Top Quark Properties at the LHC

Kelly Beernaert (DESY)
for the ATLAS & CMS collaborations

51st Rencontres de Moriond 2016, March 12th- 26th 2016

Content

- Production:
  - Production cross sections, kinematics
  - Associated production $t\bar{t}$ + W, Z, γ → see talk by Markus Seidel
  - Spin correlations ◄
  - Polarization
  - Production Asymmetries ◄
- Decay:
  - Branching ratios
  - Anomalous couplings
  - Flavour-changing neutral currents ◄
  - W helicity
- Results in single top channel → see talk by Martin zur Nedden

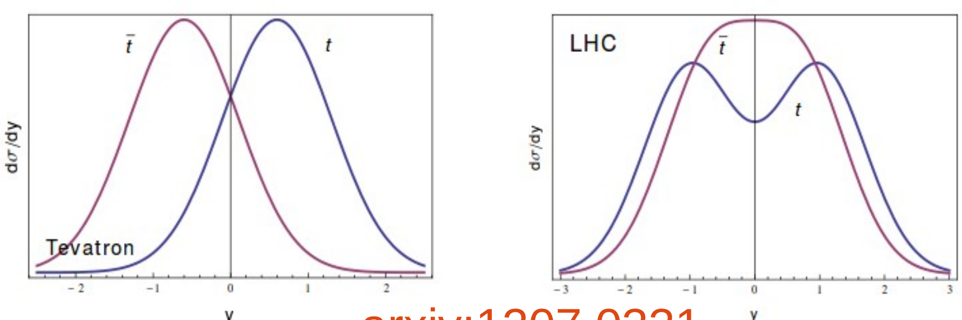
→ **only small selection of results shown with focus on most recent ones**

Introduction

- Why study top quark properties?
  - Top quark decays before it can form bound states
    - Study "bare" quark properties using the decay products
  - Top quark decays before the spin decorrelates
    - $\tau_t \sim 0.5 \times 10^{-24}$ s $< m_t / \Lambda^2_{QCD} \sim 3 \times 10^{-21}$ s
    - Study spin correlation properties
  - Heaviest particle known: ($m_t \sim 173$ GeV)
    - Large coupling to Higgs boson, plays significant role in EWSB
  - Properties measurements test SM and probe new physics
    - Increasing levels of precision and COM energy at LHC → sensitivity of several BSM models coming within reach

Top quark asymmetries

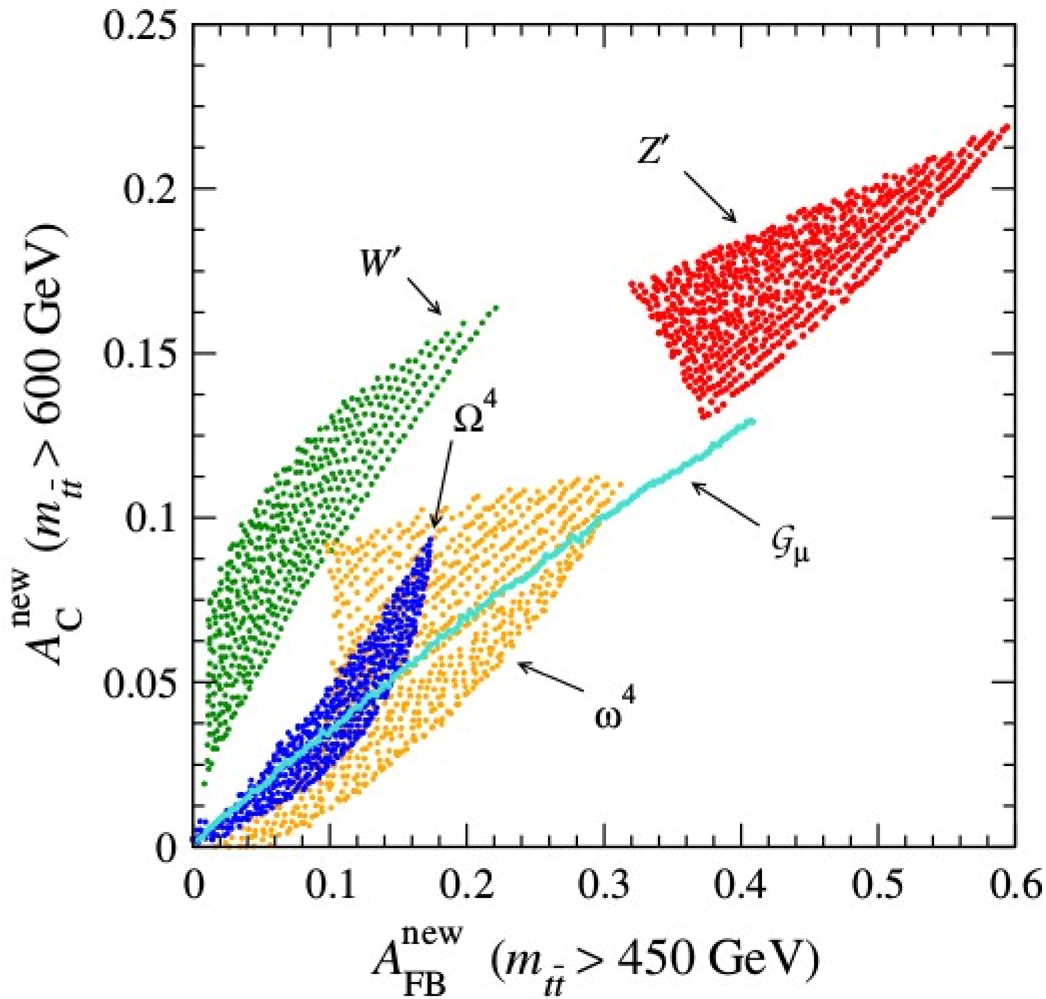
- Measurement of A_{FB} at Tevatron and A_C at LHC are complementary to evaluate new physics models
  - Various models still allowed
  - → W', G, ω, φ, Ω



arxiv:1207.0331

- Evaluate asymmetry based on <u>fully reconstructed top quarks</u> or leptons in dilepton channel

PRD 64 115013



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

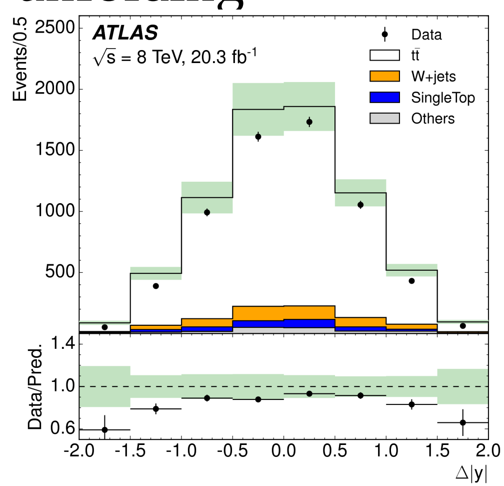
$$A_{FB} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} \quad \Delta y \equiv y_t - y_{\bar{t}}$$

Top quark asymmetries

ATLAS, 8 TeV, 20.3 fb^{-1}, lepton+jets channel

Phys. Lett. B756 (2016) 52

- Boosted regime: $m(t\bar{t}) > 0.75$ TeV
  - Leptonic decay resolved
  - Hadronic decay reconstructed as large R jet with substructure
- Full Bayesian unfolding
- Differential in $m(t\bar{t})$



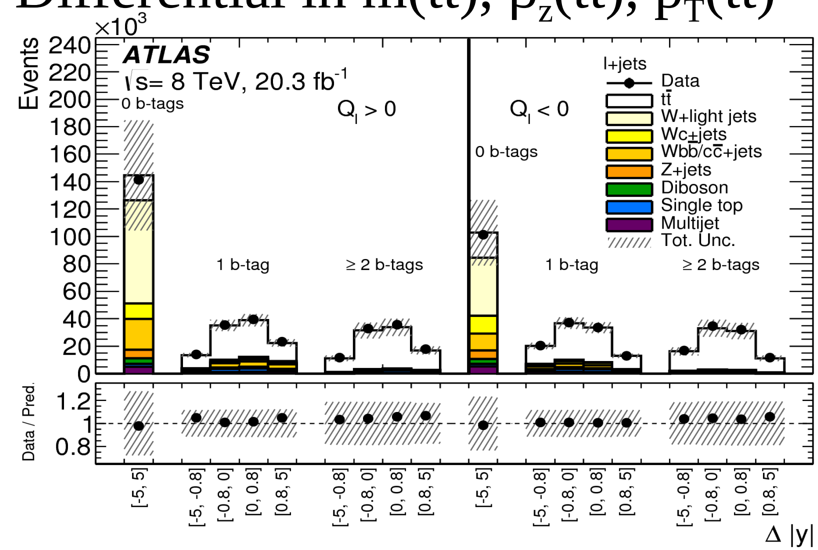
$A_C = (4.2 \pm 3.2)$ % (stat + syst)

SM pred: $A_C = (1.6 \pm 0.04)$ %

for $m(t\bar{t}) > 0.75$ TeV

Eur.Phys.J. C76 (2016) no.2, 87

- 3 signal regions: 0, 1, 2 b-tag
- Likelihood fit to reconstruct $t\bar{t}$
- Full Bayesian unfolding
- Differential in $m(t\bar{t})$, $\beta_z(t\bar{t})$, $p_T(t\bar{t})$



$A_C = (0.9 \pm 0.5)$% (stat + syst)

SM pred: $A_C = (1.11 \pm 0.04)$%

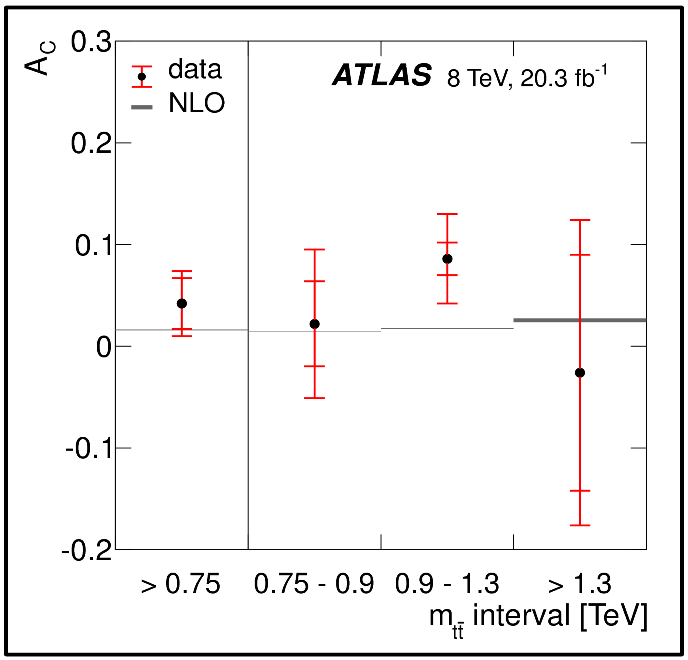
Top quark asymmetries

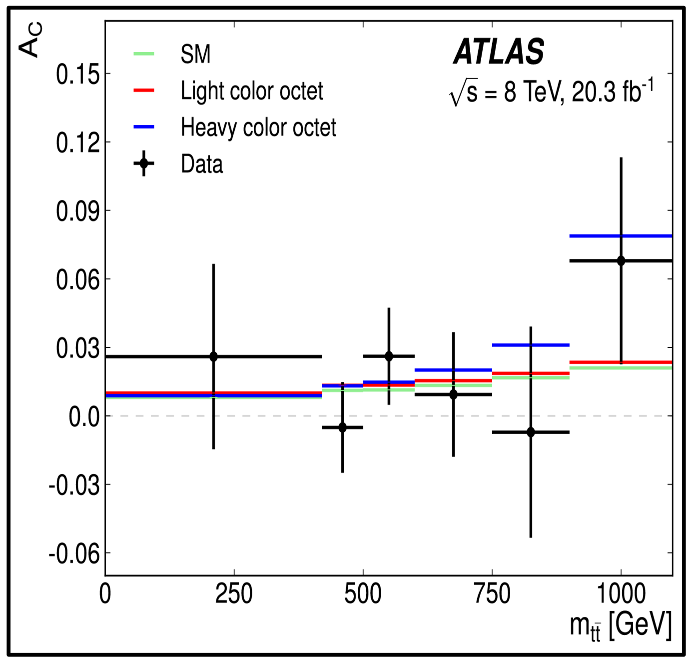
ATLAS, 8 TeV, 20.3 fb^{-1}, lepton+jets channel

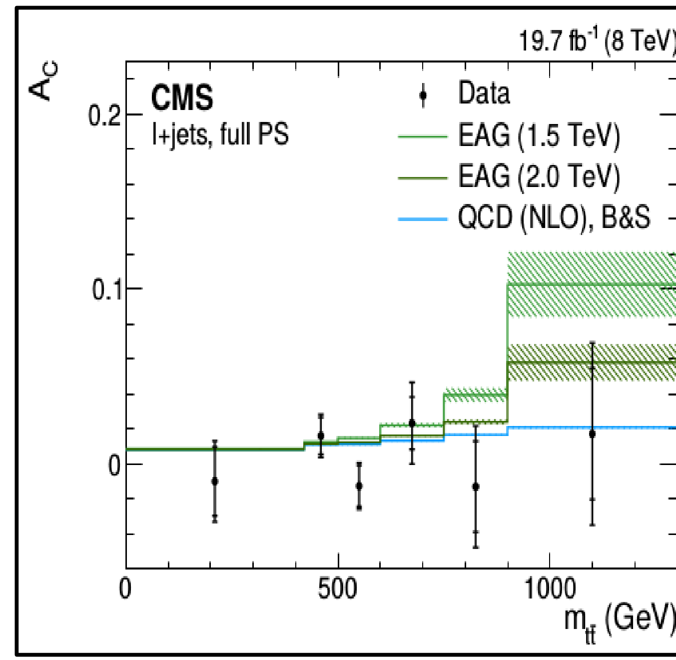
CMS, 8 TeV, 19.7 fb^{-1}, lepton+jets channel

Phys. Lett. B756 (2016) 52

arXiv:1507.03119, submitted to PLB







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Good agreement with SM

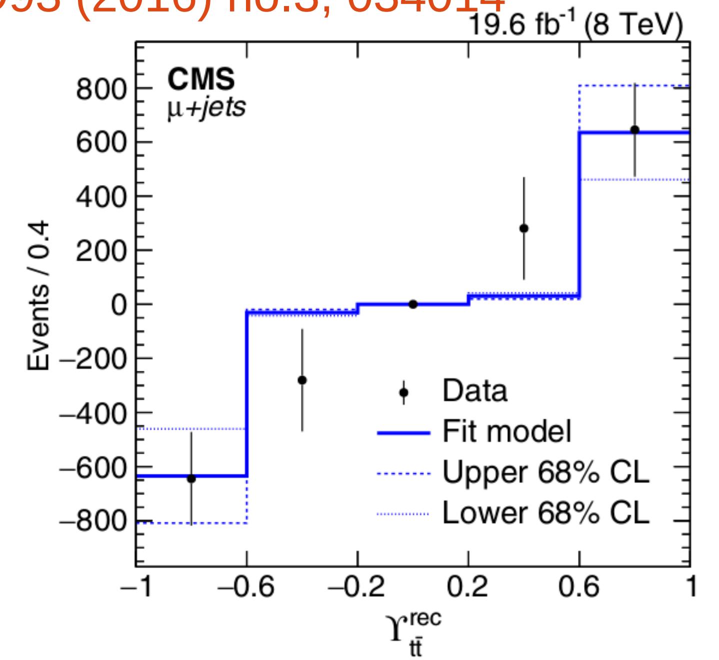
Top quark asymmetries

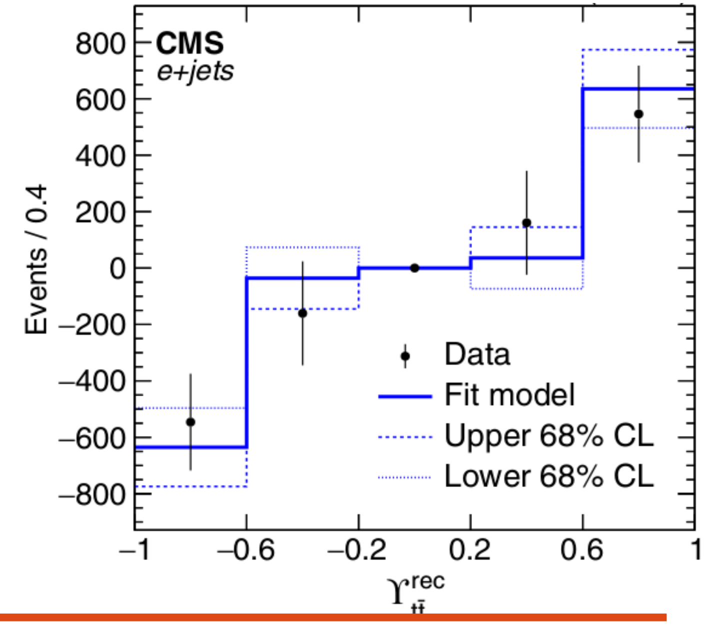
Phys.Rev. D93 (2016) no.3, 034014

CMS, 8 TeV, 19.7 fb^{-1}, lepton+jets channel

- Template method:
  - Use symmetric and asymmetric version of MC template to fit
    $$\rho^{\pm}(X) = [\rho(X) \pm \rho(-X)]/2$$
  - Smaller statistical uncertainty than unfolding, larger model dependence
  - Observable needs to be bounded:
    $$Y_{t\bar{t}} = \tanh \Delta|y|_{t\bar{t}}$$
- Fit to $Y_{t\bar{t}}$ distribution: fit parameter α of relative contribution from symmetric and anti-symmetric templates

A_C = [0.33 ± 0.42 (stat+syst)] %
SM pred: (1.11 ± 0.04)%





Top quark asymmetries

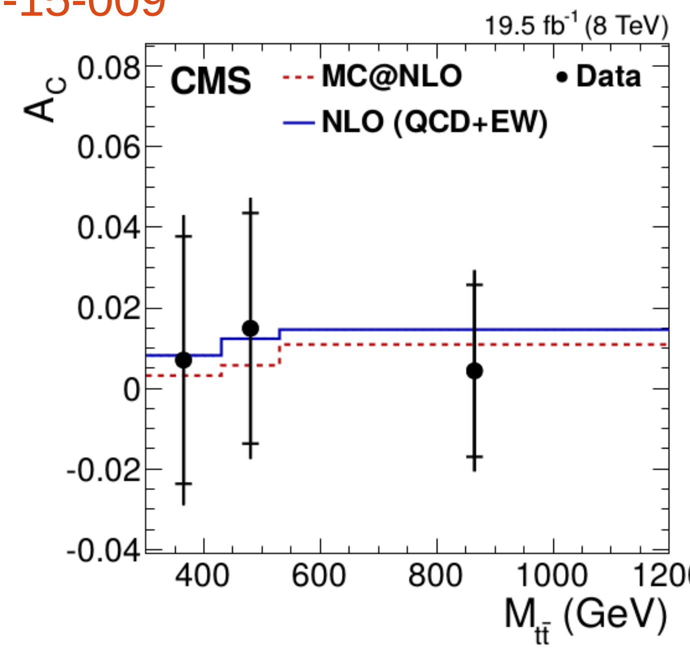
CMS, 8 TeV, 19.7 fb^{-1}, dilepton channel

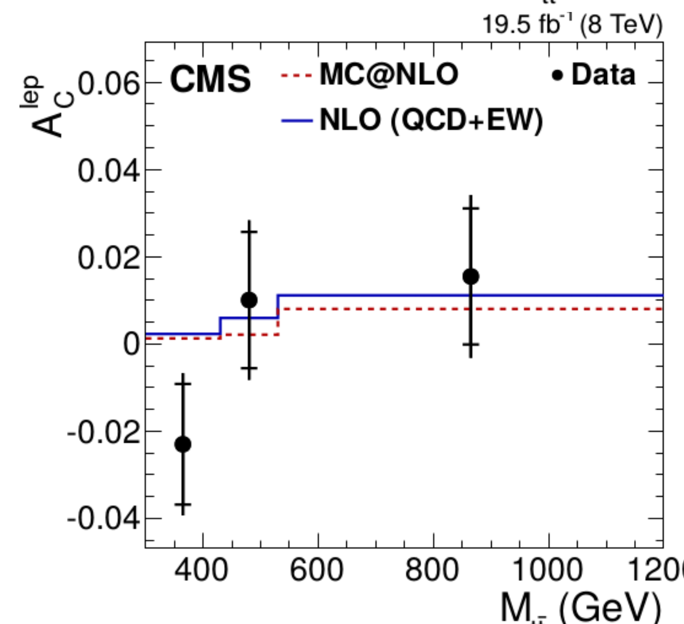
CMS-TOP-15-009

- Asymmetry defined with decay leptons and reconstructed tops

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

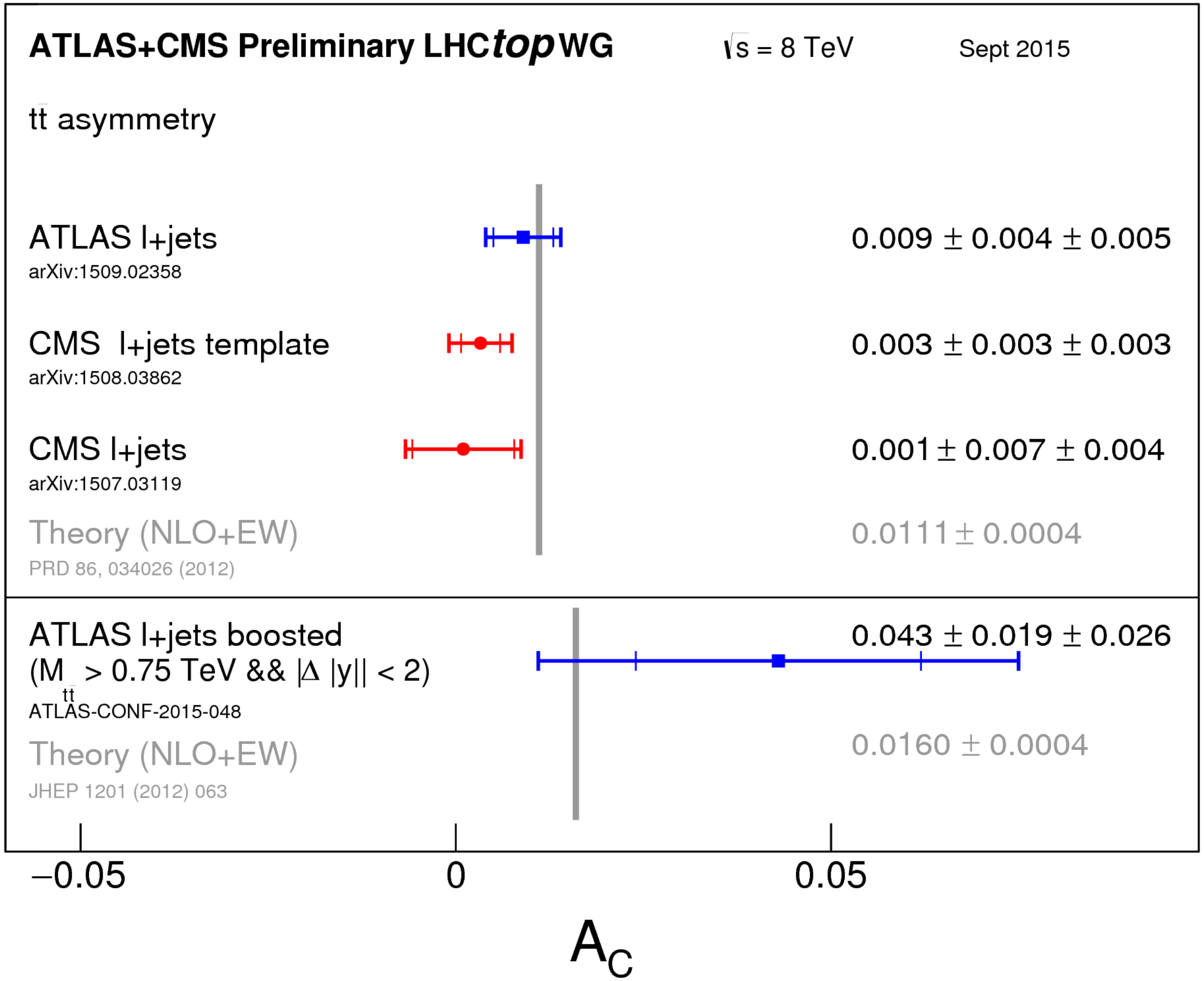
- Top reconstruction using matrix weighting technique
- Regularised unfolding to parton level
- Differential measurement in $m(t\bar{t})$, $|y(t\bar{t})|$, $p_T(t\bar{t})$





A_C = [1.1 ± 1.3 (stat+syst)] %
SM pred: (1.11 ± 0.04)%
A^{lep}_C = [0.3 ± 0.7 (stat+syst)] %
SM pred: (0.64 ± 0.03)%

Top quark asymmetries



- Good agreement between theory and experiment
- NNLO predictions are being finalized
- On experiment side: <u>statistical and systematic uncertainties are comparable in size</u>
- Several differential distributions available + results in high $m(t\bar{t})$ region where asymmetry is enhanced

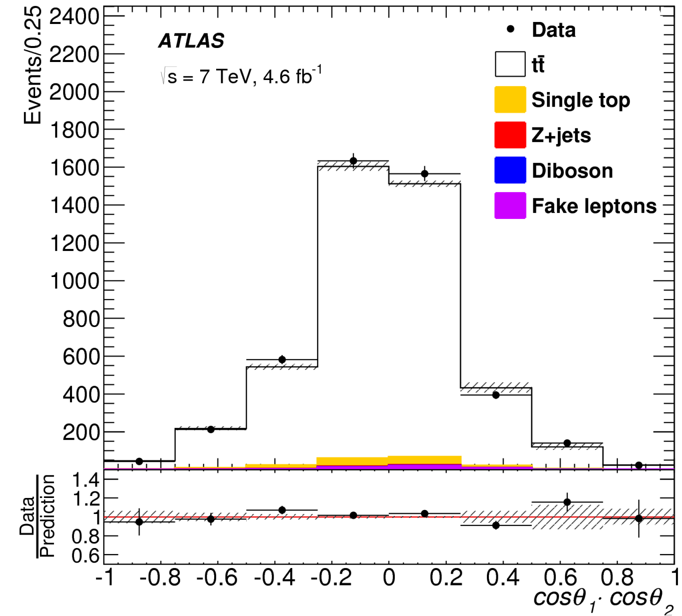
Top quark spin correlations

Phys. Rev. D 93 (2016) 012002

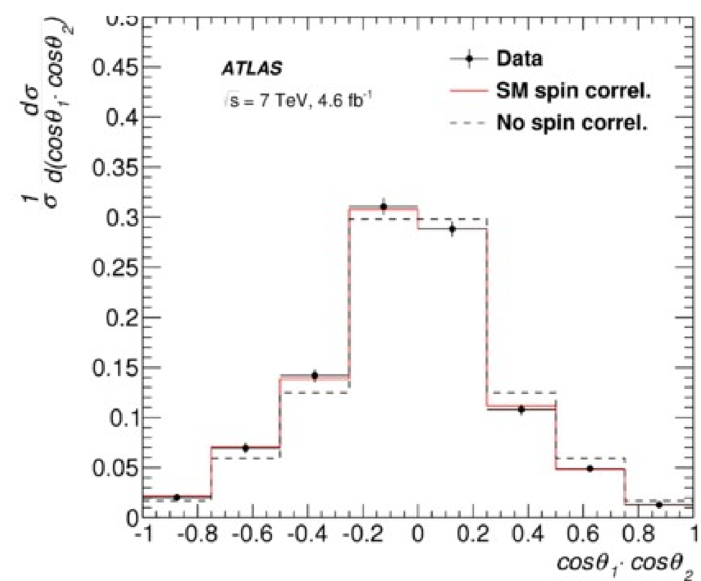
- Top quark spins are correlated in the SM
- dilepton channel, 7 TeV, reconstruction of $t\bar{t}$ final state

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

- with θ angle between lepton direction in top parent rest frame and top parent in $t\bar{t}$ rest frame



- Bayesian unfolding to parton level



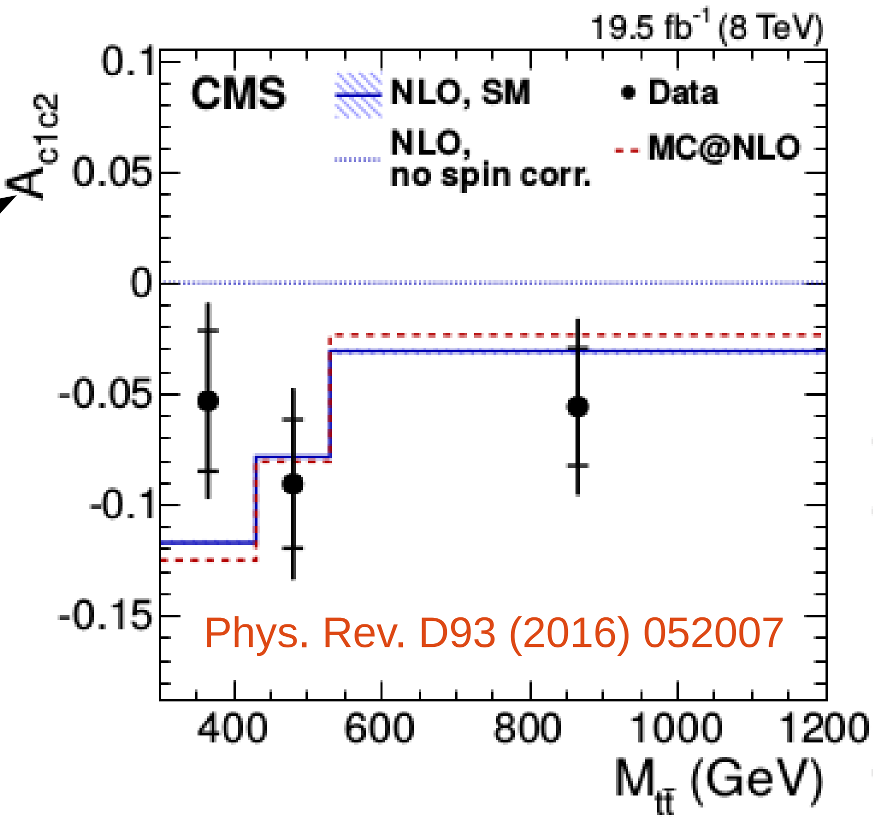
- Dominated by:
  unfolding uncertainties, theoretical modeling, jet reconstruction

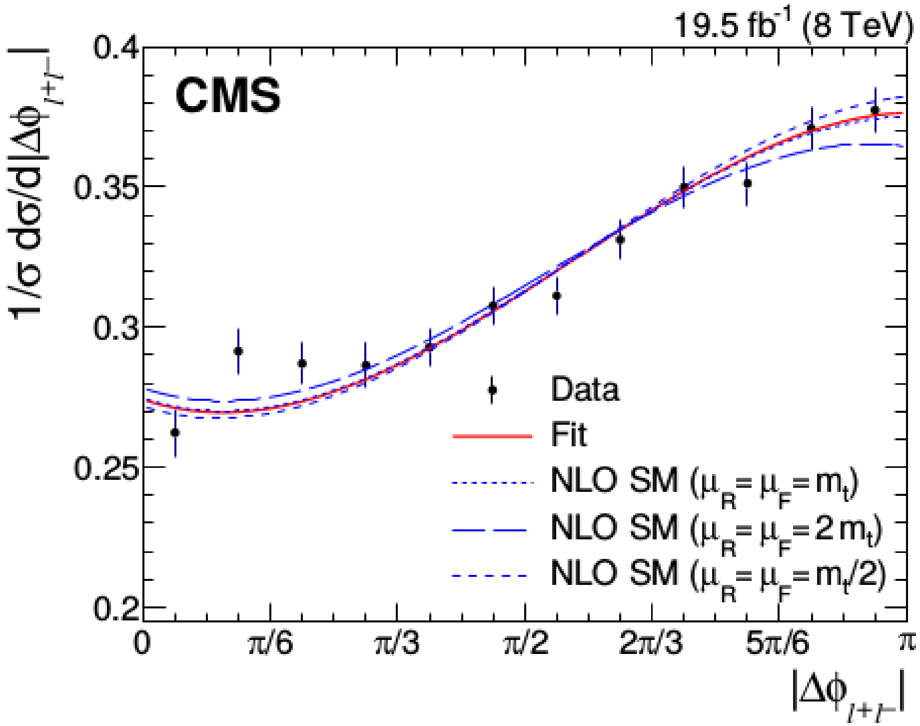
- Direct extraction of $C = -A\alpha_1\alpha_2$

$A_{hel} = 0.315 \pm 0.061\ (stat) \pm 0.049\ (syst)$

Top quark spin correlations

- dilepton channel, 8 TeV, reconstruction of ttbar final state
- Regularized unfolding to parton level
- Using asymmetries (also differentially) → direct measurement of spin correlation strength and polarization
- Dominated by: top p_T modeling & JES





- Search for top chromomagnetic couplings using differential cross sections, limit on CMDM $\mathrm{Re}(\mu_t)$ and CEDM $\mathrm{Im}(d_t)$ at 95% CL

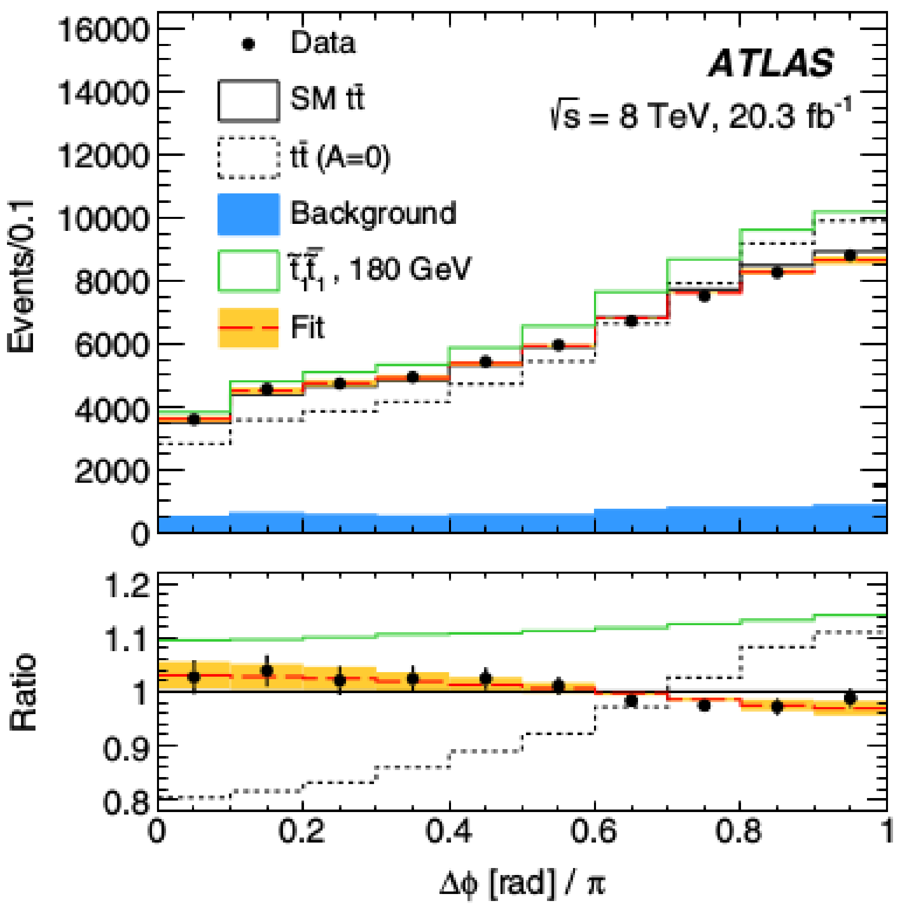
$$-0.053 < \mathrm{Re}(\mu_t) < 0.026$$

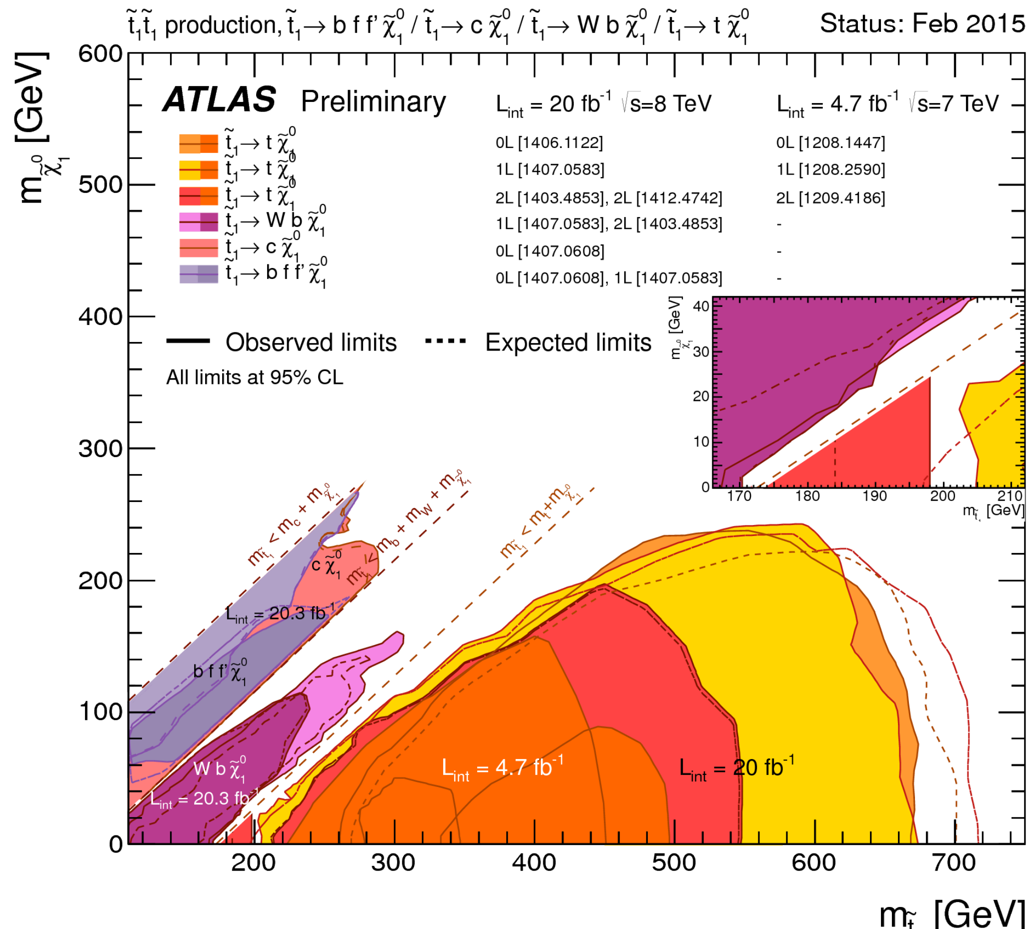
$$-0.068 < \mathrm{Im}(d_t) < 0.067$$

Top quark spin correlations

- Dominated by: hadronization and ISR/FSR
- $f^{SM} = 1.20 \pm 0.05\ (\text{stat}) \pm 0.13\ (\text{syst})$
- Top squarks in MSSM with 100% $\tilde{t} \to t\chi^0$ with mass close to m_t

PRL 114 142001 (2015)

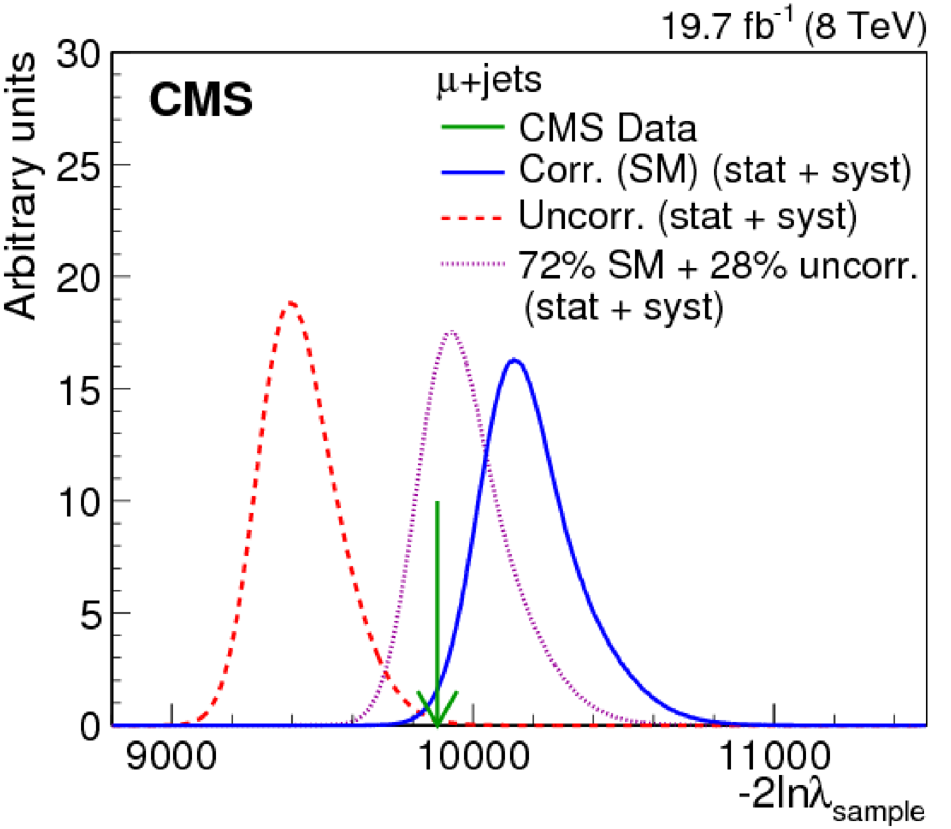




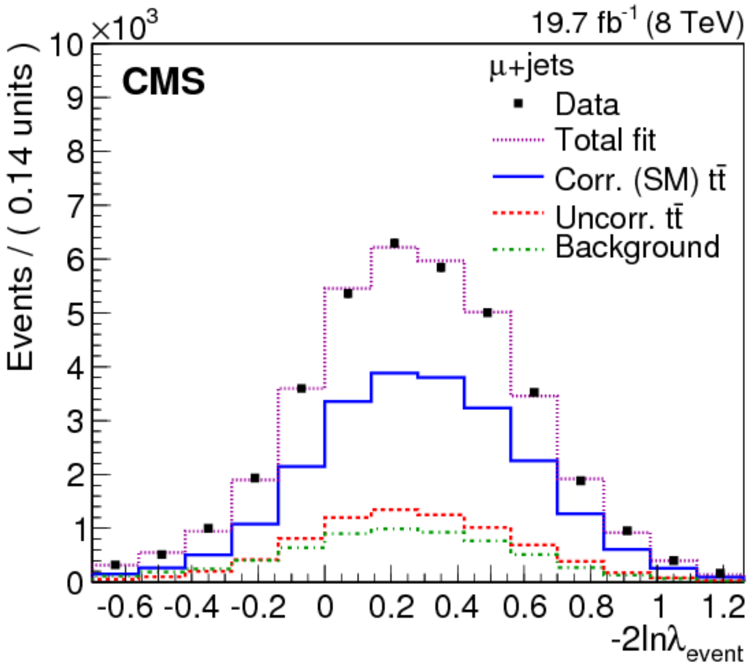
→ Excluded masses between m_t and 191 GeV at 95% CL

Top quark spin correlations

- Reconstruction in the muon+jets channel with 4,5 jets using kinematic fitter



- LO Matrix Element Method for event likelihoods (MadWeight) under SM or uncorrelated

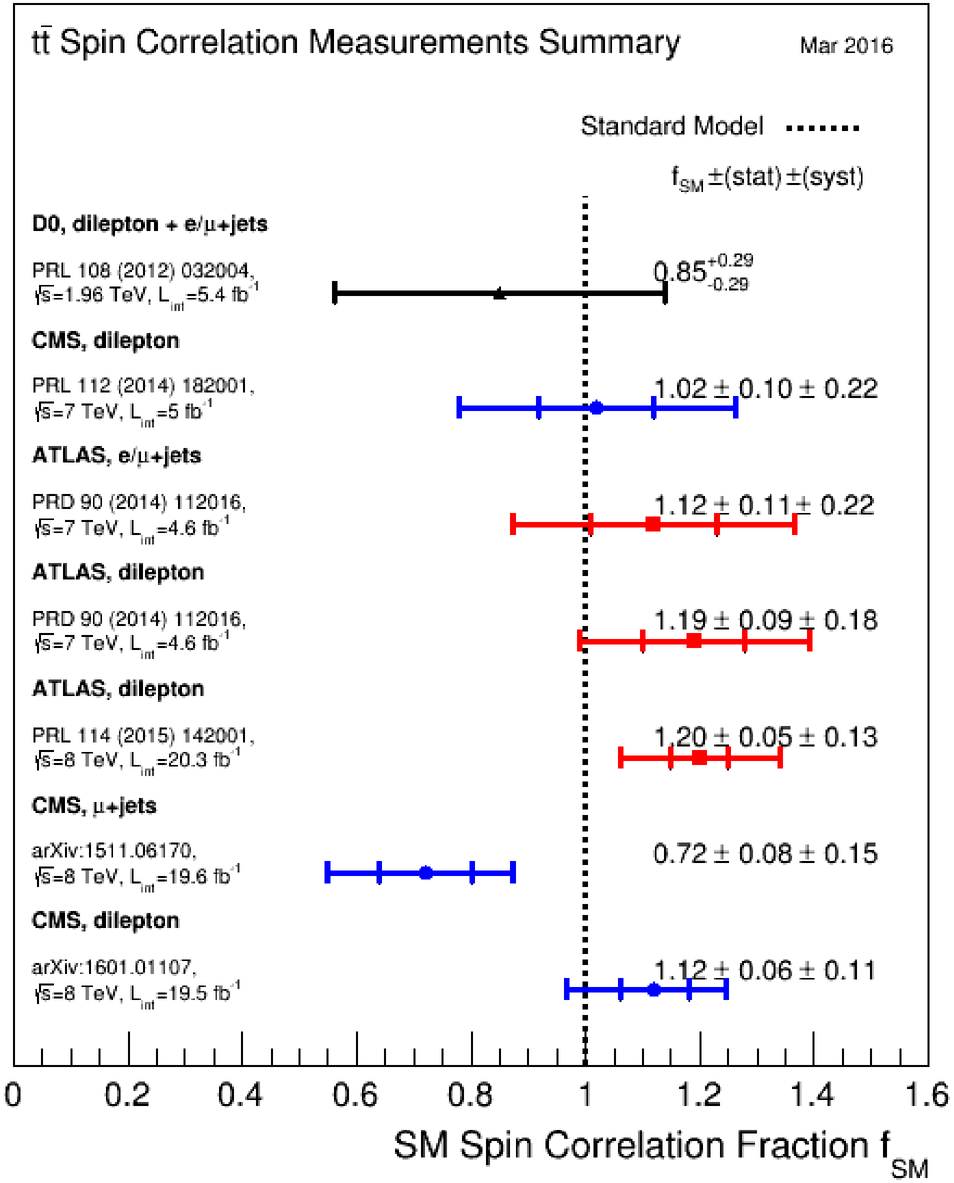


- Hypothesis testing + fit to likelihood ratio distribution
- Dominated by: hadronization uncertainty

$$f = 0.72 \pm 0.08\,(stat)^{+0.15}_{-0.13}\,(syst)$$

arXiv:1511.06170, submitted to PLB

Top quark spin correlations

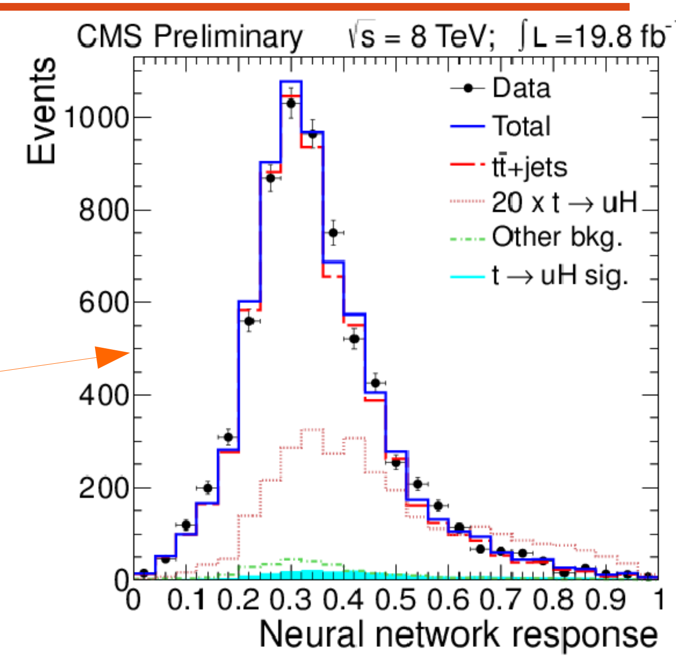


Flavour-changing neutral current

- SM: no FCNC at tree level (GIM suppression), BR ~ $O(10^{-12} – 10^{-17})$
- t → u/c + X, X = g, γ, Z and H
- BSM: 2HDM, MSSM, … → enhanced couplings → BR as high as 10^{-5}

CMS-PAS-TOP-14-020

B(t → Hc) < 1.16 % (obs) at 95% CL
B(t → Hu) < 1.92 % (obs) at 95% CL



- t → Hq → $b\bar{b}$q and t → Wb → lνb

CMS-PAS-TOP-14-019

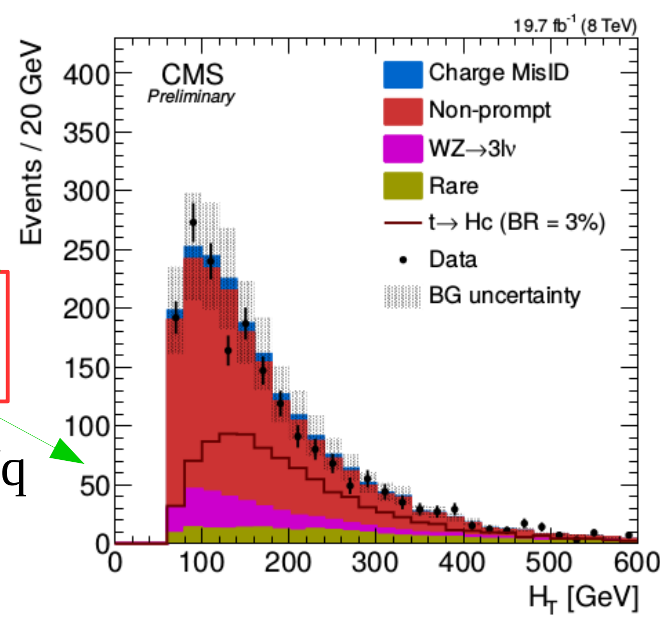
B(t → Hc) < 0.47 % (obs) at 95% CL
B(t → Hu) < 0.42 % (obs) at 95% CL

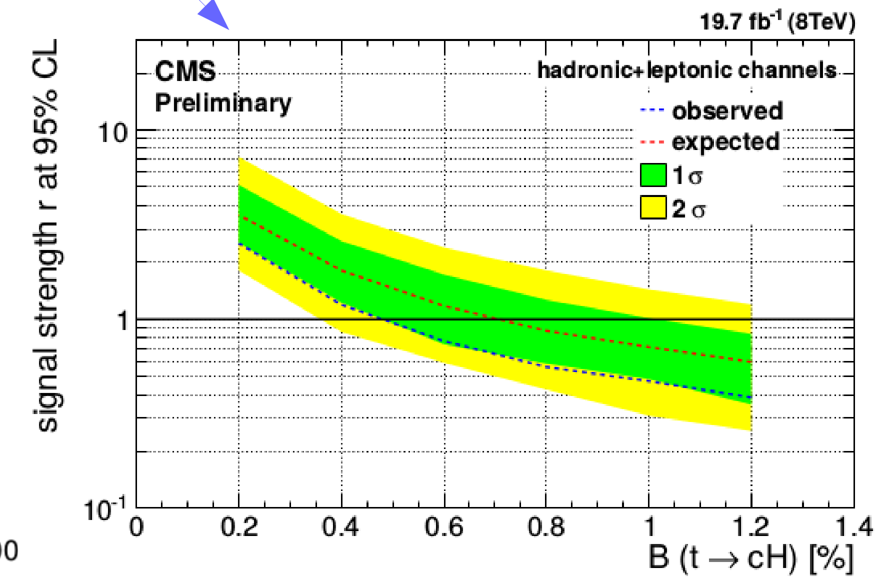
- t → Hq → γγq and t → Wb → lνb or $q\bar{q}$b

CMS-PAS-TOP-13-017

B(t → Hc) < 0.93 % (obs) at 95% CL

- t → Hq → ZZq or WWq and t → Wb → lνb





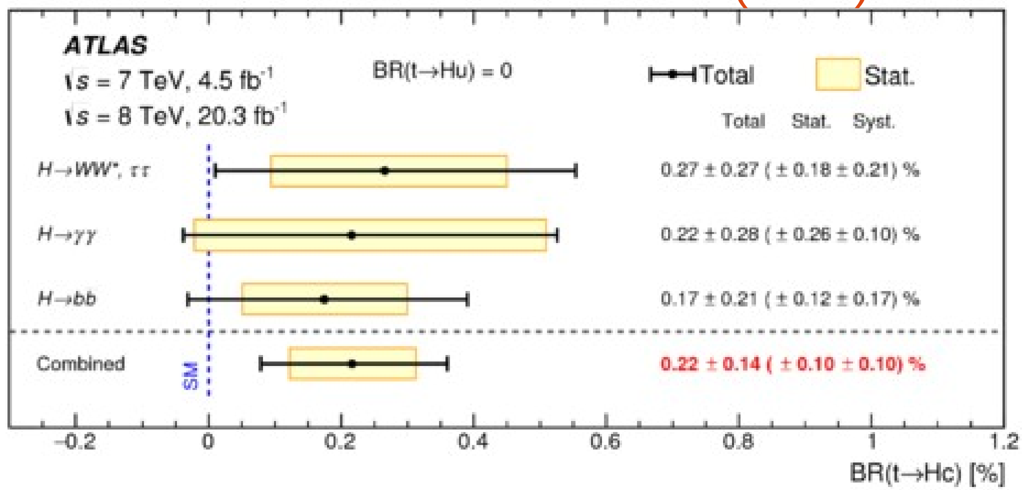
Flavour-changing neutral current

- $t\bar{t}$ production with
  - t → Hq -> $b\bar{b}$q and t → Wb → lvb
- Categories based on jet, b-tag multiplicity → (4 j, 3 b) and (4 j, 4 b) most sensitive
- Signal/background discriminant:

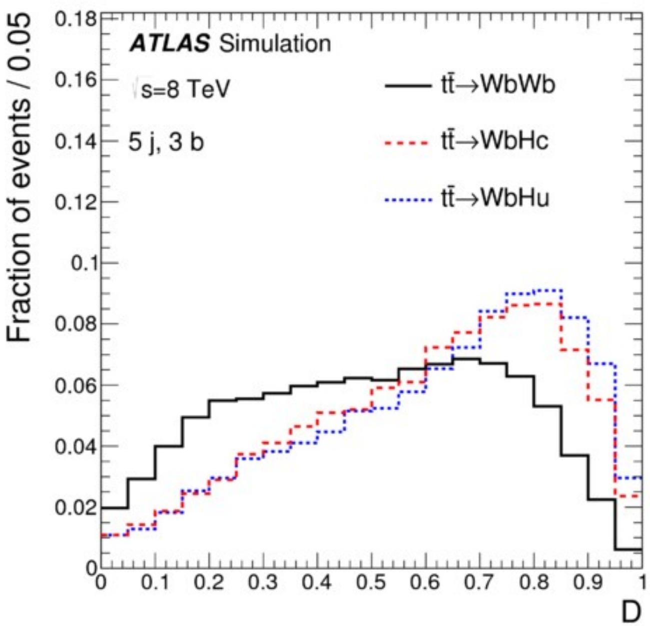
$$D(x) = \frac{P^{sig}(x)}{P^{sig}(x) + P^{bkg}(x)}$$

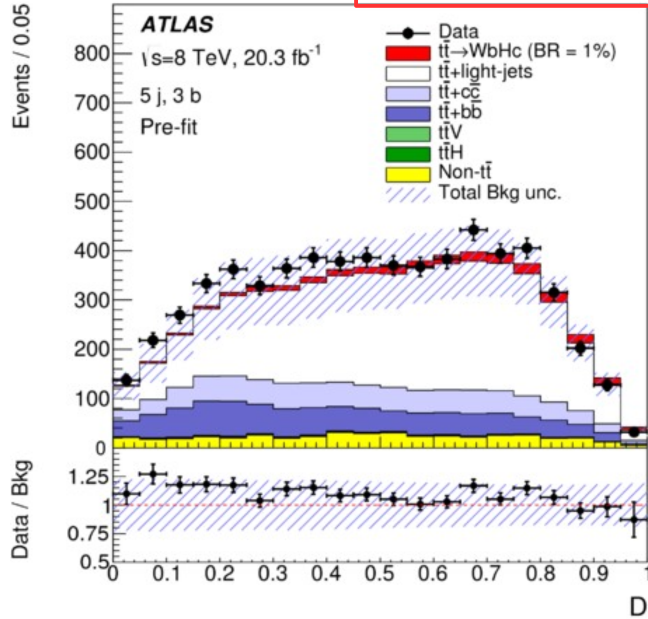
with P^{sig}, P^{bkg} PDFs using the resonances and jet flavour content of final state

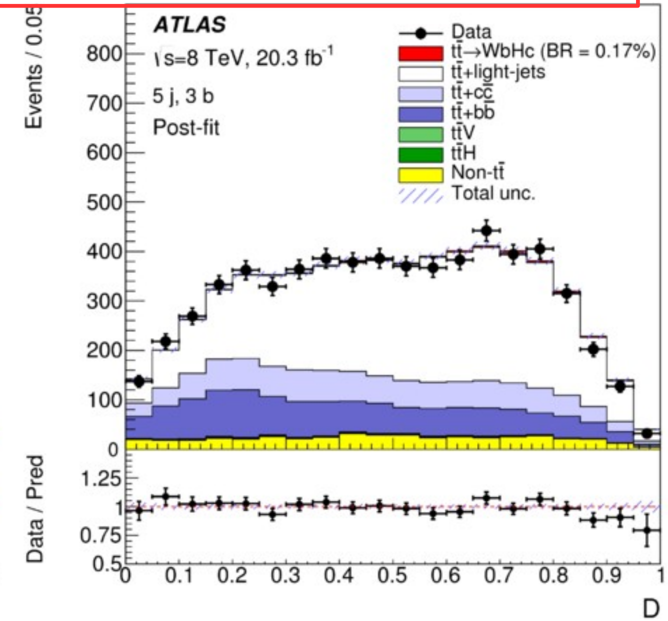
JHEP12 (2015) 061



limit at 95% CL: B(t → Hc) < 0.56 % (obs)
B(t → Hu) < 0.61 % (obs)



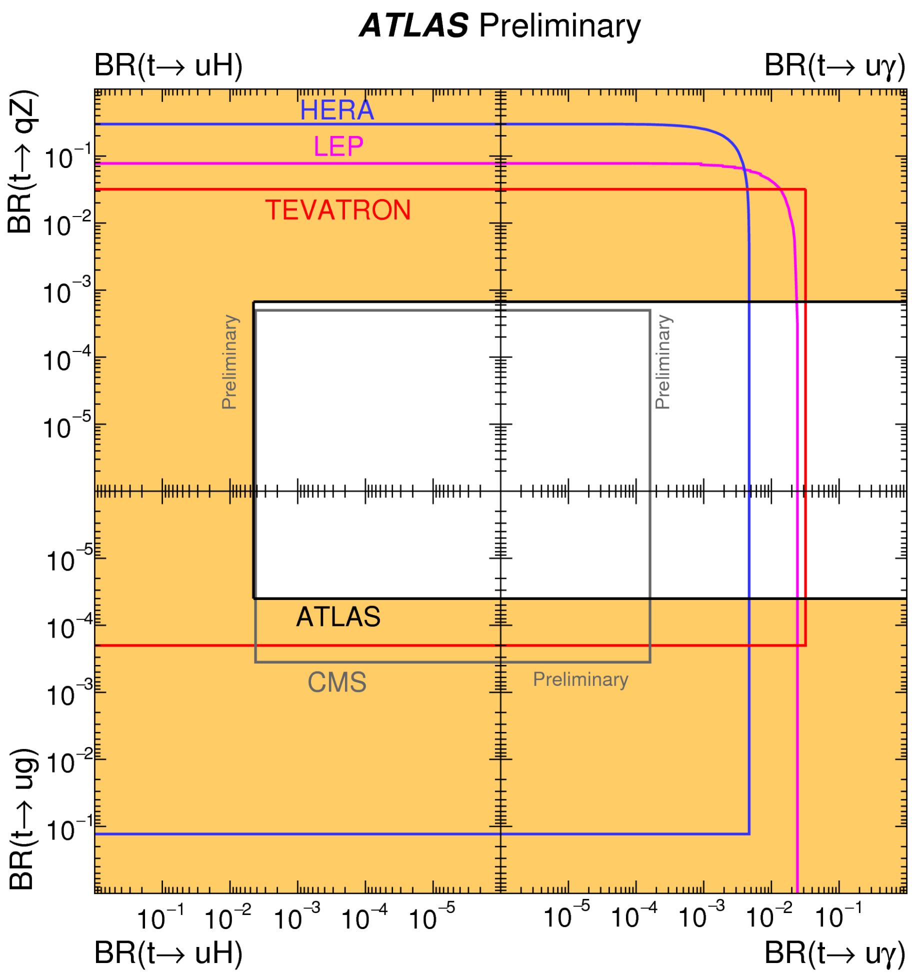




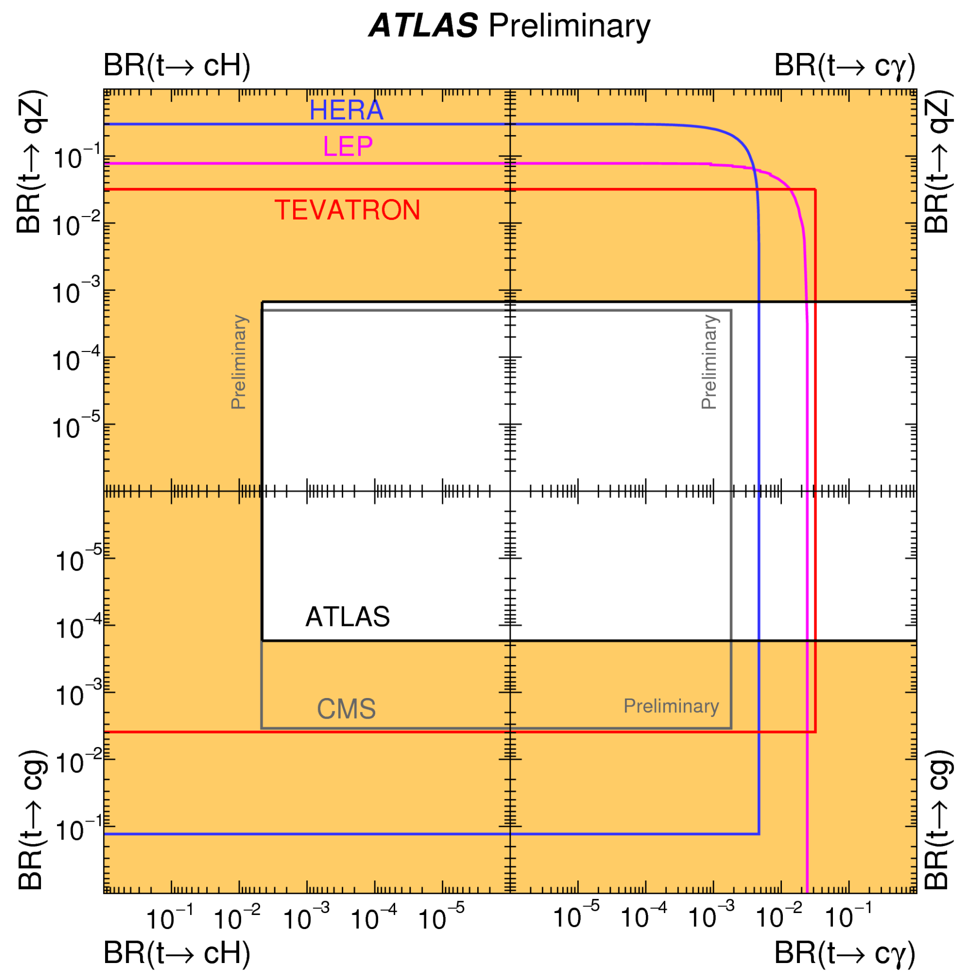
Flavour-changing neutral current

combined summary plots

q = u



q = c



- All analyses presented assume all anomalous couplings are zero, but one
- Still far above SM prediction, but sensitivity to certain BSM models getting closer or even already reached

Conclusions and outlook

- High precision measurements, dominated by systematic uncertainties → focus on improving **signal modeling, generator and theory uncertainties**
- Top charge asymmetry:
  - no deviations from SM observed
  - Measurements becoming dominated by systematic uncertainty
- FCNC: sensitivity to certain BSM models (almost) within reach
- No observation of New Physics or deviations from the SM from LHC Run I

Only a small selection of results is shown, for more information:

ATLAS Top Web pages   CMS Top Web pages

Thank you!

Back up

Charge Asymmetry

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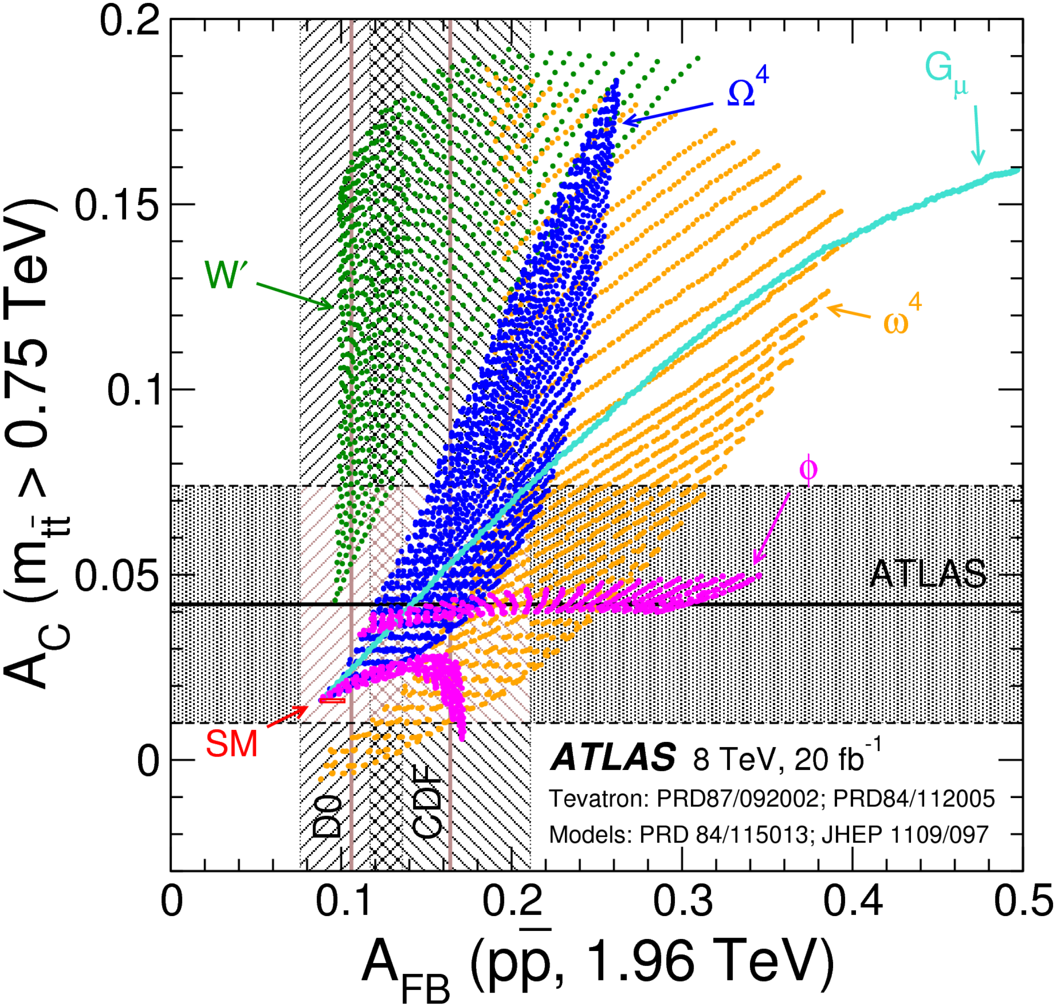

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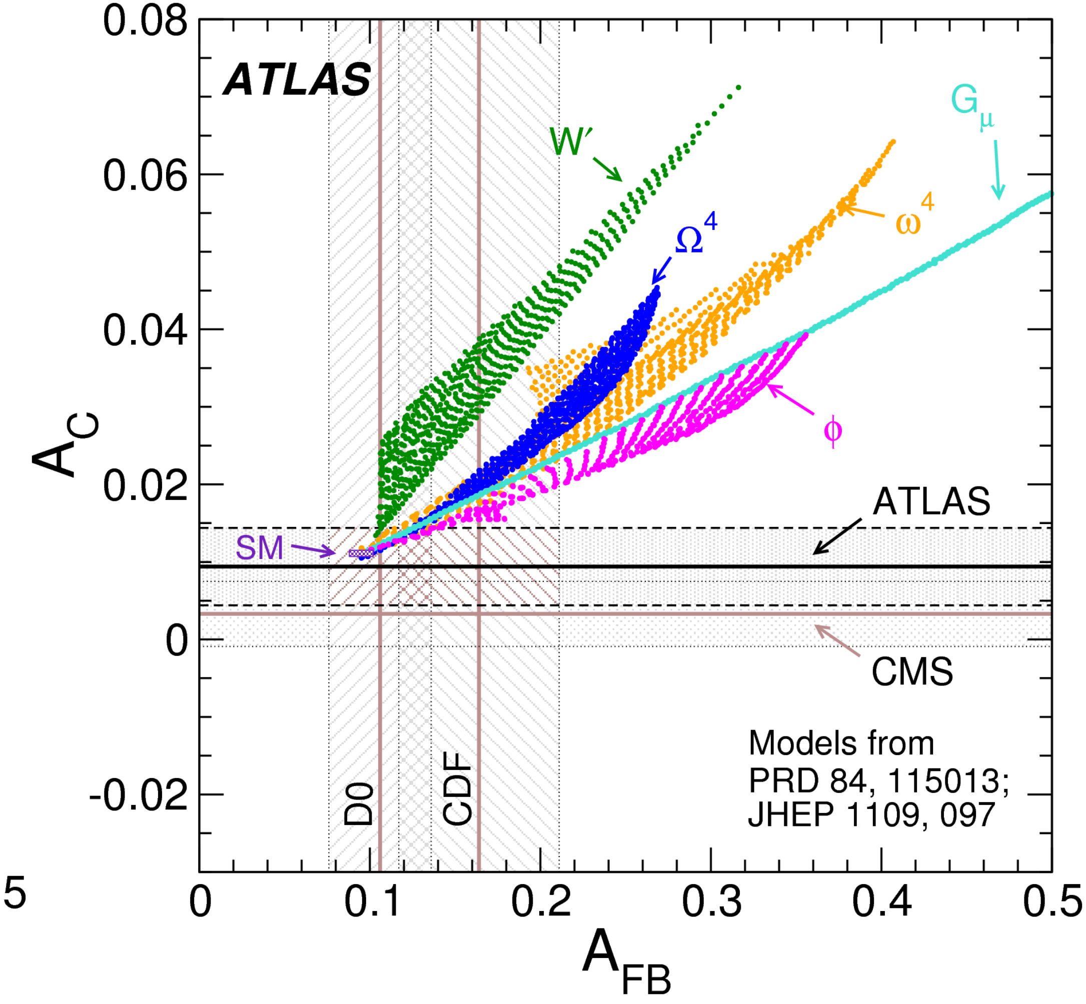
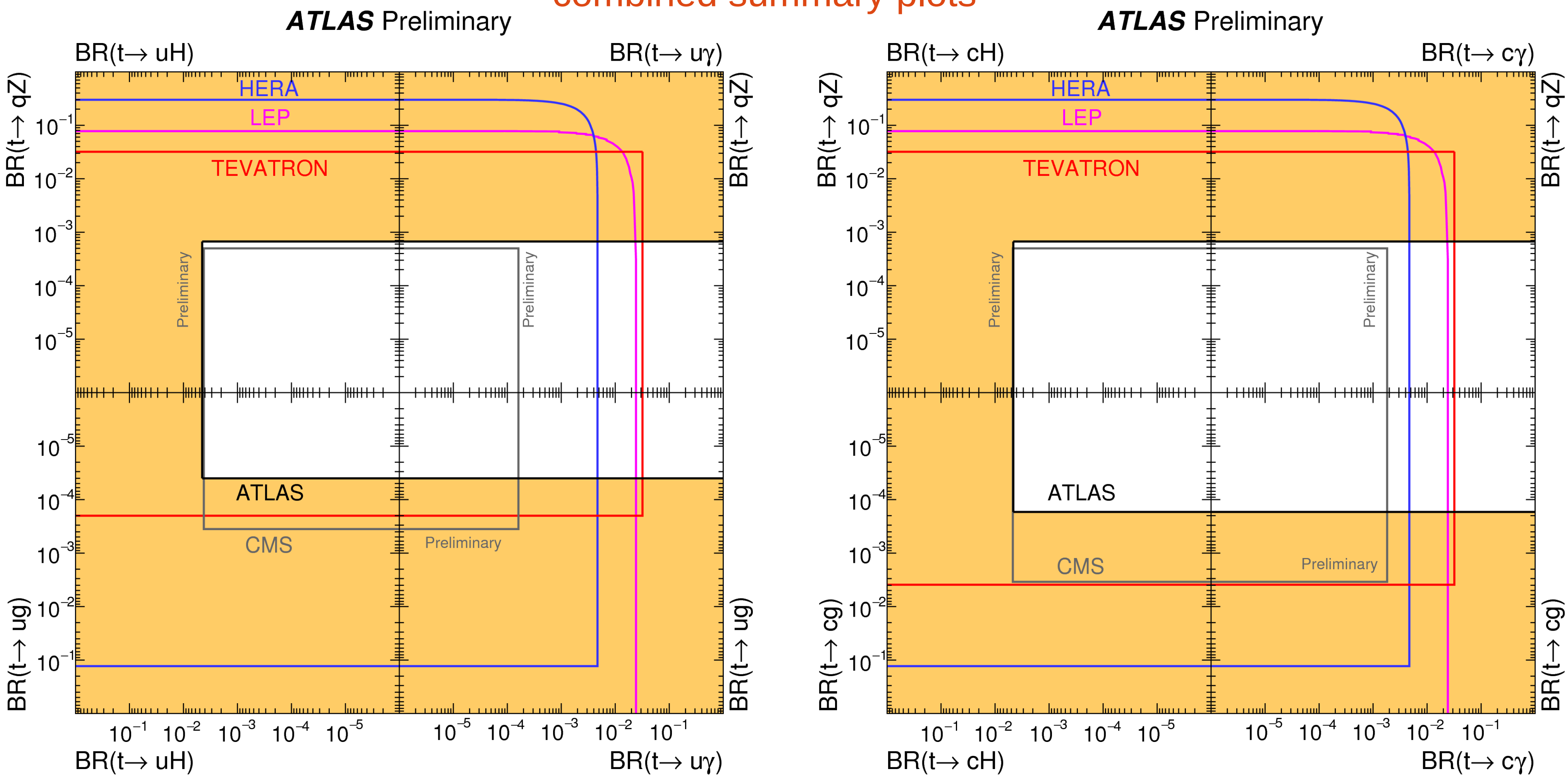


Flavour-changing neutral current

combined summary plots



- All analyses presented assume all anomalous couplings are zero, but one
- Many channels are covered → consider pursuing global approach, considering mixing of various anomalous couplings at NLO →

Phys.Rev. D91 (2015) no.7, 074017   Phys.Rev. D91 (2015) 034024