Karlsruher Institut für Technologie

$\tilde{q}\tilde{q}$-production at NLO matched with parton showers

LoopFest 2013

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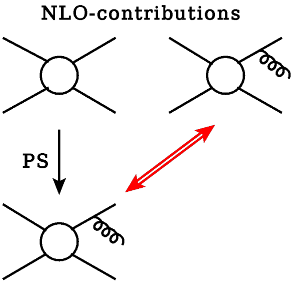
Motivation

- NLO (SUSY)-QCD-corrections to SQCD particle-production at the LHC sizeable
- (re)calculate NLO corrections to $\tilde{q}\tilde{q}$ production fully differential without assuming mass-degenerate squarks (R. Gavin's talk)
- realistic simulation: parton-level production + decay + shower + ...
- combination of fixed-order NLO calculation with parton shower non-trivial: avoid **double-counting**

- two NLO-matching-schemes:
  - MC@NLO [Frixione,Webber 2002]
  - **POWHEG** [Nason 2004]



The POWHEG-method - a short overview

- basic idea
  - generate the hardest emission first
  - then shower with a p_T-veto $\Rightarrow$ subsequent radiation is guaranteed to be softer
  - works directly for p_T-ordered shower
  - for angular-ordered shower: introduce so called truncated shower
- 'master-formula': [Frixione, Nason, Oleari 2007]

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

with the POWHEG-Sudakov

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

and the $\overline{\mathcal{B}}$-function

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

Properties of the POWHEG 'master-formula':

- NLO accuracy for infrared safe observables (not 'sensitive' to radiation $\longrightarrow$ only $\overline{\mathcal{B}}$ relevant; proof: see [Frixione, Nason, Oleari 2007])
- NLO accuracy preserved in the hard region: $\Delta_{PWG}(\Phi_n, p_T^{min}) \longrightarrow 0$, $\Delta_{PWG}(\Phi_n, p_T) \longrightarrow 1$

$$d\sigma_{PWG} \approx \frac{\overline{\mathcal{B}}(\Phi_n)}{\mathcal{B}(\Phi_n)} \mathcal{R}(\Phi_n, \Phi_{rad}) d\Phi_n d\Phi_{rad} \approx \mathcal{R}(\Phi_n, \Phi_{rad}) \left(1 + \mathcal{O}(\alpha_s)\right) \, d\Phi_n \, d\Phi_{rad}$$

- leading-log accuracy of a shower MonteCarlo in soft/collinear limit ($p_T \longrightarrow 0$) is not destroyed:

$$\frac{\mathcal{R}(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)} d\Phi_{rad} \approx \frac{\alpha_s}{2\pi} \frac{1}{t} P(z) \, dt \, dz \frac{d\varphi}{2\pi}, \quad \overline{\mathcal{B}} \approx \mathcal{B}\left(1 + \mathcal{O}(\alpha_s)\right)$$

The POWHEG-BOX [Alioli,Nason,Oleari,Re 2010]

- POWHEG-BOX provides process-independent ingredients for a POWHEG-implementation of arbitrary processes:
  - automatized subtraction-scheme (FKS-scheme [Frixione, Kunszt, Signer 1996])
  - generation of radiation phasespace
  - hardest radiation according to POWHEG-Sudakov
  - NLO distributions as 'by-product'
  - LHE-output: unweighted events which can be interfaced to shower program
- user needs to implement the process specific parts
- So far: no processes with strongly interacting BSM particles implemented $\longrightarrow$ small changes in the main routines of the code concerning the FKS subtraction

Process-dependent parts

1. Flavour structures of Born & Real processes (including charge-conjugate processes)
2. Parameters (couplings,masses,...) $\rightarrow$ read in SLHA files
3. Born phase space
4. Born squared amplitude $\mathcal{B}$, colour-correlated Born $\mathcal{B}_{ij}$
5. Virtual UV-renormalized, IR-finite part $2Re\left(\mathcal{M}_B\mathcal{M}_V^*\right)$
6. Real matrix elements squared
7. Born colour-flows in large-N_c limit

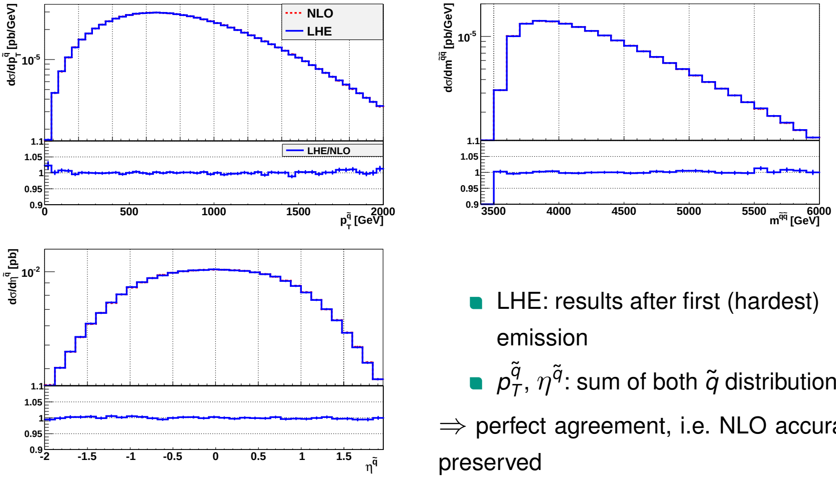
Checks and Results - Setup

- cMSSM benchmark point, first two generations are degenerate in mass:

$m_{\tilde{u}_L}$	$m_{\tilde{u}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{g}}$
1799.53	1769.21	1801.08	1756.40	1602.91

- consider only $\tilde{u}$, $\tilde{d}$, $\tilde{c}$ and $\tilde{s}$ production
- PDF-set: CT10NLO with $\alpha_s = 0.118$ [Lai,Guzzi,Huston et al. 2010]
- $\mu_R = \mu_F = \overline{m}_{\tilde{q}}$
- different parton shower programs:
  - PYTHIA 6.4.26[Sjostrand,Mrenna,Skands 2006]: p_T-ordered shower
  - HERWIG++ 2.6.1[Arnold,d'Errico,Gieseke et al. 2012]: default shower (angular ordered!) and Dipole shower[Platzer,Gieseke 2011] (p_T-ordered, only if decays are taken into account)
- cluster partons with FASTJET 3.0.3[Cacciari,Salam 2006] into jets (anti-k_T with $R = 0.4$)
- only very basic cuts: $p_T^j > 20\text{GeV}$, $|\eta_j| < 2.8$
- no hadronization or MPI considered

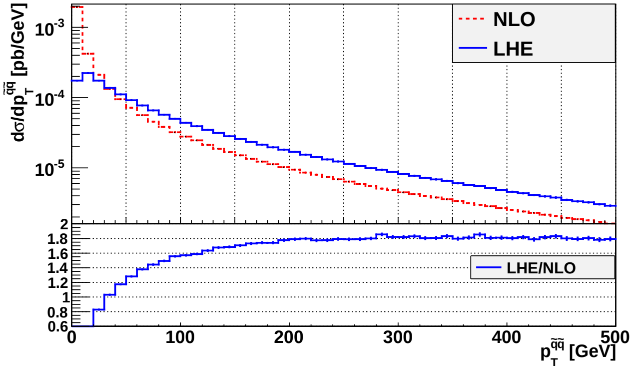
Checks - infrared safe observables



- LHE: results after first (hardest) emission
- $p_T^{\tilde{q}}$, $\eta^{\tilde{q}}$: sum of both $\tilde{q}$ distributions

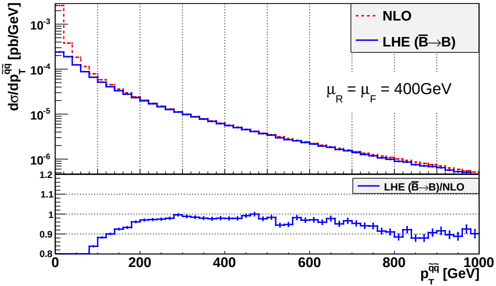
$\Rightarrow$ perfect agreement, i.e. NLO accuracy preserved

Checks - exclusive observables



- at NLO: $p_T^{\tilde{q}\tilde{q}} \leftrightarrow p_T^j$, the p_T of the radiated parton
- low $p_T^{\tilde{q}\tilde{q}}$: Sudakov damping (NLO result diverges here)
- high $p_T^{\tilde{q}\tilde{q}}$: LHE/NLO $\approx 1.8 \Rightarrow 80\%$ discrepancy!

- similar effect observed e.g. in $gg \to H$[Alioli,Nason,Oleari,Re 2009] and VV-production[Melia,Nason,Rontsch,Zanderighi 2011]
- two reasons for this discrepancy:
  1. assumption $\overline{\mathcal{B}}/\mathcal{B} \approx 1$ is not valid here: sizeable K-factor ($K = 1.2$)
  2. different scales for $\overline{\mathcal{B}}$ ($\mu = \overline{m}_{\tilde{q}}$) and for $\mathcal{R}/\mathcal{B}$ (p_T of the radiated parton)
- check these two points: perform event generation with $\overline{\mathcal{B}} \to \mathcal{B}$ and $\mu_R = \mu_F = 400\text{GeV}$



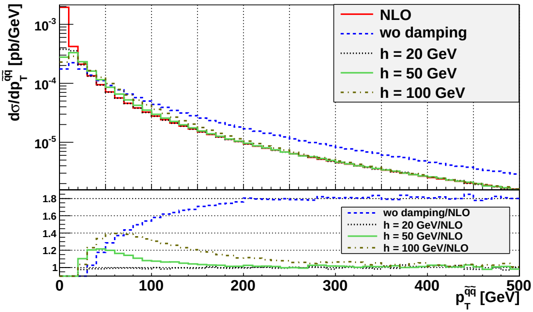
$\Rightarrow$ reproduce 'NLO' result for $p_T^{\tilde{q}\tilde{q}} \approx 400\text{GeV}$

- idea [Alioli,Nason,Oleari,Re 2009]: 'split' the real contributions in the master-formula, use only IR-singular parts for radiation generation

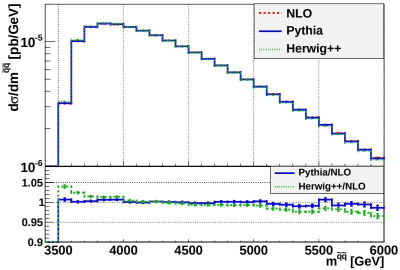
$$\mathcal{R} = \mathcal{R}_s + \mathcal{R}_r = \mathcal{F}\mathcal{R} + (1-\mathcal{F})\mathcal{R}; \quad \mathcal{F} = \frac{h^2}{p_T^2 + h^2}$$

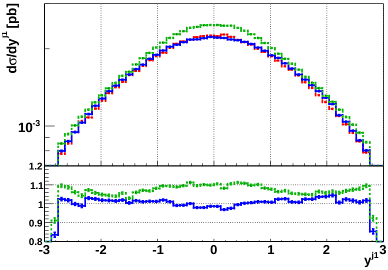
- 'new' master-formula:

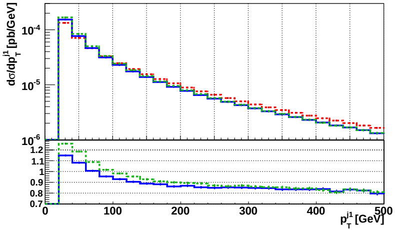
$$d\sigma_{PWG} = \overline{\mathcal{B}}_s(\Phi_n)\, d\Phi_n \left[\Delta_s(\Phi_n, p_T^{min}) + \Delta_s(\Phi_n, k_T)\frac{\mathcal{R}_s(\Phi_n, \Phi_{rad})}{\mathcal{B}(\Phi_n)}\theta(k_T - p_T^{min})d\Phi_{rad}\right] + \mathcal{R}_r d\Phi_n d\Phi_{rad}$$



Parton shower effects - PYTHIA6 vs. HERWIG++ default shower



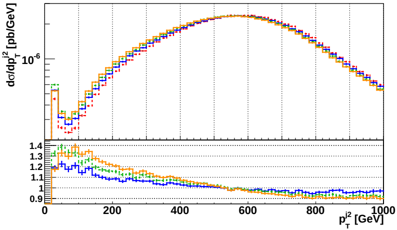


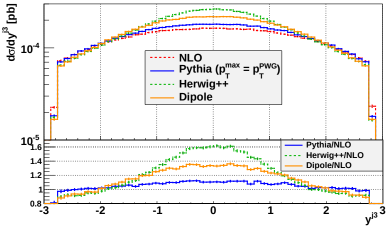


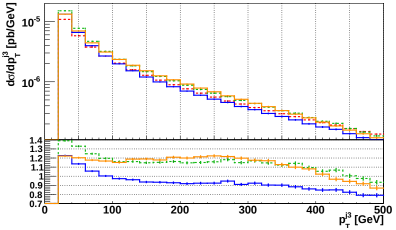
- inclusive quantities hardly affected
- p_T^{j1} softer than NLO, HERWIG++ slightly higher rates at low p_T^{j1}
- HERWIG++ predicts more central jets

Including the decays

- consider shortest 'cascade' $\tilde{q} \to q\tilde{\chi}_1^0$
- decays are performed directly in the MC programs
- problem when comparing PYTHIA6 $\leftrightarrow$ HERWIG++:
  1. **PYTHIA6**: performs decays during the 'showering step' and adds radiation to decay products, using as starting scale $m_{\tilde{q}}$
  2. **HERWIG++**: performs the decays before starting the shower
     BUT: we have to impose a p_T-veto, which is then applied to radiation off the decay products, too
     $\Rightarrow$ much smaller starting scale!
     $\Rightarrow$ PYTHIA6 produces way more radiation
- workaround: modify PYTHIA6 such that the same p_T-veto is applied in the 'showering' of the decay products







- second (and first) jet softer than NLO, good agreement for hard jets
- PYTHIA6 predicts less third jets
- third jets from PYTHIA6 again less central

Conclusions

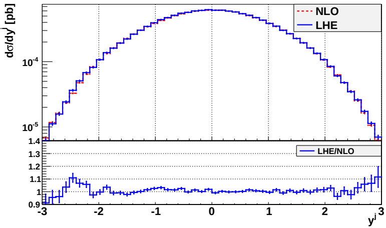
- implementation of $\tilde{q}\tilde{q}$ production in the POWHEG-BOX finished
- behaviour of infrared save observables as expected
- discrepancies in exclusive observables like $p_T^{\tilde{q}\tilde{q}}$ can be attributed to enhancement by large K-factor and different scales
- parton shower effects without decays are $\mathcal{O}(10\% - 20\%)$ for the hardest jet
- taking into account the decays $\tilde{q} \to q\tilde{\chi}_1^0$:
  - modified PYTHIA for comparison
  - observe larger differences between the showers

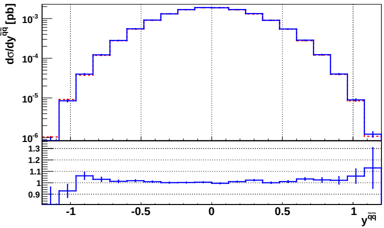
Outlook:

- add NLO corrections to decay
- include the remaining SQCD production processes ($\tilde{q}\bar{\tilde{q}}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$)

Backup

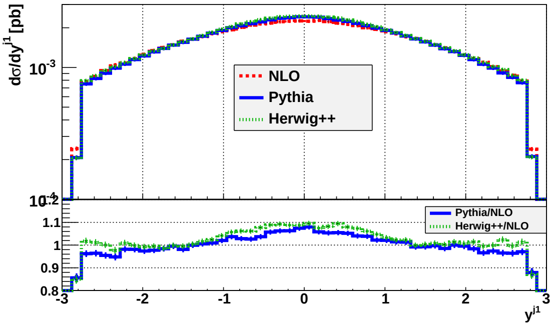
Rapidities after ’damping’



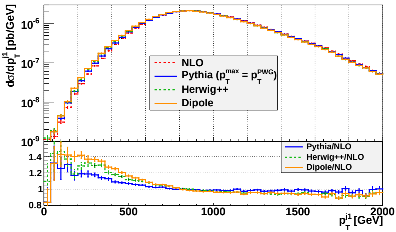


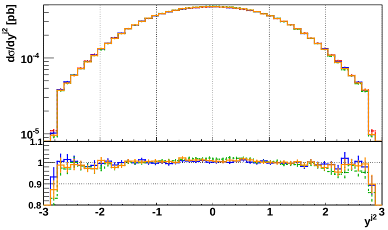
- cut $p_T^{\tilde{q}\tilde{q}} > 200\text{GeV}$
- $h = 50\text{GeV}$

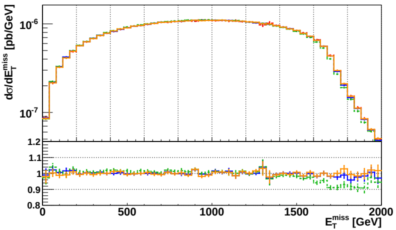
No initial state radiation - without decays



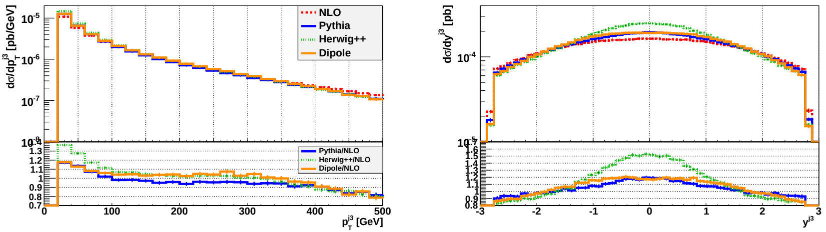
Decays included - part II



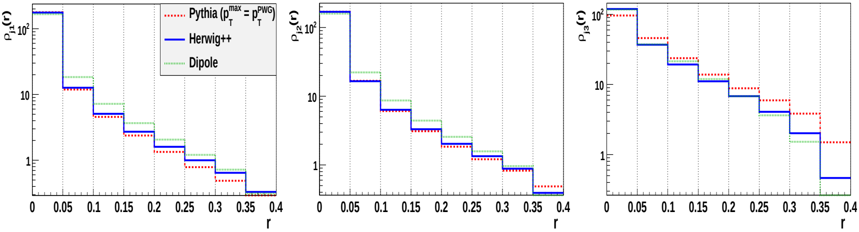




No initial state radiation - including decays



Jet shapes



$$\rho_{ji}(r) = \frac{1}{\Delta r}\frac{p_T^{ji}(r-\Delta r/2, r+\Delta r/2)}{p_T^{ji}(0,R)}, \quad \Delta r/2 \le r \le R - \Delta r/2\,,$$

- $r = \sqrt{\Delta y^2 + \Delta\phi^2}$
- $\Delta r = 0.05$
- $p_T^{ji}(r_1, r_2)$: summed transverse momentum of all partons which are clustered into the jet and lie in an annulus with inner/outer radius r_1/r_2 around the jet axis