TOP QUARK PROPERTIES USING THE ATLAS DETECTOR AT THE LHC

- TOP QUARK MASS
- TOP QUARK PAIR PRODUCTION – SPIN CORRELATIONS AND CHARGE ASYMMETRY

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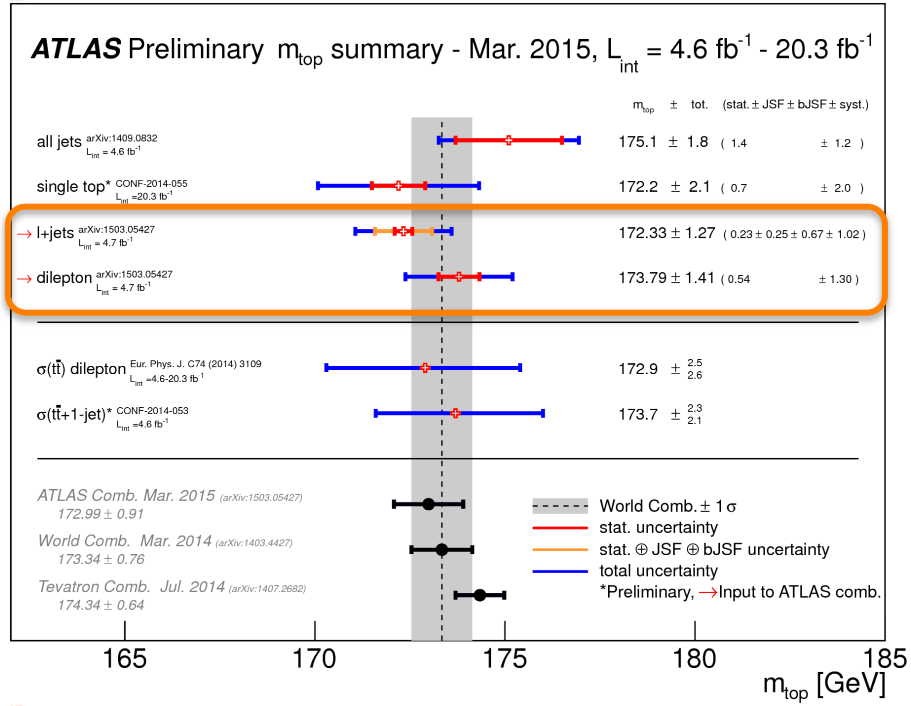
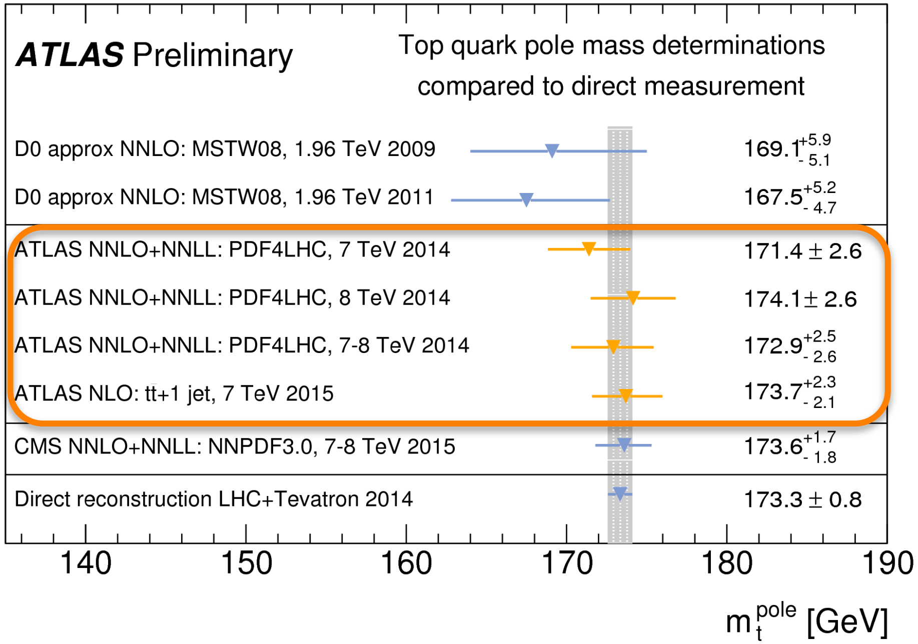
TOP QUARK MASS

- Measured using different techniques, at 7 and 8 TeV CM E, and in various channels: ttbar (lepton+jets, dilepton, all hadronic), single top t-channel.

Direct measurements of m_{top}^{MC}



Measurements of m_{top}^{pole}



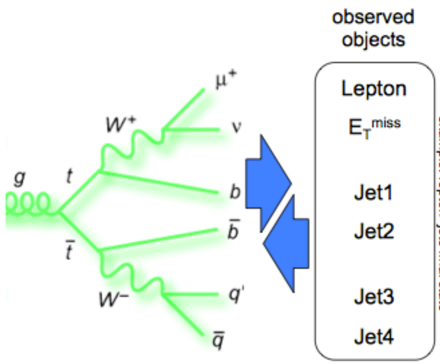
+ NEW: dilepton @ 8 TeV (arXiv:1606.02179)

Most precise determinations obtained with direct measurements (template method). But the parameter which is being measured in this case is the MC top quark mass.

Eur. Phys. J. C (2015) 75:330

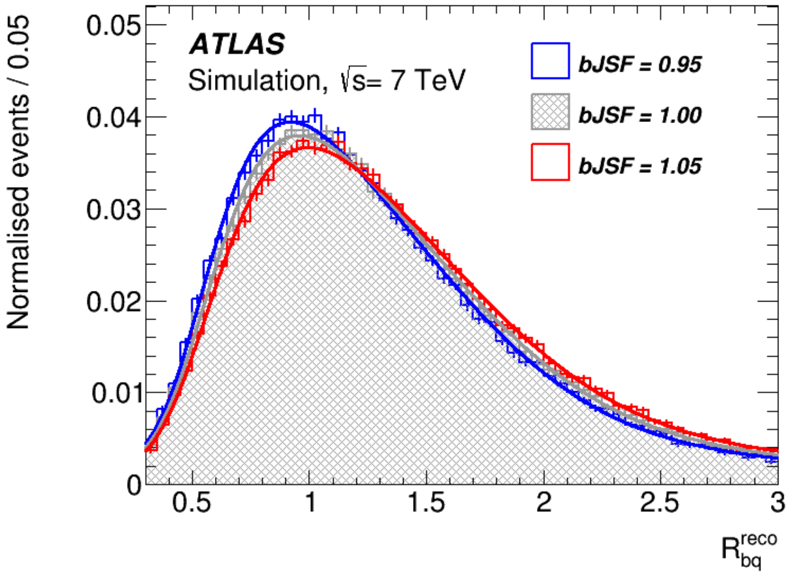
TOP QUARK MASS - ATLAS l+jets @ 7 TeV

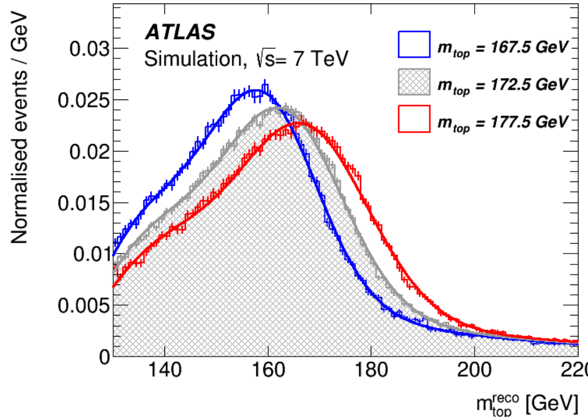
- Method: 3D template fit to m_{top}^{reco}, m_W^{reco} and R_{lb}^{reco} → m_{top}, JSF, bJSF.



Use a kinematic fit to the decay hypothesis → m_{top}^{reco}

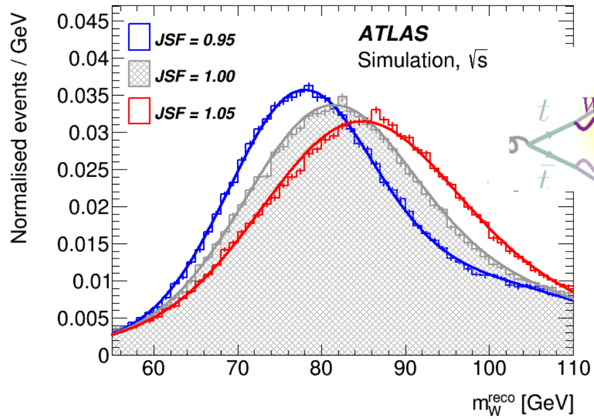
R_{lb}^{reco} sensitive to bJES → constrain bJES from data

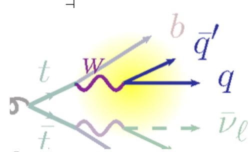




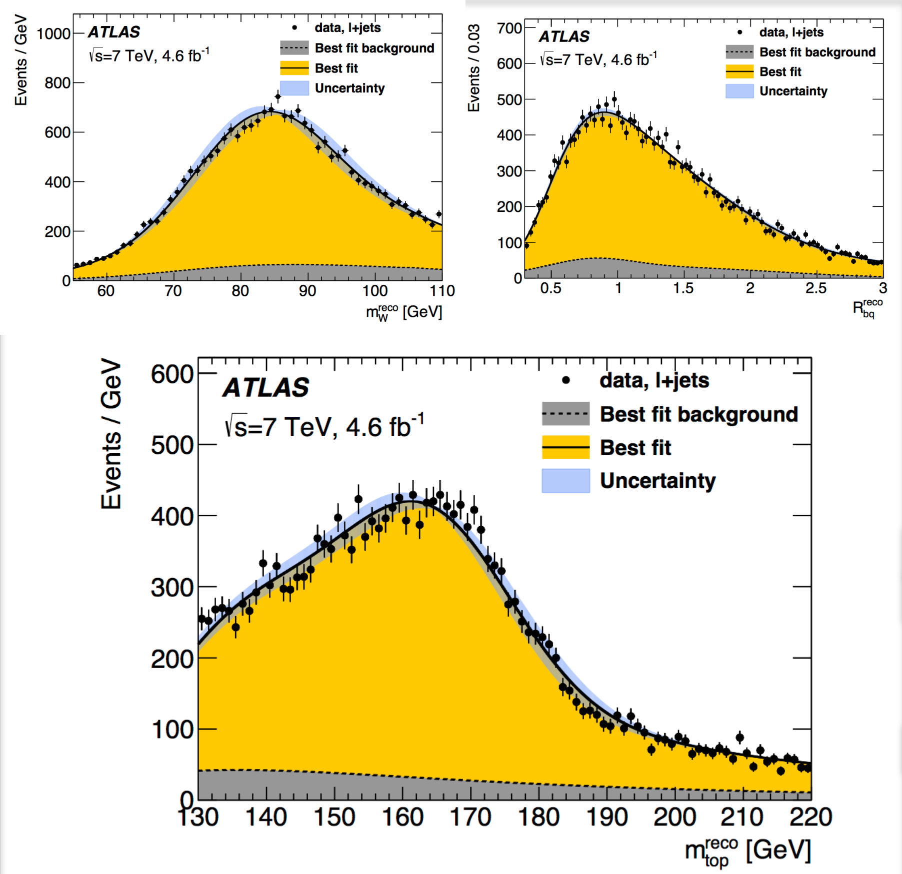
$$R_{\mathrm{lb}}^{\mathrm{reco}} = \frac{p_T^{blep} + p_T^{bhad}}{p_T^{l1} + p_T^{l2}} \quad \text{(2b-tagged jet events)}$$

$$R_{\mathrm{lb}}^{\mathrm{reco}} = \frac{p_T^{btagged}}{p_T^{average,l1,l2}} \quad \text{(1b-tagged jet events)}$$





TOP QUARK MASS - ATLAS l+jets @ 7 TeV



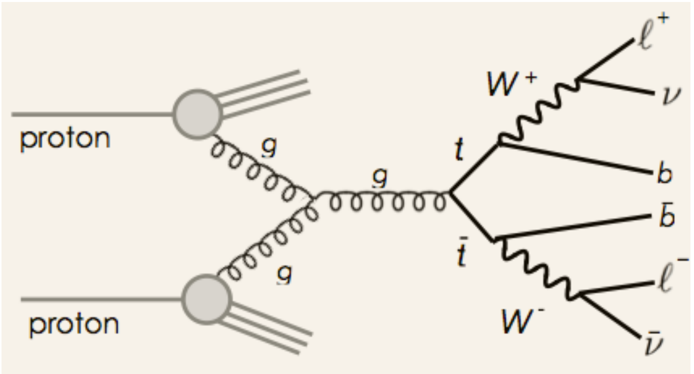
$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\ (\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF})\ \mathrm{GeV},$$
$$\mathrm{JSF} = 1.019 \pm 0.003\ (\mathrm{stat}),$$
$$\mathrm{bJSF} = 1.003 \pm 0.008\ (\mathrm{stat}),$$

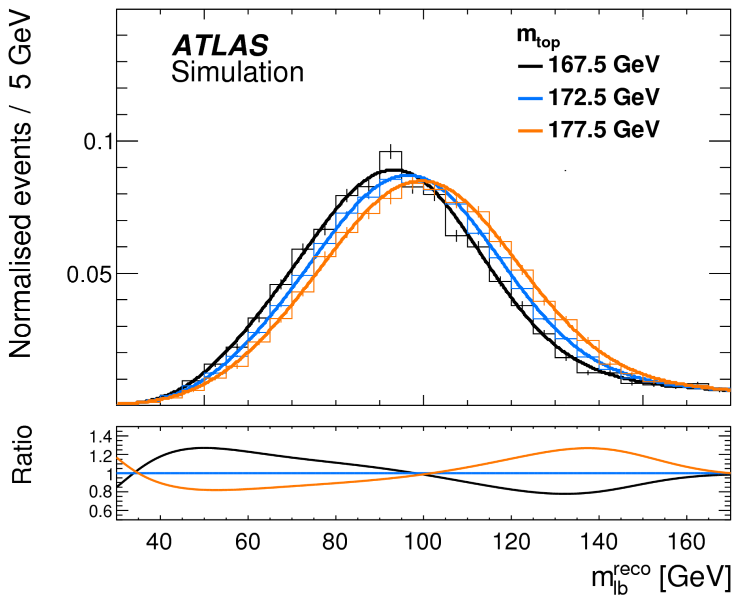
	$m_{\mathrm{top}}^{\ell+\mathrm{jets}}$ [GeV]
Results	172.33
Statistics	0.75
Method	0.11 ± 0.10
Signal Monte Carlo generator	0.22 ± 0.21
Hadronisation	0.18 ± 0.12
Initial- and final-state QCD radiation	0.32 ± 0.06
Underlying event	0.15 ± 0.07
Colour reconnection	0.11 ± 0.07
Parton distribution function	0.25 ± 0.00
Background normalisation	0.10 ± 0.00
W/Z+jets shape	0.29 ± 0.00
Fake leptons shape	0.05 ± 0.00
Jet energy scale	0.58 ± 0.11
Relative *b*-to-light-jet energy scale	0.06 ± 0.03
Jet energy resolution	0.22 ± 0.11
Jet reconstruction efficiency	0.12 ± 0.00
Jet vertex fraction	0.01 ± 0.00
b-tagging	0.50 ± 0.00
Leptons	0.04 ± 0.00
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.15 ± 0.04
Pile-up	0.02 ± 0.01
Total systematic uncertainty	1.03 ± 0.31
Total	1.27 ± 0.33

(Rel. total uncertainty: 0.7%)
Dominant uncertainties: b-tagging, JES, stat)

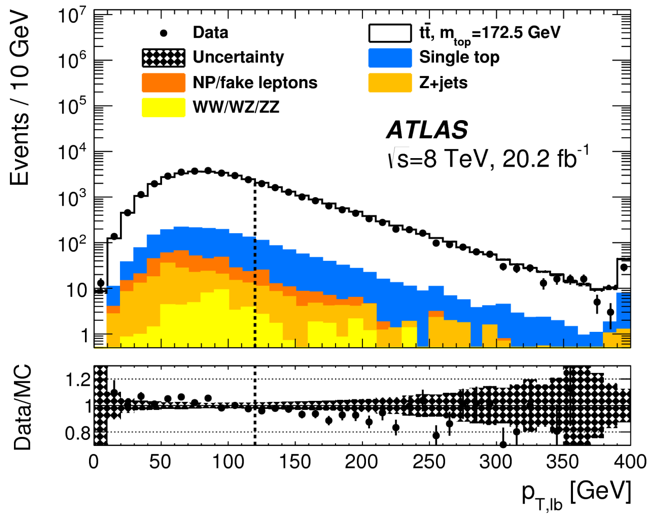
TOP QUARK MASS
ATLAS dilepton @ 7 TeV and 8 TeV

7 TeV: Eur. Phys. J. C (2015) 75:330
8 TeV: arXiv:1606.02179



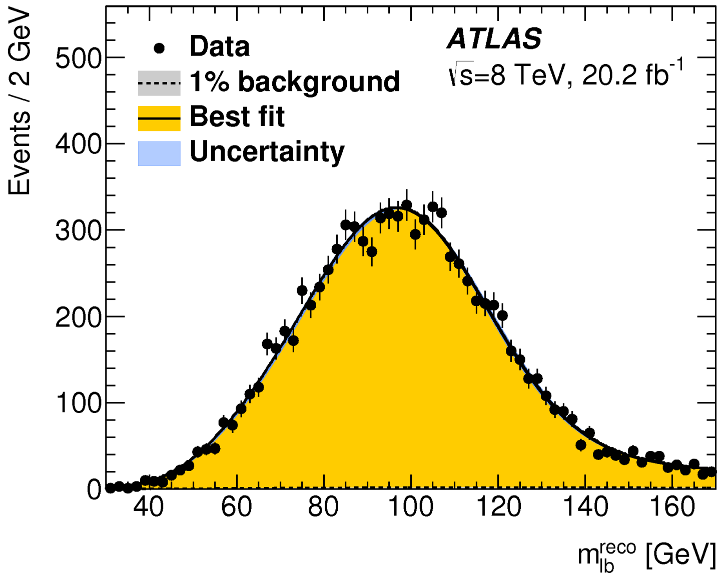


- Background fraction ≤ 2%.
- Under-constrained event kinematics.
- Use 1D template method with m_{lb} observable as estimator (exploiting a partial reconstruction).
- 8 TeV analysis: Additional cut on $p_{T,lb}$ > 120 GeV → significant reduction of JES and modelling.



7 TeV: Eur. Phys. J. C (2015) 75:330
8 TeV: arXiv:1606.02179

TOP QUARK MASS ATLAS dilepton @ 7 TeV and 8 TeV



- Best precision achieved @ 8 TeV: Rel. total uncertainty 0.5% (dominant uncertainties: JES, bJES, signal modelling).

	7 TeV m_{top}^{dil} [GeV]	8 TeV m_{top}^{dil} [GeV]
Results	173.79	172.99
Statistics	0.54	0.41
Method	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.26 ± 0.16	0.09 ± 0.14
Hadronisation	0.53 ± 0.09	0.22 ± 0.08
Initial- and final-state QCD radiation	0.47 ± 0.05	0.23 ± 0.05
Underlying event	0.05 ± 0.05	0.10 ± 0.11
Colour reconnection	0.14 ± 0.05	0.03 ± 0.11
Parton distribution function	0.11 ± 0.00	0.05 ± 0.00
Background normalisation	0.04 ± 0.00	0.03 ± 0.00
W/Z+jets shape	0.00 ± 0.00	0
Fake leptons shape	0.01 ± 0.00	0.08 ± 0.00
Jet energy scale	0.75 ± 0.08	0.54 ± 0.04
Relative b-to-light-jet energy scale	0.68 ± 0.02	0.30 ± 0.01
Jet energy resolution	0.19 ± 0.04	0.09 ± 0.03
Jet reconstruction efficiency	0.07 ± 0.00	0.01 ± 0.00
Jet vertex fraction	0.00 ± 0.00	0.02 ± 0.00
b-tagging	0.07 ± 0.00	0.03 ± 0.02
Leptons	0.13 ± 0.00	0.14 ± 0.00
E_T^{miss}	0.04 ± 0.03	0.01 ± 0.01
Pile-up	0.01 ± 0.00	0.05 ± 0.01
Total systematic uncertainty	1.31 ± 0.23	0.74 ± 0.25
Total	1.41 ± 0.24	0.84 ± 0.25

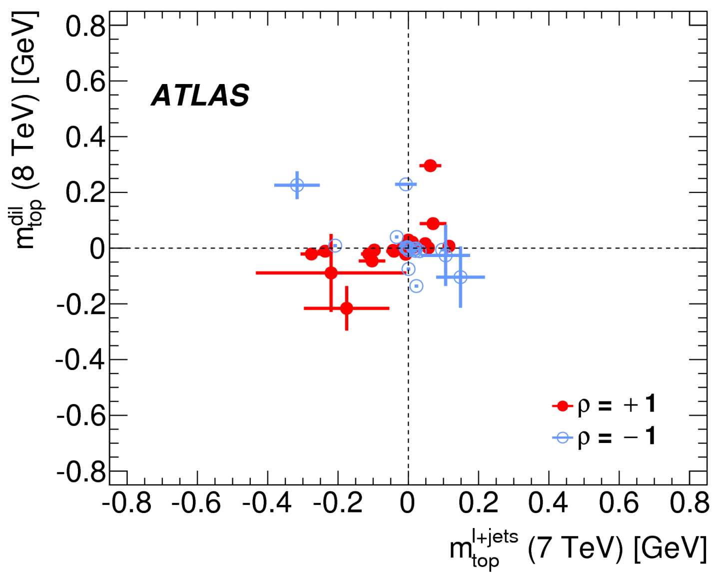
8 TeV $m_{top} = 172.99 \pm 0.41\ (\mathrm{stat}) \pm 0.74\ (\mathrm{syst})\ \mathrm{GeV}$

7 TeV $m_{top}^{dil} = 173.79 \pm 0.54\ (\mathrm{stat}) \pm 1.30\ (\mathrm{syst})\ \mathrm{GeV}.$

TOP QUARK MASS COMBINATION

arXiv:1606.02179

- The 3 measurements combined using the BLUE method taking correlations into account.



	m_{top}^{all} [GeV]
Results	172.84
Statistics	0.34
Method	0.05
Signal Monte Carlo generator	0.14
Hadronisation	0.23
Initial- and final-state QCD radiation	0.08
Underlying event	0.02
Colour reconnection	0.01
Parton distribution function	0.08
Background normalisation	0.04
W/Z+jets shape	0.09
Fake leptons shape	0.05
Jet energy scale	0.41
Relative b-to-light-jet energy scale	0.25
Jet energy resolution	0.08
Jet reconstruction efficiency	0.04
Jet vertex fraction	0.02
b-tagging	0.15
Leptons	0.09
E_T^{miss}	0.05
Pile-up	0.03
Total systematic uncertainty	0.61
Total	0.70

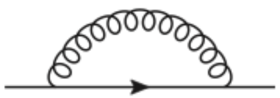
$$m_{top} = 172.84 \pm 0.34\ (\text{stat}) \pm 0.61\ (\text{syst})\ \text{GeV},$$

(Rel. total uncertainty: 0.4%)
Dominant uncertainties: JES, stat, bJES, Hadronisation)

TOP QUARK MASS

Alternative Techniques

- Measure an observable that can be theoretically calculated using a well defined top mass scheme (e.g. pole mass).

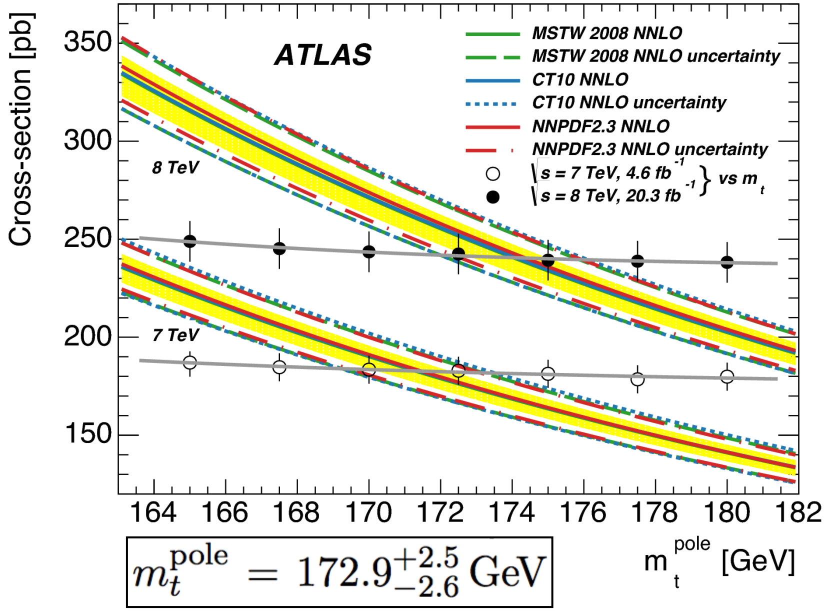


arXiv:1412.3649 [hep-ph]

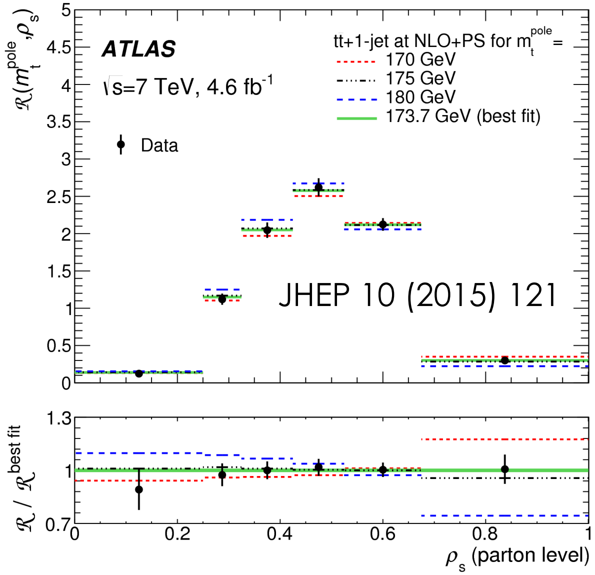
$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(R = 1\,\mathrm{GeV}) + \Delta_{t,\mathrm{MC}}(R = 1\,\mathrm{GeV})$$
$$\Delta_{t,\mathrm{MC}}(1\,\mathrm{GeV}) \simeq \mathcal{O}(1\,\mathrm{GeV})\,.$$

- Observables used:
  - Top quark pair cross section (predictions at NNLO+NNLL).
  - Normalised ttbar+1-jet differential cross section as a function of the inverse of the invariant mass of the ttbar+1-jet system (predictions at NLO+PS) (better sensitivity).

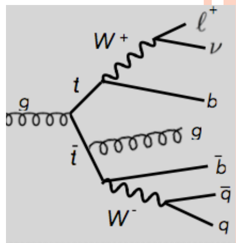
Eur. Phys. J. C74 (2014) 3109



$$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}$$



JHEP 10 (2015) 121

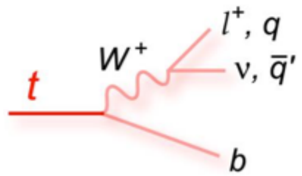


$$m_t^{\mathrm{pole}} = 173.7 \pm 1.5\,(\mathrm{stat.}) \pm 1.4\,(\mathrm{syst.})\,^{+1.0}_{-0.5}\,(\mathrm{theo.})\,\mathrm{GeV}$$

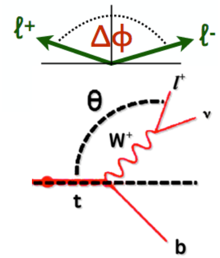
TOP SPIN CORRELATIONS IN TOP PAIRS

- The top spin information is transferred to the decay products without dilution.

top lifetime	$<$	QCD timescale	$\ll$	spin-flip timescale
10^{-25} s	$<$	10^{-24} s	$\ll$	10^{-21} s



- Negligible polarisation in SM QCD top pair production, but spins of the top and anti-top are correlated.
- The amount of spin correlation is sensitive to the production mechanism (many BSM scenarios predict different spin correlations).
- Latest measurements performed with lepton angular distributions in dilepton events:
  - Indirect measurement: $\Delta\Phi_{ll}$ (best probe in laboratory frame)
  - Direct measurement: $\cos\theta_1 \cos\theta_2$ (in the top rest frame)



$$\frac{1}{N}\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + B_1\cos\theta_1 + B_2\cos\theta_2 - C_{\text{helicity}}\cos\theta_1 \cdot \cos\theta_2\right),$$

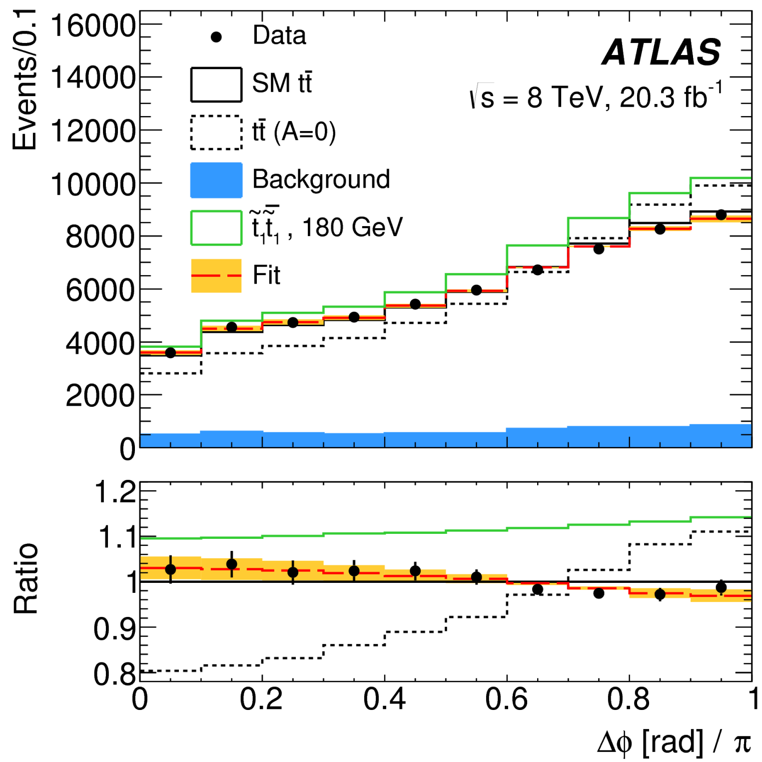
$$\boxed{C_{\text{helicity}} = -A_{\text{helicity}}\alpha_1\alpha_2} \quad \boxed{A_{\text{helicity}} = (N_{\text{like}} - N_{\text{unlike}})/(N_{\text{like}} + N_{\text{unlike}})}$$

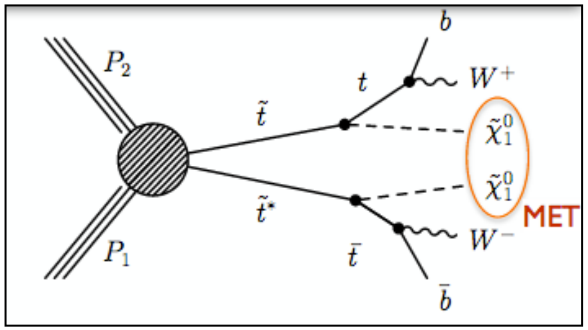
$$\boxed{A^{\text{SM}}_{\text{helicity}} = 0.318 \pm 0.005}$$

TOP SPIN CORRELATIONS @ 8 TeV, dilepton

- Quantify spin correlation strength as fraction "f_{SM}" of SM expectation.
- Template fit using MC with and without spin correlations.
- Search for stop quark production
  - squarks have spin 0 → daughter top quarks look similar to uncorrelated ttbar events.
  - But only 1/6 of ttbar cross section for $m_{stop} = m_{top}$.
  - Exclusion of $m_{top} < m_{stop} < 191$ GeV @ 95%CL (assuming 100% BR stop→top +LSP).

Phys. Rev. Lett. 114, 142001 (2015)





$$f_{\rm SM} = 1.20 \pm 0.05\,({\rm stat}) \pm 0.13\,({\rm syst})$$

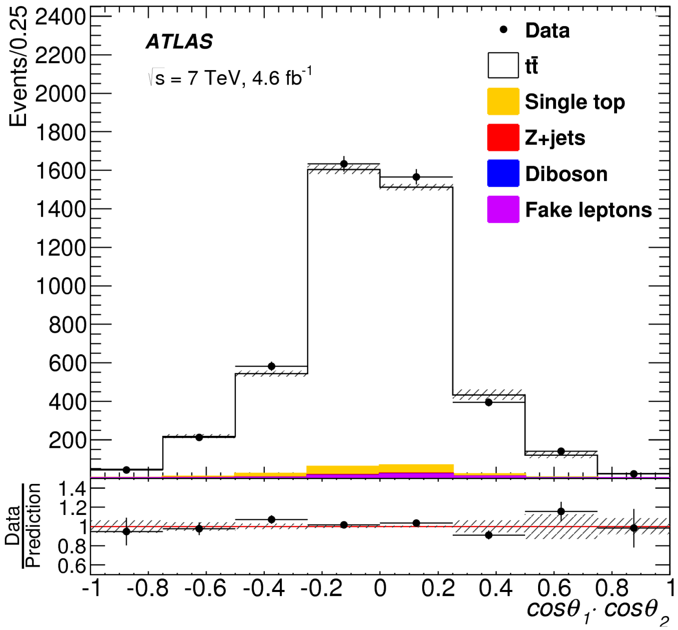
$$A_{\rm helicity} = 0.38 \pm 0.04$$

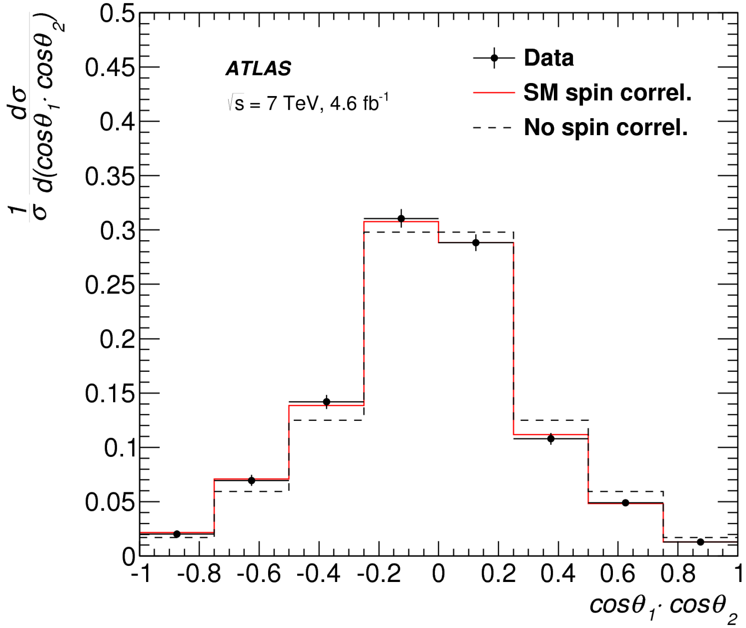
(in agreement with SM predictions)

TOP SPIN CORRELATIONS @ 7 TeV, dilepton

Phys. Rev. Lett. D 93, 012002 (2016)

- Distribution of $\cos\theta_1 \cos\theta_2$ is reconstructed using a “topology reconstruction method”.
- Unfolded to parton level using an Iterative Bayesian Method.





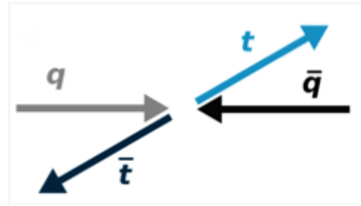
(in agreement with SM predictions)

$$A_{\text{helicity}} = 0.315 \pm 0.061(\text{stat.}) \pm 0.049(\text{syst.})$$

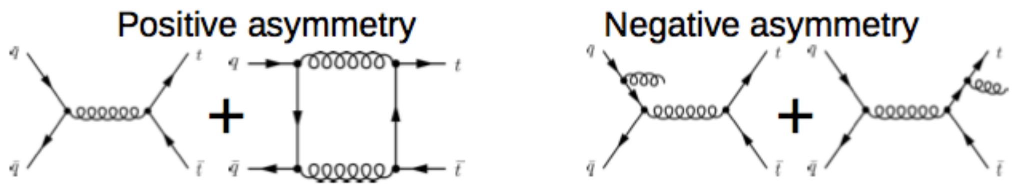
Dominant uncertainties: Unfolding method, signal modelling, jets

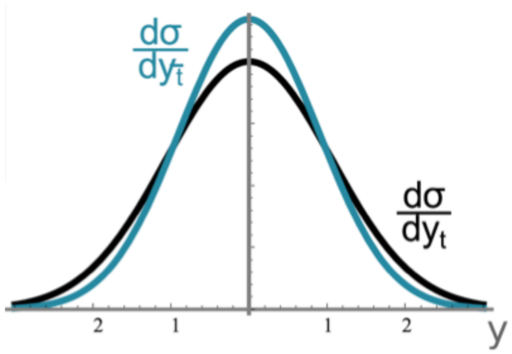
CHARGE ASYMMETRY

Kühn, Rodrigo, JHEP 1201 (2012) 063
Bernreuther, Si, Phys. Rev. Lett. D 86 (2012) 034026



- At LO tops and anti-tops are symmetric.
- At higher orders: interference of diagrams → connects the direction of top and initial quark and direction of anti-top and initial anti-quark.





- Only in qqbar initial state (not for the dominant gg fusion).
- Relatively a small effect in the SM.

  Ac: 1% A_{ll}: 0.6%

- Can be enhanced in BSM scenarios (axigluons, Z' bosons, KK gluons).

Measurements of inclusive and differential observables in full and fiducial phase space available.

Measured Observables

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

$\Delta|y| = |y_t| - |y_{\bar{t}}|$ NLO QCD: 0.0111±0.0004

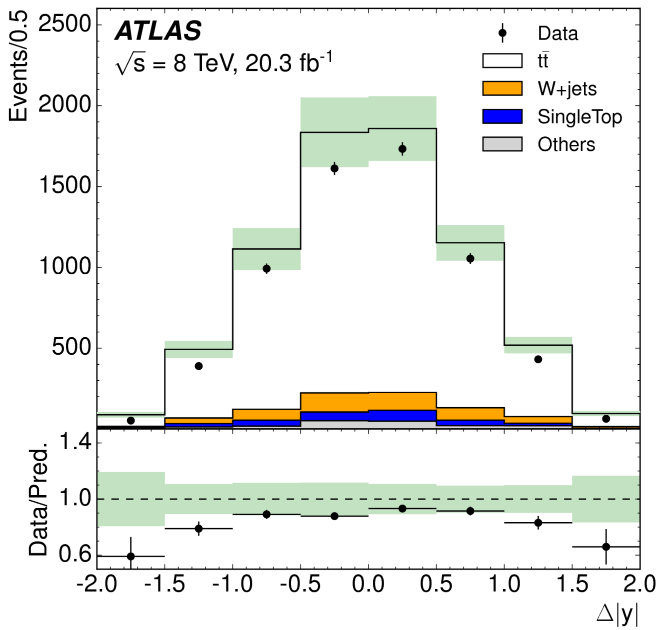
In dilepton channel:

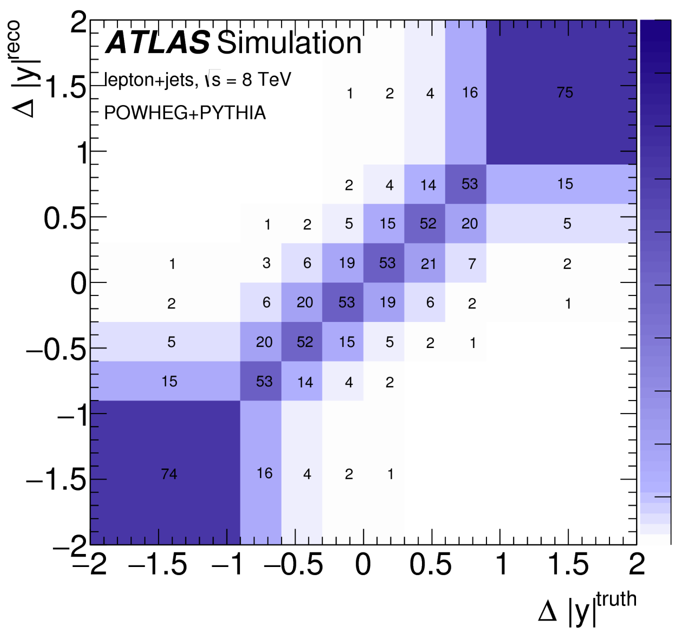
$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}$$

$\Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$ NLO QCD: 0.0064±0.0003

CHARGE ASYMMETRY MEASUREMENTS

- Measurements performed in l+jets (including also boosted top specific analysis) and dilepton channels.
- Different methods to reconstruct the ttbar kinematics (e.g. likelihood fit in l+jets, specific technique to deal with boosted top decays in l +jets boosted, KIN method in dilepton).
- A Bayesian unfolding used to correct to parton level (the likelihood is extended with nuisance parameter terms to take systematics into account).



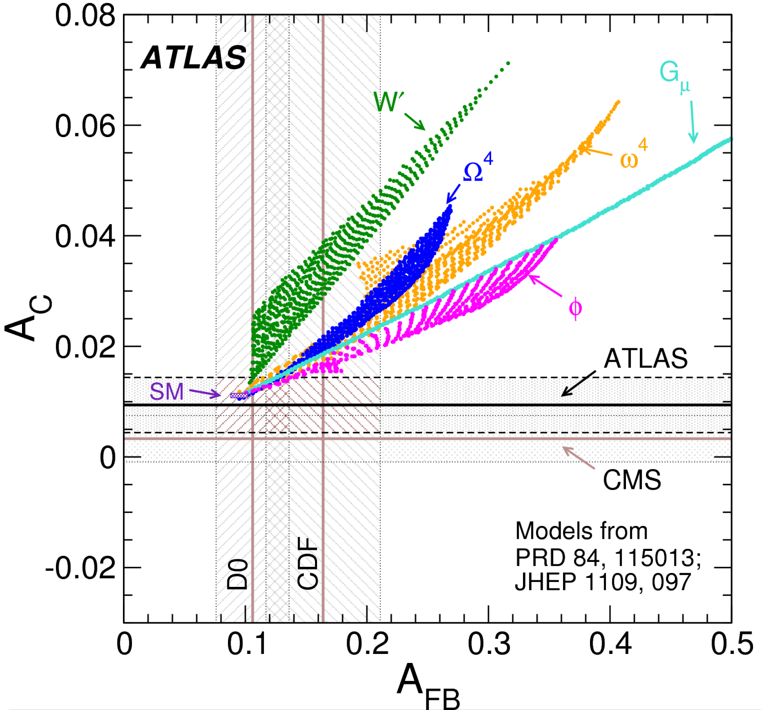


Phys. Lett. B 756, 52 (2016) 756

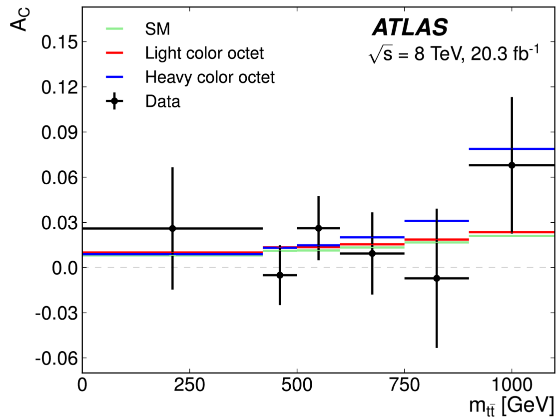
Eur. Phys. J. C76 (2016) 87

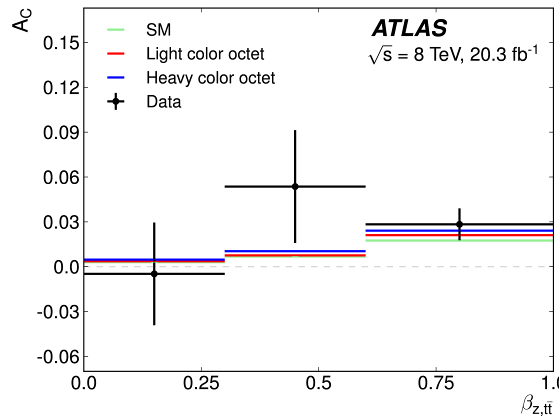
CHARGE ASYMMETRY @ 8 TeV l+jets

- Inclusive and differential measurements as a function of invariant mass, p_T and longitudinal boost β_z of the ttbar system provided.



$$A_C = 0.009 \pm 0.005 \text{ (stat.+syst.)}$$



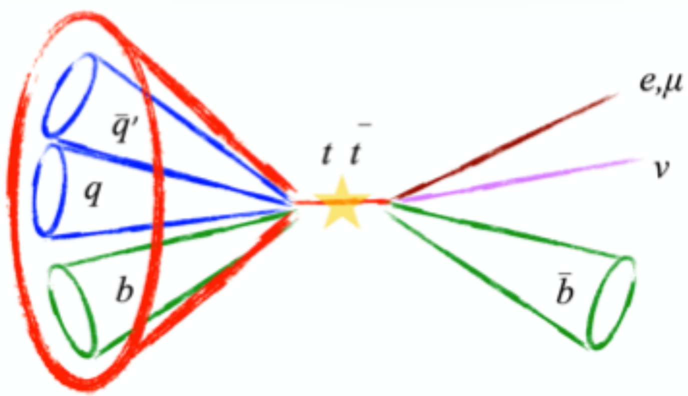


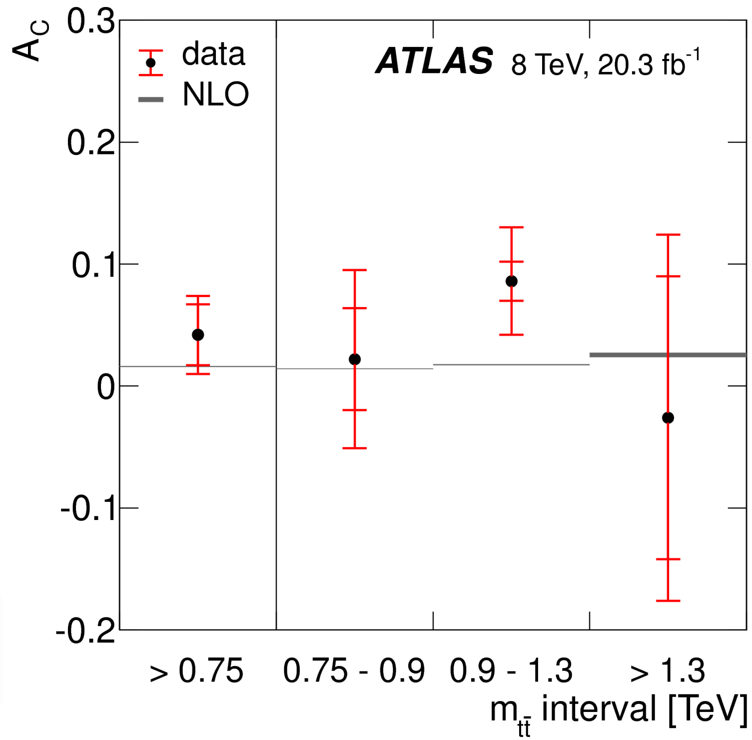
- Precision dominated by statistical uncertainty (dominant systematic uncertainties signal modelling and uncertainties affecting W+jets).
- All compatible with SM predictions.
- Limits set on the parameters (i.e. mass and couplings) of BSM models .

CHARGE ASYMMETRY @ 8 TeV l+jets BOOSTED TOP QUARKS

Phys. Lett. B (2016) 756

- Measurement in events where top quark pairs are produced with large invariant mass (> 750 GeV).
- Used reconstruction techniques designed to deal with collimated decay topology of boosted tops.
- Hadronic top reconstructed as a single large-R jet and tagged using jet substructure variables.
- This kinematic regime has a higher sensitivity for the SM asymmetry and BSM models that introduce massive new states.





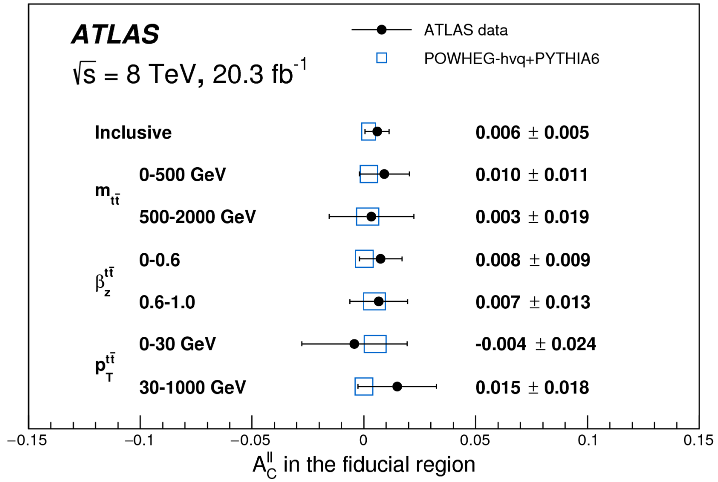
Measurements compatible with SM. Precision limited by statistics.

$$m_{t\bar{t}} > 750\text{GeV}, -2 < \Delta|y| < 2. \quad A_C = (4.2 \pm 3.2)\%$$

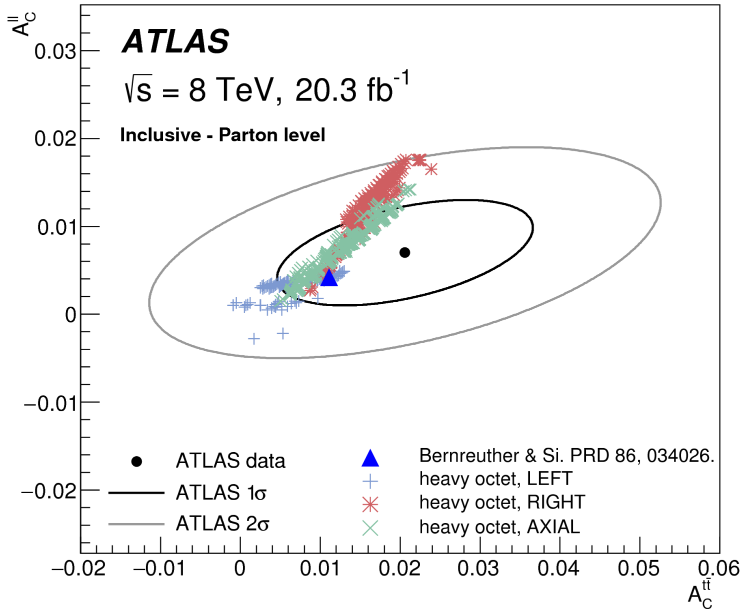
arXiv:1604.05538

CHARGE ASYMMETRY @ 8 TeV dilepton

- A_C and A_{ll} inclusive and differential measurements provided in fiducial and full phase space.
- Inclusive measurements also compared with BSM compatible with Tevatron results.



Measurements compatible with SM. Precision limited by statistics (dominant systematics being signal modelling and kinematic reconstruction).



CONCLUSIONS

- Run-1 legacy measurements available for top quark mass and angular distributions in top pair events sensitive to spin correlations and charge asymmetry effects.
- Allow for stringent test of the SM, being also sensitive to new physics.
- Top quark mass:
  - Best precision achieved using the standard "template" method to determine the MC top quark mass with 0.4% precision.
  - Direct pole top quark mass determinations reaching 1.3% precision.
- Spin correlations and charge asymmetry measurements all compatible with SM predictions, allowing to set limits on BSM scenarios.
- Statistical uncertainties still important in top quark mass and charge asymmetry measurements.