Measurement of the mass difference between top and antitop quarks

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Introduction

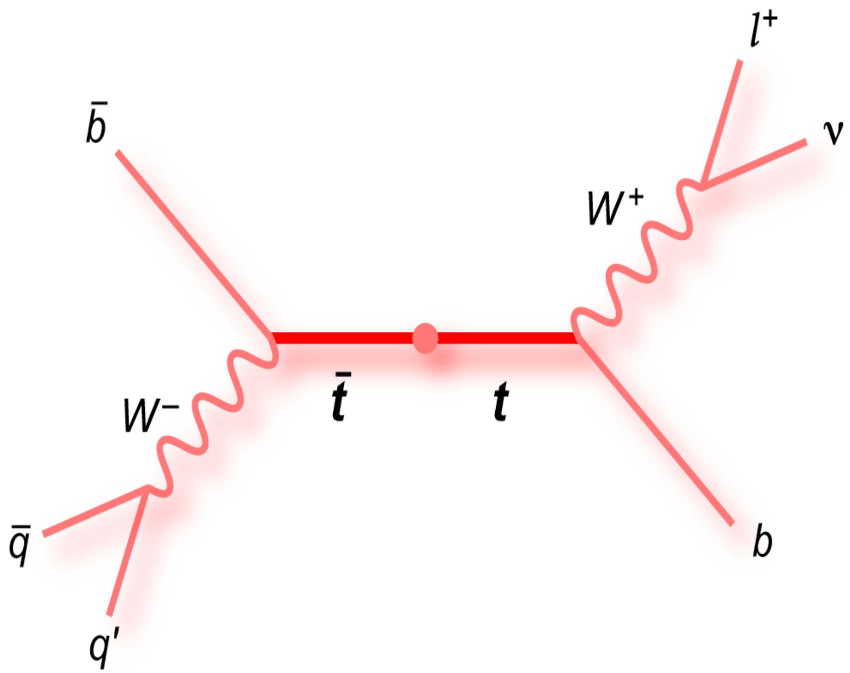
Measurement of the top-antitop mass difference

- Test of **CPT invariance**: equality of particle and antiparticle masses?
- **Full 2011 dataset** of CMS analyzed: 4.96 ± 0.11 fb^{-1} at a center of mass energy of 7 TeV
- Measurement performed using events with a **muon or electron and four jets**
- **Top quark pair events** are selected with one hadronically decaying W boson $\mathrm{t} \to \mathrm{bW} \to \mathrm{bqq'}$ and one leptonically decaying W boson $\mathrm{t} \to \mathrm{bW} \to \mathrm{b}\ell\nu_\ell$
- **Data split in ℓ^- and ℓ^+ samples** that contain, respectively, three-jet decays of the associated top or antitop quarks
- The **ideogram likelihood method** is used to measure the mass of the top quark m_{t} and the antitop quark $m_{\bar{\mathrm{t}}}$
- The **mass difference** is obtained: $\boxed{\Delta m_{\mathrm{t}} \equiv m_{\mathrm{t}} - m_{\bar{\mathrm{t}}}}$

Event reconstruction and selection

Event reconstruction

- Events are reconstructed using the particle-flow (PF) algorithm
  - Information of all CMS sub-detectors used to identify individual muons, electrons, photons, charged and neutral hadrons

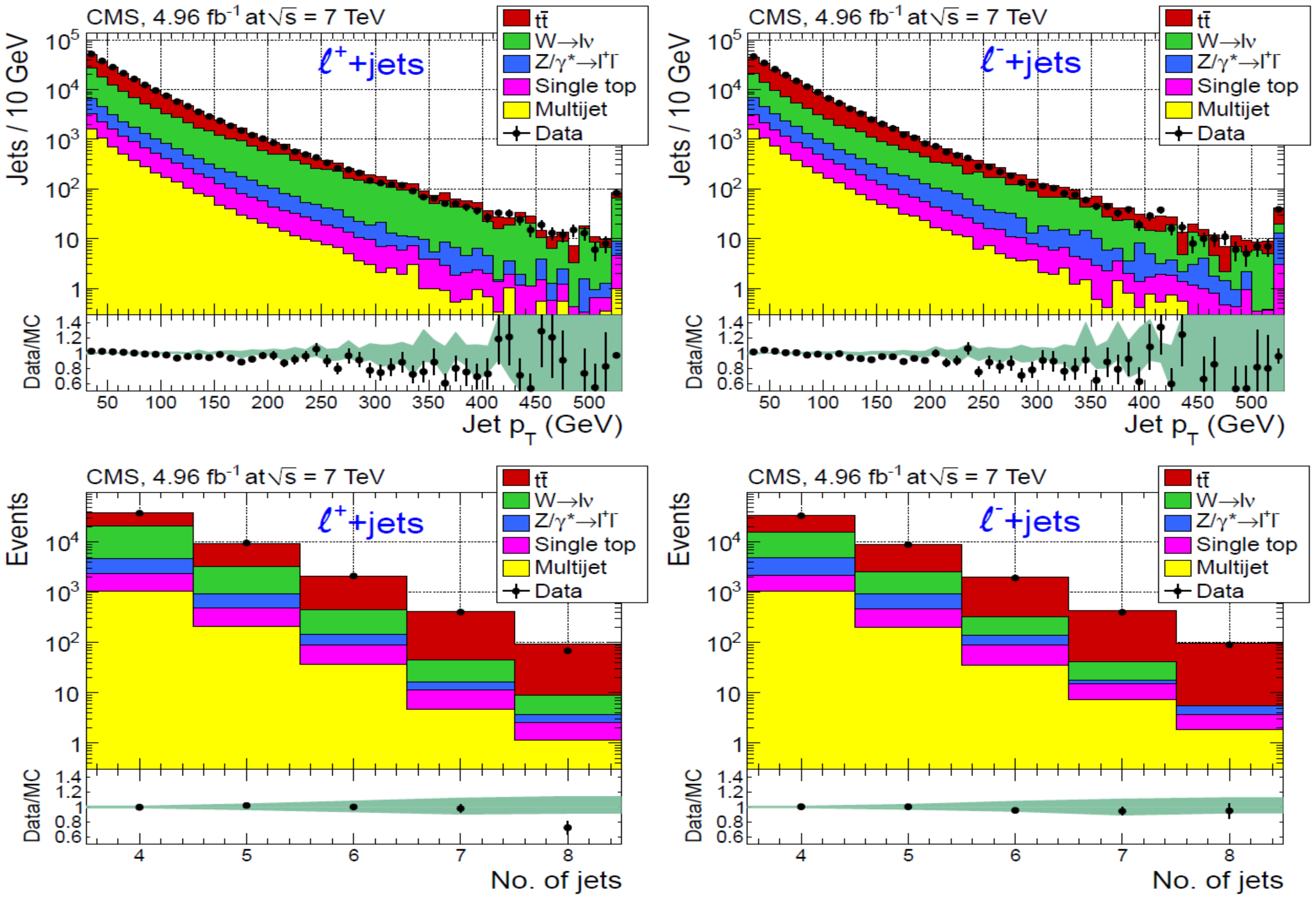


Selection

- At least 4 jets with
  $p_T > 30$ GeV and $|\eta| < 2.4$
- ***μ*+jets channel**:
  – one isolated muon with
  $p_T > 20$ GeV and $|\eta| < 2.1$
- **e+jets channel**:
  – one isolated electron with
  $p_T > 30$ GeV and $|\eta| < 2.5$

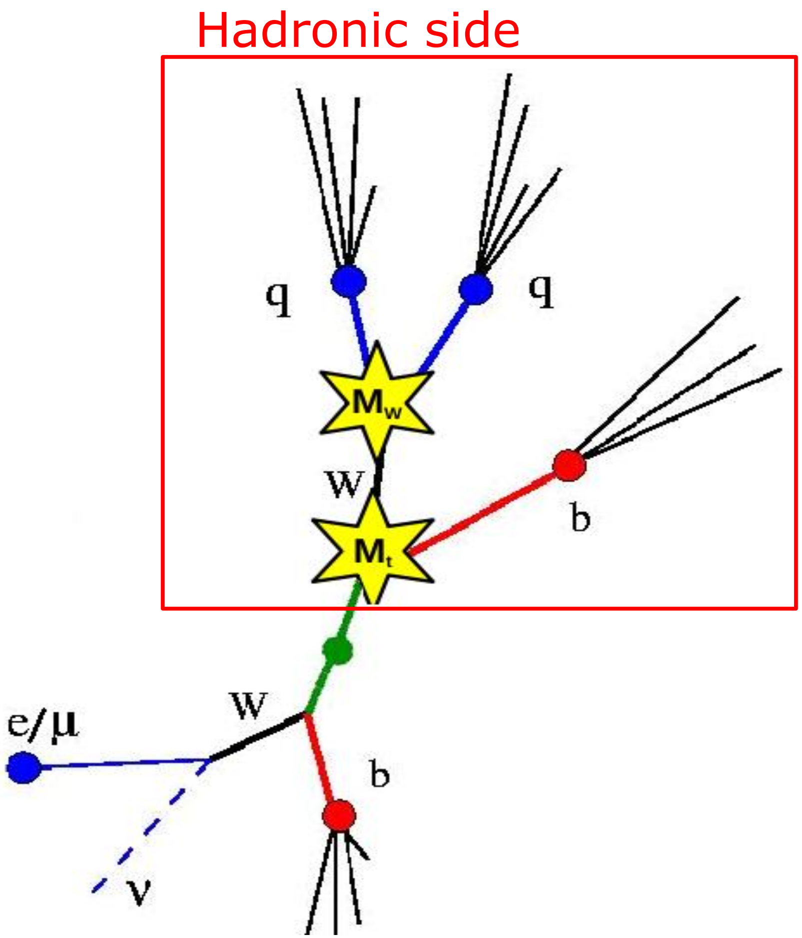
Comparison of simulation and data

- Multijet background estimated from data using an inverted lepton-isolation criterion
- Split in ℓ^++jets and ℓ^-+jets samples
- Simulation normalized to observed number of events: good agreement



Kinematic fit

- For each event, the 4 highest-p_T jets are considered: 12 possible jet-quark assignments



- For each jet combination
  - Jet energies get corrected to the parton level
  - Kinematic fit is applied to the hadronic side

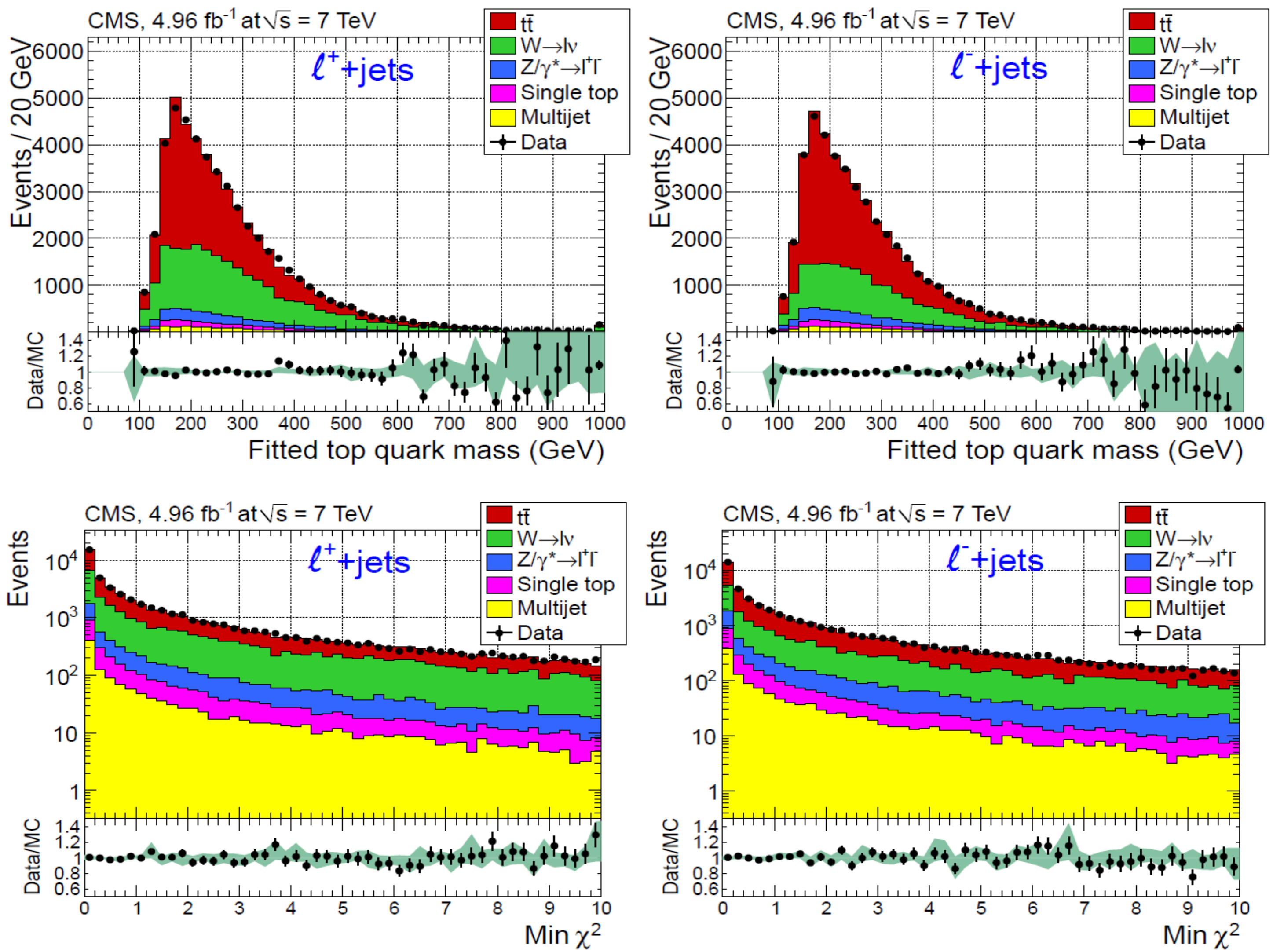
Kinematic fit

- Momenta of the two jets assigned to the W boson are varied, **using m_W as constraint**
  - modifies the reconstruction of the mass of the three-jet decays of the top quark
- Fit returns χ_i^2, fitted mass m_i and the uncertainty σ_i on the fitted mass, for each jet combination *i*

- The kinematic fit **improves the resolution** of the top-quark mass!

Fitted top quark mass

- **Fitted top quark mass** distributions (top) for the smallest χ_i^2 values (bottom), show good agreement for data and simulation
- **Note:** ideogram method uses kinematic output of *all* jet combinations!



The ideogram method

Ideogram likelihood method ➢ *similar to CMS top mass measurement*

- Likelihood defined as function of top-quark mass m_{t}

$$\mathcal{L}_{\mathrm{event}}(x; y \mid m_{\mathrm{t}}) = f_{\mathrm{t\bar{t}}}\, P_{\mathrm{t\bar{t}}}(x; y \mid m_{\mathrm{t}}) + (1 - f_{\mathrm{t\bar{t}}}) P_{\mathrm{bkg}}(x)$$

- $P_{\mathrm{t\bar{t}}}(x; y|m_{\mathrm{t}})$ and $P_{\mathrm{bkg}}(x|m_{\mathrm{t}})$ are the **probability densities** for $\mathrm{t\bar{t}}$ and background events

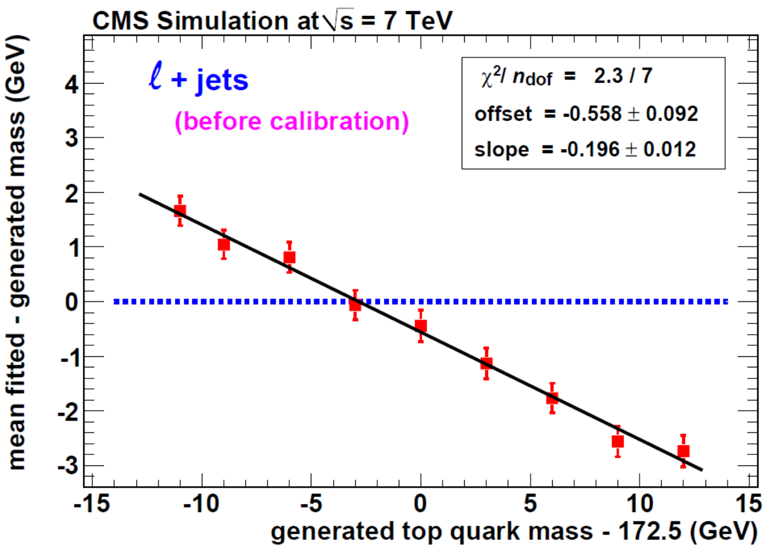
- x represents observables:
  - ➢ number of b-tagged jets
  - ➢ lepton charge
  - ➢ set of mass variables m_i from the kinematic fit

- y represents the variables χ_i^2 and σ_i from the kinematic fit

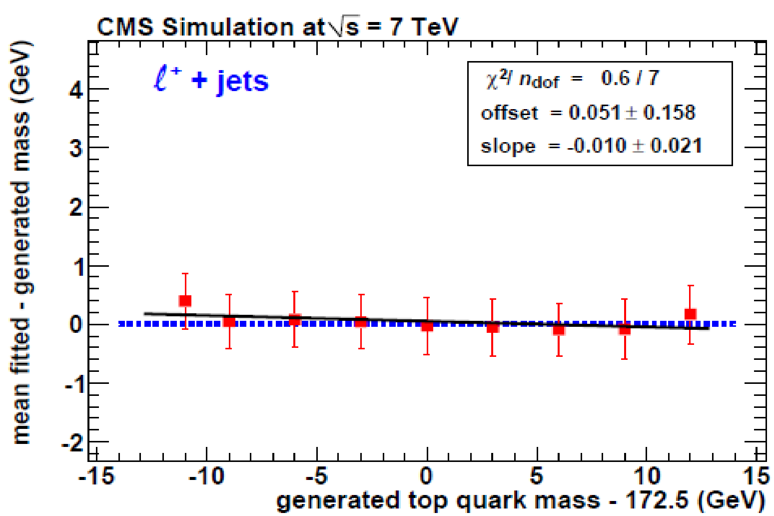
- **The fitted top-quark mass and its statistical uncertainty are extracted from the combined likelihood** (product of individual event likelihoods)

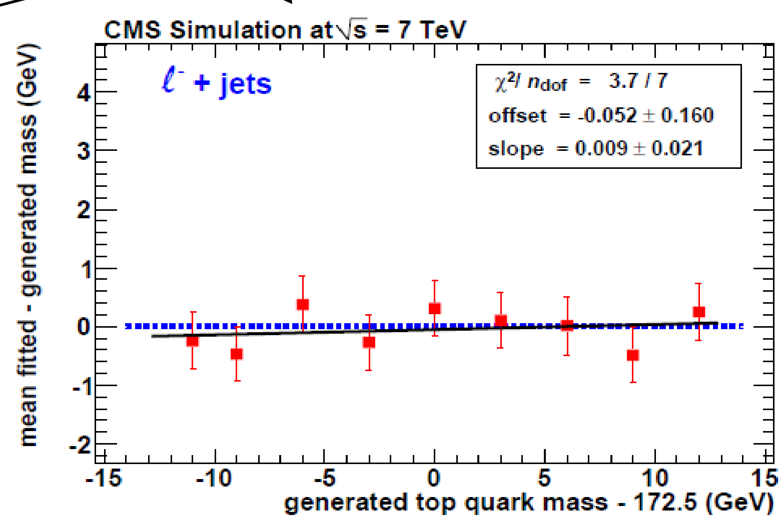
Calibration of individual mass measurements

- The likelihood defined in the ideogram method is a simplified model
  - **To be corrected for a possible bias** of the estimated mass
  - **Calibration of the procedure** using pseudo-experiments



- Nine samples of simulated $t\bar{t}$ events are generated for top-quark masses between 161.5 and 184.5 GeV
- **Bias on the estimated top mass; correct for the bias using the fitted linear calibrations;** demonstration





Measurement of the top-antitop mass difference

- Applying the analysis seperately to ℓ^-+jets events and ℓ^++jets events, and taking the difference of the two extracted values:

$$\Delta m_{\mathrm{t}} = m_{\mathrm{t}}^{\mathrm{ideogram}} - m_{\bar{\mathrm{t}}}^{\mathrm{ideogram}}$$

μ+jets channel

$$\Delta m_{\mathrm{t}} = 0.13 \pm 0.61\,(\mathrm{stat.})\,\mathrm{GeV}$$

e+jets channel

$$\Delta m_{\mathrm{t}} = -1.28 \pm 0.70\,(\mathrm{stat.})\,\mathrm{GeV}$$

Combined μ+jets and e+jets samples

$$\Delta m_{\mathrm{t}} = -0.44 \pm 0.46\,(\mathrm{stat.})\,\mathrm{GeV}$$

- Compatible with the expectation from the hypothesis of CPT symmetry, even ignoring systematic uncertainties

- The average fitted top-quark mass is also in agreement with other measurements:

$$m_{\mathrm{t}} = 173.36 \pm 0.23\,(\mathrm{stat.})\,\mathrm{GeV}$$

Systematic uncertainties (1)

- **Many systematic uncertainties** relevant for the absolute measurement of m_t are **reduced** in this context

Sources of systematic uncertainties treated

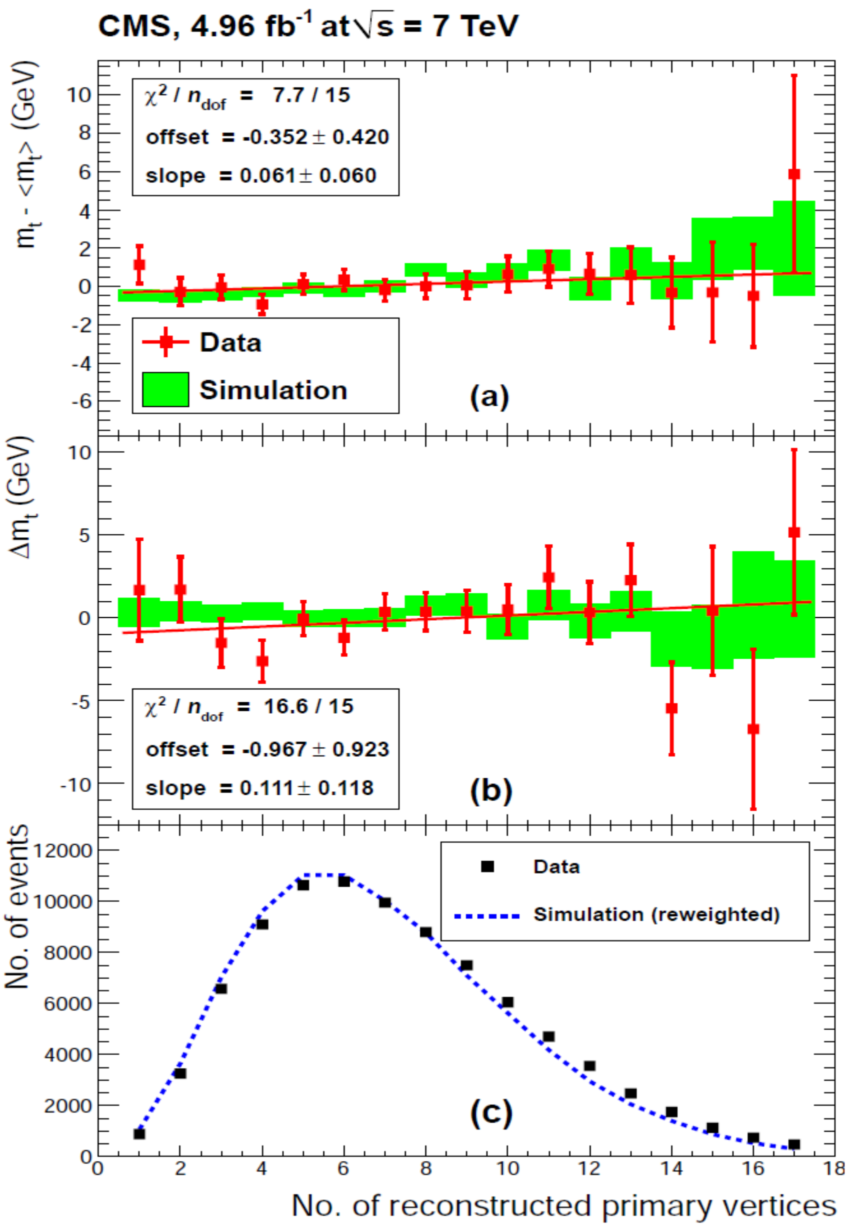
- **Jet energy scale**
  - Top and anti-top quarks at the LHC are produced with slightly different rapidity distributions, so an η-dependence for jet response can lead to a residual effect on Δm_t

- **Difference in W^+/W^- production**
  - Different background composition for W+jets in ℓ^++jets and ℓ^-+jets channels

- **Jet energy resolution**
  - Asymmetry of background composition can cause a residual effect, due to the η-dependency of the JER uncertainties

- **Jet energy scale for b and $\bar{\mathrm{b}}$**
  - PYTHIA simulation describes differences in fragmentation of b and $\bar{\mathrm{b}}$ jets.

Systematic uncertainties (2)



- **Pilup**
  - Uncertainty in pileup modeling and pileup reweighting of simulated events
  - No effects of the number of pileup events on the measurement is observed
- **B-tagging efficiency**
  - Can affect the impact of background processes on the Ideogram method
- **Method calibration**
  - Difference in mass bias between ℓ^-+jets and ℓ^++jets of -0.11 ± 0.14 GeV (simulated $t\bar{t}$ events at mass 172.5 GeV)
- **Parton distribution functions**
  - Determine e.g. the difference in production of W^+ and W^-

Estimated systematics

Overview of estimated systematic effects

Source	Estimated effect (GeV)
Jet energy scale	$0.04 \pm \mathbf{0.08}$
Jet energy resolution	$0.04 \pm \mathbf{0.06}$
b vs. $\overline{\mathrm{b}}$ jet response	$\mathbf{0.10} \pm 0.10$
Signal fraction	$\mathbf{0.02} \pm 0.01$
Difference in W^+/W^- production	$\mathbf{0.014} \pm 0.002$
Background composition	$\mathbf{0.09} \pm 0.07$
Pileup	$\mathbf{0.10} \pm 0.05$
b-tagging efficiency	$\mathbf{0.03} \pm 0.02$
b vs. $\overline{\mathrm{b}}$ tagging efficiency	$\mathbf{0.08} \pm 0.03$
Method calibration	$0.11 \pm \mathbf{0.14}$
Parton distribution functions	**0.088**
Total	$\boxed{0.27}$

Conclusion

- **Mass difference between top quark and the antitop quark** is measured

- Masses are measured with the **Ideogram method** using the lepton+jets top quark pair event sample collected by the CMS experiment, with an integrated luminosity of $4.96 \pm 0.11\ \mathrm{fb}^{-1}$

- This yields **world's most precise measurement**:

$$\boxed{\Delta m_{\mathrm{t}} = -0.44 \pm 0.46\,(\mathrm{stat.}) \pm 0.27\,(\mathrm{syst.})\ \mathrm{GeV}}$$

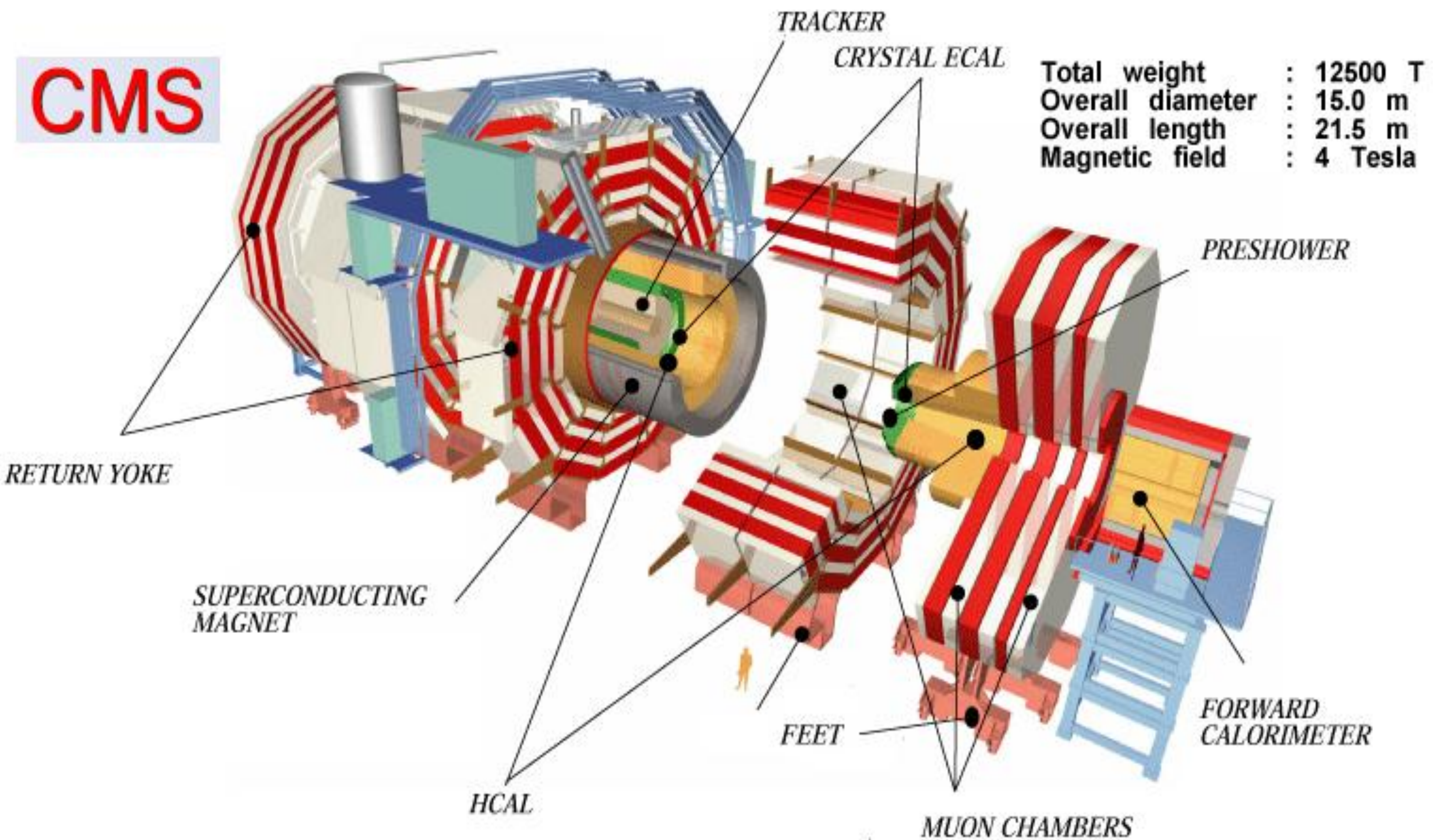
  - 2 to 3 times more precise than other measurements
    - D0, arXiv: 0906.1172
    - CDF, arXiv: 1103.2782
    - D0, arXiv: 1106.2063
    - CDF, note 10777

- The measurement is **in agreement with the consequence of CPT invariance**, which requires no mass difference

References: *CMS-TOP-11-019, arXiv:1204.2807, Accepted by JHEP*

BACKUP

The CMS detector



Relative isolation & Nr of selected events

Relative isolation I_{rel}

- I_{rel} is calculated from the PF particles (other than the leptons) within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the axis of the lepton:

$$I_{\mathrm{rel}} = (I_{\mathrm{charged}} + I_{\mathrm{photon}} + I_{\mathrm{neutral}}) / p_{\mathrm{T}}$$

  - I_{charged}, I_{photon}, I_{neutral} = transverse energy deposited by respectively charged hadrons, photons and neutral particles
  - p_{T} = transverse momentum of lepton

Number of events after selection

Sample	μ^++jets	μ^-+jets	e^++jets	e^-+jets
$t\bar{t}$	15028 ± 56	15006 ± 56	10649 ± 47	10611 ± 47
W+jets	11180 ± 149	7314 ± 121	7783 ± 125	5523 ± 105
Z/γ^*+jets	1410 ± 25	1516 ± 26	1607 ± 27	1685 ± 27
Single top	951 ± 7	850 ± 7	675 ± 6	610 ± 6
Multijet	483 ± 90	196 ± 57	722 ± 246	1413 ± 485
Total	29050 ± 185	24882 ± 147	21436 ± 281	19842 ± 499
Observed	27038	23928	22999	21111

The ideogram method (1)

Ideogram likelihood method

- Likelihood defined as function of top-quark mass m_{t}

$$\mathcal{L}_{\mathrm{event}}(x; y \mid m_{\mathrm{t}}) = f_{\mathrm{t\bar{t}}} P_{\mathrm{t\bar{t}}}(x; y \mid m_{\mathrm{t}}) + (1 - f_{\mathrm{t\bar{t}}}) P_{\mathrm{bkg}}(x)$$

  - Fraction $f_{\mathrm{t\bar{t}}}$ of the $\mathrm{t\bar{t}}$ component of the simulation
  - $P_{\mathrm{t\bar{t}}}(x; y \mid m_{\mathrm{t}})$ and $P_{\mathrm{bkg}}(x)$ are the **probability densities** for $\mathrm{t\bar{t}}$ and background events

$$P_{\mathrm{t\bar{t}}}(x; y \mid m_{\mathrm{t}}) = P_{\mathrm{t\bar{t}}}(n_{\mathrm{b}}) \cdot P_{\mathrm{t\bar{t}}}(q^{\ell}) \cdot P_{\mathrm{t\bar{t}}}(x_{\mathrm{mass}}; y \mid m_{\mathrm{t}})$$

$$P_{\mathrm{bkg}}(x) = P_{\mathrm{bkg}}(n_{\mathrm{b}}) \cdot P_{\mathrm{bkg}}(q^{\ell}) \cdot P_{\mathrm{bkg}}(x_{\mathrm{mass}})$$

  - Probability densities $P(n_{\mathrm{b}})$ and $P(q^{\ell})$ for the **number of b-tagged jets** n_{b} and the **lepton charge** q^{ℓ}
    - B-tagging reduces impact of non-$\mathrm{t\bar{t}}$ background
    - W+jets and single top depend on the lepton charge
  - x_{mass} represents the set of mass variables m_i, and y the values of the parameters χ_i^2 and σ_i from the kinematic fit

The ideogram method (2)

- **The $t\bar{t}$ probability for each event:**

  - Sum over all jet combinations
  - Reflects probability that the jet combination with highest weight corresponds to the correct jet-parton matching

$$P_{t\bar{t}}(x_{\text{mass}}; y \mid m_t) = \sum_{i=1}^{12} w_i \left(f_{gc} \int dm' G(m_i \mid m', \sigma_i) B(m' \mid m_t, \Gamma_t) + (1 - f_{gc}) W(m_i \mid m_t) \right)$$

  - Jet combination **weight** (next slide)
  - Probability for **correct jet combinations**: convolution of a Gaussian resolution function and a Breit-Wigner distribution
  - Probability for **wrong jet combinations**;

The ideogram method (3)

- **Jet combination weight:**

$$w_i = \exp\left(-\frac{1}{2}\chi_i^2\right) w_{\mathrm{b}}$$

$$w_{\mathrm{b}} = \prod_j p^j$$

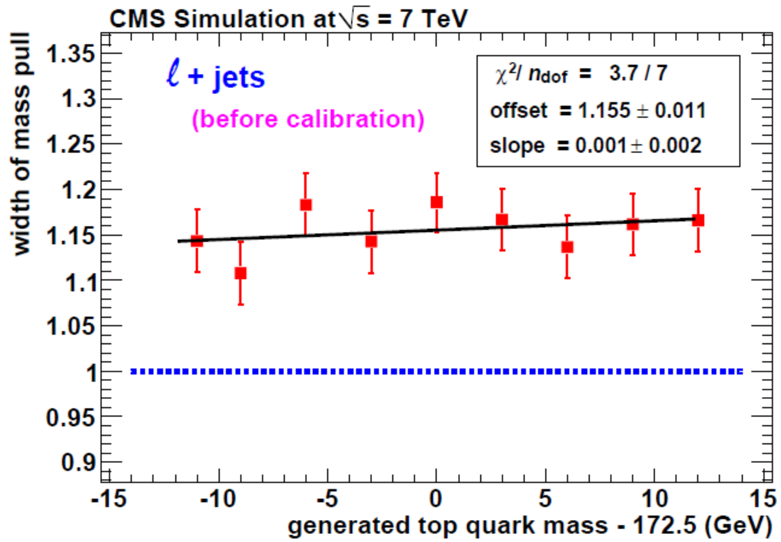
- The probabilities p^j depend on the flavour assigned to jet *j* and whether it is b-tagged, and equals ε_b , $(1-\varepsilon_b)$, ε_l or $(1-\varepsilon_l)$, with:
  – **b-tagging efficiency ε_b** = 60.6 ± 2.5 %
  – **rate for tagging light flavor jets**
  ε_l = 1.4 ± 0.3 %

- **Background probability** $P_{\mathrm{bkg}}(x_{\mathrm{mass}})$ determined by fit of analytical function to simulated m_i distribution of W+jets

- Combined likelihood for full event sample = product of individual event likelihoods

- **The fitted top-quark mass and its statistical uncertainty are extracted from this combined likelihood**

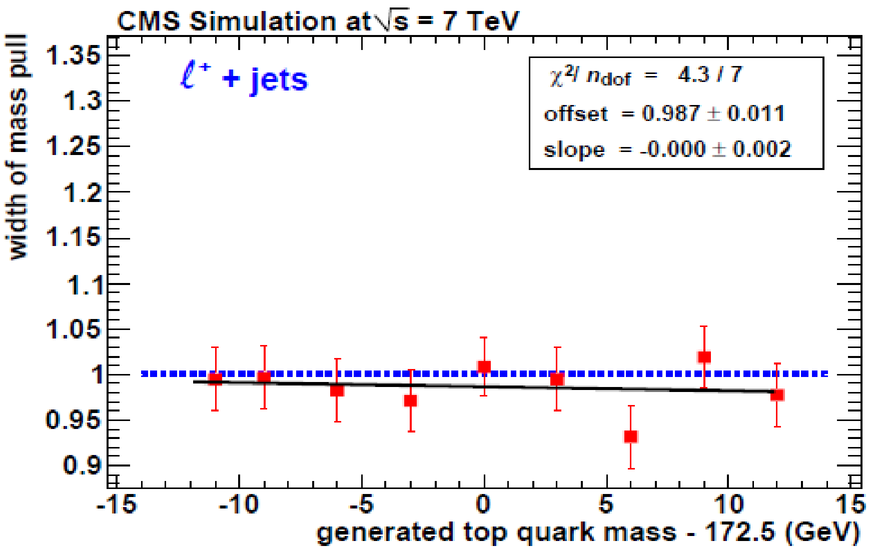
Calibration of statistical uncertainties

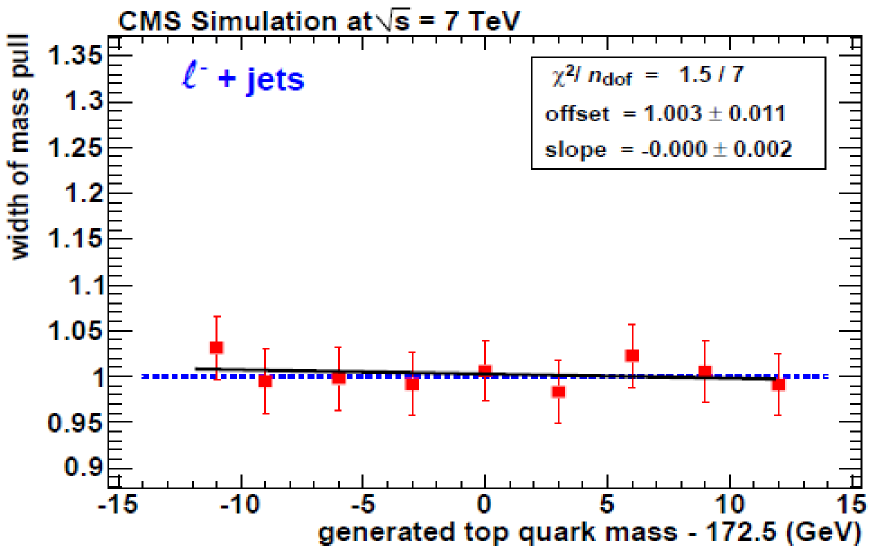


- **Width of pull distributions**

  $$\text{pull} = \left(m_j - \langle m \rangle\right) / \sigma_j$$

- **Scaling up the statistical uncertainties** on the mass measurement to calibrate the width of the mass pull distributions:





Treatment of systematic uncertainties (1)

- **Jet energy scale**
  - JES uncertainties measured using 2012 data
  - Energy of jets changed within the p_T and η–dependent uncertainties
- **Jet energy resolution**
  - JER in data is 10% worse than in simulation; resolution in simulation degraded accordingly
  - The uncertainty on this 10% depend on η and ranges from 10% to 20%
- **Jet energy scale for b and $\bar{\mathrm{b}}$**
  - Compared the reconstructed p_T to the original parton p_T
  - Ratio of b to $\bar{\mathrm{b}}$ response found to be 0.999 ± 0.001
  - 100% of shift of 0.10 GeV quoted as systematic uncertainty
- **Signal fraction**
  - Fraction of the $\mathrm{t}\bar{\mathrm{t}}$ signal in simulation changed by ±20%
- **Difference in W^+/W^- production**
  - Varied the ℓ^+ and ℓ^- backgrounds by 2% in opposite directions affecting the relative ratio W^+/W^- by 4%, the uncertainty on the measurement by CMS

Treatment of systematic uncertainties (2)

- **Background composition**
  - Studied effect of removing completely each source of background from the calibration procedure
  - Quoted 30% of total shift of measurement when removing the W+jets background, Z+jets and single top, and 100% on multijet background
- **Pileup**
  - Changed the mean value of the number of interactions by ± 0.6
- **B-tagging efficiency**
  - Changed the b-tagging efficiency by ±4%
  - Applied in the same direction for the ℓ^+ and ℓ^- samples for the b-tagging efficiency, and in opposite directions for the b vs $\bar{\mathrm{b}}$ tagging efficiency

Negligible systematic uncertainties

- **ISR/FSR, ME-PS matching and factorization scale**
  - Found to be statistically compatible with 0
- **Trigger**
  - Lepton not used in mass reconstruction; small effect estimated
- **Misassignement of lepton-charge**
  - Effect on measurement below 1%

Other measurements

Other measurements of the top-antitop mass difference

- D0 collaboration,“Direct measurement of the mass difference between top and antitop quarks”, *Phys. Rev. Lett.* **103** (2009) 132001, arXiv: 0906.1172

$$\Delta m_{\mathrm{t}} = 3.8 \pm 3.7\,\mathrm{GeV}$$

- CDF collaboration,“Measurement of the mass difference between *t* and $\bar{t}$ quarks”, *Phys. Rev. Lett.* **106** (2011) 152001, arXiv: 1103.2782

$$\Delta m_{\mathrm{t}} = -3.3 \pm 1.4\,(\mathrm{stat.}) \pm 1.0\,(\mathrm{syst.})\mathrm{GeV}$$

- D0 collaboration,“Direct measurement of the mass difference between top and antitop quarks”, *Phys. Rev. D* ***84*** (2011) 052005, arXiv: 1106.2063

$$\Delta m_{\mathrm{t}} = 0.8 \pm 1.8\,(\mathrm{stat.}) \pm 0.5\,(\mathrm{syst.})\mathrm{GeV}$$

- CDF collaboration,“Measurement of the mass difference between *t* and $\bar{t}$ quarks”, CDF note 10777 (preliminary) (2012)

$$\Delta m_{\mathrm{t}} = -1.95 \pm 1.11\,(\mathrm{stat.}) \pm 0.59\,(\mathrm{syst.})\mathrm{GeV}$$