Measurement of the Top Quark Mass at $\sqrt{s}$ = 7 TeV

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On behalf of the CMS Collaboration

Top Quark Mass

- Top quark mass is a fundamental parameter of the Standard Model
- The top quark is the most massive known particle
  - Top quark mass affects Standard Model observables via radiative corrections
  - Important input to electroweak fits
  - Provides constraints on Higgs boson and other hypothetical particles
- Precisely measured at the Tevatron: $m_{top} = 173.2 \pm 0.9$ GeV/c^2
- Presented here are the first measurements at CMS
  - Use all data from 2010 (35.9 ± 1.4 pb^{-1})

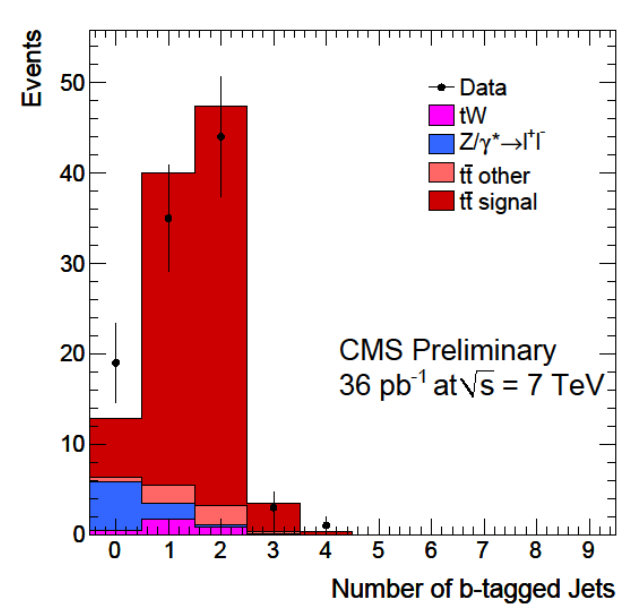
$\bar{t}t$ Decay Channels

- "Lepton": e or μ
- Dilepton channel (bblνlν)
  - Low branching ratio (0.065), but very clean
  - 2 neutrinos → under-constrained system
  - Top quark mass measured with two different methods, AMWT and KINb
  - arXiv:1105.5661, CMS-PAS-TOP-10-006
- Lepton+Jets channel (bbjjlν)
  - High branching ratio (0.35)
  - Lepton can be used to eliminate large multijet background
  - Mass measured with Ideogram method
  - CMS-PAS-TOP-10-009

Dilepton Channel

Event Selection

- Inclusive single lepton and dilepton triggers
  - Triggers evolve with LHC luminosity
- 2 isolated, prompt leptons of opposite sign (ee, μμ or eμ):
  - p_T > 20 GeV/*c* and |η|< 2.5 (e) / 2.4 (μ)
  - Invariant mass M > 12 GeV/c^2 (quarkonia veto)
  - Z^0-veto for ee and μμ: M < 76 GeV/c^2 or M > 106 GeV/c^2
- At least 2 jets with p_T > 30 GeV/*c*, |η|< 2.5
  - Anti-k_T (R = 0.5) jets
  - Use the entire detector ("particle flow")
- Missing E_T > 30 GeV (ee, μμ) / 20 GeV (eμ)
- b-tag driven jet selection:
  - Give b-tagged jets priority to avoid ISR/FSR



Event Yield

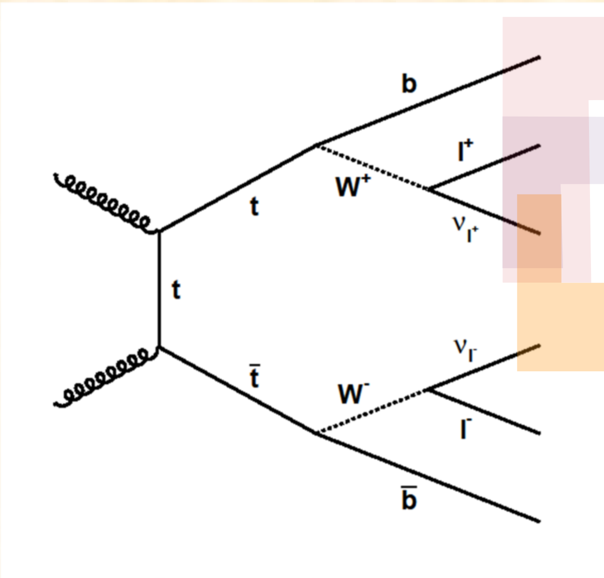
- 102 events selected
- Good agreement between data and simulation

Selection cut	Data	Total expected	$t\bar{t}$ signal	Total background
		pre-tagged sample		
$\geq$2 isolated leptons	27257	28934 ± 49	158.8 ± 0.9	28775 ± 49
opposite sign	26779	28545 ± 42	157.3 ± 0.9	28388 ± 42
Z/quarkonia-veto	2878	2873 ± 27	139.3 ± 0.8	2734 ± 27
$\geq$2 jets	204	193 ± 2	103.1 ± 0.7	90 ± 2
$\not{E}_{\mathrm{T}}$	102	$108.5 \pm 0.9\,^{+3}_{-2}$	$92.1 \pm 0.7\,^{+2}_{-1}$	$16.3 \pm 0.7\,^{+1}_{-1}$
		b-tagged sample		
$= 0$ b-tag	19	$15.9 \pm 0.6\,^{+13}_{-8}$	$6.9 \pm 0.2\,^{+7}_{-3}$	$9.0 \pm 0.6\,^{+6}_{-5}$
$= 1$ b-tag	35	$40.9 \pm 0.5\,^{+17}_{-14}$	$35.7 \pm 0.4\,^{+9}_{-8}$	$5.1 \pm 0.4\,^{+8}_{-6}$
≥ 2 b-tags	48	$51.7 \pm 0.5\,^{+14}_{-16}$	$49.5 \pm 0.5\,^{+11}_{-15}$	$2.2 \pm 0.2\,^{+3}_{-1}$

- Quoted uncertainties are statistical, except last four rows, which contain uncertainties for jet energy scale variation.
  - In the last three rows the b/mis-tagging efficiency variation is also included.

Top Quark Mass Reconstruction

- Dilepton decay: $t\bar{t} \rightarrow (l^+ \nu_l b)\ (l^- \bar{\nu}_l \bar{b})$ ➡ 6 final state particles



$$P(t) = P(b) + P(W^+)$$

$$P(W^+) = P(l^+) + P(\nu_l)$$

$$\vec{p}_T = \vec{p}_T(\nu_l) + \vec{p}_T(\bar{\nu}_l)$$

System is under-constrained!

- Observed: 4 particles + Missing E_T
- Neutrinos escape unobserved → 6 unknowns
- Five constraints:
  - Transverse momentum conservation (2)
  - Invariant masses of $M_W = M(l\nu)$ (2)
  - Top and anti-top have the same mass (1)

Analytical Matrix Weighting Technique (AMWT)

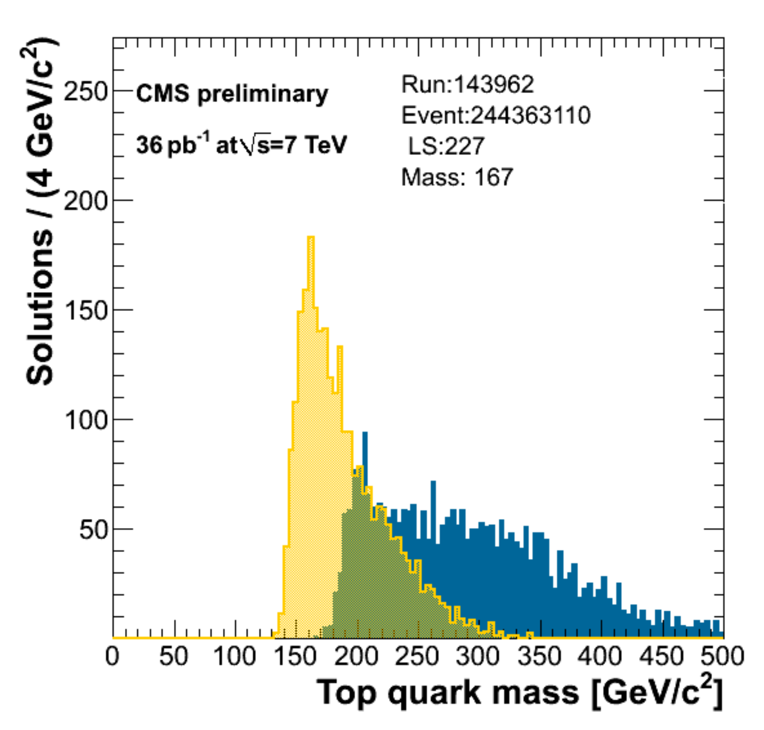
- Use m_{top} itself as the missing constraint
  - Solve the kinematic equations analytically for values of m_{top} between 0 and 700 GeV/c^2
  - Up to 8 solutions for every m_{top}
  - Jets and missing E_T are smeared to account for jet energy resolution
- Assign a weight to each solution:

$$W = f(x) f(\bar{x}) p(E^*_{\ell^+} \mid m_{top}) p(E^*_{\ell^-} \mid m_{top})$$

  - f(x) = parton distribution function (CTEQ6.1)
  - $p(E_l \mid m_{top})$ = probability of lepton energy in top rest frame
- Add all weights for all solutions with a given m_{top}
- Estimator for each event is the mass with the highest weight (m_{peak})

Full Kinematic Analysis (KINb)

- Reconstruct each event 10^4 times per lepton-jet assignment varying:
  - Jets and missing E_T, according to data distributions
  - $p_z(tt)$, randomly drawn from simulation
- Numerically solve for top quark mass, accepting solutions if the two decay legs agree to within $\Delta m_{top} < 3$ GeV/c^2
- Choose the lepton-jet assignment with the most solutions
- Construct distribution of the number of solutions as a function of m_{top}
- Mass estimator is the result of a Gaussian fit around the peak

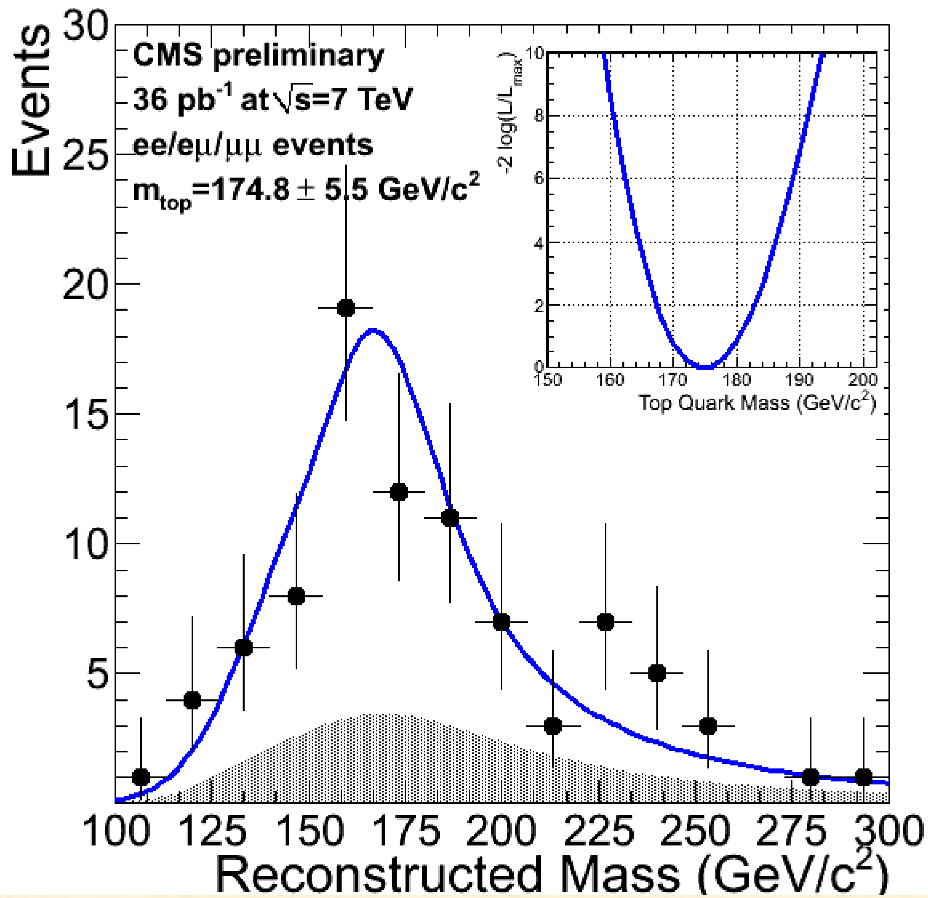


Likelihood Fit

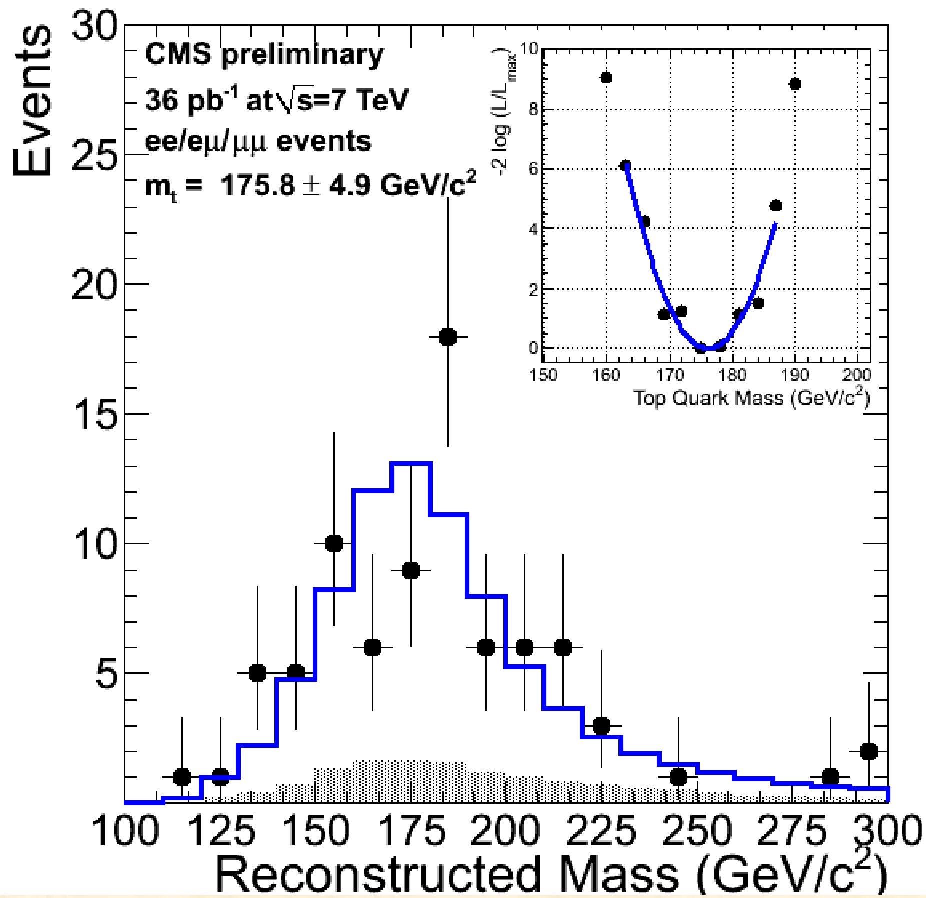
- Measure mass using a maximum likelihood fit of the peak mass distribution to templates from simulation
  - Signal templates generated for 17 top quark masses from 151 to 199 GeV/c^2 in intervals of 3 GeV/c^2
- Background: Drell-Yan, single top and non-dilepton tt
  - Drell-Yan templates are from data, others from simulation
- Concurrent fit of the 3 b-tagging multiplicities (0, 1 or 2 tags)
  - Templates restricted to 100-300 GeV/c^2
- Minimum of -ln(likelihood) gives estimate of top quark mass
- Method is linear in m_{top} and unbiased after calibration

Results of the Fit

KINb



AMWT



- Shaded distribution is background only, blue curve is MC total
- Inset shows likelihoods as a function of m_{top}

Systematics and Combination

Source	KINb	AMWT	Correlation factor	Combination
jet energy scale	+3.1/-3.7	3.0	1	3.1
b-jet energy scale	+2.2/-2.5	2.5	1	2.5
Underlying event	1.2	1.5	1	1.3
Pileup	0.9	1.1	1	1.0
Jet-parton matching	0.7	0.7	1	0.7
Factorization scale	0.7	0.6	1	0.6
Fit calibration	0.5	0.1	0	0.2
MC generator	0.9	0.2	1	0.5
Parton density functions	0.4	0.6	1	0.5
b-tagging	0.3	0.5	1	0.4

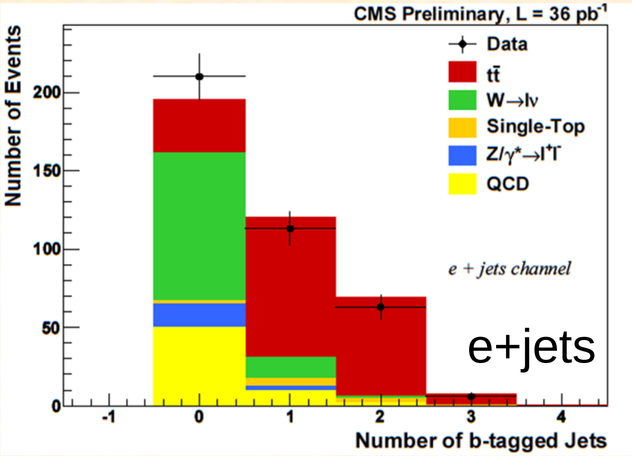
- Systematic uncertainties evaluated using pseudoexperiments
  - Dominant systematic uncertainty is the jet energy scale
- Measurements combined using the BLUE method
  - Statistical correlation: 0.57

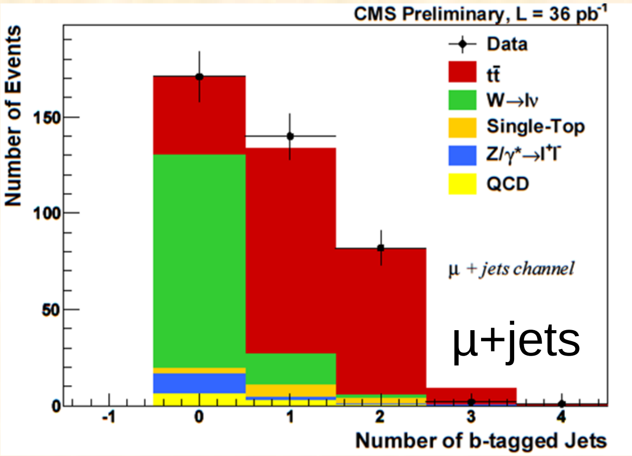
Method	Measured m_{top} (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$	0.65
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$	0.35
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$	χ^2/dof=0.040 (p-value=0.84)

Lepton+Jets Channel

Event Selection

- Single electron or single muon trigger
  - Muon with p_T > 9 - 15 GeV/c or electron with E_T > 10 - 22 GeV
- Exactly one isolated, prompt lepton
  - Electrons: p_T > 30 GeV/*c* and |η|< 2.5
  - Muons: p_T > 20 GeV/*c* and |η|< 2.1
  - Veto events with second lepton
- Four or more jets
  - p_T > 30 GeV/*c* and |η|< 2.4

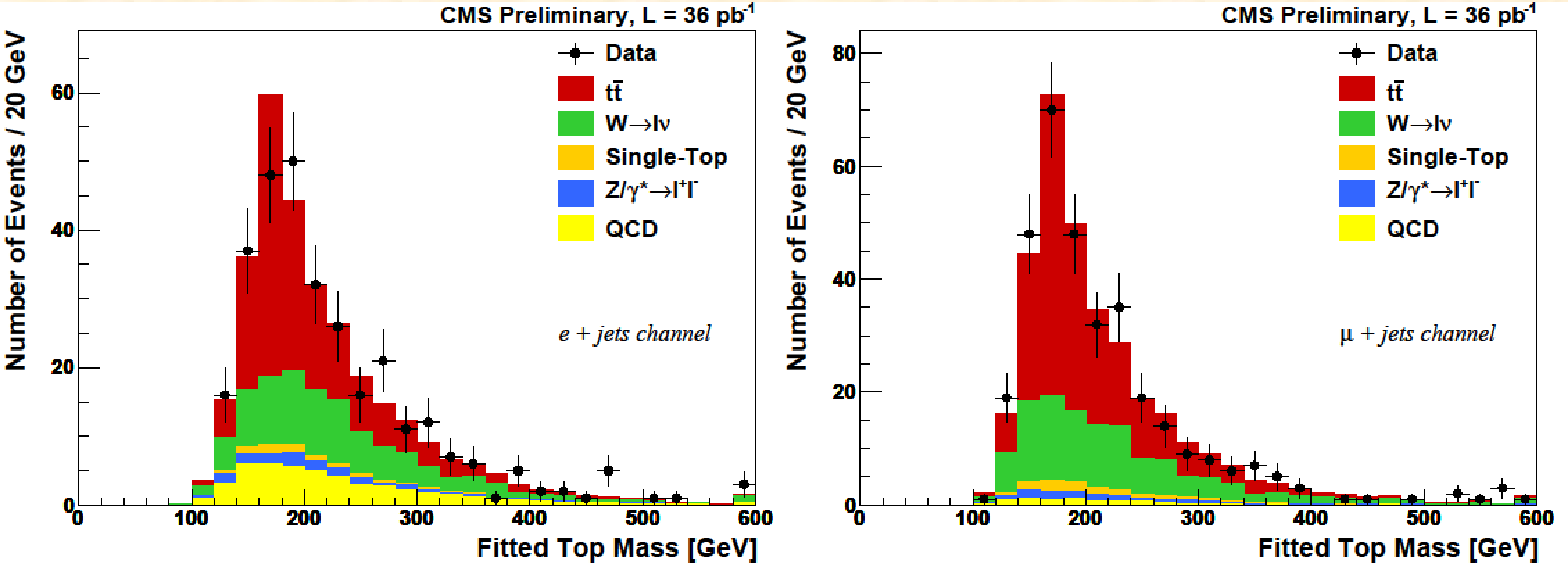




	Data	Total expected	$t\bar{t}$	Single-Top	$W \to l\nu$	$Z/\gamma* \to l^+l^-$	QCD
			muon+jets channel				
Events	396	358 ± 37	209 ± 33	12 ± 1	116 ± 9	12 ± 1	9.0 ± 1.0
Fraction	-	100%	59%	3%	32%	3%	2%
			electron+jets channel				
Events	392	345 ± 32	169 ± 27	9.5 ± 0.6	99 ± 7	16 ± 1	52 ± 8
Fraction	-	100%	50%	3%	28%	4%	16%

Kinematic Fit

- Fully reconstruct each event assuming that it is tt and perform fit
  - Phys. Rev. D 58, 052001, 1998 (used at the Tevatron and at Delphi)
- 12 possible jet assignments and 2 possible $p_z(\nu) \rightarrow$ 24 solutions
  - Requires at least one solution with $\chi^2 < 10$



b-tagging

- The probability to observe n_{btag} events is included in the likelihood:

$$P_{t\bar{t}}(x \mid m_t) = P_{t\bar{t}}(n_{btag}) \cdot P_{t\bar{t}}(x_{mass} \mid m_t)$$

$$P_{bkg}(x) = P_{bkg}(n_{btag}) \cdot P_{bkg}(x_{mass})$$

  – x is the set of observables in an event and m_t is the assumed mass

- An additional weight from b-tagging is computed for each solution
  – Combined with weight from fit

Assumed flavor	Observed flavor	Weight P_j
b	b	ϵ_b
b	l	$(1-\epsilon_b)$
l	b	ϵ_l
l	l	$(1-\epsilon_l)$

$$w_{btag} = \prod_j P_j$$

$$w_i = e^{-\frac{\chi^2}{2}} w_{btag}$$

Likelihood

- Likelihood to observe event as a function of the top quark mass:

$$\mathcal{L}_{event}\left(x|m_{\mathrm{t}}, f_{\mathrm{t\bar{t}}}\right) = f_{\mathrm{t\bar{t}}} P_{\mathrm{t\bar{t}}}\left(x|m_{\mathrm{t}}\right) + \left(1 - f_{\mathrm{t\bar{t}}}\right) P_{\mathrm{bkg}}\left(x\right)$$

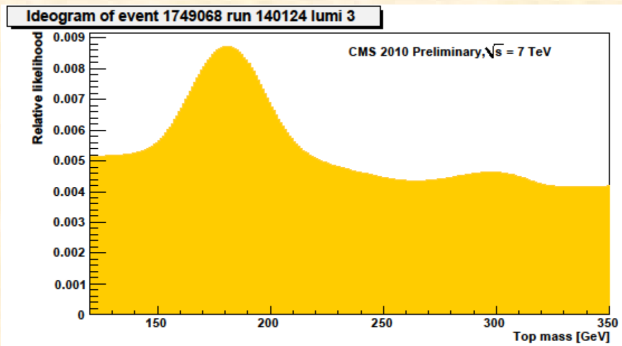
  - f_{tt} is the fraction of signal in the data sample
  - P_{bkg} is the background probability density function
    - Derived from simulation
  - P_{tt} is the signal PDF

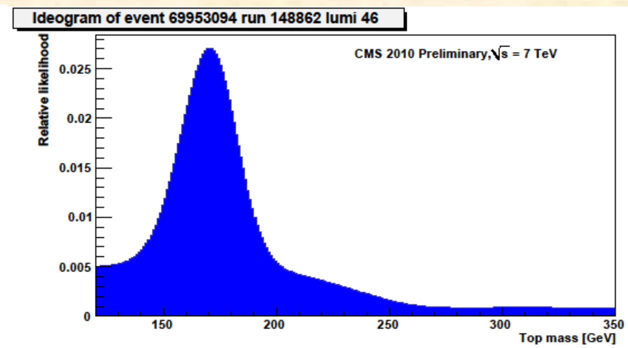
$$P_{\mathrm{t\bar{t}}}\left(x_{\mathrm{mass}}|m_{\mathrm{t}}\right) = \sum_{i}^{24} w_i \left(f_{cp} \cdot \int_{m_{min}}^{m_{max}} dm' G\left(m'|m_i, \sigma_i\right) BW\left(m'|m_{\mathrm{t}}, \Gamma_{\mathrm{t}}\right) + (1 - f_{cp}) WP(m_i|m_{\mathrm{t}}) \right)$$

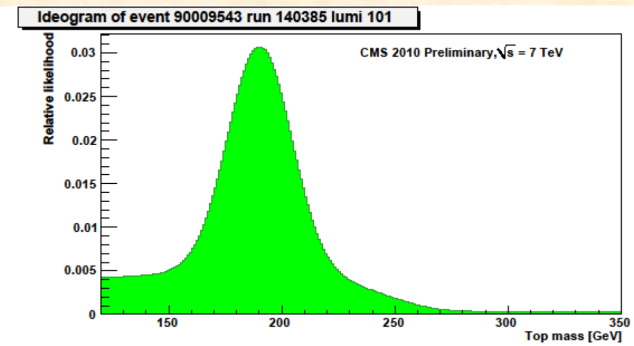
    - f_{cp} is the probability of getting the correct permutation
    - G is a Gaussian function centered at the fitted mass and with the width set to the uncertainty of the fitted mass
    - BW is a relativistic Breit-Wigner distribution with Γ_t = 2 GeV
    - The wrong permutation (WP) is derived from simulation

Ideogram Likelihoods

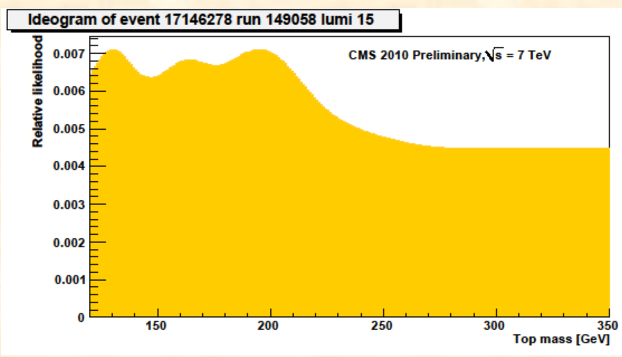
Examples of Ideogram likelihoods as a function of the top quark mass for 6 different events:

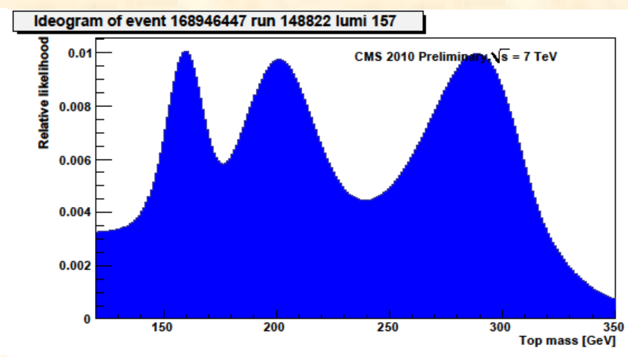


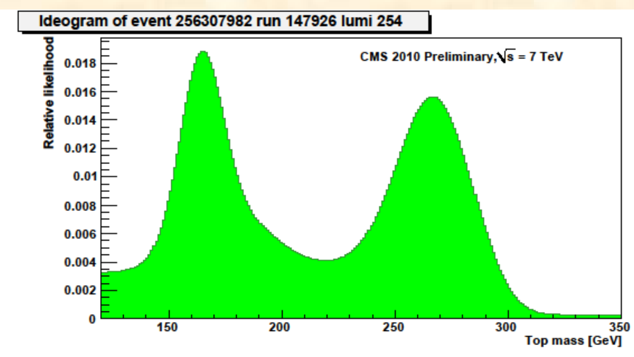




0 b-tags **1 b-tag** **2 b-tags**



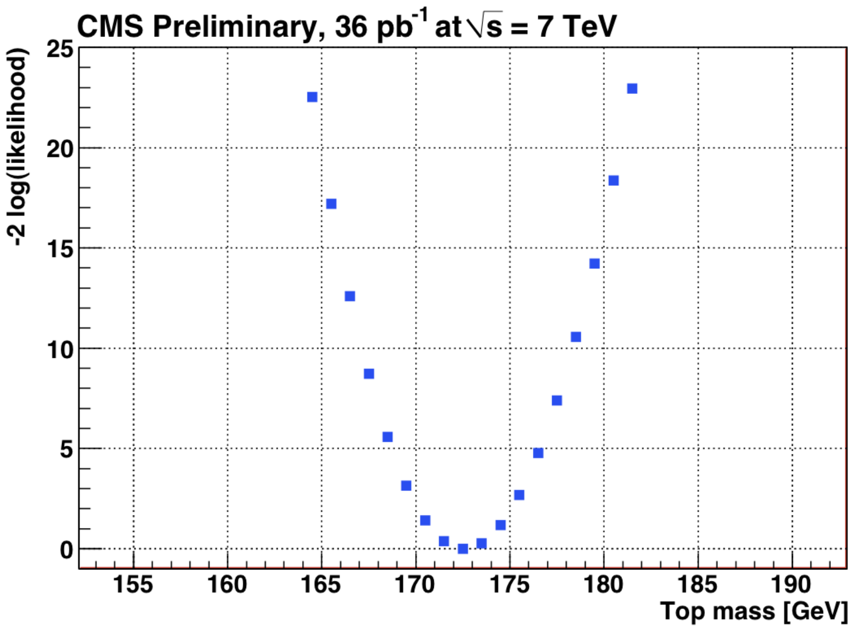


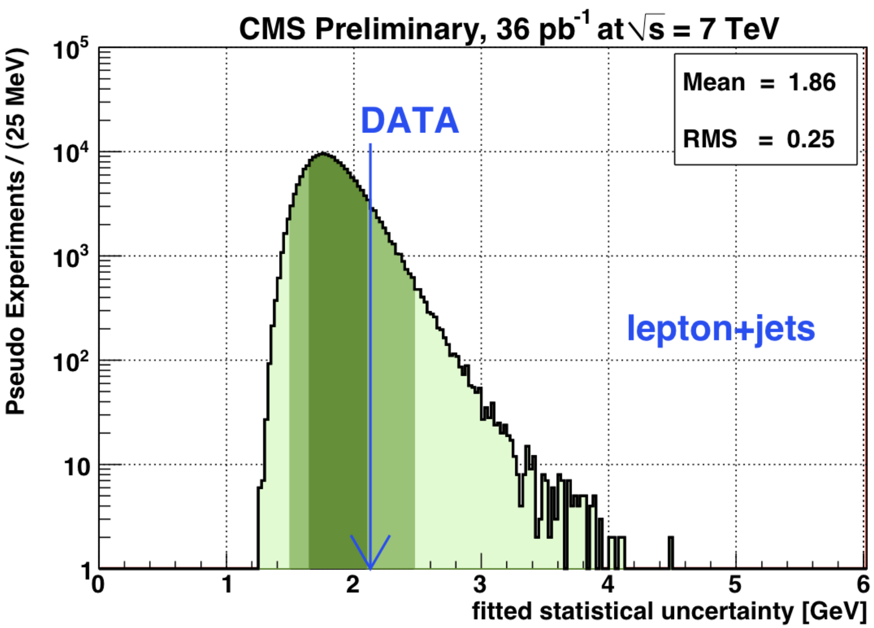


Result of the Fit

- Sample likelihood is the product of all event likelihoods
- Minimum of –ln(likelihood) is computed by fitting a parabola to the three lowest points

- Result: m_{top} = 173.1 ± 2.1 (stat) GeV/c^2





Systematics

Source	Ideogram analysis δm_{t} (GeV)
JES (overall data/MC)	+2.4-2.1
JER (10% effect)	0.07
MET (10% effect)	0.4
Factorization scale	1.1
ME-PS matching threshold	0.4
ISR/FSR	0.2
Underlying event	0.2
Pile-up effect	0.1
PDF	0.1
Background	0.5
B-tagging	0.05
Fit calibration statistics	0.1
Total systematic uncertainty	+2.8- 2.5

- Jet energy calibrations are newer than in the dilepton analysis
  - Jet energy scale is still the dominant uncertainty

Combination

- Dilepton: m_{top} = 175.5 ± 4.6 (stat) ± 4.6 (syst) GeV/c^2
- Lepton+Jets: m_{top} = 173.1 ± 2.1 (stat) $^{+2.4}_{-2.1}$ (JES) ± 1.4 (o. syst) GeV/c^2

- Lepton+Jets and Dilepton results combined using BLUE method
  - Samples are non-overlapping so statistical uncertainties are uncorrelated
  - Systematic uncertainties mostly correlated
    - Lepton+Jets uses improved jet calibrations

- Combined result:

m_{top} = 173.4 ± 1.9 (stat) ± 2.7 (syst) GeV/c^2

Conclusion and Outlook

- We have measured the top quark mass with 36 pb^{-1} (2010 data)
  - Dilepton channel
  - Lepton+Jets channel
- Combined result is $\mathbf{m_{top} = 173.4 \pm 1.9\ (stat) \pm 2.7\ (syst)\ GeV/}\boldsymbol{c}^2$
- Working on updating the analyses with 2011 data
- With more statistics, more difficult measurements become possible
  - All-hadronic channel
  - Channels with taus