Theoretical Considerations on Top Mass Observables

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LHC Top Working Group, November 2015

Outline

- Some general consideration on top Mass measurement
- Top mass in production and decay
- Perturbative and non-perturbative theoretical errors
- Pole mass and $\overline{\rm MS}$ mass
- How to think of top mass measurements "Which mass are we measuring": is this the question?
- New generators
- Hadronization errors

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Measuring the Top Mass

- m_t is a parameter of the Standard Model. We measure it by comparing Standard Model predictions with experimental measurements as a function of m_t.
- We should pick observables particularly sensitive m_t.
- The theoretical uncertainty on our measurement can be inferred from the uncertainty of the theoretical prediction.

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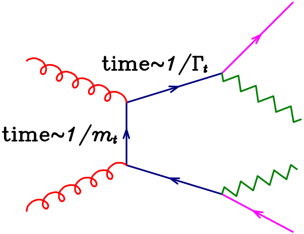

- The Top mass enters in both production and decay.
- The two phenomena are relatively independent, they take place at two widely different timescales.
- Top mass observables may be sensitive to either or both phenomena.

- From decay:
  - Reconstructing the mass of the W and b jet
  - End point spectrum of the lepton and the b jet/hadron
  - From the shape of the lepton or the b jet spectrum (Kawabata, Franceschini).
- From production: from the Top production cross section

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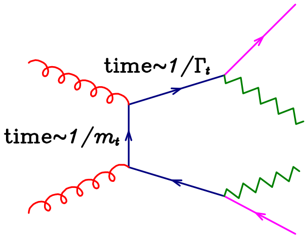

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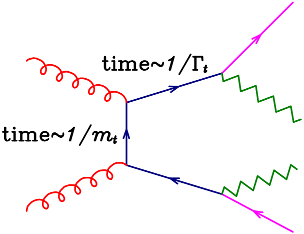

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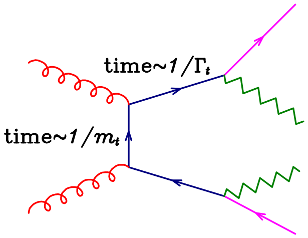

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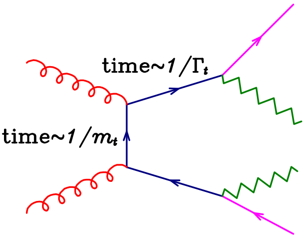

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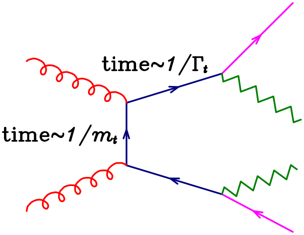

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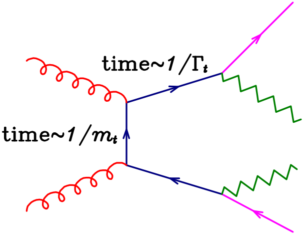

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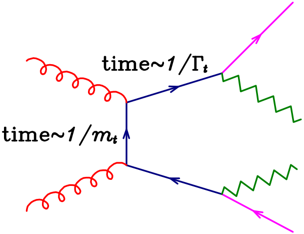

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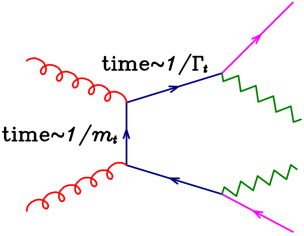

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Theoretical errors: perturbative and non-perturbative

- "Perturbative" errors: vary scales, shower cutoff, etc.. In other words: things that we know how to discuss
- "Non Perturbative" errors: even the most elementary task, like assignign the top decay products to the top quark, becomes a difficult question to answer.
  - Since the top is coloured, the associated *b* hadronic system must include particles not arising from top decay.
  - We don't have a theory, only models; we should explore variations in our models, constrain the variations using data, assess the error due to the unknown physics of hadron formation.

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$\overline{\mathrm{MS}}$ versus pole mass

Even if we demonstrate that hadronization effects yield a negligible error on the top mass, and that we should only worry about perturbative issues, a problem of non-perturbative nature arises if we measure the top pole mass (using observables that are sensitive to the mass of the top decay products), and then we relate it to short distance parameters of the theory like the top $\overline{\mathrm{MS}}$ mass.

It is often stated that when expressing the top $\overline{\mathrm{MS}}$ mass we are subject to an error ranging from 100 to 200 MeV related to infrared renormalons.

It is possible, also thank to the recent progress illustrated in the previous talk, to make some progress on this issue.

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(Marquard,A.V.Smirnov,V.A.Smirnov,Steinhauser, Feb.2015):

$m_{t,\mathrm{pole}} = m_{t,\overline{\mathrm{MS}}}(1+0.4244\alpha_s+0.8345\alpha_s^2+2.375\alpha_s^3+(8.49\pm0.25)\alpha_s^4)$

The last term correspondo to a correction of 200 MeV.
Pole mass affected by IR renormalons:

$$m_{t,\mathrm{pole}} = m_{t,\overline{\mathrm{MS}}}\left(1+\sum_{n=0}^{\infty} r_n \alpha_s^{n+1}\right),$$

For large n (Beneke,Braun,1994; Beneke 1994):
$(\partial\alpha_s/\partial\log\mu^2 = -b_0\alpha_s^2 - b_1\alpha_s^3\ldots)$

$$r_n \to N\, m_t (2b_0)^n \Gamma(n+1+b)\left(1+\sum_{k=1}^{\infty}\frac{s_k}{n^k}\right), \qquad b=\frac{b_1}{b_0^2},$$

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Renormalons, Factorial growth and power corrections

Factorially divergent perturbative expansion: breaks down when $(2b_0)^n\alpha_s^n n!$ for some n stops decreasing.

Take the ratio of two subsequent terms:

$$\frac{(2b_0)^{n+1}\alpha_s^{n+1}(n+1)!}{(2b_0)^n\alpha_s^n n!} \approx 1 \Longrightarrow (2b_0)\alpha_s n \approx 1 \Longrightarrow n \approx \frac{1}{2b_0\alpha_s}$$

Size of the last good term (using $n! \approx n^n e^{-n}$ and $\alpha_s = \frac{1}{b_0 \log\frac{\mu^2}{\Lambda^2}}$):

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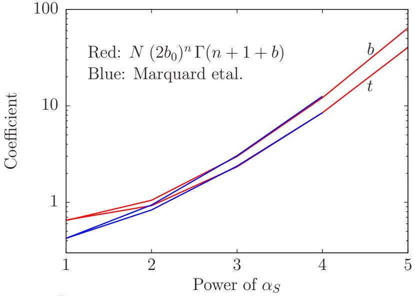
Is Beneke's formula consistent with Marquard etal result?
Fitting α_s^4 coefficient with Beneke's formula, we get $N = 0.726$, and fit well α_s^3 coeff. for t and b, and α^4 for b, use it to predicts c_j, $j \geqslant 5$!!!



Assuming $\alpha_s = 0.1088$, we get the $\mathcal{O}(\alpha_s^5)$ contribution:

$$M_{\text{pole}} = 163.643 + 7.557 + 1.617 + 0.501 + 0.195 + 0.10\,\text{GeV}$$

The terms in the perturbative expansion reach their minimum at order $8 \sim 9$, with last correction ≈ 0.043 GeV.
Alternatively:$\Lambda_6 = 0.094 \Longrightarrow N\Lambda_6 = 0.068\,\text{GeV}$ can be considered an estimate of the renormalon ambiguity in the determination of the pole mass.

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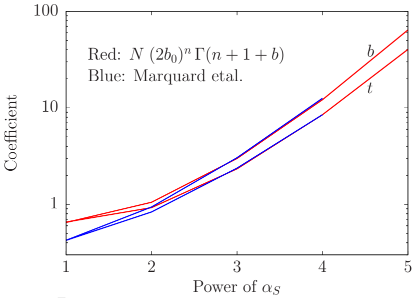

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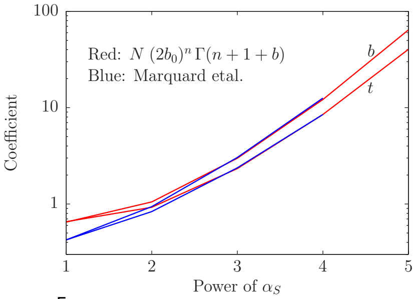

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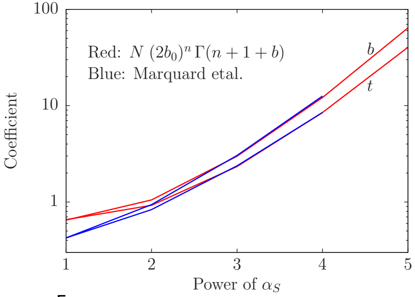

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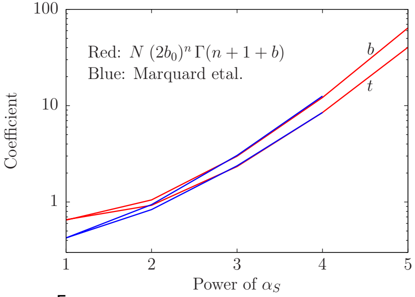
Fitting α_s^4 coefficient with Beneke's formula, we get $N = 0.726$, and fit well α_s^3 coeff. for t and b, and α^4 for b,
use it to predicts c_j, $j \geqslant 5$!!!



Assuming $\alpha_s = 0.1088$, we get the $\mathcal{O}(\alpha_s^5)$ contribution:

$$M_{\text{pole}} = 163.643 + 7.557 + 1.617 + 0.501 + 0.195 + 0.10\,\text{GeV}$$

The terms in the perturbative expansion reach their minimum at order $8 \sim 9$, with last correction ≈ 0.043 GeV.
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The message is:
In view of the fact that the renormalon may not be so important
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General strategy (perturbative)

- Choose observables that are sensitive to the top mass
- Compute these observables with the most precise tools available
- Estimate the impact of theoretical errors on the top mass measurement

Notice:

- Observables with small perturbative corrections are better
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Use a generic, LO Shower MC to compute:

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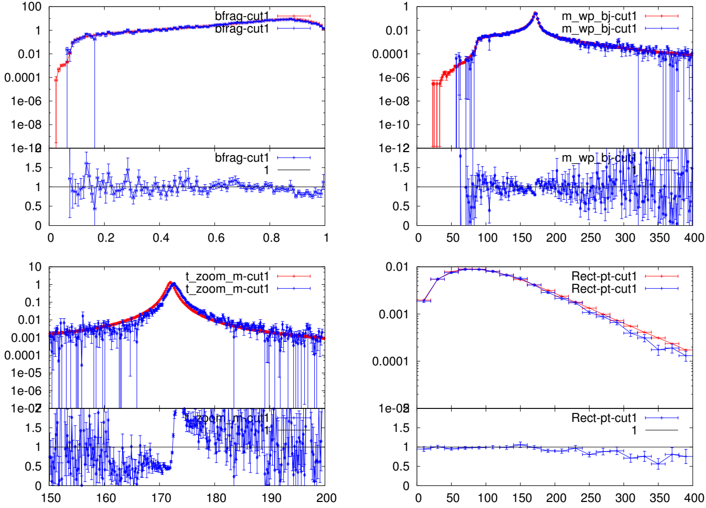
First 64K of fully Pythia8 showered events from *bb4l* generator (blue) compared with Campbell,Ellis,Re,P.N, 2014.



(notice 0.5 GeV difference in mass ...)

Non-perturbative error

- Rigorous approaches (Hoang): collect non-perturbative effects into universal factors that can be computed in other processes (still far from practical).
- Explore the freedom in changing parameters/features of hadronization model (Skands, Sjöstrand, colour reconnection sensitivity).
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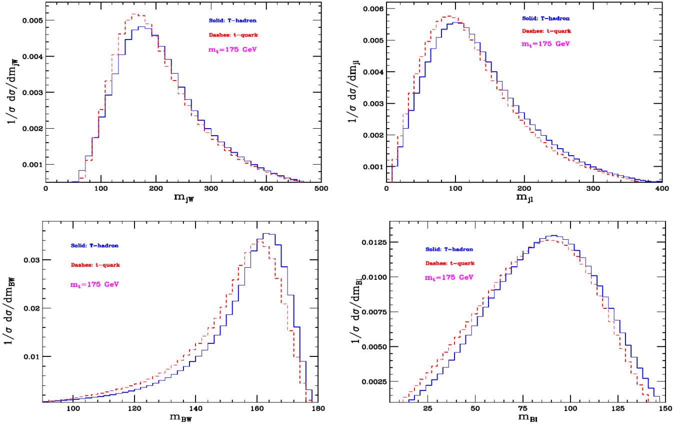
Another study: compare MC results for long-lived (hadronizing) top (in blue) to standard result (red) (Corcella,Mangano).

pp collisions at $\sqrt{s} = 8$ TeV, dilepton channel, k_T algorithm, $R = 0.7$, $p_{T,j} > 30$ GeV, $p_{T,\ell} > 20$ GeV, MET> 20 GeV, $|\eta_{j,\ell,\nu}| < 2.5$ (preliminary)



Conclusions

- The renormalon ambiguity in the top pole mass may be much smaller then previously thought. We should not be afraid to focus upon variables that are pole mass dependent.
- "what kind of mass" in event generators: if we examine closely this question we see that it is more appropriate to ask instead "what kind of accuracy".
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