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

Paolo Nason

Work done in collaboration with
Silvia Ferrario-Ravasio, Carlo Oleari and Tomáš Ježo

Milano-Bicocca University and INFN

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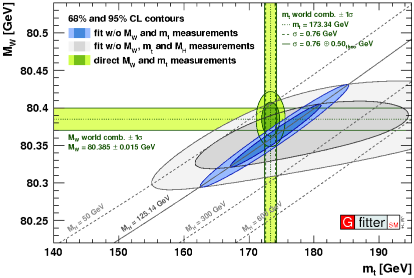
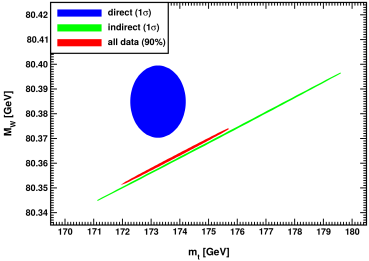
Outline

- Top, precision physics, vacuum stability
- Top mass measurements: issues on the “Monte Carlo Mass”
- Pole mass and $\overline{\mathrm{MS}}$ mass
- Perturbative and non-perturbative theoretical errors
- New generators
- Exploring error sources for m_t measurements.

Top and precision physics



From PDG:



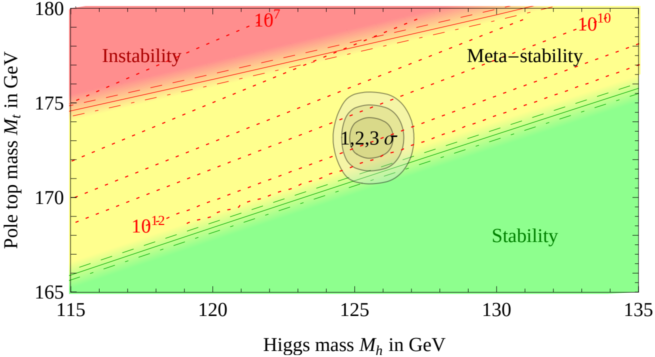
$$\Delta G_\mu / G_\mu = 5 \cdot 10^{-7}; \quad \Delta M_Z / M_Z = 2 \cdot 10^{-5};$$

$$\Delta\alpha(M_Z)/\alpha(M_Z) = \begin{cases} 1 \cdot 10^{-4} (\text{Davier et al.; PDG}) \\ 3.3 \cdot 10^{-4} (\text{Burkhardt, Pietrzyk}) \end{cases}$$

M_W can be predicted from the above with high precision, provided M_H and M_T (entering radiative corrections) are also known (and depending on how aggressive is the error on $\alpha(M_Z)$).

Top and vacuum stability

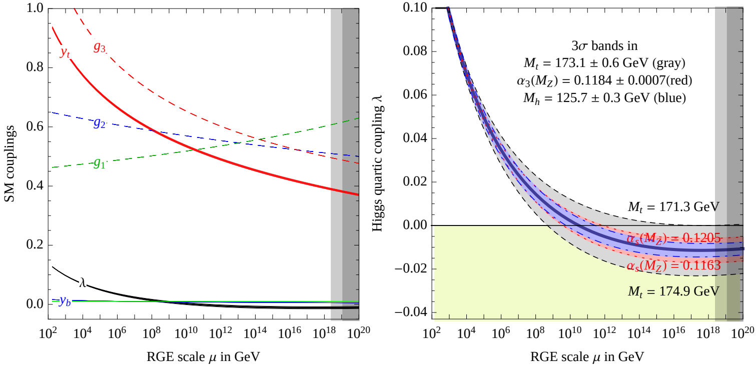
Degrassi et al. 2012



With current value of M_t and M_H the vacuum is metastable.
No indication of new physics up to the Plank scale from this.

Top and vacuum stability

Degrassi et al. 2012

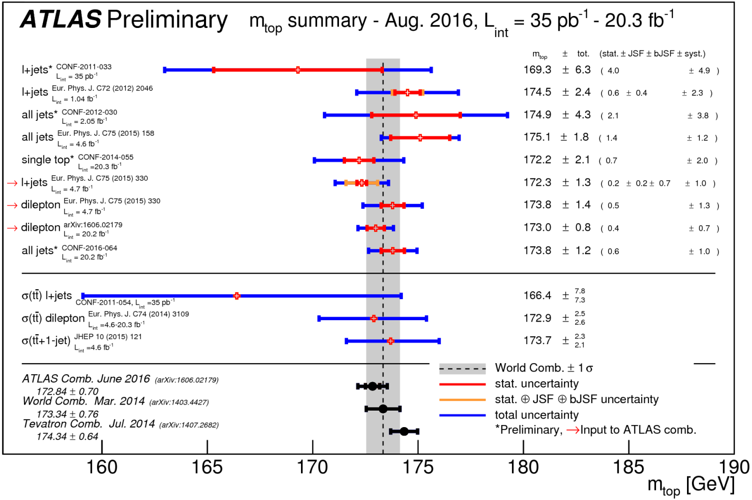


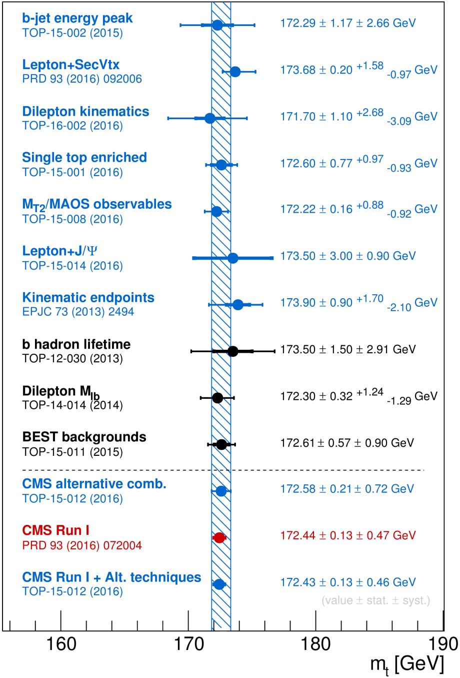
The quartic coupling λ_H becomes tiny at very high field values, and may turn negative, leading to vacuum instability.
M_t as low as 171 GeV leads to $\lambda_H \to 0$ at the Plank scale.

Top mass

- Top mass: fundamental parameter of the Standard Model.
- Ideal measurement: $t\bar{t}$ production at threshold at e^+e^-.
- LHC has the opportunity to measure it.

Lots of methods:





Several methods explored by CMS (see PAS TOP-15-012).

Notice: they do not increase precision with respect to PRD 93 (2016) 072004:

"The top quark mass is measured using the lepton+jets, all-jets and dilepton decay channels, giving values of

$172.35 \pm 0.16(\text{st}) \pm 0.48(\text{sy})$,

$172.32 \pm 0.25(\text{st}) \pm 0.59(\text{sy})$,

$172.82 \pm 0.19(\text{st}) \pm 1.22(\text{sy})$

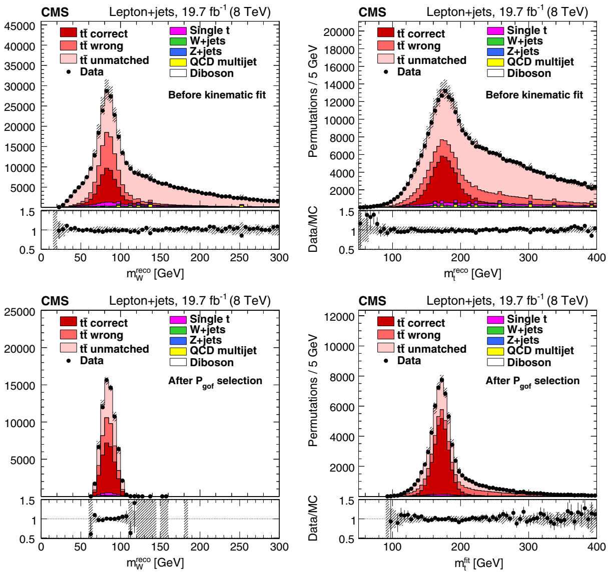
GeV respectively.

Amazingly consistent determinations with different methods.
Most precise technique:

- Semileptonic decays: lepton + missing E_t + 4 jets, 2 b-tagged jets.
- Assuming on-shell W the neutrino kinematics can be further constrained (up to a two-fold ambiguity). Remaining two-fold ambiguity on b-jets assignment.
- Assuming on-shell W the jet energy scale can be fitted together with m_t.

The apparent consistency and precision of the experimental results conflicts with several nagging theoretical doubts that are constantly raised by the theoretical community.

Semileptonic, CMS



Top resolution:

$\approx \pm 15\,\text{GeV}$

Top mass at hadron colliders

- Generator m_{top} parameter fitted to an experimentaly defined $m_{\text{top}}^{\text{reco}}$, essentially made up of a W and a b-jet.
- Doubts on the relation of this mass parameter the so called "Monte Carlo" mass to a theoretically well-defined mass
- There is an intrinsic uncertainty in relating the top pole mass to the top $\overline{\text{MS}}$ mass, due to infrared renormalons, usually quoted to be few hundred MeV.

Second objection: Mass renormalon

Second objections seems much less severe than thought before.

- In reality, no renormalon ambiguity should be present at all in top mass determination, since the top width screens soft emission at a GeV scale.
  In other words: if one computed a mass observable with very high accuracy in the pole mass scheme, one should find a renomalon that exactly cancels when the pole mass is used to compute the $\overline{\mathrm{MS}}$ mass.
- Mass renormalon ambiguities seem to be of the order of 100 MeV, rather than the 1 GeV figure advocated by some authors Beneke, Marquard, Steinhauser, P.N. 2016. No need to worry about it now.

Notice: Mass renormalon ambiguity is not related to the first objection.

First objection: which mass

Is a severe objection.

How to deal with it:

- Find “golden” observables for which a good answer can be found.
- Rephrase the problem: rather than “which mass” we should ask what is the theoretical error in the relation of the “theoretical” mass to the measured (mass sensitive) distributions.

“golden” observables

- Butenschoen,Dehnadi,Hoang,Mateu,Preisser,Stewart,2016 Use jet mass, related via SCET to the top mass and to a parametrization of non-perturbative effects used in e^+e^- shape variables. Theory only available for e^+e^- production at the moment. (current top mass determination from highly boosted top jets has a 10 GeV error, TOP-15-015-pas.pdf)
- Agashe,Franceschini,Kim,Schulze,2016: peak of b-jet energy insensitive to production dynamics (present error: 2.6 GeV).
- Kawabata,Shimizu,Sumino,Yokoya,2014: shape of lepton spectrum. Can be related to top mass via a perturbative QCD calculation. Since the observable does not involve jets, it is assumed to be calculable with reduced uncertainties.

Error on "theoretical mass"

- 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`.[1]

[1] If you don't know what this is, it means that you missed the presentation at the 2015 Milan Christmas workshop: "Sül tratamént de resunans str'ett in di câlcol NLO e in di generatôr NLO+PS"

Error on “theoretical mass”: our task

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

- compare three NLO+PS generators: hvq, $t\bar{t}$_dec, $b\bar{b}$4l.
- studied the effect of scale variations in the $t\bar{t}$_dec and $b\bar{b}$4l generators.
- studied the α_s sensitivity of the results in the $b\bar{b}$4l generator.
- studied the PDF error in the $b\bar{b}$4l generators.
- performed an initial study of hadronization uncertainties by comparing two shower generators: Pythia8 and Herwig7.

Our attitude

- Theoretical ambiguities should show up if we vary perturbative parameters and hadronization models.
- We focus upon the $pp \to l\bar{\nu}_l \bar{\ell}\nu_\ell b\bar{b}$. When looking at the lepton spectrum of the b-jet energy, this should not be a limitation.
  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.

ALL VERY PRELIMINARY!!!

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 $pp \to b\bar{b}e^{+}\nu_{e}\mu^{-}\bar{\nu}_{\mu}$, As presented in Tomáš's talk.

Invariant mass of top decay products

$$m_{W-bj}$$

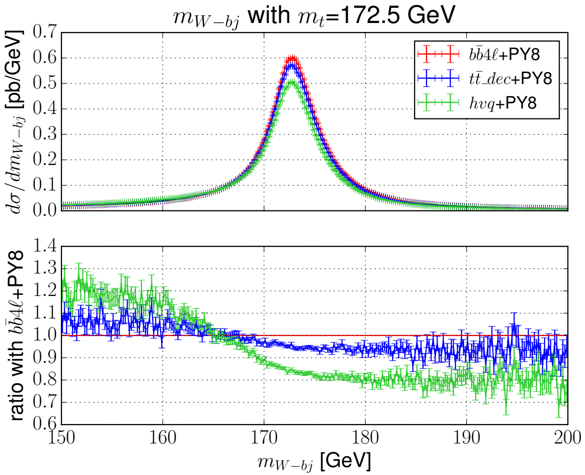
We take m_{W-bj} as a proxy for all top-mass sensitive observables that rely upon the mass of the decay products.
Experimental effects are simply represented as a smearing of this distribution.
Here we will show results with no smearing, and with a Gaussian smearing with $\sigma = 15\,\text{GeV}$.
We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

- Effects that displace the peak. These 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:

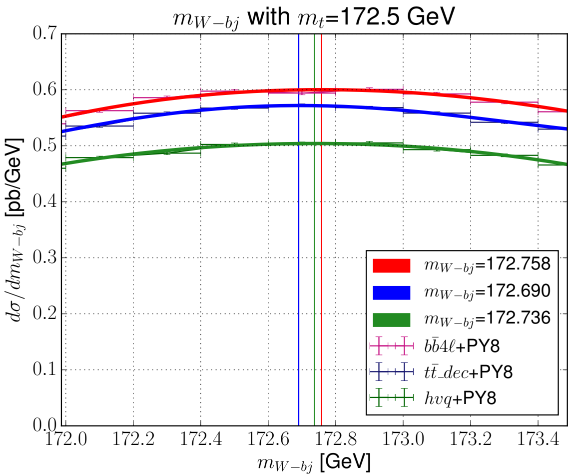
- Jets are defined using the anti-k_T algorithm with $R = 0.5$. The $b/\bar{b}$ jet is defined as the jet containing the hardest $b/\bar{b}$.
- $W^{\pm}$ is defined as the hardest $l^{\pm}$ paired with the hardest matching neutrino.
- The $W - bj$ system is obtained by matching a $W^{+/-}$ with a $b/\bar{b}$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

Comparison of hvq, $t\bar{t}$_dec and $b\bar{b}4l$



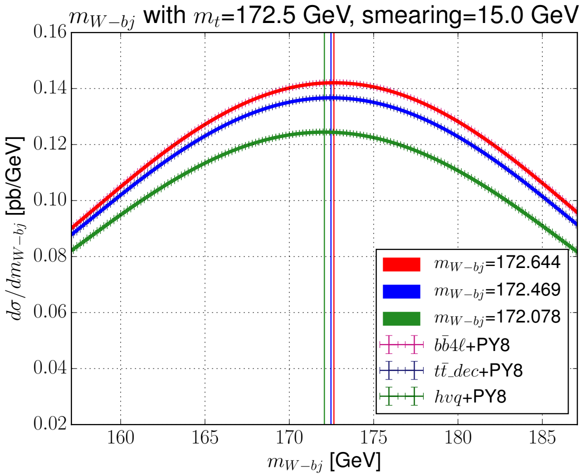
Peak not appreciably displaced; $b\bar{b}4l$-hvq shape differences.

Comparison of hvq, $t\bar{t}$_dec and $b\bar{b}$4l



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

Comparison of hvq, $t\bar{t}$_dec and $b\bar{b}$4l



Smearing: hvq and $b\bar{b}$4l differ by 566 MeV!

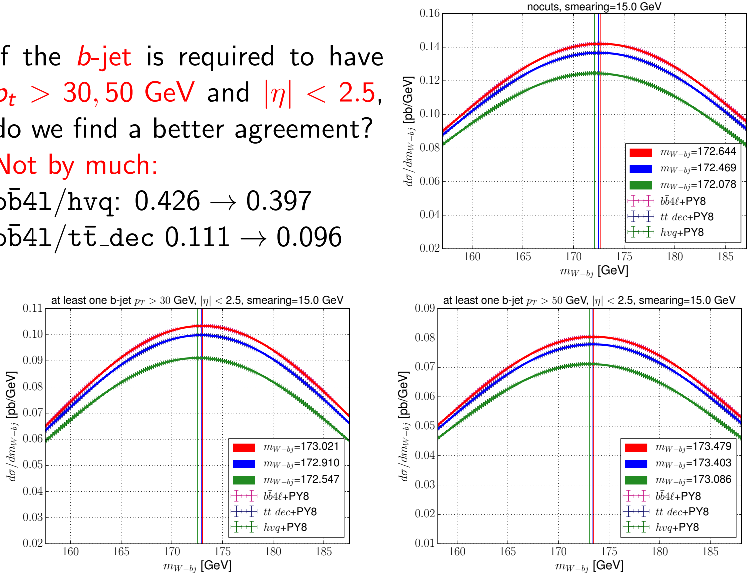
Comparison of hvq, $t\bar{t}$_dec and $b\bar{b}$4l

If the *b*-jet is required to have $p_t > 30, 50$ GeV and $|\eta| < 2.5$, do we find a better agreement?

Not by much:

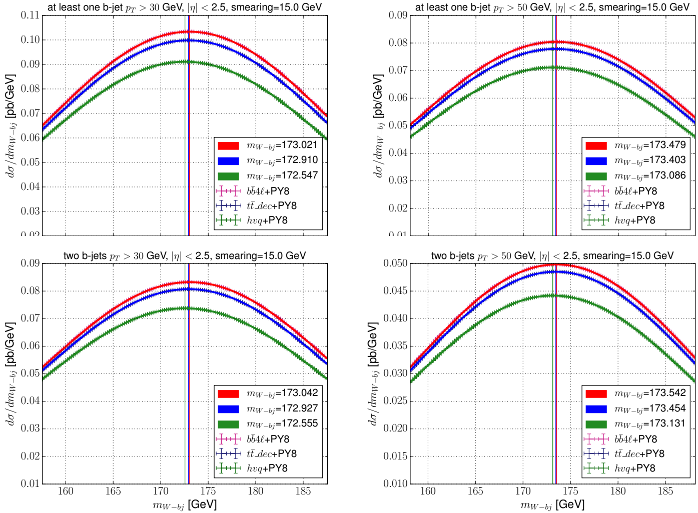
$b\bar{b}$4l/hvq: $0.426 \to 0.397$

$b\bar{b}$4l/$t\bar{t}$_dec $0.111 \to 0.096$

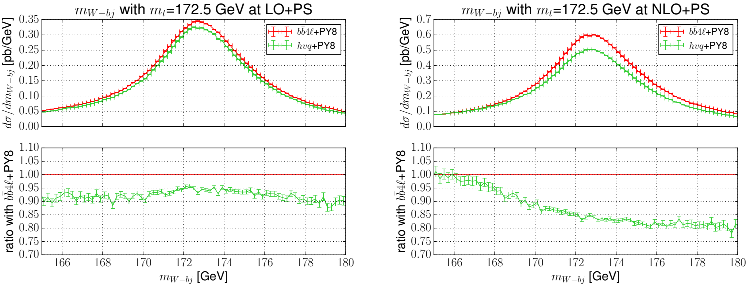


Comparison of hvq, $t\bar{t}$_dec and $b\bar{b}4l$

If we require both b-jets to have $p_t > 30, 50$ GeV and $|\eta| < 2.5$ in order to suppress Wt background? Not many differences...



Comparison of hvq and $b\bar{b}4l$ at (N)LO+PS

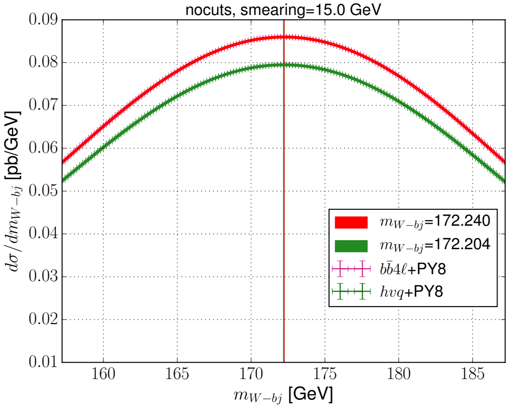


Around the peak reagion hvq/$b\bar{b}4l$ ratio is

- LO: 90-95% with a change in slope ≈ 5%;
- NLO: 80-100% with a change in slope ≈ 20%;

⇒ Different normalization is due to *Wt* contribution that (at LO) doesn't affect the shape around the peak.

Comparison of hvq and $b\bar{b}4l$ at LO



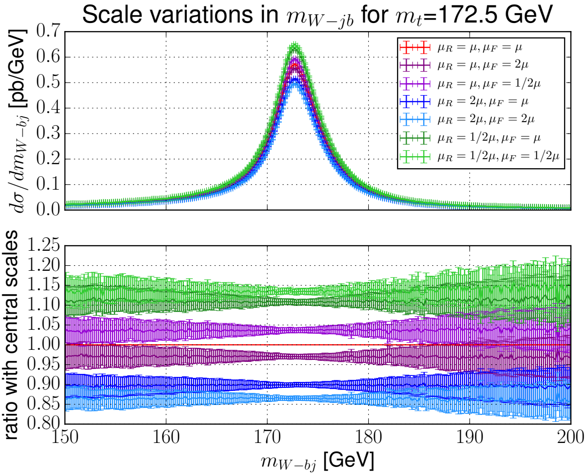
Good agreement for hvq and $b\bar{b}4l$, even if smearing and no cuts to suppress Wt background are applied: the big discrepancies in m_{W-bj} shape among the generators are thus due to radiative corrections in top decay!

NLO-PS comparison summary

- Without smearing, negligible differences in peak position.
- With smearing:
  - $b\bar{b}$4l and $t\bar{t}$_dec display minor differences.
  - hvq displays substantial differences.

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

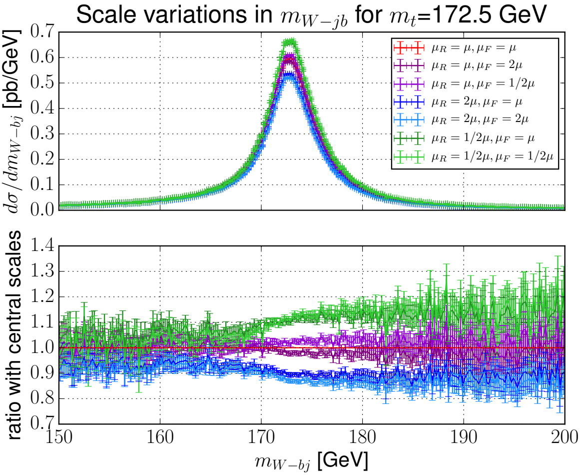
Scale variations in $t\bar{t}$_dec



$t\bar{t}$_dec: no appreciable scale variation effects. Why? NWA?

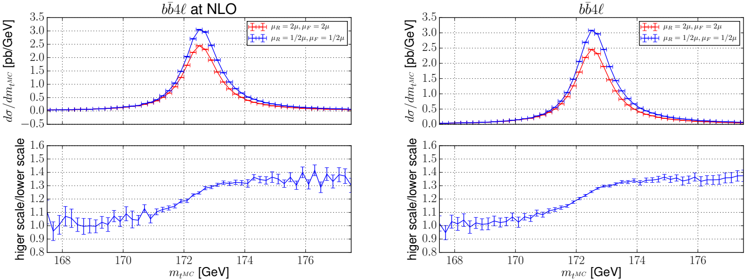
Dynamic scales choice:

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



Scale variations in $b\bar{b}41$: NLO vs LHE+PS level.

To compare scale variation effects at NLO (left) and at LHE+PS (right) level, we use top MC truth virtuality (b-jet at NLO not well described).

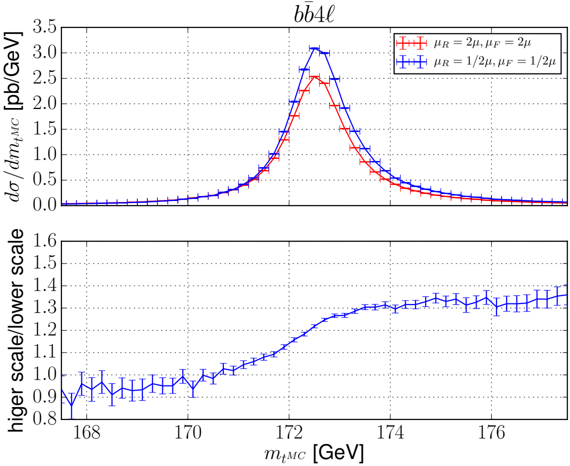


Same scale variation pattern for m_t^{MC} at NLO, LHE+PS and m_{W-bj} at NLO+PS: it is a genuine NLO effect!

This is in fact sort of obvious for the MC-truth top mass ...

Scale variations in $b\bar{b}4l$: fixed scales.

If we choose fixed scales instead of dynamic ones, i.e. $\mu = m_t^{pole}$, we find a similar behavior...

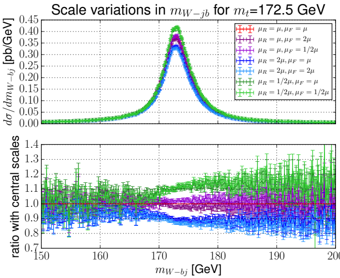


Scale variations in b$\bar{\text{b}}$41: *Wt* background.

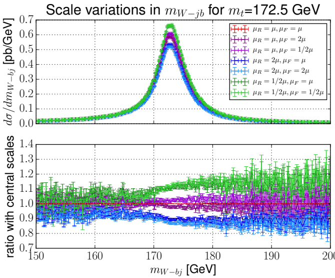
In t$\bar{\text{t}}$_dec *Wt* contribution is implemented only at LO level, so it doesn't participate to the change in shape of the distributions due to scale variations. If we suppress this contribution with selection cuts (left) in b$\bar{\text{b}}$41, do we flatten the scale variation?

- leptons: $p_T > 20$ GeV, $|\eta| <2.4$, $m(e^+, \mu^-) > 12$ GeV;
- 2 b-jets with $p_T > 30$ GeV, $|\eta| <2.5$.

CUTS

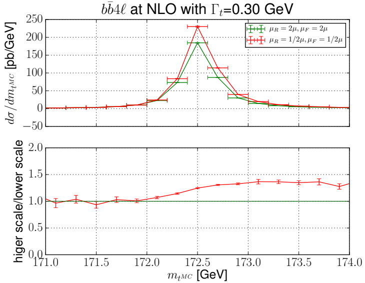


NO CUTS



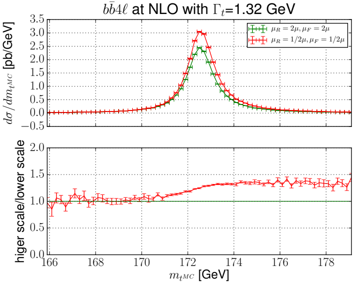
No variation: the difference with t$\bar{\text{t}}$_dec is probabily due to NWA.

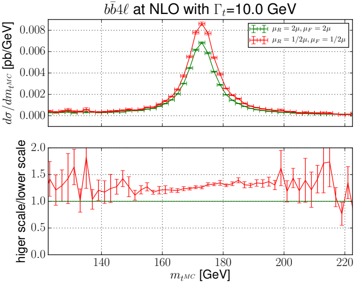
Scale variations in bb̄41: Γ_t effects.



If the effect is due to interference between radiation in production and decay, it should be sensitive to the width of the top. We plot scale variations in the range $m_t^{MC} = [m_t^{pole} - 5\Gamma_t, m_t^{pole} + 5\Gamma_t]$ for $\Gamma_t = \{0.30, 1.32, 10.0\}$ GeV.

Similar shape!





Scale variations in $b\bar{b}41$: Γ_t effects.

The scale dependence in the peak region is quite surprising.
Is it due to genuine interference effects?
On peak:

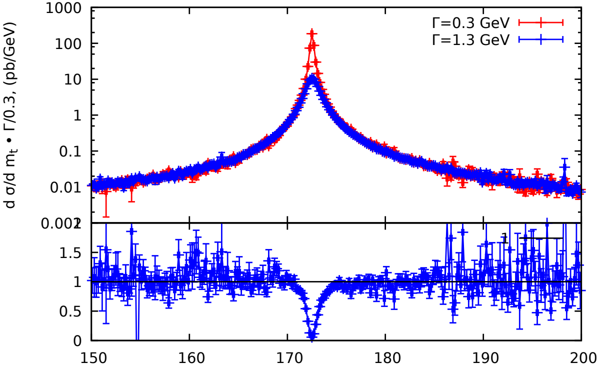
$$\sigma \approx \sigma_{t\bar{t}} \left(\frac{\Gamma_{bW}}{\Gamma} \right)^2$$

When the top is off shell:

$$\sigma \approx \sigma_{bW\bar{t}} \left(\frac{\Gamma_{bW}}{\Gamma} \right)$$

with very little residual Γ dependence. Thus, it is no surprise that the scale dependence when m_{tW} is below and above the peak is independent of Γ.
As Γ decreases, the peak region prevails, and the impact of scale variation on the extracted mass is reduced.

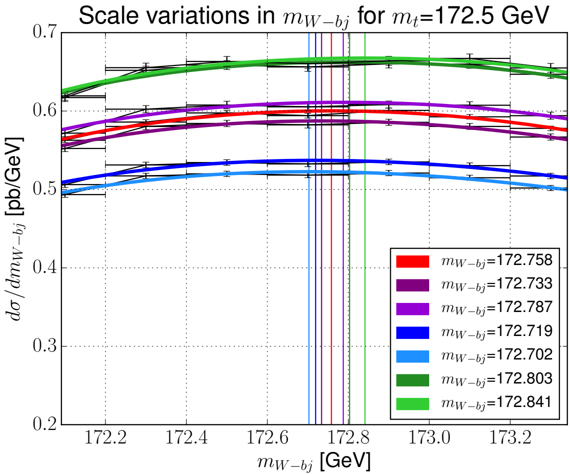
Scale variations in $b\bar{b}41$: Γ_t effects.



Scale variation in mass extraction is reduced from 0.145 to 0.055 GeV when going from $\Gamma = 1.32$ to $\Gamma = 0.3$ GeV.

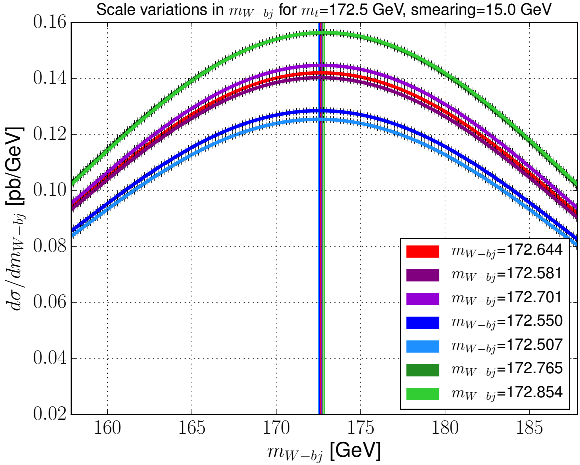
It seems that scale variation is induced by interference effects ... (but we are not yet totally convinced)

Scale variations: impact on extracted m_t, no smearing

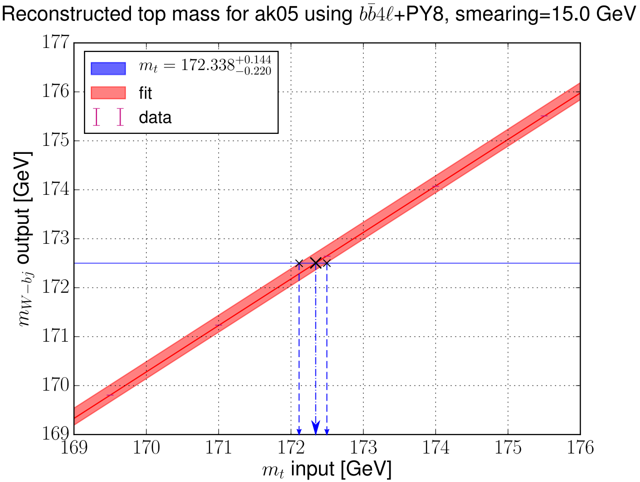


Difference between the minimum and the maximum: 139 MeV...

Scale variations: impact on extracted m_t, smearing



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



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 `bb̄4l`: $^{+144}_{-220}$ MeV impact on mass determination.
- Scale variations in `tt̄_dec`: negligible effect.

(Needs further study).

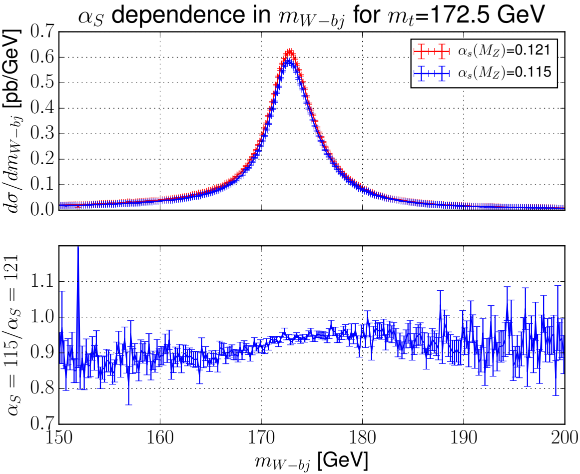
Consider that:

- 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.

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.

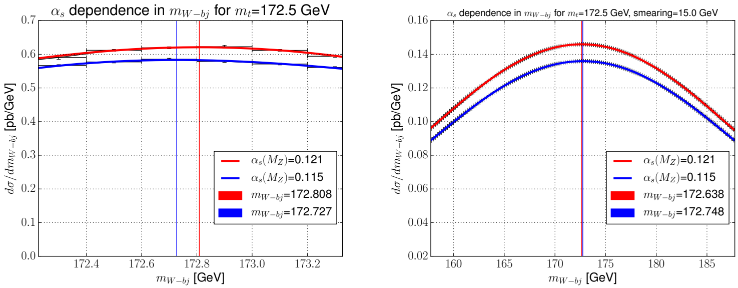
α_s dependence

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



α_s dependence

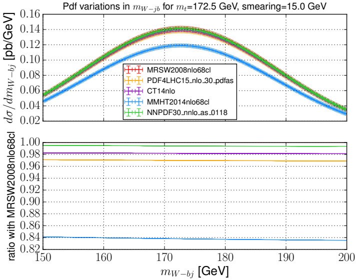
α_s dependence arises only from the different structure of the *b*-jet.

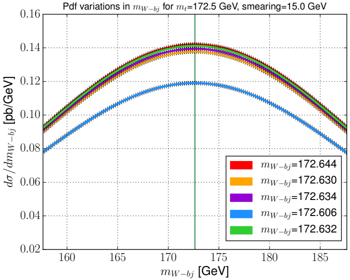


The displacement given by a difference in α_s of the 5% is 81 MeV without smearing, 110 MeV with a 15 GeV smearing. (Small but irreducible!)

PDF dependence

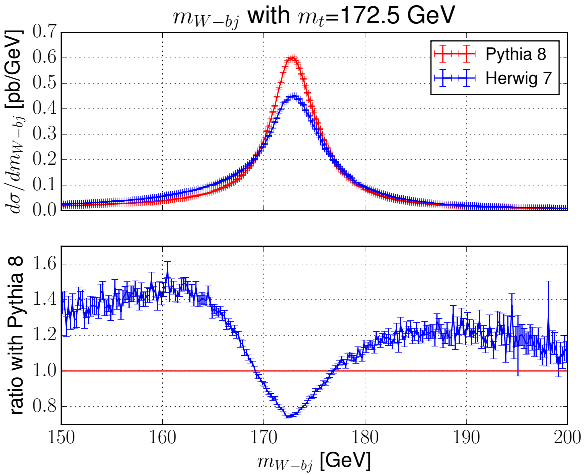
Varying the PDF, even if smearing is applied, there is no significant displacement of the peak





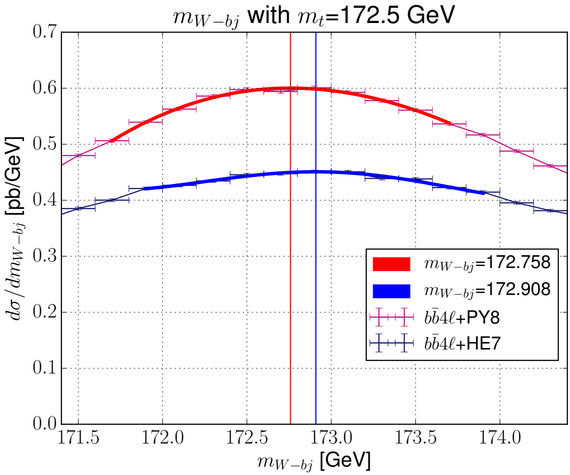
Because of this, the only effect from the PDF choice is the value of α_s (because it affects the b-jet shape).

Shower Uncertainties: Herwig7 and Pythia8



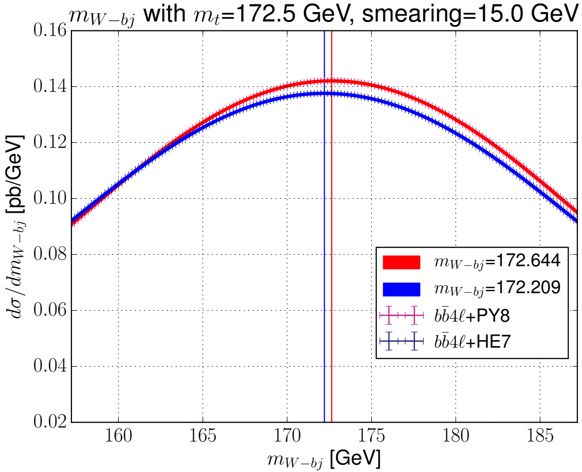
Marked differences in distributions.

Shower Uncertainties: Herwig7 and Pythia8



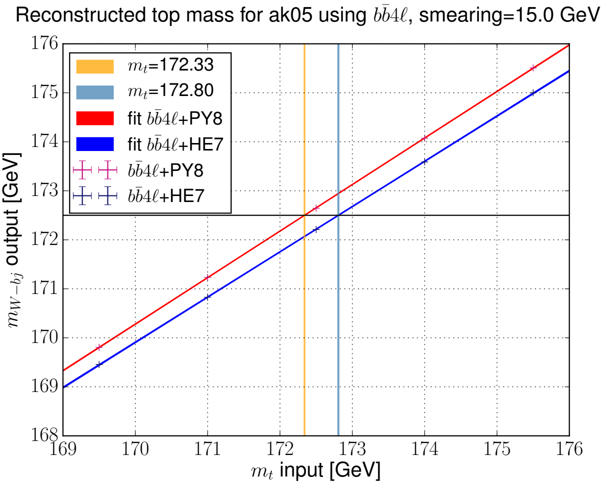
Small difference in mass peak (150 MeV)

Shower Uncertainties: Herwig7 and Pythia8



After smearing, larger mass difference (435 MeV).

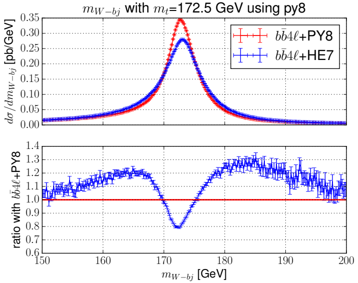
Mass extraction example. Herwig7 vs. Pythia8

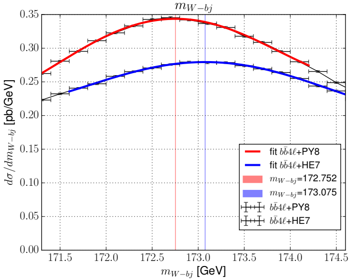


Assuming that we measure $m_{Wb_j} = 172.5\,\text{GeV}$, the extracted mass differs by 470 MeV.

Shower Uncertainties: Herwig7 and Pythia8 using LO events

If we shower LO events, the hardest emission from top resonance is entirely hanlded by the shower, thus we find bigger displacement (323 MeV vs 150 MeV found using NLO events).

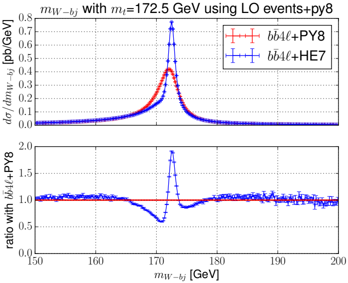




We notice that also at LO, Herwig7 distribution is wider than Pythia8 one: the usage of NLO or LO events doesn't modify that much the shape of the distribution.

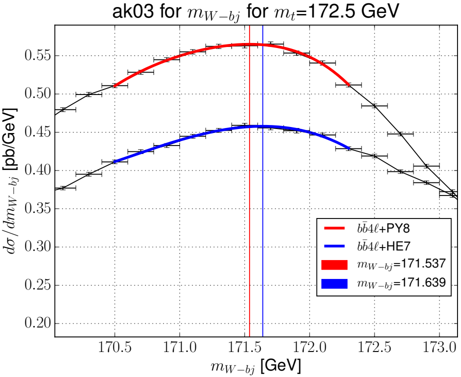
Shower Uncertainties: Herwig7 and Pythia8 without UE and hadronization

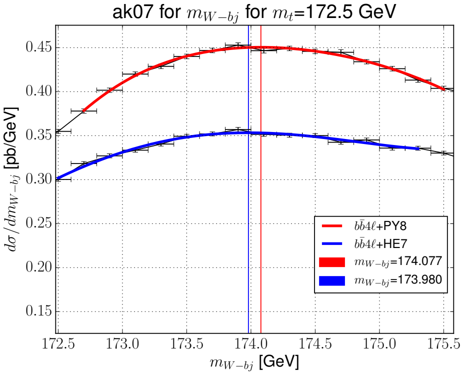
Is the reconstructed peak mostly determined by hadronization effects? Yes!



Switching off UE and hadronization we see a more marked difference in the peak at LO because the b-jet is modelled in a more similar way in the NLO case (since the hardest emission is built by POWHEG).

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



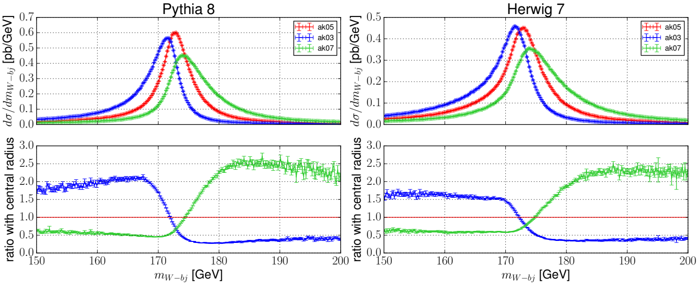


Difference: -0.102 GeV and +0.097 GeV for $R = 0.3$ and 0.7. The peak abscissas stay close even if the shape is different! (e.g. the `Pythia8` maximum is $\sim$ 0.1 pb higer than `Herwig7` one).

Summary:

	Pythia8			Herwig7		
R	0.3	0.5	0.7	0.3	0.5	0.7
$\sigma = 0$	171.537	172.758	174.099	171.639	172.908	173.980
$\sigma = 15$	169.083	172.644	176.049	168.916	172.209	175.644

- If we apply smearing, the displacement is:
  - 0.167 MeV for $R = 0.3$;
  - 0.435 MeV for $R = 0.5$;
  - 0.385 MeV for $R = 0.7$.
- Comparable displacement for $R \geq 0.5$, while the difference becomes smaller for $R = 0.3$.



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 all the tested R values; with smearing differences ~ 0.5 GeV for $R \geq 0.5$, ~ 0.2 GeV for $R = 0.3$.
- Further variation of Shower part must be considered!!!
- Must find ways to further constrain B-jet shape that leads to bigger variations when smearing is applied.

Summary of uncertainties

Error source	No Smearing	15 GeV Smearing
`hvq` vs $\mathtt{b\bar{b}4l}$	0.022 GeV	0.566 GeV
Scale variation, $\mathtt{b\bar{b}4l}$	0.139 GeV	0.347 GeV
$\alpha_s \pm 5\%$, $\mathtt{b\bar{b}4l}$	0.081 GeV	0.110 GeV
Herwig7 vs Pythia8	0.150 GeV	0.435 GeV

Forgetting about `hvq`:

- largest potential uncertainty from Shower stage.
- Surprisingly important scale dependence uncertainty
- Only parameter affecting *b*-jet shape: modest effect.
- Uncertainties seem relatively comparable to what is currently quoted by experiments.

Summary and prospects

- bb̄4l and tt̄_dec give similar results for central scales.
  hvq very different (discarded).
- Scale variation effects seem important as far as the bb̄4l generator is concerned ($^{+144}_{-220}$ MeV). We see no scale variation effects in the tt̄_dec (to be understood).
- We need a method to estimate scale variation effects in radiation (especially for *b* radiation)
- Sensitivity to PDF's seems mostly due to the α_s value.
- Indication of large uncertainties **IN SHAPE** from shower model, probably due to differences in *b*-jet modeling. Must find a way to constrain this differences from data.