# The Top quark mass, theory

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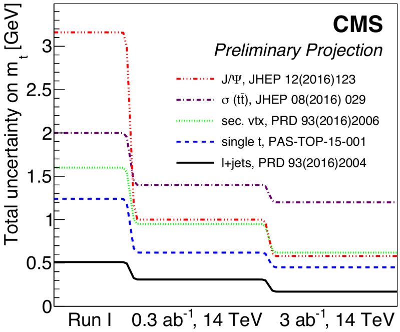
# Expectations

- CMS Projection: 0.1% accuracy at $3ab^{-1}$, 14 TeV;
- Improvements expected from high statistics
- More effective constraints on models using differential distributions
- More possibilities from data driven constraints.




CMS FTR-16-006

(Projections above to be scrutinized better for this workshop)

# Expectations

- Direct reconstruction currently the most sensitive.
  But thorough scrutiny of theoretical uncertainties/issues mandatory for all methods (this may render other methods competitive).
- Different methods have in general different theoretical issues
- One issue affects all measurements: there is no "Particle Level" top definition. This means that
  - Ultimately, all methods will be affected by hadronization issues.
  - The extracted mass is always a parameter in the calculation/simulation of the observable.

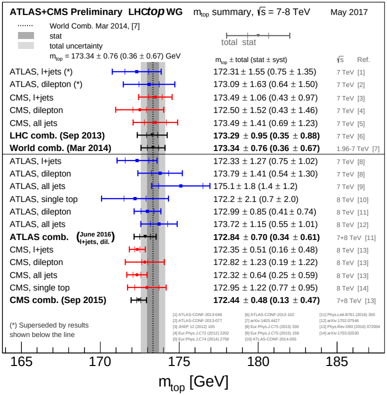
# Sources of uncertainty

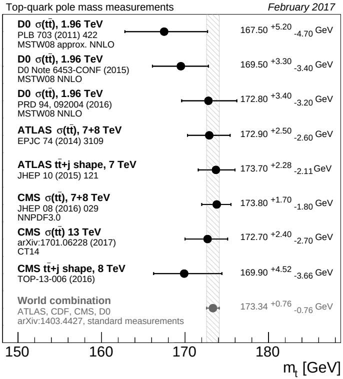
- From MC modeling:
  - Jets and $B$ jets
  - $B$ fragmentation properties
  - NLO+PS: NLO matching dependence, Finite lifetime effects
  - Colour reconnection uncertainties
  - Hadronization model uncertainties
  - Interpretation of the generator mass parameter.
  - ...
- From more general issues:
  - Interference of radiation in production and decay
  - Process dependence in jet properties
  - ...

# Goals of the Theory Top Mass Group

- To clarify as much as possible the present controversies on the top mass measurement.
- To attempt to quantify the theory uncertainties in top mass measurements, most likely to give "conservative" and an "aggressive" estimates.
- A projection of the theoretical error in direct measurements.
- Statements about "ultimate" precision limits in alternative techniques.
- A summary of research directions and key questions to be resolved that can lead to progress in this field.

# Controversies: Pole mass versus “?”




- Some measurements are classified as “Pole Mass” measurements
- Direct measurements do not state what they measure, or are presented as “Monte Carlo mass measurements”.
- EW fits, or vacuum stability studies, use the mass from direct measurements as “Pole mass”, often enlarging the error.

# Different views Concerning Direct Measurements

In the theoretical community there are different views regarding the interpretation of Direct Measurements.

It is often claimed that the mass parameter in the Monte Carlo cannot be related to any well-defined renormalization scheme, and thus one should favour observables that can be computed at least at NLO or even at NNLO, so that the distinction of the various schemes becomes apparent.

We can call this view "A".

# Monte Carlo mass: view "A"

Reminder:

- A LO calculation in the Pole mass or $\overline{\mathrm{MS}}$ scheme yields the same functional form in terms of the mass.
- An NLO (or higher orders) calculations yields a different functional form.
- The extracted mass in the Pole mass or $\overline{\mathrm{MS}}$ scheme, is the same if we use a LO calculation, but differs if we use an NLO calculation, the difference being of order $m_t \alpha_s(m_t)$.
- The extracted mass values are related; at NLO: $m_{\mathrm{pole}} = m_{MS}(1 + 0.42\,\alpha_s(m_{MS})\ldots)$ (more than 7 GeV difference ...)

# Monte Carlo mass: view "A"

- According to this view, the mass extracted in direct measurement should be qualified as being made in a "Monte Carlo scheme", with no precise relation to the pole or MSbar mass.
- No precise statement is made on the size of the difference between such "Monte Carlo" mass and some well defined field theoretical mass.

Since no precise statement is made about this difference, and since the differences in mass due to the scheme choice are of order $\alpha_s(m_t)m_t$, this point of view does not exclude that the MC and pole mass difference could be of order $\alpha_s(m_t)m_t$.

Notice that this is the only possible justification for not including the direct measurements in the Pole Mass measurement table.

# Monte Carlo mass: view "B"

A different concept of "Monte Carlo mass" has been put forward in Hoang,Stuart,2008, followed by several publications.

- It is argued that the generator mass is different from the pole mass, because the MC generators do not have renormalon ambiguities, while the pole mass has.
- The MC generator mass has a close relation to low-scale short distance masses such as the MSR mass, $m^{(\mathrm{MSR})}(Q_0)$, where $Q_0$ is the shower cutoff.
- Several studies performed in the context of mass measurements from boosted top (parton showers are based on quasi-collinear limit), with attempts to quantify numerically the relation of the generator mass of a specific Monte Carlo to the MSR mass and other mass schemes.
- The difference between the generator masses and $m^{\mathrm{pole}}$ is claimed to be of order $Q_0\alpha_s(Q_0)$.

# Monte Carlo mass: View “C”

Other authors (P.N., 2018), argue *against* the MC mass concept, for several reasons:

- The Monte Carlo accuracy depends upon the observables. Thus, for example, the $t\bar{t}$ cross section in a Monte Carlo is only LO accurate. The mass of the top decay products is accurate to all orders (with caveats, beware of renormalons ...) if the top mass parameter is interpreted as the pole mass.
- According to this view, when considering observables closely related to the mass of the top decay products, the Monte Carlo mass plays the role of the top pole mass, up to corrections of the order of a typical hadronic scale $\Lambda$.
- Pole mass renormalon problem not so important; other (renormalons associated with jets, etc.) non perturbative effects may be much more relevant.
- $\mathcal{O}(\Lambda)$ ambiguities can and should be studied and estimated by usual means (variations in shower and hadronization parameters, comparisons of different MC generators, etc.).

# Differences in views

- Can we dismiss view "A"? I.E., can we exclude differences of parametric order $\alpha_s m_t$? How about $\alpha^k m_t$ (for $k$ not too large, beware of renormalons ...)?
  we (authors of the talk) agree on that; does anybody disagree?
- Views "B" and "C" are not so distant: they both admit that the top mass from direct measurements differs from the Pole mass by some low scale.
  - In view "B" such scale is the shower cutoff, $Q_0$, that is considered a *perturbative* scale, such that there is a perturbative relation between the MC mass and the pole mass.
  - In view "C", the shower cutoff is viewed as not different from a typical hadronic scale $\Lambda$.

# Differences in views

- In view "B" one seeks a (possibly universal, i.e. good for all observables) relation of the Monte Carlo mass to the MSR mass and other mass schemes.
- View "C" does not dismiss this possibility. However, as long as a convincing demonstration of such relation is not available, it favours the study of low-scale uncertainties by varying parameters and Monte Carlo models to asses the error in the extracted mass. This method has often been used in the past to estimate non-perturbative errors, and has proven to be reasonably effective. It is admitted, however, that, strictly speaking, in this way we only get a lower bound on the error.

There are many more issues than those listed above. We plan to discuss them more carefully in the writeup.

# Goals: theoretical error in direct measurements

Quoting a projection for the theoretical error can only be a very speculative goal, because

- Projections on the experimental errors go below the 200 MeV. In order to match this error, we need better theoretical understanding of hadronization scale phenomena.
- The Pole Mass renormalon issue may become relevant here, but this is not a problem in principle (the top finite width screens the effect of the renormalon in the top self-energy. The renormalon remains only if one insists using the Pole Mass scheme, but with appropriate choices of scheme it can be avoided.)

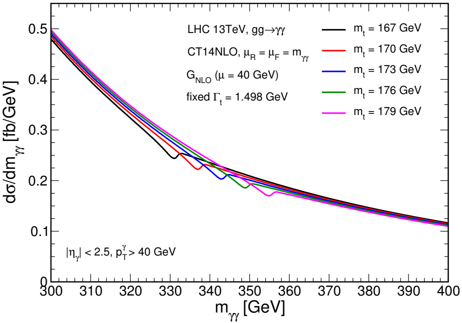
In our opinion, the only statement that can be made now is that it is not unrealistic to expect that progress in theory will match the accuracy of the experiments in direct measurements.

# Goals: Alternative Techniques

- Techniques exploiting kinematic endpoints (T2, $j/\Psi$+lepton, $b$-jet+ lepton),
- Butenschoen,Dehnadi,Hoang,Mateu,Preisser,Stewart,2016 Use boosted top jet mass + SCET.
- Agashe,Franceschini,Kim,Schulze,2016: peak of $b$-jet energy insensitive to production dynamics.
- Kawabata,Shimizu,Sumino,Yokoya,2014: shape of lepton spectrum. Insensitive to production dynamics and claimed to have reduced sensitivity to strong interaction effects.
- Frixione, Mitov: Selected lepton observables.
- Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos ,2013; Bayu etal: $M_t$ from $t\bar{t}j$ kinematics.
- $t\bar{t}$ threshold in $\gamma\gamma$ spectrum (needs very high luminosity), Kawabata,Yokoya,2015

# Goals of the workshop: alternative techniques

$\gamma\gamma$ spectrum at LHC
Kawabata,Yokoya, 2016
Aims to avoid theoretical problems present in direct measurements.
Needs further theoretical scrutiny (higher $t\bar{t}$ excitations, possibly coloured, may decay in $\gamma\gamma + X$).




- HL Projected error: 2-3 GeV for HL;
- HE Projected error: 0.3-0.6 GeV (depending upon signal/background ratio)

A systematics of 1 GeV from the EM calorimeter calibration should also be added. Theoretical error: to be investigated.

# Goals of the workshop: alternative techniques

- Is often assumed that the total cross section is free of $\mathcal{O}(\Lambda/m_t)$ ambiguities. Is that so in practice? (the selection of $t\bar{t}$ events may introduce such ambiguities, and MC dependences)
- How about leptonic observables?
- Are there alternative techniques that may be free from such ambiguities?

# Research directions: Monte Carlo studies

Current Monte Carlo studies:

- Fragmentation uncertainties (Corcella, Franceschini,Kim 2018)
- Colour reconnection effects in Monte Carlo generators (Argyropoulos and Sjöstrand 2014, Christiansen and Skands 2015.)
- Simulation of fictitious top-flavoured hadrons (Corcella)
- NLO+PS Monte Carlo of increasing accuracy (Jezo,Oleari, Ferrario-Ravasio,P.N.2018.)
- Jet grooming techniques to reduce mass uncertainties in direct measurements (Andreassen,Schwartz 2017)
- Studies comparing lepton observables with different Fixed-Order calculations ((Heindrich etal,2017).)

# Research directions: Monte Carlo studies

In general, we need to come up with an acceptable procedure to determine the theoretical error using Monte Carlo's.

Main idea: if two state of the art Monte Carlo's (or the same Monte Carlo with differnt tune), both yielding a satisfactory fit to the data, extract different values of the top mass, that mass range is a lower bound on the theoretical error.
Questions to answer:

- What does "satisfactory fit to the data" means in the framework of top mass measurements? What observables should be fitted to better constrain top mass measurements? (question addressed by: Corcella,Franceschini,Kim,2018)
- What should be varied maintaining these constraints ( Parton Shower dependence, Shower cutoff dependence, Hadronization model dependence ...)

# Research direction: Conceptual studies

- Are there systematic shifts between the Monte Carlo mass parameter and well-defined field theoretical ones?
- What can we say in general about non-perturbative corrections in top mass measurements?

For the first item, studies in this direction for boosted tops (Hoang), and for the second item a study of the role of IR renormalons in top mass measurements in simplified contexts (Ferrario Ravasio, Oleari, P.N.), are likely to be completed before the end of the workshop.

# What can be included in the Yellow Report

- At the moment we have 8 pages allocated for the top mass measurements.
- We can assume to have 3 pages for a discussion of the theoretical issues.
- A concise discussion of the issues presented in these slides, with references for further extensions, can be fitted in this space.
- A figure for the top mass measurement from the $\gamma\gamma$ spectrum at the HE-LHC may be fitted in, as an invitation to seek orthogonal direction of research.