Top quark pair property measurements using the ATLAS detector at the LHC

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on behalf of the ATLAS collaboration

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Bundesministerium
für Bildung
und Forschung

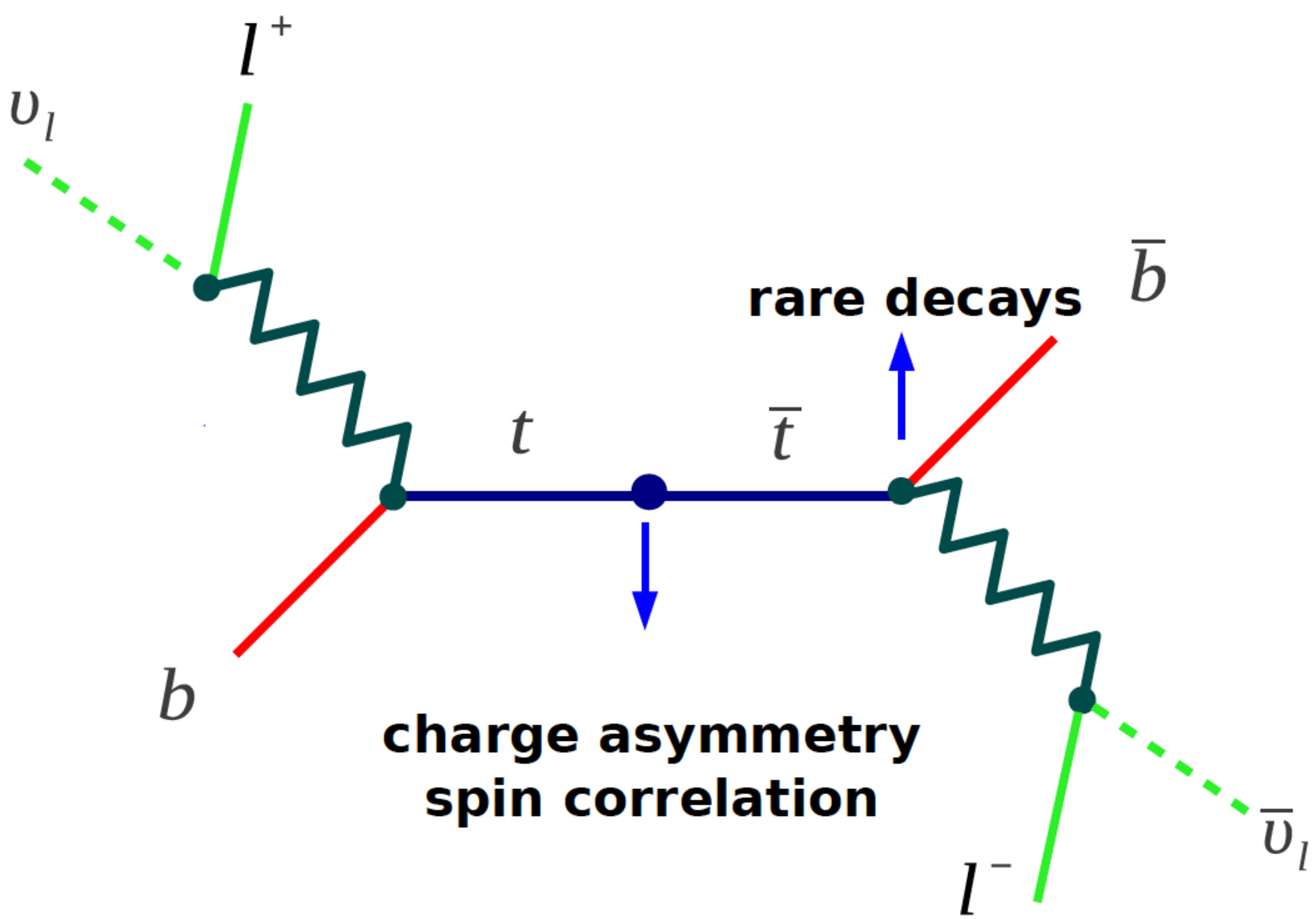
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

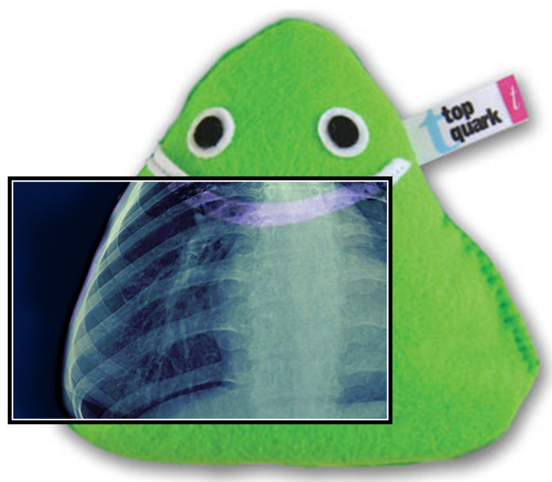
FSP 103
ATLAS

ATLAS

Why Study Top Quark Properties?

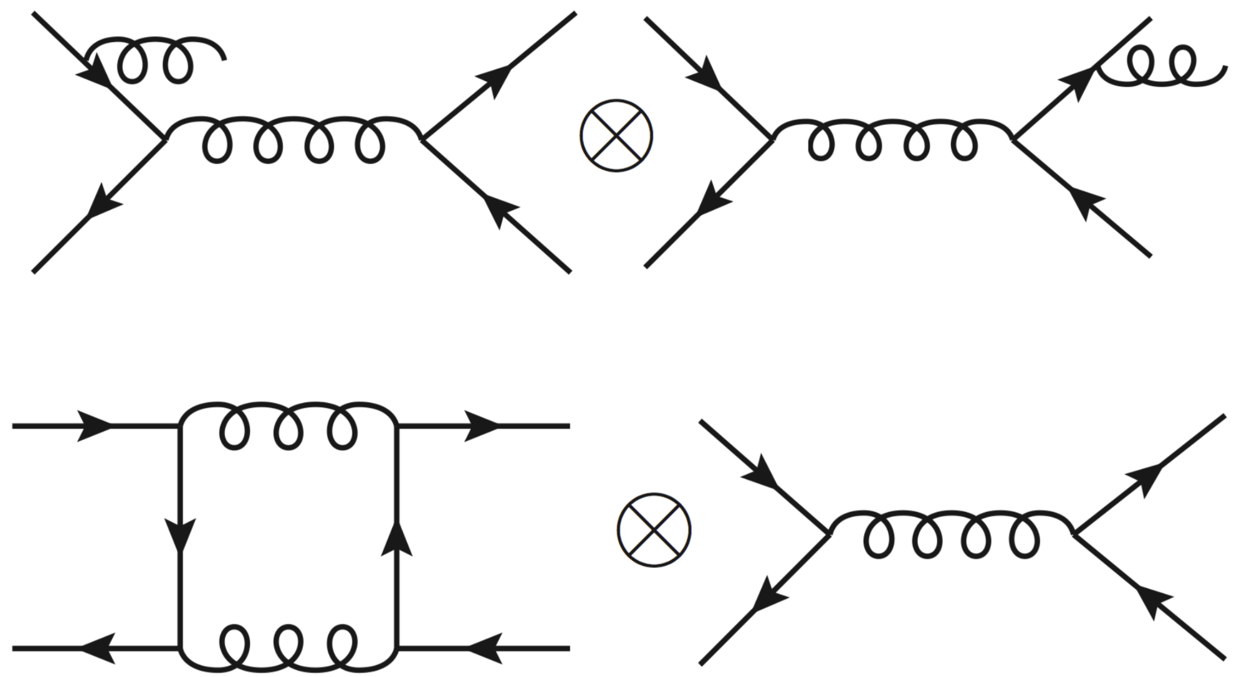
- **Heaviest fundamental particle discovered so far** → $m_t = 173.34 \pm 0.76\ \mathrm{GeV}$ [arXiv:1403.4427]
- **Extremely short lifetime** → a unique opportunity to study a bare quark
- **Strong coupling to Higgs** → special role in the Standard Model
- **A window to new physics?**
- **High production rate at the LHC** → precision measurements and detailed studies of properties





Where charge asymmetry comes from?

- @LO: Top quark and Top anti-quark are symmetric
- @NLO and higher orders correction: Top pair production via $q\bar{q}$ **annihilation** mainly causes an asymmetry in Top quark and Top anti-quark rapidity by the interference of ISR with FSR and Born with box diagram

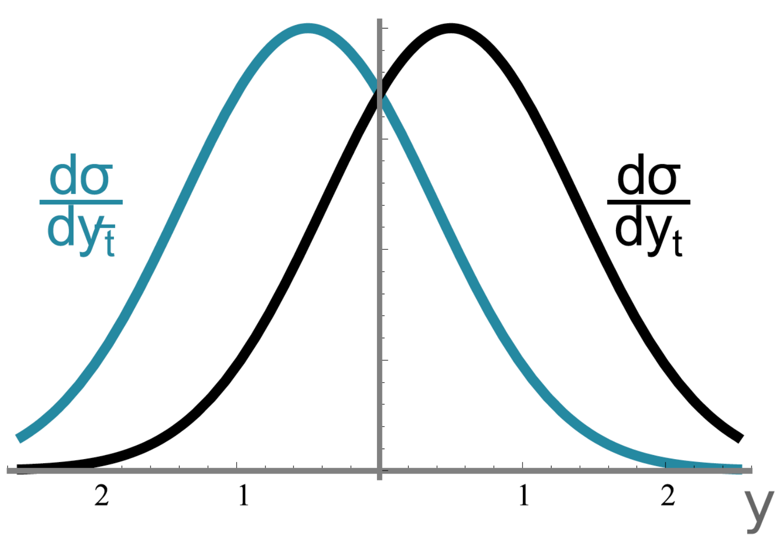


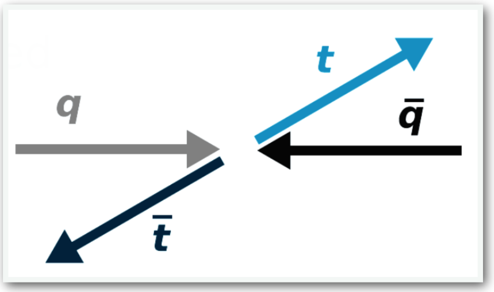
A_{FB} Forward-backward asymmetry

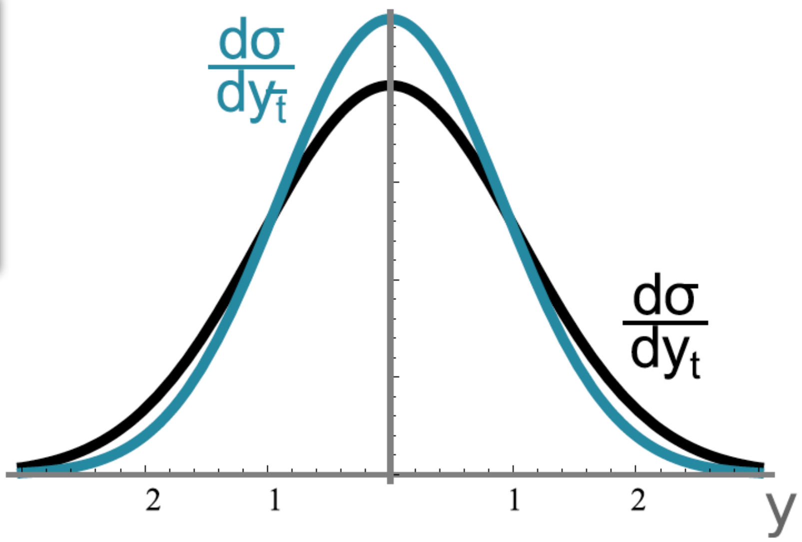
- ***$p\bar{p}$* collisions @Tevatron**
- Direction of incoming quark almost always coincides with that of proton
- Allows to define a direct ***A_{FB}*** measurement
- **SM: 8 - 9%**
- $q\bar{q} \to t\bar{t}$ **~ 80%**

A_C Charge asymmetry

- ***pp* collisions @LHC**
- **Valence** quarks carry on average larger fraction of the proton momentum than the **sea** quarks
- **Top quarks** (**anti-quarks**) are more forward (central)
- **SM: ~1%**
- $q\bar{q} \to t\bar{t}$ **~ 20% @ 8 TeV**







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

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

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

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

A_C measurement in single lepton channel @8 TeV

- Data sample enriched in top-quark pairs selected:
  - ≥4 jets, 1 high p_T lepton and E_T(Miss)
- Events are reconstructed via **kinematic likelihood fit**
- Δ|y| **unfolded to parton level** via Fully Bayesian unfolding algorithm
- Data statistics is the limiting factor
- Dominant source of uncertainty: $t\bar{t}$ **modeling**
- Most significant deviation w.r.t. SM observed in $m_{t\bar{t}} > 900$ GeV interval, reaching **~1σ**

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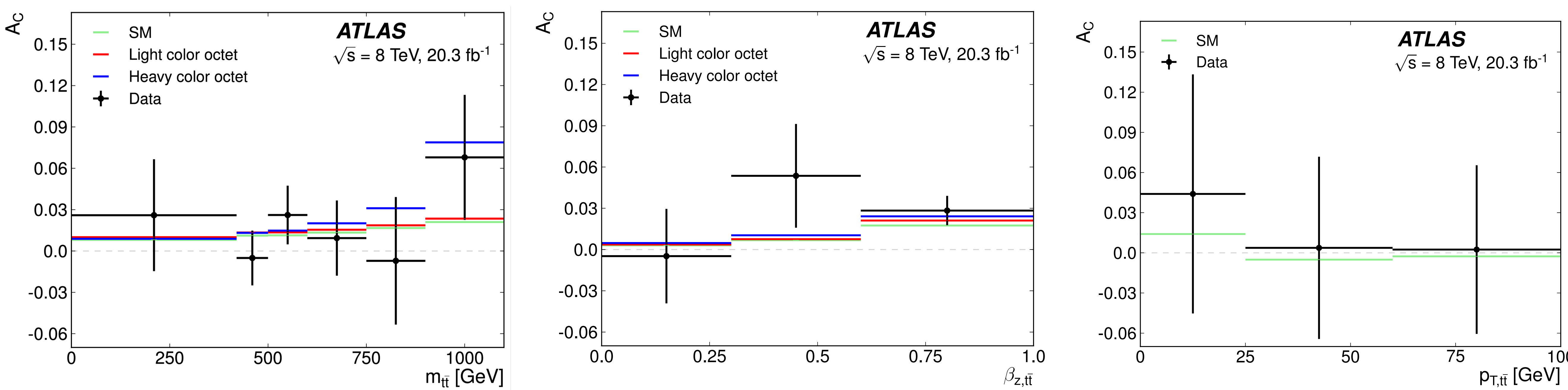
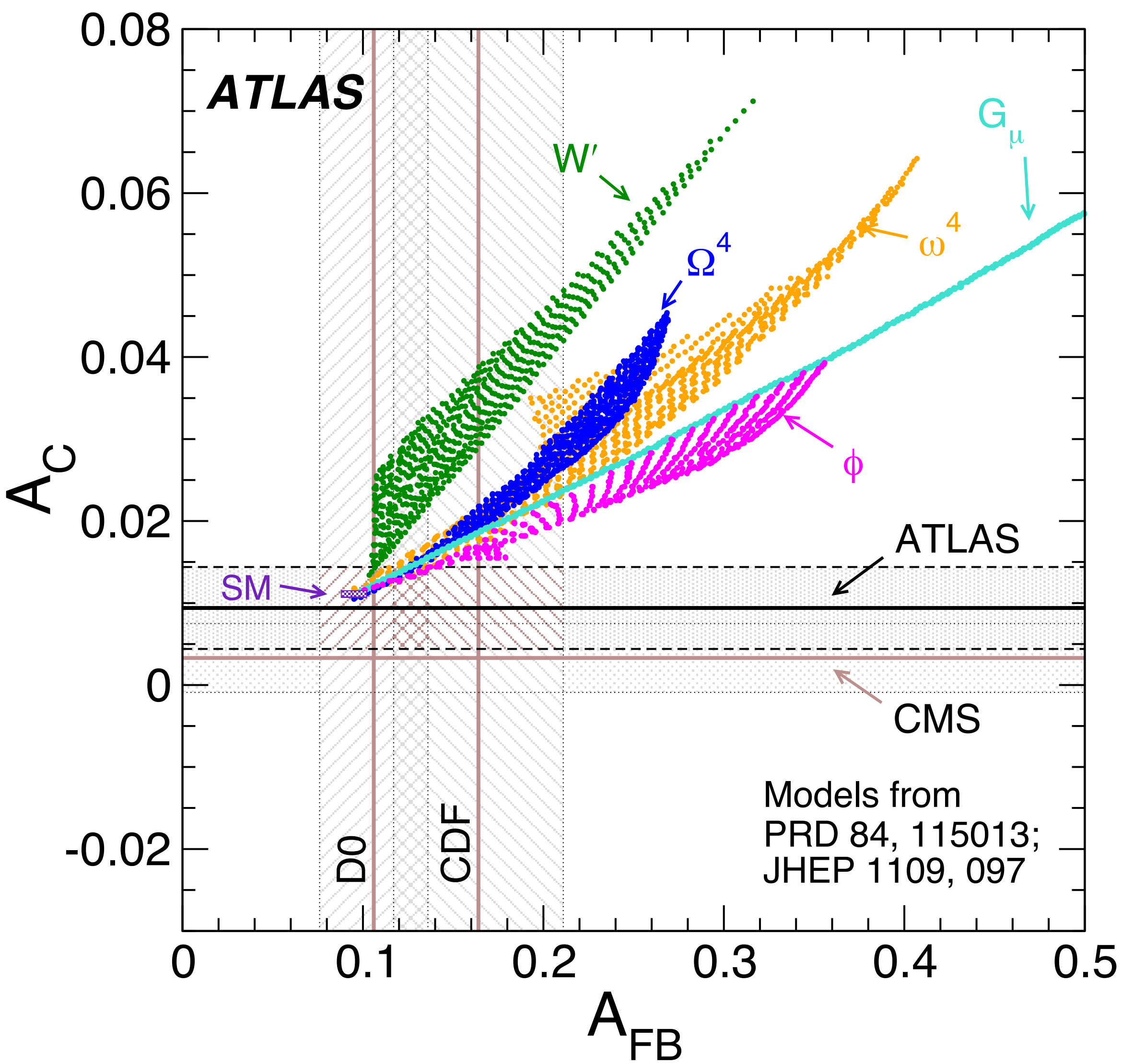
Results

- Inclusive result: **A_C =0.009±0.005** , SM_{NLO}: **A_C =0.0111±0.0004**
- Differential measurement w.r.t. **Top pair system mass**, **transverse momentum** and **longitudinal boost β_Z** compatible with SM





Impact on Beyond Standard Model physics

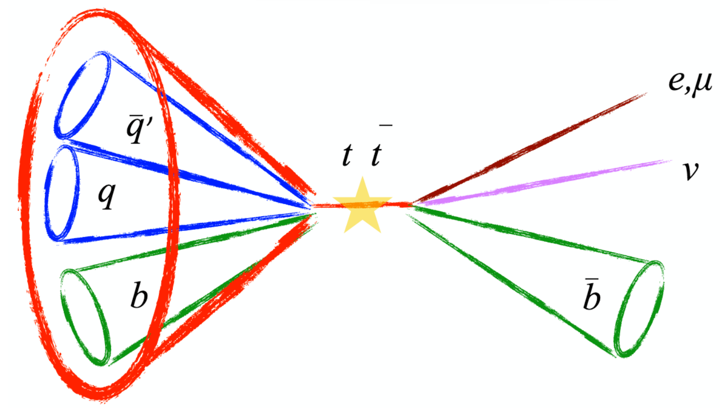
- BSM models:
  - W′ boson
  - heavy axigluon (Gμ)
  - scalar iso-doublet (ϕ)
  - colour-triple scalar (ω^4)
  - colour-sextet scalar (Ω^4)
- Limits set to the parameters (i.e. masses and couplings) describing various BSM models

Charge Asymmetry in Boosted Top

A_C measurement in lep.+jets channel @8 TeV in boosted topology

- Hadronic Top quark decay reconstructed as a single large radius jet
- Offers more precise reconstruction of $m_{t\bar{t}}$ for highly boosted Top quarks
- Provides accurate A_C measurement for $t\bar{t}$ invariant mass in **TeV range**
- Large-radius jet: R=1.0 and p_T > 300GeV and well separated from small-radius jet and the lepton
- Δ|y| **unfolded to parton level** via Fully Bayesian unfolding algorithm
- Differential measurement w.r.t. top pair system mass
- Most significant deviation w.r.t. SM observed in $m_{t\bar{t}} = 0.9\text{-}1.3$ TeV interval, reaching **1.6σ**
- Data statistics is the limiting factor
- Dominant source of uncertainty: $t\bar{t}$ **modeling**

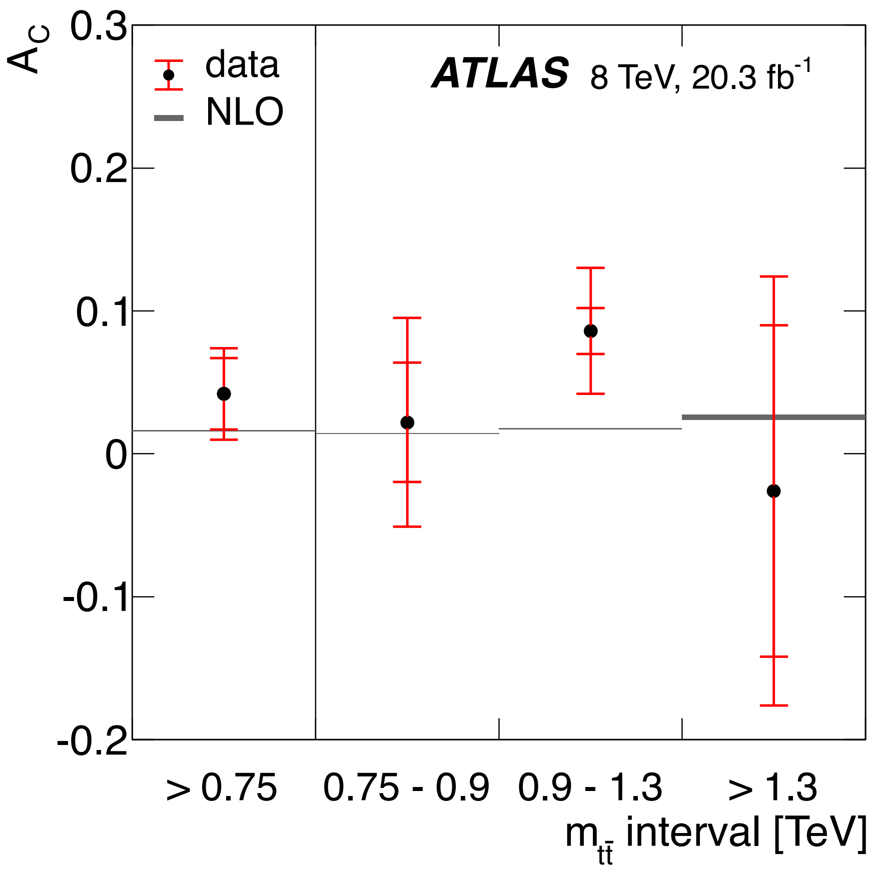
Physics Letters B (2016), Vol. 756, pp. 52-71



Results

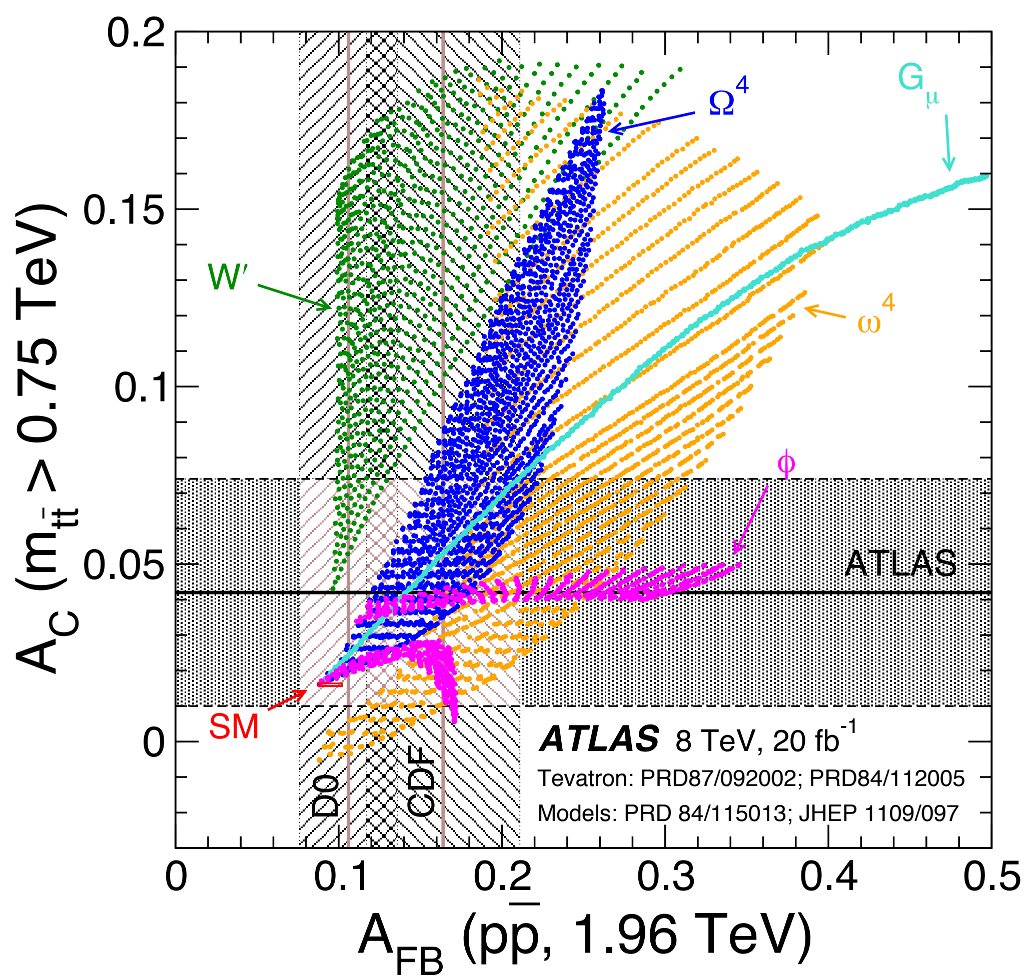
- In fiducial space $m_{t\bar{t}} > 0.75$ TeV and $-2 < \Delta|y| < 2$:
  - ***A_C* = (4.2 ± 3.2)%**, less than **1σ** from **SM prediction of 1.60 ± 0.04%**
- Differential measurement:

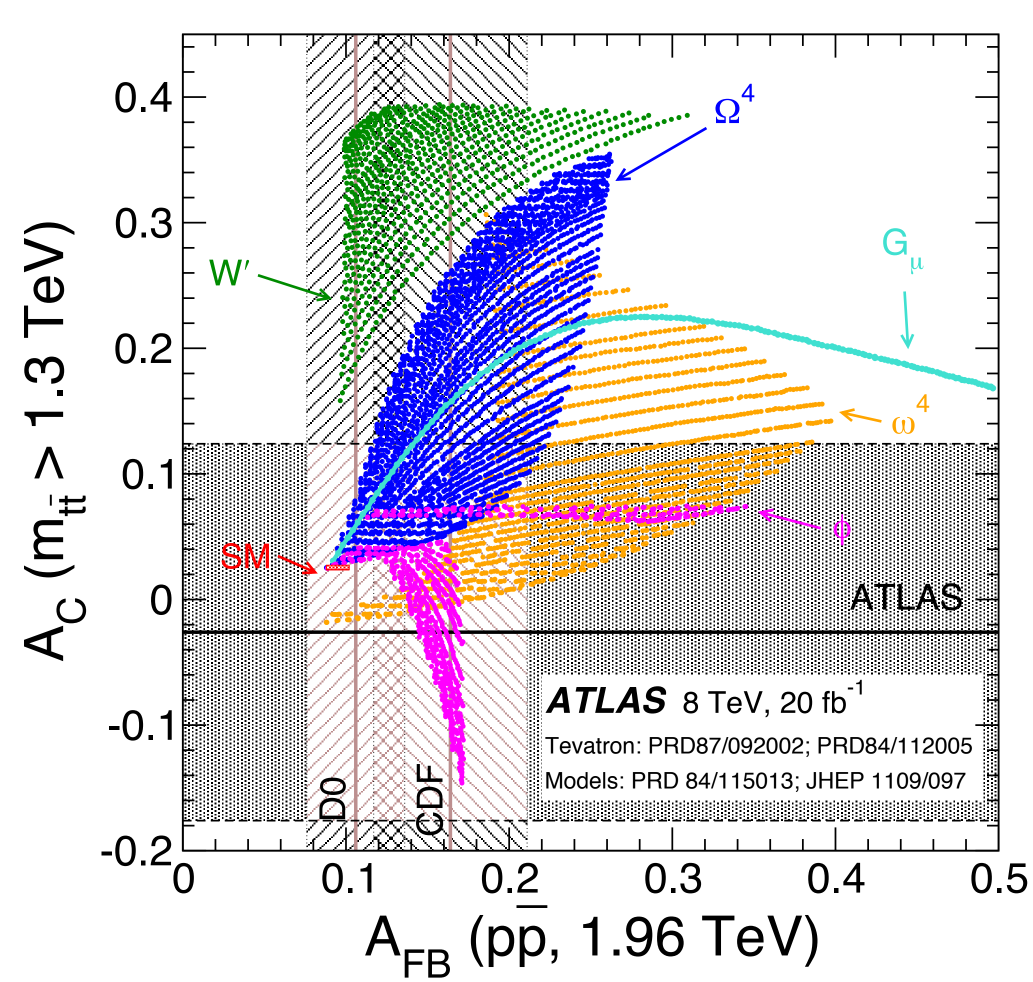
$m_{t\bar{t}}$ interval	> 0.75 TeV	0.75 – 0.9 TeV	0.9 – 1.3 TeV	> 1.3 TeV
Measurement	(4.2 ± 3.2)%	(2.2 ± 7.3)%	(8.6 ± 4.4)%	(−2.9 ± 15.0) %
SM prediction	(1.60 ± 0.04)%	(1.42 ± 0.04)%	(1.75 ± 0.05)%	(2.55 ± 0.18)%



Achievements and Impact on BSM physics

- Provide a constraint on extensions of the SM
- Disfavouring the t-channel **W′ boson model** in the highest $m_{t\bar{t}}$ bin
- Complementary to previous ATLAS measurement
- Extended the reach of previous ATLAS and CMS measurements to beyond 1 TeV

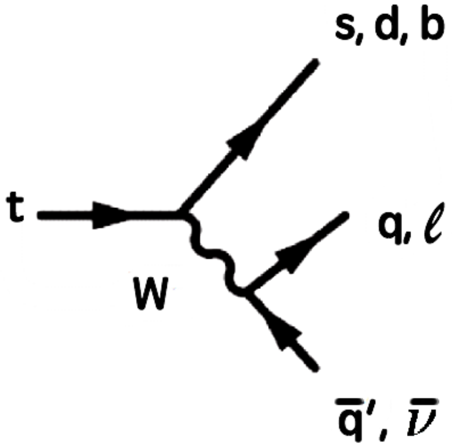




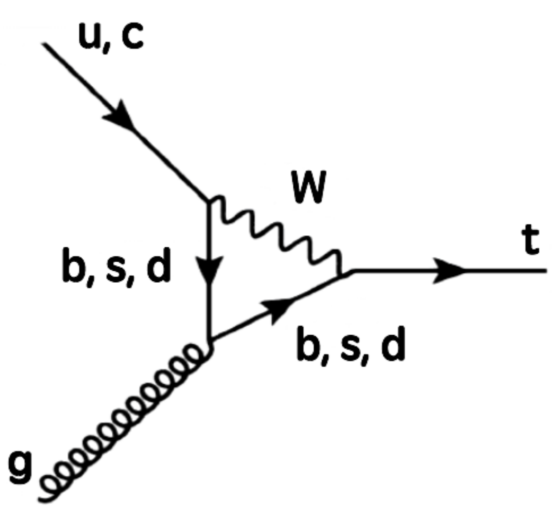
Flavour changing neutral current decay

- Forbidden at tree level in SM
- Heavily suppressed at higher orders via GIM suppression
- BSM can enhance FCNC up to ~ 10^{-4}
- Has not been observed yet, but potentially can indicate new physics if observed
- "**Data statistic**" is the limiting factor. Run II with larger $t\bar{t}$ cross section and integrated luminosity will soon improve the current limits

Top quark in SM



BR~ 100%



GIM

BR~ 10^{-13} - 10^{-14}

[K. Agashe et al., arXiv:1311.2028]

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

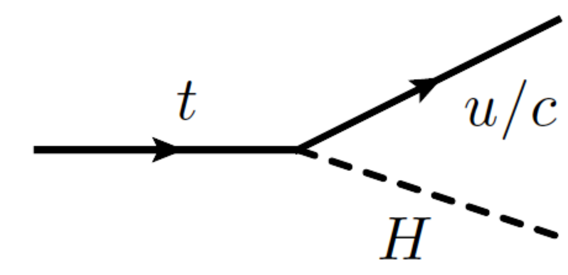
FCNC in Top Decay ($t \rightarrow Hq$)

JHEP 12 (2015) 061

Search for FCNC Top quark decays t → Hq @8 TeV

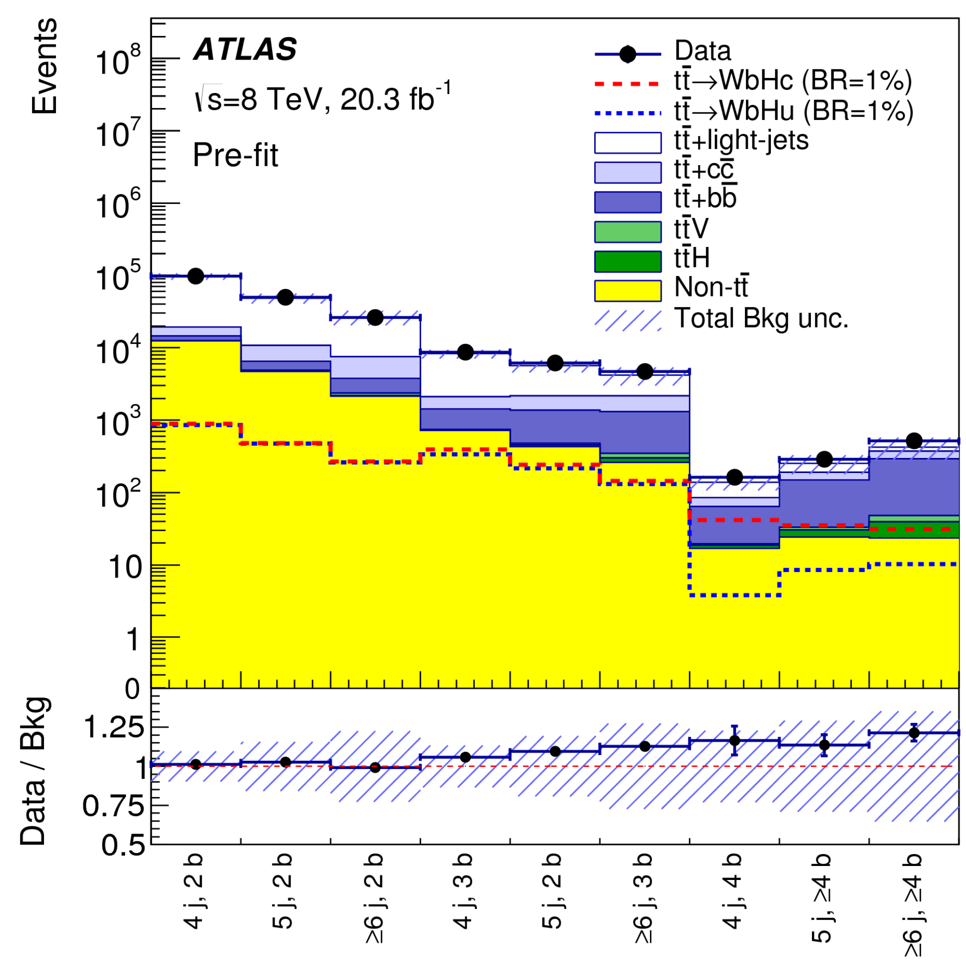
- **Top quark**^{SM} decays via leptonic channel
- **Top quark**^{FCNC} decays via $H \rightarrow b\bar{b}$
- ⩾4 jets, ⩾2 b-tagged, 1 high p_T lepton
- Categorised in 9 channels:
  - jets(4,5, ⩾6), b-tagged jets (2, 3, ⩾4)
- Binned likelihood fit on sig-bkg discriminant (**D**), in all channels
- Dominant systematic unc.: $t\bar{t}$ ***+jets*** modeling and ***b-tagging***

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \rightarrow hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$



[1]

$$\mathcal{L}_{Htc} = -\frac{1}{\sqrt{2}}\,\bar{c}\left(\eta^L_{ct}P_L + \eta^R_{ct}P_R\right)t\,H + \text{H.c.}$$

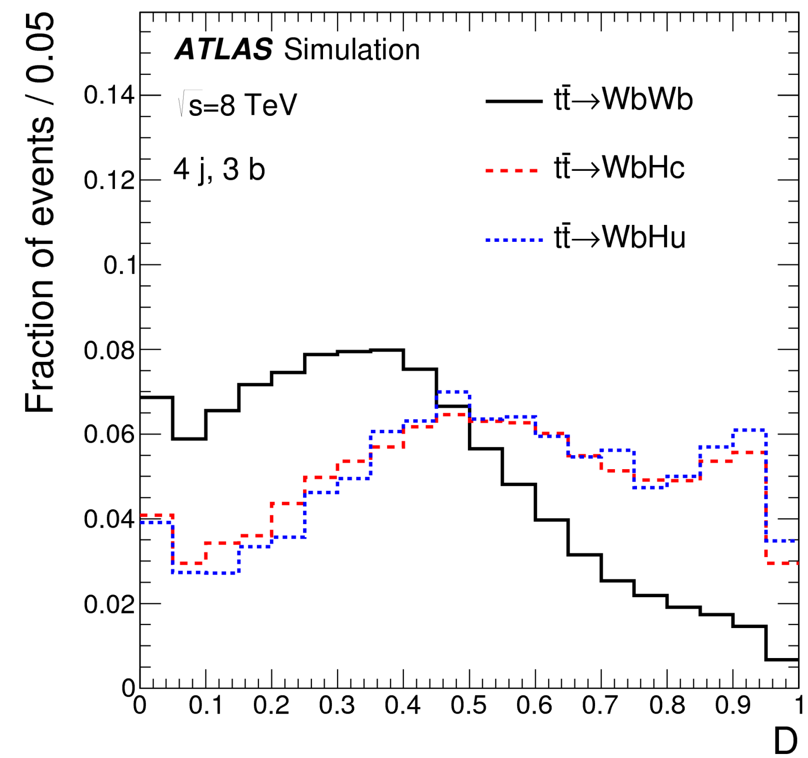


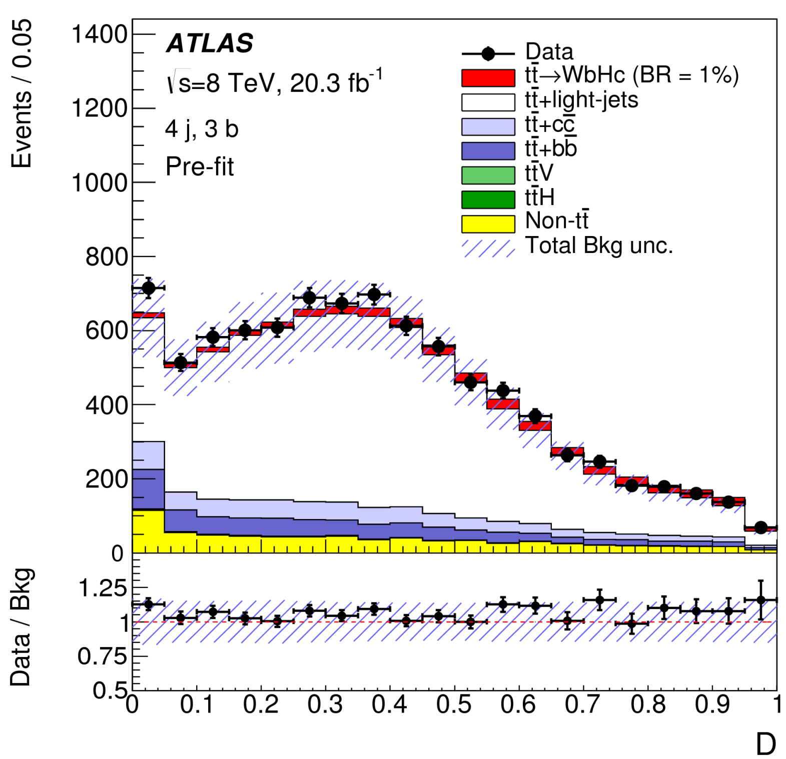
[1]: Nucl.Phys.B821:215--227,2009

FCNC in Top Decay ($t \to Hq$)

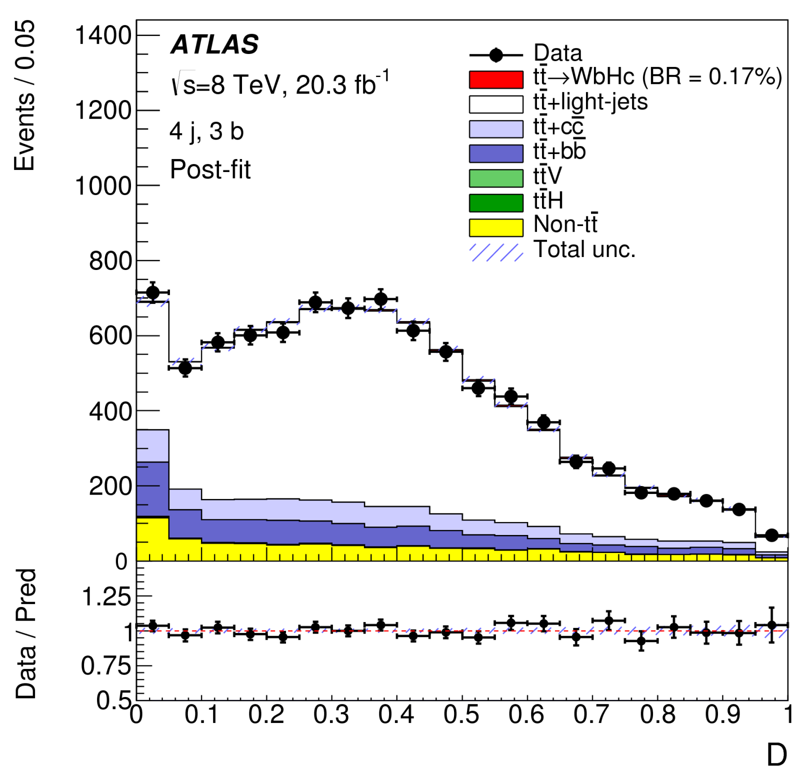
Discrimination of signal from background

- Signal-to-background ratio is very low
- Sig-bkg discriminant: $D(x) = \dfrac{p^{Sig}(x)}{p^{Sig}(x) + p^{Bkg}(x)}$
- $\mathbf{p^{Sig}(x)}$ and $\mathbf{p^{Bkg}(x)}$ are probability density functions for a given event under signal and background hypothesis
- x represents the four-momentum vectors of all final-state particles at the reco. level + b-tagging info

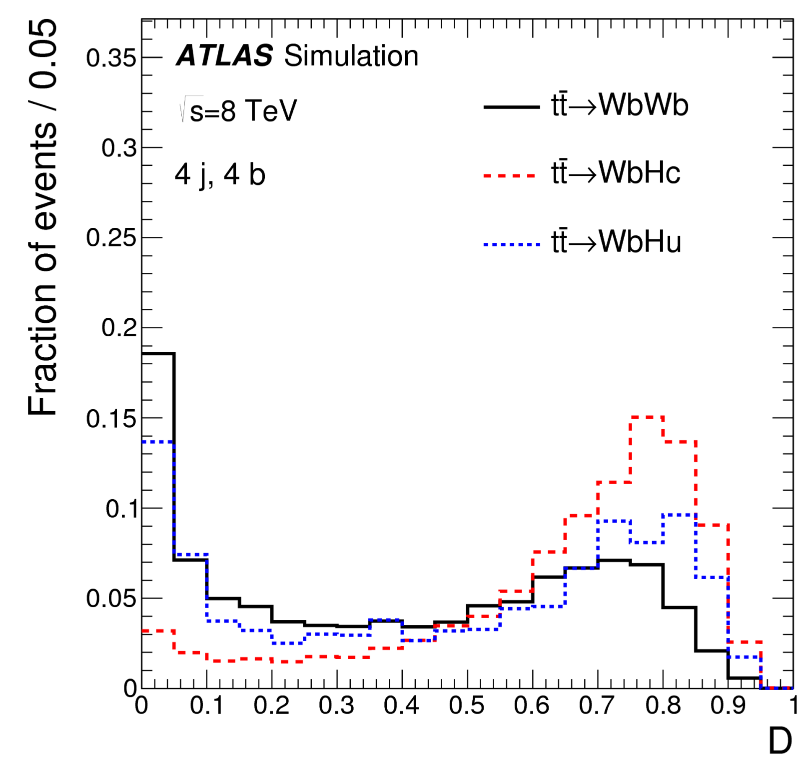




pre-fit



post-fit



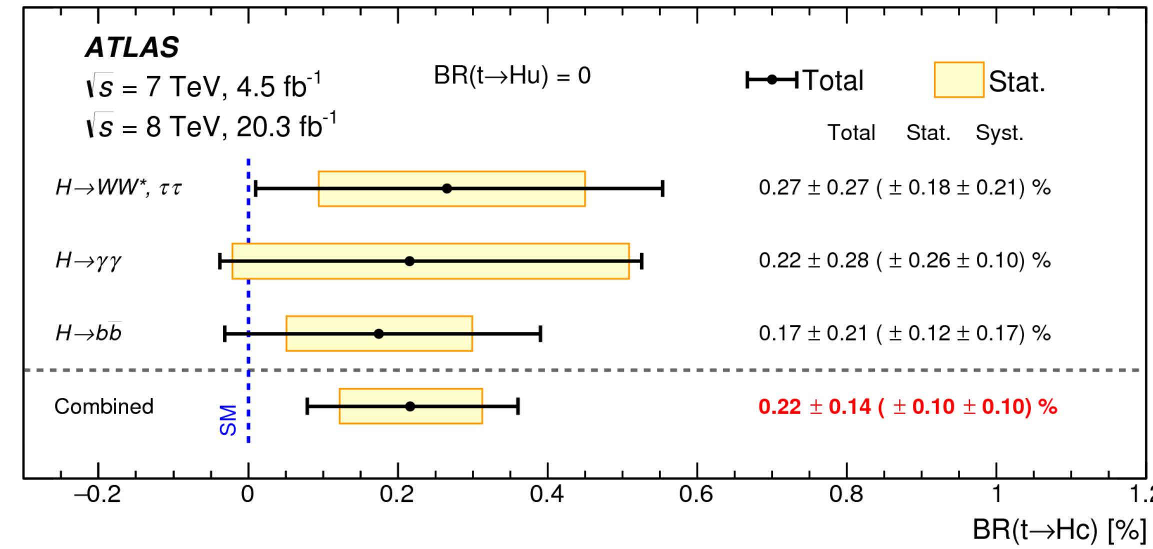
See backup for more plots

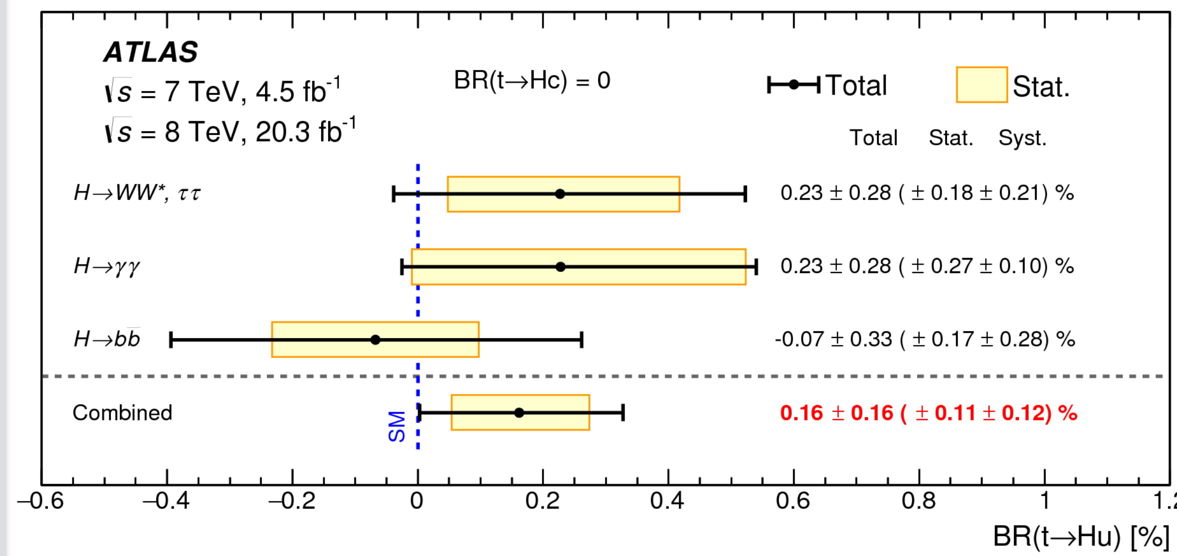
FCNC in Top Decay (t → Hq)

Results

- Observed (expected) 95% CL limits set:
- **BR(t→Hc) < 5.6 x 10^{-3} (4.2 x 10^{-3}) ⇨ |λ_{tcH}| < 0.14 (0.12)**
- **BR(t→Hu) < 6.1 x 10^{-3} (6.4 x 10^{-3}) ⇨ |λ_{tuH}| < 0.15 (0.15)**
  - **Where λ_{tqH} is non-flavour-diagonal Yukawa coupling in** $\mathcal{L}_{FCNC} = \lambda_{tcH}\bar{t}Hc + \lambda_{tuH}\bar{t}Hu + h.c.$
- Combination with other results:
  - $t\bar{t} \rightarrow WbHq\ ,\ H \rightarrow \gamma\gamma$: [JHEP06(2014)008]
  - $t\bar{t} \rightarrow WbHq\ ,\ H \rightarrow W^+W^-\ ,\ \tau^+\tau^-$: [Phys. Let. B 749 (2015) 519-541]
- **BR(t→Hc) < 4.6 x 10^{-3} (2.5 x 10^{-3}) ⇨ |λ_{tcH}| < 0.13 (0.10)**
- **BR(t→Hc) < 4.5 x 10^{-3} (2.9 x 10^{-3}) ⇨ |λ_{tuH}| < 0.13 (0.10)**

☆ **No significant excess of events above the backgrounds expectations found**





Conclusion

The Most restrictive direct bounds on tqH(q=u,c) interactions measured so far

FCNC in Top Decay ($t \to qZ$)

Eur. Phys. J. C76 (2016) 12

Search for FCNC Top quark decays t → qZ @8 TeV

- **Top quark**^{SM} decays via leptonic channel
- **Top quark**^{FCNC} decays via $Z \to \ell\ell$
- 3 isolated high p_T leptons
- ⩾2 jets, 1-2 b-tagged and E_T(Miss)
- Reconstruction via χ^2 method:

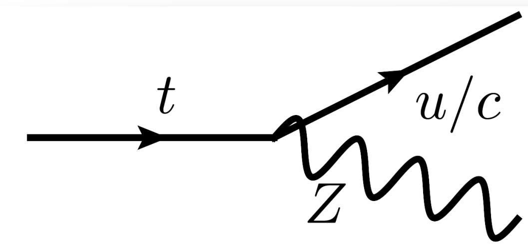
$$\chi^2 = \frac{\left(m^{\text{reco}}_{j_a \ell_a \ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b \ell_c \nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c \nu} - m_W\right)^2}{\sigma^2_W}$$

- Reconstruction quality cut (χ^2<6)

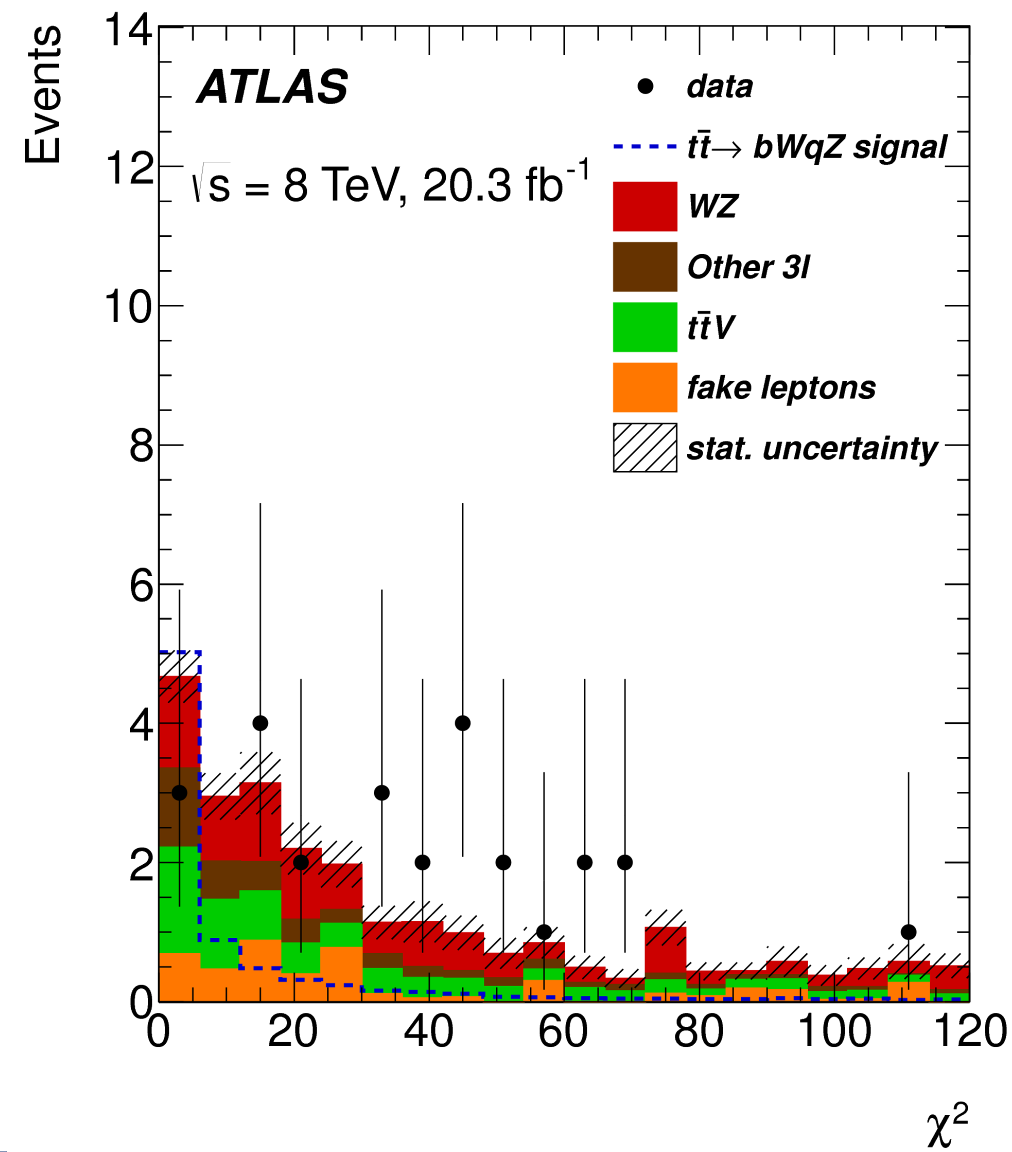
Result

- Upper limit on BR (t → qZ) at 95% CL is set:
  - **Observed: 7 x 10^{-4}**
  - **Expected: 8 x 10^{-4}**

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$



$$\mathcal{L}_{Ztc} = -\frac{g}{2c_W}\bar{c}\gamma^\mu\left(X^L_{ct}P_L + X^R_{ct}P_R\right)t\,Z_\mu - \frac{g}{2c_W}\bar{c}\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(\kappa^L_{ct}P_L + \kappa^R_{ct}P_R\right)t\,Z_\mu + \text{H.c.} \quad [2]$$



[2]: Nucl.Phys.B812:181--204,2009

Conclusion

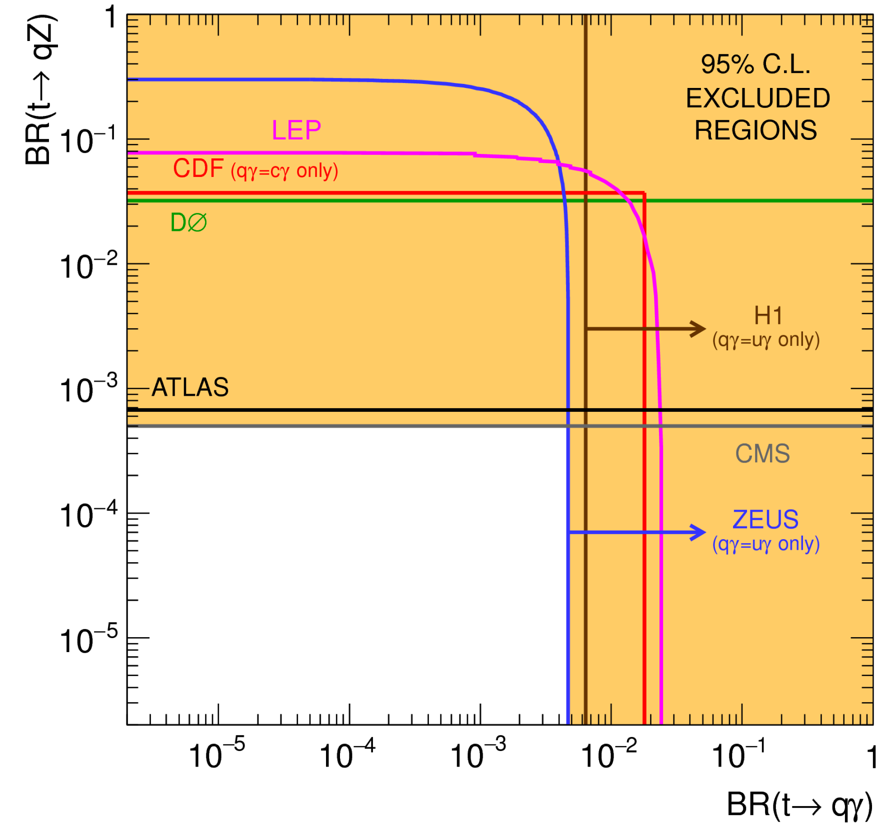
- No evidence of FCNC in top decays is found
- Almost sensitivity to exclude t→Hc in 2HDM(FV)
- More statistics is needed

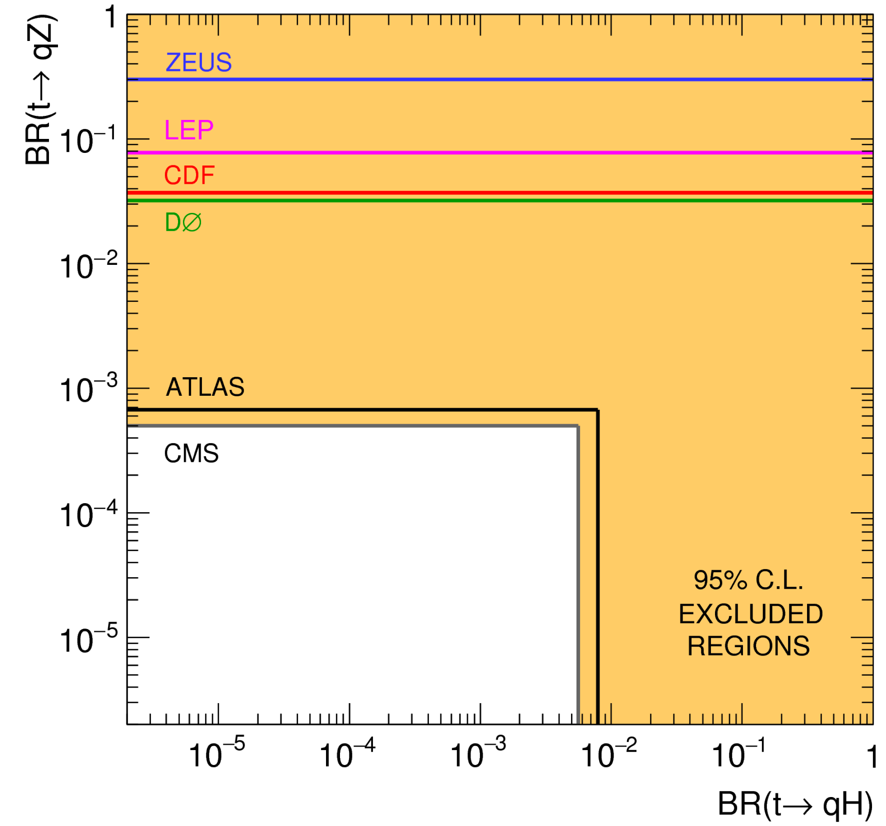
single top-quark production via FCNC @8TeV in ATLAS:

BR(t→gu) < 4 x 10^{-5} and BR(t→gc) < 20 x 10^{-5}

[Eur. Phys. J. C (2016) 76:55]

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$





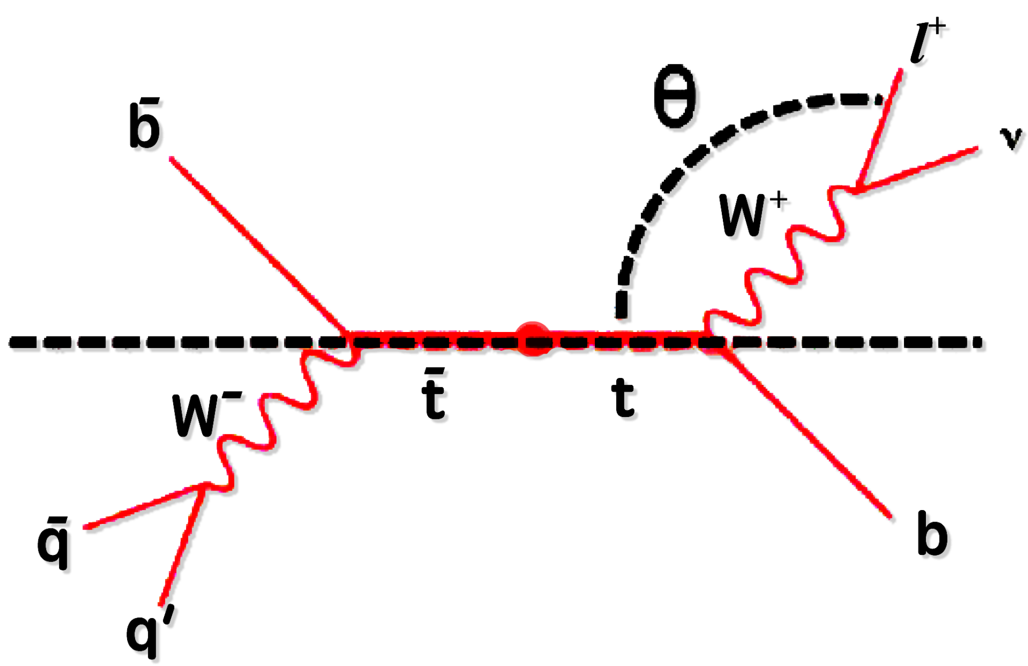
Spin Correlation in Top Decay

Polarisation power

- Spin information can be accessed via the angular momentum of the Top quark decay products
- The amount of spin correlation is sensitive to the production mechanism
- Many BSM scenarios predict different spin correlation, e.g. models including axigluons, W' bosons, extra right handed top-quark coupling, etc.
- Polar angles of leptons in helicity basis:

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

Top quark polarisation · Top anti-quark polarisation · Spin correlation

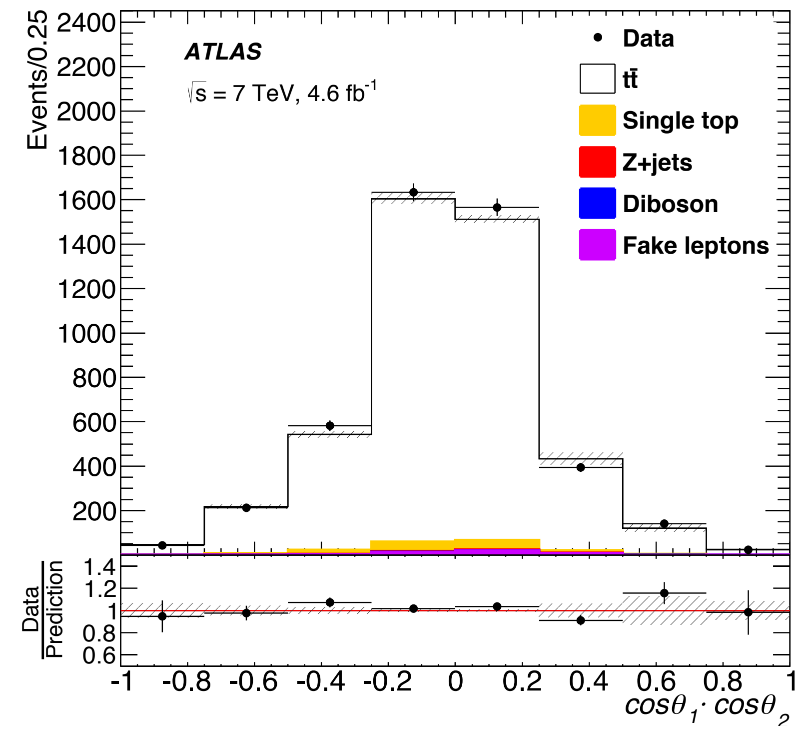


Spin Correlation in Top Decay

Phys. Rev. D 93, 012002 (2016)

Polar angles correlation measurement @ 7 TeV

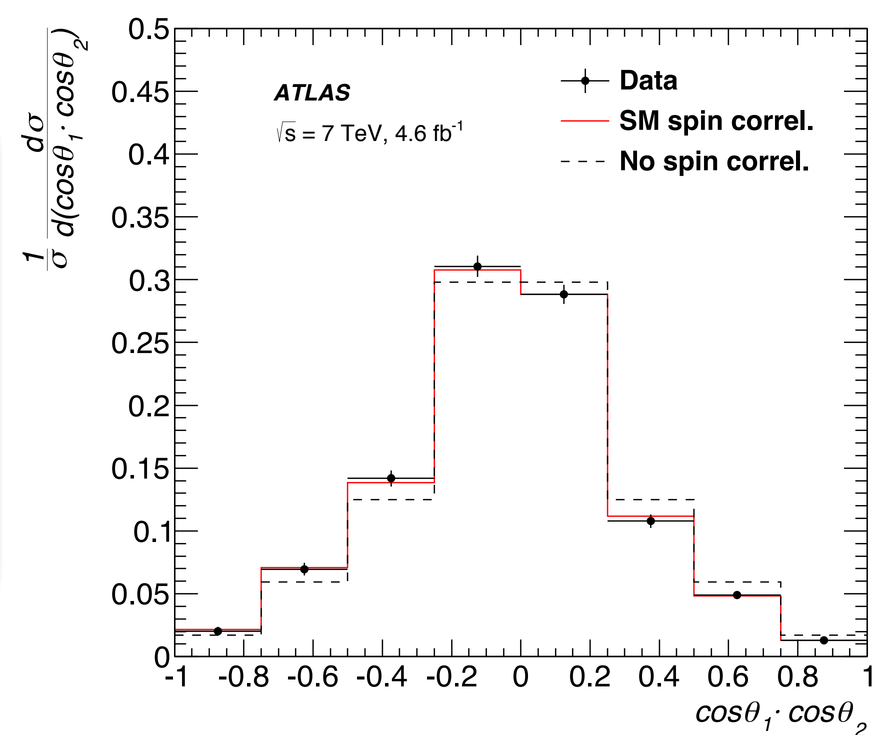
- Events are selected in **dilepton** topology with **two jets**
- Distribution of $\cos\theta_1 . \cos\theta_2$ is reconstructed via "**topology reconstruction method**"
- **Unfolded to parton level** via Fully Bayesian unfolding algorithm
- Dominant syst. unc. : **Unfolding method**, **signal modeling** and **jet reco.**



Results

- In terms of $A_{helicity}$ = (N_{like} - N_{unlike}) / (N_{like} + N_{unlike}) [*]:
  - $A_{helicity}$ **= 0.315 ± 0.061(stat.) ± 0.049 (syst.)**
  - **NLO QCD prediction:** $A_{helicity}$ **=0.31** [Phys.Rev.Lett. 87 (2001) 242002]

☆ **In good agreement with SM prediction**



[*]: N_{like} (N_{unlike}): # of events where top quark and top anti-quark are parallel (anti-parallel)

Summary

The Top Quark

- Has very special properties
- Can open a window to BSM physics
- Good probe for the Standard Model

Property Measurements @ Run I

- Charge asymmetry measurement: performed in resolved and boosted topology
- FCNC searches in Top quark decay: performed in ($t \to qZ$) and ($t \to Hq$)
- Spin correlation: polar angles correlation measurement in dilepton channel
- ☆ **No significant deviations, validated the Standard Model with different measurements**
- More interesting measurements upcoming. Stay tuned!

Run II Property measurements @ 13 TeV

- Will soon start a new era of Top quark analyses

Backup

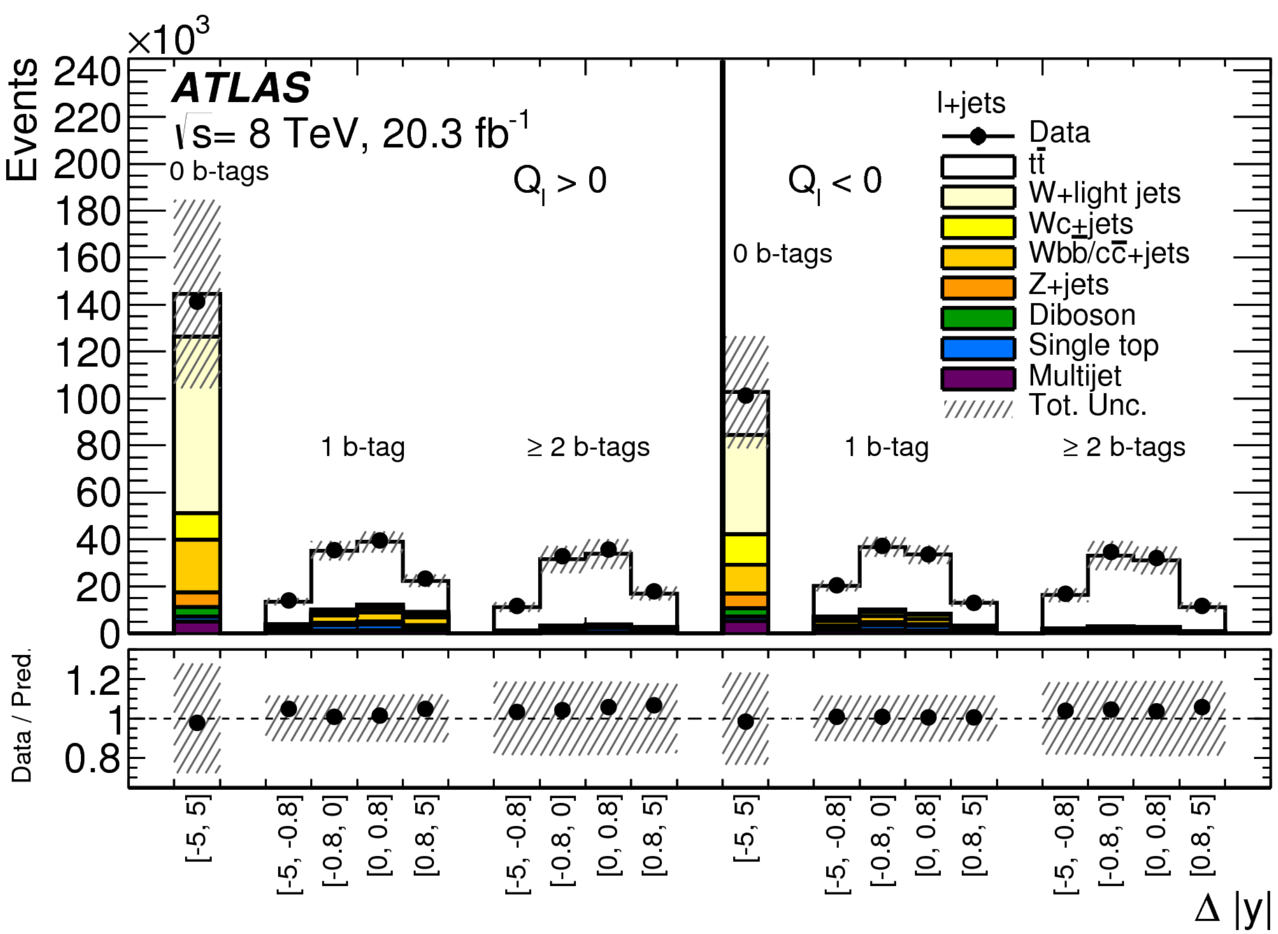
A_C	$m_{t\bar{t}}$ [GeV] < 420	420–500	500–600	600–750	750–900	> 900
Data	0.026 ± 0.041	-0.005 ± 0.020	0.026 ± 0.021	0.009 ± 0.027	-0.007 ± 0.046	0.068 ± 0.044
SM	$0.0081^{+0.0003}_{-0.0004}$	0.0112 ± 0.0005	$0.0114^{+0.0003}_{-0.0004}$	$0.0134^{+0.0003}_{-0.0005}$	$0.0167^{+0.0005}_{-0.0006}$	$0.0210^{+0.0003}_{-0.0002}$
Light BSM	0.0100 ± 0.0004	0.0134 ± 0.0006	$0.0135^{+0.0004}_{-0.0005}$	$0.0155^{+0.0005}_{-0.0006}$	$0.0186^{+0.0007}_{-0.0008}$	$0.0235^{+0.0006}_{-0.0005}$
Heavy BSM	0.0089 ± 0.0004	0.0132 ± 0.0006	$0.0148^{+0.0004}_{-0.0005}$	$0.0201^{+0.0004}_{-0.0006}$	$0.0310^{+0.0006}_{-0.0007}$	$0.0788^{+0.0007}_{-0.0006}$

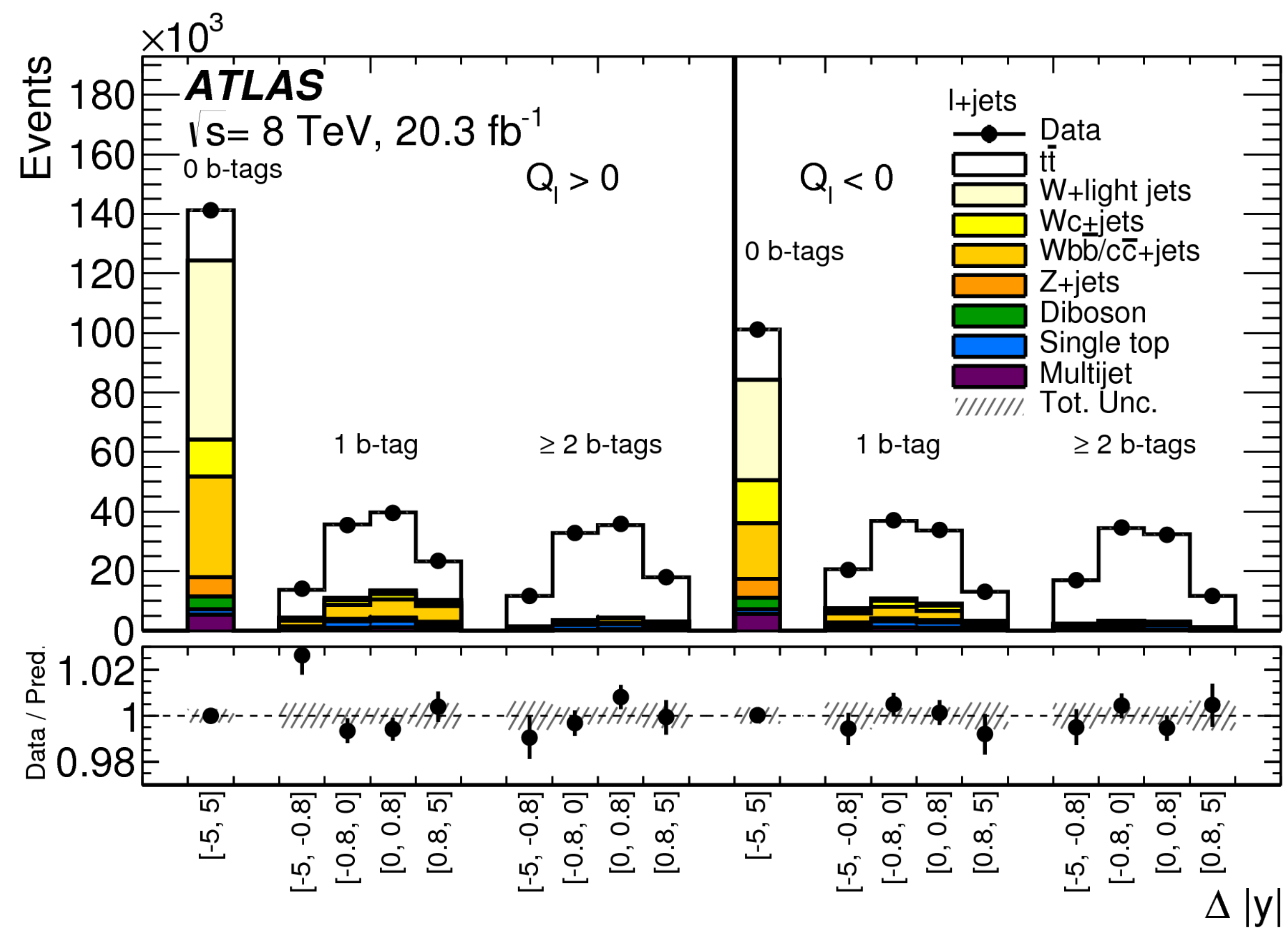
A_C	$\beta_{z,t\bar{t}}$ < 0.3	0.3–0.6	0.6–1.0
Data	-0.005 ± 0.034	0.054 ± 0.038	0.028 ± 0.011
SM	0.0031 ± 0.0003	$0.0068\ ^{+0.0002}_{-0.0003}$	$0.0175\ ^{+0.0007}_{-0.0008}$
Light BSM	0.0037 ± 0.0004	0.0075 ± 0.0004	$0.0211\ ^{+0.0007}_{-0.0008}$
Heavy BSM	0.0048 ± 0.0004	0.0103 ± 0.0004	$0.0242\ ^{+0.0007}_{-0.0008}$

A_C	$p_{T,t\bar{t}}$ [GeV] < 25	25–60	> 60
Data	0.044 ± 0.088	0.004 ± 0.066	0.002 ± 0.062
SM	0.0141 ± 0.0007	-0.0051 ± 0.0003	-0.0026 ± 0.0002

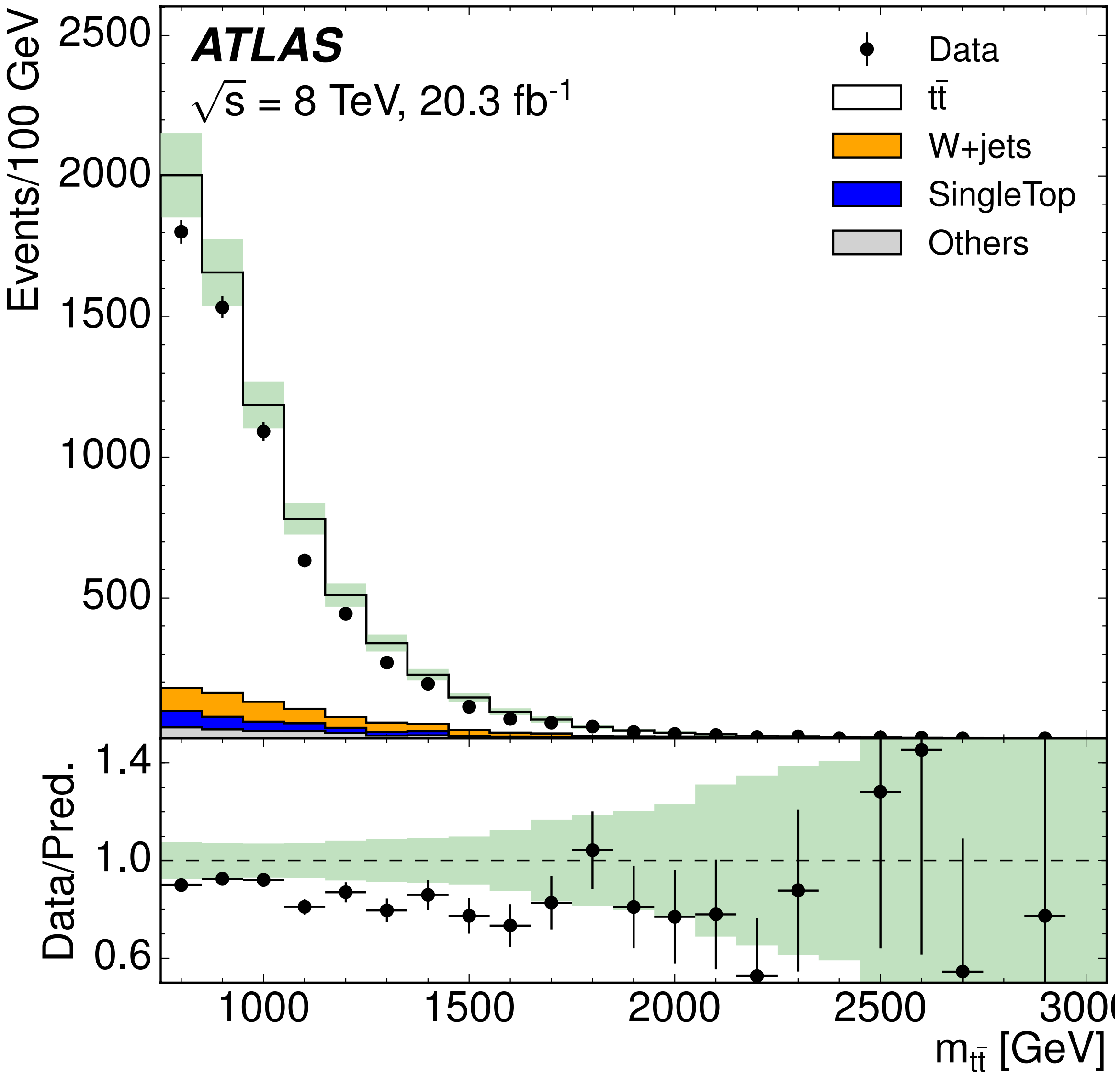
	Source of systematic uncertainty	δA_C
(a)	Jet energy scale and resolution	0.0016
	Multijet background normalisation	0.0005
(b)	Initial-/final-state radiation	0.0009
	Monte Carlo sample size	0.0010
	PDF	0.0007
	Statistical uncertainty	0.0044
	Total uncertainty	0.0049

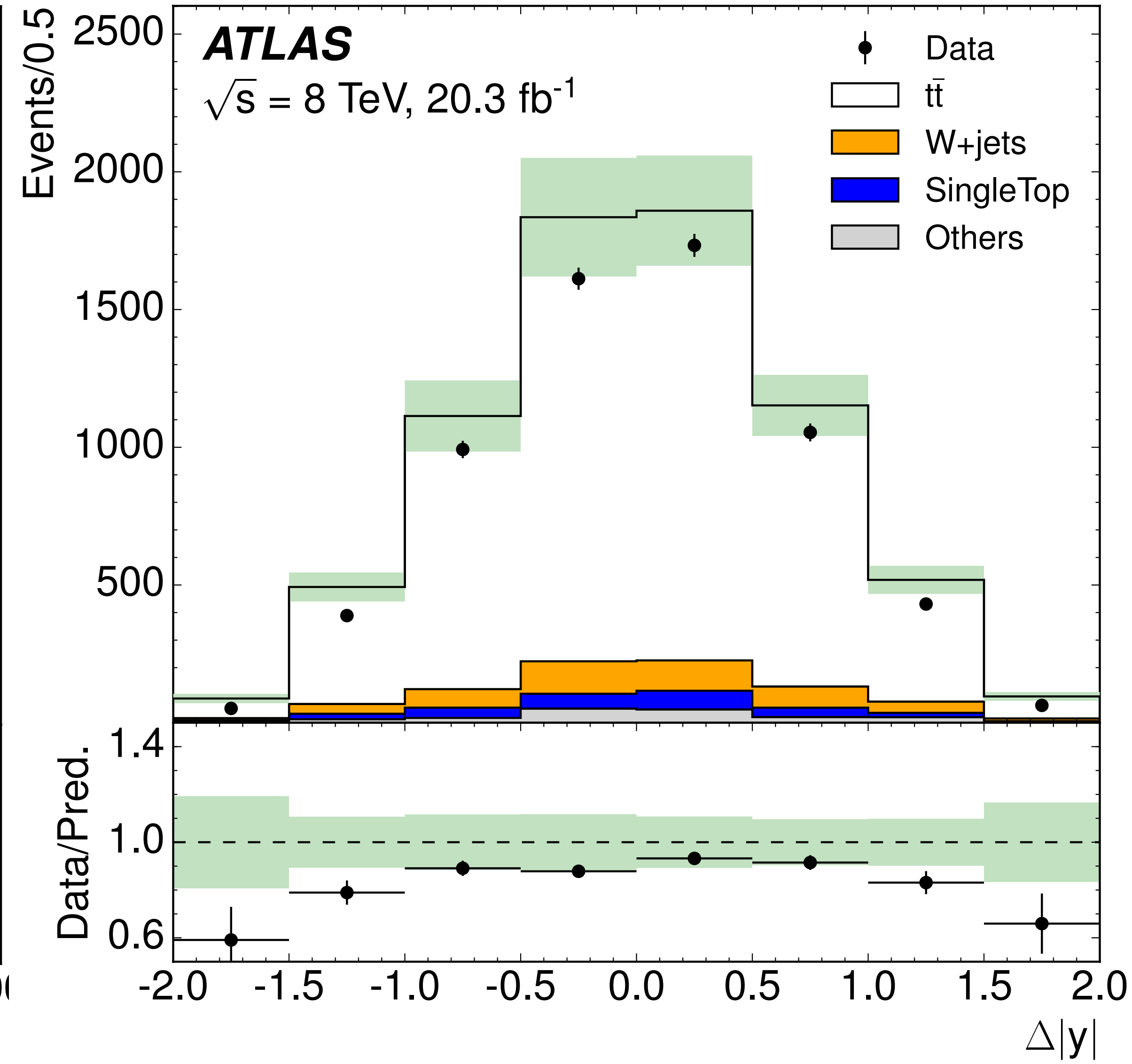
Charge Asymmetry - Backup





Charge Asymmetry (Boosted) - Backup



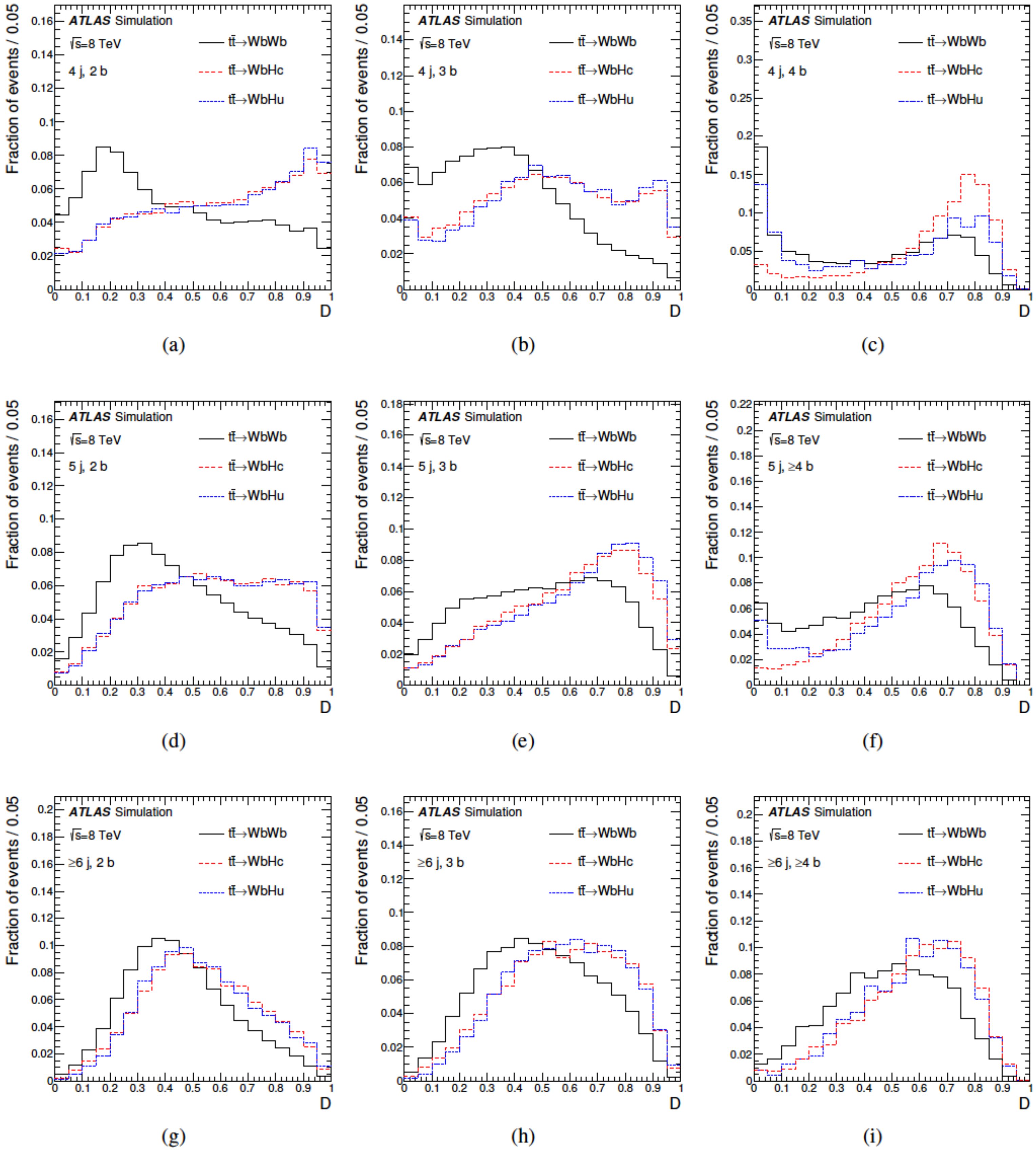


$m_{t\bar{t}}$ interval	> 0.75 TeV	0.75 – 0.9 TeV	0.9 – 1.3 TeV	> 1.3 TeV
Measurement	(4.2 ± 3.2)%	(2.2 ± 7.3)%	(8.6 ± 4.4)%	(−2.9 ± 15.0) %
SM prediction	(1.60 ± 0.04)%	(1.42 ± 0.04)%	(1.75 ± 0.05)%	(2.55 ± 0.18)%

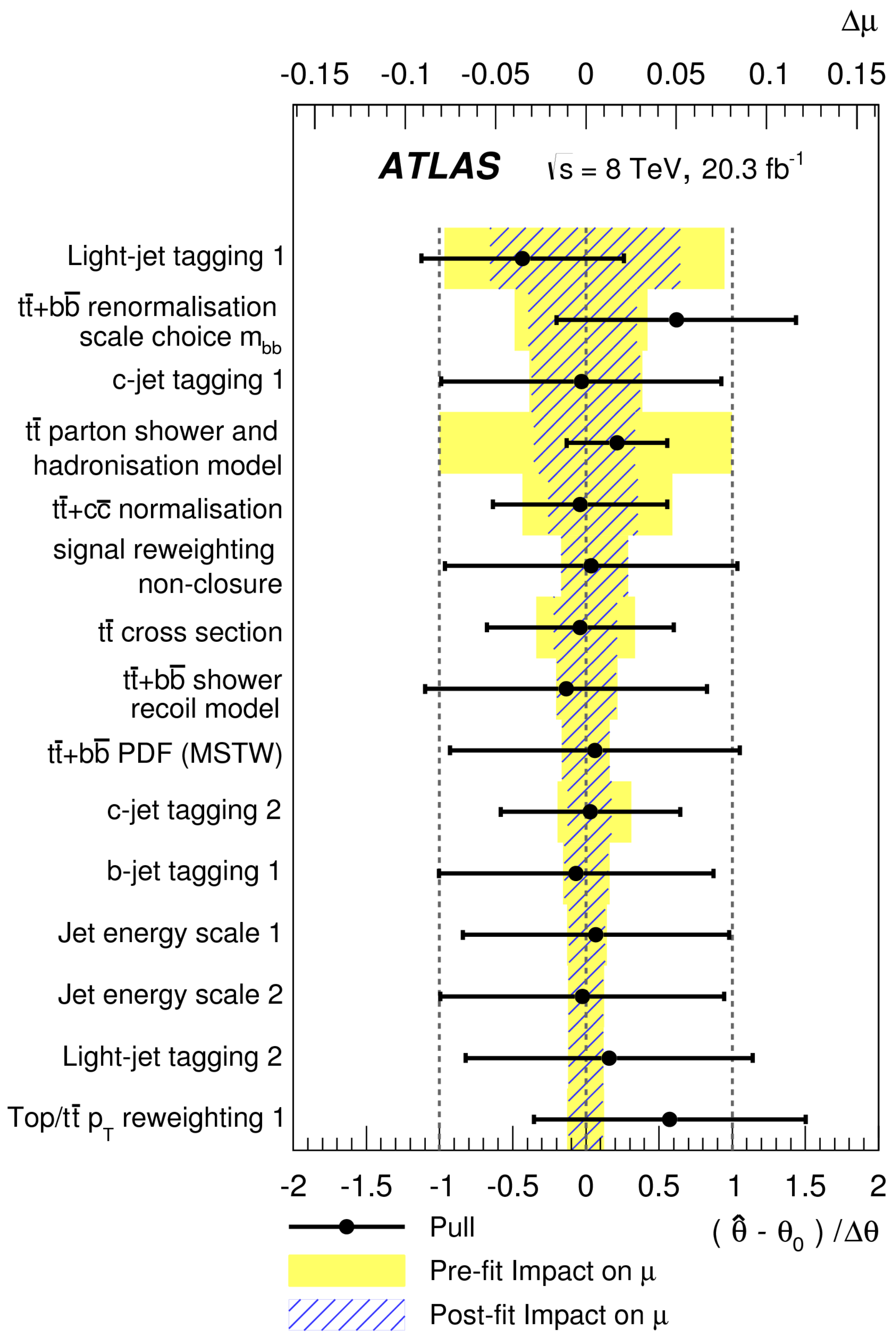
FCNC (t → Hq) - Backup

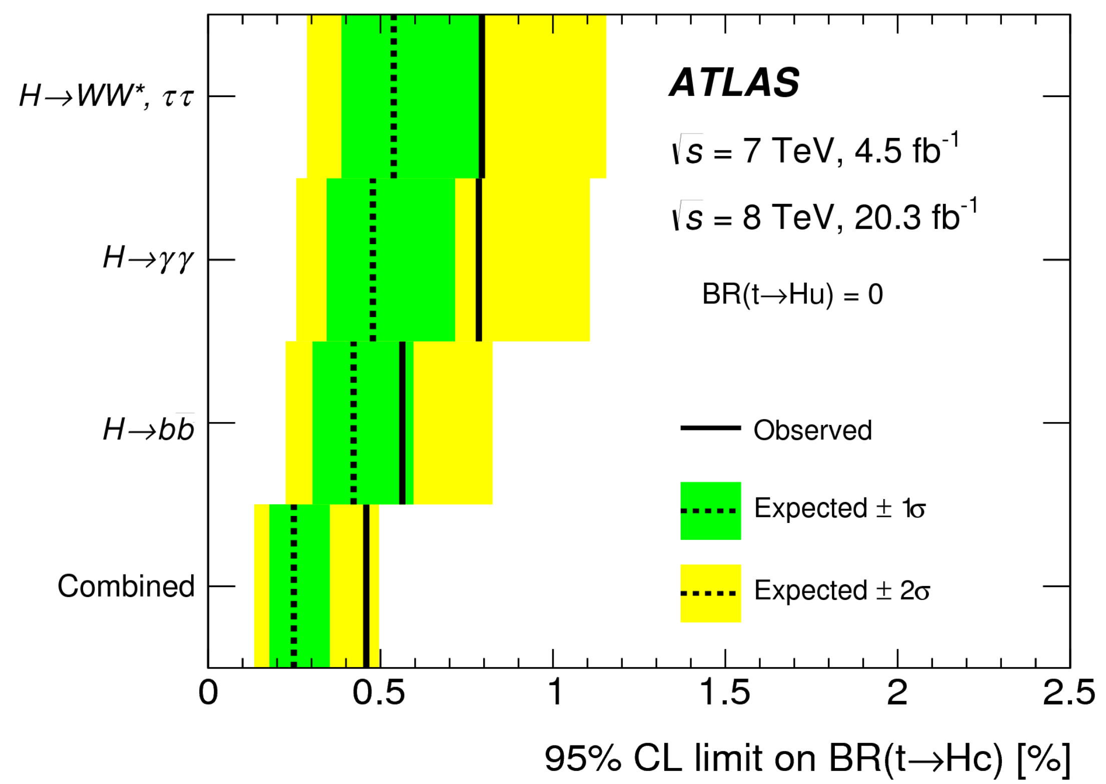
- Discriminant between signal and background:

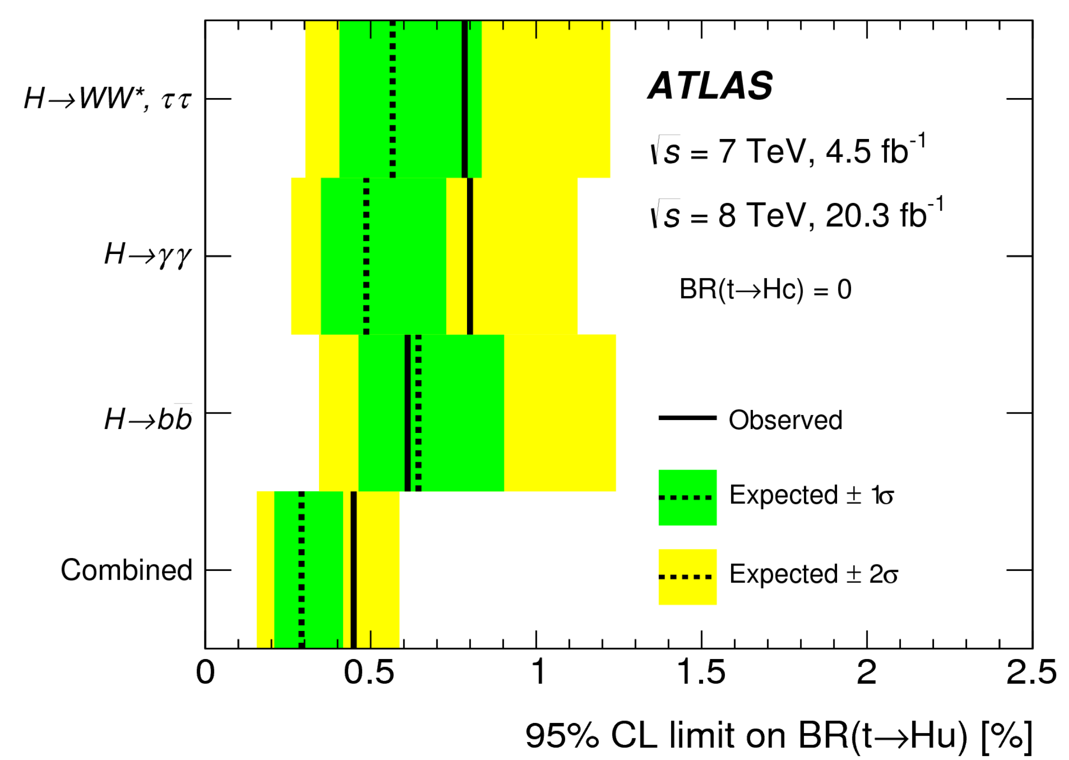
$$D(x) = \frac{p^{Sig}(x)}{p^{Sig}(x) + p^{Bkg}(x)}$$



FCNC (t → Hq) - Backup

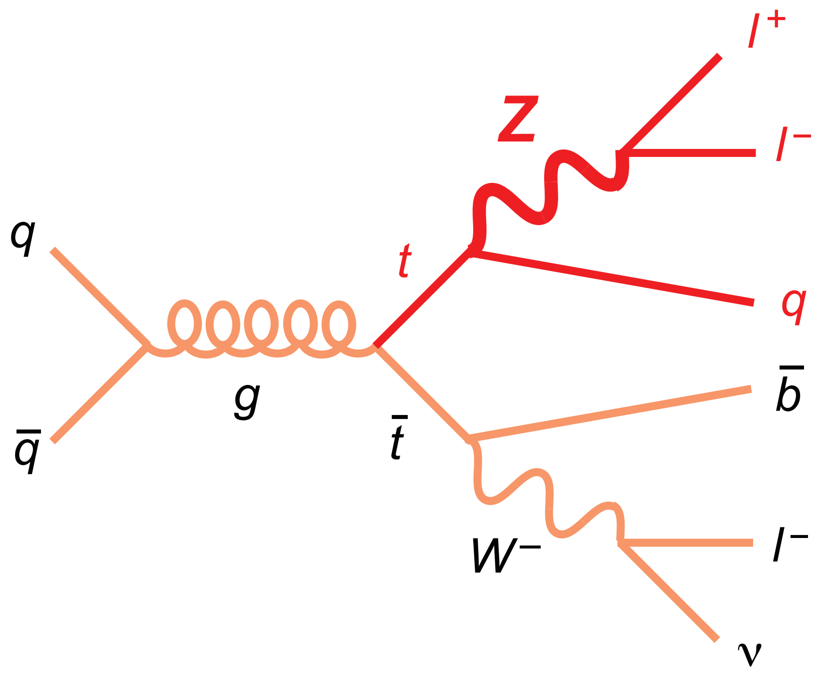


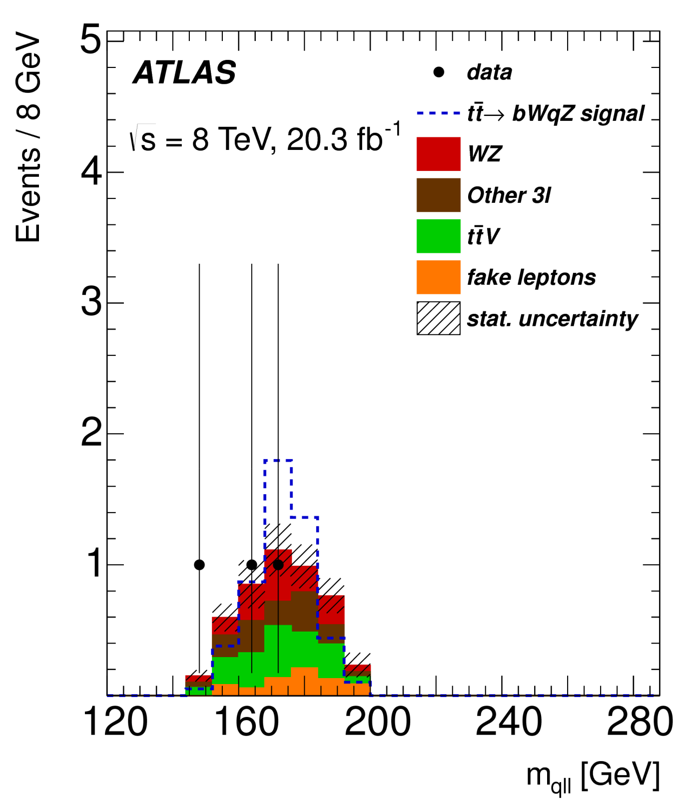


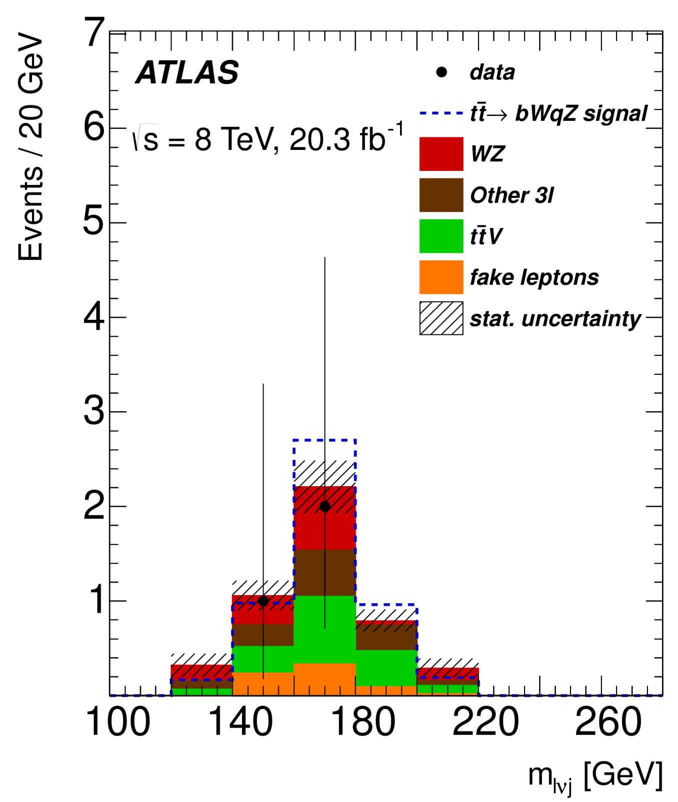


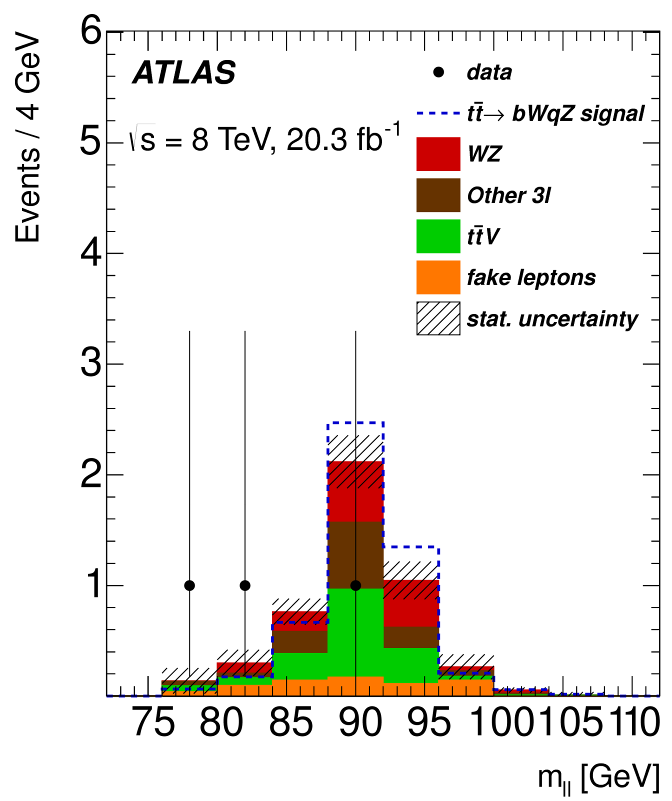
FCNC ($t \to qZ$) - Backup

Sample	Yields
WZ	$1.3 \pm 0.2 \pm 0.6$
$t\bar{t}V$	$1.5 \pm 0.1 \pm 0.5$
tZ	$1.0 \pm 0.1 \pm 0.5$
Fake leptons	$0.7 \pm 0.3 \pm 0.4$
Other backgrounds	$0.2 \pm 0.1 \pm 0.1$
Total background	$4.7 \pm 0.4 \pm 1.0$
Data	3
Signal efficiency [$\times 10^{-4}$]	$7.8 \pm 0.1 \pm 0.8$









Topology reconstruction method:

- Using kinematic properties of Top quark and Top anti-quark:

$$
\begin{aligned}
p_{\nu,x} + p_{\bar{\nu},x} &= E_x^{\text{miss}}, \\
p_{\nu,y} + p_{\bar{\nu},y} &= E_y^{\text{miss}}, \\
(p_{\ell^-} + p_{\bar{\nu}})^2 &= m_{W^-}^2, \\
(p_{\ell^+} + p_{\nu})^2 &= m_{W^+}^2, \\
(p_{W^-} + p_{\bar{b}})^2 &= m_{\bar{t}}^2, \\
(p_{W^+} + p_{b})^2 &= m_{t}^2,
\end{aligned}
$$

- Using the two highest-ranked (first in b-tagging, then in p_T) jets in the algorithm
- The b-ℓ pari with lower invariant mass is first considered
  - If no solution found, Top quark mass is varied from the nominal value in steps of 1.5 GeV in range of [157.5, 187.5] GeV
  - If still no solution found, the alternative b-ℓ pair considered and the process repeated
  - If more than a solution found, the one with the minimum neutrinos transverse momentum product is selected
- **70% of signal** simulated events and **50% of background** events are reconstructed

Spin Correlation in Top Decay - Backup

Bin range	−1 : −0.75	−0.75 : −0.5	−0.5 : −0.25	−0.25 : 0	0 : 0.25	0.25 : 0.5	0.5 : 0.75	0.75 : 1
Generator modeling	6.9	3.2	1.6	0.5	0.8	2.2	1.0	0.0
ISR/FSR	2.0	0.9	0.6	0.3	0.3	1.1	1.0	0.8
PDF	0.5	0.3	0.1	0.0	0.0	0.2	0.2	0.0
UE/color reconnection	1.5	1.1	1.0	0.7	0.1	0.5	0.6	3.1
JES/jet reconstruction	4.5	3.0	1.1	0.6	0.9	1.1	1.8	3.1
b-tagging SF	0.0	0.3	0.0	0.1	0.0	0.1	0.2	0.0
E_T^{miss}	0.5	0.6	0.4	0.1	0.1	0.3	0.2	0.0
Lepton reconstruction	1.5	0.6	0.1	0.3	0.1	0.5	0.6	0.8
Luminosity uncertainty	0.5	0.1	0.0	0.1	0.0	0.1	0.2	0.0
Background uncertainty	1.5	0.6	0.4	0.1	0.1	0.4	0.6	0.8
Bayesian unfolding method	10.9	0.6	2.3	1.4	1.0	2.6	0.6	7.8
Total	13.9	4.9	3.3	1.8	1.7	3.9	2.7	9.3
Top quark mass (±1 GeV)	0.1	0.2	0.1	0.2	0.1	0.3	0.0	0.6

Bin range	Unfolded data $1/\sigma\ d\sigma/d(\cos\theta_1 \cdot \cos\theta_2) \pm$ stat. $\pm$ syst.	MC@NLO prediction $1/\sigma\ d\sigma/d(\cos\theta_1 \cdot \cos\theta_2) \pm$ stat.
−1.00 : −0.75	0.0202 ± 0.0020 ± 0.0028	0.0215 ± 0.0005
−0.75 : −0.50	0.0696 ± 0.0037 ± 0.0034	0.0707 ± 0.0008
−0.50 : −0.25	0.1418 ± 0.0045 ± 0.0047	0.1384 ± 0.0010
−0.25 : 0	0.3106 ± 0.0062 ± 0.0057	0.3079 ± 0.0014
0 : 0.25	0.2882 ± 0.0059 ± 0.0048	0.2884 ± 0.0013
0.25 : 0.50	0.1078 ± 0.0033 ± 0.0042	0.1118 ± 0.0009
0.50 : 0.75	0.0489 ± 0.0024 ± 0.0013	0.0484 ± 0.0006
0.75 : 1.00	0.0129 ± 0.0009 ± 0.0012	0.0129 ± 0.0003