NLO VBF Monte Carlo Generator(s)

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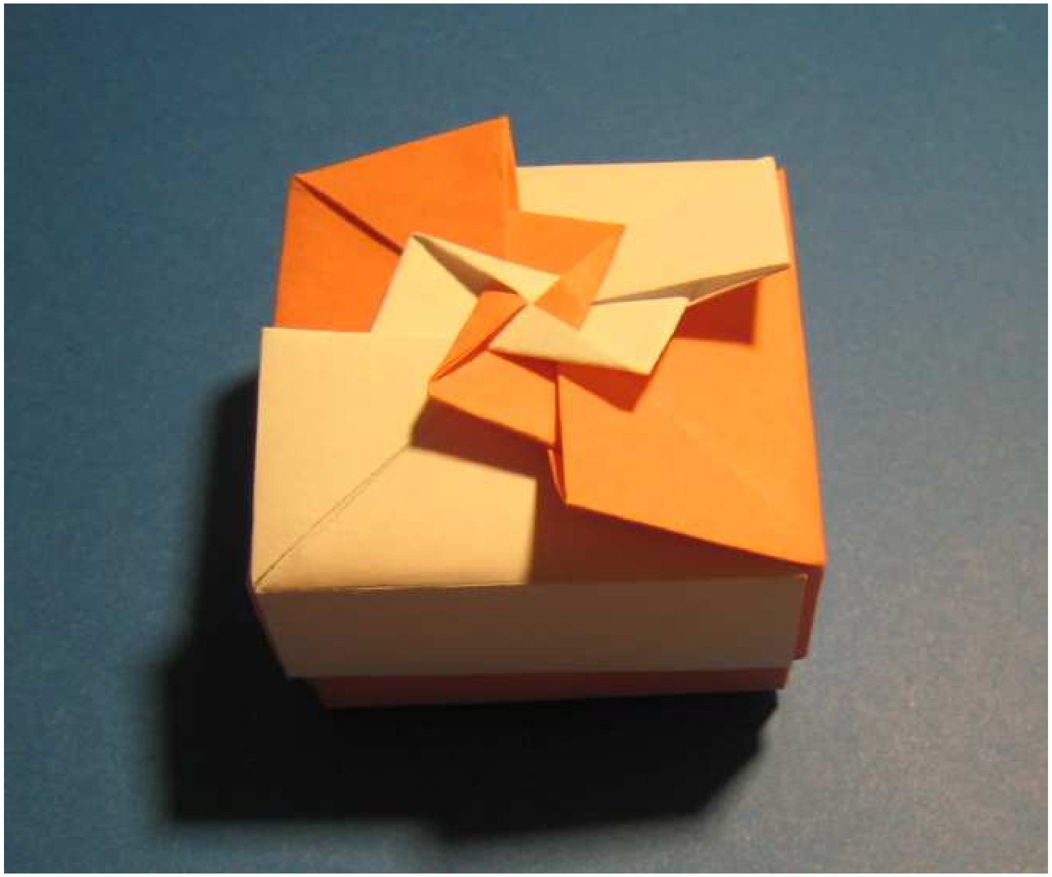
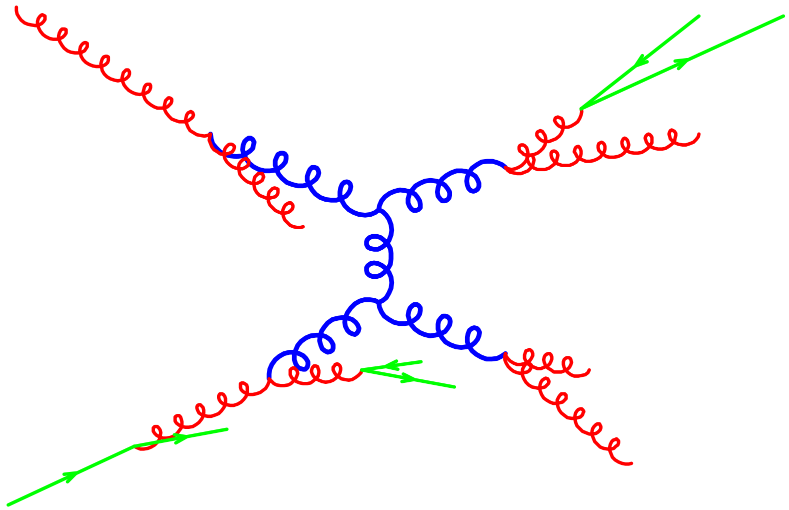
- Shower Monte Carlo + NLO
- POWHEG
- Higgs boson in VBF:
  POWHEG results
- Conclusions



[a]On behalf of the VBF group: Ansgar Denner, Sinead Farrington, Christoph Hackstein and Daniela Rebuzzi.

Dominant corrections



Collinear-splitting processes in the initial and final state (always with transverse momenta $> \Lambda_{\mathrm{QCD}}$) are strongly enhanced. This is due to the fact that, in perturbation theory, the denominators in the propagators are small.

- The algorithms that evaluate (and resum) all these enhanced contributions are called shower algorithms.
- Shower algorithms give a description of a hard collision up to distances of order $1/\Lambda_{\mathrm{QCD}}$.
- At larger distances, perturbation theory breaks down and we need to resort to non-perturbative methods (i.e. lattice calculations). However, these methods can be applied only to simple systems. The only viable alternative is to use models of hadron formation.

SMC

- In high-energy collider physics not many questions can be answered without a Shower Monte Carlo (SMC).

- The name shower comes from the fact that we dress a hard event with QCD radiation.

- In general, the accuracy of SMC programs is Leading Order + Leading Log. They resum the largest logarithmic terms coming from the collinear (and soft) regions.

- Events are then characterized by a small number of high-p_T, well-separated, final-state partons + many collinear partons, whose collinear divergences have been correctly resummed.

NLO

LO matrix elements are (often, but not always) good for shapes. Uncertain absolute normalization

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 + b_0\,\alpha_s(\mu_0)\log\left(\mu^2/\mu_0^2\right)}, \qquad b_0 = \left.\frac{11C_A - 4n_f T_F}{12\pi}\right|_{n_f=5} \approx 0.6$$

$$\alpha_s^n(2\mu) \approx \alpha_s^n(\mu)\left[1 - b_0\alpha_s(\mu)\log(4)\right]^n \approx \alpha_s^n(\mu)\left(1 - n\alpha_s(\mu)\right)$$

For $\mu = 100$ GeV, $\alpha_s = 0.12$, normalization uncertainty:

$W + 1J$	$W + 2J$	$W + 3J$
$\pm 12\%$	$\pm 24\%$	$\pm 36\%$

To improve on this, we need to go to NLO

- Positive experience with NLO calculations at LEP, HERA and Tevatron
- NLO results are cumbersome to compute: typically made up of an n-body (Born + virtual + soft and collinear remnants) and $(n+1)$-body (real emission) terms, both divergent (finite only when summed up).
- Merging NLO with shower is a natural extension of present approaches
  - MC@NLO [Frixione, Webber]
  - POWHEG [Nason]

POsitive-Weight Hardest Emission Generator

- ✓ it is a method for interfacing NLO calculations with parton shower programs [Nason, hep-ph/0409146]

- ✓ it generates the hardest emission first, with NLO accuracy. The produced events have positive weights. The acronym comes from this feature

- ✓ it is independent from parton-shower programs. It can be interfaced with any programs that comply with the LHE format: PYTHIA, HERWIG . . .
  It is then possible to compare the different outputs

- ✓ No need to implement new interfaces
  Two possible ways to interface to shower Monte Carlo programs
  1. Les Houches Event format. The event is written on a file that is subsequently showered by HERWIG, PYTHIA. . .
  2. on the fly. We provide UPINIT and UPEVNT directly running in HERWIG and PYTHIA

Higgs boson in VBF: analysis cuts

We have used the POWHEG BOX to generate events for Higgs boson in VBF

- pp collider at 7 TeV
- jet clustered with k_T algo, $R = 0.7$
- jet defined by

$$p_{Tj} > 20\ \text{GeV}, \qquad |y_j| < 5$$

- tagging jets

$$p_T^{\text{tag}} > 30\,\text{GeV}, \qquad |y_{j_1} - y_{j_2}| > 4.2\,, \qquad y_{j_1} \cdot y_{j_2} < 0\,, \qquad m_{jj} > 600\,\text{GeV}$$

$$\text{veto jet :} \quad \min\left(y_{j_1}, y_{j_2}\right) < y_j < \max\left(y_{j_1}, y_{j_2}\right)$$

- info on the jet shape. If $\vec{p}^{\,j}$ is the momentum of the jet, then

$$p_T^{\text{rel},j} = \sum_{k^i \in p^j} \frac{|\vec{k}^i \times \vec{p}^{\,j}|}{|\vec{p}^{\,j}|}$$

Higgs boson in VBF: results

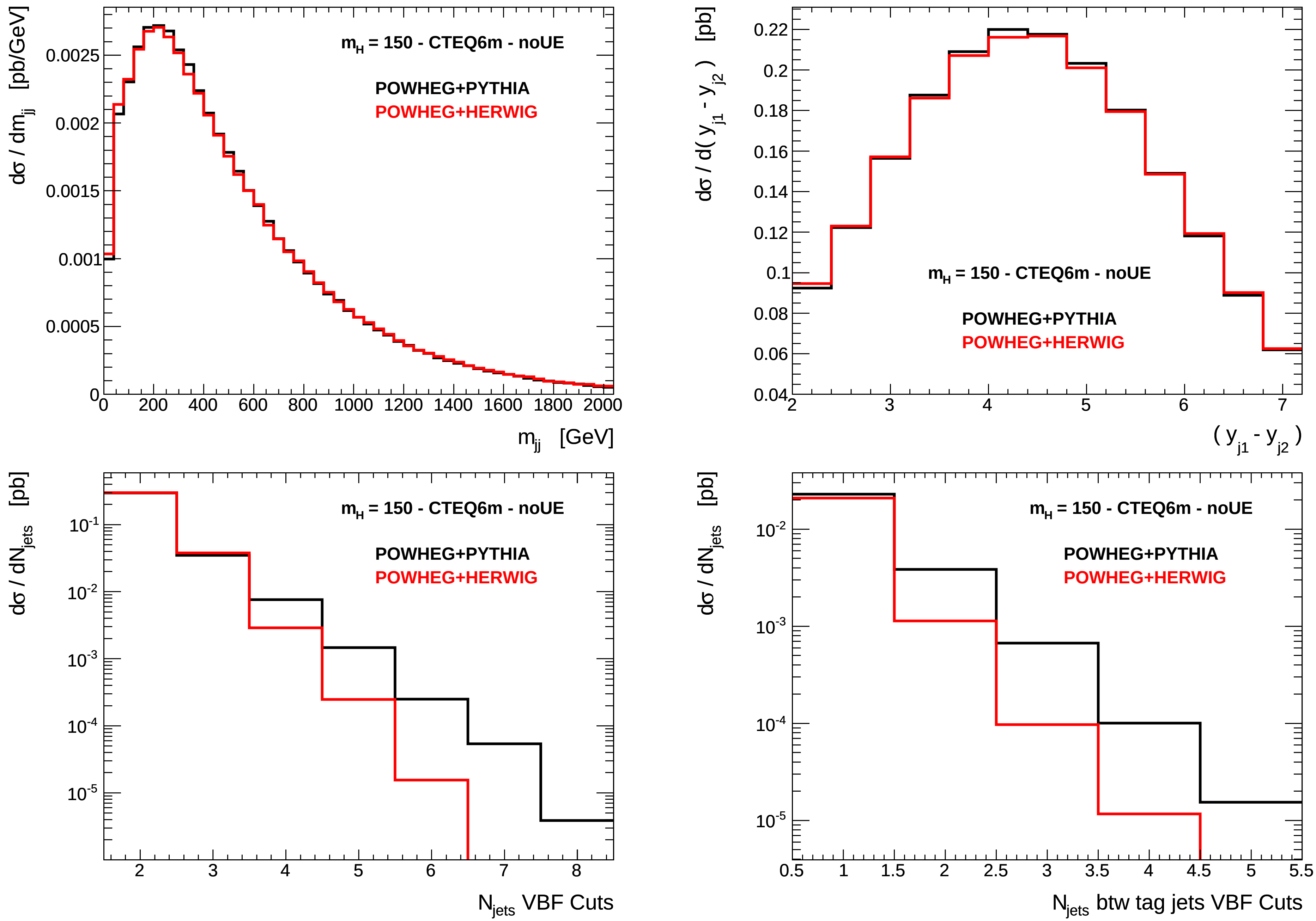
- comparisons among
  - POWHEG + HERWIG (ver 6.510)
  - POWHEG + PYTHIA (ver 6.4.21)
  - HERWIG alone
  - PYTHIA alone
- for $m_H = 150, 200, 300, 400, 500$ GeV
- for two pdf sets: CTEQ6m and MSTW2008NLO (and the respective LO ones when used with HERWIG and PYTHIA alone)
- without and with underlying events
  - HERWIG $\Longrightarrow$ `IPROC` (no `+10000`)
    It contains only soft UE. NO Multiple Interactions (provided by the JIMMY package).
  - PYTHIA $\Longrightarrow$ `mstp(81)=1` and new p_T-ordered shower (MI included in the default mode)

Higgs boson in VBF: results

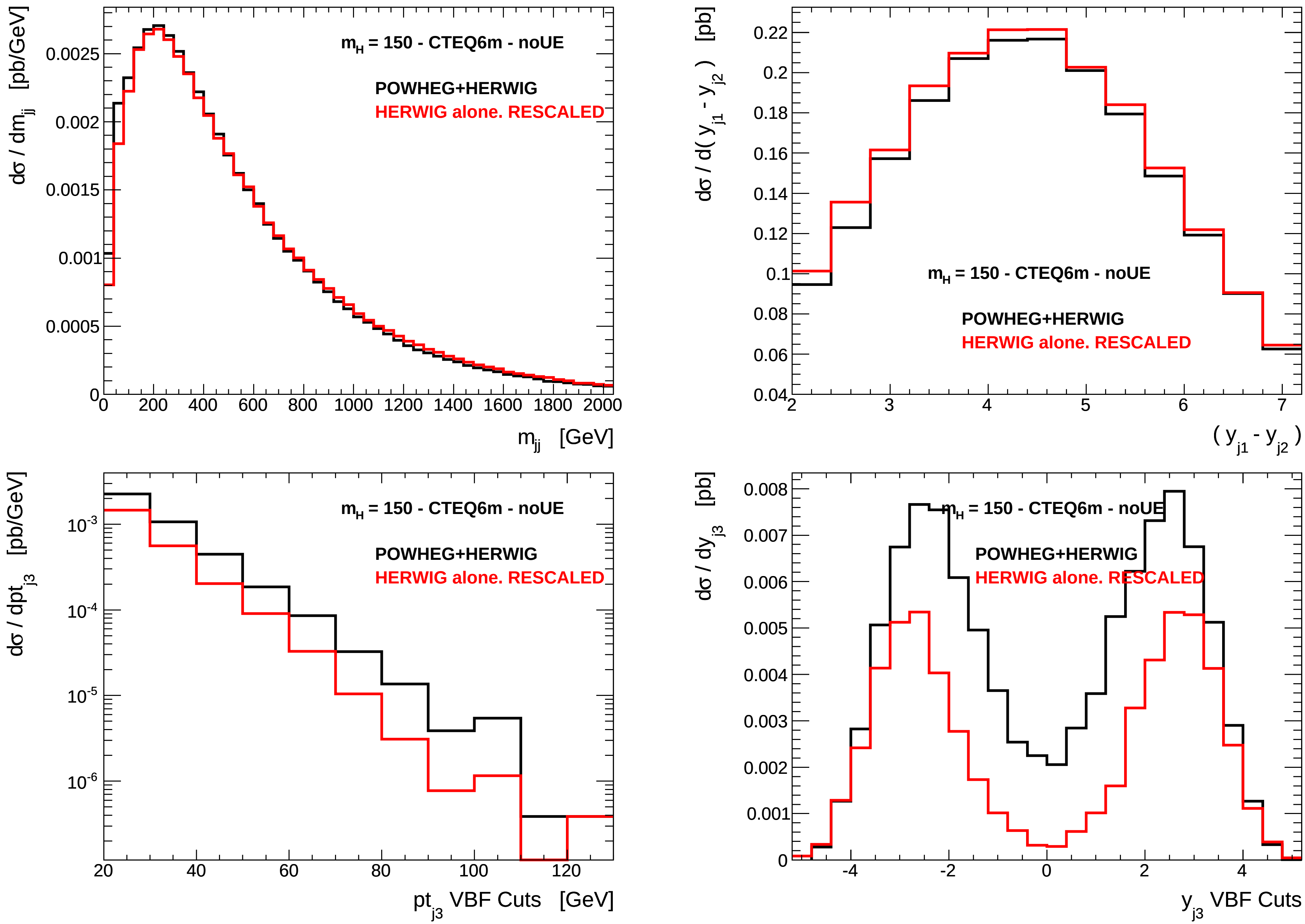
- We will present results mostly for $m_H = 150$ GeV.

- Same conclusions for all the Higgs boson masses up to 500 GeV

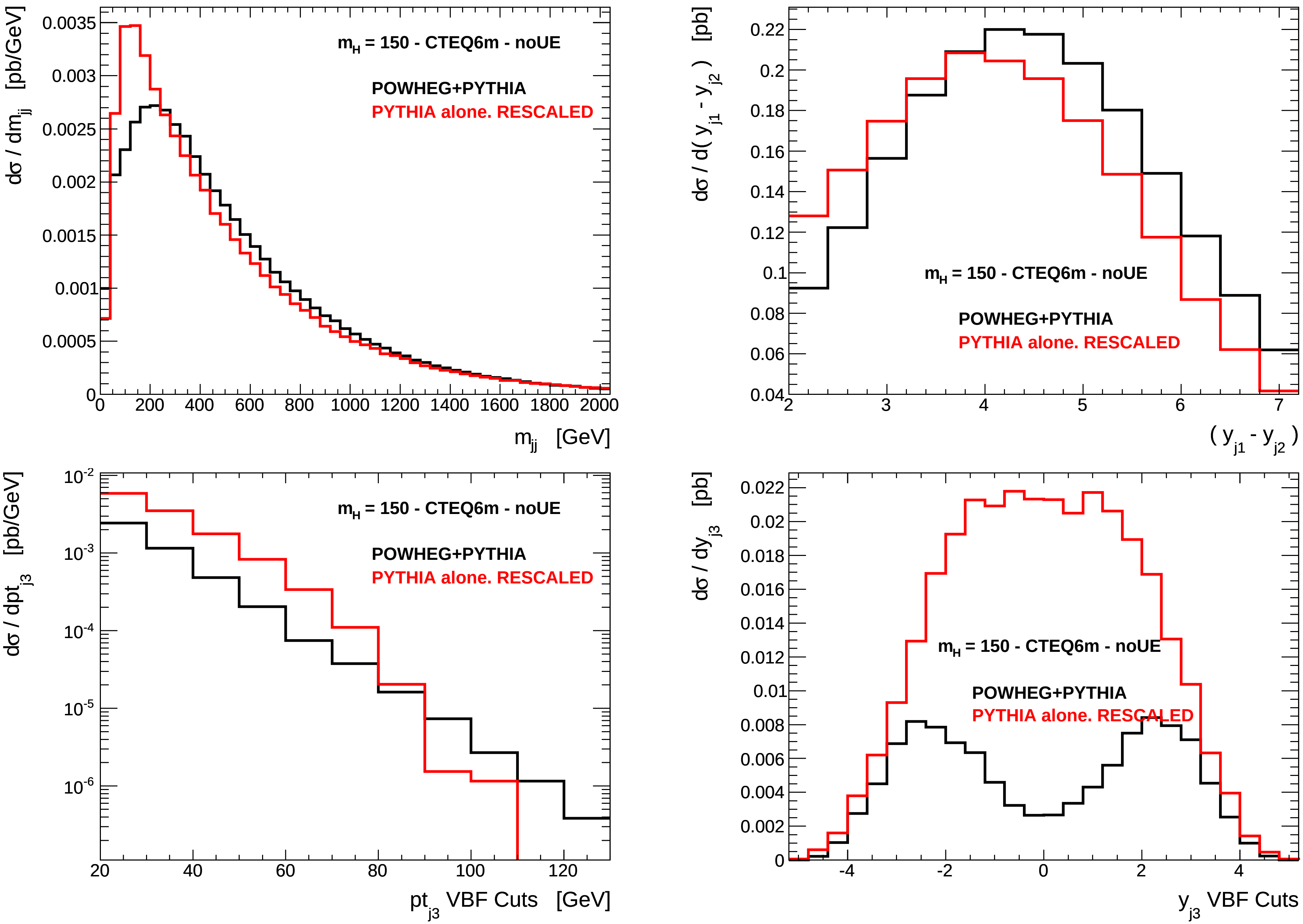
- Results from the analysis of 500.000 events generated by the POWHEG BOX



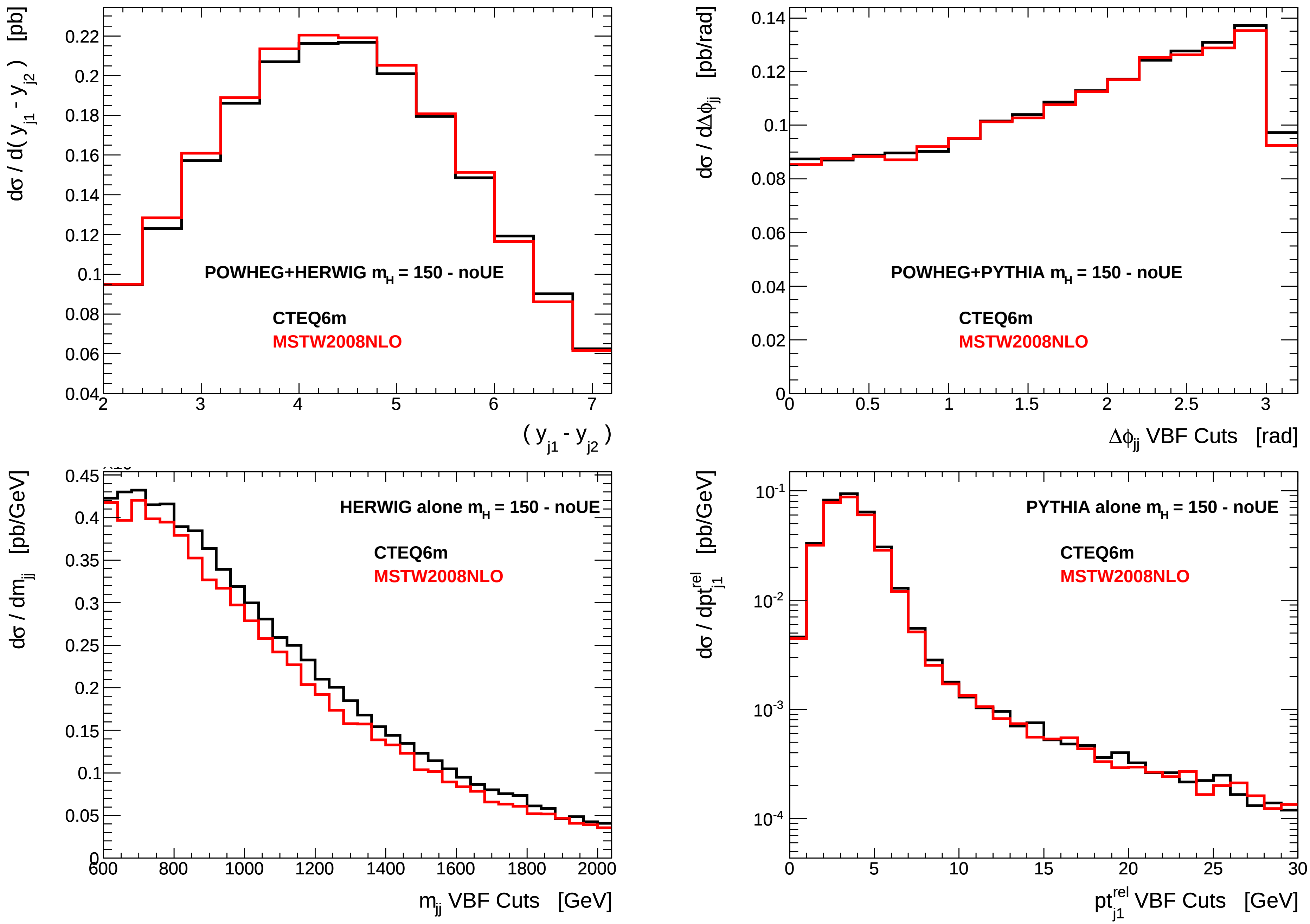
PYTHIA jets tend to be harder than HERWIG's ones. $N_{\rm jets}$ is correct up to 3 (NLO), since generated by POWHEG



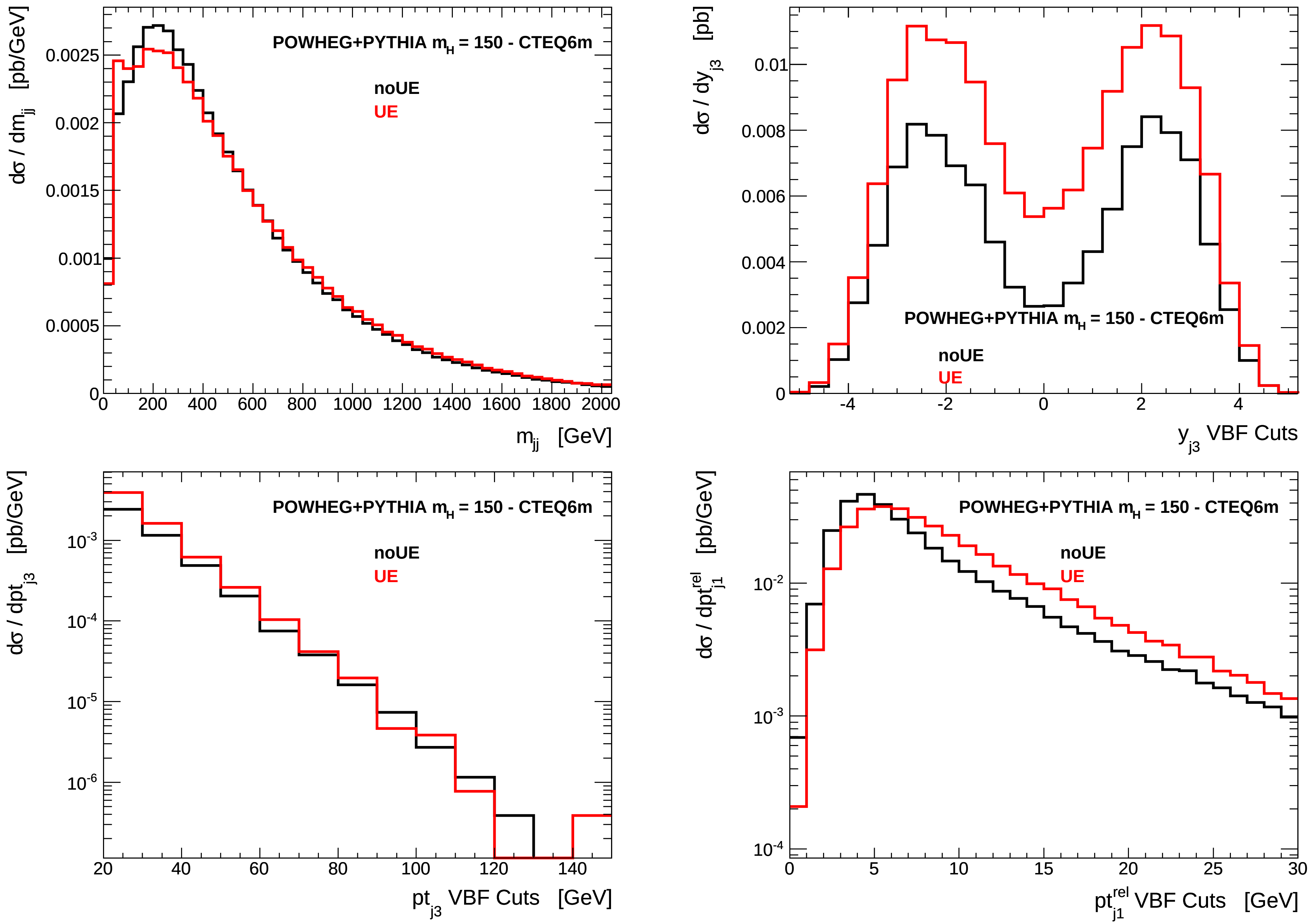
Neither HW alone nor PY alone are expected to describe correctly the 3rd jet. HW results rescaled to the NLO total Xsec



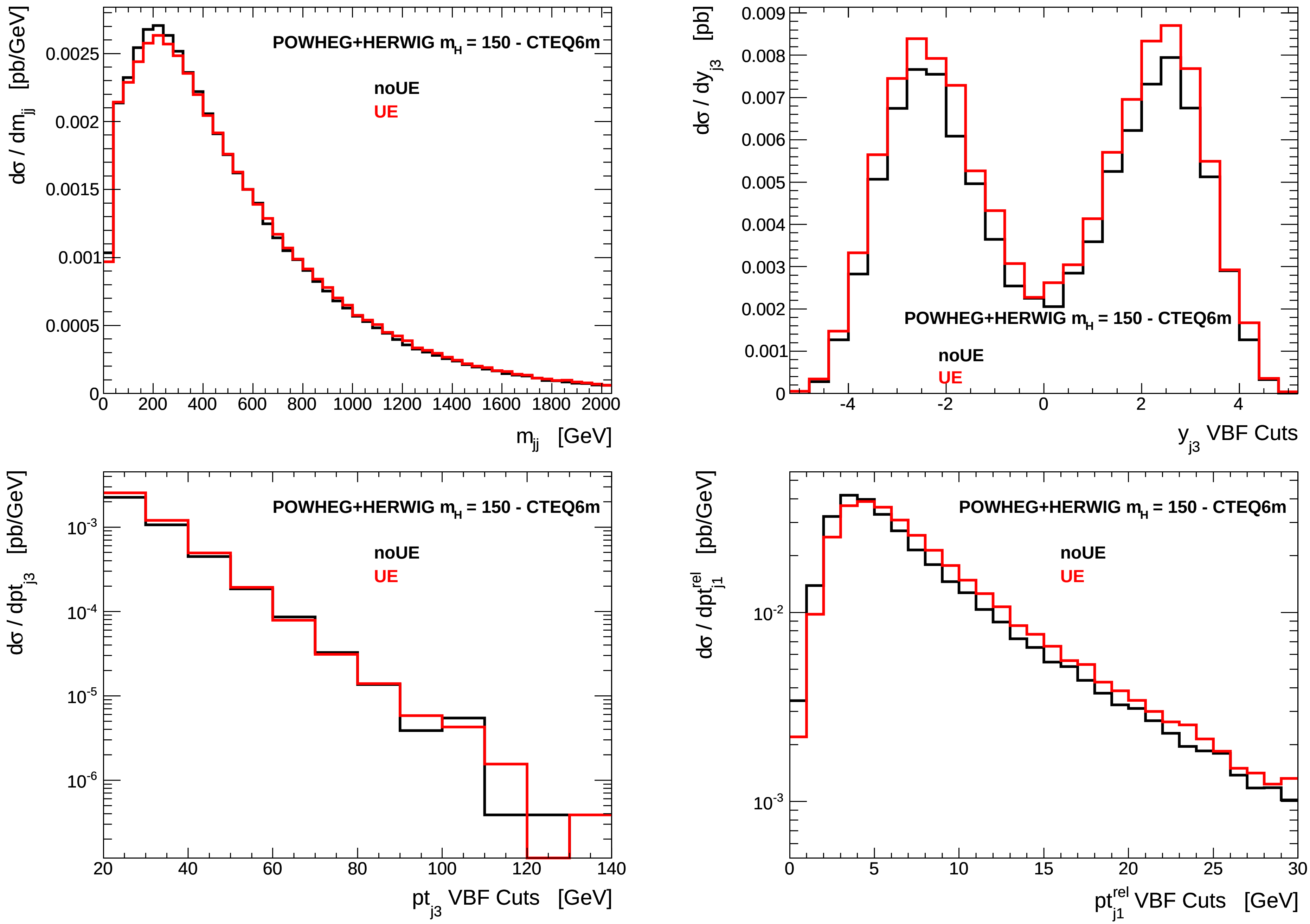
Harder PY jets "mimic" tagging jets. Wrong shapes for m_{jj} and $(y_{j1} - y_{j2})$. Same for y_{j3}. PY results rescaled to the NLO total Xsec



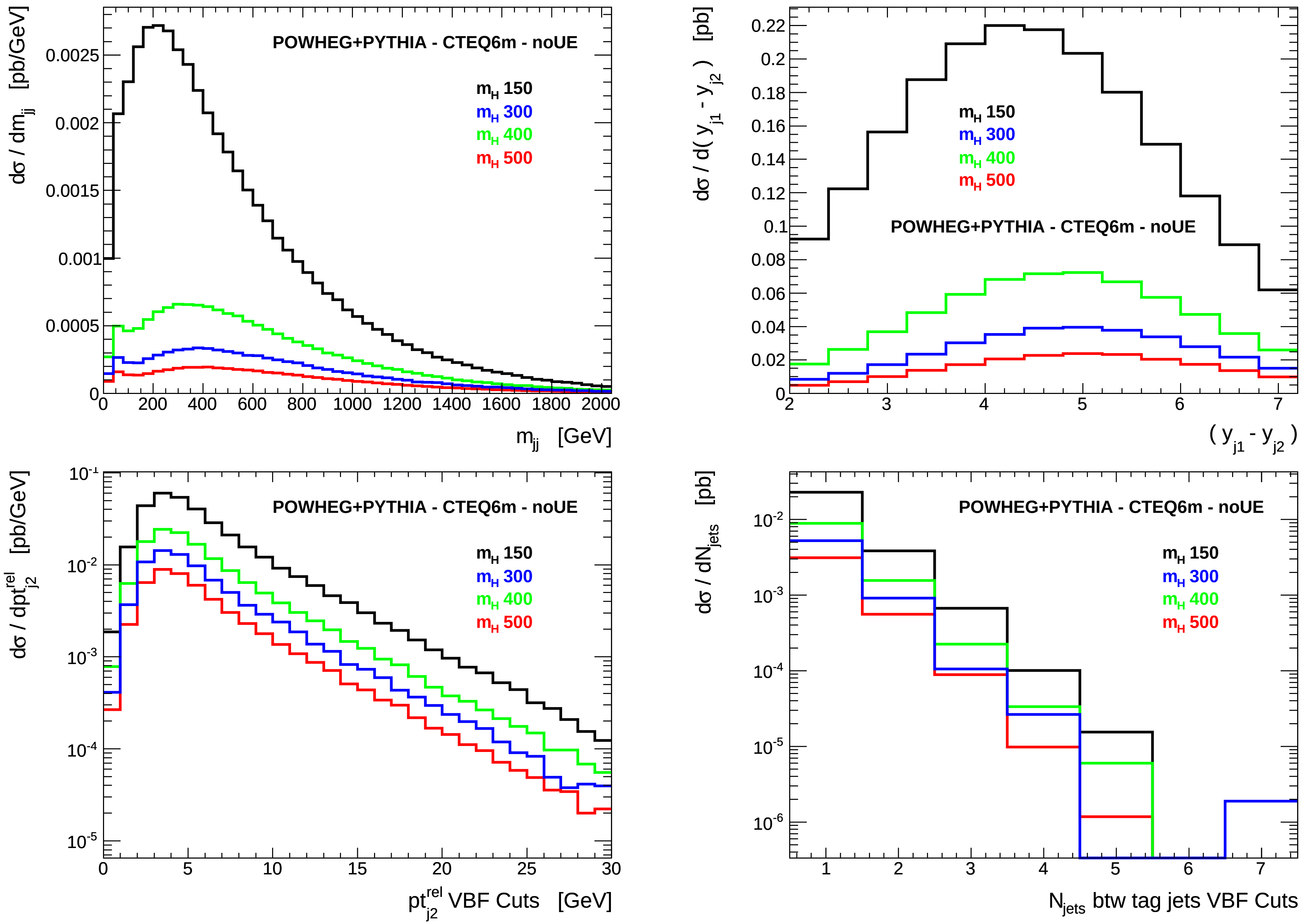
Mild dependence with POWHEG (only 1st emission). When run alone, larger differences with HW than with PY



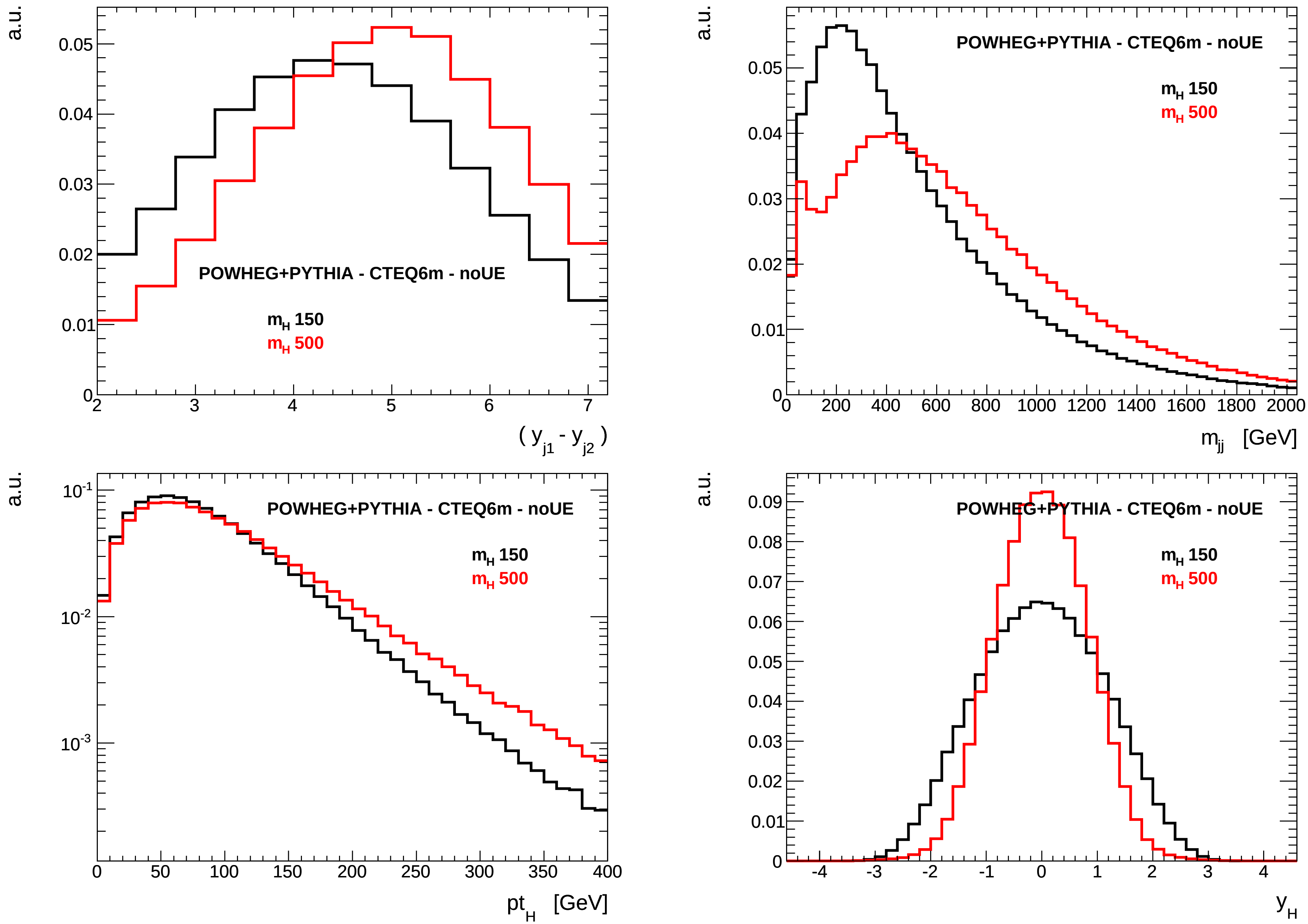
PYTHIA UE + MI events affect appreciably event shapes: low m_{jj} extra peak, y_{j3}, p_T^{rel}



Do not forget that HERWIG only has soft UE. NO MI



Shift of m_{jj} and $(y_{j1} - y_{j2})$ peak to higher values. Need to compare with ggH for new VBF cuts. H in VBF less promising



Plots normalized to 1 to show differences in shape

Higgs boson in VBF

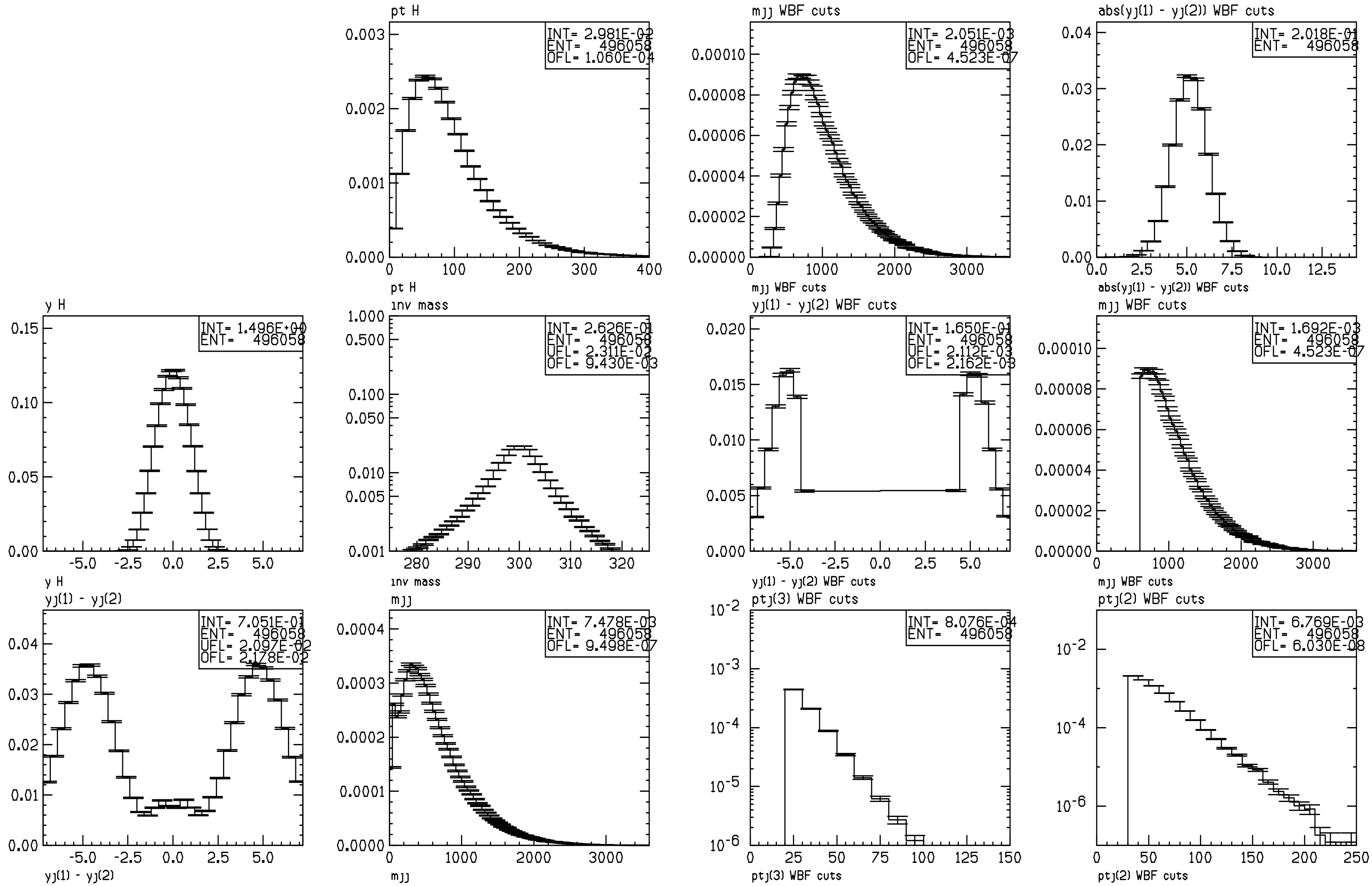
Plots for all the runs in

http://virgilio.mib.infn.it/~oleari/public/VBF_H_Plots.tgz

In the following, an example of the output result file (in `topdrawer` format) that can be found there for

POWHEG + HERWIG, no UE, MSTW2008NLO pdf, $m_H = 300$ GeV

with error bars (`HERWIG-lhef_noUE_MSTW2008NLO_H300.top`)



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OFL= 1.060E-04
mjj WBF cuts
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OFL= 4.523E-07
abs(yj(1) - yj(2)) WBF cuts
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ENT= 496058
y H
INT= 1.496E+00
ENT= 496058
inv mass
INT= 2.626E-01
ENT= 496058
UFL= 2.311E-02
OFL= 9.430E-03
yj(1) - yj(2) WBF cuts
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OFL= 4.523E-07
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UFL= 2.097E-02
OFL= 2.178E-02
mjj
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OFL= 9.498E-07
ptj(3) WBF cuts
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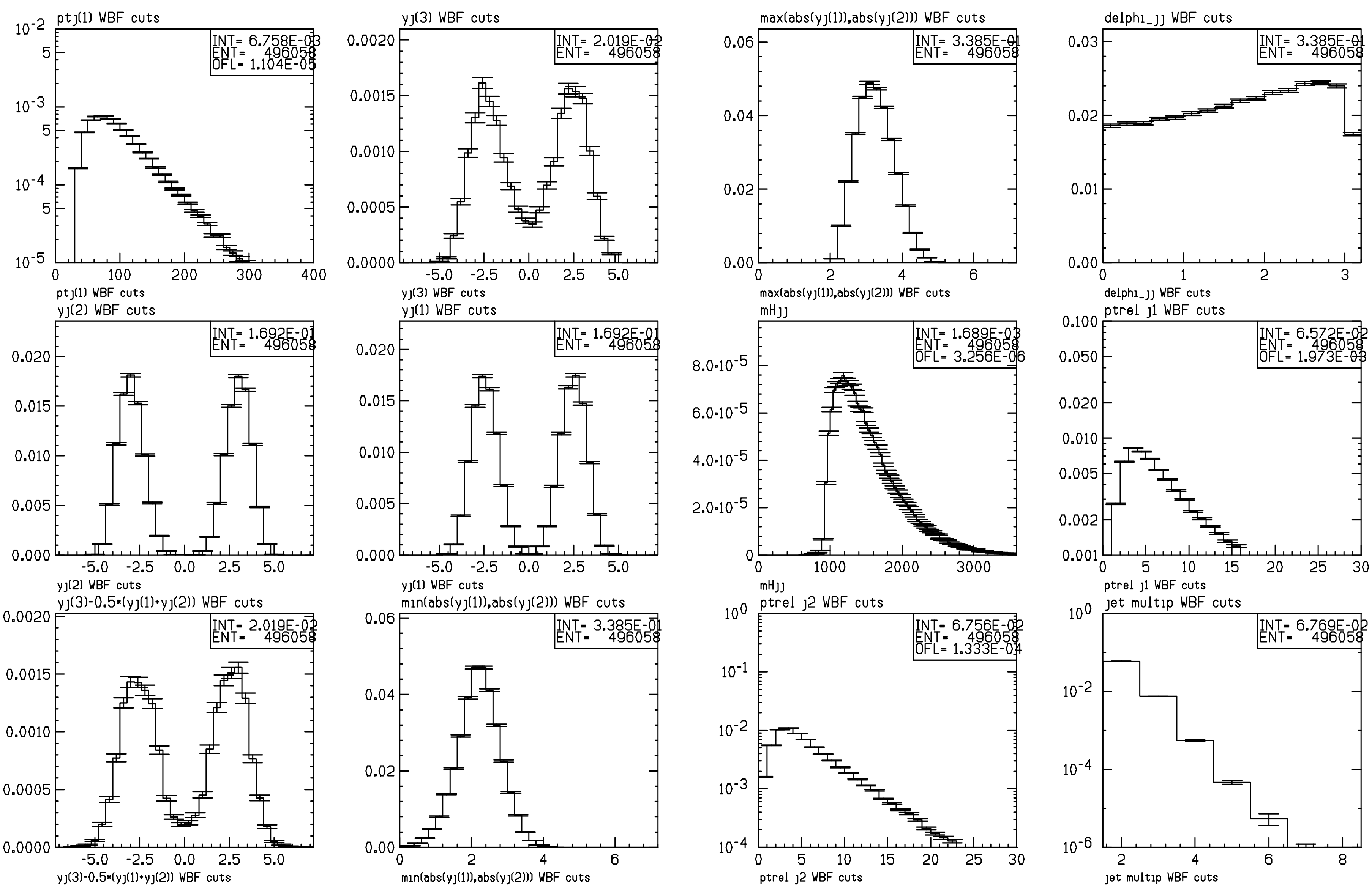
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delphi_jj WBF cuts
INT= 3.385E-01
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yj(2) WBF cuts
INT= 1.692E-01
ENT= 496058
yj(1) WBF cuts
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mHjj
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OFL= 3.256E-06
ptrel j1 WBF cuts
INT= 6.572E-02
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OFL= 1.973E-03
yj(3)-0.5*(yj(1)+yj(2)) WBF cuts
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ENT= 496058
min(abs(yj(1)),abs(yj(2))) WBF cuts
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ENT= 496058
ptrel j2 WBF cuts
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ENT= 496058
OFL= 1.333E-04
jet multip WBF cuts
INT= 6.769E-02
ENT= 496058

Conclusions

- ✓ For the experimentalists: please use the most up-to-date tools. SMC programs, if not merged with hard matrix elements (ME), cannot describe hard jets beyond the LO ones.

- ✓ For the theorists: if you are interested in turning your "favorite" NLO calculation into POWHEG, an easy-to-use tool is available: the POWHEG BOX.

  This is a computer framework, presented in [Alioli, Nason, Oleari and Re, arXiv: 1002.2581], that implements in practice the theoretical construction of the POWHEG formalism, for generic NLO processes, according to the general formulation of POWHEG. The only ingredients to be provided are: lists of the Born and real processes, the Born phase space, the Born squared amplitudes, the color-correlated and spin-correlated amplitudes, the real squared amplitude and the finite part of the virtual corrections.

- ✓ **Many thanks** to Andrea Benaglia, who has run the POWHEG BOX code for Higgs boson production in VBF and has produced all the plots.