Top Quark Properties and Mass Measurements @ LHC

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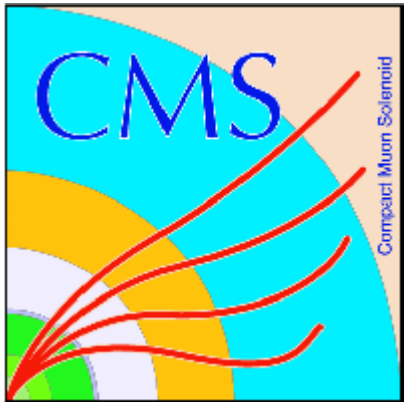
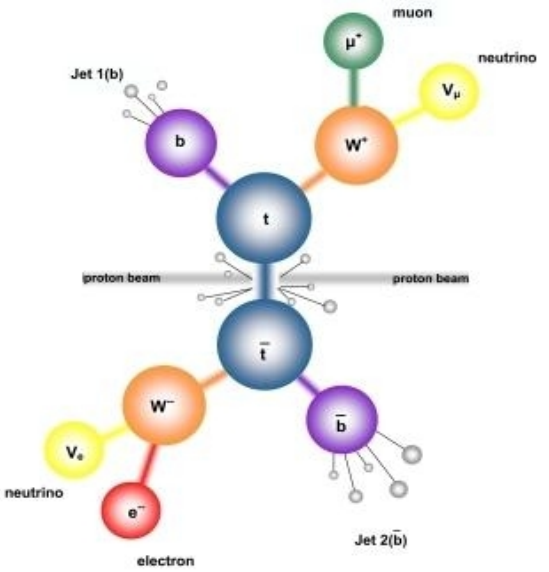
On behalf of the ATLAS & CMS Collaborations



Top Quark Production & Decay

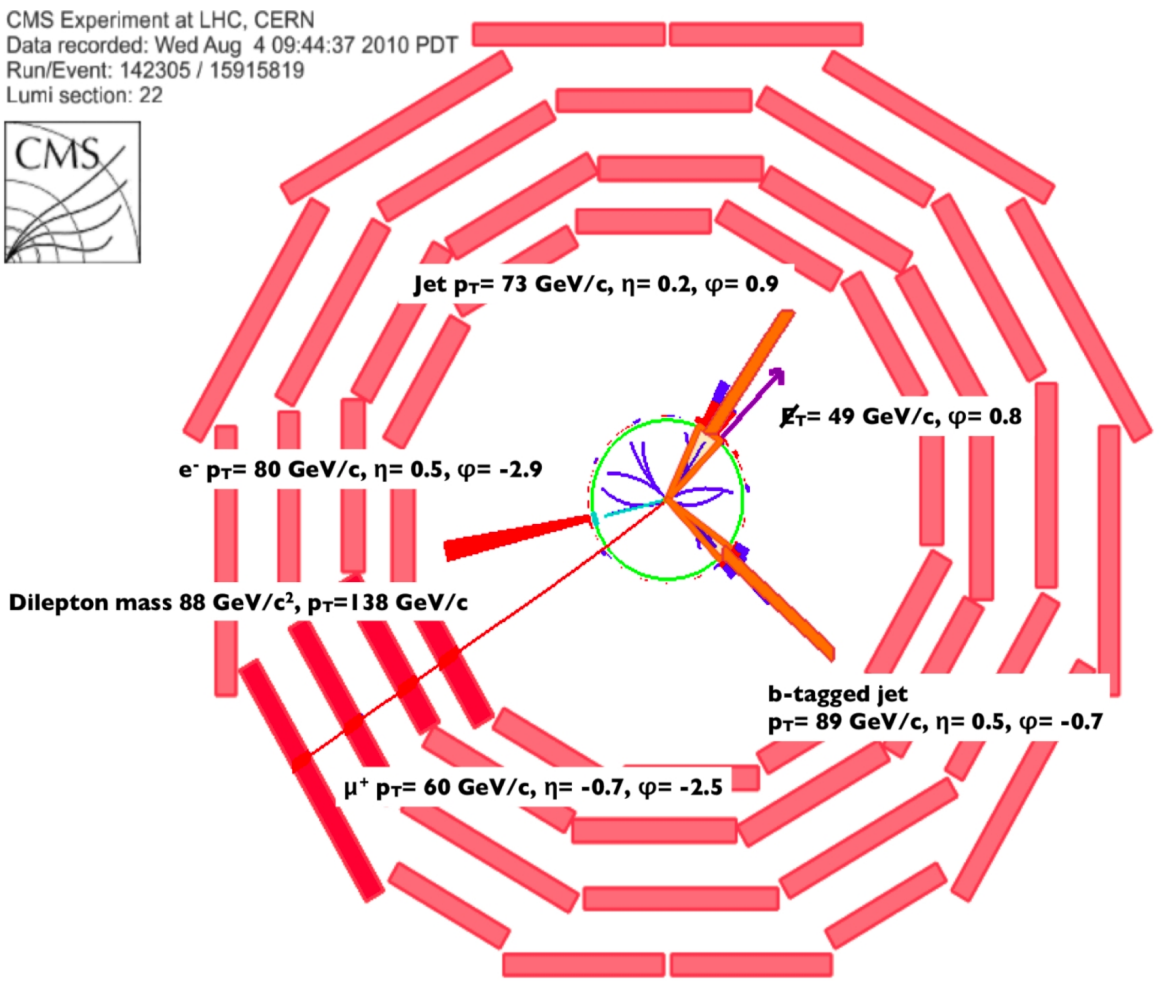
- Why is the top quark more interesting than others ?
  - Heaviest quark
  - Mass close to the EW symmetry breaking scale : may play a special role in the EW mechanism ?
  - Strongly coupled to massive gauge bosons in many BSM models
  - Hint of new physics in anomalous production rates or decay ratios
  - Mass involved in many precision measurements

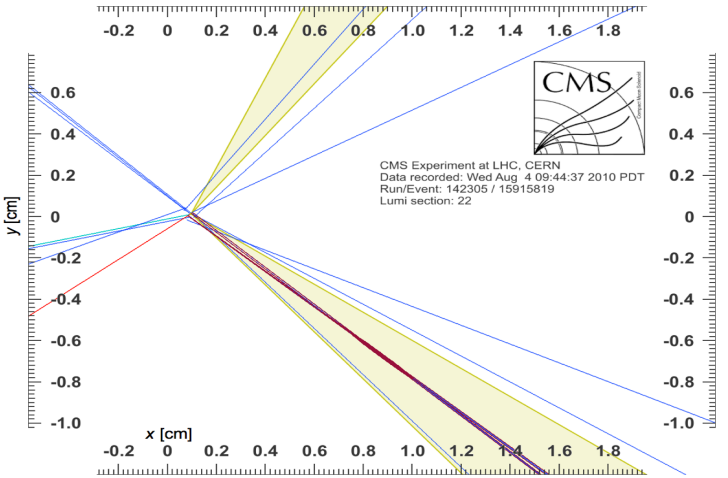
- Very short lifetime 5×10^{-25} s
  - Decays before hadronization
- Allows to observe a «bare» quark : direct measurements of its properties
  - Charge
  - Spin
  - Mass
  - Couplings

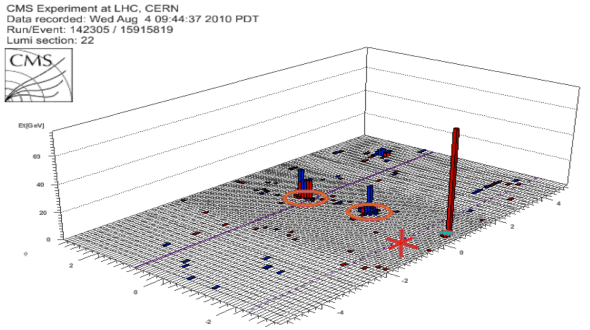


- Branching Ratio ~100% : $t \rightarrow bW$

Top Quark Pair Event







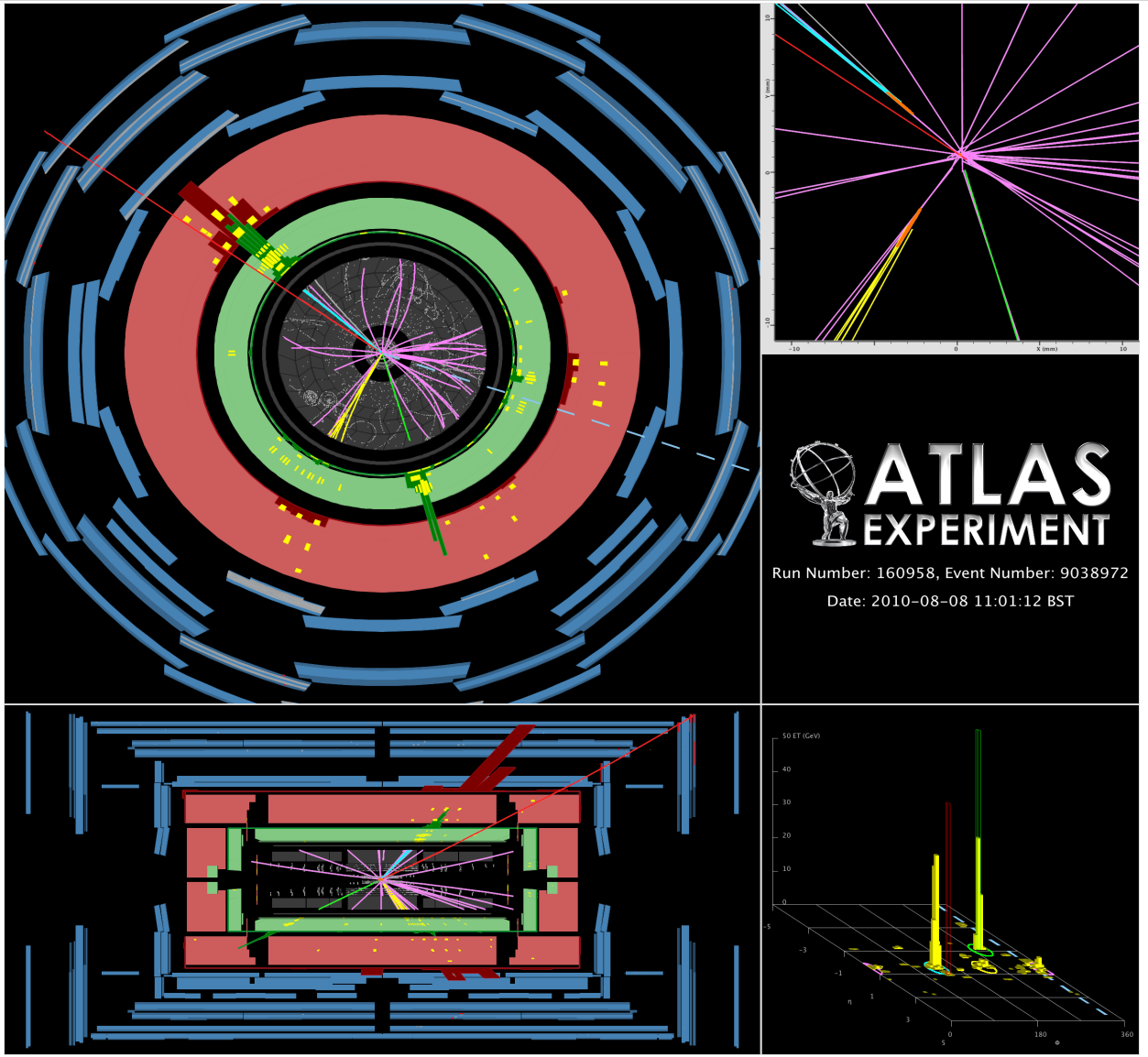
$t \rightarrow Wb \rightarrow e\nu b$

$t \rightarrow Wb \rightarrow \mu\nu b$

1 b-tagged jet

$E_T^{miss} \sim 50$ GeV

Top Quark Pair Event



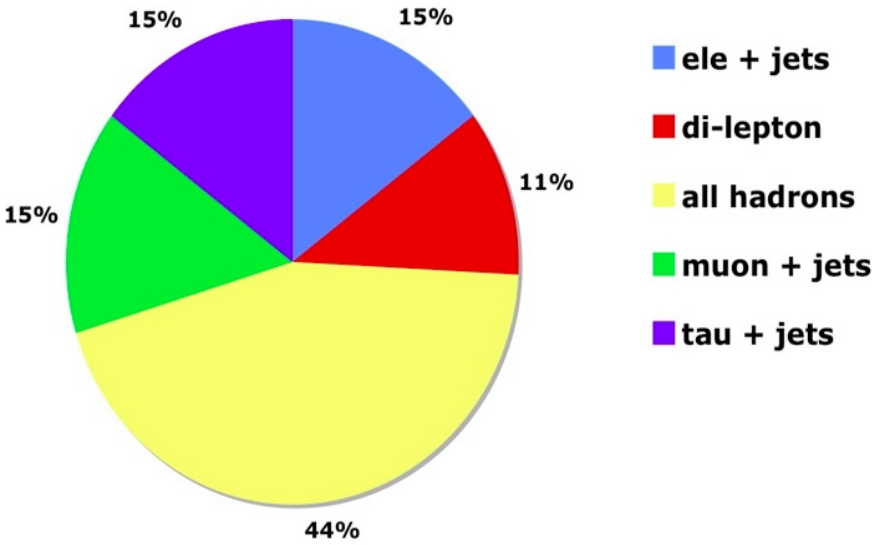
$t \rightarrow Wb \rightarrow e\nu b$
$t \rightarrow Wb \rightarrow \mu\nu b$

2 b-tagged jets

$E_T^{miss} \sim 30$ GeV

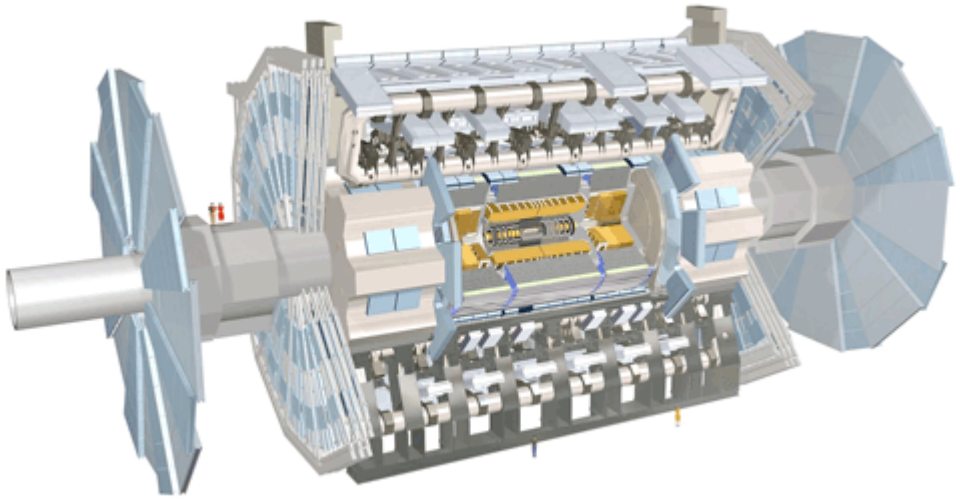
Top Quark Pairs Selection and SM Background

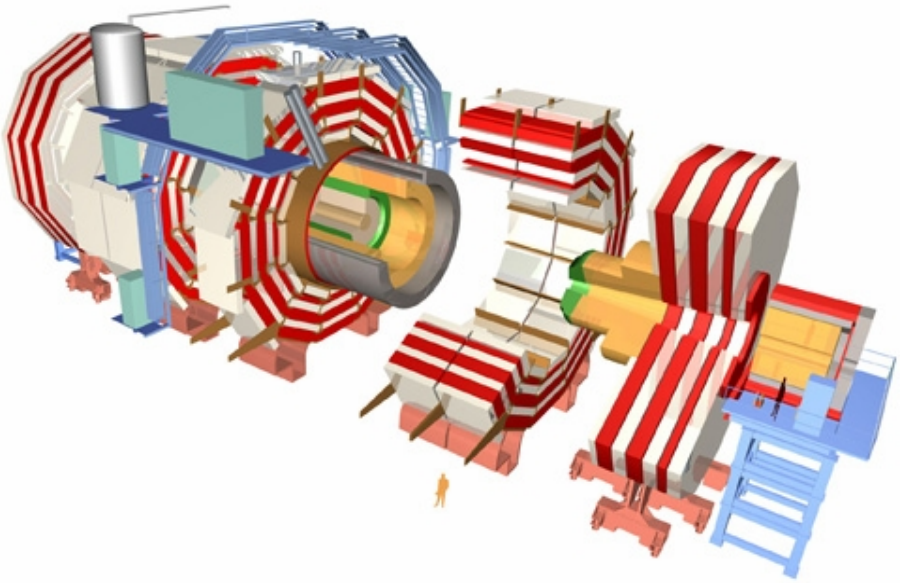
- Background reduction :
  - One or two leptonic decay of W
  - Large missing transverse energy
  - W transverse mass
  - B-jet identification :
    - Displaced vertices
    - Large impact parameter tracks



	ℓ+jets channels	Dilepton channels	
W+jets/Z+jets	**50%**	**55%**	Derived from data
Single Top	20%	15%	Derived from MC
QCD (fake leptons)	**25%**	15%	Derived from data
Dibosons	1%	15%	Derived from MC

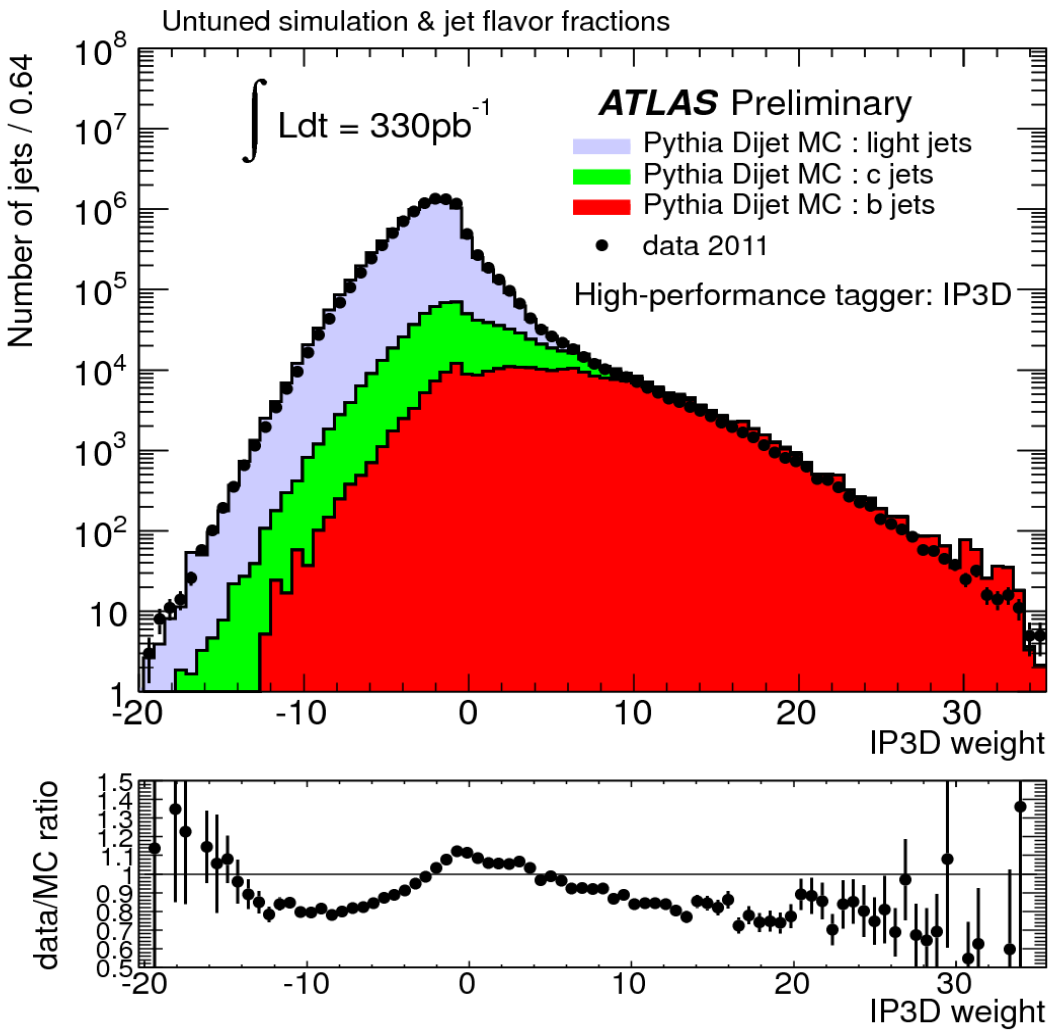
ATLAS & CMS



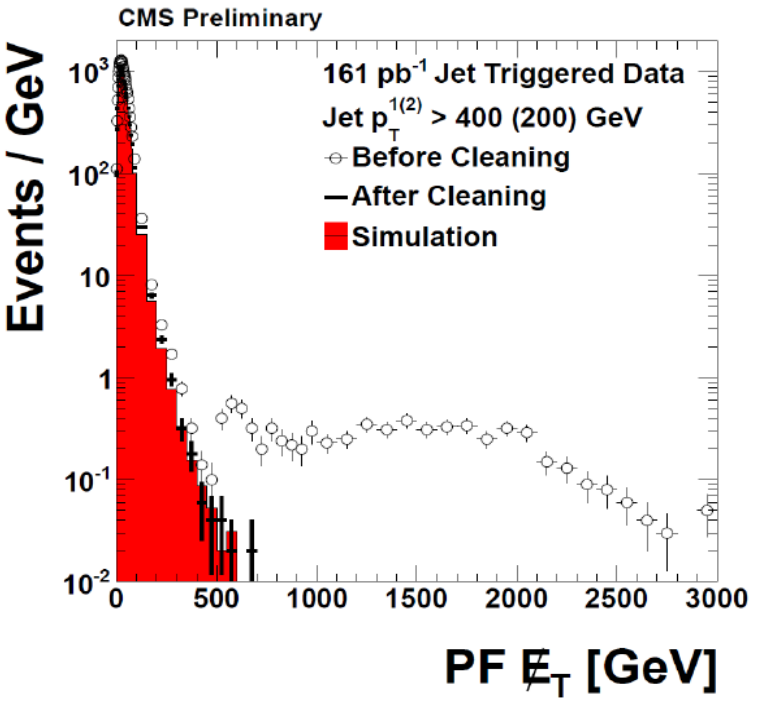


	ATLAS	CMS
Magnets	2T solenoid+toroid	4T solenoid
Muons	$\sigma/p_T \approx 2\%$@50GeV $\sigma/p_T \approx 10\%$@1TeV(ID+MS)	$\sigma/p_T \approx 1\%$@50GeV $\sigma/p_T \approx 5\%$@1TeV(ID+MS)
EM Calorimeter	$\sigma/E \approx 10\%/\sqrt{E}+0.007$ GeV	$\sigma/E \approx 2\text{-}5\%/\sqrt{E}+0.005$ GeV
Hadronic Calorimeter	$\sigma/E \approx 50\%/\sqrt{E}+0.03$ GeV	$\sigma/E \approx 100\%/\sqrt{E}+0.05$ GeV
Tracking	Silicon pixels & strips,TRT $\sigma/p_T \approx 5.10^{-4} p_T+0.01$	Silicon pixels & strips $\sigma/p_T \approx 1.5.10^{-4} p_T+0.005$

Detectors performance



- Impressive achievement from both experiments to understand the performances of the detector after only two years of running !



List of presented results

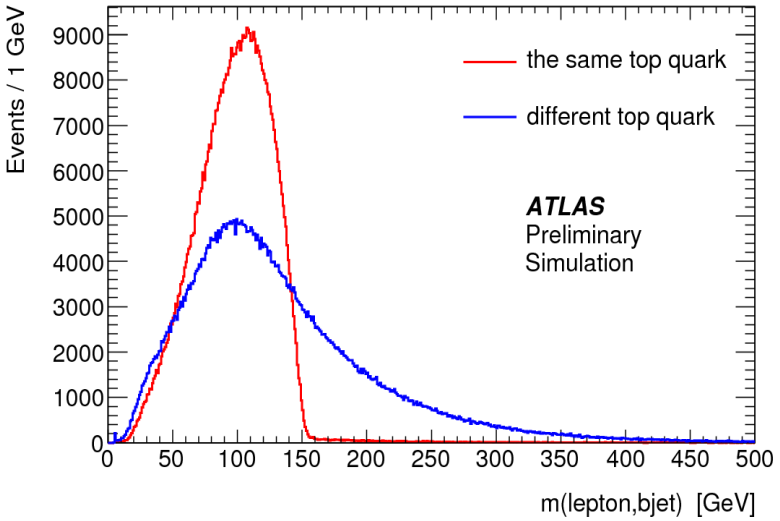
- Top quark charge
- $t\bar{t}$ spin correlation
- W polarization from top quark decay
- Flavor changing neutral current in top quark decay
- Probing EW coupling in $t\bar{t}\gamma$
- Top quark mass measurement
- Mass difference between top and anti-top quarks
- Not covered in this talk :
  - $t\bar{t}$ asymmetry (See talk from T.J Kim)
  - Search for m($t\bar{t}$) resonances (See talk from T. Orimoto)

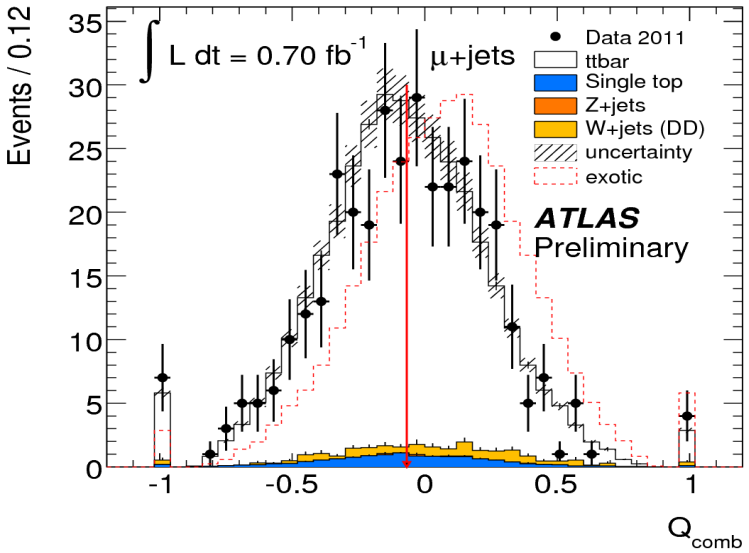
Top Quark Charge

ATL-CONF-2011-141

0.70 fb^{-1}

- Top quark charge :
  - SM : $t^{(+2/3)} \rightarrow b^{(-1/3)}\ W^{(+1)} \rightarrow b^{(-1/3)}\ \ell^{+}\ \nu$
  - Exotic : $t^{(-4/3)} \rightarrow b^{(-1/3)}\ W^{(-1)} \rightarrow b^{(-1/3)}\ \ell^{-}\ \nu$
- Event selection :
  - $t\bar{t} \rightarrow W^{+/-}b\ jjb \rightarrow \ell^{+/-}\nu b\ jjb$
  - At least one jet b-tagged with secondary vertex
- **Method 1** : $Q_{COMB} = Q_{b\text{-jet}} \cdot Q_{\ell}$
  - Estimate the b-jet charge using weighted sum of the 10 most energetic tracks
    - Requires a second jet with secondary vertex tagging
  - Find the correct lepton/b-jet assignement using invariant mass constraint $m(\ell,b) < M_{top}$





Top Quark Charge

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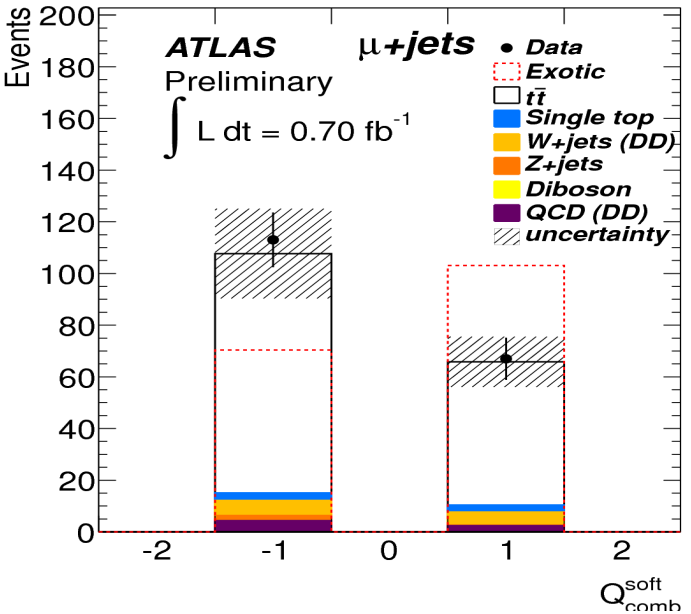
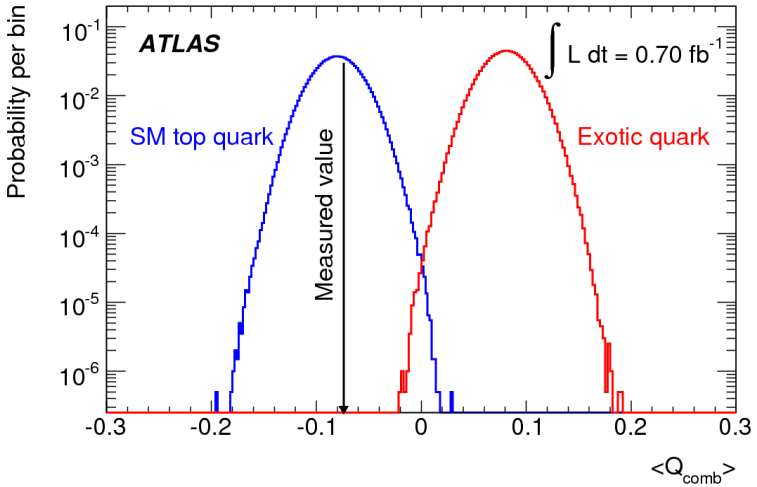
- **Method 2** : $Q_{COMB} = Q_{soft\ \mu} \cdot Q_{\ell}$
  - Use semi-leptonic B hadron decays
    - Requires one jet tagged with a soft muon $P_T^{\mu} > 4$ GeV
    - BR(b → μνX)~11% (same sign)
    - BR(b → c → μνX)~10% (opposite sign)
      - Suppressed with P_T^{rel} cut > 800 MeV
      - Correct for remaining contaminatio
  - Lepton/b-jet pairing using Kinematic Likelihood Fitter (full event reconstruction)
- **Result :**
  - Both methods lead to measured Q_{COMB} more than 5σ away from the expected valu in the exotic model assumption



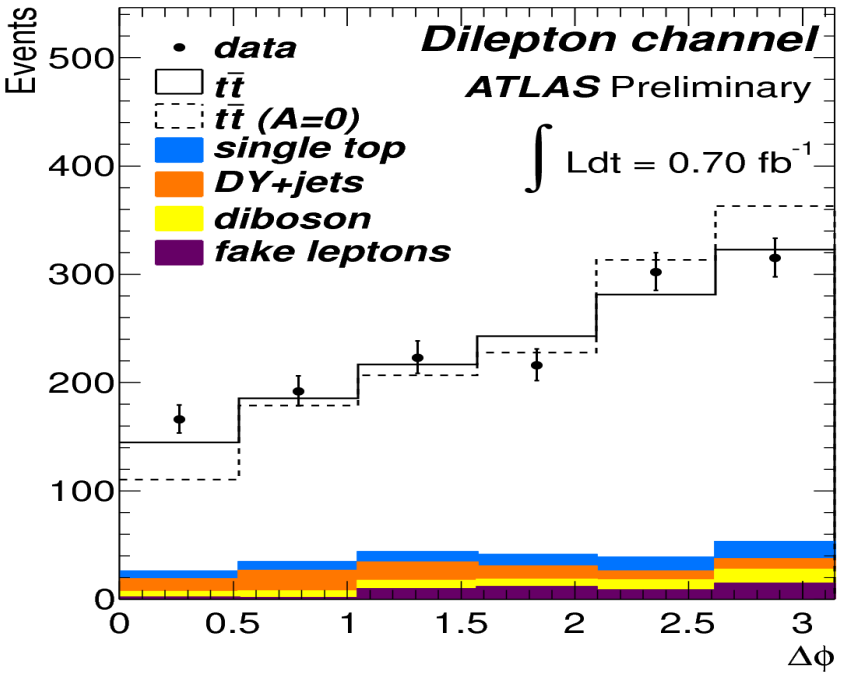


$t\bar{t}$ Spin Correlation

ATL-CONF-2011-117

0.70 fb^{-1}

- **Motivation** :
  - Top quark pair is unpolarized but their spins are correlated
  - Test of QCD prediction & BSM production modes ($t \rightarrow H^{+}b$)
- V-A coupling fixes the angular distributions of the decay products according to the top polarization
  - Spin measured through angular distributions of decay products
  - Difference in azimuthal angle sensitive to spin correlation
  - Event selection : $t\bar{t} \rightarrow \ell^{+}\nu b\, \ell^{-}\nu b$
- Binned Likelihood fit
  - Assuming $f^{SM} + f^{UC} = 1$



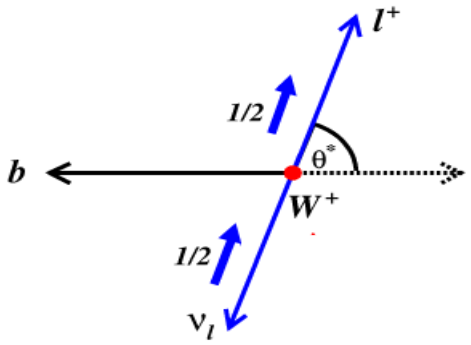
Channel	f^{SM}
ee	0.89 +/- 0.40
eμ	0.67 +/- 0.37
μμ	1.46 +/- 0.33
Combination	**1.06 +/- 0.21**

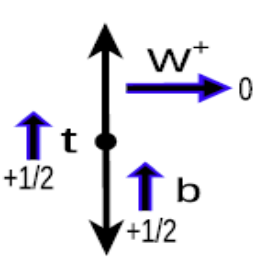
W Polarization

ATL-CONF-2011-122

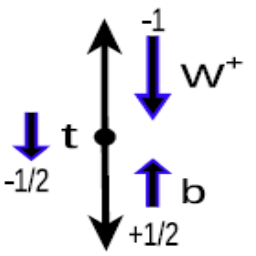
0.70 fb^{-1}

- **Motivation** : constraint on anomalous contributions to the Wtb vertex
- In SM : almost no right-handed W
  - F_0 = 0.687 +/- 0.005
  - F_L = 0.311 +/- 0.005
  - F_R = 0.0017 +/- 0.0001
- **Cos θ*** = angle between charged lepton and top direction in W rest-frame

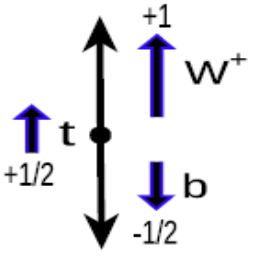




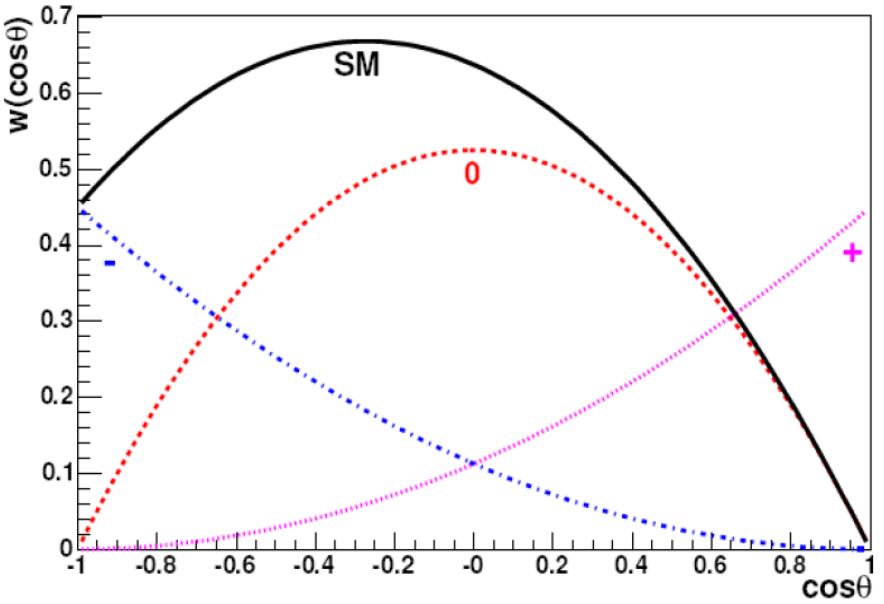
Longitudinal W
F_0



Left-handed W
F_L



Right -handed W
F_R

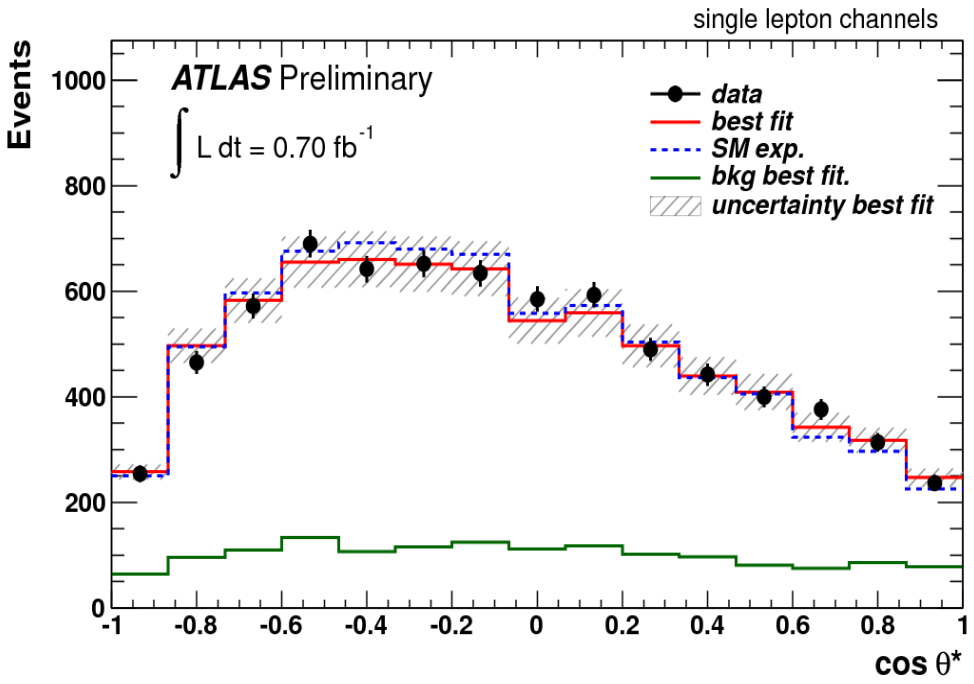


W Polarization

ATL-CONF-2011-122

0.70 fb^{-1}

- Measurement performed in ℓ+jets channel from template fit :
  - F_L = 0.35 +/- 0.04 (stat) +/- 0.04 (syst)
  - F_0 = 0.57 +/- 0.07 (stat) +/- 0.09 (syst)
  - F_R = 0.09 +/- 0.04 (stat) +/- 0.08 (syst)
- Combined all ℓ+jets and dilepton channels (assuming F_R = 0)
  - F_L = 0.25 +/- 0.08 (stat+syst)
  - F_0 = 0.75 +/- 0.08 (stat+syst)



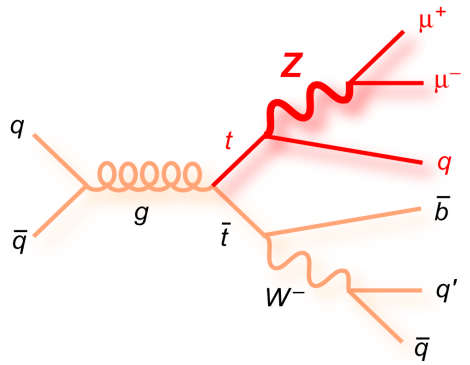
- Statistical and systematic errors already comparable with TeVatron results
- More data needed to start testing the SM

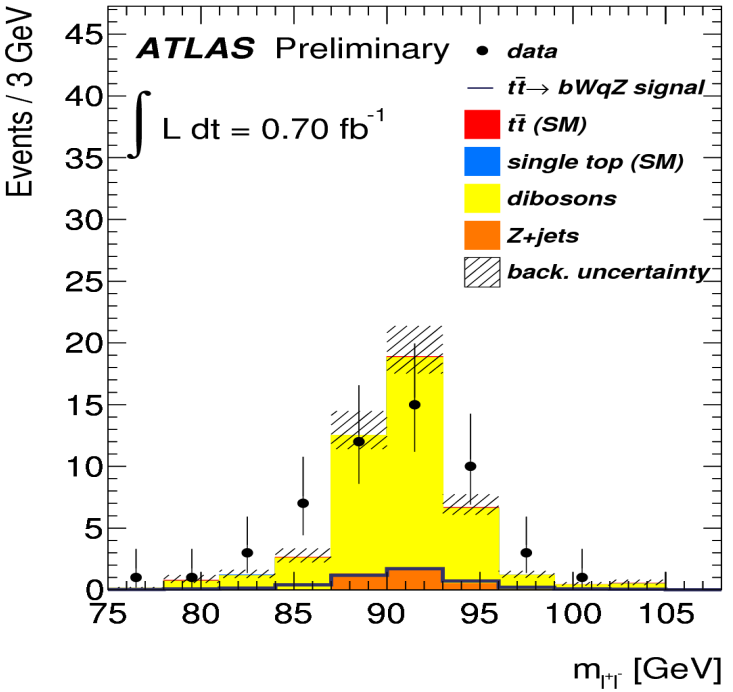
Flavor Changing Neutral Current

ATL-CONF-2011-154

0.70 fb^{-1}

- FCNC forbidden in SM at tree level very small at loop level
  - BR(t → uZ) = 8.10^{-17}
  - BR(t → cZ) = 1.10^{-14}
  - Limit from TeVatron : BR(t → qZ) < 3.2%
  - BR enhanced in SUSY & Topcolour assisted Technicolour models
- Event selection : $t\bar{t}$ → Wq **Z**q → ℓνj $\ell^+\ell^-$j
  - 3 leptons, E_T^{miss} and 2 jets (no btag)
    - 2 leptons with same flavour, opposite sign, within Z mass window +/- 15 GeV
  - kinematic fit of the 2 top quarks masses
    - χ^2 minimization of $m_t, m_t, m_W, m_{Z\,fit}$
- Limit : BR(t → Zq) < 1.1% @ 95 % CL



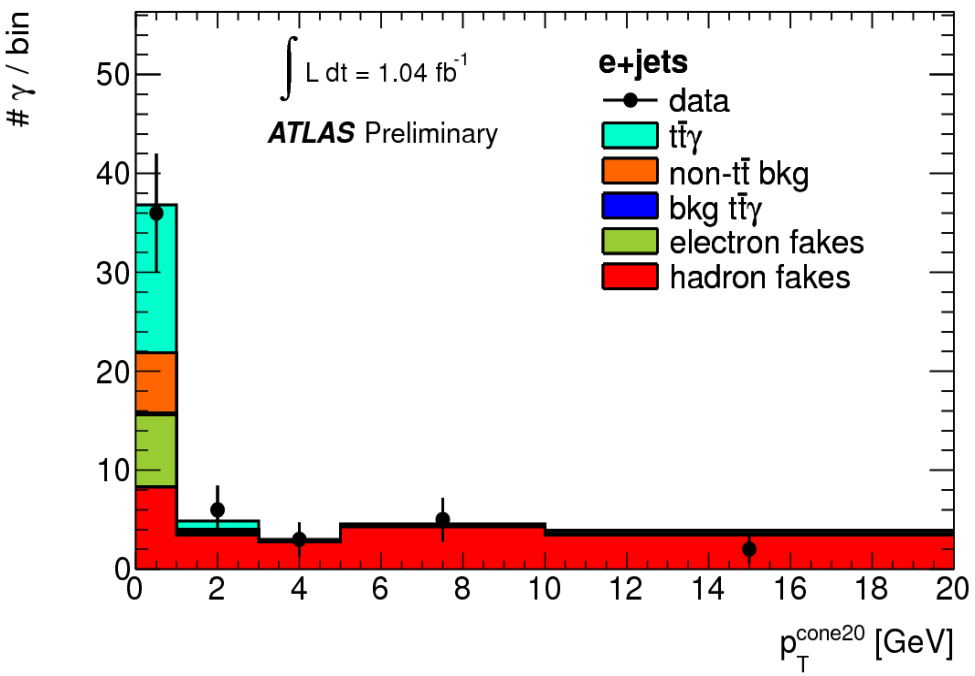


$t\bar{t}\gamma$ Cross-Section Measurement

ATL-CONF-2011-153

1.04 fb^{-1}

- Investigate EW couplings of the top quark
- Processes :
  - Radiative top quark production (top decay without photon radiation)
  - Radiative top quark decay (photon from on-shell top quark or from its decay products)
  - SM cross-section: σ= 2.1 +/- 0.4 pb
- Event selection : $t\bar{t}\gamma \rightarrow \ell\nu b\, jjb\, \gamma$ (b-tag)
  - Main background from electrons and hadrons faking photons
  - Small irreducible background from hard photon radiation



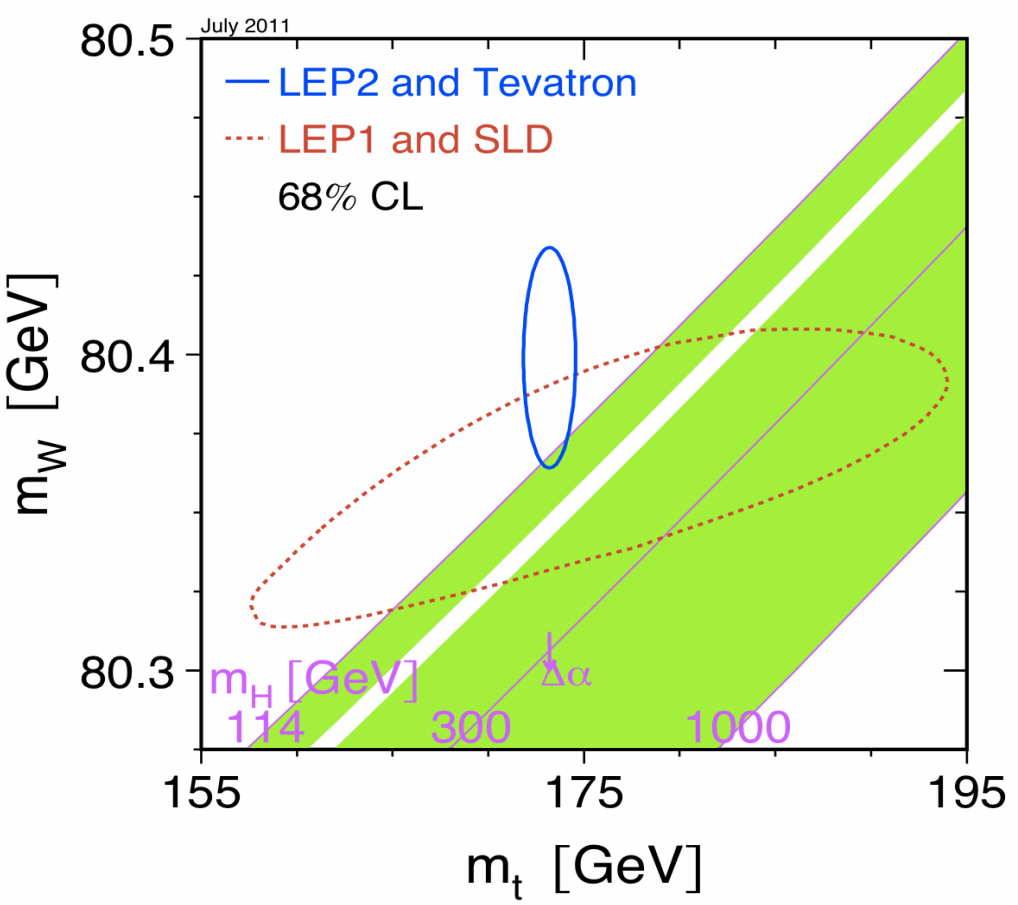
Cross-section measured from template fit :

$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5\,(\text{stat.}) \pm 0.7\,(\text{syst.}) \pm 0.08\,(\text{lumi.})\,\text{pb}$$

Top Quark Mass Measurement

- The top quark mass is one of the most important inputs to the global electroweak fit :
  - Provides constraints on the SM
  - Indirect limits on the Higgs mass
- Methods used to measure the top quark mass :
  - Template Fit
    - ATLAS 0.7 fb^{-1}
  - Kinematic Fit and Matrix Weighting Method
    - CMS 36 pb^{-1}
  - Cross-section
    - ATLAS 35 pb^{-1}
    - CMS 1.14 fb^{-1}
  - Ideogram
    - CMS 36 pb^{-1}

$M_{top} = 173.2 +/- 0.9 \text{ GeV}/c^2$

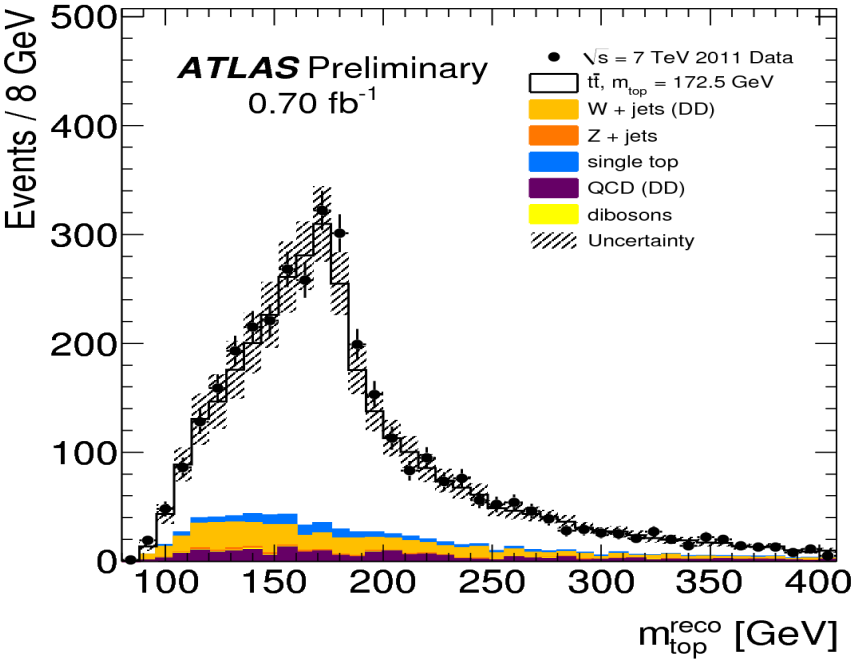


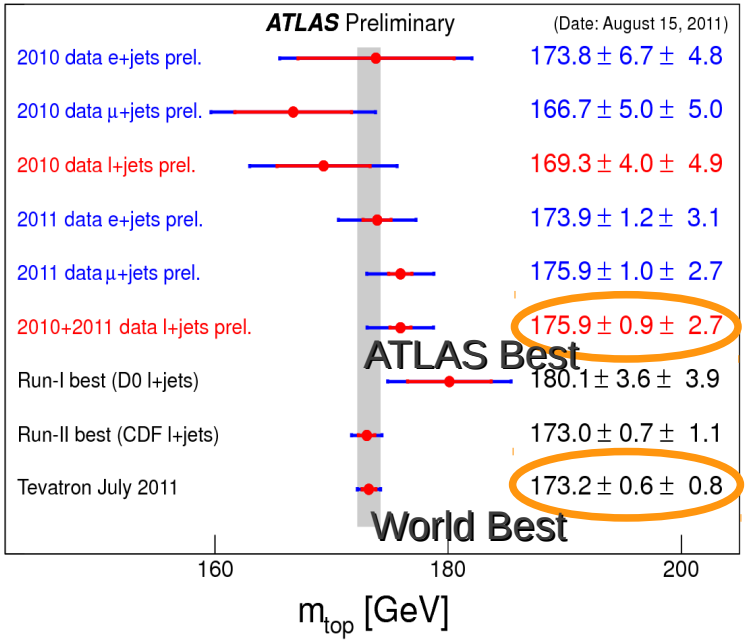
Top Mass from Template Fit

ATL-CONF-2011-120

0.70 fb^{-1}

- 2D template analysis in lepton+jets channels
- Fit templates to determine simultaneously :
  - Top Mass
  - Jet Energy Scale
  - Background level





- **Combination with 2010 data :**

  M_{top} = 175.9 GeV +/- 0.9 (stat) +/- 2.7 (syst)

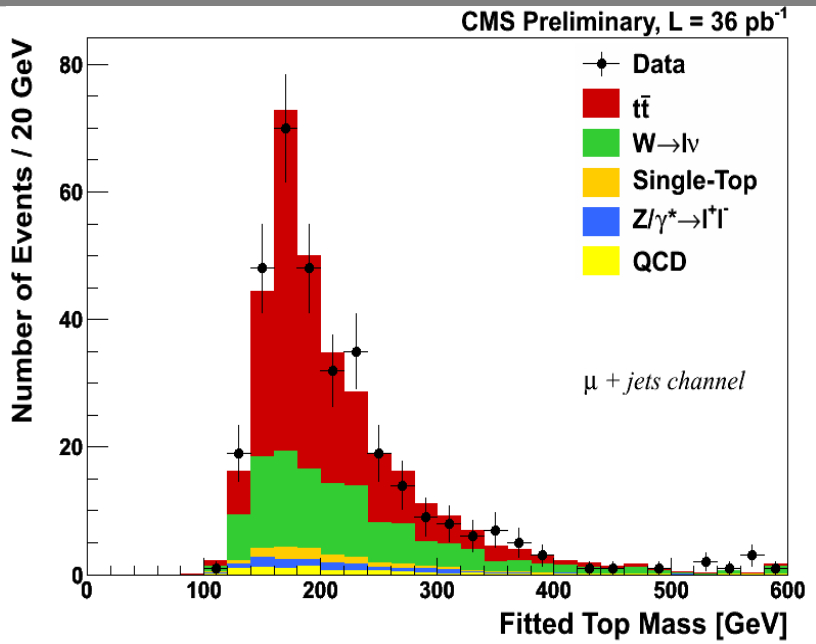
- **Statistical error** comparable to TeVatron
- Systematics limited (JES)

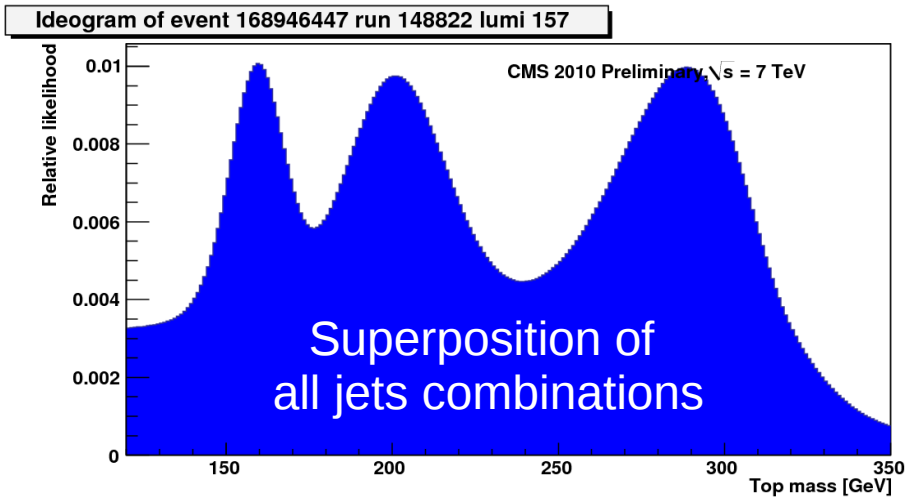
Top Mass from Ideogram

CMS PAS TOP-10-009

36 pb^{-1}

- Select lepton + jets events, with b-tagging
- Extract best fitted hadronic top mass for each event (m_{fit}) and each jets combination
- Compute a probability for each event to measure m_{fit} assuming m_{top}
- Leading systematics from Jet Energy Scale





- Main CMS top mass result, combining the electron+jets and muon+jets channels

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.8}_{-2.5}(\text{syst}) \text{ GeV}.$$

- Combination with the CMS measurement in the di-lepton channel

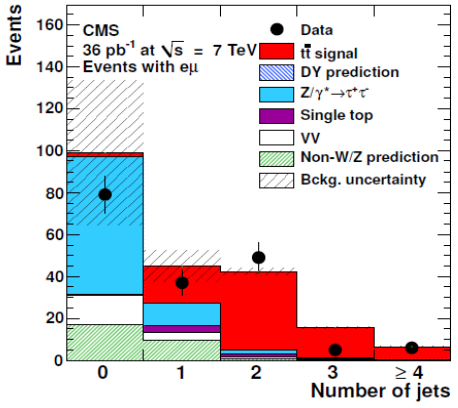
$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst}) \text{ GeV}.$$

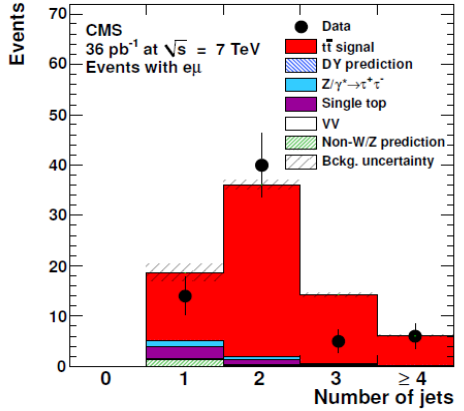
Top Mass from Dileptons

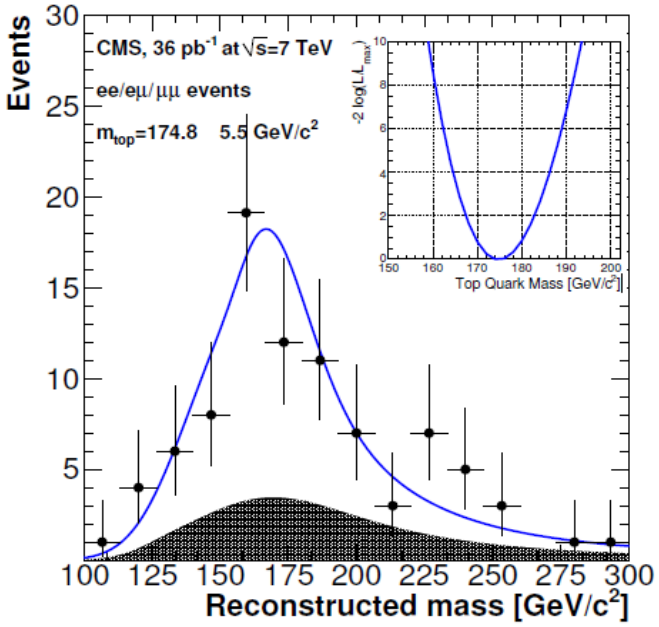
CMS PAS TOP-11-002

36 pb^{-1}

- Combination of Matrix Weighting Technique and full kinematic reconstruction method
- Use dilepton events separated in samples :
  - Lepton flavor (ee,μμ,eμ)
  - Number of b-tagged jets
- Leading systematics from Jet Energy Scale







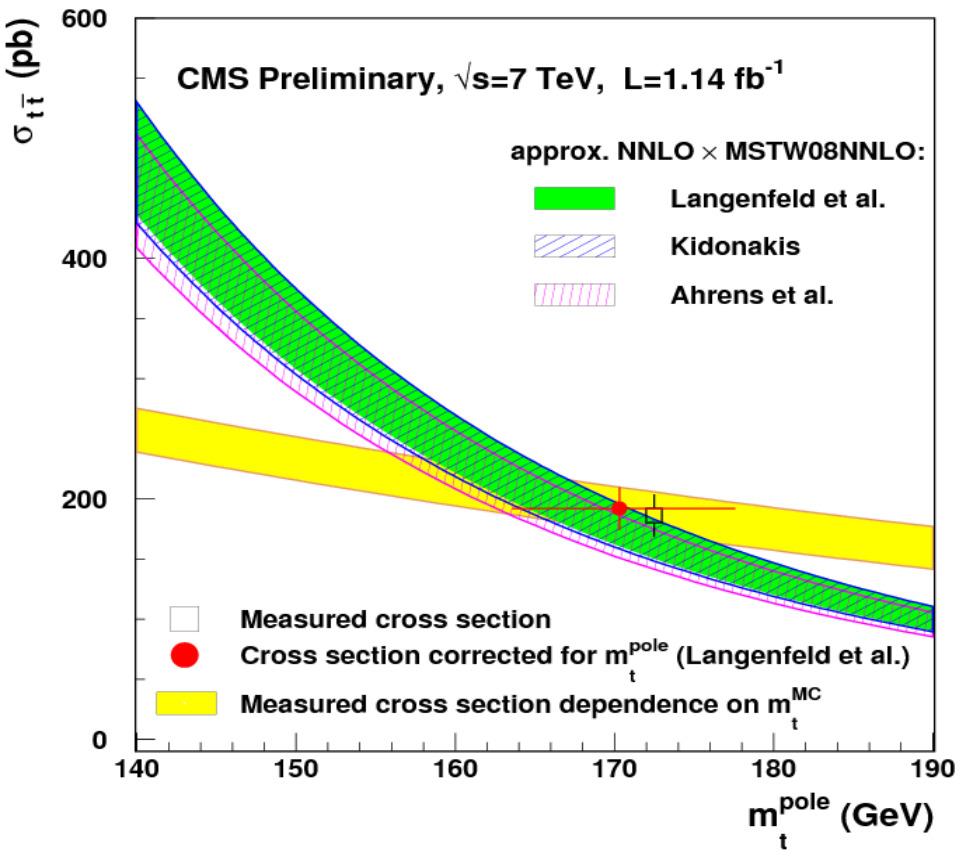
Method	Measured m_{top} (in GeV/c^2)
AMWT	$175.8 \pm 4.9\,(\text{stat.}) \pm 4.5\,(\text{syst.})$
KINb	$174.8 \pm 5.5\,(\text{stat.})^{+4.5}_{-5.0}\,(\text{syst.})$
Combined	$175.5 \pm 4.6\,(\text{stat.}) \pm 4.6\,(\text{syst.})$

Top Mass from Cross-Section

CMS PAS TOP-11-008

1.14 fb^{-1}

- The result is not competitive in precision, but :
  - provides the top quark mass value in an exact definition of the mass-pole
  - Important cross-check, complementary to direct top mass measurements
- Likelihood Fit on the mass dependence
- Uncertainty of the theory includes :
  - Variation of the renormalization, factorization scales
  - Error due to experimental uncertainties in the PDFs
  - Variation of the strong coupling constant in the PDF

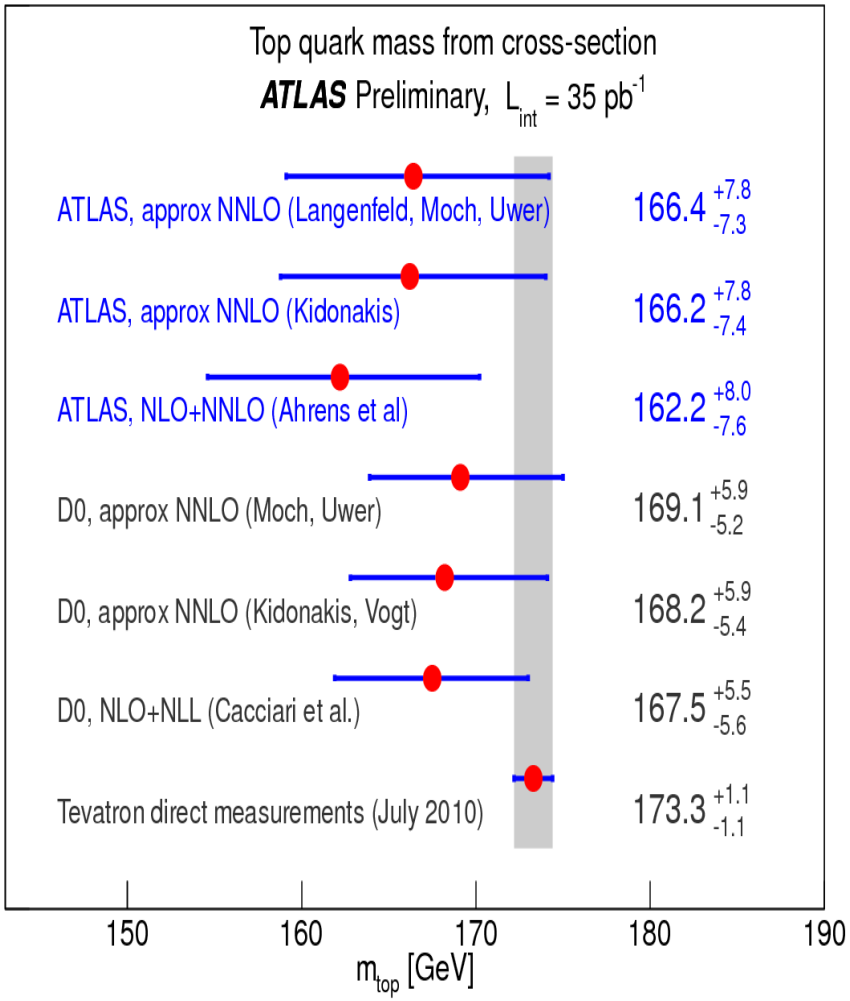


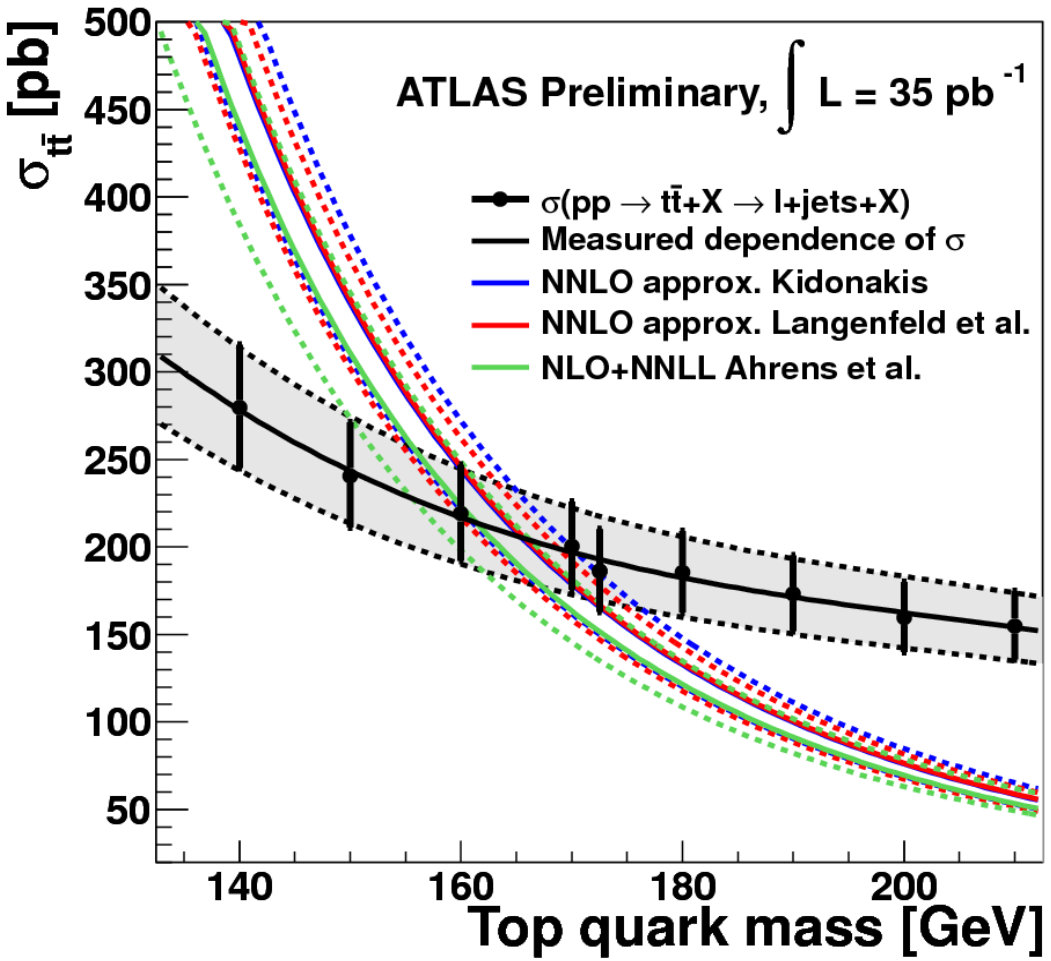
Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\text{MS}}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Top Mass from Cross-Section

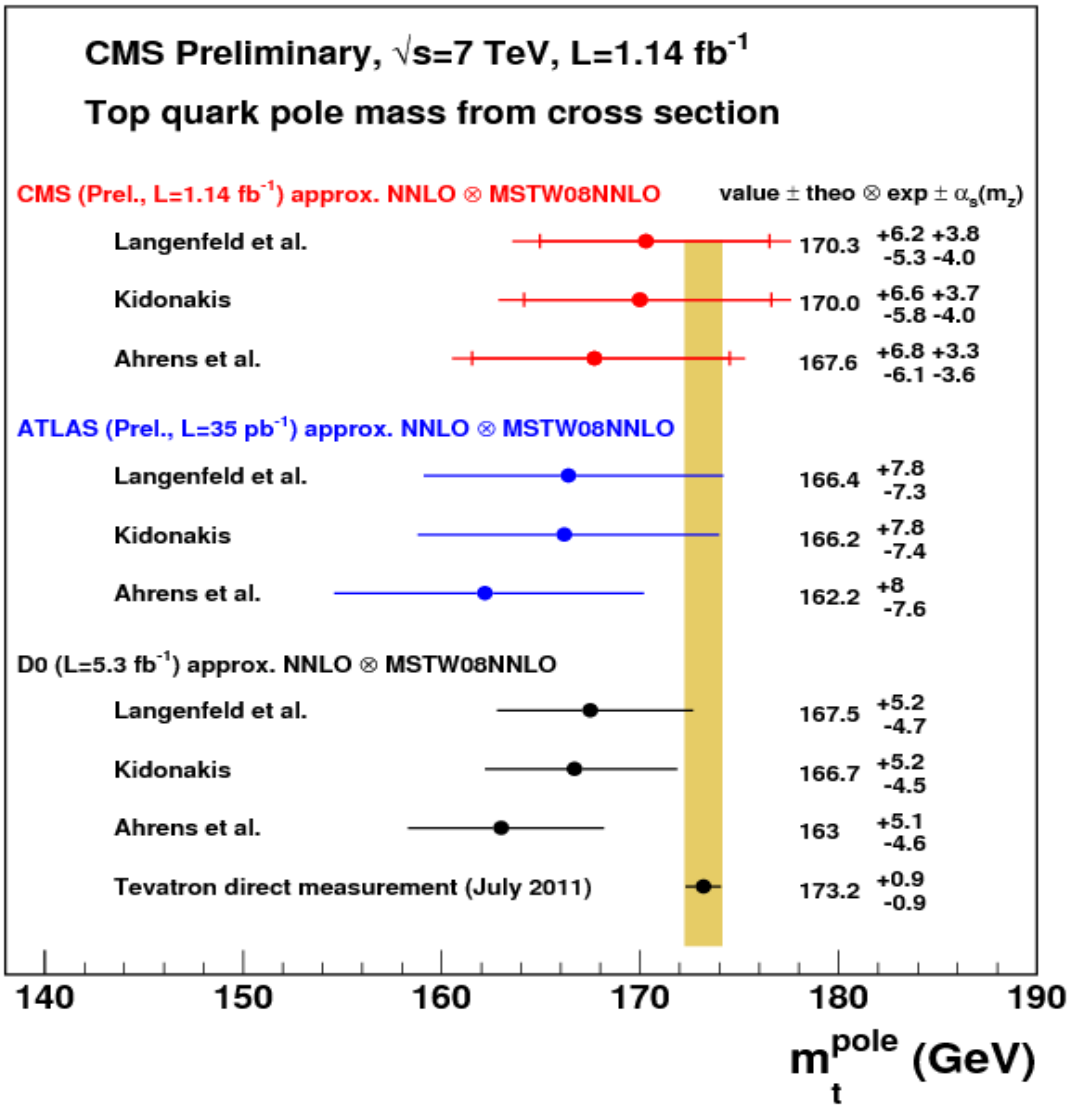
ATL-CONF-2011-054

35 pb^{-1}





Top Quark Pole Mass from Cross-Section



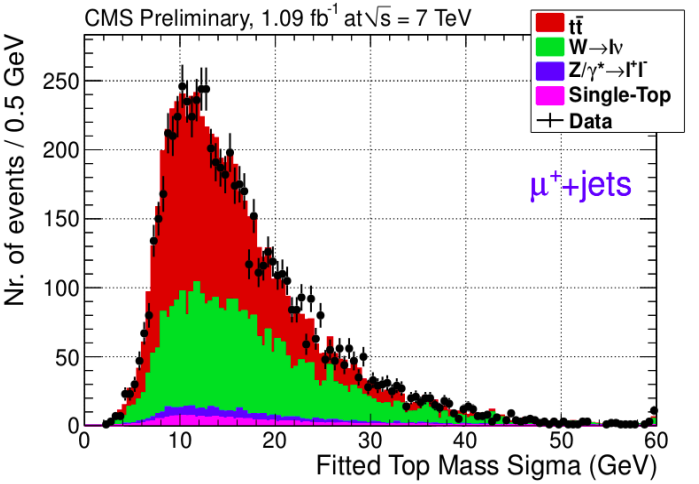
$t\bar{t}$ Mass Difference

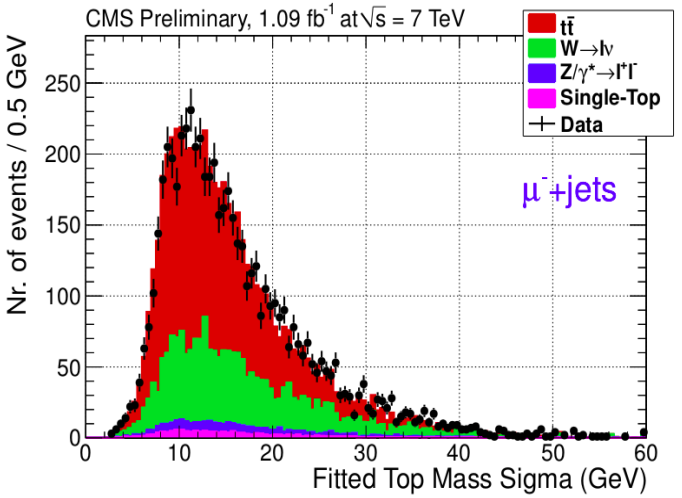
CMS PAS TOP-11-019

1.09 fb^{-1}

World best result

- **Motivation** : direct measurement of CPT violation
- Select events with a muon and multi-jets in the final state
  - One of the two top quarks decays hadronically [t → bW → bq$\bar{q}$]
  - The other top quark decays in the muon channel [t → bW → bμν$_\mu$]
- The muon charge allows to split the data sample in two sub-samples, where top or antitop quarks decay hadronically.
- Ideogram method is used to measure the mass of the top quarks. Many systematics cancel with the substraction





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

Summary

- ATLAS and CMS have already (within only 2 years !) performed a complete first survey of the phase space of the top quark mass and properties.

- The results are
  - Very competitive with TeVatron in precision
  - Better than TeVatron for limits
  - Systematics limited in e.g. in the mass determination
  - Unfortunately in agreement with Standard Model expectations

- 5 times more data to be analyzed