Typeset with TeXmacs

Jets with POWHEG

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Plan of the talk

- `POWHEG` status
- `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

Positive Weight Hardest Emission Generator

A method to interface NLO calculations with Parton Shower (NLO+PS)

- Formulation of the method: P.N. 2004
- First implementation: $hh \to ZZ + X$, Ridolfi, P.N. 2006
- General formulation of the method: Frixione, Oleari, P.N. 2007
- `POWHEG BOX`: Alioli, Oleari, Re, P.N. 2010

`POWHEG BOX`: fortran framework for the implementation of NLO processes in `POWHEG`, requiring only the Born, the Real and the finite part of the virtual corrections.
All previous processes of the Bicocca group are being transferred to the `POWHEG BOX`: uniform framework.

POWHEG and MC@NLO

POWHEG has been estensively compared to MC@NLO, for all processes available there (all but VBF Higgs production, $hh\to Z/W+\mathrm{jet}$, Dijet production).

Remarkable agreement found for most distribution, few discrepancies (dip in rapidity distribution of the radiated jet, Higgs pt spectrum in $gg\to H$)

Differences have been thoroughly studied. They have been understood and explained in a few publications, on the basis of a formula that should describe equally well POWHEG and MC@NLO;

NLO+PS

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

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

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:

$$\underbrace{\bar{B}^s(\Phi_B)d\Phi_B}_{\substack{\text{provided by }\texttt{MCatNLO}\\ \mathcal{S}\text{ event}}} \underbrace{\left[\underbrace{\Delta^s_{t_0} + \Delta^s_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r}_{\text{generated by }\texttt{HERWIG}}\right]}_{\text{demonstrated in P.N. 2004}} + \underbrace{\left[R(\Phi) - R^s(\Phi)\right] d\Phi}_{\substack{\text{provided by }\texttt{MCatNLO}\\ \mathcal{H}\text{ event}}}$$

More synthetically

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

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

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 $t = t_{\mathtt{powheg}}$
- The event is passed to a SMC, imposing no radiation with $t > t_{\mathtt{powheg}}$.
- Interfacing to angular ordered SMC's requires truncated showers to maintain coherence of soft radiation (P.N. 2004)

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)
- $hh \to Z + \mathrm{jet}$, Preliminary (Alioli, Oleari, Re, P.N., 2010)
- Dijet production, Preliminary (Alioli, Hamilton,Oleari, Re, P.N., 2010)

Several `POWHEG` efforts:

- The Milano Bicocca group (the `POWHEG BOX`)
- The `HERWIG++` team (Hamilton,Richardson,Tully, 2008,2009;)
- `SHERPA` (Hoeche,Krauss,Schonherr,Siegert,2010)

Remember: `POWHEG` is a method, not a program (several implementations)

An important advantage of `POWHEG` is the complete separation of the hardest radiation generation and the subsequent shower.
The Bicocca team is working in this direction. The `POWHEG BOX` has been developed to encourage people to implement their NLO calculation as NLO+PS generators that can be interfaced to any shower program.

Other efforts (`HERWIG++` and `SHERPA`) are more bundled with the corresponding shower program.

$Z + \mathrm{jet}$ 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` works: Processes like VBF, Dijet production, tW, and the re-implementation of gluon fusion Higgs, W/Z production, heavy flavour production, have gone through in a short time without problems.

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.

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).

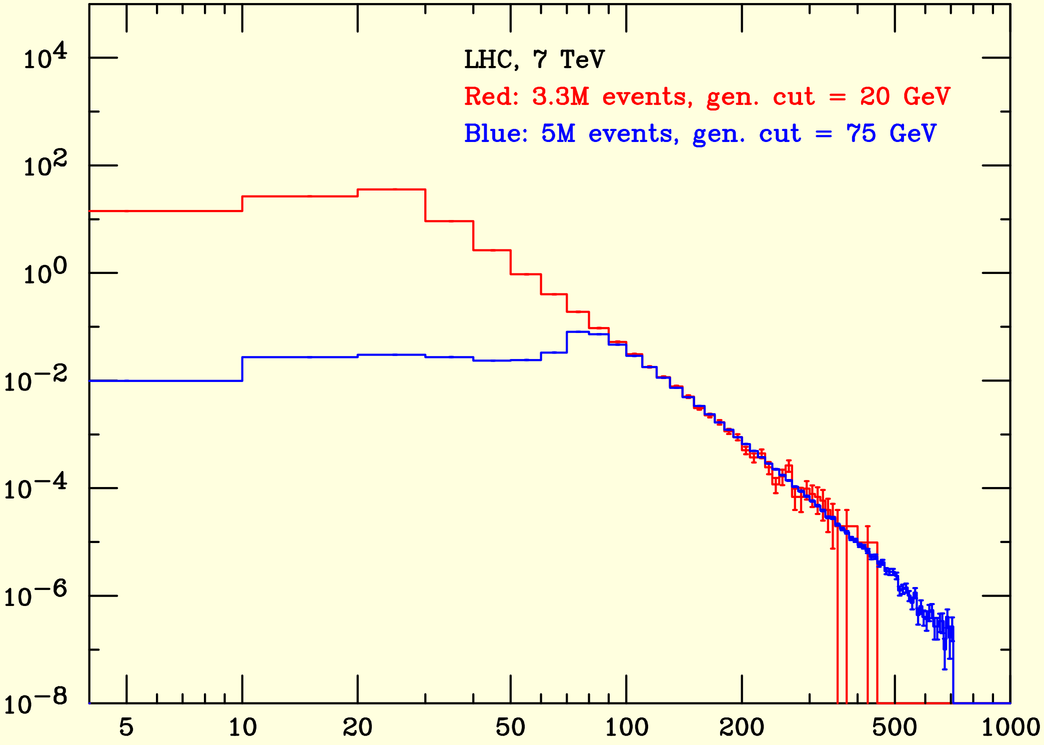
The shower can lead to a jet k_T which is larger than the generation cut. Thus, the final analysis must be performed with a cut on the jet k_T that is somewhat larger than the generation cut.

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 $k_T^2/(k_T^2+p_{T\,\rm supp}^2)$ (or any other power), where k_T is the parton transverse momentum in the underlying Born configuration. Events are generated with the inverse weight $(k_T^2+p_{T\,\rm supp}^2)/k_T^2$: Weighted sample.

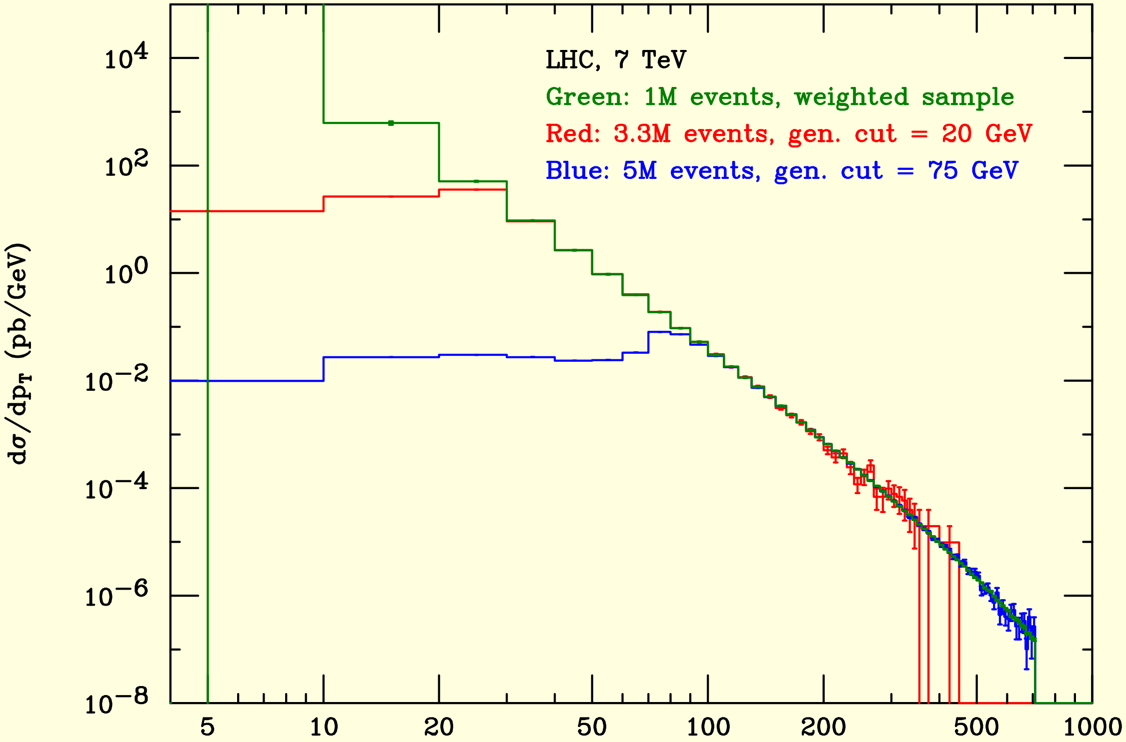
Combining these two options, and using a large enough $p_{T\,\rm supp}$ value, one can populate the large p_T region and get the jet p_T spectrum with a single sample. Samples obtained with a generation cut, and positive weight, begin to agree with the weighted sample in the region where the generation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

Example in dijet production

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

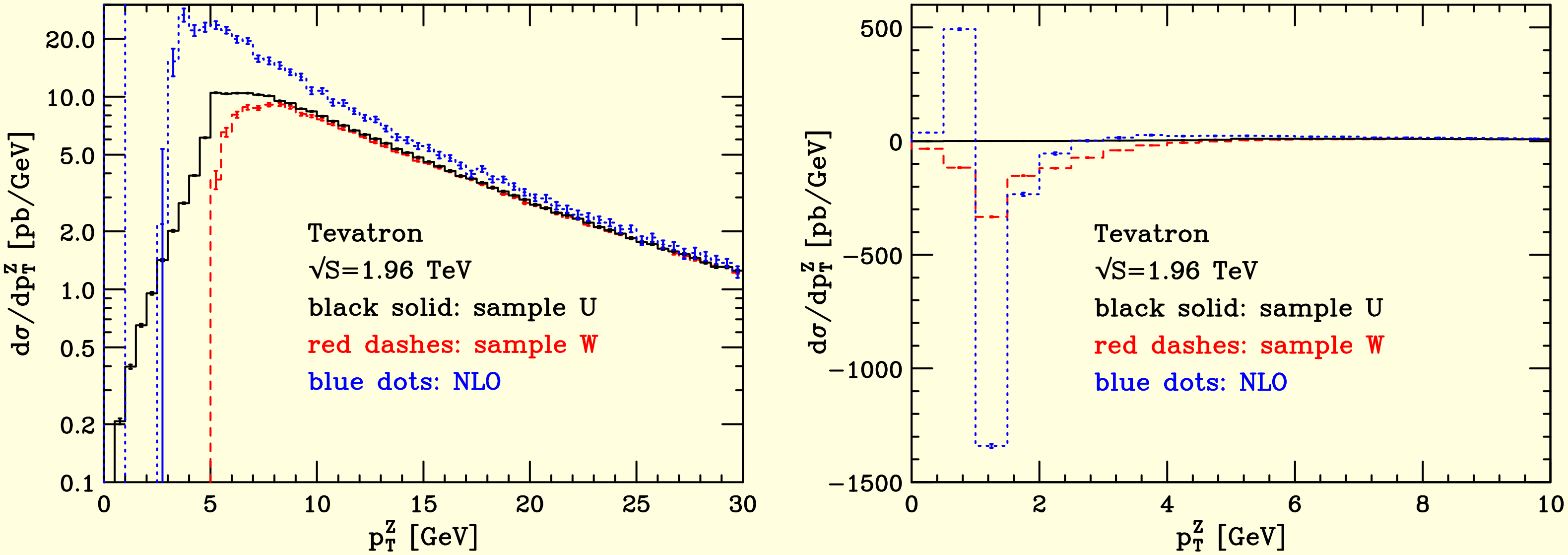
$$\left(\frac{k_T^2}{k_T^2+p_{T\,\mathrm{supp}}^2}\right)^3,$$

$p_{T\,\mathrm{supp}}=400\,\mathrm{GeV}$.
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`-Z generator, but not in the `POWHEG`-$Z + \mathrm{jet}$ one!

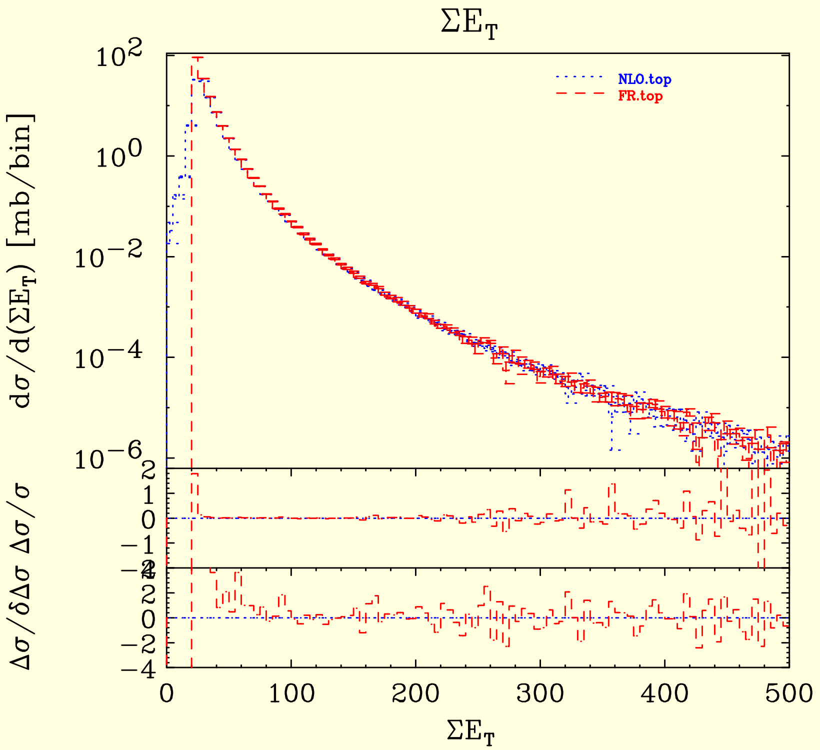
Problem: to build a jet sample that at low k_T has the predictivity of the `POWHEG`-Z generator, and at larger k_T has the `POWHEG`-$Z + \mathrm{jet}$ NLO accuracy.
Studies to perform such merging are under way.
They amount to extending the CKKW ME+PS methods to NLO.

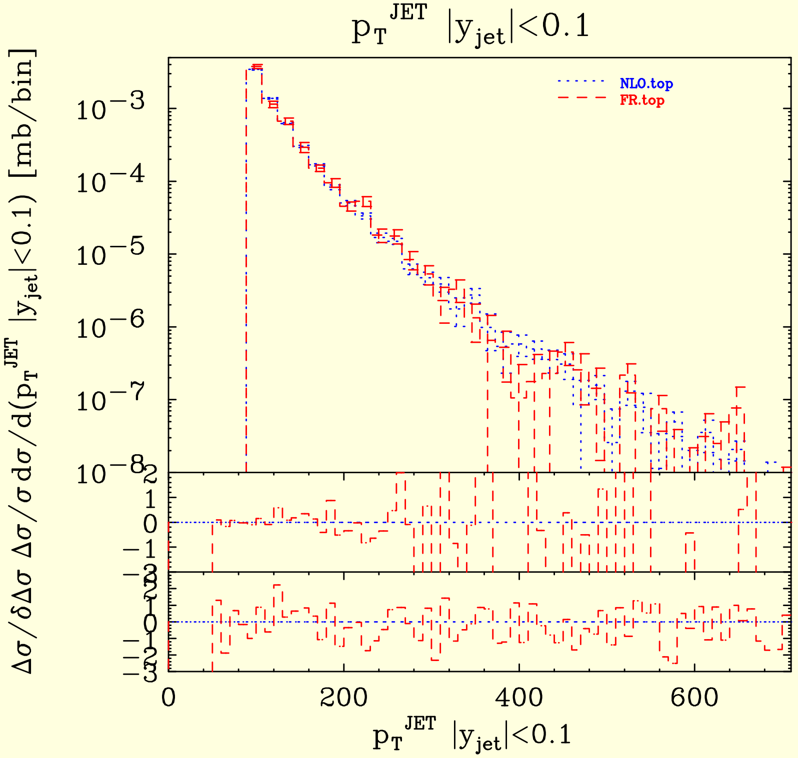
Merging `POWHEG`-W, `POWHEG`-$t\bar{t}$ output to ME+PS generator output has been studied in Hamilton, P.N., April 2010; now, in the W/Z case, we have the opportunity to extend NLO accuracy to the radiation of the hardest jet)

Dijets

Matrix elements for Born, Real, Virtual are all in the literature (Ellis, Sexton,1986; Kunszt, Soper,1992). We only needed to compute the planar colour amplitudes to assign colour at the end.

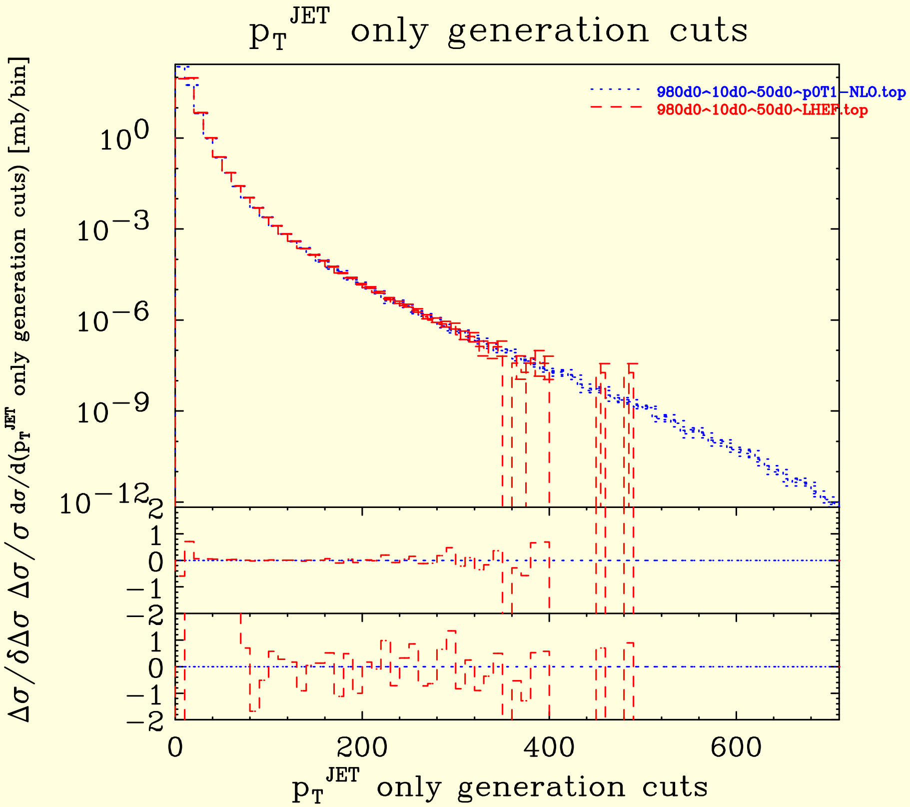
The `POWHEG BOX` also implements a partonic NLO generator, in order to check the validity of the NLO formulae against existing programs. We compared it with the program of Frixione and Ridolfi, 1997, for several distributions.

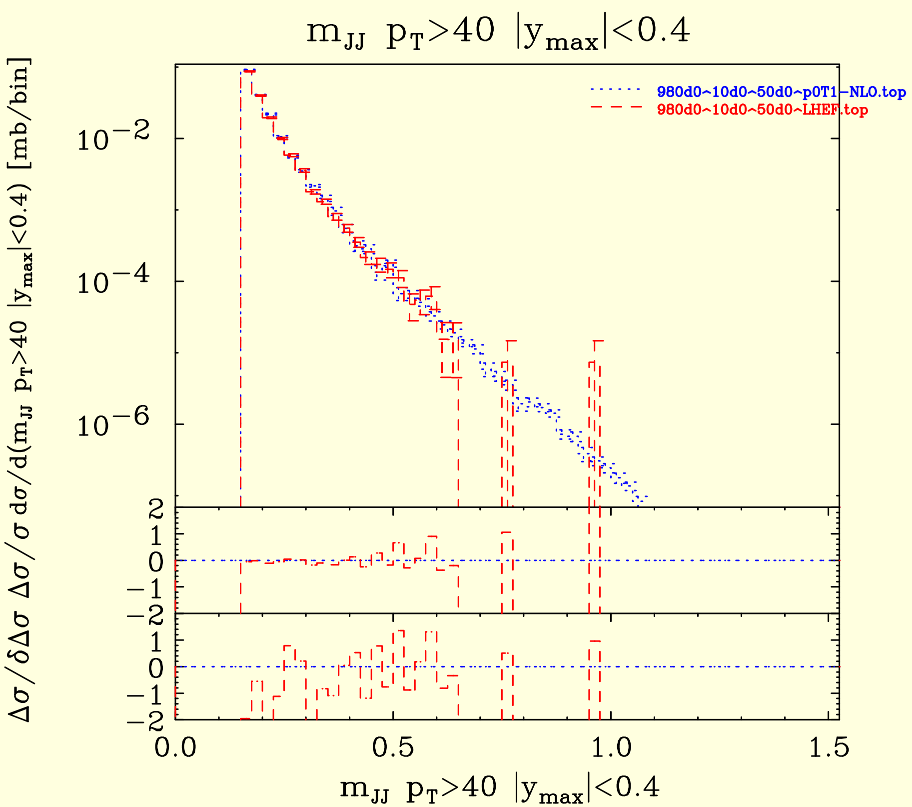


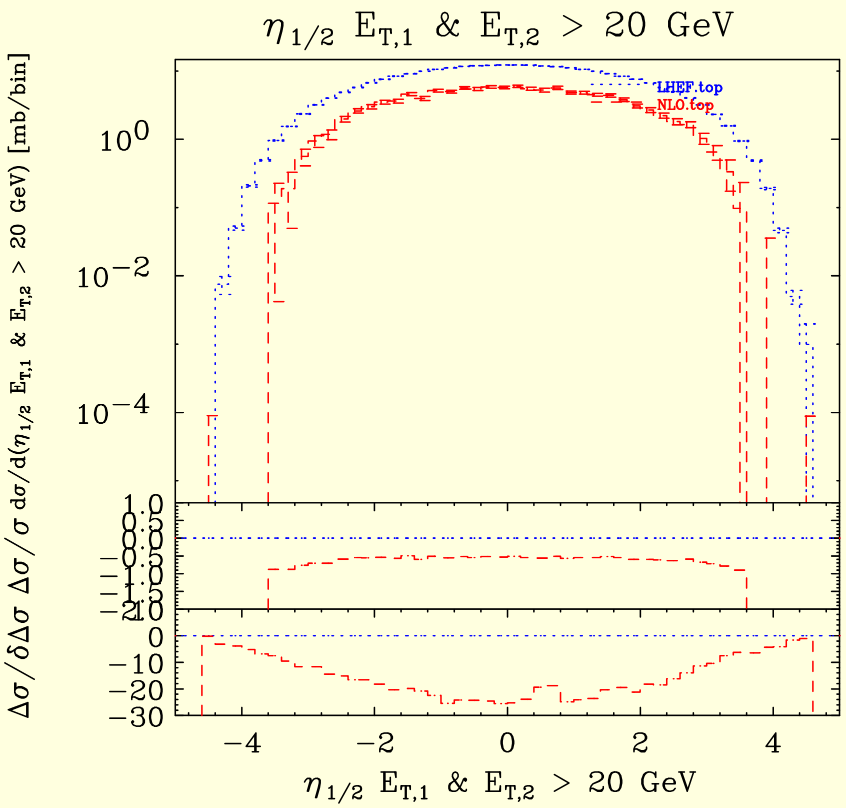


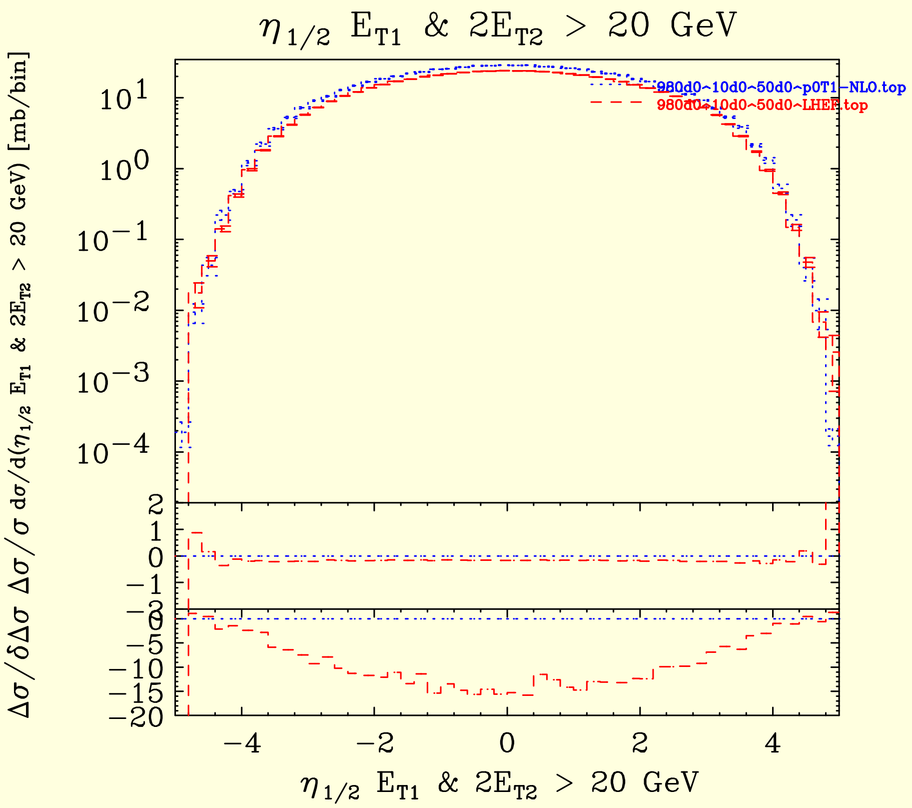
Agree (as long as we don;t get close to the generation cut).

Comparison of NLO with bare POWHEG









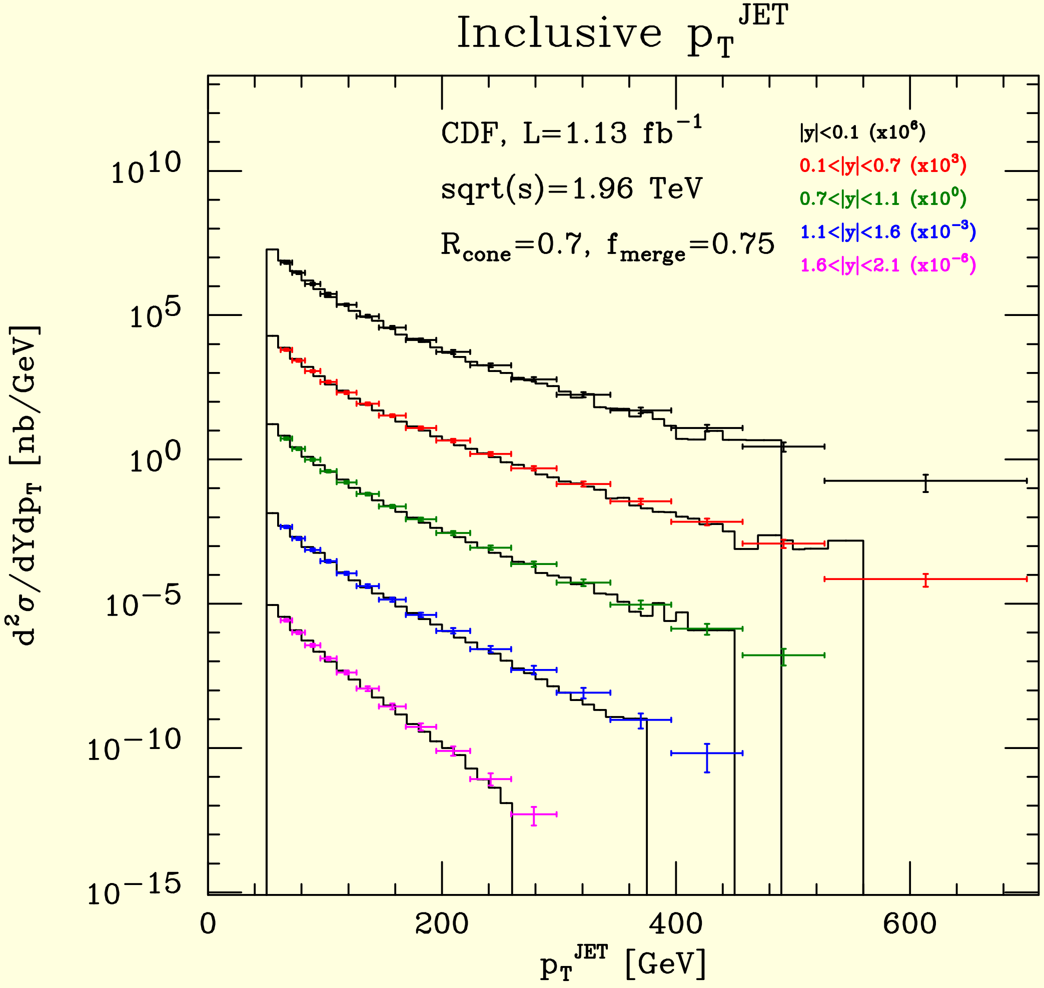
Large differences between NLO and bare `POWHEG` when symmetric cuts on the two hardest jets are imposed. These quantities are known to be affected by large Sudakov effects (included in `POWHEG`, but not in the NLO) (Frixione and Ridolfi, 1997).

Comparison with data

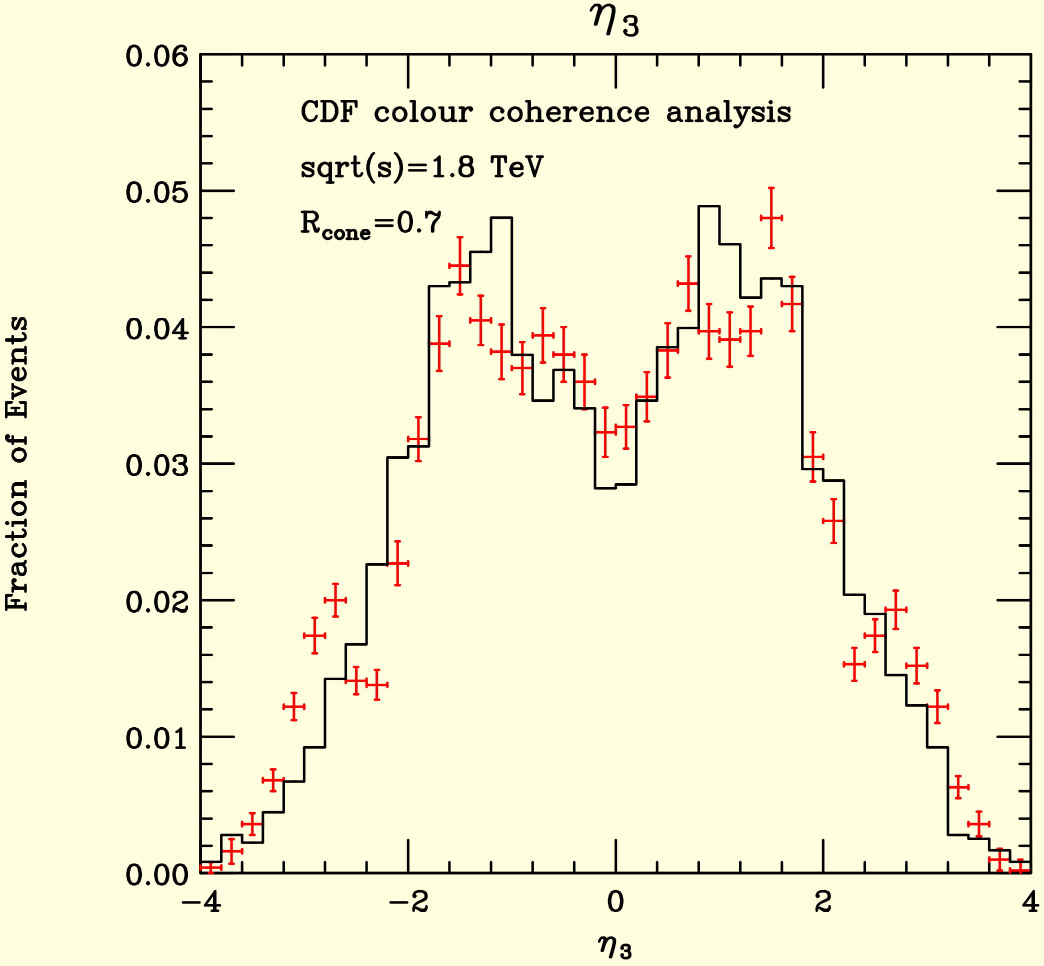
"Minimal" comparison of `POWHEG` output to CDF published data.

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

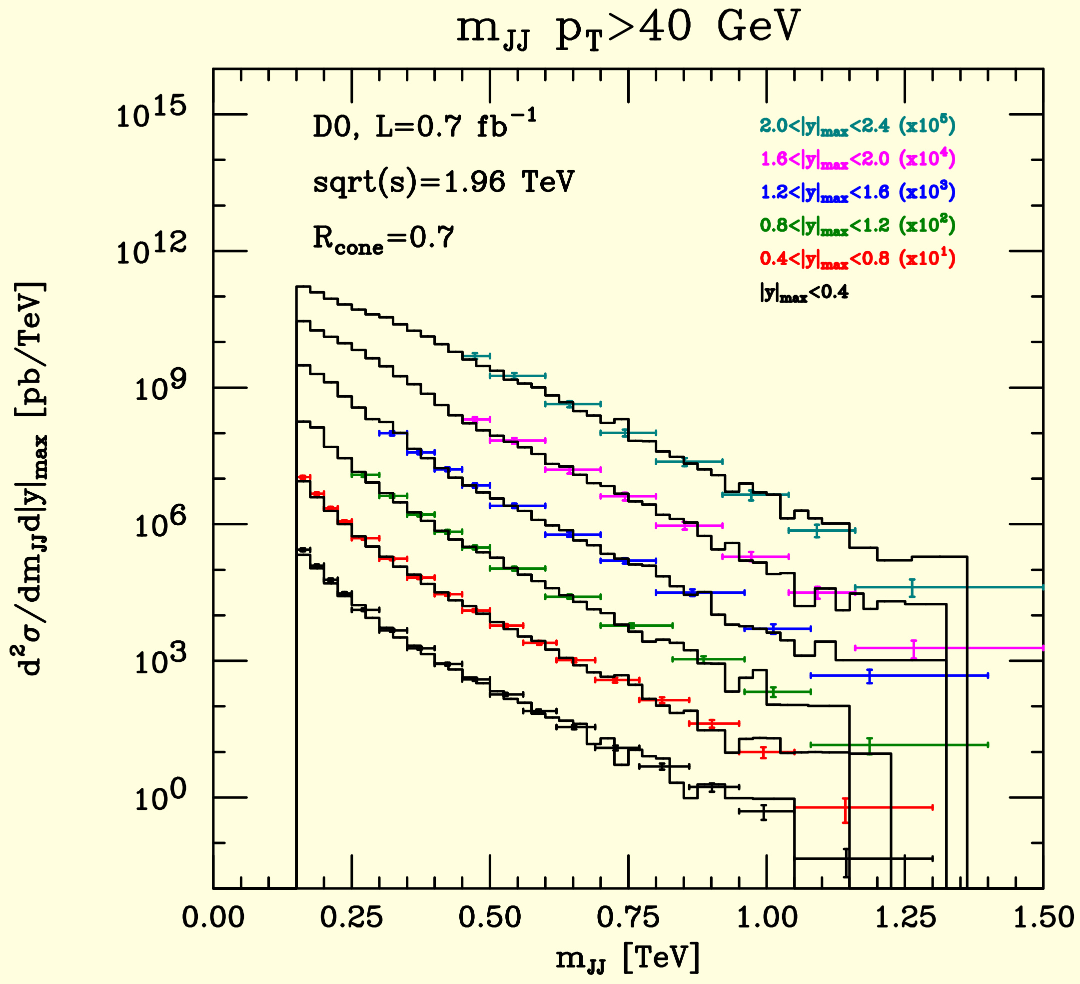
No scale or pdf uncertainty has been included.



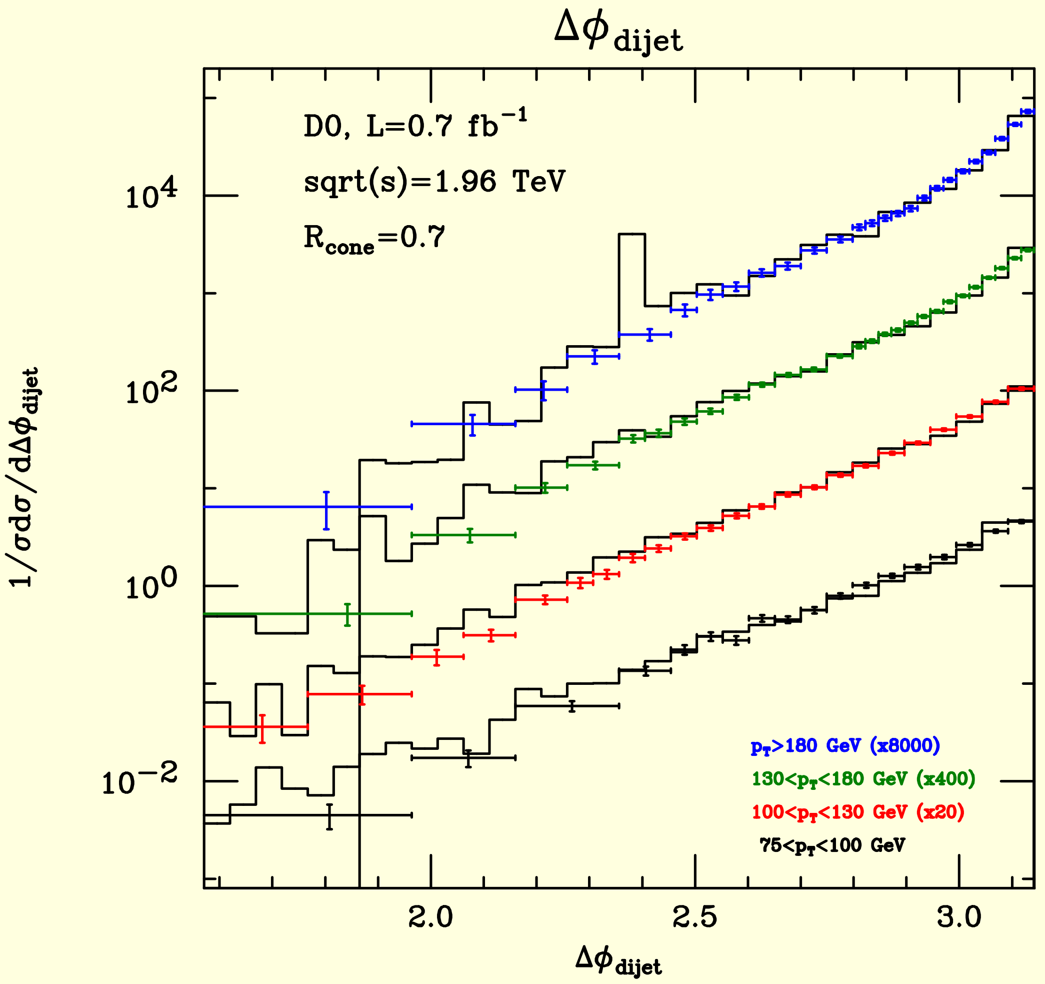
Pseudorapidity of the third hardest jet. Coherence dip.



D0 jets results



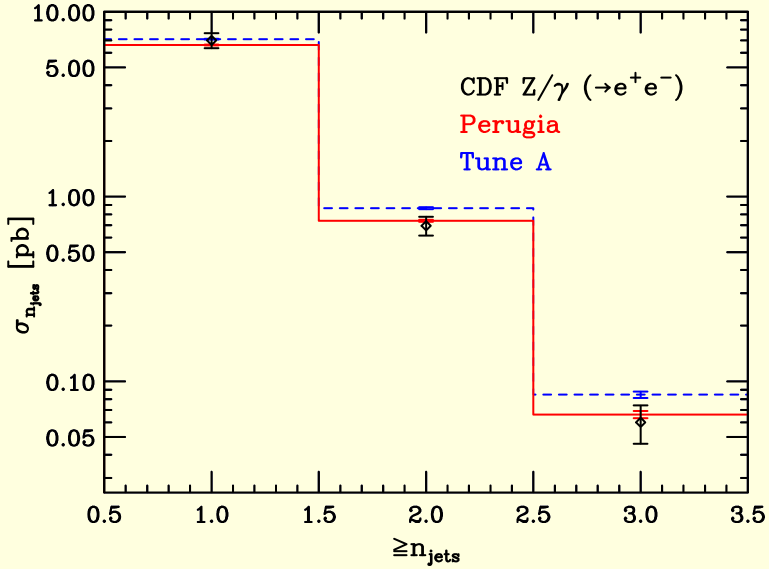
Frixione and Ridolfi, 1997,

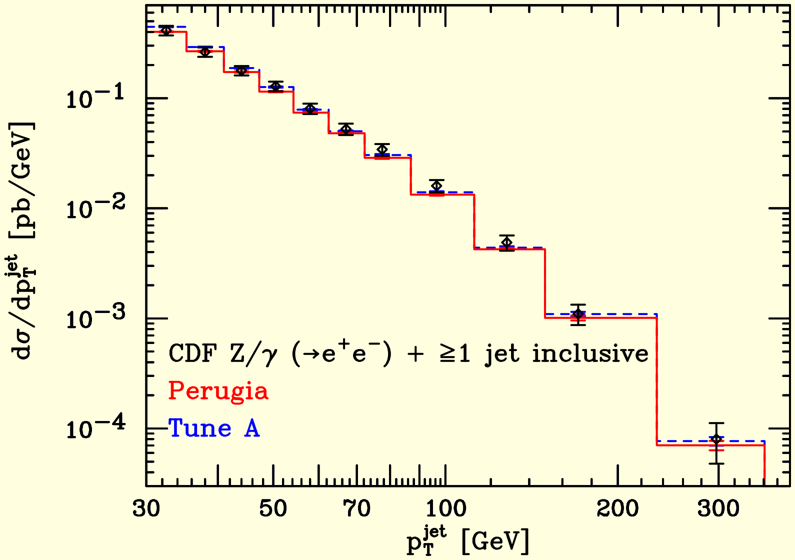

$\Delta\phi_{\rm dijet}$
D0, L=0.7 fb^{-1}
sqrt(s)=1.96 TeV
$R_{\rm cone}$=0.7
10^4
10^2
10^0
10^{-2}
$1/\sigma d\sigma/d\Delta\phi_{\rm dijet}$
2.0
2.5
3.0
$\Delta\phi_{\rm dijet}$
p_T>180 GeV (x8000)
130<p_T<180 GeV (x400)
100<p_T<130 GeV (x20)
75<p_T<100 GeV

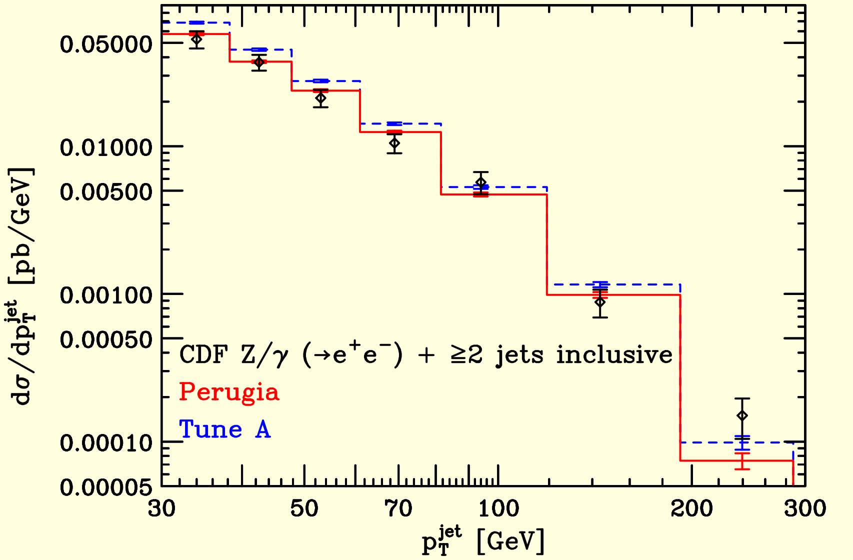
CDF $Z/\gamma(\to e^+e^-)+\mathrm{jets}$

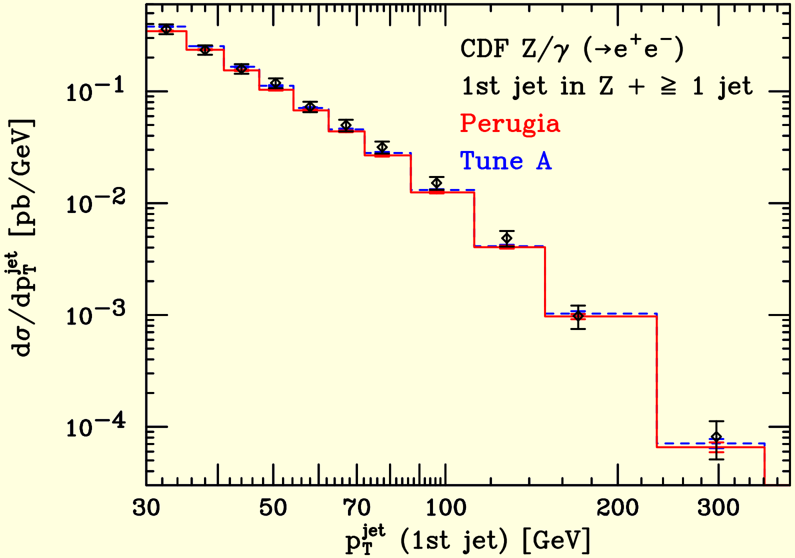
Cuts: $66\,\mathrm{GeV} < M_{ee} < 116\,\mathrm{GeV},\quad p_T^e > 25\,\mathrm{GeV},\ |\eta^{e_1}| < 1,\ 1.2 < |\eta^{e_2}| < 2.8$
$|y^{\mathrm{jet}}| < 2.1,\quad p_T^{\mathrm{jet}} > 30\,\mathrm{GeV},\ \Delta R_{e,\mathrm{jet}} > 0.7$

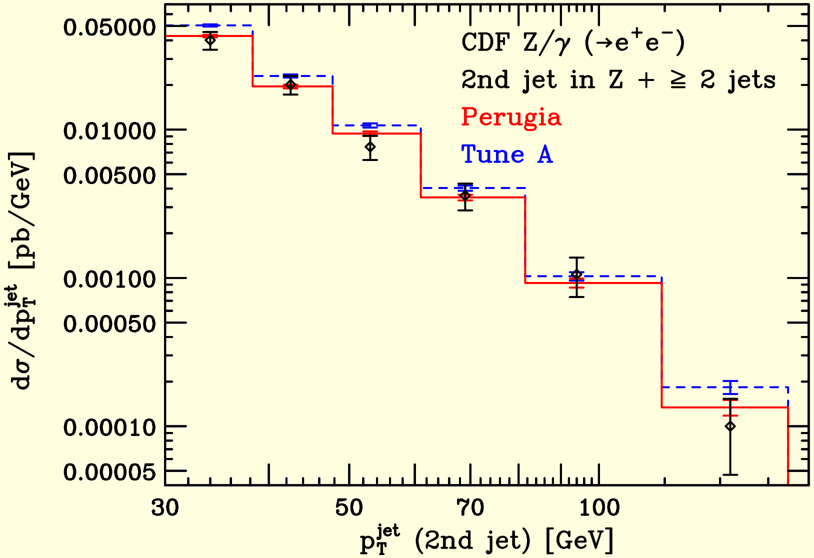
Jets reconstructed using the CDF midpoint algorithm.




CDF Z/γ (→e⁺e⁻) + ≧1 jet inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
10⁻¹
10⁻²
10⁻³
10⁻⁴
30
50
70
100
200
300
p_T^jet [GeV]


CDF Z/γ (→e⁺e⁻) + ≧2 jets inclusive
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
0.05000
0.01000
0.00500
0.00100
0.00050
0.00010
0.00005
30
50
70
100
200
300
p_T^jet [GeV]


CDF Z/γ (→e⁺e⁻)
1st jet in Z + ≧ 1 jet
Perugia
Tune A
dσ/dp_T^jet [pb/GeV]
10⁻¹
10⁻²
10⁻³
10⁻⁴
30
50
70
100
200
300
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]
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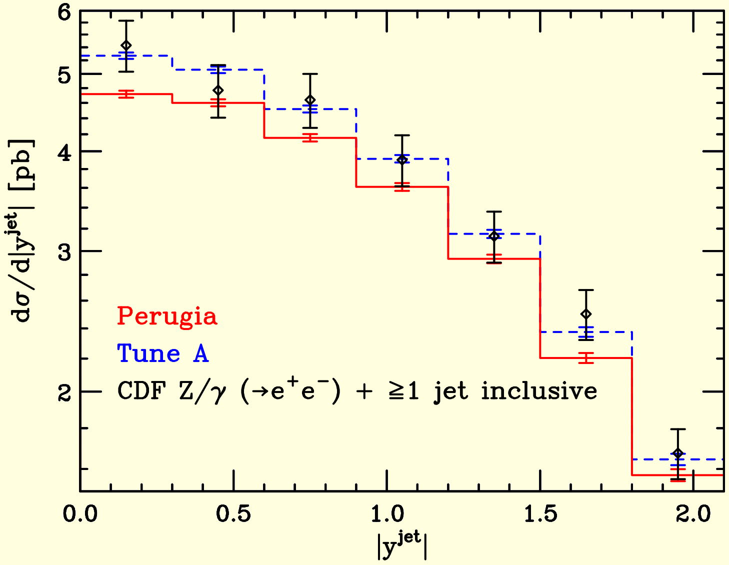
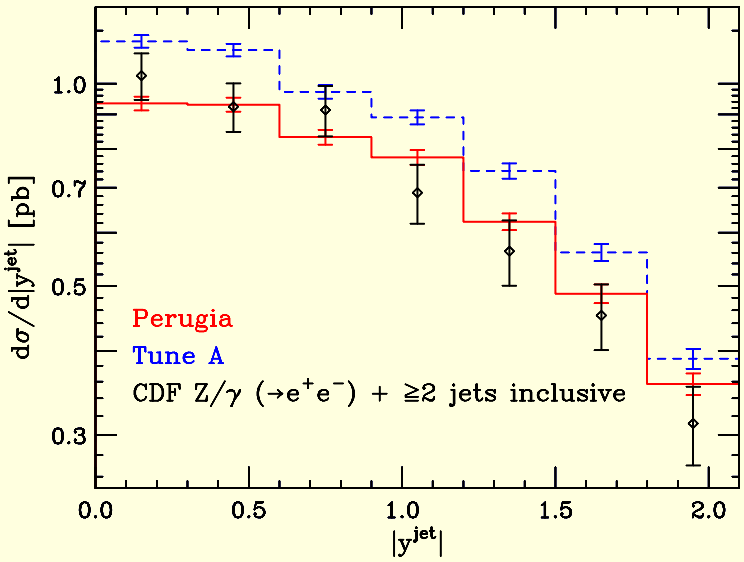
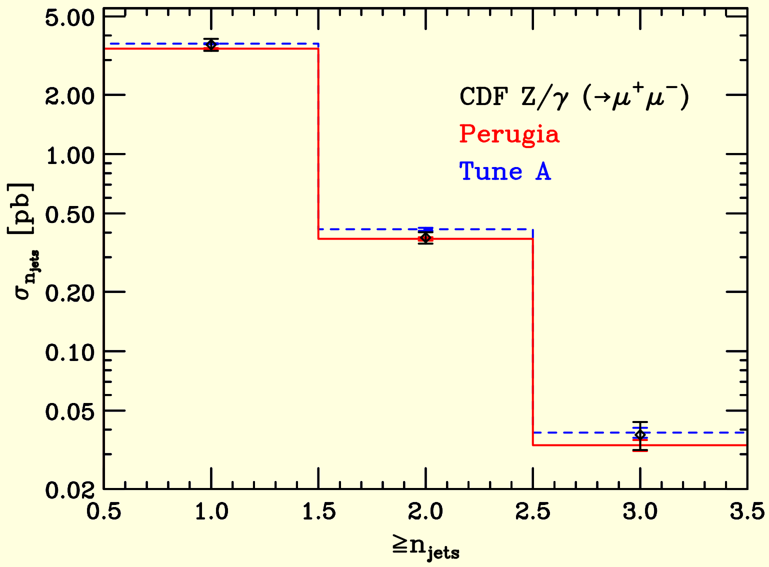
0.01000
0.00500
0.00100
0.00050
0.00010
0.00005
30
50
70
100
p_T^jet (2nd jet) [GeV]

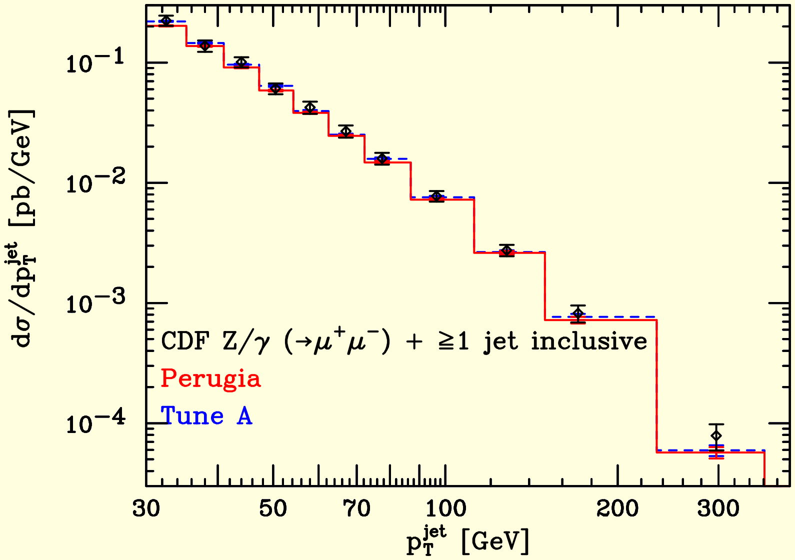

6
5
4
3
2
0.0
0.5
1.0
1.5
2.0
$d\sigma/d|y^{jet}|$ [pb]
$|y^{jet}|$
Perugia
Tune A
CDF Z/γ ($\rightarrow e^+e^-$) + ≧1 jet inclusive

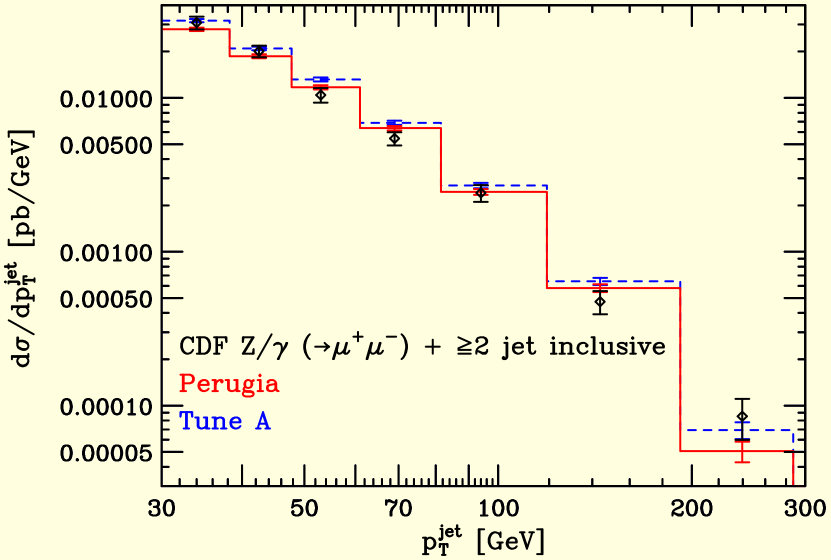

1.0
0.7
0.5
0.3
0.0
0.5
1.0
1.5
2.0
$d\sigma/d|y^{jet}|$ [pb]
$|y^{jet}|$
Perugia
Tune A
CDF Z/γ ($\rightarrow e^+e^-$) + ≧2 jets inclusive

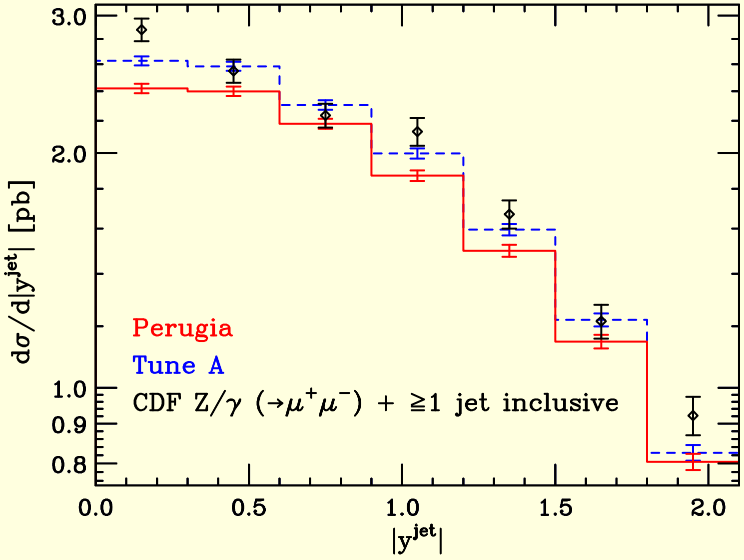
CDF $Z/\gamma(\rightarrow \mu^+\mu^-) + \text{jets}$

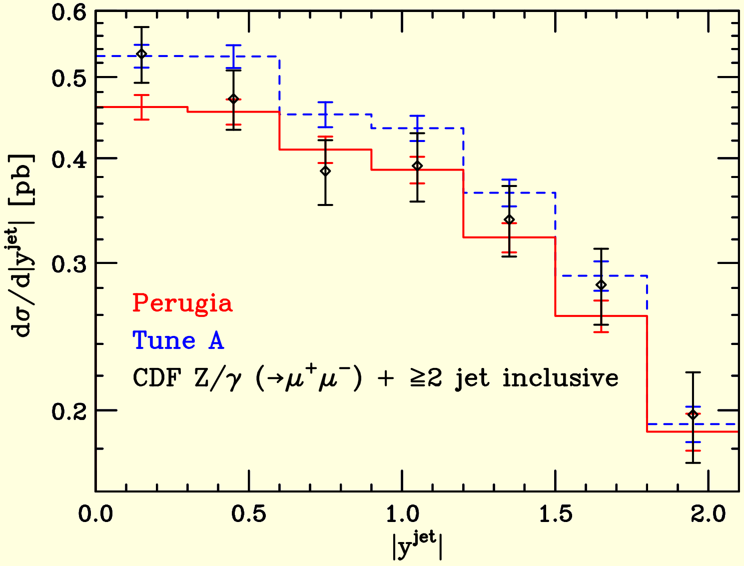
$66\,\text{GeV} < M_{\mu\mu} < 116\,\text{GeV}, \quad p_T^{\mu} > 25\,\text{GeV}, \; |\eta^{\mu}| < 1, \; |y^{\text{jet}}| < 2.1$
$p_T^{\text{jet}} > 30\,\text{GeV}, \quad \Delta R_{\mu,\text{jet}} > 0.7$;




CDF Z/γ ($\rightarrow\mu^+\mu^-$) + ≧1 jet inclusive
Perugia
Tune A
$d\sigma/dp_T^{jet}$ [pb/GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
30
50
70
100
200
300
p_T^{jet} [GeV]


CDF Z/γ ($\rightarrow\mu^+\mu^-$) + ≧2 jet inclusive
Perugia
Tune A
$d\sigma/dp_T^{jet}$ [pb/GeV]
0.01000
0.00500
0.00100
0.00050
0.00010
0.00005
30
50
70
100
200
300
p_T^{jet} [GeV]

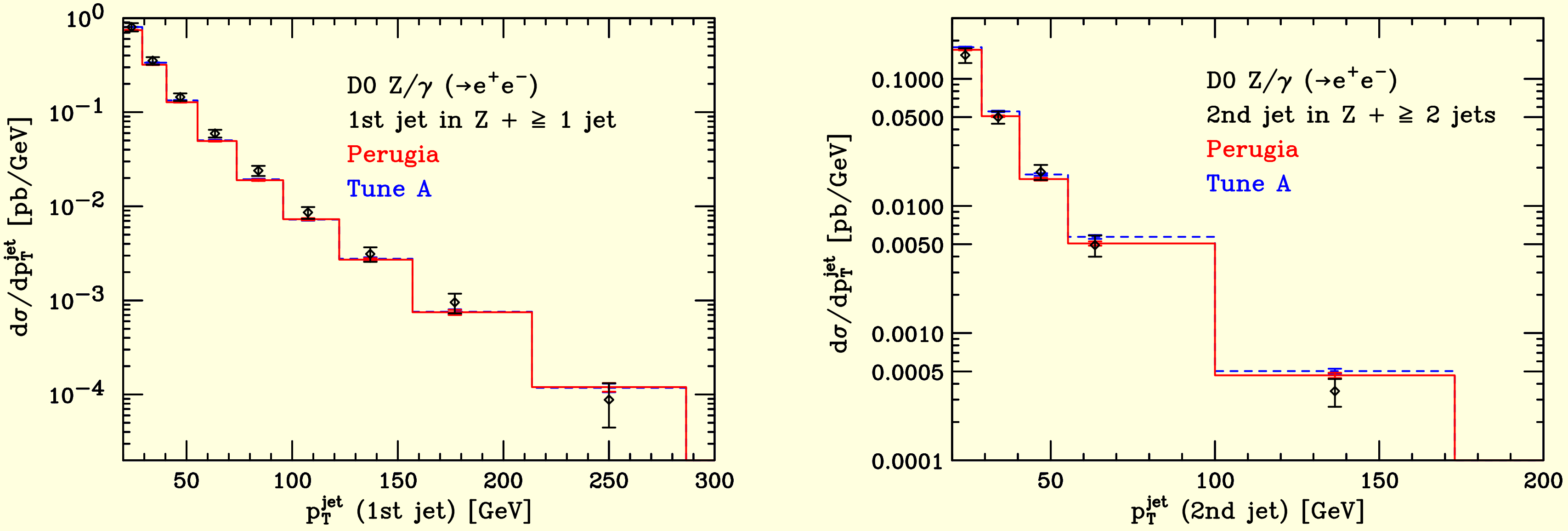

Perugia
Tune A
CDF Z/γ ($\rightarrow\mu^+\mu^-$) + ≧1 jet inclusive
$d\sigma/d|y^{jet}|$ [pb]
3.0
2.0
1.0
0.9
0.8
0.0
0.5
1.0
1.5
2.0
$|y^{jet}|$

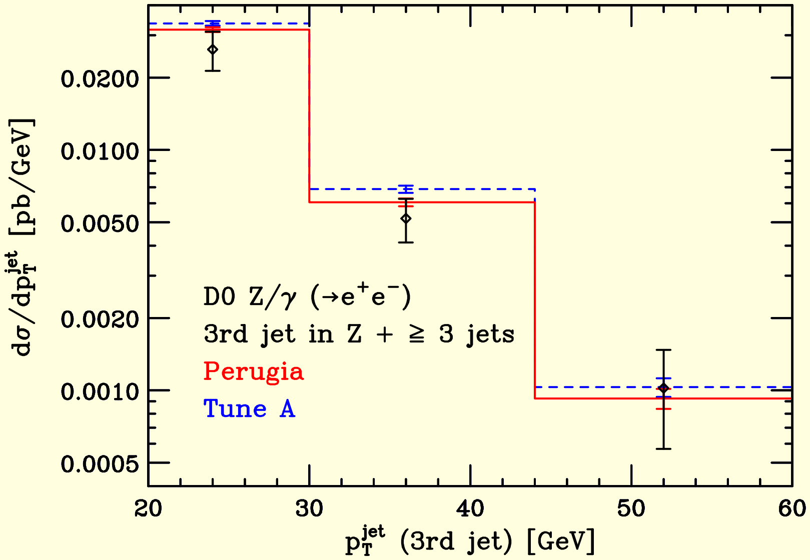

Perugia
Tune A
CDF Z/γ ($\rightarrow\mu^+\mu^-$) + ≧2 jet inclusive
$d\sigma/d|y^{jet}|$ [pb]
0.6
0.5
0.4
0.3
0.2
0.0
0.5
1.0
1.5
2.0
$|y^{jet}|$

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

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

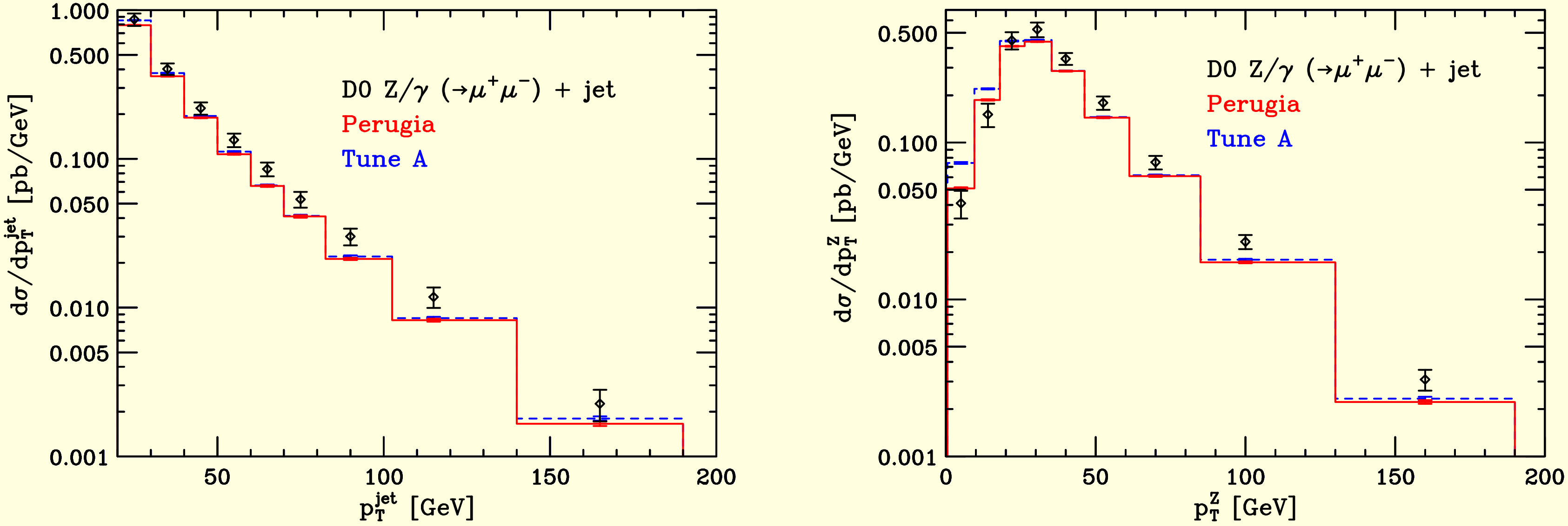
$|y^{\text{jet}}| < 2.5, \quad p_T^{\text{jet}} > 20\,\text{GeV}$

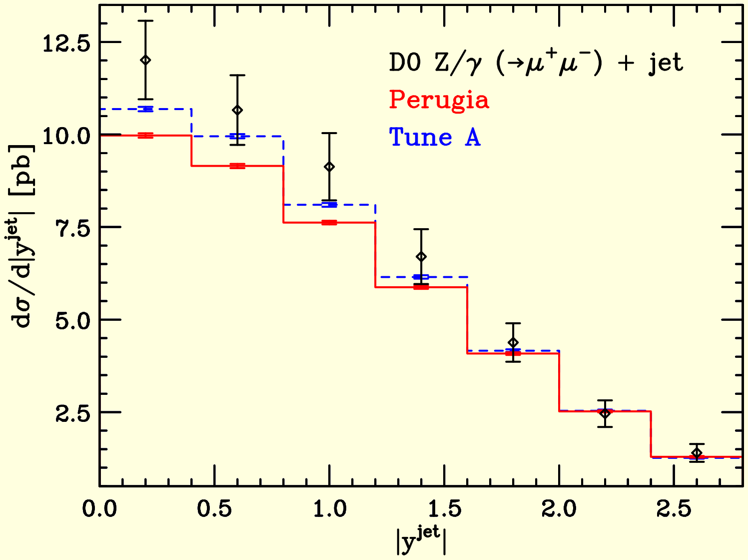


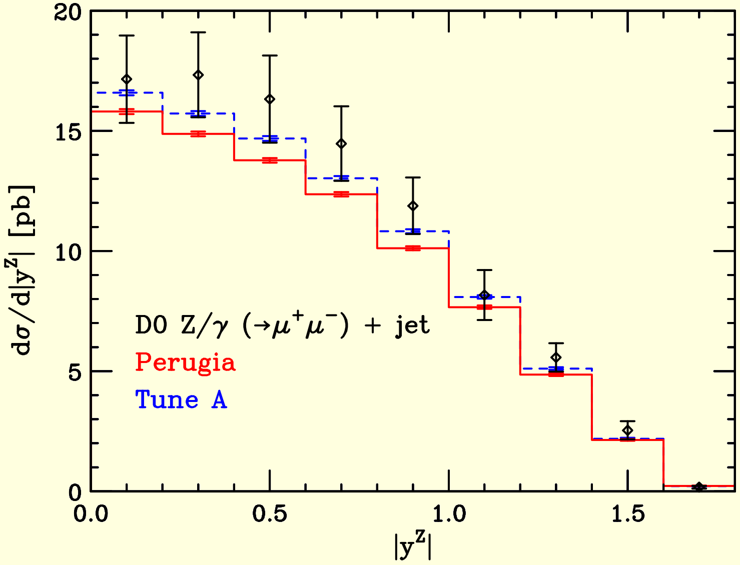

D0 Z/γ (→e⁺e⁻)
3rd jet in Z + ≧ 3 jets
Perugia
Tune A
0.0200
0.0100
0.0050
0.0020
0.0010
0.0005
20
30
40
50
60
dσ/dp_T^jet [pb/GeV]
p_T^jet (3rd jet) [GeV]

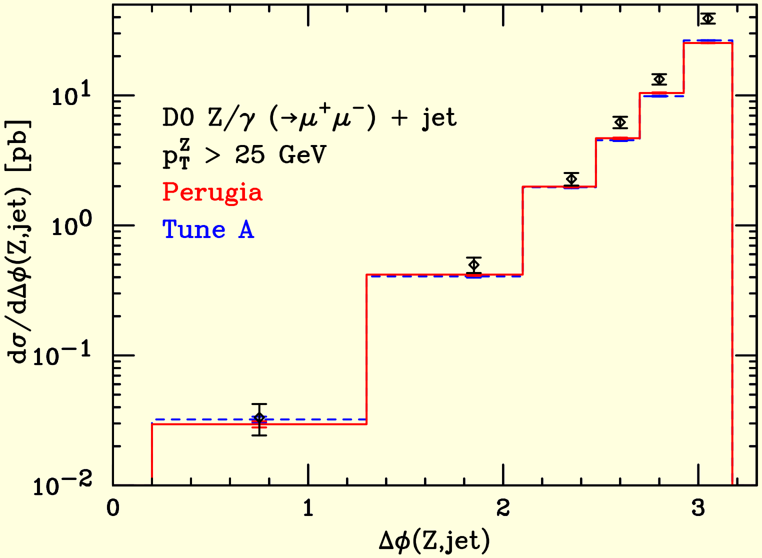
D0 $Z/\gamma(\rightarrow\mu^+\mu^-)+\text{jets}$

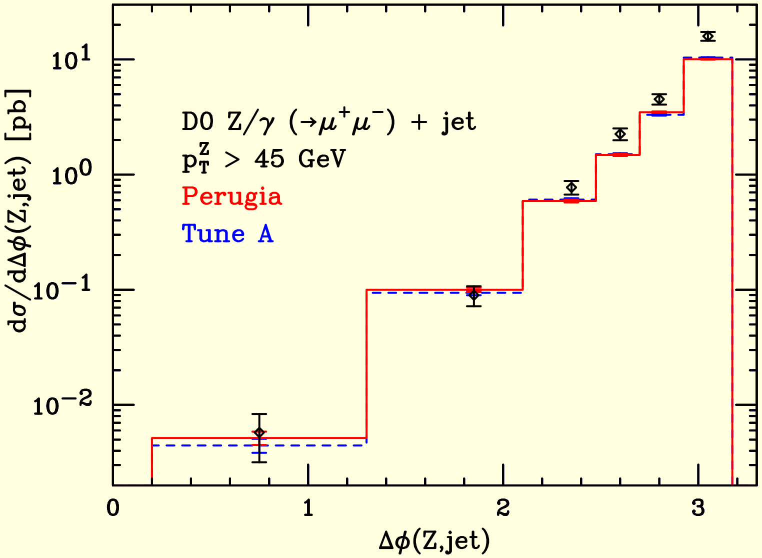
$66\,\text{GeV} < M_{\mu\mu} < 116\,\text{GeV}, \quad p_T^\mu > 25\,\text{GeV}, \; |\eta^\mu| < 1.7,$
$|y^{\text{jet}}| < 2.8, \quad p_T^{\text{jet}} > 20\,\text{GeV}, \quad \Delta R_{\mu,\text{jet}} > 0.5;$




D0 Z/γ (→μ⁺μ⁻) + jet
Perugia
Tune A
dσ/d|y^jet| [pb]
|y^jet|
12.5
10.0
7.5
5.0
2.5
0.0
0.5
1.0
1.5
2.0
2.5


D0 Z/γ (→μ⁺μ⁻) + jet
Perugia
Tune A
dσ/d|y^Z| [pb]
|y^Z|
20
15
10
5
0
0.0
0.5
1.0
1.5


D0 Z/γ (→μ⁺μ⁻) + jet
p_T^Z > 25 GeV
Perugia
Tune A
dσ/dΔφ(Z,jet) [pb]
Δφ(Z,jet)
10^1
10^0
10^−1
10^−2
0
1
2
3


D0 Z/γ (→μ⁺μ⁻) + jet
p_T^Z > 45 GeV
Perugia
Tune A
dσ/dΔφ(Z,jet) [pb]
Δφ(Z,jet)
10^1
10^0
10^−1
10^−2
0
1
2
3

- 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.

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:

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

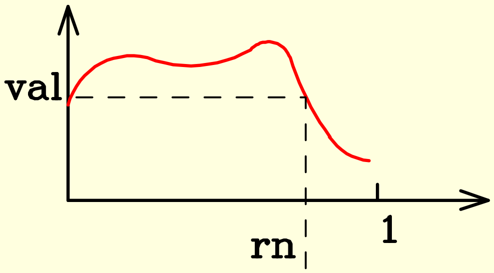
If $\bar{B}$ turns negative, it means that NLO effects are larger than LO effects, and that the whole result is invalid.

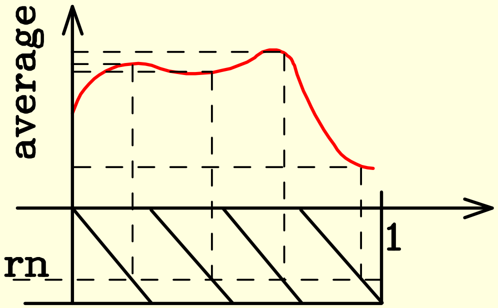
Underlying Born configurations are generated according to the $\bar{B}$ function. What is done in practice is to define a function

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

We generate points in Φ_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:

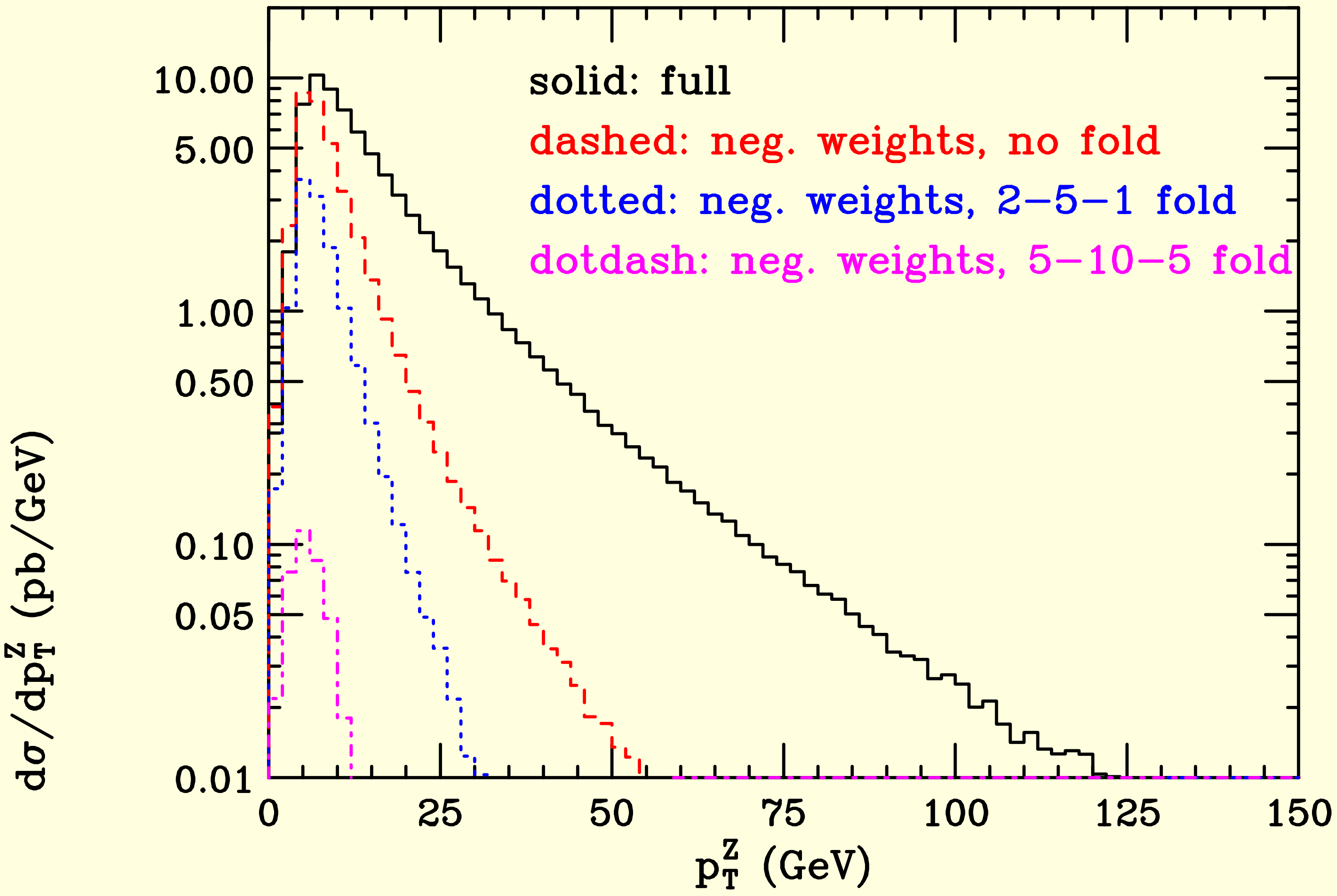




It is clear that, as the number of folds increases, the "folded" $\tilde{B}$ becomes closer to $\bar{B}$, and its negative weigths disappear if $\bar{B}$ is positive.

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

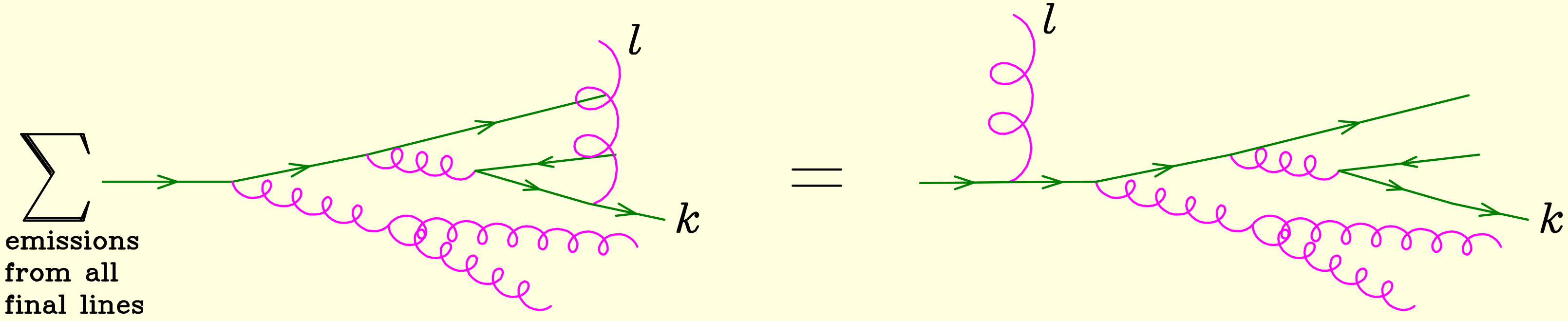
In `POWHEG`, when set up to output negative weights, the results are independent upon folding and the negative weight fraction, whatever folding numbers are used



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 ($1^{\rm st}$ `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