}}{\Gamma^j_{tot,0}}\big) + d\sigma_0 d\Gamma^i_0 d\Gamma^j_1 + d\sigma_0 d\Gamma^i_1 d\Gamma^j_0 + d\sigma_1 d\Gamma^i_0 d\Gamma^j_0 \Big]$$

➡ Negative cross sections possible

2. Expansion in α_s of numerator to NLO

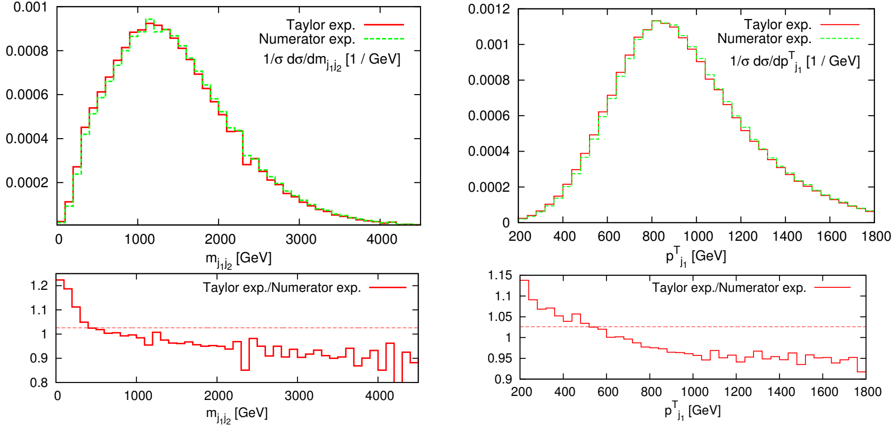
$$d\sigma^{NLO} = \frac{1}{\Gamma^i_{tot,NLO}\,\Gamma^j_{tot,NLO}} \Big[d\sigma_0 d\Gamma^i_0 d\Gamma^j_0 + d\sigma_0 d\Gamma^i_0 d\Gamma^j_1 + d\sigma_0 d\Gamma^i_1 d\Gamma^j_0 + d\sigma_1 d\Gamma^i_0 d\Gamma^j_0 \Big]$$

➡ Summing all decay channels does not reproduce production cross section

Combining production and decays at NLO

Comparison of Taylor expansion and Numerator expansion

$$\sigma_{\text{Taylor}} = 1.09\text{ fb} \quad \text{vs.} \quad \sigma_{\text{Numerator}} = 1.12\text{ fb} \quad ➡ \ 2.6\ \%$$



Differential K-factors with Decays at NLO

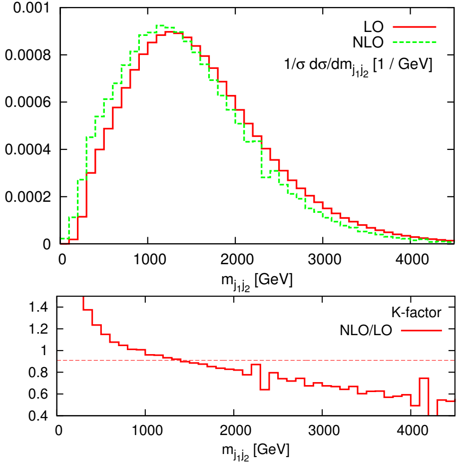
- Taylor expansion of whole expression
- NLO corrections to decays negative:

$$\sigma_{\text{LO}} = 1.195 \text{ fb}$$
$$\sigma_{\text{NLO}} = 1.094 \text{ fb}$$

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

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

- Strong phase space dependence as also observed in *[Hollik, Lindert & Pagani, '12]*



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

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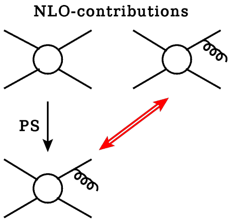


- Realistic predictions for measurements:
  Combination of NLO parton level results with Parton Showers
- Avoid double-counting:
  Contributions in real parts of NLO result and radiation added by shower
- POWHEG method: *[Nason, '04; Frixione, Nason & Oleari, '07]*
  Generate hardest emission first, 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

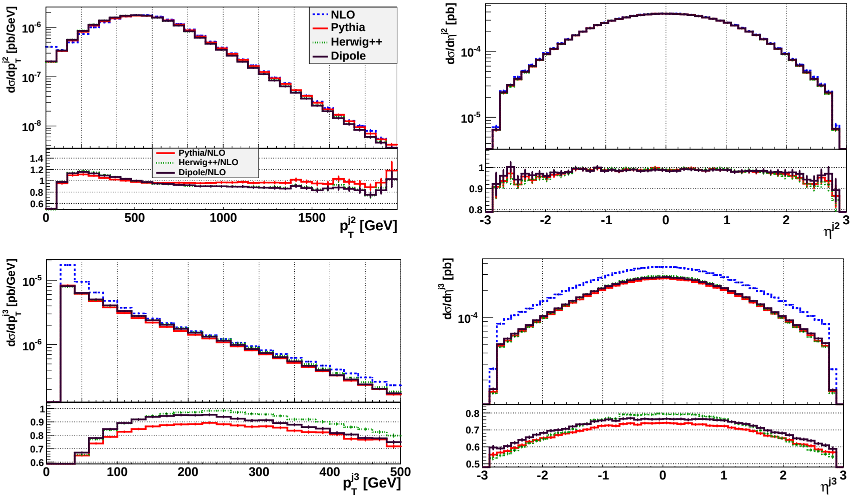
Effects of different Parton Showers

- 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 Default: Angular-ordered shower with p_T-veto (w/o soft, wide-angle radiation)
    $\rightarrow$ Estimate importance of missing contributions

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

➡ Match full process (production & decay @ NLO) with POWHEG method:
Starting scale for shower unambiguously p_T^{PWG}

Parton Shower Effects with Decays at NLO



Impact on total rates: $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}^*$

SUSY searches in 2-jet events performed by ATLAS (A-loose)

$$p_T^{j_1} > 130\,\text{GeV}, \quad p_T^{j_2} > 60\,\text{GeV}, \quad \not{E}_T > 160\,\text{GeV}, \quad \frac{\not{E}_T}{m_{\text{eff}}} > 0.2, \quad m_{\text{eff}}^{\text{incl}} > 1\,\text{TeV},$$

$$\Delta\phi(j_{1/2}, \vec{\not{E}}_T) > 0.4, \quad \Delta\phi(j_3, \vec{\not{E}}_T) > 0.4 \quad \text{if} \quad p_T^{j_3} > 40\,\text{GeV}$$

[ATLAS-CONF-2013-047]

Method for theoretical predictions used by ATLAS:

- Production at LO (CTEQ6L1) rescaled with K-factor from PROSPINO
- Multiplied with NLO branching ratios calculated by SDECAY
- Decays + showering performed by HERWIG++ and PYTHIA

$\tilde{q}\tilde{q}$	PYTHIA	HERWIG++
Full NLO	0.883 fb	0.895 fb
ATLAS	0.855 fb	0.858 fb

$\tilde{q}\tilde{q}^*$	PYTHIA	HERWIG++
Full NLO	0.0797 fb	0.0807 fb
ATLAS	0.0664 fb	0.0667 fb

➡ Not in all cases sufficient to use approximate approach applied by ATLAS

Conclusions

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Summary

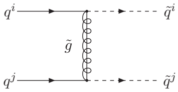
- Squark pair production (and squark anti-squark) at NLO completed
- Combined with decay $\tilde{q} \to q + \tilde{\chi}_1^0$ at NLO
- NLO calculations matched to parton showers in the POWHEG-BOX
- Output interfaced to PYTHIA, Dipole and default shower of HERWIG++
- Treating different subchannels independently reasonable
- Important to take full NLO corrections into account: distributions, total rates

Outlook

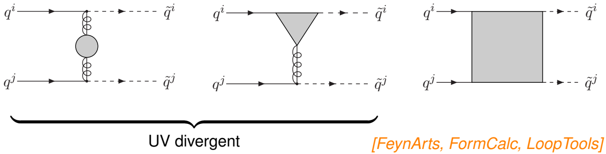
- $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}^*$ @ NLO with NLO decays publicly available via POWHEG BOX
- Add $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$ production and decays including spin correlations to our framework

Elements of the NLO calculation I

Tree level



Virtual corrections



[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: $\tilde{g}_s^{(0)} = g_s + \delta g_s$

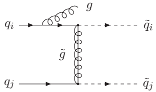
  Decouple heavy particles from running of α_s to match experimental value

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

Elements of the NLO calculation II

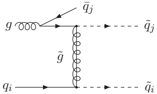
Real corrections

$qq \to \tilde{q}\tilde{q}g$



soft + collinear
Divergencies

$qg \to \tilde{q}\tilde{q}\bar{q}$



collinear
Divergencies

[Madgraph]

Catani-Seymour subtraction formalism

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

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

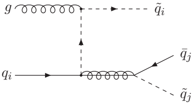
$$\sigma^{NLO} = \int d\Phi_3 \, [d\sigma^R - d\sigma^A] + \int d\Phi_2 \, [d\sigma^V + \int d\Phi_1 d\sigma^A]$$

- $d\sigma^A$ 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]

On-shell intermediate states

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 $d\sigma_{\mathrm{sub}}$

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

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

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

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

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

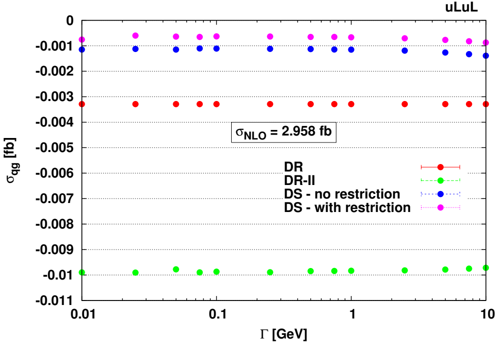
- Subtraction term in both schemes identical

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

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

On-shell subtraction methods

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

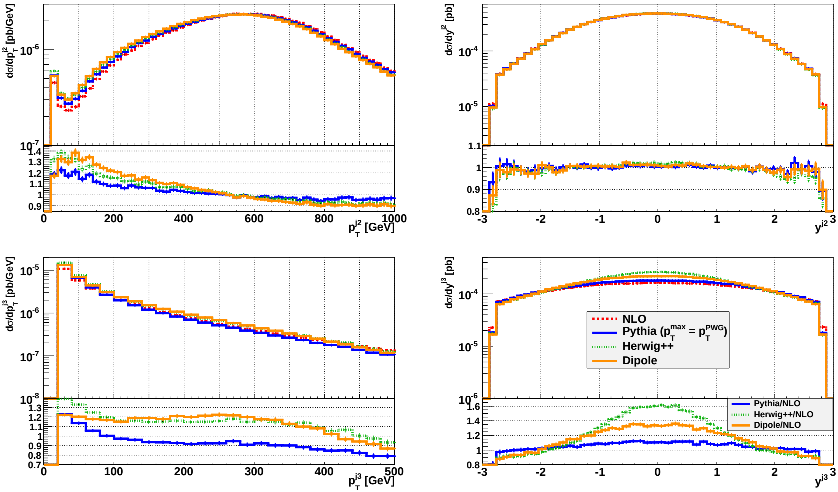
Parameter Point

CMSSM-point	m_0	$m_{1/2}$	A_0	$tan(\beta)$	$sgn(\mu)$
10.3.6*	550 GeV	825 GeV	0 GeV	10	$+1$
10.4.5	690 GeV	1150 GeV	0 GeV	10	$+1$

CMSSM-point	$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$	$m_{\tilde{\chi}_1^0}$
10.3.6*	1799.53	1769.21	1801.08	1756.40	1602.91	290.83
10.4.5	1746.64	1684.31	1748.25	1677.82	1840.58	347.71

CMSSM-point	$\text{BR}(\tilde{u}_L \to u\tilde{\chi}_1^0)$	$\text{BR}(\tilde{u}_R \to u\tilde{\chi}_1^0)$	$\text{BR}(\tilde{d}_L \to d\tilde{\chi}_1^0)$	$\text{BR}(\tilde{d}_R \to d\tilde{\chi}_1^0)$
10.3.6*	0.0098	0.566	0.0121	0.254
10.4.5	0.0137	0.998	0.0160	0.998

Parton Shower Effects with Decays at LO



Powheg Master Formula

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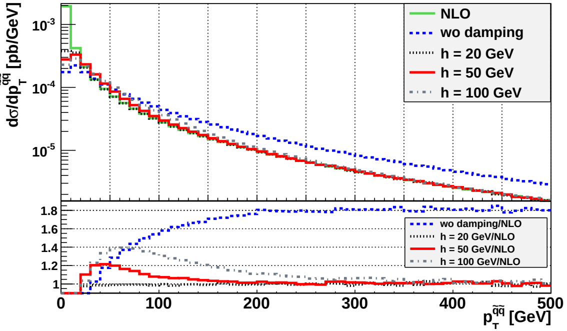
$$d\sigma_{PWG} = \overline{\mathcal{B}}(\Phi_n)\, d\Phi_n \left[\Delta(\Phi_n, p_T^{min}) + \Delta(\Phi_n, k_T)\frac{\mathcal{R}_s(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)}\theta(k_T - p_T^{min}) d\Phi_{rad}\right]$$

$$+ \quad (\mathcal{R} - \mathcal{R}_s) d\Phi_{n+1},$$

$$\overline{\mathcal{B}}(\Phi_n) = \left[\mathcal{B}(\Phi_n) + \mathcal{V}(\Phi_n) + \int \mathcal{R}_s(\Phi_n, \Phi_{rad}) d\Phi_{rad}\right],$$

$$\Delta(\Phi_n, p_T) = \exp\left[-\int d\Phi'_{rad} \frac{\mathcal{R}_s(\Phi_n, \Phi'_{rad})}{\mathcal{B}(\Phi_n)} \theta(k_T(\Phi_n, \Phi'_{rad}) - p_T)\right].$$

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

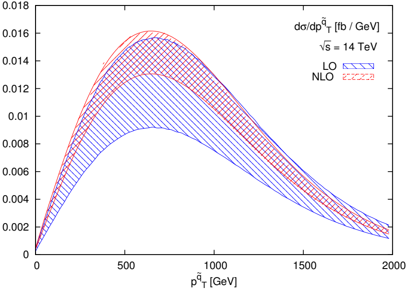


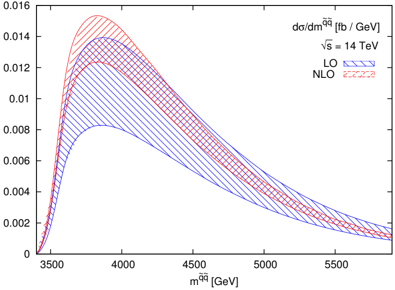
$$d\sigma_{PWG} \rightarrow \left(\frac{\overline{\mathcal{B}}}{\mathcal{B}} \mathcal{R}_s + (\mathcal{R} - \mathcal{R}_s) \right) d\Phi_{n+1} = \left[(1 + \mathcal{O}(\alpha_s)) \mathcal{R}_s + (\mathcal{R} - \mathcal{R}_s) \right] d\Phi_{n+1}$$

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

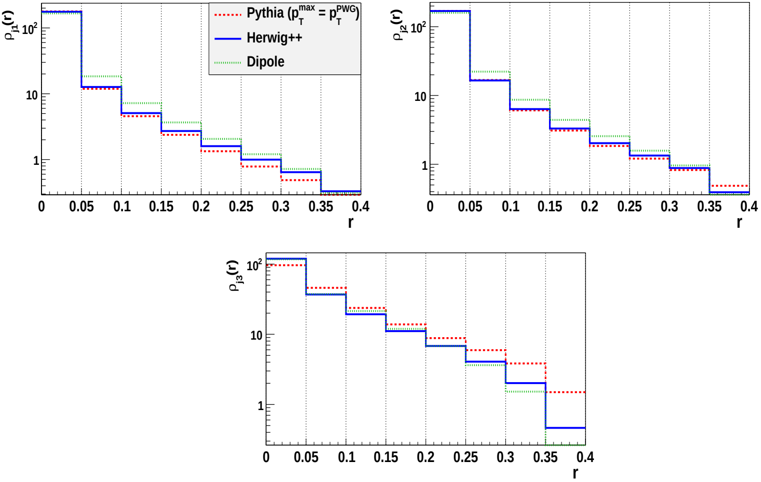
$$\mathcal{F} = \frac{h^2}{p_T^2 + h^2}$$

Errorbands


dσ/dp^q̃_T [fb / GeV]
√s = 14 TeV
LO
NLO
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^q̃_T [GeV]


dσ/dm^q̃q̃ [fb / GeV]
√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^q̃q̃ [GeV]

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