Simulating top quark pair events with additional jets at the LHC

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In short

Recent studies by the ATLAS and CMS collaborations [1–3] show that distributions of additional jets in top quark pair events are not described to within experimental uncertainty by next-to-leading-order Monte Carlo generators interfaced with parton showers.

We studied the description using Powheg + Pythia 8. The goal was to understand the effects of various parameters and identify the settings that give the best description of the data.

We found that the description is largely insensitive to variations in Pythia 8, except for the definition of the parton shower matching scale. Very good agreement with data could only be achieved by damping resummation in Powheg if the highest-$p_\perp$ emission has rapidity $|y| > 1.5$ in the laboratory frame.

Top quarks matter

Top quark pair ($t\bar{t}$) production is a prototype process for new heavy particle production. It is also an important background to many new physics signals, due to the high invariant mass of the $t\bar{t}$ system and multitude of different final states. Its high mass makes the top quark couple very strongly to Higgs bosons.

→ *New physics hides under the top quark, and the quark's a key to understanding the standard model.*

Additional jets and gaps

We used data from ref. [1] to test Monte Carlo predictions. It has been corrected for experimental effects → easier to compare to simulation.

Gap fraction: fraction of $t\bar{t}$ events that *do not* contain an additional jet with $p_\perp > Q_0$ in a given rapidity region. Studied as a function of Q_0.

Gap event. No gap event if additional jet has $p_\perp > Q_0$.

Figure 1: Simple examples of $t\bar{t}$ events with and without gap. Shown in red is the leading additional jet and in gray the two b-jets and leptons from $t\bar{t}$ decay. The veto region is indicated by dashed lines, assuming massless additional jets, so that $y = \eta$.

Gap fractions were measured in four rapidity regions:

$$|y| < 0.8, \quad 0.8 < |y| < 1.5, \quad 1.5 < |y| < 2.1, \quad \text{and } |y| < 2.1$$

Why are we interested in gap fractions? They are sensitive to the distribution of additional jets, and to the parton shower in simulation. Good for testing and constraining theory!

Results of simulation with Powheg + Pythia 8

We defined a *baseline setup* to compare against, in which Powheg and Pythia 8 used default settings and matching was performed using the unmodified *main31* program. It was in agreement with the data in all veto regions except in $|y|$ between 1.5 and 2.1 ("problematic" region).

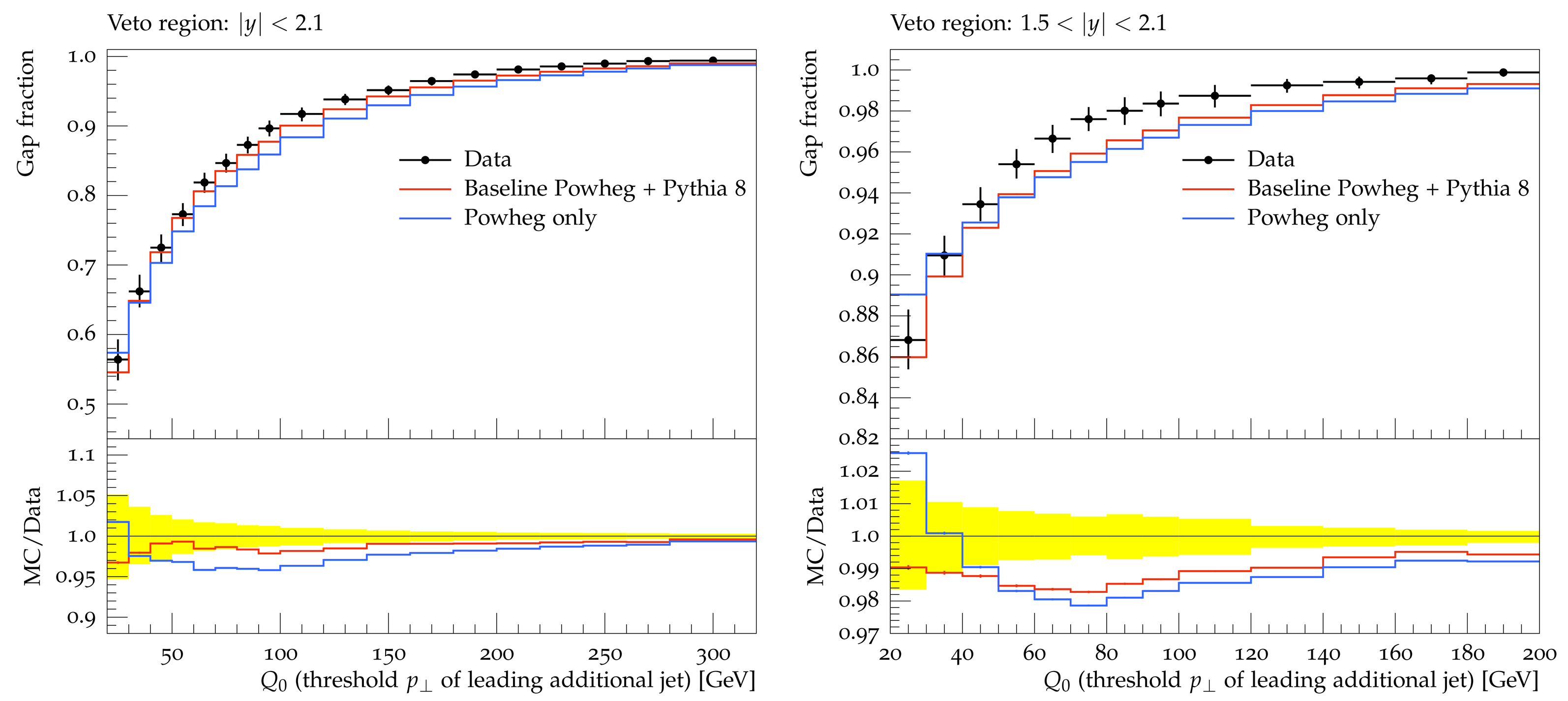

Figure 2: Gap fractions in the inclusive and the problematic veto region. Comparison of baseline MC prediction and prediction of Powheg NLO matrix elements alone to ATLAS data. Error bars show statistical uncertainty, yellow band statistical and systematic uncertainty added in quadrature.

An overview over the most important studied variations:

Variation	Affects	Size of effect
Damping resummation in Powheg	Highest-$p_\perp$ emission	Large
α_s renorm. scale in Powheg Sudakov form factor	Highest-$p_\perp$ emission	Large
Definition of matching scale	Parton shower emissions	Large
PDF choice in Powheg	Hard process, highest-$p_\perp$ emission	Medium
PDF choice in Pythia 8	Initial-state-radiation rates, multiple parton interactions	Small
Top quark decay (modes, generator)	Ideally nothing?	Small
Hadronisation	Jet structure and $p_\perp$	Tiny
Multiple parton interactions	Jet multiplicity and $p_\perp$	Tiny

The only thing found that can fix the discrepancy: damping resummation in Powheg only for emissions with $|y| > 1.5$ to scale $h = m_{\text{top}}/2$. Shown in Fig. 3.

Ongoing discussion on how physically sensible rapidity-dependent damping is.

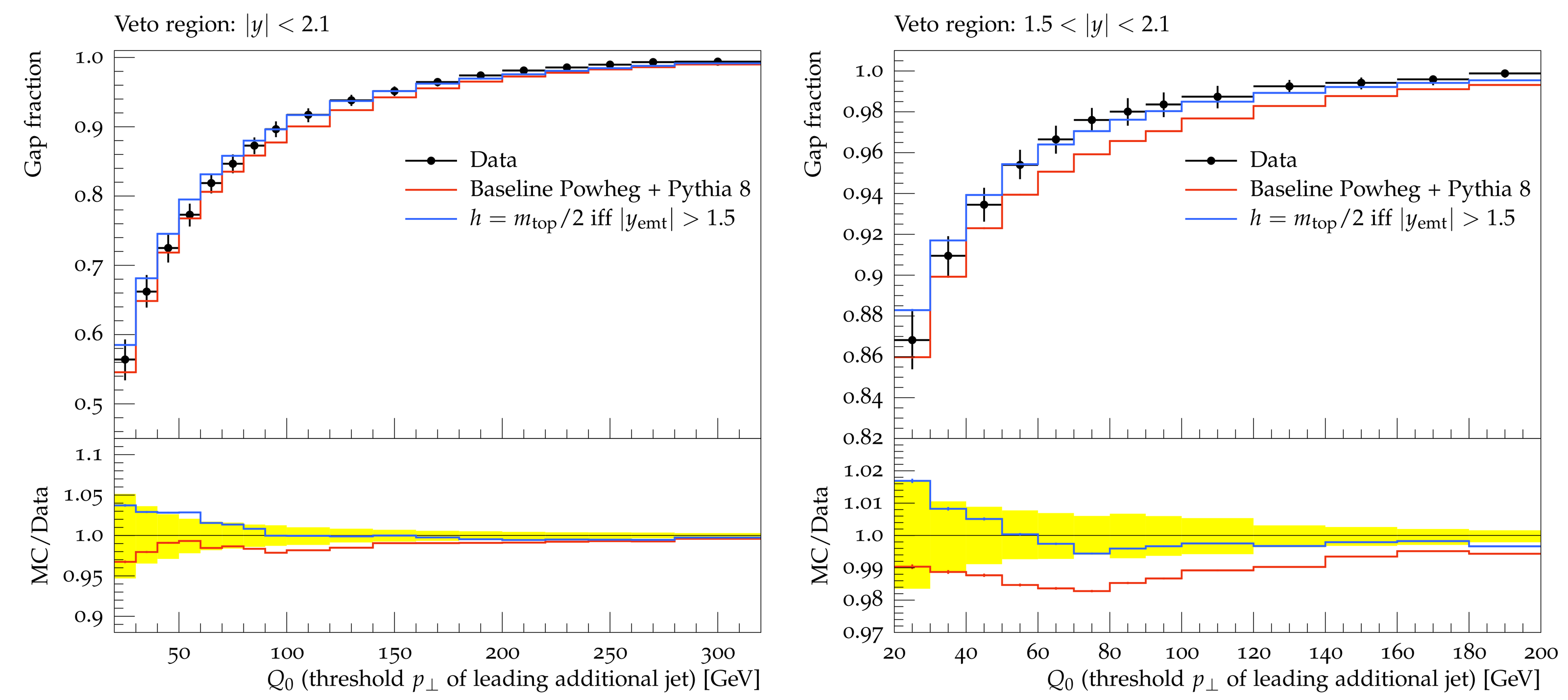

Figure 3: Damping resummation for emissions with $|y| > 1.5$ in Powheg. Agreement in the problematic rapidity region (right) has been achieved!

Remarks

Challenge: we are demanding percent-level predictions of very exclusive QCD observables that rely on the parton shower to get jet spectra right. Justifies tuning? What can be expected?

Gained: suitable definition of matching scale and choice of PDF set.

Need to consider other observables as well: $p_\perp$ of $t\bar{t}$ system, number of additional jets, etc.

Powheg and Pythia 8 do not include effects of soft gluons emitted at wide opening angles. Softness is relative to the hard process, so these may be important in $t\bar{t}$ events. Limits the quality of the description?

I would like to thank my supervisor Keith Hamilton for his excellent guidance throughout this work.

The presented work is fully documented here:

References

[1] ATLAS Collaboration, *Measurement of $t\bar{t}$ production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, Eur. Phys. J. C 72 (2012) 2043, [arXiv:1203.5015].

[2] CMS collaboration, *Measurement of jet multiplicity distributions in top quark events with two leptons in the final state at a centre-of-mass energy of 7 TeV*, CMS-PAS-TOP-12-023 (2012).

[3] CMS collaboration, *Measurement of the Jet Multiplicity in dileptonic Top Quark Pair Events at 8 TeV*, CMS-PAS-TOP-12-041 (2013).

Interpretation of Fig. 2: At higher Q_0, including the Pythia 8 parton shower increases gap fractions, because shower emissions ending up outside of the jet cones deplete the jets' $p_\perp$. This shifts gaps to lower Q_0. At low Q_0, the parton shower decreases gaps, because it may generate the veto jet. This is a small effect in the inclusive veto region (left), where the veto jet is almost always the one generated by Powheg, but a large effect in the exclusive veto region (right).

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