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

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On behalf of the ATLAS collaboration

1) Introduction
2) Charge Asymmetry at 8 TeV
3) FCNC top quark decays at 13 TeV
4) Spin correlations 8 TeV
5) Colour flow 13 TeV

1 Top quark properties?

m_{top} = 173.1 ± 0.6 GeV (PDG 2017)

m_{hf} = O(1 GeV)

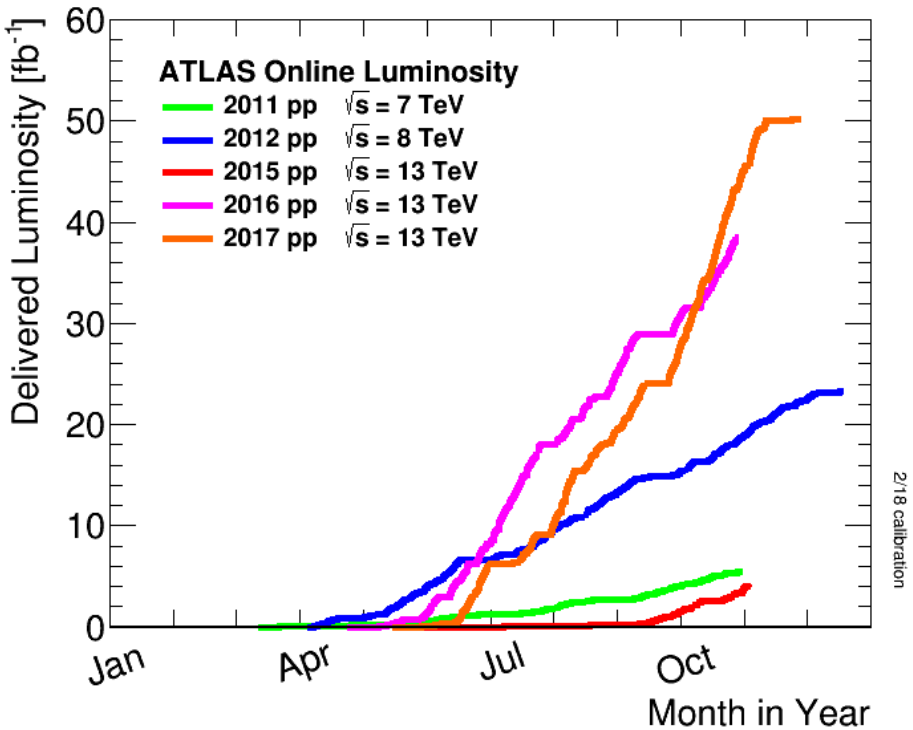
m_{light} = O(1)
or O(100) MeV

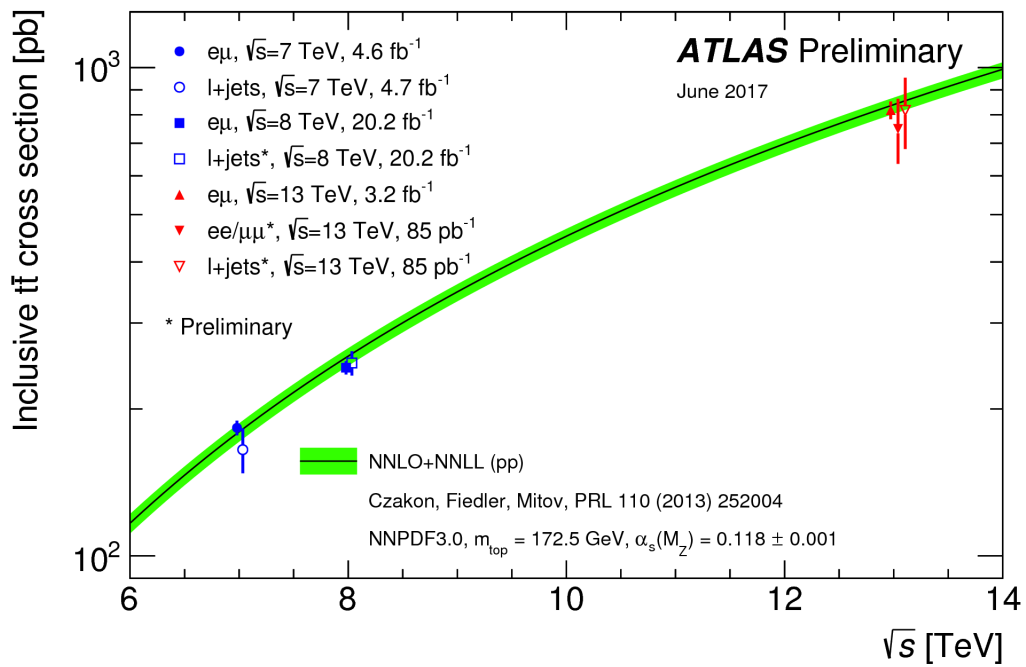
BSM effects
~ mass expected
in top quark
properties

1 ATLAS top quark pairs

Large statistics at 8 (20/fb) and 13 TeV (36/fb) after event selection
O(10^5) in di-lepton, O(10^6) in lepton+jets channel (8 TeV)

$t\bar{t}$ production: pp → gg → $t\bar{t}$ (~80-90%) and pp → $q\bar{q}$ → $t\bar{t}$ (~20-10%)





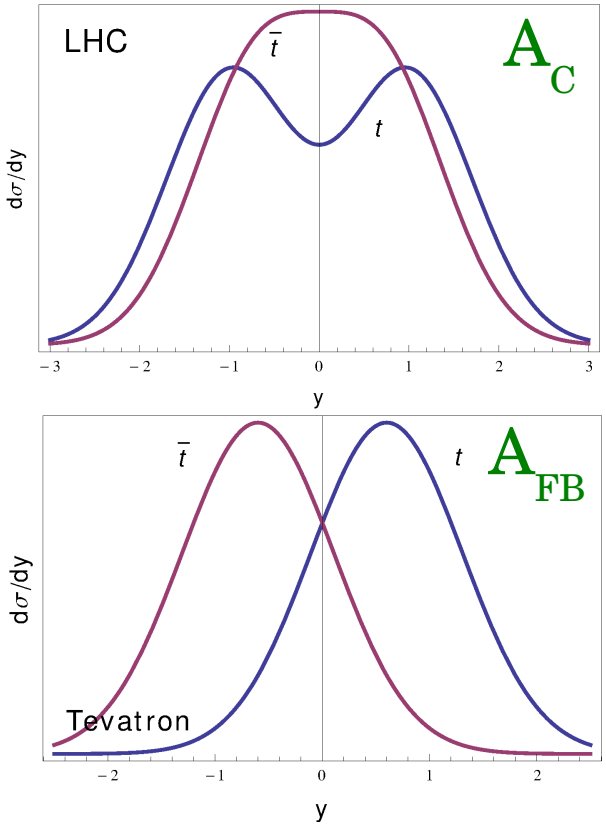
2 Charge Asymmetry A_C

"Charge Asymmetry" really means t vs $\bar{t}$ asymmetry

$pp \to t\bar{t}$: symmetric at LO
$pp \to gg \to t\bar{t}$: symmetric to all orders
$pp \to q\bar{q} \to t\bar{t}(g)$: small asymmetry in HO

At LHC t more forward, $\bar{t}$ more central
$\Rightarrow$ difference of t and $\bar{t}$ rapidities:

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



[arXiv:1207.0331]

"Charge Asymmetry" is "$t\bar{t}$ rapidity difference asymmetry"

$$A_C = (N(\Delta|y|>0) - N(\Delta|y|<0)) / (N(\Delta|y|>0) + N(\Delta|y|<0))$$

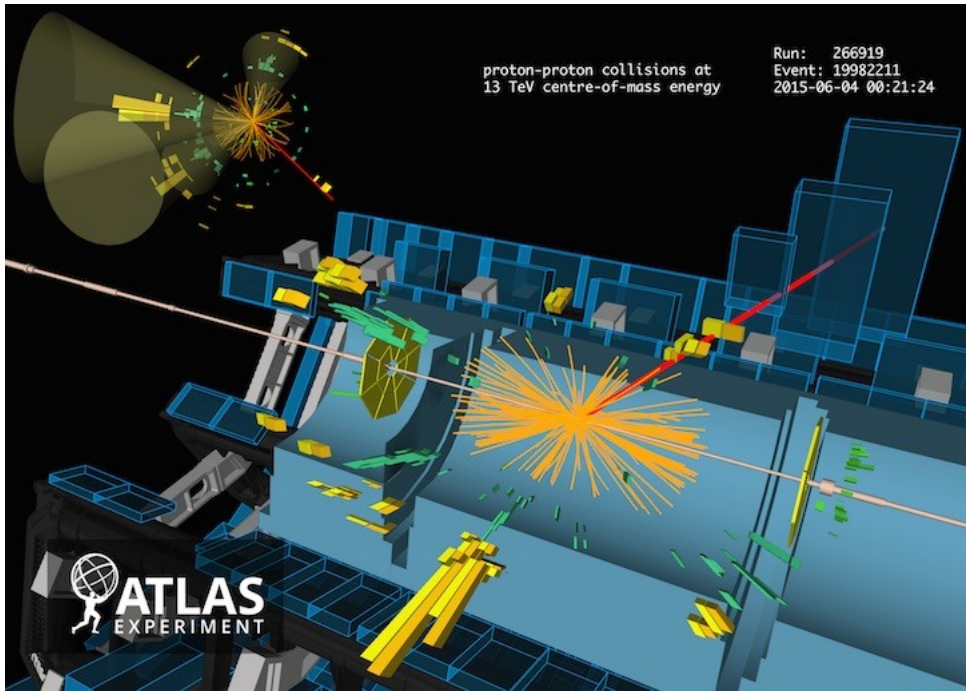
Of course with BSM everything is possible ...

[Phys. Rev. D94 (2016) 032006,
Phys. Lett. B756 (2016) 52,
Eur. Phys. J. C76 (2016) 87]

2 A_C measurements 8 TeV

Lepton (e, μ) + jets (boosted)

[Phys. Lett. B756 (2016) 52, Eur. Phys. J. C76 (2016) 87]



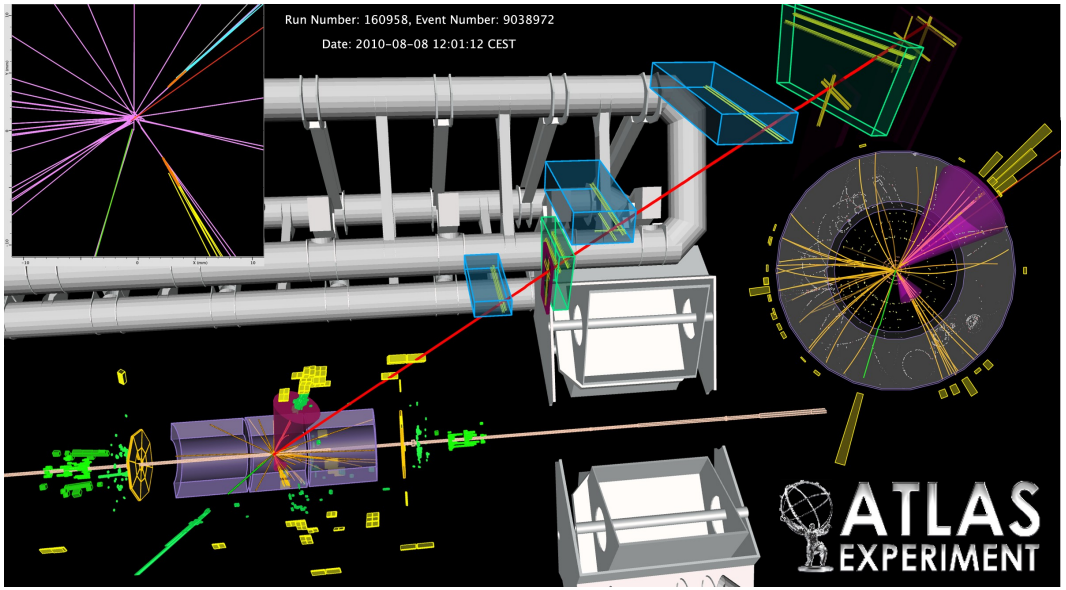
$t \to bW^+ (W^+ \to q\bar{q})$

$\bar{t} \to \bar{b}W^- (W^- \to l^-\nu)$

Boosted: $bq\bar{q}$ in one R=1 jet

Di-lepton (ee, μμ, eμ)

[Phys. Rev. D94 (2016) 032006]



$t \to bW^+ (W^+ \to l^+\nu)$

$\bar{t} \to \bar{b}W^- (W^- \to l^-\bar{\nu})$

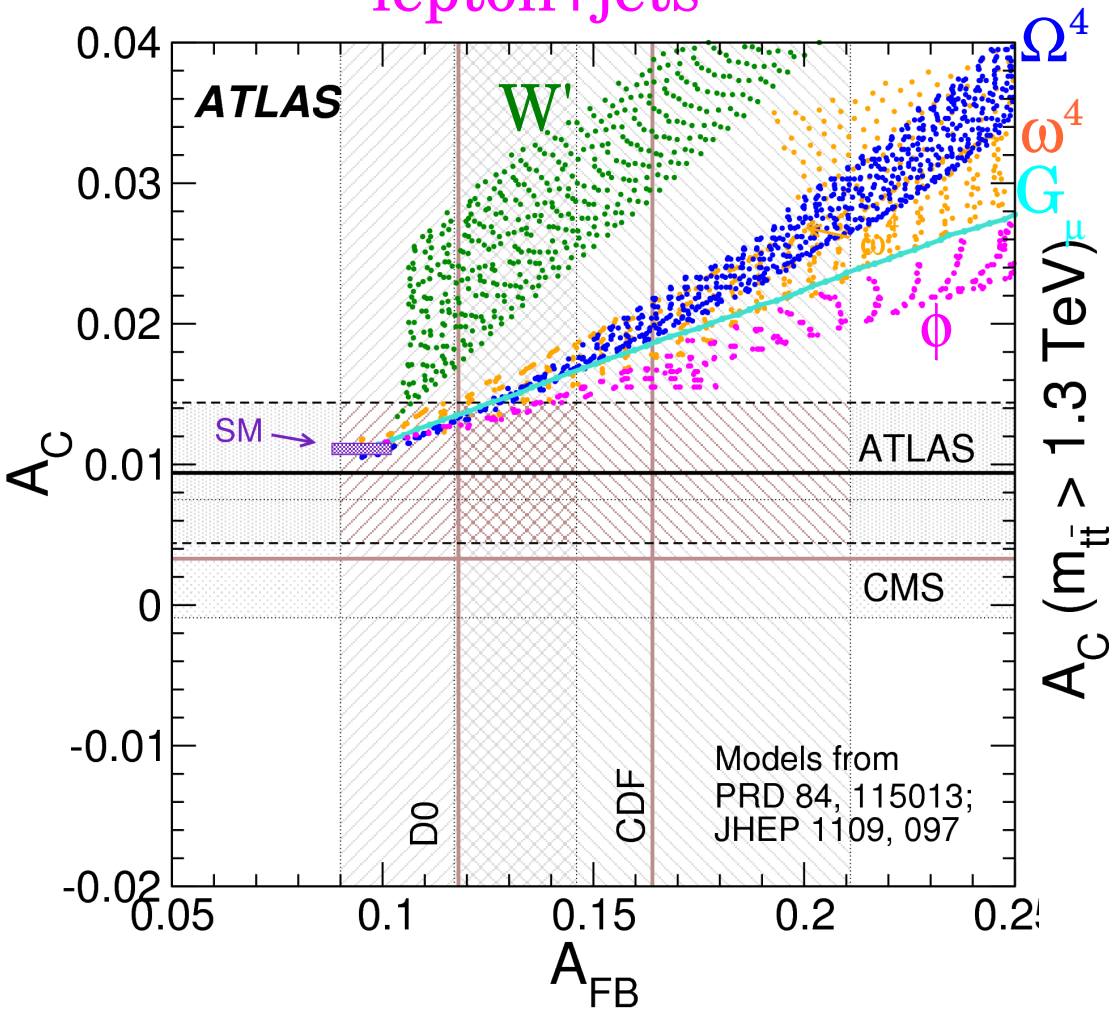
Unfold (fully bayesian) to "$t\bar{t}$ parton level"

In-situ calibration W+jets bkg

DY and $Zb\bar{b}$ bkg from CRs

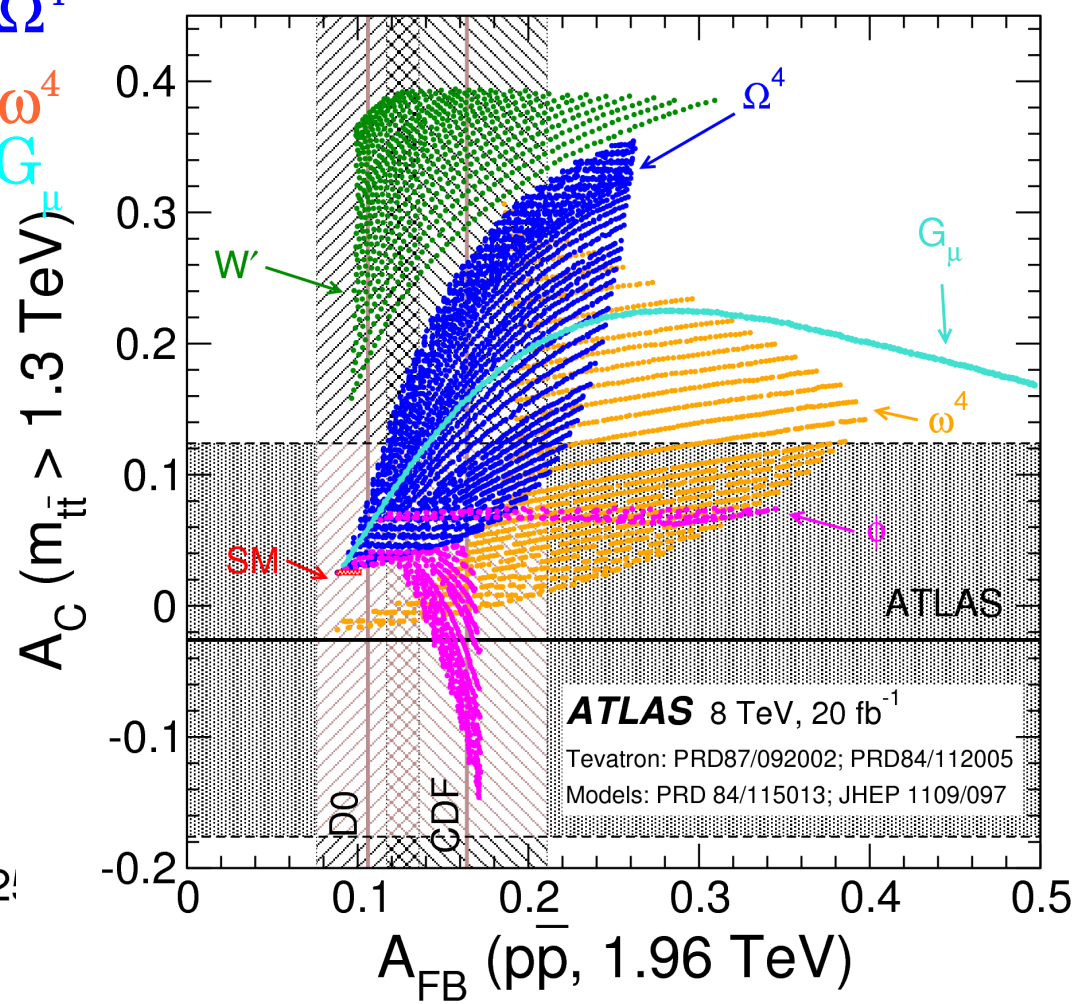
2 A_C measurements 8 TeV

lepton+jets



[Eur. Phys. J. C76 (2016) 87]

lepton+jets boosted



[Phys. Lett. B756 (2016) 52]

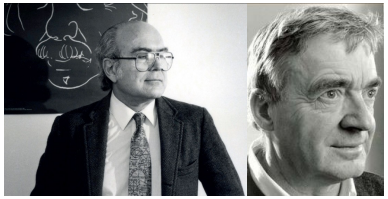
SM prediction consistent with A_C (and A_{FB}) measurements

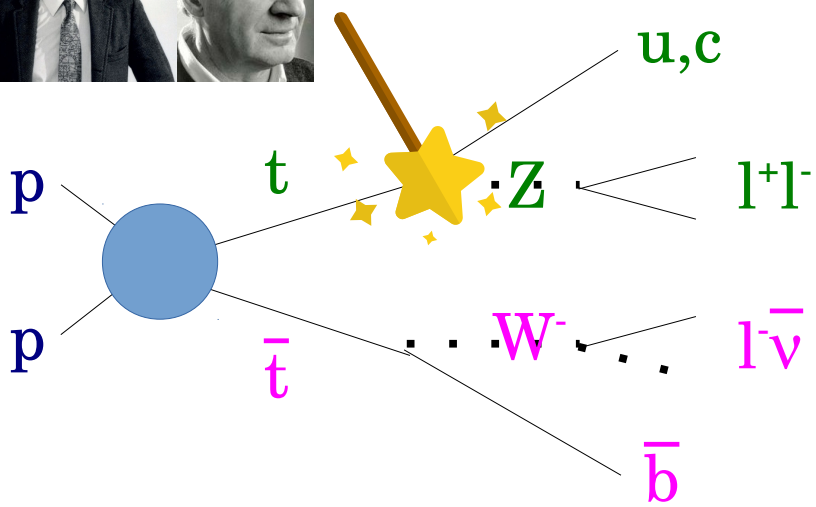
(ATLAS+CMS combination: arXiv:1709.05327, sub. to JHEP)

3 FCNC top decays: t→qZ

$t \to qZ\ (Z \to l^+l^-)$; $\bar{t} \to \bar{b}W^-\ (W^- \to l^-\bar{\nu})$

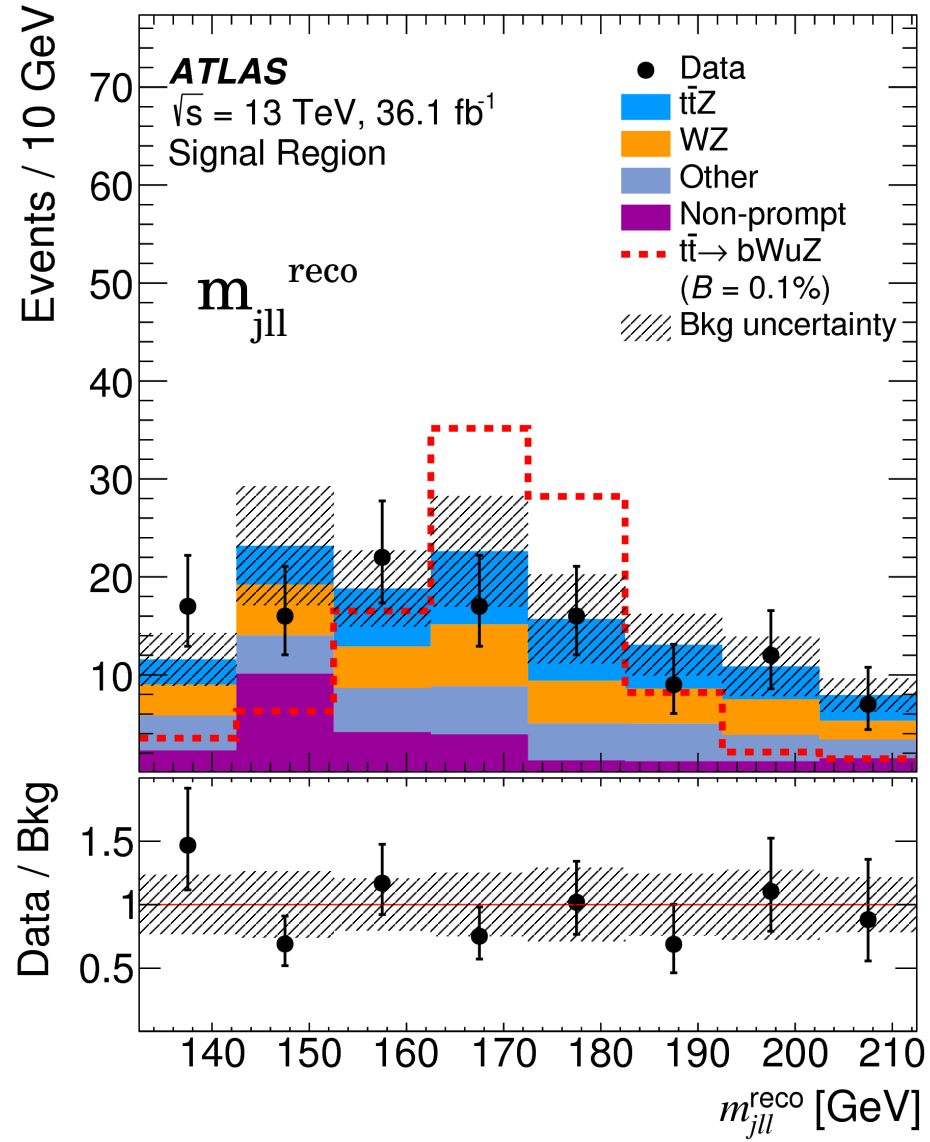
SM BR(t→qZ) ≈ 10^{-14}, BSM up to 10^{-4}





Select 3-lepton events in 13 TeV data

Bkg: pp → WW, ZZ, WZ, $t\bar{t}Z$, tZ;
study in 5 CRs



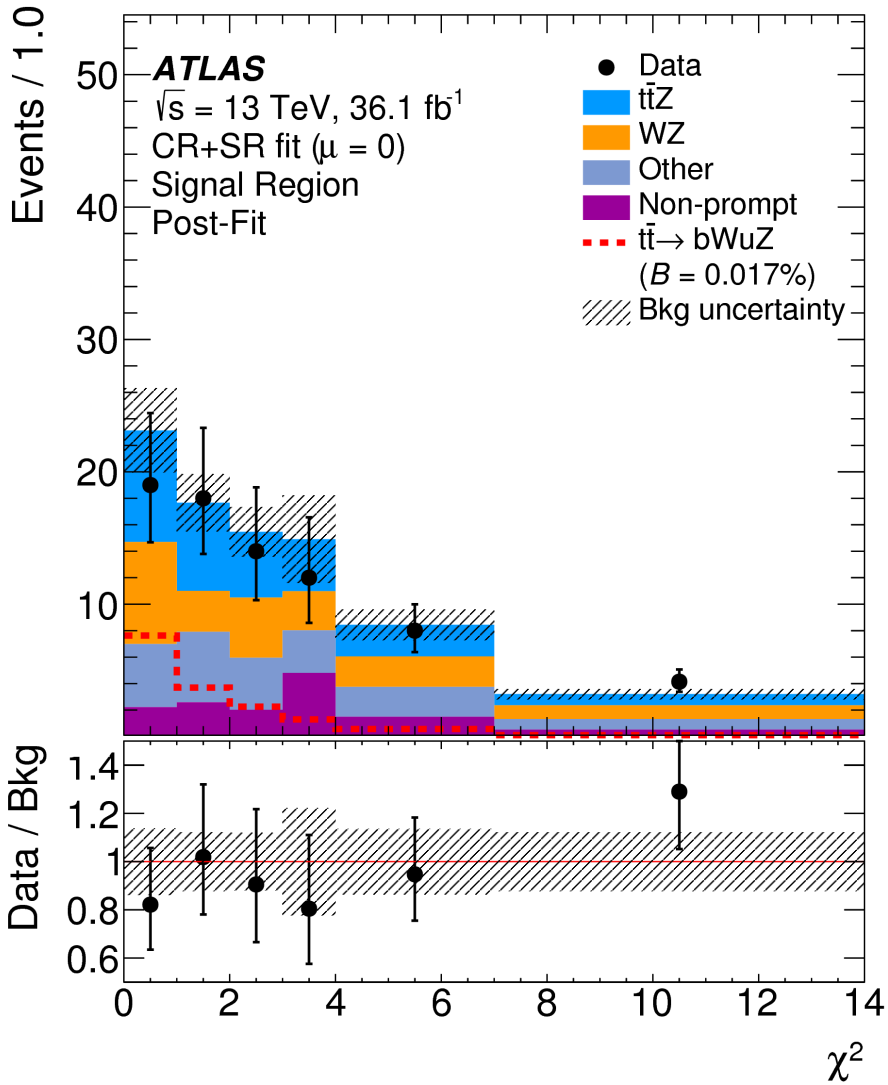
[arXiv:1803.09923, sub. to JHEP]

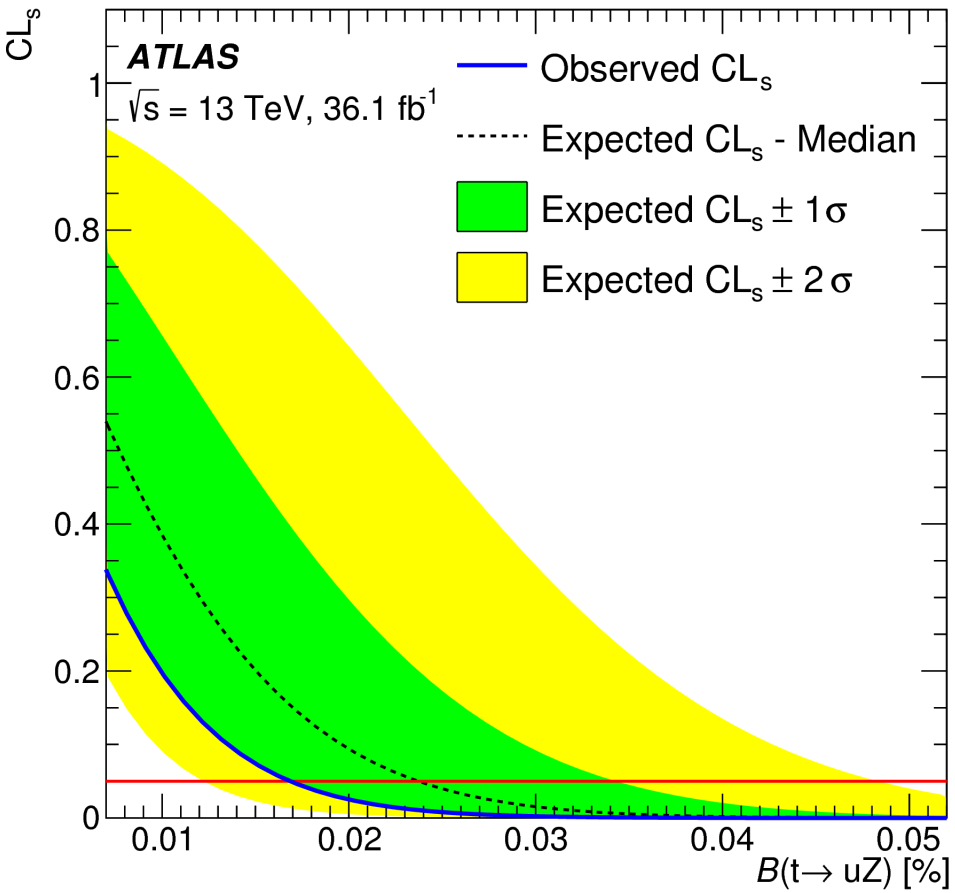
3 FCNC top decays: t→qZ

χ^2 of kin. fit in SR + 5 kin. dist's in CRs

BR(t→uZ) < $1.7 \cdot 10^{-4}$ (95% CL)

BR(t→cZ) < $2.4 \cdot 10^{-4}$



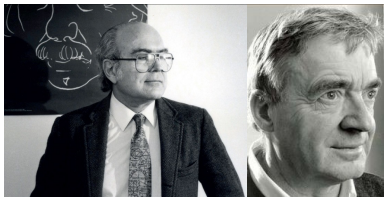


(bkg) modeling dominant uncertainty

[arXiv:1803.09923, sub. to JHEP]

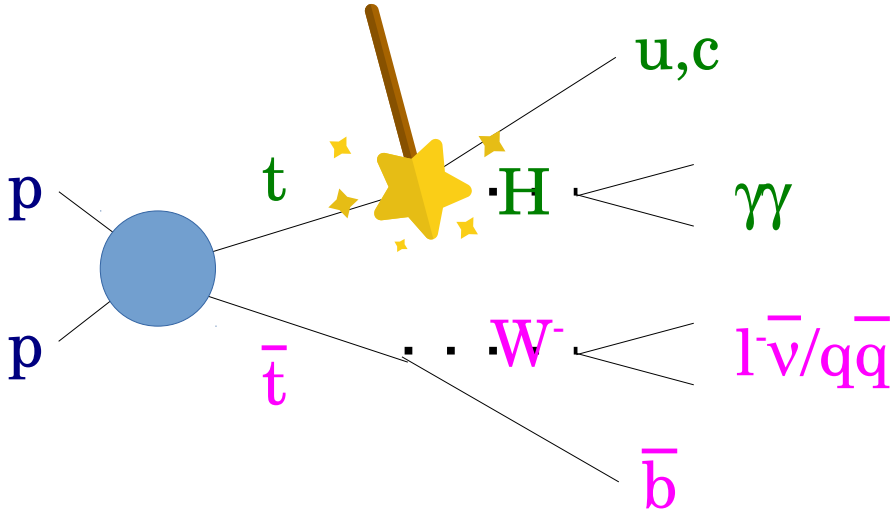
3 FCNC top decays: t→qH

$t \to qH(H\to\gamma\gamma)$, $\bar{t} \to \bar{b}W^- (W^-\to l^-\bar{\nu}/q\bar{q})$



In SM BR(t→qH) ≈ 10^{-15}
BSM up to 10^{-3}

[JHEP 10 (2017) 129]



Select di-photon + jets (and lepton) events in 13 TeV data
Di-photon mass $100 < m_{\gamma\gamma} < 160$ GeV

Hadronic selection
No lepton
4 jets, 1+ b-tag

Leptonic selection:
1 lepton
2+ jets, $p_t > 30$ GeV
$m_T > 30$ GeV

3 FCNC top decays: t→qH

Hadronic selection [JHEP 10 (2017) 129]

$m_{j\gamma\gamma}$ and m_{jjj} for all jjjj perm's

$152 < m_{\gamma\gamma j} < 190$ GeV and

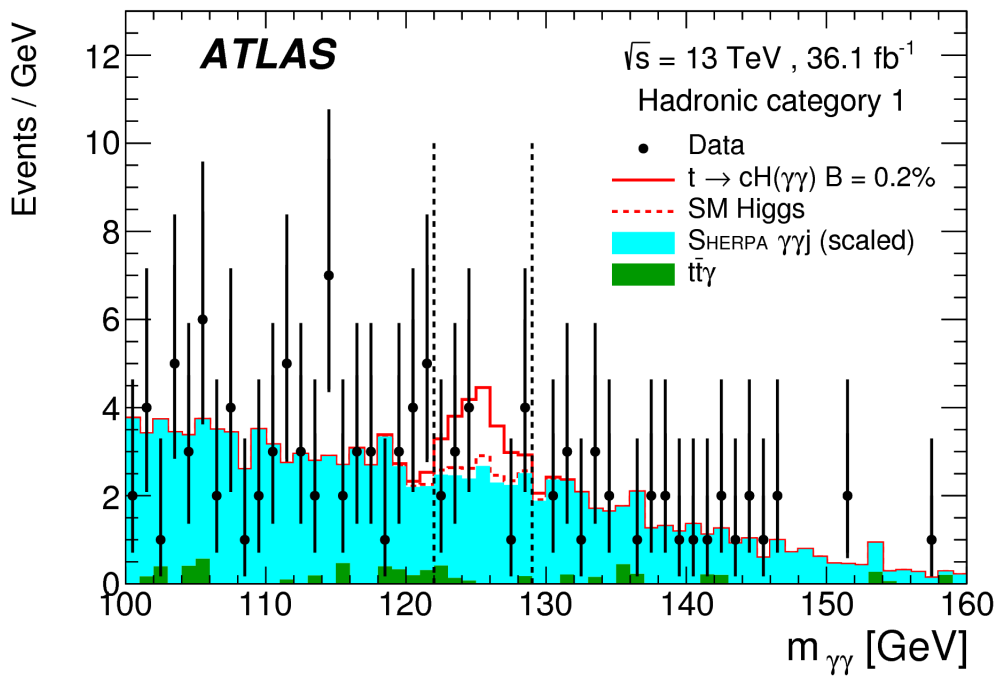
$120 < m_{jjj} < 220$ GeV

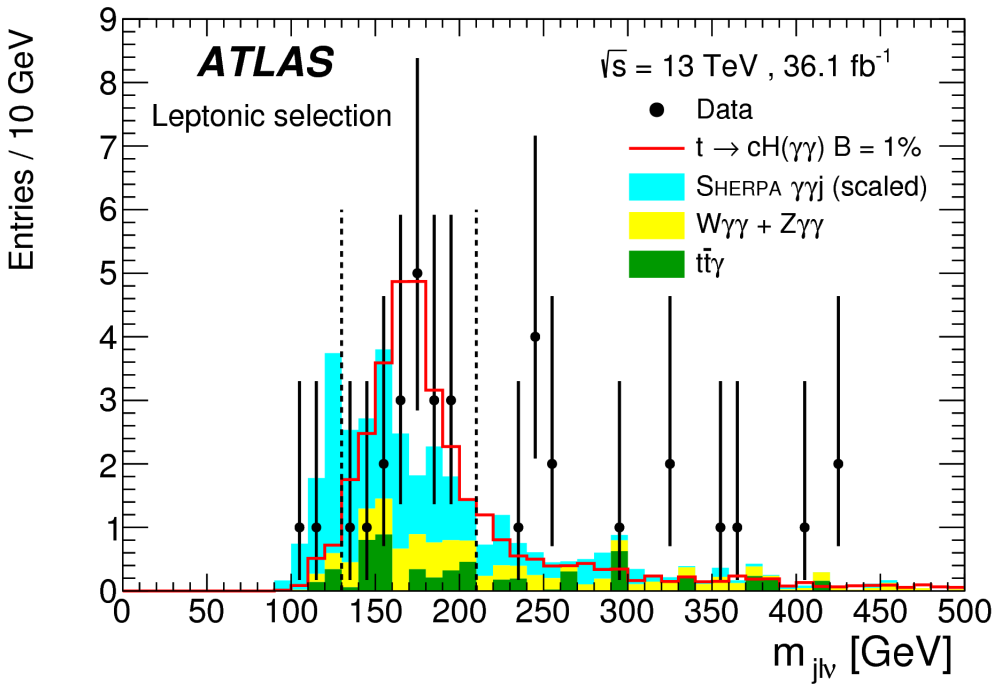
Leptonic selection

$m_{j\gamma\gamma}$ and $m_{jl\nu}$ for all jj perm's

$152 < m_{\gamma\gamma j} < 190$ GeV and

$130 < m_{jl\nu} < 210$ GeV





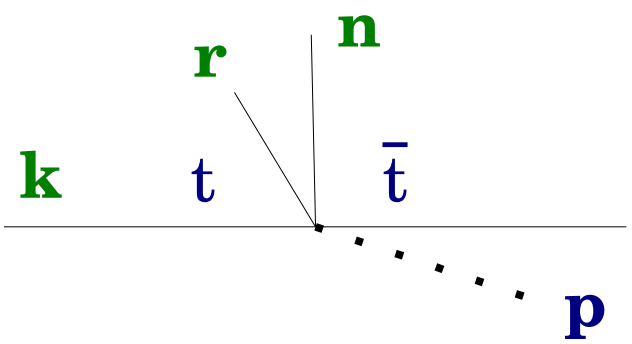
$BR(t \to c(u)H) < 2.2 \cdot 10^{-3}$ (95% CL)

Uncertainty dominated by JES, modeling, $\sigma_{t\bar{t}}$, $BR(H \to \gamma\gamma)$

4 $t\bar{t}$ spin correlation 8 TeV

[JHEP 03 (2017) 113]

Di-lepton selection essentially as for A_C



Coordinate system for "spin density matrix"

k: direction of t in $t\bar{t}$ cms

n: transverse to plane of beam (**p**=(0,0,1)) and **k** (**n** ~ **p**×**k**)

r: transverse to **k** and **n** (**r** ~ **k**×**n**)

[Bernreuther, Heisler, Si, JHEP 12 (2015) 026]

Observables:

Angles $\theta_{+(-)}^{a}$ of $t(\bar{t})$ lepton in $t(\bar{t})$ rest frame w.r.t. axis a

Reconstruct $t\bar{t}$ system using "ν weighting" from $\mathbf{p}_{t,miss}$ and kinematics

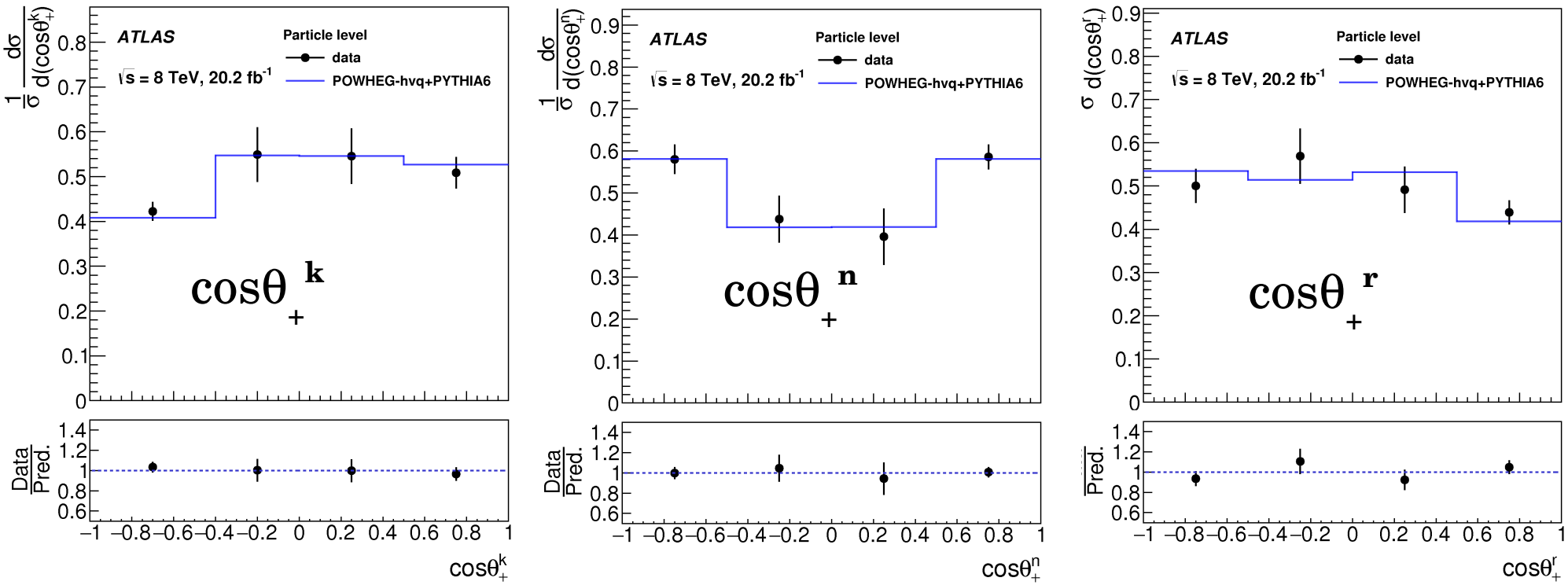
Unfold (fully bayesian) to "$t\bar{t}$ parton level" or "pseudo-top particle level"

4 $t\bar{t}$ spin correlation 8 TeV

$$1/\sigma\, d^2\sigma/(d\cos\theta_+^{\,a} d\cos\theta_-^{\,b}) =$$

$$1/4(\,1 + B_+^{\,a}\cos\theta_+^{\,a} + B_-^{\,b}\cos\theta_-^{\,b} - C(a,b)\cos\theta_+^{\,a}\cos\theta_-^{\,b}\,)$$

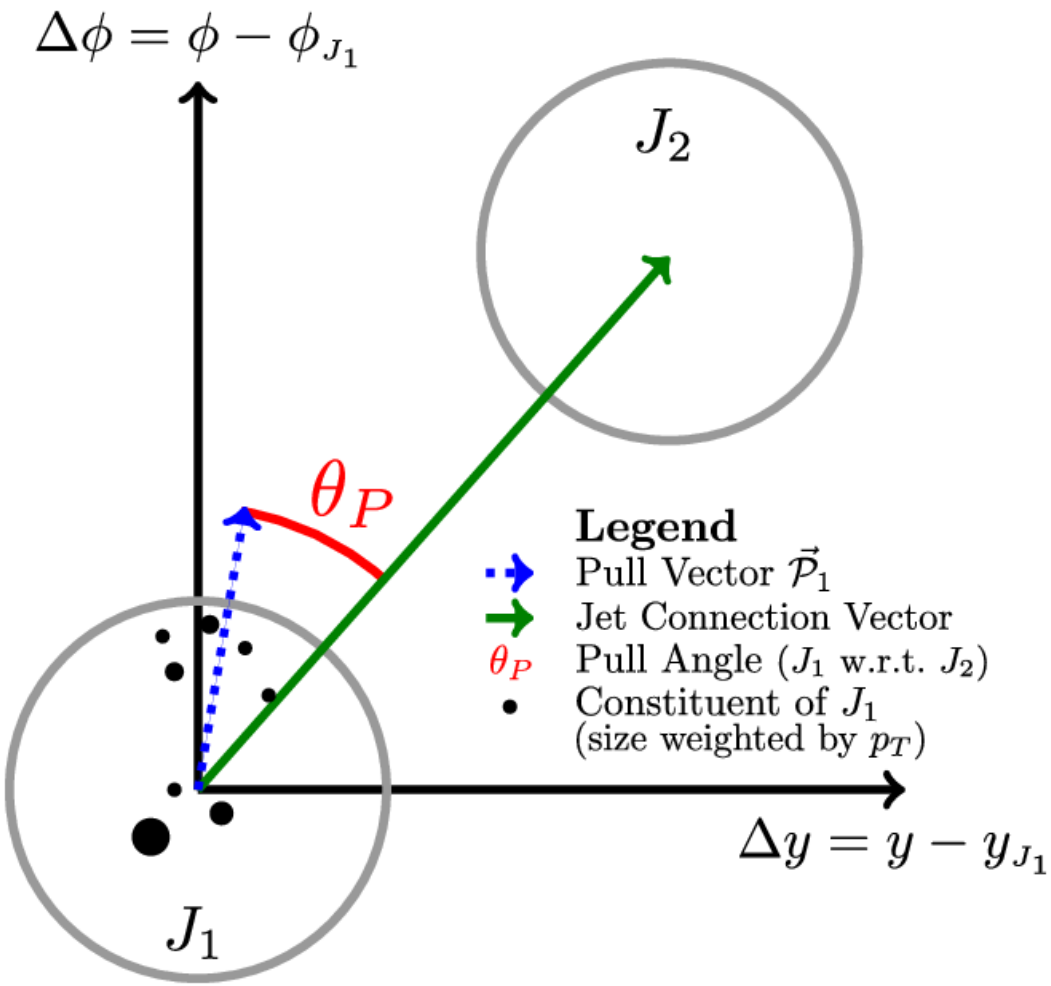
[JHEP 03 (2017) 113]



Plus 3 angles w.r.t. $\bar{t}$ and 9 combinations … SM in agreement

5 Colour flow l+jets 13 TeV

[ATLAS-CONF-2017-069]



Jet pull vector:

$$\mathbf{p} = \sum_{i \text{ in } J} (p_{t,i} / p_{t,J}) \, |\Delta \mathbf{r}_i| \, \Delta \mathbf{r}_i$$

$\Delta \mathbf{r}_i = (\Delta y_i, \Delta \phi_i)$ w.r.t. jet axis (y_J, ϕ_J)

Calculated from charged particles after "ghost association" to jets

Jet pull angle θ_P between $\mathbf{p}_1$ and vector connecting jets J_1 and J_2

1) $t \to bW(W \to q\bar{q})$: use $q\bar{q}$ jets
   Colour singlet

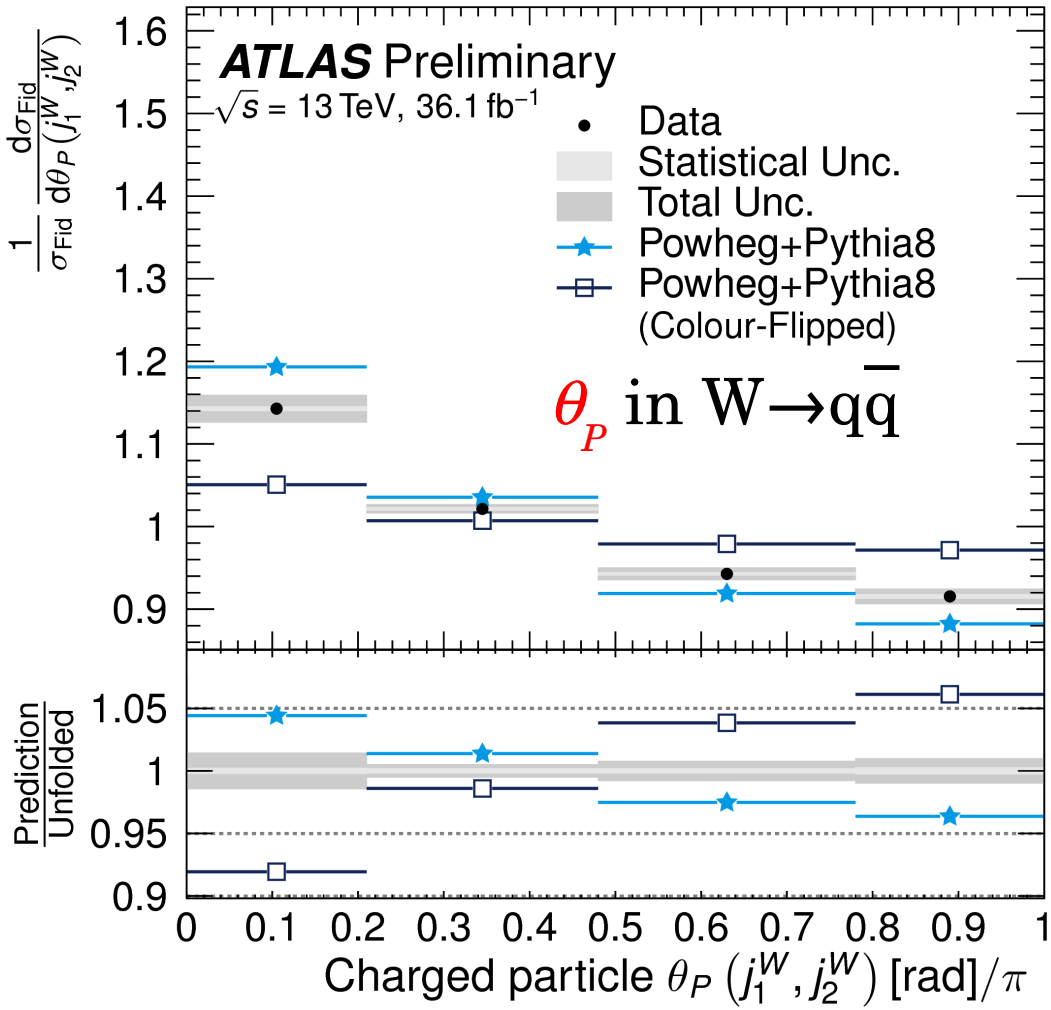
2) $t\bar{t} \to WW + b\bar{b}$: use $b\bar{b}$ jets
   Colour connection diluted

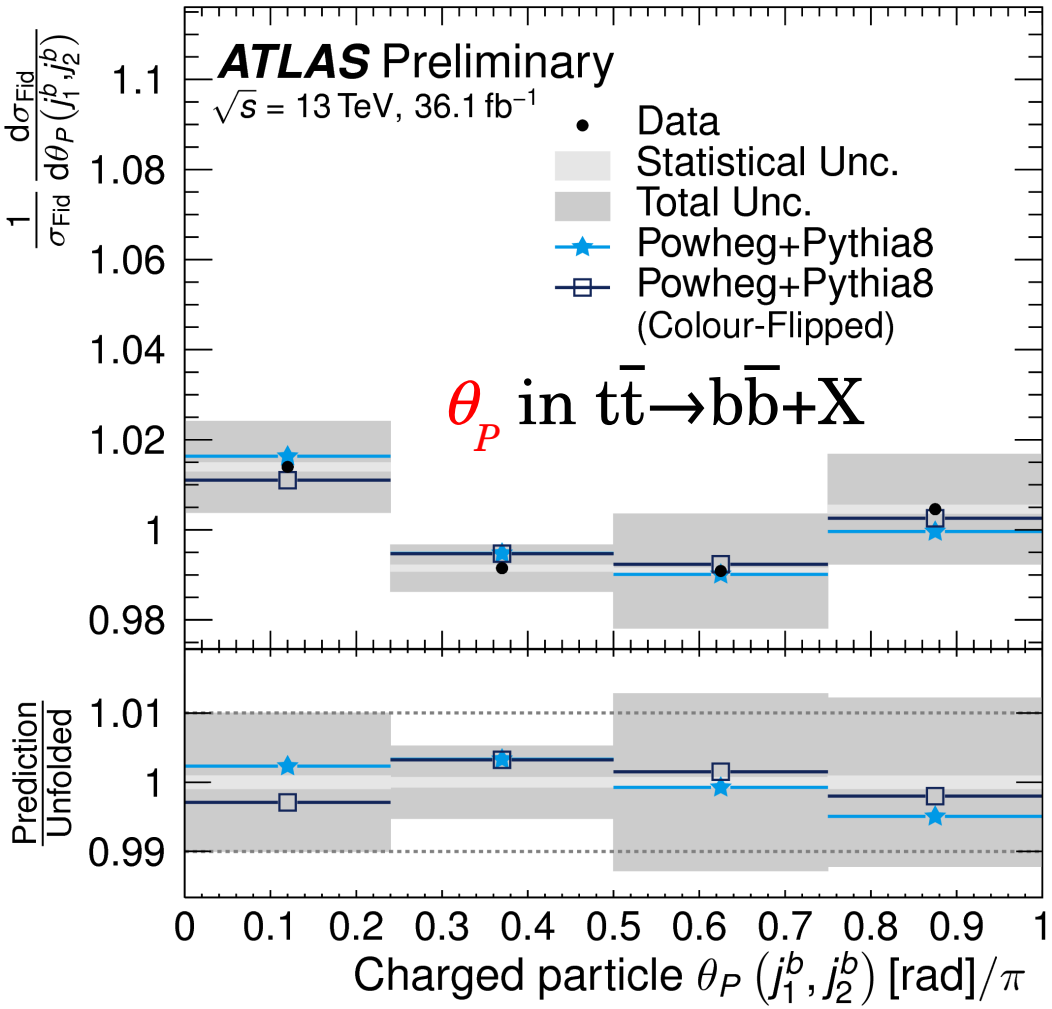
5 Colour flow l+jets 13 TeV

Unfold (iterative bayesian) to "pseudo-top particle level"

Consistency of MC models with data not great [ATLAS-CONF-2017-069]

"colour-flipped" strawman non-SM significantly worse in $q\bar{q}$





Summary

- Top quark (pair) properties in pp with ATLAS
  - 8 TeV (20/fb) and 13 TeV (36/fb)
- "Charge asymmetry" at 8 TeV
  - lepton+jets (boosted), di-lepton, SM predictions consistent
- FCNC decays $t \rightarrow qZ$ and $t \rightarrow qH$ (13 TeV)
  - Beginning to probe BSM predictions
- Spin correlation 8 TeV di-lepton
  - Complete set of measurements, SM predictions consistent
- Colour flow in lepton+jets $t\bar{t}$ (13 TeV)
  - Consistent with QCD
- Still hope for BSM but hiding places become narrow!

Outtakes

$t\bar{t}$ spin correlation 8 TeV

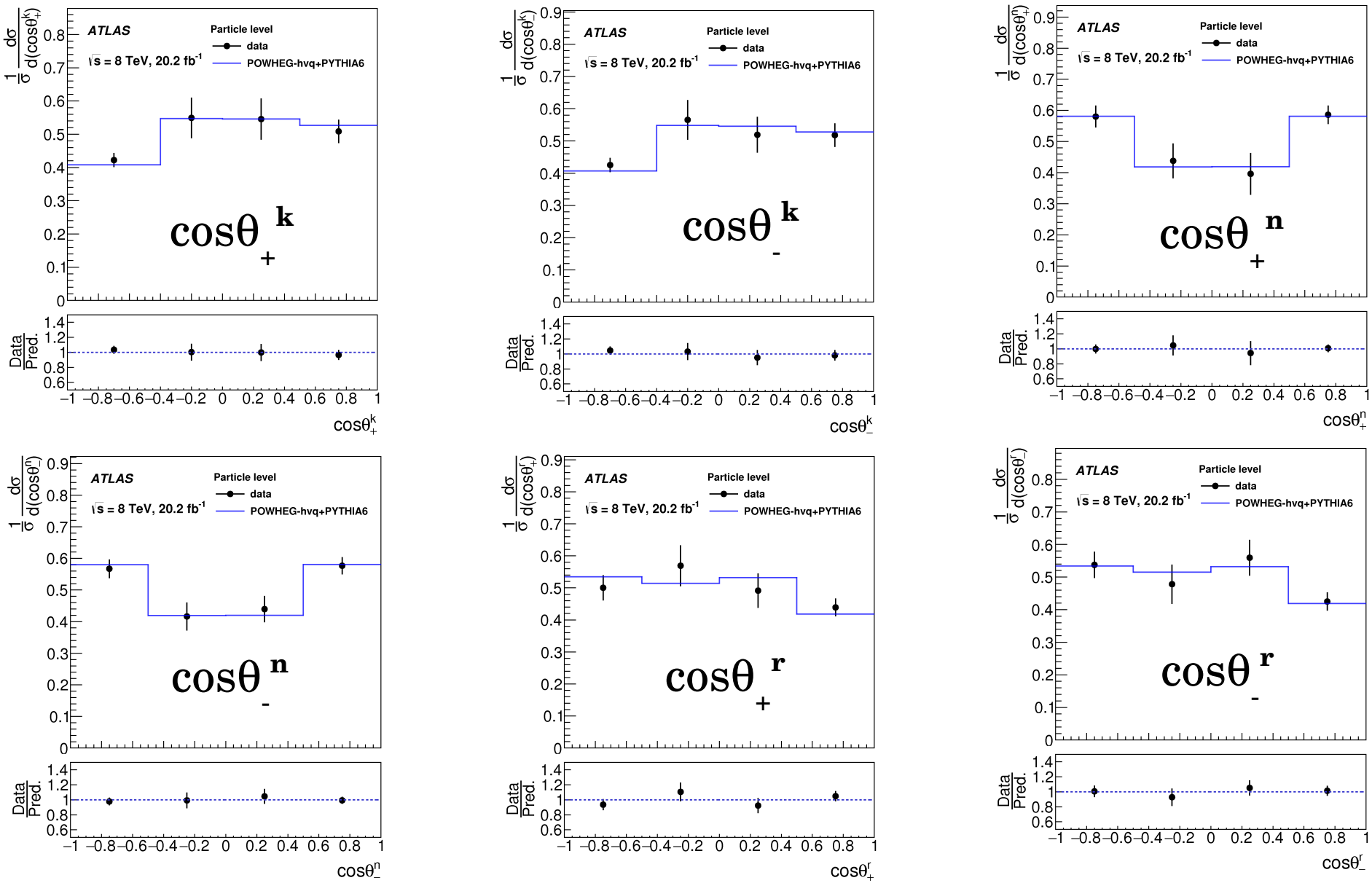
$$1/\sigma\, d^2\sigma/(d\cos\theta_+^a d\cos\theta_-^b) =$$

[JHEP 03 (2017) 113]

$$1/4(\,1+B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b \;-\; C(a,b)\cos\theta_+^a\cos\theta_-^b\,)$$

Expectation values	NLO predictions	Observables
B_+^k	0.0030 ± 0.0010	$\cos\theta_+^k$
B_-^k	0.0034 ± 0.0010	$\cos\theta_-^k$
B_+^n	0.0035 ± 0.0004	$\cos\theta_+^n$
B_-^n	0.0035 ± 0.0004	$\cos\theta_-^n$
B_+^r	0.0013 ± 0.0010	$\cos\theta_+^r$
B_-^r	0.0015 ± 0.0010	$\cos\theta_-^r$
$C(k,k)$	0.318 ± 0.003	$\cos\theta_+^k \cos\theta_-^k$
$C(n,n)$	0.332 ± 0.002	$\cos\theta_+^n \cos\theta_-^n$
$C(r,r)$	0.055 ± 0.009	$\cos\theta_+^r \cos\theta_-^r$
$C(n,k)+C(k,n)$	0.0023	$\cos\theta_+^n \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^n$
$C(n,k)-C(k,n)$	0	$\cos\theta_+^n \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^n$
$C(n,r)+C(r,n)$	0.0010	$\cos\theta_+^n \cos\theta_-^r + \cos\theta_+^r \cos\theta_-^n$
$C(n,r)-C(r,n)$	0	$\cos\theta_+^n \cos\theta_-^r - \cos\theta_+^r \cos\theta_-^n$
$C(r,k)+C(k,r)$	-0.226 ± 0.004	$\cos\theta_+^r \cos\theta_-^k + \cos\theta_+^k \cos\theta_-^r$
$C(r,k)-C(k,r)$	0	$\cos\theta_+^r \cos\theta_-^k - \cos\theta_+^k \cos\theta_-^r$

$t\bar{t}$ spin correlation 8 TeV

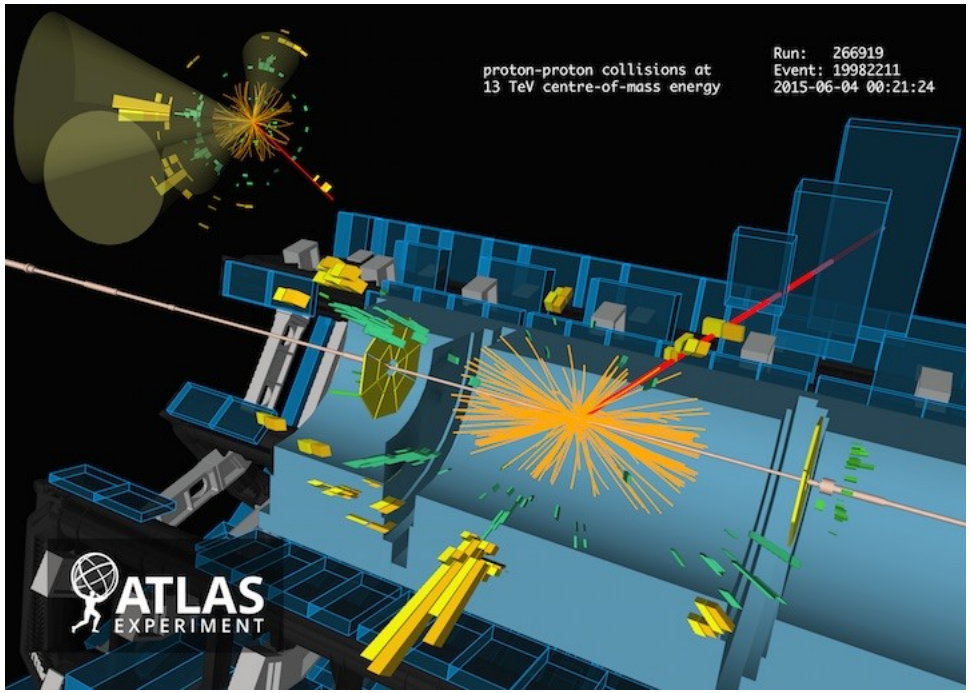


[JHEP 03 (2017) 113]

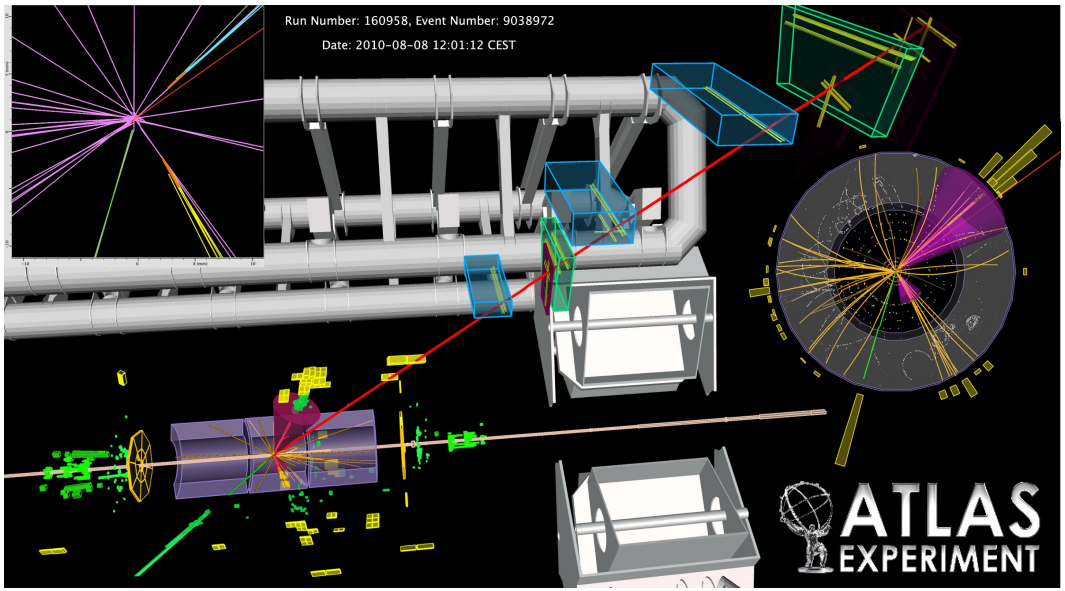
plus 9 combinations … SM prediction in agreement

A_C measurements (8 TeV)

Lepton (e, μ) + jets



Di-lepton (ee, μμ, eμ)



$p_{t,l}$>25 GeV, $|\eta_l|$<2.5 (2.47), anti-k_t R=0.4 jets, p_t>25 GeV, $|\eta|$<2.5

1 l, 4 jets, 0,1,2+ b-tags

$M_{t,W}+E_{t,miss}$>60 GeV,

$E_{t,miss}$>40(20) GeV (0,1) b-tag

2 +/- l, m_{ll}>15 GeV, 2+ jets,

1 b-tag, $E_{t,miss}$>30 GeV (ee or μμ)

H_t>130 GeV (eμ)

Unfold (FBU) to "$t\bar{t}$ parton level", constrain e.g. W+jets bkg