Top quark mass and properties at ATLAS

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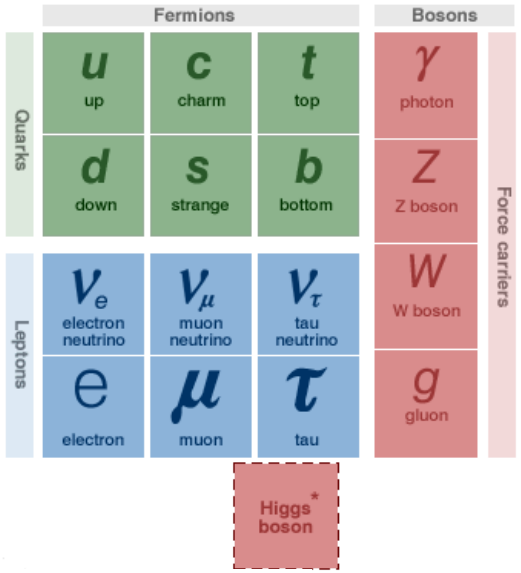
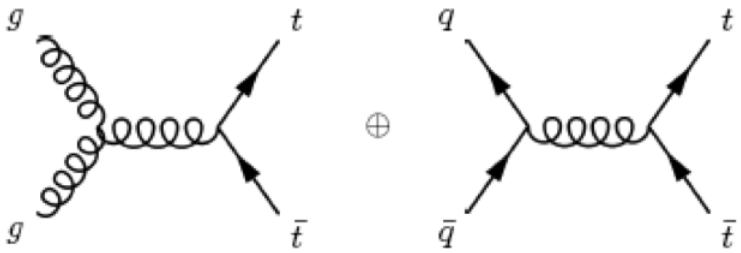
14th April 2011, Deep Inelastic Scattering 2011
Newport News, VA, USA

Top quark

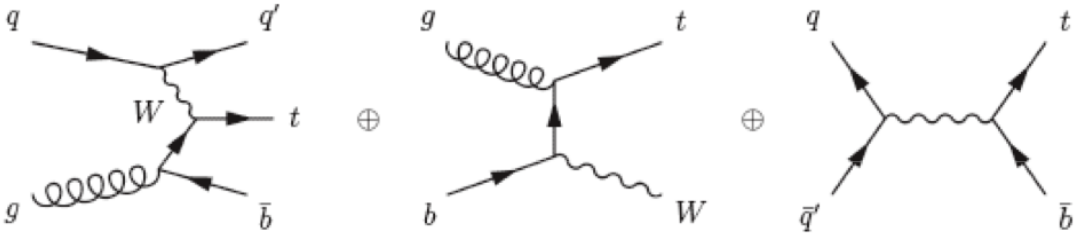
- First observed in 1995 by CDF and DØ (Tevatron);
  [F Abe et al,PRL,74:2626-2631,1995; S. Abachi et al,PRL,74:2632-2637,1995]
- Completes the 3 family structure of SM;
- Mass $\sim 173.3 \pm 1.1$ GeV [arXiv:1007.3178];
- Electric charge = 2/3|e|, Spin = 1/2;
- Fast decay: $\tau \sim 4 \times 10^{-25}$ s, Γ = 1.42 GeV;
- Dominant decay to $t \to Wb$:
  $|V_{\rm tb}| > 0.999 \Rightarrow \mathrm{BR}(t \to Wb) \sim 1$
- Production mechanisms at the LHC:
  - top pair production:





$\sigma(pp \to t\bar{t}) \sim 165\,^{+11}_{-16}$ pb [Phys. Rev. D78 (2008) 034003]

  - single top production:



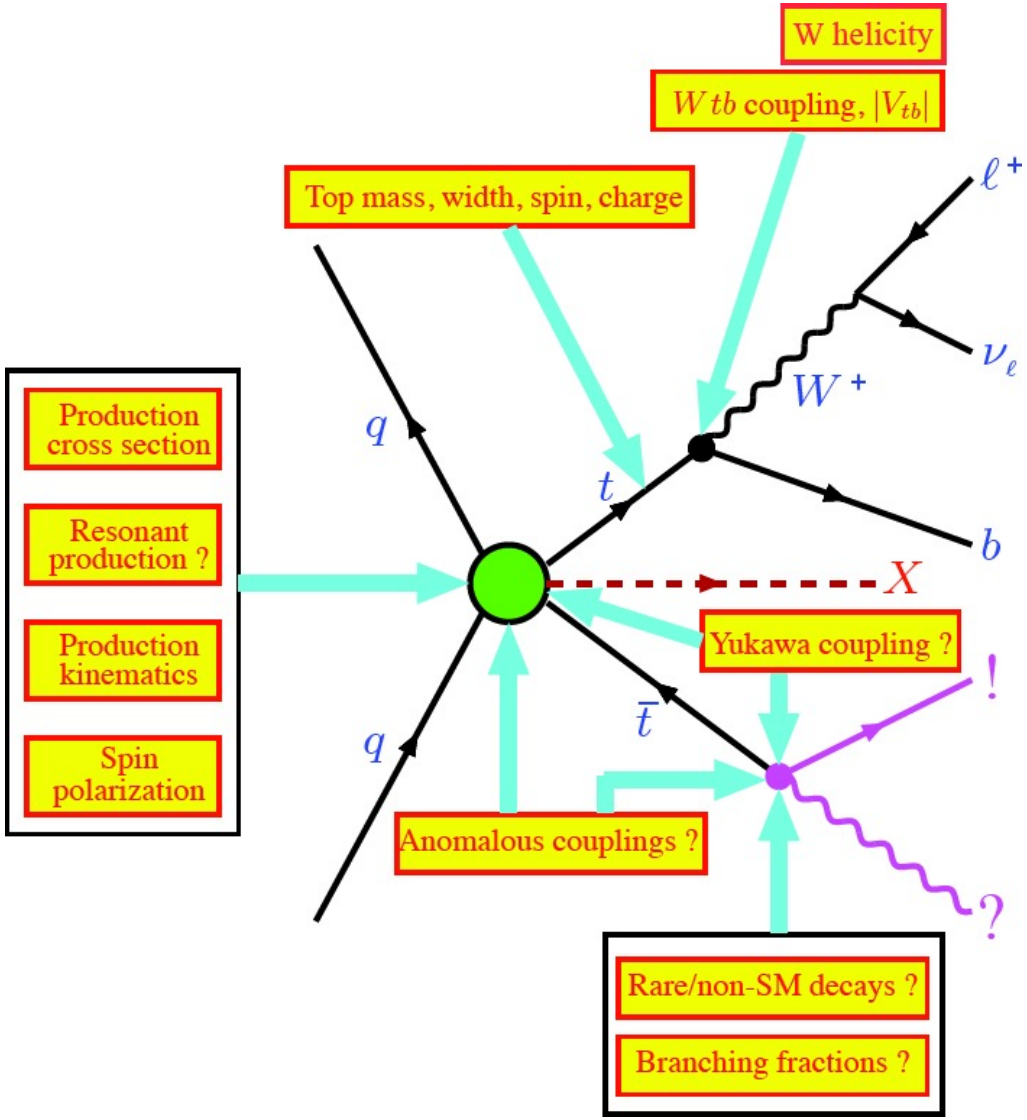
$\sigma \sim 66$ pb $\quad \sigma \sim 15$ pb $\quad \sigma \sim 4$ pb

Phys. Rev. **D83** (2011) 034019
hep-ph/0305252 (2002)
hep-ph/0204244 (2002)

Why the Top quark @ LHC ?

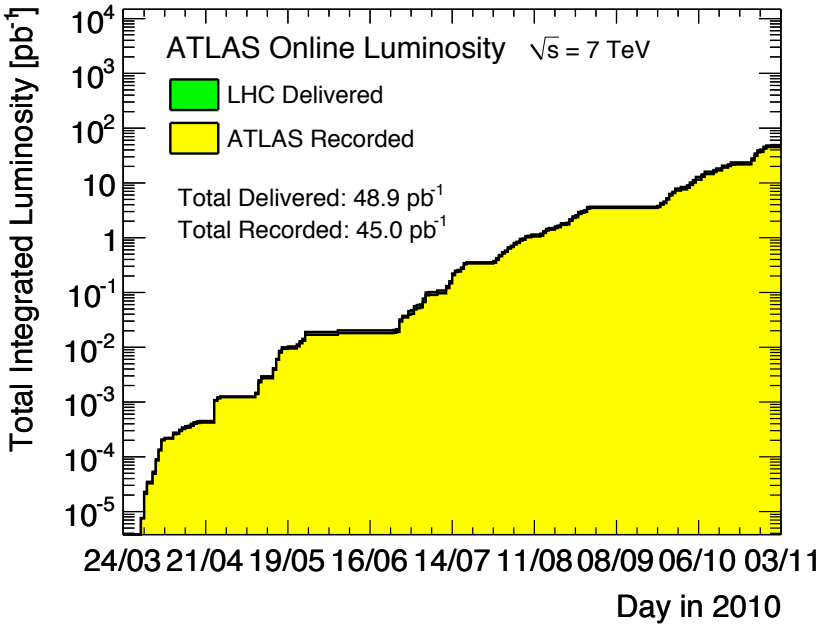
☞ It has a rich phenomenology

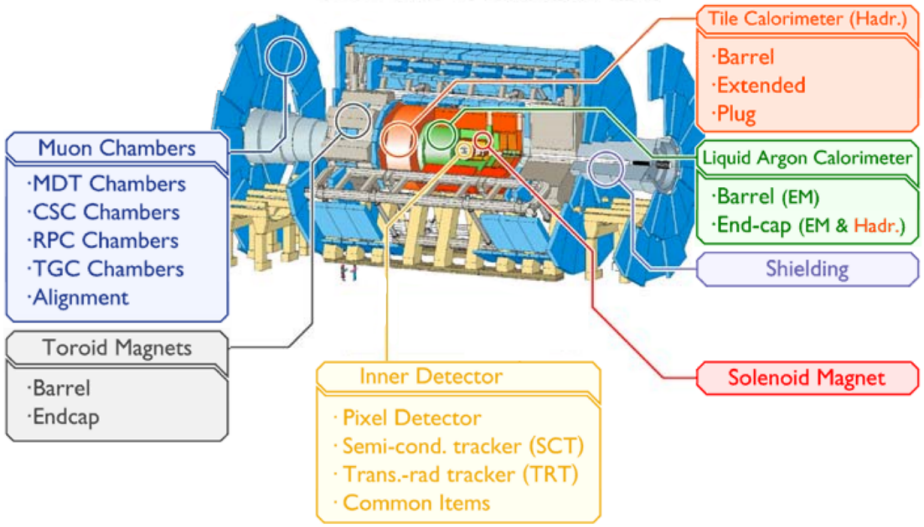
- $t\bar{t}$ production
  - $\sigma_{t\bar{t}}$
  - Mass
  - Charge
  - FCNC
  - $t\bar{t}$ resonances
  - W polarization
  - Anomalous couplings
  - $t\bar{t}$ Spin correlations
- Single top production
  - cross section
  - FCNC
  - polarization



ATLAS detector – Current status

- 45 pb^{-1} of data recorded in 2010;
- Single lepton triggers $\approx$ 35 pb^{-1};
- Maximum instantaneous luminosity exceeded $2 \times 10^{-32} cm^{-2}\ s^{-1}$;
- Very good data-taking efficiency in ATLAS, and very high fraction of good quality data;
- 2011 data-taking in progress: 25.9 pb^{-1} of data recorded.



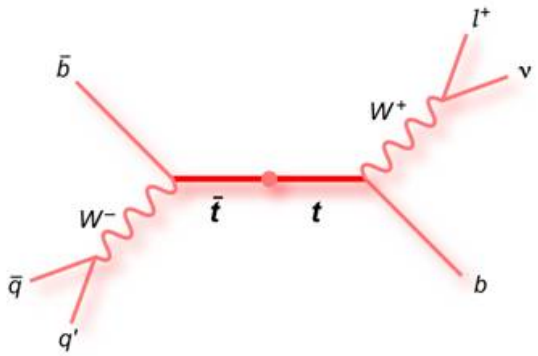


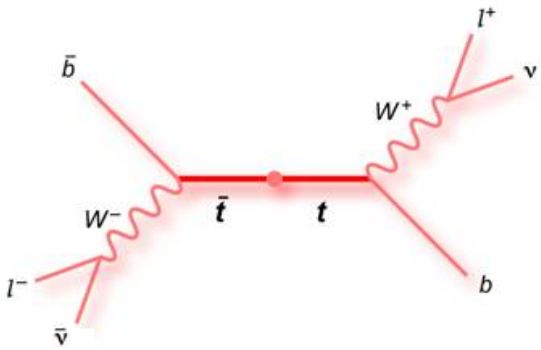
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

General $t\bar{t}$ selection

- **Cosmics, pile-up rejection:** $>$ 4 tracks from primary vertex
- **Trigger:** Single lepton trigger (electron or muon)
- **Leptons:** isolated electron or muon, $p_{\mathrm{T}} > 20$ GeV
- **Jets:** anti-k_t, R = 0.4, $|\eta| < 2.5$





semileptonic

- 1 lepton
- $\geq$ 4 jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$
- e: $\not{E}_T > 35 GeV$ and $m_T(W) > 25$ GeV
- μ: $\not{E}_T > 20 GeV, \not{E}_T + m_T(W) > 60$ GeV
- At least one jet is required to be b-tagged

dileptonic

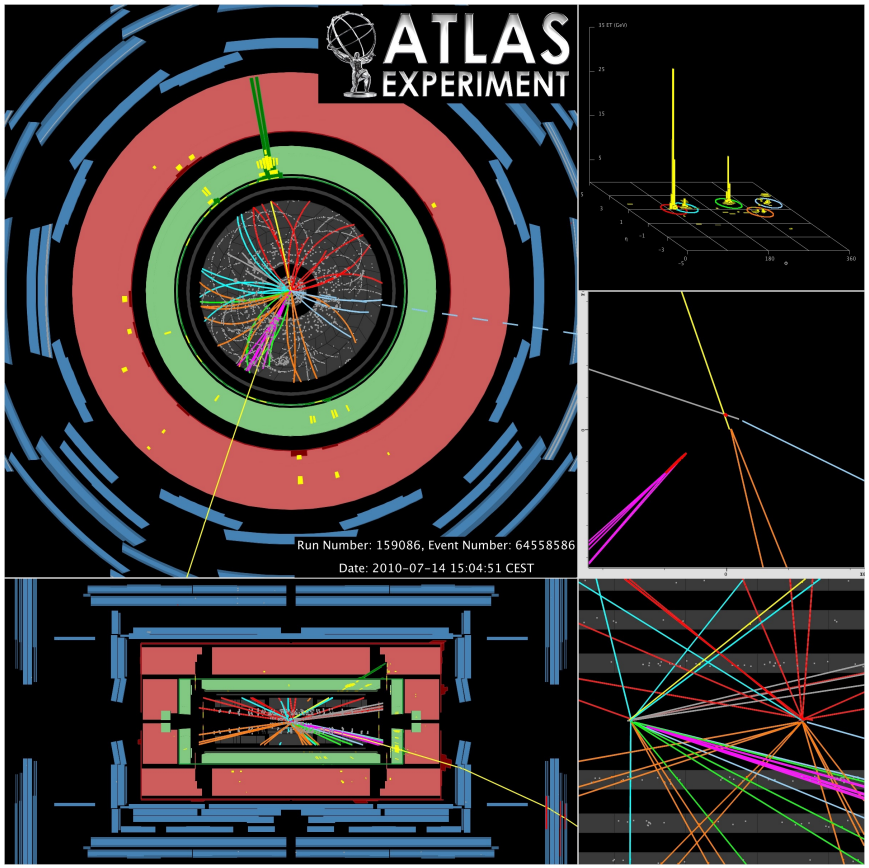
- 2 leptons with opposite charge
- $\geq$ 2 jets with $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$
- $ee/\mu\mu$: $|M_{ll} - M_Z| < 10$ GeV, $\not{E}_T > 40$ GeV
- $e\mu$: $H_T > 130$ GeV
- No b-tag requirement

- $t\bar{t}$ signal generated with NLO generator MC@NLO v3.41 and using NLO parton density function (PDF) set CTEQ66.
- Background model is a combination of data-driven methods (QCD, W/Z+jets) and MC events (diboson/singletop/$\tau^+\tau^-$) depending on each analysis.
- Signal templates for W helicity studies were generated with `PROTOS` generator.

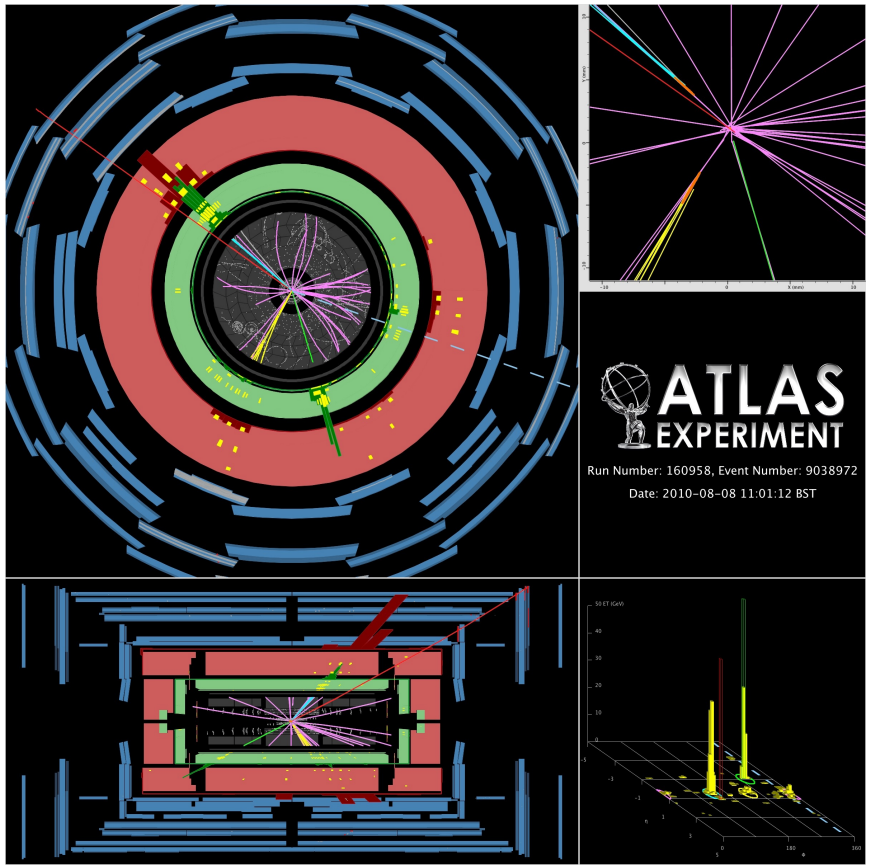
$t\bar{t}$ semi and dileptonic events

☞ top candidates seen in ATLAS:

semileptonic e+jets w/btag



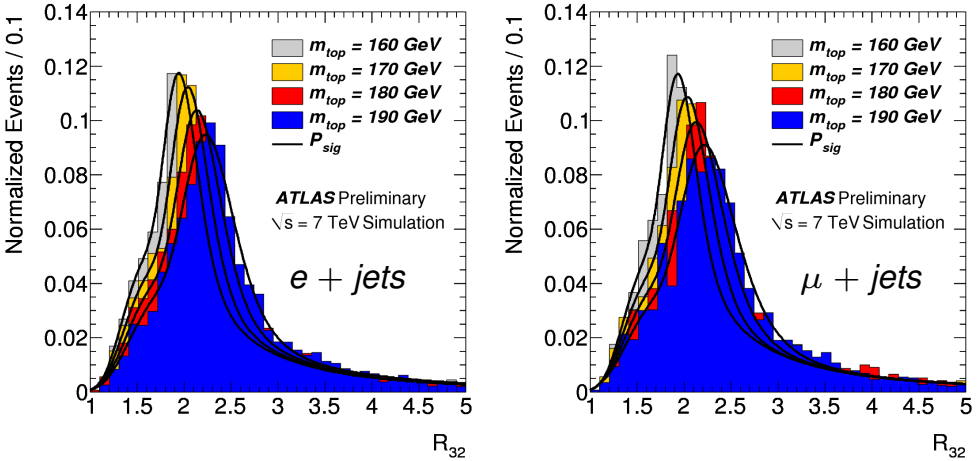
dileptonic $e\mu$+jets w/2 btag



Top quark mass

- 3 complementary methods developed to reduce JES uncertainty on top mass measurement.
- The 1D template analysis to measure the top quark mass is based on the ratio:

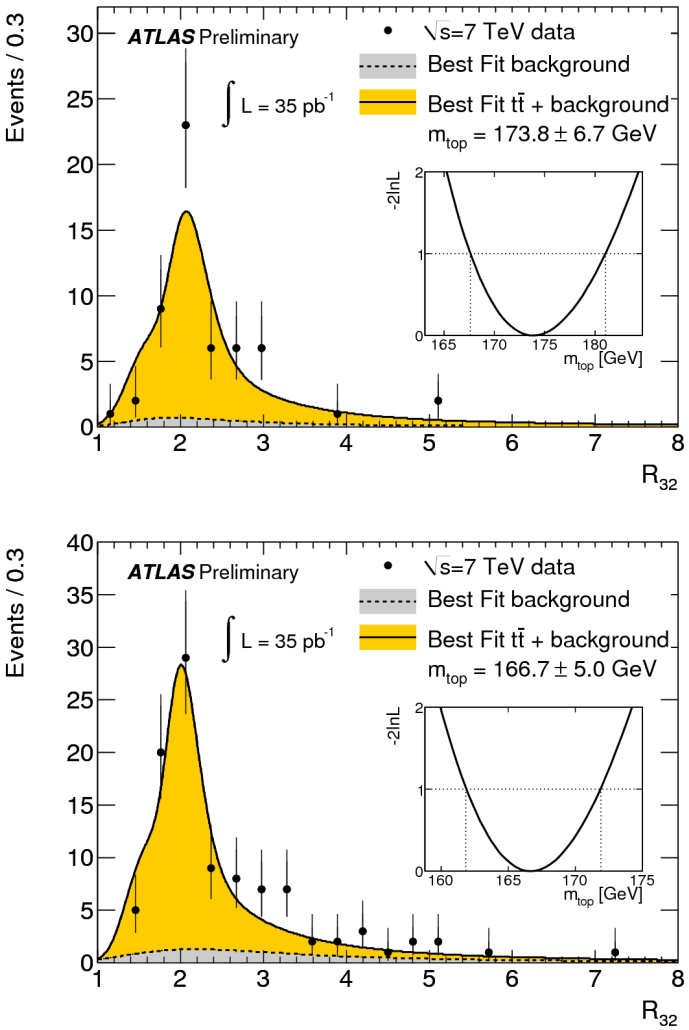
$$R_{32} = \frac{m_{top}^{reco}}{m_W^{reco}} = \frac{m_{jjb}}{m_{jj}} \text{ (low sensitivity to JES)}$$



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

Dominant systematics

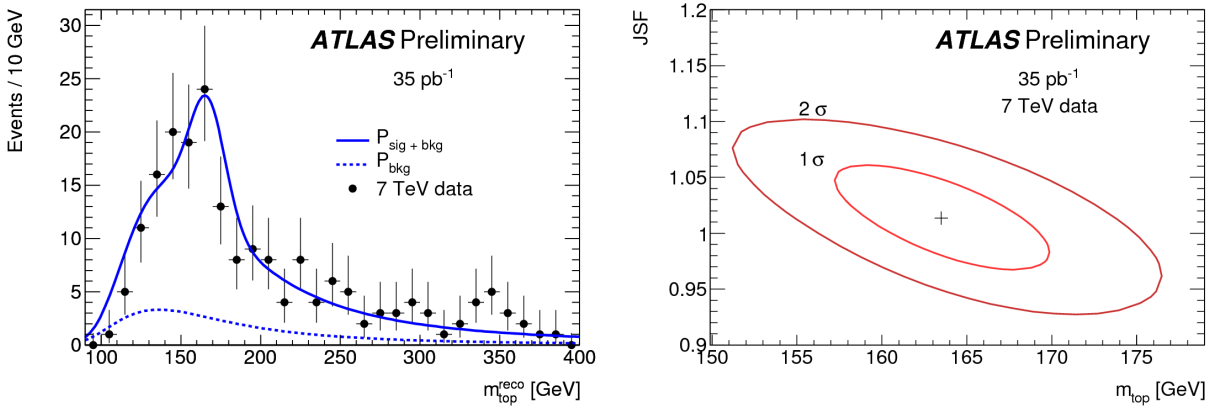
	Uncertainty [GeV]	
	Electron channel	Muon channel
Statistical uncertainty	6.7	5.0
ISR and FSR (signal only)	2.2	2.6
Jet energy scale ($\pm 1\sigma$) plus 5% for close by jets	2.3	1.9
b-jet energy scale ($\pm 2.5\%$)	2.5	2.5
Total systematic uncertainty	4.8	5.0



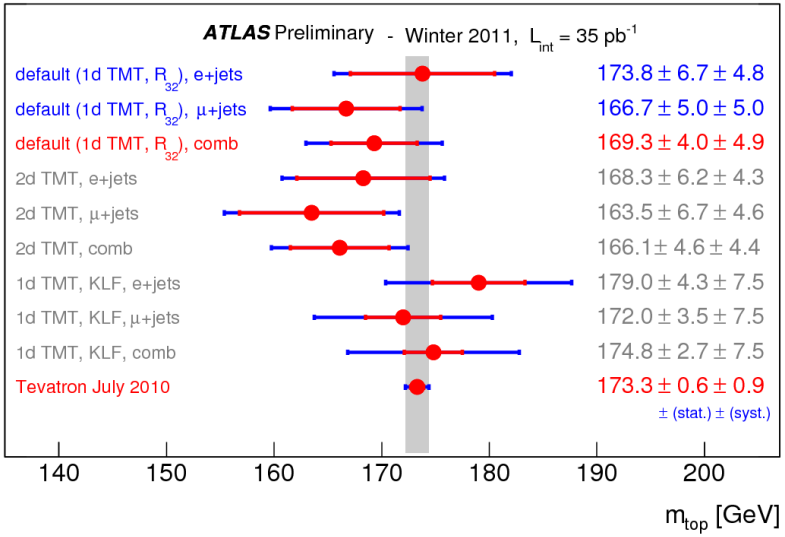
Top quark mass

- The 2-dimensional JSF template analysis complements and cross-checks the top quark mass measurement:

$$m_{top} = 166.1 \pm 4.6(stat) \pm 4.4(sys) \text{ GeV}$$

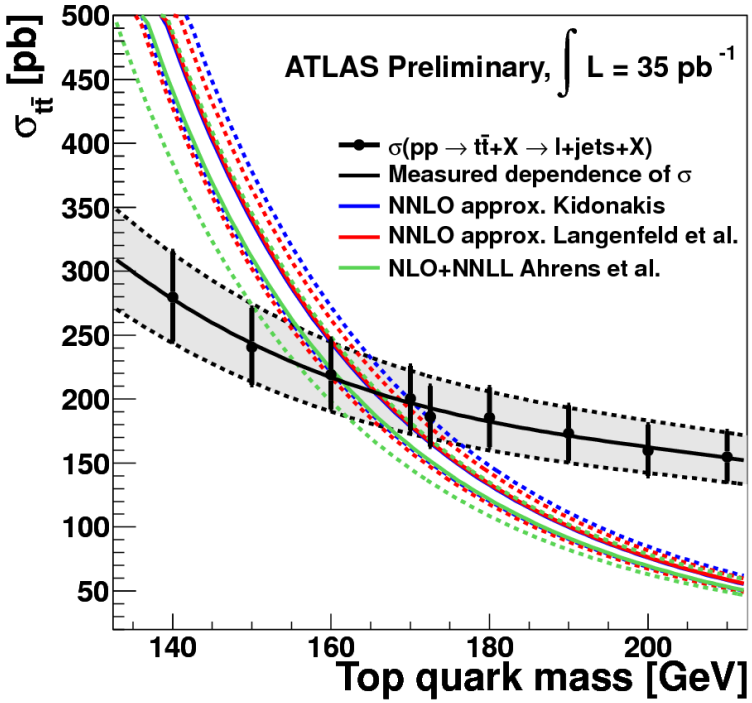


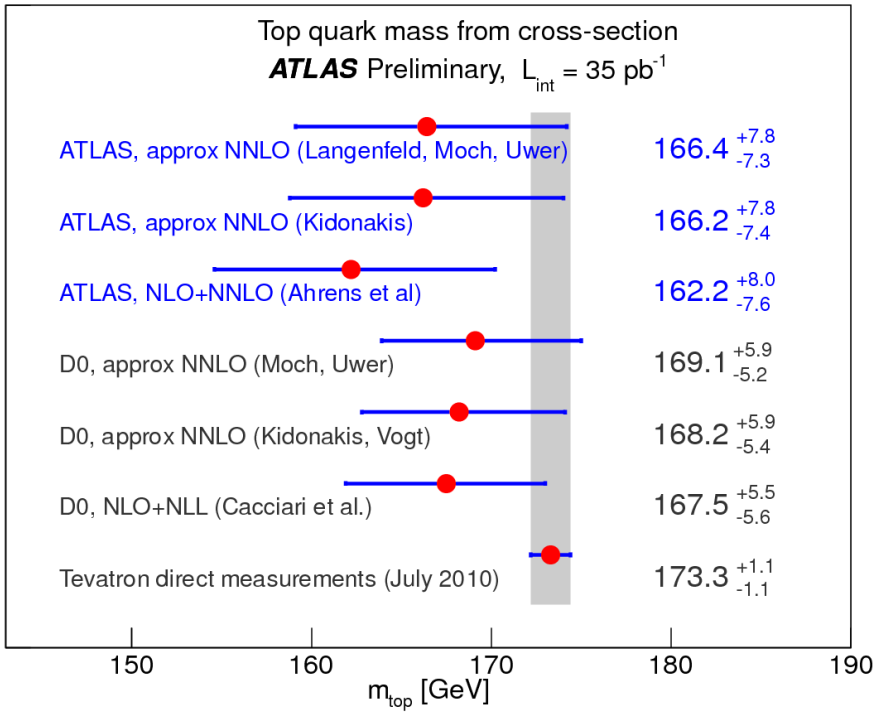
- Summary of top quark mass measurements with different methods:



Top quark mass

- Top quark mass from the $t\bar{t}$ cross section measurement.
- Top quark mass is unambiguously defined as the pole mass and x-sec inferred from higher-order perturbative corrections.

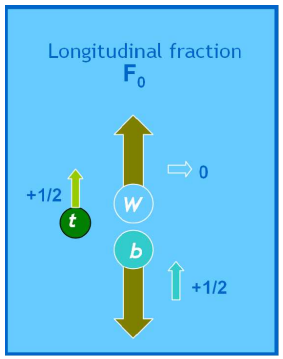


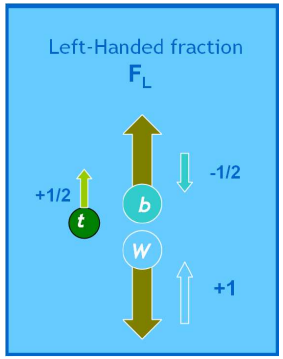


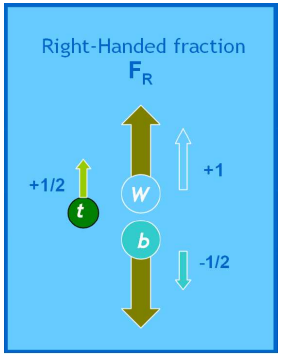
W helicity

testing a SM prediction

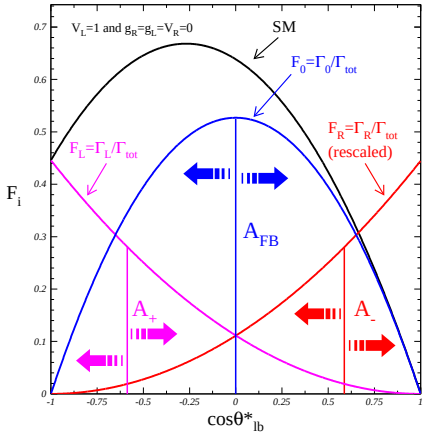
[Phys. Rev. D 45 (1992) 124]

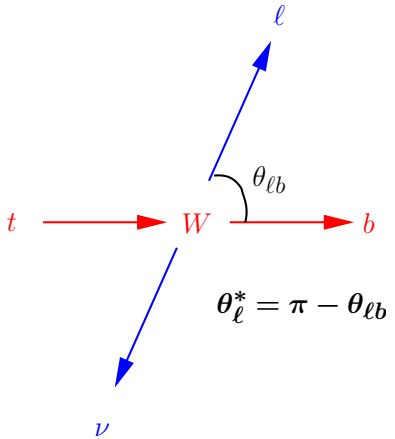






SM: $F_0 = 0.698$ (LO) $F_L = 0.301$ (LO) $F_R = 0.00041$ (LO)



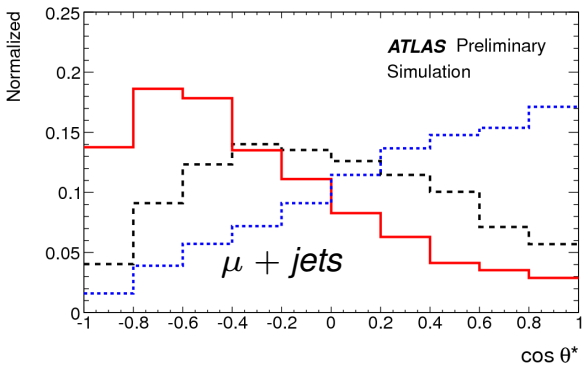


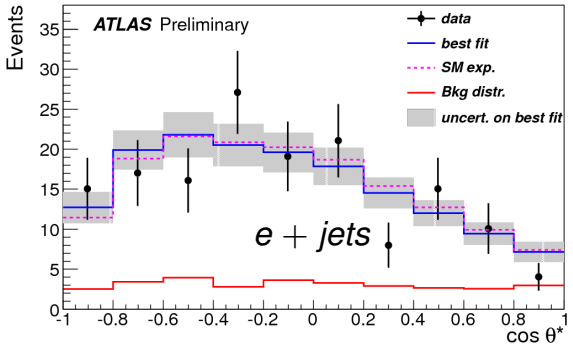
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

$$A_z = \frac{N(\cos\theta^*_\ell > z) - N(\cos\theta^*_\ell < z)}{N(\cos\theta^*_\ell > z) + N(\cos\theta^*_\ell < z)} \quad A_{FB} = -0.227 \quad A_+ = 0.544 \quad A_- = -0.841$$

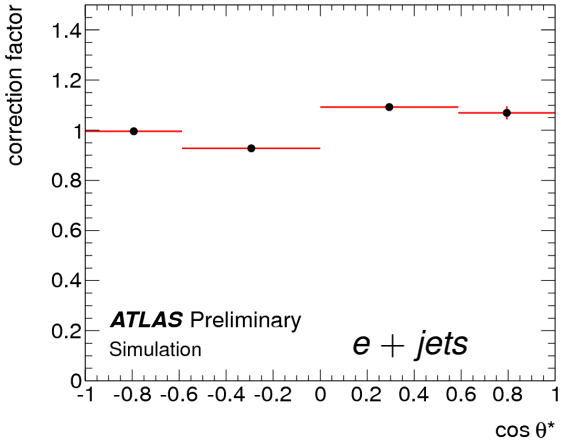
W helicity

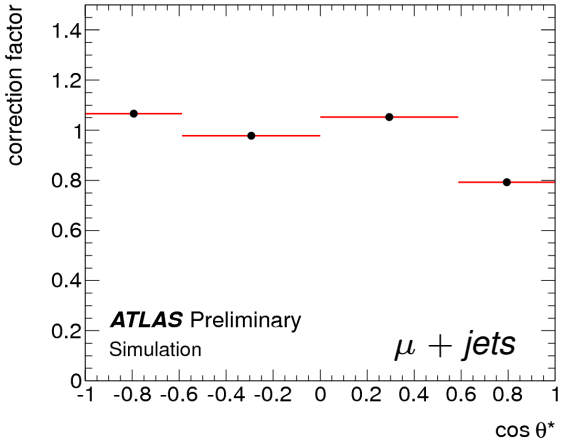
- Templates method:





- Correction function method:





	e+jets	μ+jets	combined
TEMPLATES METHOD			
F_0	0.60 ± 0.20	0.56 ± 0.18	0.59 ± 0.12
F_L	0.40 ± 0.20	0.44 ± 0.18	0.41 ± 0.12
F_R	Fixed to 0	Fixed to 0	Fixed to 0
CORRECTION FUNCTION METHOD			
A_{FB}	-0.30 ± 0.13	-0.29 ± 0.10	-0.29 ± 0.08
A_+	0.50 ± 0.12	0.50 ± 0.09	0.50 ± 0.07
A_-	-0.85 ± 0.09	-0.87 ± 0.05	-0.86 ± 0.04
F_0	0.64 ± 0.27	0.66 ± 0.19	0.65 ± 0.15
F_L	0.36 ± 0.17	0.36 ± 0.12	0.36 ± 0.10
F_R	0.00 ± 0.13	-0.02 ± 0.08	-0.01 ± 0.07

Measurements dominated by stat. uncertainty.

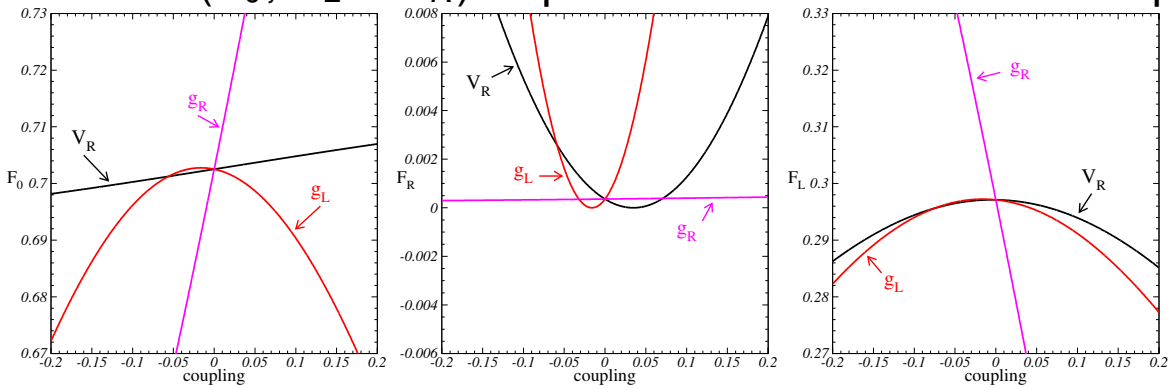
Main systematics:
ISR/FSR; Bkg. model; JES.

W helicity

General Wtb vertex

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-}$$

- W helicity fractions (F_0, F_L e F_R) depend on the anomalous couplings:

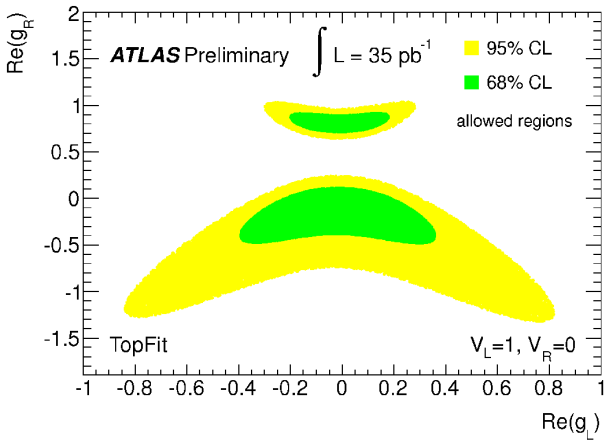


- Allowed regions for Wtb anomalous couplings, obtained w/ A_+ and A_- (`TopFit`):

$$\mathrm{Re}\,(V_R) \in [-0.44, 0.48]$$

$$\mathrm{Re}\,(g_L) \in [-0.24, 0.21]$$

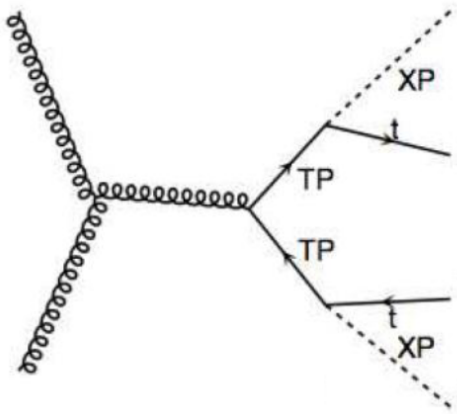
$$\mathrm{Re}\,(g_R) \in [-0.49, 0.15]$$



Nucl. Phys. B 840 (2010) 349, 1005.5382 [hep-ph]; Eur. Phys. J. C 50 (2007) 519, hep-ph/0605190

$t\bar{t}$ + anomalous E_T^{miss}

- Search for anomalous missing transverse energy in a final state with a single lepton and four or more jets.
- Search for a pair-produced top partner (T) decaying to a top quark and a long-lived neutral particle (A_0) which escapes undetected:

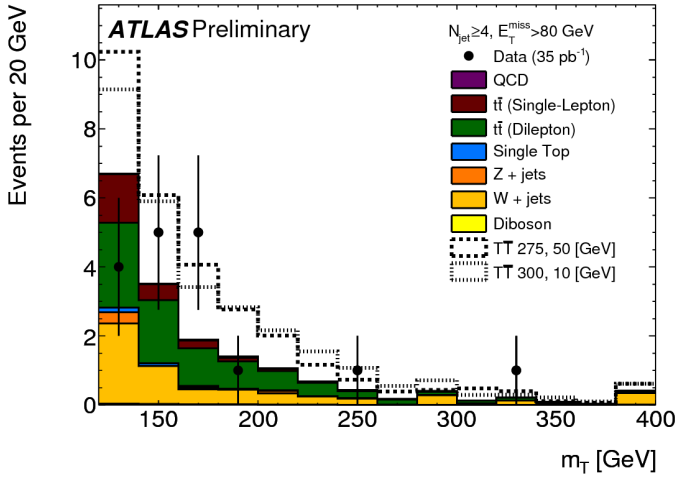


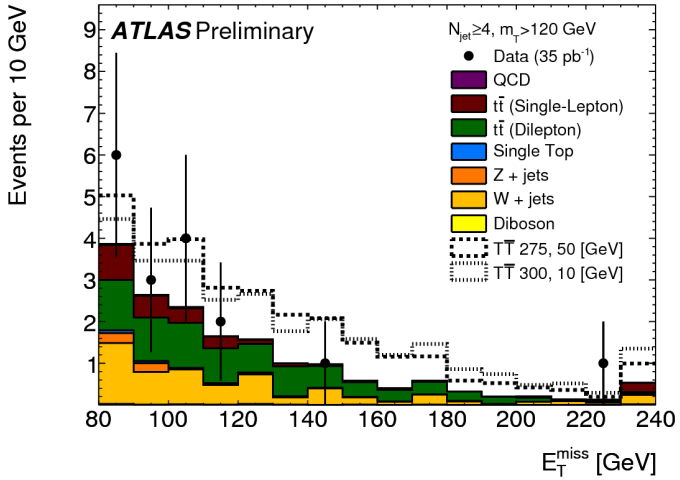
Alwall, Feng, Kumar *et al.* (2010)
Berger, Cao (2009)

- Selection: $E_T^{miss} > 80$ GeV, $m_T > 120$ GeV; dilepton veto: $p_T > 15$ GeV, tracks, loose electrons. $m_T = \sqrt{2p_T^l E_T^{miss}(1 - \cos(\phi^l - \phi^{E_T^{miss}}))}$

$t\bar{t}$ + anomalous E_T^{miss}

- No disagreement between data and SM expectation:





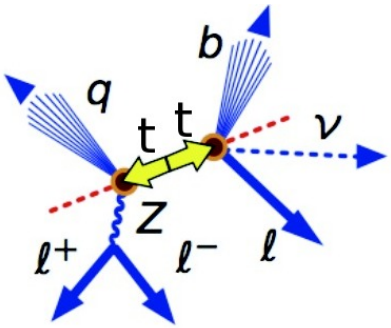
Source	Yield
Single-Lepton $t\bar{t}/W$	8.4 ± 1.6
Dilepton $t\bar{t}$	7.6 ± 2.0
Z+jets	0.4 ± 0.1
Dibosons	$0.2 \pm <0.1$
Single Top	0.4 ± 0.1
QCD	0.2 ± 0.6
Total Background	17.2 ± 2.6
Data	17

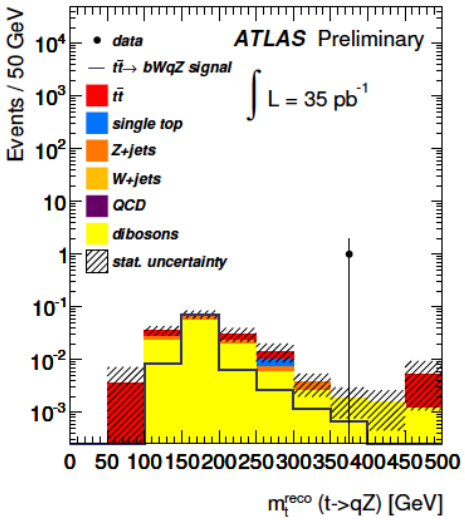
Systematics	Relative Error
Dilepton $t\bar{t}$, Single Top, Dibosons, Z+jets	
Cross Section	15%
Dilepton Veto	15%
Jet Energy Scale & Resolution	11%
Luminosity	3.4%
Lepton ID	3%
Monte Carlo Statistics	1%
Total	25% (2.1 events)
Single Lepton Backgrounds	
Spread in $S(m_T)$	15%
Normalization	10%
b-Tag Veto	3%
QCD Shape	1%
Total	18% (1.6 events)
QCD	
Normalization in Control Regions	100%
Muon Statistics	0.6 events
Total	0.6 events

- $m_T > 300$ GeV ($m_{A_0} = 10$ GeV), $m_T > 275$ GeV ($m_{A_0} = 50$ GeV) exclusion at 95% CL

FCNC

- $t \to qZ$ analysis (cut-based):





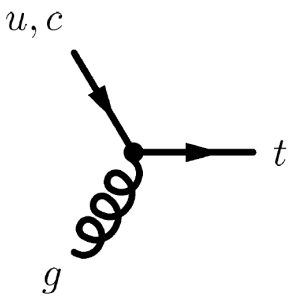
Systematics	e		μ	
	Background	Signal	Background	Signal
Jet energy scale	13%	2%	10%	2%
Electron identification	10%	5%	3%	1%
Pile-up	8%	1%	6%	1%
ISR/FSR	34%	3%	47%	3%
Top quark mass	9%	1%	3%	1%
SM $t\bar{t}$ generator	10%	—	25%	—
SM $t\bar{t}$ fragmentation	26%	—	26%	—
Z+jets cross-section	25%	—	25%	—

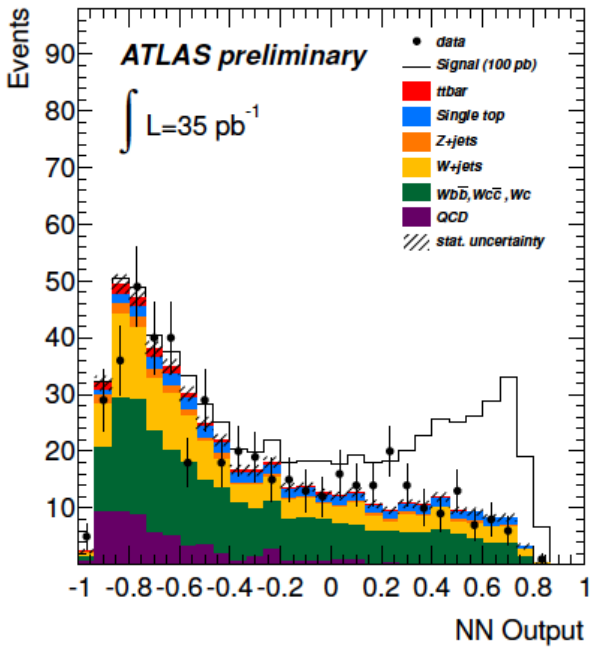
- Upper limits on the FCNC top quark decay BR at 95% CL:

	observed	(-1σ)	expected	$(+1\sigma)$
without systematics	16%	8%	11%	15%
with systematics	17%	9%	12%	16%

FCNC

- $qg \rightarrow t$ analysis (neuronal network):





Systematics	(-1σ)	median	$(+1\sigma)$
Cross section and QCD multijet uncertainties	9.6	13.7	19.7
Luminosity	9.8	13.8	20.0
Jet energy scale	10.2	14.8	21.1
Jet reco. efficiency	9.5	13.7	19.7
Jet energy resolution	9.6	13.9	20.2
b-tagging, mis-tagging	9.6	13.9	19.5
Electron trigger, eff. and ID	9.8	13.9	20.0
Electron energy scale	9.9	14.3	20.0
Electron energy resolution	9.6	14.1	19.9
Muon trigger, eff. and ID	9.3	13.2	19.2
Muon momentum resolution and energy scale	9.7	13.9	19.6
HF fraction	9.6	14.2	20.5
PDF	9.5	13.3	19.4
ISR	11.1	15.7	22.9
FSR	9.5	13.3	19.4
Pile-up	9.7	13.9	19.7
W+jets shape	9.5	13.7	19.8
All systematics	12.0	17.4	25.6

- Upper limits on the FCNC single top quark production at 95% CL:

	expected			observed
	(-1σ)	median	$(+1\sigma)$	
only normalization uncertainties	9.6 pb	13.7 pb	19.7 pb	15.6 pb
with systematics	12.0 pb	17.4 pb	25.6 pb	17.3 pb

Conclusions

- Top quark mass measurement compatible with the world average:

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

- Helicity fractions and angular asymmetries measurements are consistent with SM values.

	Template method	Asymmetry method
F_L	0.41 ± 0.12	0.36 ± 0.10
F_0	0.59 ± 0.12	0.65 ± 0.15
F_R	Fixed 0	-0.01 ± 0.07

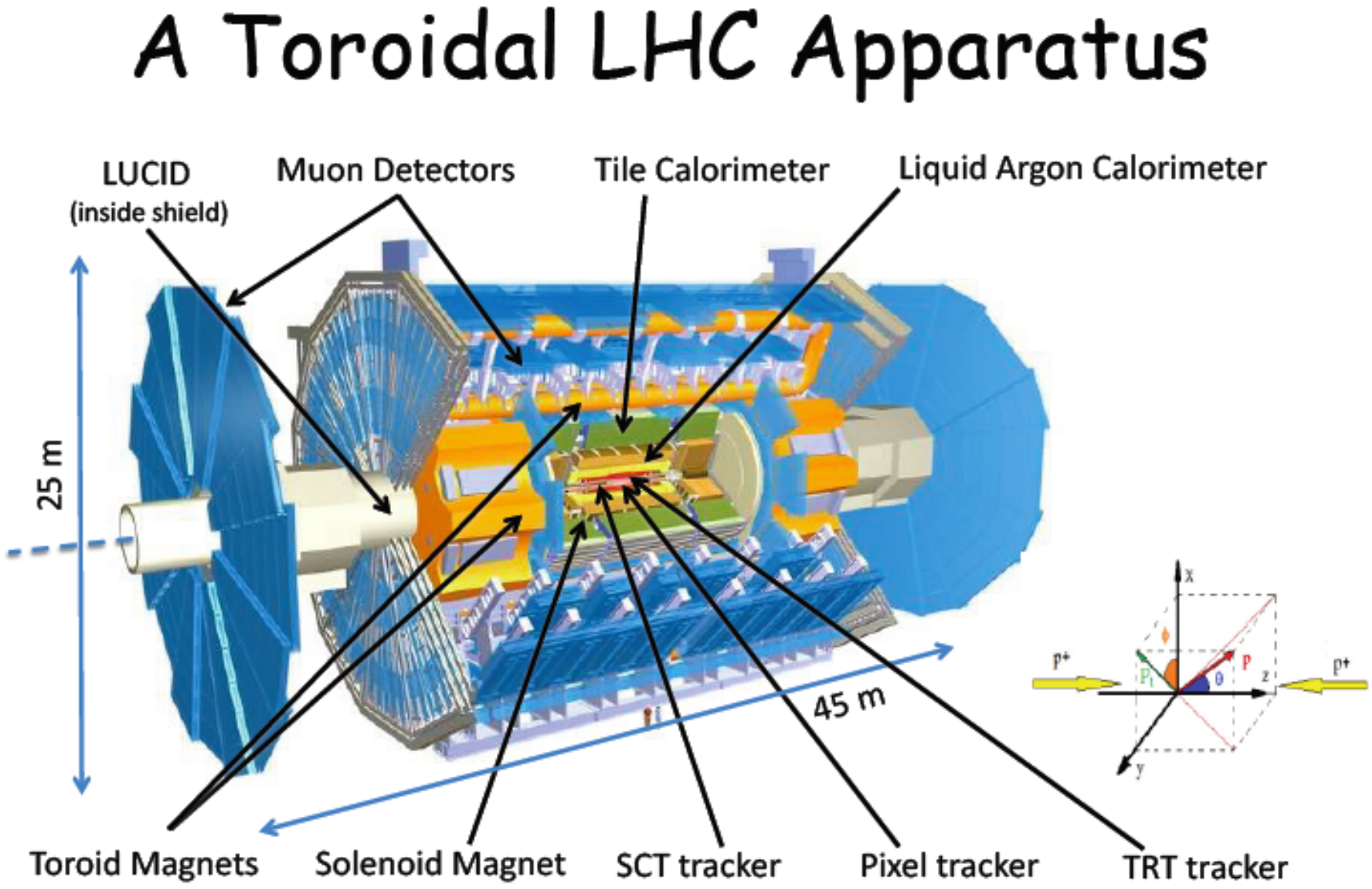
$$\mathrm{Re}\,(V_R) \in [-0.44, 0.48]$$

$$\mathrm{Re}\,(g_L) \in [-0.24, 0.21]$$

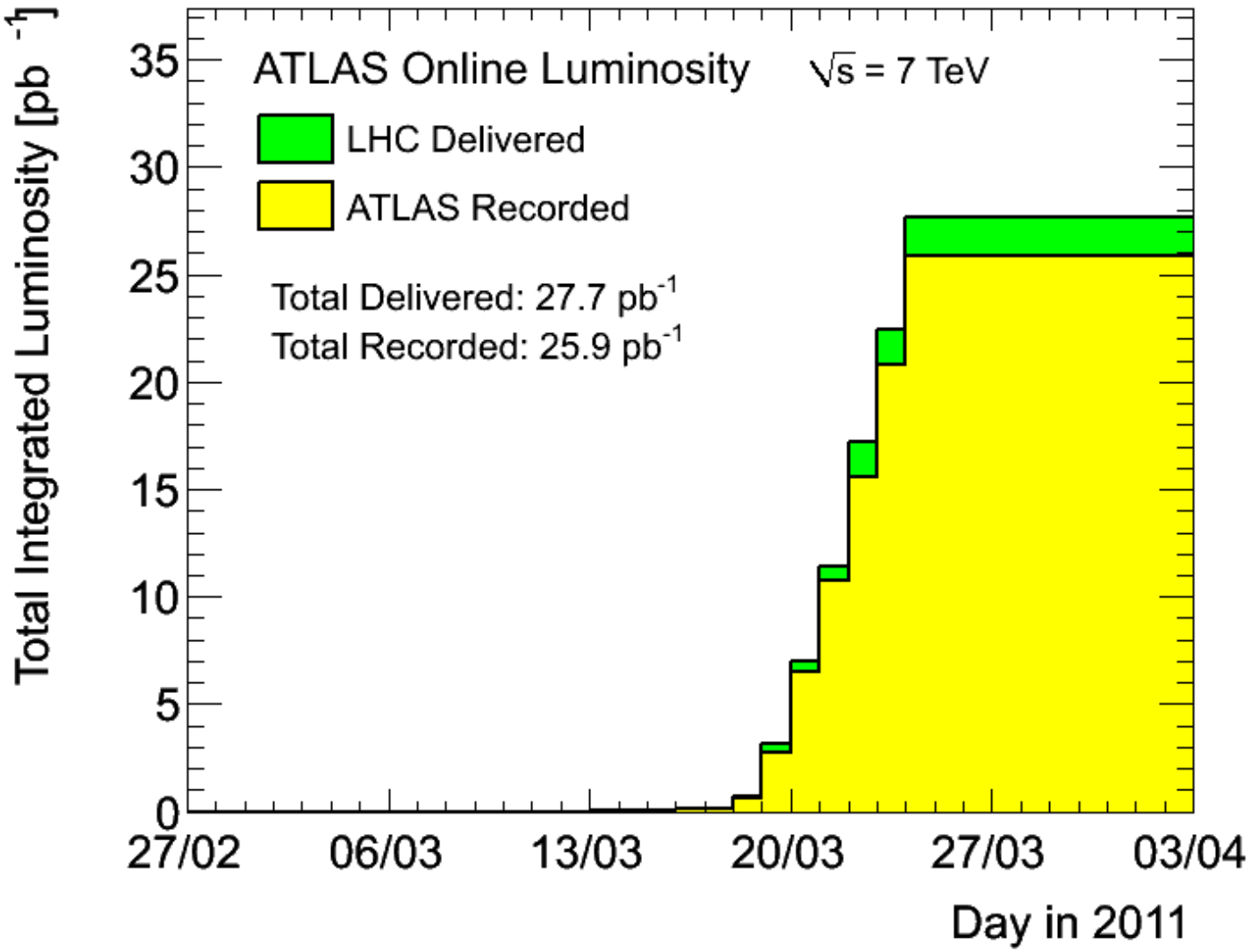
$$\mathrm{Re}\,(g_R) \in [-0.49, 0.15]$$

- No evidence was found of $t\bar{t}$ events with anomalous E_T^{miss} above those predicted by the Standard Model. Exclusion limits at 95 % CL were set for m_T (as a funtion of m_{A_0}).
- No evidence was found for FCNC processes. Limits were set at 95 % CL.
- The era of top quark precision measurements at LHC has started:
  - The increase on statistics predicted for 2011 will improve the measurements.
  - Improved detector understanding and advanced analysis techniques will reduce systematics.

BACKUP — ATLAS DETECTOR



BACKUP — Luminosity 2011



BACKUP — Systematics top mass 1D template analysis

	Uncertainty [GeV]	
	Electron channel	Muon channel
Statistical uncertainty	6.7	5.0
Method calibration	0.7	0.5
Signal MC generator(POWHEG vs. MC@NLO)	0.7	0.6
Hadronization POWHEG (PYTHIA vs. HERWIG)	1.0	0.5
Pileup	0.6	0.8
ISR and FSR (signal only)	2.2	2.6
Proton PDF	0.6	0.5
W/Z+jets background normalization ($\pm 100\%$)	1.3	1.7
W/Z+jets background shape	0.6	1.0
QCD background normalization ($\pm 100\%$)	0.8	0.7
QCD background shape	0.6	0.5
Jet energy scale ($\pm 1\sigma$) plus 5% for close by jets	2.3	1.9
b-jet energy scale ($\pm 2.5\%$)	2.5	2.5
b-tagging efficiency and mistag rate	0.6	0.5
Jet energy resolution	0.6	1.1
Jet reconstruction efficiency ($\pm 2\%$)	0.6	0.5
Total systematic uncertainty	4.8	5.0