A Study of the Top Mass Determination Using New NLO+PS generators

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Work done in collaboration with
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- We rely only upon full generators in order to determine the theoretical uncertainties (we ignore problems related to mass renormalons, MC mass definitions, etc.)
- We determine the errors by fitting "pseudo" (generated by us) data with different generators, and extracting the generator mass parameter.
- We study three observables:
  1. invariant mass of the top decay products;
  2. b-jet energy peak (Franceschini etal, 2015);
  3. lepton energy spectrum (Kawabata etal, 2014) $\rightarrow$ just started!

ALL VERY PRELIMINARY!!!

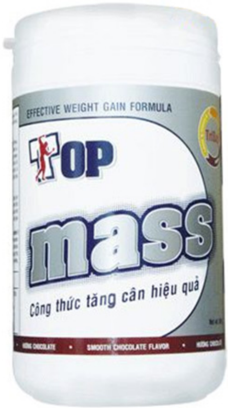
Outline

We have:

- compared three NLO+PS generators:
  `hvq`, `ttb_NLO_dec`, `b_bbar_4l`.
- studied the effect of scale variations in the `ttb_NLO_dec` and `b_bbar_4l` generators.
- studied the α_s sensitivity of the results in the `b_bbar_4l` generator.
- studied the PDF error in the `b_bbar_4l` generators.
- performed an initial study of hadronization uncertainties by comparing two shower generators: `Pythia8` and `Herwig7`.

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.
- `ttb_NLO_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.
- `b_bbar_4l`:(Ježo etal, 2016) Full NLO with off shell effects for $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$, As presented in Tomáš's talk.



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 $\sigma = 15\,\text{GeV}$.

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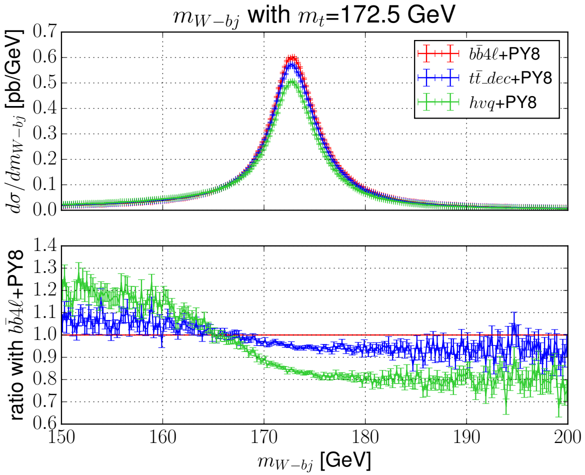
We look for:

- Effects that displace the peak. These constitute an irreducible 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).

Comparison of hvq, ttb_NLO_dec and b_bbar_4l



Peak not appreciably displaced; b_bbar_4l-hvq shape differences.

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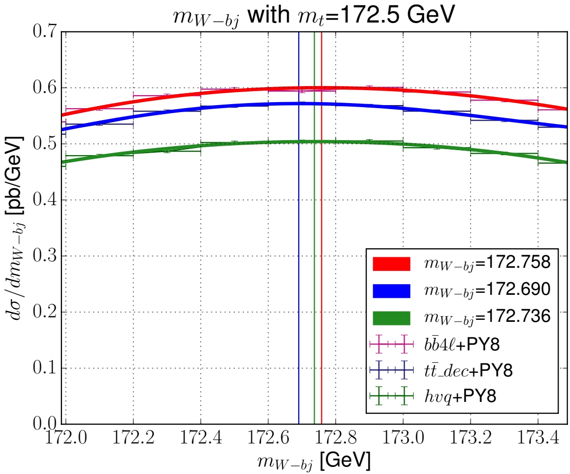
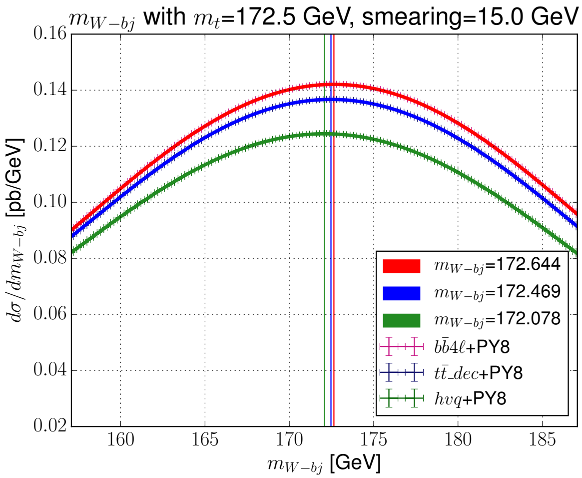


Polynomial fit to get peak position. No smearing. Negligible displacement.

Comparison of hvq, ttb_NLO_dec and b_bbar_4l



Smearing: hvq and b_bbar_4l differ by 566 MeV!

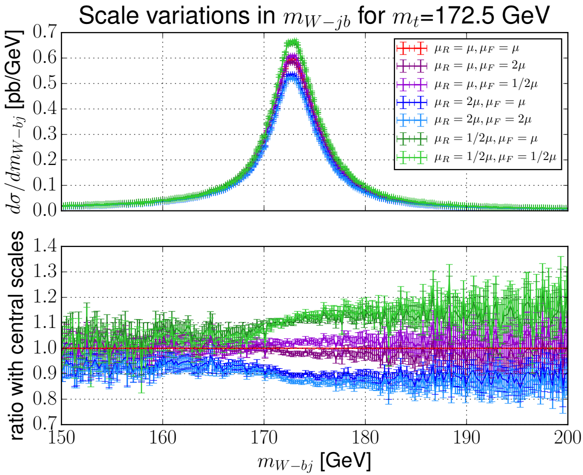
NLO-PS comparison summary

- Without smearing, negligible differences in peak position.
- With smearing:
  - `b_bbar_4l` and `ttb_NLO_dec` display minor differences.
  - `hvq` displays substantial differences.

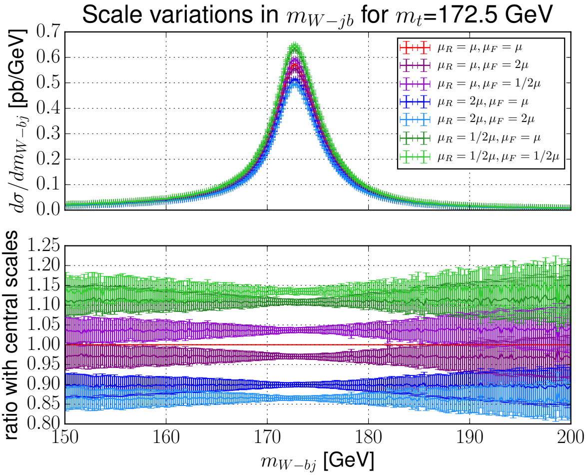
Since the `hvq` implementation is in many ways two, we do not plan to use it to estimate the errors.

Dynamic scales choice:

$$\mu^2 = E_t^T \cdot E_{\bar{t}}^T \; ; \quad E^T = \sqrt{p^2 + |\vec{p}_T|^2}$$

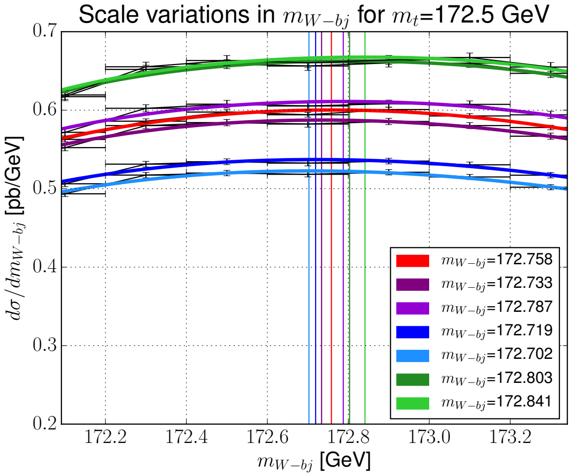


Scale variations in ttb_NLO_dec



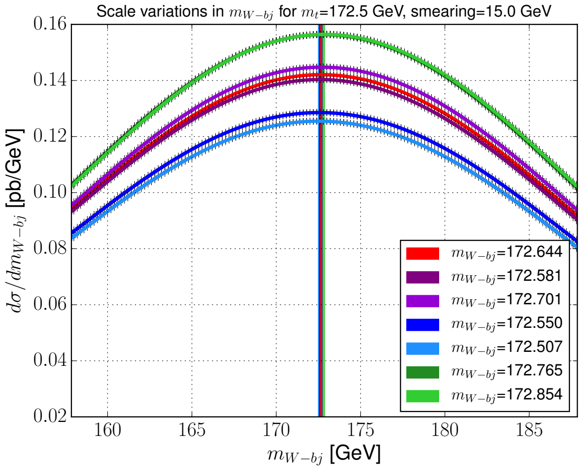
ttb_NLO_dec: no appreciable scale variation effects. Why? (needs further study).

Scale variations: impact on extracted m_t, no smearing



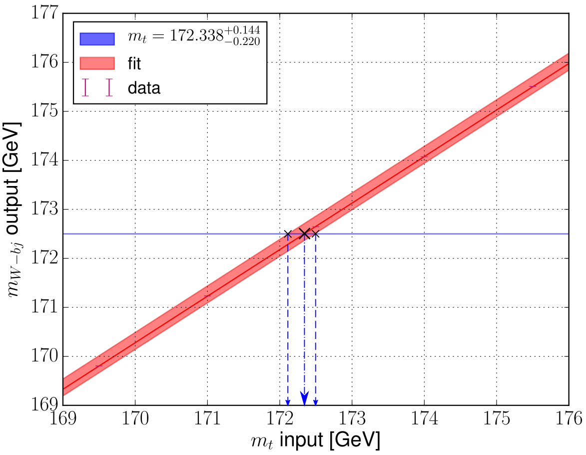
Difference between the minimum and the maximum: 139 MeV...

Scale variations: impact on extracted m_t, smearing



... and it becomes 347 MeV for 15 GeV smearing.

Reconstructed top mass for ak05 using $b\bar{b}4\ell$+PY8, smearing=15.0 GeV



Since m_t and m_{W-bj} are strongly correlated, we find a comparable spread: 347 MeV in m_{W-bj} corresponding to an uncertanty of $+0.144\,,-0.220$ GeV on m_t.

Scale variations: Summary

- Scale variations in `b_bbar_4l`: $^{+144}_{-220}$ MeV impact on mass determination.
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Consider that:

- Scale variations in POWHEG behave as a factor that only depends upon the underlying Born kinematics.
  Thus, they don't affect radiation.
- Suitable scale variation in the radiation procedure should also be considered, since it may affect the B-jet shape.

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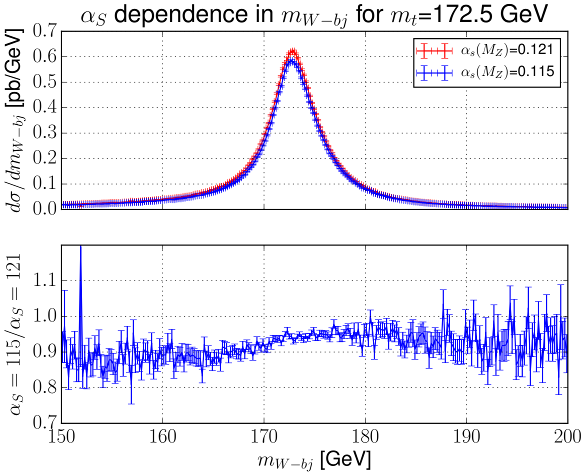
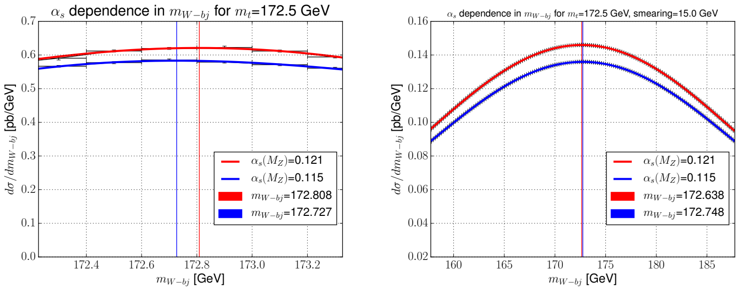
A change in the value of α_s does affect radiation. Thus, a study on α_s dependency may also give some indication on the sensitivity to B-jet shape uncertainties.

α_s dependence

This study cannot be performed using reweighting, if we want also to consider the effect of changing α_S in radiation.



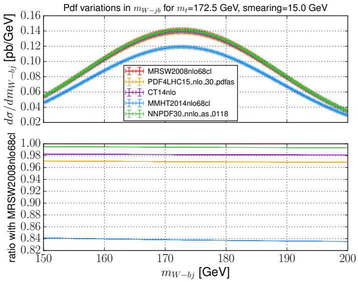
α_s dependence arises only from the different structure of the b-jet.

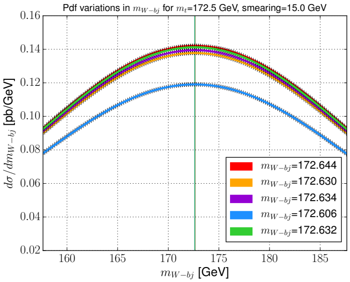


The displacement given by a difference in α_s of the 5% is 81 MeV without smearing, 110 MeV with a 15 GeV smearing. (Small but irreducible!)

PDF dependence

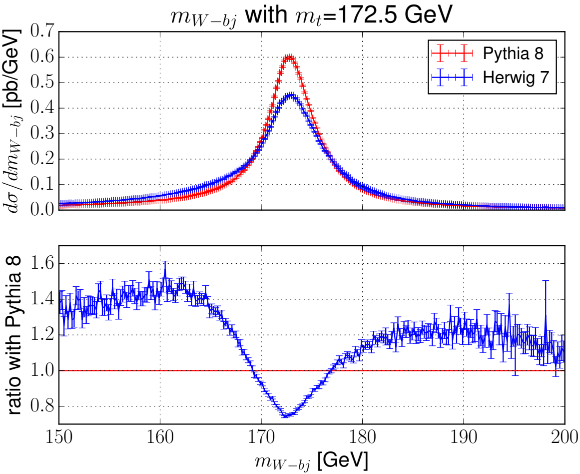
Varying the PDF, even if smearing is applied, there is no significant displacement of the peak





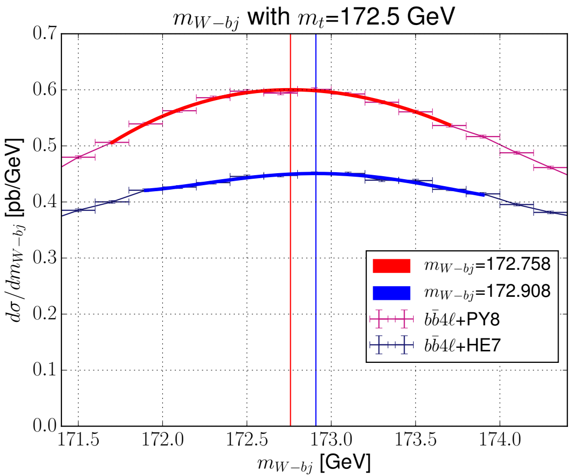
Because of this, the only effect from the PDF choice is the value of α_s (because it affects the b-jet shape).

Shower Uncertainties: Herwig7 and Pythia8



Marked differences in distributions.

Shower Uncertainties: Herwig7 and Pythia8



Small difference in mass peak (150 MeV)

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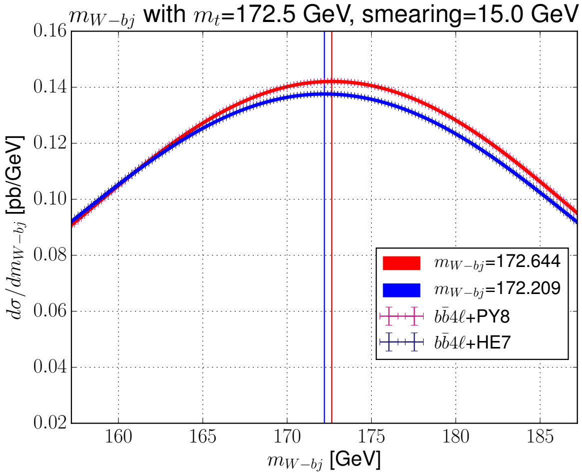
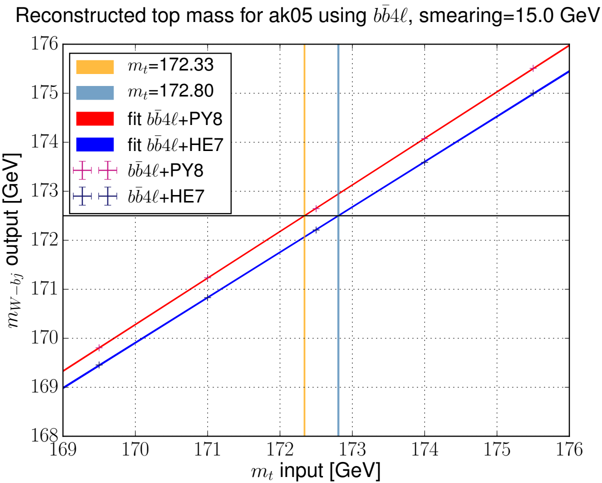


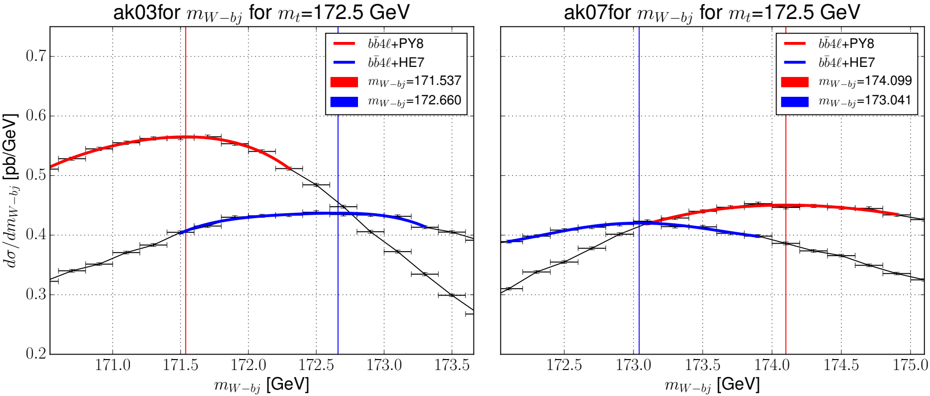
After smearing, larger mass difference (435 MeV).

Mass extraction example. Herwig7 vs. Pythia8



Assuming that we measure $m_{Wb_j} = 172.5\,\text{GeV}$, the extracted mass differs by 470 MeV.

Large difference in shape: is the closeness of the peak position accidental? Try different cone sizes:

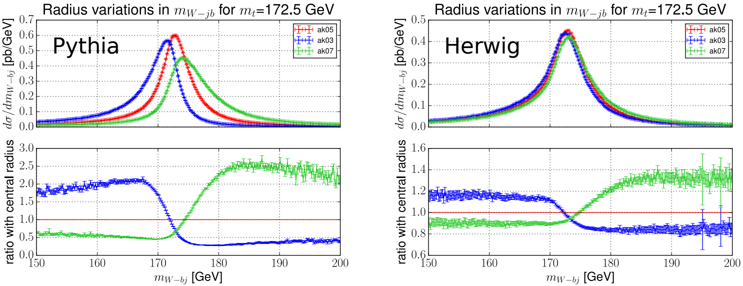


Difference: 1.123 GeV and -1.058 GeV for $R = 0.3$ and 0.7!

Even larger differences if data smearing is included.
Summary:

	Pythia8			Herwig7		
R	0.3	0.5	0.7	0.3	0.5	0.7
$\sigma = 0$	171.537	172.758	174.099	172.660	172.908	173.041
$\sigma = 15$	169.083	172.644	176.049	171.386	172.209	173.013

- R dependence of m_{W-bj} much stronger in Pythia8.
- Data constraints on B-jet shape needed to reduce this error.



Summary of Shower comparison

- Large differences in shape in `Herwig7-Pythia8` comparison
- Peak position with smearing differs by 470 MeV.
- The peak position with no smearing very close for $R = 0.5$ jets, large differences for smaller/larger R's.
- Further variation of Shower part must be considered!!!
- Must find ways to further constrain B-jet shape.

Summary and prospects

- b_bbar_4l and ttb_NLO_dec give similar results for central scales.
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- Sensitivity to PDF's seems mostly due to the α_s value.
- Indication of large uncertainties from shower model, probably due to differences in b-jet modeling. Must find a way to constrain this differences from data.

B-jet energy peak position

E_{bj}

b-jet energy peaks (R. Franceschini et al.)

- At LO, in the top frame

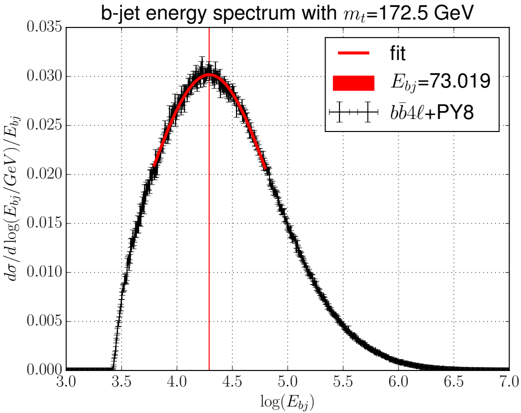
$$\boxed{E_b = \frac{m_t^2 + m_b^2 - m_W^2}{2m_t}}.$$

- In the lab frame the lepton is boosted: the spectrum stretches out but the peak position doesn't change.
- If we go beyond LO and we add hadronization effects, the relation becomes more complicated but for small variation of m_t the peak position is given by

$$\boxed{E_b = A + B \cdot m_t}$$

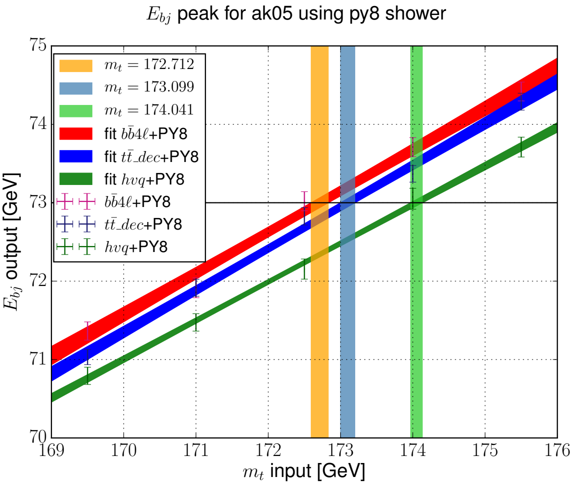
with A and B to be determined via MC simulations.

- We use $\frac{d\sigma}{d\log(E_{bj})}\frac{1}{E_{bj}}$; fit the peak with a gaussian.



- No smearing has been applied (for the moment).
- Event selection cuts: $p_T^{\ell} > 20$ GeV, $|\eta^{\ell}| < 2.4$, $m(e^+, \mu^-) > 12$ GeV, $p_T^{bj} > 30$ GeV, $|\eta^{bj}| < 2.5$.

Mass extraction from E_{b_j}: NLO-PS comparison

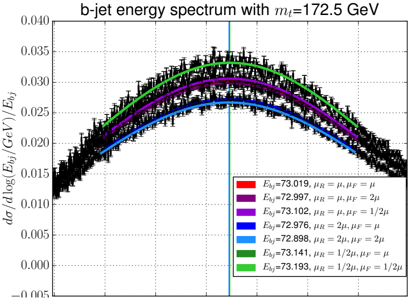


Huge differences `hvq`, not negligible differences between `b_bbar_4l` and `ttb_NLO_dec` (387 MeV).

Scale dependence in ttb_NLO_dec and b_bbar_4l

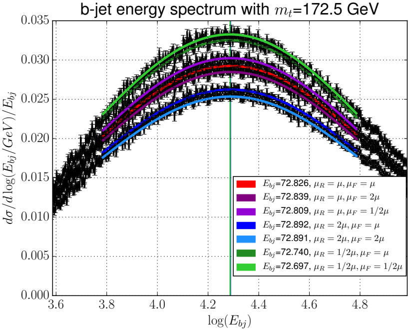
b_bbar_4l:

- central: 73.019 GeV
- min: $\mu_F = \mu_R = 2\mu$, 72.898 GeV
- max: $\mu_F = \mu_R = \frac{1}{2}\mu$, 73.193 GeV
- max-min: ΔE_{bj} =0.295 GeV



ttb_NLO_dec:

- central: 72.826 GeV
- min: $\mu_F = \mu_R = \frac{1}{2}\mu$, 72.697 GeV
- max: $\mu_F = \mu_R = 2\mu$, 72.891 GeV
- max-min: ΔE_{bj} =0.194 GeV



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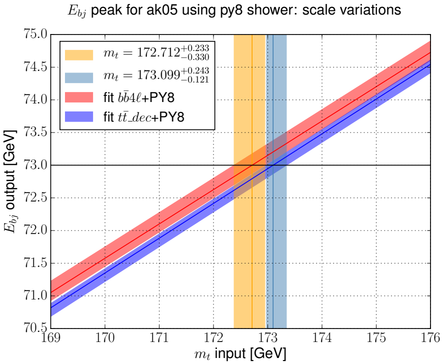
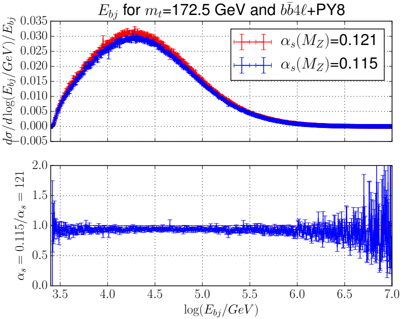


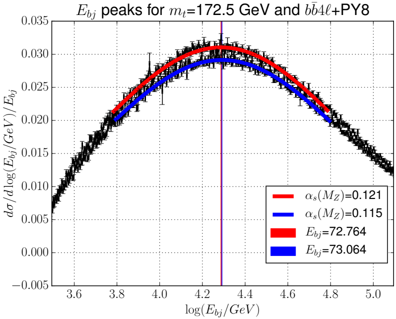
- `b_bbar_4l`: ΔE_{bj} =295 MeV $\Rightarrow$ δm_t =563 MeV $= 1.91 \Delta E_{bj}$
- `ttb_NLO_dec`: ΔE_{bj} =194 MeV $\Rightarrow$ δm_t =364 MeV $= 1.88 \Delta E_{bj}$

$\Rightarrow$ The error on the extracted mass increases by a factor ~ 2

Indeed $E_b^{LO} = \frac{1}{2} m_t + \frac{m_b^2 - m_w^2}{2 m_t}$

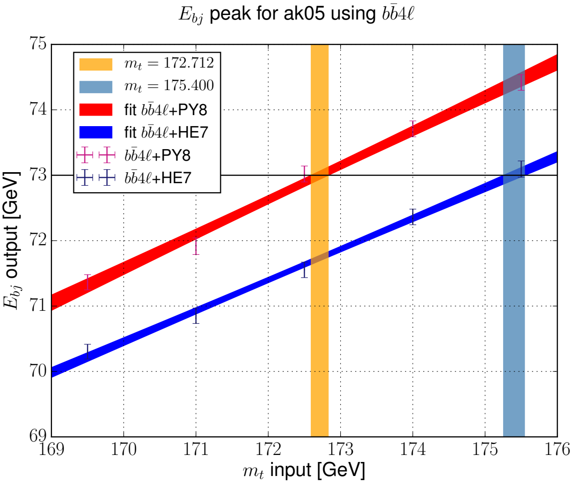
Different α_s influences the emissions from the b quark and thus the energy peak of the B-jet.





A 5% variation of α_s leads to ΔE_{bj}=300 MeV, that roughly corresponds to 600 MeV uncertainty on m_t.

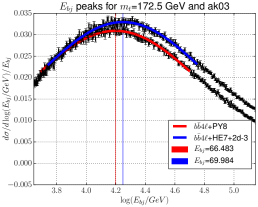
Mass extraction from E_{b_j}: Shower uncertainties

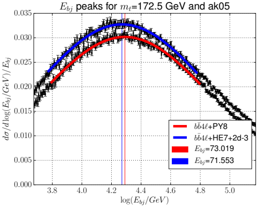


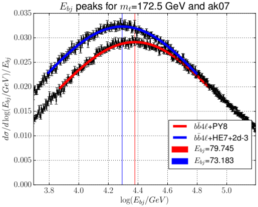
Different of B-jet shapes lead a displacement of 2.7 GeV!

Even larger differences if we vary the radius size, for example for $m_t = 172.5$, we find the following E_{bj} peak positions

	$R = 0.3$	$R = 0.5$	$R = 0.7$
Pythia8	66.483 GeV	73.019 GeV	79.745 GeV
Herwig7	69.984 GeV	71.553 GeV	73.183 GeV
ΔE_{bj}	-3.501 GeV	+1.466 GeV	+6.562 GeV







Summary and prospects

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Uncertainties on the extracted m_t using E_{bj} peak bigger than using m_{W-bj} due to major sensitivity on b-jet structure.

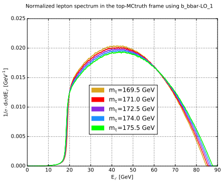
Extra material

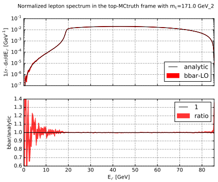
Weight function method, Kawabata et al.

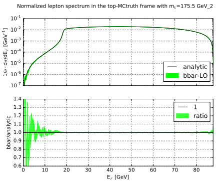
Method for reconstructing the parent particle mass using only lepton energy distribution that works if $\Gamma \ll m$:

1. for different values of m, compute $\mathcal{D}_0(E;m)$, the normalized lepton energy distribution in the rest frame of the parent particle with mass m;
2. compute a weight function given by
$$W(E_\ell;m) = \int dE\,\mathcal{D}_0(E;m)\frac{1}{E\,E_\ell}f(\rho)$$
with $\rho = \log(E_\ell/E)$ and f an odd function of ρ, like
$$f(\rho) = n\tanh(n\rho)/\cosh(n\rho)\,;$$
3. construct a weighted integral $I(m)$ using the lepton energy distribution $\mathcal{D}(E_\ell)$ in a laboratory frame
$$I(m) = \int dE_\ell\,\mathcal{D}(E_\ell)\,W(E_\ell;m)\,;$$
4. obtain the zero of $I(m)$ as the reconstructed mass:
$$I(m = m^{\text{rec}}) = 0.$$

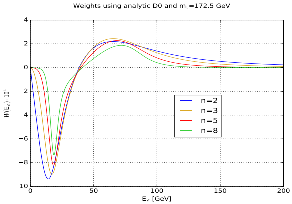
- We checked this method for $\Gamma_t = 10^{-2}$ GeV using LO events generated with `b_bbar_4l`.
- At LO the analytic expression of $\mathcal{D}_0(E; m)$ for $\Gamma_t = 0$ is known, so we can compare it with the simulation.



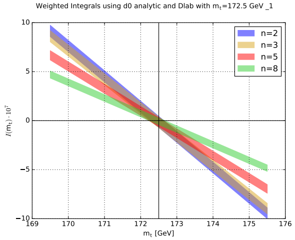


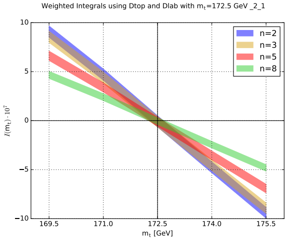


- We build $W(E_\ell; m)$ using both the analytic $\mathcal{D}_0(E; m)$ and the histogram obtained from the simulation.

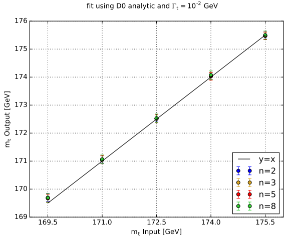


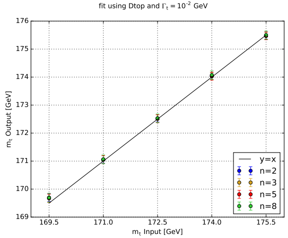
- We compute $I(m)$ for $m = \{169.5, 171.0, 172.5, 174.0, 175.5\}$ using $\mathcal{D}(E_\ell)$ evaluated at $m_t = 172.5$ GeV.



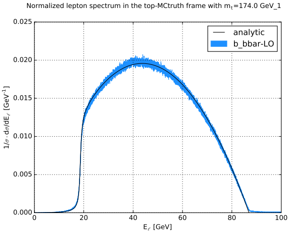


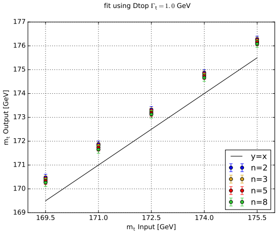
- We vary m_t and we get the following reconstructed top mass



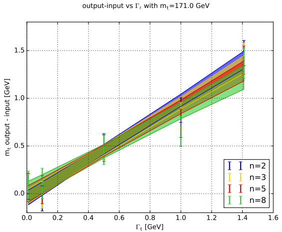


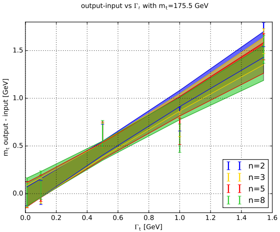
- We evaluated the effect of finite Γ_t: $\mathcal{D}_0(E;m)$acquires a tail and the reconstructed mass is bigger than the input m_t





- We found $m^{\rm rec} - m_t^{\rm input} \approx \Gamma_t$





Fit $y = A + Bx$: dependence on f but not on m_t

- Since $A \approx 0$ and B doesn't depend on m_t one can solve

$$\boxed{m^{\text{rec}} = m_t + B \cdot \Gamma_t(m_t)}$$

  to find m_t.

- The error on m_t is then given by

$$\boxed{\Delta m^{\text{rec}} = \sqrt{\sigma_A^2 + (\sigma_B \cdot \Gamma_t(m_t))^2 + 2\sigma_{AB} \cdot \Gamma_t(m_t)}} \approx 0.1 \text{ GeV}.$$

- A finite width introduces a new error in the determination of m_t.
- TODO: validate this approach at NLO.
- TODO: estimate the impact of the shower: is the lepton spectrum really independent on it?

Interface with PS

- No standard interface for multiple emissions, usually radiation in resonance decays remains unrestricted.
- We can leave it unrestricted and then veto the event if the radiation from the resonances is harder than the one generated by POWHEG BOX.

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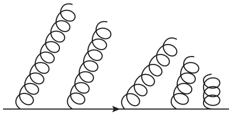

✓ `Herwig7` is angular ordered:
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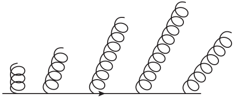

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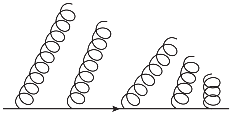

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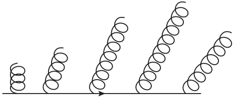
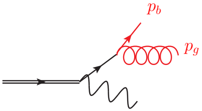


- `Pythia8` provides its own mechanism for vetoing radiation from resonance decay, invoking a function that returns the scale given by the user for vetoing radiation in decay: good agreement with both veto procedures.

Implementation of the veto in Herwig7

- hardness definition in case of radiation from b quarks in t decay is



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with p_b and p_g in the t frame.

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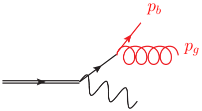

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  - the hardest emission takes place in the hardest line;
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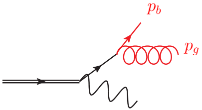

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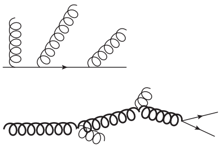

✓ **bottom**: follow the fermion line, $\texttt{St}_\texttt{b} = \max\left(2p_b \cdot p_g \frac{E_g}{E_b}\right)$;

✓ **gluon**: follow the hardest line and stop when $g \to qq$. $\texttt{St}_\texttt{g} = \max\left(2p_1 \cdot p_2 \frac{E_1\, E_2}{E_1^2 + E_2^2}\right)$, with $p_{1,2}$ the momenta of partons emitted by the gluon in the t frame.

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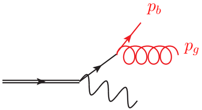

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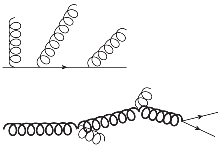

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- If $\mathtt{Pst} < \max(\mathtt{St_b}, \mathtt{St_g})$, the event is reshowered.