Top quark properties at CMS and ATLAS

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On behalf of the ATLAS and CMS Collaborations

52nd Rencontres de Moriond on
QCD and High Energy Interactions

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Top quark properties at the LHC

Over 30 years after its discovery SM top quark well established experimentally

Many measurements on top quark mass, production cross sections in pairs: tt(+X); single: (tW, tq in *t*- and *s*-channels), all agree with SM predictions within uncertainties

LHC: precision era

>10 million top quarks produced per experiment at 8 TeV [to add: 7 TeV, 13 TeV data]

huge amount of top quarks available for precision measurements

Use top quarks to investigate limits of the SM:

- ★ Go as precise as possible: test SM comparing data to theory predictions
- ★ Use the data to constrain BSM theoretical predictions (e.g.: using effective field theory)
- ★ Measure rare processes involving top quarks, with much lower cross sections
- ★ Search directly for signs of new physics at production or decay

Experimental take on top quark properties
(Outline of this talk)

Angular measurements
— top spin
— top polarisation ***(see also talk by Regina Valls)***
— W polarisation in top decays

Charge and mass measurements
— charge asymmetry
— CP violation
— top width
— mass difference ***(talk by James Monk)***

Production and decay
— EWK couplings (+top charge): e.g. ttH, tt+Z, tt+γ processes ***(talks by Nicolas Chanon, Lana Beck)***
— FCNC couplings (searches): e.g. ggWb, tZ, tH processes

Limits on new physics
— Re-interpreting these measurements contrasting with beyond standard model physics models

Presenting latest measurements, mostly using LHC data at 8 TeV

More results can be found

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Typical top quark event selection

Focusing on final states with 1 or 2 leptons (electrons and/or muons)

Decays involving taus / full hadronic: more challenging to reach high precision

Events triggered with lepton triggers

Selection criteria mostly defined by trigger (+ detector acceptance) limitations and background rejection

Objects selection according to topology

-number of jets/b-jets

-number of isolated electrons/muons

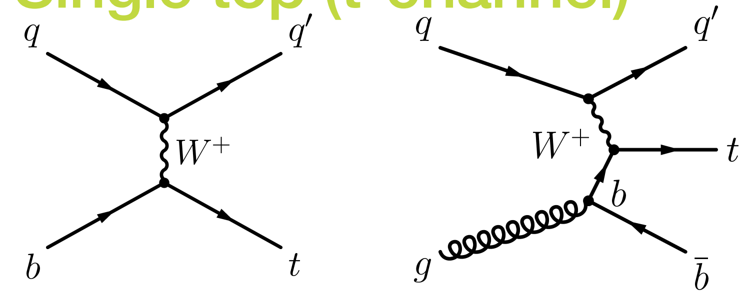
-(additional selection criteria to reduce backgrounds, e.g. $M_{\ell+\ell-}$ or missing transverse energy for Z boson or non-prompt leptons rejection)

Several measurements require reconstruction of the tt system

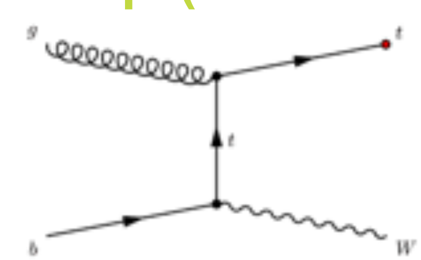
-kinematic fit

-reconstruct missing information (e.g. neutrino pZ) from top and W masses constrains

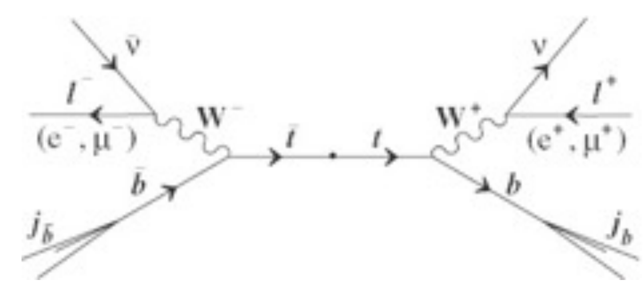
Single top (t-channel)



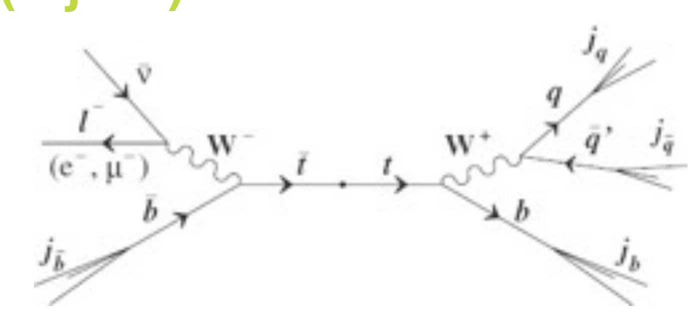
Single top (tW-channel)



tt (dilepton)



tt (l+jets)



Top properties:

Angular measurements

Spin correlations and top polarisation

tt, dilepton ATLAS Collaboration: arXiv:1612.07004

Angular observables: $\theta^{k,r,n}$

angles between a top decay particle (in top rest frame) and the axis **k, r, n** with

- **k** : helicity axis (top quark direction in tt rest frame)
- **n** : transverse to the top quark production plane
- **r** : orthogonal to k and n

frame boosts: full tt system reconstruction!

SM prediction:

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}\left(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b\right),$$

a,b → **chosen axes**
+,- → **top charge**

each top ~ unpolarized (unlike EWK single top)
top / anti-top spins are correlated

Polarisation : $B^a = 3 < \cos\theta^a >$

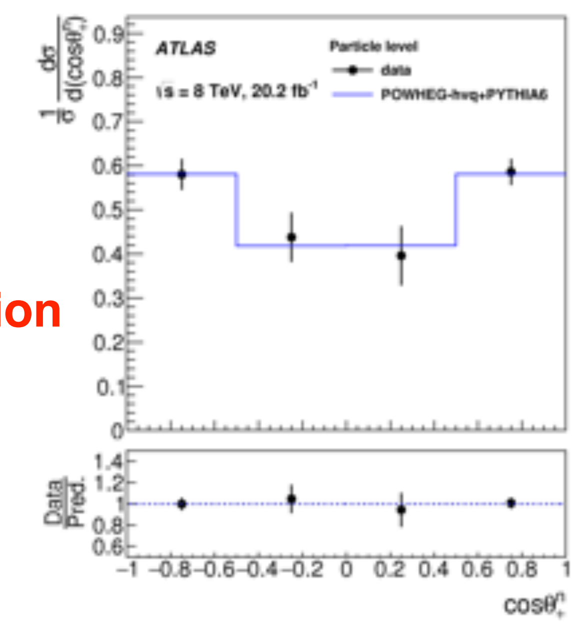
Spin correlation between axis a,b: $C(a,b) = -9 < \cos\theta^a_+ \cos\theta^b_- >$

Spin correlations and top polarisation

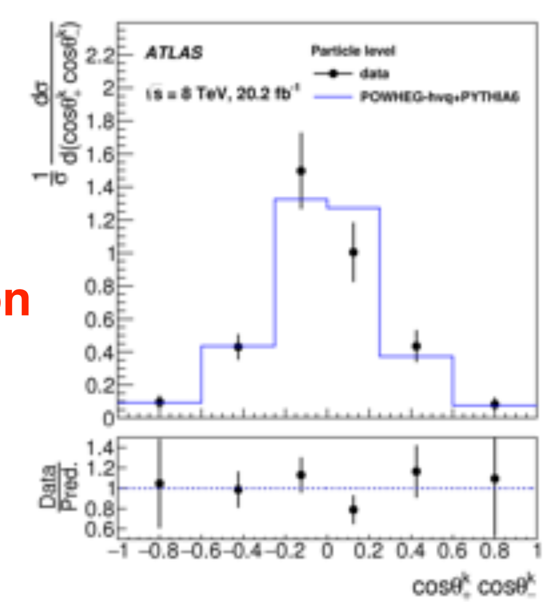
tt, dilepton   ATLAS Collaboration: arXiv:1612.07004

Angular observables:
data to predictions comparison

Polarisation



Spin correlation

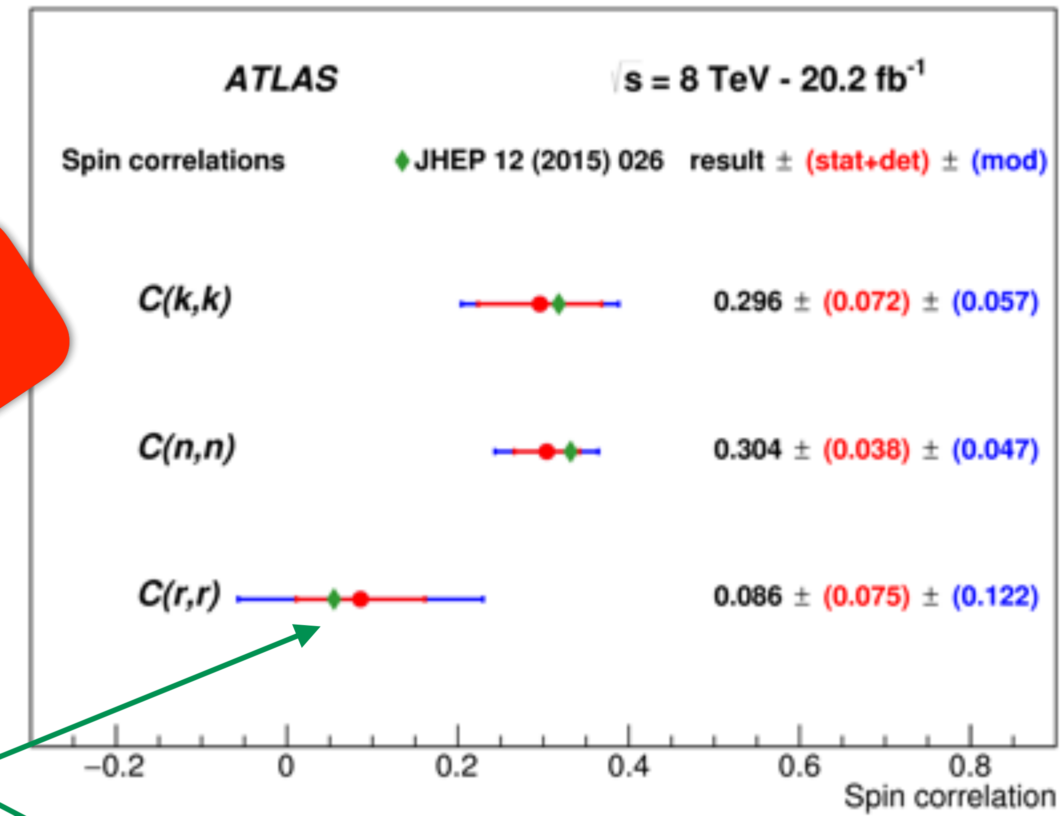


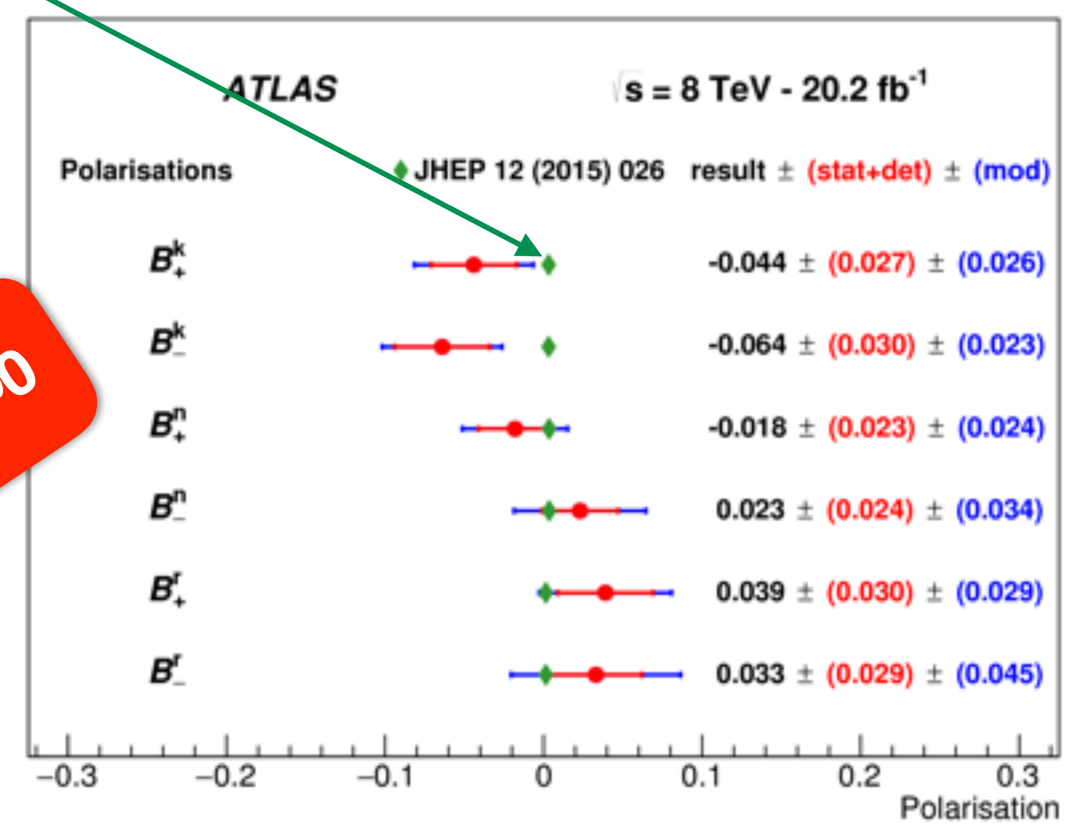
Measurements in agreement with the SM predictions

Sizeable spin correlations

✦ **SM predictions**

Polarization~0





Spin correlations and top polarisation

tt, dilepton CMS Collaboration: PRD 93 (2016) 052007

Angular observables: θ,ϕ,φ

angles defined for each lepton as

- θ : between lepton (in parent top rest frame) and top quark momentum (in tt centre of mass frame)
- φ : between the two leptons (in their parent quark rest frame)
- ϕ : azimuthal lepton angle **in the <u>lab frame</u>** ➡ **no need to reconstruct full tt system!**

SM prediction: 4 asymmetries ➡ 1 polarization

Polarisation :

$$A_{P\pm} = \frac{N\left(\cos\theta^{\star}_{\ell^{\pm}} > 0\right) - N\left(\cos\theta^{\star}_{\ell^{\pm}} < 0\right)}{N\left(\cos\theta^{\star}_{\ell^{\pm}} > 0\right) + N\left(\cos\theta^{\star}_{\ell^{\pm}} < 0\right)}$$

Spin correlations and top polarisation

tt, dilepton

CMS Collaboration: PRD 93 (2016) 052007

Angular observables: θ,ϕ,φ

angles defined for each lepton as

- θ : between lepton (in parent top rest frame) and top quark momentum (in tt centre of mass frame)
- φ : between the two leptons (in their parent quark rest frame)
- ϕ : azimuthal lepton angle **in the lab frame** ➡ **no need to reconstruct full tt system!**

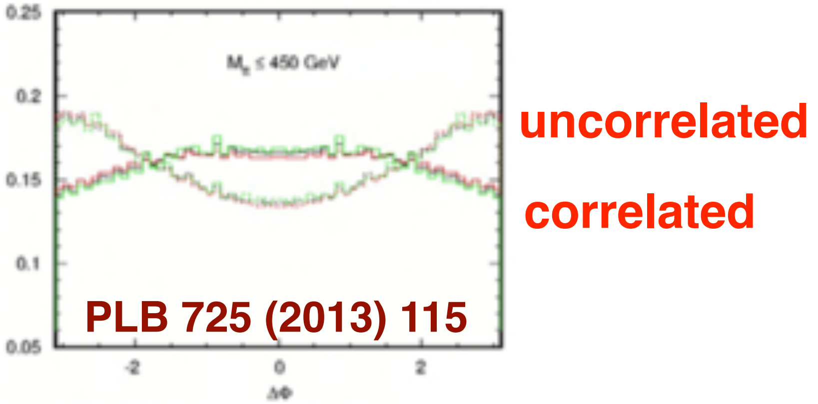
SM prediction: 4 asymmetries ➡ 1 polarization + 3 spin related observables

Polarisation :

$$A_{P\pm} = \frac{N\left(\cos\theta^{\star}_{\ell^\pm} > 0\right) - N\left(\cos\theta^{\star}_{\ell^\pm} < 0\right)}{N\left(\cos\theta^{\star}_{\ell^\pm} > 0\right) + N\left(\cos\theta^{\star}_{\ell^\pm} < 0\right)}$$

Correlated tt spins:

$$A_{\Delta\phi} = \frac{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) - N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}{N(|\Delta\phi_{\ell^+\ell^-}| > \pi/2) + N(|\Delta\phi_{\ell^+\ell^-}| < \pi/2)}$$



C_{hel}:

$$A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)}$$

D:

$$A_{\cos\varphi} = \frac{N\left(\cos\varphi > 0\right) - N\left(\cos\varphi < 0\right)}{N\left(\cos\varphi > 0\right) + N\left(\cos\varphi < 0\right)}$$

Spin correlations and top polarisation

tt, dilepton

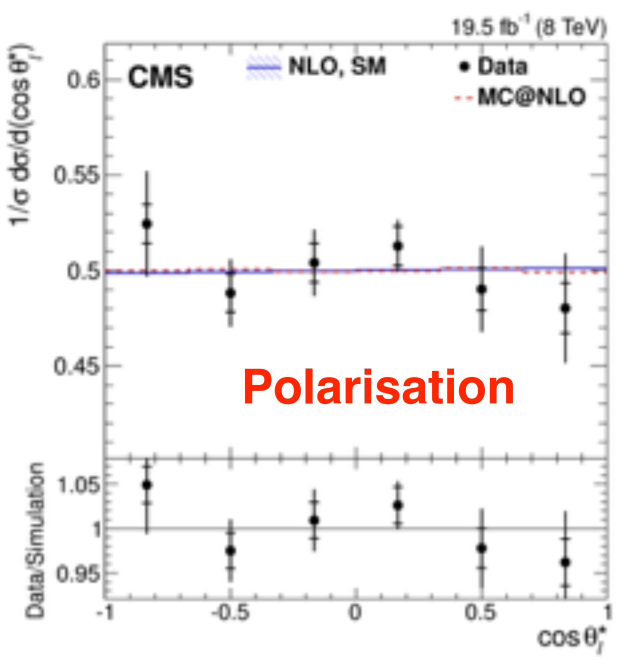
CMS Collaboration: PRD 93 (2016) 052007

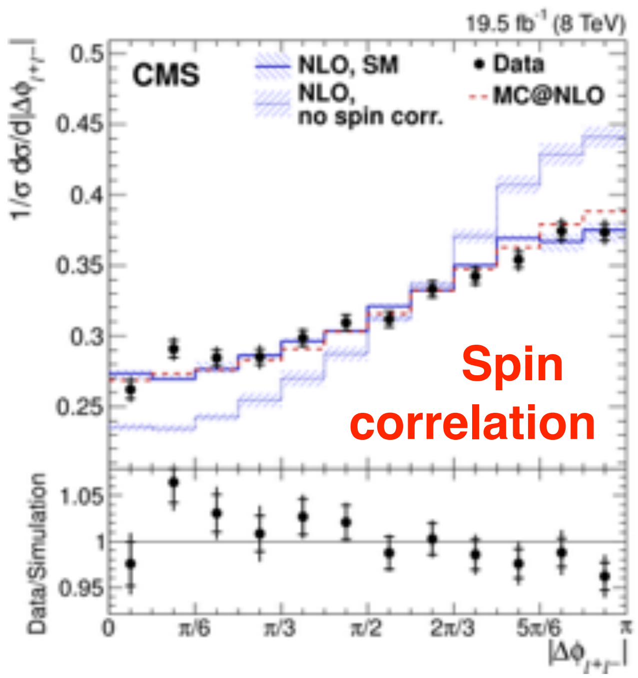
Asymmetry variable	Data (unfolded)	MC@NLO simulation	NLO, SM	NLO, no spin corr.
$A_{\Delta\phi}$	$0.094 \pm 0.005 \pm 0.012$	0.113 ± 0.001	$0.107\,^{+0.006}_{-0.009}$	$0.202\,^{+0.006}_{-0.009}$
$A_{\cos\varphi}$	$0.102 \pm 0.010 \pm 0.012$	0.114 ± 0.001	0.114 ± 0.006	0
$A_{c_1c_2}$	$-0.069 \pm 0.013 \pm 0.016$	-0.081 ± 0.001	-0.080 ± 0.004	0
A_P	$-0.011 \pm 0.007 \pm 0.028$	0	0.002 ± 0.001	—
A_P^{CPV}	$0.000 \pm 0.006 \pm 0.005$	0	0	—

Sizeable spin correlations

Top polarisation ~0

Angular observables:
data to predictions comparison





Measurements in agreement with the SM predictions

tt, l+jets arXiv:1612.02577
PRD 93 (2016) 052007

W boson polarisation

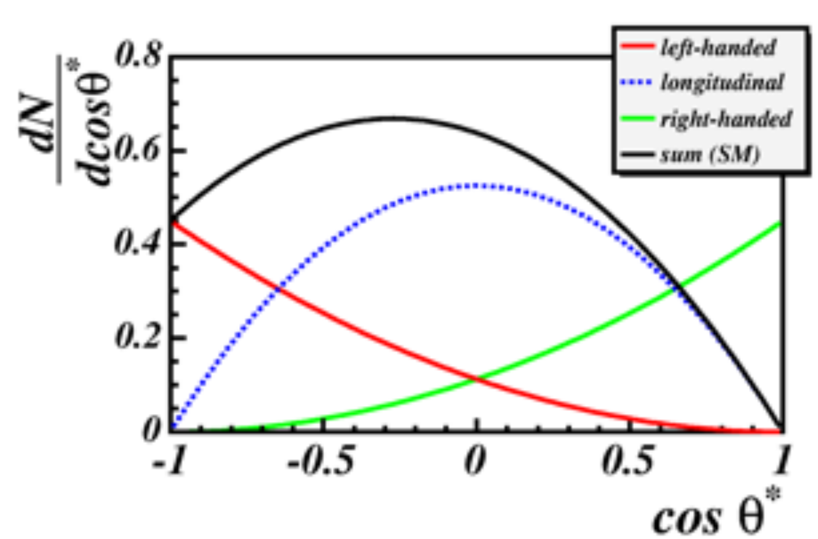
Angular observable: θ*

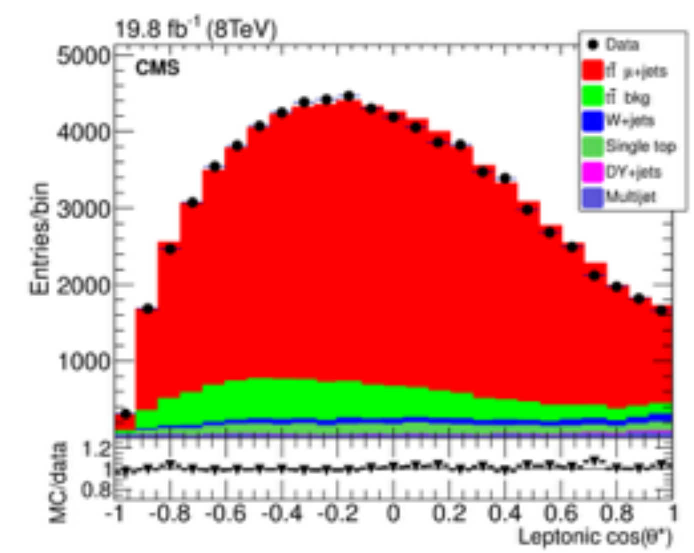
angle between the down-type fermion from W decay (in top rest frame) and the reverse direction b quark from top decay (in W rest frame)

SM prediction:

$F_0 \sim 0.7$ $F_L \sim 0.3$ $F_R \sim 0$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}(1-\cos\theta^*)^2\, F_L + \frac{3}{8}(1+\cos\theta^*)^2\, F_R$$





tt, l+jets

arXiv:1612.02577
PRD 93 (2016) 052007

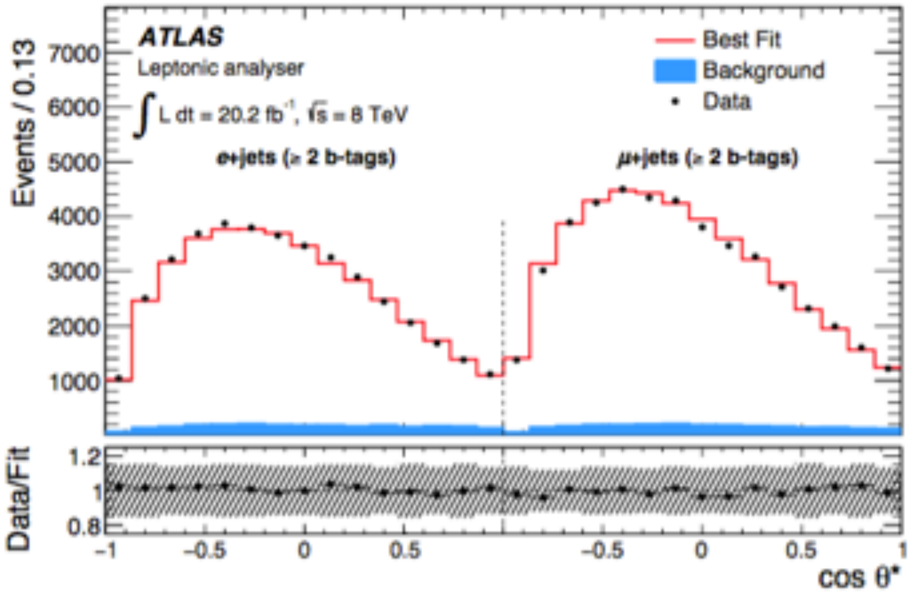
W boson polarisation

ATLAS

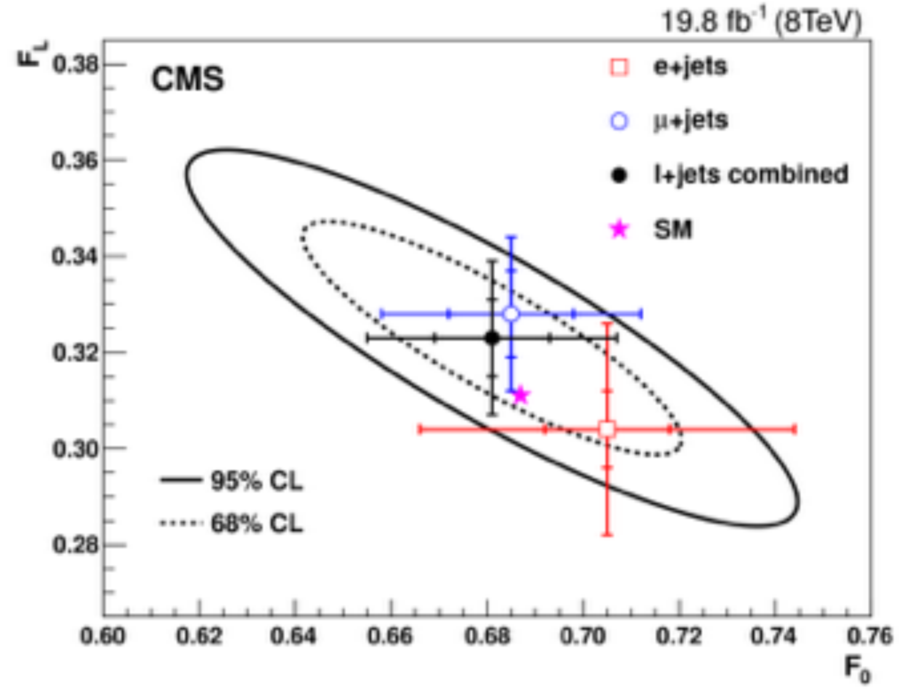
Leptonic analyser (≥2 b-tags)
$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) $^{+0.015}_{-0.014}$ (syst.)
$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) $^{+0.013}_{-0.012}$ (syst.)
$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ± 0.012 (syst.)

Results for hadronic decay also available

cos θ*: data to predictions comparison



CMS



$F_0+F_L+F_R=1$ ➡ measured fractions are correlated

Measurements in agreement with the SM predictions

Top properties:

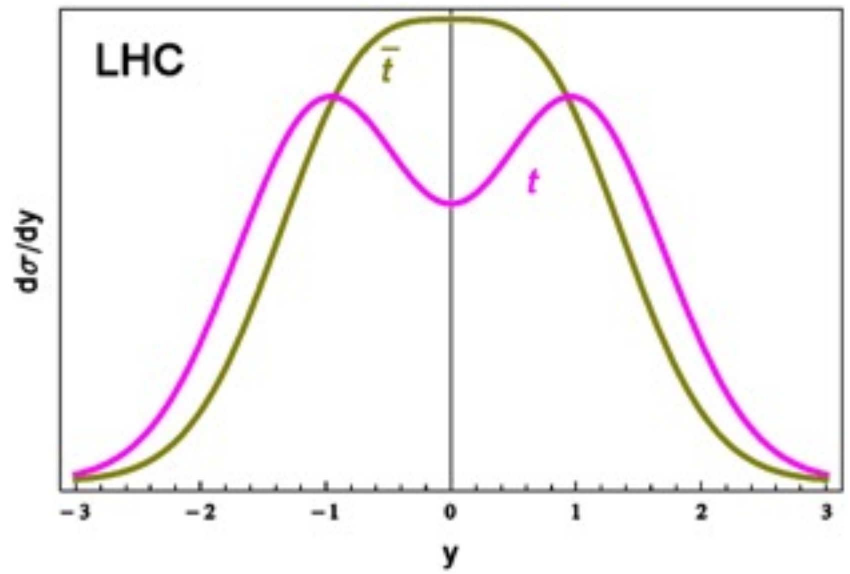
Charge asymmetry and mass measurements

Charge asymmetry

tt, dilepton PRD 94 (2016) 032006
PLB 760 (2016) 365

tt, l+jets EPJC 76 (2016) 87
PRD 93 (2016) 034014

Charge asymmetry in pp collisions: mild effect (qq diagrams)



top quark rapidity distribution slightly broader than anti-top

Asymmetries observables:

event count according to top quark charge and rapidity

$\Delta|y| = |y_{top,\ lepton+}| - |y_{antitop,\ lepton-}|$

N^+ ➨ $\Delta|y|>0$
N^- ➨ $\Delta|y|<0$

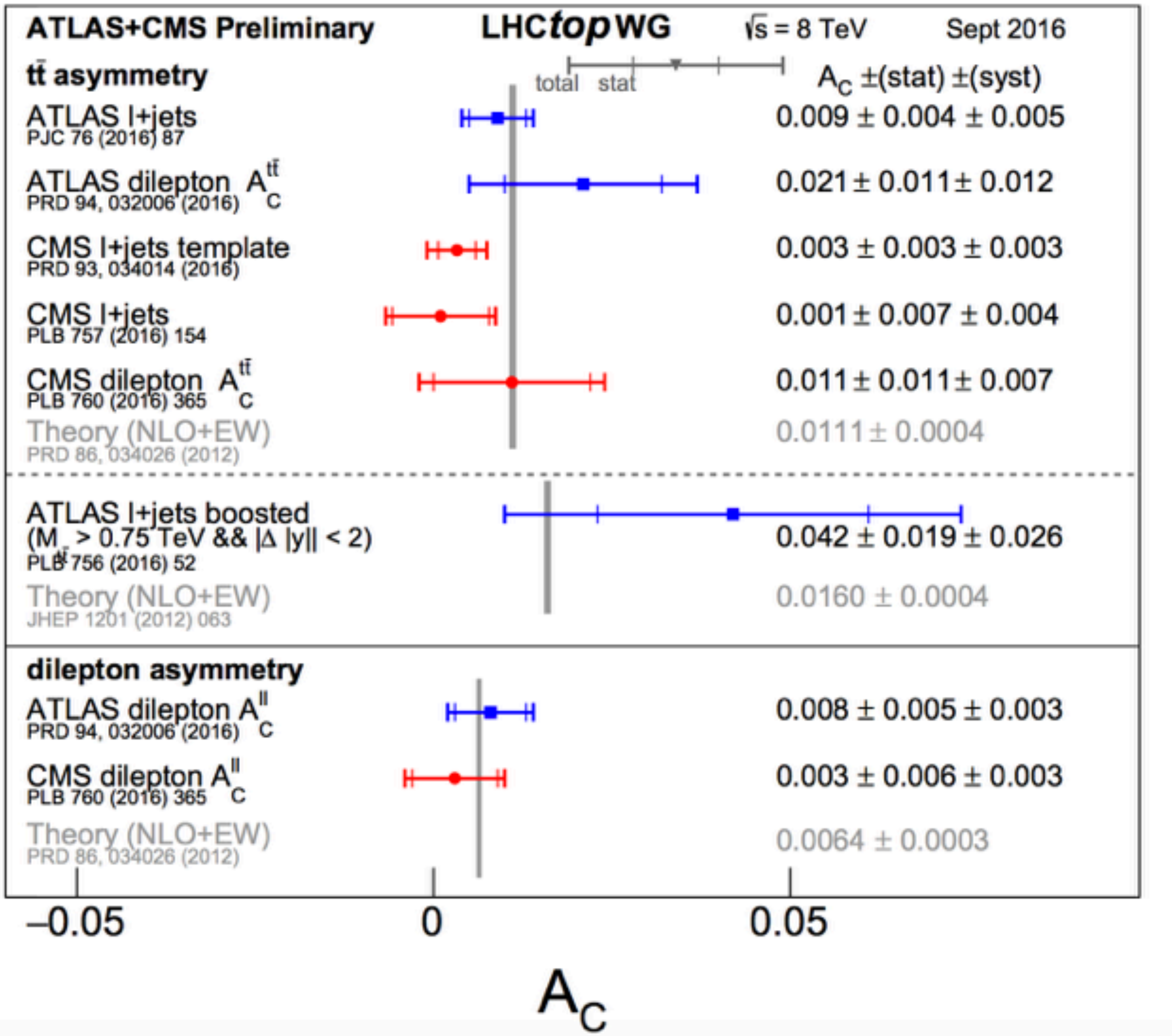
$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

— top charge asymmetry — **requires top reconstruction**
— in dilepton channel only : lepton charge asymmetry — **direct measurement**
— also as functions of top kinematics variables

Charge asymmetry

tt, dilepton PRD 94 (2016) 032006
PLB 760 (2016) 365

tt, l+jets EPJC 76 (2016) 87
PRD 93 (2016) 034014



Measurements in agreement with the SM predictions

tt, dilepton TOP-16-001

CP violation

Commonly studied in strange and bottom quark sectors, now: also top sector!

CMS

Observables:

formed from products $v_1 \cdot (v_2 \times v_3)$ **spin/p vectors of top decay products**

— odd under T transformations

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$
$$O_3 = Q_\ell \, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{b\bar{b}\,\text{CM}} \propto Q_\ell \, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$
$$O_4 = Q_\ell \, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell \, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$
$$O_7 = q \cdot (p_b - p_{\bar{b}}) \, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{\text{lab}} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z.$$

— if CPT is valid: also under CP !

$$A_{CP}(O_i) = \frac{N_{\text{events}}(O_i > 0) - N_{\text{events}}(O_i < 0)}{N_{\text{events}}(O_i > 0) + N_{\text{events}}(O_i < 0)}$$

~ 0 for SM

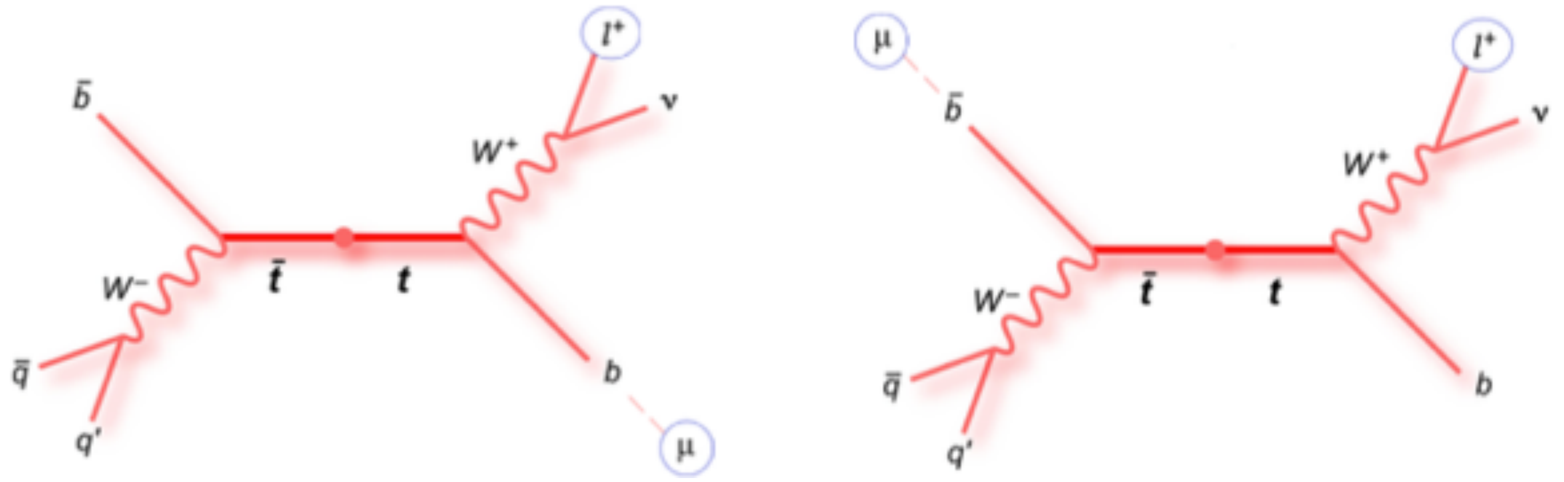
Charge of b quark: kinematic reconstruction of top system constrains: m_t and m_W : ~60% correct assignments

CP violation

tt, dilepton JHEP 02 (2017) 071
TOP-16-001

ATLAS

Charge of b quark: soft muon from b-decay



Observables: sign (charge) relations soft/isolated μ

$$A^{\mathrm{ss}} = r_b A^{b\ell}_{\mathrm{mix}} + r_c \left(A^{bc}_{\mathrm{dir}} - A^{c\ell}_{\mathrm{dir}}\right) + r_{c\bar{c}} \left(A^{bc}_{\mathrm{mix}} - A^{c\ell}_{\mathrm{dir}}\right)$$

$$A^{\mathrm{os}} = \widetilde{r}_b A^{b\ell}_{\mathrm{dir}} + \widetilde{r}_c \left(A^{bc}_{\mathrm{mix}} + A^{c\ell}_{\mathrm{dir}}\right) + \widetilde{r}_{c\bar{c}} A^{c\ell}_{\mathrm{dir}}$$

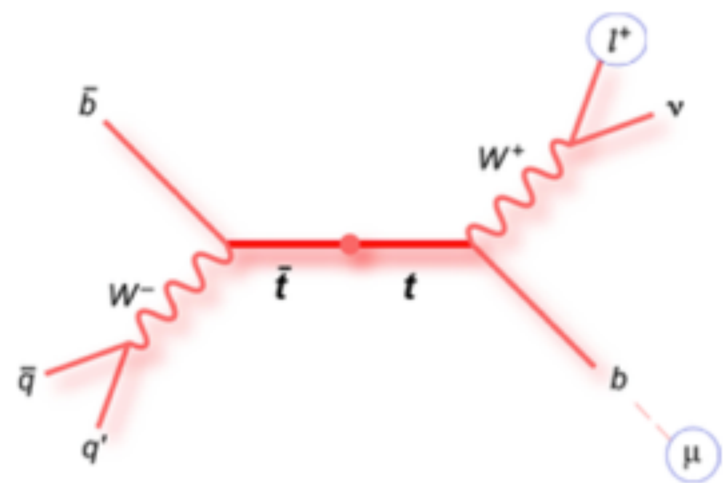
tt, dilepton JHEP 02 (2017) 071
TOP-16-001

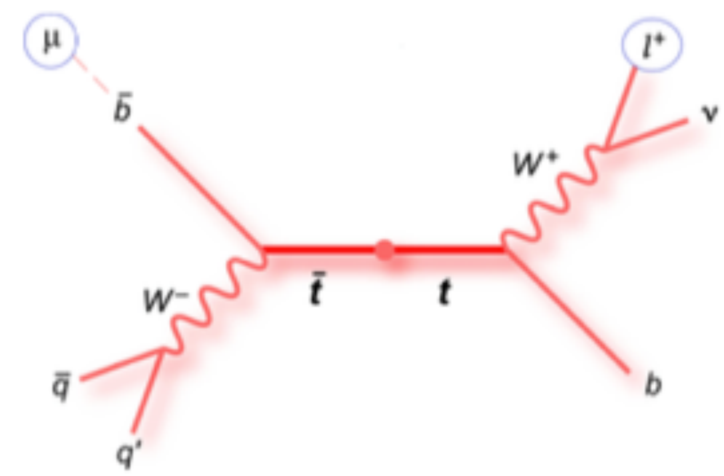
CP violation

Commonly studied in strange and bottom quark sectors, now: also top sector!

ATLAS

Charge of b quark: soft muon from b-decay





Observables: sign (charge) relations soft/isolated μ

$$A^{ss} = r_b A^{b\ell}_{\rm mix} + r_c\left(A^{bc}_{\rm dir} - A^{c\ell}_{\rm dir}\right) + r_{c\bar{c}}\left(A^{bc}_{\rm mix} - A^{c\ell}_{\rm dir}\right)$$

$$A^{os} = \widetilde{r}_b A^{b\ell}_{\rm dir} + \widetilde{r}_c\left(A^{bc}_{\rm mix} + A^{c\ell}_{\rm dir}\right) + \widetilde{r}_{c\bar{c}} A^{c\ell}_{\rm dir}$$

related to
b ➡ $\bar{b}$, b ➡ c

$$A^{b\ell}_{\rm mix} = \frac{\Gamma\left(b\to\bar{b}\to\ell^+X\right) - \Gamma\left(\bar{b}\to b\to\ell^-X\right)}{\Gamma\left(b\to\bar{b}\to\ell^+X\right) + \Gamma\left(\bar{b}\to b\to\ell^-X\right)},$$

$$A^{bc}_{\rm mix} = \frac{\Gamma\left(b\to\bar{b}\to\bar{c}X\right) - \Gamma\left(\bar{b}\to b\to cX\right)}{\Gamma\left(b\to\bar{b}\to\bar{c}X\right) + \Gamma\left(\bar{b}\to b\to cX\right)},$$

$$A^{b\ell}_{\rm dir} = \frac{\Gamma\left(b\to\ell^-X\right) - \Gamma\left(\bar{b}\to\ell^+X\right)}{\Gamma\left(b\to\ell^-X\right) + \Gamma\left(\bar{b}\to\ell^+X\right)},$$

$$A^{c\ell}_{\rm dir} = \frac{\Gamma\left(\bar{c}\to\ell^-X_L\right) - \Gamma\left(c\to\ell^+X_L\right)}{\Gamma\left(\bar{c}\to\ell^-X_L\right) + \Gamma\left(c\to\ell^+X_L\right)},$$

$$A^{bc}_{\rm dir} = \frac{\Gamma\left(b\to cX_L\right) - \Gamma\left(\bar{b}\to\bar{c}X_L\right)}{\Gamma\left(b\to cX_L\right) + \Gamma\left(\bar{b}\to\bar{c}X_L\right)},$$

SM : all asymmetries ~0

tt, dilepton JHEP 02 (2017) 071
TOP-16-001

CP violation

ATLAS

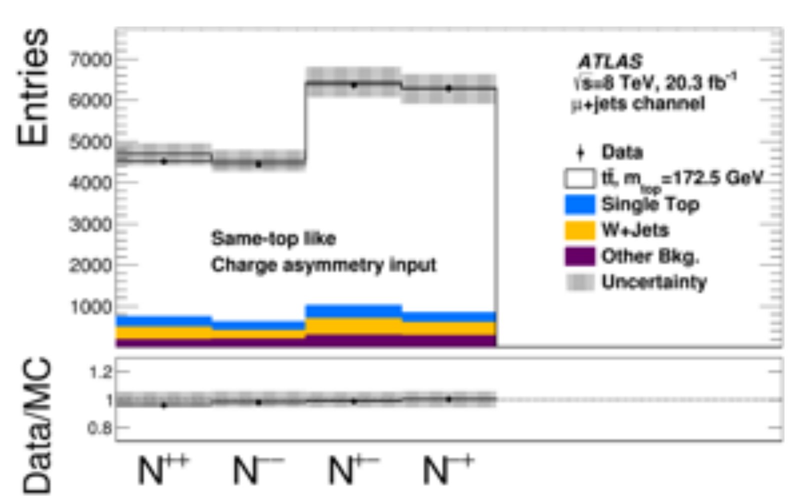
	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	± 0.8	0.05	± 0.23	-		$< 10^{-2}$	[19]
A^{os}	0.4	± 0.5	-0.03	± 0.13	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	± 2.8	0.2	± 0.7	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{dir}$	0.5	± 0.5	-0.03	± 0.14	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{dir}$	1.0	± 1.0	-0.06	± 0.25	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	± 1.1	0.07	± 0.29	-		$< 10^{-7}$	[97]

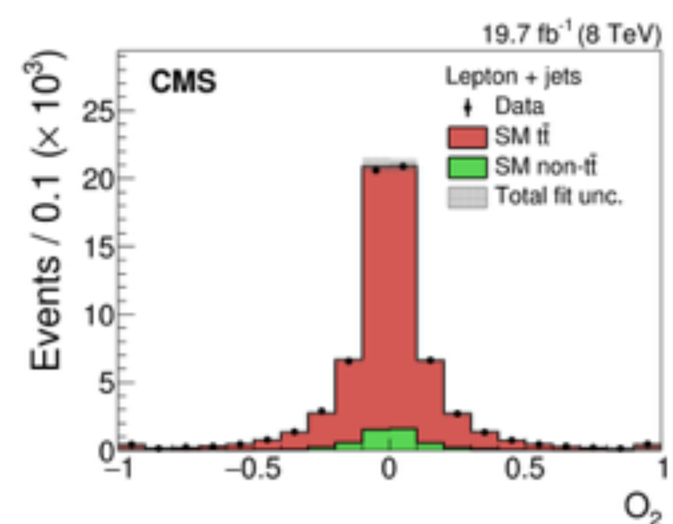
CMS

	A'_{CP} (%) e + jets	A'_{CP} (%) μ + jets	A'_{CP} (%) ℓ + jets	A_{CP} (%) ℓ + jets
O_2	$-0.19 \pm 0.61 \pm 0.59$	$+0.46 \pm 0.57 \pm 0.65$	$+0.16 \pm 0.42 \pm 0.44$	$+0.3 \pm 1.1$
O_3	$+0.02 \pm 0.61 \pm 0.59$	$-0.59 \pm 0.57 \pm 0.65$	$-0.31 \pm 0.42 \pm 0.44$	-0.8 ± 1.6
O_4	$-0.17 \pm 0.61 \pm 0.59$	$-0.10 \pm 0.57 \pm 0.65$	$-0.13 \pm 0.42 \pm 0.44$	-0.4 ± 1.7
O_7	$-0.38 \pm 0.61 \pm 0.59$	$+0.43 \pm 0.57 \pm 0.65$	$+0.06 \pm 0.42 \pm 0.44$	$+0.1 \pm 0.8$

All asymmetries ~0

CP violation observables: data to predictions comparison





13 TeV data

tt, and tW dilepton   CMS Collaboration: TOP-16-019

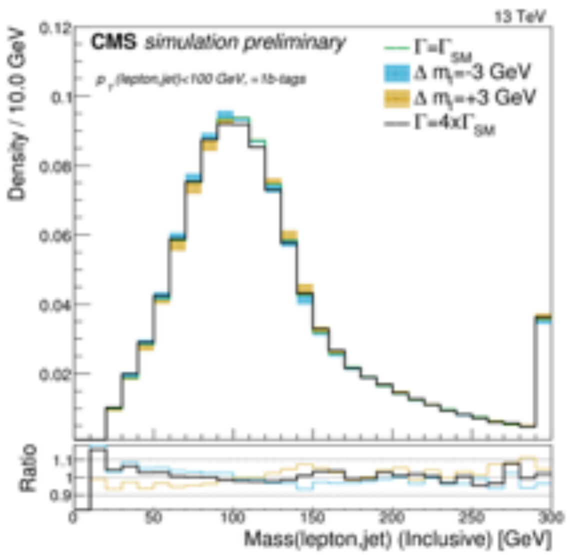
Top quark width

Important property → 1/lifetime

Sensitive distribution: invariant mass (lepton,b)

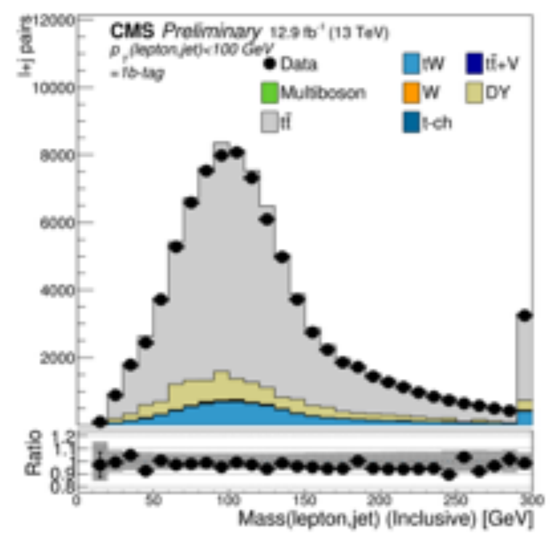
(which for lepton,b correctly matched to parent top drops at $M_{lb} = \sqrt{(m_t^2 - m_W^2)}$)

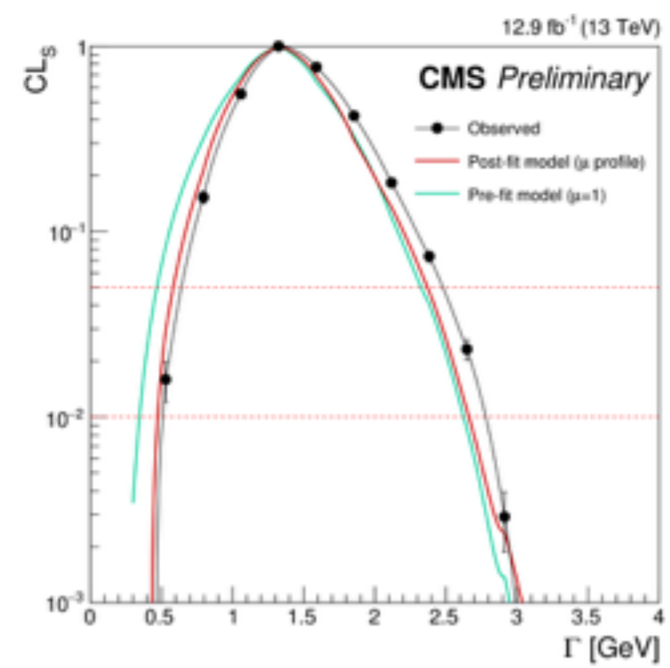
Hypotheses tested: Γ_{SM} and wide top with 4x Γ_{SM}



Compare data to templates with

Γ_{SM} vs. 4x Γ_{SM}





0.6<Γ<2.5 at 95%CL

(expected: 0.6<Γ<2.4 GeV for m_t = 172.5 GeV)

Top properties:

Production and decay (couplings)

tt, single top, several final states

arXiv:1509.00294,JHEP02(2017)079,1702.01404

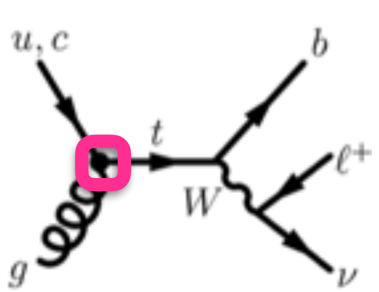
Flavour Changing Neutral Current

Tiny expected signals against (overwhelming) SM backgrounds

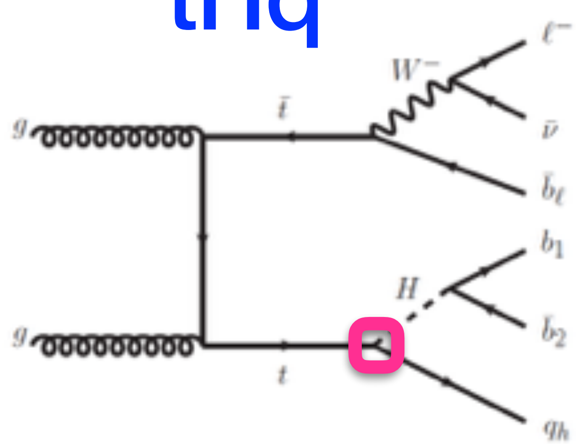
— Signal may be large in BSM models!
— Include more final states (e.g. several decay modes of Higgs)
— Signal / background separation : multivariate techniques (Neural Networks, Boosted Decision Trees)

Final states:

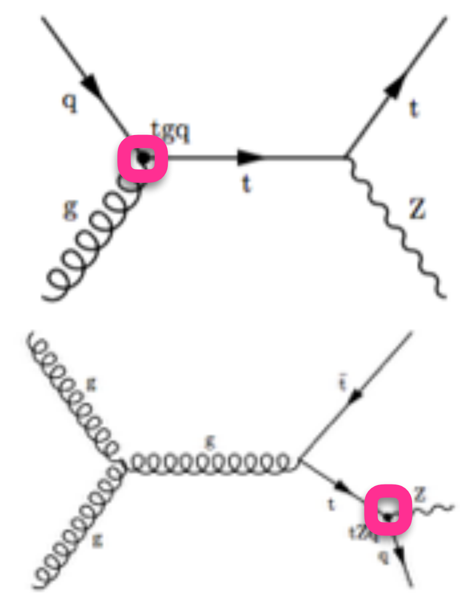
Wb



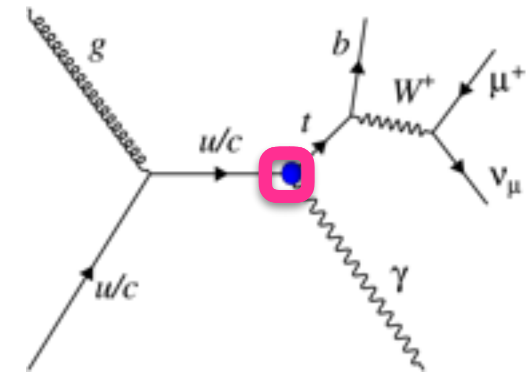
tHq



tZ



tγ



Couplings:

t→ug
t→cg

t→Hc
t→Hu

t→ug, t→cg
t→uZ, t→cZ

t→uγ
t→cγ

ATLAS

$\sigma_{qg \to t} \times B(t \to Wb) < 3.4\text{pb}$

$\sigma_{qg \to t} \times B(t \to W\,b) < 2.9\text{pb}$

ATLAS

$B(t \to Hc) < 0.40\%$

$B(t \to Hu) < 0.55\%$

CMS

$B(t \to Zu) < 0.022\%$

$B(t \to Zc) < 0.049\%$

CMS

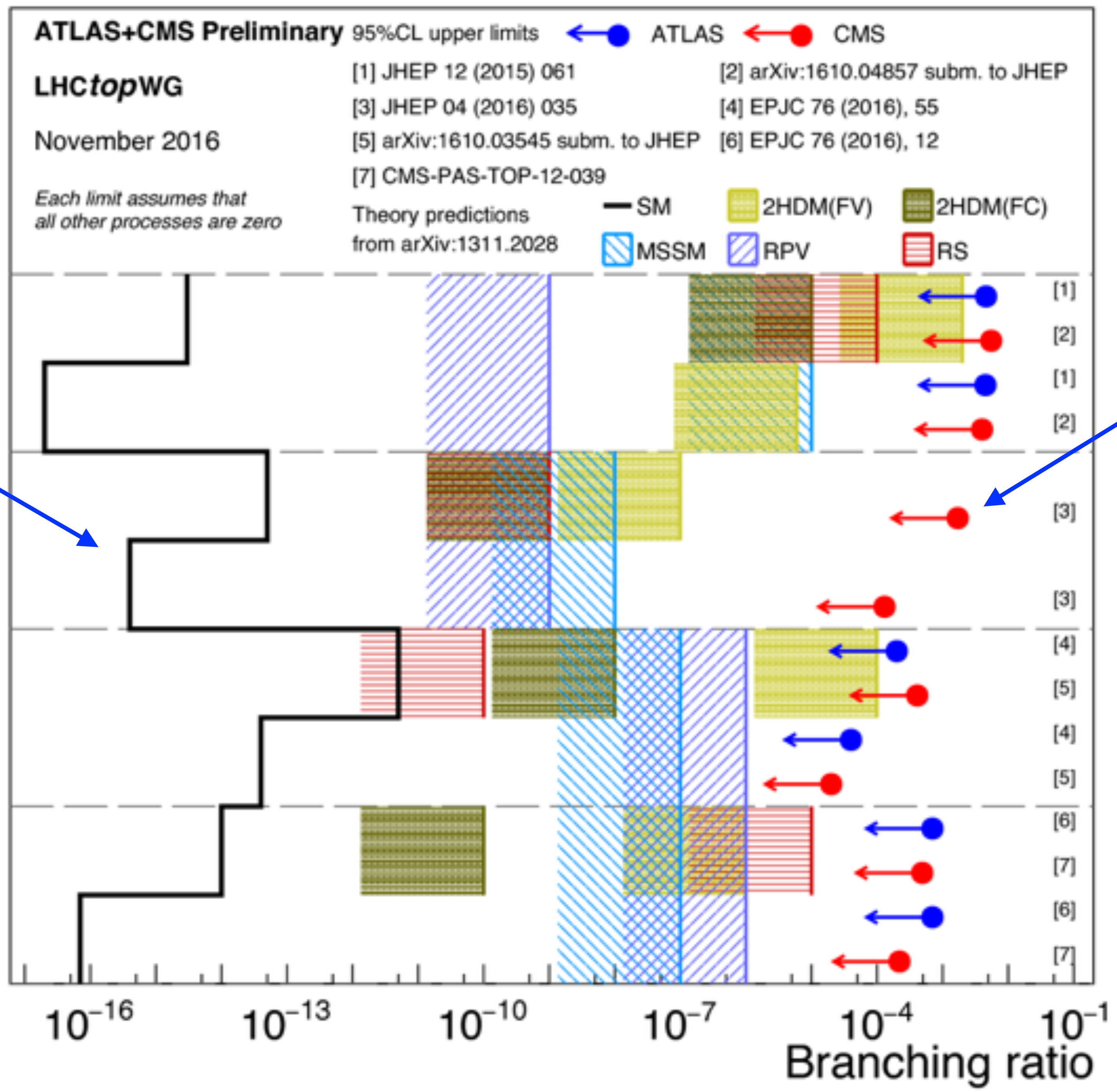
$B(t \to u\gamma) < 0.022\%$

$B(t \to c\gamma) < 0.049\%$

Flavour Changing Neutral Current

SM prediction

Upper limits



Top properties:

Beyond direct searches: limits on new physics from top properties measurements

Re-interpreting the measurements

All measurements present remarkable agreement with SM

Direct/derived constrains to new physics. Examples:

Spin correlation & polarisation angles:

Effective Lagrangian for anomalous ttg interaction :

$$\mathcal{L}_{\mathrm{eff}} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu},$$

$$\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{SM}} + \mathrm{Re}(\hat{\mu}_t)\left(\frac{1}{\sigma}\frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{NP}}$$

Likewise, polarisation asymmetry relates to d_t

$$-0.053 < \mathrm{Re}(\hat{\mu}_t) < 0.026$$

$$-0.068 < \mathrm{Im}(\hat{d}_t) < 0.067$$

at 95% CL

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$-0.068 < {\rm Im}(\hat{d}_t) < 0.067$

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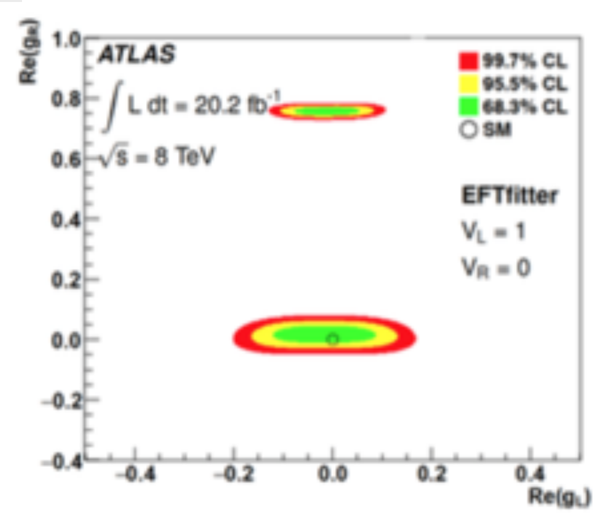
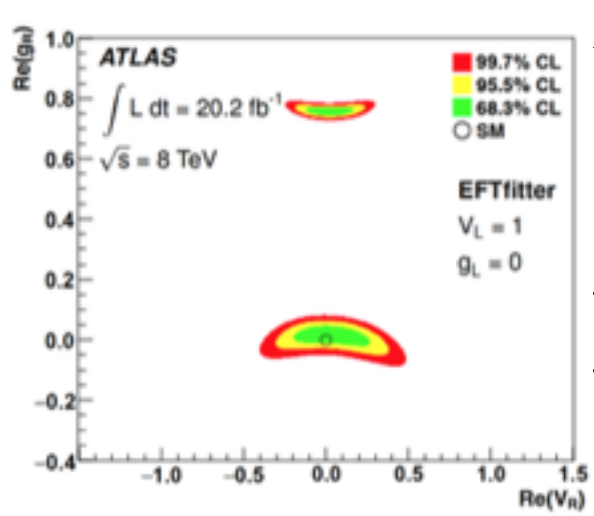
Likewise, polarisation asymmetry relates to $\hat{d}_t$

W helicity fractions:

Generalised Wtb vertex Lagrangian:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)\,t\,W^-_\mu + {\rm H.c.}$$





V's and g's : couplings directly related to helicity fractions

Re-interpreting the measurements

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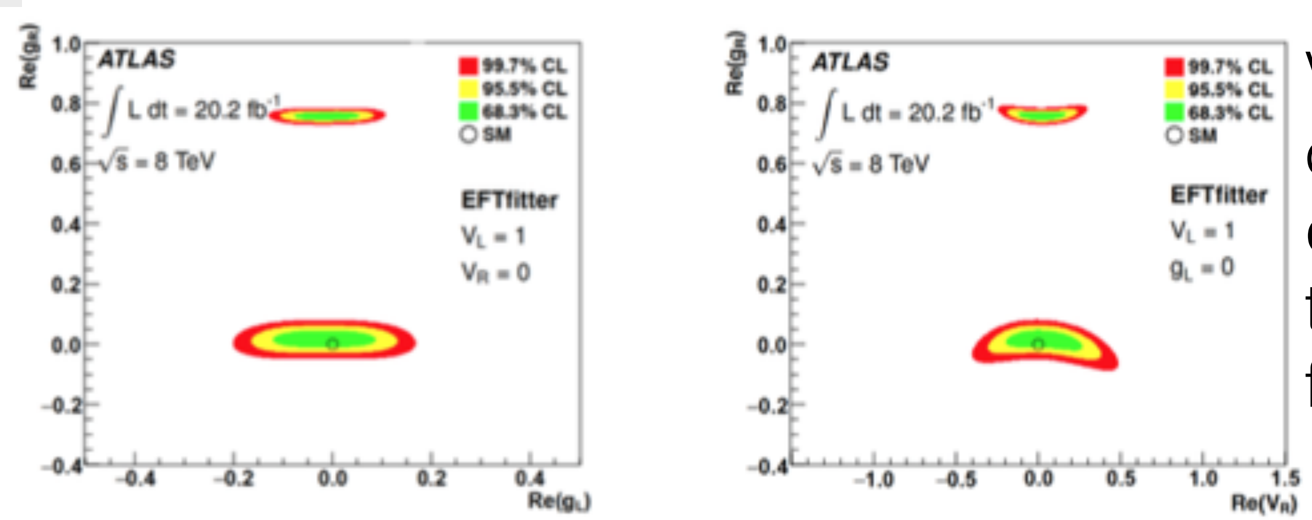
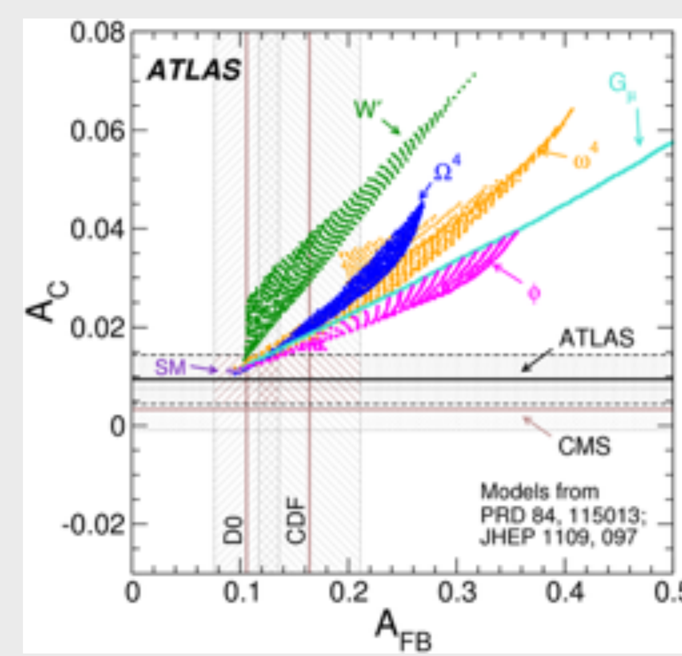


V's and g's : couplings directly related to helicity fractions

Charge asymmetry:

Comparison with BSM models



Top properties:

Conclusions

Conclusions

Latest LHC measurements in top quark properties, mostly at 8 TeV, were presented

Several aspects of top production scrutinised

angular distributions, charge asymmetries, production and decay

8 TeV measurements confirm SM predictions

no signs in direct searches, limits on new physics using EFT

Large datasets, several measurements already limited by systematic uncertainties

New data at 13 TeV being analysed

Now, focus in improving analyses techniques and beating systematic uncertainties

Top properties:

Backup slides

Typical uncertainties

Dominant for ATLAS
Dominant for CMS

Experimental

Width
WPol

Leptons

— Reconstruction, ID **Width**
— momentum scale, resolutions

Jets

— Reconstruction, ID **Width**
— momentum scale, resolutions **Pol, SpinCorr** **WPol**
— b-tagging/mistag **CP, WPol**

Data taking

— pileup
— luminosity, etc **Width**

Background determination

WPol

— shape and normalizations
— modelling (MC)
— data-driven methods

Theory (modelling)

ChAsym, Pol, SpinCorr, CP, WPol

MC generation

— Generator choice
— hadronization model **Pol**
— underlying event
— inputs to theory:
  — Q^2 scales, PDF, top mass, etc
— potential mis-modelling of top dynamics (e.g. top p_T distribution) **SpinCorr**

Analysis-dependent

— unfolding procedure, etc

Statistical

ChAsym **ChAsym, Pol, SpinCorr**

— data integrated luminosty
— limited amount of Monte Carlo

FCNC: typical BDT/NN variables and uncertainties

Example: bjet+single lepton final state

- the invariant masses m_{Hq} and m_{Hb} of the reconstructed top quarks,
- the energy of the u or c jet from the $\mathrm{t} \to \mathrm{qH}$ in the rest frame of its parent top quark,
- the azimuthal angle between the reconstructed top quarks directions,
- the azimuthal angle between the reconstructed W boson and the associated b jet directions,
- the azimuthal angle between the Higgs boson and the associated jet directions,
- the azimuthal angle between the directions of the b jets resulting from the Higgs boson decay.

Channel	SS dilepton	Trilepton	$\gamma\gamma$ hadronic	$\gamma\gamma$ leptonic	b jet + lepton
Integrated luminosity	2.6	2.6	2.6	2.6	2.6
Pileup	1.0	1.0	0.3	0.8	0.2–3.0
Higgs boson branching fraction	5.0	5.0	5.0	5.0	5.0
$\mathrm{t\bar{t}}$ cross section	7.5	7.5	7.5	7.5	7.5
Jet energy scale	0.5	0.6	1.2	1.0	5.2–15
Jet energy resolution	0.8	2.2	2.7	0.4	2.2–7.8
Signal PDF	6.0	6.0	5.9	5.2	<1–9.0
Top quark p_{T} correction	—	—	1.4	3.2	0.8–4.3
$E_{\mathrm{T}}^{\mathrm{miss}}$	4.0	4.0	—	—	0.2–2.5
Trigger efficiency	1.0–2.0	—	1.0	1.0	<0.1–0.4
Identification and isolation					
- muon	1.0–2.0	1.0–3.0	—	0.3	0.01–0.04
- electron	2.0–4.0	2.0–6.0	—	0.3	<0.1–0.2
$\mathrm{t\bar{t}W}$ normalization	11.0	11.0	—	—	—
$\mathrm{t\bar{t}Z}$ normalization	13.0	13.0	—	—	—
WZ normalization	15.0	15.0	—	—	—
Lepton misidentification					
- electron	40.0	40.0	—	—	—
- muon	30.0	30.0	—	—	—
Charge misidentification	20.0	—	—	—	—
Photon identification efficiency	—	—	5.2	5.2	—
Corrections per photon					
- energy scale	—	—	0.1	0.1	—
- energy resolution	—	—	0.1	0.1	—
- material mismodeling	—	—	0.3	0.3	—
- nonlinearity	—	—	0.1	0.1	—
Jet identification efficiency	—	—	2.0	2.0	—
b jet identification efficiency	—	—	2.9	3.5	—
Higgs boson background					
- cross section scale factors	—	—	9.3	9.3	—
- PDF	—	—	8.1	8.1	—
b jet CSV distribution					
- purity	—	—	—	—	1.0–3.4
- statistical precision	—	—	—	—	1.0–24
$\mathrm{t\bar{t}}$ + heavy flavor jets	—	—	—	—	0.3–1.0
Modeling W decay daughters	—	—	—	—	1.6–2.7
Generator parameters					
- QCD scale	—	—	—	—	1.0–4.9
- matching parton-jet threshold	—	—	—	—	1.3–9.4
- top quark mass	—	—	—	—	0.8–4.1

Uncertainties in %

CP violation in tt (CMS)

Optimal variables (example)

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$$\mathcal{O}_2 \xrightarrow{lab} \sqrt{S}\left[(\vec{p}_b+\vec{p}_{\bar{b}})\cdot\left((\vec{p}_{\mu^+}\times\vec{p}_{j1})+(\vec{p}_{\mu^-}\times\vec{p}_{\bar{j}1})\right)\right]$$
$$\xrightarrow{CP} (-)\sqrt{S}\left[(\vec{p}_b+\vec{p}_{\bar{b}})\cdot\left((\vec{p}_{\mu^-}\times\vec{p}_{\bar{j}1})+(\vec{p}_{\mu^+}\times\vec{p}_{j1})\right)\right]$$

j1 —> hardest jet from W decay

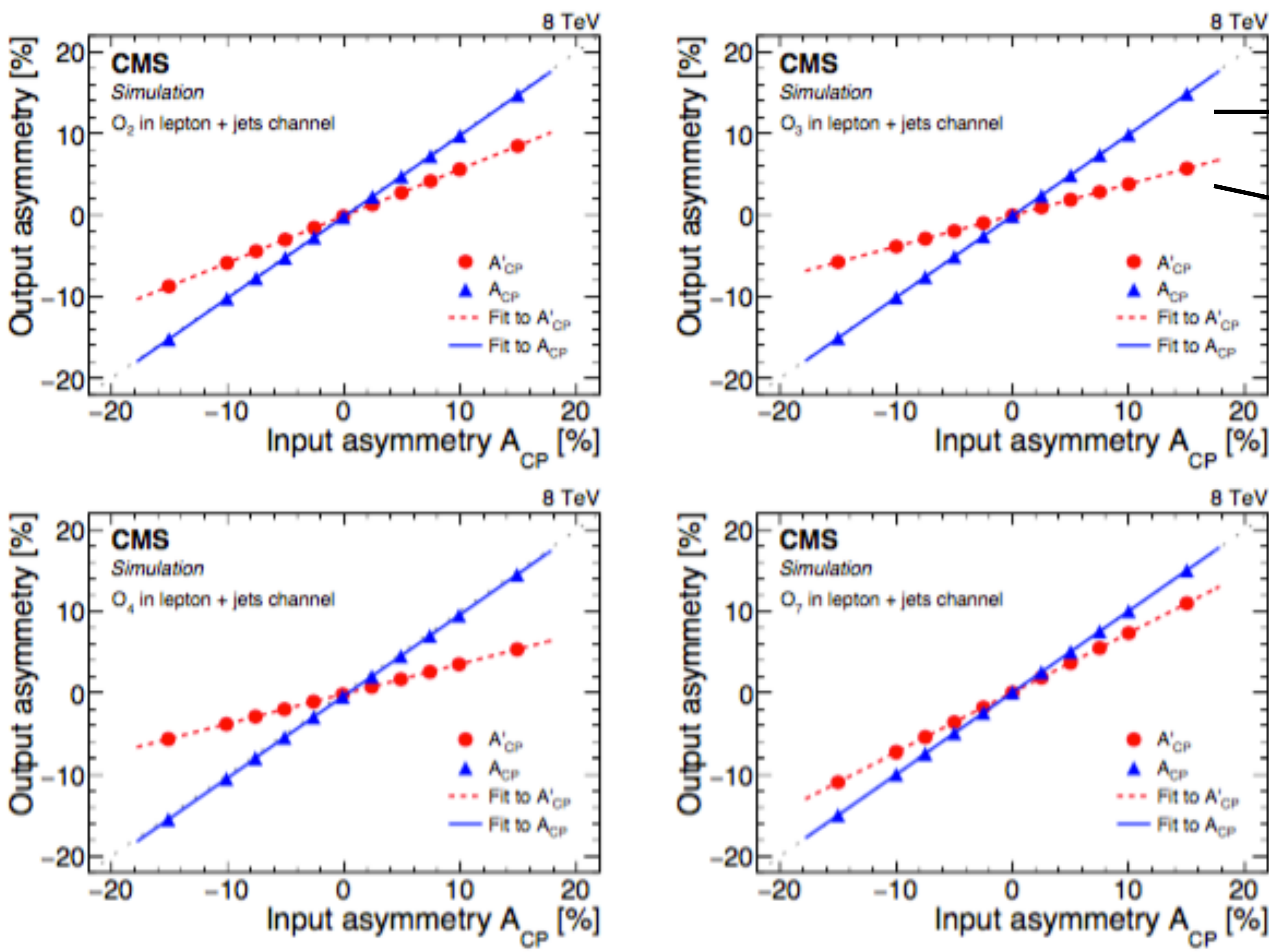
** observable doesn't depend on b quark charge **

If CP is conserved, $\boxed{\vec{p}_{\bar{j}1} \xrightarrow{CP} -\vec{p}_{j1}}$ that is

Probability of a jet (q) from a $W^+ \rightarrow$ j1j2 to be the hardest
= Probability of a jet (qbar) from a $W^- \rightarrow$ j1j2 to be the hardest

CP violation in tt   (CMS)

Systematic uncertainties



corrected by detector effects

uncorrected by detector effects

Detector/reconstruction may induce fake asymmetries

"Dilution factor" estimated from control sample :

- estimated in side bands (no b-tag)
- dominant syst uncertainty: statistical uncertainty on the side band

"Dilution factor" may make up real asymmetries

- measure both A_{CP} and A'_{CP}

CP violation in b (ATLAS)

Optimal variables in detail:

In terms of probabilities:

$$A^{ss} = \frac{P(b \to \ell^+) - P(\bar{b} \to \ell^-)}{P(b \to \ell^+) + P(\bar{b} \to \ell^-)}, \qquad A^{os} = \frac{P(b \to \ell^-) - P(\bar{b} \to \ell^+)}{P(b \to \ell^-) + P(\bar{b} \to \ell^+)}$$

In terms of nr of positive/negative lepton charges:

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^+} - \frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+} + \frac{N^{--}}{N^-}\right)}, \qquad A^{os} = \frac{\left(\frac{N^{+-}}{N^+} - \frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+} + \frac{N^{-+}}{N^-}\right)}$$

In terms of CP asymmetries:

$$A^{ss} = r_b A^{b\ell}_{\rm mix} + r_c \left(A^{bc}_{\rm dir} - A^{c\ell}_{\rm dir}\right) + r_{c\bar{c}} \left(A^{bc}_{\rm mix} - A^{c\ell}_{\rm dir}\right)$$
$$A^{os} = \widetilde{r}_b A^{b\ell}_{\rm dir} + \widetilde{r}_c \left(A^{bc}_{\rm mix} + A^{c\ell}_{\rm dir}\right) + \widetilde{r}_{c\bar{c}} A^{c\ell}_{\rm dir}$$

$$r_b = \frac{N_{r_b}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_b = \frac{N_{\widetilde{r}_b}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}},$$
$$r_c = \frac{N_{r_c}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_c = \frac{N_{\widetilde{r}_c}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}},$$
$$r_{c\bar{c}} = \frac{N_{r_{c\bar{c}}}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}}, \qquad \widetilde{r}_{c\bar{c}} = \frac{N_{\widetilde{r}_{c\bar{c}}}}{N_{\widetilde{r}_b} + N_{\widetilde{r}_c} + N_{\widetilde{r}_{c\bar{c}}}}.$$

$$N_{r_b} = N\left[t \to \ell^+\nu\left(b \to \bar{b}\right) \to \ell^+\ell^+X\right],$$
$$N_{r_c} = N\left[t \to \ell^+\nu(b \to c) \to \ell^+\ell^+X\right],$$
$$N_{r_{c\bar{c}}} = N\left[t \to \ell^+\nu\left(b \to \bar{b} \to c\bar{c}\right) \to \ell^+\ell^+X\right],$$
$$N_{\widetilde{r}_b} = N\left[t \to \ell^+\nu b \to \ell^+\ell^-X\right],$$
$$N_{\widetilde{r}_c} = N\left[t \to \ell^+\nu\left(b \to \bar{b} \to \bar{c}\right) \to \ell^+\ell^-X\right],$$
$$N_{\widetilde{r}_{c\bar{c}}} = N\left[t \to \ell^+\nu(b \to c\bar{c}) \to \ell^+\ell^-X\right].$$