Top Quark Production and Decay in Herwig

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Based on work by: J. Bellm, K. Cormier, S. Plätzer, C. Reuschle, P. Richardson, S. Webster

Herwig 7.1

Heavy Flavours in Herwig 7.0

- Angular-ordered shower for both the production and decay of heavy partons.
- Dipole shower for the production of heavy partons only.
- Automated NLO matching to both showers using MC@NLO and Powheg-type matching schemes.

New HF features in Herwig 7.1 - Released earlier this year

- NLO Multi-jet Merging - The primary new feature in Herwig 7.1
- Full revision of heavy quark treatment in the dipole shower
- Dipole shower for top quark decays.

Outline

1. Treatment of Massive Quarks in the Dipole Shower
2. Top Quark Decays in the Dipole Shower
3. Multi-jet Merging in Top Pair Production
4. Shower Starting Scales in MC@NLO for $pp \to t\bar{t}$

Dipole Shower - Massive Quark Treatment

We have fully revised the kinematics used to describe splittings off dipoles involving massive partons.

Initial-Final Dipoles

- Important for the first few emissions in $t\bar{t}$ production.
- Previously:
  - Inconsistent definition of p_{T} between the ordering variable and physical transverse momentum.
  - Did not agree with the massless dipole splitting kinematics in the massless limit.
- A new (fully covariant) formulation which fixes these issues is implemented in Herwig 7.1.

Dipole Shower - Massive Quark Treatment

We have fully revised the kinematics used to describe splittings off dipoles involving massive partons.

Final-Final Dipoles

- Massive spectator and emitter $\rightarrow$ most algebraically involved.
- As in the IF case, previously we used an inconsistent definition of the transverse momentum.
- Introduce a new formulation based on a modified version of the quasi-collinear Sudakov parametrisation:
  - Standard:
$$q_i^\mu = \alpha(z)\tilde{p}_{ij}^\mu + \beta(z)n^\mu + k_{\mathrm{T}}^\mu$$
  - Modified:
$$q_i^\mu = \alpha(z)q_{ij}^\mu + \beta(z)n^\mu + k_{\mathrm{T}}^\mu \,, \qquad q_{ij} = q_{ij}(\tilde{p}_{ij}, \tilde{p}_k)$$

Dipole Shower - Massive Quark Treatment

We have fully revised the kinematics used to describe splittings off dipoles involving massive partons.

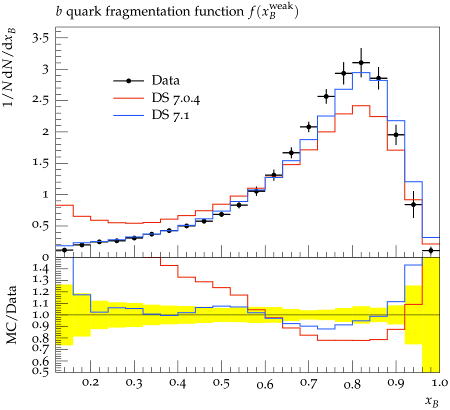
Jacobian Corrections

- Need to perform variable changes between the Catani-Seymour splitting variables and our evolution/generated variables.
- Previously for each massive dipole the Jacobian expressions were missing mass terms.
- e.g. Simplest case: final-initial dipole, $(z, x) \rightarrow (z, p_{\mathrm{T}})$

$$\frac{\mathrm{d}x}{x\,(1-x)} = -\frac{\mathrm{d}p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}\left[\frac{1}{1+(1-z)m_{\mathrm{i}}^2/p_{\mathrm{T}}^2 + zm_{\mathrm{j}}^2/p_{\mathrm{T}}^2 - z(1-z)m_{\mathrm{ij}}^2/p_{\mathrm{T}}^2}\right]$$

- These corrections have significant effects on results.

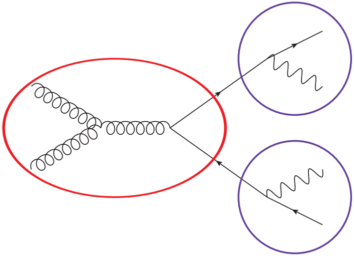
These changes have fixed the outstanding problems, (see Simon Plätzer's talk at HF@LHC 2016), with B-fragmentation in the Dipole Shower.



SLD_2002_S4869273, arXiv:hep-ex/0202031

Dipole Shower - Top Quark Decays

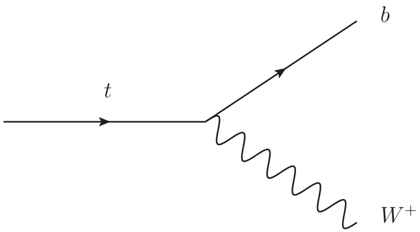
- The Dipole Shower has been extended to include the showering of top quark decays.
- We use the Narrow Width Approximation $\rightarrow$ the production and decay processes are showered independently



- Note: Currently limited to on-shell top quarks in the Dipole Shower.

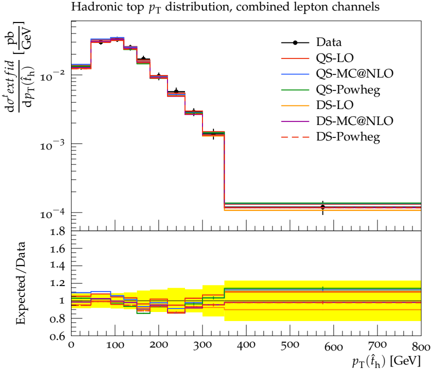
Dipole Shower - Top Quark Decays

- Conserve the momentum of the incoming top quark and absorb recoil amongst the outgoing particles.
- The splitting kinematics are identical to the massive final-final dipole.

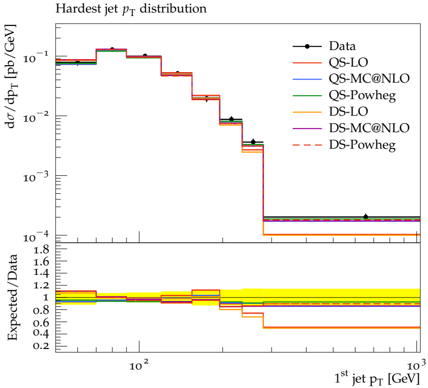


- The first emission can be performed at NLO accuracy using the builtin POWHEG correction.
  [P. Richardson, A. Wilcock, arXiv:1303.4563]
- All SM decays can be performed and showered in the dipole shower, including the NLO correction for each decay.

Both showers in Herwig can now handle top quark production and decay at NLO.



ATLAS_2015_I1345452, arXiv:1502.05923



ATLAS_2014_I1304688, arXiv:1407.0891

NLO Multi-jet Merging in $pp \to t\bar{t}$

- A new algorithm for merging NLO multi-jet matrix elements with parton showers has been implemented in Herwig 7.1
  [J. Bellm, S. Gieseke, S. Plätzer, arXiv:1705.06700]

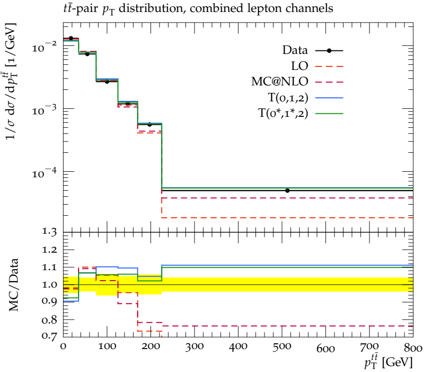
- It is built on the Matchbox implementation for NLO matching in Herwig.

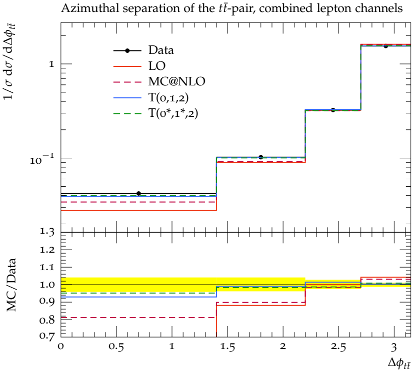
- Currently implemented for the dipole shower only.

- With the new developments in the Dipole Shower for massive quarks, we can produce NLO multi-jet merged $pp \to t\bar{t}$ events.

NLO Multi-jet Merging in $pp \to t\bar{t}$

$p_{\mathrm{T}}(t\bar{t})$ and $\Delta\phi(t\bar{t})$

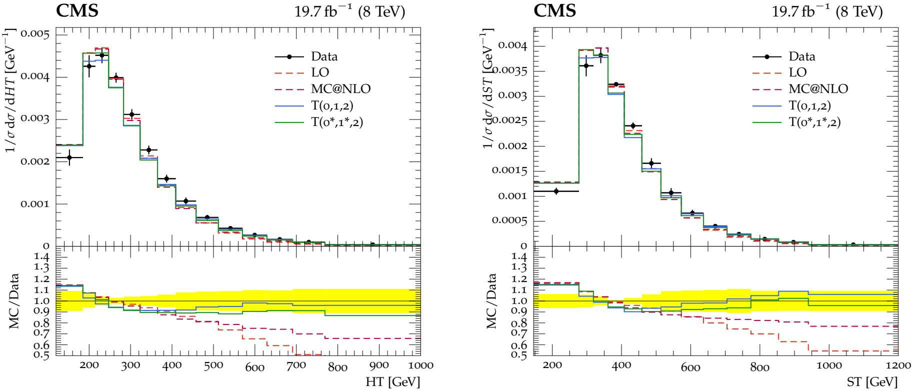




ATLAS_2015_I1404878, arXiv:1511.04716

NLO Multi-jet Merging in $pp \to t\bar{t}$

$$H_{\mathrm{T}} = \sum_{\mathrm{alljets}} p_{\mathrm{T}}^{\mathrm{jet}} \qquad S_{\mathrm{T}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}^{\mathrm{lepton}}$$

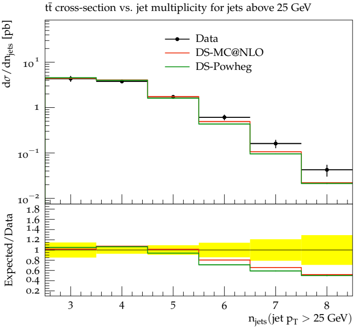


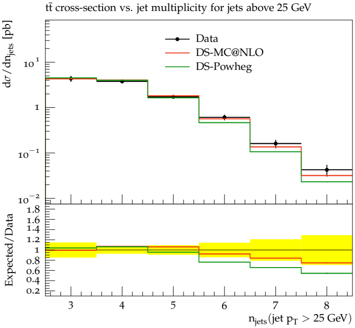
CMS_2016_I1473674, arXiv:1607.00837

Shower Starting Scale in MC@NLO

Observation: In some observables the agreement between MC@NLO and Powheg depends strongly on the choice of the scale $\mu = \mu_{\mathrm{R}} = \mu_{\mathrm{F}}$

$$\mu = \frac{m_{\mathrm{T},t} + m_{\mathrm{T},\bar{t}}}{2} \qquad \mu = m_{t\bar{t}} = \sqrt{(p_t + p_{\bar{t}})^2}$$





ATLAS_2014_I1304688, arXiv:1407.0891

Shower Starting Scale in MC@NLO

- In MC@NLO the cancellation between the real matrix element and the shower kernel subtraction piece is non-exact.
- It follows that H-events with a soft NLO emission will be produced.
- Therefore we cannot simply take the transverse momentum of the emission as the shower starting scale
- Powheg-type matching does not suffer from this issue and we can simply use $Q_{\mathrm{shower}} = p_{\mathrm{T,hardemission}}$.

Shower Starting Scale in MC@NLO

- The default choice for MC@NLO events in Herwig is:

$$Q_{\rm shower} = \mu_{\rm F} = \mu_{\rm R}$$

- In Herwig 7.1 we have introduced a new optional choice for the shower starting scale in $pp \to t\bar{t}$ events,

$$Q^2_{\rm shower} = m^2_{\rm T,mean} = \frac{1}{n_{\rm out}} \sum_{i=1}^{n_{\rm out}} m^2_{{\rm T},i}$$

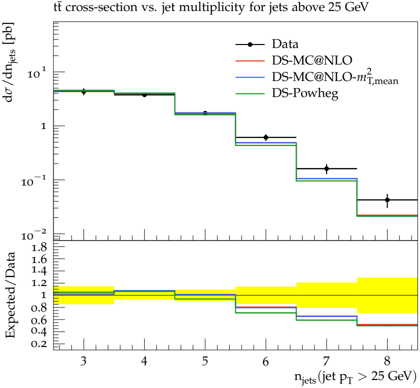
  $m^2_{{\rm T},i}$ - the transverse mass of the ith particle outgoing from the hard process.

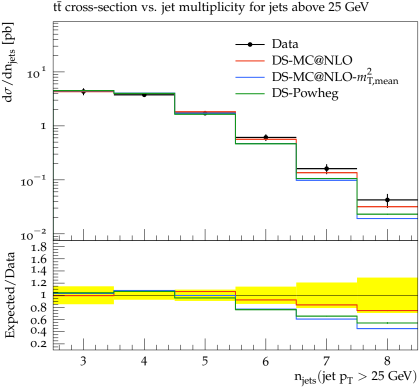
- **As with other scale choices, there is no correct or incorrect choice of the shower starting scale.**

Shower Starting Scale in MC@NLO

$$\mu = \frac{m_{\mathrm{T},t} + m_{\mathrm{T},\bar{t}}}{2}$$

$$\mu = m_{t\bar{t}} = \sqrt{(p_t + p_{\bar{t}})^2}$$





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Shower Starting Scale in MC@NLO

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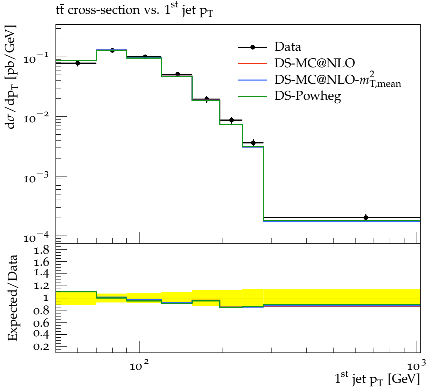

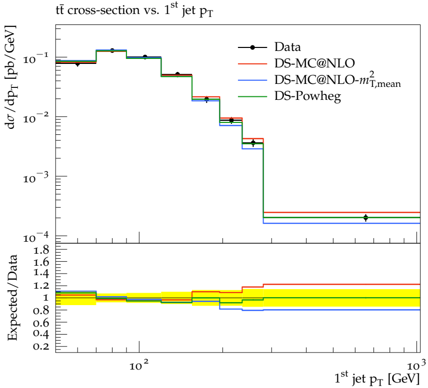

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Summary

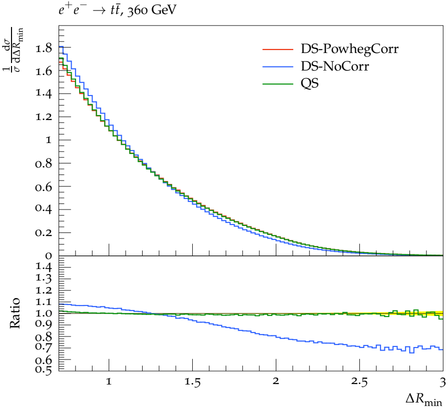
- The treatment of heavy quarks in the Dipole Shower has been reviewed and improved.
- The Dipole Shower has been extended to include the showering of top quark decays.
- Herwig now has a built-in multi-jet merging algorithm which can be used to produce improved results for $pp \to t\bar{t}$ with the Dipole Shower
- We have added a new optional shower starting-scale for MC@NLO $pp \to t\bar{t}$ events

An upcoming publication on $t\bar{t}$-production and decay, and the associated parton shower and matching uncertainties, in Herwig is in the works.

Backup: Dipole Shower Decay Tests

360 GeV, $e^+e^- \to t\bar{t}$, clustered to three jets using the k_T-algorithm.

ΔR_min - The smallest jet separation



Backup: Dipole Shower Decay Tests

360 GeV, $e^+e^- \to t\bar{t}$, clustered to three jets using the k_{T}-algorithm.

$$y_3 = \frac{2}{s}\min_{ij}\left(\min\left(E_i^2, E_j^2\right)(1-\cos\theta_{ij})\right), \text{ for 3-jet} \to \text{2-jet event.}$$