Merging Matrix Elements and Parton Showers with SHERPA

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Combining ME and PS

How to simulate hard processes with additional hard radiation ?

The Matrix Element domain:

- ME is exact at some given order in the coupling constant including all quantum interferences and correlations
- Account for high energetic and well separated parton configurations
- For soft and collinear kinematics a fixed order calculation is not adequate due to the lack of multiple unresolved gluon emissions

The Parton Shower domain:

- Relates partons produced in a hard interaction to partons at the hadronization scale
- Includes logarithmically enhanced soft and collinear contributions of parton emissions
- Not enough high energetic gluons are emitted that have a large angle from the shower initiator

Combining ME and PS – CKKW

Combine LO Matrix Elements and Parton Showers according to CKKW

S. Catani,F. Krauss, R. Kuhn, B. Webber, JHEP 0111:063,2001

F. Krauss, JHEP 0208:015,2002

Aim:

- Good description of soft and hard region
- Avoid double counting of equivalent phase space configurations
- Universality of fragmentation (energy independent)

Solution:

- Divide multi-jet phase space into two regimes (Durham measure $Q_{\rm cut}$)
  - Jet production through ME's (if available)
  - Jet evolution down to fragmentation scale by the PS
- Reweight ME's to get exclusive samples at resolution scale $Q_{\rm cut}$

  $\Rightarrow$ This allows to add samples of different jet multiplicities
- Veto on PS configurations that have already been taken into account by a higher order ME

Combining ME and PS – CKKW

Method:

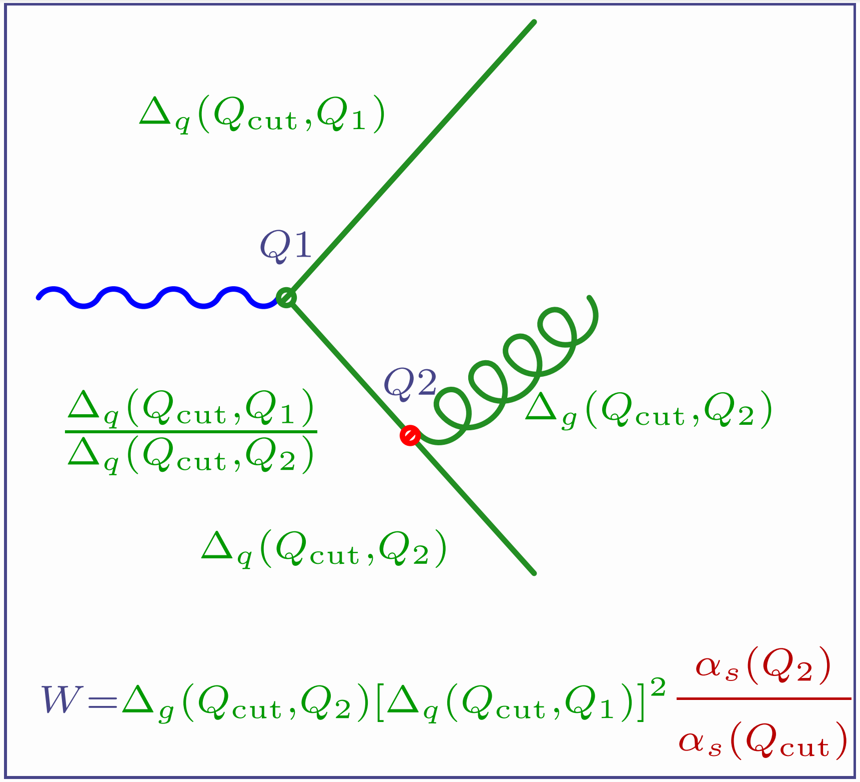
- Select a jet multiplicity with probability:

$$P_n = \frac{\sigma_n}{\sum_{i=0}^{N} \sigma_i}$$

  where σ_n is the n-jet matrix element taken at Durham resolution $y_{\rm cut} = Q^2_{\rm cut}/Q^2$. Use $Q_{\rm cut}$ as scale for PDF's and α_S.
- Generate final state momenta p_i according to the ME
- k_T cluster backwards initial and final state particles until a core $2 \to 2$ process remains, this results in a chain of resolutions for 1,2,..,n jets
- Recalculate α_S at each vertex in the tree at the corresponding k_T scale
- Apply Sudakov weights
  - $\Delta_{q,g}(Q_{\rm cut}, Q_{\rm prod})$ for outgoing partons
  - $\Delta_{q,g}(Q_{\rm cut}, Q_{\rm prod})/\Delta_{q,g}(Q_{\rm cut}, Q_{\rm dec})$ for lines between $Q_{\rm prod} > Q_{\rm dec}$

Combining ME and PS – CKKW

- Reject events with a combined coupling and Sudakov weight smaller than a random number $R \in [0,1]$
- Start the initial or final state parton shower for each parton of the event, starting at the scale where it was produced
- Veto on emissions above the scale $Q_{\rm cut}$



- ➔ Yields an inclusive sample with up to n-jets described by matrix elements
- ➔ Allows for a process independent implementation
- ➔ Although parts of the higher order corrections are included the production rate is still leading order

Combining ME and PS – CKKW and Variants

The algorithm has been implemented in SHERPA in full generality

T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S.S., J. Winter, JHEP 0402 (2004) 056

- Relies on built-in ME generator AMEGIC++ and the APACIC++ showers
- Proved to be successful in e^+e^- collisions
- For hadron collisions the study of systematics has started
  - W/Z+jets @ Tevatron: F. Krauss, A. Schälicke, S.S., Phys. Rev. D 70(2004)114009
  - W/Z+jets @ LHC: F. Krauss, A. Schälicke, S.S., Phys. Rev. D 72(2005)054017
  - e^+e^-+jets vs. Tevatron data: D0 note 5066
  - WW+jets: T. Gleisberg et al., Phys. Rev. D 72(2005)034028
  - pure jets, H+jets, WBF in preparation

There exist now several variants of the algorithm, they differ:

- In the jet definition used for the matrix element evaluation
- The way the ME rejection weights are constructed
- Their choices for parton shower starting scales and emission vetoing

Combining ME and PS – CKKW and Variants

The M. L. Mangano (MLM) prescription

M. L. Mangano et al. Nucl.Phys.B 632:343,2002

- N-jet samples from Alpgen passed for showering to HERWIG/PYTHIA
- Match the N ME partons to $N + M$ jets after showering
- Different samples can then be added without double counting

The Lönnblad prescription

L. Lönnblad, JHEP 0205:046,2002 and L. Lönnblad, N. Lavesson, JHEP 0507:054,2005

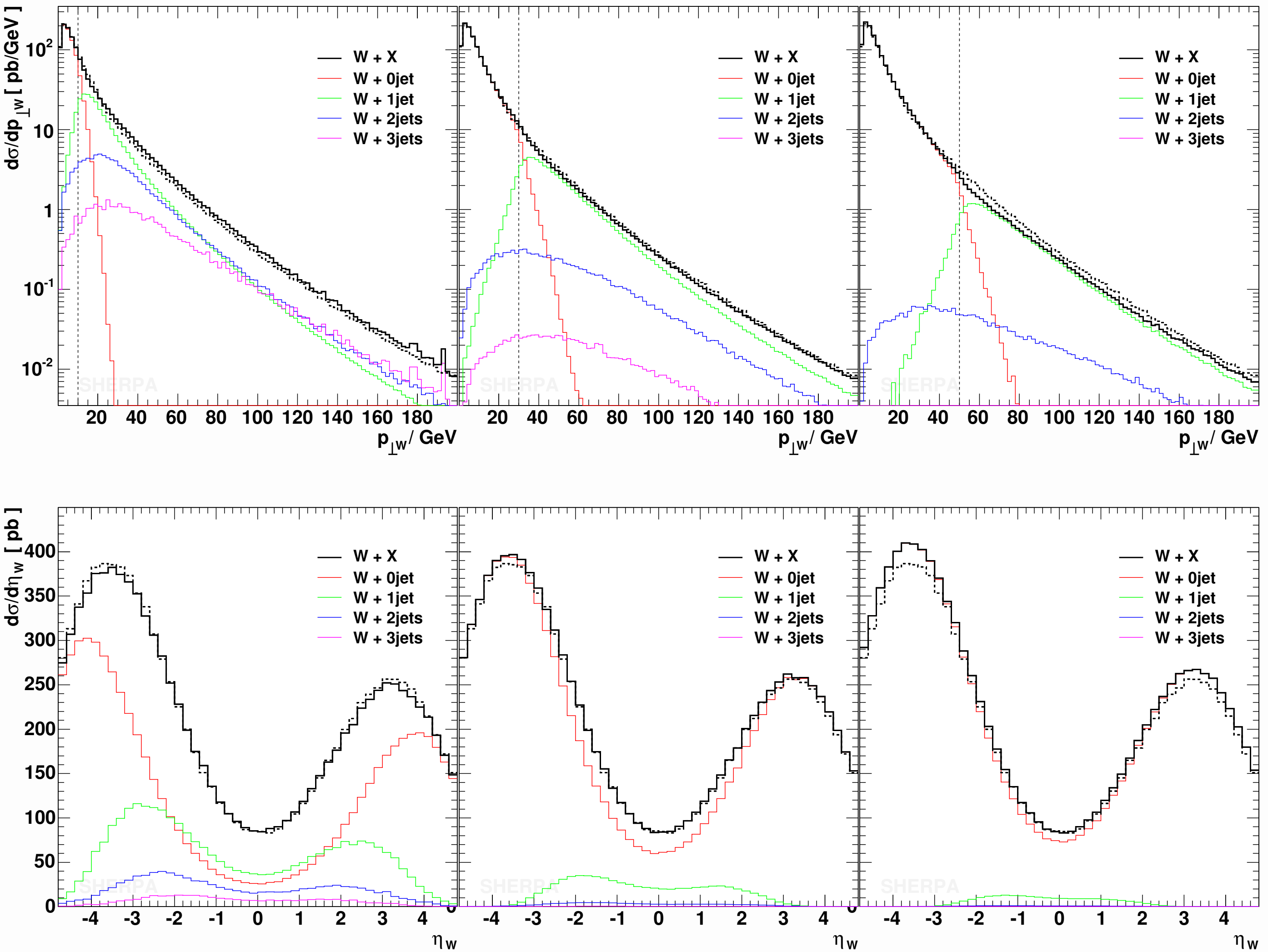
- Via the LHA interface ME's are passed to the ARIADNE dipol cascade
- The Sudakov weights are constructed using ARIADNE itself

➔ **All prescriptions have similar systematics**

- Residual dependence on the phase space separation cut $Q_{\rm cut}$
- Variations with the number of ME legs taken into account
- Dependencies on the internal jet algorithm

Consistency checks: Variation of the separation cut

$p_\perp$ and η distribution of the W^- in $p\bar{p} \to e^- \, \bar{\nu}_e + X$ @ $\sqrt{s} = 1.96\,\mathrm{TeV}$



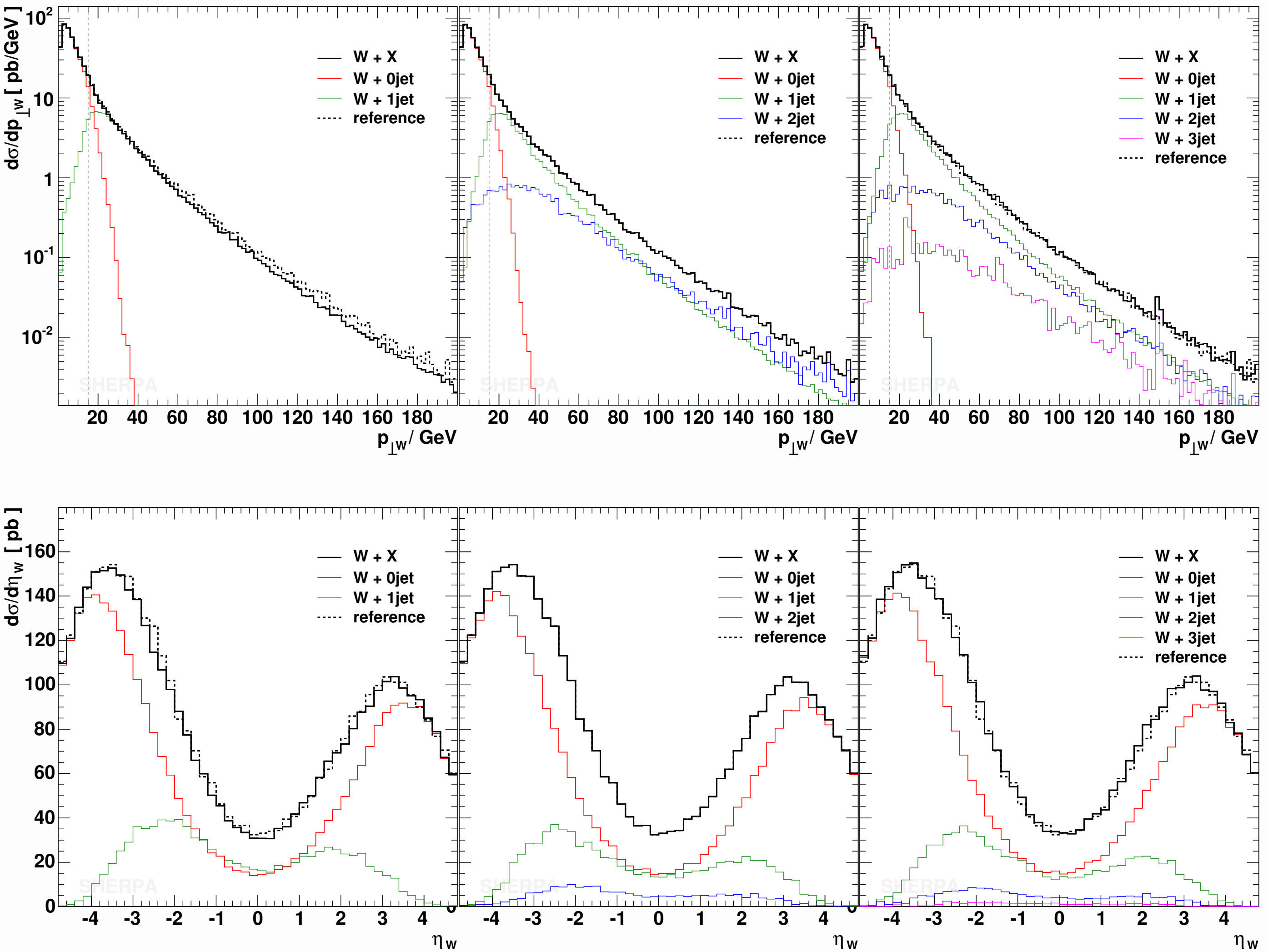
$p_{\perp W^-}$ distribution

η_{W^-} distribution

$Q_{\rm cut}$=10 GeV $Q_{\rm cut}$=30 GeV $Q_{\rm cut}$=50 GeV dashed $Q_{\rm cut}$=20 GeV

Consistency checks: Variation of the maximal jet multiplicity

$p_{\perp W^-}$ and η_{W^-} in $p\bar{p} \to e^- \, \bar{\nu}_e + X$ @ $\sqrt{s} = 1.96$ TeV (Q_{cut}= 15 GeV)



$p_{\perp W^-}$ distribution

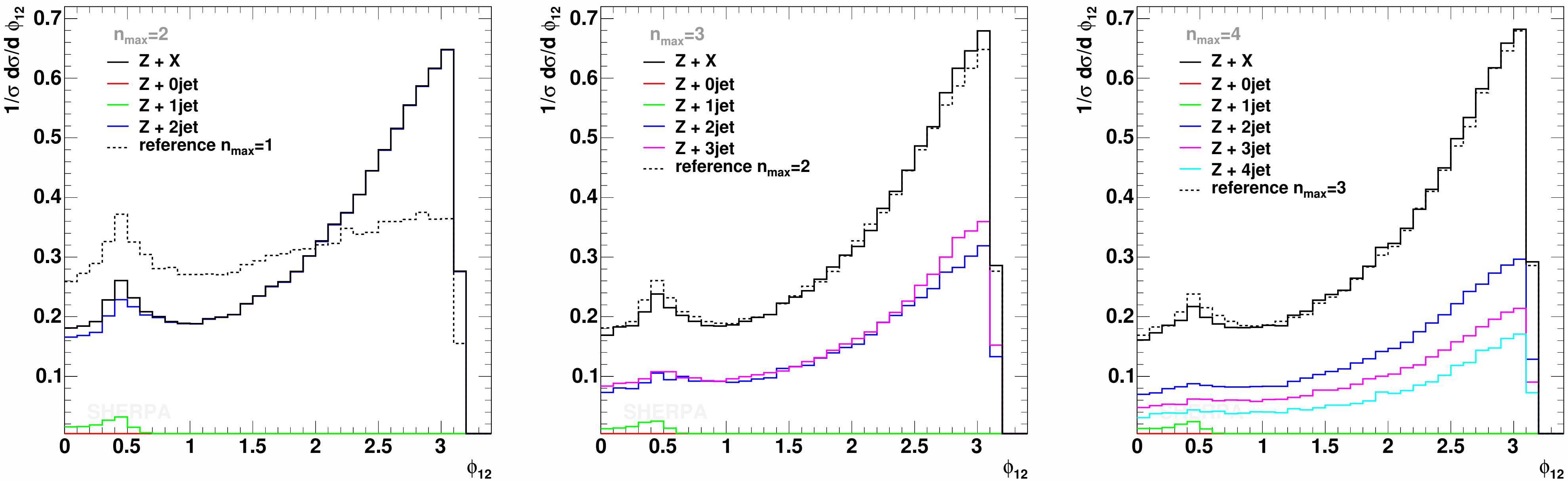
η_{W^-} distribution

$n_{\max}$=1 $n_{\max}$=2 $n_{\max}$=3

dashed $n_{\max} = 2$

Consistency checks: Variation of the maximal jet multiplicity

The $\Delta\Phi$ separation of the two hardest jets in $pp \rightarrow e^+e^- + X$ @ LHC

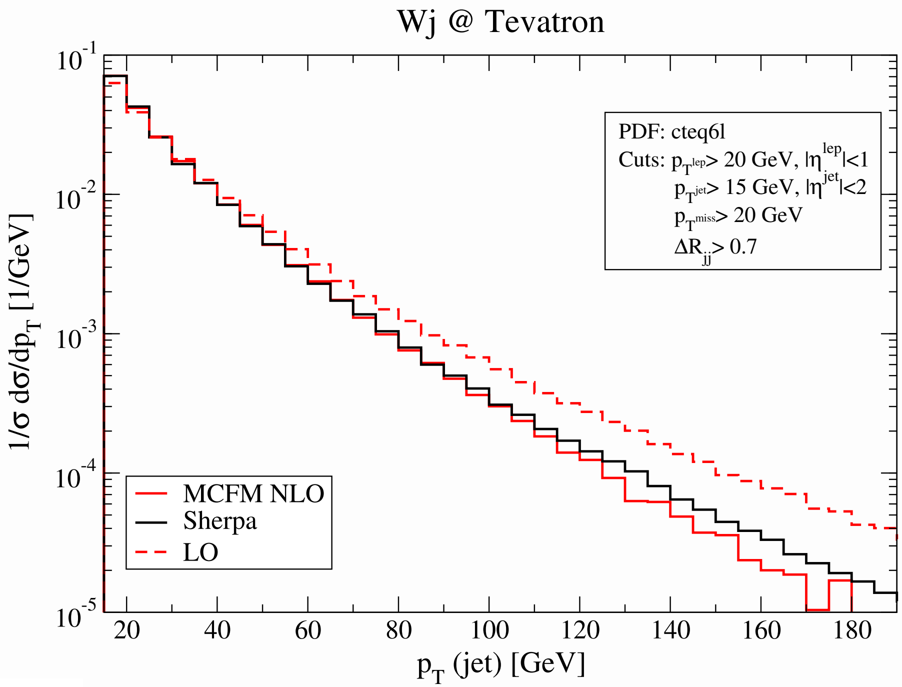


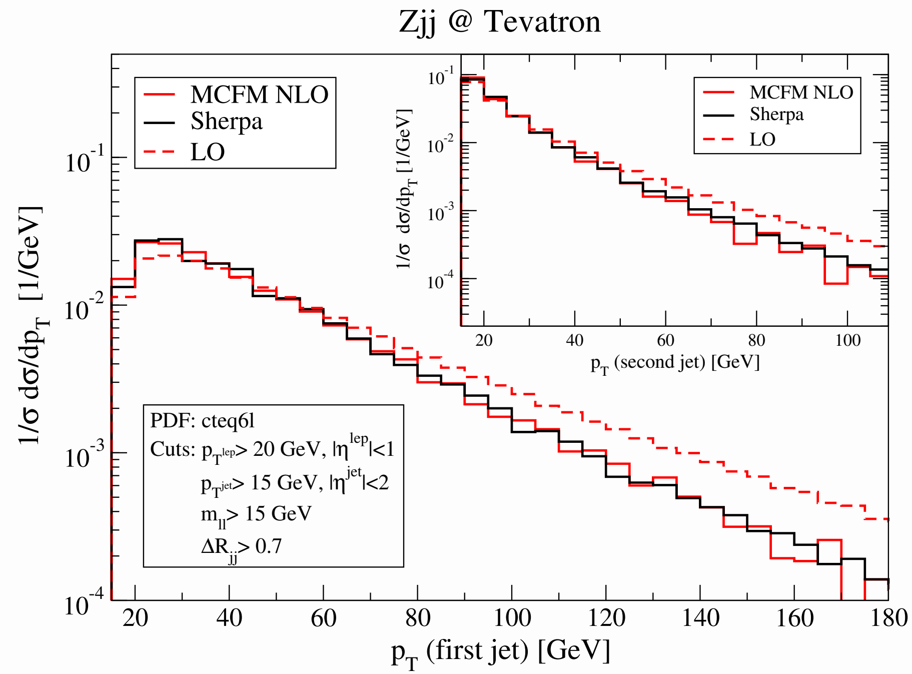
$n_{\max}$=2 $n_{\max}$=3 $n_{\max}$=4

dashed reference $\tilde{n}_{\max} = n_{\max} - 1$

The $p_\perp$ of the jets in exclusive W/Z+jets production

Take pure Sudakov and α_S reweighted ME's, compare to naive LO and NLO predictions



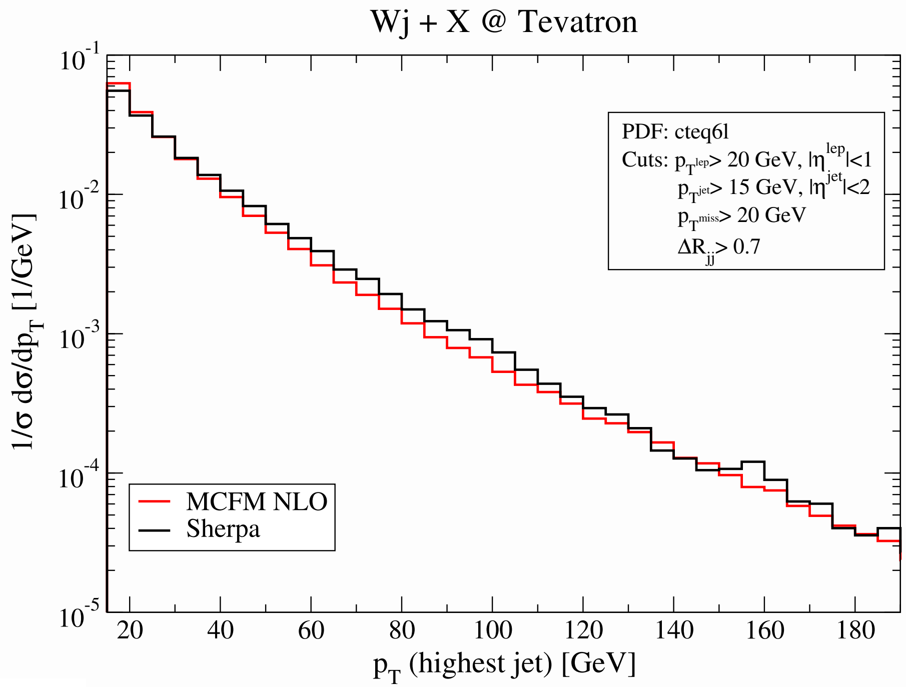


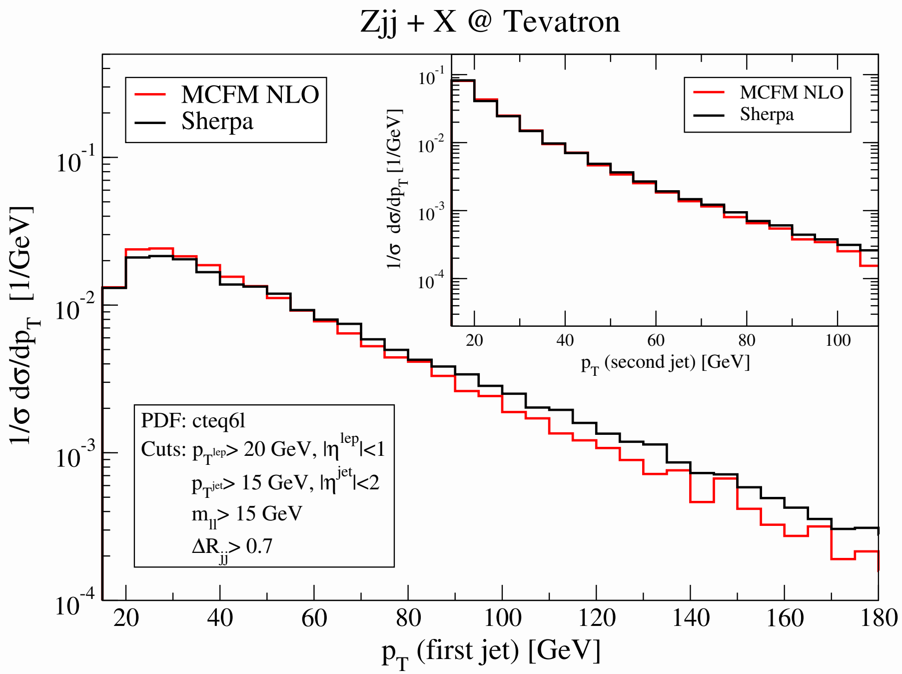
- At NLO a high $p_\perp$ jet is very likely to emit a further jet passing the jet criteria, removing the event from the sample
- CKKW reweighting has very similar impact on distributions

Inclusive W/Z+jet production @ Tevatron

The $p_\perp$ of the jets in inclusive W/Z+jets production

Take Sudakov and α_S reweighted ME's with the showers attached, compare to NLO predictions obtained with MCFM





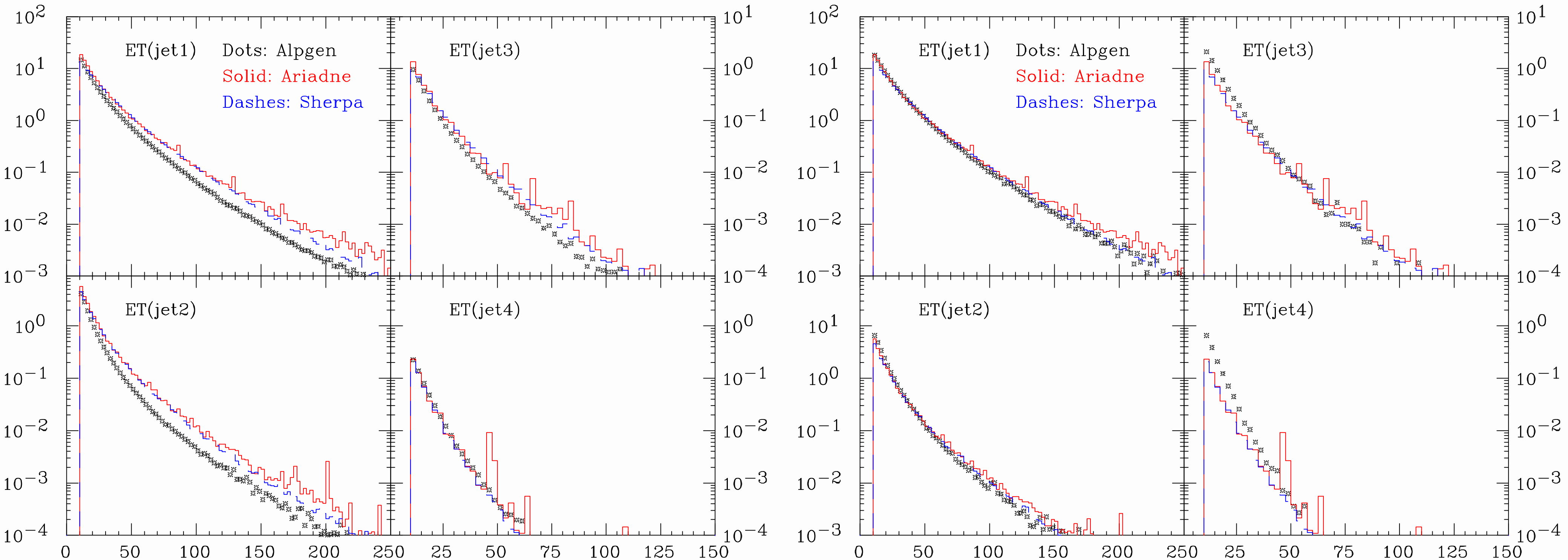
- The CKKW prescription seems to reproduce the NLO shapes for the jet distributions in the exclusive and inclusive case
- Note: The rates are not NLO

Comparison with MLM and Lönnblad scheme for W+jets

➔ Detailed comparison of the three merging approaches started

First results in the HERA/LHC workshop proceedings, hep-ph/0601012 and hep-ph/0601013

E_T spectra of jets at Tevatron energies

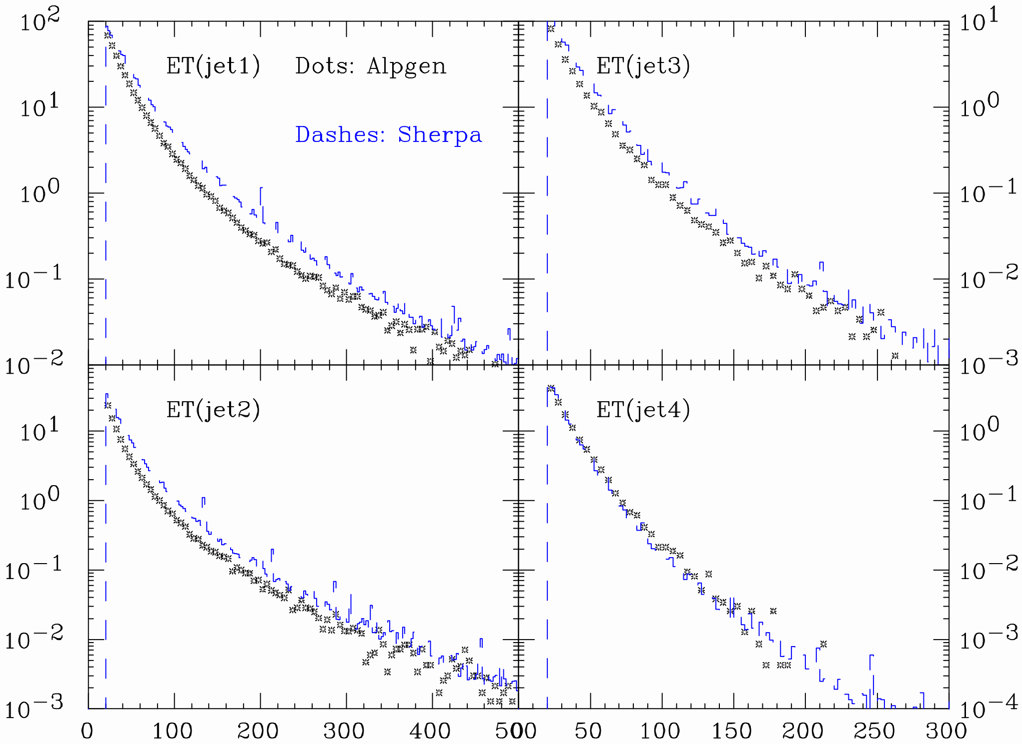


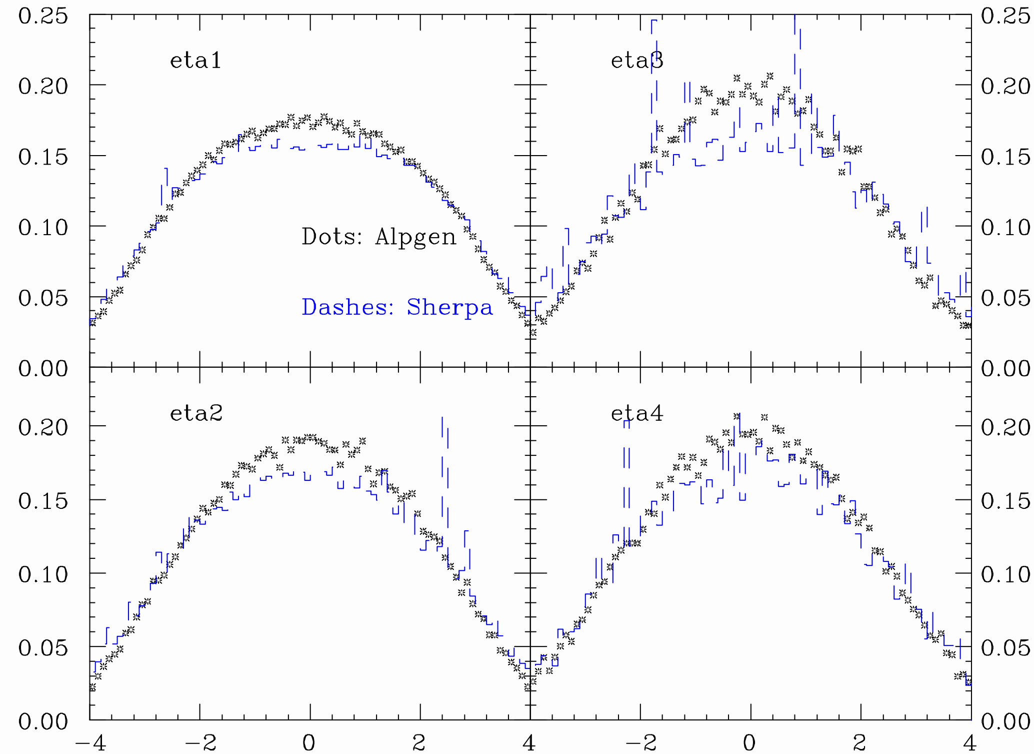
Alpgen default

Alpgen $\mu_R \times 0.5$

Comparison with MLM and Lönnblad scheme for W+jets

E_T and η spectra of jets for the LHC

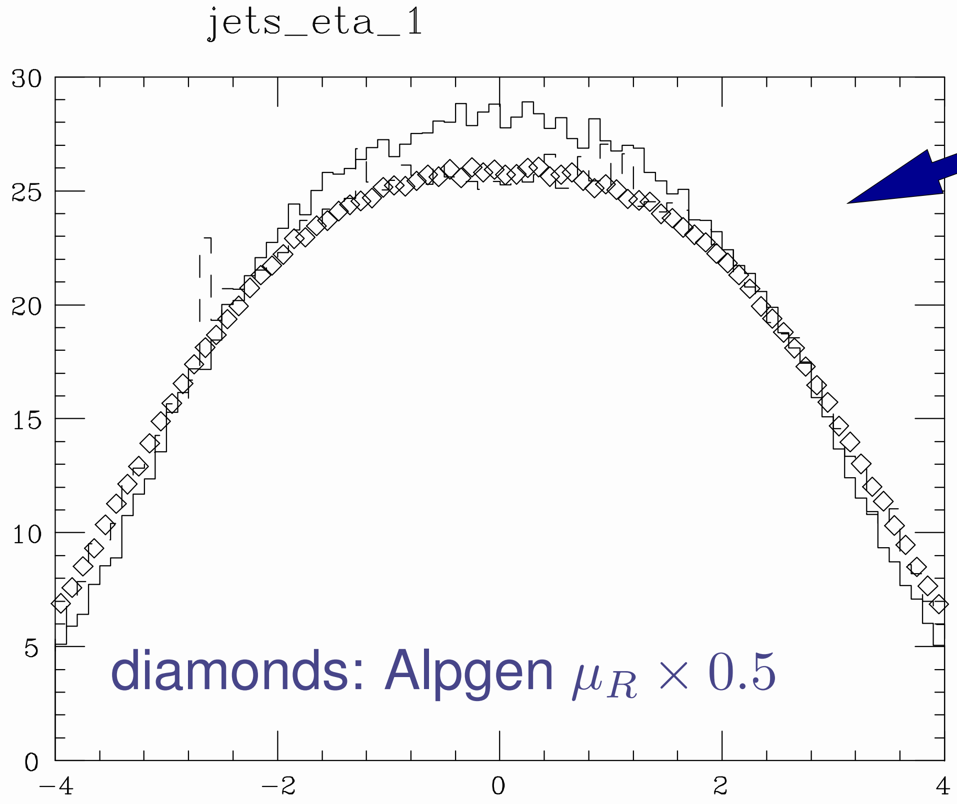


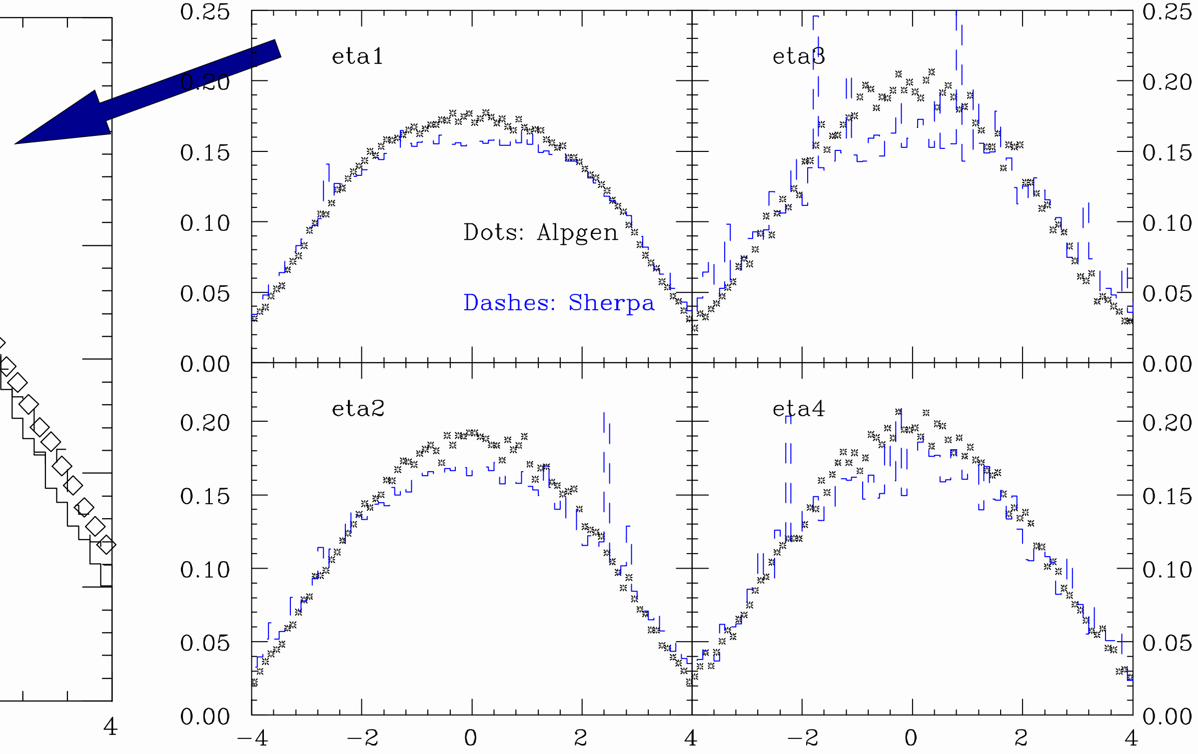


- Same pattern w.r.t. Tevatron

Comparison with MLM and Lönnblad scheme for W+jets

E_T and η spectra of jets for the LHC

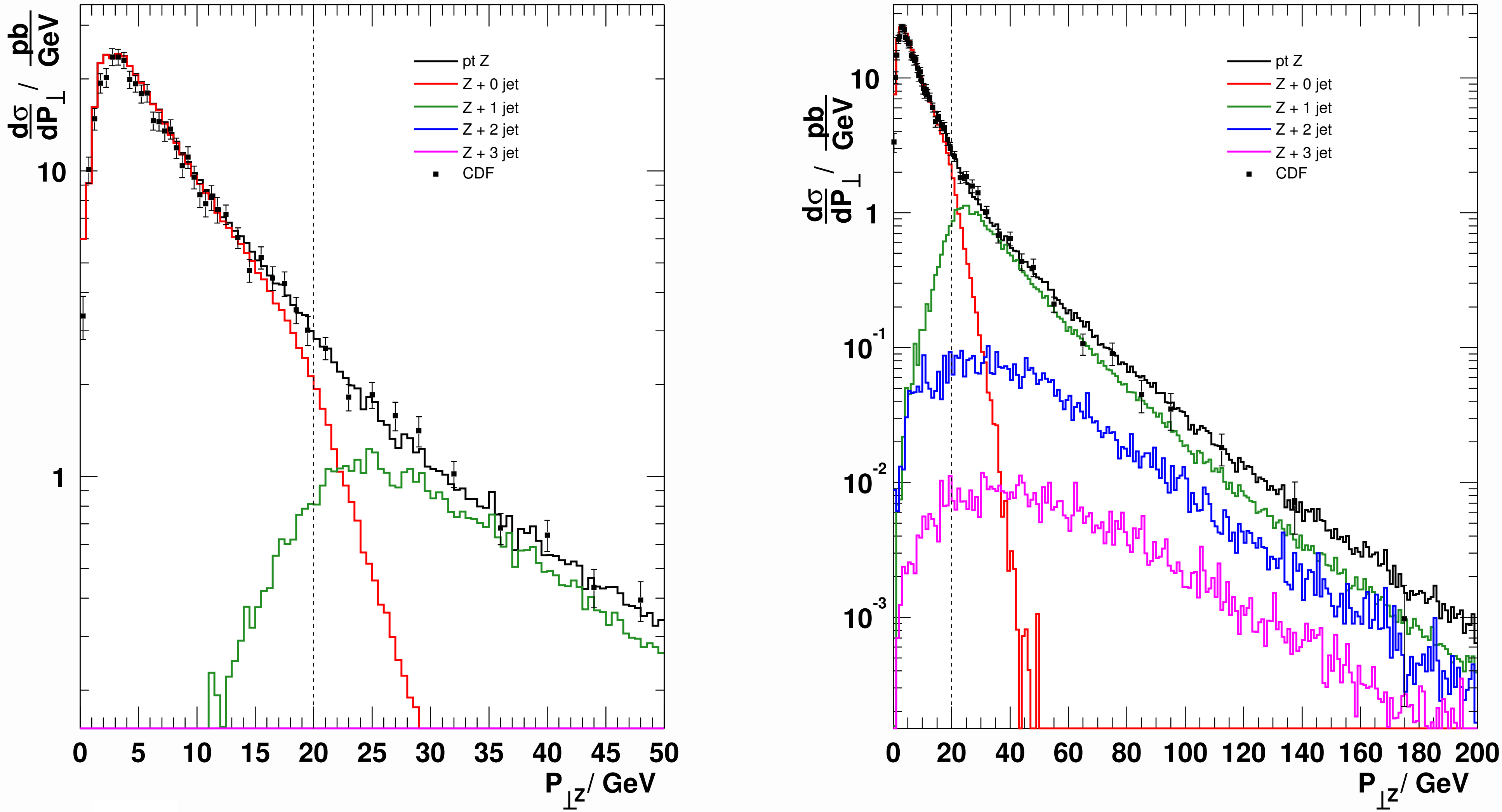




- Same pattern w.r.t. Tevatron
- Once tuned to Tevatron data we expect the same extrapolation to LHC

Comparison with Tevatron data @ $\sqrt{s} = 1.8\text{TeV}$

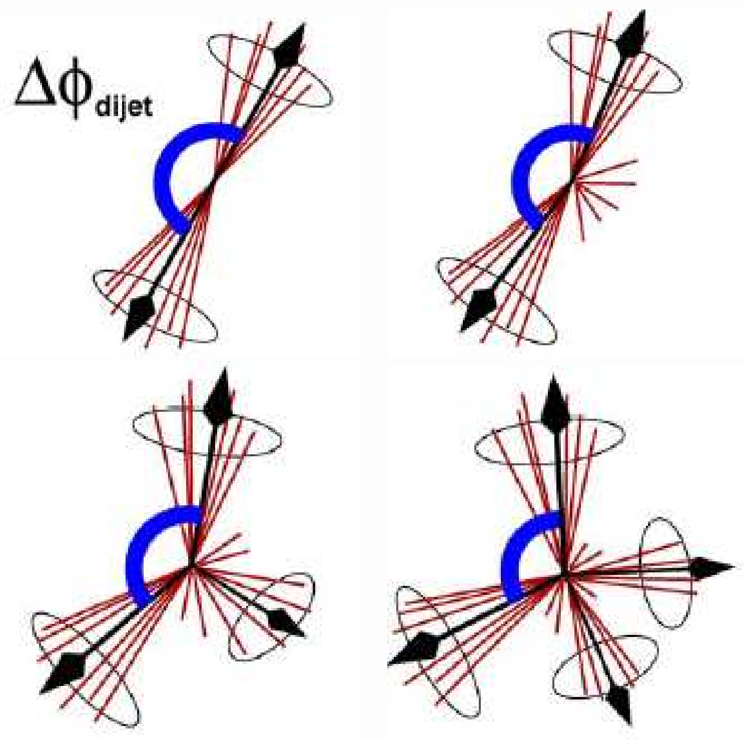
$p_\perp$ distribution of the Z measured by CDF Phys.Rev.Lett.84:845-850,2000

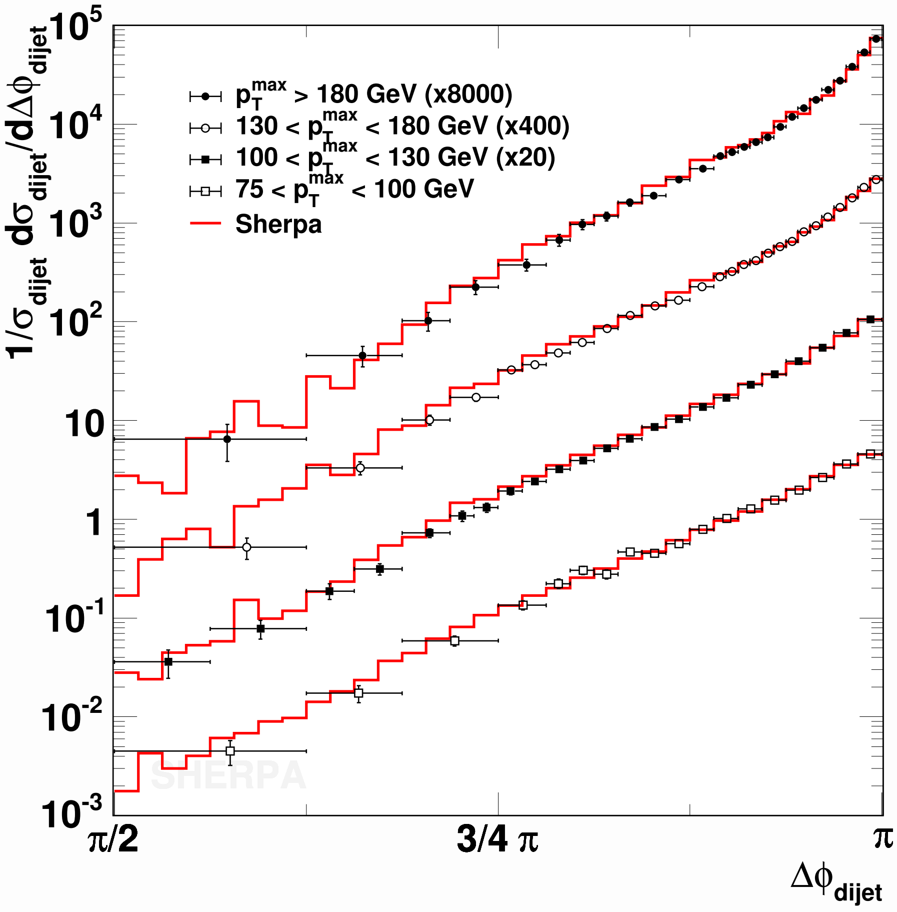


➔ **Distribution multiplied by appropriate K-factor!**

The dijet azimuthal decorrelation measured by D0 in Run II

V. M. Abazov et al., Phys.Rev.Lett94:221801,2005





Conclusions/Outlook

Summary

- The CKKW prescription provides improved predictions for multi-jet events
- Soft- and hard kinematics are well described
- Shapes look next-to-leading like, but rates are leading order only
- Comparison of different implementations has started

Things to do

- Validation of more channels: Jets, Heavy flavours, $gg \to H$, WBF, ...
- Systematic tuning to Tevatron data
- Study the impact of the underlying event