Selected topics from angular distributions in ttbar events

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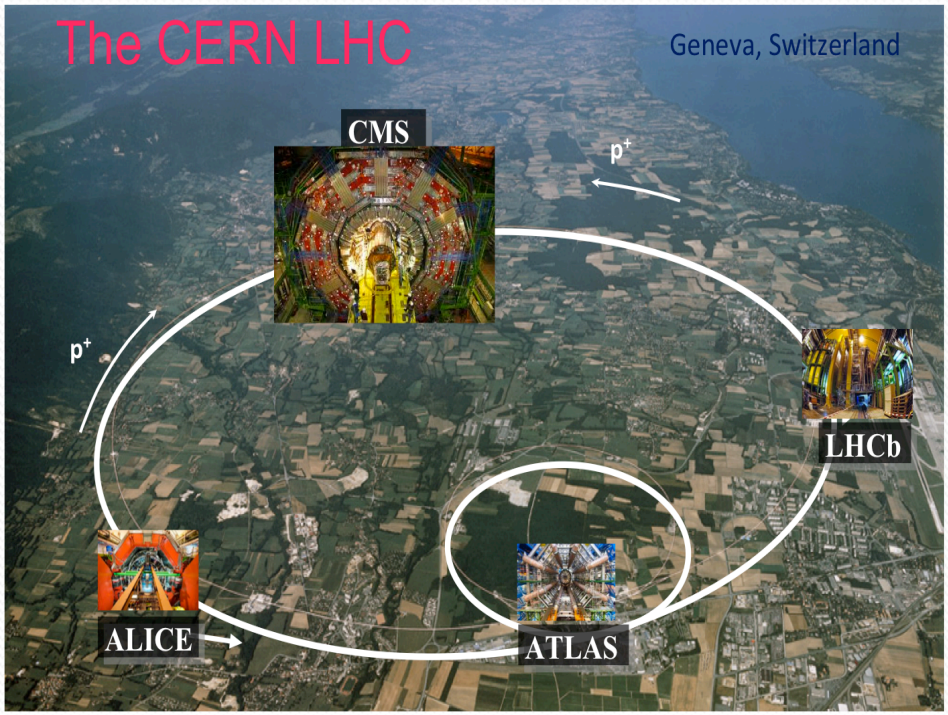
(on behalf of the ATLAS and CMS Collaborations)

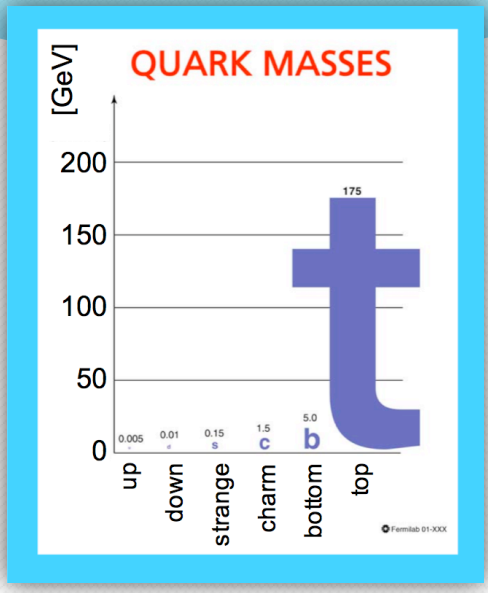


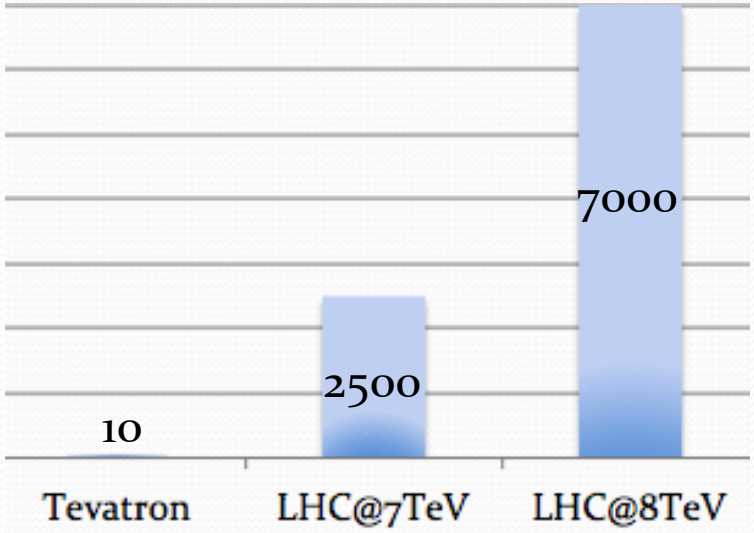
3rd Annual Large Hadron Collider Physics Conference

St. Petersburg, Russia, August 31 – September 5, 2015

Introduction

- Top quark is special in the Standard Model:
  - VERY heavy
  - Decays before hadronization – we study bare quark
- Probe of new physics beyond electroweak scale
  - Production – top can be produced in decays of new particles (incl. virtual)
  - Decay – top can decay into new particles
- LHC is a top factory





Top quark pairs per hour at peak luminosity

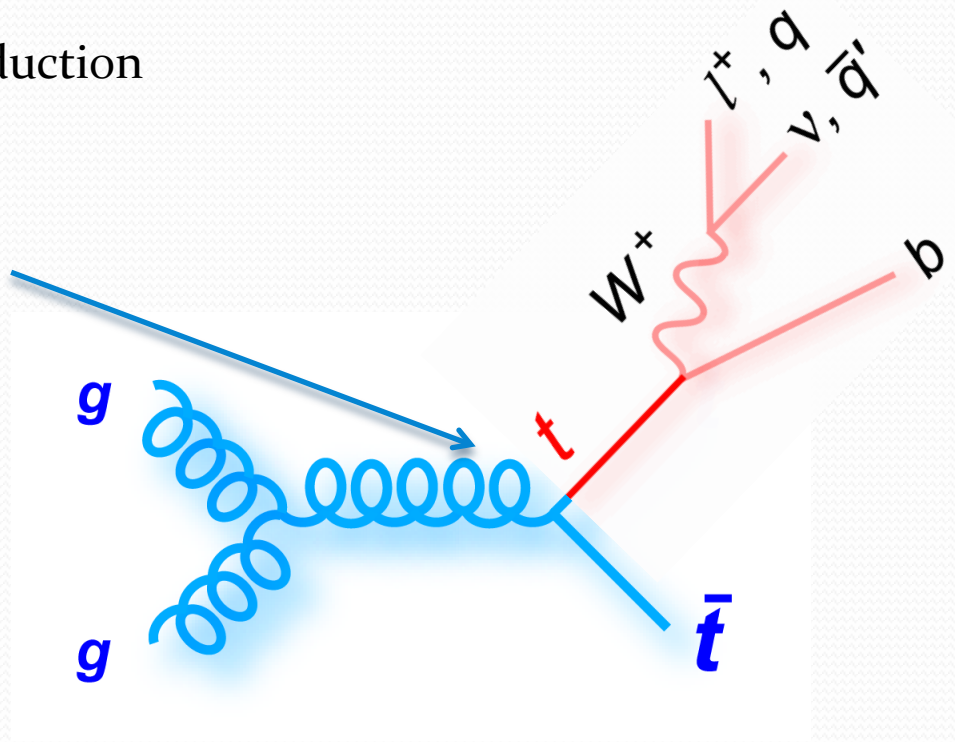
Measuring top properties

- This talk is focused on top pair production

Production:
- Charge Asymmetry
- Color flow
- t-tbar Spin Correlation

NEW

Decay:
- Branching ratios
- W polarization in top decays

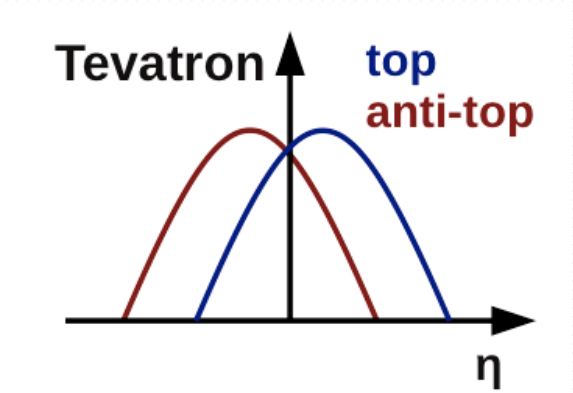


Other measurements:
- Top mass & production (ttbar and single top), BSM Searches

Charge Asymmetry

-NLO effect originating from interference of q-qbar diagrams producing top pairs
- Can be largely enhanced by new physics, such as W' or axigluon models

Tevatron (p-pbar machine) top quarks are preferentially emitted in the direction of the incoming quark, anti-tops in the direction of the incoming anti-quark.



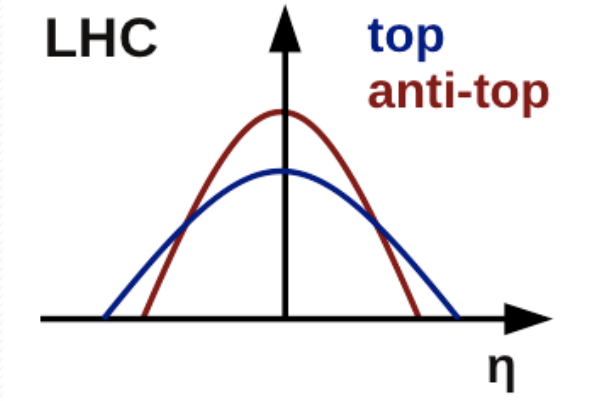
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

LHC has symmetric initial state (pp):
- Quarks are mostly valence and anti-quarks are from the sea

- The PDF's are not symmetric – quarks carry more momentum than anti-quarks

- Rapidity distribution of tops is broader

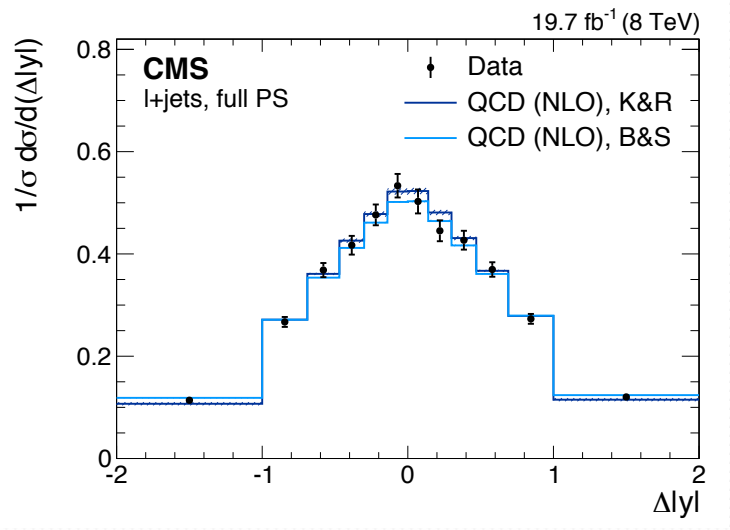


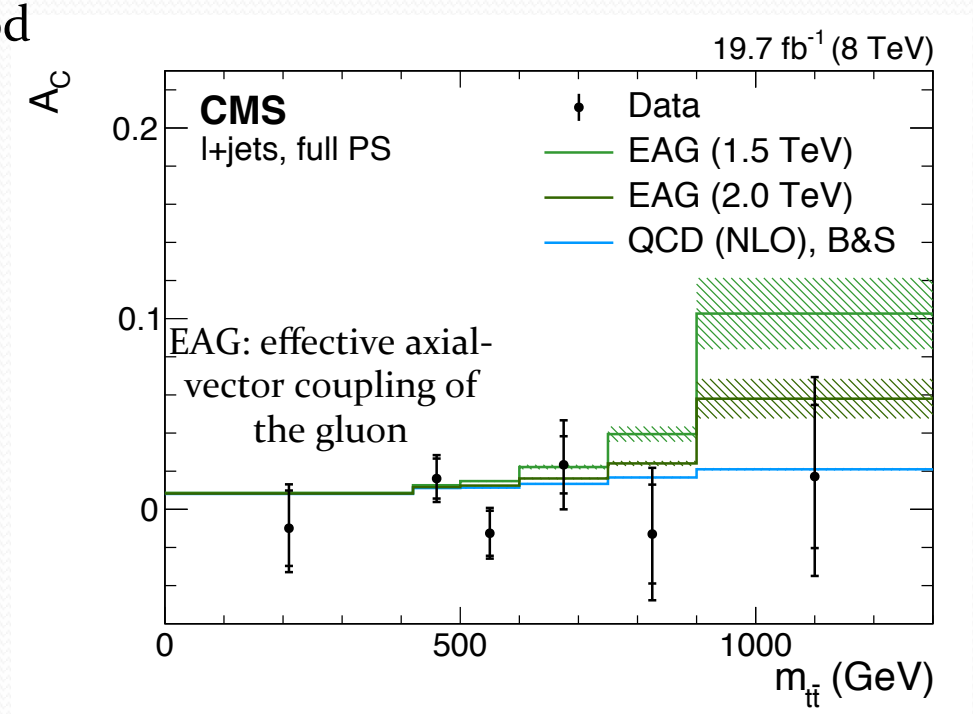
$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

A_C in lepton + jets events

- Full 8 TeV CMS dataset (~19.7 fb^{-1})
- One lepton (e or μ), ≥ 4j, ≥ 1b-tag
- ttbar association based on likelihood
- Unfolded to parton level

- Differential distributions (in m_{tt} , y_{tt} , p^T_{tt}) sensitive to BSM physics



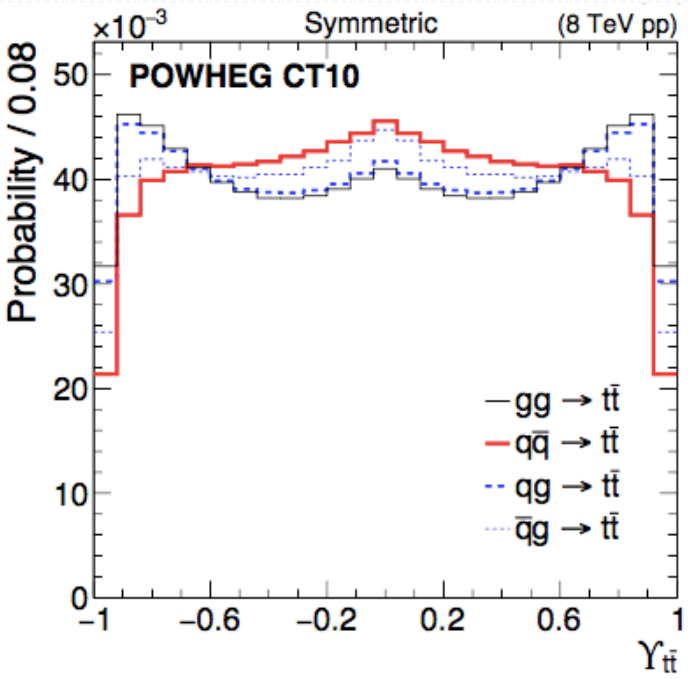


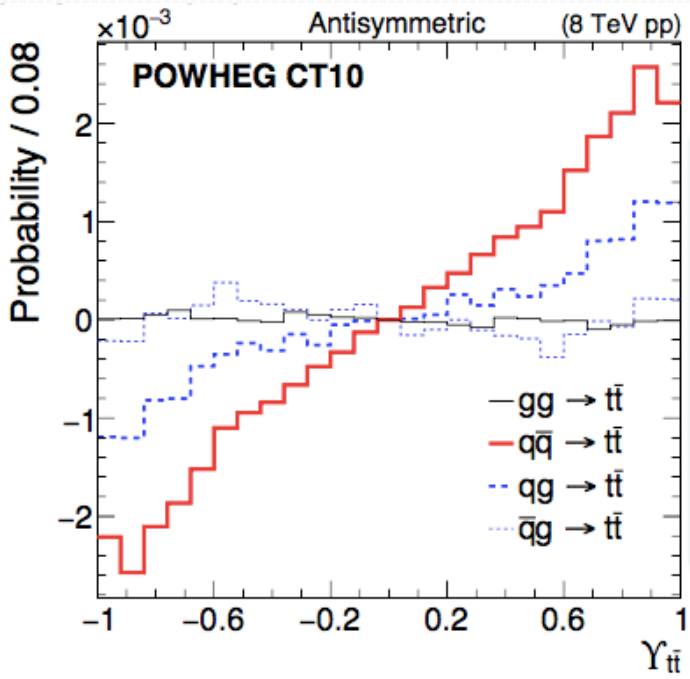
Full phase space	0.0010 ± 0.0068 (stat.) ± 0.0037 (syst.)
Theoretical prediction [Kühn, Rodrigo] [9]	0.0102 ± 0.0005
Theoretical prediction [Bernreuther, Si] [39]	0.0111 ± 0.0004

Submitted to PLB
arXiv:1507.03119

A_C (l+jets) - Template Method

- 8TeV data, looser cuts, larger sample
- Two-stage maximum-likelihood fit used sequentially for sample composition and $A_{c.}$
- Two templates for different initial states constructed from POWHEG with CT10 PDFs
- Template fit to bounded sensitive variable $\Upsilon_{t\bar{t}} = \tanh\Delta|y_{t\bar{t}}|$
- Alternative to unfolding: fit data to linear combination of symmetric and anti-symmetric templates at reconstruction level

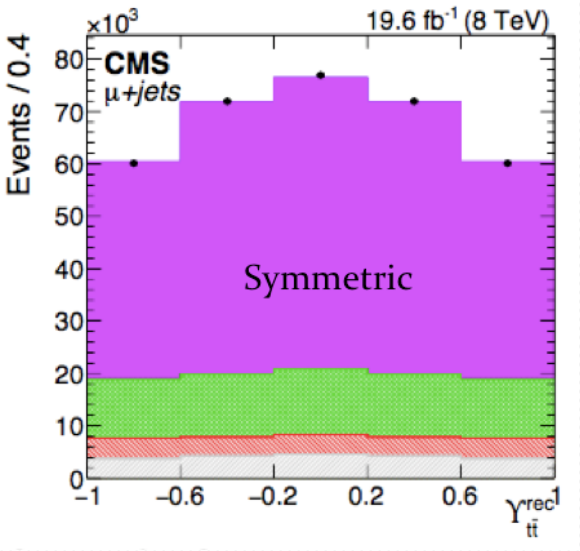


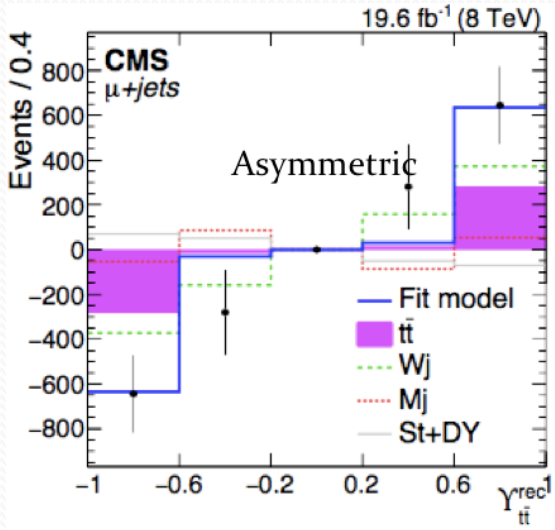


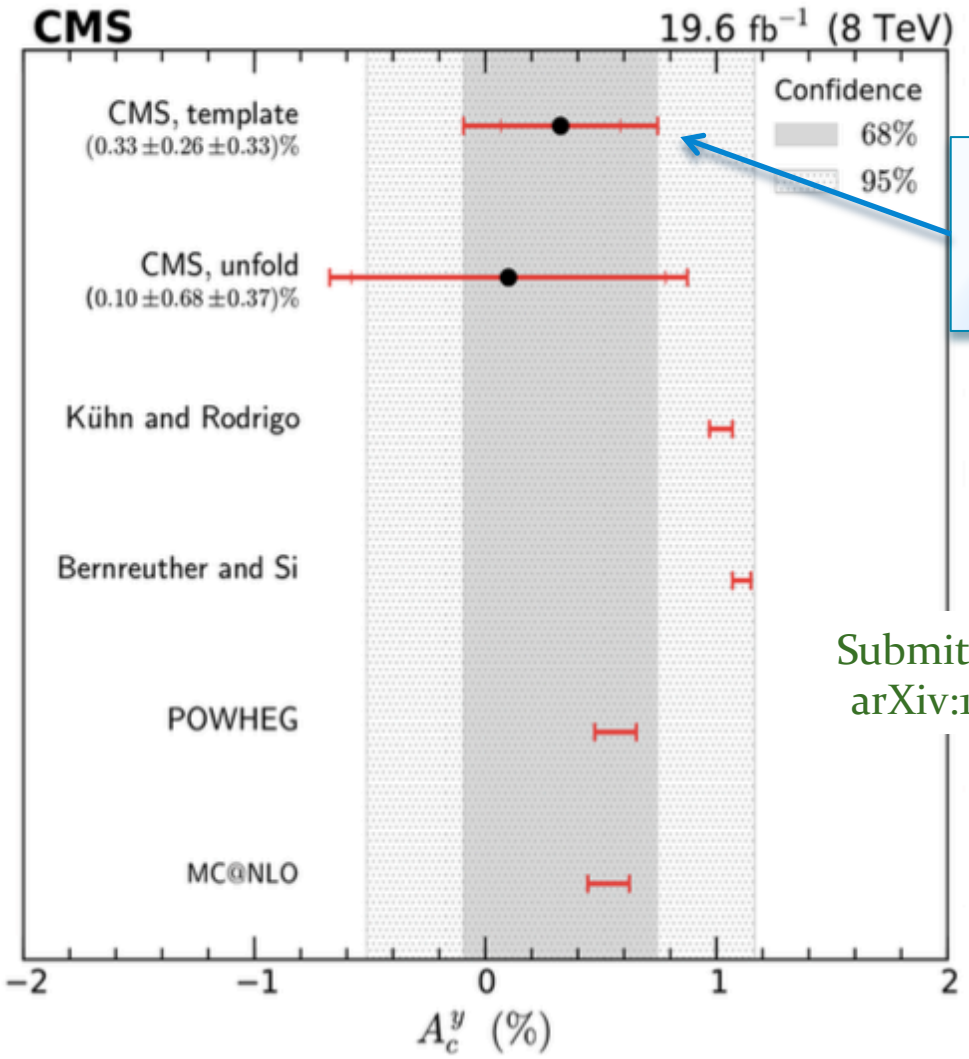
Significantly smaller statistical uncertainties with slightly larger model dependence than traditional unfolding methods

Submitted to PRD
arXiv:1508.03862

A_C (l+jets) - Template Method





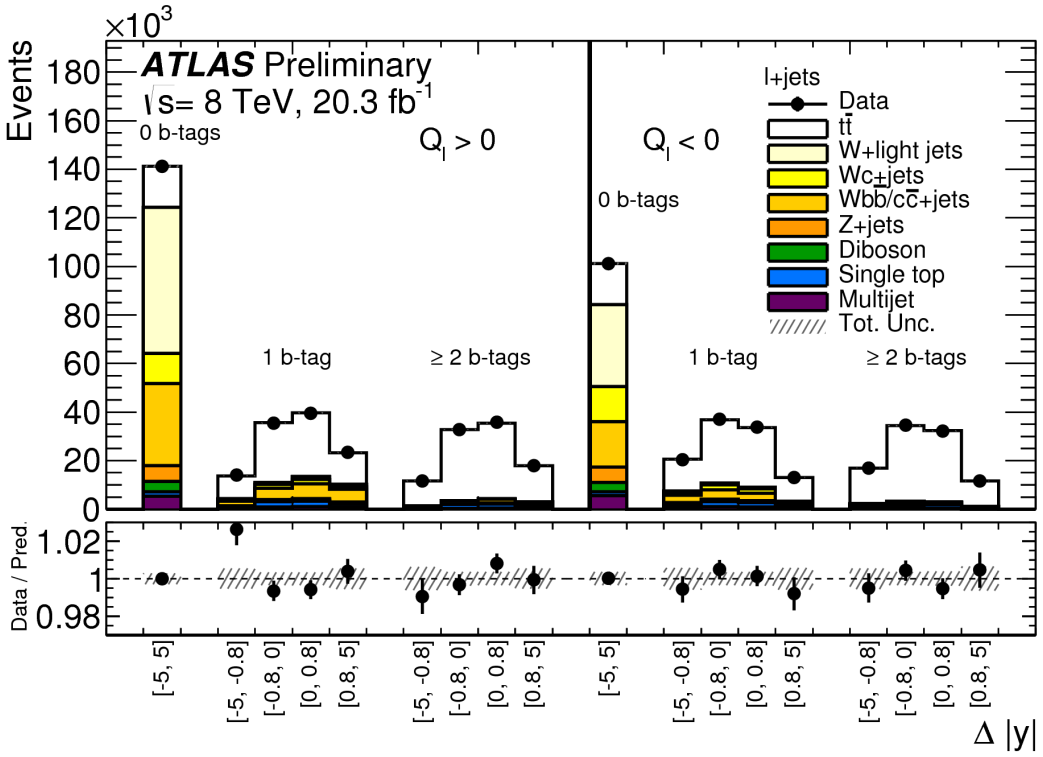


Much improved uncertainty

Submitted to PRD
arXiv:1508.03862

A_C (l+jets) – Brand New from ATLAS

- 8 TeV ATLAS dataset (20.3 fb^{-1})
- One lepton (electron or muon), at least 4 jets
- ttbar association based on likelihood
- Measurement performed in 18 channels based on lepton charge, number of b-jets (0, 1 ≥2), and rapidity bins
- Simultaneous Bayesian unfolding and in-situ W+jets calibration
- Main uncertainty is data statistics, followed by JES/JER and MC statistics

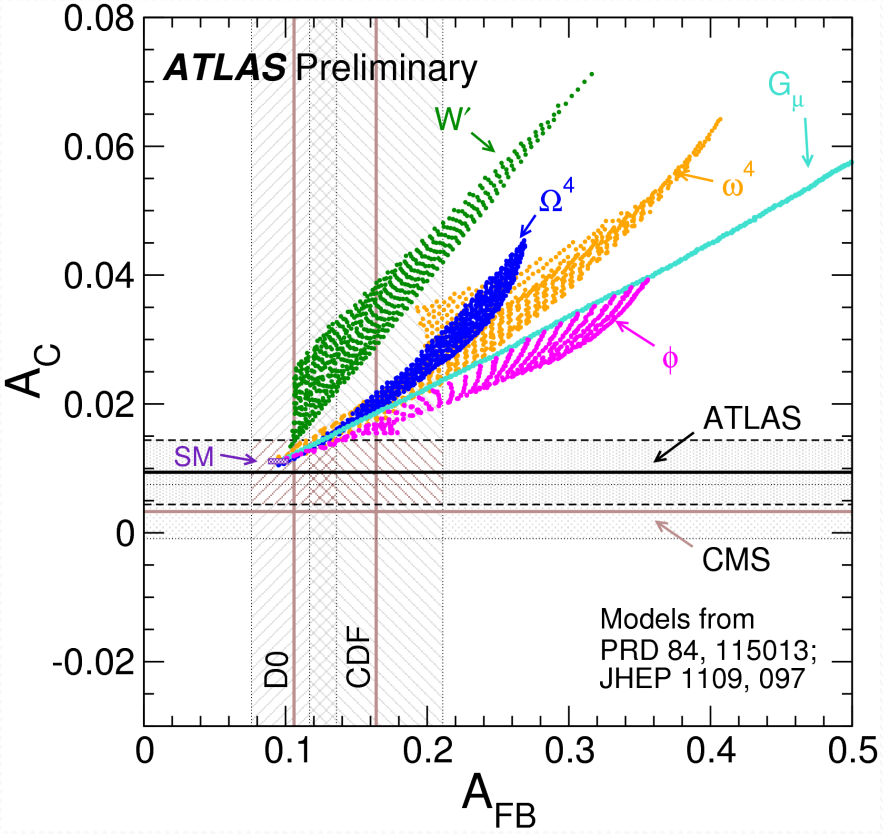


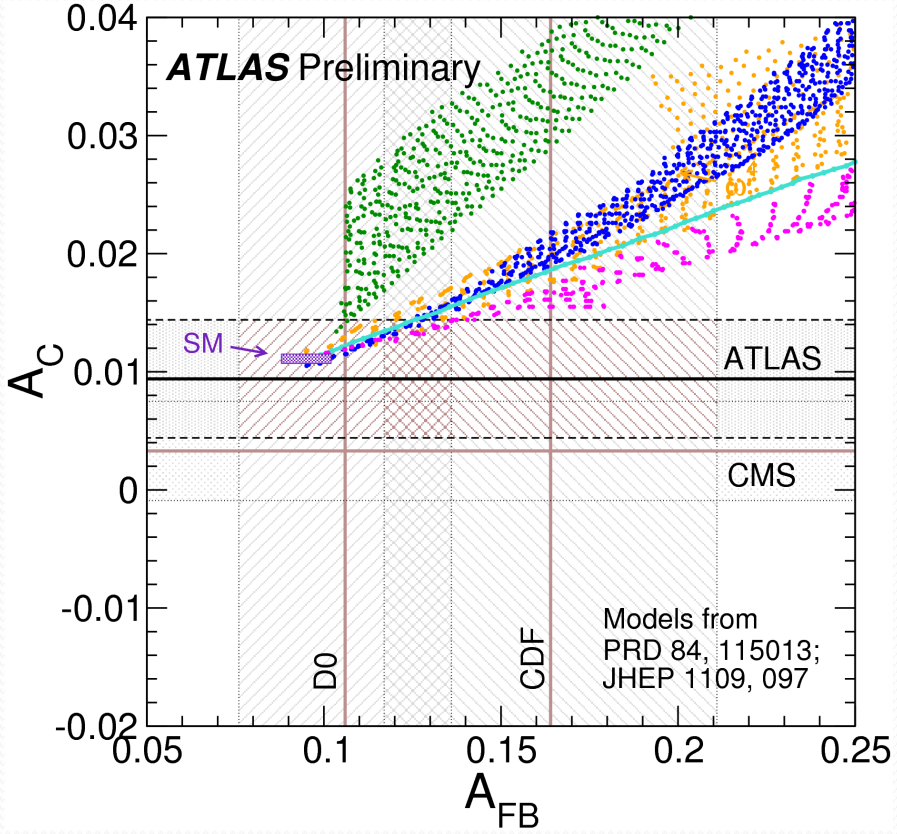
ATLAS: $A_C = 0.009 \pm 0.005$

Prediction : $A_C = 0.0111 \pm 0.0004$ PRD 86, 034026(2012)

Differential measurements as a function of the invariant mass, transverse momentum and longitudinal boost of the ttbar system compatible with SM predictions

A_C (l+jets) – Brand New from ATLAS





Large phase-space of parameters describing various BSM models is excluded

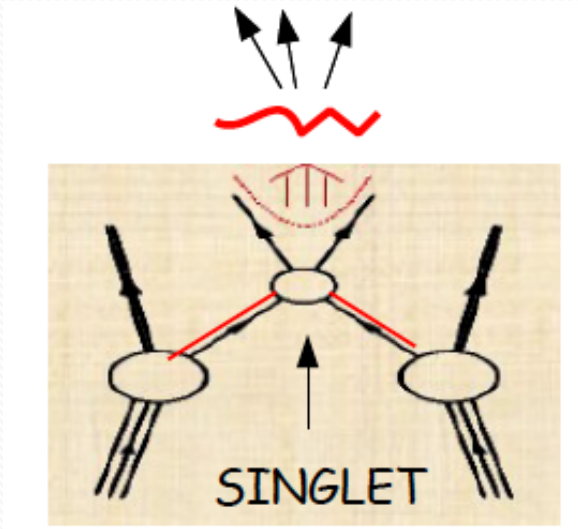
To be submitted to EPJC

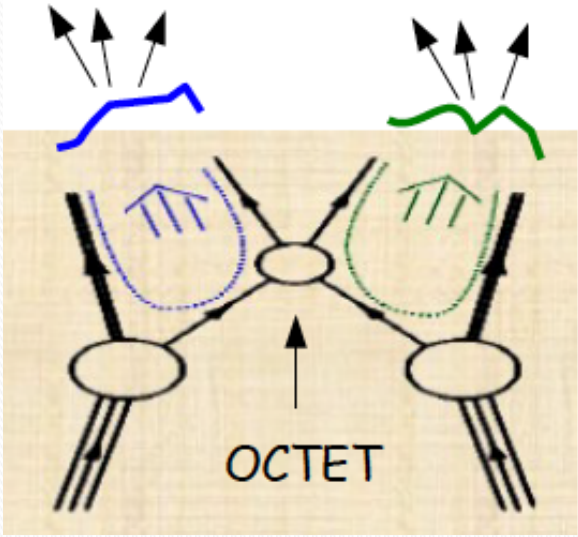
Color Flow

- QCD color charge is conserved locally, i.e. it "flows" just like electric charge

- Quarks carry one color (triplet)
- Gluons carry a color and an anti-color (octet)
- Others (W, Z, H, etc.) carry no color (singlet)

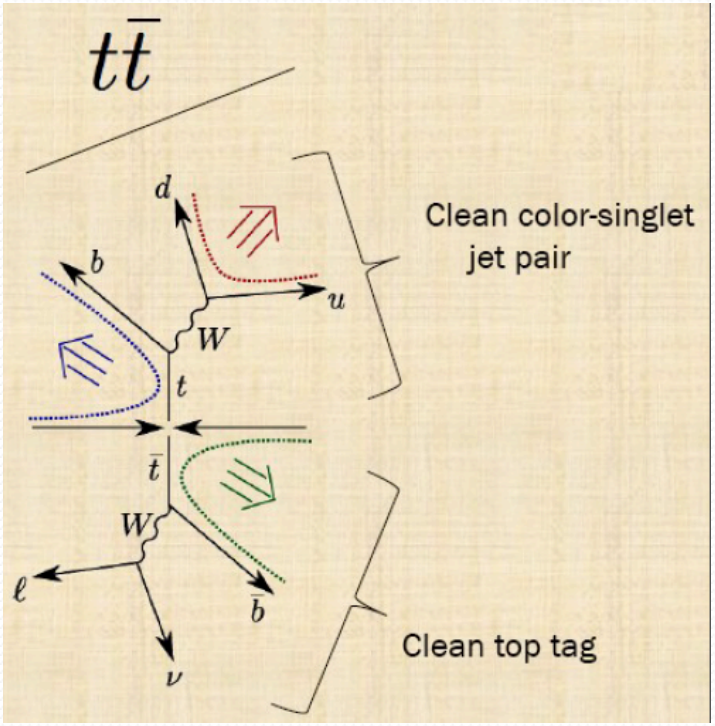
- Pulling apart a color from its anti-color requires lot of energy (~1GeV/fm)
  - Described through a color string or color connection picture
- Eventually color strings "break" by pulling quarks out of the vacuum
- Particles created during hadronization should be concentrated along angular region spanned by the color connected partons





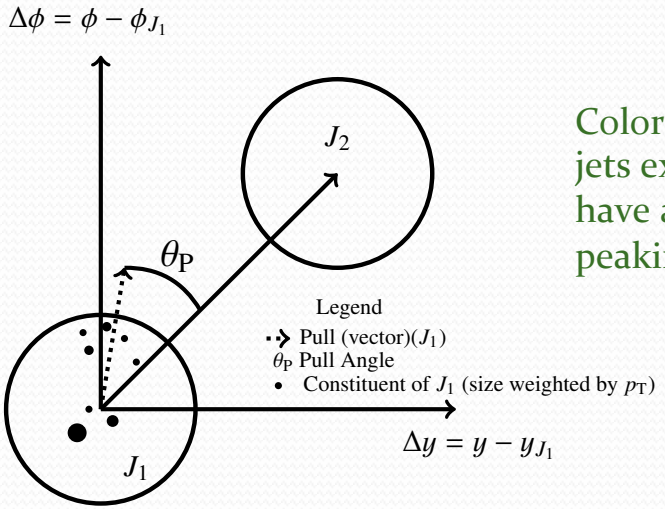
Color Flow

- ttbar lepton+jets sample ideal for the study of color flow



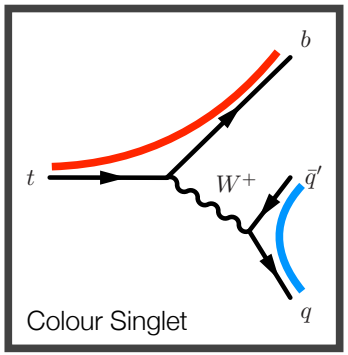
- W➔jj decay is pure color singlet
- Each of the two b quarks is color connected to one of the beam remnants in a color-octet pattern

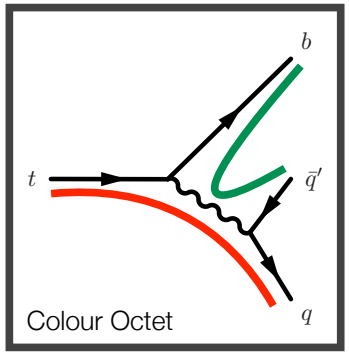
- Jet pull angle sensitive to color flow



Color connected jets expected to have a pull angle peaking at zero.

- Color flow pattern is tested comparing data to two ttbar MC models: SM and one in which the W boson is a color octet



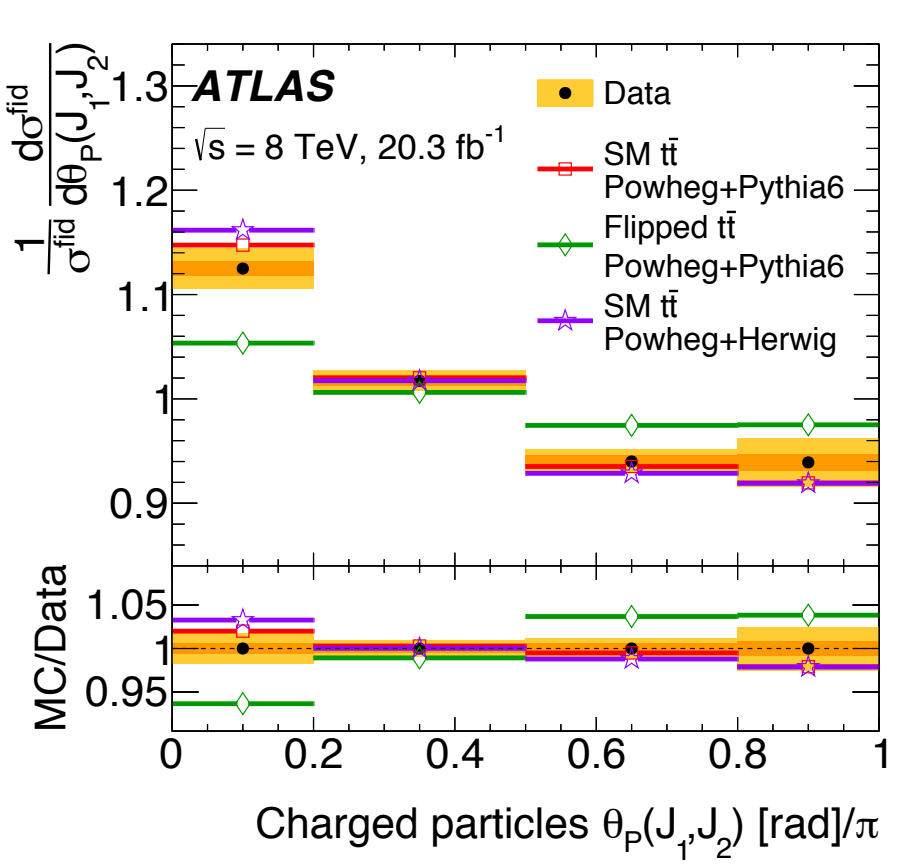


Color Flow

- Full 8TeV ATLAS dataset (20.3fb^{-1})
- One lepton (electron or muon)
- At least four jets (2 tagged as originating from b-quark)
- Large MET

- Pull angle measured using all particles and charged particles only
- Measurement unfolded for detector acceptance and resolution
- Jet pull angle presented as a normalized $t\bar{t}$ differential x-sec

Submitted to PLB
arXiv:1506.05629v1



- Color octet model disfavored at the 3 SD level
- Jet pull angle useful variable in future SM measurements and BSM searches.

Spin correlations

- Spins of top and anti-top are correlated in SM

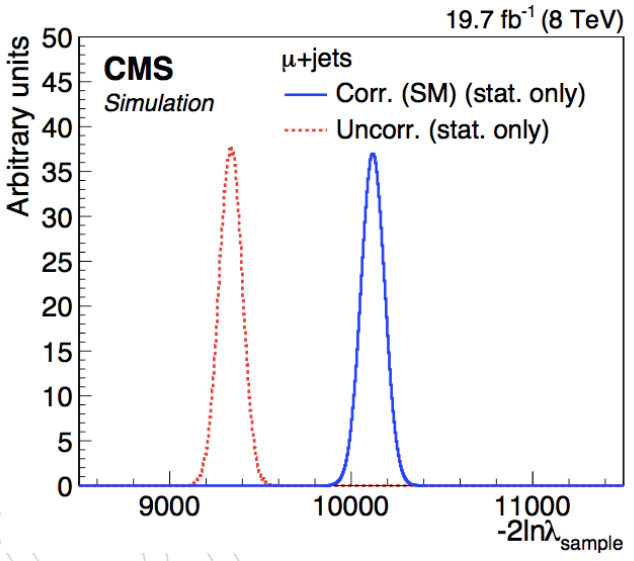
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+\, d\cos\theta_-} = \frac{1}{4}\left(1 + \underbrace{\alpha_+ P_+ \cos\theta_+}_{\approx 0} + \underbrace{\alpha_- P_- \cos\theta_-}_{\approx 0} + \underbrace{A\alpha_+\alpha_- \cos\theta_+ \cos\theta_-}_{\text{Correlation}}\right)$$

- Top lifetime < hadronization timescale < spin decorrelation timescale
  - Top quarks decay before their spins decorrelate
  - Spin correlation propagated to the decay products
  - Precise measurement gives information on the strength of the SM couplings and relative contribution of production modes of ttbar pairs
- Spin correlation strength

$$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

Asymmetry between the number of ttbar pairs with aligned and anti-aligned spins

- Use a ME method with separate matrix elements for the correlated SM and uncorrelated cases
  - Calculate likelihoods for each event under the two hypotheses
  - Test statistics based on the ratio $\lambda_{event}=P(H_{uncor})/P(H_{cor})$

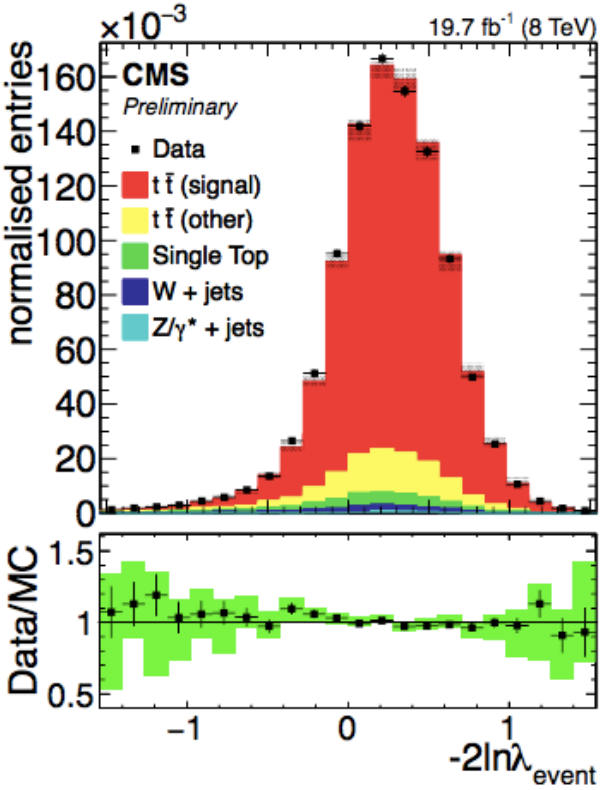


Spin correlations

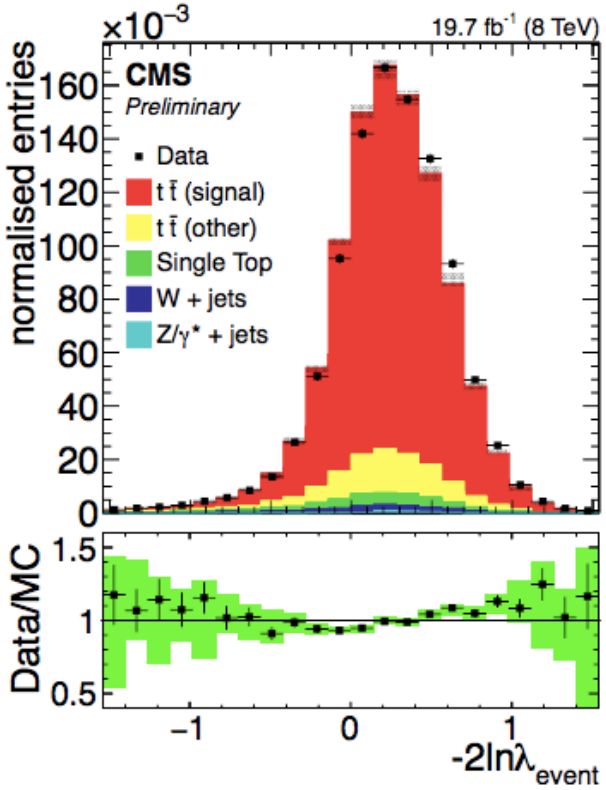
- Full 8TeV CMS dataset (19.7fb^{-1})
- One muon
- At least four jets (2 tagged as originating from b-quark)
- Kinematic fitter to reconstruct ttbar pairs (W mass, m_{top}=$m_{antitop}$)
- Keep only events with χ^2/dof<5

Process	Yield
W+jets	722 ± 20
Z/γ^*+jets	139 ± 18
t, $\bar{t}$, s channel	41 ± 3
t, $\bar{t}$, t channel	314 ± 10
t, $\bar{t}$, tW	935 ± 20
$t\bar{t}$ other	3896 ± 24
$t\bar{t}$ signal	31992 ± 69
Total simulation	38039 ± 81
Data	37775

Test statistics compared with correlated and uncorrelated simulations



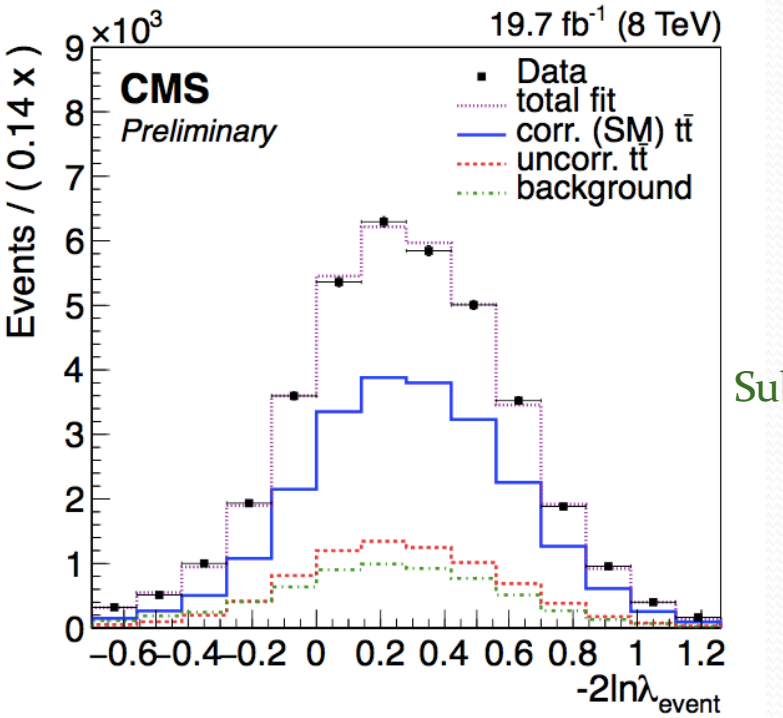
(a) $t\bar{t}$ SM correlated



(b) $t\bar{t}$ uncorrelated

Spin correlations

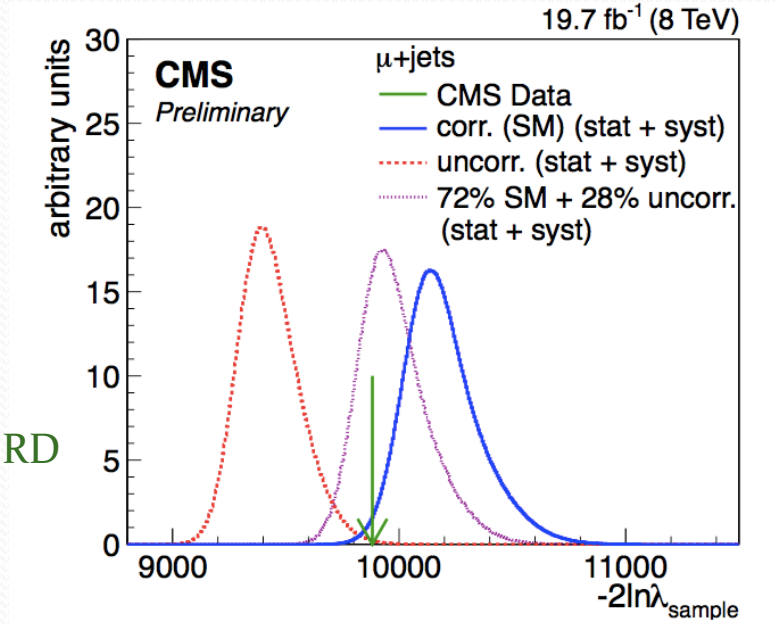
- Fraction of events with SM spin correlation from template fit to $-2\ln\lambda_{event}$



$$f = 0.72 \pm 0.09(stat)^{+0.15}_{-0.13}(syst)$$

TOP-13-015
Submitted to PRD
arXiv:xx.xx

- Compatibility test using sample with measured SM fraction



- Data agree with SM hypothesis within 2.2SD and with uncorrelated hypothesis within 2.9SD
- ATLAS dilepton also agrees with SM within 2 SD – PRL 114, 142001 (2015)

Conclusions:

- Top quark is truly a unique particle in the SM
  - Measurements of its production and decay properties allow for precision tests of the SM as well as indirect window to the BSM world
- ATLAS and CMS have a very rich program of top properties:
  - Presented new results on Charge Asymmetry, Color Flow and Spin correlations
  - Results are most precise to-date and use new/alternative methods
- LHC Run-II started. Most of the analyses will benefit from larger datasets, some will also benefit from higher energy.
- **Stay tuned for updates**