LUND UNIVERSITY

PYTHIA8 and UNLOPS

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Outline

- Introduction
- The UNLOPS scheme (+NNLO)
- Matching and merging in PYTHIA8
- The NLO+PS tool chain

How to generate NLO predictions

- Rapidity-distribution of a Higgs?
  Easy! Generate plain Higgs to NLO
- $p_\perp$-distribution of a Higgs?
  Generate Higgs + 1-jet to NLO.
  But need to resum for small $p_\perp$.
- $p_\perp$-distribution of photons from Higgs?
  Plain NLO Higgs? Is only LO for $p_{\perp\gamma} > m_h/2$.

We need to combine NLO calculations for several jet multiplicities.

Multi-jet merging and matching — CKKW(-L)

Same problem as combining tree-level MEs:

- Add showers
- No double-counting (use a merging scale, t_{ms})
- No under-counting
- Sudakov form factors
- α_S-running
- (PDF ratios)

Multi-jet merging and matching to NLO

- Sudakov form factor already includes virtual α_S correction.
- $\alpha_S(p_\perp)$ already includes α_S corrections
- Ratio of PDFs already includes α_S corrections

Do not destroy NLO accuracy for n-jet observables when adding $n+1$-jet NLO.

Related to Unitarity

A Parton shower is unitary. When adding an emission it removes the event with one jet less.

This is done with the help of the no-emission probability = Sudakov form factor $\times$ PDF ratio.

$$\Pi_i(\rho_i, \rho_{i+1}) = \exp\left(-\int_{\rho_{i+1}}^{\rho_i} d\rho dz\, \alpha_S \frac{F_{i+1}}{F_i} P_{i+1}\right)$$

When an PS emission is added to a 0-jet ME, the 0-jet contribution is automatically multiplied by the Sudakov (no-emission probability).

In a CKKW-Like merging the one jet is added using the full matrix element above the merging scale, while the 0-jet contribution is multiplied with the no-emission probability above the merging scale.

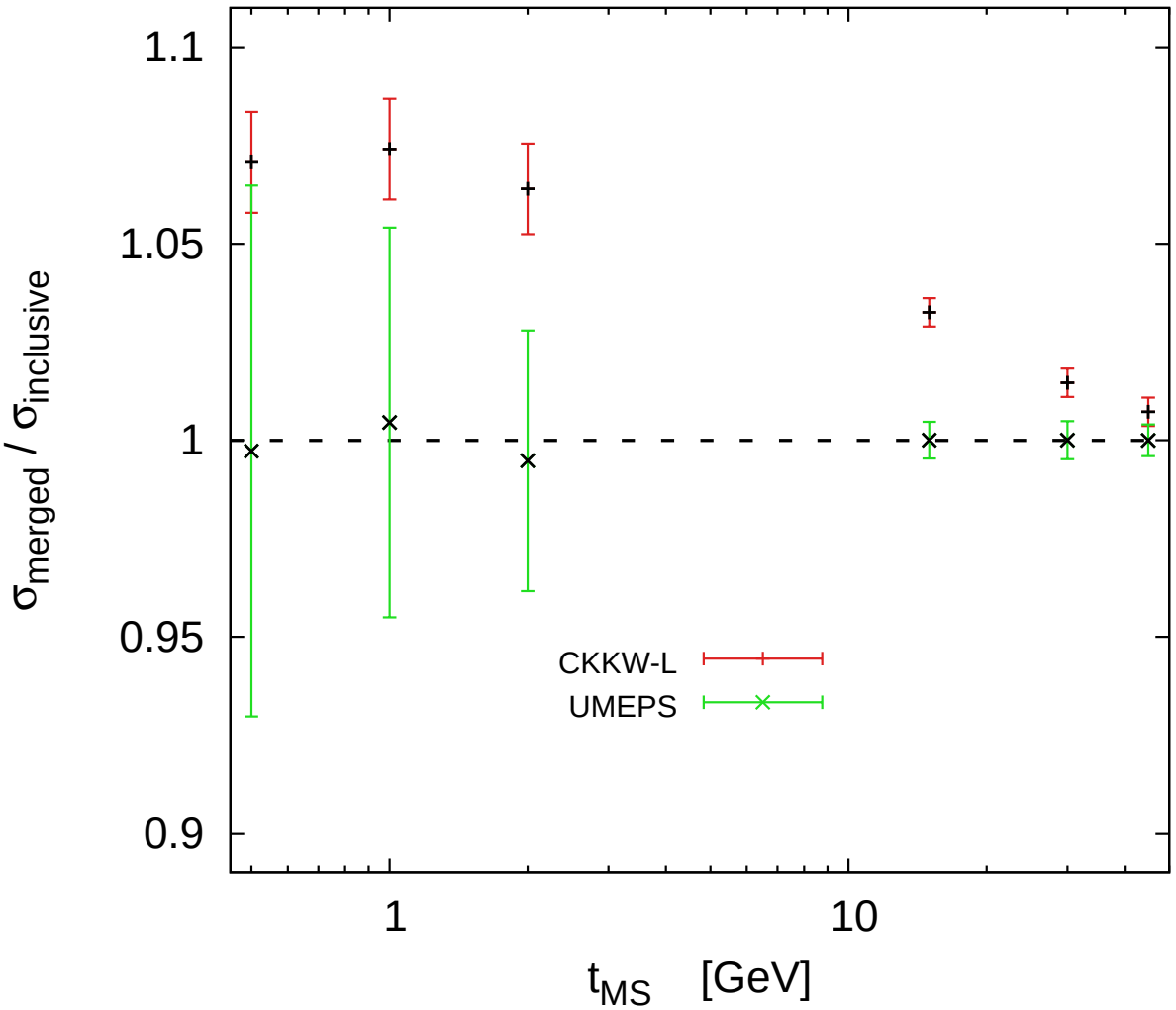
But the Sudakov only exponentiates the (approximate) PS splitting function.

This breaks the unitarity. Typically an effect $\sim \alpha_S^2 L^3(t_{\rm ms})$.

Blows up for small $t_{\rm ms}$.

Enter the UMEPS scheme

- Don't multiply the 0-jet sample with a Sudakov
- When adding the one-jet ME events we multiply by the no-emission probability above the $p_\perp$ of the first jet.
- But we also integrate out (recluster) the jet and add this 0-jet state to our 0-jet sample with negative weight.
- Corresponds to the 0-jet Sudakov but with ME-corrections in the exponent.
- We subtract what we add and restore unitarity.


1.1
1.05
1
0.95
0.9
1
10
$\sigma_{merged} / \sigma_{inclusive}$
t_{MS} [GeV]
CKKW-L
UMEPS

The UNLOPS scheme for multi-jet NLO merging

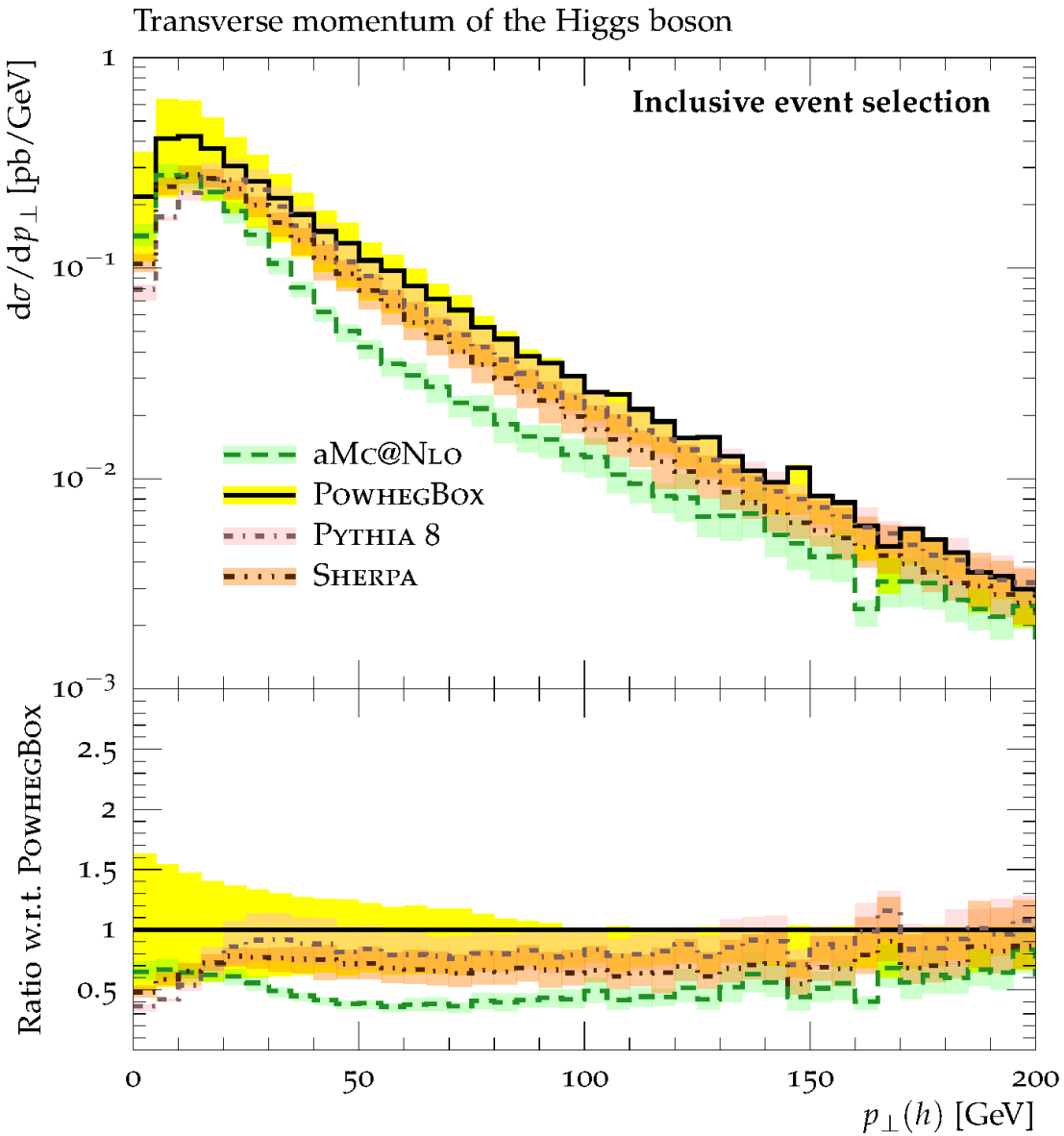
- Take a UMEPS run combining $0 + 1 + \cdots +$ *N*-jet ME's
- Add NLO generated samples for $0 + 1 + \cdots +$ *M*-jets ($M < N$) and shower below the merging scale.
- In the Sudakov, PDF and α_s-reweighting in the UMEPS reweighting: expand out in orders of α_s and subtract the α_s^0 and α_s^1 terms.
- Subtract reclustered NLO samples (m>0).

Done.

Pros and Cons of UNLOPS

- t_{ms} can be taken arbitrarily small.
- All (m<M)-jet observables correct to NLO.
- Use arbitrary M.
- 0-jet observables to NNLO in principle possible

- Need to combine many event samples.
- Need “exclusive” NLO events.
- Lots of negative weights (large for small t_{ms}).



http://phystev.cnrs.fr/wiki/2013:groups:sm:higgs:hdijetsresults

Towards NNLO

In UNLOPS, the 0-jet contribution is given only by the (exclusive) 0-jet NLO ME. If we had a a corresponding exclusive NNLO ME we could use that instead.

Exclusive (below t_{ms}) 0-jet NNLO
+ inclusive (above t_{ms}) 1-jet NLO
= full NNLO

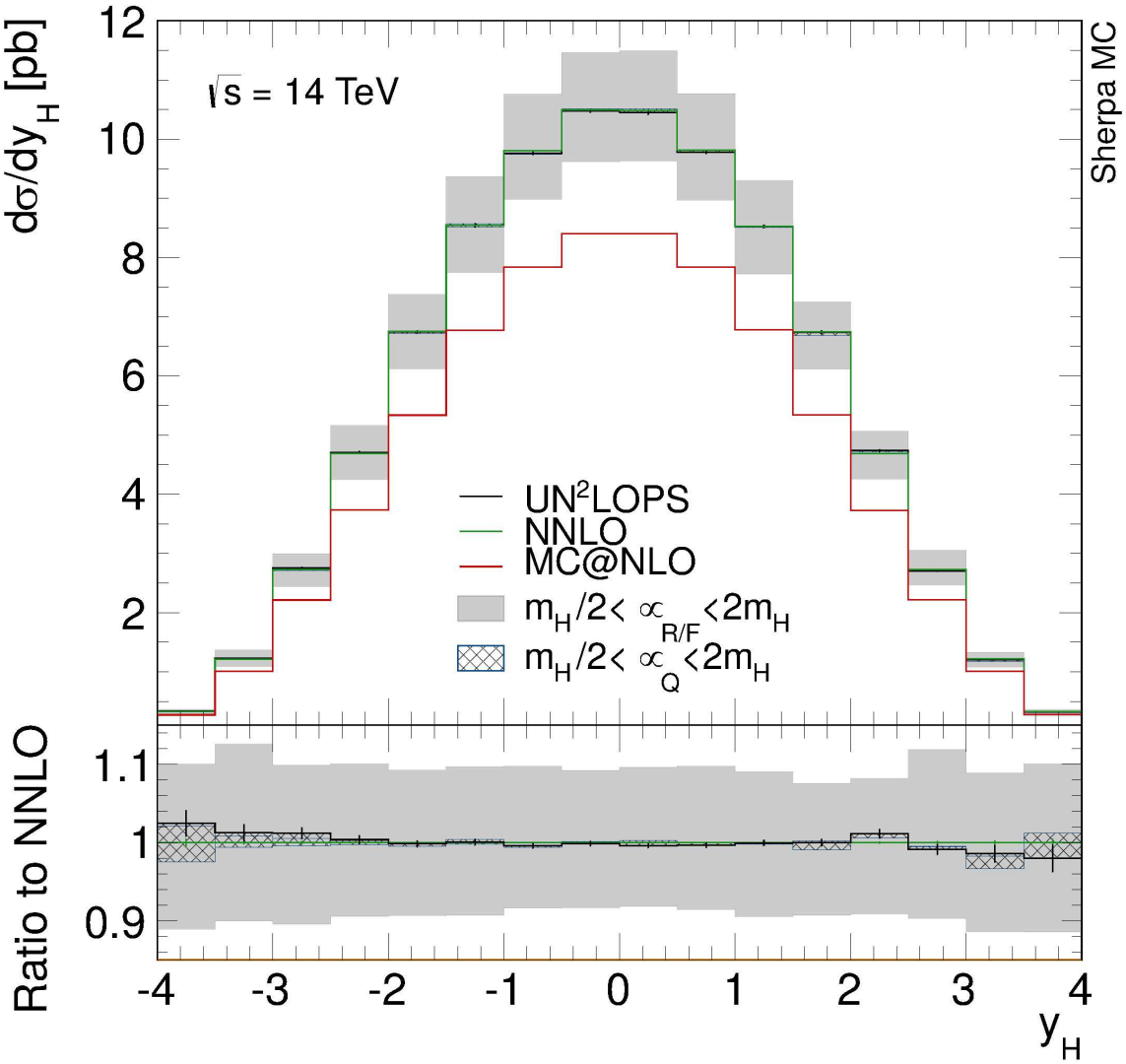
We would have to expand out the UMEPS-weights one order higher in α_S — cumbersome but doable.

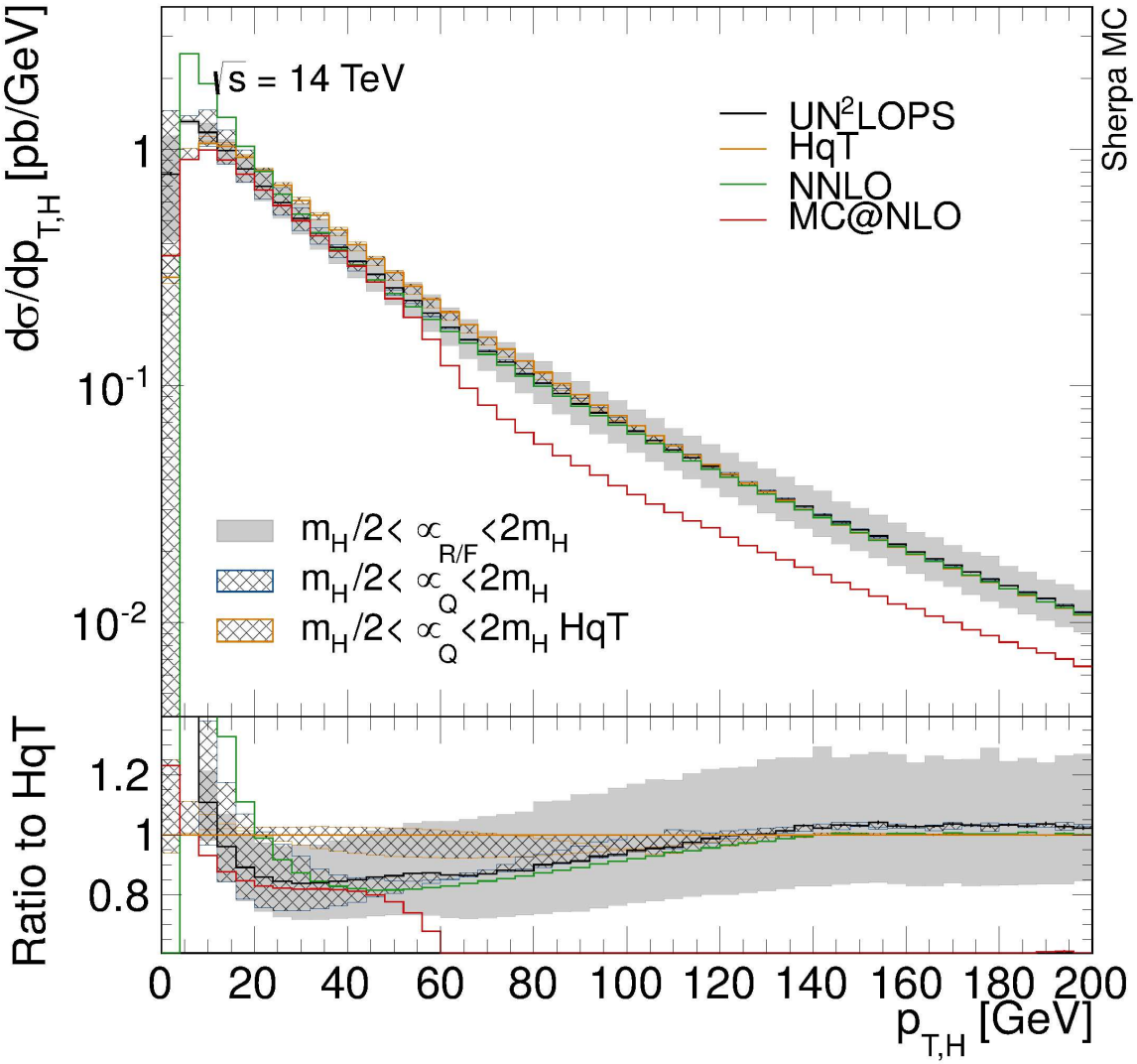
UN^{2}LOPS

Höche, Li and Prestel:
Drell-Yan to NNLO arXiv:1405.3607
Higgs to NNLO: arXiv:1407.3773

Use compact NNLO jet-vetoed ME's from effective theory.

(plus lots of technical details)


dσ/dy_H [pb]
√s = 14 TeV
Sherpa MC
UN²LOPS
NNLO
MC@NLO
m_H/2< μ_R/F <2m_H
m_H/2< μ_Q <2m_H
Ratio to NNLO
y_H


√s = 14 TeV
UN²LOPS
HqT
NNLO
MC@NLO
Sherpa MC
dσ/dp_T,H [pb/GeV]
1
10^-1
10^-2
m_H/2< ∝_R/F <2m_H
m_H/2< ∝_Q <2m_H
m_H/2< ∝_Q <2m_H HqT
Ratio to HqT
1.2
1
0.8
0
20
40
60
80
100
120
140
160
180
200
p_T,H [GeV]

Matching and Merging in PYTHIA8

UNLOPS is implemented in PYTHIA8, and well described in the on-line manual.

It is not completely automatized. See `main89.cc` in the examples directory.

You need to generate LHEF-files with MadGraph5_aMC@NLO with
1...N-jet tree-level events and
0...M-jet NLO events
separately.

Also in PYTHIA8

- UMEPS
- CKKW-L
- MLM
- FxFx
- + first ever tree-level ME matching

You can also run PYTHIA8 with the PowhegBox (see `main31.cc`).

Special care is taken to account for the difference in the $p_\perp$-definition in Powheg and the $p_{\perp\text{evol}}$ in PYTHIA8. (Vetoed showers, but not truncated)

The NLO tool chain

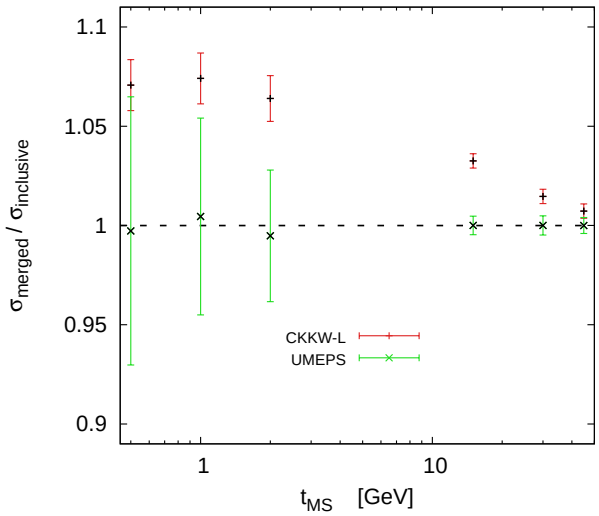
- NLO ME event generators
- Les Houches Event files
- Parton shower (merging and matching)
- HepMC
- (Rivet or other analysis)

LHEF version 3

- Better handling of multiple weights, with possibility to supply info on scale variations etc.
- Allows for several scales (per event μ_F, μ_R and μ_Q)
- Event groups for handling of counter events

`http://home.thep.lu.se/~leif/LHEF`

Events in a group should be handled together in an analysis — one histogram fill instead of several.



UNLOPS would also benefit from pre-weighted events at small t_{ms}.

HepMC version 3

(complete rewrite, work in progress)

- Allows for event groups
- (includes all LHEF3 information)
- Named weights
- ...
- Backwards compatible

`http://hepmc.web.cern.ch/hepmc/`

Summary

- UNLOPS works
- PYTHIA8 can handle it
- Look out for UN^{2}LOPS

Outlook

- UNLOPS needs event group handling for statistics.
- Also needs pre-weighted events for efficiency.
- There are some issues with radiation off tops before/after decays.
- How do we treat W/Z-strahlung diagrams (weak showers)
- Need to think more about b-jets.
- Is adding underlying events trivial?
- We need tuning for multi-jet NLO merging.

References

(only arxiv numbers)

- Original first-emission matching: Bengtsson, Phys. Lett. B185 (1987) 435
- CKKW(-L): Catani, hep-ph/0109231; Lönnblad, hep-ph/0112284
- UMEPS: Lönnblad, 1211.4827
- UNLOPS: Lönnblad, 1211.7278; Plätzer: 1211.5467
- Les Houches comparison + LHEF3: Butterworth, 1405.1067
- FxFx: Frederix, 1209.6215
- MC@NLO: Frixione, hep-ph/0204244
- POWHEG: hep-ph/0409146
- MadGraph5_aMC@NLO: Alwall, arXiv:1405.0301