NLO matching schemes & Pythia

LHCtopWG meeting, May 15, 2020

Stefan Prestel (Lund)

Event generators have moved to NLO (QCD) for most LHC analyses. For Pythia, this is thanks to Powheg-Box and aMC@NLO. Thanks!

All event generators offer NLO matching and NLO merging schemes. For the latter, Pythia offers two schemes, FxFx and UNLOPS.

To understand the differences, it is useful to think about x-section like a "shower person":

$$\begin{aligned}\sigma(\text{inclusive } 0 \text{ jet}) &= \sigma(\text{exactly } 0 \text{ jet}) + \sigma(1 \text{ or more jets}) \\ &= \underbrace{\sigma(\text{exactly } 0 \text{ jet})}_{\text{exclusive}} + \sigma(\text{exactly } 1 \text{ jet}) + \underbrace{\sigma(2 \text{ or more jets})}_{\text{inclusive}}\end{aligned}$$

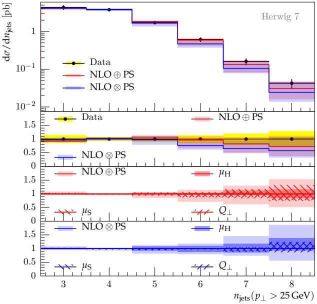
Precision event generator error budgets

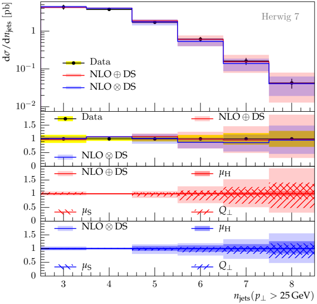
Plots from HERWIG: arXiv:1810.06493

Any precise calculation is only as good as its error budget.

Many variations can contribute:

- ◇ *Fixed-order scale variations*
- ◇ *Matching scheme & matching parameters*
- ◇ *Shower construction*
- ◇ *PS phase-space constraints*
- ◇ *All-order PS scale variations*
- ◇ *Non-perturbative variations*





Not much to say here – minimum requirement!

Suggestion: In NLO matched PYTHIA generation

- correlate fixed-order $\mu_r^\updownarrow$ with parton-shower $\mu_r^\updownarrow$ as baseline
- use envelope of correlated & uncorrelated as conservative band

Issue: On top of "regularizing subtractions", NLO+PS methods also contain "overlap removal subtractions" or "shower counter terms":

Overlap between shower and real (making real "unweightable") & overlap between shower "virtuals" and fixed-order loops needs to be removed.

Note: "Overlap removal subtractions" do not necessarily have to be negative, nor produce negative weights.

POWHEG-BOX provides NLO matched input by producing an *exclusive* 0-jet calculation and an *inclusive* 1-jet calculation with NLO-correct rate.

1. PYTHIA should respect the exclusive 0-jet calculation – almost no showering.
   - Can use vetoed shower vs. small PS starting scale to assess impact of shower on Born-like inputs.
2. PYTHIA needs to divide up the inclusive 1-jet calculation into exclusive "bins" by showering $\rightarrow$ avoid "too hard" emissions.
   - Can vary $p_\perp$ definition `POWHEG:pTemt` to determine impact of subsequent shower.

Note: Such changes should only be considered for "trouble-shooting".
Note: ME-corrected splitting probabilities are allowed & preferred (can these lead to inconsistent setups?)

aMC@NLO provides NLO matched input by producing a shower-subtracted *inclusive* 0-jet calculation with NLO-correct rate.

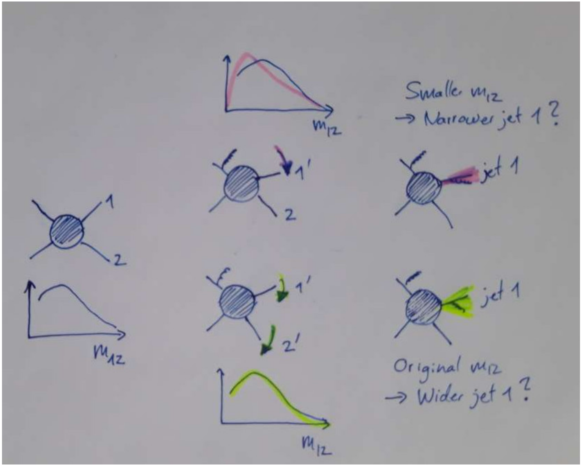
1. PYTHIA needs to divide up the inclusive 0-jet calculation into exclusive "bins" by showering. The shower must run with the same settings used in the shower subtraction:
   - kernels have to be identical
   - phase space coverage has to be identical
   - phase space mapping has to be identical
2. aMC@NLO "steers" phase space coverage by assigning shower starting scales.

Note: Changes to the kernels are not allowed, i.e. ME-corrected splitting probabilities not possible.
Note: Might use different starting scale assignments to highlight "matching uncertainty".

If you see large differences between POWHEG and MC@NLO in hard jets, try using (NLO) merging to assess the impact of additional hard jets. If so, check at least two schemes, for example

- FxFx vs. MINLO
- FxFx vs. UNLOPS (using either Powheg or MC@NLO samples)

Question: Why does the phase-space mapping influence distributions – shouldn't observables be independent of technical tricks?
Answer: Yes, but...we use the events as *input* for subsequent shower:



⇒ When in doubt, check global/local final-state mappings, or global/local(dipole) initial-state showers.

Matrix element corrections amend the splitting probability of the shower to reproduce tree-level results for *specific processes*.
Typical behavior:

- MECs make emission spectrum softer compared to a shower (if PS had previously produced the spectrum).
- MECs by themselves *do not* open up more phase space.

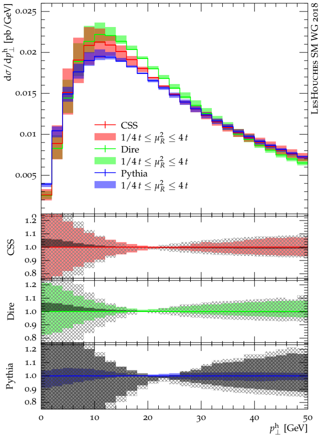
MECs can be stacked for resonance production/decay processes (*top: MEC for radiation off t, for radiation off b, for radiation off W decay products*). Right now in PYTHIA, it's "all or nothing" in these cases.

Note: In FSR, MECs will also handle producing mass corrections.
Note: Any change in the splitting probability requires consistent changes in the shower subtractions.

Shower construction: Shower scale variations

Plot from arXiv:1803.7977

Current PS are spin-averaged, large-N_c & recover soft/collinear single real-emission pattern ⇒ Large uncertainties.

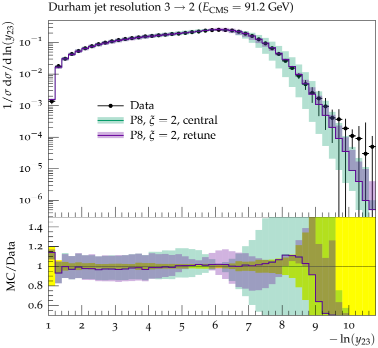


◇ Scale variations:
`UncertaintyBands:doVariations = on` for automatic variations of μ_r in shower (`fsr:muRfac=0.5 isr:muRfac=0.5`...)

◇ Splitting kernel variations (`fsr:cNS=2.0 isr:cNS=-2.0`...)

PYTHIA still has no NLO tune endorsed by the authors, since an NLO tune is conceptually challenging.

Suggestion: If you want to changes tunes at NLO, only change to tunes that work well in an LO setup.



Note that there's always the danger of inconsistent NLO+PS setups:

- Mass treatment in $g \to b\bar{b}$ splitting. Not all setups are consistent!
- MECs are not supported by aMC@NLO.
- Shower phase-space limitations may lead to inconsistent setups

Summary

- Several sources of uncertainty/modeling in matched/merged calc^s.
- Advisable to use several matching methods, but also merging (to assess impact of additional hard jets) and PS scale variations (to assess impact of additional soft jets)

Some questions

- Are the trends in ATLAS and CMS consistent?
- Is there a consistent analysis setup (similar cuts, unfolded data, no ad-hoc corrections to data...)?
- Can we pinpoint problematic phase space regions, by e.g. using merged calculations to assess impact of hard additional jets?

Thanks for your time!