Measurement of the top quark mass in the dilepton channel at CMS

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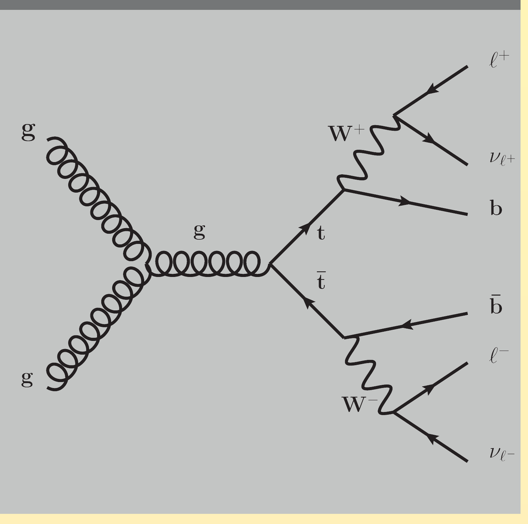
Abstract

We present a measurement of the top quark mass $\mathbf{m_{top}}$ in the dilepton decay channel $\mathbf{t\bar{t} \to (\ell^+\nu_\ell b)(\ell^-\bar{\nu}_\ell\bar{b})}$ in pp collisions at $\sqrt{s} = 7$ TeV. The data sample of the measurement corresponds to an integrated luminosity of $\mathbf{2.3\ fb^{-1}}$ collected with the CMS detector at the LHC. Events are selected by requiring two leptons, at least two jets and missing transverse energy. The mass is reconstructed from the kinematic characteristics of the events with a full kinematic analysis. A set of templates is constructed from simulated samples and a likelihood fit is performed to derive the mass. Result yields a measurement of $\mathbf{m_{top} = 173.3 \pm 1.2(stat.) \pm 2.6(syst.) \frac{GeV}{c^2}}$.

The dilepton channel

- Dilepton channel, $\mathbf{t\bar{t} \to (l^+\nu_l b)\ (l^-\bar{\nu}_l\bar{b})}$:
  - Smallest branching fraction
  - Expected to be the least contaminated by background processes
  - two neutrinos in the final state: under-constrained system
- Top pair decay kinematics
  - only 18 parameters measured from the event
  - $\mathbf{W}$, neutrino masses are constrained
  - $\mathbf{m_t = m_{\bar{t}}}$
  - $\sum \mathbf{p_T}$ of the neutrinos constrained by the $\not{E}_T$ system
  - one degree of freedom left



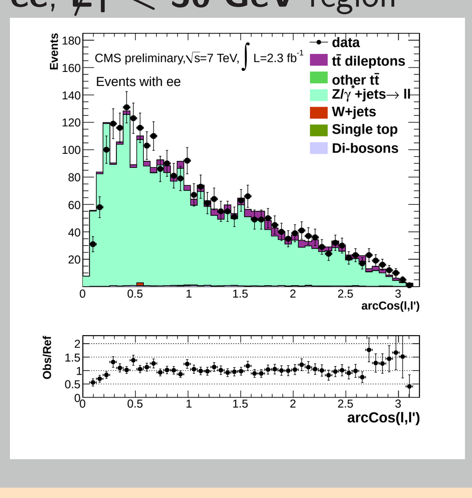
Event selection

- Events pass standard dilepton triggers and are reconstructed using `Particle Flow`
- Two isolated, oppositely charged leptons $(\mathbf{e}, \mu)$ with $\mathbf{p_T > 20\ \frac{GeV}{c}}$, $|\eta| < \mathbf{2.4}$
- $|\mathbf{m_{ll'} - 91}| \geq \mathbf{15\ \frac{GeV}{c^2}}$ (out of $\mathbf{Z}$ mass window)(ee, $\mu\mu$ only)
- Dilepton mass $\mathbf{m_{ll'} > 12\ \frac{GeV}{c^2}}$
- At least two jets reconstructed with `AntiKt5` algorithm, with $\mathbf{p_T > 30\ \frac{GeV}{c}}$, $|\eta| < \mathbf{2.4}$
  - Energy corrections and jet identification algorithms are applied
- Classify jets with an high efficiency `b-tagging` algorithm, and require at least $\mathbf{1}$ `b-tagged` jet in the event
- Selected leptons and jets required to originate from the same primary interaction vertex
- Missing transverse energy $\not{E}_T > \mathbf{30\ GeV}$ (ee, $\mu\mu$ only)

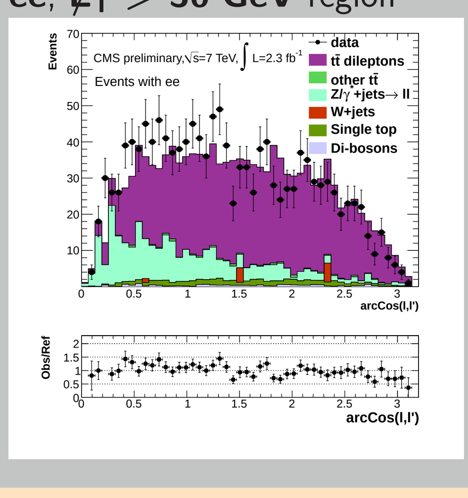
Control of the Drell-Yan contamination in the selected sample

- Use angle between the two leptons ($\theta_{\ell\ell'} = \mathbf{arccos}\left[\frac{\vec{p}_\ell \cdot \vec{p}_{\ell'}}{|\vec{p}_\ell||\vec{p}_{\ell'}|}\right]$): correlated for DY, random for other processes
- Use data-driven shapes taken from low $\not{E}_T$ region ($< \mathbf{30\ GeV}$)
- Shape for $\mathbf{t\bar{t}}$ and other processes taken from MC
- Perform a fit of the templates in the signal region ($\not{E}_T > \mathbf{30\ GeV}$)

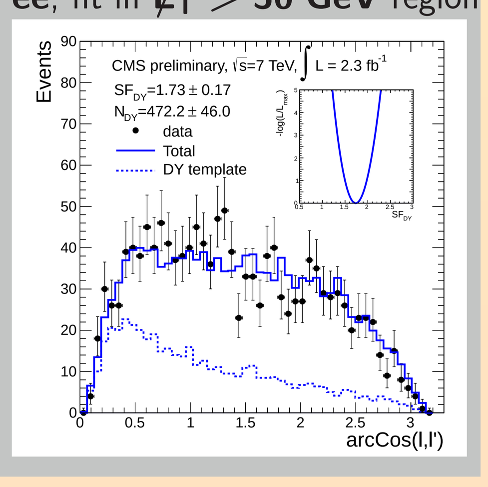
→ ee, $\not{E}_T < \mathbf{30\ GeV}$ region



→ ee, $\not{E}_T > \mathbf{30\ GeV}$ region



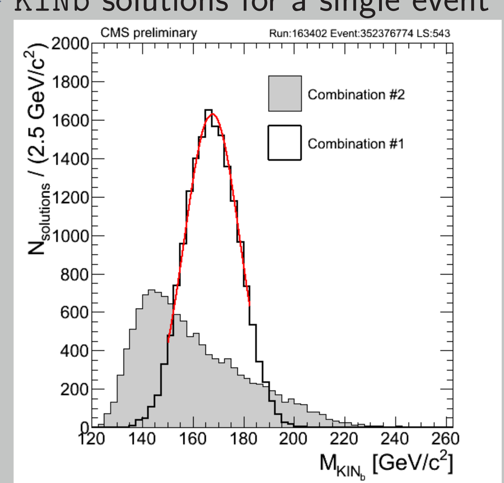
→ ee, fit in $\not{E}_T > \mathbf{30\ GeV}$ region



`KINb` algorithm

- Solve several times the equations for kinematics ($\mathbf{5 \cdot 10^4}$)
- Each time vary jet kinematics according to resolution
- $\not{E}_T$ constrains the neutrinos' momenta
- $\mathbf{p_z^{t\bar{t}}}$ constrains the $\mathbf{t\bar{t}}$ system (minimal dependence on $\mathbf{m_{top}}$)
- Repeat for each lepton-jet combination
  - only the two jets with highest `CSV` discriminator are used
  - one loose `CSV b-tag` is required in the event
- $\mathbf{m_{top}}$ estimated from the peak of the combination with largest number of solutions

→ `KINb` solutions for a single event



Object	Parameter	Type	$\mathbf{N_{parameters}}$	Total
jets	$\mathbf{(E, \vec{p})}$	measurement	2×4	8
charged leptons	$\mathbf{(E, \vec{p})}$	measurement	2×4	16
neutrinos	$\mathbf{\vec{E}_T^{miss}}$	measurement	2	18
	$\mathbf{m_\nu = 0}$	constraint	2	20
$\mathbf{W}$ boson mass	$\mathbf{m_W}$ =80.398±0.025$\mathbf{\frac{GeV}{c^2}}$	constraint	2	22
$\mathbf{t}$ mass	$\mathbf{m_t = m_{\bar{t}}}$	constraint	1	23
$\mathbf{t\bar{t}}$ longitudinal balance	$\mathbf{p_z \sim \mathcal{G}aus(0, \sigma)}$	hypothesis (MC)	1	24

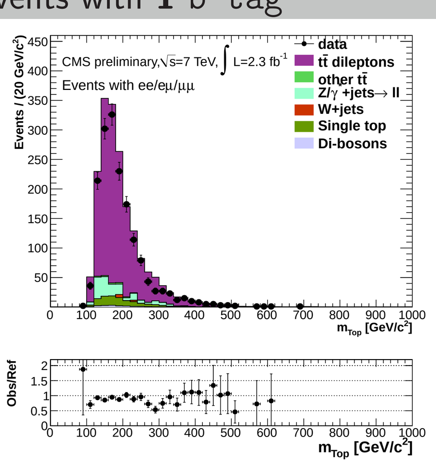
Sample selected for the measurement

- Require $\not{E}_T > \mathbf{30\ GeV}$ for all channels (similar resolution)
- `KINb` rejects **29%** (**17%**) of background (signal) events (no solutions)
- Uncertainty contains lumi (4.5%), theoretical cross section, `JES`, `JER`, `PU` contamination, trigger and selection efficiencies, statistics of the `MC` samples
- Good agreement between data and expectations

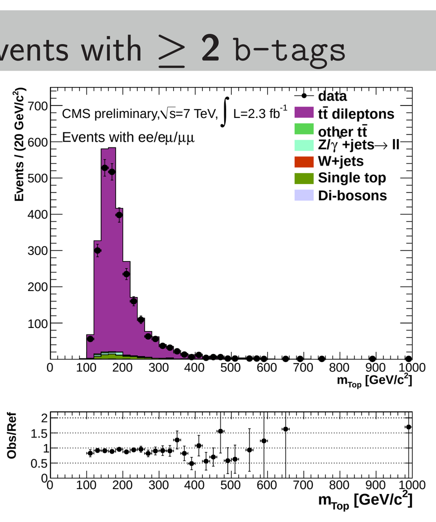
Process	Pre-selection	KINb	=1 b-tags	$\geq$ 2 b-tags
Di-bosons	73 ± 14	55 ± 10	18 ± 4	4 ± 1
Single top	247 ± 92	182 ± 68	88 ± 33	76 ± 29
W+jets	22 ± 10	16 ± 8	8 ± 6	-
$\mathbf{Z}/\gamma^* \to \ell\ell$	1091 ± 97	756 ± 71	238 ± 29	47 ± 11
other $\mathbf{t\bar{t}}$	32 ± 4	28 ± 3	11 ± 2	14 ± 2
$\mathbf{t\bar{t}}$ dileptons	5057 ± 463	4209 ± 385	1379 ± 127	2623 ± 240
total expected	6522 ± 482	5246 ± 398	1742 ± 134	2765 ± 242
data	6358	5047	1692	2620

Reconstructed top mass:

→ Events with $\mathbf{1}$ `b-tag`



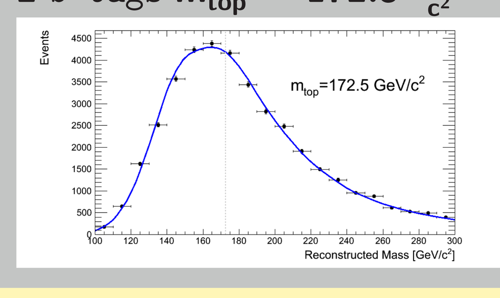
→ Events with $\geq \mathbf{2}$ `b-tags`



Modeling the signal component

- Generated signal MCs, from $\mathbf{161.5\ \frac{GeV}{c^2}}$ to $\mathbf{184.5\ \frac{GeV}{c^2}}$
- Mass reconstructed by using the `KINb` method
- Categorizing by $= \mathbf{1}$ and $\geq \mathbf{2b - tags}$
- Distributions fitted with a Gaussian+Landau template
- Free parameters assumed to be linear functions of $\mathbf{m_{top}}$
- $\mathbf{m_{top} \to (m_{top} - 172) \cdot slope + intercept}$

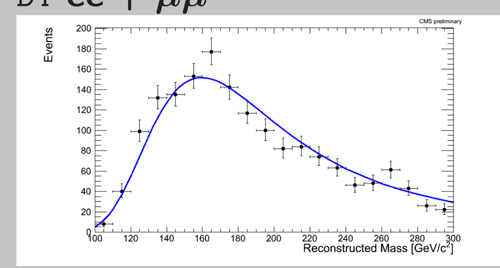
→ 2 `b-tags` $\mathbf{m_{top}^{gen} = 172.5\ \frac{GeV}{c^2}}$



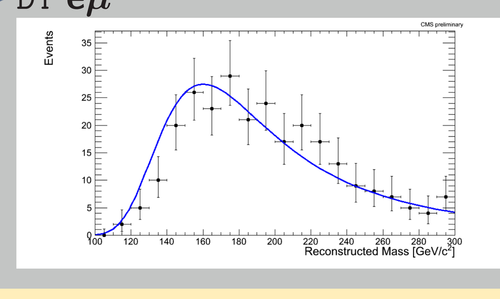
Modeling the background component

- `VV`, `W+jets`, `single-t` and non-dilepton $\mathbf{t\bar{t}}$ fit together
  - Landau curves are used in a combined fit in all channels
- DY: separate fit for same flavour and opposite flavour
  - ee + $\mu\mu$: $\mathbf{Z \to ll}$ events inside $\mathbf{Z}$ mass peak
  - eμ: samples with $\mu \to \tau$ replacement in $\mathbf{Z} \to \mu\mu$ data
  - Landau curves are used to fit DY shape in all channels

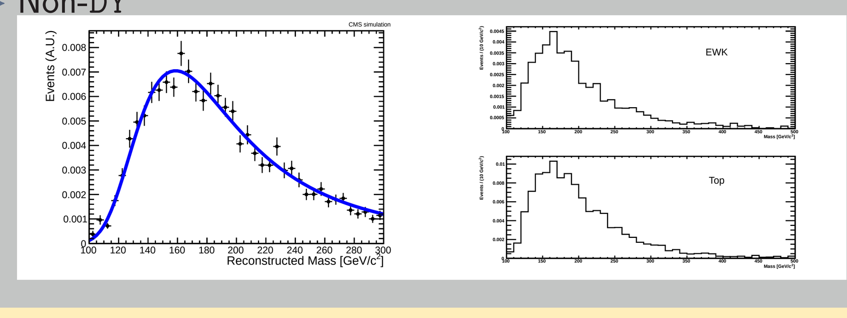
→ DY $\mathbf{ee} + \mu\mu$



→ DY eμ



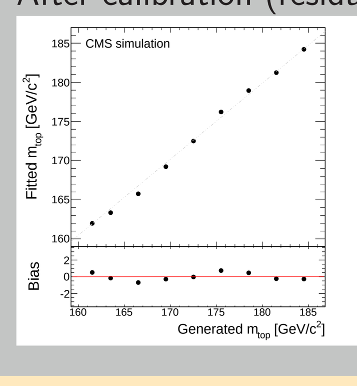
→ Non-DY



Calibration of the top mass fit

- Pseudo-experiments are used to calibrate the result of the fit
- Include signal and background according to expectations
- $\mathbf{N^{events}}$ drawn from Poisson distributions around the average
- Determine distribution of the biases for each mass point
- Correction is determined from the average biases
- Transformation $\mathbf{m_{top} \to m_{top} \cdot (1 - slope) + bias}$
- Residual bias remains with $\mathbf{0.4\ \frac{GeV}{c^2}}$ envelope
- Envelope is assigned as intrinsic systematic of the method

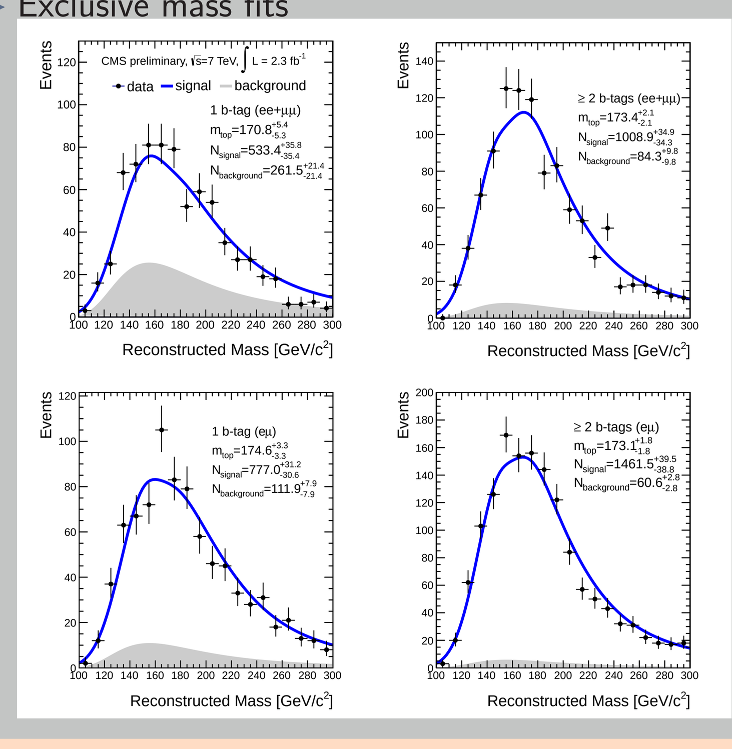
→ After calibration (residual)



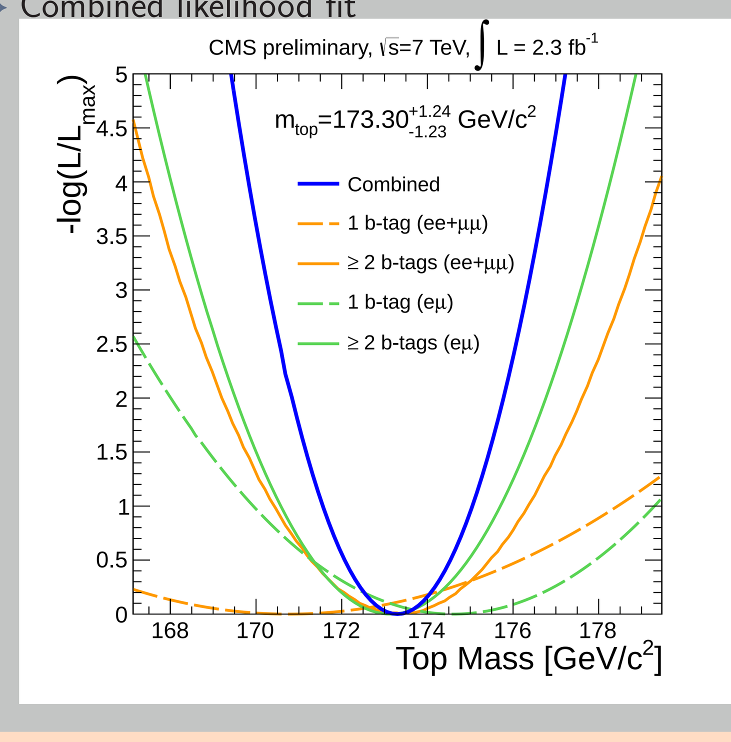
Fit results

- Perform an unbinned likelihood fit
  - $\mathcal{L}(\mathbf{m_t}) = \mathcal{L}_{shape}(\mathbf{m_t}) \times \mathcal{L}_{n_b}$
    - $\mathcal{L}_{shape}(\mathbf{m_t}) = \frac{e^{-(n_s+n_b)}(n_s+n_b)^N}{N!} \prod_{i=1}^{N} \frac{n_s\mathcal{P}_s(m_i|m_t)+n_b\mathcal{P}_b(m_i)}{n_s+n_b}$
    - $\mathcal{L}_{n_b} = \mathcal{G}_{auss}(\mathbf{n_b}, \mathbf{\bar{n}_b}, \sigma_{\mathbf{n_b}})$
  - Number of background events allowed to float constrained within the uncertainty
  - Combine the fit to $\mathbf{4}$ exclusive categories: same/op flavour dileptons w/ $= \mathbf{1}/\geq \mathbf{2}$ `b-tags`
  - Results in agreement in the different categories
- Individual results are combined in a single fit of the top quark mass

→ Exclusive mass fits



→ Combined likelihood fit



Systematic uncertainties

- Two main sources of systematics:
  - Physics object calibration: jet/lepton energy scale, resolution, `b-tagging` performance
  - Modeling of the signal: $\mathbf{Q^2}$ scale, `PDF` uncertainty, contamination from `ISR`/`FSR`, pileup scenario, `MC` generator (`MADGRAPH` vs. `POWHEG`)
- Measurement is expected to be mostly affected by the `JES` uncertainty
- Systematic uncertainties are evaluated by varying the relevant quantities
- For each variation, pseudo-experiments determine the average $\mathbf{m_{top}}$ fit using the standard calibration
- The difference with respect to the nominal expectation for the $\mathbf{m = 172.5\ \frac{GeV}{c^2}}$ sample is assigned as the bias

Table: Summary of the systematic uncertainties

Source	$\Delta\mathbf{m_{top}}$ $(\frac{GeV}{c^2})$
JES	$^{+1.90}_{-2.00}$
flavor-JES	$^{+1.08}_{-1.13}$
JER	± 0.30
Fit calibration	± 0.40
DY normalization	± 0.4
Factorization scale	± 0.41
Jet parton matching scale	± 0.65
Pile-up	± 0.19
$\mathbf{b}$-tagging uncertainty	± 0.30
mis-tagging uncertainty	± 0.43
LES	$^{+0.12}_{-0.18}$
MC generator	± 0.14
PDF	± 0.4
Total	$^{+2.49}_{-2.59}$

Conclusions

Our measurement:

$$\mathbf{m_{top} = 173.3 \pm 1.2(stat.) \pm 2.6(syst.)\ \frac{GeV}{c^2}}$$

- In good agreement with world average
- In agreement with other dilepton channel measurements