Top quark physics

- Experimental results from ATLAS -

CORFU 2014, September 8th 2014

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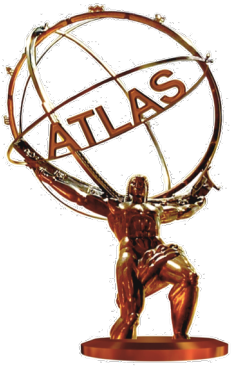
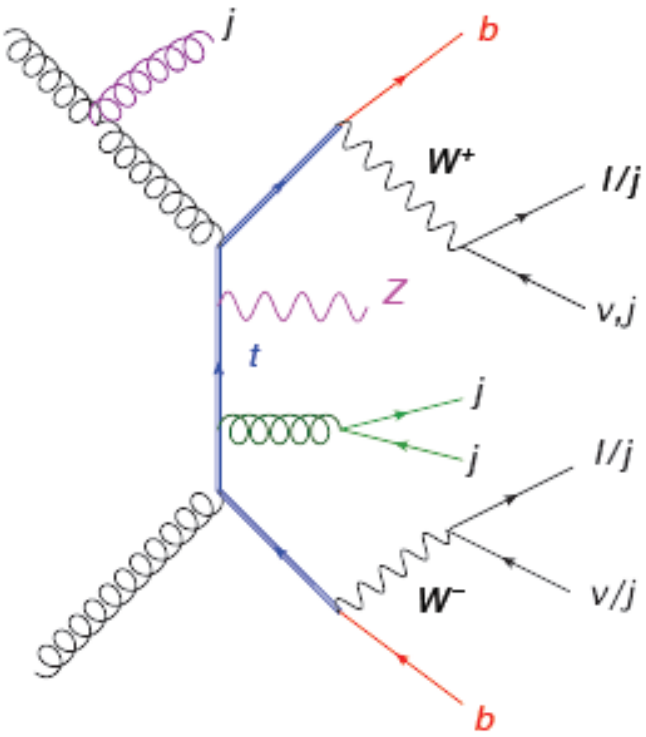


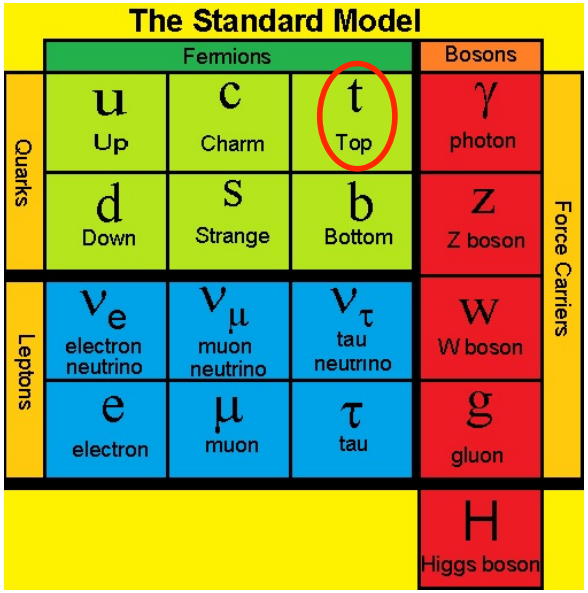
Outline

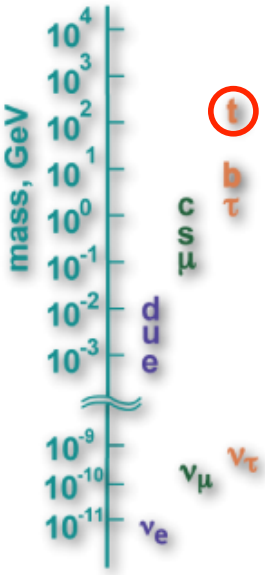
- The top quark in the Standard Model of Particle Physics
- Top quark physics in ATLAS (summary of Run I results)
  - Top production: inclusive and differential production cross-section
    - Top quark pairs
    - Single top production
  - Top quark properties:
    - Mass
    - Spin correlations
    - Charge asymmetries
    - Couplings:
      - Constraints on the *Wtb* vertex (*W* polarisation)
      - *tt*+*Z*/*W*



TOP QUARK IN THE STANDARD MODEL

The top quark





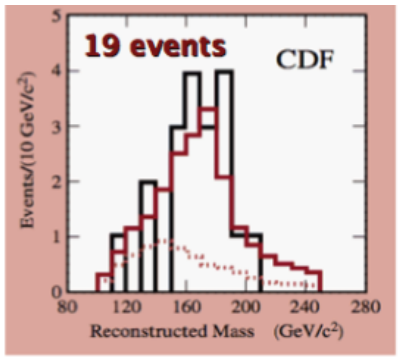
- Completes the 3 family structure of SM
- Electric charge = 2/3|e|
- Spin = 1/2, Isospin (T_3) = +1/2
- Mass ~173.34 ± 0.76 GeV
- Fast decay: $\tau \sim 4 \cdot 10^{-25}$ s, Γ = 1.42 GeV
- Dominant decay to $t \rightarrow Wb$:

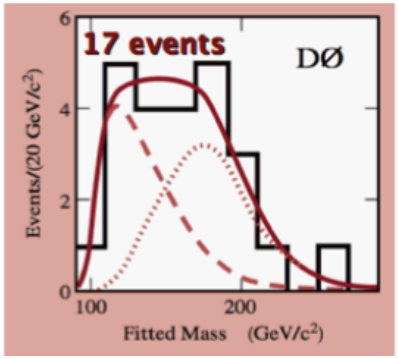
  $|V_{tb}| > 0.999$ ➔ BR($t \rightarrow Wb$) ~100%

  BR($t \rightarrow Ws$) ≤0.18%

  BR($t \rightarrow Wd$) ≤0.02%

Top quark discovery in 1995 by CDF and D0 at Tevatron (Fermilab)



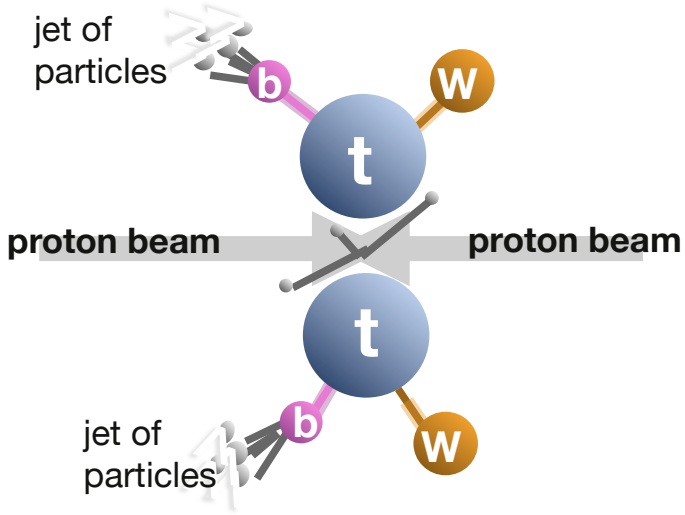


F. Abe *et al*. (CDF collaboration), PRL 74:2626-2631 (1995)
S. Abachi *et al*. (D0 collaboration),PRL 74:2632-2637 (1995)

Why is the top quark so important?

The top quark is the **heaviest fundamental particle**, leading to unique properties from both the theoretical and experimental sides:

- Yukawa coupling almost unity
- can play an important role in the observations related to the electroweak symmetry breaking
- short lifetime ➔ decays before hadronising ➔ properties studied through its decay products
- sensitive to new physics in production and decay

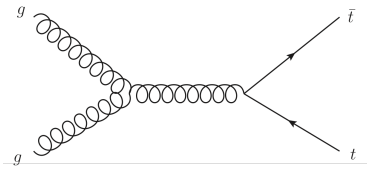


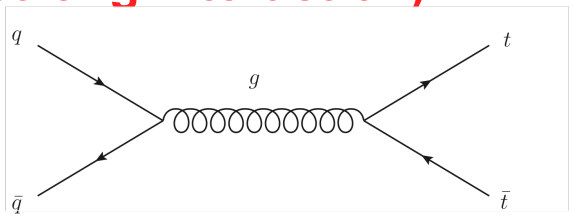
Deviation of the measured top quark properties from the SM predictions would be a signal of new physics.

After ~20 years, top physics has entered the precision era!

Top quark production

Top pair production (strong interaction)





gluon fusion **quark-antiquark annihilation**

$\sigma(\sqrt{s}=7\ \text{TeV}) = 177.3 \pm 9.0^{+4.6}_{-6.0}\ \text{pb}$

$\sigma(\sqrt{s}=8\ \text{TeV}) = 252.9 \pm 11.7^{+6.4}_{-8.6}\ \text{pb}$

@ NNLO + NNLL
m_{top} = 172.5 GeV

Czakon *et al.*, PRL 110 252004 (2013)

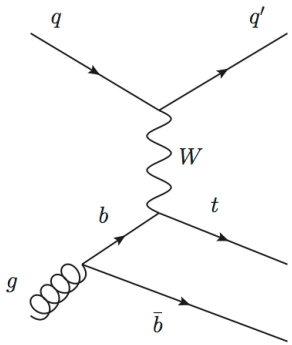
Long standing theoretical effort

JHEP 0910 (2009) 042
Kidonakis, PRD 83, 091503 (2011)
Kidonakis, PRD 82, 054018 (2010)
Kidonakis, PRD 81, 054028 (2010)

Single top production (electroweak interaction)

@ NLO + NNLL
m_{top} = 172.5 GeV

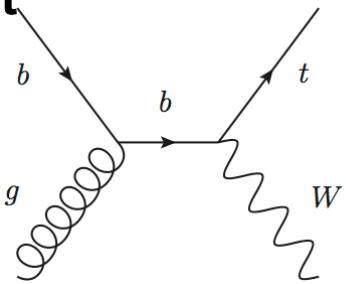
t-channel



$\sigma(\sqrt{s}=7\ \text{TeV}) = 64.57^{+2.63}_{-1.74}\ \text{pb}$

$\sigma(\sqrt{s}=8\ \text{TeV}) = 87.76^{+3.44}_{-1.91}\ \text{pb}$

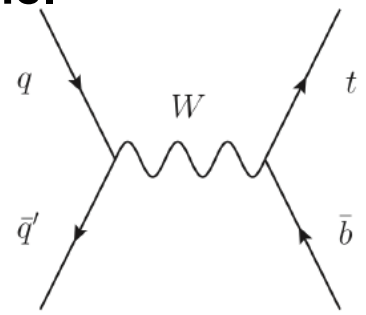
Wt



$\sigma(\sqrt{s}=7\ \text{TeV}) = 15.74^{+1.17}_{-1.21}\ \text{pb}$

$\sigma(\sqrt{s}=8\ \text{TeV}) = 22.37^{+1.52}_{-1.52}\ \text{pb}$

s-channel



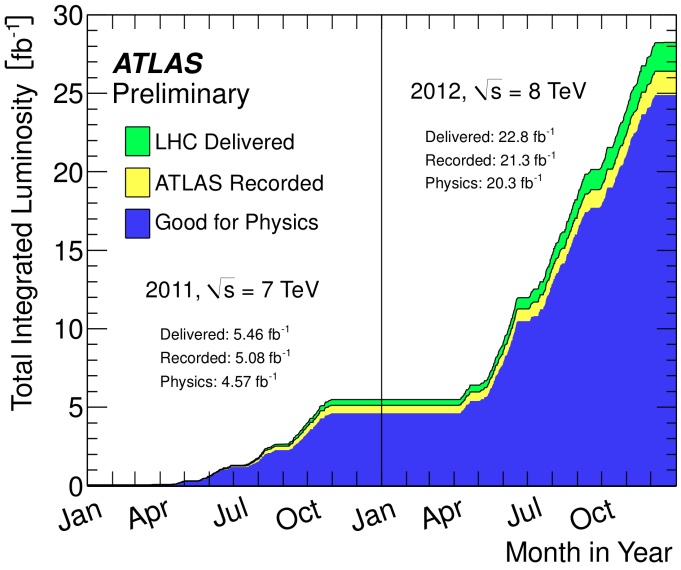
$\sigma(\sqrt{s}=7\ \text{TeV}) = 4.63^{+0.20}_{-0.18}\ \text{pb}$

$\sigma(\sqrt{s}=8\ \text{TeV}) = 5.61^{+0.22-}_{0.22}\ \text{pb}$

Top quark production at the LHC

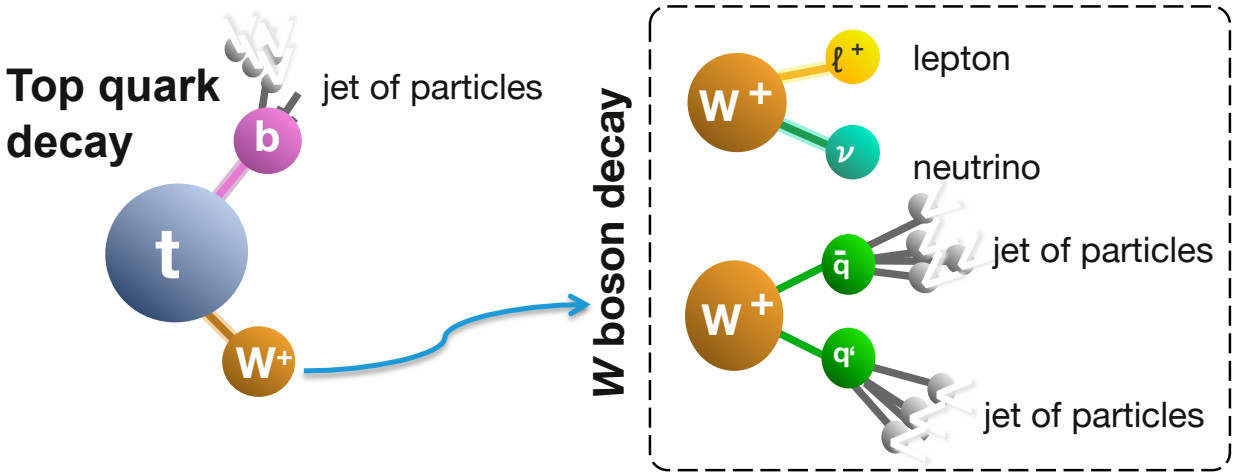
LHC run I phase (2010-2012):

- in 2010 → $\sqrt{s}$ = 7 TeV, L~45 pb^{-1}
- in 2011 → $\sqrt{s}$ = 7 TeV, L~5 fb^{-1}
- in 2012 → $\sqrt{s}$ = 8 TeV, L~21 fb^{-1}



At peak instantaneous luminosity,
~2 top pairs/sec
~1 single top/sec
were produced in ATLAS during 2012 data-taking!
➔ Overall ~15M top quarks produced in 2011 & 2012!

Top quark decay



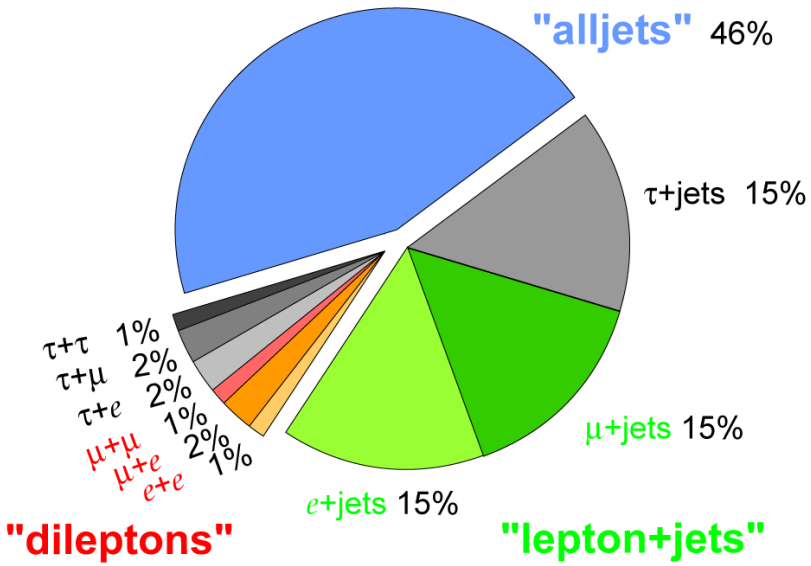
Different sub-channels depending on *W* decay

A) Dilepton
- Final state: 2 leptons, 2 *b*-jets and 2 neutrinos
- Low branching ratio, small backgrounds

B) All hadronic
- Final state: 4 jets (2 *b*-jets)
- Higher branching ratio, large backgrounds (QCD)

C) Lepton+jets
- Final state: 1 lepton, 4 jets (2 *b*-jets) and 1 neutrino
- Reasonable branching ratio, moderate backgrounds

Top Pair Branching Fractions



Final state objects

The reconstruction of top quark events (i.e. all its final state objects: electrons, muons, jets, E_T^{miss} and *b*-tagging) requires information from all the ATLAS subdetectors
➔ A proper/precise understanding of the detector is required.

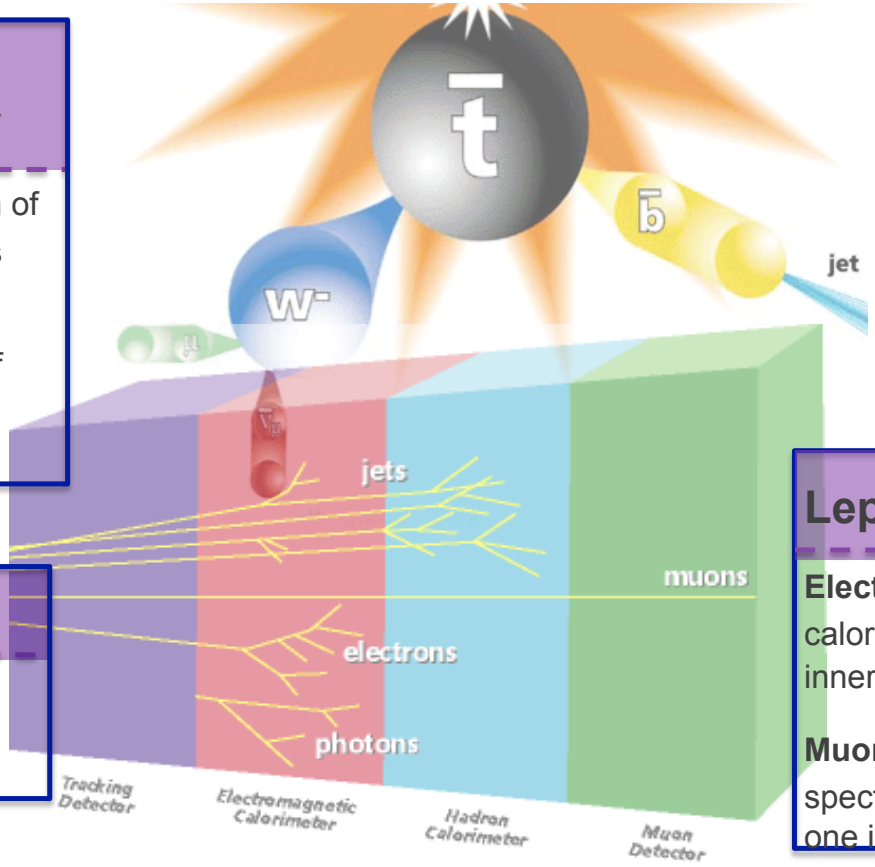
Missing transverse energy

Measure of the momentum of weakly interacting particles (as neutrinos).

Calculated from the sum of all energy deposits in the calorimeters.

b-jets

Originating from the hadronization of b-quarks.



Jets

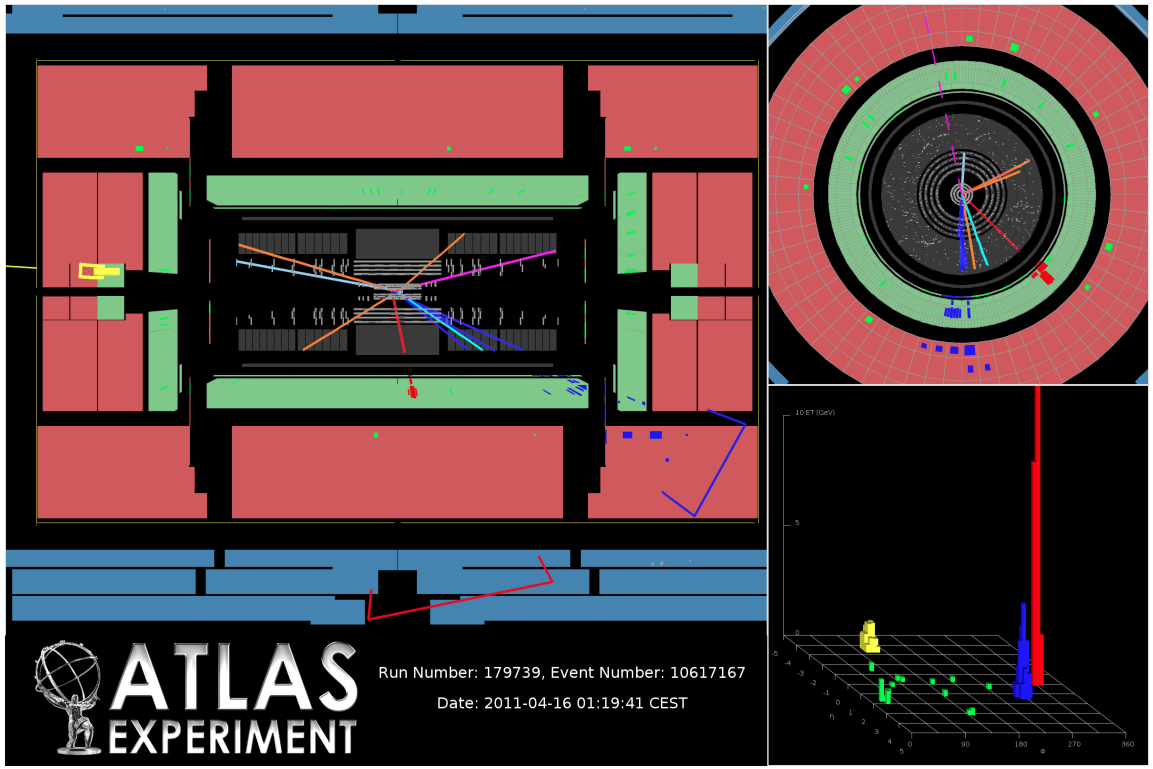
Reconstructed using the information of the calorimeters.

Leptons

Electrons: energy deposits in the calorimeter matched to a track in the inner detector.

Muons: track in the muon spectrometer combined with another one in the inner detector.

TOP QUARK PHYSICS IN ATLAS



Cross-section measurements

Top quark pairs

- dilepton inclusive cross-section
- lepton+jets differential cross-section

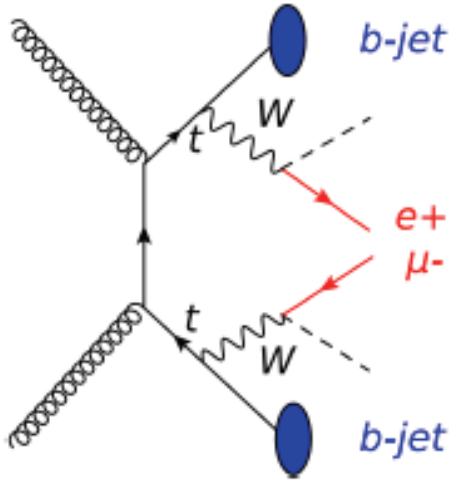
➔ Summary different channels

Single top quark production

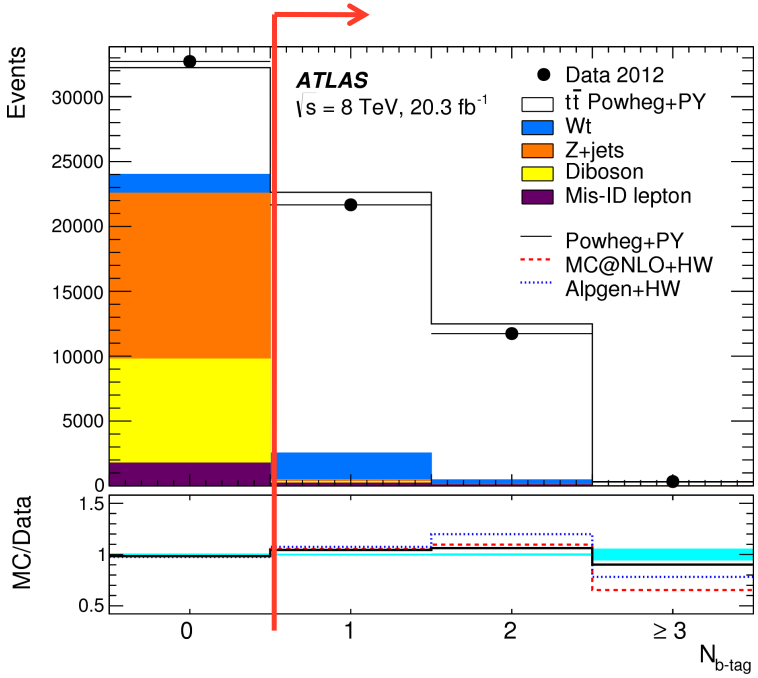
- t-channel at 7 TeV (inclusive and differential cross-section, top and antitop ratio)
- t-channel at 8 TeV (inclusive and fiducial cross-section)

➔ Summary different channels

ttbar inclusive cross-section: dilepton



arXiv:1406.5375



- Measurement at 7 and 8 TeV
- Event selection: $e+\mu$ OS final state, >= 1 *b*-jet
- Simultaneously determine: σ_{tt} and ε_b
- Count event with =1 (N_1) or =2 (N_2) *b*-jets

$$N_1 = L\sigma_{tt}\varepsilon_{e\mu}\,2\varepsilon_b(1-C_b\varepsilon_b) + N_1^{bkg}$$

$$N_2 = L\sigma_{tt}\varepsilon_{e\mu}C_b\varepsilon_b{}^2 + N_2^{bkg}$$

where C_b : tagging correlation coefficient

$$\sigma_{t\bar{t}}(\sqrt{s} = 7\,TeV) = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\ \text{pb}$$

$$\sigma_{t\bar{t}}(\sqrt{s} = 8\,TeV) = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\ \text{pb}$$

stat. syst. lumi. E_{beam}

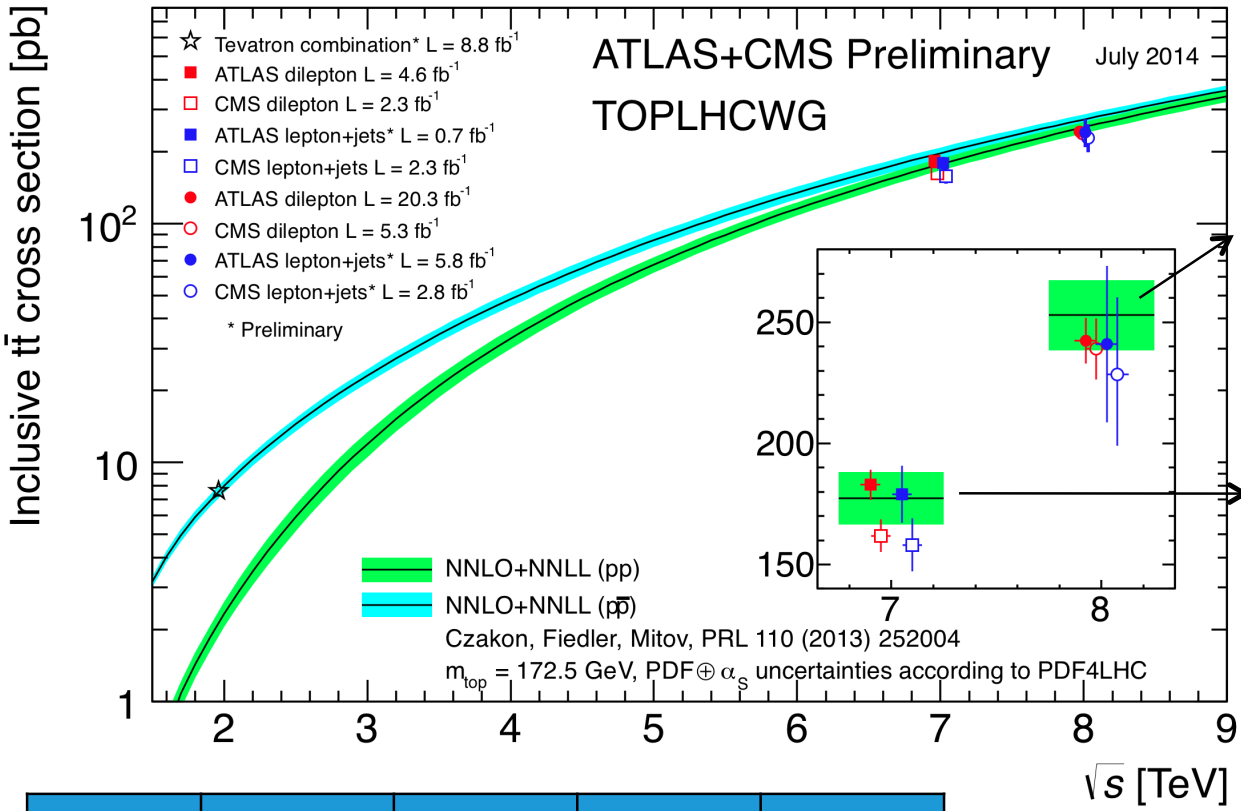
Exp. prec.	7 TeV	8 TeV
stat.	1.7%	0.7%
syst.	2.3%	2.3%
lumi.	2.0%	3.1%
E_{beam}	1.8%	1.7%
total	3.9%	4.3%

→ impressive precision

NNLO+NNLL theo. unc: 5.3% 5.7%

7 TeV 8 TeV 4.6+20.3 fb^{-1} dilep.

ttbar inclusive cross-section: summary



8 TeV:
ATLAS and CMS results are in good agreement with NNLO+NNLL prediction

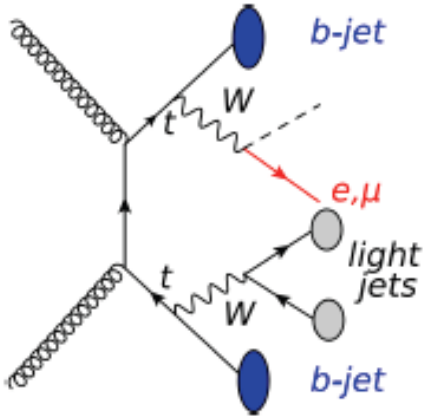
7 TeV:
~2σ tension between ATLAS and CMS measurements

Exp. prec.	Tevatron D0	Tevatron CDF	LHC 8 TeV ATLAS	LHC 8 TeV CMS
stat.	2.6%	4.0%	0.7%	0.8%
syst.	4.3%	4.7%	2.3%	4.7%
lumi.	6.1%	2.0%	3.1%	2.6%
total	7.8%	6.5%	4.3%	5.5%

Impressive experimental precision at Tevatron and LHC matching NNLO+NNLL precision of ~5%

7 TeV
8 TeV
0.7-20.3 fb-1
dilep.
lep.+ jets
all jets

Differential cross-section

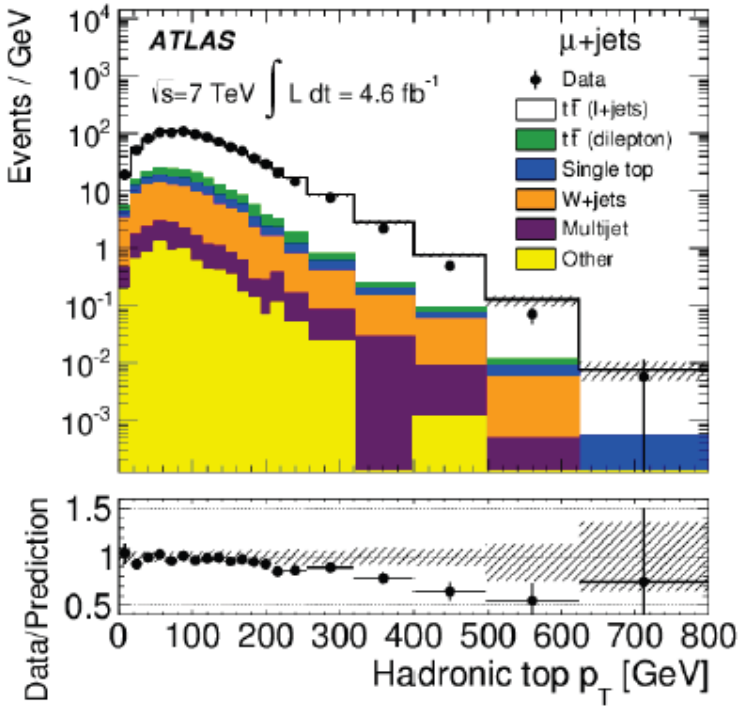


Event selection:

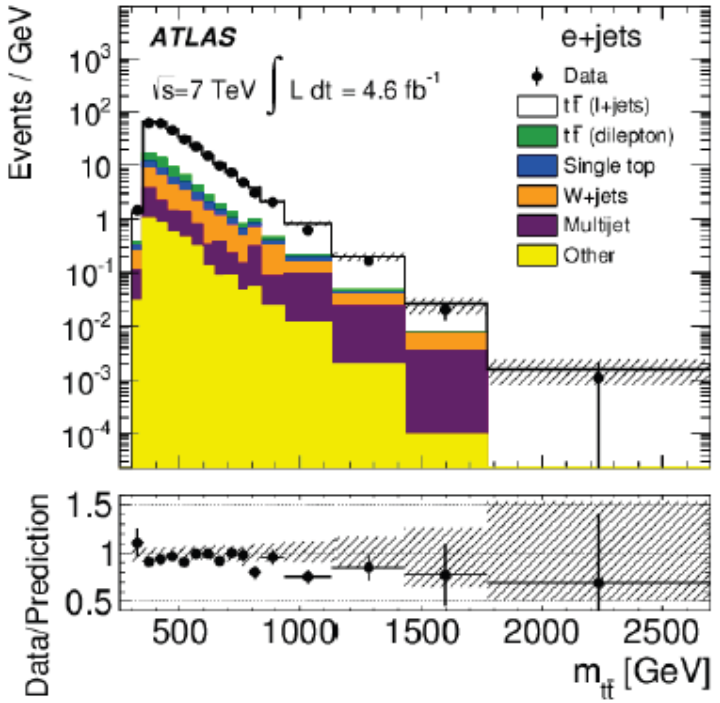
- exactly 1 *e* or μ,
- >= 4 jets and >= 1 *b*-jet @ 80% eff.
- MET > 30 GeV, $m_T(W)$>35 GeV
- cut on quality of ttbar system reconstruction

Phys. Rev. D 82 (2010) 114030

Data/Monte Carlo comparisons (MC prediction: Alpgen +Herwig) of top p_T and top-antitop system kinematics m_{tt}, y_{tt} and $p_{T,tt}$.



Top p_T: prediction overshoots data for p_T>200 GeV



m_{tt}: data/MC agreement within uncertainties

Measured distributions

7 TeV

4.6 fb^{-1}

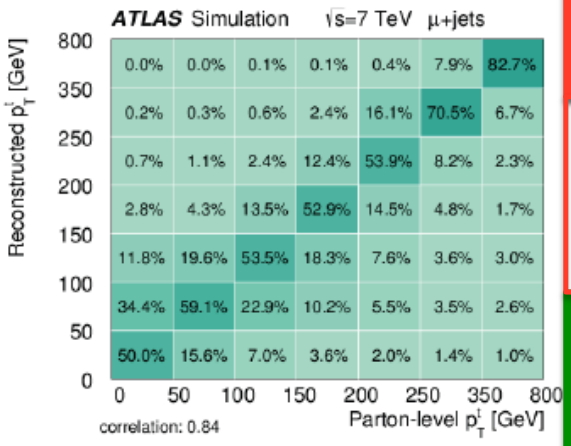
lep.+ jets

Differential cross-section

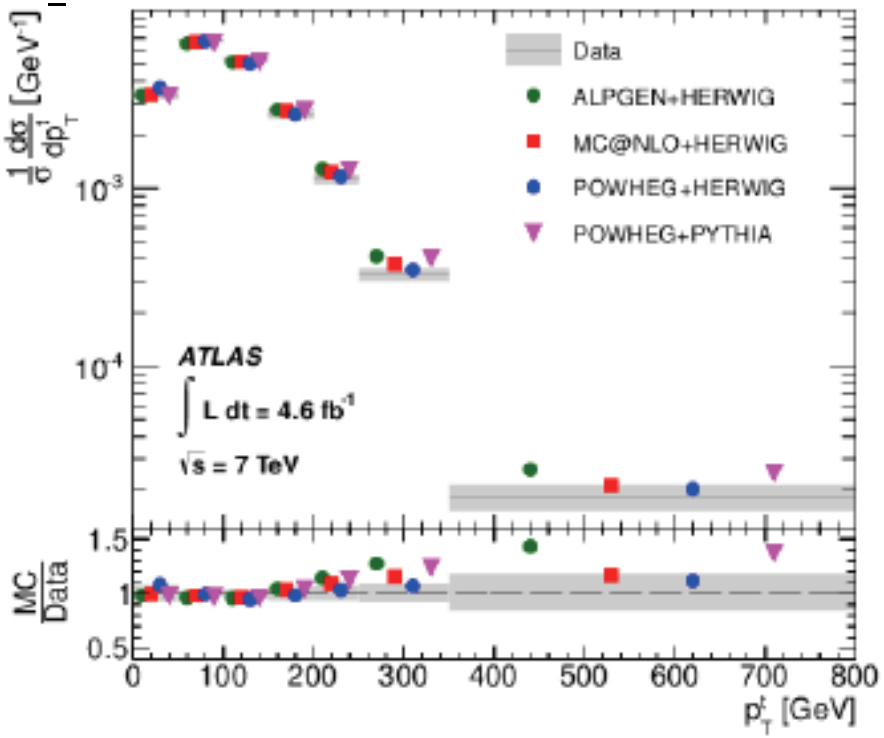
Phys. Rev. D 82 (2010) 114030

Unfolding

- subtract background and correct for detector effects
- regularized matrix inversion: Singular Value Decomposition



Top p_T compared to various MC predictions



Main modelling unc.:

- Parton Distribution Functions
- Parton shower and hadronization details
- Renormalization and Factorization scale

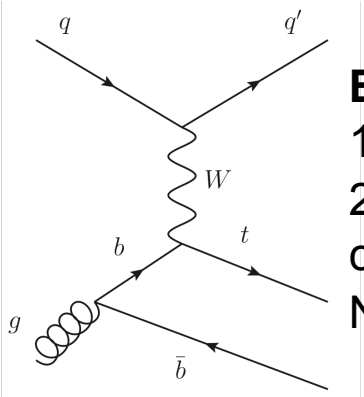
➔Data-simulation understanding can be improved by generator tuning.

- ATLAS: NLO QCD gives good agreement at low top p_T
- Both ATLAS and CMS data lower than NLO QCD predictions at high p_T
- NLO+NNLL in better agreement Powheg+Herwig

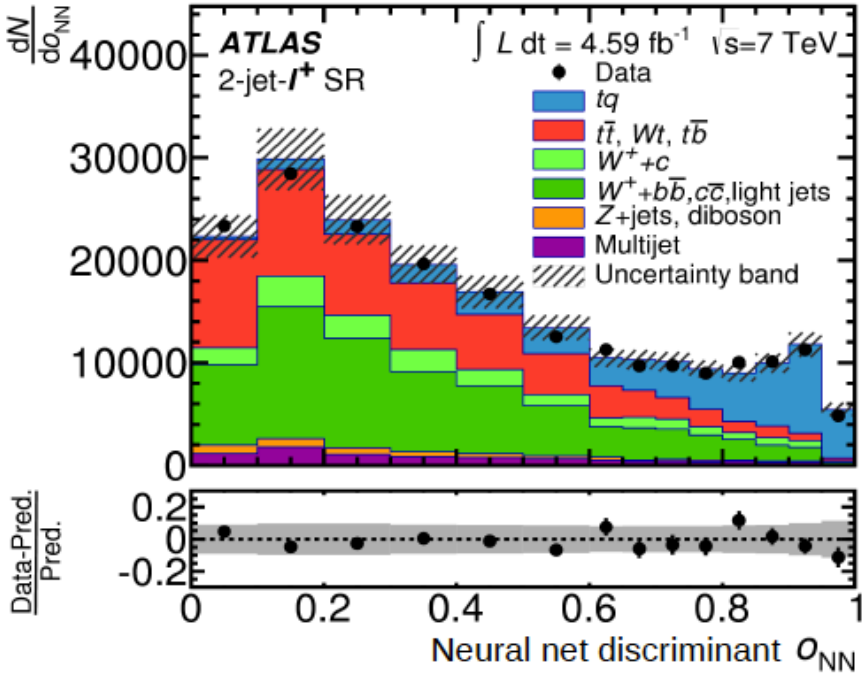
7 TeV | 4.6 fb^{-1} | lep.+ jets

Single top t-channel: cross-section

arXiv:1406.7844



Event selection:
1 lepton
2 or 3 jets with 1 or 2 *b*-tag
cut on MET and $m_T(W)$
NN discrimant



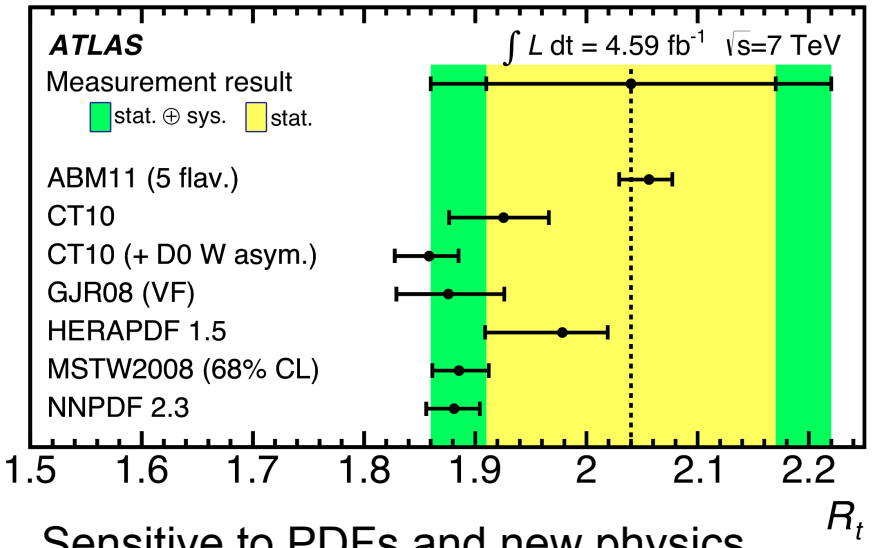
Dominant bkgs: top quark pairs and W+jets

Ratio of top and antitop cross-sections

$$\sigma(tq) = 46 \pm 1(\text{stat.}) \pm 6(\text{syst.})\text{pb}, \quad \text{prec.}: 13\%$$

$$\sigma(\bar{t}q) = 23 \pm 1(\text{stat.}) \pm 3(\text{syst.})\text{pb}, \quad \text{prec.}: 13\%$$

$$R_t = \frac{\sigma(tq)}{\sigma(\bar{t}q)} = 2.04 \pm 0.13(\text{stat.}) \pm 0.12(\text{syst.})$$



Sensitive to PDFs and new physics

$|V_{tb}|$ from σ: $\left|V_{tb}\right| = 1.02 \pm 0.07$

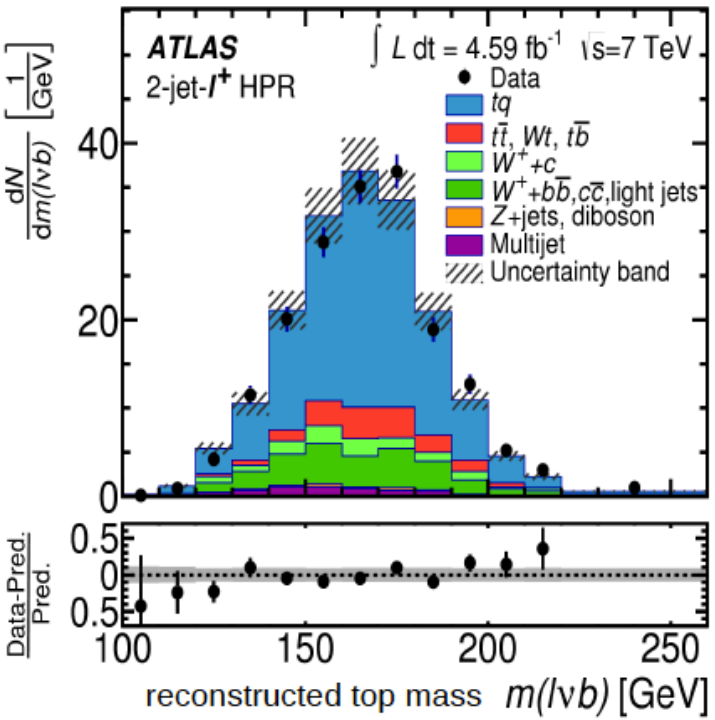
7 TeV
4.6 fb-1
lep.+ jets

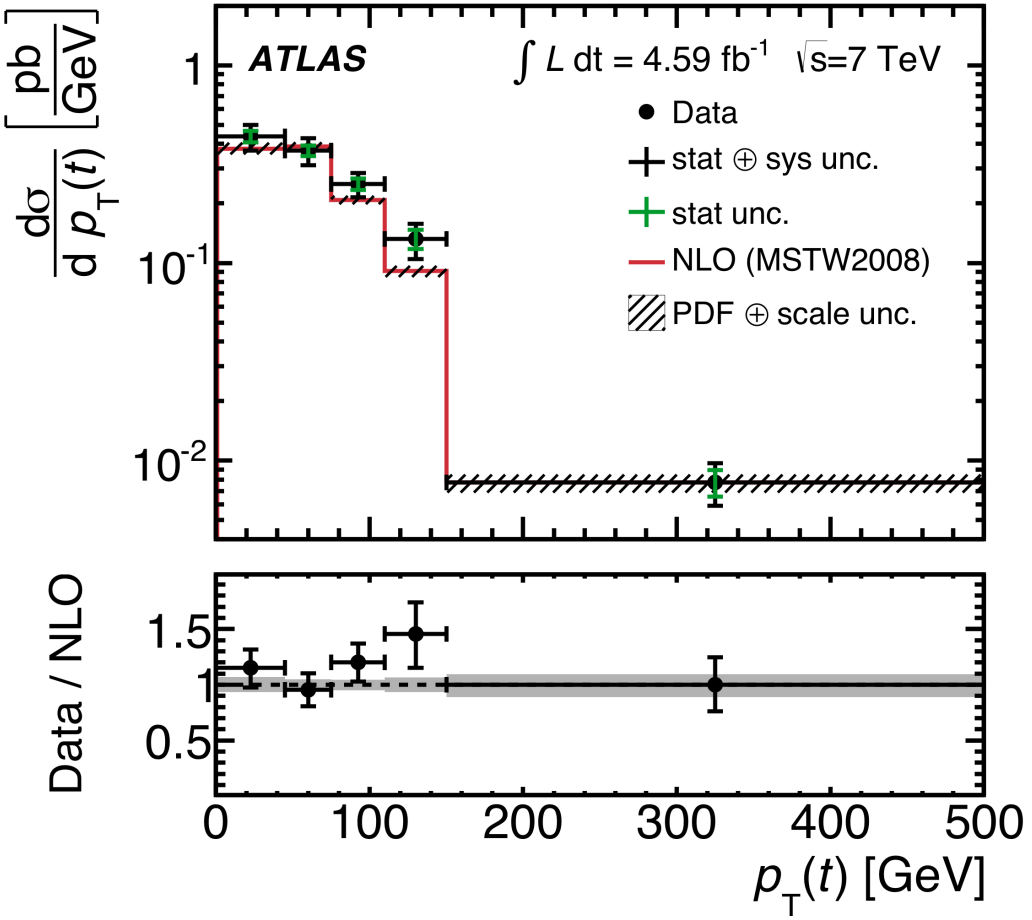
Single top t-channel: diff. cross-section

arXiv:1406.7844

First differential cross section measurement for single top production

In high purity region NN>0.8





Good description of data by NLO QCD.

7 TeV | 4.6 fb-1 | lep.+ jets

Single top t-channel: fiducial cross-section

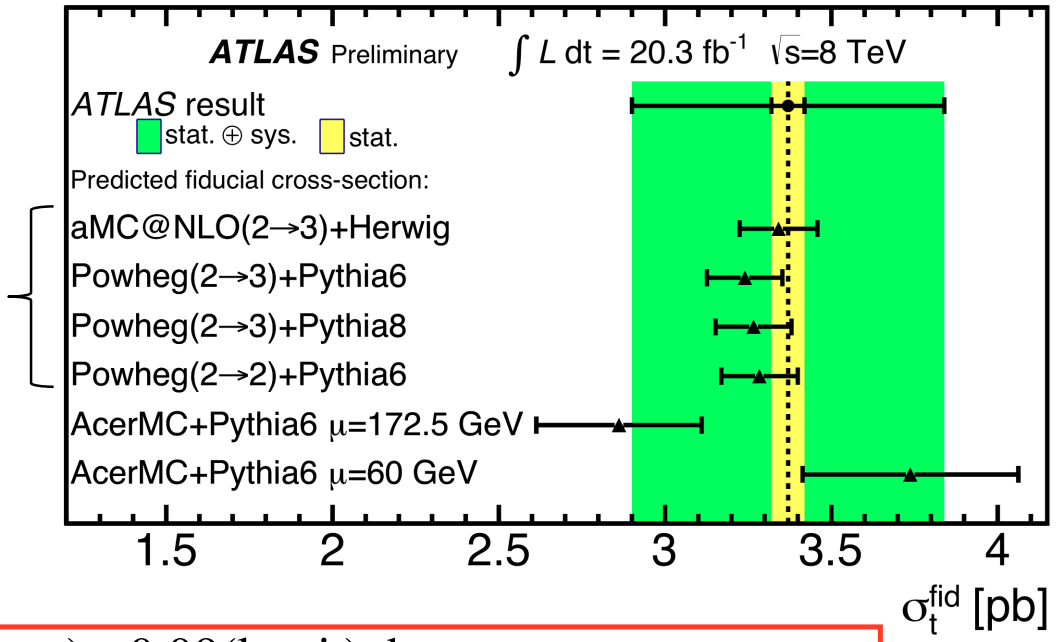
ATLAS-CONF-2014-007

First fiducial cross-section measurement for single top production

- Fiducial cross-section: defined for stable particle entering the detector acceptance
- Signal extraction via likelihood to a NN discriminant based on kinematic variables
- Reduce systematic uncertainties due to generator or PDF choice
- Extrapolation for fiducial to total cross-section based on various MC

- NLO QCD based MC give best description of fiducial cross-section
  ➔ extrapolate to total cross-section

- NLO+NNLL theory uncertainty smaller than extrapolation differences from various MC



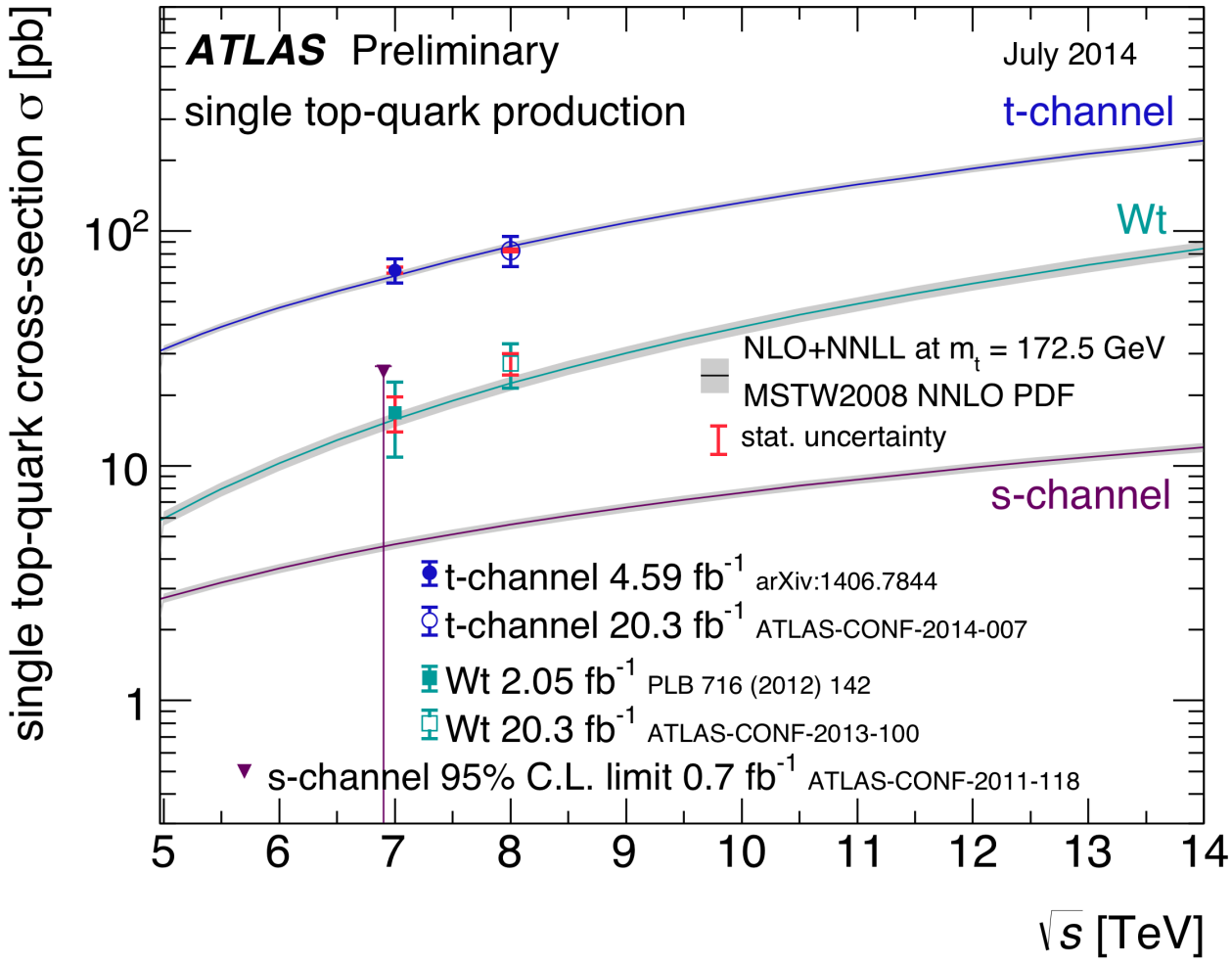
$$\sigma_{fid} = 3.37 \pm 0.05(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.09(\text{lumi.})\text{pb}$$

$$\sigma_{total} = 82.6 \pm 1.2(\text{stat.}) \pm 11.4(\text{syst.}) \pm 3.1(\text{PDF}) \pm 2.3(\text{lumi.})\text{pb}, \quad \text{prec.: } 14\%$$

Main uncertainties: JES η-intercalibration (7.9%), t-channel generator (7.9%).

8 TeV | 20.3 fb^{-1} | lep.+ jets

Electroweak single top production: summary



7 TeV 8 TeV 2.0 - 20.3 fb^{-1} dilep. lep.+ jets

- ***t*-channel process:** precision ~13% ➔ tool for studying precise couplings, BSM.
- **associated *W*+*t* production**: evidence at 7 TeV in ATLAS; observed in CMS at 8 TeV.
- ***s*-channel:** observed at Tevatron; more work needed to observe it at LHC.

Top quark properties

- Mass
- Spin correlations
- Charge asymmetries
- Couplings:
  - Constraints on the *Wtb* vertex (*W* polarisation)
  - *tt*+*Z*/*W*

Top quark mass

Different measurement methods with different sensitivities to systematics, two main classes of measurements:

Direct mass measurement (standard)

- reconstruct top decay products with kinematic fit based on likelihood or χ^2 fit
  - exploit known m_W to constrain physics and detector effects
  - fit m_{top} with n additional parameters, ex: jet/*b*-jet scale factors ($E^{jet}_{data}/E^{jet}_{MC}$)
- different methods: templates, ideogram method, matrix elements, etc.
- recent measurements precision <1%

Indirect mass measurement

- from inclusive and tt+jets cross-section
  - precision <4.7%
- using *B*-hadron lifetime
- *J/ψ* final states
- kinematic end-points

Template methods are used in ATLAS top mass analyses

- MC: parametrise the distribution of a m_{top} sensitive observable
- Real data: use that parametrisation to obtain a m_{top} value that best fits the observable distribution in data

Top quark mass

Lepton+jets channel: 3D template fit

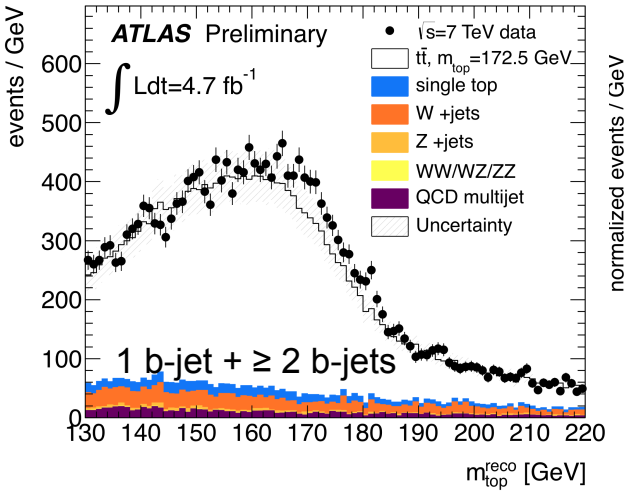
ATLAS-CONF-2013-046

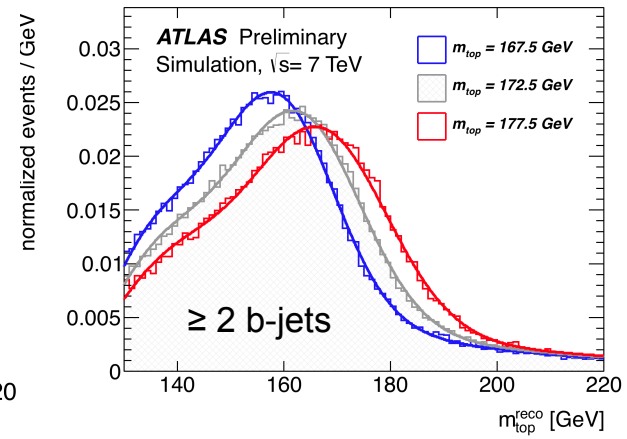
- m_{top} sensitive observable: top quark mass from an event kinematic fit
- include m_W (and other observable: R_{lb}) to control possible differences in the jet (b-jet) energy scale JSF (bJSF) between real data and MC

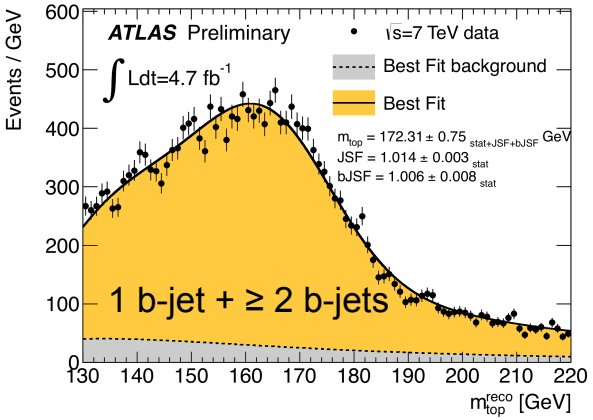
$$R_{lb}^{reco,\,2b} = \frac{p_T^{bhad} + p_T^{blep}}{p_T^{Wjet1} + p_T^{Wjet2}}$$

$$R_{lb}^{reco,\,1b} = \frac{p_T^{bjet}}{p_T^{Wjet1} + p_T^{Wjet2}}$$

Observable \ Dependency	m_t	JSF	bJSF
m_t^{reco}	✓	✓	✓
m_W^{reco}		✓	
R_{lb}^{reco}	mild		✓







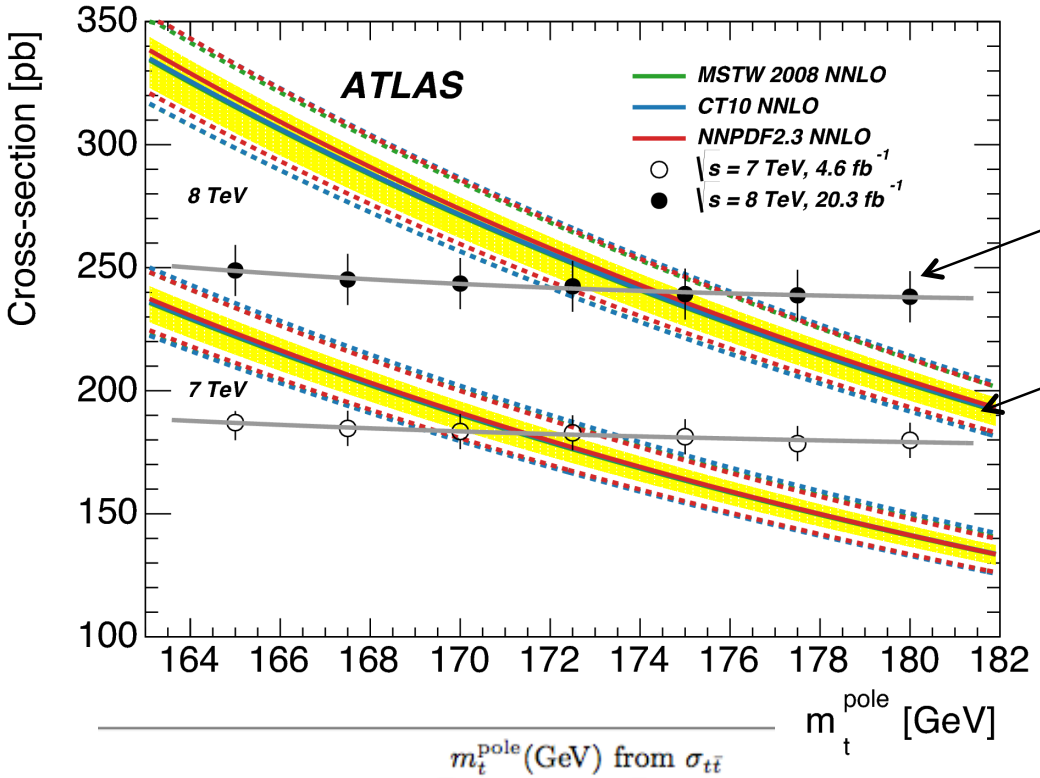
$$m_{top} = 172.31 \pm 0.75(\text{stat.} + \text{JSF} + \text{bJSF}) \pm 1.35(\text{syst.})\ \text{GeV}$$

Top quark mass from cross-section

Mass derived from cross-section

arXiv:1406.5375

Comparing NNLO+NNLL QCD top pair cross section to data to determine top mass in a well defined renormalisation scheme (here: pole mass) and theory uncertainties



m_{top} dependence of measured cross section ~0.28%/GeV

NNLO+NNLL cross-section prediction for various PDFs (band scale uncertainty)

PDF	m_t^{pole}(GeV) from $\sigma_{t\bar{t}}$ $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
CT10 NNLO	171.4 ± 2.6	174.1 ± 2.6
MSTW 68 % NNLO	171.2 ± 2.4	174.0 ± 2.5
NNPDF2.3 5f FFN	$171.3^{+2.2}_{-2.3}$	174.2 ± 2.4

$$m_{top} = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

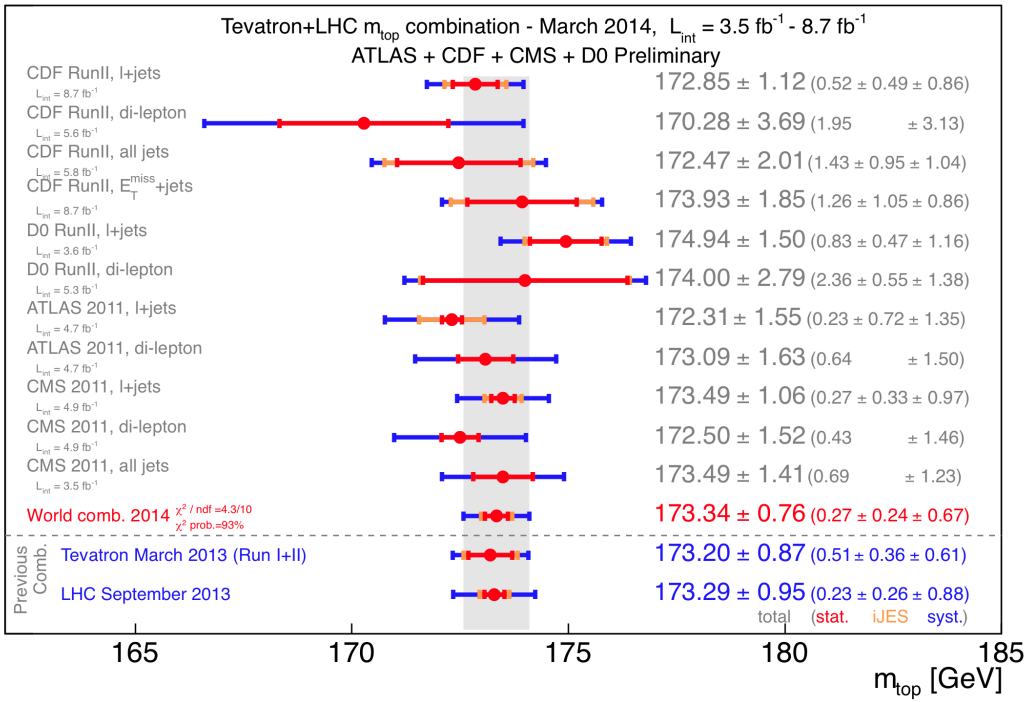
- New calculations of the top quark pole mass in *ttg* events: Eur.Phys.J. C73 (2013) 2438

Top quark mass: summary

First combination of LHC & Tevatron results → first world top-quark mass

- Best Linear Unbiased Estimate (BLUE)

arXiv: 1403.4427



Since then new results from:

- CMS at 8 TeV
- D0, the single most precise result
- ATLAS result from cross-section

$$m_{top} = 173.34 \pm 0.27(\text{stat.}) \pm 0.71(\text{syst.})\ \text{GeV}$$

Top-antitop mass difference

Physics Letters B 728C (2014), pp.363-379

$$\Delta m_{top} = 0.67 \pm 0.61(\text{stat.}) \pm 0.41(\text{syst.})\ \text{GeV}$$

7 TeV | 4.7 fb^{-1} | lep.+ jets

Spin correlations

- Although top quarks produced via strong interaction are essentially unpolarised, a correlation of the top and antitop spins is predicted (sensitive to new physics).
- The products of the top quark decay carry information about its spin.
- The double differential angular distribution for pairs of top quarks is given by:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d^2\cos\theta_1 d^2\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2) \quad \text{with} \quad C = -A\alpha_1\alpha_2$$

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

$\cos\theta_i$ in the spin (helicity) basis

C → spin correlaion strenght

α_i → spin analyzing power

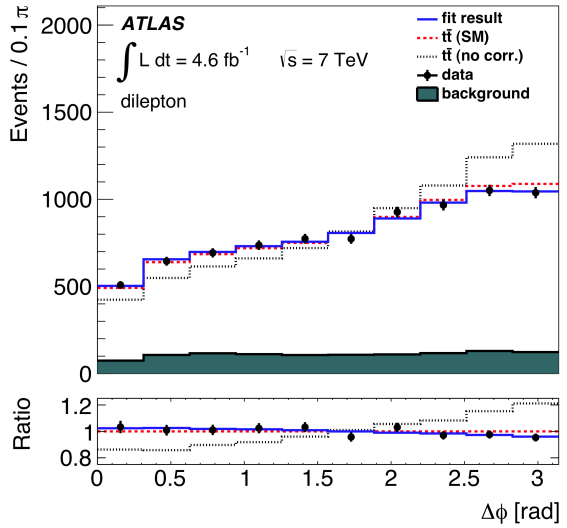
α	*b* quark	lepton	*d* quark	*u* quark
LO	-0.41	1.00	1.00	-0.31
NLO	-0.39	0.998	0.93	-0.31

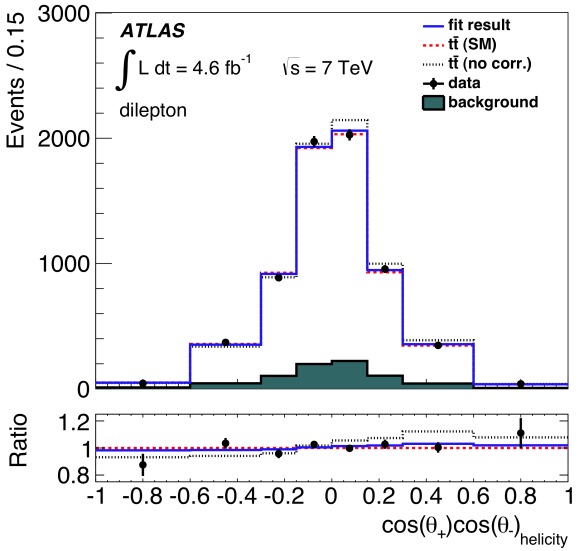
- Measurement strategy:
  - kinematic reconstruction of the top quark pairs
  - Several sensitive observables to spin correlation, as:
    - $\Delta\phi$ between the two leptons (dilepton ch.) or the lepton and the down-type quark from the W or the b-quark from the top (l+jets ch.)
    - $\cos\theta_1 \cdot \cos\theta_2$ computed in the top-antitop rest frame system or computed in the maximal spin correlation basis
  - a binned maximum likelihood fit to data is performed for each observable
    - signal templates generated with MC@NLO with and without spin correlation

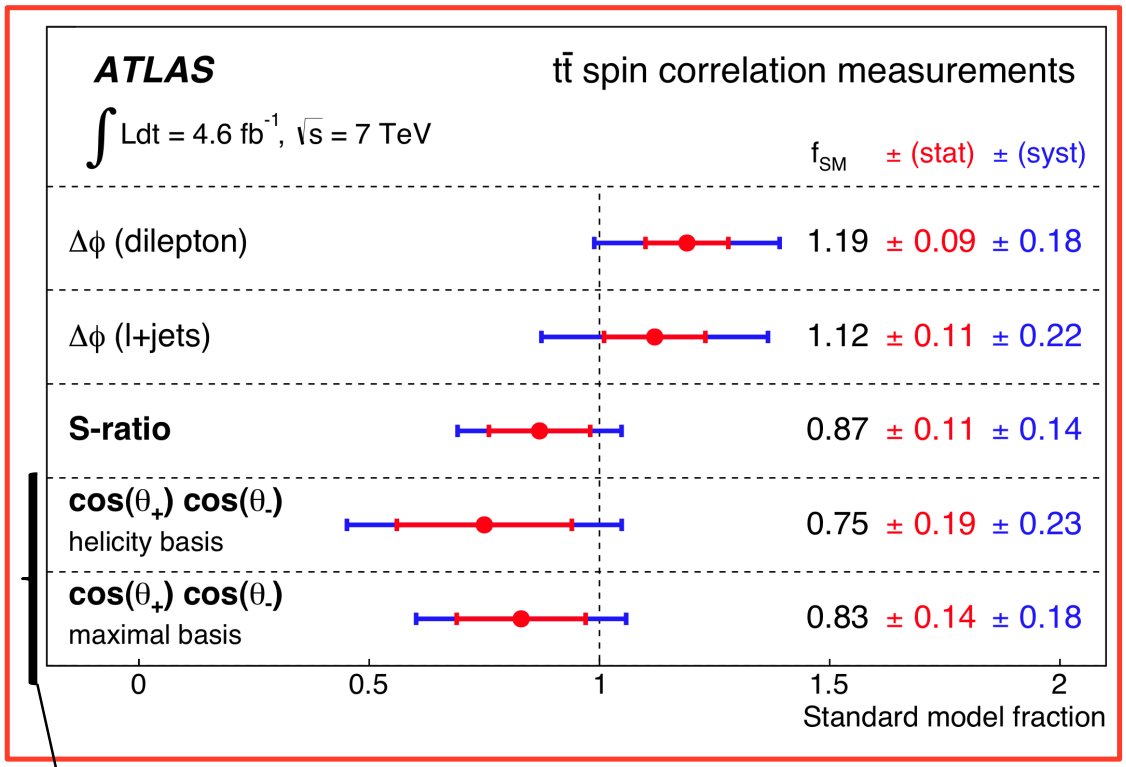
➔ the fit determines the fraction of events in data with a correlation like in the SM

Spin correlations

$$\text{Dist.} = f_{SM} \times \text{Dist.}_{SM} + (1 - f_{SM}) \times \text{Dist.}_{\text{No corr.}} + \text{Dist.}_{\text{Bkg.}}$$







$$A_{\text{helicity}} = 0.23 \pm 0.06(\text{stat.}) \pm 0.07(\text{syst.})$$

$$\text{SM}: A_{\text{helicity}} = 0.31$$

$$A_{\text{maximal}} = 0.37 \pm 0.06(\text{stat.}) \pm 0.08(\text{syst.})$$

$$\text{SM}: A_{\text{maximal}} = 0.44$$

arXiv:1407.4314

7 TeV | 4.6 fb^{-1} | dilep. lep.+ jets

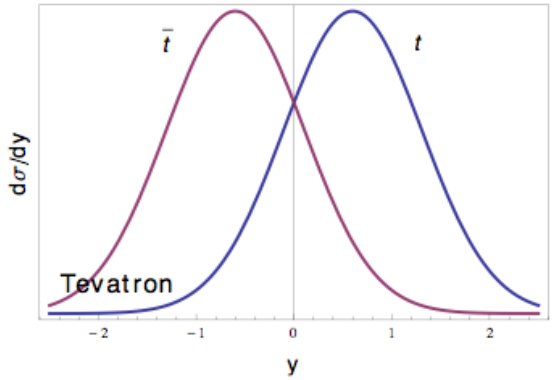
Charge asymmetry

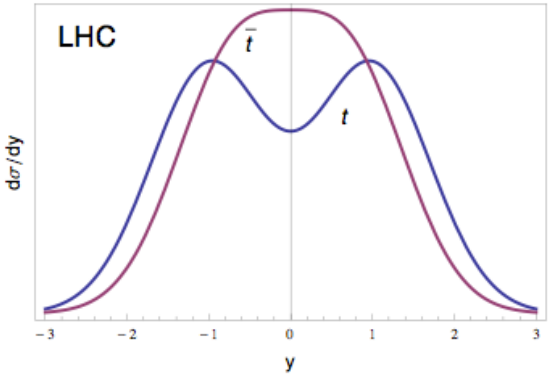
Charge asymmetry studies events with top quark pairs represent an important test of QCD at high energy and it is sensitive to BSM physics:

- At LO the top quark pair production is symmetric under the top and antitop exchange
- At NLO an asymmetry is introduced due to the interference effects

➔At Tevatron (ppbar collisions, qqbar dominant): top are forward, antitop backward

➔ At LHC (pp collisions, gg dominant): antitop are more central than top





$$A_{FB} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

with $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$

SM $NLO\ QCD + EW : A_{FB} \approx 0.088$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$

SM $NLO\ QCD + EW : A_C^{t\bar{t}} \approx 0.0115$ Phys.Rev.D 86, 034026

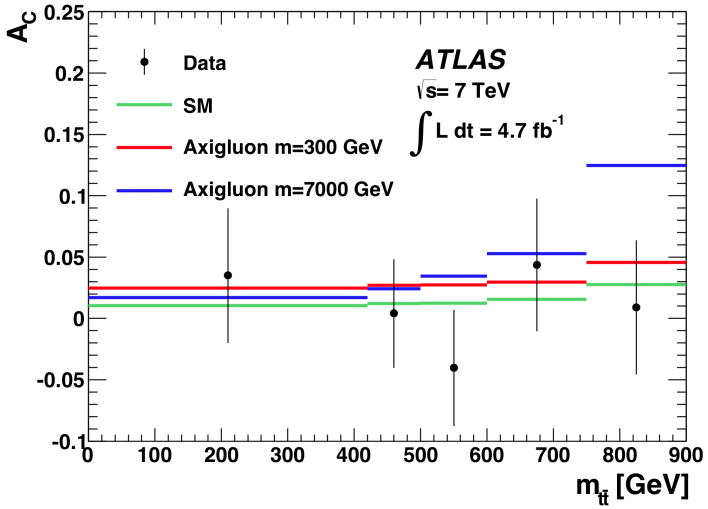
BSM enhancement possible

Top based charge asymmetry

JHEP02 (2014) 107

A_c^{ttbar} measurement:

- use kinematic fit based on a likelihood approach to reconstruct the top and antitop
- correct for detector effects using a Bayesian unfolding

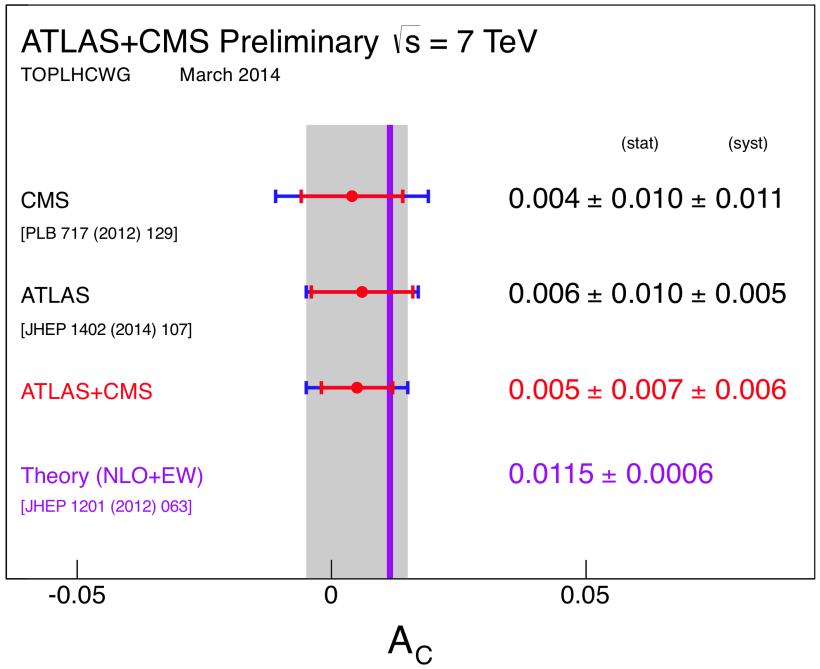


➔ **Inclusive result**:

$$A_C^{t\bar{t}} = 0.006 \pm 0.010(\text{stat.} + \text{syst.})$$

➔ **Differential measurements**:

m_{tt}, y_{tt} and $p_{T,tt}$
also for β (ttbar velocity)>0.6



➔ **ATLAS+CMS combination:**

$$A_C^{t\bar{t}} = 0.005 \pm 0.007(\text{stat.}) \pm 0.006(\text{syst.})$$

All measurements consistent with the SM.

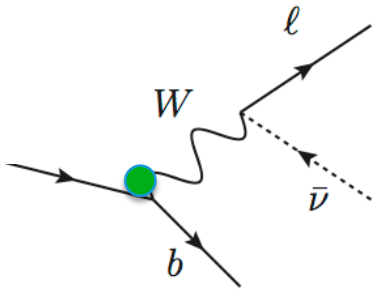
ATLAS-CONF-2014-012

7 TeV | 4.7 fb^{-1} | lep.+ jets

Top couplings: *Wtb* vertex

The *Wtb* vertex Lagrangian:

$$SM \Rightarrow \quad L_{Wtb}^{SM} = -\frac{g}{\sqrt{2}} \bar{u}_b \gamma^\mu V_{tb} P_L u_t W_\mu^+ + \text{h.c.}$$



A general extension:

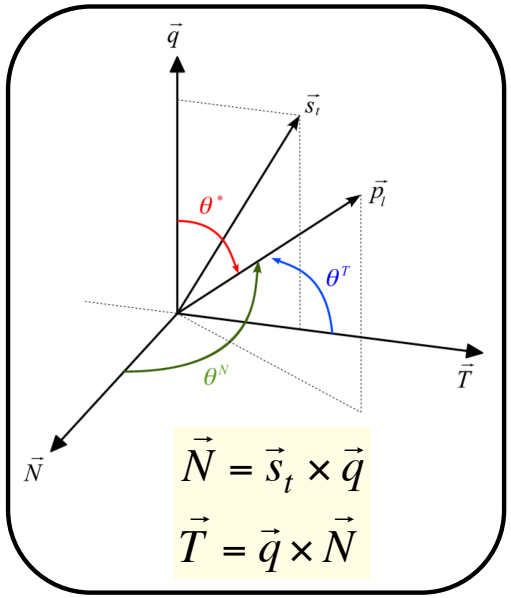
Nucl.Phys. B812 (2009) 181-204
Eur.Phys.J. C50 , 519 (2007)

$$L_{Wtb} = -\frac{g}{\sqrt{2}} \bar{u}_b \gamma^\mu \left(V_L P_L + V_R P_R\right) u_t W_\mu^+ - \frac{g}{\sqrt{2}} \bar{u}_b \frac{i\sigma^{\mu\nu} q_\nu}{M_W} \left(g_L P_L + g_R P_R\right) u_t W_\mu^+ + \text{h.c.}$$

$SM \Rightarrow$ $V_{L=}V_{tb}\sim 1$ $\quad V_R=g_L=g_R=0$

$V_{L,R}$ and $g_{L,R}$
left and right - handed vector and tensor couplings

Angular observables to probe the *Wtb* vertex:



Nucl. Phys. B 840(2010)349

- For unpolarised top quark decays, the only meaningful direction in the top RF is the one of the *W* boson momentum (q)

- For polarised (spin direction s_t) top quarks produced via electroweak interaction, further directions may be considered: N and T.

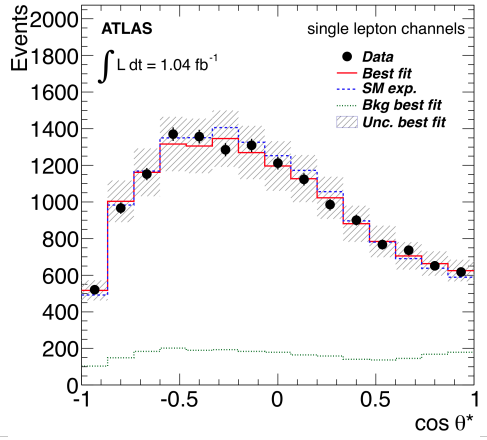
- Three angular distributions: θ_l^*(q,l), θ_l^N(N,l) and θ_l^T(T,l)

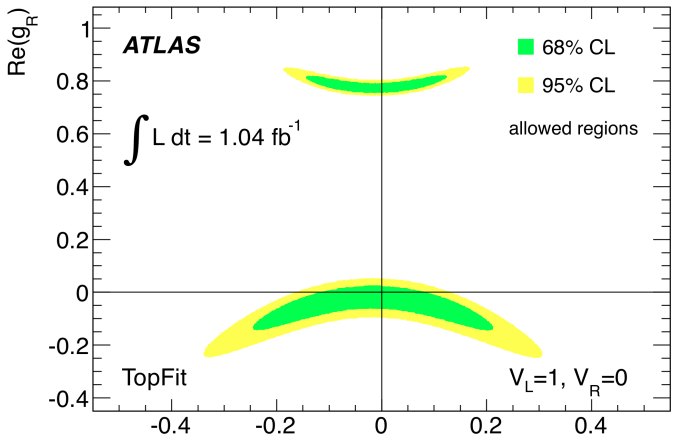
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^X} = \frac{3}{8}(1+\cos\theta_l^X)^2 \mathbf{F_+^X} + \frac{3}{8}(1-\cos\theta_l^X)^2 \mathbf{F_-^X} + \frac{3}{4}\sin^2\theta_l^X \mathbf{F_0^X}$$

$$A_{FB}^X = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)} \propto \left(F_+^X - F_-^X\right)$$

Top couplings: *Wtb* vertex

W helicity fractions (top quark pair events)



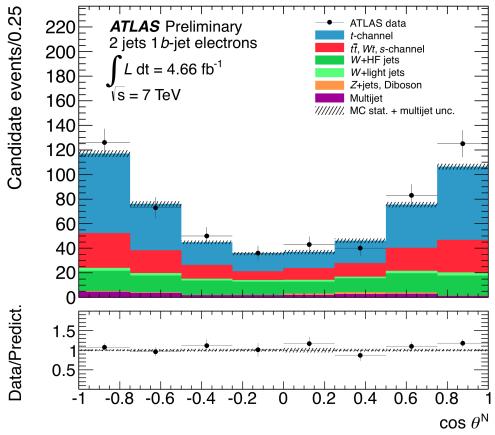


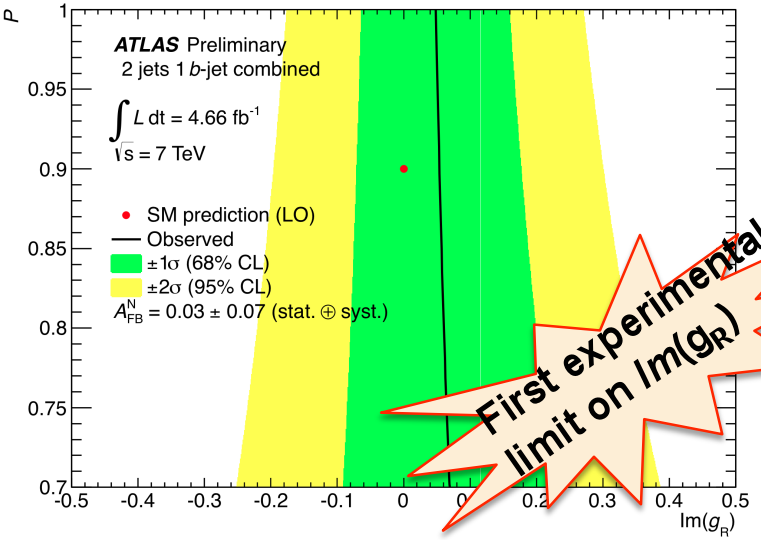
JHEP 1206 (2012) 088

- limits to the real part of V_R, g_L and g_R
- in the limit $m_b << m_t$, only one linear term with new couplings interfering with V_L: $Re(g_R)$
- not sensitive to their complex phases

A_{FB}^N (single top quark decays)

$$A_{FB}^{N} \approx -0.64 \cdot P \cdot Im(V_L g_R^*)$$





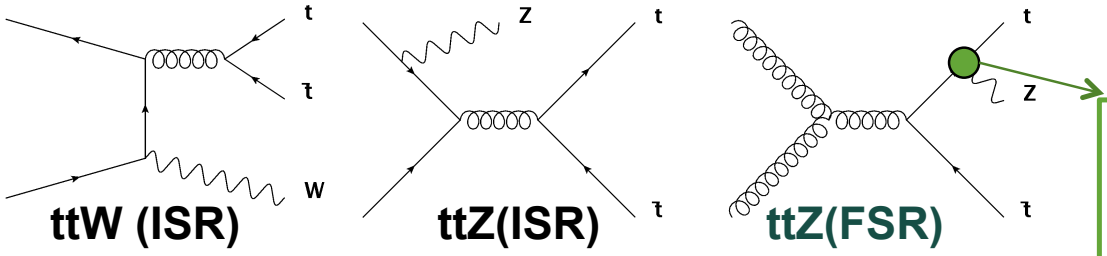
ATLAS-CONF-2013-032

$$A_{FB}^{N} = 0.031 \pm 0.065\,(\text{stat.})\,^{+0.029}_{-0.031}\,(\text{syst.})$$

7 TeV | 1.04 – 4.7 fb^{-1} | dilep. | lep.+ jets

Top couplings: *ttZ* and *ttW*

Top antitop production in association with *W/Z* bosons



ttZ and *ttW* processes are very rare: σ(NLO QCD)~200 fb.

The *tZ* vertex allows the first measurement of weak NC interaction of the top quark ➔ weak isospin T_3

Experimental signature: number of leptons (multiple jets and *b*-jets also required)

ttZ	tt→ dilepton	tt→ l+jets	tt→ all-had.
Z→ll	4l + 2j(2b)	3l + 4j(2b)	2l (OS) + 6j(2b)
Z→jj, Z→νν	2l (OS) + ≥2j(≥2b)	1l + ≥4j(≥2b)	0l + ≥6j(≥2b)

Main background contributions:
-fake leptons
-charge mis-identification

ttW	tt→ dilepton	tt→ l+jets	tt→ all-had.
W→lν	3l + 2j(2b)	2l (OS or SS) + 4j(2b)	1l + 6j(2b)
W→jj	2l (OS) + ≥2j(≥2b)	1l + ≥4j(≥2b)	0l + ≥6j(≥2b)

Analysis strategies:

2l (e or μ) **OS:**
=2l, ≥ 3 jets, ≥ 1 *b*-jet
small signal on large background (ttbar and *Z*+jets)
➔ Neural network used

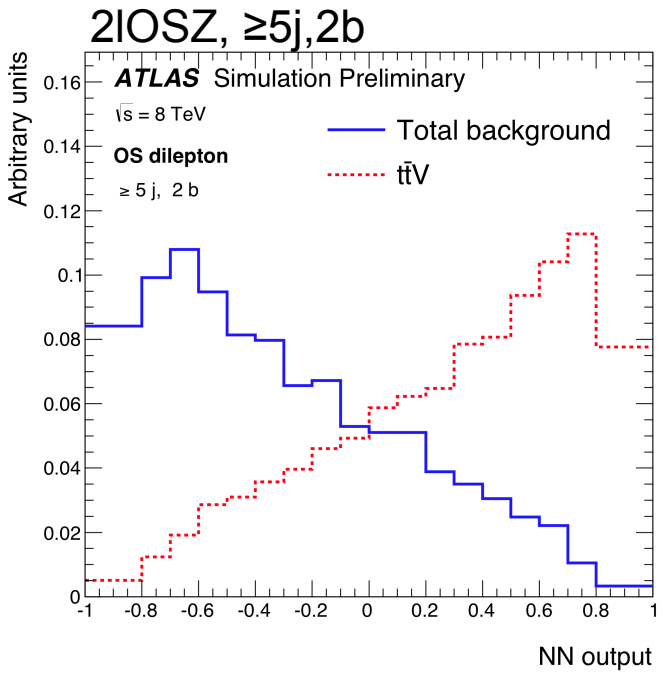
3l (e or μ) **and 2l SS** (only $\mu\mu$):
signal and background comparable
➔ cut and count technique used

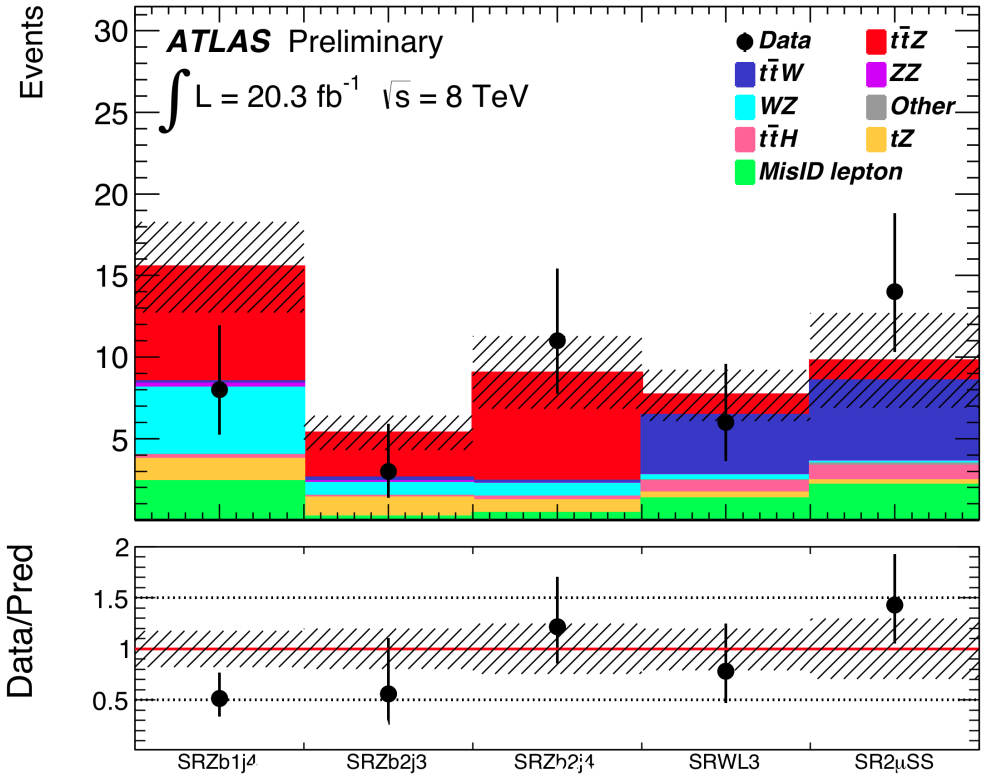
Top couplings: *ttZ* and *ttW*

ATLAS-CONF-2014-038

2lOS → 6 regions
Zveto: (3j,1b+2b), **(4j,1b+2b)***, **(≥5j,1b+2b)***
Zwindow: (3j,2b), (4j,2b), **(≥5j,2b)***
signal regions, *NN used
control regions

3l and 2lSS → 5 regions
3lZwindow: **(≥4j,1b), (3j,≥2b), (≥4j, ≥2b)**
3lZveto: **(3j+2j, ≥2b)**
2lSS: **(≥2j, ≥2b)**
signal regions





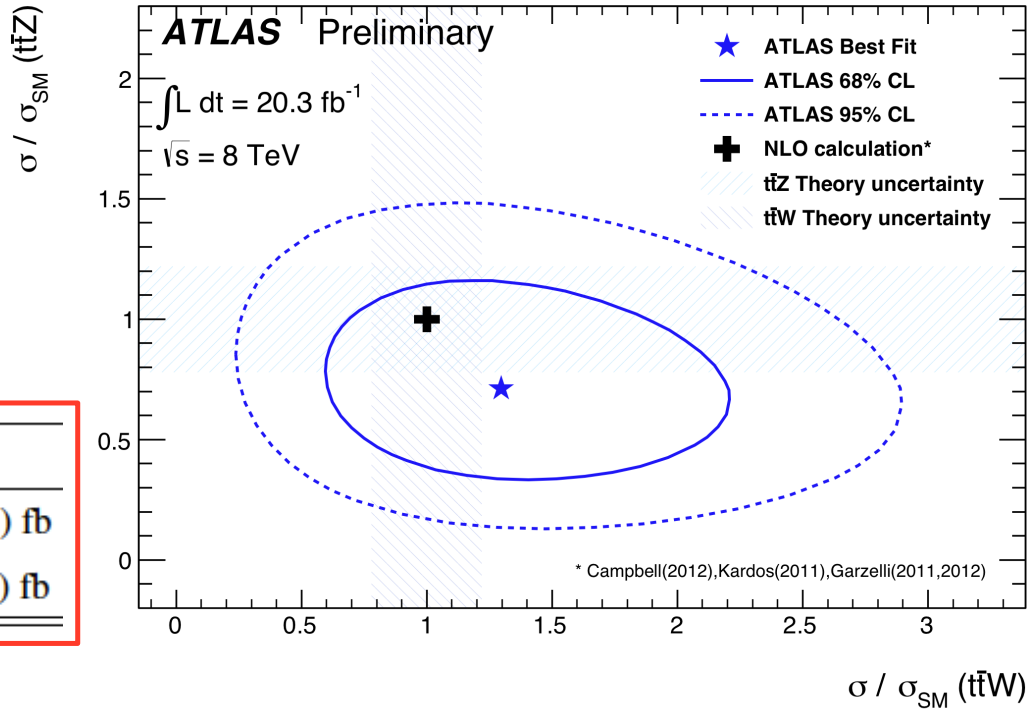
8 TeV
20.3 fb^{-1}
dilep. lep.+ jets all jets

Top couplings: *ttZ* and *ttW*

Combination

ATLAS-CONF-2014-038

Process	Signal Strength	Observed σ	Expected σ
$t\bar{t}V$	$0.89^{+0.23}_{-0.22}$	4.9	4.9 → assuming ttZ/ttW SM cross-sections ratio
$t\bar{t}W$	$1.25^{+0.57}_{-0.48}$	3.1	2.4 → assuming ttZ cross-section
$t\bar{t}Z$	$0.73^{+0.29}_{-0.26}$	3.2	3.8 → assuming ttW cross-section



Process	Measured cross-sections
$t\bar{t}Z$	$150^{+58}_{-54}(\text{total}) = 150^{+55}_{-50}(\text{stat.}) \pm 21(\text{syst.})$ fb
$t\bar{t}W$	$300^{+140}_{-110}(\text{total}) = 300^{+120}_{-100}(\text{stat.})^{+70}_{-40}(\text{syst.})$ fb

8 TeV | 20.3 fb^{-1} | dilep. | lep.+ jets | all jets

Summary

- The top quark physics at LHC entered in the precision era.

- In this talk, some of the latest ATLAS results have been presented:
  - production cross-section via strong (top quark pairs) and electroweak (single top) interaction
    - differential measurements sensitive to details of MC generator modelling/theory predictions
  - mass
  - spin correlations
  - charge asymmetries
  - couplings:
    - *Wtb* vertex
    - *ttZ/W*

- **All measurements are compatible with the SM ➔ setting constraints on new physics**
- In many analysis, precision limited by systematic uncertainties.

➔ Stay tuned for few more Run I results!

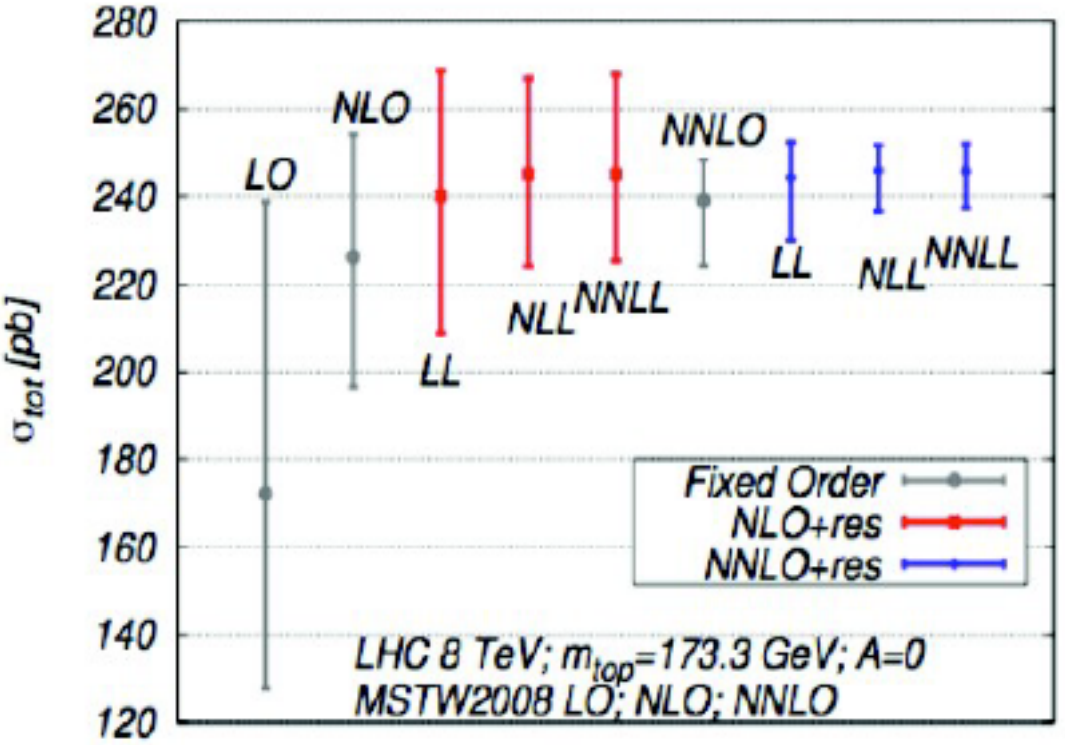
THANKS FOR YOUR ATTENTION!

More results available in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

BACK-UP

ttbar inclusive cross-section

Theoretical effort on higher order QCD calculations:
1989 NLO
1998 NLO+NLL
2008 NLO+NNLL
2013 NNLO+NNLL



Czakon *et. al*: arXiv:1303.6254
Czakon *et al.*: arXiv:1303.7215

- cross-section increases ~10% from NLO to NNLO+NNLL QCD
- precision improves from ~12% to ~3% (scales)
  ~8% to ~5% (PDF) ➔ unc. dominates!
- electroweak corrections also sizeable $\alpha_S^2 \sim \alpha_{EW}$

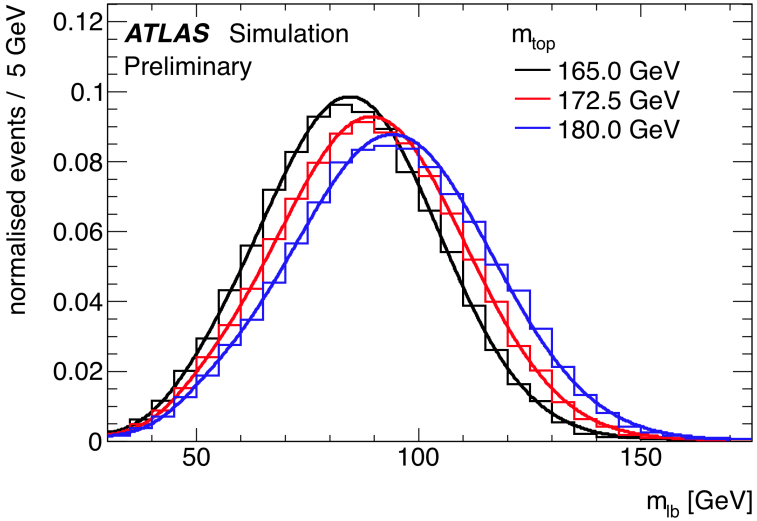
NNLO QCD calculation mandatory for precision analysis

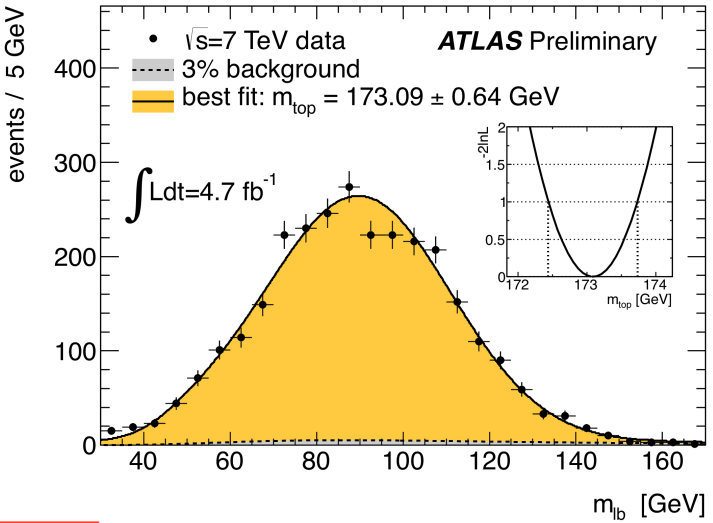
Top quark mass

Dilepton channel: 1D template method

ATLAS-CONF-2013-077

- observable: average m_{lb}
- small background (~3%), mainly from single top *Wt* channel
- main systematic uncertainties: jet and *b*-jet energy scale



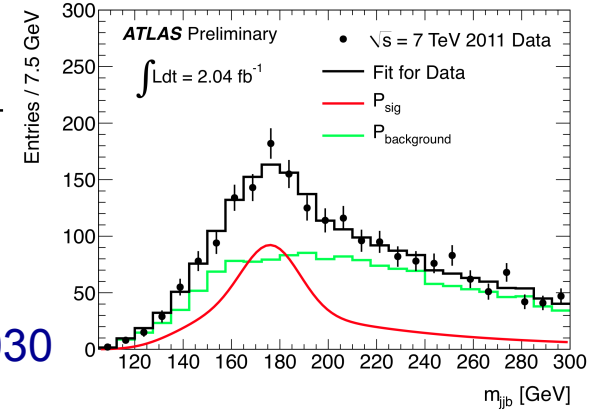


$$m_{top} = 173.09 \pm 0.64(\text{stat.}) \pm 1.50(\text{syst.})\ \text{GeV}$$

All-hadronic channel: 1D template method

$$m_{top} = 174.9 \pm 2.1(\text{stat.}) \pm 3.8(\text{syst.})\ \text{GeV}$$

ATLAS-CONF-2012-030



Spin correlations

- four sensitive observables to spin correlation
  - $\Delta\phi$ between the two leptons (dilepton ch.) or the lepton and one jet (l+jets ch.)
  - "S-ratio" of matrix elements for top quark production via fusion of like-helicity gluons
  - $\cos\theta_1 \cdot \cos\theta_2$ computed in the top-antitop rest frame system
  - $\cos\theta_1 \cdot \cos\theta_2$ computed in the maximal spin correlation basis

- The "S-ratio" of matrix elements $\mathcal{M}$ for top quark production and decay from the fusion of like-helicity gluons ($g_R g_R + g_L g_L \to t\bar{t} \to (b\ell^+\nu)(\bar{b}\ell^-\bar{\nu})$) with SM spin correlation and without spin correlation at LO [74],

$$S = \frac{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{corr}}{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{uncorr}} \qquad (6)$$
$$= \frac{m_t^2\{(t\cdot\ell^+)(t\cdot\ell^-) + (\bar{t}\cdot\ell^+)(\bar{t}\cdot\ell^-) - m_t^2(\ell^+\cdot\ell^-)\}}{(t\cdot\ell^+)(\bar{t}\cdot\ell^-)(t\cdot\bar{t})},$$

where t, $\bar{t}$, ℓ^+ and ℓ^- are the 4-momenta of the top quarks and the charged leptons. Since the like-helicity gluon–gluon matrix elements are used for the construction of the S-ratio, it is particularly sensitive to like-helicity gluon–gluon initial states. To measure this observable, and the two others described below, the top quark and the top antiquark have to be fully reconstructed.

Lepton & top based charge asymmetries

ATLAS-CONF-2012-057

A_c^{ll} and A_c^{ttbar} measurements:

- A_c^{ll}: no reconstruction needed
- A_c^{ttbar}:
  - use matrix element method to reconstruct top and antitop
  - correct for detector effects using calibration

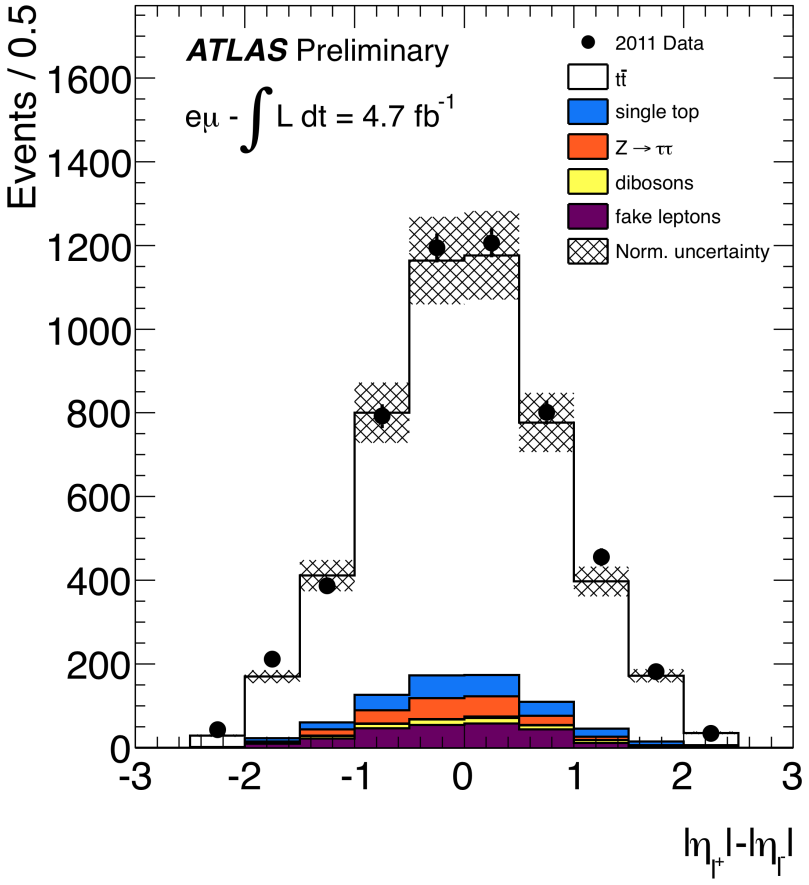
➔ **Inclusive results**:

$$A_C^{ll} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$$

$$SM : A_C^{ll} = 0.0049 \pm 0.0001$$

$$A_C^{t\bar{t}} = 0.057 \pm 0.024(\text{stat.}) \pm 0.015(\text{syst.})$$

$$SM : A_C^{t\bar{t}} = 0.0123 \pm 0.0005$$



7 TeV | 4.7 fb-1 | dilep.

Top couplings: ttZ and ttW

ATLAS-CONF-2014-038

	Trilepton and same-sign dilepton			Opposite-sign dilepton	
Analysis strategy	comparable signal and background: cut and count			small signal in huge background multivariate techniques	
	$3\ell Z$	$3\ell Z$veto	2μSS	2ℓOSZveto	2ℓOSZ
Z-mass selection	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	-	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
Additional selection			$E_T^{miss} > 40$ GeV $H_T > 240$ GeV	$E_T^{miss} > 40$ GeV $_{(ee,\mu\mu)}$ $H_T > 130$ GeV $_{(e\mu)}$ $\Delta R_{ave}^{jj} > 0.75$	$\Delta R_{ave}^{jj} > 0.75$
Lepton flavour Signal Main background	all trilepton $t\bar{t}Z$ tZ, WZ and fakes	all trilepton $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	$\mu\mu$ $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	all dilepton $t\bar{t}Z$ and $t\bar{t}W$ $t\bar{t}$+jets	ee, $\mu\mu$ $t\bar{t}Z$ dominated Z+jets
Validation regions	(3j + 2j + 1j, 1b) (CRZ)	(1b) (CRW)	$E_T^{miss} < 40$ GeV		
Regions in the fit (**Signal region**, control region)	**(≥ 4j, 1b) (SRB1J4)** **(3j, ≥ 2b) (SRB2J3)** **(≥ 4j, ≥ 2b) (SRB2J4)**	**(3j + 2j, ≥ 2b) (SRW3ℓ)**	**(≥ 2j, ≥ 2b) (SR2μSS)**	(3j, 1b + 2b) **(4j, 1b + 2b)** **(≥ 5j, 1b + 2b)**	(3j, 2b) (4j, 2b) **(≥ 5j, 2b)**

Table 8: Summary of the $t\bar{t}V$ event selection and analysis strategies in three channels. In the last row signal-rich regions are shown in bold.

Top couplings: ttZ and ttW

ATLAS-CONF-2014-038

Variable	Definition
$M_{uu}^{Pt_{ord}}$	Mass of the two untagged jets with the highest p_T in events with exactly two tagged jets or mass of the two untagged jets with the highest p_T after discarding the jet with second highest b-tagging weight in events with exactly one tagged jet
$Cent_{jet}$	Sum of p_T divided by sum of E for all jets
H1	2nd Fox-Wolfram moment
$H1_{jet}$	2nd Fox-Wolfram moment built from jets only
M_{jj}^{MindR}	Mass of the combination between any two jets with the smallest ΔR
$maxM_{lepb}^{MindR}$	Maximum mass between a lepton and the tagged jet with the smallest ΔR
p_T^{jet3}	Third leading jet p_T
p_T^{jet4}	Fourth leading jet p_T
ΔR_{ave}^{jj}	Average ΔR for all jet pairs
$N_{jets}^{\lvert M(jj)-M(V)\rvert<30}$	Number of jet pairs with mass within a window of 30 GeV around 85 GeV
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
M_{bb}^{MaxPt}	Mass of the combination of two tagged jets with the largest vector sum p_T
M_{bj}^{MaxPt}	Mass of the combination of a tagged jet and any jet with the largest vector sum p_T
$\Delta R_{lep1,lep2}$	Δ R between the two leptons

Table 5: The variables considered for use within the Neural Network analysis in the opposite-sign dilepton channel. The definition of Fox-Wolfram moments can be found in Ref. [65].

8 TeV
20.3 fb^{-1}
dilep. lep.+ jets all jets

Top couplings: ttZ and ttW

ATLAS-CONF-2014-038

	Trilepton and same-sign dilepton channels		
Process	Signal Strength	Observed σ	Expected σ
$t\bar{t}V$	$0.91^{+0.27}_{0.24}$	4.6	4.6
$t\bar{t}W$	$1.31^{+0.62}_{-0.50}$	3.0	2.3
$t\bar{t}Z$	$0.72^{+0.33}_{-0.28}$	2.8	3.4

	Opposite-sign dilepton channel		
Process	Signal Strength	Observed σ	Expected σ
$t\bar{t}V$	$0.77^{+0.63}_{-0.56}$	1.4	1.7
$t\bar{t}W$	$0.57^{+2.48}_{-2.30}$	0.3	0.4
$t\bar{t}Z$	$0.77^{+0.69}_{-0.59}$	1.4	1.5

Combination

Process	Signal Strength	Observed σ	Expected σ
$t\bar{t}V$	$0.89^{+0.23}_{-0.22}$	4.9	4.9
$t\bar{t}W$	$1.25^{+0.57}_{-0.48}$	3.1	2.4
$t\bar{t}Z$	$0.73^{+0.29}_{-0.26}$	3.2	3.8

8 TeV
20.3 fb^{-1}
dilep. lep.+ jets all jets