Top-quark mass determination using new NLO+PS generators

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*In collaboration with T. Ježo, P. Nason and C. Oleari [1712.XXXX]

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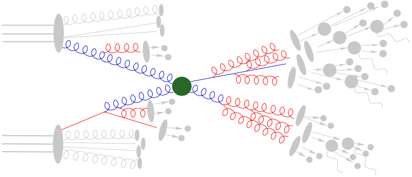

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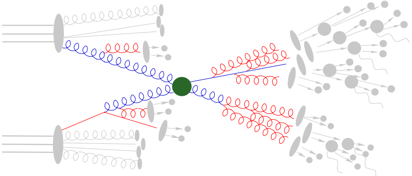

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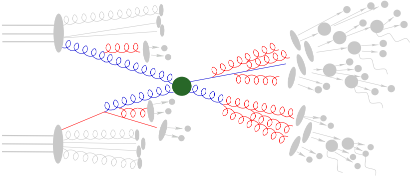

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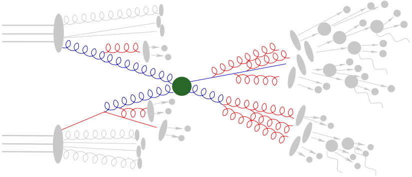

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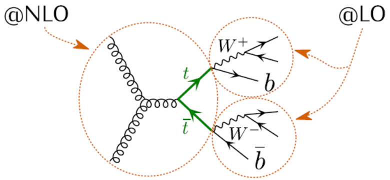
- Vetoed shower: emissions harder than the first one are vetoed.
- The SMC `Pythia` and `Herwig` offer the possibility to complete events generated with `POWHEG BOX` (LHIUP).

Three current implementation of top pair production in POWHEG BOX

1. *hvq* [arXiv:0707.3088]



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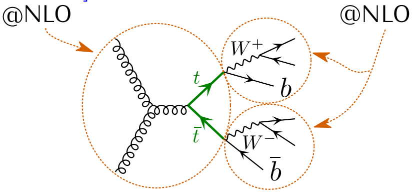

   - ⇒ NLO corrections in production and decay using NWA.
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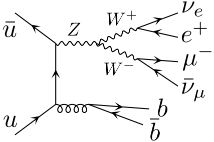
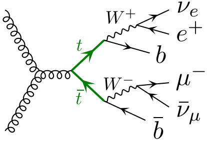
3. $b\bar{b}4\ell$ [arXiv:1607.04538]

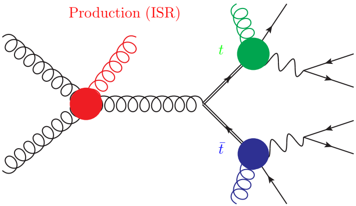




   - ⇒ $pp \to b\bar{b}\ell\bar{\nu}_\ell\bar{l}\nu_l$ at NLO.
   - ⇒ Exact spin correlation and offshell effects at NLO
   - ⇒ Interference with process sharing the same final state at NLO.
   - ⇒ Interference of radiation in production and decay.

Interface between POWHEG BOX RES and SMC

- New resonance-aware formalism that generates emissions preserving the virtuality of the intermediate resonances. This new formalism also offers the opportunity to generate multiple emissions.



$$d\sigma = \tilde{B}\, d\Phi_b \prod_{\alpha_{\rm ISR}, \alpha_b, \alpha_{\bar{b}}} \left[\Delta_\alpha(k_\perp^{\rm min}) + \Delta_\alpha(k_\perp^\alpha) \frac{R_\alpha(\Phi_b, \Phi_{\rm rad}^\alpha)}{B(\Phi_b)} d\Phi_{\rm rad} \right] .$$

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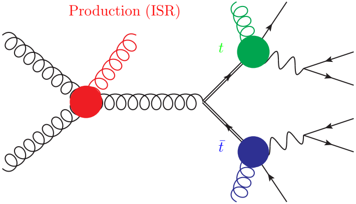

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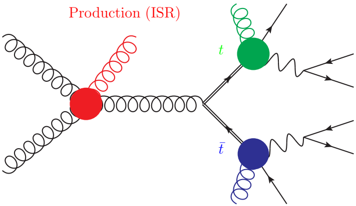

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- The SMC programs `Pythia8` and `Herwig7` veto radiation in production harder than the `POWHEG` one. Radiation from resonances is left, by default, unrestricted.
- We implemented the `PowhegHooksBB4L` and `bb4lShowerVeto` classes to perform the veto also in the resonances decay.

Our strategy

Experimental analyses based on *hvq*: we want to show it is obsolete and it should be replaced with $b\bar{b}4\ell$ (or with $t\bar{t}dec$ for semileptonic or hadronic top decay). In order to do this, we employed a simplified version of the **template method**.

1. We generate samples $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ for $m_t = m_{t,c} = 172.5$ GeV with the *hvq*, $t\bar{t}dec$ and $b\bar{b}4\ell$ generators and we shower them with `Pythia 8` and `Herwig 7`.

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2. We consider a generic observable that can be written as
$$O = O_c + B(m_t - m_{t,c}) + \mathcal{O}(m_t - m_{t,c})^2.$$
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3. We generate samples for several m_t values for *hvq* that we shower with `Pythia 8` in order to extract the B coefficient of a given observable. We choose the value $b\bar{b}4\ell$+`Pythia 8` as reference sample, the mass extracted using another generator is given by
$$m_t = m_{t,c} - \frac{O_c - O_c^{\text{ref}}}{B}$$

Reconstructed top mass

- We take m_{Wb_j} as a proxy for all top-mass sensitive observables that rely upon the mass of the decay products.
  $\Rightarrow$ $W^{\pm}$ = hardest $\ell^{\pm}$ + corresponding hardest (anti-)neutrino;
  $\Rightarrow$ B-jet: jet containing the hardest $\bar{B}$ (B) hadron;
  $\Rightarrow$ We assume to know the b flavour in the B-jet to match it with the W.

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$$\tilde{f}(m_{Wb_j}) = \frac{b\left[1 + d\left(m_{Wb_j} - a\right)\right]}{\left(m_{Wb_j} - a\right)^2 + b^2} + e\,, \quad m_{Wb_j}^{\max} = a + \frac{\sqrt{1 + d^2\, b^2} - 1}{2d}$$

1. $m_{Wb_j}^{\max}$ is assigned to the bin with highest y value;
2. We set Δ equal to the FWHM.
3. We find the values of the parameters that minimize the χ^2in the range $[m_{Wb_j}^{\max} - \Delta, m_{Wb_j}^{\max} + \Delta]$.
4. From the fitted function we extract $m_{Wb_j}^{\max}$
5. If $\tilde{\chi}^2 < 2$ we stop; otherwise $\Delta \to 0.95 \times \Delta$ and we go to step 3.

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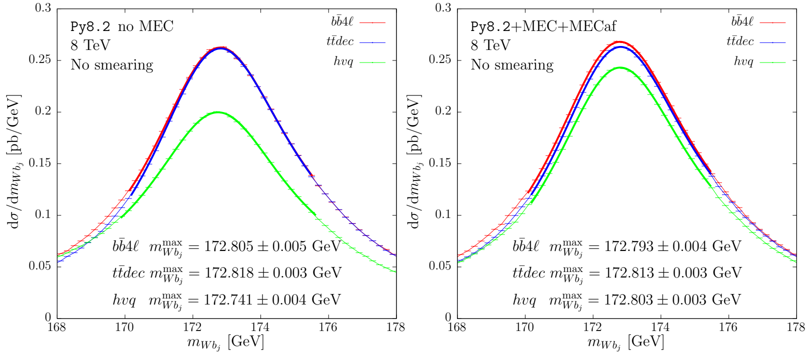
- We can assume $B \simeq 1$, thus

$$\boxed{\Delta m_t \simeq -\Delta m_{Wb_j}^{\max}}$$

Reconstructed top mass: which NLO generator?

Brief look without smearing:
Large shape differences with *hvq* if MEC are off.
With MEC, differences among the generators of the order of 10-20 MeV.



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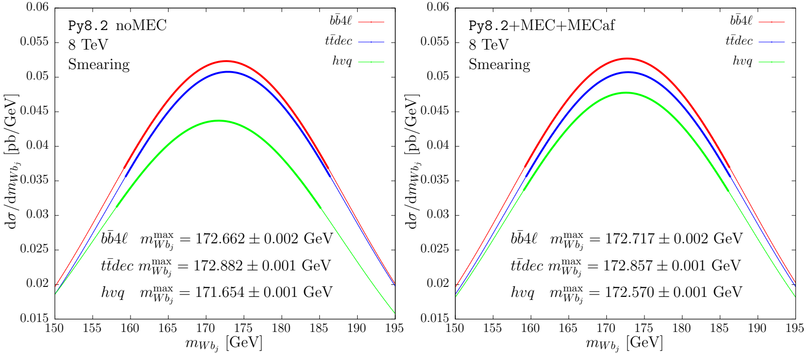


Scale: envelope of 7 scale choices

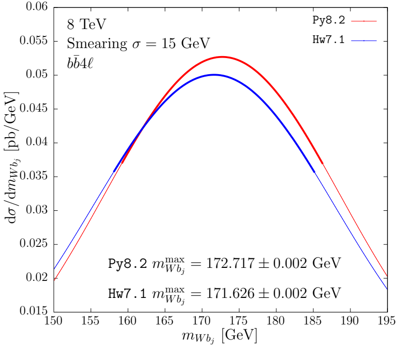
PDF: rwgt members of `PDF4LHC15_nlo_30_pdfas` (hvq only)

α_S: `NNPDF30_nlo_as115`, `NNPDF30_nlo_as121`

	% − $bb4\ell$	(μ_R, μ_F)	PDF	α_S
$b\bar{b}4\ell$	+0 MeV	$^{+86}_{-53}$ MeV	-	±64 MeV
$t\bar{t}dec$	**+140 MeV**	$^{+6}_{-6}$ MeV	-	±54 MeV
hvq	**−147 MeV**	$^{+7}_{-7}$ MeV	±5 MeV	±9 MeV

Reconstructed top mass: which SMC generator?

$b\bar{b}4\ell$



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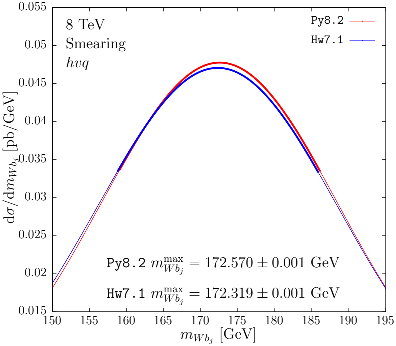

- 1 GeV displacement between Py8.2 and Hw7.1;
- 0.25 GeV displacement between Py8.2 and Hw7.1;

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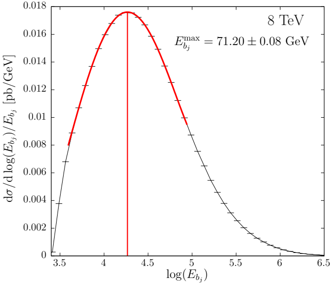
- We fit $\frac{d\,\sigma}{d\,\log E_{b_j}}\frac{1}{E_{b_j}}$ to a fourth order polynomial.



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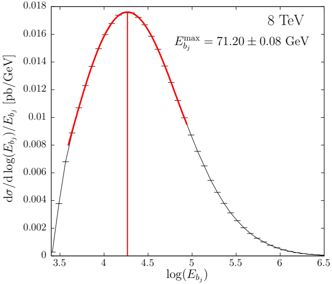
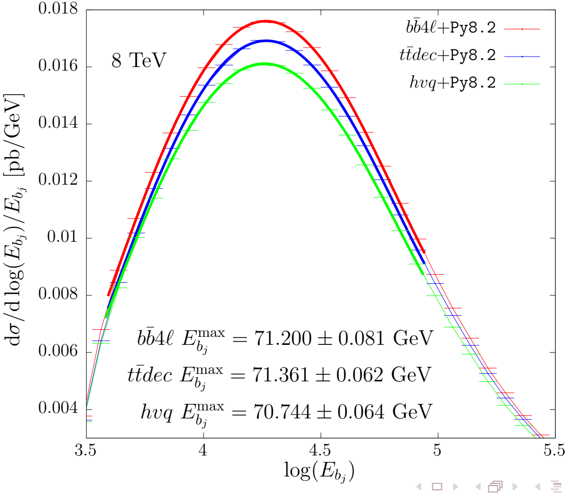


- We find $B \simeq \frac{1}{2} \Rightarrow \boxed{\Delta m_t \simeq -2\Delta E_{b_j}^{\max}}.$

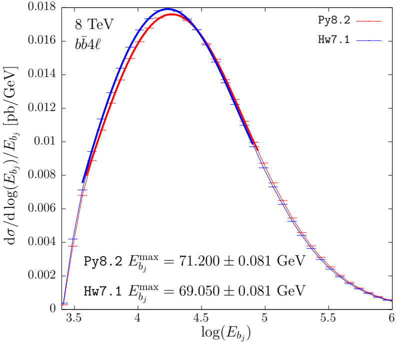
B-jet energy peaks: which NLO generator?

Large differences between $b\bar{b}4\ell$ and hvq that does not contain radiative correction in decays and the Wt contribution. ($+456 \pm 103$ MeV)
Small differences between $b\bar{b}4\ell$ and $t\bar{t}dec$ that has radiative correction in decays, implemented using NWA, and the Wt at LO. (-161 ± 102 MeV)



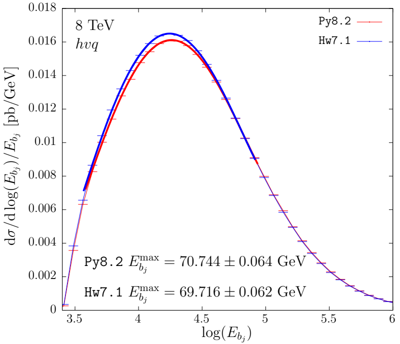
B-jet energy peaks: which SMC generator?

$b\bar{b}4\ell$



- 2 GeV displacement between Py8.2 and Hw7.1;
- $\boxed{\Delta m_t \simeq -4 \text{ GeV}}$

hvq



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with $j = 1, 2, 3$.

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- Assume $\langle O_i \rangle = O_{c,i} + B_i \left(m_t^j - m_{t,\,c}^j \right)$, thus the extracted mass corresponding to the observable i is given by

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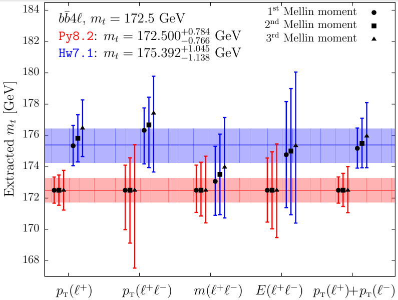
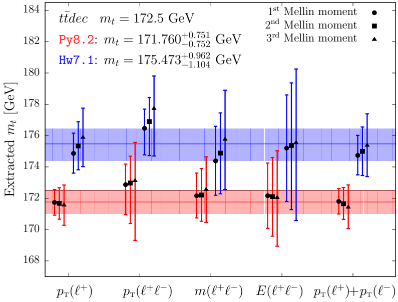
- Obtain $O_{c,i}$ and its uncertainty due to PDF and scale variations. Combine all the errors in quadrature and $m_{t,i}$ and $\Delta m_{t,i}$.
- Average all the measurements using as covariance matrix

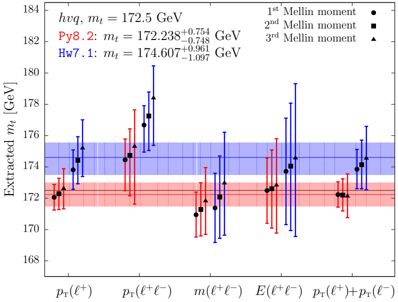
$$V_{ik} = \Delta m_{t,i}{}^2 \delta_{ik} + (1-\delta_{ik}) \min\left(\Delta m_{t,i}{}^2,\, \Delta m_{t,k}{}^2,\, \rho_{ik} \Delta m_{t,i} \Delta m_{t,k} \right)$$

where ρ_{ik} is the statistical correlation between O_i and O_k.

Leptonic observables







Summary and Outlooks

- **Which Observable**?
  - smeared m_{Wb_j}: oversimplification; small sensitivity to the production mechanism (small pdf/scale variations);
  - E_{b_j}: small sensitivity to the production mechanism, large shower uncertainties.
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  - leptonic observables: sensitivity to the production mechanism, large shower uncertainties.
- **Which NLO generator** (using `Pythia8`+MEC)?
  - $b\bar{b}4\ell$ generator is the most accurate one and should be preferred if possible.
  - smeared m_{Wb_j}: *hvq* and $t\bar{t}dec$ lead to a systematic uncertainty of roughly 150 MeV.
  - $E_{b_j}^{\max}$: $t\bar{t}dec$ $\Delta m_t \simeq 0.3 \pm 0.2$ GeV, *hvq* $\Delta m_t \simeq 0.9 \pm 0.2$ GeV.
  - leptonic observables: $t\bar{t}dec$ m_t 700 MeV smaller than the nominal value, *hvq* not accurate for observables depending on spin correlations although better average ($m_t = 172.2$ GeV).

Summary and Outlooks

- Pythia8 or Herwig7?
  - *hvq* must be showered with both showers, the difference leads to a systematic uncertainty of **250 MeV** when using m_{Wb_j}, **2 GeV** when using E_{b_j}/leptonic observables.
  - when using $b\bar{b}4\ell$ (or $t\bar{t}dec$), the difference between Pythia8 and Herwig7 is greater than **1 GeV** even for m_{Wb_j}, **4 GeV** E_{b_j}, **3 GeV** leptonic observables.
  - matching procedure in Herwig7 introduces new systematic errors and requires further investigation.


YOU CAN NEVER HAVE
TOO MANY BACKUP SLIDES

“Measurement” of the top-quark mass

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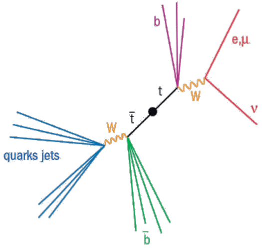

$\Rightarrow$ B-jet;

$\Rightarrow$ W decay products:

$\rightarrow$ charged lepton + neutrino

$\rightarrow$ two light jets

“Measurement” of the top-quark mass

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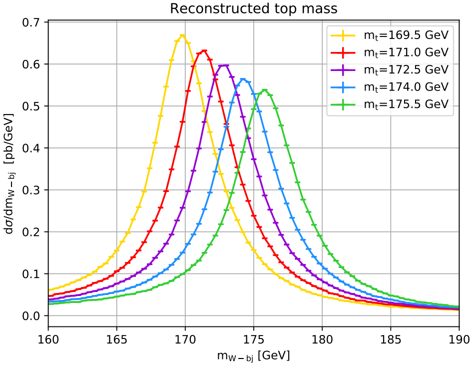

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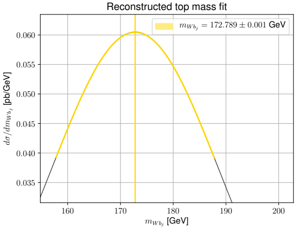

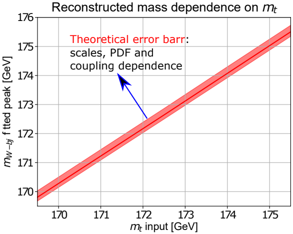

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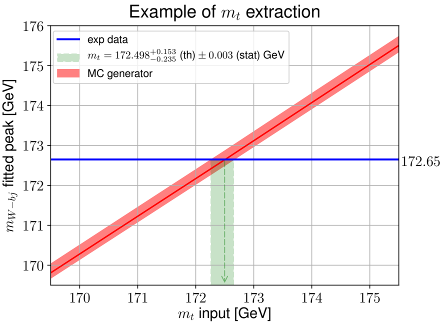

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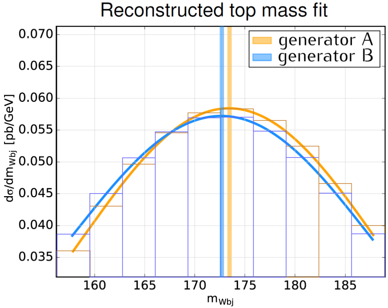
  5. m_t can depend on the MC used



$\Rightarrow$ if A is more accurate than B, use A;
$\Rightarrow$ otherwise $|m_t^A - m_t^B|$ contributes to the systematic uncertanty;

Phenomenological setup

- Process: $pp \to b\,\bar{b}\,e^+\,\mu^-\,\nu_e\,\bar{\nu}_\mu$, dominated by top pair production plus leptonic decay, at $\sqrt{s} = 8$ TeV.
- Central PDF: `MSTW2008`.
- Dynamic scale choice

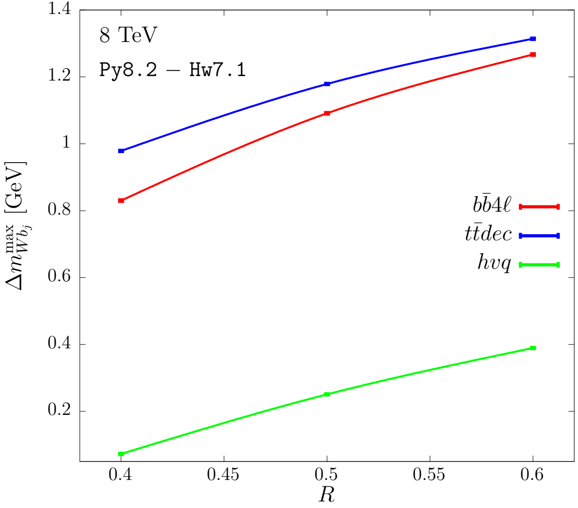
  $t\bar{t}$ events: $\mu = \left[(E_t^2 - p_{z,t}^2)(E_{\bar{t}}^2 - p_{z,\bar{t}}^2)\right]^{1/4}$ $\quad Z\bar{b}b$ events: $\mu = \frac{p_Z^2}{2}$
- Scale variations

  $(K_\mathrm{F}, K_\mathrm{R}) = (1,1)\,,\,(2,2)\,,\,\left(\frac{1}{2},\frac{1}{2}\right)\,,\,(1,2)\,,\,\left(1,\frac{1}{2}\right)\,,\,(2,1)\,,\,\left(\frac{1}{2},1\right)$
- PDF
  - Rwgt using several sets: `PDF4LHC15`, `NNPDF3.0`, `CT14nlo`, `MMHT2014`.
  - Rwgt 30 pdf inside the set `PDF4LHC15_nlo_30_pdfas`, Gaussian symmetric error, for *hvq* only.
- α_S: Use `NNPDF30_nlo_as_0115` and `NNPDF30_nlo_as_0121`; half difference.

Physics objetcs

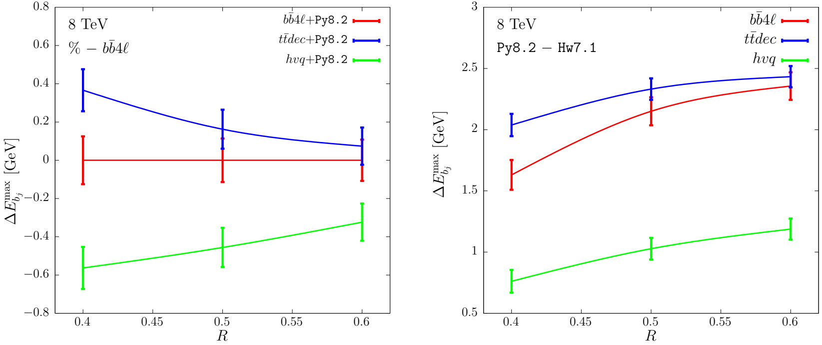
- B hadrons are considered as stable.
- Jets reconstructed using anti-$k_\perp$ algorithm for $R = 0.5$.
- Impose selection cuts to suppress the Wt background:
  $\Rightarrow$ 2 opposite charged leptons with: $p_\perp(\ell) > 20$ GeV, $|\eta(\ell)| < 2.4$
  $\Rightarrow$ 2 B-jet with opposite b flavour with: $p_\perp(j_\mathrm{B}) > 30$ GeV, $|\eta(j_\mathrm{B})| < 2.5$
- We assume to know neutrinos momentum. W^+ reconstructed merging the hardest ℓ^+ and the hardest neutrino; W^- reconstructed merging the hardest ℓ^- and the hardest anti-neutrino.
- Reconstructed t: W^+ and jet containing the hardest b-flavoured hadron; reconstructed $\bar{t}$: W^- and jet containing the hardest $\bar{b}$-flavoured hadron.

m_{Wb_j} extracted peak (with smearing): difference between `Pythia8` and `Herwig7` for different jet radius values.



E_{b_j}: R dependence

$E_{b_j}^{\max}$: difference with $b\bar{b}4\ell$ (left) for all generators showered with `Pythia8`, and difference between `Pythia8` and `Herwig7` (right) for all generators for several values of the jet radius.



E_{b_j}: scale, PDF and α_S dependence

E_{b_j}: independent from the production mechanism, indeed small dependence on scale/PDF.

	$\% - b\bar{b}4\ell$	(μ_R, μ_F)	PDF	α_S	stat
$b\bar{b}4\ell$	+0 MeV	$^{+22}_{-15}$ MeV	-	±35 MeV	±81 MeV
$t\bar{t}dec$	+161 MeV	$^{+22}_{-24}$ MeV	-	±17 MeV	±62 MeV
hvq	−456 MeV	$^{+32}_{-47}$ MeV	±30 MeV	±25 MeV	±64 MeV

Leptonic observables

First Mellin moment for $m_t = m_{t,c}$ for all generators showered with `Pythia8`. The angular coefficients have been obtained by considering three m_t values: 169.5, 172.5, 175.5 GeV.

Obs	gen	B	$\langle O_c \rangle$ [GeV]	$\% - b\bar{b}4\ell$ [MeV]	(μ_F, μ_R) [MeV]	PDF [MeV]	α_S [MeV]
$\langle p_T(\ell^+) \rangle$	$b\bar{b}4\ell$	0.17 ± 0.04	56.653 ± 0.050	-	$^{+79}_{-86}$	-	$\pm 26\ (\pm 92)$
	$t\bar{t}dec$	0.19 ± 0.02	56.804 ± 0.033	$+151 \pm 60$	$^{+84}_{-86}$	-	$\pm 41\ (\pm 23)$
	hvq	0.19 ± 0.02	56.738 ± 0.032	$+85 \pm 59$	$^{+82}_{-86}$	± 130	$\pm 49\ (\pm 23)$
$\langle p_T(\ell^+\ell^-) \rangle$	$b\bar{b}4\ell$	0.30 ± 0.05	69.759 ± 0.059	-	$^{+710}_{-444}$	-	$\pm 85\ (\pm 110)$
	$t\bar{t}dec$	0.30 ± 0.02	69.660 ± 0.040	-100 ± 71	$^{+538}_{-361}$	-	$\pm 78\ (\pm 28)$
	hvq	0.29 ± 0.02	69.201 ± 0.038	-558 ± 71	$^{+553}_{-367}$	± 95	$\pm 95\ (\pm 27)$
$\langle m(\ell^+\ell^-) \rangle$	$b\bar{b}4\ell$	0.31 ± 0.08	108.685 ± 0.099	-	$^{+234}_{-341}$	-	$\pm 57\ (\pm 191)$
	$t\bar{t}dec$	0.31 ± 0.03	108.812 ± 0.065	$+127 \pm 119$	$^{+244}_{-259}$	-	$\pm 33\ (\pm 46)$
	hvq	0.33 ± 0.03	109.200 ± 0.064	$+515 \pm 118$	$^{+247}_{-265}$	± 395	$\pm 68\ (\pm 45)$
$\langle E(\ell^+\ell^-) \rangle$	$b\bar{b}4\ell$	0.55 ± 0.14	186.803 ± 0.163	-	$^{+342}_{-385}$	-	$\pm 540\ (\pm 305)$
	$t\bar{t}dec$	0.56 ± 0.05	187.005 ± 0.107	$+201 \pm 195$	$^{+448}_{-434}$	-	$\pm 474\ (\pm 76)$
	hvq	0.56 ± 0.05	186.809 ± 0.105	$+6 \pm 194$	$^{+441}_{-427}$	± 1068	$\pm 559\ (\pm 74)$
$\langle p_T(\ell^+) + p_T(\ell^-) \rangle$	$b\bar{b}4\ell$	0.38 ± 0.08	113.322 ± 0.095	-	$^{+165}_{-184}$	-	$\pm 93\ (\pm 178)$
	$t\bar{t}dec$	0.39 ± 0.03	113.598 ± 0.063	$+276 \pm 114$	$^{+165}_{-174}$	-	$\pm 72\ (\pm 44)$
	hvq	0.39 ± 0.03	113.425 ± 0.062	$+104 \pm 113$	$^{+165}_{-174}$	± 259	$\pm 101\ (\pm 43)$

Radiation scale in POWHEG BOX

- In the **POWHEG** formalism, the emission probability at a scale μ is given by the Sudakow form factor

$$\Delta(\mu) = \exp\left[-\int d\phi^{\text{rad}}\theta\left(k_\perp(\mu') - k_\perp(\mu)\right)\frac{\alpha_S(\mu')}{2\pi}\frac{R_s\left(k_\perp(\mu')\right)}{B}\right],$$

  where $k_\perp(\mu)$ is the transverse momentum of the emitted particle corresponding to the scale μ.

- In the Fortran code **POWHEG BOX** $\mu = k_\perp$ and there is no way to change the definition of the scale of the emission.
- Since $\alpha_S(\mu) = \alpha_S(\mu; \alpha_S(m_Z)) = \frac{\alpha_S(m_Z)}{1+\beta_0\alpha_S(m_Z)\log\left(\frac{\mu^2}{m_Z^2}\right)}$ instead of changing μ, is possible to change the reference value of $\alpha_S(m_Z)$.
- For an average $k_\perp$=30 GeV, we get:

$$\alpha_S(k_\perp; 0.118) = 0.1402$$

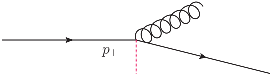
$$\alpha_S(2k_\perp; 0.118) = 0.1253 \quad \alpha_S(0.5k_\perp; 0.118) = 0.1590$$

$$\alpha_S(k_\perp; 0.115) = 0.1360 \quad \alpha_S(k_\perp; 0.121) = 0.1444$$

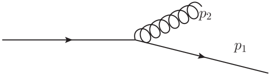
- α_S variations should be enhanced by a factor 4 to get the corresponding uncertainty on the scale of the emission.

Interface between POWHEG BOX and SMC

- The radiation provided by the SMC with transverse momentum larger than scalup $= k_\perp^{\texttt{POWHEG}}$ must be vetoed: vetoed showers.



ISR: $\left(k_\perp^{\texttt{POWHEG}}\right)^2 = p_\perp^2$



FSR: $\left(k_\perp^{\texttt{POWHEG}}\right)^2 = 2p_1 \cdot p_2 \frac{E_2}{E_1}$

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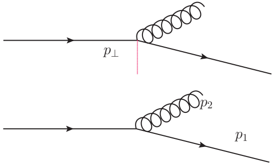

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$$\left(k_\perp^{\texttt{POWHEG}}\right)^2 = d_{12} = 2p_1 \cdot p_2 \frac{E_1\, E_2}{(E_1 + E_2)^2}$$

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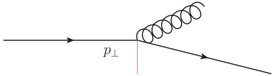

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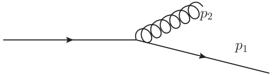

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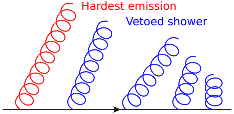
- In Pythia8, it is possible to veto using this "improved" definition: PowhegHooks.

Interface between POWHEG BOX and SMC

- Pythia8 is a $k_\perp$-ordered shower and the hadronization model employed is the Lund string fragmentation one.



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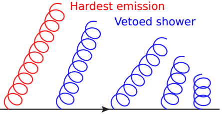

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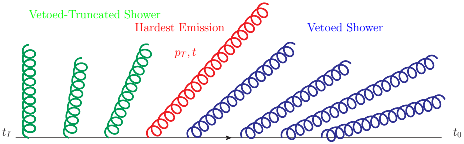
- Herwig7 is an angular-ordered shower and it employs the cluster model.



$\Rightarrow$ Truncated-vetoed showers often give rise to little contribution; so only a vetoed shower is implemented.

POWHEG BOX RES

- Technical problems of processes containing resonances whose decay products can radiate:
  1. NLO computation: we need a subtraction scheme that constructs the counterterms to real diagrams preserving the virtuality of the resonances, in order not to spoil the cancellation of the infra-red poles. This simply results in poor convergence.
  2. Hardest emission generation (more severe): in POWHEG formalism, the emission probability is described by R/B. If R contains an onshell resonance, while B does not, the ratio R/B is large, also for high transverse momentum radiation. Moreover it does not approach the Altarelli-Parisi splitting function in the infrared limit, as it is required by the POWHEG method, giving rise to unphysical distortions of the distributions.

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- If we can separate the resonances in different singular regions (e.g. $pp \to t\bar{t}$), we can write

$$d\sigma = \tilde{B} d\Phi_b \prod_{\alpha_{\mathrm{ISR}}, \alpha_b, \alpha_{\bar{b}}} \left[\Delta_\alpha(k_\perp^{\mathrm{min}}) + \Delta_\alpha(k_\perp^\alpha) \frac{R_\alpha(\Phi_b, \Phi_{\mathrm{rad}}^\alpha)}{B(\Phi_b)} d\Phi_{\mathrm{rad}} \right] .$$

The multi-emission formalism is crucial for process where ISR is much more likely: in this way the first emission is generated by POWHEG BOX RES instead of the PS.

POWHEG BOX RES and SMC: general algorithm

- When a LH event is read we get
  1. Production process (ISR): Read scalup from the file. For remnant we set scalup $= \sqrt{\hat{s}}/2$.
  2. t (ot $\bar{t}$) resonance: If an emission is present,

$$\boxed{\mu_t^2 = 2p_b \cdot p_g \frac{E_g}{E_b}}$$

     in the top frame. Otherwise $\mu_t^2 = 0.8$ GeV^2.*
  3. Check that the PS generates emissions off the top decay products with a $k_\perp$ smaller than μ_t.

*For *hvq* and remnant events in $b\bar{b}4\ell$ emissions in decay are not generated, thus no veto is performed.

POWHEG BOX RES and PYHTIA 8 and HERWIG 7

We implemented subroutines to veto radiation in the t resonance:

- PYTHIA 8: It is possible to use PowhegHooks to veto radiation in production. We implemented PowhegHooksBB4L for emissions in decay:
  1. FSREmissionVeto (default):
     - After each emission, we decide if keeping or rejecting it.
     - It employs the POWHEG BOX definition of $k_\perp$.
  2. ScaleResonance:
     - μ_t is used as starting scale for the shower off the t $(\bar{t})$ resonance.
     - The shower scale is the PYHTIA transverse momentum.

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- HERWIG 7: we implemented two alternatives
  1. bb4lShowerVeto (default):
     - After each emission, we decide if keeping or rejecting it.
     - Herwig7 provides us the $k_\perp$ and the momenta of the emitted particles are not known yet.
  2. bb4lFullShowerVeto:
     - before the hadronization phase, we look at the emissions originated from the t decay chain, if every emission is softer than the POWHEG one the event is accepted, otherwise it is reshowered.
     - $k_\perp$ is computed using the "improved" POWHEG BOX definition.
     - Partons have been reshuffled and the $k_\perp$ computed contains ambiguity due to this procedure.

Matching procedures

- We now compare the results obtained with $b\bar{b}4\ell$+`Pythia8` using the different matching procedures. Results are expressed in GeV.

Observable	`FSREmission`	`FSR+PowhegHooks`	`ScaleResonance`
$m_{Wb_j}^{\max}$	172.793 ± 0.004	172.828 ± 0.005	172.816 ± 0.004
$m_{Wb_j}^{\max}$ (smear)	172.717 ± 0.002	172.794 ± 0.002	172.737 ± 0.002
$E_{b_j}^{\max}$	71.200 ± 0.081	71.204 ± 0.082	71.179 ± 0.082

- We now compare the results obtained with $b\bar{b}4\ell$+`Herwig7` using the different matching procedures. Results are expressed in GeV.

Observable	`bb4lShowerVeto`	`bb4lFullShowerVeto`
$m_{Wb_j}^{\max}$	172.727 ± 0.005	172.776 ± 0.005
$m_{Wb_j}^{\max}$ (smear)	171.626 ± 0.002	171.829 ± 0.002
$E_{b_j}^{\max}$	69.050 ± 0.081	69.190 ± 0.082