CKKW matrix element merging in Herwig++

Jonathan Tully

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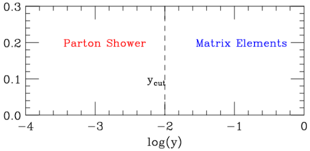
work in collaboration with Peter Richardson

Implementation of a modified CKKW merging algorithm based on POWHEG shower restructuring in Herwig++[6].

- Merging combines parton showers with exact matrix elements improving descripion of hard jets.
- NLO matching combines (N)LL PS with NLO cross sections ($\mathcal{O}(\alpha_S)$ correction only).
  - MC@NLO[5], **POWHEG**[3]
- Tree level merging combines (N)LL PS with all tree level MEs up to maximum multiplicity.
  - **CKKW**[1, 2], **CKKW-L**[4], MLM, Pseudo-Shower[7]
- Implementation of a modified CKKW merging algorithm based on POWHEG shower restructuring for $e^+e^- \rightarrow \mathrm{jets}$.
- Aim to avoid worst of problems with merging in angular ordered shower.

- ME merging methods split phase space into two regions: ME + PS
  - smooth coverage + no double counting
- define jet resolution cut y_{cut} in some jet measure eg Durham

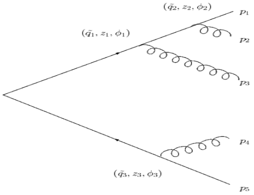
$$y_{dur} = 2\frac{\min(E_1^2, E_2^2)}{s}(1 - \cos\theta_{1,2}) \quad (1)$$



- CKKW replaces **approx splitting functions** with **exact MEs** above y_{cut}
- CKKW procedure
  1. jet multiplicity n selected $\propto \sigma_n(y_{cut})$
  2. n momenta distributed according to corresponding MEs
  3. n momenta clustered giving ‘shower history’
  4. reweighted with appropriate Sudakov weights
  5. vetoed shower below y_{cut} from history end points

- A number of issues/difficulties with implementing CKKW
  - Scale definition inconsistencies
  - Choice of initial shower conditions
  - Shower colour structure
- In particular problems when not using a p_T ordered shower
  - Smooth merging and y_{cut} independence not achieved
  - Shower may not produce all radiation
- Discontinuities at partonic level in the jet parameter[8]
- Herwig++ is an angular ordered shower
- Modifications aim to remove the worst of these problems

- Based on POWHEG shower restructuring with truncated showers[3, 10]
- Key element is inverse momentum reconstruction
  - Undoes rescaling boosts
  - Recursive Sudakov decomposition

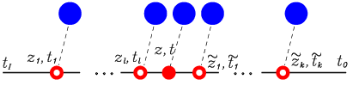


momenta + shower history $\rightarrow$ shower variables

- Shower procedes as single shower with forced splittings and truncated showers
  - Fills gaps in shower
  - Exact mappings to shower variables
  - Unambiguous intitial shower conditions
  - Shower colour structure preserved

- POWHEG separates hardest shower emission
- Nason explicitly writes shower line with hardest emission

$$\mathbb{S}(t_I) = \Delta(t_I, t_0)\langle\mathbb{I}| + \sum_{l,k=0}^{\infty} \int$$

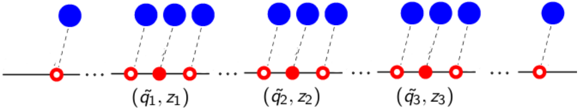


- All other emissions vetoed at p_{Th}
- Results in remnant Sudakov Form Factor

$$\Delta_R(t_i, t_f; p_{Th}) = \exp\left(-\int \mathrm{d}z\mathrm{d}tF(z,t)\Theta(k_T - p_{Th})\right) \quad (2)$$

- shower $\rightarrow$ truncated shower + hardest emission + vetoed showers

- Generalise to shower line with set of 'hard emissions' (above $k_{Tcut} = \sqrt{y_{cut} s}$)

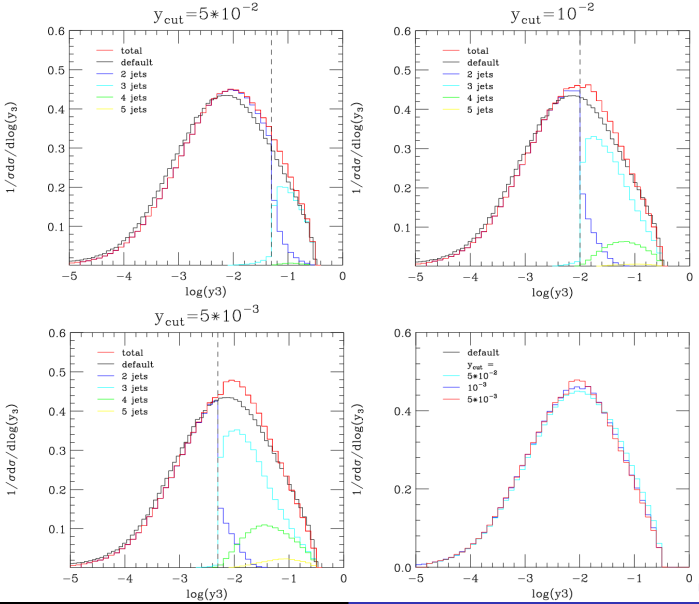


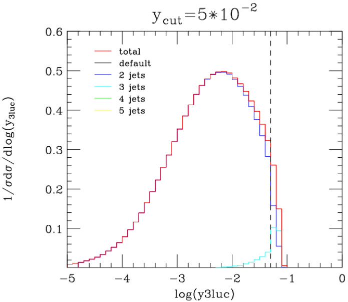
- Remnant Sudakovs between hard emissions with fixed k_{Tcut}

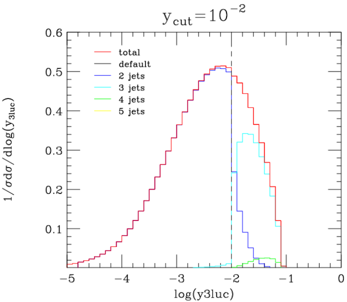
$$\Delta_R(\tilde{q}_i, \tilde{q}_f; k_{Tcut}) = \exp\left(-\int \mathrm{d}z\mathrm{d}t F(z,t)\Theta(p_T - k_{Tcut})\right) \quad (3)$$

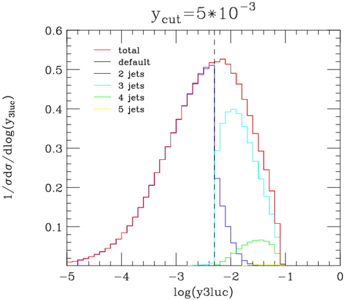
- Sudakov factors built from shower history exactly as in standard CKKW
  - with Θ-fn since $\tilde{q} \neq k_{Tcut}$
- Multiple truncated showers shower between hard emissions

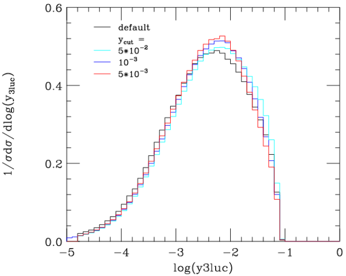
1. n jet (at y_{cut}) event samples produced in MadGraph[9]
2. Multiplicity chosen according to cross section, event chosen
3. Momenta clustered giving shower history
4. Shower variables to produce shower history calculated
   - Defines a set of 'hard emissions'
5. Reweighting with Sudakov and α_S weights
   - Analytically calculated with exact shower variables
6. Shower begins from clustered $q\bar{q}$ state
7. Truncated showers evolve along each line
   - With y_{cut} veto, no flavour changing
8. Hard emissions forced when get to relevant scales
   - If there is another hard emission along line go to 7.
9. Vetoed emissions evolve to hadronization scale


$y_{cut}=5*10^{-2}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_3)$
log(y3)
$y_{cut}=10^{-2}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_3)$
log(y3)
$y_{cut}=5*10^{-3}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_3)$
log(y3)
default
y_{cut} =
$5*10^{-2}$
10^{-3}
$5*10^{-3}$
$1/\sigma d\sigma/d\log(y_3)$
log(y3)

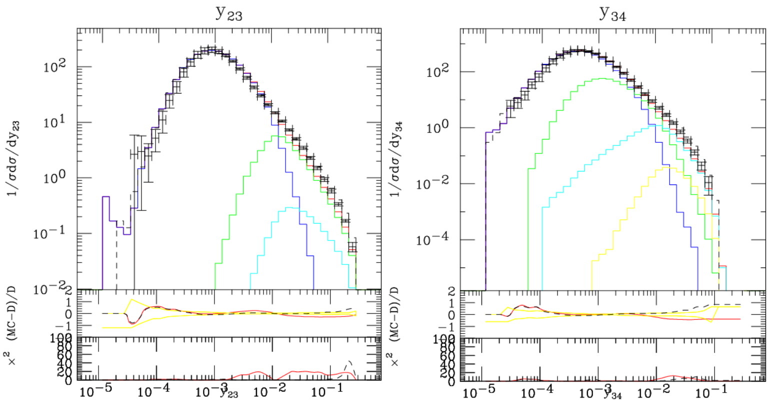

$y_{cut}=5*10^{-2}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_{3luc})$
log(y3luc)


$y_{cut}=10^{-2}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_{3luc})$
log(y3luc)

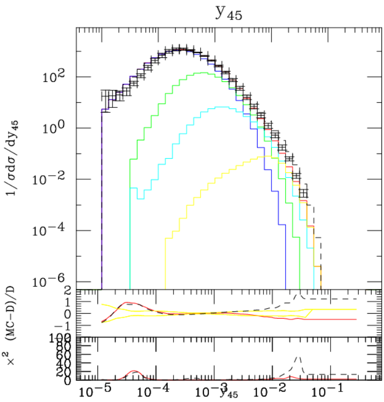

$y_{cut}=5*10^{-3}$
total
default
2 jets
3 jets
4 jets
5 jets
$1/\sigma d\sigma/d\log(y_{3luc})$
log(y3luc)


default
y_{cut} =
$5*10^{-2}$
10^{-3}
$5*10^{-3}$
$1/\sigma d\sigma/d\log(y_{3luc})$
log(y3luc)

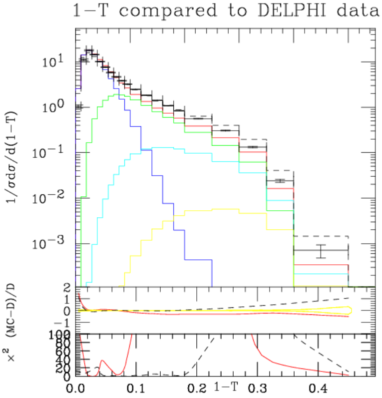
Hadronic jet resolution with $y_{cut} = 10^{-2}$ (Durham k_T)

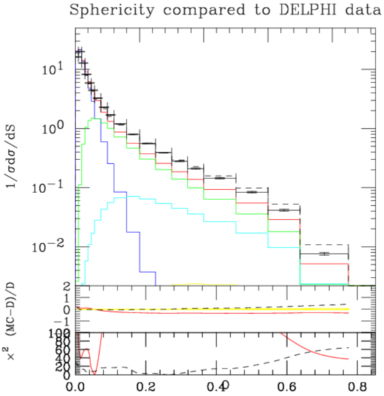


Hadronic jet resolution with $y_{cut} = 10^{-2}$ (Durham k_T)



Hadronic event shapes with $y_{cut} = 10^{-2}$ (Durham k_T)





Modification still to be made

- Currently clustering is in terms of jet measure
  - Durham and Luclus
- Possibility of unordered emissions in clustered history
  - Some forced unordered emissions
  - Will effect contributions for $n > 3$ jets
- Plan to move to CKKW-L style clustering
  - All allowed ordered histories considered
  - History chosen according to shower probability
- Code already in place

Summary

- Modified CKKW algorithm implemented in Herwig++ for $e^+e^- \to \mathrm{jets}$
  - POWHEG style restructuring with truncated showers
  - Exact mappings to shower variables avoiding scale mismatches
- Sensitive partonic plots appear free of discontinuities
- Changes to be made with ordering
- Plan to extend to hadron-hadron

[1] S. Catani, F. Krauss, R. Kuhn and B. R. Webber, "QCD matrix elements + parton showers," JHEP **0111**, 063 (2001) [arXiv:hep-ph/0109231].

[2] A. Schalicke and F. Krauss, "Implementing the ME+PS merging algorithm," JHEP **0507**, 018 (2005) [arXiv:hep-ph/0503281].

[3] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms," JHEP **0411**, 040 (2004) [arXiv:hep-ph/0409146].

[4] L. Lonnblad, "Combining matrix elements and the dipole cascade model," Acta Phys. Polon. B **33**, 3171 (2002).

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[10] K. Hamilton, P. Richardson and J. Tully, "A Positive-Weight Next-to-Leading Order Monte Carlo Simulation of Drell-Yan

Vector Boson Production," JHEP **0810**, 015 (2008) [arXiv:0806.0290 [hep-ph]].