TOP-QUARK MASS MEASUREMENTS WITH CMS

XXII INTERNATIONAL WORKSHOP ON
DEEP-INELASTIC SCATTERING AND RELATED SUBJECTS

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The top-quark mass in the Standard Model: How fundamental is this parameter?

- key role in the prediction of many observables either directly or via electroweak radiative corrections
  \[ m_W = f(m_{\text{top}}^2, \ln m_H) \]

- key input to electroweak fit, which enables comparisons between experimental results and predictions within and beyond the SM

- highest Yukawa coupling to the Higgs boson: probe for the stability of the electroweak vacuum and Higgs boson properties

Figure 1: Contours of 68% and 95% confidence level obtained from scans of fits with fixed variable pairs \( M_W \) vs \( m_{\text{top}} \). The narrower blue and larger grey allowed regions are the results of the fit including and excluding the \( M_H \) measurements respectively.
The top-quark mass in the Standard Model: What can we tap into?

- a reconstructed invariant mass, a parameter of MC event generator
  - believed to be close to the pole mass at the level of $< 500 \text{ MeV}/c^2$
  - cf. M. Mangano’s talk, given at the TOP2013 conference

- the pole mass from the $t\bar{t}$ cross section measurement
  - uncertainty of $\delta m_{\text{top}} \sim \Lambda_{\text{QCD}}$ since the top-quark is a coloured object
  - relation between the pole mass and the $\overline{\text{MS}}$ mass known to the 3-loop level in QCD but might receive large electroweak corrections
Outline

Motivation

Standard methods
- Using $\ell + \text{jets}$ events
- Kinematic phase space in MC models
- Combination of the standard measurements

Alternative methods
- Top-quark pole mass from $\sigma_{\bar{t}t}$
- Kinematic endpoint method
- B hadron lifetime technique ($L_{xy}$)
- Comparison to the standard measurements and outlook
- Using exclusive b decays

Conclusion

Figure 2: Overview of the CMS standard top-quark mass measurements, their combination, and the Tevatron and World Average.
Top-quark mass in the $\ell + \text{jets}$ channel

**The golden channel**

- selecting events with 1 isolated lepton (e or $\mu$) and $\geq 4$ jets (of which 2 b-tagged jets) among $\sqrt{s} = 8$ TeV data ($19.7$ fb$^{-1}$)
- using a kinematic fit to check compatibility of an event with the $t\bar{t}$ hypothesis and improve resolution

**The ideogram method**

- Performing a joint likelihood fit of:
  - the fitted top-quark mass
  - the unconstrained W-boson reconstructed mass
- Using the convolution of a Breit-Wigner function with:
  - a Gaussian one for correct permutations
  - a Crystal Ball one for wrong or unmatched permutations

$m_{\text{top}} = 172.04 \pm 0.19 \text{ (stat.+JSF)} \pm 0.75 \text{ (syst.) GeV/c}^2$

*Figure 3: Fitted top-quark mass distribution after the goodness-of-fit selection and weighting (left) and the 2D likelihood (right).*
Kinematic phase space in MC models

- Different ME generators, hadronization models, UE tunes compared to CMS standard MC (MADGRAPH+PYTHIA6 with Z2* tune)
- Probing variables sensitive to color-(re)connection effects
- Following the golden channel strategy (selection criteria, kinematic fit, 2D likelihood procedure) → but instead of correcting kinematic biases, studying them

Figure 4: Measurements in dependency of the opening angle between the jets in terms of the separation in $\eta - \phi$ space (left), of the transverse momentum of the hadronically decaying top-quark (center), and of its pseudo-rapidity (right).

Fair agreement between data and MC within statistical uncertainties

→ more data needed to further constrain model uncertainties
Combination of the standard measurements

The Best Linear Unbiased Estimate method

- from several unbiased estimates $y_i$ of the top-quark mass with their error matrix $E$
- to the linear combination of the individual estimates $\hat{y} = \alpha_i \cdot y_i$ that has the minimum possible variance $\sigma^2 = E_{ij} \cdot \alpha_i \cdot \alpha_j$

Sources of systematic uncertainties

- Experimental uncertainties: fit calibration, lepton energy scale, jet energy resolution, pile-up, $E_T$, JES dependency on $p_T$ and $\eta$... 
- Modeling of hadronization: b fragmentation, flavor-dependent JSF... 
- Modeling of the hard scattering process: PDF, renormalization and factorization scales, ME-PS matching threshold, ME generator... 
- Modeling of non-perturbative QCD: underlying event modeling, color (re)connection modeling...

$m_{top} = 172.2 \pm 0.1 \text{ (stat.)} \pm 0.7 \text{ (syst.) GeV/c}^2$

Figure 5: Overview of the CMS standard top-quark mass measurements, their combination, and the Tevatron and World Average.
Top-quark pole mass from $\sigma_{t\bar{t}}$

- Using the measurement of $\sigma_{t\bar{t}}$ derived at $\sqrt{s} = 7$ TeV from data collected in the dileptonic decay channel ($2.3 \text{ fb}^{-1}$)
  
  $\rightarrow$ arXiv:1208.2671

- Constraining $\alpha_S$ at the scale of the Z-boson mass to the current world average and assuming that the measured $\sigma_{t\bar{t}}$ is not affected by non-SM physics

- Constructing a Bayesian prior from the expected $\sigma_{t\bar{t}}$:
  - expected $\sigma_{t\bar{t}}$ calculated to NNLO by the program $\text{TOP}\,++\,2.0$
  - soft-gluon resummation performed at NNLL accuracy
  - dependence on $m_{t\bar{t}}^{\text{pole}}$ described by a 3rd-order polynomial divided by $(m_{t\bar{t}}^{\text{pole}})^4$

Figure 6: Predicted $t\bar{t}$ cross section at NNLO+NNLL as a function of the top-quark pole mass, using 5 different NNLO PDF sets, compared to the cross section measured by CMS assuming $m_{t\bar{t}} = m_{t\bar{t}}^{\text{pole}}$. 

$m_{t\bar{t}}^{\text{pole}} = 176.7^{+3.8}_{-3.4}$ GeV/c$^2$
Kinematic endpoint method

Testing a new technique of mass extraction

- selecting dileptonic $t\bar{t}$ events among $\sqrt{s} = 7$ TeV data ($5.0 \, \text{fb}^{-1}$)
- testing mass determination method that may be used in beyond SM physics scenarios
  $\leftrightarrow$ topological resemblance: 2 cascade decays ending in invisible particles

Strategy

- Underconstrained system
  $\leftrightarrow \mu_{bb}$: variable designed on purpose, weakly-correlated to the invariant mass $M_{b\ell}$
- $\mu_{bb}^{\text{max}}$ and $M_{b\ell}^{\text{max}}$ correlated to the top-quark mass
- Assuming $m_{\nu} = 0$ and $M_W = 80.4$ GeV/c$^2$ in the joint unbinned likelihood fit procedure
- No MC calibration needed

$$m_{\text{top}} = 173.9 \pm 0.9 \text{ (stat.)}^{+1.7}_{-2.1} \text{ (syst.)} \text{ GeV/c}^2$$

Figure 7: Simultaneous fit of the $\mu_{bb}$ (left) and $M_{b\ell}$ (right) distributions. The red line is the full fit, while the blue and green curves are for the background and signal shapes.
B hadron lifetime technique ($L_{xy}$)

Use of the kinematics of the top-quark decay products

- selecting among $\sqrt{s} = 8$ TeV data
  - events with 1 charge isolated lepton (e or $\mu$), $\geq 4$ jets
  - events with 1 electron, 1 muon, and $\geq 2$ jets
- starting from the fact that, in the rest frame of the top-quark, the top-quark decay products momenta are correlated to $m_{\text{top}}$
- considering the B-hadron decay length $L_{xy}$ to be analogously correlated to $m_{\text{top}}$ as most of the energy is transferred from the b-quark to the B-hadron

The B-hadron lifetime technique

- selecting the secondary vertex with the largest $L_{xy}$ and the median $\hat{L}_{xy}$ of the distribution of secondary vertices with maximal $L_{xy}$
- exploiting the linear dependency of $\hat{L}_{xy}$ on the top-quark mass of $O(0.0025 - 0.0030 \text{ cm})$ per GeV/c$^2$
  - calibration based on pseudo-experiments

$m_{\text{top}} = 173.5 \pm 1.5 \text{ (stat.)} \pm 1.3 \text{ (syst.)} \pm 2.6 (p_T(t))$ GeV/c$^2$

Figure 8: $\hat{L}_{xy}$ as a function of $m_{\text{top}}$ from simulation (left) and inclusive fit to the flavour content of a dijet sample based on the secondary vertex mass distribution (right).
Comparison to the standard measurements and outlook

Figure 9: Comparison of the previous CMS top-quark-mass combination and measurements obtained using alternative analysis techniques.

Figure 10: Projection of the top-quark-mass precision obtained with different measurement methods, for various integrated luminosity.

- Using 5 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV as a baseline for the projection
- Assuming jet reconstruction is not affected by the increase of PU
- Systematics uncertainties differing from standard measurements:
  - Pole mass from $\sigma_{t\bar{t}}$: theoretically defined
  - Endpoint method: analytical calculation but b-JES sensitive
  - $L_{xy}$ technique: no JES dependency but good understanding of B-hadron fragmentation and top-quark $p_T$ needed
Leptonic final states with $b \rightarrow J/\psi + X \rightarrow \mu^+\mu^- + X$

- Selecting events with 1(2) isolated lepton(s) (e or $\mu$), 1 opposite-sign di-muon pair whose invariant mass is around the $J/\psi$ one, and satisfying a jet criterion, among $\sqrt{s} = 8$ TeV data (19.8 fb$^{-1}$)

![Figure 11: Di-muon invariant mass after requiring 1 isolated lepton (e or $\mu$), a di-muon pair, and a jet criterion.](image1)

- Using the correlation between the the top-quark mass and the invariant mass of the combination $J/\psi + \ell$

  $\rightarrow$ systematic uncertainties mainly imputable to b-fragmentation, not impacted by jet-related sources

![Figure 12: Di-muon invariant mass and top-quark mass estimate after the final selection.](image2)
 Conclusion

- Dileptonic and all-jets channels becoming competitive to the semi-leptonic one
- Efforts ongoing for harmonization of systematic uncertainties
- NLO-multileg generators expected to provide a finer description
- $b$-JES, soft QCD, and more generally models expected to be better constrained by data
- Multiple techniques to measure the top-quark mass
- Studying kinematic dependencies and colour (re)connection effects

For more top-quark related results from the CMS collaboration: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
Top-quark mass measurement using the dilepton channel

The smallest branching ratio but the channel least contaminated by background processes

- selecting events with 2 oppositely charged leptons, $\geq 2$ jets, and $\slashed{E}_T > 40$ GeV among $\sqrt{s} = 7$ TeV data (5.0 fb$^{-1}$)
- b-tagging algorithm to classify jets, Z and low-mass Drell-Yan vetos

The analytical matrix weighting technique (AMWT)

- For each $t\bar{t}$ event, kinematic properties fully specified by the 4-momenta of the 6 particles in the final state
  $\leftrightarrow$ system closed only if $m_{\text{top}}$ is used as a constraint
- Kinematic equations solved many times per event using a serie of top-quark mass hypotheses
  $\leftrightarrow$ weight assigned to each solution
- Sources of improvement of the method:
  - Fraction of correctly assigned jets increased using leading b-tagged jets
  - Analytical method to determine the momenta of $\nu$

$$m_{\text{top}} = 173.3 \pm 1.2 \text{ (stat.)}^{+2.5}_{-2.6} \text{ (syst.)} \text{ GeV/c}^2$$

Figure 13: Distribution of the reconstructed mass in data and simulation for a top-quark mass hypothesis of 172.5 GeV/c$^2$ with the AMWT.
The analytical matrix weighting technique (AMWT)

- The top-quark mass is used as a constraint to close the kinematic system.
- To determine a preferred value of $m_{\text{top}}$, a weight is determined as:

$$w = \left( \sum F(x_1)F(\bar{x}_2) \right) \cdot p(E_{\ell+}^* | m_{\text{top}}) \cdot p(E_{\ell-}^* | m_{\text{top}})$$

where $x_i$ are the Björken values of the initial state partons, $F(x)$ is the parton distribution function, and $p(E^* | m_{\text{top}})$ the probability of observing a charged lepton of energy $E^*$ in the rest frame of the top-quark given a top-quark mass of $m_{\text{top}}$.

- Each event is reconstructed 1,000 times drawing a random number for the jet momenta. The weight is averaged over all resolution samples.

- For each event, the $m_{\text{top}}$ hypothesis with maximum average weight is taken as the reconstructed top-quark mass $m_{\text{AMWT}}$.

- Using simulated $t\bar{t}$ samples generated with $m_{\text{top}}$ values between 151 and 199 GeV/c$^2$ in steps of 3 GeV/c$^2$, a binned likelihood fit is performed for $100 < m_{\text{AMWT}} < 300$ GeV/c$^2$. 
Top-quark mass from all-hadronic channel

The all-jets channel

- selecting events with \( \geq 6 \) jets (of which \( \geq 2 \) b-tagged jets)
  among \( \sqrt{s} = 7 \) TeV data (3.54 fb\(^{-1}\))
- using a kinematic least-squares fit
  \( \rightarrow \) repeating the fit procedure for each jet permutation
- additional criterion on the separation of the 2 b-quark candidates
- multijet background estimated through an event mixing technique

The ideogram method

- Performing a joint likelihood fit of:
  - the fitted top-quark mass distribution
  - the mean of the unconstrained 2 W-boson masses
- Using analytic expressions for the probability densities:
  - convolution of a Breit-Wigner function and a Gaussian one for correct permutations
  - sum of a Landau function and a Gaussian one for wrong and unmatched permutations
- 1D analysis: \( m_{\text{top}} \) only free parameter,
  2D analysis: cross-check

\[
m_{\text{top}} = 173.49 \pm 0.69 \text{ (stat.)} \pm 1.21 \text{ (syst.) GeV/c}^2
\]

Figure 14: The 1D likelihood profile with the JES fixed to unity.
**The ideogram method**

- For each event, a likelihood to observe the event is calculated:
  
  $\mathcal{L}_{\text{event}}(x|m_{\text{top}}, f_{\text{tt}}) = f_{\text{tt}} \cdot P_{\text{tt}}(x|m_{\text{top}}) + (1 - f_{\text{tt}}) \cdot P_{\text{bkg}}(x)$

  where $x$ is the set of variables which characterizes the event, $f_{\text{tt}}$ is the fraction of $t\bar{t}$ events in the data sample, and $P_{\text{tt}}$ and $P_{\text{bkg}}$ the probability densities for $t\bar{t}$ and background events respectively.

- The probabilities are calculated as a weighted sum over all possible combinations from the kinematic fit:
  
  $w_i = \exp \left( -\frac{1}{2} \chi^2 \right) \cdot w_{\text{btag}}$ with $w_{\text{btag}} = \prod_{j \in \text{jets}} p^j$

  where the b-tag probability $p^j$ can be either $\epsilon_l$, $(1 - \epsilon_l)$, $\epsilon_b$, or $(1 - \epsilon_b)$ depending on the hypothesized flavor of the jet (light or b-jet).

- Considering the number of b-tagged jets $n_{\text{btag}}$, signal and background probabilities to observe a set of mass variables $x_{\text{mass}}$ can be written as:
  
  $P_{\text{tt}}(x|m_{\text{top}}) = P_{\text{tt}}(n_{\text{btag}}) \cdot P_{\text{tt}}(x_{\text{mass}}|m_{\text{top}})$ and $P_{\text{bkg}}(x) = P_{\text{bkg}}(n_{\text{btag}}) \cdot P_{\text{bkg}}(x_{\text{mass}})$

- The $t\bar{t}$ signal probability can be expressed as:
  
  $P_{\text{tt}}(x_{\text{mass}}|m_{\text{top}}) = \sum_{i=1}^{24} w_i \left( f_{cp} \cdot \int_{m_{\text{min}}}^{m_{\text{mass}}} dm' \cdot G(m'|m_i, \sigma_i) \cdot BW(m'|m_{\text{top}}, \Gamma_{\text{top}}) + (1 - f_{cp}) \cdot WP(m_i|m_{\text{top}}) \right)$

- The overall sample likelihood is calculated by combination:
  
  $\mathcal{L}_{\text{sample}}(m_{\text{top}}, f_{\text{tt}}) = \prod_j \mathcal{L}_{\text{event},j}(m_{\text{top}}, f_{\text{tt}})$
Bi-Event Subtraction Technique (BEST)

- testing mass determination method that may be used in beyond SM physics scenarios
- subtracting combinatorial background due to inclusion of particles which do not come from the cascade decay of interest
  - combining jet information from a different event several times for the same decay chain reconstruction
  - \( m_{jj}^{\text{same}} \) dijet invariant mass distribution from one sample
  - \( m_{jj}^{\text{bi}} \) dijet invariant mass distribution from a bi-event sample not coming from a W
  - \( m_{jj}^{\text{BEST}} = m_{jj}^{\text{same}} - C_{jj}^{\text{BEST}} \cdot m_{jj}^{\text{bi}} \) showing a W-boson mass peak almost without combinatorial background

Figure 15: Dijet invariant mass distribution (left) and \( W+b \) invariant mass distribution (right) using BEST.
Top quark-antiquark mass difference

A test of CPT symmetry

- selecting semi-leptonic $t\bar{t}$ events among $\sqrt{s} = 8$ TeV data (18.9 fb$^{-1}$)
- measuring $\Delta m_t = m_t - m_{\bar{t}}$

The ideogram likelihood method

- Using a kinematic fit to reconstruct the mass of the hadronically decaying top-quark assuming $m_{W^-} = m_{W^+} = 80.4$ GeV/c$^2$
- Applying the analysis separately to $\ell^+ + \text{jets}$ events and to $\ell^- + \text{jets}$ events

Figure 16: Distributions of the fitted top-quark mass for $\ell^+ + \text{jets}$ events (left) and $\ell^- + \text{jets}$ events (right).
Color (re)connection effects

Figure 17: Data-to-simulation scale factors for the average $p_T$ of charged particles as function of $p_T(t\bar{t})$.

- selecting a high purity dilepton sample
- characterizing the soft charge activity after the subtraction of the estimated contribution from the hard process
- using the $t\bar{t}$ system direction for each event to factorize the recoil contribution
- comparing data to MC for several Perugia 11 variations

Figure 18: Data-to-simulation scale factors for the average $p_T$ of charged particles as function of the angle to the $t\bar{t}$ direction.
Top-quark production

- Pair production at the LHC:
  - @ 7 TeV: $\sigma_{t\bar{t}} = 139 \pm 10\text{(stat.)} \pm 26\text{(syst.)} \pm 3\text{(lum.)} \text{ pb}$
  - @ 8 TeV: $\sigma_{t\bar{t}} = 239 \pm 2\text{(stat.)} \pm 11\text{(syst.)} \pm 6\text{(lum.)} \text{ pb}$
  - 85% gluon fusion

- Decay width $\sim 1.4 \text{ GeV/c}^2$; lifetime $\sim 5 \cdot 10^{-25}$ s
- Decaying into b-quarks through W-boson emission instead of hadronizing