Top quark mass measurement at the LHC

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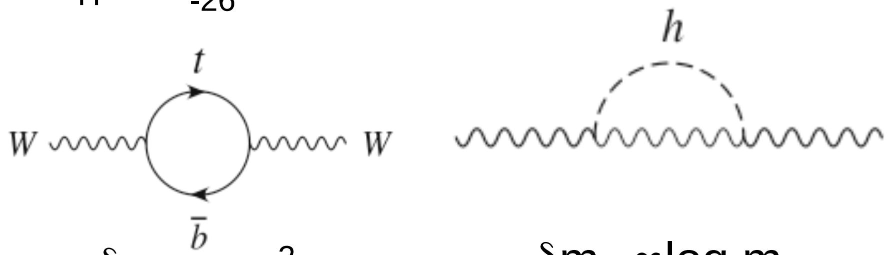
on behalf of the ATLAS and CMS collaborations

- **Introduction**
- **Lepton+jet channel**
- **Dilepton channel**
- **Mass from cross section**

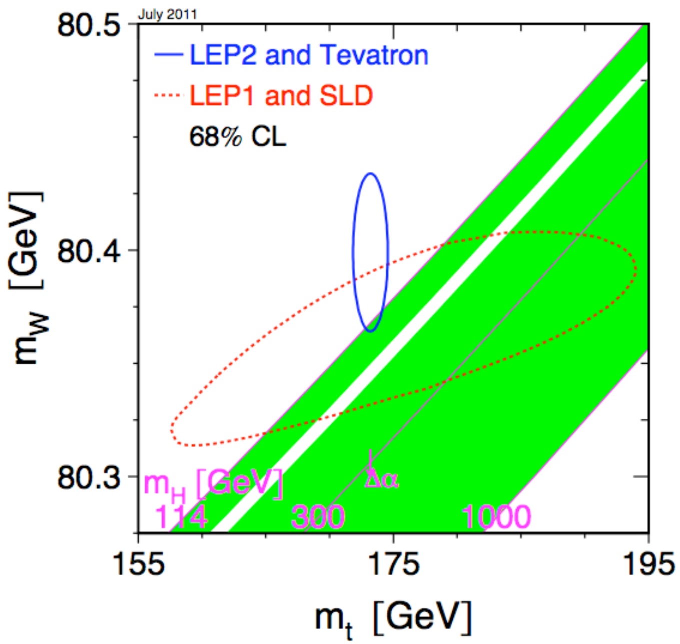
Introduction

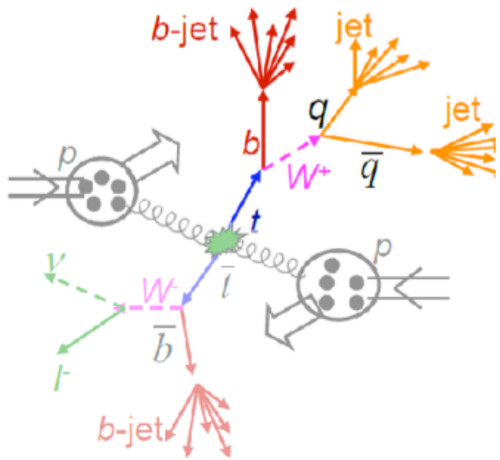
- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  - Indirect constraint on the Higgs boson mass via EW corrections
  - ⇒ $m_H = 92^{+34}_{-26}$ GeV or <161 GeV



$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$

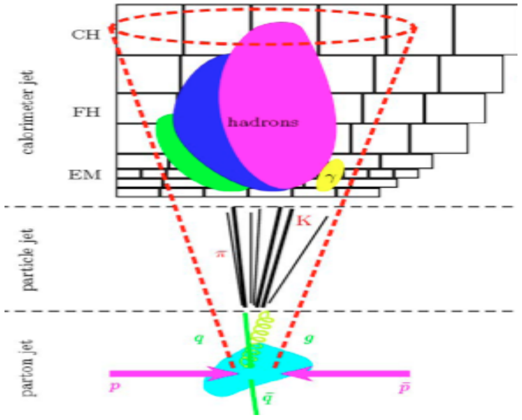
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for new Physics

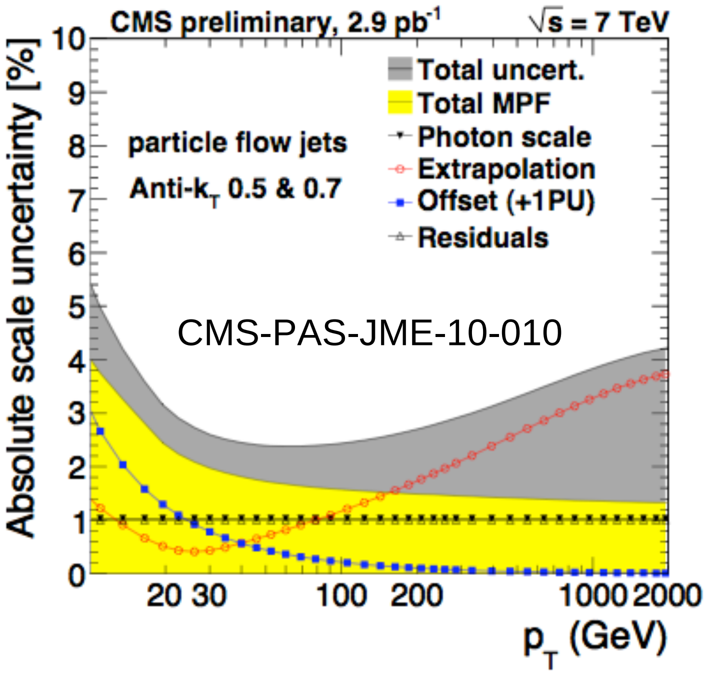




Challenge: jet reconstruction

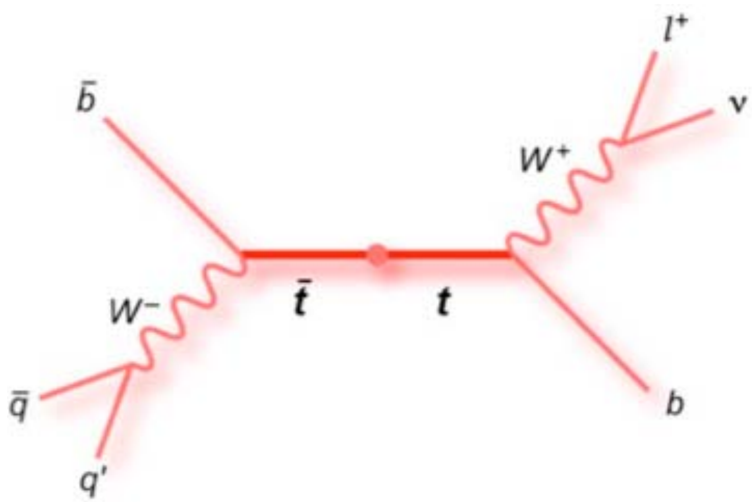
- Top mass measurement needs parton information, but we measure jets
- Use calorimeter information to correct jets to particle level
- Jet energy scale (JES) is the main source of uncertainty
  - Look at quantities insensitive to JES (e.g. lepton p_T)
  - "b-jet" tag helps reducing number of permutations
- JES "in-situ" calibration in ttbar events
  - Use W→jj constraint to measured W mass
  - Can be used in lepton+jets (and all-hadronic) channel

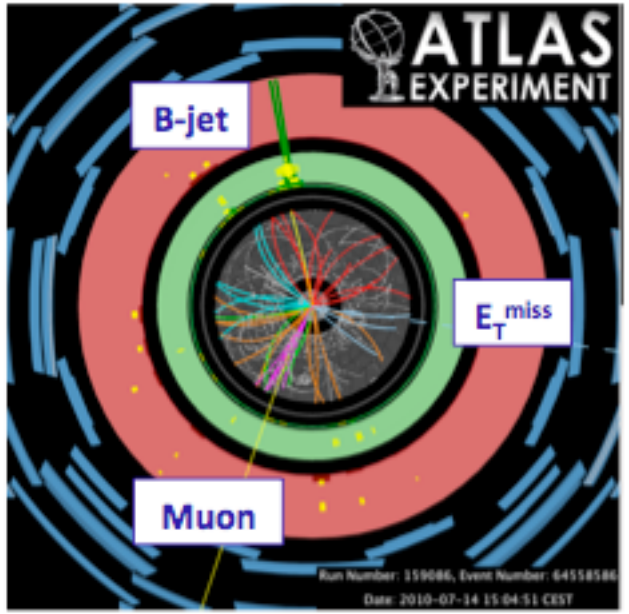




Lepton+jet channel

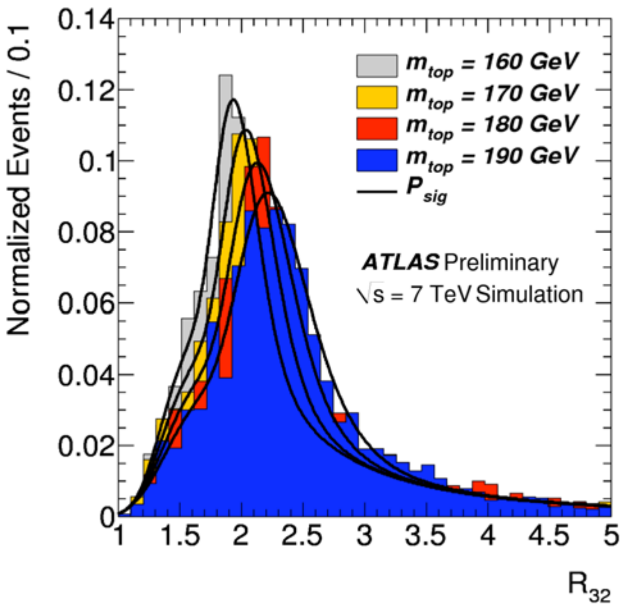
- Best channel (for now) to measure top quark mass
- Compromise between large branching ratio (BR=30%) and a good background rejection
- Well defined final state (1 lepton, one neutrino, 2 b-jets, W→qq')



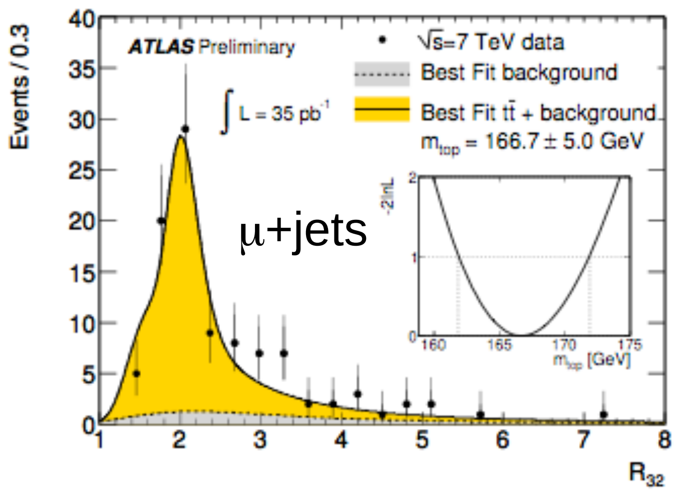


Template method

- Choose a variable sensitive to top mass
- Predict the distribution with MC templates vs top mass
- Evaluate likelihood for each top mass
- Maximize likelihood
- JES is dominant source of uncertainty
- Complementary methods developed to reduce JES uncertainty:
  - 1D template analysis is based on the ratio R_{32}=M(jjb)/M(jj)
  - Template fit to m_{top} from kinematic reconstruction
  - 2D JSF template analysis: simultaneous fit to m_{top} and JES



simple reconstruction method:
m_{top}^{reco} = jet triplet that maximizes p_T
m_W^{reco} = untagged jet-pair, or jet pair with DR_{min} in the top rest frame



Combined (e/μ+jets) for L=35/pb:

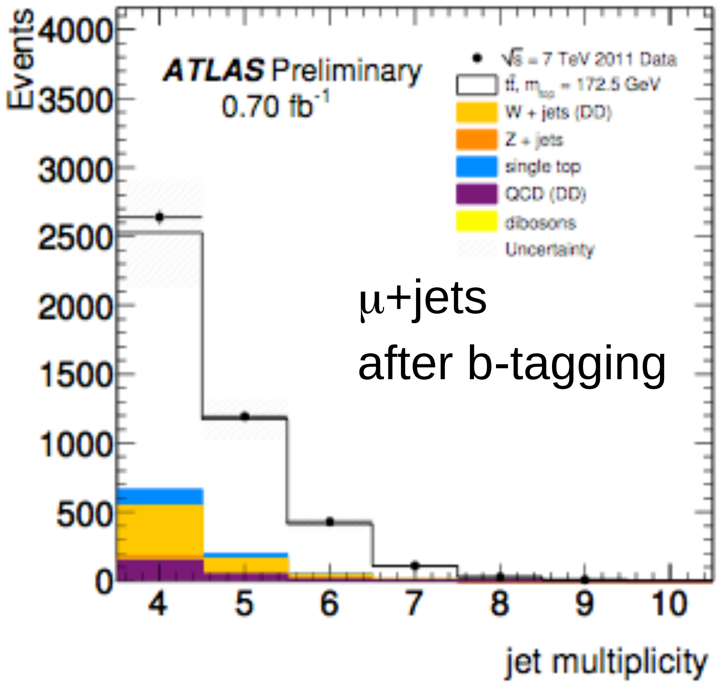
$$m_{top} = (169.3 \pm 4.0 \pm 4.9)\ \text{GeV}$$

ATLAS-CONF-2011-033

Update: Event selection

- Inclusive single lepton triggers
- Leading isolated prompt lepton (e or μ)
  - Electrons p_T>25 GeV, muons p_T>20 GeV
  - Veto events with 2nd lepton
- Missing transverse energy:
  - muons: MET>20 GeV and MET+m_T(W)>60 GeV
  - electrons: MET>35 GeV and m_T(W)>25 GeV
- At least 4 jets with p_T>25 GeV, $|\eta|$<2.5
- Require ≥1 b-tagged jet (b-tagging eff. 50%)

ATLAS-CONF-2011-120



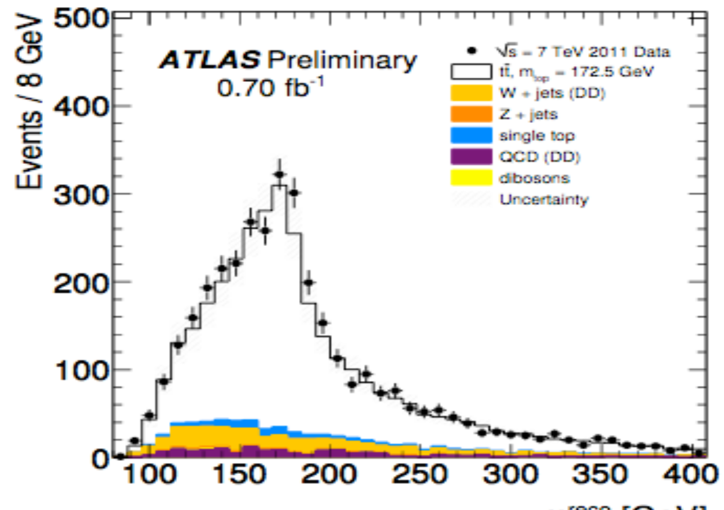
	e+jets	μ+jets
$t\bar{t}$ signal	1900 ± 170	2820 ± 260
$t\bar{t}$ fully hadronic	1.3 ± 0.6	1.3 ± 0.5
W + jets (DD)	230 ± 170	380 ± 280
Z + jets	25 ± 12	31 ± 11
QCD (DD)	40 ± 40	160 ± 160
single top	98 ± 10	141 ± 14
dibosons	4.3 ± 0.9	6.6 ± 1.2
Total background	400 ± 180	720 ± 320
Signal / Background	4.7 ± 2.1	3.9 ± 1.8
Total expected	2300 ± 240	3500 ± 400
Total data	2499	3662

Template analysis

- 2-d template analysis: m_{top} and Jet energy Scale Factor (JSF) determined simultaneously from distributions of reconstructed m_{top} and m_W
  - similar to CDF PRD73 (2006) 032003
- Take information from hadronically decaying W mass to constrain JES
  - in-situ jet energy rescaling, determine m_{top}

- How is the association done?
  - Each light jet pair with $50<m_W<100$ GeV is combined with b-tagged jet
  - Triplet with maximum p_T is chosen as top candidate
  - Measure mass of hadronic top: $t \rightarrow W(qq')b$
  - 2-jet inv. mass constrained to m_W (Γ_W=2.2 GeV)
- Signal template: for m_{top} and m_W
- Background template: includes single top, mass-dep.

- Fit data (i.e. m_{top}^{reco}) to sum of signal and background PDF (probability density function)



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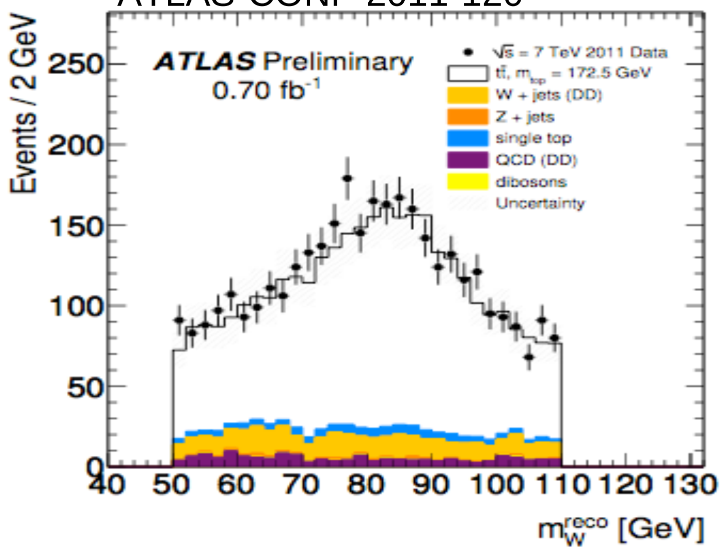

Mass measurement

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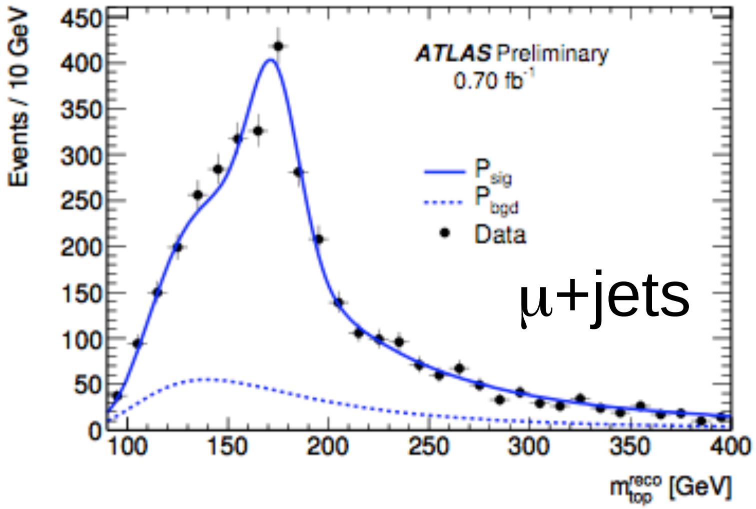
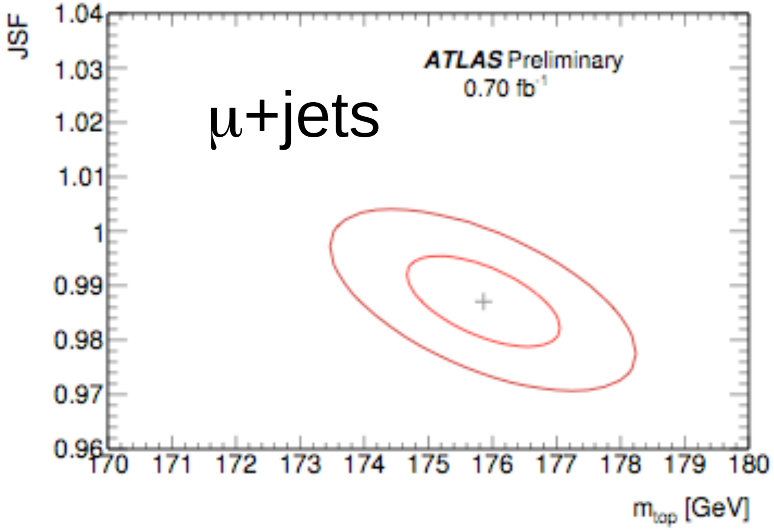




	e+jets	μ+jets
Statistics	1.2	1.0
Method calibration	< 0.05	0.1
Signal MC generator	1.2	1.2
Hadronization	< 0.05	0.4
Pileup	< 0.05	< 0.05
Color reconnection	0.6	0.9
ISR and FSR (signal only)	1.6	0.7
Proton PDF	0.1	0.1
W+jets background normalization	0.2	0.1
W+jets background shape	< 0.05	0.1
QCD background normalization	0.4	0.4
QCD background shape	0.2	0.3
Jet Scale Factor	1.0	0.7
Jet energy scale	0.7	0.8
b-jet energy scale	2.0	1.7
b-tagging efficiency and mistag rate	0.1	0.3
Jet energy resolution	0.3	0.2
Jet reconstruction efficiency	< 0.05	< 0.05
Missing transverse energy	0.1	0.1
Total systematic uncertainty (in GeV)	3.1	2.7

JES calibration "in situ": constrain M_{jj} to M_W

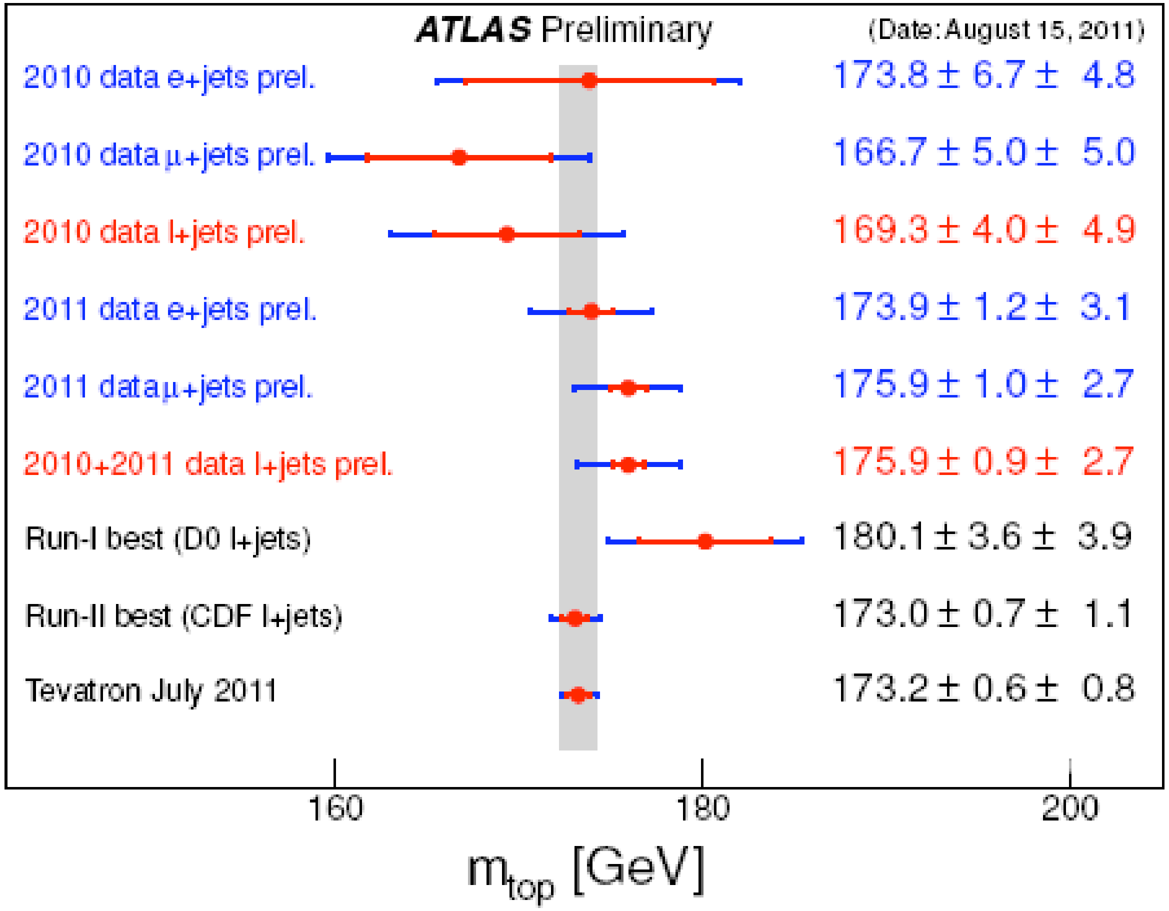
Simultaneous fit to m_{top} and JSF

⇨m_{top}=175.9 ±0.9(stat)±2.7(syst) GeV

(combination of 2010-2011 ATLAS measurements)

Combination

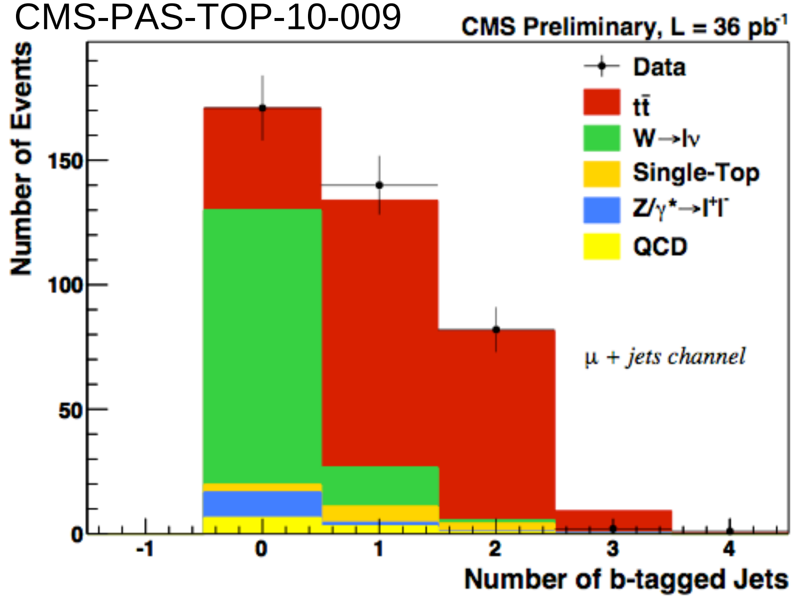
2010-2011 results are combined with BLUE:



Lepton+jets: Ideogram method

- Inclusive single lepton trigger
- Leading isolated prompt lepton (e or μ)
  - Electrons p_T>30 GeV, $|\eta|$<2.5
  - Muons p_T>20 GeV, $|\eta|$<2.4
  - Veto events with 2nd lepton
- At least 4 jets with p_T>30 GeV, $|\eta|$<2.5

CMS-PAS-TOP-10-009



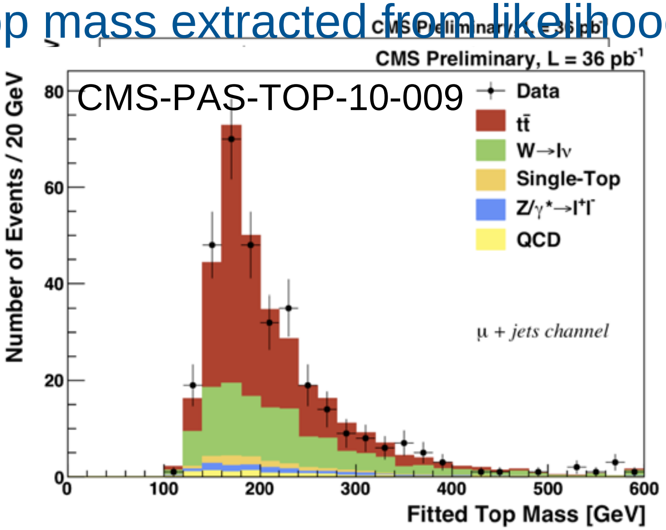
	Data	Total expected	$t\bar{t}$	Single-Top	$W \rightarrow l\nu$	$Z/\gamma* \rightarrow l^+l^-$	QCD
			muon+jets channel				
Events	396	358 ± 37	209 ± 33	12 ± 1	116 ± 9	12 ± 1	9.0 ± 1.0
Fraction	-	100%	59%	3%	32%	3%	2%
			electron+jets channel				
Events	392	345 ± 32	169 ± 27	9.5 ± 0.6	99 ± 7	16 ± 1	52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

Mass reconstruction

- Ideogram method:
  - Used at LEP (W) & Tevatron (Top)
  - Resolve ambiguity in event kinematics with proper weighting
  - Mass described in event-by-event likelihood
- Kinematic fit applied to all 24 jet-quark assignments
- Event likelihood calculated as function of assumed top mass
  - 303 events in e+jets, 334 in μ+jets channel
- Top mass extracted from likelihood

CMS-PAS-TOP-10-009

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



Product of likelihoods of all events:

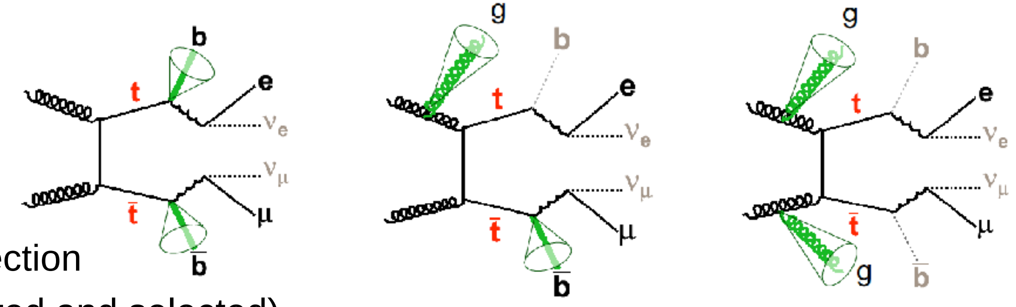
$$\mathcal{L}_{\text{sample}}(m_t, f_{t\bar{t}}) = \Pi_j \mathcal{L}_{\text{event},j}(m_t, f_{t\bar{t}})$$

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.4}_{-2.1}(\text{JES}) \pm 1.4(\text{other syst}) \;\; \text{GeV}$$

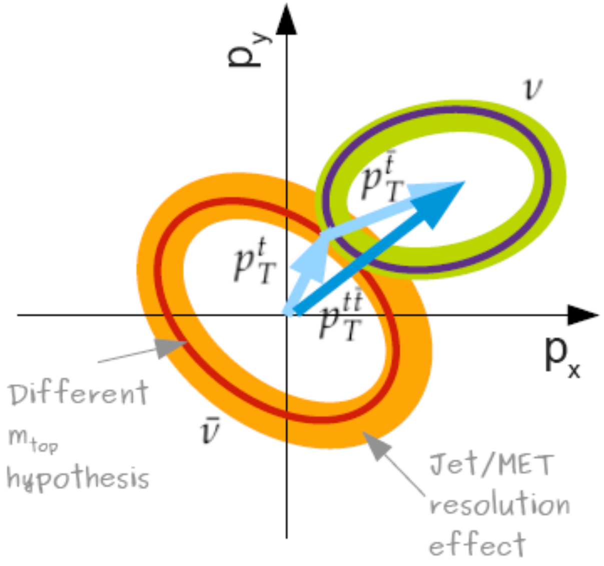
Dilepton channel: challenges

- Combinatorics
  - Identify top quark decay products
  - Ambiguity
  - ISR/FSR introduces further complexity for selection

  (~70% of the events have both b-jets reconstructed and selected)



- Missing transverse energy
  - Constrains the contribution from undetected particles
  - In the dilepton channel: 2 neutrinos ⇒ $\vec{E}_T^{miss} = \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$
- Jet energy scale
  - m_{top} reconstruction requires measuring the parton energy
  - parton→jet affected by resolution and absolute energy scale
- Pileup
  - Jet energy scale, MET measurement, extra jets/leptons
  - $N_{pileup} \approx 2.1$ for most of data collected in 2010

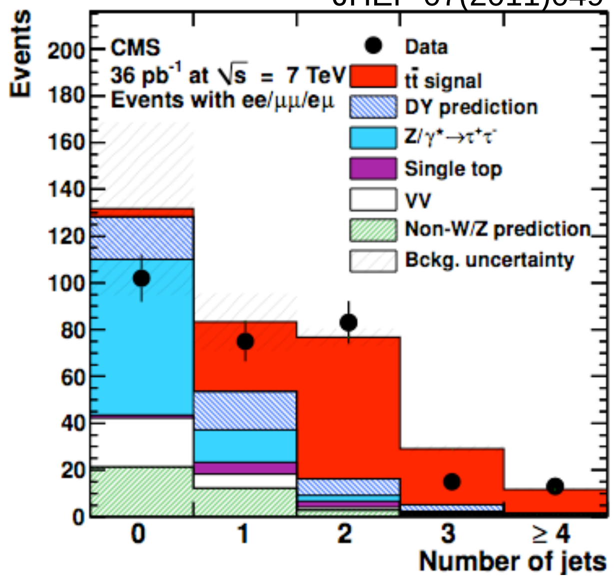


Event selection

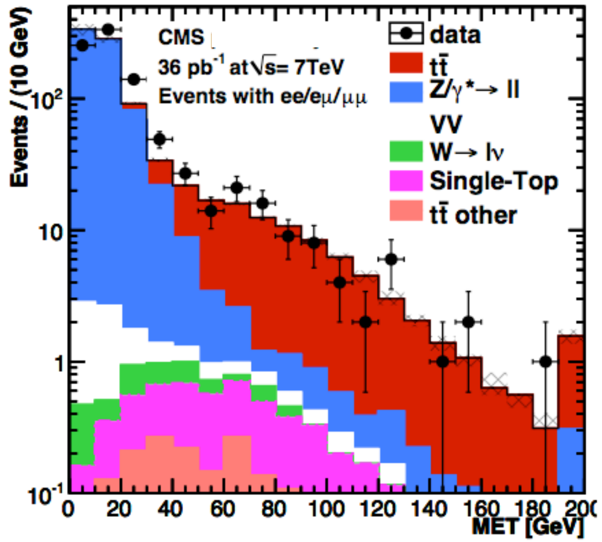
JHEP 07(2011)049

Two leptons, at least two jets, and MET

- Trigger: inclusive single lepton
- ≥2 isolated leptons, p_T>20 GeV, $|\eta|$<2.5
- Leading Σp_T opposite sign dileptons
- ≥2 jets, p_T>30 GeV, $|\eta|$<2.5
  - Anti-k_T (R=0.5), particle flow (PF) algorithm
- MET>30 GeV (20) GeV for the ee/$\mu\mu$ (eμ) channel



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
$E\!\!\!/_T$	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	$51.7 \pm 0.5\,^{+14}_{-16}$	$49.5 \pm 0.5\,^{+11}_{-15}$	$2.2 \pm 0.2\,^{+3}_{-1}$

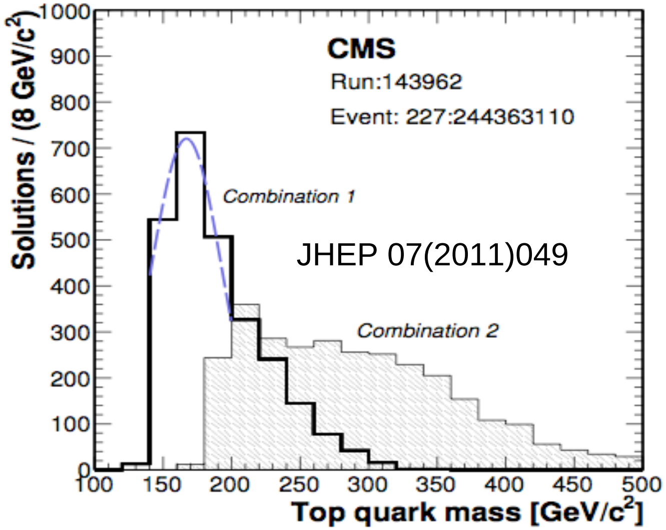


- Classify events according to b-tag

KINb and AWMT methods

KINb

- Full Kinematic Analysis
  - original method from CDF, PRD 73 (2006) 112006
- Equations solved for each lepton-jet combination
- p_z distribution is assumed
- Accept solutions if two decay legs agree within Δm_{top}<3 GeV



AWMT

- Analytical Matrix Weighting Technique
  - Original method from D0, PRL 80 (1998) 2063
- Iterate over values of m_{top} hypothesis from 100 to 700 GeV
  - solve kinematic equations for fixed values of m_{top}
  - Assign weights to each solution based on pdf and kinematic quantities

$$w = \left\{\sum F(x_1)F(\bar{x}_2)\right\} p(E^*_{\ell^+}|m_t)p(E^*_{\ell^-}|m_t)$$

- From inclusive weight distribution estimate top mass
- For each event, take value of top mass with highest sum of weights (m_{peak})

Reconstructed mass

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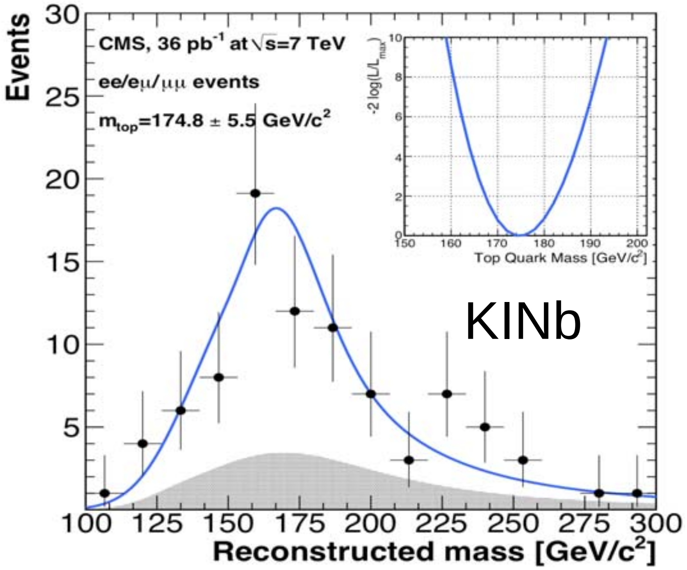
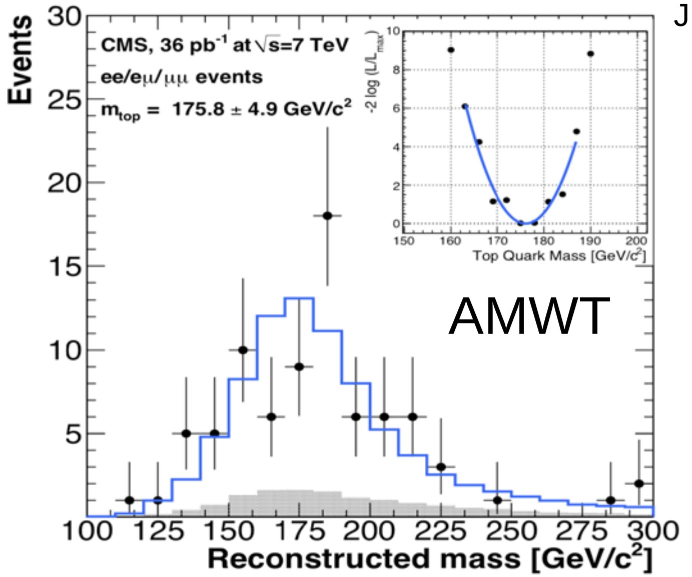




- JET energy scale (JES) is the largest unc.
  - JES is varied up and down and difference in m_{top} is accounted for as systematics
  - Flavor (b) specific uncertainty added in quadrature
- Other systematics:
  - Difference with respect to reference sample used for signal
  - MC: compare Alpgen and Powheg with Madgraph
  - Vary factorization/matching scale, ISR/FSR

Source	KINb	AMWT
Overall jet energy scale	+3.1/−3.7	3.0
b-jet energy scale	+2.2/−2.5	2.5
Lepton energy scale	0.3	0.3
Underlying event	1.2	1.5
Pileup	0.9	1.1
Jet-parton matching	0.7	0.7
Factorisation scale	0.7	0.6
Fit calibration	0.5	0.1
MC generator	0.9	0.2
Parton density functions	0.4	0.6
b-tagging	0.3	0.5

Combined measurement

- Combine measurements using Best Linear Unbiased Estimator (BLUE)
  - correlation factor determined from pseudo-experiments

- Dilepton channel: combination of KINb and AMWT results
  - correlation factor is 0.57

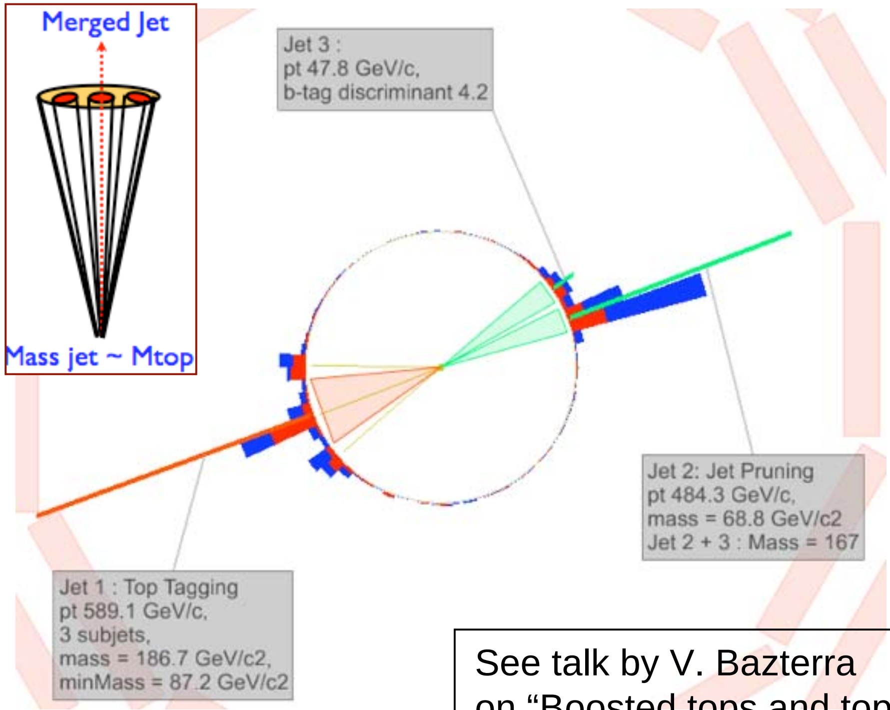
Method	Measured $m_{\rm top}$ (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9\,({\rm stat.}) \pm 4.5\,({\rm syst.})$	0.65
KINb	$174.8 \pm 5.5\,({\rm stat.})^{+4.5}_{-5.0}\,({\rm syst.})$	0.35
Combined	$175.5 \pm 4.6\,({\rm stat.}) \pm 4.6\,({\rm syst.})$	$\chi^2/{\rm dof} = 0.040$ (p-value $= 0.84$)

- Combination of dilepton and lepton+jet measurements:
  - samples are uncorrelated

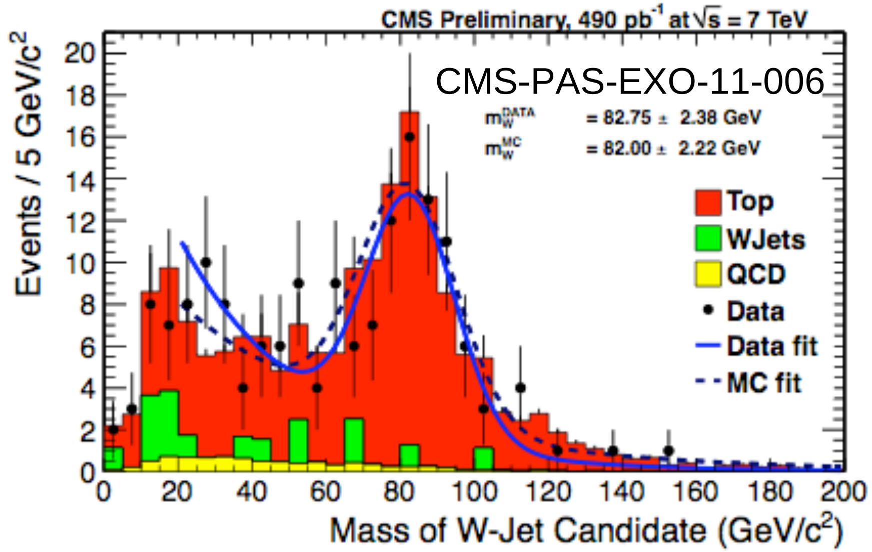
$$m_{\rm t} = 173.4 \pm 1.9({\rm stat}) \pm 2.7({\rm syst})\ \ {\rm GeV}$$

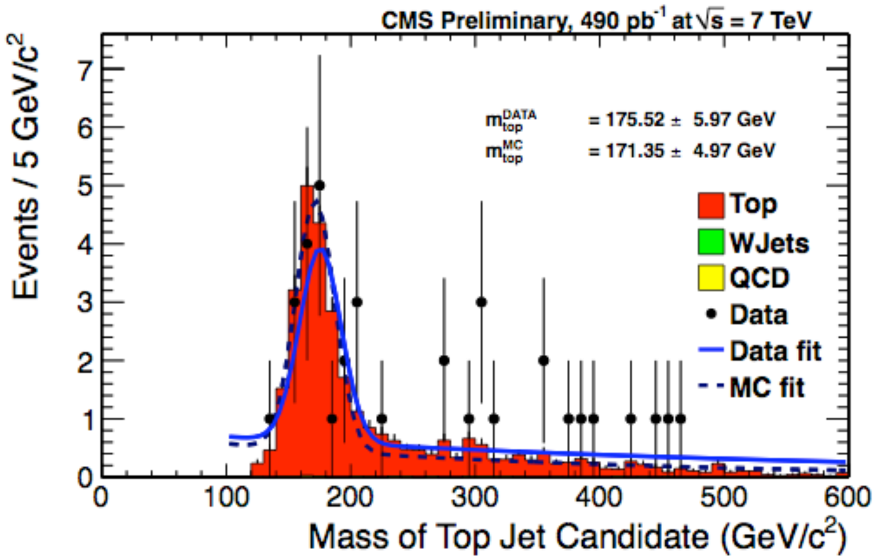
CMS-PAS-TOP-10-009

Boosted jet topology



See talk by V. Bazterra on “Boosted tops and top tagging”



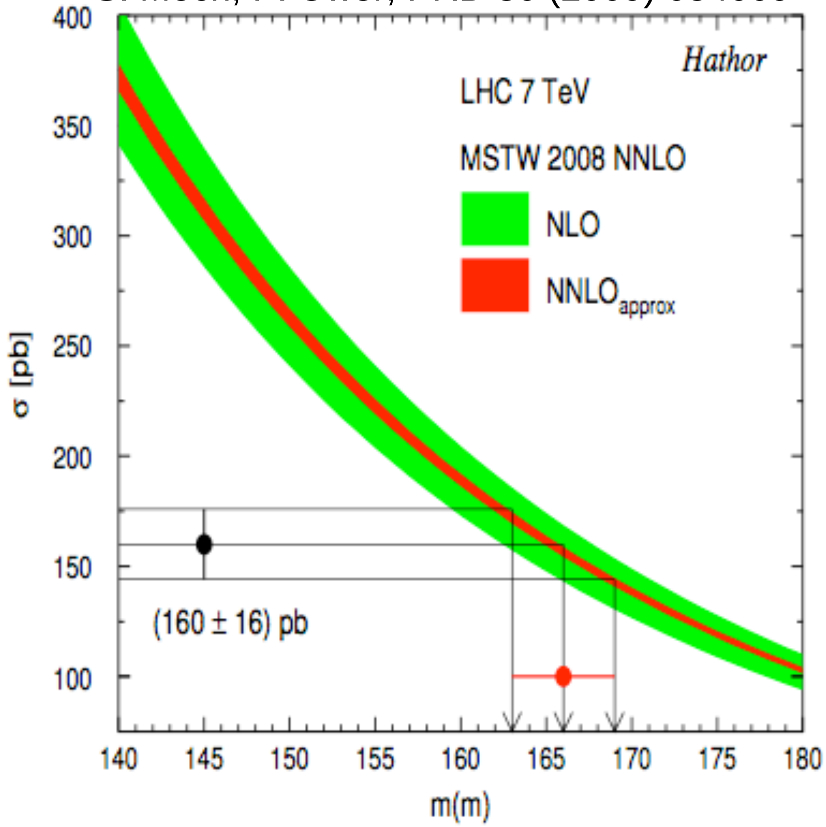


- Using top-tagging
- Still statistically limited
- Could provide precise measurement
- Need to understand biases

Top mass from cross section

- Direct m_{top} measurements rely on details of kinematics, reconstruction, calibration
- Experimental measurement has small uncertainty: ~0.75%
- What mass is measured?
  - Could be interpreted as pole mass
- Compare theory prediction (measured) cross section vs pole mass (=m_{top})
- Exploit relation of cross section and mass:
  - $\Delta\sigma/\sigma = -A \bullet \Delta m/m$ (A=4-5)

S. Moch, P. Uwer, PRD 80 (2009) 054009



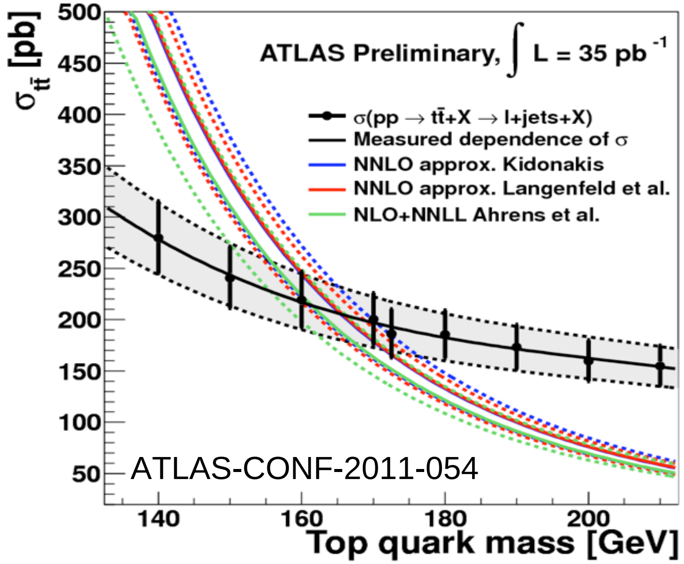
Results

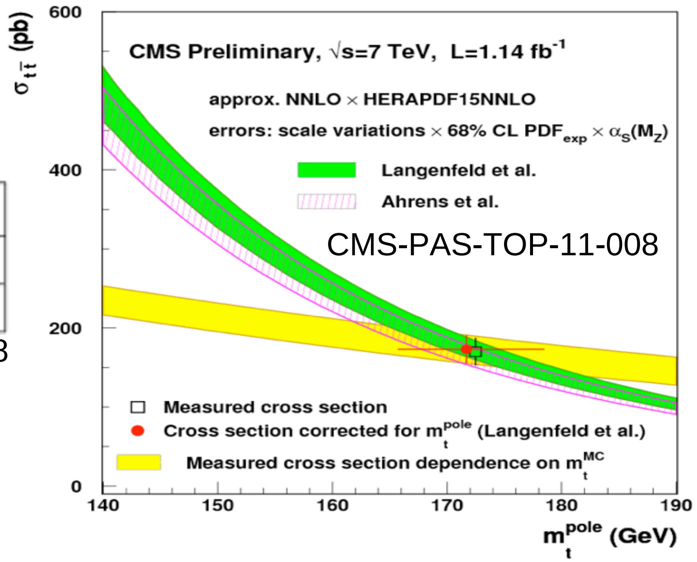
- determine top quark pole mass using the experimental ttbar production cross section
  - from lepton+jets channel (ATLAS) with 35/pb

$$m_{\rm top}^{\rm pole} = (166.4\,^{+7.8}_{-7.3})\ \ {\rm GeV}$$

  - from dilepton cross section (CMS) with 1.1/fb

$$m_t^{pole} = 170.3^{+7.3}_{-6.7}\,{\rm GeV}$$





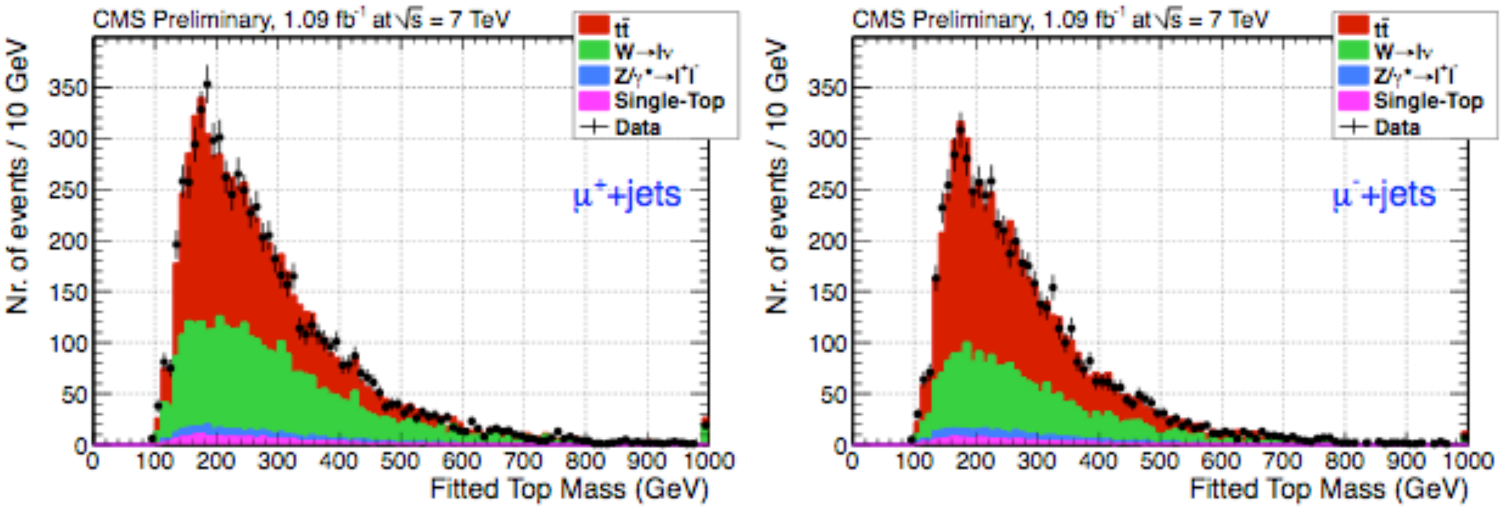
Also determine m(MSbar):

Approx. NNLO × HERAPDF15NNLO	$m_t^{\rm pole}$ / GeV	$m_t^{\overline{\rm MS}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

CMS-PAS-TOP-11-008

Top-antiTop mass difference

- Test of CPT invariance: particle and anti-particle have same mass
  - If masses are different →CPT violation
  - Top quark is unique because it decays before hadronizing
- use μ+jet ttbar events: positive/negative muons (L=1.1/fb)
- Measure mass in both samples (ideogram method)

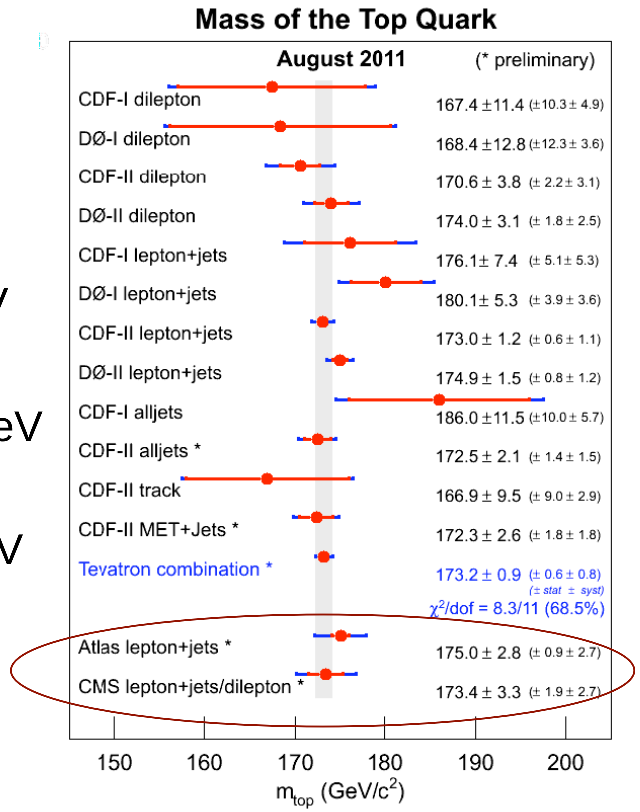


Most precise top mass difference (statistically limited): CMS-PAS-TOP-11-019

$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

Summary

- First results from LHC on top quark mass
  - good understanding of detectors
  - not yet competitive with Tevatron, but not too far
- Direct measurements:
  - CMS (dilepton), 36/pb: m_{top}=175.5 ± 4.6(stat) ± 4.6(syst) GeV
  - CMS (l+jets), 36/pb: m_{top}=175.5 ± 2.1(stat) $^{+2.8}_{-2.5}$ (syst) GeV
  - CMS (combined), 36/pb: m_{top}=173.4 ± 1.9(stat) ± 2.7(syst) GeV
  - ATLAS (l+jets), 0.70/fb: m_{top}=175.9 ± 0.9(stat) ± 2.7(syst) GeV
- Indirect measurement from cross-section



We are working on it … we hope it will be beautiful when we will finish

backup

Pole mass and MSbar

- In some approx NNLO (Langenfeld et al., Ahrens et al.), calculation is done using both pole mass and running mass (in MSbar scheme) definition
- Top quark mass is obtained with HERAPDF taking into account experimental PDF uncertainty, variation of normalization/factorization scales, and α_S values

$$m_t^{\overline{MS}} = m_t^{pole} / \left(1 + \frac{4}{3}\frac{\alpha_S(m_t^{\overline{MS}})}{\pi} + 8.2364\left(\frac{\alpha_S(m_t^{\overline{MS}})}{\pi}\right)^2 + 73.638\left(\frac{\alpha_S(m_t^{\overline{MS}})}{\pi}\right)^3\right)$$

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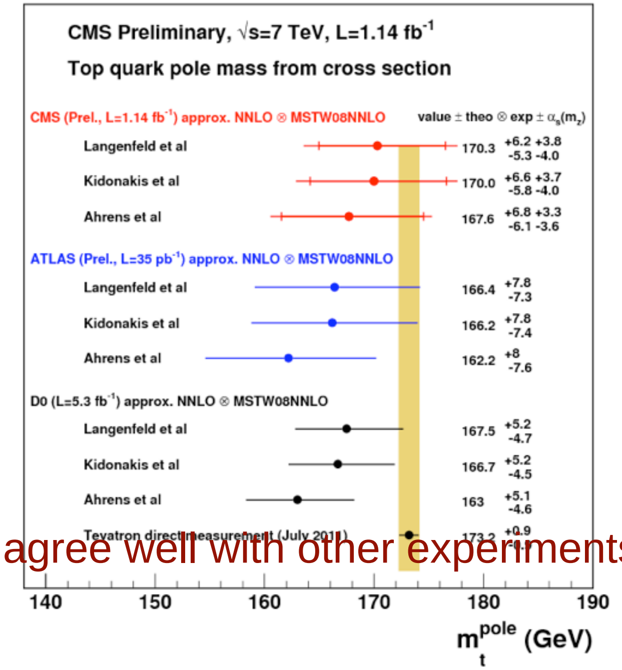
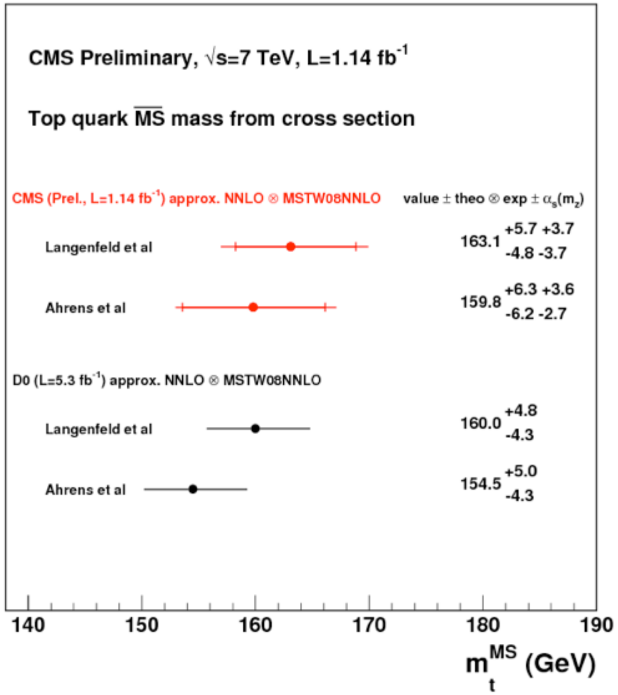
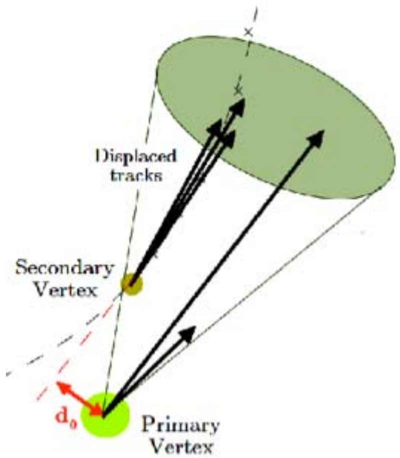


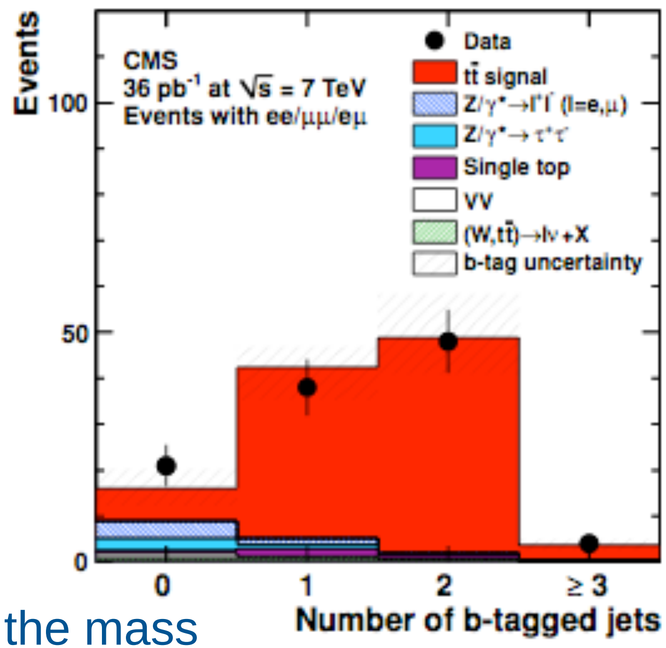


- Results agree well with other experiments

b-tagging: dilepton events

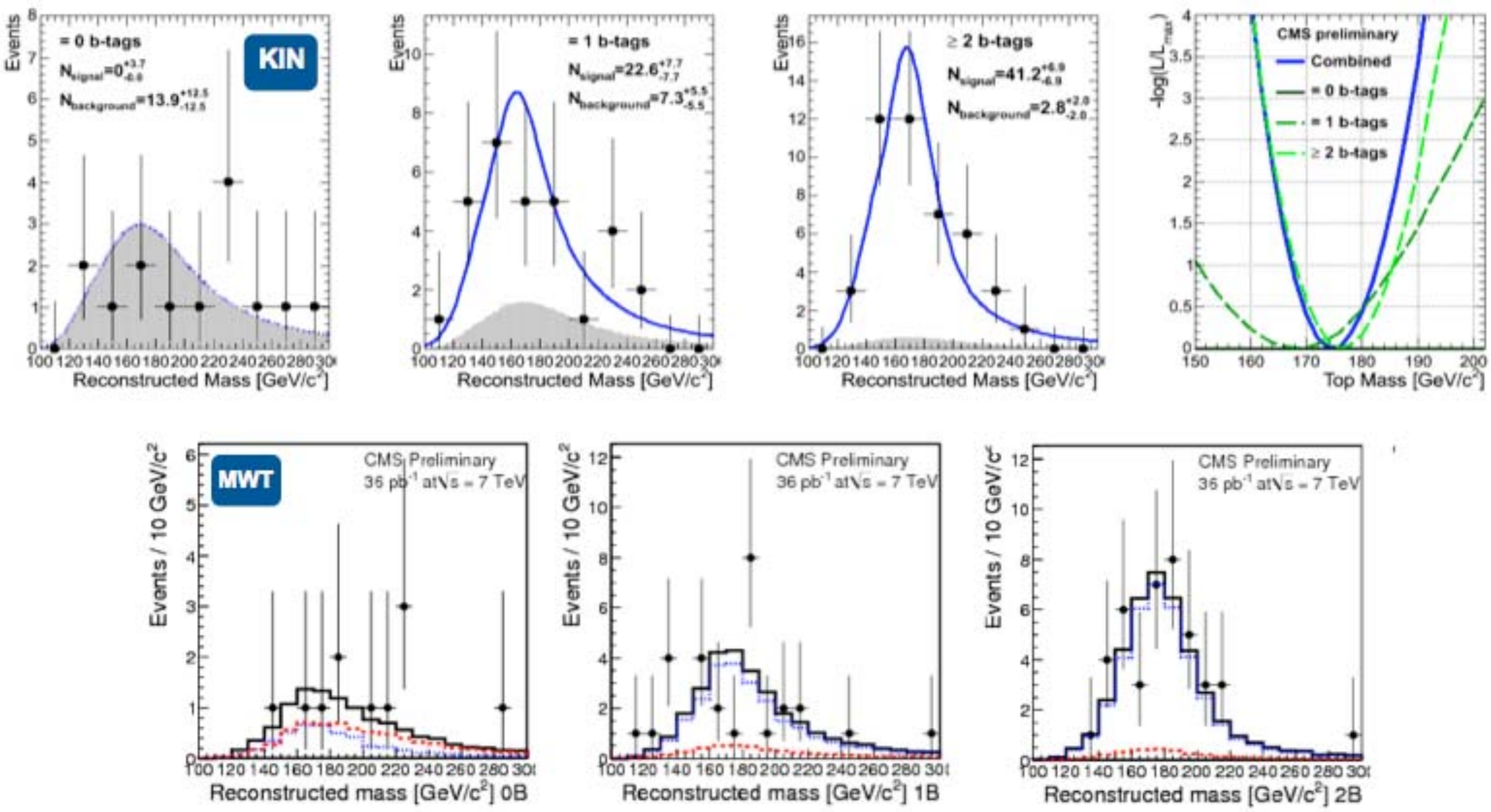
- Good agreement of b-tag multiplicity is observed





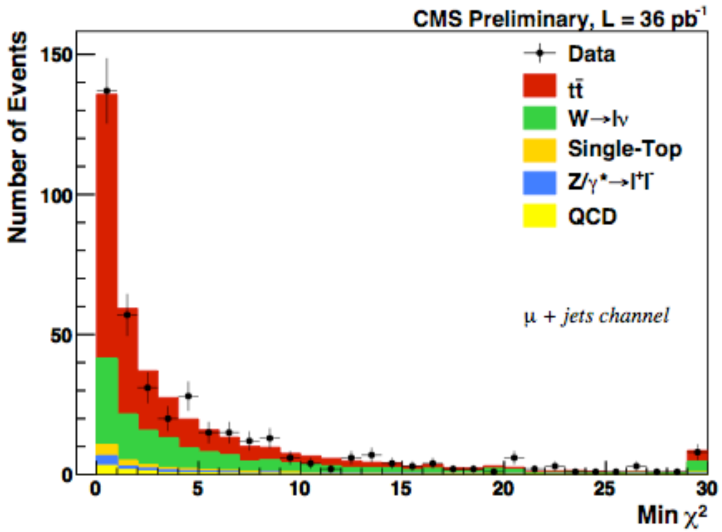
- b-tagging information used to rank the jets which enter the mass reconstruction (not used in event selection)
  - Loose discriminant ($\varepsilon_b \approx 80\%$, $\varepsilon_q \approx 10\%$)
  - Prefer b-tagged jets for mass reconstruction
  - Increase good jet assignment by 16% (with respect to p_T-based selection)

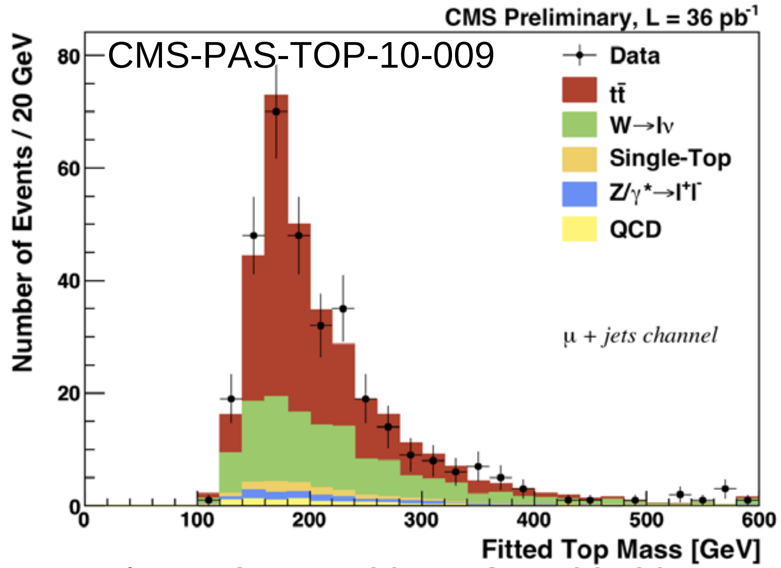
Top mass fits by category



Mass reconstruction

- Ideogram method:
  - Used for the W mass measurement (DELPHI) and Top mass at Tevatron
  - Resolve ambiguity in event kinematics with proper weighting
  - Mass described in event-by-event likelihood
- Full kinematic reconstruction, assuming events are from ttbar pairs
  - Inputs to the fitter: 4-momenta of lepton and four leading jets, MET, and their resolutions
- 12 possible jet-quark assignment: each permutation weighted by χ^2 probability
  - 303 events in e+jets, 334 in μ+jets channel
  - b-tagging information not used in the selection, but used in the likelihood calculation





Analysis strategy

For each event:

- Select muon (p_T>20 GeV) or ele (p_T>30 GeV) and 4 leading jets with p_T>30 GeV (same selection as cross section analysis)
- Try all 12 jet assignments, x2 neutrino solutions each, and apply kinematic fit (complete fit, using 1 lepton, 4 jets, MET)
- Construct event-by-event likelihood L(m_{top}) taking all solutions from the fit into account (that converge and have χ^2<10)

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

signal

background

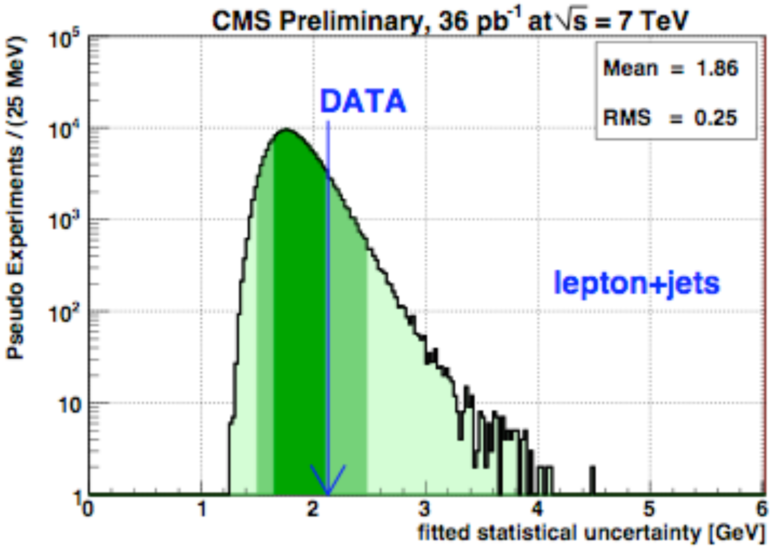
f_{ttbar}:fraction of ttbar events in sample

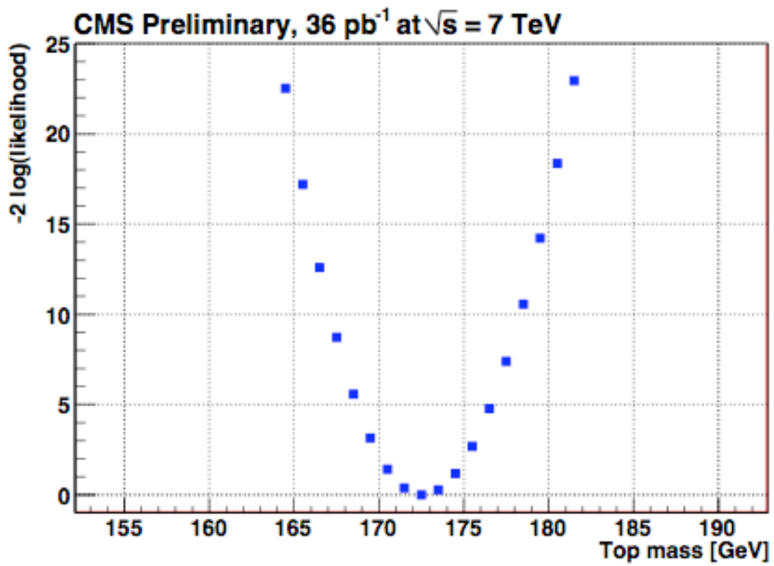
Event likelihood

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

- m_t: assumed value of top quark mass
- x: set of observables in the event from kinematic fit (fitted mass and uncertainty, χ^2, number of b-tagged jets)
- f_{ttbar}: fraction of ttbar signal in the data sample
- P_{ttbar}: probability density for signal
  - Sum over permutation and their individual weights
  - Correct permutation: analytical function
  - Wrong permutation: shape from MC simulation
- P_{bkg}: probability density for background
  - W+jets, shape from MC simulation
- Likelihood is calculated using evaluation of analytical functions derived (calibrated) from MC

Results





CMS-PAS-TOP-10-009

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

Product of likelihoods of all events:

$$\mathcal{L}_{\text{sample}}(m_t, f_{t\bar{t}}) = \Pi_j \mathcal{L}_{\text{event},j}(m_t, f_{t\bar{t}})$$

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.4}_{-2.1}(\text{JES}) \pm 1.4(\text{other syst})\ \text{GeV}$$

b-tagging

- b-tagging information is not used in the selection, but used in the likelihood
  - Include likelihood to observe n_{btag} in a signal/background event

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

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

- calculate additional weight which quantifies agreement between “flavor” hypothesis and the observed results
- additional weight (w_{btag}) is calculated for each permutation, and combined with the weight from the goodness-of-fit, as final weight for each jet combination

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

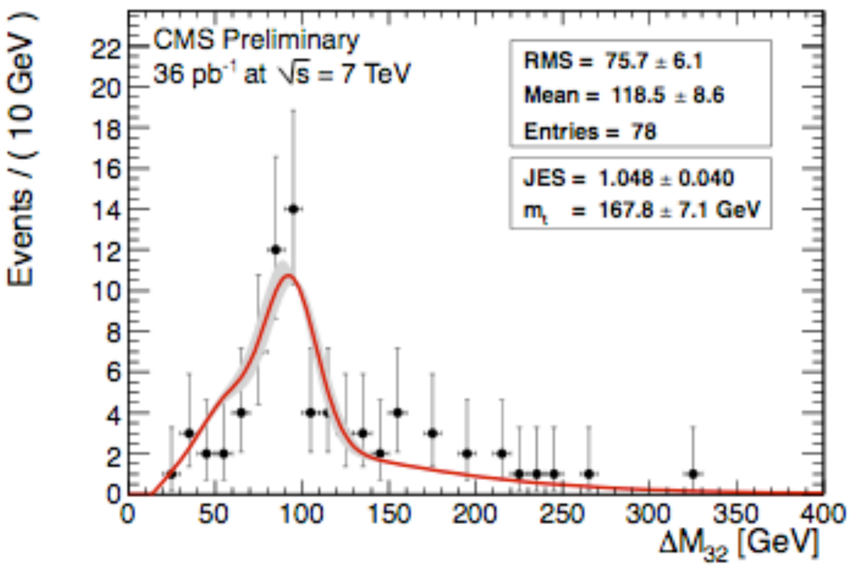
$$w_i = w_{fit} \times w_{btag}$$

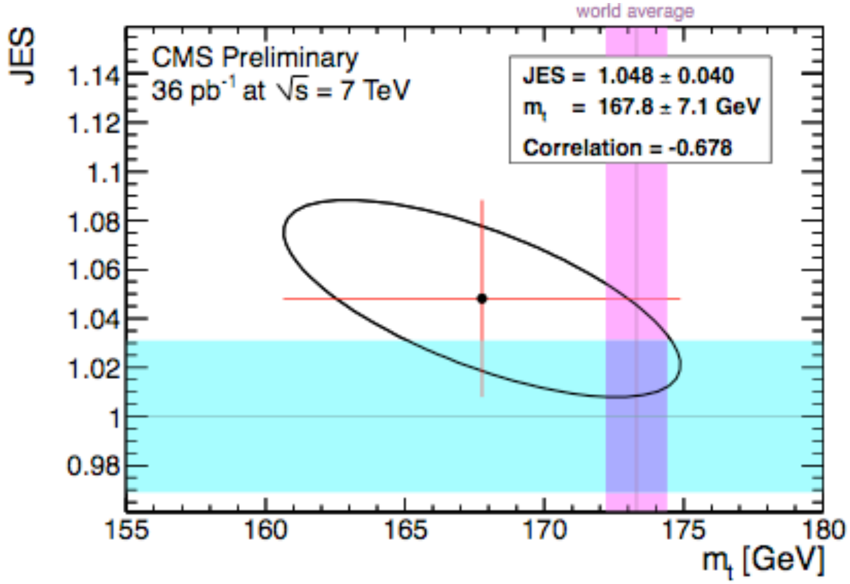
Assumed flavor	Observed flavor	Weight
b	b	ϵ_b
b	l	$(1-\epsilon_b)$
l	b	ϵ_l
l	l	$(1-\epsilon_l)$

Top mass+JES template

CMS-PAS-TOP-10-009

- Double b-tagged analysis in μ+jet channel
- Correct jet-quark assignment (M3 definition with b-tagging)
  - Hadronic ttbar jets: 3 jets with maximum vector p_T sum (1 b-tag)
  - Hadronic W jets: 2 untagged jets from hadronic ttbar jets
- M2 and ΔM_{32}=M3-M2 fitted with templates





$$m_t = 167.8 \pm 7.1(\text{stat+JES}) \pm 3.1(\text{syst})\ \text{GeV}$$
$$\text{JES} = 1.048 \pm 0.040(\text{stat}+m_t) \pm 0.015(\text{syst})$$