P. Nason, INFN Milano-Bicocca

NLO corrections in parton showers with positive weights

version 2

History and Motivations

SMC programs normally accurate at LL level

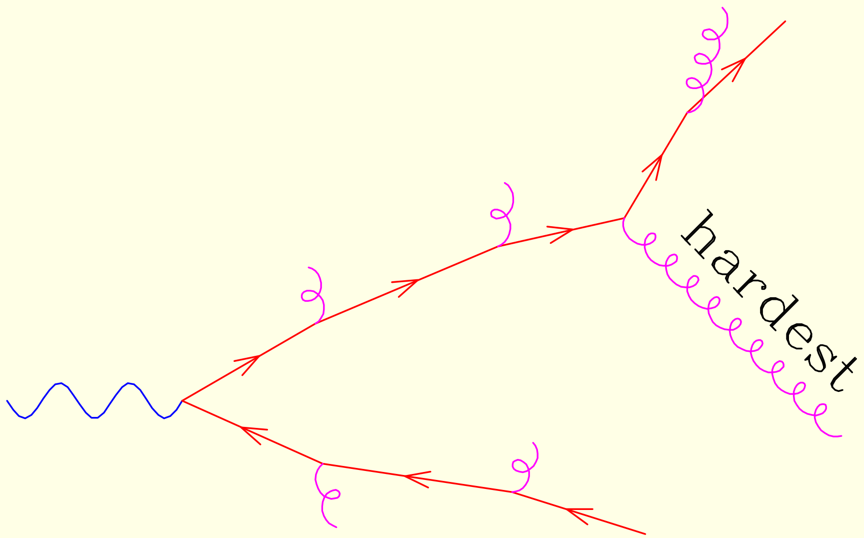
Naturally interfaced to Born processes (i.e. Matrix Element generators)

Many available NLO results for collider processes:

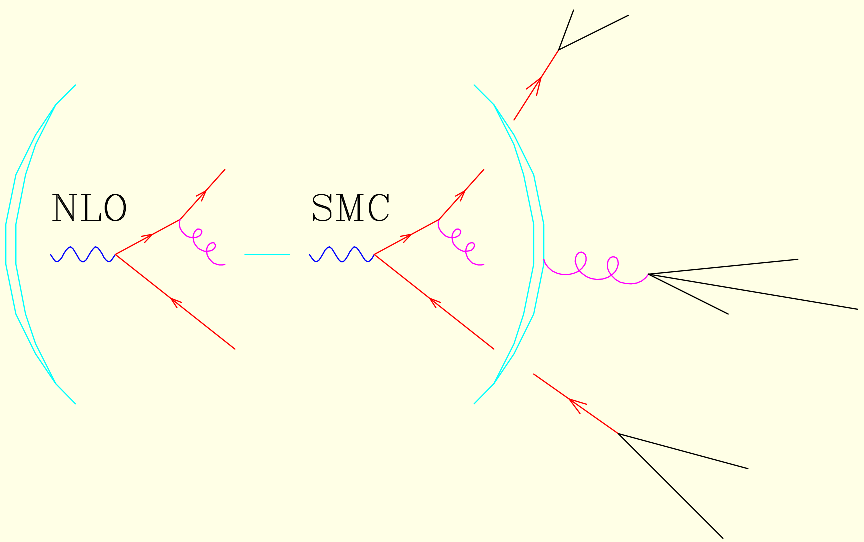
How do we implement them in a SMC program?

Complex overcounting puzzle!!!

MC@NLO solution (2002, Webber+Frixione)

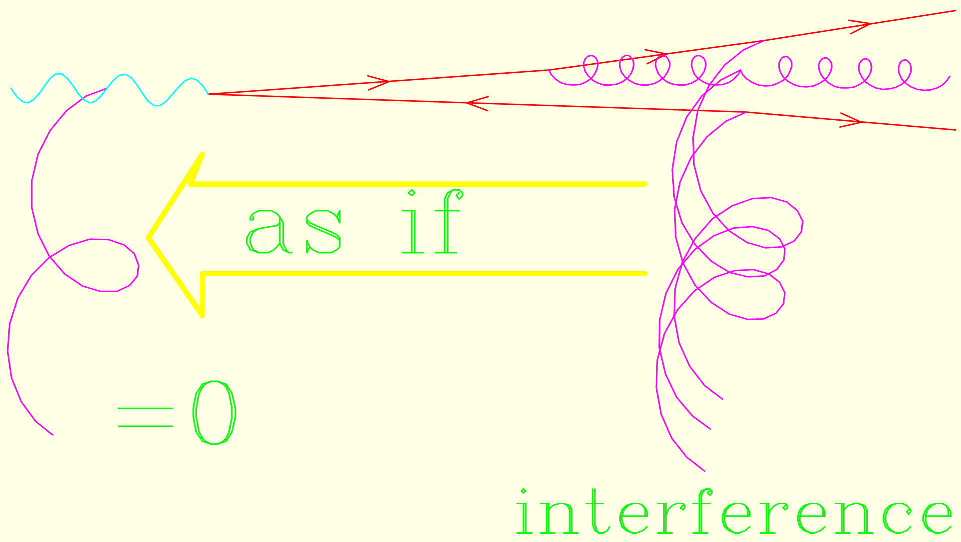


In angular ordered SMC hardest emission not necessarily first; Needs to be corrected according to exact NLO result.



MC@NLO approach: add hard processes initiated according to difference between the exact NLO and the SMC NLO

Difference ⇒ negative weights!!!



Angular ordering accounts for soft gluon interference.
Intensity for “photon” jets $= 0$ instead of $2C_\mathsf{F} + C_\mathsf{A}$.
Intensity for gluon jets: $= C_\mathsf{A}$ instead of $2C_\mathsf{F} + C_\mathsf{A}$.

Consistent with a boosted jet pair, in the case of a photon jet.

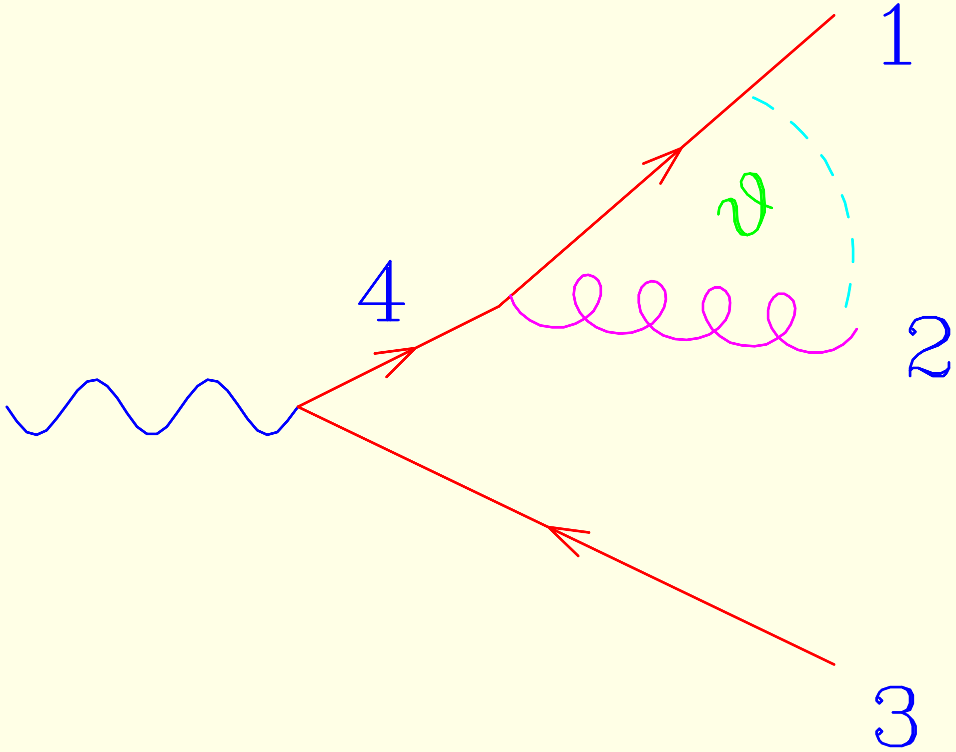
In angular ordered SMC large angle soft emission is generated first
Difficult to correct it explicitly
Hardest emission (i.e. highest p_T) happens later.

Remedy: generate hardest emission first (PN, 2004)

Recipe

- Generate event with harderst emission
- Pair the nearest partons in the event
- Generate all subsequent emissions with a p_{T} veto equal to the hardest emission p_{T}
- Generate an angular ordered shower associated with the paired parton, stopping at the angle of the paired partons
- Generate all subsequent (vetoed) showers

Example: e^+e^-



Generate hardest emission according to NLO calculation.

Nerby partons: $1, 2$

Truncated shower: from $1, 2$ pair, from maximum angle down to θ same colour as 4

Shower from 3: from maximum angle to cutoff

Showers from $1, 2$: from θ to cutoff.

All showers are vetoed at the p_{T} of the $1, 2$ emission.

NLO correction

Typically implemented with the subtraction method

Initial state: Ellis+Ross+Terrano in $e^+e^- \to X$ (1981),

Final state: Mele+Nason+Ridolfi in $h_1 h_2 \to ZZ + X$ (1991)

$$\begin{aligned} d\sigma &= B(p_1 \ldots p_m) d\Phi_m + V(p_1 \ldots p_m) d\Phi_m \\ &+ [R(p_1 \ldots p_{m+1}) d\Phi_{m+1} - C(p_1 \ldots p_{m+1}) d\Phi_{m+1} \mathbb{P}] \end{aligned} \tag{1}$$

where $\mathbb{P}$ defines a soft-collinear insensitive projection of the $m+1$ body final state to an m body final state

Assume that a set of variables v describes the Born process $p_1 \ldots p_m$ and a set v, r describes the real emission process $p_1 \ldots p_{m+1}$ in such a way that

- $\mathbb{P}[p_1 \ldots p_{m+1}](v, r) = [p_1 \ldots p_m](v)$
- $d\Phi_v$ is the Born phase space
- $d\Phi_v, d\Phi_r$ is the Real phase space

The NLO generation of the hardest emission is performed according to

$$d\sigma = \bar{B}(v, \mu_v) d\Phi_v \left[\Delta(v, 0) + \Delta(v, k_T(v, r)) \frac{R(v, r)}{B(v)} d\Phi_r \right],$$

where

$$\bar{B}(v) = B(v) + V(v) + \int d\Phi_r \, [R(v, r) - C(v, r)]$$

$$\Delta(v, p_\mathrm{T}) = \exp\left[-\int \frac{R(v, r)}{B(v)} \theta(k_T(v, r) - p_\mathrm{T}) d\Phi_r \right],$$

and $k_T(v, r)$ is the transverse momentum of the emitted parton.

Behaviour

Notice

$$\int \Delta(v, k_T(v,r)) \frac{R(v,r)}{B(v)} d\Phi_r = \int dp_\mathsf{T} \frac{d\Delta(v,pt)}{dp_\mathsf{T}}$$

So

$$\int d\sigma = \int \bar{B}(v,\mu_v) d\Phi_v$$

For large p_T

$$d\sigma \approx \bar{B}(v) \frac{R(v,r)}{B(v)} \approx R(v,r) \quad \text{up to higher order}$$

For small p_T

$$\Delta(v,p_\mathsf{T}) \approx \exp\left[- \int \frac{\alpha_\mathsf{S}({k_T}^2)}{2\pi} P(z) \theta(k_T(\theta,z) - p_\mathsf{T}) \frac{d\theta^2}{\theta^2} dz \right],$$

same as in Sudakov for standard SMC!

($P(z)$ is the Altarelli-Parisi splitting kernel)

Strategy

SMC's to do final showering already exist
Most of them implement a p_T veto
Most of them comply with a standard interface to hard process
(so called Les Houches interface, LHI from now on).
So!

- Construct a generator for the hardest event
  INDEPENDENT from specific SMC's implementations
  Output on LHI

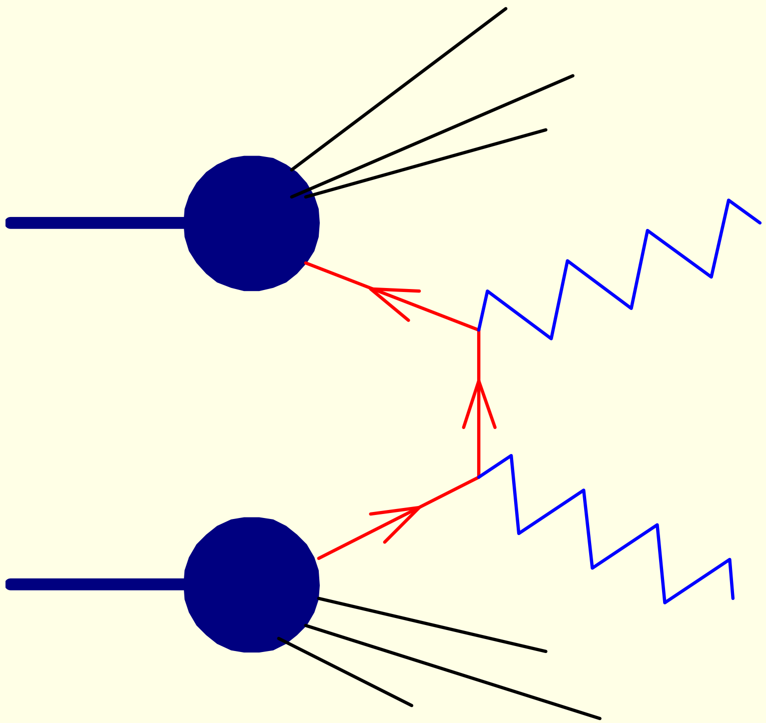
- Construct a generator capable to add truncated showers
  to events from the LHI
  Output again on LHI

- Use standard SMC to perform the p_T vetoed final shower
  from the event on LHI.

Three independent items! Several solutions possible by different research groups
(Ongoing work with S. Frixione and G. Ridolfi).

First example: ZZ production in hadron collisions

(with G. Ridolfi)



NLO process known (Ridolfi, P.N.)
Intermediate complexity
Hadrons in initial state
Similar to WZ,WW and $Q\bar{Q}$
(Mangano, Ridolfi, Frixione, P.N.).

Treatment of initial state radiation similar in ZZ, WZ, WW and $Q\bar{Q}$ case;
Same used in Frixione-Kunszt-Signer general subtraction method.

v and r variables

v variables: choose Mzz, Yqq and θ as, where

- M_{ZZ}: invariant mass of the ZZ pair
- Y_{ZZ}: rapidity of ZZ pair
- θ: go in the (longitudinally) boosted frame where $Y_{ZZ} = 0$.
  go to the ZZ rest frame with a transverse boost
  In this frame θ is the angle of a Z to the beam direction.

r variables:

- $x = M_{ZZ}/s$, where s is the invariant mass of the incoming parton system
  Thus $1 - x$ is the fraction of energy lost by radiation of a soft parton
- y: cosine of the angle of the radiated parton to the beam direction in the partonic CM frame.
- ϕ: radiation azimuth.

Few tricks to do it

$$\bar{B}(v) = B(v) + V(v) + \int d\Phi_r \; [R(v,r) - C(v,r)]$$

Seems to need one r integrations to get weight of each v point.

In fact, write

$$\tilde{B}(v,r) = N[B(v) + V(v)] + R(v,r) - C(v,r)\,, \qquad N = \frac{1}{\int d\Phi_r}\;.$$

so that

$$\bar{B}(v) = \int \tilde{B}(v,r) d\Phi_r\;.$$

Use standard procedures (SPRING-BASES, Kawabata)
to generate unweighted events for $\tilde{B}(v,r) d\Phi_r\, d\Phi_v$.
discard r (same as integrating over it!).

$$\Delta(v, p_\mathrm{T}) = \exp\left[-\int \frac{R(v,r)}{B(v)}\theta(k_T(v,r) - p_\mathrm{T}) d\Phi_r\right] ,$$

Look for an upper bounding function;

$$\frac{R(v,r)}{B(v)} \leq U(v) = N \frac{\alpha_S(k_T)}{(1-x)(1-y^2)}$$

Generate x, y according to

$$\exp\left[-\int N \frac{\alpha_S(k_T)}{(1-x)^2(1-y^2)}\theta(k_T(v,r) - p_\mathrm{T}) d\Phi_r\right] \tag{2}$$

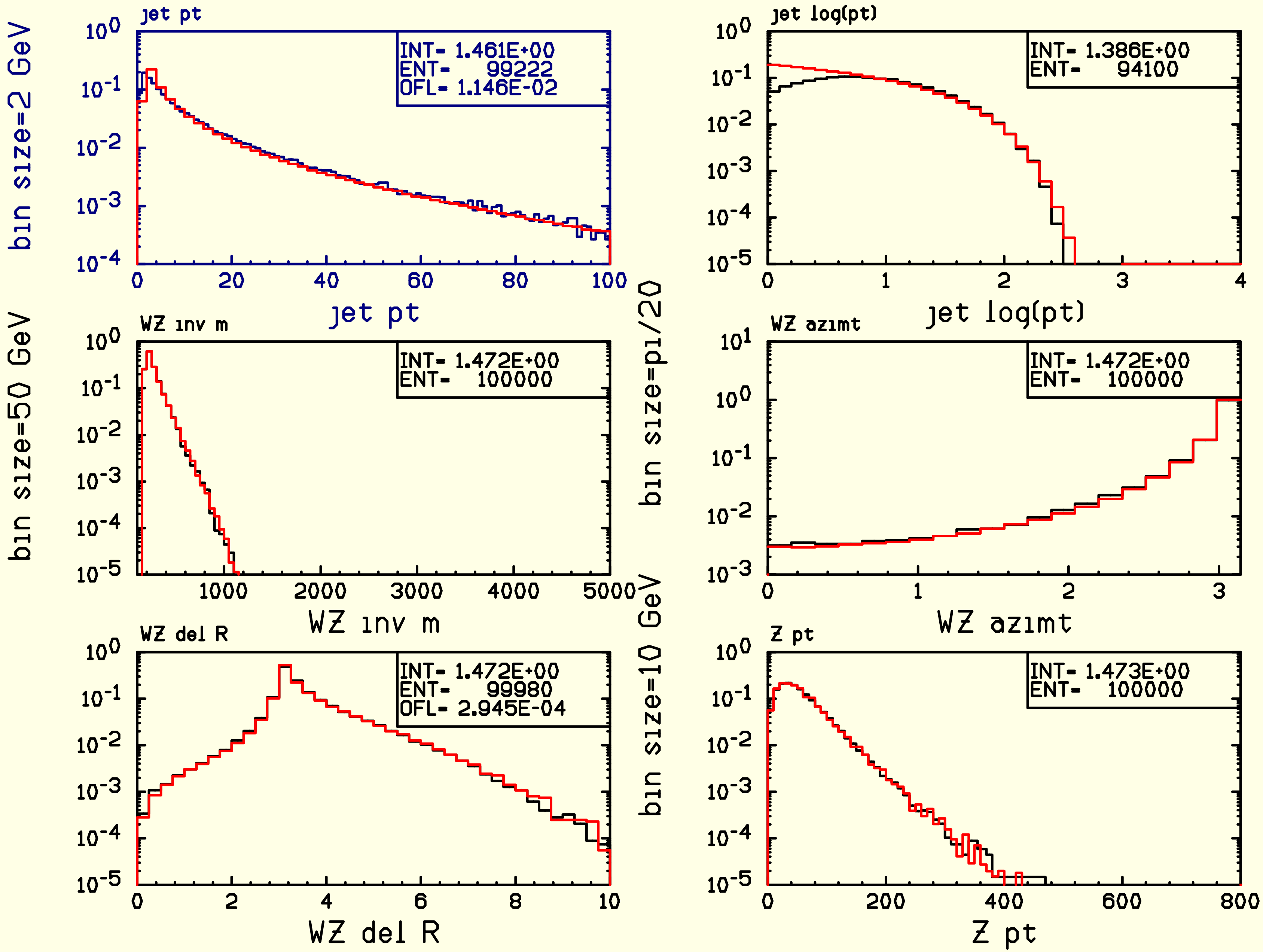
accept the event with a probability

$$\frac{R(v,r)}{B(v)U(v)} .$$

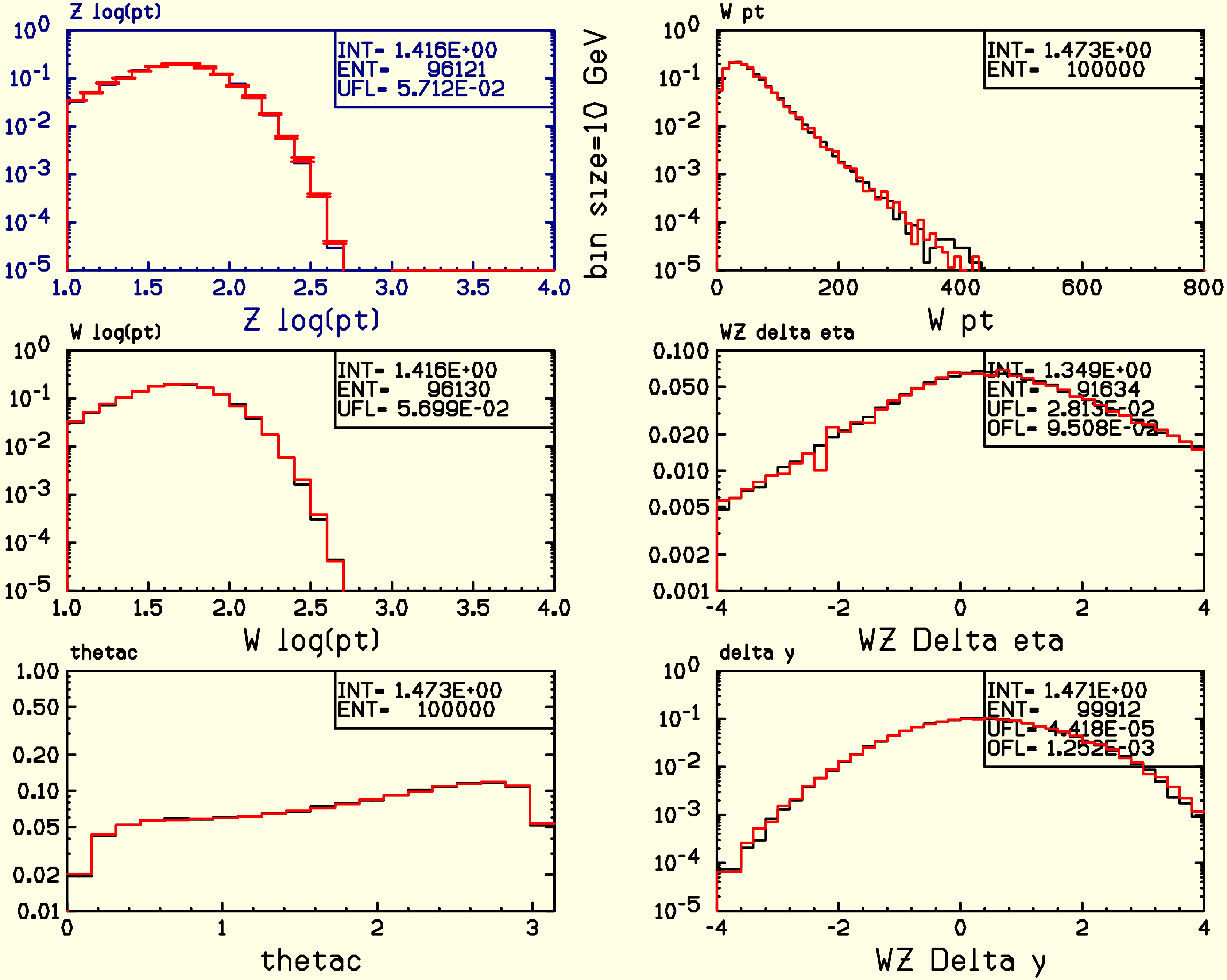
If the event is rejected generate a new one for smaller p_T, and so on (This procedure reconstructs the exact emission probability).

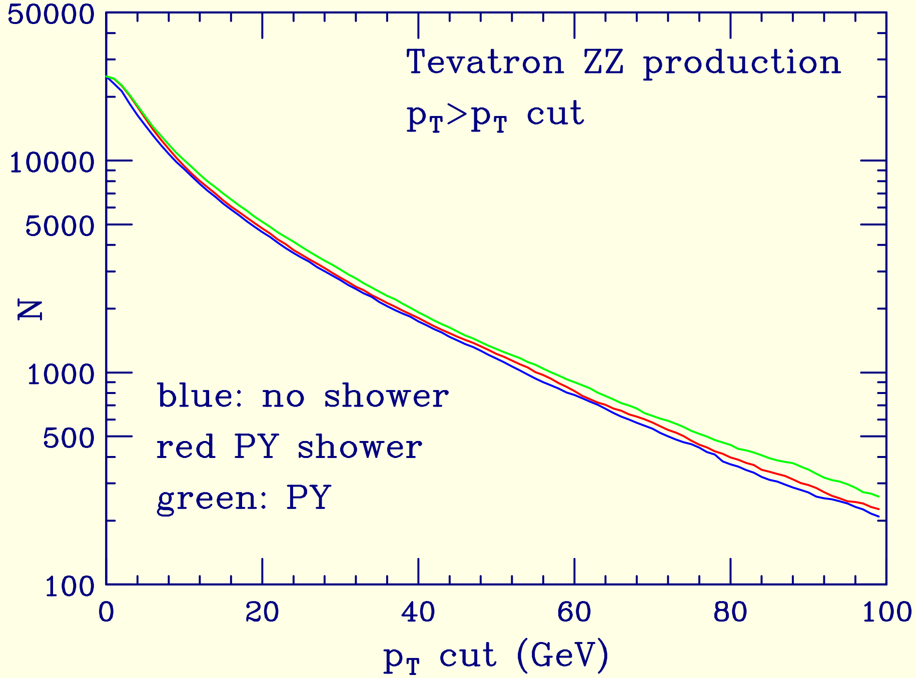
In the ZZ case, an event is generated with about six calls ro $R(v,r)$.

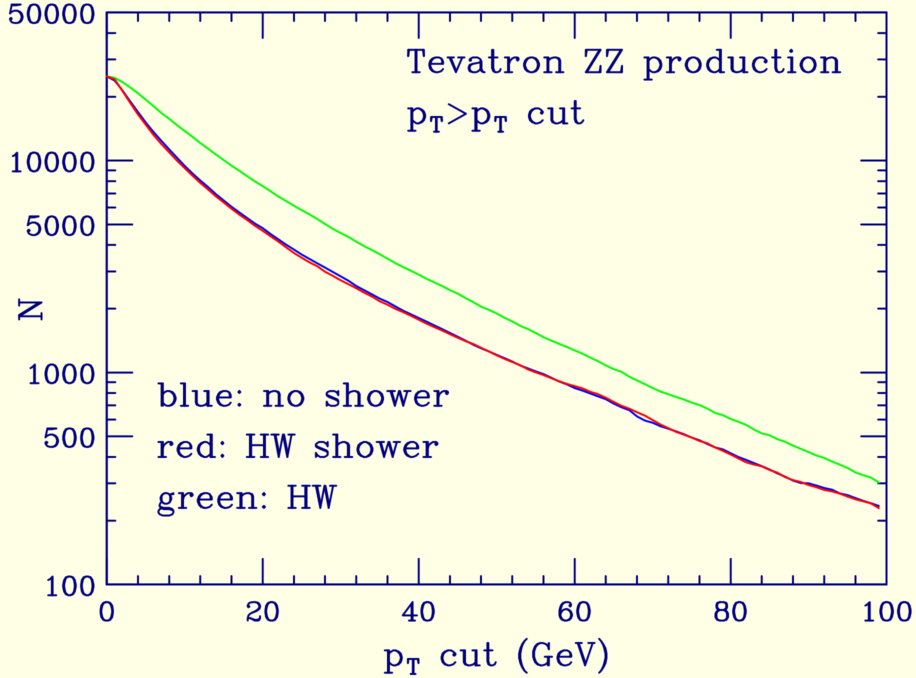
Compare to fixed order NLO (red histograms)



Compare to fixed order NLO (red histograms)

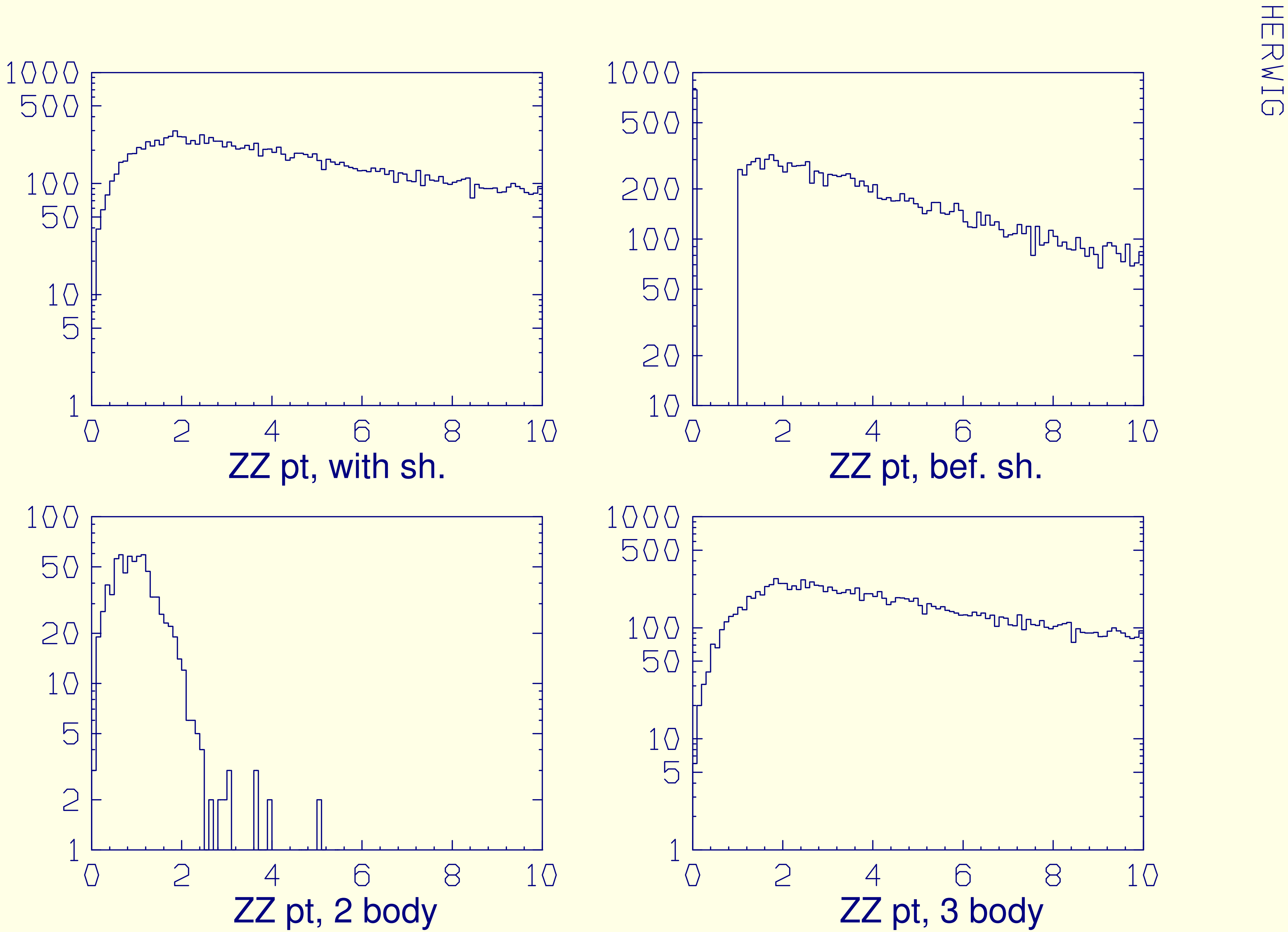


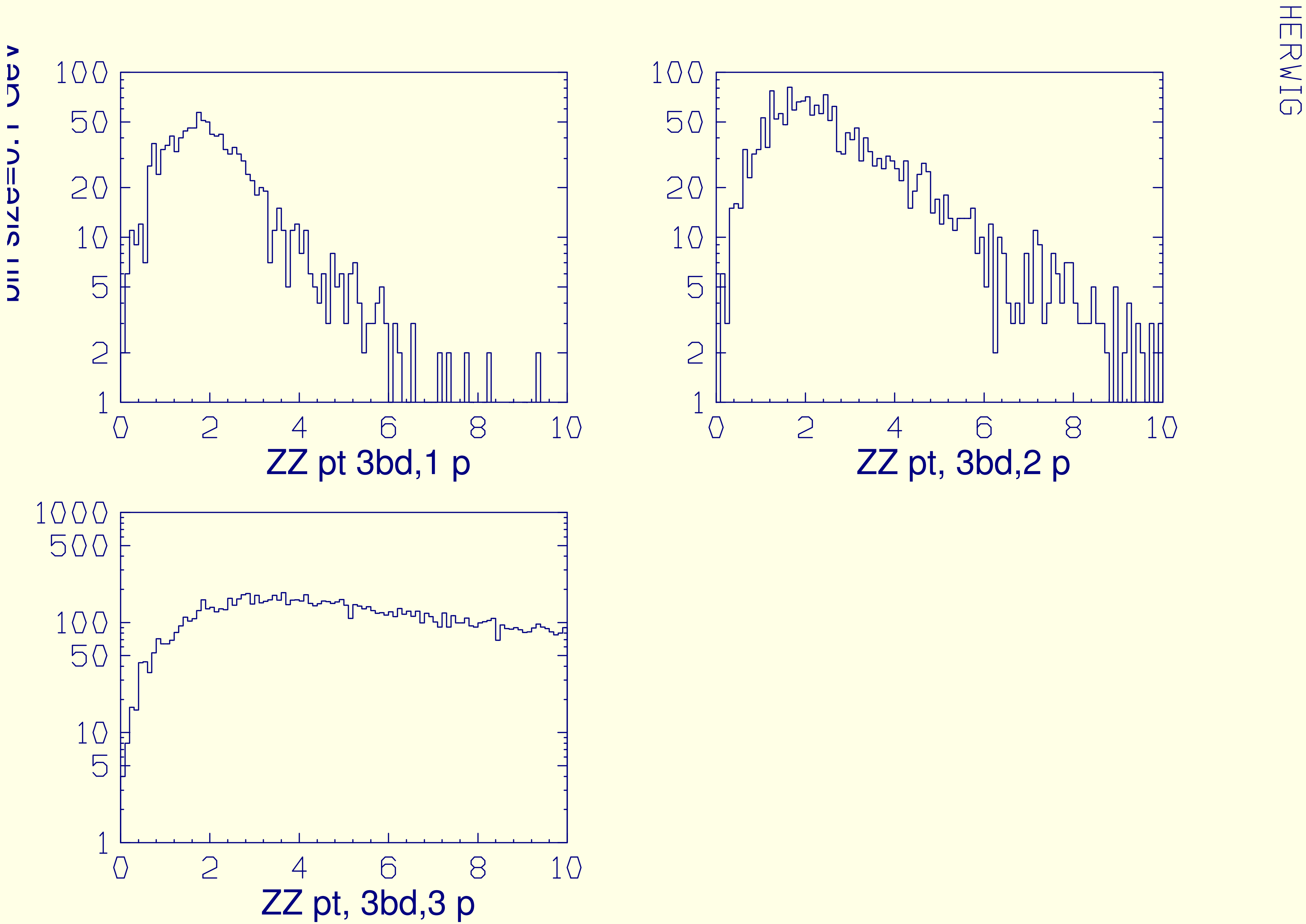


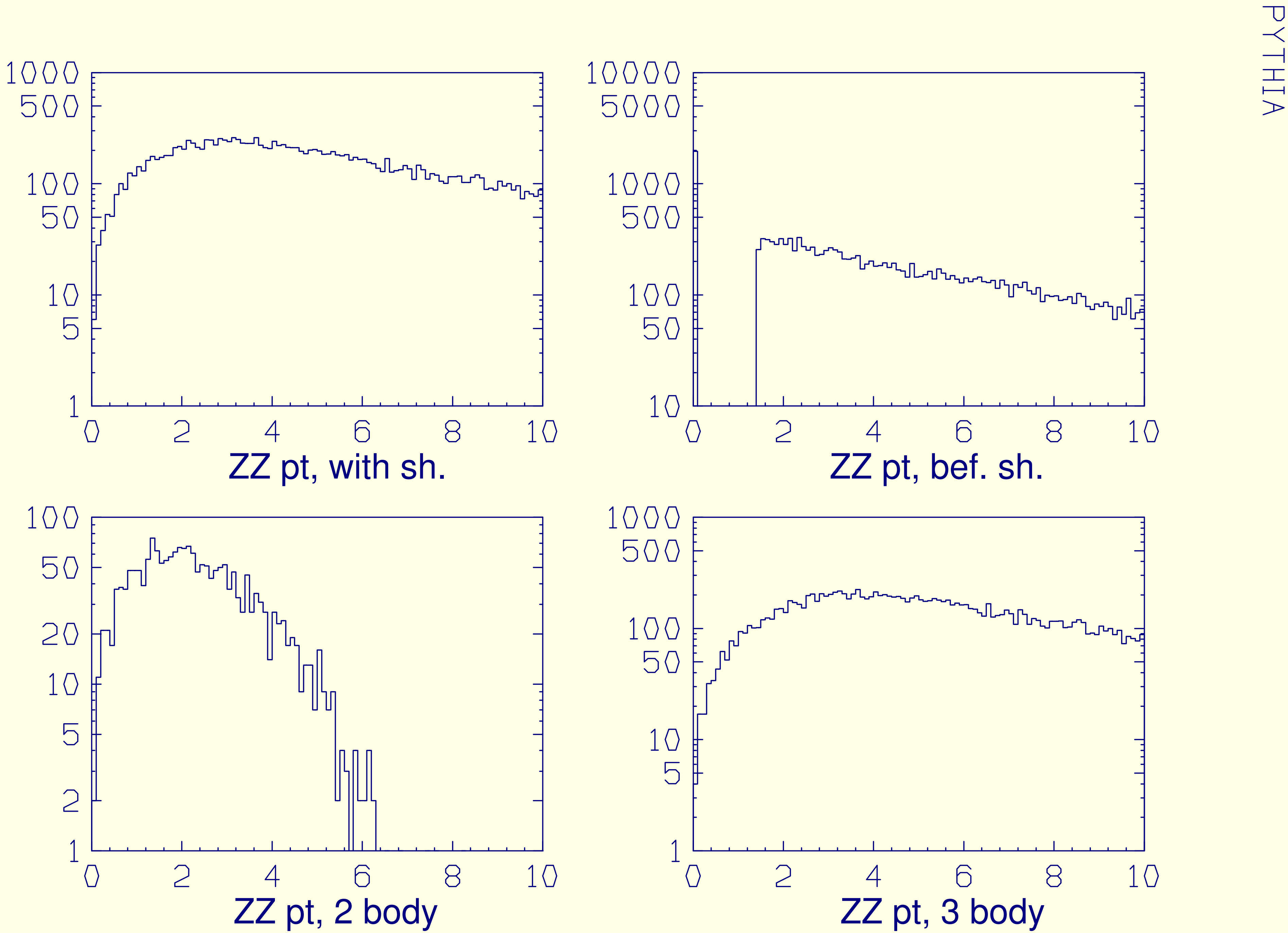


Focus upon p_T spectrum now (interface tuning). Default MC parameters

(NOT TO BE USED TO DRAW CONCLUSIONS ABOUT SMC'S!)


HERWIG
ZZ pt, with sh.
ZZ pt, bef. sh.
ZZ pt, 2 body
ZZ pt, 3 body


ZZ pt 3bd,1 p
ZZ pt, 3bd,2 p
ZZ pt, 3bd,3 p
HERWIG


PYTHIA
ZZ pt, with sh.
ZZ pt, bef. sh.
ZZ pt, 2 body
ZZ pt, 3 body

Conclusions

- Proof of concept: MC+NLO with positive weight possible and easy
- Final state radiation easy; Initial state radiation presents no problems
- Interface to different SMC's under studies
- Formulation of general method for NLO processes under work
- Truncated shower: interesting topic to develop