Top quark pair properties using the ATLAS detector at the LHC

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on behalf of the ATLAS collaboration

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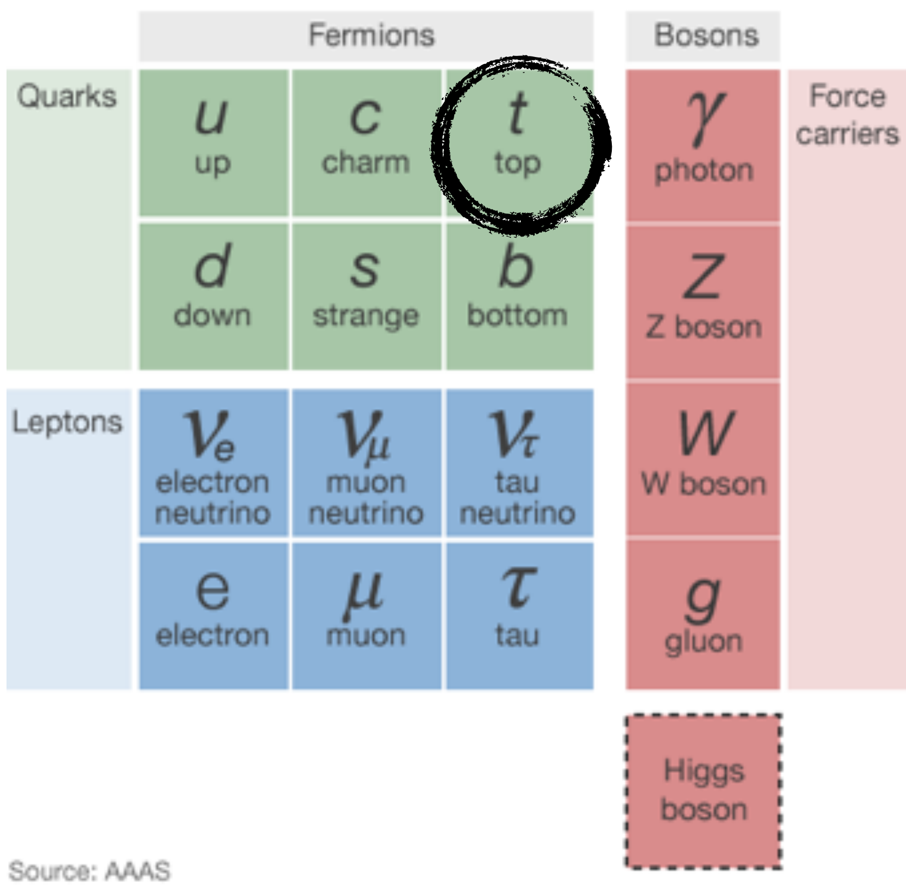
Phenomenology 2015
Pittsburgh, May 4-6

Top quark



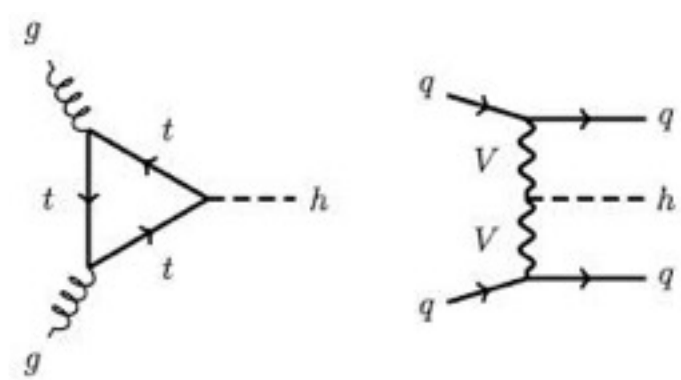
- First observed in 1995 by CDF and DØ (Tevatron)

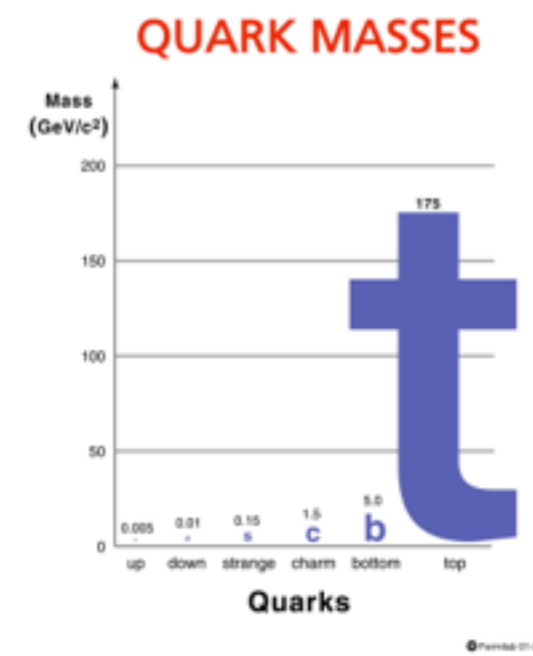
[F Abe et al,PRL,74:2626-2631,1995; S. Abachi et al,PRL,74:2632-2637,1995]

- Mass = 173.34 ± 0.76 GeV [arXiv:1403.4427]

Heaviest of all fundamental particles in the SM

Largest mass ➙ Largest coupling to SM Higgs





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Why studying top properties?

- Test Standard Model (SM) predictions
- Search for new Physics

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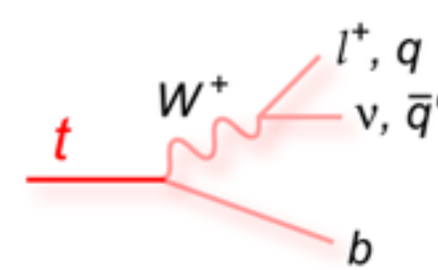
- Decays before hadronization: $\tau \sim 10^{-25}$ s

(spin information passes to the decay products)

- Dominant decay to t ➞ Wb:

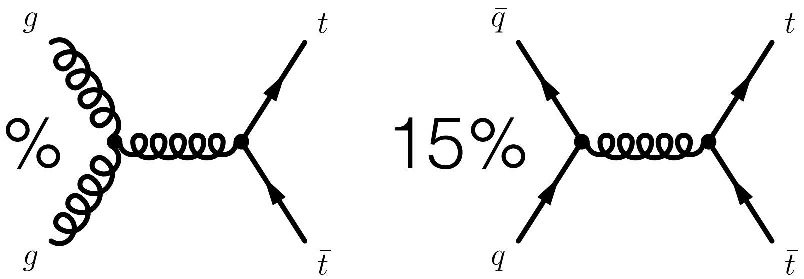
($|V_{tb}| > 0.999 \Rightarrow$ BR(t ➝ Wb) ~ 1)



Top production at the LHC

85%

15%

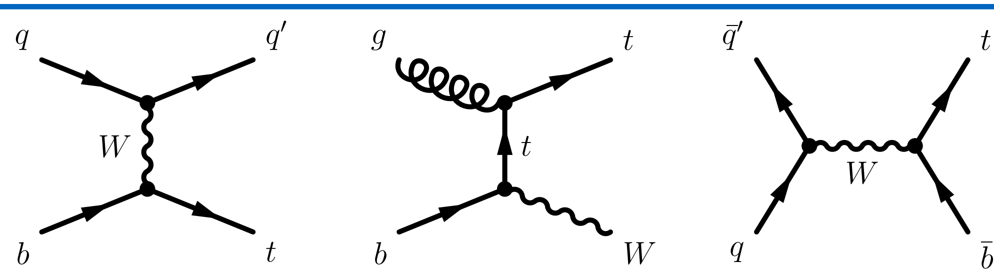


pair production

$$\sqrt{s} = 7 \rightarrow \sigma_{t\bar{t}} = 177^{+10}_{-11}\ pb$$

$$\sqrt{s} = 8 \rightarrow \sigma_{t\bar{t}} = 253^{+13}_{-15}\ pb$$

M.Cacciari et al., P.L. B 710 612(2012);
P.Barnreuther et al., P.R.L. 109 132001(2012);
M.Czakon and A.Mitov, J.H.E.P. 1212 054(2012);
M.Czakon and A.Mitov, J.H.E.P. 1301 080(2013);
M.Czakon, P.Fiedler and A.Mitov, P.R.L. 110 252004 (2013).



single top production

$$\sqrt{s} = 7 \rightarrow \sigma_t = 64.57^{+2.63}_{-1.74}\ pb,\ \sigma_{Wt} = 15.74^{+1.17}_{-1.21}\ pb,\ \sigma_s = 4.63^{+0.20}_{-0.18}\ pb$$

$$\sqrt{s} = 8 \rightarrow \sigma_t = 87.76^{+3.44}_{-1.91}\ pb,\ \sigma_{Wt} = 22.37^{+1.52}_{-1.52}\ pb,\ \sigma_s = 5.61^{+0.22}_{-0.22}\ pb$$

N.Kidonakis, P.R. D 83, 091503(R) (2011);
N.Kidonakis, P.R. D 82, 054018 (2010);
N.Kidonakis ,P.R. D 81, 054028 (2010)

@NNLO + NNLL
m_{top}=172.5 GeV

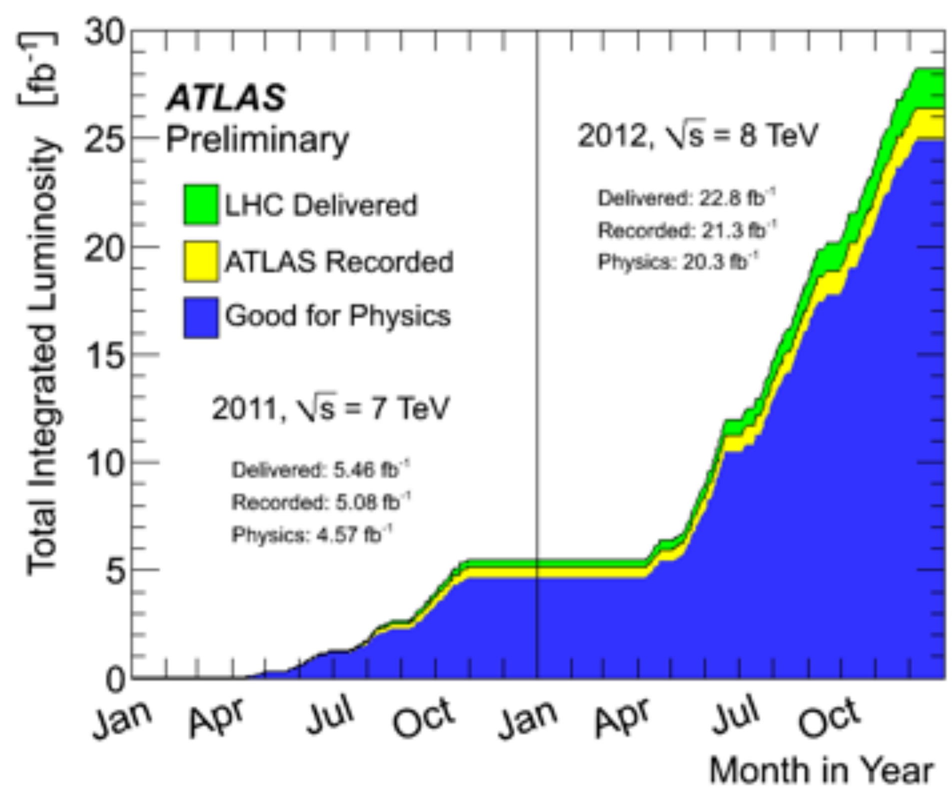
- At peak instantaneous luminosity @ ATLAS were produced:

  ~2 top pairs/sec

  ~1 single top/sec

(during 2012 data-taking)

- **Overall** ~ **15M** top quarks produced in 2011 & 2012!



Top mass

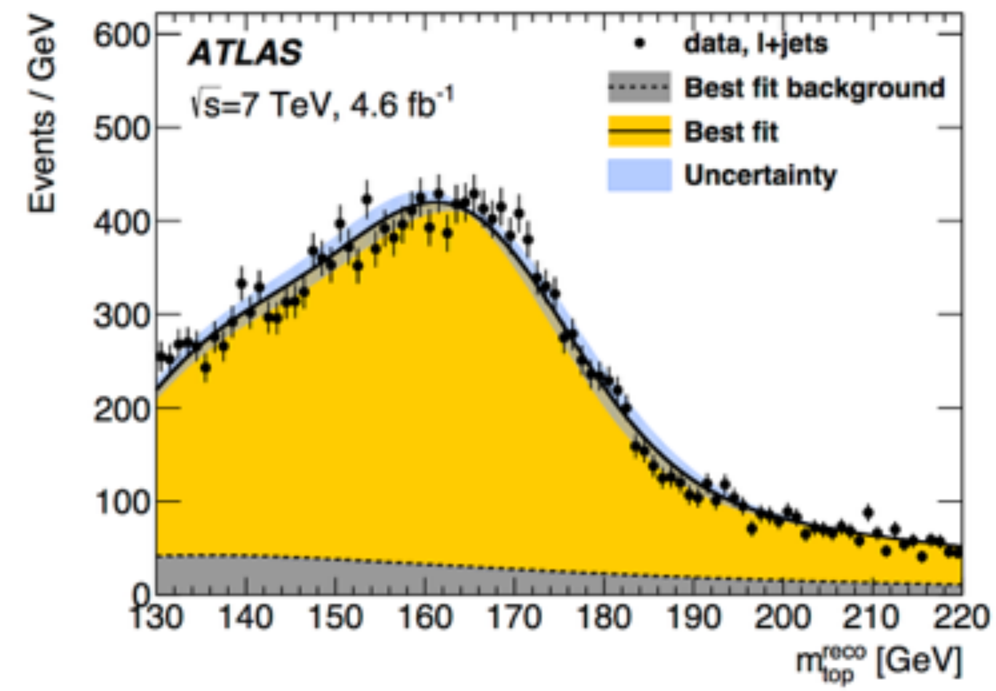
- **Direct measurements** @ 7 TeV (4.6 fb^{-1})
  [arXiv:1503.05427]

$$t\bar{t} \to \ell + \text{jets and } t\bar{t} \to \ell^+\ell^- + \text{jets}$$

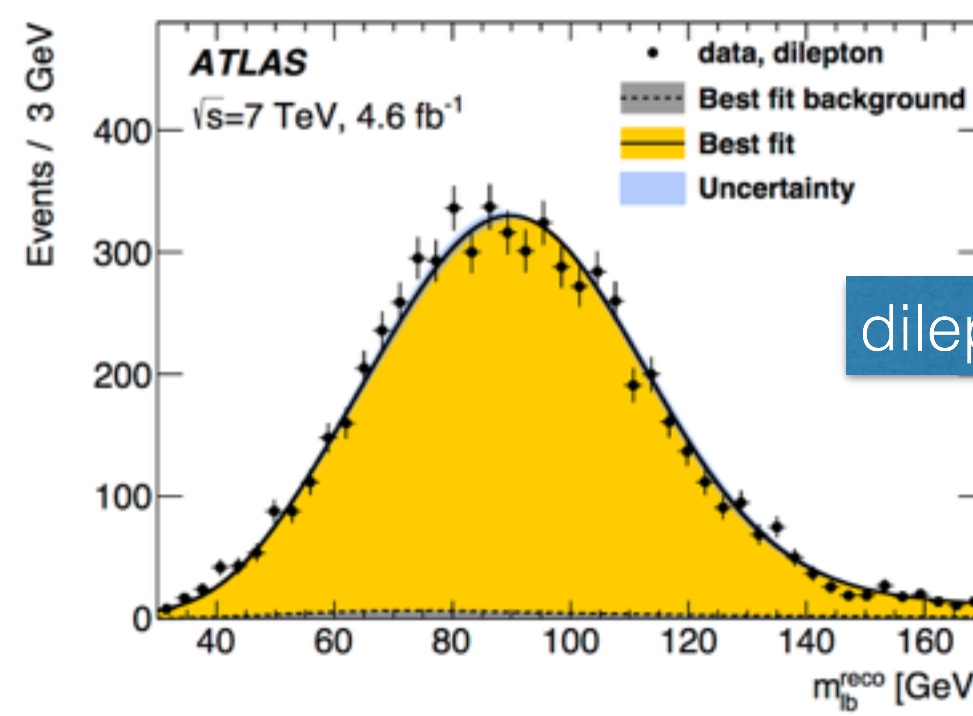
- The **lepton+jets analysis** implements a **3D template** fit to simultaneously determine m_{top} along with a global jet energy scale factor (JSF) and a relative b-to-light quark jet energy scale factor (bJSF), to mitigate the JES and bJES systematic uncertainties.
  - Observables: m_t, m_W and $R_{bq}^{\text{reco}} = \frac{p_T^{b_{\text{had}}} + p_T^{b_{\text{lep}}}}{p_T^{W_{j1}} + p_T^{W_{j2}}}$
  - $m_t = 172.33 \pm 0.75(\text{stat} + \text{JSF} + \text{bJSF}) \pm 1.02(\text{syst})$ GeV
- The **dilepton analysis** uses a 1-dimensional template method relying on the m_{lb} observable.
  - $m_t = 173.79 \pm 0.54(\text{stat}) \pm 1.30(\text{syst})$ GeV

Main systematics:
- l+jets: JES, btag
- dilep: JES, bJES

lepton + jets



dilepton

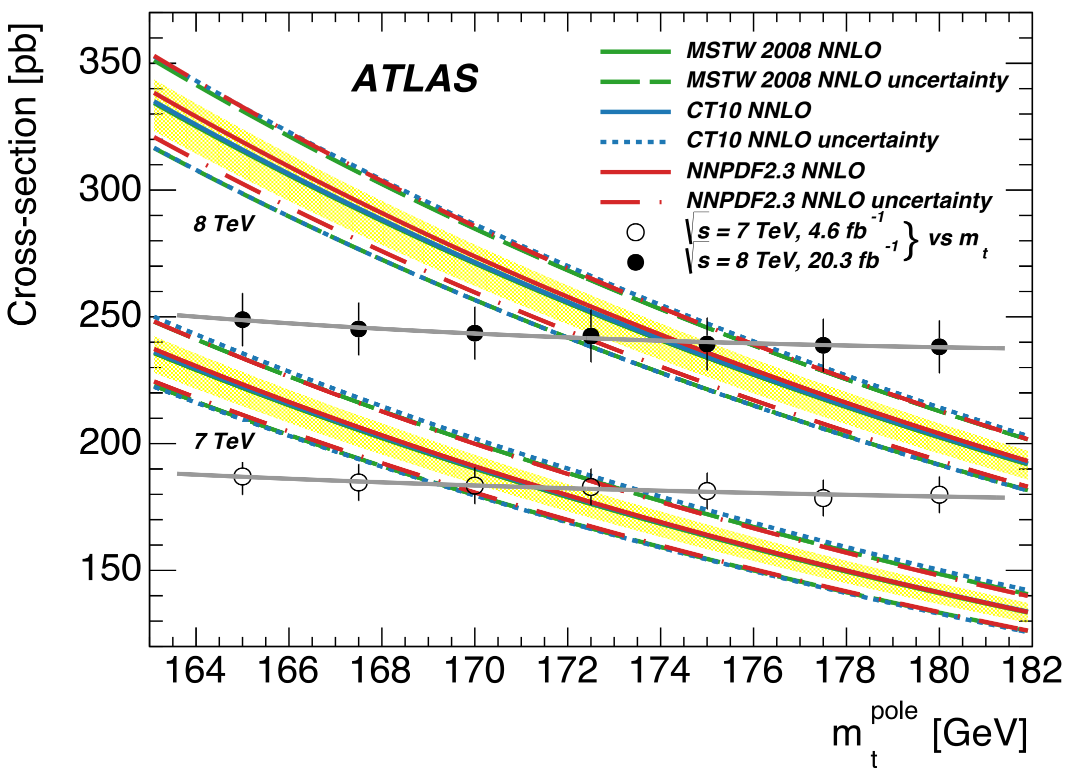


Top pole mass

- Top-quark mass derived from the kinematical reconstruction does not correspond to a well-defined renormalisation scheme leading to a theoretical uncertainty in its interpretation
- Alternative methods extract top quark mass in a well-defined scheme

From precision measurements of $\sigma_{t\bar{t}}$ in eμ channel @ 7+8 TeV [Eur.Phys.J. C74 (2014) 10, 3109]

$$\sigma_{t\bar{t}}^{theo}(m_t^{\text{ref}}) = \sigma(m_t^{\text{ref}}) \left(\frac{m_t^{\text{ref}}}{m_t^{\text{pole}}}\right)^4 (1 + a_1 x + a_2 x^2)$$



Main systematics: $t\bar{t}$ modelling, PDFs, knowledge of the integrated luminosities and LHC beam energy.

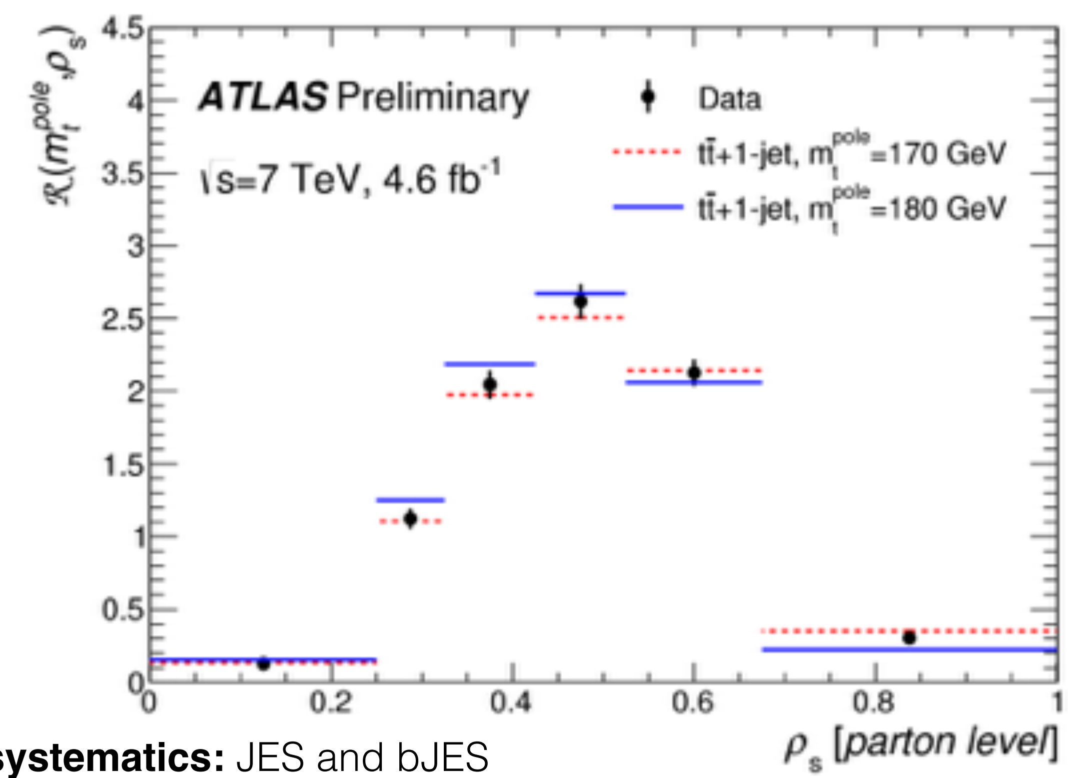
$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}$$

From $t\bar{t}$ +1jet events in single lepton channel @ 7 TeV

[ATLAS-CONF-2014-053]

Extracted from differential cross-section as a function of ρ_s

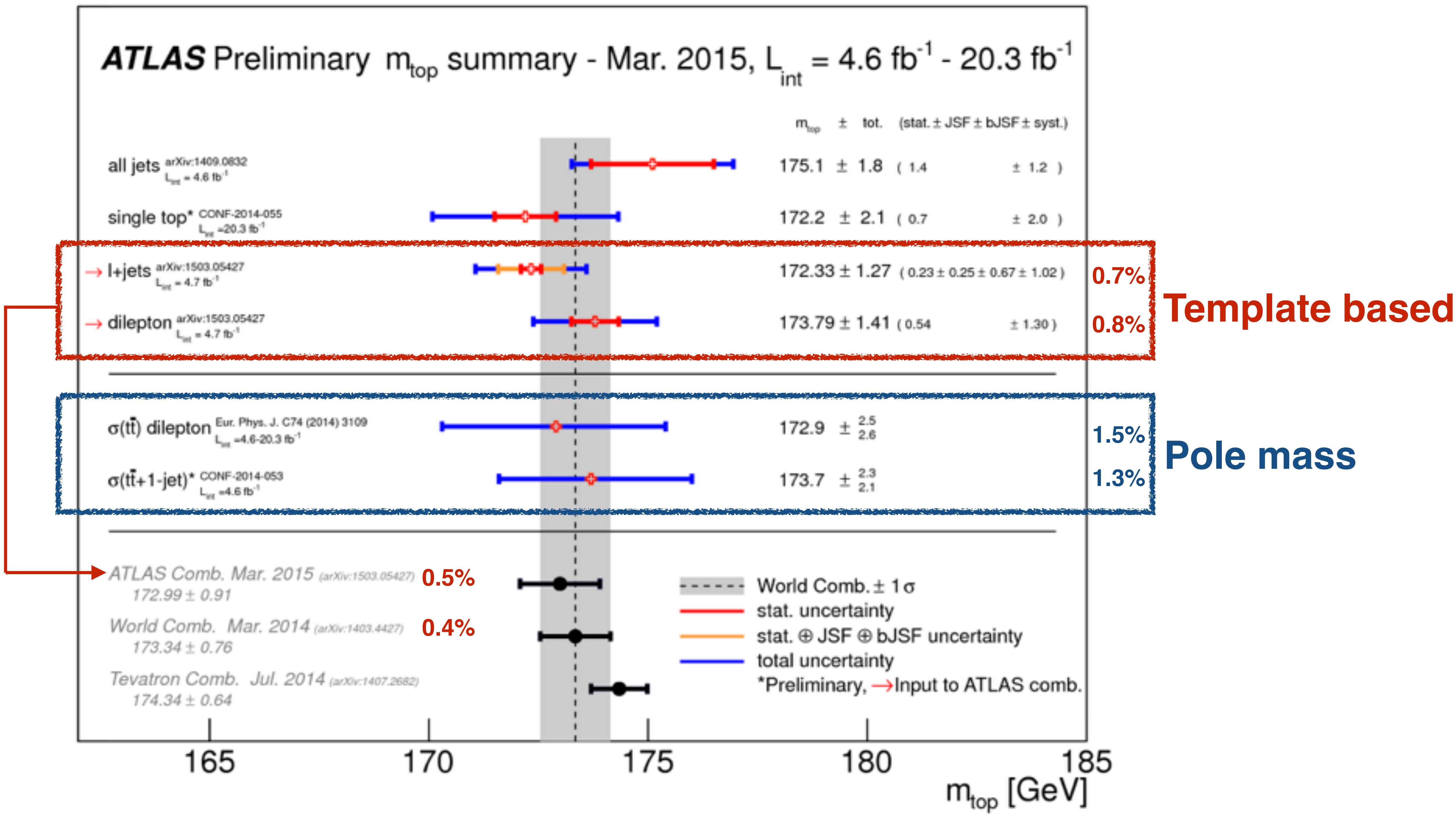
$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1j}} \frac{d\sigma_{t\bar{t}+1j}}{d\rho_s}(m_t^{\text{pole}} \rho_s), \;\; \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}, \;\; m_0 = 170 \text{ GeV}$$



Main systematics: JES and bJES

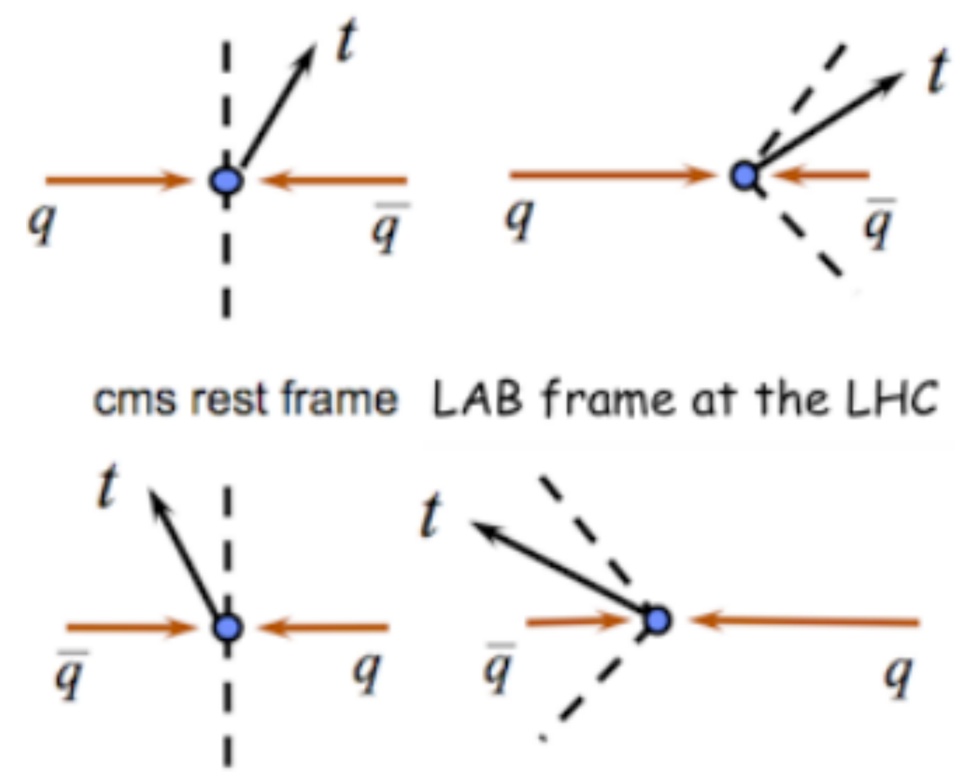
$$m_t^{\text{pole}} = 173.7 \pm 1.5(\text{stat.}) \pm 1.4(\text{syst.})^{+1.0}_{-0.5}(\text{theo.}) \text{ GeV}$$

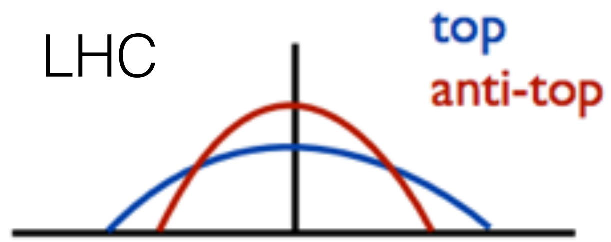
Top mass comparison



$t\bar{t}$ charge asymmetry

- At the LHC the dominant mechanism for the $t\bar{t}$ production is the **gluon fusion (~85 %)** which is **charge symmetric**
- The $t\bar{t}$ production via **$q\bar{q}$ or qg (~15 %) is charge asymmetric** and small in most of the phase space
- Valence quarks on average have large momentum than anti-quarks → rapidity distribution of **top quark is wider than anti-top**
- In the lab frame, top quarks preferentially emitted in the forward/backward directions while anti-top quarks are produced more centrally





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

Observable:

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

ATLAS charge asymmetry (1)

Single lepton channel @ 7 TeV

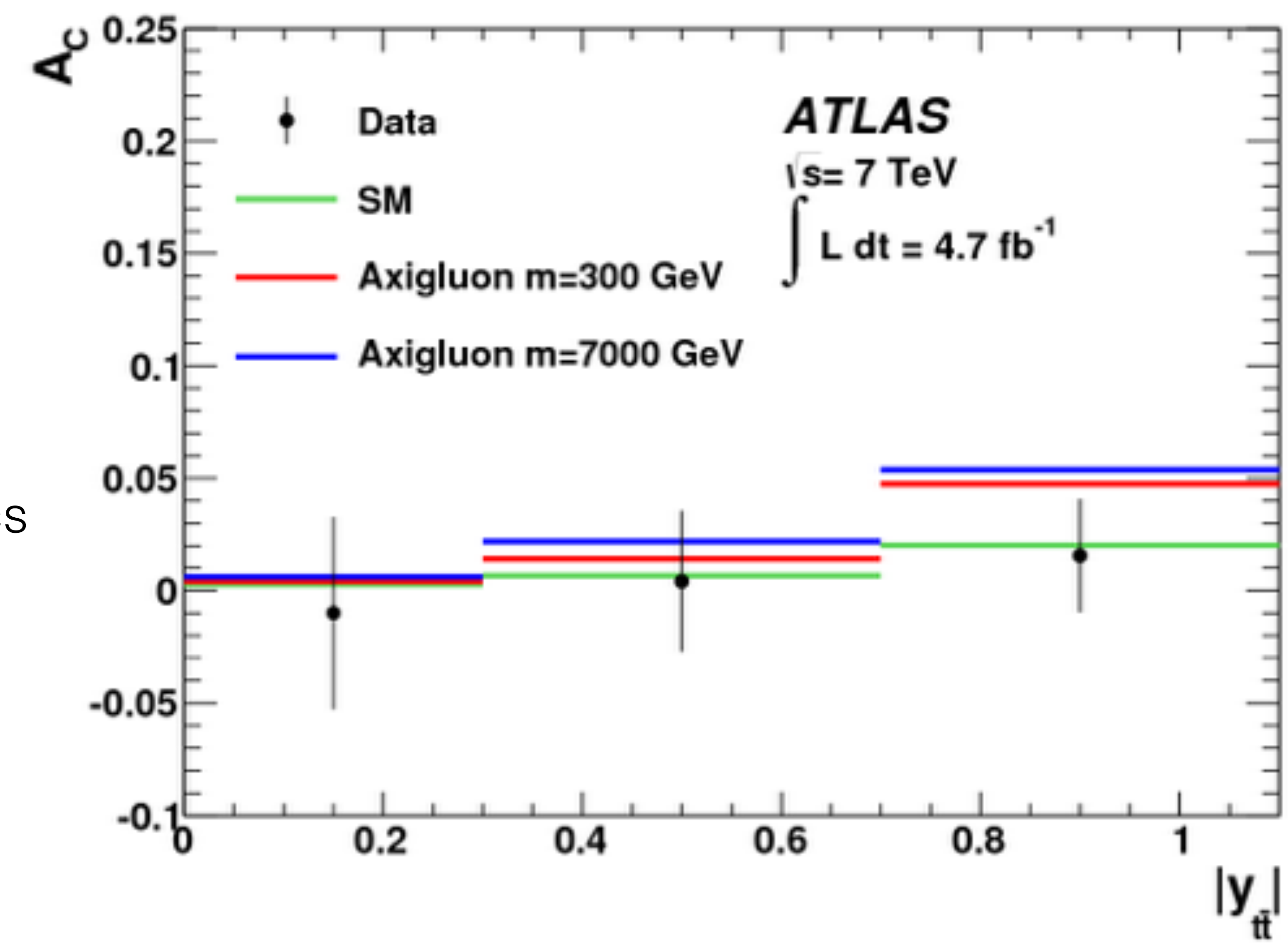
[JHEP02(2014)107]

- A kinematic fit based on a likelihood approach is used to reconstruct tt̄ system
- Inclusive result: $A_C^{t\bar{t}} = 0.006 \pm 0.010$

SM: 0.0123 ± 0.0005 (NLO+EW)

[PRD 86, 034026 (2012)]

- Differential measurements: m(tt̄), p_T(tt̄), y(tt̄)
- Differential distributions can point to new physics



- **Main systematics:**

Jet energy scale and resolution

Lepton energy scale and resolution

ATLAS charge asymmetry (2)

Dilepton channel @ 7 TeV
[arXiv:1501.07383]

- Can measure lepton and top quark based asymmetry
- The neutrino weighting technique is used to reconstruct the kinematics
- Inclusive result:

$A_C^{\ell\ell} = 0.024 \pm 0.015(\text{stat.}) \pm 0.009(\text{syst.})$ **SM:** 0.0070 ± 0.0003 (NLO)
[Phys.Rev. D86 (2012) 034026]

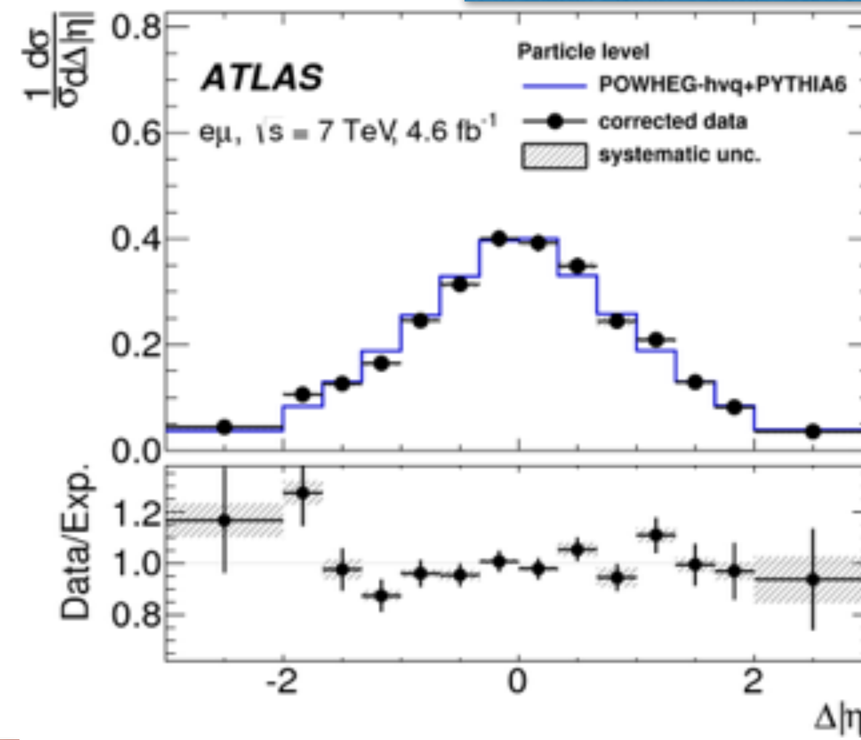
$A_C^{t\bar{t}} = 0.006 \pm 0.025(\text{stat.}) \pm 0.017(\text{syst.})$ **SM:** 0.0123 ± 0.0005 (NLO+EW)
[PRD 86, 034026 (2012)]

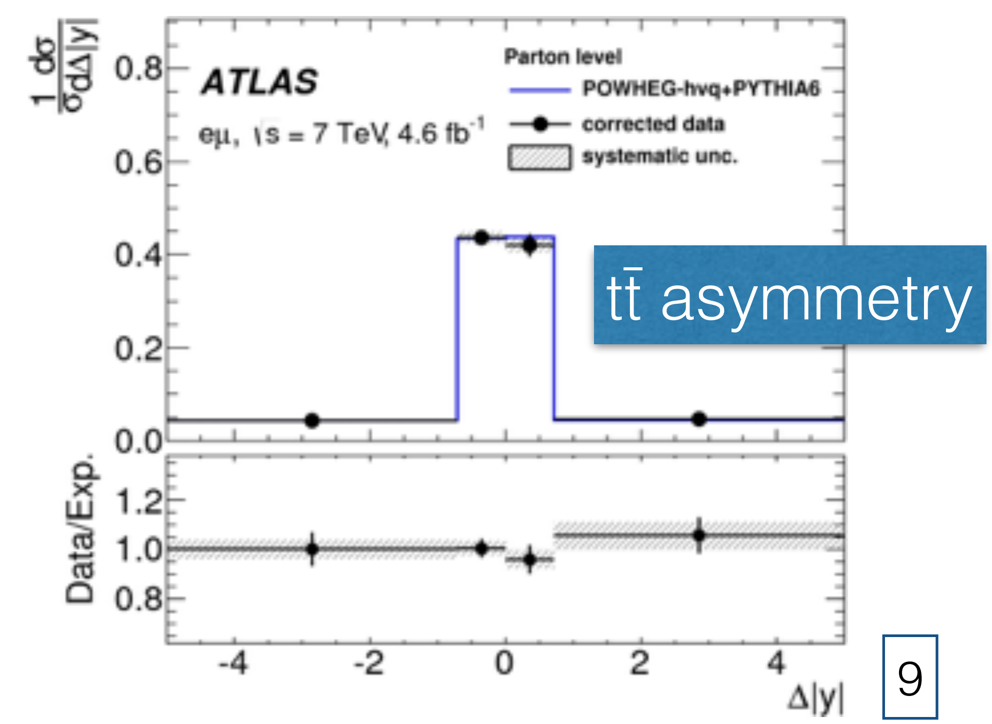
- **Main systematics:**

$A_C(ll)$: lepton reconstruction

$A_C(t\bar{t})$: lepton reconstruction, jet reconstruction and $E_T$miss

lepton asymmetry



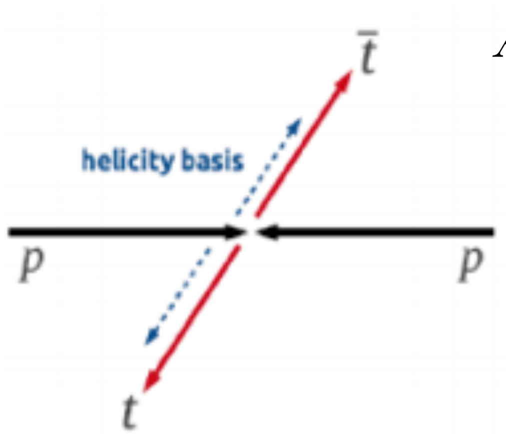


Spin Correlation

- Top quark pairs produced by the strong interaction are unpolarised (LO), but have correlated spins
- Since top quark decays before hadronisation → spins are unaffected by strong interactions
- Assuming SM decay of top quarks we can measure the spin correlation in $t\bar{t}$ → Probing new physics at the production.
- Spin information influences angular distributions of decay products
  - Can use this to determine the degree of correlation of the $t\bar{t}$ spins

Helicity basis: Vector defined along direction of top quark in $t\bar{t}$ rest frame

Degree of spin correlation can be then defined, where ↑ and ↓ denote spins measured with respect to the basis



$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}} = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

$A_{measured} = A_{SM} \times f_{SM}$, $A_{SM} = 0.31$

$f_{SM} = 0$ -> no correlation

$f_{SM} = 1$ -> correlation -> SM prediction

ATLAS spin correlation (1)

Dilepton and single lepton @ 7 TeV (4.6 fb⁻¹)

[Phys. Rev. D. 90, 112016 (2014)]

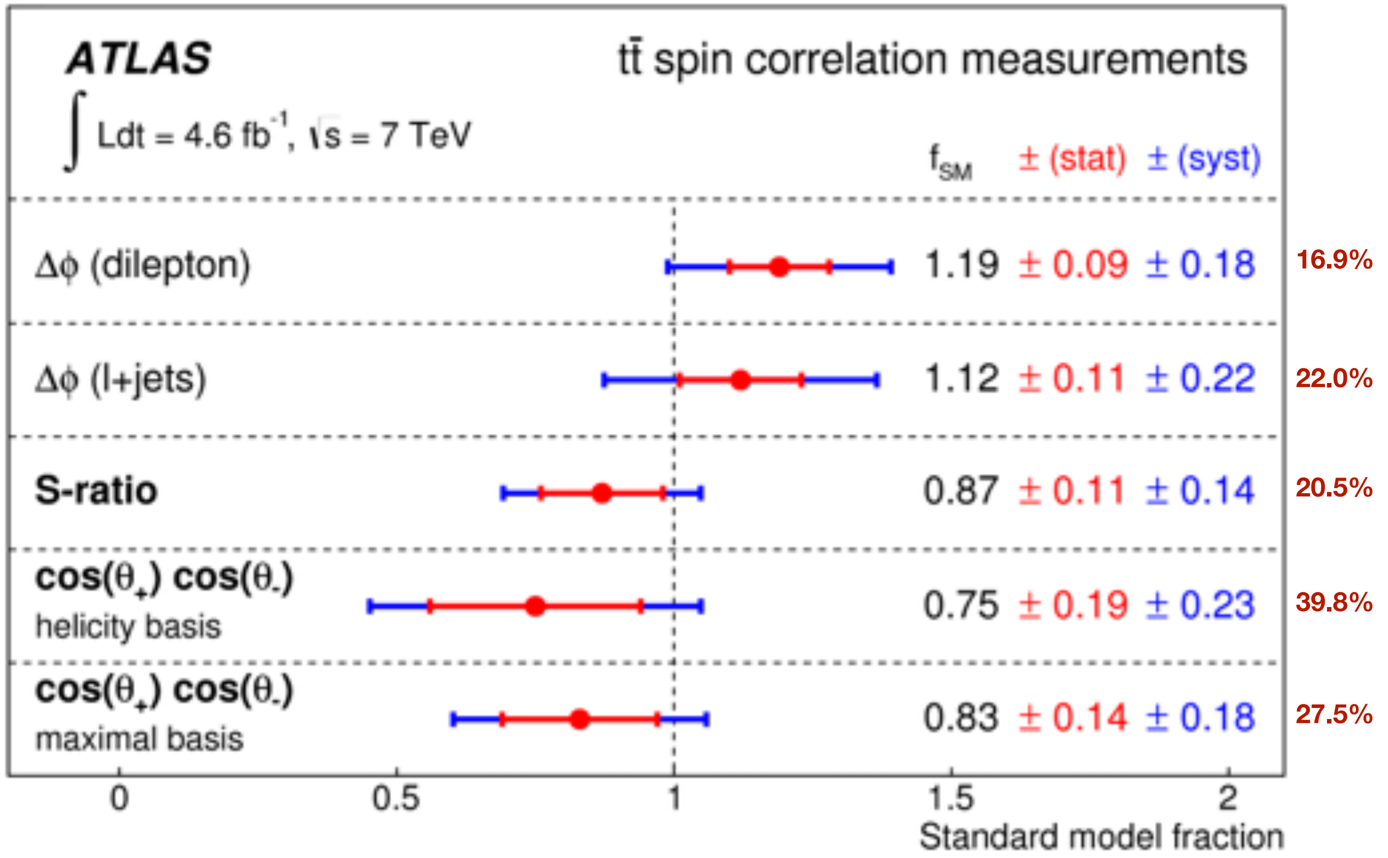
Several observables sensitive to different sources of new physics in tt̄ production are used to extract the spin correlation strength:

- Δϕ between the two leptons - lepton and jets (lab frame)
- $\cos(\theta_+)\cos(\theta_-)$ in the helicity and maximal bases
- "S ratio"

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

- **Main systematics:** JES, JER, Renormalization/ factorization scale

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos(\theta_+)d\cos(\theta_-)} = \frac{1}{4}(1 + A\alpha_+\alpha_-\cos(\theta_+)\cos(\theta_-))$$

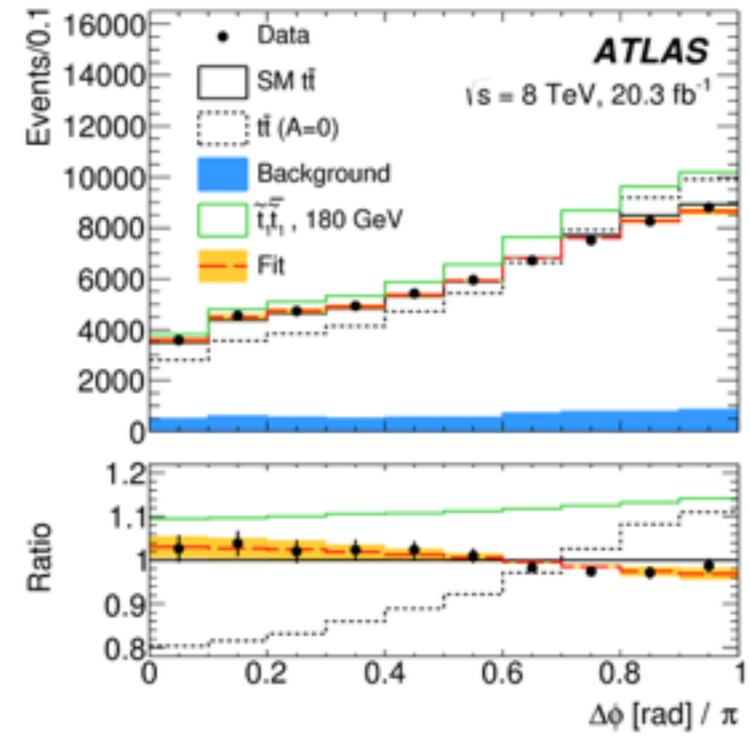


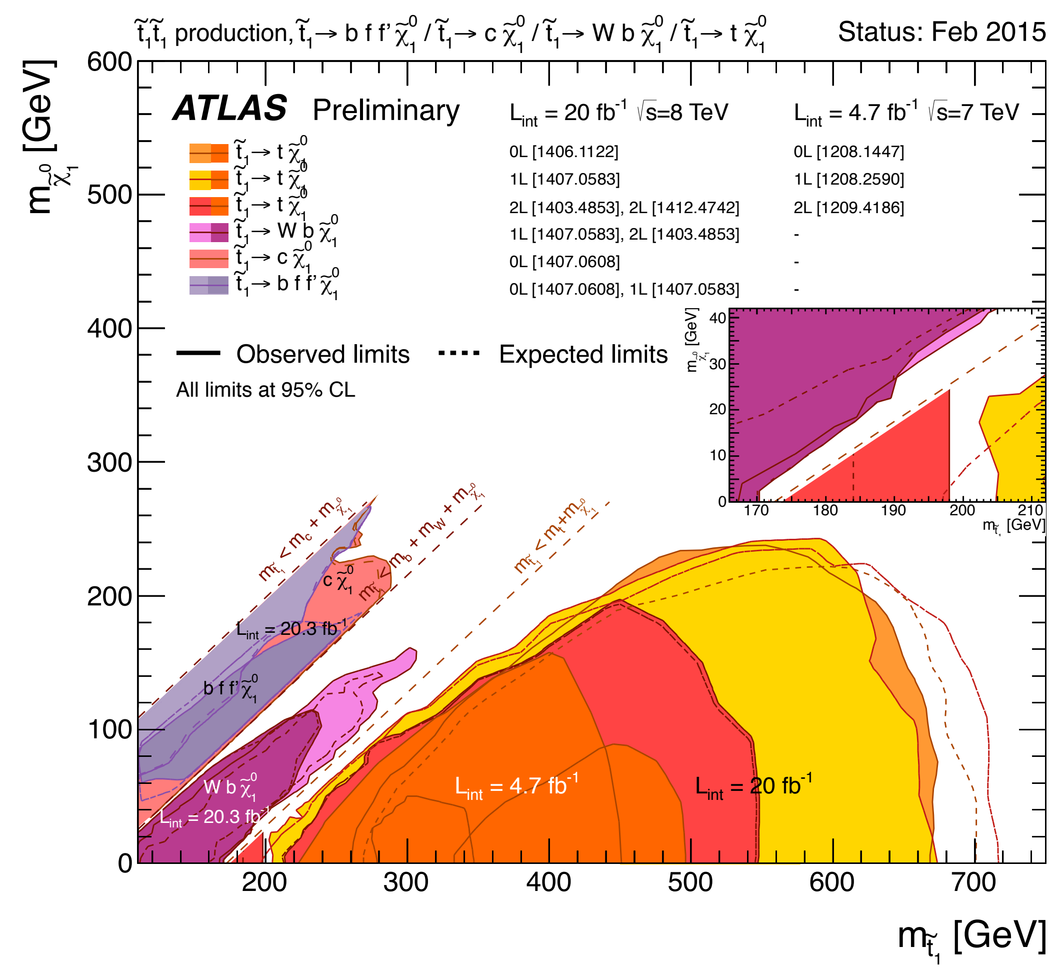
ATLAS spin correlation (2)

Dilepton @ 8 TeV (20.3 fb⁻¹)

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

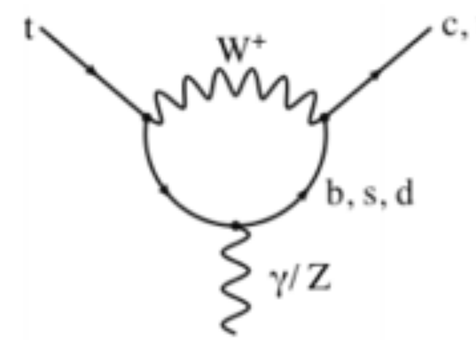
- Extract the spin correlation strength from Δϕ between the two leptons:
- **f_{SM}=1.20± 0.05 (stat) ± 0.13 (syst)**
- Since stops are scalars, if produced in pairs they would have no spin correlation (f_{SM}=0).
- If the top squarks decay to tops + very light neutralinos the Δϕ distribution would look similar to uncorrelated $t\bar{t}$
- Assuming 100% BR($\tilde{t}_1 \to t\tilde{\chi}_1^0$) and the production of predominantly right-handed top quarks, top squark masses between m_{top} and 191 GeV can be excluded.
- **Main systematics:** Parton shower and fragmentation, ISR/FSR

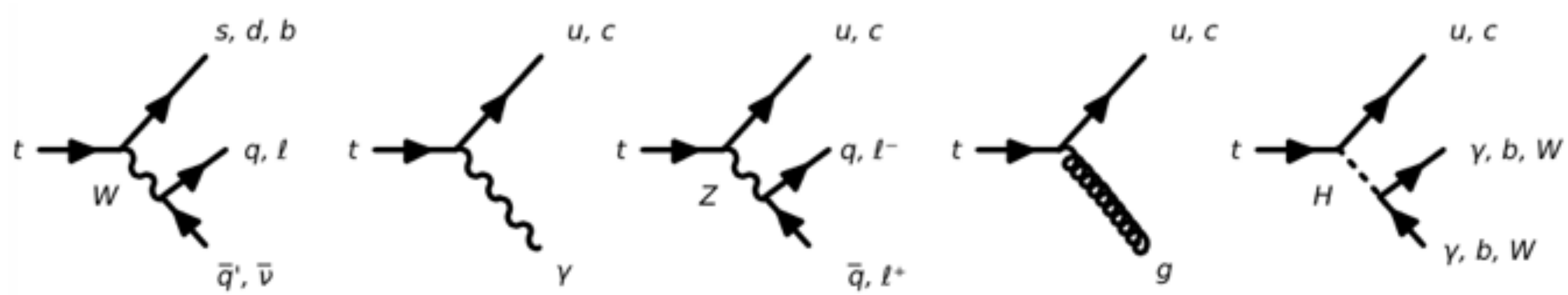




FCNC top decays

- Flavour-changing neutral current (FCNC) transition is an interaction process where a fermion undergoes the change of flavour without changing its electric charge;
- FCNC amplitudes at tree level are forbidden by the Glashow-Iliopoulos-Maiani (GIM) mechanism in the SM;
- However, GIM-highly suppressed FCNC transitions are possible in the SM in the higher orders via penguin and box diagrams;
- Some extensions of the SM could introduce FCNC decays at tree level including new particles making flavour violation a good flag of new physics.





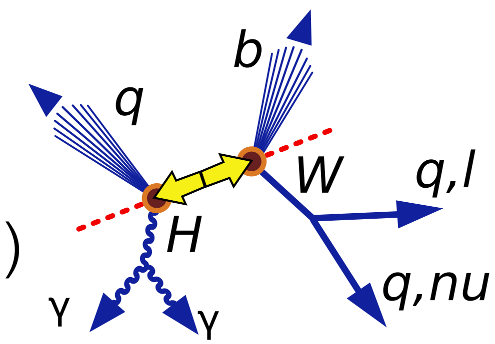
	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	RS
$t \to q\gamma$	$\sim 10^{-14}$	$\sim 10^{-9}$	$\sim 10^{-7}$	$\sim 10^{-9}$	$\sim 10^{-8}$	$\sim 10^{-9}$	$\sim 10^{-9}$
$t \to qZ$	$\sim 10^{-14}$	$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-10}$	$\sim 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-5}$
$t \to qg$	$\sim 10^{-12}$	$\sim 10^{-7}$	$\sim 10^{-4}$	$\sim 10^{-8}$	$\sim 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-10}$
$t \to qH$	$\sim 10^{-15}$	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-6}$	—

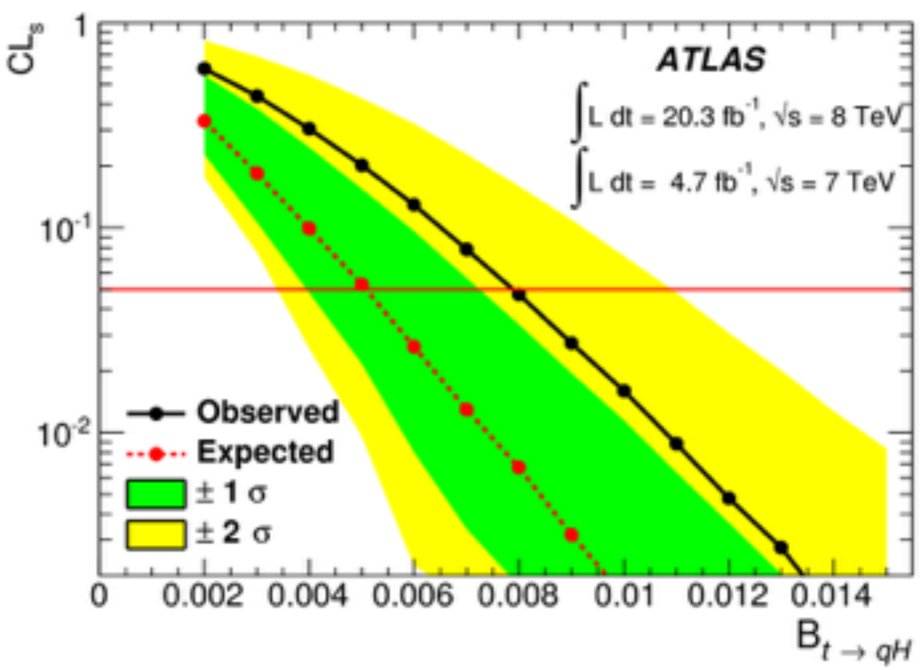
[Acta Phys. Polon. B35 (2004) 2695–2710; arXiv:1311.2028]

ATLAS top FCNC decay measurements

t→qH (hadronic and leptonic W decay, H→γγ)

@ 7+8 TeV
(full datasets)





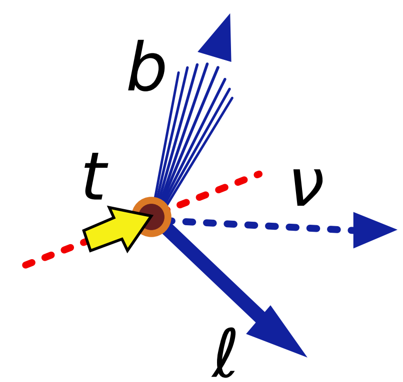
BR(t→cH) = 0.79% (0.51% expected)

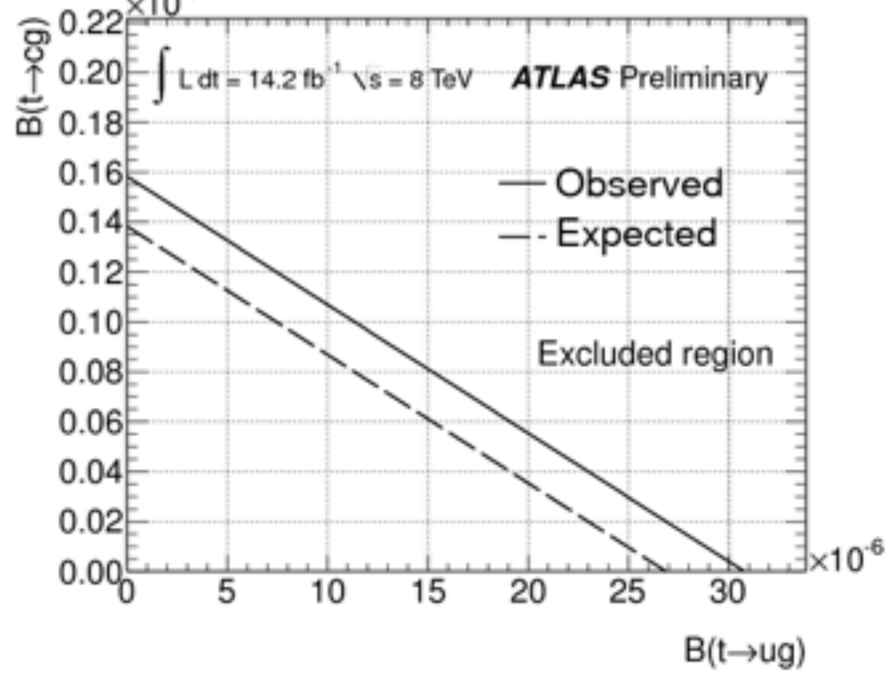
Main systematics: photon ID, JES, b-tag

[JHEP 06 (2014) 008]

qg→t

@ 8 TeV
(14.2 fb^{-1})





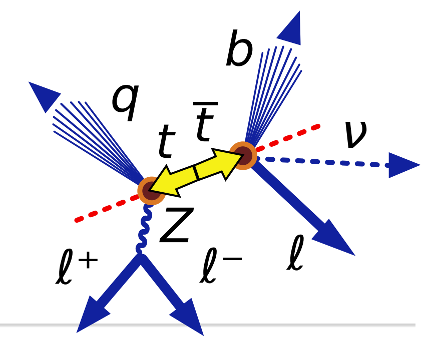
BR(t → ug) < 3.1 × 10^{-5}
BR(t → cg) < 1.6 × 10^{-4}

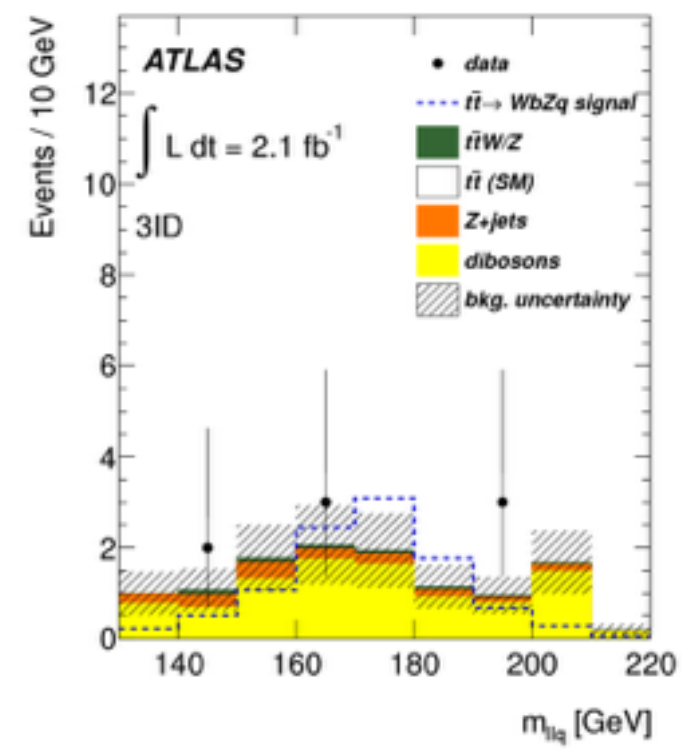
Main systematics: b-tag, met, background modeling

[ATLAS-CONF-2013-063]

t→qZ (trilepton, 3ID with 2ID+TL combination)

@ 7 TeV
(2.1 fb^{-1})





BR(t → qZ) < 0.73%

Main systematics:
- 3ID: ZZ and WZ simulation modelling
- 2ID+TL: fake-TL estimation

[JHEP 09 (2012) 139]

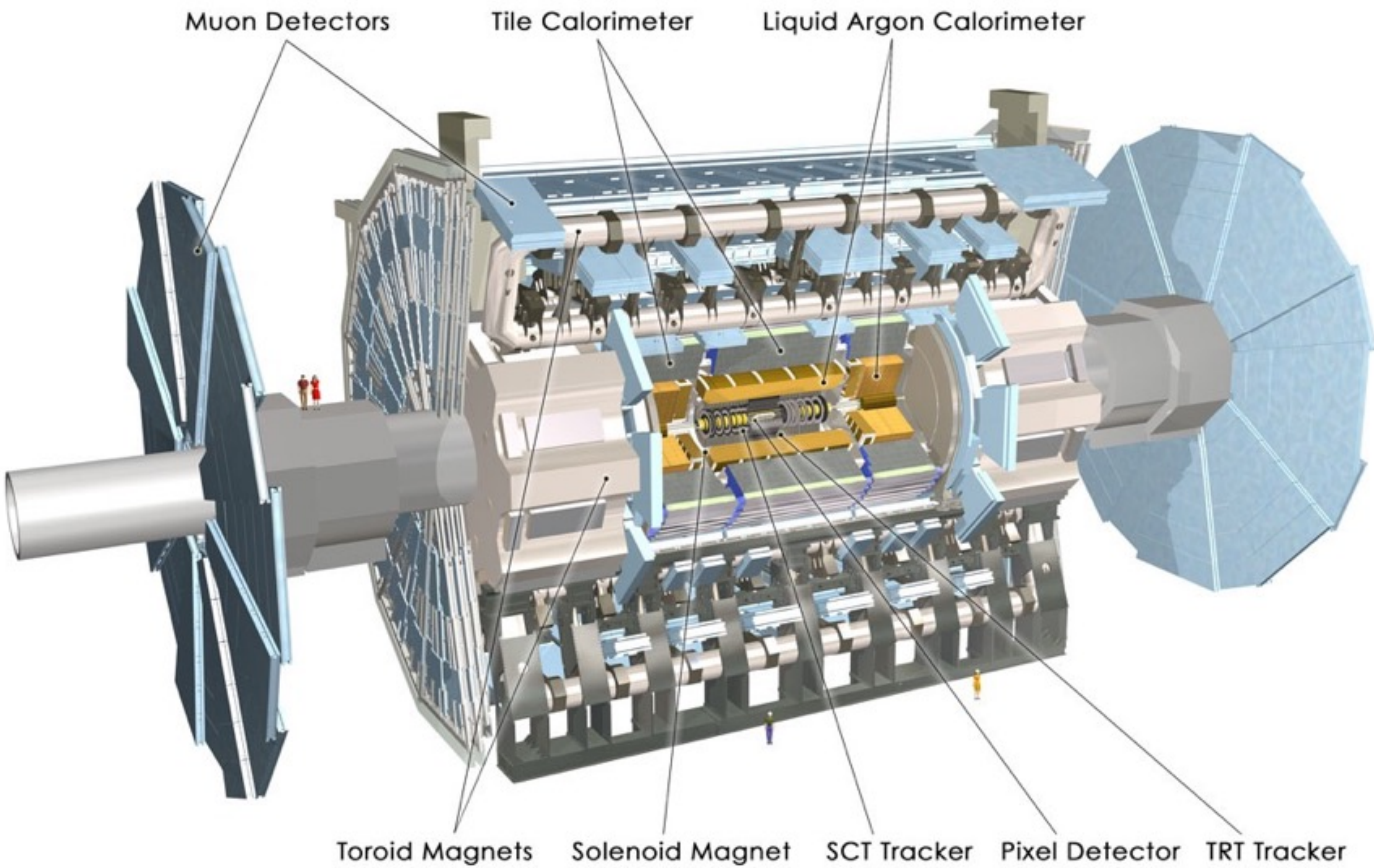
Conclusions

- Since the beginning of LHC era many precision measurements of top quark properties have been done, most of them allowing to constrain possible new physics contributions;
- Top quark studies with the ATLAS detector well under way ⇒ now addressing Precision Top Quark Measurements!
- Top quark mass known with precision < 1 GeV!
- A variety of top quark properties in $t\bar{t}$ production and decay have been measured and presented
- All results in good agreement with SM ⇒ no new physics seen in top quark physics:
  - Many measurements are dominated by systematic uncertainties
- A few 8 TeV analysis in the pipeline
- Study of the systematics (e.g. JES, $t\bar{t}$ modelling) will be crucial for Run-2
- Also, more statistic will allow more differential measurements.

for more detailed information check ATLAS top quark physics results website: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Backup Slides

ATLAS detector



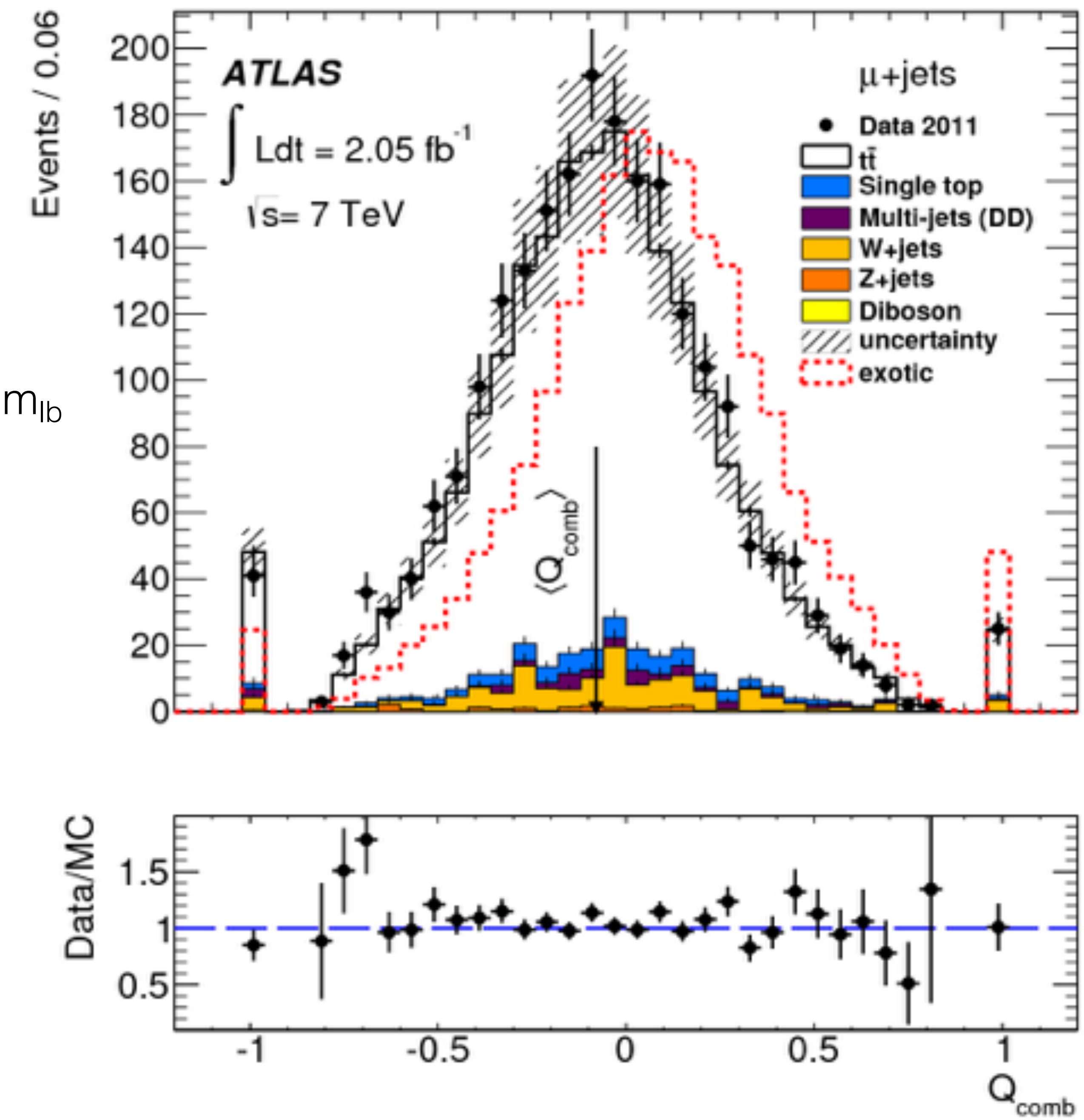
Top Quark Charge

$t\bar{t}$ → l+jets analysis @ 7 TeV (2.05 fb^{-1})
[JHEP11 (2013) 031]

- W charge from lepton, b-jet charge from weighted sum of associated tracks
- Lepton and b-jet paired using invariant mass, m_{lb}

$$Q_{\rm comb} = Q^{\ell}_{\rm b-jet} \cdot Q_{\ell}$$

- **Q = 0.64 ± 0.02 (stat) ± 0.08 (syst)**
- Confirmation of SM
- Exclude models that propose -4/3e at 8σ
- **Main systematics:** JES, parton shower



ATLAS measurement of Top quark polarization in $t\bar{t}$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos(\theta_i)d\cos(\theta_j)} = \frac{1}{4}\left[P_{\alpha_i}\cos(\theta_i) + P_{\alpha_j}\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)\right]$$

- P_{SM} = 0.003 ± 0.001 [PRL 111 (2013) 232002]
- l+jets (w/ b-tagging) and dilepton (wo/ b-tagging) @ 4.6 fb^{-1} of 7 TeV
- Template fit to reconstruct cos(θ)
- Two hypotheses tested:

  - CP conserving (CPC): top and anti-top have the same P

$$\alpha_l P_{CPC} = -0.035 \pm 0.014(\text{stat.}) \pm 0.037(\text{syst.})$$

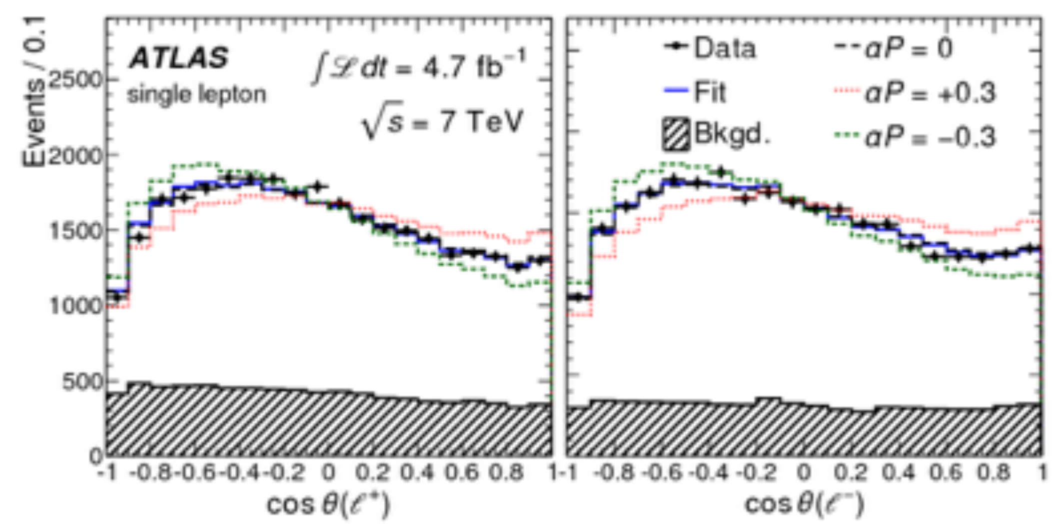
  - CP violating (CPV): top and anti-top have opposite P

$$\alpha_l P_{CPV} = 0.020 \pm 0.016(\text{stat.})^{+0.013}_{-0.017}(\text{syst.})$$

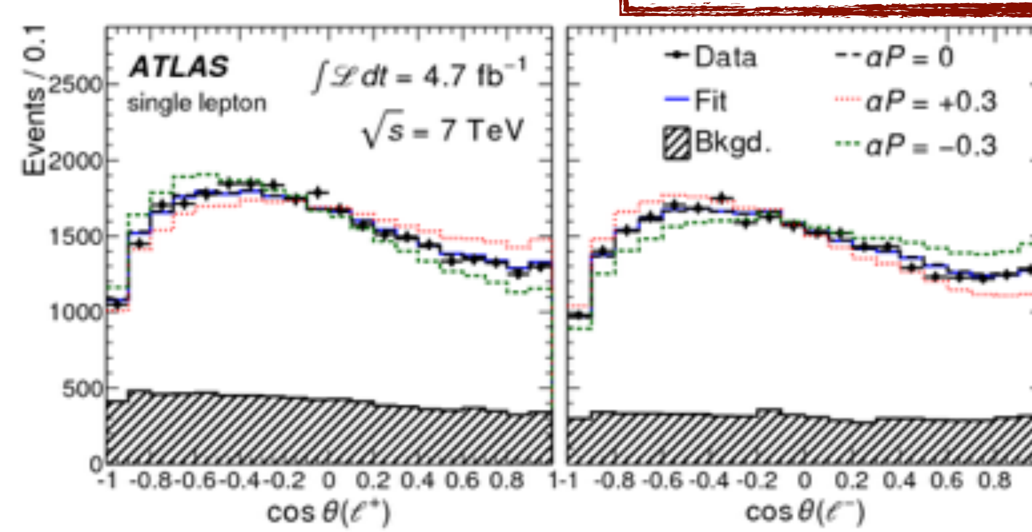
- **No deviation from the SM prediction of negligible polarization is observed for either the CP conserving or maximally CP violating scenario!**

- **Main systematics:** Jet Reconstruction, $t\bar{t}$ modeling

CP Conserving

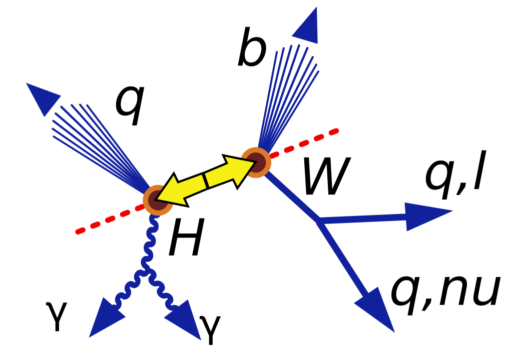


CP Violating

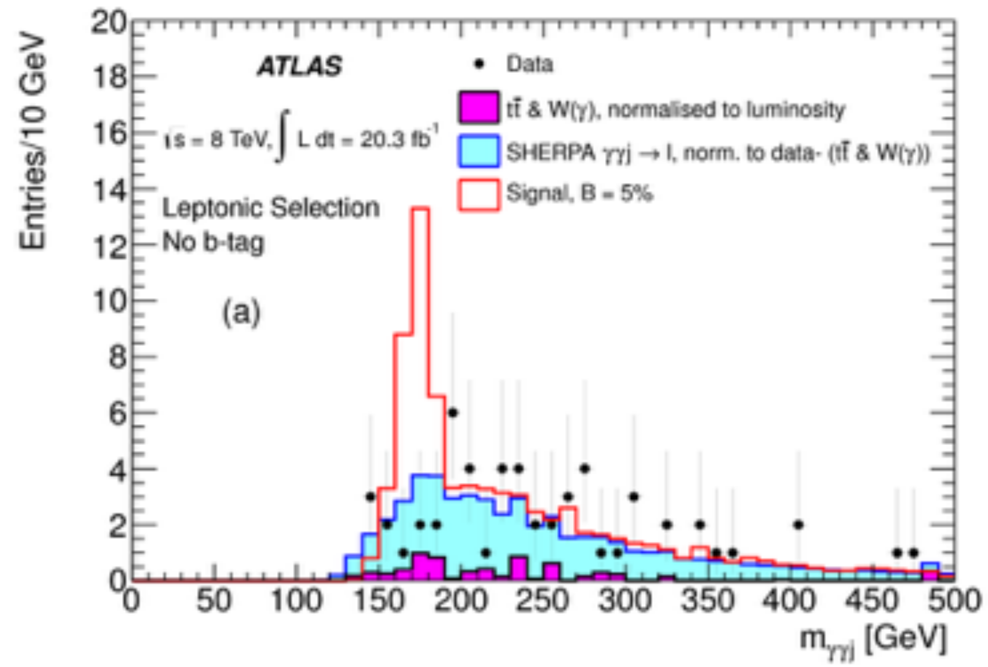


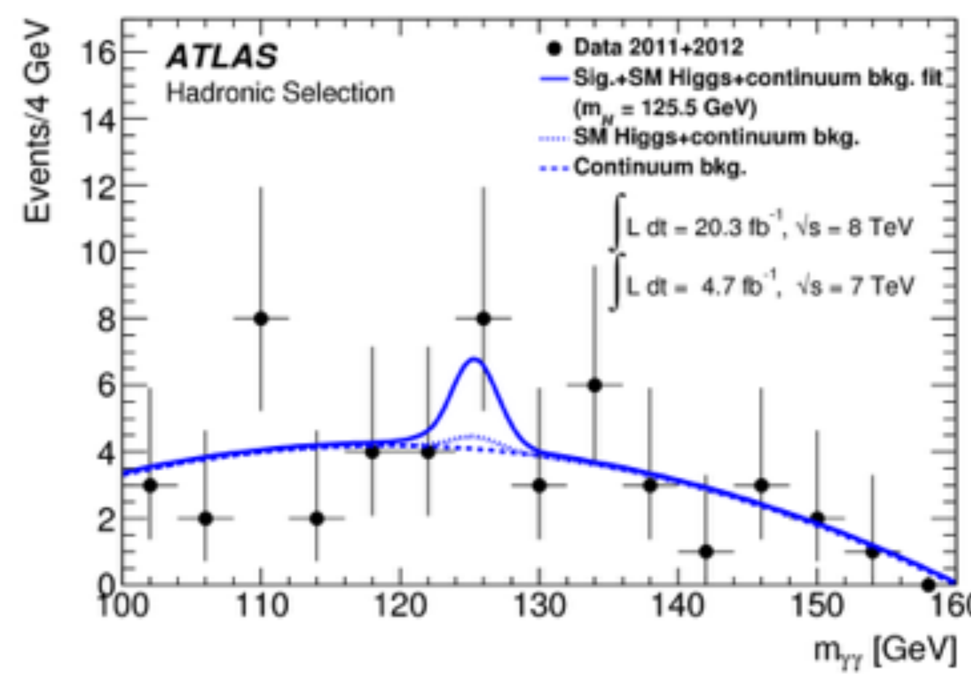
[Phys. Rev. Lett 111, 232002 (2013)]

FCNC $t \rightarrow qH$

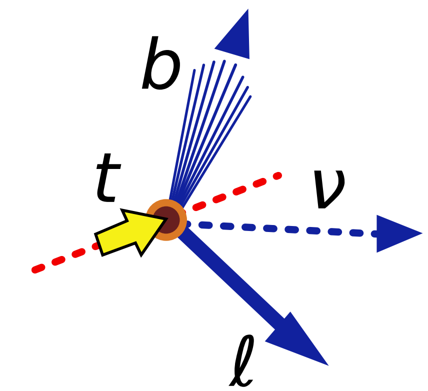


- ≥ 2 photons ($p_T(\gamma 1) > 40$ GeV, $p_T(\gamma 2) > 30$ GeV)
- two topologies searched for:
- hadronic
    - =0 leptons
    - =4 jets (1 b-tagged)
    - 156 GeV < m(top FCNC) < 191 GeV
    - 130 GeV < m(top SM) < 210 GeV
- leptonic (=1 lepton)
    - $m_T(W) > 30$ GeV
    - ≥ 2 jets (1 b-tagged)
    - 156 GeV < m(top FCNC) < 191 GeV
    - 135 GeV < m(top SM) < 205 GeV
- maximum likelihood fit is performed

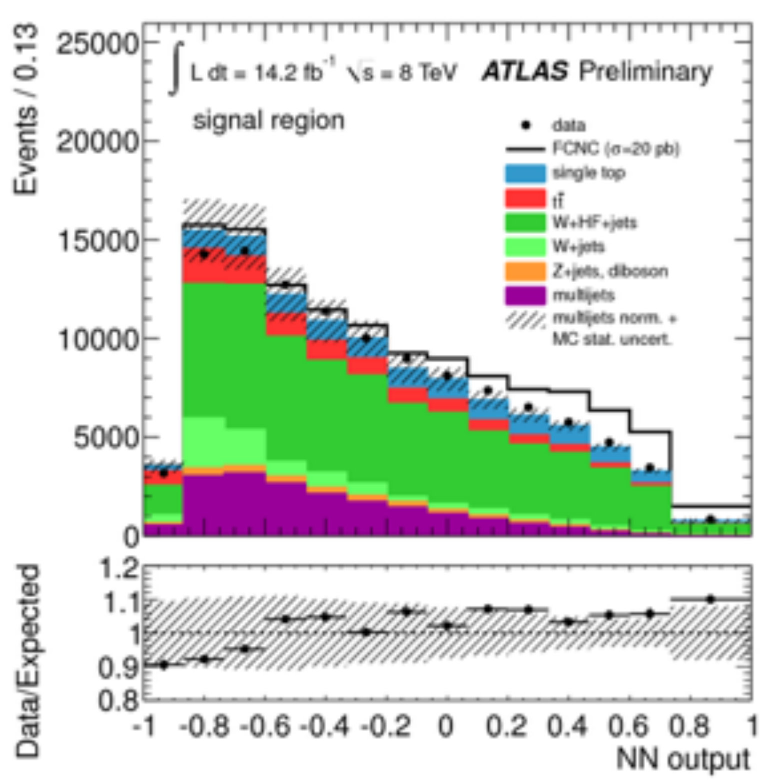


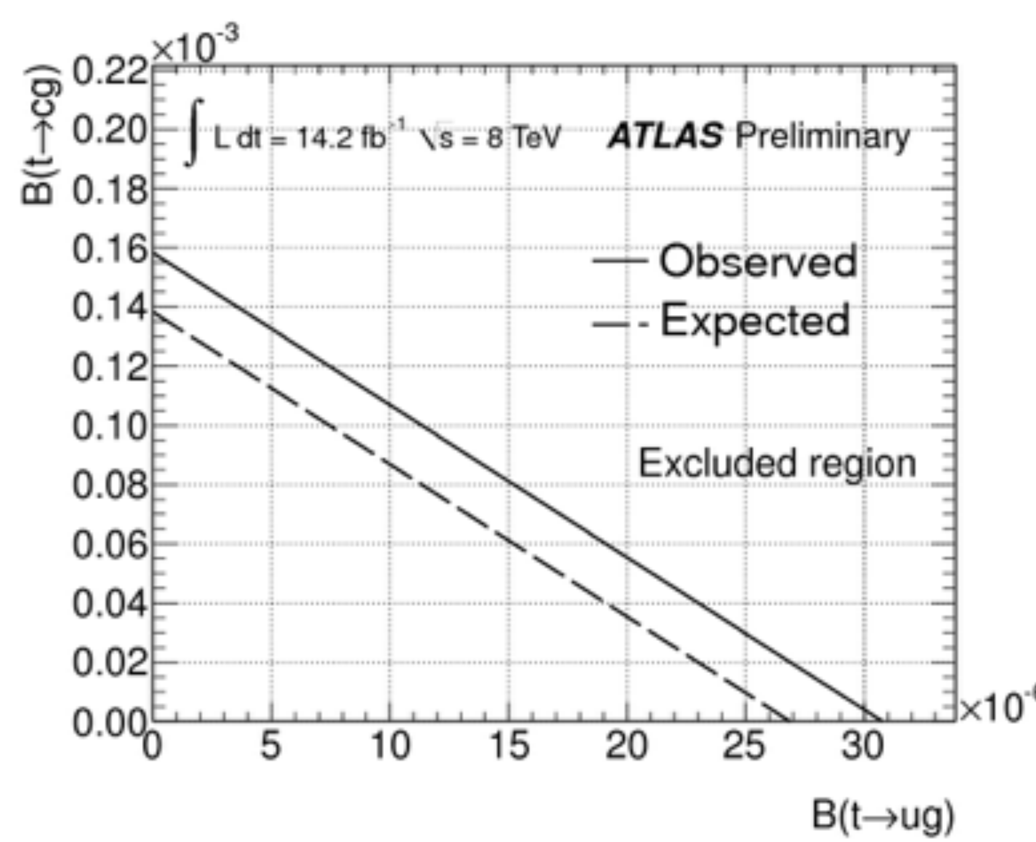


FCNC gq → t



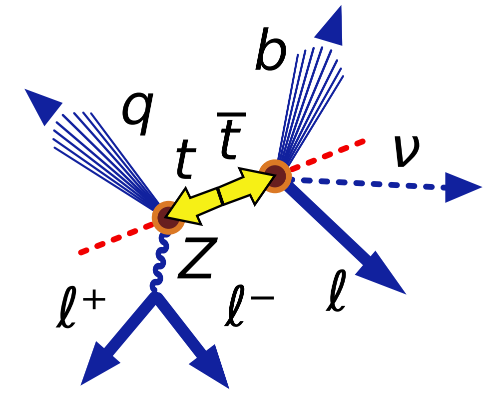
- $t\bar{t}$ production with t → qg decay dificult to distinguish from multijet production
- search for single top production via FCNC (strong sector)
- = 1 lepton (>25 GeV), $E_T$miss >30 GeV
- 1 jet (=1 b-tagged), m_T(W) > 50 GeV
- MVA method (neural-network with 13 variables) used to improve analysis





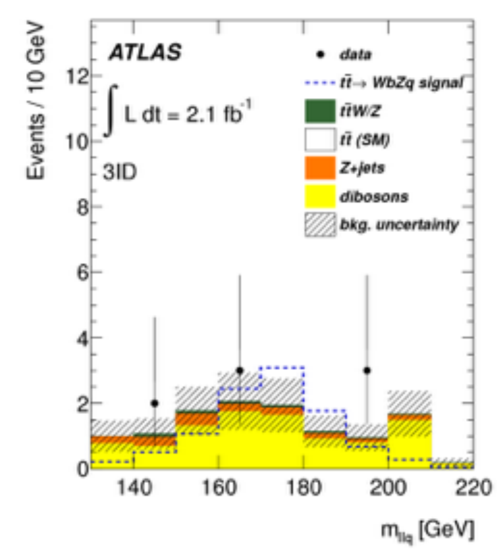
FCNC $t \rightarrow qZ$

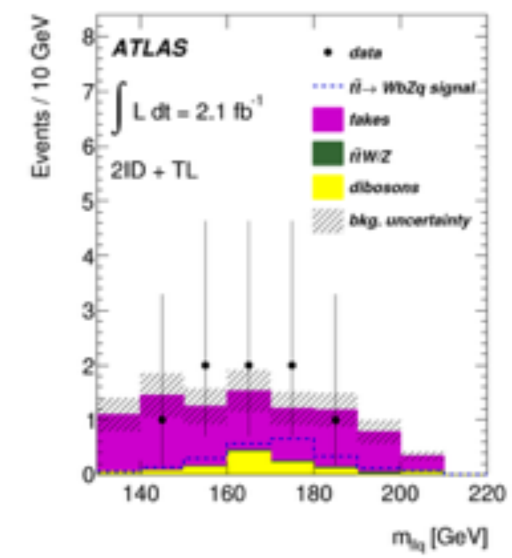
@ 7 TeV (2.1 fb^{-1})



- two orthogonal analyses:
  - 3ID: 3 fully identified leptons (e, μ); main background from ZZ and WZ production
    - $p_T(l_1) < 25$ GeV, $pT(l_{2,3}) < 20$ GeV,
  - 2ID+TL: 2 fully identified leptons (e, μ) and the third one is allowed to be a high quality inner detector track (TL); main background from jets faking TL
    - $p_T(ID) < 20$ GeV, $p_T(TL) < 25$ GeV,
- $p_T(\mu) < 150$ GeV
- leptons from same vertex
- 2 leptons with same flavour and opposite charges ($|m_{PDG} - m_{ll}| < 15$ GeV)
- ≥ 2 jets; $p_T > 25$ GeV; $|\eta_{j1,j2}| < 2.5$ (1 b-tagged in 2ID+TL)
- $E_T$miss > 20 GeV
- |m(top FCNC,top SM) − 172.5 GeV| < 40 GeV
- |m(W) − 80.4 GeV| < 30 GeV

	3ID	2ID+TL
ZZ and WZ	9.5 ± 4.4	1.0 ± $^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	
Z+jets	1.7 ± 0.7	7.6 ± 2.2
Single top	0.01 ± 0.01	
2+3 fake leptons	0.0 ± $^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	(0.205 ± 0.024)%	(0.045 ± 0.007)%





channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%