Top Mass extraction studies using NLO+PS generators with increasing accuracy.

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Work done in collaboration with
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Available Generators

- Modern generators for $t\bar{t}$ production have become available in recent times:
  - `MC@NLO` Frixione,Webber,P.N. and `POWHEG` Frixione,Ridolfi,P.N. `hvq` traditional NLO+PS $t\bar{t}$ generators. Do not include either exact spin correlations in decays or radiative corrections in decays. Routinely used by LHC experiments.
  - `ttb_NLO_dec` Campbell,Ellis,Re,P.N.. Includes exact spin correlations and NLO corrections in decay. Off shell effects included approximately (in such a way to be LO exact).
  - `b_bbar_4l` Ježo,Lindert,Nason,Oleari,Pozzorini,P.N. 2016 Includes exact NLO matrix element for $pp \to l\bar{\nu}_l \bar{\ell}\nu_\ell b\bar{b}$. It uses a recently introduced method for dealing with (coloured) narrow resonance in `POWHEG`.

Our task

We (Ferrario-Ravasio, Ježo, Oleari, P.N.) are tackling the following tasks:

- compare three NLO+PS generators: `hvq`, `tt̄_dec`, `bb̄4l`.
- studied the effect of scale variations in the `tt̄_dec` and `bb̄4l` generators.
- studied the α_s sensitivity of the results in the `bb̄4l` generator.
- studied the PDF error in the `bb̄4l` generators.
- performed an initial study on shower and hadronization uncertainties by comparing two shower generators: `Pythia8` and `Herwig7`.

(As of now) most disturbing differences found in the last item.
This talk will focus upon `Pythia8` and `Herwig7` comparison.

Our task

- We focus upon the $pp \to l\bar{\nu}_l \bar{\ell}\nu_\ell b\bar{b}$ process. This is OK for lepton observables, but also for the b-jet energy peak.
  If we assume that the W can be fully reconstructed, our results will also imply a lower bound on the error in semileptonic and fully hadronic $t\bar{t}$ events, which is our main goal.
- Our most studied mass sensitive observable is the mass of the Wj_b system with matching signs.
- We look for parameter/setup variations that can lead to a displacement of the peak in m_{Wj_b} (this leads to an "irreducible" theoretical error on the top mass extraction).
- We also extract the mass after smearing the peak with a Gaussian, with half width equal to 15 GeV. This leads to an error that is related to the experimental resolution on our observable.
- "Irreducible errors" can actually be reduced. Some parameter/setup variations may be constrainable by data.

General approach

Assuming we have an observable O sensitive to the top mass, we will have in general

$$O = O_{\mathrm{c}} + B(m_t - m_{t,\mathrm{c}}) + \mathcal{O}((m_t - m_{t,\mathrm{c}})^2)$$

where $m_{t,\mathrm{c}} = 172.5$ GeV is our central value for the top mass. O_{c} and B differ for different generator setup. Given an experimental result for O, the extracted mass value is

$$m_t = m_{t,\mathrm{c}} + (O_{\mathrm{exp}} - O_{\mathrm{c}})/B$$

By changing the generator setup $O_{\mathrm{c}}, B \to O'_{\mathrm{c}}, B'$:

$$m_t - m'_t = -\frac{O_{\mathrm{c}} - O'_{\mathrm{c}}}{B} - (O_{\mathrm{exp}} - O'_{\mathrm{c}})(B - B')/(BB') \approx -\frac{O_{\mathrm{c}} - O'_{\mathrm{c}}}{B}.$$

General approach

Thus:

- Compute the B coefficient using a single setup for the generator.
- Compute the O_{c} coefficient (i.e. the value of the observable for $m_t = m_{t,\mathrm{c}}$) for all different setup we want to explore.
- Extract the difference in the extracted m_t between different setups, according to the equation

$$\Delta m_t = -\frac{\Delta O_{\mathrm{c}}}{B}.$$

NLO+PS generators

- `hvq`: (Frixione,Nason,Ridolfi, 2007), the first POWHEG implementation of $t\bar{t}$ production.
  NLO corrections only in production. Events with on-shell t and $\bar{t}$ are produced, and then "deformed" into off-shell events with decays, with a probability proportional to the corresponding tree level matrix element with off-shell effects and decays.
  Radiation in decays is only generated by the shower.
- `tt̄_dec`: (Campbell etal, 2014) Full spin correlations, exact NLO corrections in production and decay in the zero width approximation. Off shell effects implemented via a reweighting method, such that the LO cross section includes exactly all tree level off-shell effects.
- `bb̄4l`:(Ježo etal, 2016) Full NLO with off shell effects for $pp \to b\bar{b}e^{+}\nu_{e}\mu^{-}\bar{\nu}_{\mu}$,

Invariant mass of top decay products

$$m_{W-bj}$$

m_{W-bj}

We take m_{W-bj} as a proxy for all top-mass sensitive observables that rely upon the mass of the decay products.
Experimental effects are simply represented as a smearing of this distribution.
Here we will show results with no smearing, and with a Gaussian smearing with $\sigma = 15\,\text{GeV}$.
We look for:

- Effects that displace the peak. These lead to an intrinsic error on the extraction of the mass.
- Effects that affect the shape of the peak in a wide region. These will affect the mass determination if the experimental smearing is included.

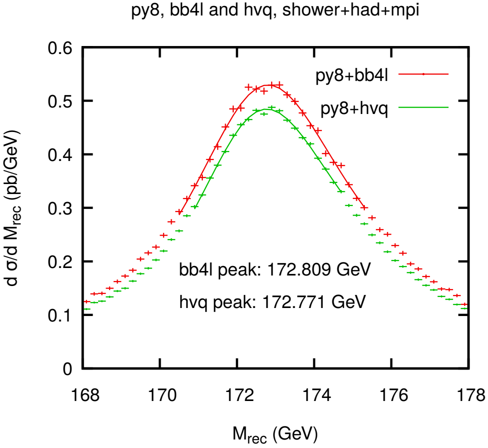
$W - bj$ is defined in the following way:

- Jets are defined using the anti-k_T algorithm with $R = 0.5$. The $b/\bar{b}$ jet is defined as the jet containing the hardest $b/\bar{b}$.
- $W^{\pm}$ is defined as the hardest $l^{\pm}$ paired with the hardest matching neutrino.
- The $W - bj$ system is obtained by matching a $W^{+/-}$ with a $b/\bar{b}$ jet (i.e. we assume we know the sign of the b).

In this case, $B \approx 1$!

Pythia8, POWHEG-hvq - POWHEG-bb4l comparison

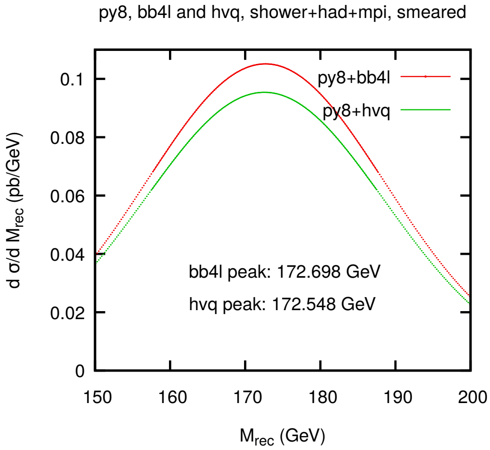
Now see what happens if we go from the old hvq to the new bb4l NLO+PS generator, using Pythia8 for the shower.



bb4l − hvq: 38 MeV

Pythia8, POWHEG-hvq - POWHEG-bb4l comparison

Same, accounting for experimental errors by smearing the peak with a gaussian distribution with a width of 15 GeV.

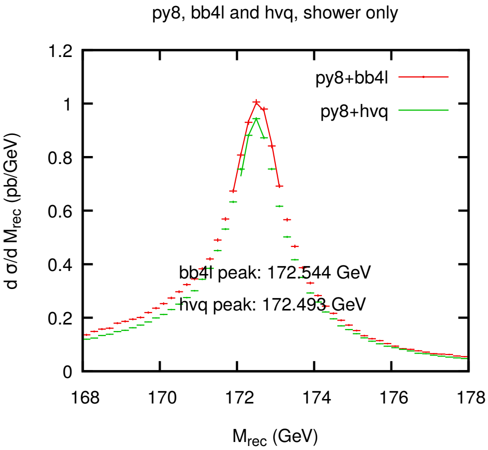


Smearing, $\sigma = 15$ GeV,

bb4l − hvq: 150 MeV

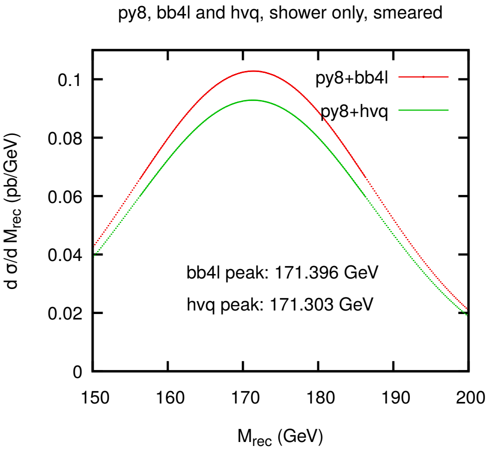
Pythia8, POWHEG-hvq - POWHEG-bb4l comparison

Same stuff, no hadronization and mpi;



bb4l − hvq: 51 MeV

No hadronization and mpi, with smearing;



Smearing, $\sigma = 15$ GeV,

bb4l $-$ hvq: 93 MeV

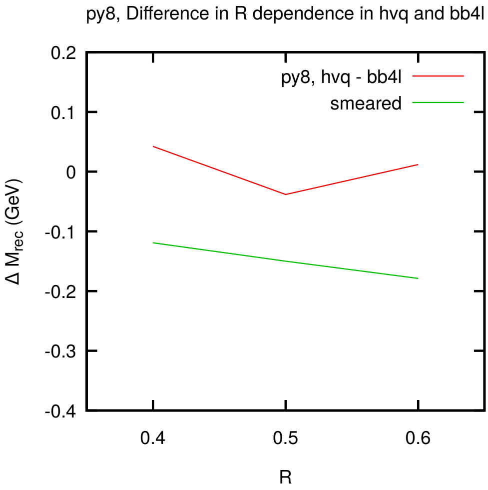
Pythia8, POWHEG-hvq - POWHEG-bb4l comparison

Summary of POWHEG-hvq hw7 - POWHEG-bb4l (with Pythia8) comparison:

M_{rec} (GeV)						
	Full			Shower only		
	bb4l	hvq	Δ	bb4l	hvq	Δ
$\sigma = 0$	172.809	172.771	0.038	172.544	172.493	0.051
$\sigma = 15$	172.698	172.548	0.150	171.396	171.303	0.093

Very modest and consistent difference Is it stable under change of the R parameter?

Pythia8, POWHEG-hvq - POWHEG-bb4l comparison: R dependence



Fairly stable.

	No smearing		15 GeV smearing	
	with MEC [GeV]	Δ_{MEC} [MeV]	with MEC [GeV]	Δ_{MEC} [MeV]
`bb̄4l`	172.816 ± 0.013	$+32 \pm 18$	172.721 ± 0.004	$+58 \pm 6$
`tt̄_dec`	172.818 ± 0.007	-17 ± 9	172.873 ± 0.002	-23 ± 3
`hvq`	172.800 ± 0.007	$+59 \pm 10$	172.568 ± 0.002	$+911 \pm 4$

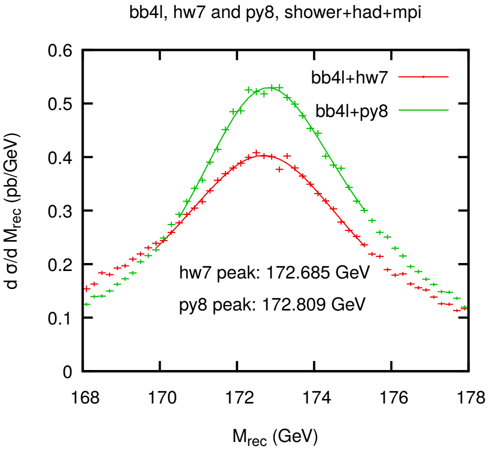
Agreement of `hvq` and `bb̄4l`: MEC in `hvq` is crucial!
MEC $\approx$ NLO corrections in decay.
We thus understand its agreement with `bb̄4l` and `tt̄_dec`.

	No smearing				15 GeV smearing			
	Δ_0	$\mu_{\mathrm{F/R}}$	pdf	α_{s}	Δ_0	$\mu_{\mathrm{F/R}}$	pdf	α_{s}
$\mathtt{b\bar{b}4l}$	$+0$	${}^{+24}_{-32}$	${}^{+3}_{-24}$	± 41	$+0$	${}^{+87}_{-56}$	${}^{+5}_{-33}$	± 193
$\mathtt{t\bar{t}\_dec}$	-1	${}^{+4}_{-5}$	${}^{+3}_{-15}$	± 37	-152	${}^{+9}_{-8}$	${}^{+5}_{-25}$	± 189
`hvq`	$+16$	${}^{+2}_{-3}$	${}^{+3}_{-12}$	± 11	$+154$	${}^{+8}_{-7}$	${}^{+6}_{-23}$	± 25

Very small scale variation for `hvq` and $\mathtt{b\bar{b}4l}$ (we understand why)

α_s variation: substitute for scale uncertainty in radiation from *b*.
Very little effect in `hvq`. We understand why:
radiation from *b* in only done by Pythia there.

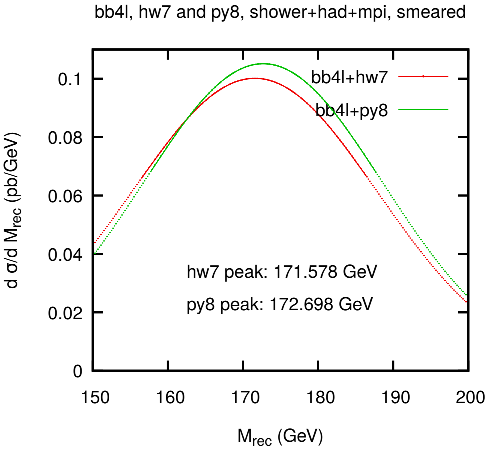
POWHEG-bb4l, Herwig7 - Pythia8 comparison



hw7 − py8: −0.124 MeV

POWHEG-bb4l, Herwig7 - Pythia8 comparison

Same, accounting for experimental errors by smearing the peak with a gaussian distribution with a width of 15 GeV.

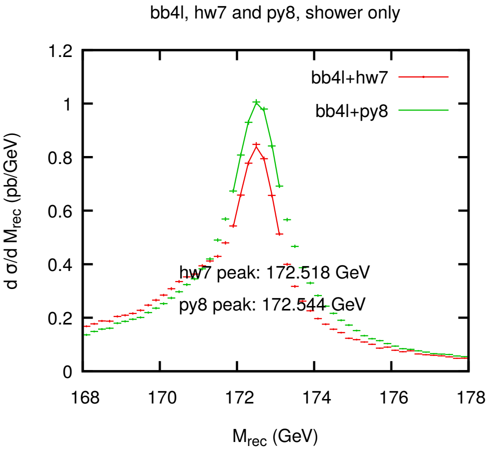


Smearing, $\sigma = 15$ GeV,

hw7 − py8: -1.12 MeV

POWHEG-bb4l, Herwig7 - Pythia8 comparison

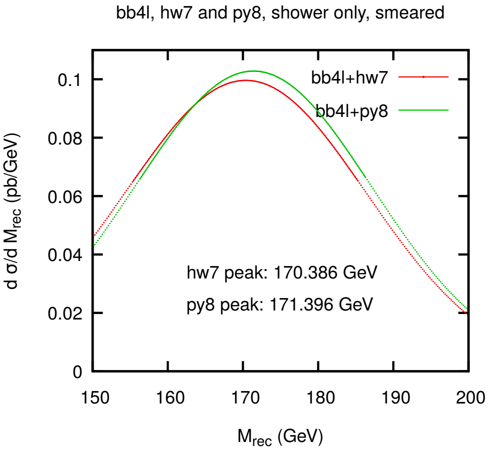
Same stuff, no hadronization and mpi;



hw7 − py8: −0.026 MeV

POWHEG-bb4l, Herwig7 - Pythia8 comparison

No hadronization and mpi, with smearing;



Smearing, $\sigma = 15$ GeV,

hw7 − py8: -1.01 MeV

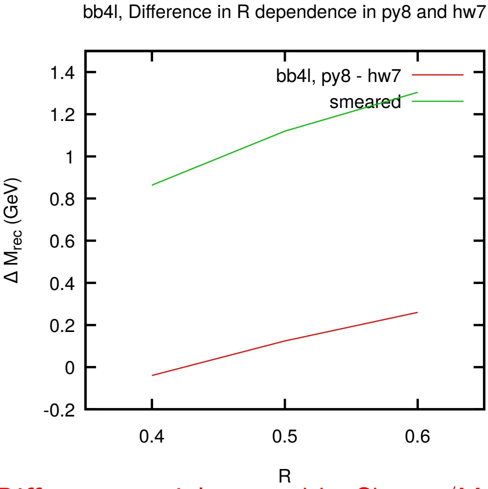
POWHEG-bb4l, Herwig7 - Pythia8 comparison

Summary of POWHEG-bb4l hw7 - py8 comparison:

M_{rec} (GeV)						
	Full			Shower only		
	hw7	py8	Δ	hw7	py8	Δ
$\sigma = 0$	172.685	172.809	0.124	172.518	172.544	0.026
$\sigma = 15$	171.578	172.698	1.12	170.386	171.396	1.01

Modest differences in the unsmeared case; but with smearing, we see very large differences.

POWHEG-bb4l, Herwig7 - Pythia8 comparison



Different slope in their R dependence: at least one of them needs tuning to fit it. This may reduce the differences in extracted mass.

Differences mainly caused by Shower/Matching effects.

Jet energy peak

Agashe,Franceschini,Kim,Schulze,2016

	$E_{b-\text{jet peak}}$ (GeV)	
	bb4l	hvq
hw7	68.88 ± 0.40	69.67 ± 0.26
py8	71.24 ± 0.40	70.77 ± 0.27
hw7, no had.	68.09 ± 0.45	68.30 ± 0.28
py8, no had	69.64 ± 0.44	69.04 ± 0.27

Here $B = 0.45$, so:

- bb4l, hw7 - py8: $\Delta m_t = 5$ GeV, (only shower: 3.4 GeV)
- hvq, hw7 - py8: $\Delta m_t = 2.4$ GeV (only shower: 0.74 GeV)

Lepton Observables

Frixione, Mitov, 2014

Deviations in top mass values:
comparison of bb4l and ttbNLOdec, both with Pythia8

	ΔM_{top} (GeV)		
	Mom 1	Mom 2	Mom 3
$p_t(l^+)$	-0.8 $\pm$ 0.4	-0.7 $\pm$ 0.3	-0.6 $\pm$ 0.5
$p_t(l^+l^-)$	1.1 $\pm$ 0.3	1.6 $\pm$ 0.2	2.6 $\pm$ 0.3
$m(l^+, l^-)$	-0.8 $\pm$ 0.6	-0.6 $\pm$ 0.4	-0.1 $\pm$ 0.7
$E(l^+l^-)$	-0.3 $\pm$ 0.5	-0.4 $\pm$ 0.4	-0.3 $\pm$ 0.5
$p_t(l^+) + p_t(l^-)$	-0.4 $\pm$ 0.4	-0.5 $\pm$ 0.3	-0.9 $\pm$ 0.4

Generally good agreement between the two;
the only (marginal) exception of $p_t(l^+l^-)$.

Lepton Observables

Deviations in top mass values:
comparison of bb4l and hvq, both with Pythia8

	$\Delta M_{\rm top}$ (GeV)		
	Mom 1	Mom 2	Mom 3
$p_t(l^+)$	-0.1 $\pm$ 0.4	0.2 $\pm$ 0.3	0.6 $\pm$ 0.5
$p_t(l^+l^-)$	2.4 $\pm$ 0.3	2.8 $\pm$ 0.2	3.8 $\pm$ 0.3
$m(l^+, l^-)$	-1.8 $\pm$ 0.6	-1.2 $\pm$ 0.4	-0.4 $\pm$ 0.6
$E(l^+l^-)$	0.2 $\pm$ 0.5	0.4 $\pm$ 0.4	0.9 $\pm$ 0.5
$p_t(l^+) + p_t(l^-)$	-0.1 $\pm$ 0.4	-0.1 $\pm$ 0.3	-0.2 $\pm$ 0.4

Good agreement for 1st, 4th and 5th observable. These are the observables that were argued to be less sensitive to shower and spin correlation effects by Frixione and Mitov.

Lepton Observables

Deviations in top mass values:
comparison of Pythia8 and Herwig7, both with bb4l

	ΔM_{top} (GeV)		
	Mom 1	Mom 2	Mom 3
$p_t(l^+)$	3.4 ± 0.4	4.0 ± 0.2	4.9 ± 0.4
$p_t(l^+ l^-)$	4.6 ± 0.3	5.3 ± 0.2	6.5 ± 0.2
$m(l^+, l^-)$	0.7 ± 0.5	1.2 ± 0.3	1.8 ± 0.5
$E(l^+ l^-)$	2.8 ± 0.4	3.0 ± 0.3	3.3 ± 0.4
$p_t(l^+) + p_t(l^-)$	3.2 ± 0.4	3.7 ± 0.2	4.2 ± 0.3

Bad agreement in general, also for 1st, 4th and 5th observable.

Lepton Observables

Deviations in top mass values:
comparison of Pythia8 and Herwig7, both with hvq

	ΔM_{top} (GeV)		
	Mom 1	Mom 2	Mom 3
$p_t(l^+)$	2.0 ± 0.4	2.6 ± 0.3	3.5 ± 0.5
$p_t(l^+l^-)$	2.7 ± 0.3	3.3 ± 0.2	4.2 ± 0.3
$m(l^+, l^-)$	0.6 ± 0.6	1.2 ± 0.4	2.0 ± 0.7
$E(l^+l^-)$	1.4 ± 0.5	1.6 ± 0.4	1.8 ± 0.5
$p_t(l^+) + p_t(l^-)$	2.0 ± 0.4	2.5 ± 0.3	3.2 ± 0.4

Still bad, although better than bb4l.

Lepton Observables

Deviations in top mass values:
comparison of bb4l and hvq, both with hw7

	ΔM_{top} (GeV)		
	Mom 1	Mom 2	Mom 3
$p_t(l^+)$	-1.5 $\pm$ 0.4	-1.2 $\pm$ 0.3	-0.8 $\pm$ 0.4
$p_t(l^+l^-)$	0.5 $\pm$ 0.3	0.8 $\pm$ 0.2	1.4 $\pm$ 0.2
$m(l^+, l^-)$	-1.9 $\pm$ 0.5	-1.2 $\pm$ 0.4	-0.2 $\pm$ 0.5
$E(l^+l^-)$	-1.2 $\pm$ 0.4	-1.1 $\pm$ 0.3	-0.7 $\pm$ 0.4
$p_t(l^+) + p_t(l^-)$	-1.3 $\pm$ 0.4	-1.3 $\pm$ 0.2	-1.2 $\pm$ 0.3

Still bad.

Checks and attempts to solve the issue

- B radiation in POWHEG: new impementation of B radiation Buonocore, Tramontano, P.N., from Buonocore master thesis. Irrelevant differences observed.
- 3 alternative (and orthogonal) implementation of NLO+PS shower matching in Herwig7 (also with the help of the authors). 2.5 alternative implementation of the interface with Pythia8. Found equivalent results.
- Herwig7 implements an angular ordered shower. There are issues related to the need of truncated-vetoed shower in the interface with POWHEG. There are, in Herwig7, variants in the implementation of the shower initial conditions that are equivalent to the inclusion of truncated shower. We have tried them, and found no important differences.

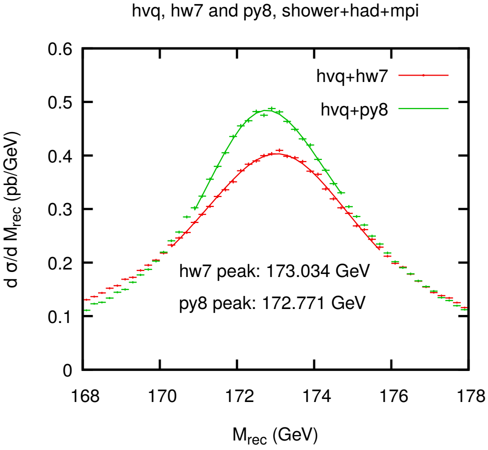
Conclusions

- Useful theoretical work can be done studying of oversimplified observables with state of the art generators.
- This work does not imply that the experimental results are flawed. It must be carried out to expose possible sources of error that might have been overlooked.
- Further work should be carried out to see if there are oversimplified observables that can mimic experimental constraints on the event structure that should be satisfied by generators.
- Surprising results for “golden” observables: also lepton observables influenced by the shower ...

BACKUP

Example: POWHEG-hvq, Pythia8 - Herwig7 comparison

The POWHEG-hvq generator interfaced to Pythia8 is widely used now by the experimental collaborations. We consider the differences we get when switching to Herwig7.

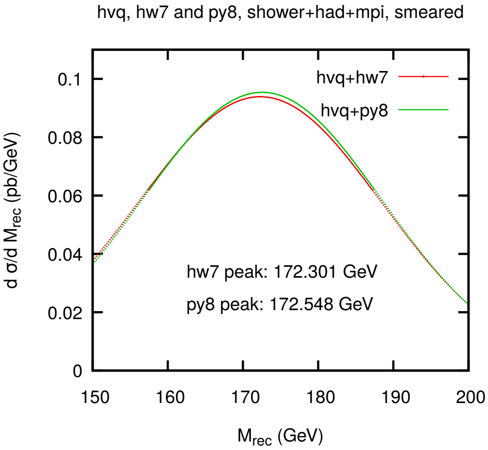


Peak position obtained by fitting peak distribution with a skewed Lorentian:

hw7 − py8: 263 MeV

Example: POWHEG-hvq, Pythia8 - Herwig7 comparison

Same, accounting for experimental errors by smearing the peak with a gaussian distribution with a width of 15 GeV.



$$f_{sm}(x) \propto \int \mathrm{d}y f(y) \times \exp\left[-\frac{(y-x)^2}{2\sigma^2}\right],$$

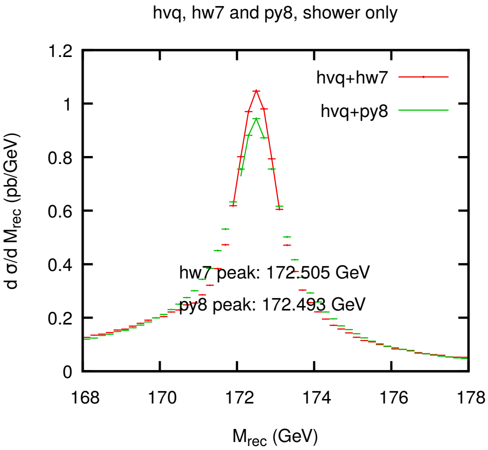
$\sigma = 15$ GeV,

Peak from a fit with a 4th degree polynomial.

hw7 − py8: −247 MeV

Example: POWHEG-hvq, Pythia8 - Herwig7 comparison

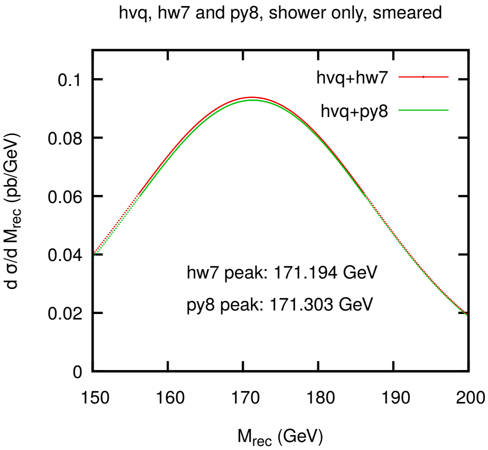
Same stuff, no hadronization and mpi;



hw7 − py8: 12 MeV

Example: POWHEG-hvq, Pythia8 - Herwig7 comparison

No hadronization and mpi, with smearing;



Smearing, $\sigma = 15$ GeV,

hw7 − py8: −109 MeV

Example: POWHEG-hvq, Pythia8 - Herwig7 comparison

Summary of POWHEG-hvq - py8 comparison:

M_{rec} (GeV)						
	Full			Shower only		
	Herwig7	Pythia8	Δ	Herwig7	Pythia8	Δ
$\sigma = 0$	173.034	172.771	0.263	172.505	172.493	0.012
$\sigma = 15$	172.301	172.548	-0.247	171.194	171.303	-0.109

Sizeable difference, but well below the current $\pm 0.6 GeV$ experimental results.

The different shape around the peak region is worrysome.

Hadronization seems to be responsible for the discrepancy.