Mauro Moretti
Dip. di Fisica, Univ. di Ferrara
INFN Sezione di Ferrara

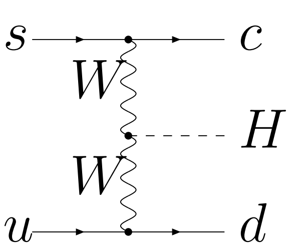
Studies of Higgs production through Weak Boson Fusion at the LHC

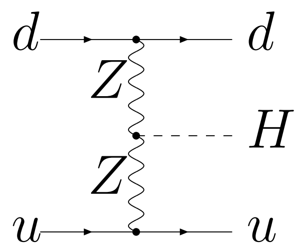
in collaboration with
the ALPGEN team (M.L. Mangano, F. Picinini, R. Pittau, A.D. Polosa)
V. Del Duca and D. Zeppenfeld

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

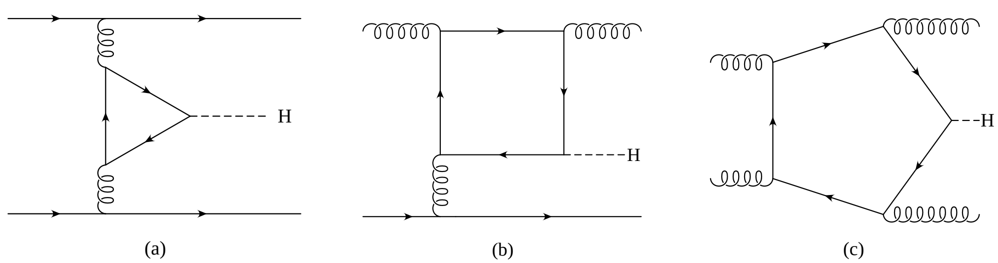
Weak Boson Fusion will be an important channel for Higgs boson search at LHC and even more for the determination of its couplings to fermions and gauge bosons

Typical signature: $H + 2$ forward jets





Another possible contribution is Higgs production through gluon fusion with two additional jets, which is at one loop perturbative order but important because of $\mathcal{O}(\alpha_s)^4$ against $\mathcal{O}(\alpha_w^2)$ of WBF



V. Del Duca et al., *Phys. Rev. Lett.* 87 (2001) 122001

Since QCD $H + 2$ jets is a background to WBF for Higgs coupling studies, it is important to study the features of the two different processes

What is available in the literature:

- WBF at QCD NLO

  T. Han, G. Valencia and S. Willenbrock, *Phys. Rev. Lett.* 69 (1992) 3274
  T. Figy, C. Oleari and D. Zeppenfeld, Phys. Rev. **D68** (2003) 073005

- QCD production of $H + 2$ jets at LO in the limit $m_t \to \infty$ and keeping the complete m_t dependence

  V. Del Duca et al., *Phys. Rev. Lett.* 87 (2001) 122001
  V. Del Duca et al., Nucl. Phys. **B616** (2001) 367
  V. Del Duca et al., Phys. Rev. **D67** (2003) 073003

- LO calculation of $pp \to H + 3$ jets in the limit $m_t \to \infty$

  V. Del Duca, A. Frizzo and F. Maltoni, JHEP **0405** (2004) 064

- very recent calculation of virtual corrections to $H + 4$ parton processes, essential ingredient for the calculation of NLO corrections to $pp \to H + 2$ jets

  K. Ellis, W. Giele and G. Zanderighi, hep-ph/0506196

The parton level analysis carried out so far show particular features (such as a correlation in $\Delta\phi_{jj}$ between the tagging jets, see below) allowing to distinguish between WBF and gluon fusion production

On the other hand the picture could be changed once the higher order QCD radiation effects are taken into account. This is what has been found in the analysis by

K. Odagiri, JHEP **03030** (2003) 009

where the final state $H + 2$ jets has been generated starting from the kernel process $gg \rightarrow H$ and adding QCD radiation with `HERWIG` Parton Shower, i.e. neglecting exact matrix elements for hard QCD radiation

The situation can be improved if the combined information of matrix elements and Parton Shower can be used. This can be done for instance with the help of the `ALPGEN` event generator

M.L. Mangano, M. Moretti, F. P., R. Pittau, A.D. Polosa, JHEP **0307** (2003) 001

In `ALPGEN v2.0` the effective coupling ggH in the limit $m_t \to \infty$ has been implemented at the Lagrangian level

M.A. Shifman, A.I. Vainshtein, M.B. Voloshin and V.I. Zakharov, Sov. J. Nucl. Phys **30** (1979) 711

J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. **B106** (1976) 292

This approximation has been shown to be very good for m_H and $p_j^T < m_t$

V. Del Duca et al., *Phys. Rev. Lett.* 87 (2001) 122001

V. Del Duca et al., Phys. Rev. **D67** (2003) 073003

The process $pp \to H + N$ jets ($N < 8$, only processes with up to 4 quarks) has been introduced (and interfaced to the Parton Shower) with exact LO QCD matrix elements for up to N additional partons

Our aim is to study the effects of higher order QCD radiation (and eventually hadronisation) with the `HERWIG` Parton Shower on top of parton level events of the form $pp \to H + 2$ jets and $pp \to H + 3$ generated with `ALPGEN`

$m_H = 120$ GeV

Event selection:

$$p_\perp^{j_{1,2}} \geq 30 \text{ GeV}, \quad p_\perp^{j_n} \geq 20 \text{ GeV}, \ (n > 2) \quad |\eta_j| \leq 5, \quad R_{jj} \geq 0.6$$
$$|\eta_{j1} - \eta_{j2}| \geq 4.2, \quad \eta_{j1} \cdot \eta_{j2} \leq 0, \quad M_{j_1 j_2} \geq 600 \text{ GeV}$$

PDF set: CTEQ5L

- jets are ordered in $p_\perp$ ($p_\perp^{j_n} > p_\perp^{j_{n+1}}$)
- cuts are applied at the level of reconstructed jets
- when partonic level plots are shown cuts are applied to partons

Scales (affecting much more QCD Higgs productions than WBF):

$$\alpha_s^{2+N\text{jets}}(\mu_R) \to \alpha_s^2(M_H)\Pi_i\alpha_s(p_i^T) \qquad \mu_F = (\Pi_i p_i^T)^{(1/N)} \qquad (1)$$

Jets defined according to the routine `GETJET` (cone algortihm), which uses a simplified version of the UA1 jet algorithm.

The following plots are obtained from *two different samples* analized with *the same cuts at the level of reconstructed jets*

- sample $\mathcal{S}_1$

$$p_\perp^{j_{1,2}} \geq 30 \text{ GeV}, \quad p_\perp^{j_n} \geq 20 \text{ GeV}, \ (n > 2) \quad |\eta_j| \leq 5, \quad R_{jj} \geq 0.6$$
$$|\eta_{j1} - \eta_{j2}| \geq 4.2, \quad \eta_{j1} \cdot \eta_{j2} \leq 0, \quad M_{j_1 j_2} \geq 600 \text{ GeV}$$

- sample $\mathcal{S}_2$

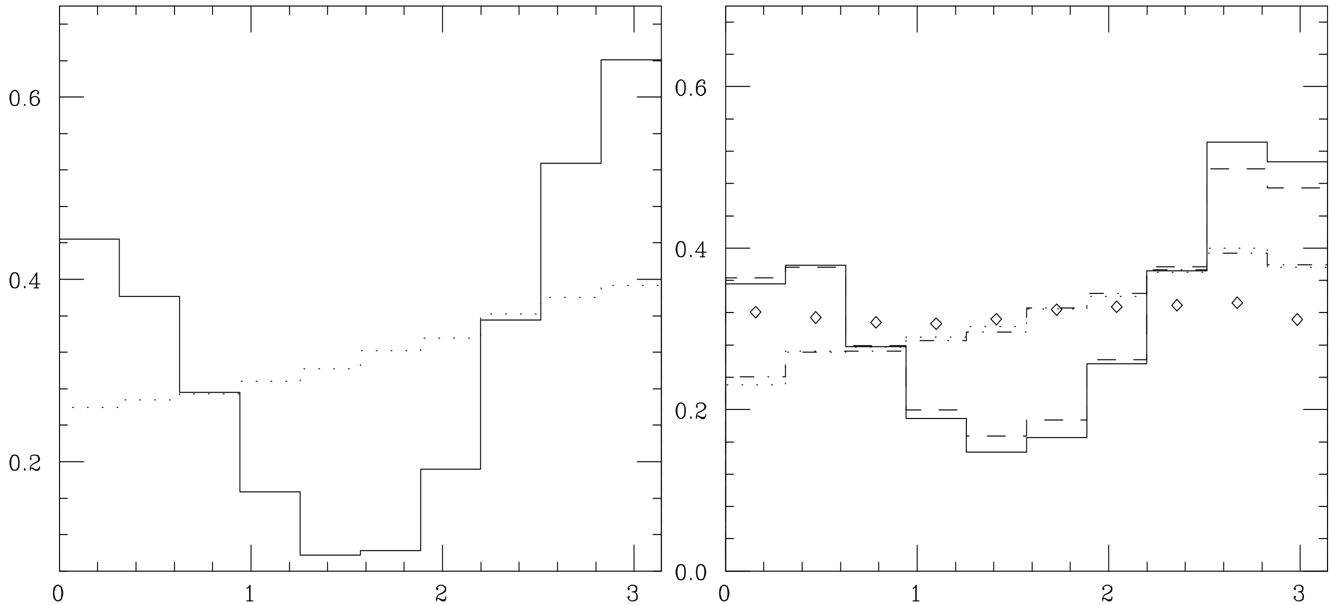
$$p_\perp^{j_{1,2}} \geq 15 \text{ GeV}, \quad p_\perp^{j_n} \geq 10 \text{ GeV}, \ (n > 2) \quad |\eta_j| \leq 5, \quad R_{jj} \geq 0.3$$
$$|\eta_{j1} - \eta_{j2}| \geq 3.2, \quad \eta_{j1} \cdot \eta_{j2} \leq 0, \quad M_{j_1 j_2} \geq 500 \text{ GeV}$$

In the analisys which follows we shall refer to jets. To be more precise these are cluster (cone algorithm, routine GETJET) of partons after the shower. Neither adronization or beam soft activity are included.

We shall discuss a number of issues crucial in identifying WBF-like events.

- Azimuthal correlation among the two tagging jets (to discriminate among ggH and WBF events; in ggH events this is important on its own to pick up the CP nature of the higgs boson)
- Rapidity distribution of extra jets
- Production of additional jets
- Impact of the shower on this very exclusive event selection (strong impact on “acceptance”).
- Rapidity gap (implying a careful handling of matching procedure)

Azimuthal correlation between the tagging jets

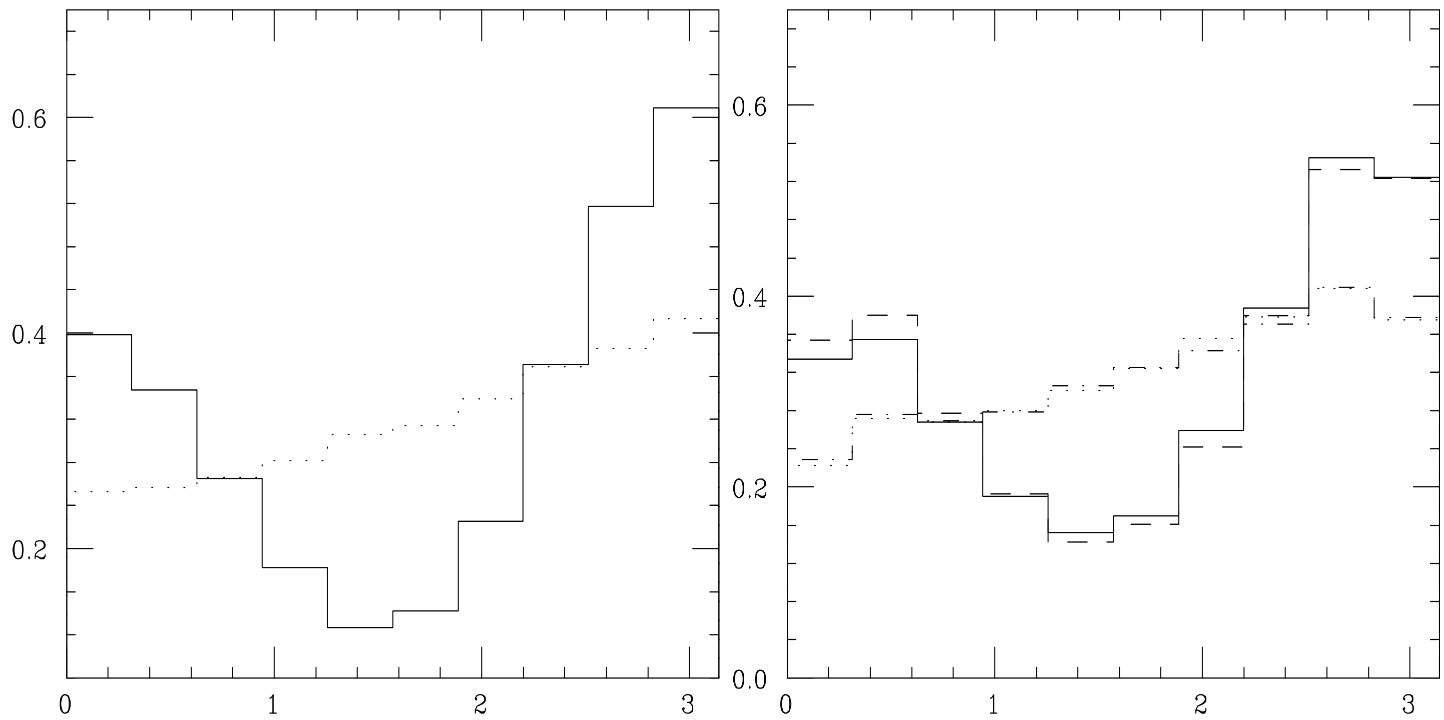


Left: $\frac{1}{\sigma}d\sigma/d\phi_{jj}$ distribution at LO partonic level for the process $pp \to H + 2$ jets.
Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma}d\sigma/d\phi_{j_1 j_2}$ distribution with Parton Shower (j_1 and j_2 are the leading p_T jets) on top of $pp \to H + 2$ jets generated events. Solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$, diamonds: Parton Shower on top of $pp \to H$

- parton shower radiation complitely misses azimuthal correlation
- the *shape* of azimuthal distribution is *independent* from cuts at the event geration level

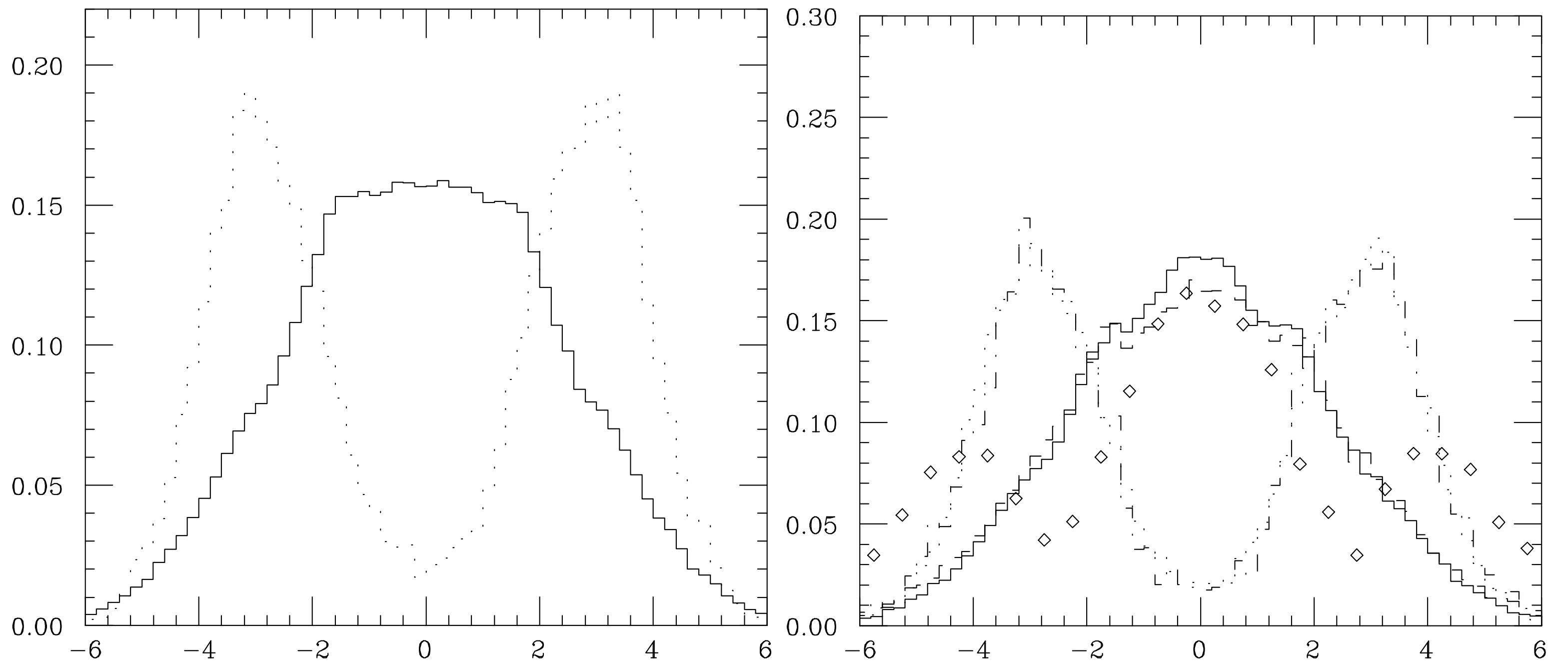
Azimuthal correlation between the tagging jets



Left: $\frac{1}{\sigma} d\sigma/d\phi_{jj}$ distribution at LO partonic level for the process $pp \to H + 3$ jets.
Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma} d\sigma/d\phi_{j_1 j_2}$ distribution with Parton Shower (j_1 and j_2 are the leading p_T jets) on top of $pp \to H + 3$ jets generated events. Solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$.

The presence of additional hard radiation doesn't change the $\Delta\phi_{jj}$ azimuthal correlation



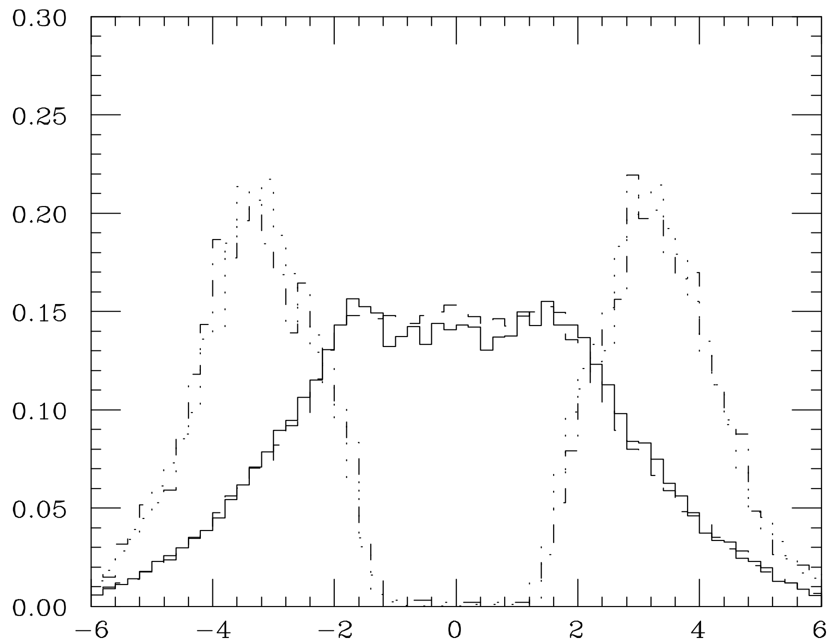
Left: $\frac{1}{\sigma} d\sigma / dy_{\rm rel}$ distribution at LO partonic level for the process $pp \to H + 3$ jets. Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma} d\sigma / dy_{\rm rel}$ distribution with Parton Shower on top of $pp \to H + 3$ jets generated events. Solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$, diamonds: Parton Shower on top of $pp \to H$

$$y_{\rm rel} = y_3 - (y_1 + y_2)/2$$

- shape not much affected by showering effects
- shape independent from cuts at the generation level

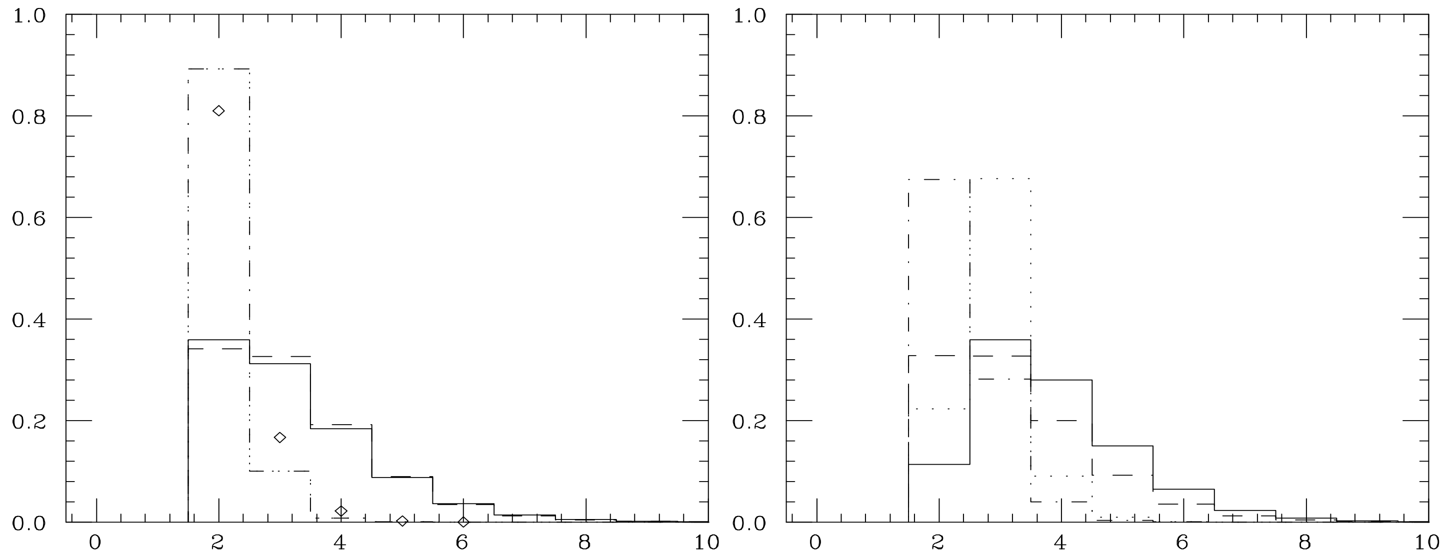
Rapidity gaps survival: central-jet veto



Left: $\frac{1}{\sigma} d\sigma/dy_{\rm rel}$ distribution with Parton Shower on top of $pp \to H + 2$ jets generated events; Solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$, diamonds: Parton Shower on top of $pp \to H$

- again shape independent from cuts at the generation level
- the shape (as well as the *amount*) of third jet rapidity strongly discriminates among ggH and WBF

Jet multiplicity

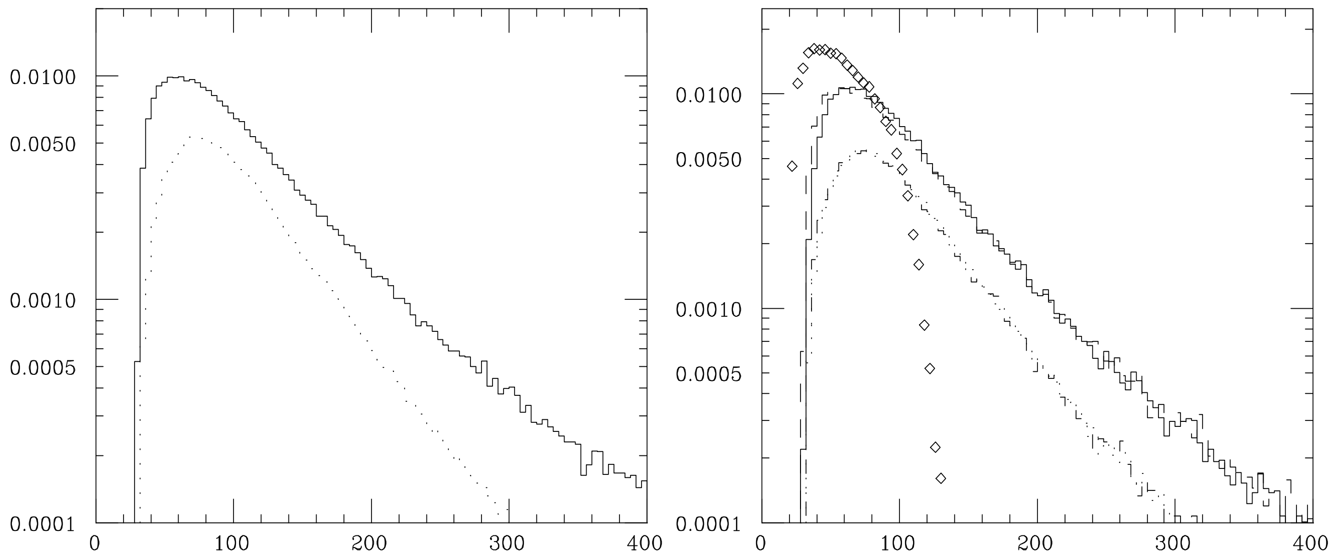


Left: $\frac{1}{\sigma}d\sigma/dn_{\text{jets}}$ distribution with Parton Shower on top of $pp \longrightarrow H + 2$ jets generated events. Solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$, diamonds: Parton Shower on top of $pp \rightarrow H$

Right: $\frac{1}{\sigma}d\sigma/dn_{\text{jets}}$ distribution with Parton Shower on top of $pp \longrightarrow H + 3$ jets generated events

- While in WBF the number of jets is peaked at the number of final-state partons, a larger jet activity is present in gg fusion events.
- jet activity is strongly dependent from generation level cuts (recall that the cuts applied to to reconstructed jets are the same for both data sample)

Leading p_T

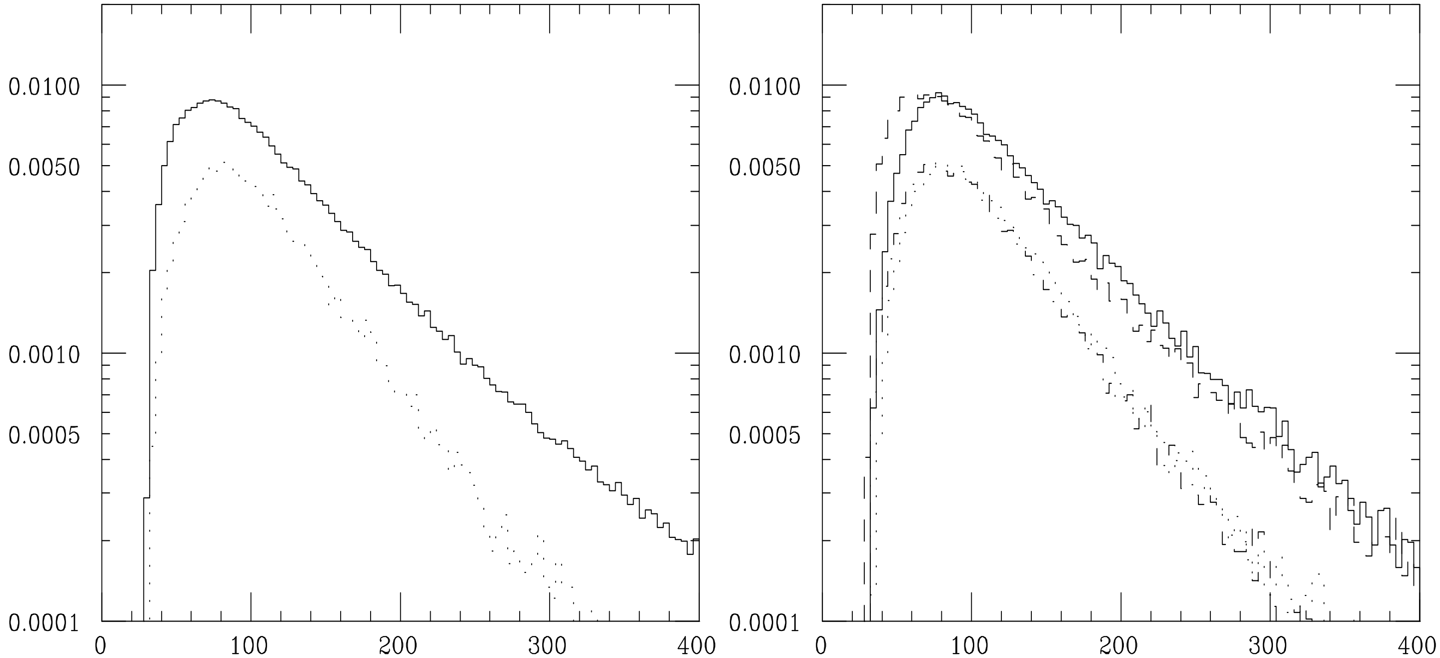


Left: $\frac{1}{\sigma} d\sigma / dp_1^T$ distribution at parton level of $pp \rightarrow H + 2$ jets generated events
Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma} d\sigma / dp_1^T$(/2 for WBF) distribution with Parton Shower on top of $pp \rightarrow H + 2$ jets generated events; solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$, diamonds: Parton Shower on top of $pp \rightarrow H$

- Distributions for WBF and QCD Higgs production similar, without much distorsion due to the radiation.
- If the jets come only from the shower the p_T distribution is very different.

Leading p_T

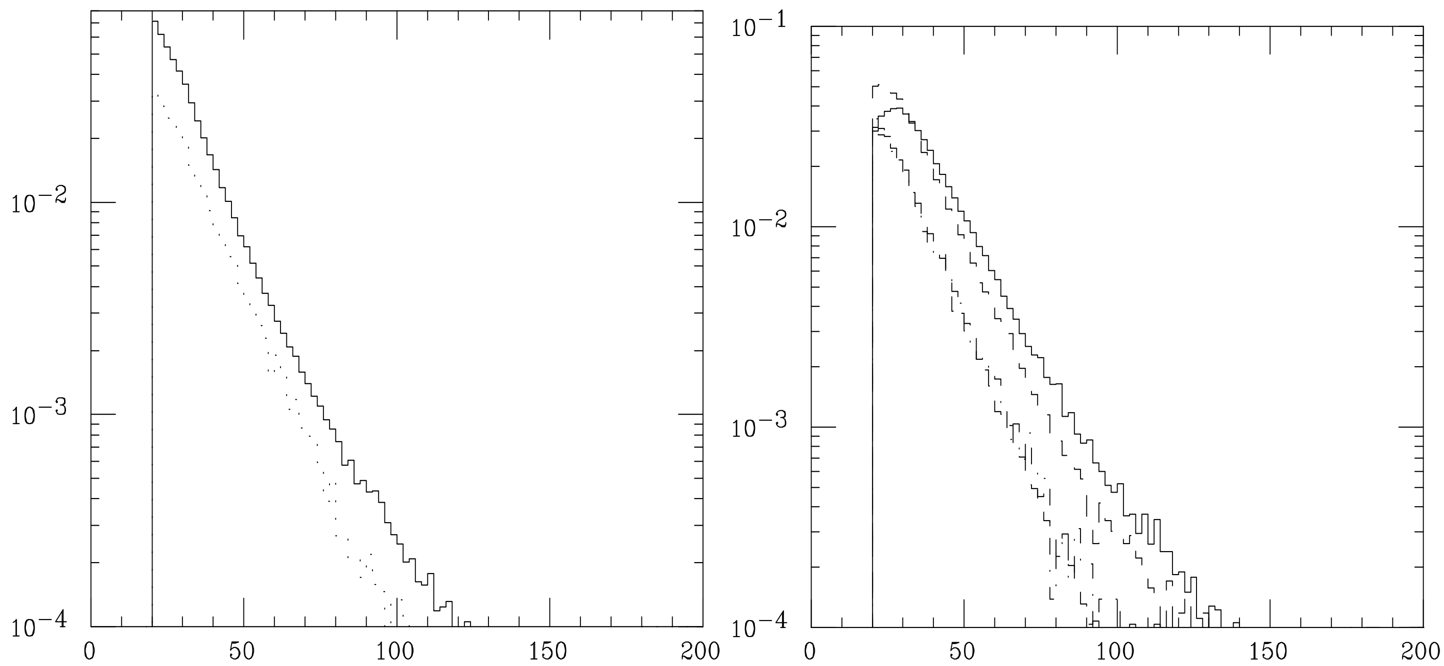


Left: $\frac{1}{\sigma} d\sigma/dp_1^T$ (/2 for WBF) distribution at parton level of $pp \to H + 3$ jets generated events Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma} d\sigma/dp_1^T$ distribution with Parton Shower on top of $pp \to H + 3$ jets generated events; solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$.

- Same as the previous one but with a high p_T tail
- some dependence on generation cuts for ggH events

p_T of the third jet

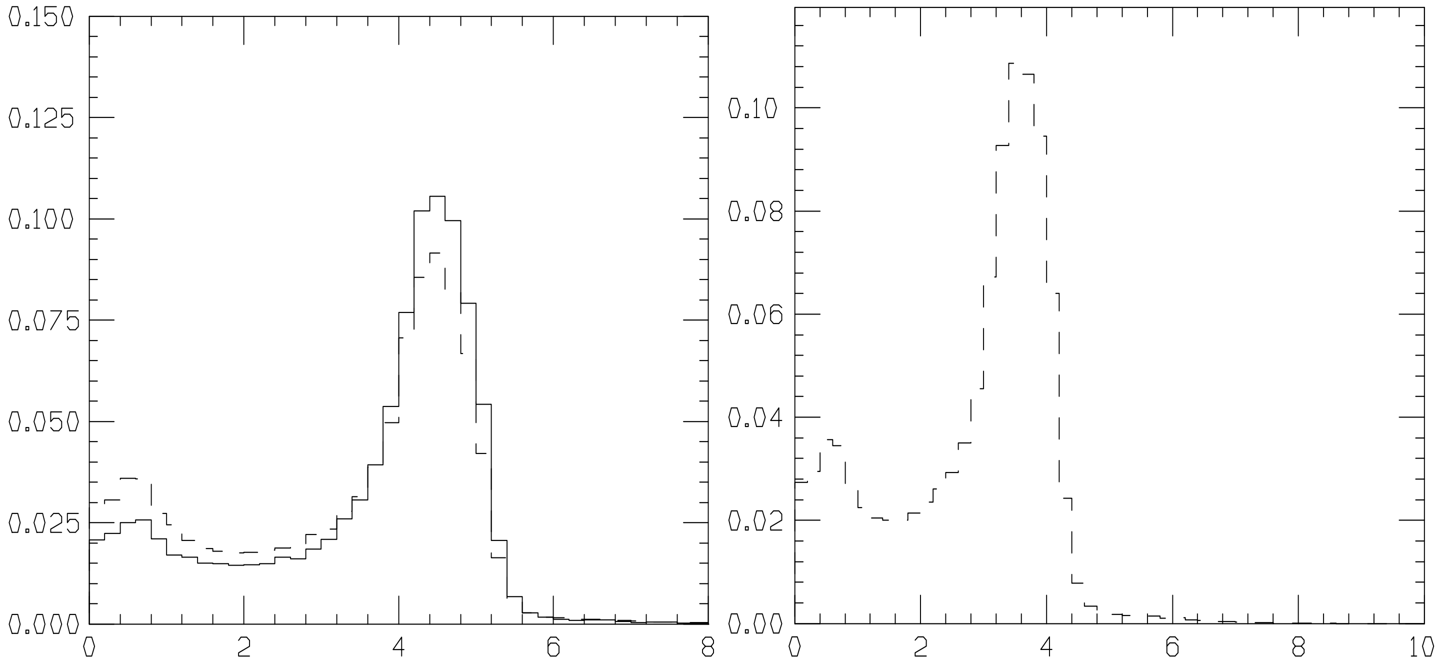


Left: $\frac{1}{\sigma} d\sigma/dp_3^T$(/2 for WBF) distribution at parton level of $pp \to H + 3$ jets generated events Solid line: QCD Higgs production; dashed line: WBF

Right: $\frac{1}{\sigma} d\sigma/dp_1^T$ distribution with Parton Shower on top of $pp \to H + 3$ jets generated events; solid ggH from sample $\mathcal{S}_1$, dash ggH from sample $\mathcal{S}_2$, dots WBF from sample $\mathcal{S}_1$, dot-dash WBF from sample $\mathcal{S}_2$.

Important dependence from cuts at the generation level for ggH events

$|\eta_1 - \eta_2|$



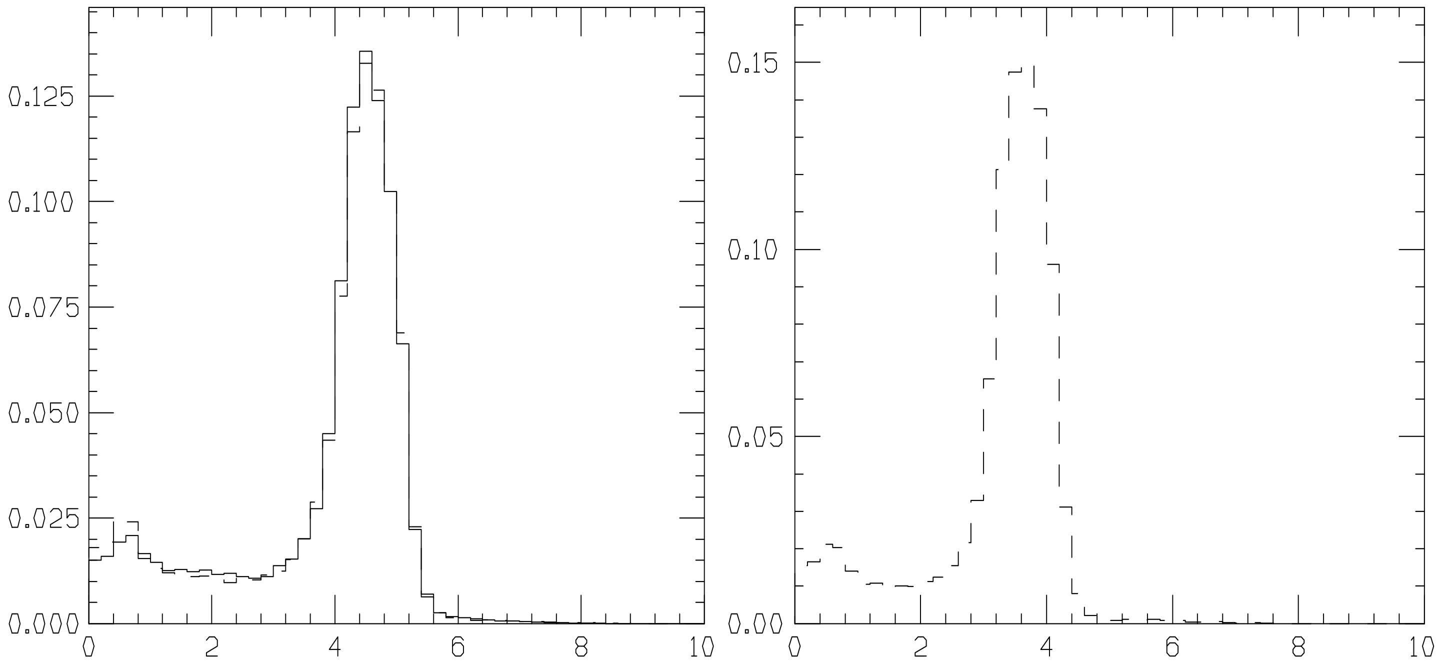
Left: $\frac{1}{\sigma} d\sigma/d|\eta_1 - \eta_2|$ distribution with Parton Shower on top of $pp \to H + 2$ jets generated events; distribution of $|\eta_1 - \eta_2|$ for the sample of events having $4.2 < |\eta_1 - \eta_2| < 5.2$ at the parton level. Solid event sample $\mathcal{S}_1$, dashes event sample $\mathcal{S}_2$.

Right: Same as Left for the sample of events having $3.2 < |\eta_1 - \eta_2| < 4.2$ at the parton level. Event sample $\mathcal{S}_2$ only.

For this very tight event selection there are important effect of showering on the acceptance:

- tagging jets become closer in rapidity after the shower and this leads to discard about 40% of the events.
- The effect is genuine and depends only mildly from event generation cuts: the fraction of events "promoted" after the shower is tiny
- This has important consequencies for NLO calculation. It might be difficult for a fixed order calculation to incorporate such an effect.

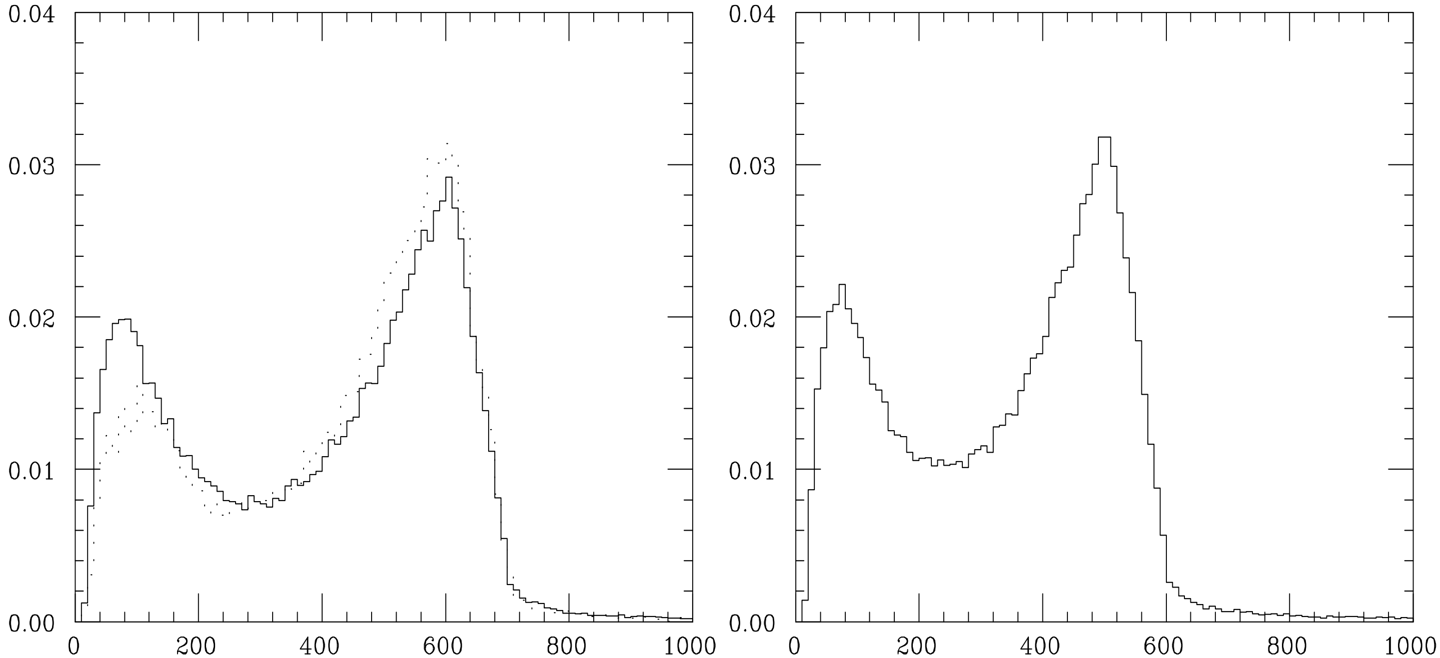
$|\eta_1 - \eta_2|$



Left: $\frac{1}{\sigma}d\sigma/d|\eta_1 - \eta_2|$ distribution with Parton Shower on top of $pp \to H + 3$ jets generated events; distribution of $|\eta_1 - \eta_2|$ for the sample of events having $4.2 < |\eta_1 - \eta_2| < 5.2$ at the parton level. Solid event sample $\mathcal{S}_1$, dashes event sample $\mathcal{S}_2$.

Right: Same as Left for the sample of events having $3.2 < |\eta_1 - \eta_2| < 4.2$ at the parton level. Event sample $\mathcal{S}_2$ only.

$m_{j_1 j_2}$



Left: $\frac{1}{\sigma}d\sigma/dp_1^T$ distribution of $m_{j_1 j_2}$ for the sample of events having $600\text{G}eV < m_{j_1 j_2} < 700\text{G}eV$ at the parton level. solid event sample $\mathcal{S}_1$, dots event sample $\mathcal{S}_2$.

Right: Same as Left for the sample of events having $500\text{G}eV < m_{j_1 j_2} < 600\text{G}eV$ at the parton level. Event sample $\mathcal{S}_2$ only.

- Azimuthal correlation and central jet rapidity require ME description (completely missed from shower). The shapes are independent from cuts at the generation level.
- The amount of jet activity (in particular the probability to emit a jet in the central region) is strongly affected from cuts at the generation level: a careful treatment of double counting effect is *mandatory* to study this issue
- The shower decrease the rapidity separation and the diijet invariant mass of the tagging jets: the effect is sizeable and looks not too strongly dependent from cuts at the generation level. A not irrelevant fraction of the tagging jets is however provided by the shower: a careful treatment of double counting effect is *mandatory* to study this issue

We have performed a study with `ALPGEN` with the matching option switched on. All the shown studies are at a preliminary level.

- we have produced two event samples made up by the sum of 0, 1, 2, 3, 4, 5 exclusive jets samples and 6 jets inclusive samples with:

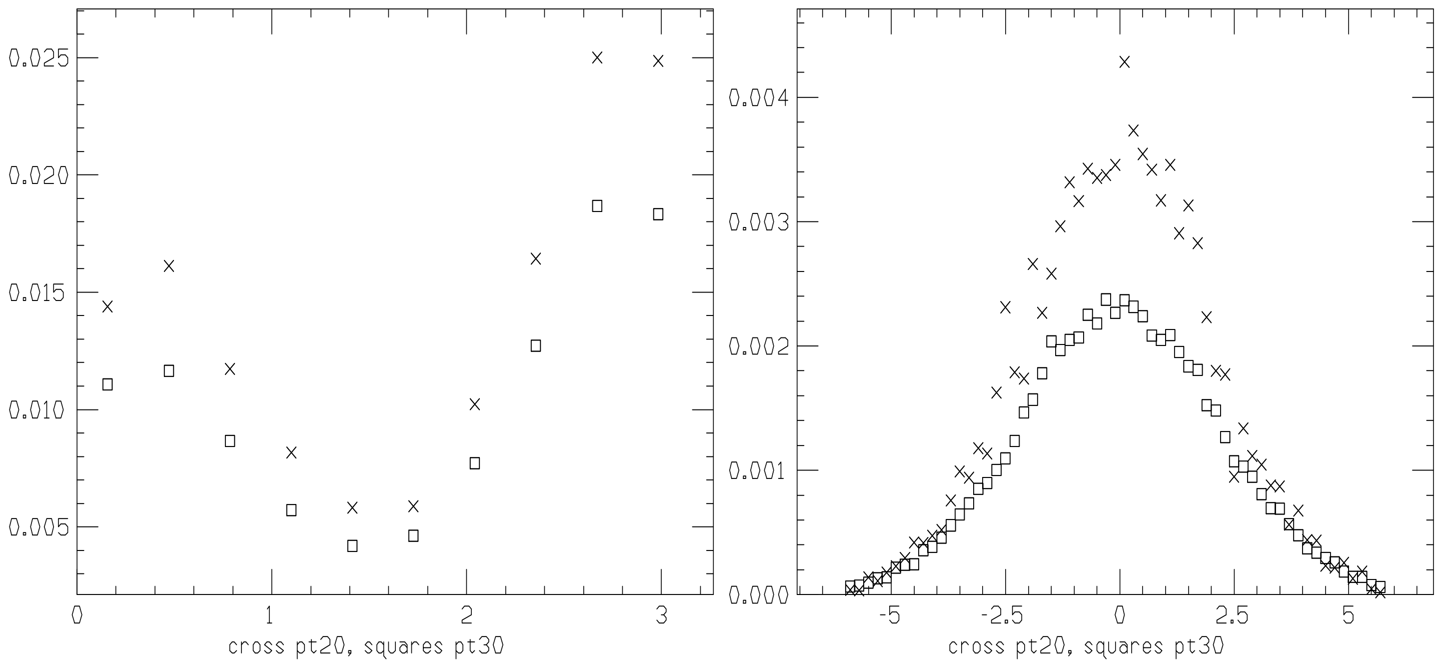
$$p_\perp^j > 20(30)\ GeV \qquad \Delta R_{j_a j_b} > 0.7 \qquad |\eta_j| < 5.5$$

  (labelled as p_{T20} and p_{T30} respectively) and matching parameters equal to the generation level cuts (recall that this is arbitrary, varying matching parameters with fixed generation level cuts helps in studying the systematics of matching procedure)

- $$\sigma_{p_{t20}} = 0.138\text{p}b \qquad \sigma_{p_{t30}} = 0.103\text{p}b$$

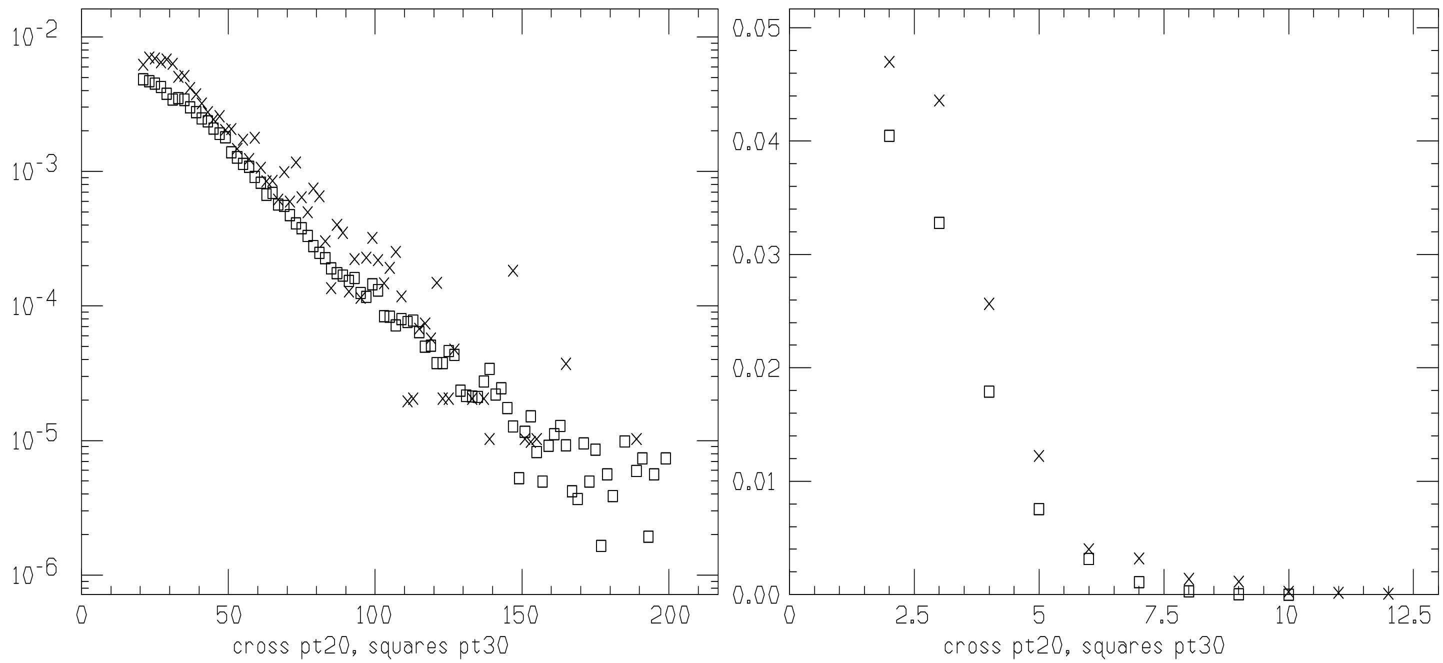
- still noticeable differencies in distributions

- a detailed study with more event samples and varying generation cuts and matching parameters is mandatory and in progress



Left: Azimuthal correlation: cross p_{T20} sample, box p_{T30} sample. Absolute normalization

Right: Third jet rapidity: cross p_{T20} sample, box p_{T30} sample. Absolute normalization



Left: $p_T^{j_3}$: solid p_{T20} sample, dots p_{T30} sample. Absolute normalization

Right: jet activity: solid p_{T20} sample, dots p_{T30} sample. Absolute normalization

Summary

- We proved the importance of the exact LO matrix element calculations for $H+$ jets final states in order to exploit all the correlations allowing to disentangle WBF from QCD Higgs production
- `ALPGEN v2.0` includes such processes with up to five jets in the final state
- While the use of the Parton Shower on the process $gg \to H$ can give unreliable results, once the complete matrix element for $H+$ jets is used, the shower doesn't alter the picture
- This has still to be proved when including hadronization *(work in progress)*
- The use of exact matrix elements for $H+$ jets final state calls for a consistent matching between matrix elements and parton shower, a problem widely studied during last years *(work in progress)*
- The availability of a NLO calculation would be useful in the study of the optimal scales