New Approaches in Determining the Top-Quark Mass

Alternative Techniques and Differential Measurements

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DESY

for the CMS Collaboration

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The Top-Quark Mass

• Extraordinary precision in ‘direct’ top-quark mass measurements
  ‣ Reconstruct event kinematics
  ‣ Calibrate to mass employed in MC (incl. PS)
  ‣ Measure “MC mass” $m_t$

• What is the top-quark mass?
  ‣ Parameter in the Lagrangian $m_0$
  ‣ Beyond LO: Renormalization
  ‣ $m_t$ becomes scheme dependent
    - Pole mass: absorb full self-energy in mass
      $\rightarrow$ ambiguity $\Lambda_{QCD}$
    - Short-distance ‘running masses’
      e.g. MSbar: absorbs UV div, only, scale dependent $\rightarrow$ not discussed here

• Studies suggest: difference between MC mass and pole mass $O(1 \text{ GeV})$
**Alternative Measurements: Outline**

- Study properties of top-quark mass in detail and from many perspectives
  - kinematic dependence of $m_t$
  - Use extraction methods complementary to standard measurements
  - Minimize dependence on simulation
  - Extract mass in well defined scheme by confronting measured and predicted observables

Diagram:
- $m_{pole}$
- $m_t$
- $dm_t/dX$
- B-hadron lifetime
- Kinematic endpoints
- Inclusive cross section
- Differential cross sections
- Direct
Dependence on Event Kinematics

- 8 (7) TeV, l+jets channel, 19 (5) fb\(^{-1}\)
- ’Direct’ measurements calibrate using MC mass
- MC mass depends on event kinematics?
- Is expected dependence described by MC?

- Measure difference between average \(m_t\) and \(m_t\) for a part of the phase-space
  - Employ 2D ideogram method to derive global JSF, \(<m_t>\)
  - Calibrate globally to MC \(m_t\)
  - Apply same procedure to subset of events according to event observable (keeping global calibration fixed)
    - light-quark jets, b-jets, hadronic top, \(H_T\)
Selected Distributions

- JES calibration factor well described, even for jets close in $\Delta R$

- Significant turn on wrt $H_T$, but well described by all predictions

- Low dependence observed wrt top-quark $p_T$ or b-jet rapidity.

⇒ All distributions well described $\rightarrow m_t$ calibration procedure validated

⇒ Data not (yet) able to clearly discriminate between predictions
Top-quark Mass from B-Hadron Lifetime

- 8 TeV, l+jets, eμ dilepton, 19 fb$^{-1}$
  - eμ: at least two opposite charged isolated leptons
  - jet with max $L_{xy}$: central rapidity
- Extract top-quark mass from $L_{xy}$
  \[ L_{xy} \approx 0.4 \frac{m_t}{m_B} \beta_B \tau_B, \mathcal{O}(7 \text{ mm}) \]
- Consider secondary vertex with max $L_{xy}$, at least 3σ significance wrt primary vertex
- Complementary approach to ‘direct’ measurements:
  - reduced sensitivity to jet-energy modelling
  - more dependence on modelling of production process
- Crucial: description of background shapes and rates
• Backgrounds from data (l+jets)
  ‣ W→lν
  ‣ QCD
• Backgrounds from data (eµ)
  ‣ Z→ll

• Cross check of L_{xy} calibration using p_T balanced dijet events
• Combine channels (using BLUE)
• Dominant uncertainties
  ‣ Background determination
  ‣ Top-quark p_T modeling

m_t = 173.5 ± 1.5(stat) ± 1.3(syst) ± 2.6(top p_T) GeV
Extraction from Endpoints

• 7 TeV, dilepton, 5 fb$^{-1}$
  ‣ 2 isolated, opposite charged leptons (e/µ), for ee,µµ veto 76 < $m_{ll}$ < 115 GeV
  ‣ 2 b-tagged high $p_T$ jets, high missing transverse energy

• Perform mass measurement with minimal input from simulation

• Construct kinematic observable with endpoint that relates to $m_t$
  ‣ transverse mass of ttbar pair $M_{T2} = \min_{p_{T\nu}^a + p_{T\nu}^b = p_{miss}^T} [\max(m_{T\nu}^a, m_{T\nu}^b)]$
  ‣ reduce sensitivity to ttbar $p_T$/ISR
    $M_{T2} \rightarrow M_{T2\perp} = \mu_{bb}$
    Endpoint $\mu_{bb}^{max} = m_t$

• Similar to $\mu_{bb}$: $\mu_{ll}$

• Invariant mass of b-jet and lepton $M_{bl}$
• Perform event-by-event combined unbinned likelihood for all observables
• For each observable analytic function for
  ‣ background
  ‣ resolution
  ‣ endpoint

• Estimate all uncertainties in data
• Dominant uncertainty: jet energy scale

\[ m_t = 173.9 \pm 0.9 \text{ (stat)} + 1.7 - 2.1 \text{ (syst)} \text{ GeV} \]

• In principle also applicable to BSM searches with undetected particles
Extraction from Inclusive Cross Section

- $7\text{ TeV, dilepton, } 2.3 \text{ fb}^{-1}$
  - based on measurement, JHEP 11 (2012) 067

- Predicted cross section shows steeper slope than measurement

- Prediction employs well defined top-quark mass in pole scheme

- Measured dependence expressed in terms of MC mass
  - Consider additional uncertainty by varying measured curve by $\pm 1 \text{ GeV}$

- Dominant uncertainties
  - Measured cross section
  - PDF

$m_{t,\text{pole}} = 176.7^{+3.0}_{-2.8} \text{ GeV (NNPDF 2.3)}$
Extraction from Differential $d\sigma/dm_{lb}$

- $8 \text{ TeV}, e\mu$ dilepton, $19 \text{ fb}^{-1}$
  - $\geq 2$ opposite charged isolated leptons
  - $\geq 2$ high $p_T$ jets, $\geq 1$ b-tagged

- Extract $m_t$ from differential cross-section ($m_{lb}$) arXiv:1006.0910

- Define $m_{lb}$: choose permutation with minimum $m_{lb}$
  - On detector level
    - leading b-jet + opposite charged leptons
  - On prediction level
    - leading b quark + leptons
    - visible phase space

- Precise knowledge of lepton kinematics, leading b-jet: less JES uncertainties
• Use MCFM to generate $m_{lb}$ (LO decay)
• Use response matrix to fold to detector level (matrices will be published)
\[ \vec{x}_{reco} = \mathcal{L} \cdot M^{resp} \cdot \vec{x}_{pred} \]
• Extract $m_t$ by product of bin-wise likelihoods
  ‣ similar to extraction from incl. $\sigma_{tt}$

• Dominant: JES, $Q^2$ scale
• No sensitivity to production mechanism
• Method for precise $m_{t,\text{pole}}$ determination
Summary

- Large variety of alternative $m_t$ measurements
- $dm_t/dX$ well described by MC
  - gained trust in MC calibration procedure
- Consistent and complementary results from direct, B-hadron lifetime methods
- Simulation-independent measurement from kinematic endpoints
  - In principle extendable to BSM searches
- Well-defined pole-mass extraction from inclusive cross section
- Robust procedure to extend to differential cross sections $\rightarrow$ higher precision

Plan to extend variety:
- Possibly study $d\sigma/dm_{lb}$ defined based on generated $b$-jets instead of partons
  $\rightarrow$ independence of pQCD accuracy
- Exploit larger statistics at 13 TeV: $m_t$ from J/Psi decays and further refined studies