Top quark mass measurements with the CMS experiment

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DIS 2016, Hamburg
WG4 Heavy Flavors, 13 April 2016

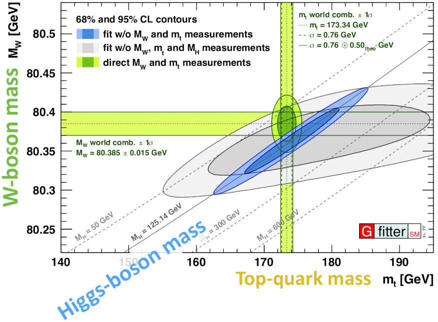
Why Measuring the Top Quark Mass?

- m_t is a fundamental parameter of the standard model
- Short lifetime $\mathcal{O}(10^{-25})s \rightarrow$ no hadronization, allows to study bare quark properties
- Direct access to top quark properties through decay products

- Allows tests of SM **self-consistency** using m_t, m_W, m_H and other inputs

Which mass are we measuring?

- Parameter in the Lagrangian
- Beyond LO: Renormalization, m_t becomes scheme dependent
- Direct measurements: **MC mass**
- Difference between MC mass – pole mass $\mathcal{O}(1\,\mathrm{GeV})$ arXiv:1405.4781, 0808.0222, 1502.01030
- See talks by M. Steinhauser, A. Hoang

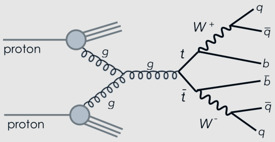


arxiv:1407.3792

Overview

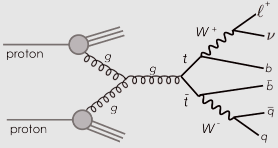
- Many top quark mass measurements published by CMS → CMS Top Quark Public Results
- Focus on selected measurements only, presenting the most precise results available

Direct: All-hadronic



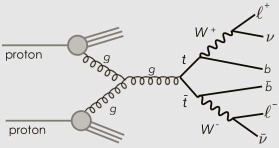
arXiv:1509.04044

Direct: Lepton + Jets



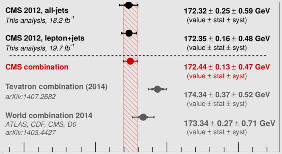
arXiv:1509.04044

Direct: Dileptonic



arXiv:1509.04044

CMS Combination



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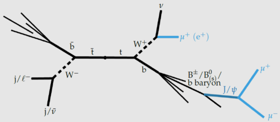
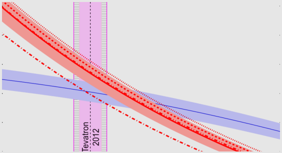
m_t from Charged Particles



arxiv:1603.06536

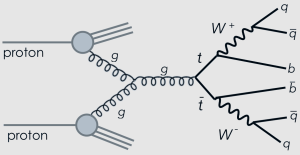
Indirect Measurement via $\sigma_{t\bar{t}}$



arxiv:1603.02303

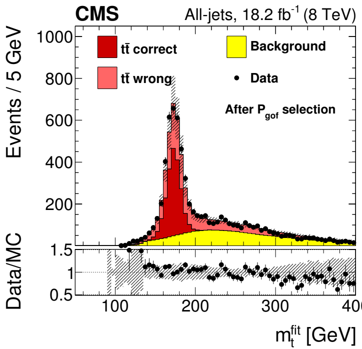
Direct m_t Measurement: All-hadronic

arXiv:1509.04044



- Largest branching ratio
- Full reconstruction possible (no neutrinos)
- Combinatorics: many possible jet-parton assignments
- Multi-jet background requires tight cuts

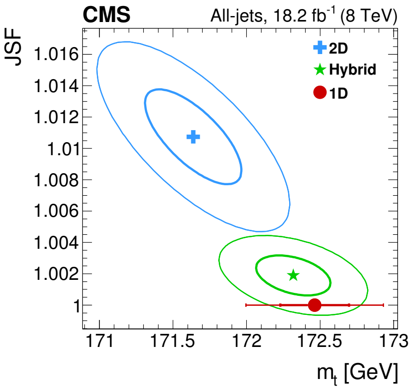
- Ideogram method: per-event likelihoods (taking into account expected contributions from correct/wrong and background hypothesis) are combined to perform the measurement
- **1D:** determine m_t from templates
- **2D:** determine m_t and global JSF simultaneously, no JSF prior used
- **Hybrid:** use Gaussian constraint, width JEC uncertainty
- Observables:
  m_t^{fit} from kinematic fit
  m_W^{reco} reconstructed from jet pair invariant mass



Direct m_t Measurement: All-hadronic

arXiv:1509.04044

- Perform kinematic reconstruction of $t\bar{t}$ system
- Choose jet-parton assignment which fits best to $t\bar{t}$ hypothesis (χ^2)
- For 2D ideogram: combine stat. uncertainty from both components



Dominant Sources of Uncertainty

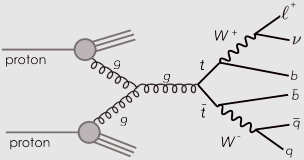
b-Dependent JEC	0.2%	$\Delta m_t = \pm 0.29$ GeV
Data Statistics	0.1%	$\Delta m_t = \pm 0.25$ GeV
Backgrounds	0.1%	$\Delta m_t = \pm 0.20$ GeV
In-Situ JEC	0.1%	$\Delta m_t = \pm 0.19$ GeV

$$m_t^{1D} = 172.46 \pm 0.23\,(\text{stat}) \pm 0.62\,(\text{syst})\,\text{GeV}$$

$$m_t^{hyb} = 172.32 \pm 0.25\,(\text{stat+JSF}) \pm 0.59\,(\text{syst})\,\text{GeV}$$

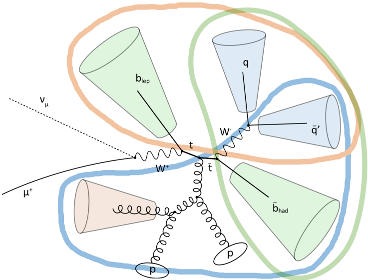
Direct m_t Measurement: ℓ+Jets

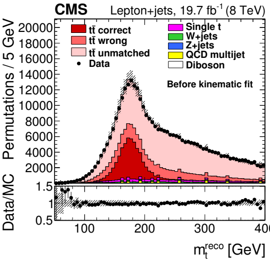
arXiv:1509.04044

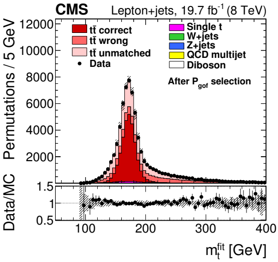


- Relatively large branching ratio, modest cuts required
- Event identification via **leptonic top**
  Full reconstruction of the **hadronic top**
- Combinatorics remain issue, typically ≥ 4 jets

- Simulated events classified in correct/wrong/unmatched permutation:







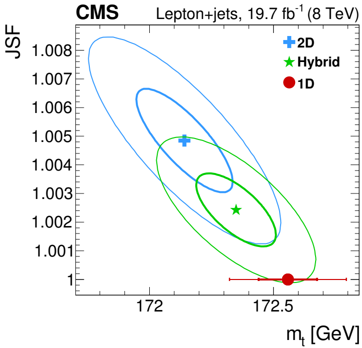
Direct m_t Measurement: ℓ+Jets

arXiv:1509.04044

- Use additional event weight: goodness-of-fit probability P_{gof} from kin. reconstruction
- Reduces impact of events with wrong jet assignment

Dominant Sources of Uncertainty

b-Dependent JEC	0.2%	$\Delta m_t = \pm 0.35$ GeV
Semileptonic b-fragmentation modeling	0.1%	$\Delta m_t = \pm 0.16$ GeV
Data Statistics	0.1%	$\Delta m_t = \pm 0.16$ GeV

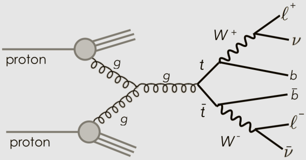


Total precision: 0.3% (0.51 GeV**)**

$$m_t^{1D} = 172.56 \pm 0.12\,(\text{stat}) \pm 0.62\,(\text{syst})\,\text{GeV}$$
$$m_t^{hyb} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\,\text{GeV}$$

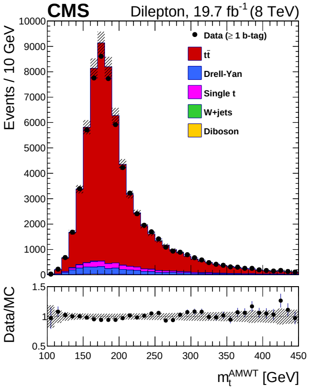
Direct m_t Measurement: Dilepton

arXiv:1509.04044



- Low backgrounds, typically only a few percent
- Simplified combinatorics: 2 lepton/b-jet permutations
- Full event reconstruction impossible due to 2 neutrinos
- Lower m_t sensitivity due to neutrino energy

- Analytical matrix weighting technique (AMWT)
- Comparable with 1D ideogram
- Scan m_t from 100 to 400 GeV
- Calculate probability of observing a charged lepton of energy E in rest frame of a top quark of mass m_t
- Assign weights using probability
- Observable is mass with highest average sum weight: m_t^{AMWT}



Direct m_t Measurement: Dilepton

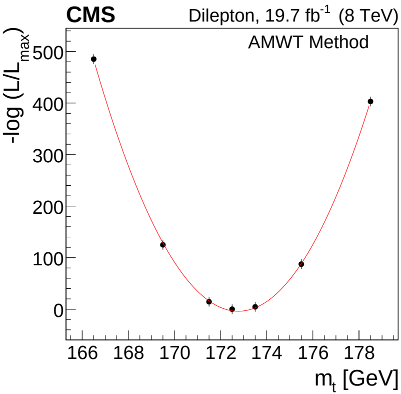
arXiv:1509.04044

- Measure mass by comparison to several $t\bar{t}$ MC simulations with different m_t hypotheses

- Calculate binned likelihoods for all m_t bins
- Mass measured from parabola fit to likelihoods

Dominant Uncertainties

Factorization and renorm. scale	0.4%	$\Delta m_t = \pm 0.75$ GeV
b fragmentation	0.4%	$\Delta m_t = \pm 0.69$ GeV



$$m_t = 172.82 \pm 0.19\,(\text{stat}) \pm 1.22\,(\text{syst})\text{ GeV}$$

Combination of the Measurements

arXiv:1509.04044

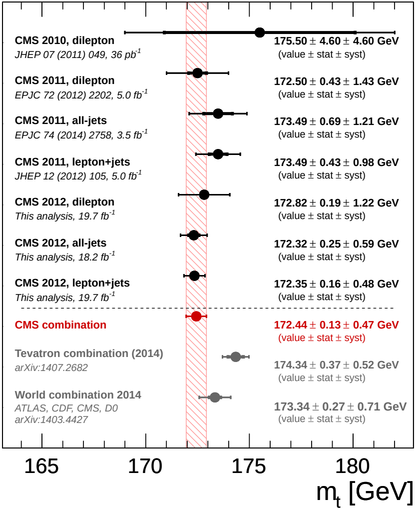
- Latest combination of measurement by the CMS experiment
- Results from 2010, 2011, and 2012
- Using BLUE method
- Takes correlation between measurements into account

Most precise combination

- Legacy results from 2010, 2011
- 2012: All-hadronic (hybrid), ℓ+jets (hybrid), Dileptonic (AMWT)

$$m_t = 172.44 \pm 0.13\,(\text{stat+JSF}) \pm 0.47\,(\text{syst})\ \text{GeV}$$

Precision $< 0.3\,\%$

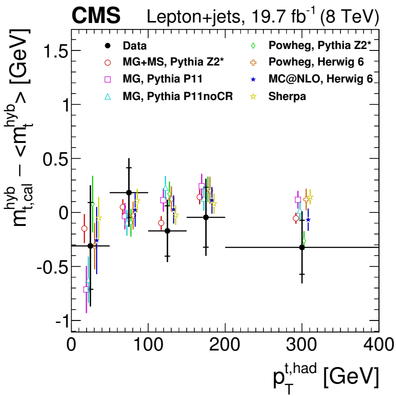


m_t as Function of Kinematic Observables

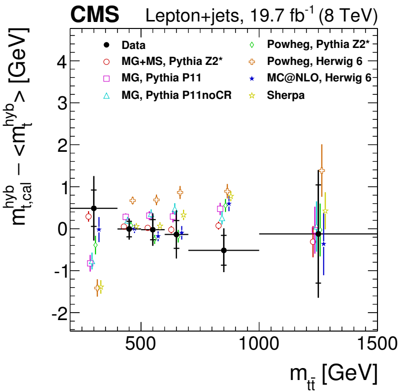
arXiv:1509.04044

- Measure m_t differentially as a function of kinematic variables
- Search for possible biases, potential limitations of current event generators
- Apply hybrid ideogram method to subset of events binned by observable

- m_t as a function of $p_T^{t,had}$
- Description of top quark p_T in MC



- m_t as a function of $m_{t\bar{t}}$
- Testing scale of the process

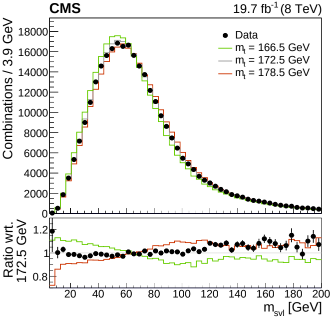


Top Quark Mass from Charged Particles

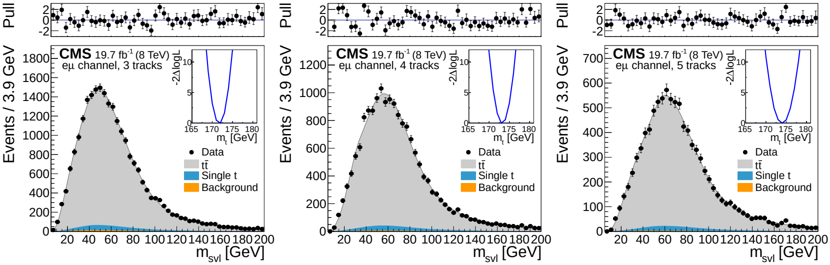
arxiv:1603.06536

Aim

- Reduce dependence on detector calibration (e.g. jet energy corrections)
- Use particle tracks only, no need to reconstruct top



- Observable m_{svl}: **invariant mass of lepton and secondary vertex** (b quark decay)
- 5 channels: dilepton, ℓ+jets
- SV track multiplicities of 3, 4, 5: suppress background
- All possible combinations of leptons and secondary vertices taken into account



Top Quark Mass from Charged Particles

arxiv:1603.06536

- Fit observed m_{svl} distributions in each category with six components: $t\bar{t}$ correct/wrong/unmatched, single-t correct/unmatched, background
- Top mass determined via maximum combined likelihood of all channels

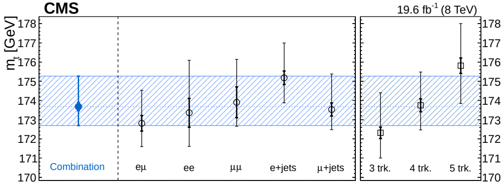
Dominant Uncertainties

$$\text{b quark fragmentation} \quad \Delta m_t = ^{+1.00}_{-0.54}\ \text{GeV}$$

$$\text{Top quark } p_T \quad \Delta m_t = +0.82\,\text{GeV}$$

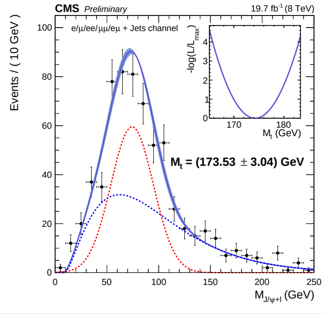
Sensitivity to experimental uncertainties: $\pm 0.44\,\text{GeV}$

$$m_t = 173.68 \pm 0.20\,(\text{stat})\ ^{+1.58}_{-0.97}\,(\text{syst})\ \text{GeV}$$



Or: $\ell + J/\Psi$ invariant mass

- BR $\approx 0.03\%$
- CMS-PAS-TOP-15-014

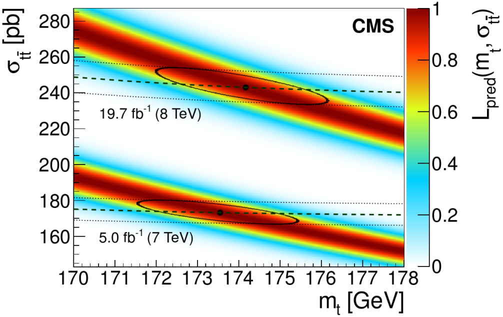


$$173.50 \pm 3.00 \pm 0.90\,\text{GeV}$$

Indirect Measurement: Pole Mass from $\sigma_{t\bar{t}}$

arxiv:1603.02303

- Measurement from the mass dependence of the inclusive $t\bar{t}$ cross section
- Provides direct access to top quark pole mass
- Measurement relies on choice of PDF set and α_s
- Cross section determined using NNPDF3.0, $\alpha_s = 0.118 \pm 0.001$
- Combination of measurements at $\sqrt{s} = 7$ TeV and 8 TeV



$$m_t^{\text{pole}} = 173.8^{+1.7}_{-1.8}\,\text{GeV}$$

- For details on the inclusive $t\bar{t}$ production cross section measurement see talk by N. Bartosik

Summary and Outlook

- Top quark mass is an important parameter to the Standard Model
- Large $t\bar{t}$ production cross section @ LHC allow precision measurements of m_t
- Latest results provide m_t (MC) with a precision of 0.3 %
- Dominating uncertainties are JEC and modeling uncertainties

- Measurements reached precision which allows to distinguish between different mass schemes (MC mass vs pole mass)
- Planned measurements of m_t at $\sqrt{s} = 13$ TeV
- Explore alternative methods, e.g. m_t^{pole} from $t\bar{t}$+jet