# Monte Carlo at NLO and jets

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# Plan of the talk

- Overview: PS (parton showers), ME+PS merging, NLO+PS merging.
- `MC@NLO` and `POWHEG`
- Dijets and $Z + \mathrm{jets}$ in `POWHEG`
- Issues with the Dijets and $Z + \mathrm{jets}$ generators
  - Generation cut
  - Low $k_T$ region in $Z + \mathrm{jets}$: merging $Z$ and $Z + \mathrm{jets}$ `POWHEG` generators

# How events are simulated today

We have three options:

- Traditional PS (Parton Shower generators)
- ME+PS generators
- NLO+PS generators

# Traditional generators

"Traditional" PS's: `PYTHIA`, `HERWIG`, `HERWIG++`; give a fair description of the bulk of the production process, where "fair" means LO

- They use LO matrix elements for the partonic production process
- They generate QCD radiation using the collinear approximation, and, to a limited extent, the soft approximation.

  For example, in $Z$ production, jets at small angle with respect to the collision axis, and to a minor extent soft jets, are well described. In short: low $p_T$ jets.
- They include more or less sofisticated models for hadron formation and for the underlying event, including multiparton collisions.

# ME+PS

Combine exact, tree-level matrix element calculations with Parton Showers. ME+PS can achieve LO accuracy for the prorduction of a fairly large number of associated jets.

In the $pp \to Z + X$ example, they achieve the accuracy:
$Z : 1$, $Z + \text{jet} : \alpha_s$, $Z + 2\,\text{jets} : \alpha_s^2$, etc.

Look out at the terminology: $Z + \text{jet}$ is a piece of the NLO correction to $Z$ production (there are also virtual terms not involving extra partons). However, it is computed at LO in ME+PS. $Z + 2\,\text{jets}$ is a piece of the NLO correction to $Z + \text{jet}$; it is also computed at LO in ME+PS. And so on ...

# NLO+PS

NLO+PS generators are able to describe the emission of the hardest jet with LO accuracy ($\alpha_s$ for $Z + \mathrm{jet}$, same as ME+PS generator), but are also capable to achieve NLO accuracy (i.e. $\alpha_s$ for $pp \to Z + X$ production) for inclusive observables.

Available generators at present:

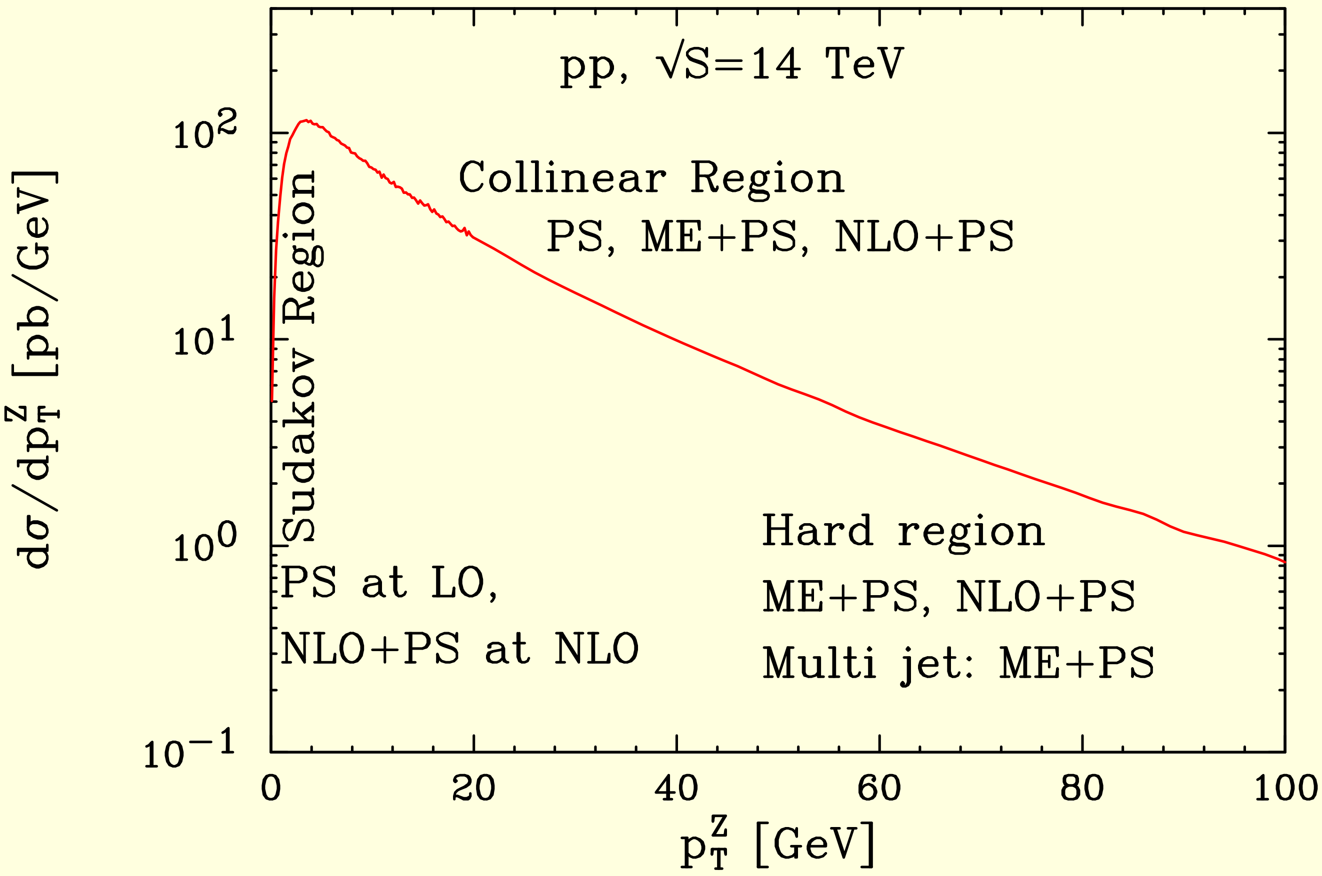
`MC@NLO` (Frixione, Webber 2002) `POWHEG` (P.N. 2004)

They use a traditional PS for radiation beyond the hardest jet, and for hadronization and event completion.

Thus, in the example of $pp \to Z + X$, only the hardest jet is described with tree level accuracy. Further jets are generated by the shower in the collinear or soft approximation.

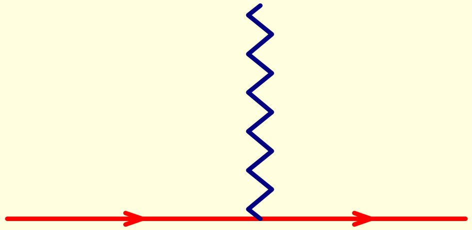
# Domain of PS, ME+PS, NLO+PS

Regions: Sudakov: $p_T \lesssim \sqrt{m_Z \Lambda_{\mathrm{QCD}}}$; collinear: $p_T \ll m_Z$; hard: $p_T \gtrsim m_Z$

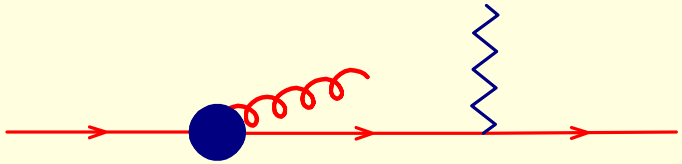


# Parton Shower basic concepts

Born cross section: partonic cross section convoluted with parton densities $B(\Phi_B)d\Phi_B$, where $\Phi_B$ is the Born phase space.



The splitting algorithm is applied to each external coloured line, recursively, according to a splitting probability $P(\Phi_r)$ ($\Phi_r = \theta, z, \phi$, radiation variables)



So: from $\Phi_B$, $\Phi_r$ we recover $\Phi$, the full kinematics of the first radiation;

The other way around, $\Phi \Rightarrow (\Phi_r, \Phi_B)$, where $\Phi_B$ is the underlying Born of $\Phi$.

Useful concept in Shower language: look at the showered event, reconstruct the shower history untill you reach the original Born configuration. This is the underlying Born.

- $P(\Phi_r)$ is such that, for $p_T \ll m_Z$, (but $p_T \gg \sqrt{m_Z\Lambda}$) we have

$$P(\Phi_r) \times B(\Phi_B) \approx R(\Phi)$$

The splitting probability yields a good approximation to the exact (tree level) cross section for one emission in the collinear limit.

- For $p_T \lesssim \sqrt{m_h\Lambda}$, $P(\Phi_r)$ is damped by a Sudakov Form Factor $\Delta(\Phi_r)$, arising from dominant virtual corrections.

- $P(\Phi_r)$ is such that (unitarity of the shower)

$$\int P(\Phi_r)\, d\Phi_r + P_0 = 1$$

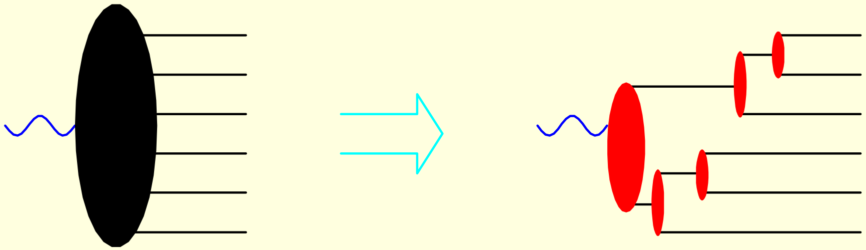
# ME+PS

## Historical approach: CKKW

Catani, Krauss, Küen, Webber (2001), (in $e^+e^-$ annihilation).

In a nut-shell:

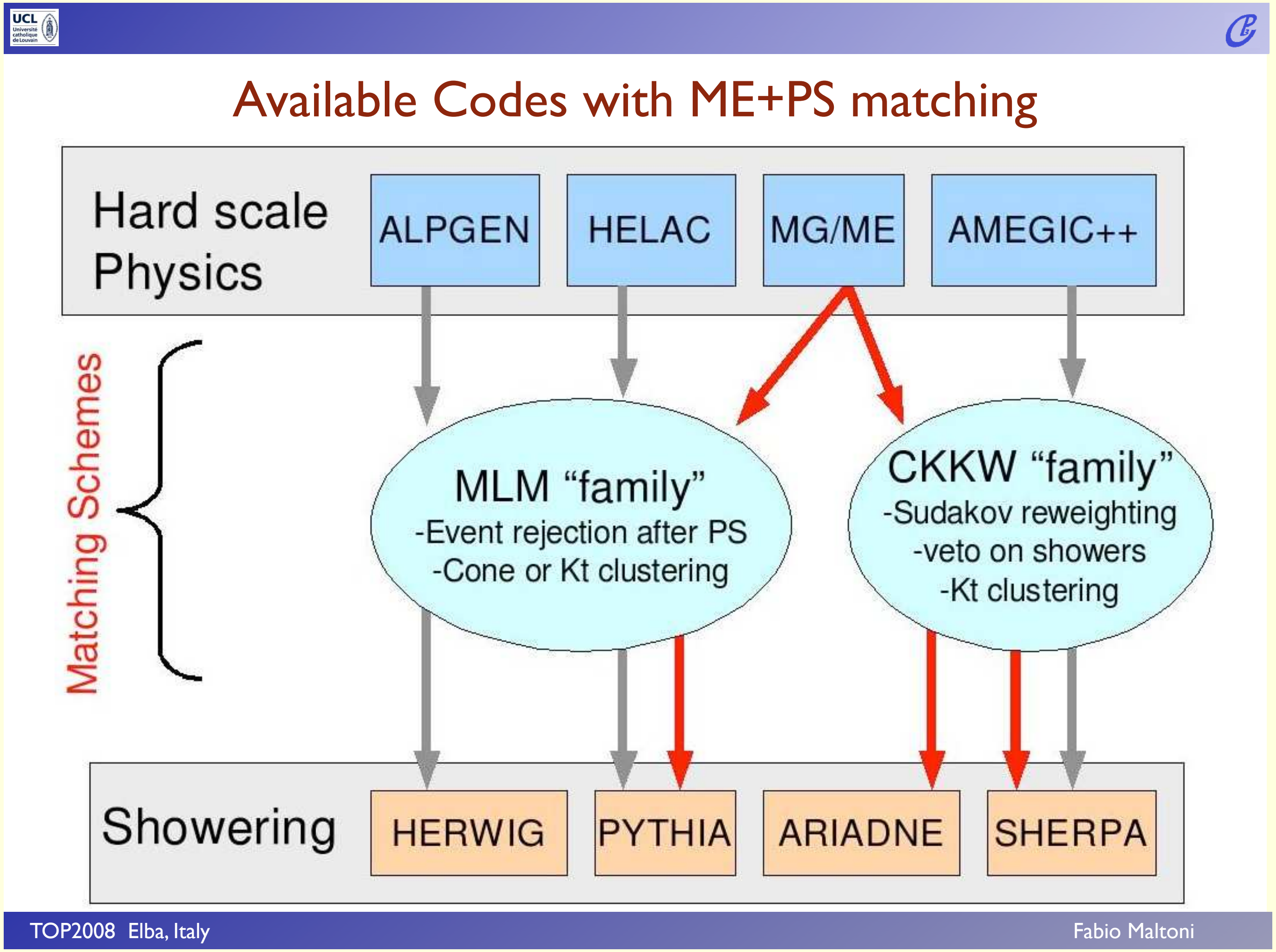
- Use exact tree level ME to compute the multiparton cross section.
  Clusterize ME partons to reconstruct a shower skeleton
  (by pairing up particles that yield smallest $t$ recursively)



Red blobs have decreasing $t$ values

- Correct exact tree level ME calculations with Sudakov form factor so that they reproduce the Shower results in the small $k_T$ limit.
- Let the Shower take care of radiation with $k_T < M_{\rm cut}$, where $M_{\rm cut}$ is a cutoff on the jet separation

Alternative methods: MLM matching (no proofs, but it seems to work).
Others: CKKW-L (Lonnblad).



# NLO+PS

Hardest radiation: as in PS, but corrected up to NLO:

$$d\sigma = \overbrace{\bar{B}^s(\Phi_B)}^{\text{NLO!}} d\Phi_B \left[ \overbrace{\Delta^s_{t_0}}^{P_0} + \Delta^s_t \overbrace{\frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}^{P(\Phi_r)} \right] + \overbrace{[R(\Phi) - R^s(\Phi)]}^{\text{ME correction}} d\Phi$$

where $R \Rightarrow R^s$ in the soft and collinear limit,

$$\bar{B}^s(\Phi_B) = B(\Phi_B) + \underbrace{\left[ \underbrace{V(\Phi_B)}_{\text{infinite}} + \underbrace{\int R^s(\Phi)\, d\Phi_r}_{\text{infinite}} \right]}_{\text{finite}}$$

The Born cross section is replaced by the inclusive cross section at fixed underlying Born

and

$$\Delta^s_t = \exp\left[ -\int_{t_l} \frac{R^s}{B} d\Phi_r \theta(t(\Phi) - t_l) \right]$$

so that

$$\Delta^s_{t_0} + \int \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r = 1 \; (\text{Unitarity})$$

## In MC@NLO: $R^s d\Phi_r = R^{\rm MC} d\Phi_r^{\rm MC}$

Furthermore:

in MC@NLO the phase space parametrization $\Phi_B$, $\Phi_r \Rightarrow \Phi$ is the one of the Shower Monte Carlo. We have:

$$\underbrace{\bar{B}^s(\Phi_B) d\Phi_B}_{\substack{\text{provided by }\texttt{MCatNLO} \\ \mathcal{S}\text{ event}}} \left[ \underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\text{generated by }\texttt{HERWIG}} \right] + \underbrace{\left[R(\Phi) - R^s(\Phi)\right] d\Phi}_{\substack{\text{provided by }\texttt{MCatNLO} \\ \mathcal{H}\text{ event}}}$$

More synthetically

$$\texttt{MCatNLO}\ \mathcal{S} = \frac{\bar{B}^s(\Phi_B)}{B(\Phi_B)} \times \texttt{HERWIG}\text{ basic process}$$

$$\texttt{MCatNLO}\ \mathcal{H} = R(\Phi) - R^s(\Phi)\text{ fed through }\texttt{HERWIG}$$

Issues:

- Must use the MC kinematic mapping $(\Phi_B, \Phi_r^{\rm MC}) \Rightarrow \Phi$.
- For $R - R^{\rm MC}$ to be non singular, the MC should reproduce exactly the soft and collinear singularities of the radiation matrix element.
  No existing PS can do that. For example, the azimuthal dependence of collinear singularities is neglected in the MC's.
  In `MC@NLO` this difference is essentially damped, by smoothly matching $R^{\rm MC}$ to $R$ in the collinear and soft limit.
- $R - R^{\rm MC}$ can be negative: negative weights in the output.

## In POWHEG: $R^s d\Phi_r = R F(\Phi)$

where $0 \leqslant F(\Phi) \leqslant 1$, and $F(\Phi) \Rightarrow 1$ in the soft or collinear limit.
$F(\Phi) = 1$ is also possible, and often adopted.
The parametrization $\Phi_B, \Phi_r \Rightarrow \Phi$ is within POWHEG, and there is complete freedom in its choice.

$$\underbrace{\bar{B}^s(\Phi_B) d\Phi_B}_{\texttt{POWHEG}} \left[ \underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\texttt{POWHEG}} \right] + \underbrace{\left[ R(\Phi) - R^s(\Phi) \right] d\Phi}_{\texttt{POWHEG}}$$

All the elements of the hardest radiation are generated within POWHEG

## Recipe

- POWHEG generates an event, with $t = t_{\texttt{powheg}}$
- The event is passed to a SMC, imposing no radiation with $t > t_{\texttt{powheg}}$.

## Improvements over MC@NLO:

- Positive weighted events: $R - R_s = R(F-1) \geqslant 0$.
- Independence on the Shower MC: The hardest emission is generated by POWHEG; subsequent (softer) emissions are generated by the shower. Can switch Shower models: very valuable for theoretical studies
- No issues with improper cancellation of PS singularities

In practice: most MC@NLO implementations are tied to fortran HERWIG. Extension to HERWIG++ or PYTHIA require considerable work.

In contrast, POWHEG can be used with any shower program one wishes, including the fortran and c++ versions of HERWIG and PYTHIA.

# Status of POWHEG

Most of it in http://moby.mib.infn.it/~nason/POWHEG,
Parts embedded in the HERWIG++ code.

- $hh \to ZZ$ (Ridolfi, P.N., 2006)
- $hh \to Q\bar{Q}$ (Frixione, Ridolfi, P.N., 2007)
- $hh \to Z/W$ (Alioli, Oleari, Re, P.N., 2008; )
  (Hamilton,Richardson,Tully, 2008;)
- $hh \to H$ (gluon fusion) (Alioli, Oleari, Re, P.N., 2008)
- $hh \to H$, $hh \to HZ/W$ (Hamilton,Richardson,Tully, 2009;)
- $hh \to t + X$ (single top) (Alioli, Oleari, Re, P.N., 2009)
- VBF Higgs, (Oleari,P.N., 2009).
- $hh \to tW$ (E. Re, 2010)
- $hh \to Z + \text{jet}$, Preliminary (Alioli, Oleari, Re, P.N., 2010)
- Dijet production, Preliminary (Alioli, Hamilton,Oleari, Re, P.N., 2010)

Ongoing effort in SHERPA with POWHEG.

# Jets at NLO

Collider experiments have compared their jet data to NLO QCD results. However, lacking a full event generators for jets, one had to

- Either correct the NLO results with the effects of higher order radiation, hadronization, and the underlying event.
- Or, correct data unfolding the above effects (no longer recommended).

This after unfolding detector effects from raw data.
All these corrections require the use of a generic Shower Monte Carlo, like `PYTHIA` or `HERWIG`.

# CDF $Z + \text{jet}$ study
# PRL 100,102001,2008

Parton to hadron correction up to 26% for 30-40 GeV jets

Possible biases due to the use of a LO shower Monte Carlo are hard to assess.

Using instead a NLO+PS generator one can produce NLO accurate event samples with parton-to-hadron effects already included.

Even better, one can run this sample through the detector simulation, and compare the output to raw data.

| $p_T^{\text{jet}}$ [GeV/c] | $\frac{d\sigma}{dp_T^{\text{jet}}} \pm$ (stat.) $\pm$ (syst.) $\pm$ (lum.) [fb/(GeV/c)] | $C_{\text{had}} \pm$ (stat.) $\pm$ (syst.) parton $\to$ hadron |
|---|---|---|
| $Z/\gamma^*(\to e^+e^-)$+jets $(N_{\text{jet}} \geq 1)$ | | |
| 30 - 35 | $413.3 \pm 13.3^{+30.4}_{-31.3} \pm 24.0$ | $1.209 \pm 0.010 \pm 0.134$ |
| 35 - 41 | $263.3 \pm 9.4^{+18.3}_{-17.4} \pm 15.3$ | $1.146 \pm 0.010 \pm 0.096$ |
| 41 - 47 | $178.3 \pm 7.5^{+12.0}_{-11.6} \pm 10.3$ | $1.114 \pm 0.011 \pm 0.077$ |
| 47 - 54 | $128.5 \pm 5.9^{+8.7}_{-8.4} \pm 7.5$ | $1.097 \pm 0.012 \pm 0.066$ |
| 54 - 62 | $80.5 \pm 4.3^{+5.5}_{-6.0} \pm 4.7$ | $1.086 \pm 0.013 \pm 0.059$ |
| 62 - 72 | $52.5 \pm 3.2^{+4.4}_{-4.3} \pm 3.0$ | $1.078 \pm 0.013 \pm 0.053$ |
| 72 - 83 | $34.2 \pm 2.4^{+2.5}_{-2.8} \pm 2.0$ | $1.072 \pm 0.015 \pm 0.049$ |
| 83 - 110 | $16.0 \pm 1.1^{+1.5}_{-1.3} \pm 0.9$ | $1.063 \pm 0.012 \pm 0.043$ |
| 110 - 146 | $4.9 \pm 0.5^{+0.5}_{-0.5} \pm 0.3$ | $1.051 \pm 0.012 \pm 0.035$ |
| 146 - 195 | $1.1 \pm 0.2^{+0.1}_{-0.1} \pm 0.06$ | $1.040 \pm 0.008 \pm 0.027$ |
| 195 - 400 | $0.08 \pm 0.03^{+0.01}_{-0.01} \pm 0.005$ | $1.021 \pm 0.005 \pm 0.013$ |
| $Z/\gamma^*(\to e^+e^-)$+jets $(N_{\text{jet}} \geq 2)$ | | |
| 30 - 38 | $52.9 \pm 3.5^{+5.3}_{-4.6} \pm 3.1$ | $1.262 \pm 0.022 \pm 0.217$ |
| 38 - 47 | $37.0 \pm 2.8^{+2.9}_{-2.8} \pm 2.1$ | $1.207 \pm 0.024 \pm 0.169$ |
| 47 - 59 | $21.2 \pm 1.8^{+1.9}_{-1.9} \pm 1.2$ | $1.164 \pm 0.025 \pm 0.130$ |
| 59 - 79 | $10.5 \pm 1.0^{+0.9}_{-1.0} \pm 0.6$ | $1.123 \pm 0.024 \pm 0.093$ |
| 79 - 109 | $5.7 \pm 0.6^{+0.7}_{-0.5} \pm 0.3$ | $1.087 \pm 0.026 \pm 0.062$ |
| 109 - 179 | $0.88 \pm 0.15^{+0.09}_{-0.10} \pm 0.05$ | $1.052 \pm 0.020 \pm 0.030$ |
| 179 - 300 | $0.15 \pm 0.04^{+0.02}_{-0.02} \pm 0.009$ | $1.026 \pm 0.010 \pm 0.008$ |

Table 1: Measured inclusive jet differential cross section in $Z/\gamma^*(\to e^+e^-)$+jets production as a function of $p_T^{\text{jet}}$ with $N_{\text{jet}} \geq 1$ and $N_{\text{jet}} \geq 2$. The systematic uncertainties are fully correlated across $p_T^{\text{jet}}$ bins. The parton-to-hadron correction factors $C_{\text{had}}(p_T^{\text{jet}}, N_{\text{jet}})$ are applied to the pQCD predictions.

# $Z + \mathrm{jet}$ and dijet production in POWHEG

$Z + \mathrm{jet}$ and dijet production at NLO are now available in POWHEG.

The $Z + \mathrm{jet}$ code has been completed more than one year ago. The code will be very soon made public, and a publication on this topic is imminent. (S.Alioli, C.Oleari, E.Re, P.N., in preparation)

Work on the dijet generator started in July this year. A pre-release version of the code is now available. We are working now on a publication (S.Alioli, K.Hamilton, C.Oleari, E.Re, P.N., in preparation)

# The POWHEG BOX

Both $Z + \text{jet}$ and the dijet generator are built in the POWHEG BOX. This is a framework for the implementation of POWHEG NLO+PS generators, given the basic ingredients of the NLO calculation (i.e. the Born cross section, the Virtual cross section, and the real cross section for the QCD emission of an extra parton).

The POWHEG BOX was built with $Z + \text{jet}$ as its first example implementation. This is because $Z + \text{jet}$ is already complex enough to cover most needs of a fully general implementation.

The POWHEG BOX has been completed and published at the beginning of 2010 (S.Alioli, C.Oleari, E.Re, P.N., Feb. 2010).

(Completion of the BOX also meant completion of the $Z + \text{jet}$ code.)

# How to use it

Check it out:

```
svn checkout [-revision n] -username anonymous -password anonymous
svn://powhegbox.mib.infn.it/trunk/POWHEG-BOX
```

Under the POWHEG directory there are subdirectories for each implemented process. Go there and look for instructions. If you have problems contact us.

Basically: POWHEG generates a user event file in the Les Houches format. Included in the process directories are programs to shower these events using fortran `PYTHIA` or `HERWIG`, and to perform an analysis. They use an internal histogramming package, and the output is written on topdrawer files.

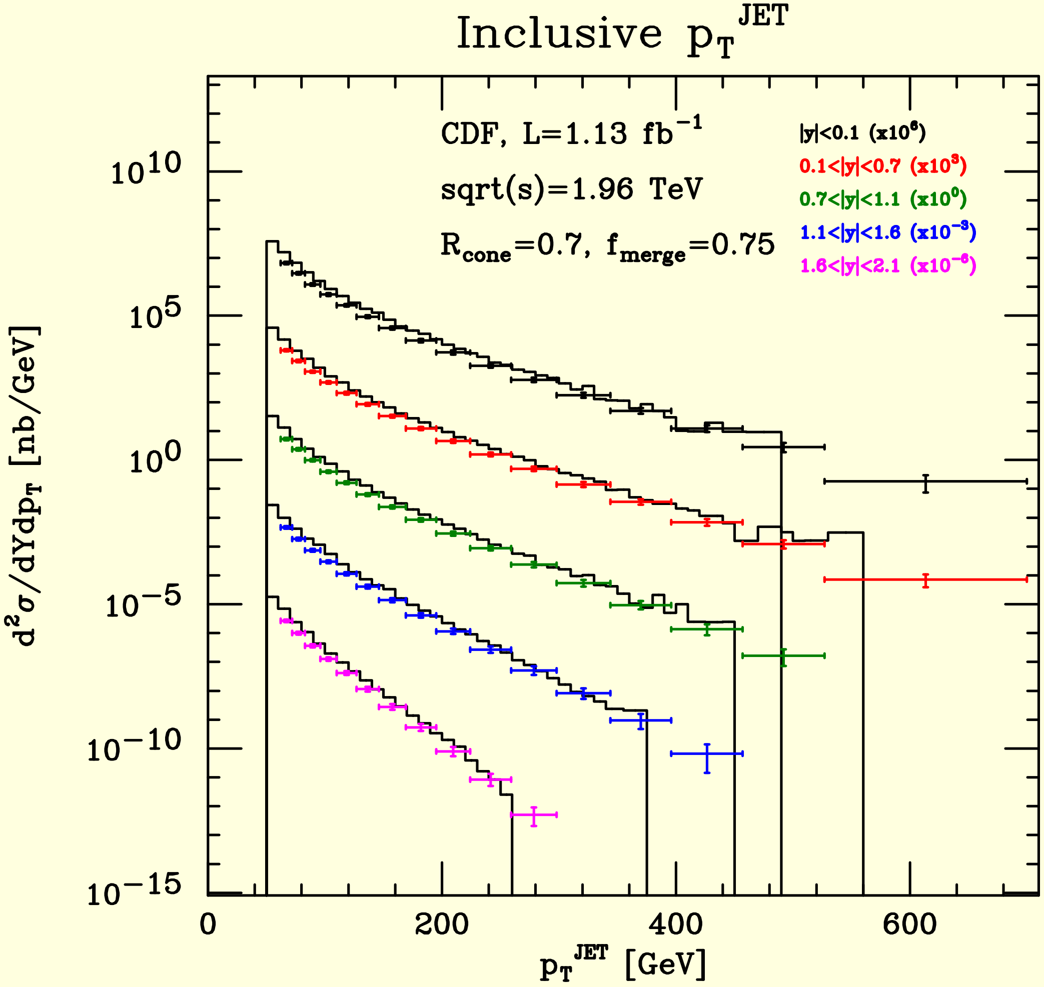
However:
Any setup for showering and analyzing a user event file in the Les Houches format can be used. Experimental collaborations should have this in their software frameworks.

# Highlights: jets

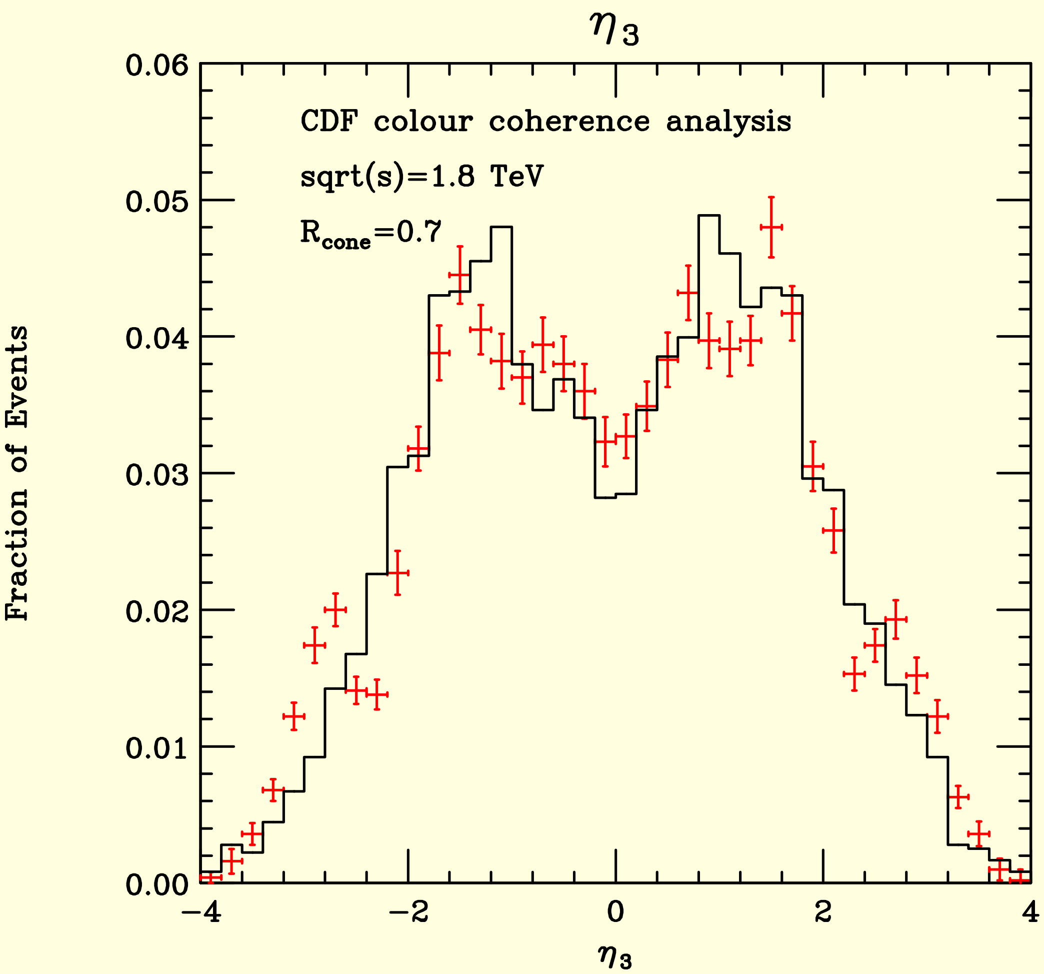
"Minimal" comparison of POWHEG output to CDF published data.

Shower by PYTHIA. No attempt to tune the Shower generator.

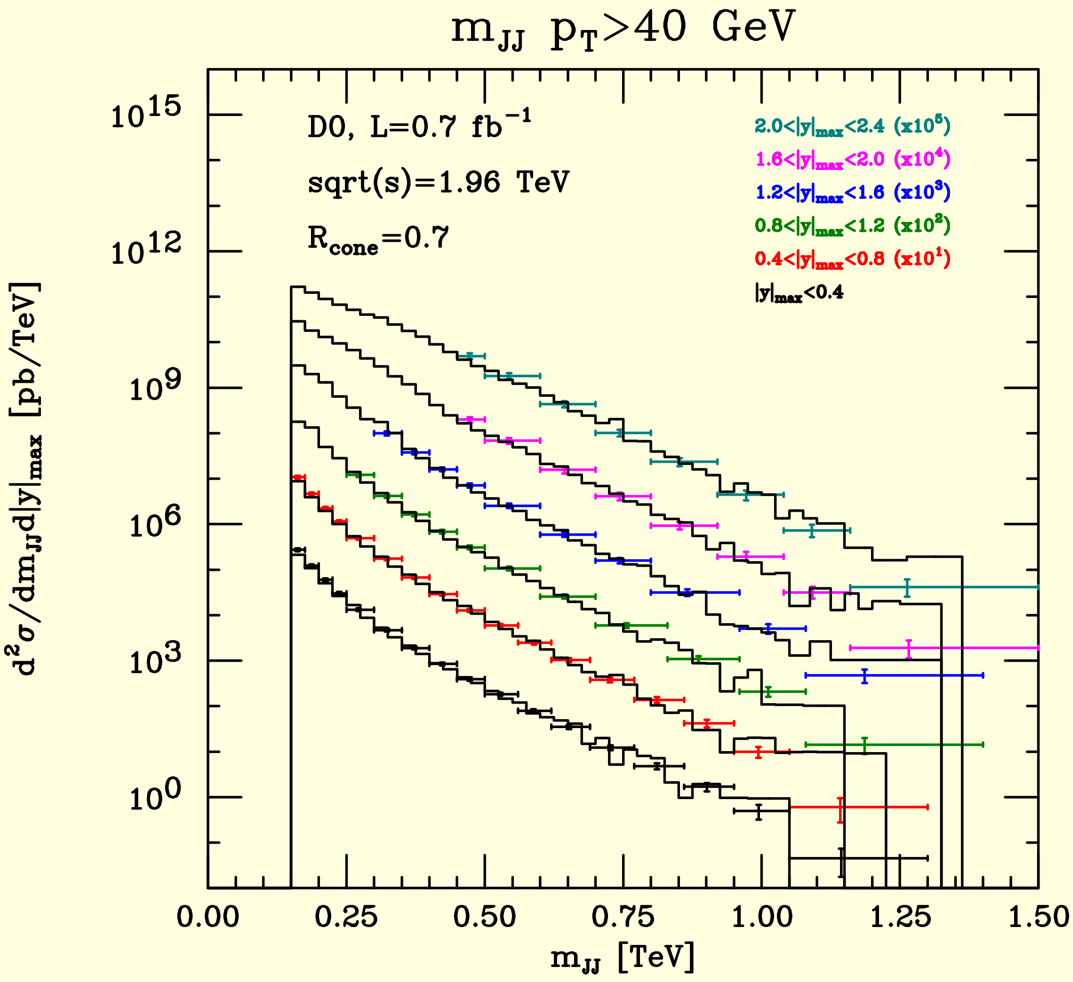
No scale or pdf uncertainty has been included.

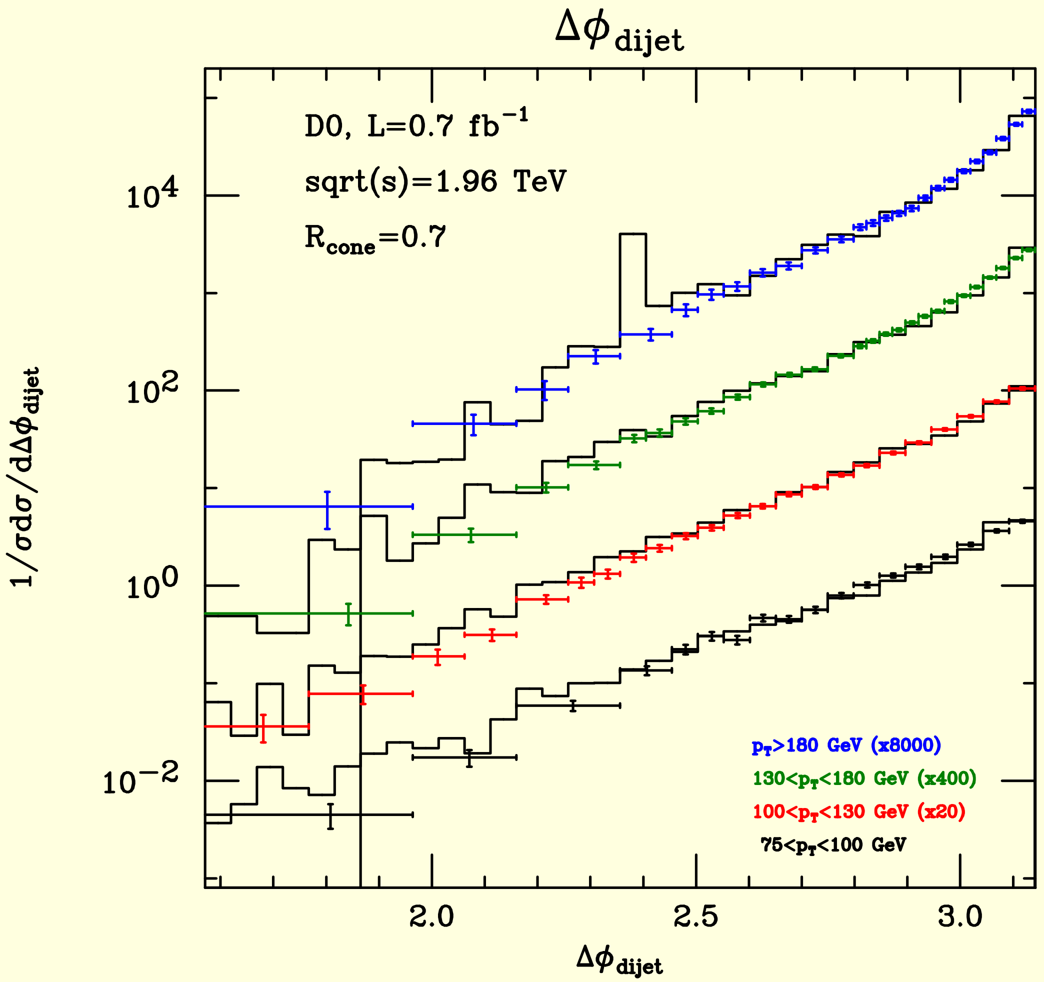


Pseudorapidity of the third hardest jet. Coherence dip.



# D0 jets results



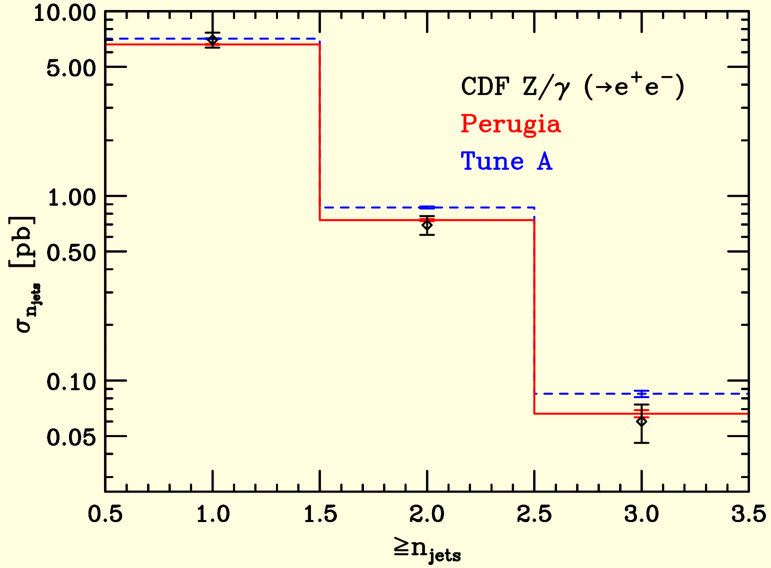


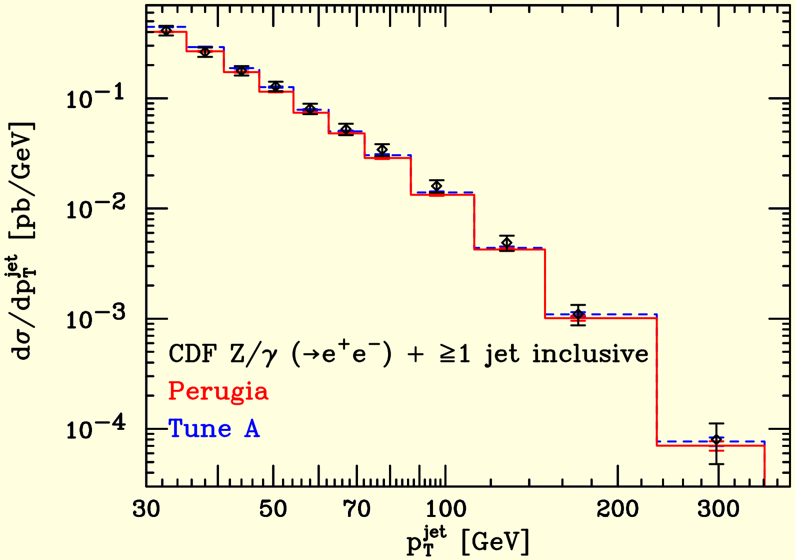
$\Delta\phi_{dijet}$
D0, L=0.7 $fb^{-1}$
sqrt(s)=1.96 TeV
$R_{cone}$=0.7
$p_T$>180 GeV (x8000)
130<$p_T$<180 GeV (x400)
100<$p_T$<130 GeV (x20)
75<$p_T$<100 GeV
$1/\sigma d\sigma/d\Delta\phi_{dijet}$
$10^4$
$10^2$
$10^0$
$10^{-2}$
2.0
2.5
3.0
$\Delta\phi_{dijet}$

# CDF $Z/\gamma(\rightarrow e^+e^-) + \text{jets}$

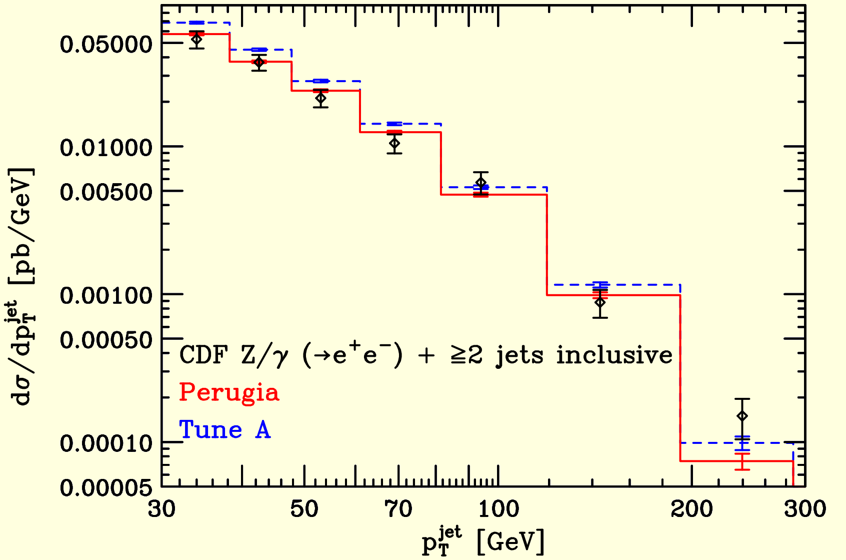
Cuts: $66\,\text{GeV} < M_{ee} < 116\,\text{GeV}, \quad p_T^e > 25\,\text{GeV}, \ |\eta^{e_1}| < 1, \ 1.2 < |\eta^{e_2}| < 2.8$
$|y^{\text{jet}}| < 2.1, \quad p_T^{\text{jet}} > 30\,\text{GeV}, \ \Delta R_{e,\text{jet}} > 0.7$

Jets reconstructed using the CDF midpoint algorithm.

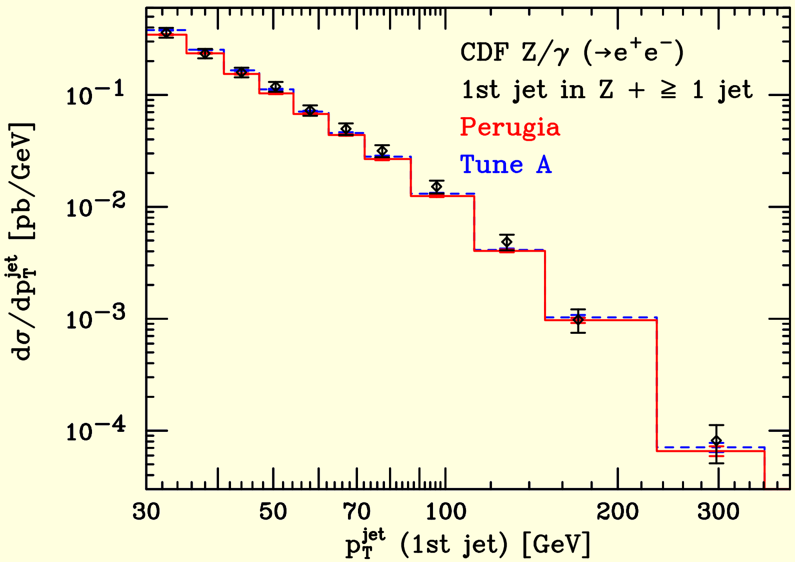




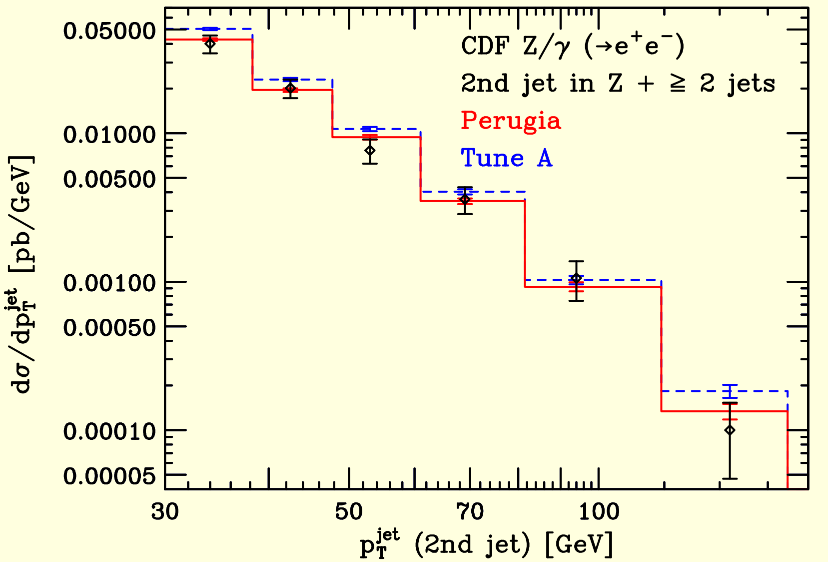
CDF Z/γ (→e+e−) + ≥1 jet inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet [GeV]

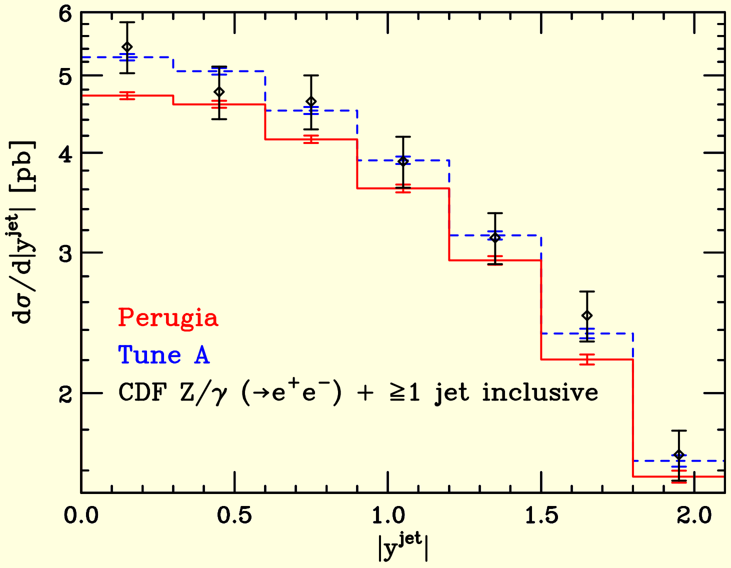
CDF Z/γ (→e+e−) + ≥2 jets inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet [GeV]

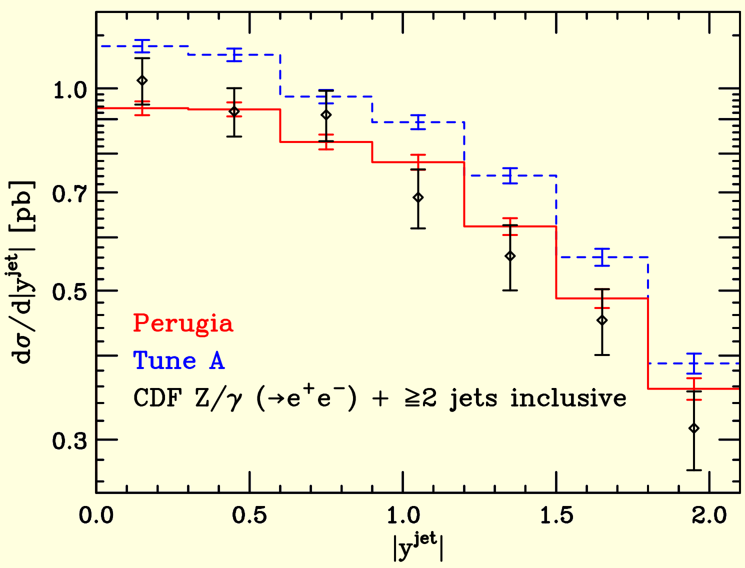
CDF Z/γ (→e+e−)
1st jet in Z + ≥ 1 jet
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet (1st jet) [GeV]

CDF Z/γ (→e+e−)
2nd jet in Z + ≥ 2 jets
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet (2nd jet) [GeV]



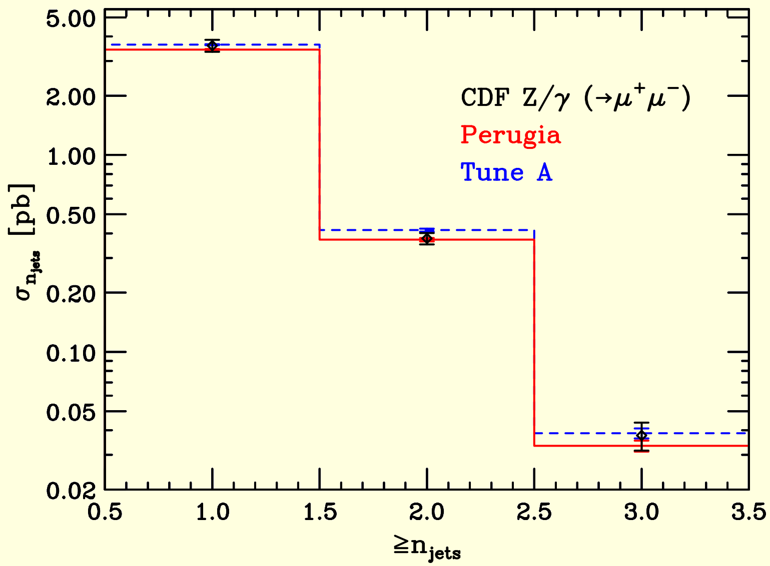
dσ/d|y^jet| [pb]
|y^jet|
Perugia
Tune A
CDF Z/γ (→e⁺e⁻) + ≧1 jet inclusive

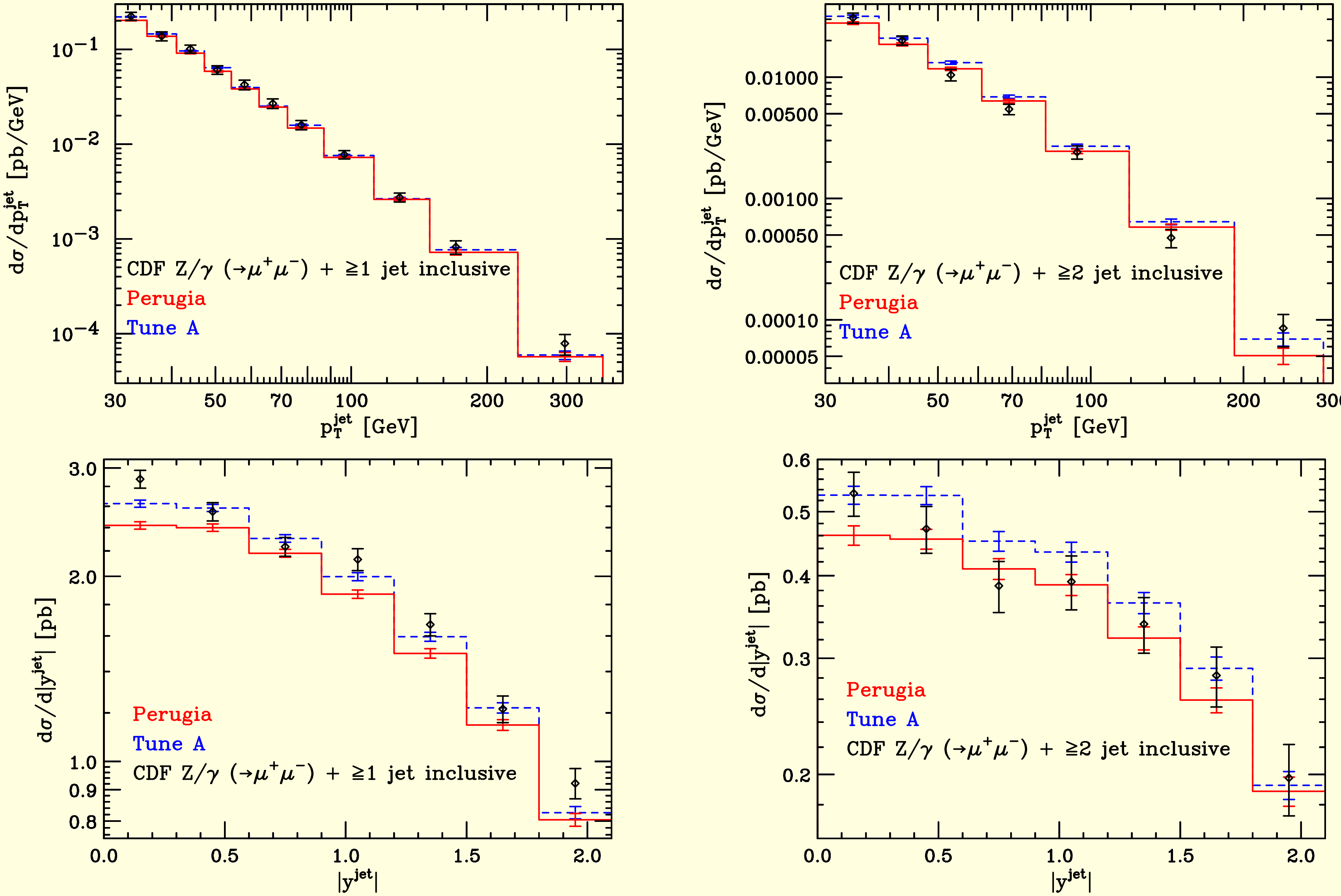



dσ/d|y^jet| [pb]
|y^jet|
Perugia
Tune A
CDF Z/γ (→e⁺e⁻) + ≧2 jets inclusive

# CDF $Z/\gamma(\to \mu^+\mu^-) + \text{jets}$

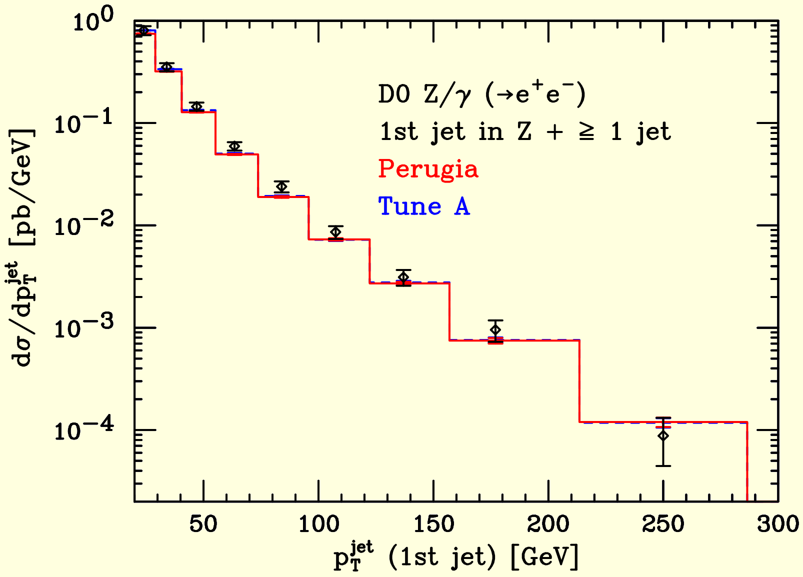
$66\,\text{GeV} < M_{\mu\mu} < 116\,\text{GeV}, \quad p_T^{\mu} > 25\,\text{GeV}, \;\; |\eta^{\mu}| < 1, \;\; |y^{\text{jet}}| < 2.1$
$p_T^{\text{jet}} > 30\,\text{GeV}, \quad \Delta R_{\mu,\text{jet}} > 0.7;$

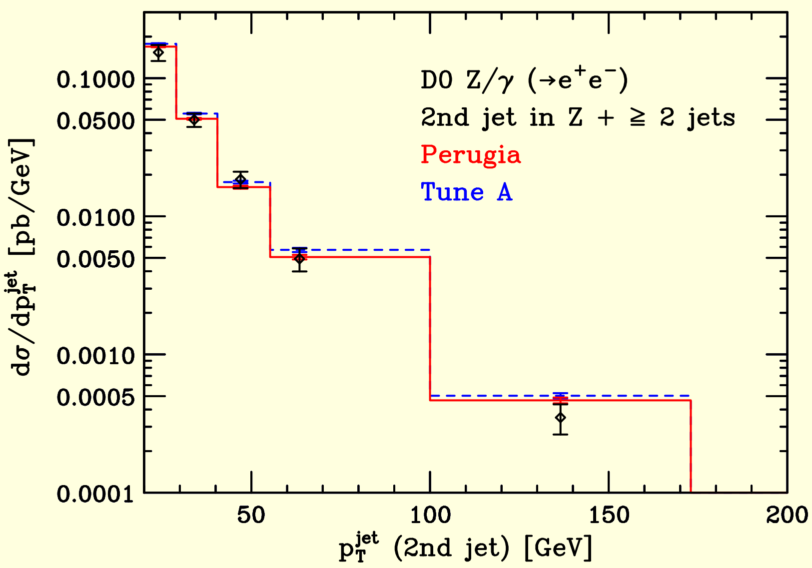


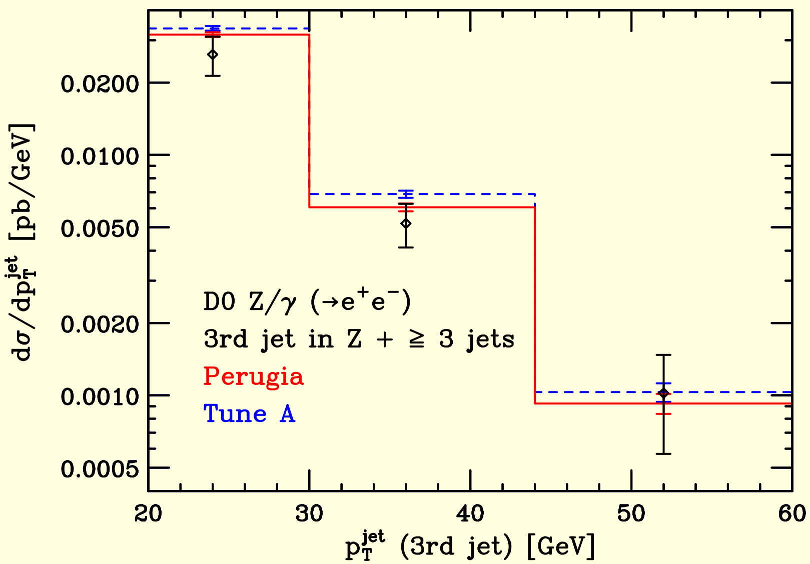

CDF Z/γ (→μ+μ−) + ≧1 jet inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet [GeV]
CDF Z/γ (→μ+μ−) + ≧2 jet inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
p_T^jet [GeV]
Perugia
Tune A
CDF Z/γ (→μ+μ−) + ≧1 jet inclusive
dσ/d|y^jet| [pb]
|y^jet|
Perugia
Tune A
CDF Z/γ (→μ+μ−) + ≧2 jet inclusive
dσ/d|y^jet| [pb]
|y^jet|

# D0 $Z/\gamma(\rightarrow e^+e^-) + \text{jets}$

$65\,\text{GeV} < M_{ee} < 115\,\text{GeV}, \quad p_T^e > 25\,\text{GeV}, \quad |\eta^e| < 1.1 \;\text{ or }\; 1.5 < |\eta^e| < 2.5$
$|y^{\text{jet}}| < 2.5, \quad p_T^{\text{jet}} > 20\,\text{GeV}$

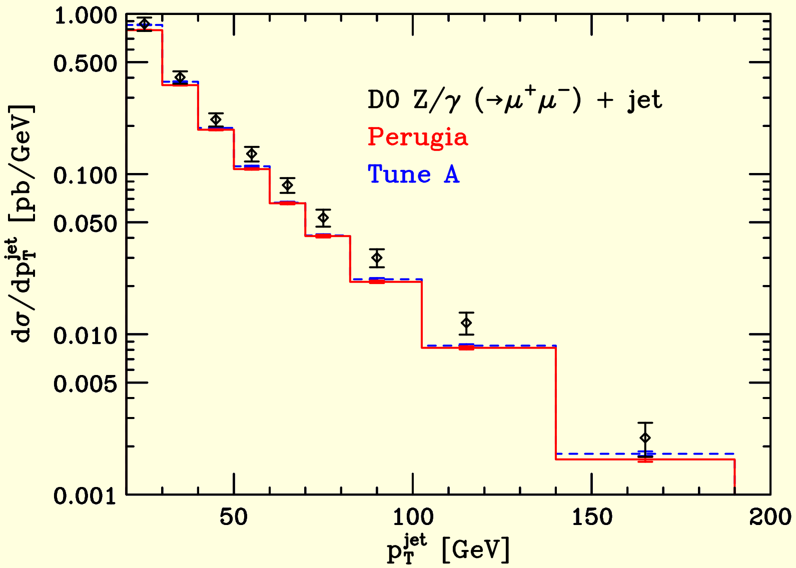


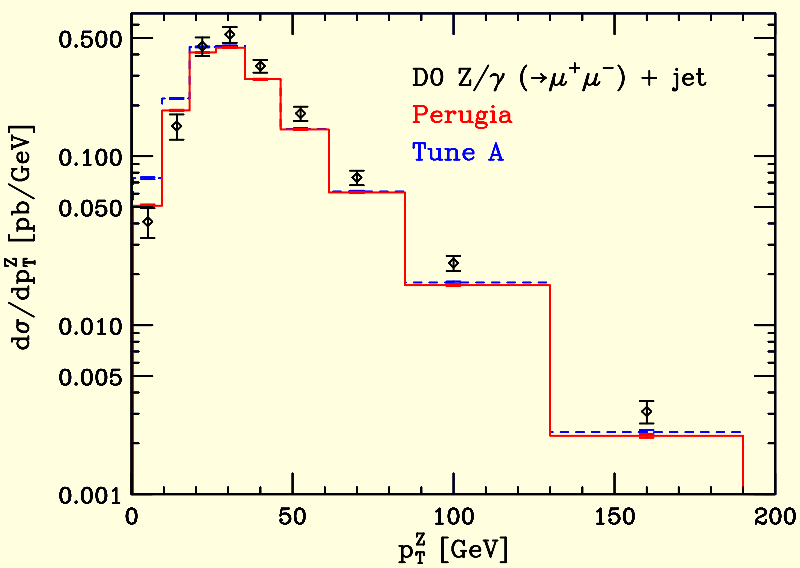



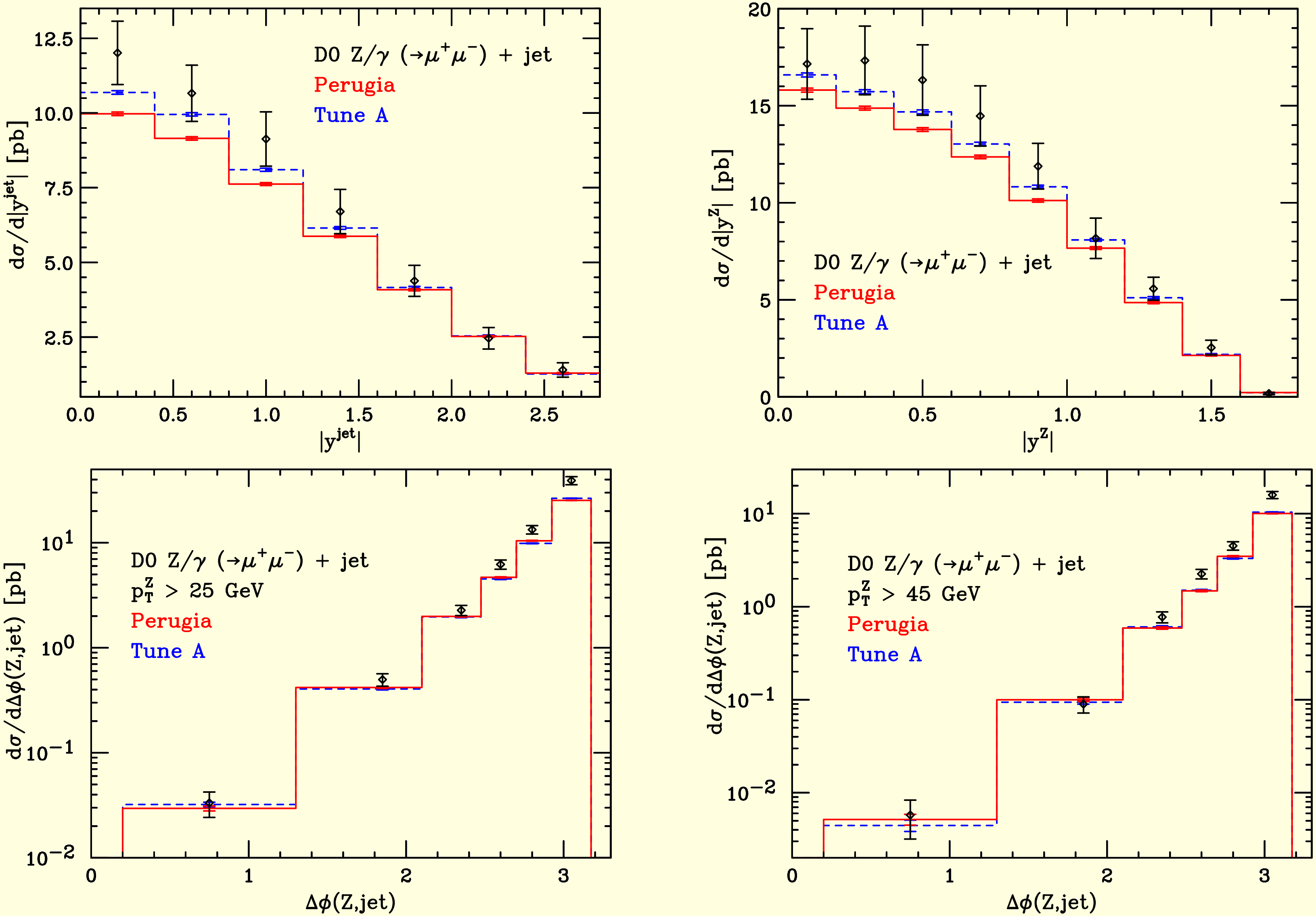

D0 Z/γ (→e⁺e⁻)
3rd jet in Z + ≧ 3 jets
Perugia
Tune A
0.0200
0.0100
0.0050
0.0020
0.0010
0.0005
dσ/dp_T^jet [pb/GeV]
20
30
40
50
60
p_T^jet (3rd jet) [GeV]

# D0 $Z/\gamma(\rightarrow \mu^+\mu^-) + \text{jets}$

$66\,\text{GeV} < M_{\mu\mu} < 116\,\text{GeV}, \quad p_T^{\mu} > 25\,\text{GeV}, \ |\eta^{\mu}| < 1.7,$
$|y^{\text{jet}}| < 2.8, \quad p_T^{\text{jet}} > 20\,\text{GeV}, \quad \Delta R_{\mu,\text{jet}} > 0.5;$




D0 Z/γ (→μ⁺μ⁻) + jet
Perugia
Tune A
dσ/d|y^jet| [pb]
|y^jet|
dσ/d|y^Z| [pb]
|y^Z|
p_T^Z > 25 GeV
p_T^Z > 45 GeV
dσ/dΔφ(Z,jet) [pb]
Δφ(Z,jet)

- Area of agreement/disagreement have the same pattern as in the comparison with the MCFM results in the CDF and D0 paper.
- No parton-to-hadron coefficient applied here!
- Sensitivity to MC tuning is comparable to the difference TH/data for several distributions. Tuning may improve the comparison.

# Issues with jets in NLO+PS

# Generation cut

In processes requiring jets (Dijets, $Z + \mathrm{jet}$) a generation cut is needed.

The Born cross section for the production of a light parton is divergent, unless we require a minimum $k_T$ on the light parton: generation cut.

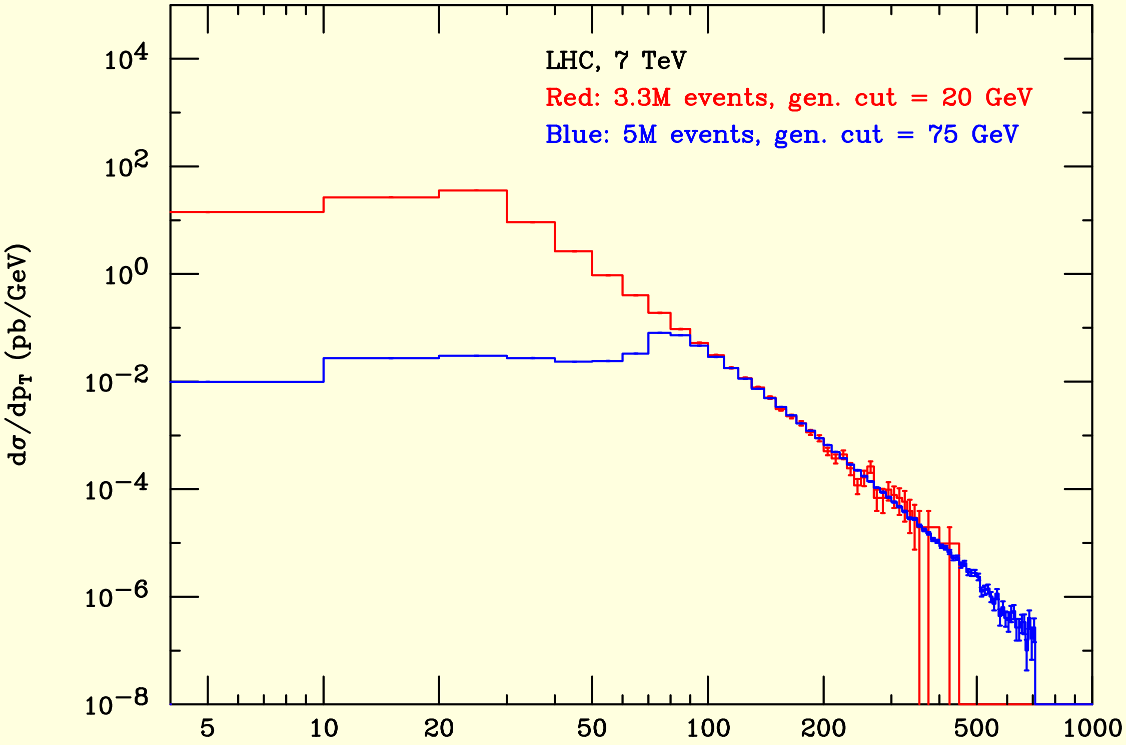
The shower can lead to a jet $k_T$ which is larger than the generation cut. Thus, the final analysis must be performed with a cut on the jet $k_T$ that is somewhat larger than the generation cut.

One must make sure that the results of the analysis are not sensitive to a reduction of the generation cut.

In NLO+PS (`POWHEG`) the generation cut is applied to the $k_T$ of the parton in the underlying Born process.

Jet $p_T$ spectrum steeply falling; difficult to cover all interesting $p_T$ range with a single run. One strategy: merge samples with different generation cuts

Blue sample coincides with red sample at around 250 GeV. Up to that point use the red sample. Above use the blue sample.



The POWHEG BOX offers the following options:

- run with a low generation cut (1 GeV), just to avoid unphysical regions in the PDF's and in the strong coupling, and allow to output negative weights (must be able to see where perturbation theory fails).
- Include a $k_T$ suppression factor in the generation. The event generation is suppressed by a factor $k_T^2/(k_T^2 + p_{T\,\mathrm{supp}}^2)$ (or any other power), where $k_T$ is the parton transverse momentum in the underlying Born configuration. Events are generated with the inverse weight $(k_T^2 + p_{T\,\mathrm{supp}}^2)/k_T^2$: Weighted sample.

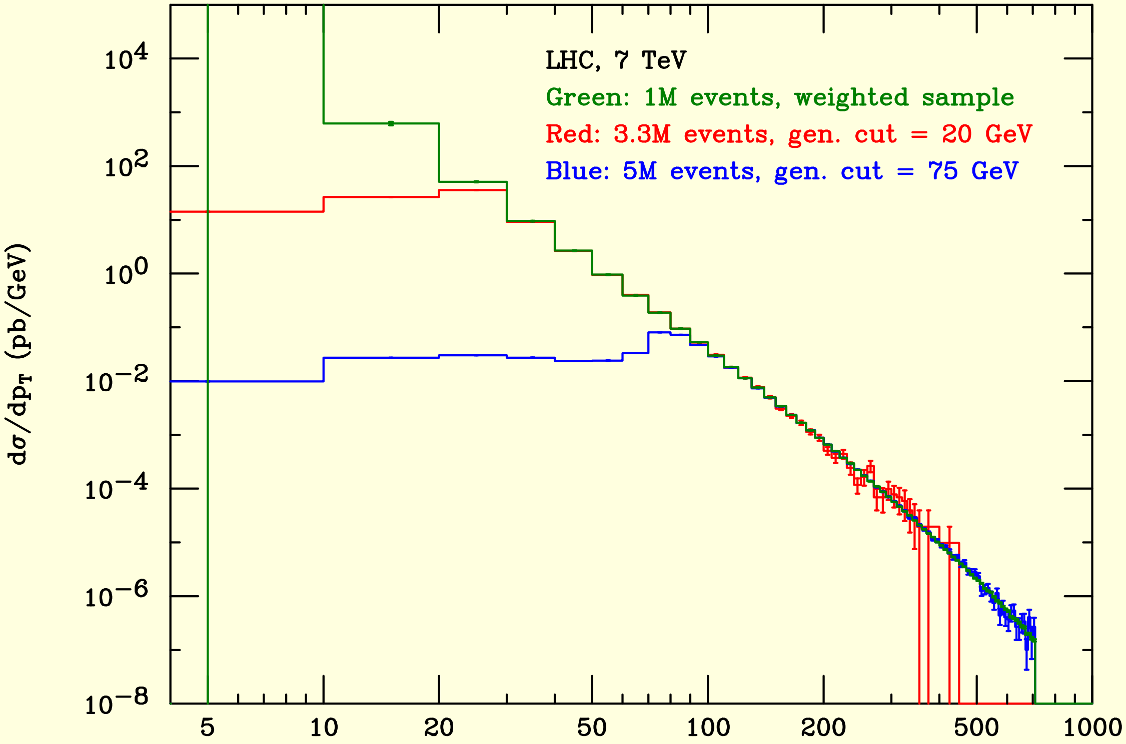
Combining these two options, and using a large enough $p_{T\,\mathrm{supp}}$ value, one can populate the large $p_T$ region and get the jet $p_T$ spectrum with a single sample. Samples obtained with a generation cut, and positive weight, begin to agree with the weighted sample in the region where the generation cut sensitivity has disappeared.

# Example in dijet production

Weighted sample,
Generation cut at 1 GeV.
$k_T$ suppression:

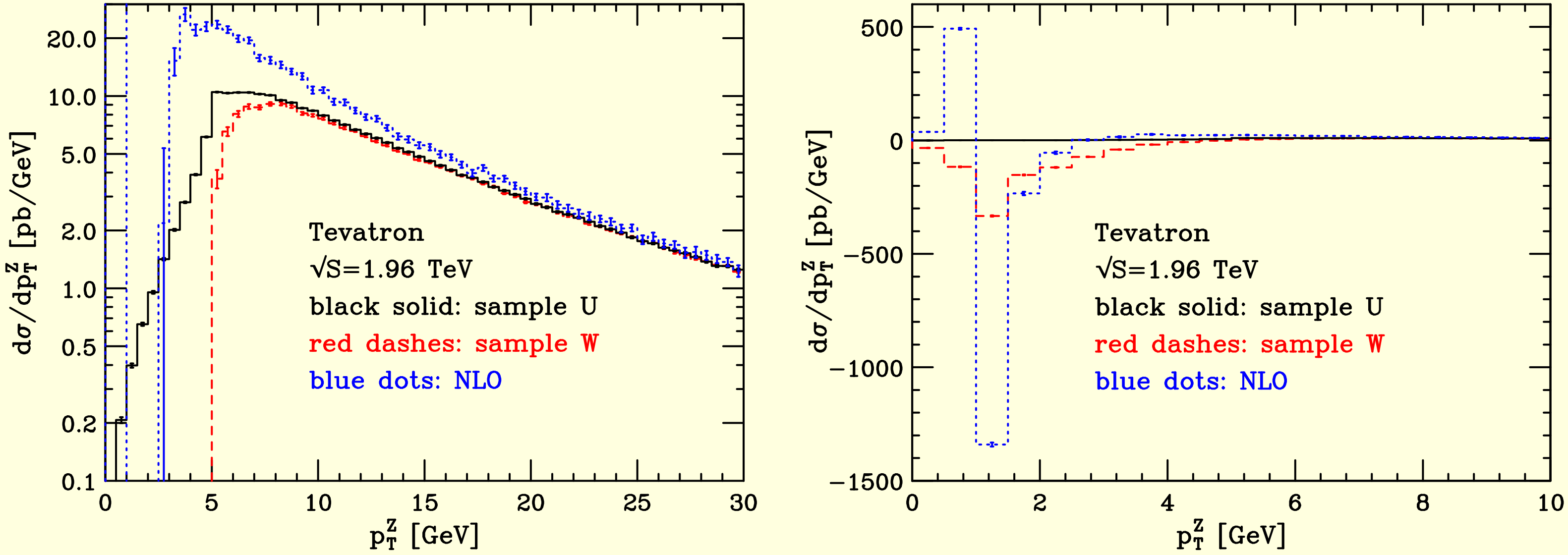
$$\left(\frac{k_T^2}{k_T^2 + p_{T\,\mathrm{supp}}^2}\right)^3,$$

$p_{T\,\mathrm{supp}} = 400\,\mathrm{GeV}$.
All $k_T$ spectrum uniformly populated.



# Example in $Z + \mathrm{jet}$ production

Sample U was produced unweighted, with positive weights, with $k_T^{\mathrm{gen}} = 5\,\mathrm{GeV}$. Sample W was produce weighted, with negative weights, $k_T^{\mathrm{gen}} = 1\,\mathrm{GeV}$.




When $p_T^Z \gtrsim 2 \times k_T^{\mathrm{gen}}$ the two distributions coincide. Notice the failure of perturbation theory around $p_T^Z \approx 5\,\mathrm{GeV}$. Below that the cross section turns negative.

# $Z + \mathrm{jet}$ at low $k_T$

The NLO calculation of $Z + \mathrm{jet}$ fails at low $k_T$, because of the appearance of large logarithms of $k_T$ at all orders in perturbation theory. These logarithms are resummed in the POWHEG generator for inclusive $Z$ production.

Problem: to build a jet sample that at low $k_T$ has the predictivity of the POWHEG-$Z$ generator, and at larger $k_T$ has the POWHEG-$Z + \mathrm{jet}$ NLO accuracy. Studies to perform such merging are under way. They amount to extending the CKKW ME+PS methods to NLO.

# Conclusions

- `POWHEG` is a viable tool for NLO jet physics
- A glimpse of CKKW at NLO: $Z + \mathrm{jet}$ and $Z$ in `POWHEG`
- The `POWHEG-BOX` shows its potential: new processes (like dijet production) are implemented in a short time.
- A new perspective: tuning NLO+PS using jets

# Issues with negative weights

The possibility to generate events with positive weights in POWHEG follows from the positivity of the $\bar{B}$ function:

$$\bar{B}(\Phi_B) = B(\Phi_B) + \underbrace{\left[\underbrace{V(\Phi_B)}_{\text{infinite}} + \underbrace{\int R(\Phi)\, d\Phi_r}_{\text{infinite}}\right]}_{\text{finite}} = B(\Phi_B) + V_{\text{sv}}(\Phi_B) + \int \hat{R}(\Phi)\, d\Phi_r$$

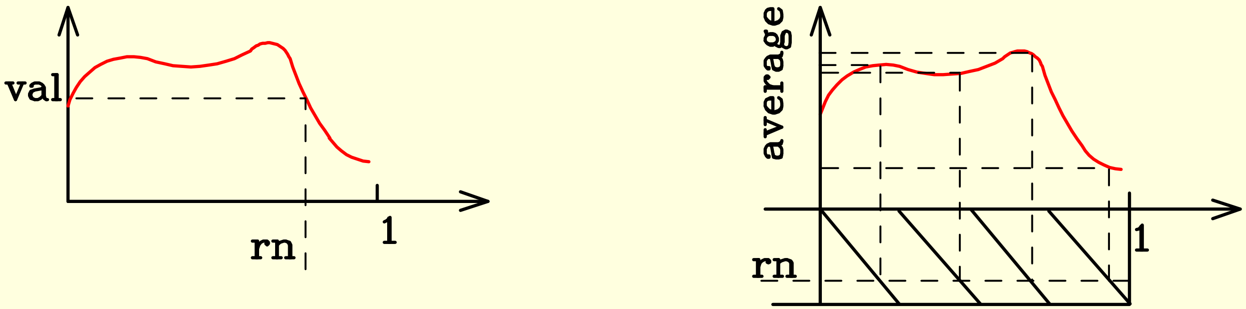
If $\bar{B}$ turns negative, it means that NLO effects are larger than LO effects, and that the whole result is invalid.

Underlying Born configurations are generated according to the $\bar{B}$ function. What is done in practice is to define a function

$$\tilde{B}(\Phi_B, X) = B(\Phi_B) + V_{\text{sv}}(\Phi_B) + \left|\frac{\partial \Phi_r}{\partial X}\right| \hat{R}(\Phi), \quad \bar{B}(\Phi_B) = \int_0^1 d^3X \;\; \tilde{B}$$

We generate points in $\Phi_B, X$ space distributed with a probability $\tilde{B}(\Phi_B, X)$.

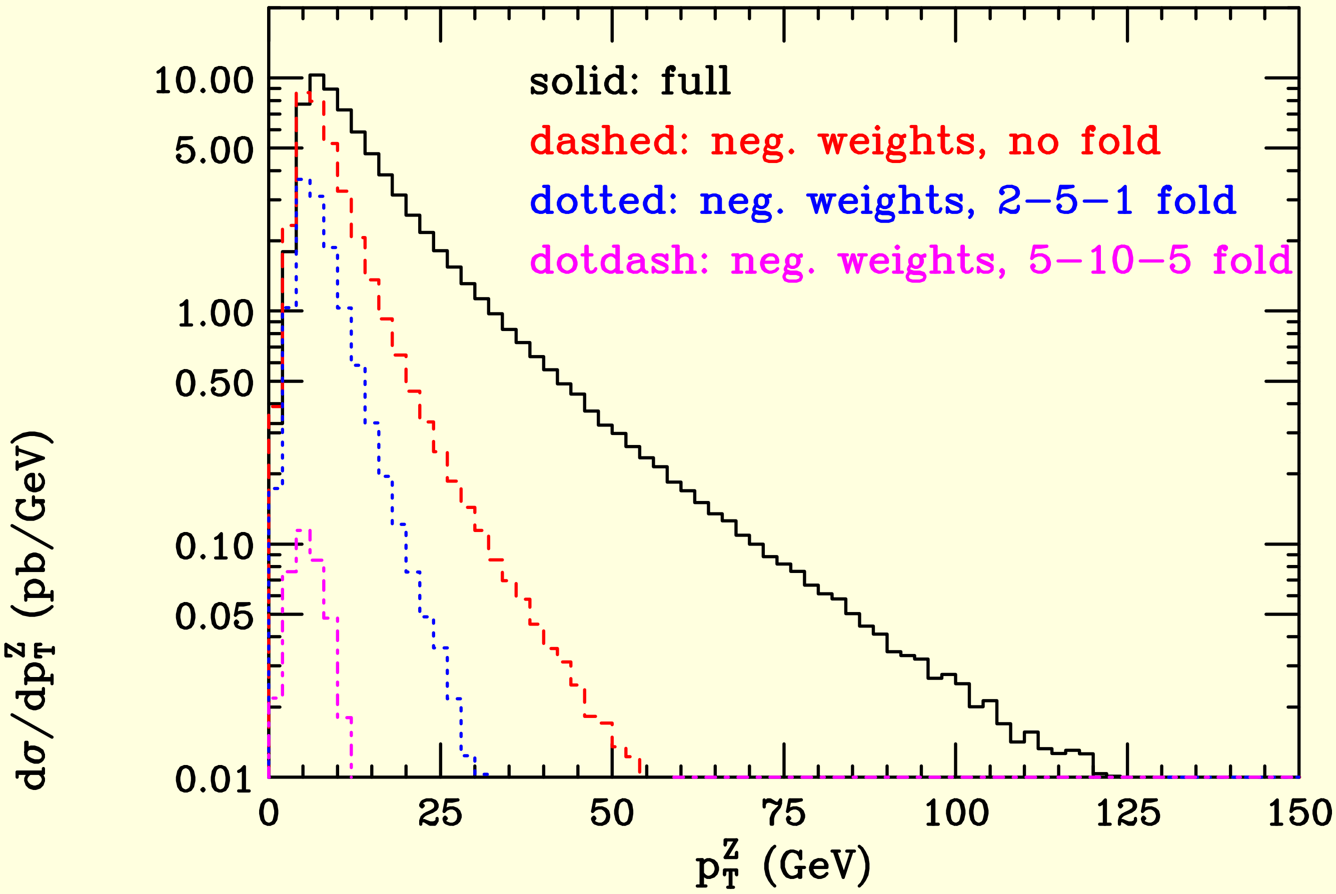
It may turn out that, while $\bar{B}$ is positive, $\tilde{B}$ is not. If this is the case, POWHEG can still generate events with positive weights, by folding up some or all of the 3 $X$ variable integration range:




It is clear that, as the number of folds increases, the “folded” $\tilde{B}$ becomes closer to $\bar{B}$, and its negative weigths disappear if $\bar{B}$ is positive.

Folding the $\tilde{B}$ function has a performance cost.

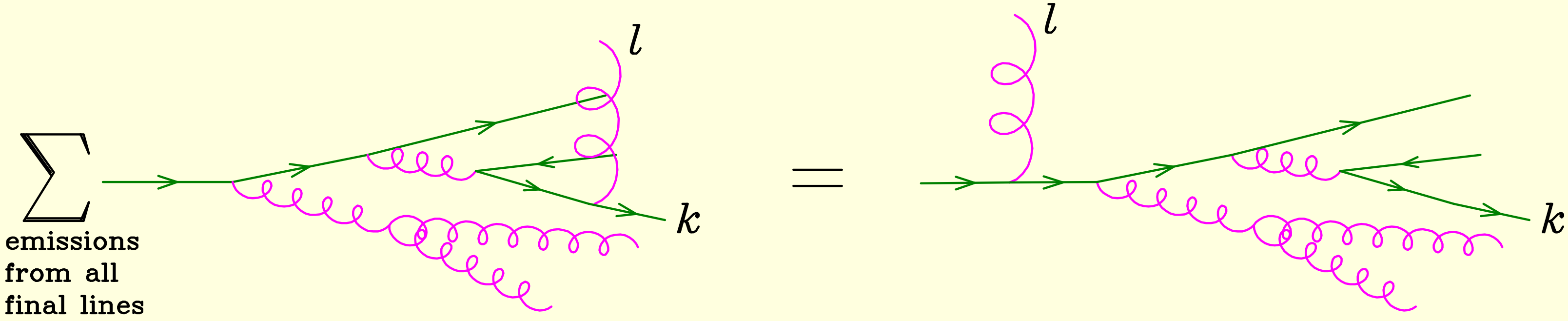
In POWHEG, when set up to output negative weights, the results are independent upon folding and the negative weight fraction, whatever folding numbers are used




Negative weights fraction for different folding numbers of the three radiation variables, in $Z + \mathrm{jet}$ production. The full result is the same in all cases.

# Thuncated Showers

In angular ordered PS (HERWIG, HERWIG++) the hardest radiation may not be the first. Earlier radiations account for coherent emission of final state partons.




In P.N. 2004 (1st POWHEG paper), it was shown that, in order to recover coherence in cases where the hardest radiation is generated first (POWHEG, but also all ME+PS generators), one should add truncated vetoed showers to the event.

Truncated showers have been implemented in HERWIG++ POWHEG for Drell-Yan processes (Hamilton, Richardson and Tully, 2008), where only minor effects were found.

Truncated showers are also needed in relatively simple processes in the basic LO shower (all processes involving more than two coloured partons).

Summarizing:

- Truncated showers should be implemented in conjunction with angular ordered shower Monte Carlo, if they are to be used interfaced to ME ot POWHEG generators, in order to preserve soft radiation coherence
- Truncated shower are also needed in HERWIG or MC@NLO for elementary processes, like parton-parton scattering or heavy flavour production, that involve more than 2 coloured partons.
- Truncated showers are irrelevant for Monte Carlo that do not implement coherence correctly (virtuality ordered showers), or that implement coherence via $p_T$ ordered dipole showers (new PYTHIA, SHERPA)
- Implementation of truncated showers for some processes have been studied by the HERWIG++ team. Up to now, no visible effects have been found