m_{top}^{pole} measurement using $t\bar{t}+1$ jet events at 8 TeV

D. Melini[a, b]

under the supervision of R.Pittau[a] and J. Fuster[b]

[a]Universidad de Granada, [b]IFIC Valencia

Final HiggsTools meeting

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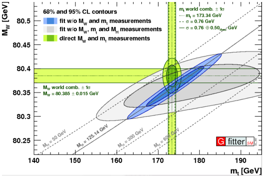
Overview

- Motivations.
- The observable.
- Event selection and system reconstruction.
- Unfolding.
- Detector and particle levels.
- Alternative renormalisation schemes.
- Conclusions.

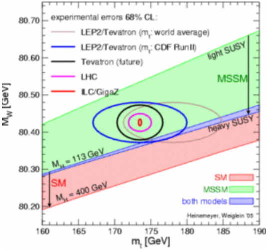
Motivations



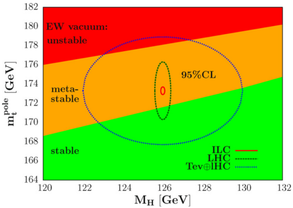
- The only (almost)free quark
- Plays a role in EW vacuum stability.
- Important in EWSB mechanism:
  - Strongest coupling to Higgs boson.
  - M_{top}, M_W, M_H test the SM.
- Important in many new physics (NP) models.
- In the SM, $m_t^{\text{pole}} \propto y_t$ (Yukawa coupling)

Measuring the Top-quark properties with high accuracy is a test on the validity of the SM.

arXiv:hep-ph/0604147



Ph.Lett. B 716 (2012) 214–219



The top-quark mass

Quarks masses are parameters of the SM Lagrangian:

- They are not observables, due to confinement.
- Some observables depend on these parameters$\rightarrow$ fit is possible!.
- Precise values depend on the renormalization scheme used.
- NLO is required to fix renormalization scheme.

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- pole mass $\rightarrow$ m^{pole}
  - on-shell renormalization
    (free particles =physical mass, quarks $\mathcal{O}(\Lambda_{\text{QCD}}) \approx 0.2\text{GeV}$ ambiguity)
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  - pole of the propagator
- running mass $\rightarrow m(\mu)$
  - MS or $\overline{\mathrm{MS}}$ renormalization
  - scale dependent
  - quite far from the pole of the propagator

NLO is necessary to have a consistent mass definition.

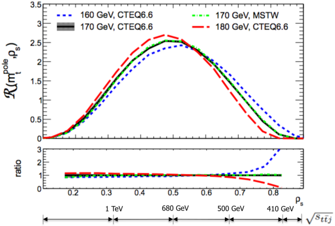
$t\bar{t}+1$ jet advantages

Why using $t\bar{t}+1$ jet events

- Large sample ($\approx 30\%$ of $t\bar{t}$ events) $\rightarrow$ high enough statistics
- NLO calculations available $\rightarrow$ fixed renormalisation scheme
- NLO corrections small $\rightarrow$ theoretical errors under control
- Jet radiation depends on m_{top}^{pole} $\rightarrow$ differential distribution enhance sensitivity

$$\mathcal{R}\left(m_t^{\text{pole}}, \rho_s\right) = \frac{1}{\sigma_{t\bar{t}+1-\text{jet}}} \frac{d\sigma_{t\bar{t}+1-\text{jet}}}{d\rho_s}\left(m_t^{\text{pole}}, \rho_s\right)$$

where $\rho_s = \dfrac{340\ \text{GeV}}{\sqrt{s_{t\bar{t}+1-\text{jet}}}}$



arXiv:1303.6415

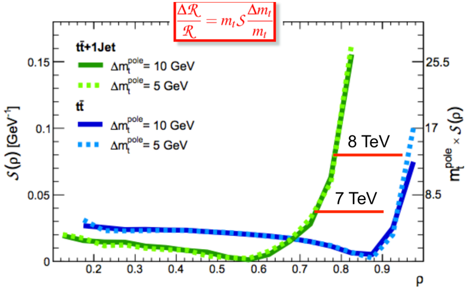
First time analysis by ATLAS @ 7 TeV (JHEP 10 (2015) 121) :

$$m_{top}^{pole} = 173.7 \pm 1.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})^{+1.0}_{-0.5}\ (\text{theo.})\ \text{GeV}$$

8 TeV improvements

8 TeV increased statistics:

- Smaller statistical errors
- Allow rebinning to increase sensitivity (reduce systematics)



$$\mathcal{S}_\Delta(\rho_s) = \frac{|\mathcal{R}(m_0 + \Delta) - \mathcal{R}(m_0 - \Delta)|}{2\Delta \cdot \mathcal{R}(m_0)}$$

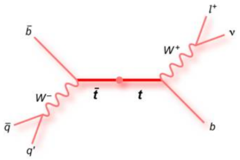
Expected gain

- $\approx$ 4 times more stat: factor $\approx$ 2 reduction of stat uncertainty .
- $\approx$ doubled sensitivity factor $\approx$ 2 reduction on every uncertainty (assuming uncertainty independent on binning).

$t\bar{t} + 1$ jet system reconstruction

Pre-selection cuts

- $= 1$ good lepton
- ≥ 4 good jets ($p_T > 25$ GeV, $\eta < 2.5$)
- ≥ 1 b-tagged jets (MV1 at 70% eff.)
- e+jets:
  - MET$>$ 30 GeV
  - MWT$>$ 30 GeV
- μ+jets:
  - MET$>$ 20 GeV
  - (MET+MWT)$>$ 60 GeV



$t\bar{t} + 1$ jet system cuts

- ≥ 5 good jets
- $= 2$ b-tagged jets
- MET$>$ 30 GeV , MWT$>$ 30 GeV
- Reconstruct neutrino and leptonic W ($W_{\text{lep}} = l + \nu$, $M_W^{\text{lep}} = M_W^{\text{PDG}}$)
- Reconstruct the hadronic W $0.9 < \frac{M_W^{\text{PDG}}}{M_W^{j_1, j_2}} < 1.25$, $\Delta K_T < 90$
- Combine Ws with b-jets, minimising top candidates mass difference
- Improve truth matching: $\frac{M_{\text{top}}^{\text{lep}}}{M_{\text{top}}^{\text{had}}} > 0.9$
- Extra-jet $p_T > 50$ GeV

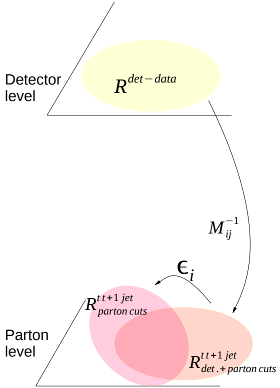
Unfolding to parton level

Unfolding to parton level

- On-shell tops and jets
- Theoretically defined as $t\bar{t}+1$ jet @NLO+PS.

Strategy - (same as 7 TeV)

- Unfold using migration matrix, M_{ij}
- Apply acceptance factor to parton level, ϵ_i



$$\mathcal{R}^{\text{parton}} = \left(\mathcal{M}^{-1} \otimes \mathcal{R}^{\text{detector}} \right) \cdot \epsilon \qquad \epsilon = \frac{\mathcal{R}^{t\bar{t}+1\text{ jet}}_{\text{parton cuts}}}{\mathcal{R}^{t\bar{t}+1\text{jet}}_{\text{parton+detector cuts}}}$$

Unfolding results

- Unfolding algorithm: iterative Bayesian (SVD method in the 7 TeV analysis)
- crosschecked with SVD algorithm
- result stable on the choice of unfolding regulator

Fit procedure

m_{top}^{pole} obtained by minimising a χ^2 function ($\Delta\chi^2 = \pm 1$ for statistical error):

$$\chi^2 = \sum_{\text{bins}} \left[\mathcal{R}^{\text{data}} - \mathcal{R}^{\text{theo}}(m_{top}^{pole})\right]_i \text{COV}_{ij}^{-1} \left[\mathcal{R}^{\text{data}} - \mathcal{R}^{\text{theo}}(m_{top}^{pole})\right]_j$$

Uncertainties - summary

List of systematics included in total error:

Data statistics
MC statistics
Signal MC generator
Shower and hadronization
Proton PDF
ISR/FSR
Color reconnection
Underlying event
JES (with b-JES)
JER
Acceptance factor modelling
Others (MET, lep, bkg, jeff,..)
Scale uncertainty
Theory PDF

Main contributions to total error come from $t\bar{t}$ MC modelling and theory scale uncertainties.

Detector and particle levels expectations

Observable loses sensitivity to m_{top}^{pole} at particle and detector level

Explanation

- High sensitivty at parton level from events with $\rho_s > 0.775$
- In particle and det. levels, bins are a mix of high sensitive events with low sensitivity ones.

detailed example follows...

Detailed two-bins example

Two-bins example explains better the big change in sensitivity. Rememeber :

$$\mathcal{S}_\Delta(\rho_s) = \frac{|\mathcal{R}(m_0+\Delta) - \mathcal{R}(m_0-\Delta)|}{2\Delta \cdot \mathcal{R}(m_0)}$$

Supposing

$$\begin{aligned}\mathcal{R}(m_0+\Delta) &= (\ 0.80\ ;\ 0.20\ )\\ \mathcal{R}(m_0-\Delta) &= (\ 0.90\ ;\ 0.10\ )\\ \mathcal{R}(m_0) &= (\ 0.85\ ;\ 0.15\ )\end{aligned}$$

and folding matrix $\begin{pmatrix} 0.7 & 0.3 \\ 0.3 & 0.7 \end{pmatrix}$

$\rightarrow$

Sensitivity in the second bin

- at parton level

  $$S_{\text{2nd bin}} = \frac{0.2-0.1}{2\Delta \cdot 0.15} = \frac{0,667}{2\Delta}$$

- at folded level in the second bin

  $$\begin{aligned}\mathcal{R}_2(m_0+\Delta) &= 0.7\cdot0.2+0.3\cdot0.8 = 0.38\\ \mathcal{R}_2(m_0-\Delta) &= 0.7\cdot0.1+0.3\cdot0.9 = 0.34\\ \mathcal{R}_2(m_0) &= 0.7\cdot0.15+0.3\cdot0.85 = 0.36\end{aligned}$$

  $$\downarrow$$

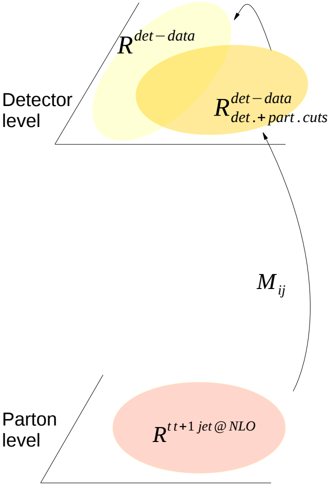
  $$S^{\text{folded}}_{\text{2nd bin}} = \frac{0.38-0.34}{2\Delta\cdot0.36} = \frac{0,111}{2\Delta}$$

$$S^{\text{folded}}_{\text{2nd bin}} << S_{\text{2nd bin}}$$

Detector level analysis

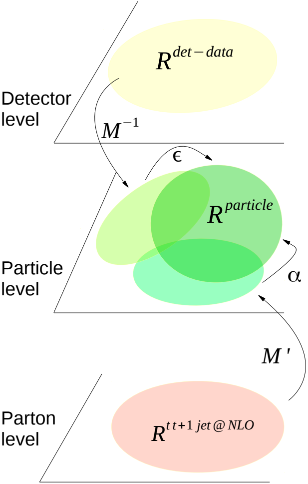
Strategy

- Fold theoretical prediction to detector level
- parton level
  matrix ↓
  detector (with acceptance cuts)
  acc. corr. ↓
  detector
- Folding with matrix: same matrix as in unfolding
- Acc. corr.: correct for events accepeted at detector level, but not at parton level.



Particle level analysis

Particle level definition
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions



Strategy

- $t\bar{t}+1$ jet system reconstructed with same algorithm as detector level.
  (only difference is a "perfect" neutrino)
- Correct data (via unfolding) & fold theoretical prediction

Final results

Our analysis:
Parton level has smallest error because of the higher sensitivity

Other analysis (ATLAS, CMS, D0):

reference	$\sqrt{s}$	m_{top}^{pole} [GeV]	error [GeV]
ATLAS-CONF-2017-044	8 TeV	173.2	± 1.7
CMS-PAS-TOP-13-006	8TeV	169.9	$^{+2.2}_{-2.5}$
FERMILAB-CONF-16-383-PPD	1.96 TeV	169.1	± 2.5

Conclusions

Summarising:

- Top quark mass is a fundamental parameter of SM.
- m_{top} needs to be computed in a well defined theoretical framework.
- Measurement performed at parton, particle and detector levels.
- Best result at parton level (higher sensitivity).
- Most precise measurement of m_{top}^{pole} so far.

Back-up

$\overline{\text{MS}}$ mass

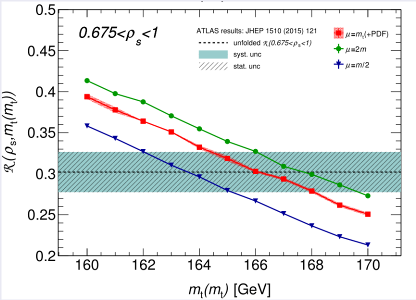
Alternative renormalisation scheme: $m_t^{\overline{\text{MS}}}$

From: arXiv:1704.00540

Use m_{top}^{pole} ($m_t^{\overline{\text{MS}}}$) relation to obtain $\sigma_{t\bar{t}+1\ \text{jet}}(m_t^{\overline{\text{MS}}})$@NLO+PS

Method applied to 7 TeV data:
$$m_t^{\overline{\text{MS}}} = 165.9^{+2.4}_{-2.0}\ \text{GeV}$$
$$m_{top}^{pole} = 173.7^{+2.3}_{-2.1}\ \text{GeV}$$

- No changes in data correction procedure.
- Just need to produce theoretical template and redo fits.
- No big changes expected in systematics



Possible to measure the top quark running mass with ≈ 1 GeV error.

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In general:

$$S_i^{\text{folded}} = w_{ii} S_i + \sum_{j \neq i} w_{ij} S_j$$

$$\text{with} \quad w_{ij} = M_{ij} \frac{R_j}{R_i^{\text{folded}}} \qquad , \sum_j w_{ij} = 1$$

- If perfectly diagonal matrix: $w_{ij} = \begin{cases} 0 \text{ if } i \neq j \\ 1 \text{ if } i = j \end{cases}$, $R_i^{\text{folded}} = R_i \quad \longrightarrow S_i^{\text{folded}} = S_i$
- If bin i has maximum sensivity ($S_i > S_j$, $\forall j \neq i$) $\longrightarrow S_i^{\text{folded}} < S_i$