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Matching Matrix Element and Parton Shower

INFN workshop on “Monte Carlo, fisica e simulazione di eventi per LHC”, 21-23 May, Frascati, 2006

From partons to jets: why do we need "matching?"

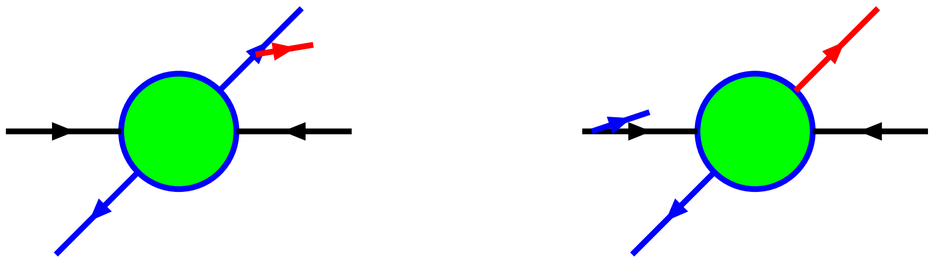
- we want to describe events with many hard jets in the final state: we need ME description AND parton evolution to hadrons (PS).
- Parton-level cuts should not be harder than jet cuts

  $p_{T parton} \geq p_{T cut} = E_{T jet}^{min}$ $\qquad \Delta R(parton{-}parton) \geq \Delta R_{cut} = \Delta R_{jet}$

  One should start from softer parton-level cuts
- Due to softer cuts some events are obatined as:

  – two (or more) hard partons are clustered in the same jet

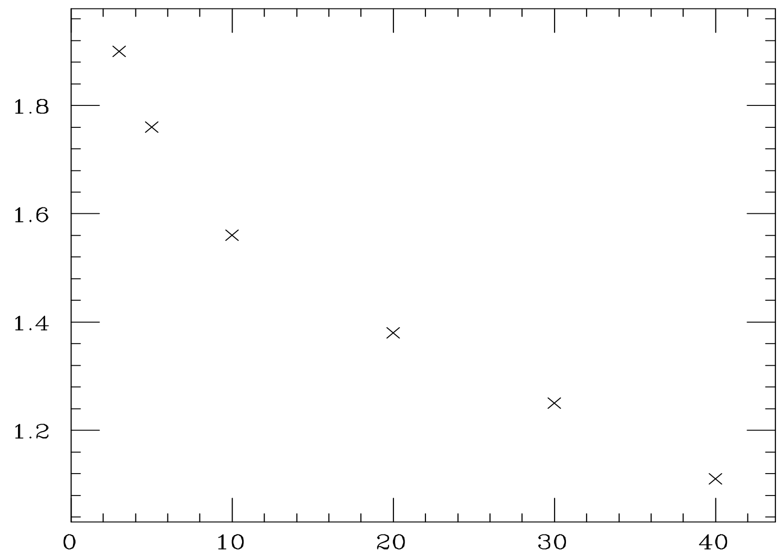
  – one (or more) jet is obtained from hard PS radiation
- double counting (suppressed by $O(\alpha_S)$)
- ME soft/collinear divergencies not dumped by Sudakov suppression.



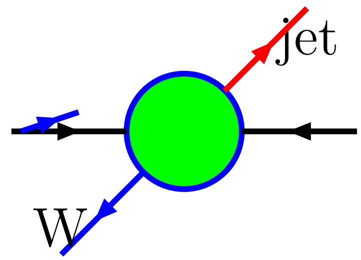
Black ME (initial partons); Blue ME (final partons); Red PS Two different emission leading to the same final state kinematics. In the left one the matrix element has no Sudakov damping for soft/collinear emission, leading to a divergent cross section.

- Ideally the final jet cross-section should be independent of the parton-level generation cuts, even in the limiting case $p_{Tmin} \to 0$ and $\Delta R_{cut} \to 0$
- The double counting effect is suppressed by at least one power of α_S. Naively it should be small so why bother?
- A fixed order calculation accounting for the emission of coloured particles (of QCD origin) is *divergent* in the IR/Collinear limit.

- This behaviour can be controlled adding toghether virtual and real contribution of the same order (not avaliable for large multiplicities), still the prediction in the soft/collinear region is unreliable: *resummation required*
- PS includes resummation, fixed order ME doesn't



Cross section (nb) for the production of a W ($\rightarrow e\nu_e$) + jets at the LHC. The hardest jet is required to have $p_T > 40$ GeV. The cross section is plotted against the cut on the parton p_T at the generation level (NO MATCHING). The soft/collinear sensitivity is clearly seen.



- The growth is due to this class of events: the ME weight grows up to ∞ for soft/collinear emission.
- Notice that this affects distributions as well
- That's why we want to describe these events with the PS and treat only hard emissions with ME

Towards matching of ME & PS

For e^+e^- physics a solution has been proposed

S. Catani et al., JHEP 0111 (2001) 063

L. Lönnblad, JHEP 0205 (2002) 046

which avoids double counting and shifts the dependence on the resolution parameter beyond NLL accuracy

The method consists in separating arbitrarily the phase-space regions covered by ME and PS, and use vetoed parton showers together with reweighted tree-level matrix elements for all parton multiplicities

Proposal to extend the procedure to hadronic collisions: no proof of NLL accuracy

F. Krauss, JHEP 0208 (2002) 015

The CKKW procedure has been successfully tested on LEP data

e.g. S. Catani et al., JHEP 0111 (2001) 063

R. Kuhn et al., hep-ph/0012025

F. Krauss, R. Kuhn and G. Soff, J. Phys. G26 (2000) L11

Recent work for hadronic collisions

- `Herwig` (P. Richardson)
- `Pythia` (S. Mrenna)

  S. Mrenna and P. Richardson, JHEP **0405** (2004) 040

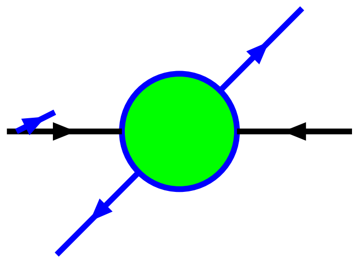
- `SHERPA with APACIC++/AMEGIC++`

  F. Krauss, A. Schälicke, S. Schumann and G. Soff, Phys. Rev. D **70** (2004) 114009

  F. Krauss, A. Schälicke, S. Schumann and G. Soff, Phys.Rev. D72 (054017) 2005.

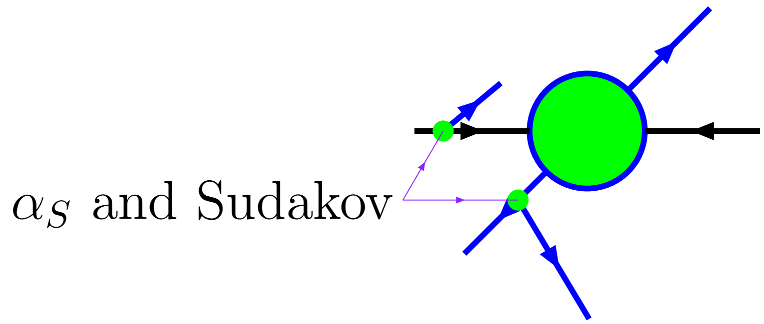
CKKW (oversimplified)

- define a resolution parameter μ (to separate among ME and PS description
- a phase space point is covered by ME only if $K_\perp$ separation among any (colour and flavour connected) particle pair is larger than μ



this phase space kinematics will not be covered by ME

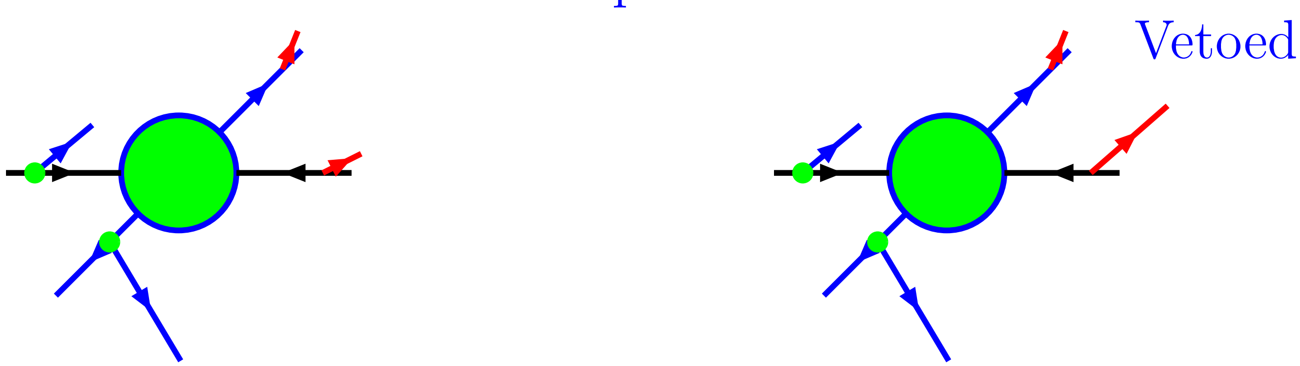
- for a phase space ME space point reconstruct a branching tree according to $K_\perp$ algorithm: two momenta are "clustered" if their $K_\perp$ separation is the smallest one. Iterate until the leading order process has been reached ($2 \to 1$ for drell-yan, $2 \to 2$ for jet and $t\bar{t}$ production, ...)



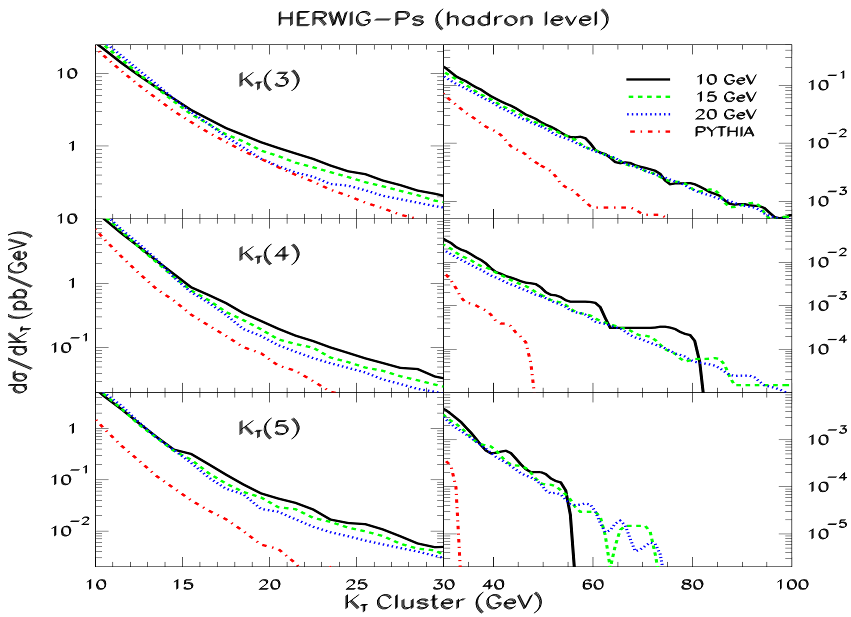
small bullets: branching

This phase space kynematics will be covered by ME and not by PS, two branchings are identified.

- the ME is reweighted with α_S at the branching scales and with the appropriate Sudakov factors (to match what the PS would have done for this kynematics)
- the PS is allowed to produce additional emissions vetoing those emission wich leads to resolved partons



Studies of CKKW proposal for hadronic colliders have been performed by S. Mrenna and P. Richardson

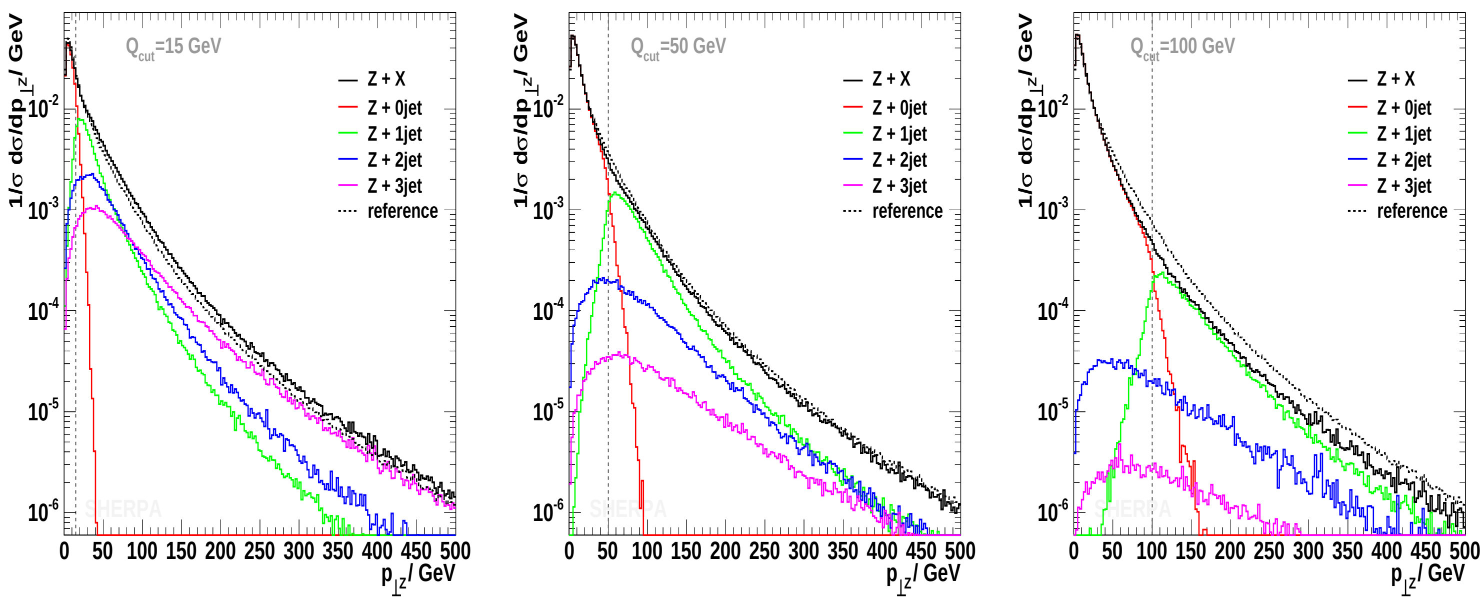


S. Mrenna and P. Richardson, JHEP **0405** (2004) 040. TEVATRON. p_T distributions of the III, IV and V jet (ordered in p_T). ME with up to four final quarks/gluon. PS Herwig, adronization level. Sime sizable dependence from resolution scale. Overall relatively good agreement (notice that this sample is a high multiplicity one and the impact on p_{tW} is mild).

Some "discontinuities" in distributions around the resolution scale.

and by

F. Krauss, A. Schälicke, S. Schumann and G. Soff.



F. Krauss, A. Schälicke, S. Schumann and G. Soff, Phys.Rev. D72 (054017) 2005.

$p_\perp(Z)$, $Q_{\rm cut} = 15$ GeV, 50 GeV and 100 GeV (from left to right).

Again some sizable dependence from resolution scale, expecially for p_{TZ} (the chosen range of parameter might be a bit too extreme).

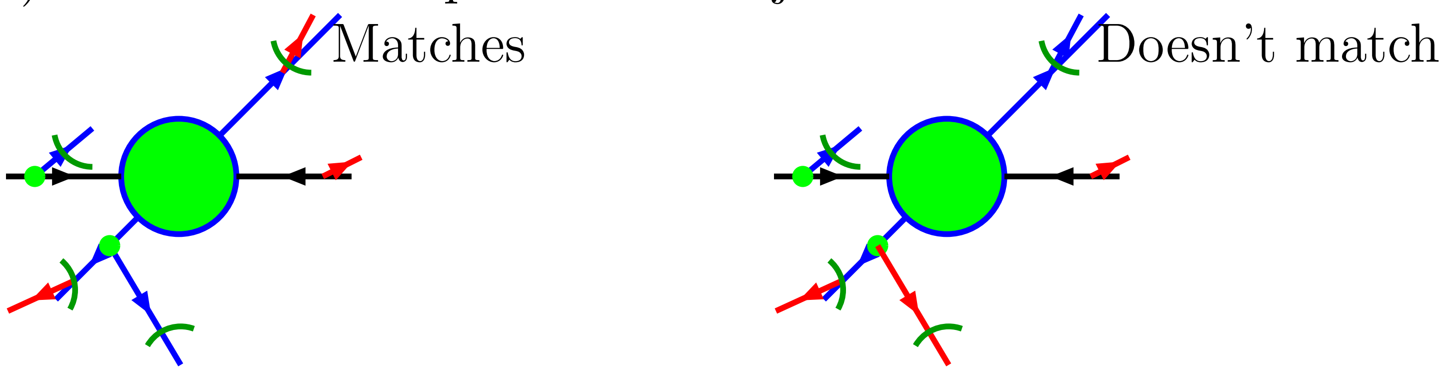
- parameter dependence needs to be accurately studied, a reliable prediction requires the existence of a region of (mild) (in)dependence from the resolution parameter.
- even assuming that CKKW procedure is NLL accurate (for hadronic collisions there is neither a proof nor a convincing argument) the accuracy ultimately depends from the implementation: at present no parton shower uses $k_\perp$ as an evolution parameter and thus some mismatch of *Log* contribution has to be expected
- BEFORE TRUSTING AN EVENT SAMPLE perform some exploration on the issue of stability at least to assess the systematic and check for the robustness of your conclusions.

An alternative proposal

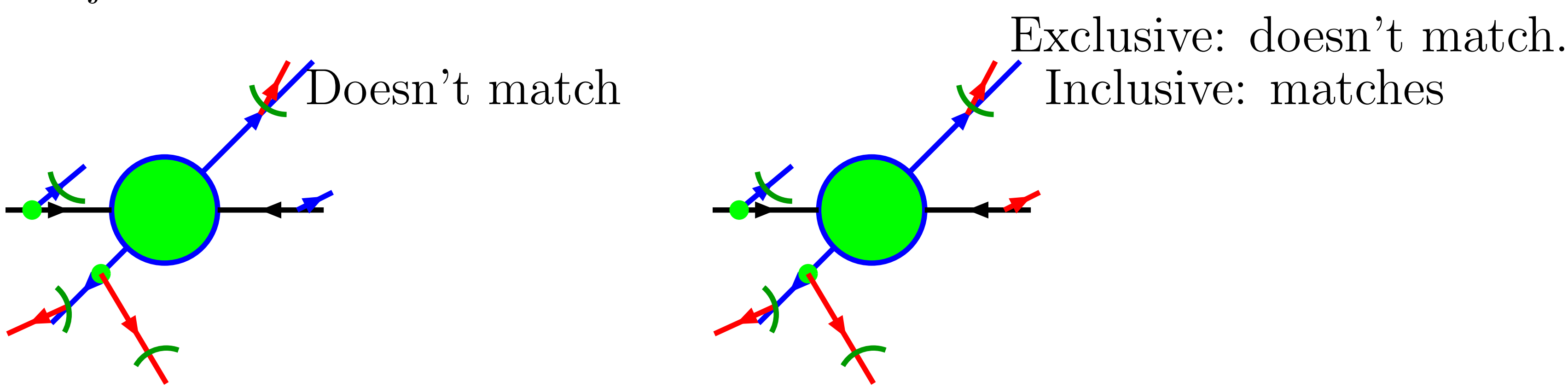
M.L. Mangano, FNAL MC Workshop, October 2002

- generate event sample ($p_T > p_{T min}$ $\Delta R > \Delta R_{min}$
- shower the event and reconstruct particle clusters (jets) with a cone algorithm
  - Note: these clusters are just a computational device to define the sample. they don't need to coincide with "experimental" jet
- define the matching of a parton (LO matrix element) and a cluster as follows: a parton matches a cluster if the separation ΔR between the parton and the cluster is smaller than $\Delta \bar{R}$ (an arbitrary fixed quantity $\Delta \bar{R} \sim \Delta R_{min}$
- reject the event if more than one parton match the same cluster or if a parton doesn't match any cluster

- for *exclusive* samples also events with number of clusters different (larger) from number of partons are rejected



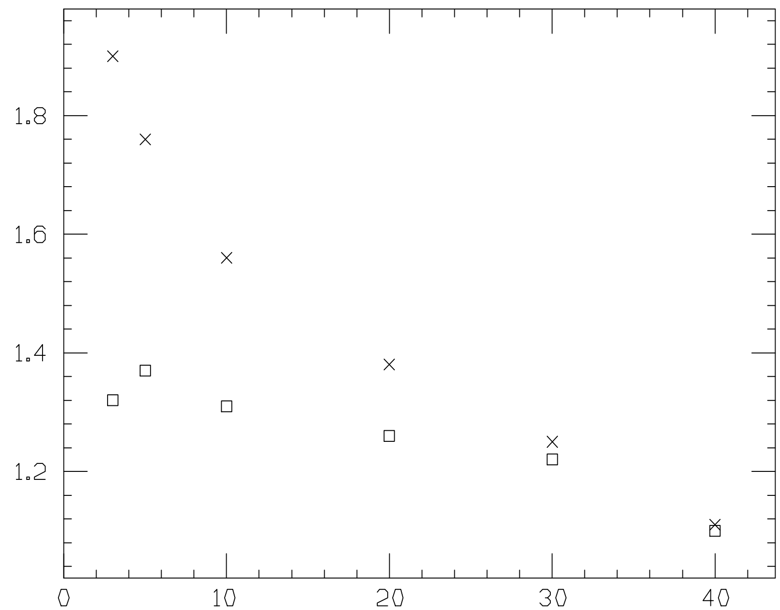
Left: all ME partons inside a distinct cone; Right two ME partons inside the same cone, one hard jets made from the shower



Left: a soft ME partons not inside a cone; Right all ME partons inside distinct cone, one extra hard jets made from the shower, since the number of jets is larger than matirx element partons, accepted only for inclusive samples

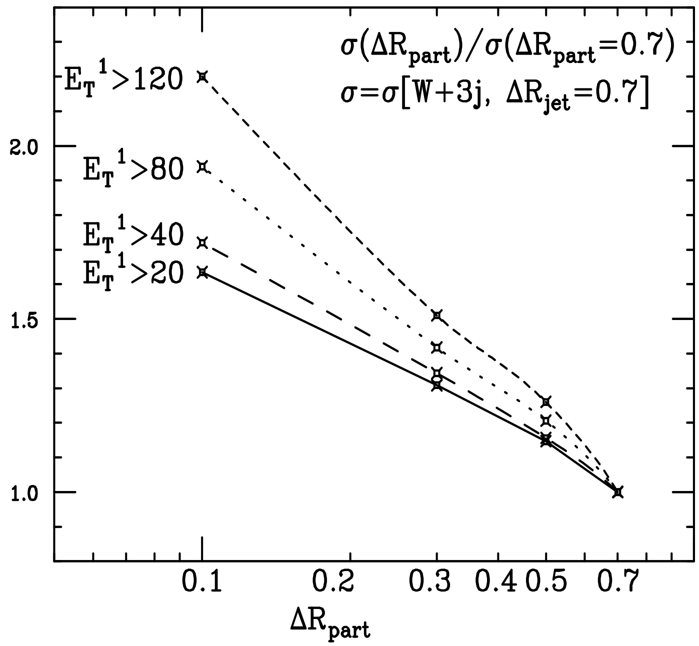
One still expects not better than LL accuracy. However we expect a strongly reduced NLL sensitivity. From the practical point of view it is enough that these residual effects are smaller than the other systematics of the calculation

Ideally the whole prescription leads to samples independent from generation cuts. In practice the dependence from generation cuts is a measure of the success of the matching prescription



Cross section (nb) for the production of a W ($\rightarrow e\nu_e$) + jets. The hardest jet is required to have $p_T > 40$ GeV. The cross section is plotted against the cut on the parton p_T at the generation level. Crosses: no matching. Boxes: matching (one-jet inclusive sample)

Example: $W + 3$ jets at Tevatron



Cross section for $W + 3$ jets at Tevatron as a function of generation cuts (ΔR_{parton} $E_{Tparton}$). The soft/collinear divergence is clearly seen. This feature is even more pronounced than in the $W + 1$ jet case: the larger the number of jets the larger the number of potentially "dangerous" *Logs*.

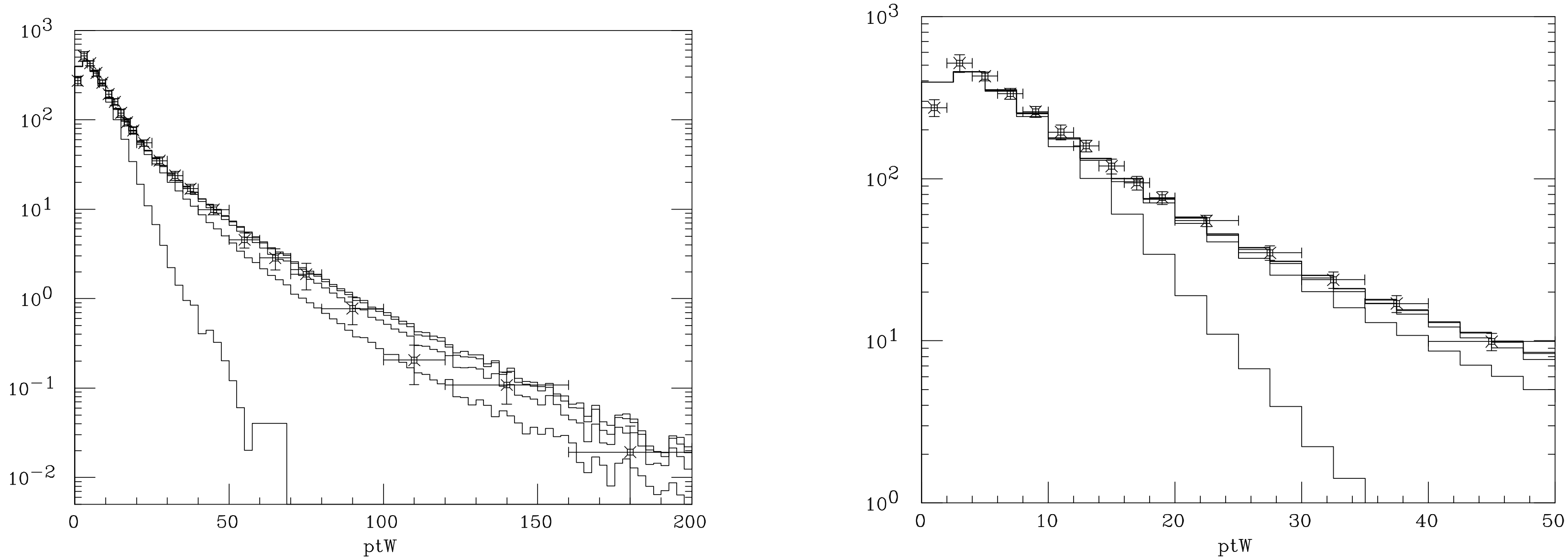
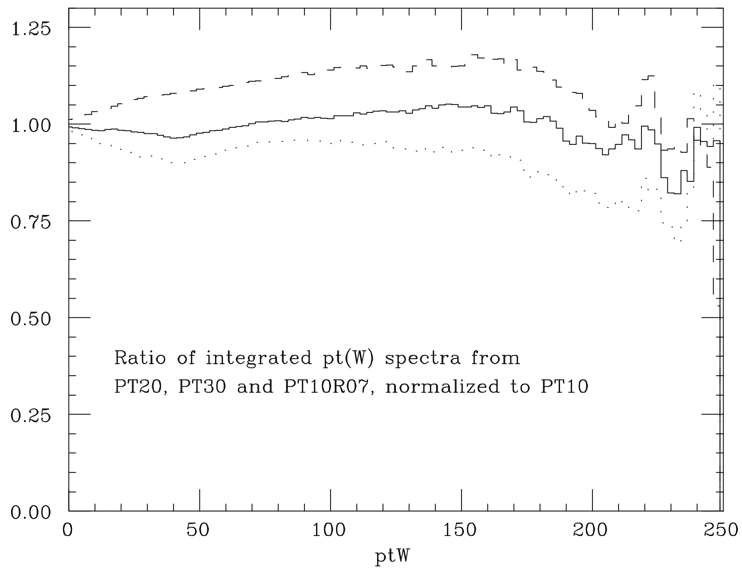


Figure 1: $p_{T,W}$ spectrum. The points represent run I CDF data. The curves correspond to the subsequent inclusion of samples with higher multiplicity, form the $W + 0$ jet, up to the $W + 4$ jets case. The right plot is the same as the left one, with an enhanced low-p_T scale.



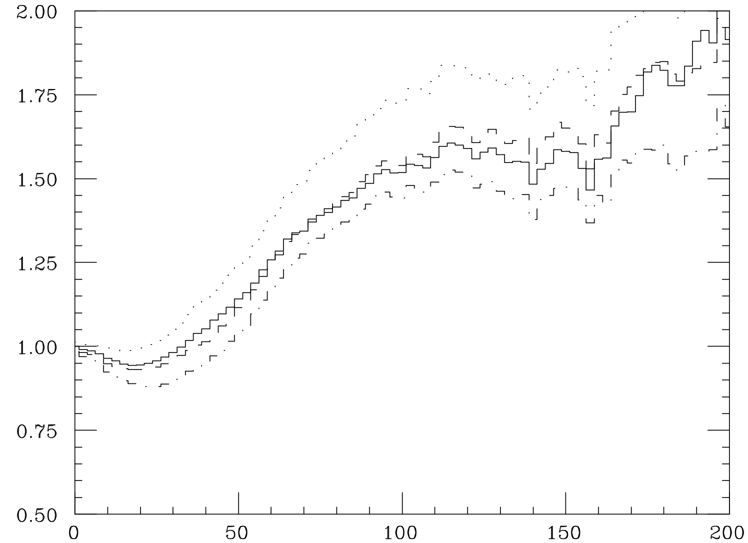


Figure 2: Effect of different genertaion cuts on the integrated $p_{T,W}$ spectrum. The right panel shows the ratios of the samples generated with PT20, PT30 and PT10R07, divided by PT10. The right panel shows all four samples divided by a plain (no ME correction) HERWIG W sample.

PT10, PT20, PT30 : $P_T > 10, 20, 30 GeV$, $\Delta R > 0.4$

PT30R07 : $P_T > 30$, $\Delta R > 0.7$

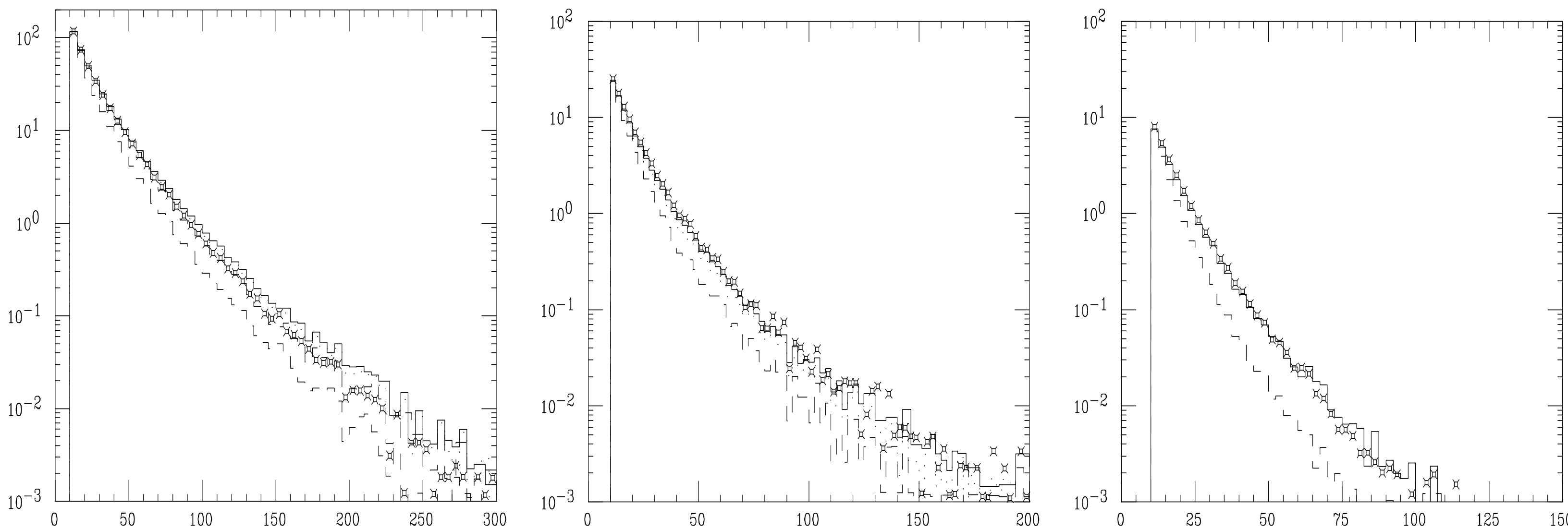


Figure 3: Inclusive jet/cluster E_T spectra, obtained via from an inclusive sample (plotted points) and by adding exclusive samples, for $N_j = 1, 2, 3$.

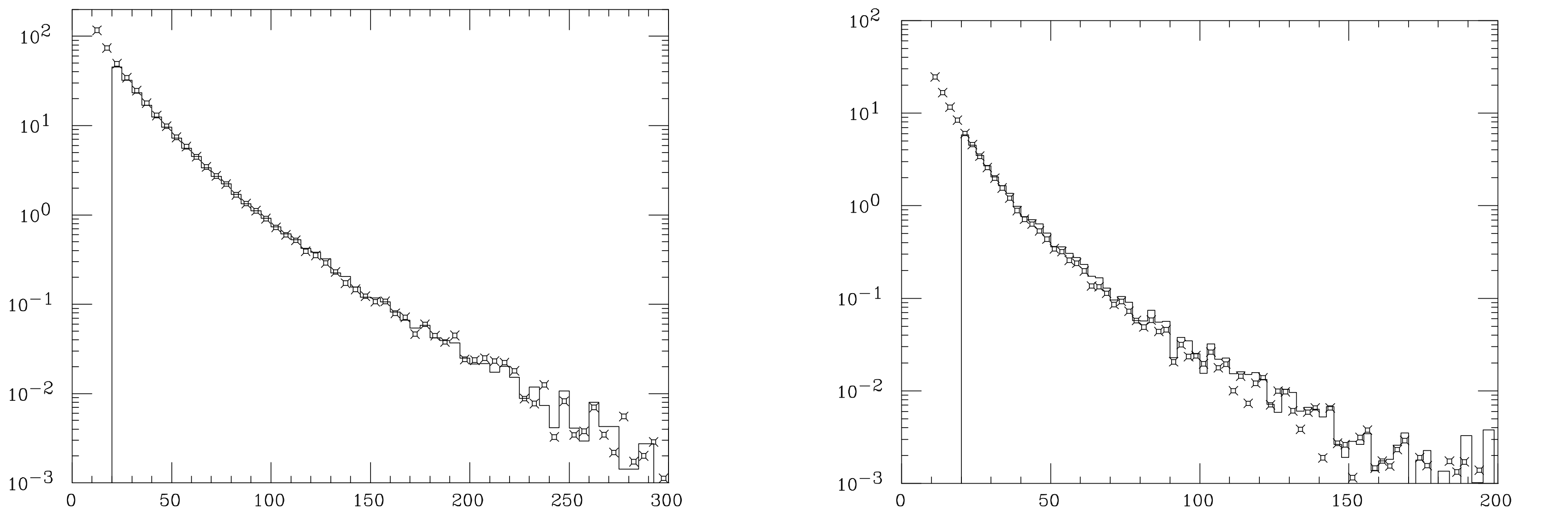
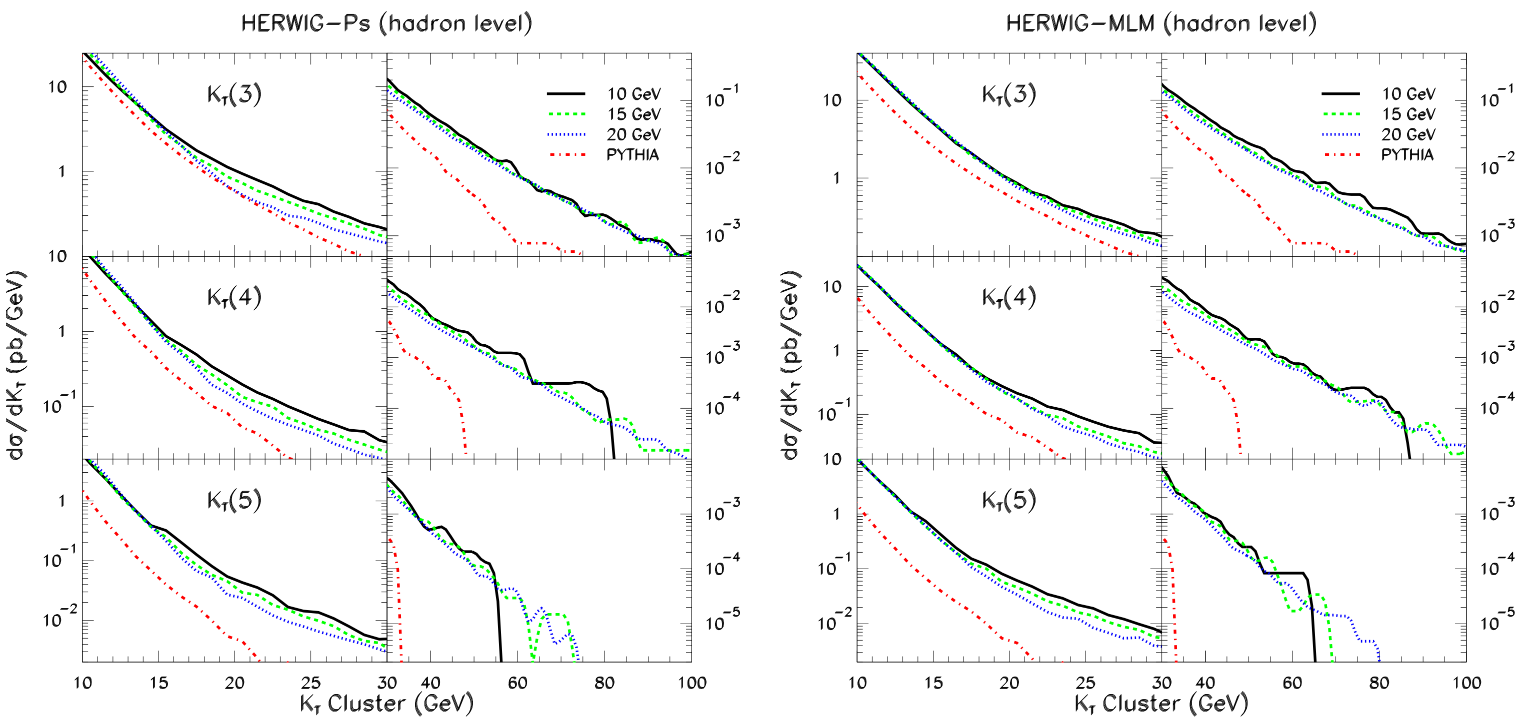


Figure 4: Effect of different generatiaon cuts on the E_T spectrum of the leading (left) and of the second (right) jet/cluster. Solid line obtained with PT20, plots with PT10.

Comparing the two approaches



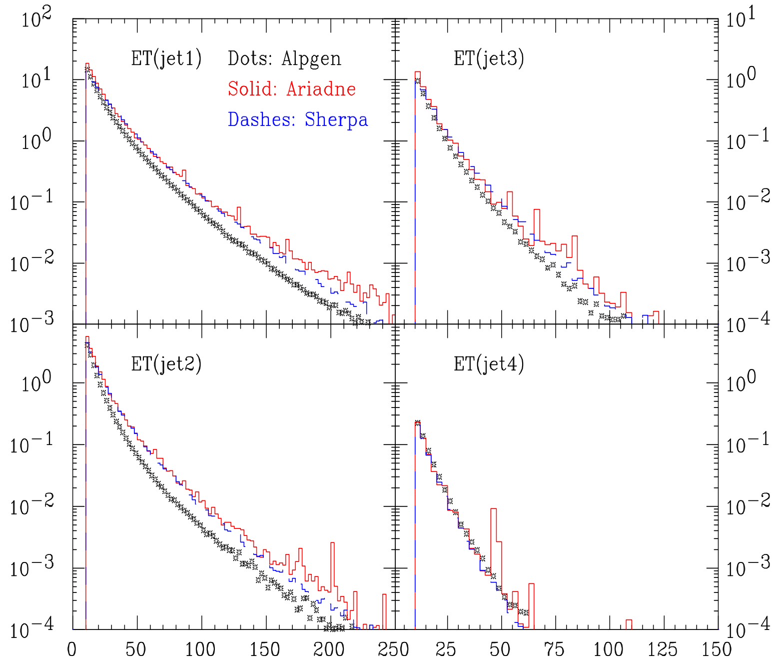
S. Mrenna and P. Richardson, JHEP **0405** (2004) 040.

TEVATRON. p_T of the III, IV and V jets (ordered in P_T) for $W+$ jets. ME with up to four final coulored partons. PS Herwig, hadronization level. Left: CKKW. Right matching

fairly comparable behaviour

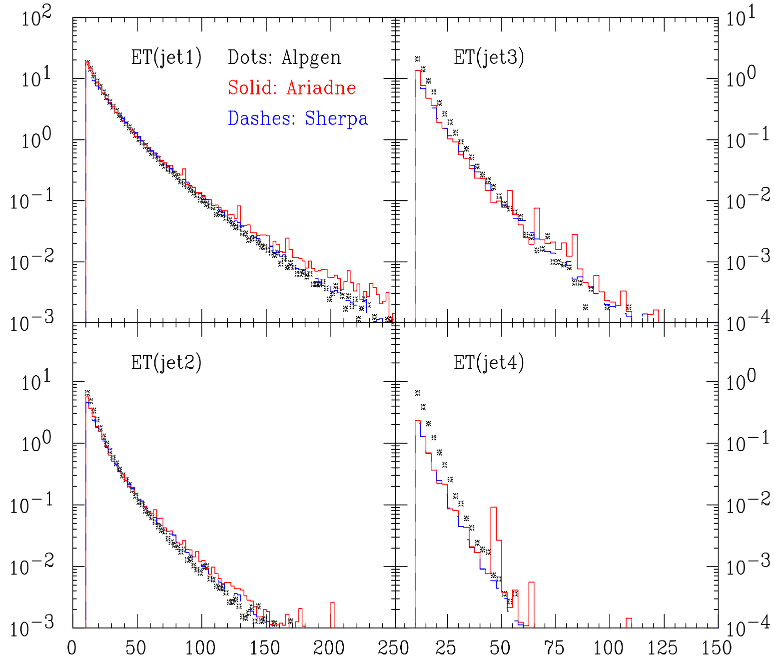
$W/Z+$ jets: ALPGEN, ARIADNE and SHERPA

Stefan Höche, Frank Krauss, Nils Lavesson, Leif Lönnblad, Michelangelo Mangano, Andreas Schälicke, Steffen Schumann, hep-ph/0602031



Inclusive E_T spectrum of the first four jets (pb/GeV). Tevatron

`ALPGEN` softer than `SHERPA`. Different PS and/or hadronization? But, with `ALPGEN` scale lowered by a factor 2:



Same as previous figure. **ALPGEN** scale lowered by a factor 2.

Conclusions

- PS (for soft/collinear regions) and ME (for hard emissions) are both required for a reliable description of jets production at high energy colliders.
- A naive merging suffers from uncontrollable systematics both at the level of absolute rates and distributions.
- Essentially two strategies have been suggested to tackle this problem: CKKW and MLM matching procedure.
- Both the approaches exhibit a strongly reduced soft/collinear sensitivity of the prediction.
- Both procedure are affected by (in)dependence from resolution/matching parameters.
- To "validate" an event sample it is advisable to study the systematic associated with parameter dependence (in particular

for the observables of interest).

Not discussed (because of lack of studies, not of time ...)

- dependence on showering algorithm, adronization and beam renmant description. (somewhat mentioned in S. Mrenna and P. Richardson.)
- PS tuning:
  - tuning a PS on data implies tuning of non perturbative and phenomenological parameters to better describe data.
  - assume the plain PS underestimate hard radiation: the tuning will adjust the PS non perturbative parameters to enhance hard radiation.
  - if ME+PS (shower only) cures the above problem one will end up, after hadronization, with too much hard radiation
  - *in principle ME+PS should be retuned*