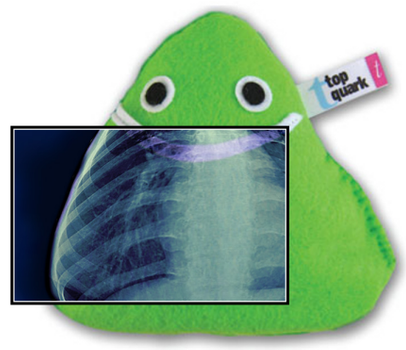
Measurements of the top quark properties in the production and decays of ttbar events at CMS

Deniz Poyraz

on behalf the CMS collaboration

13/04/2016

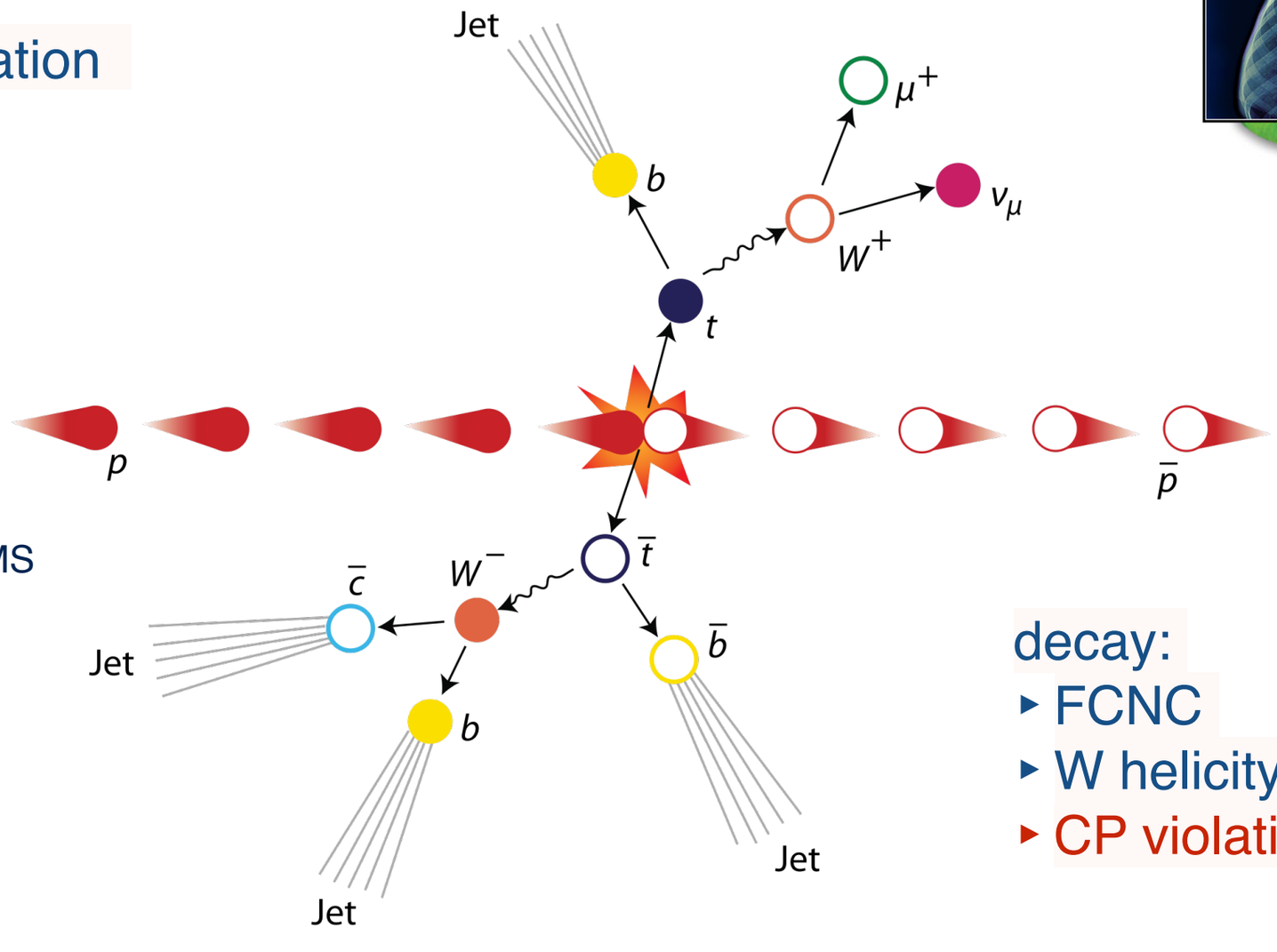
top quark properties



★ decays before hadronisation
" bare quark "

intrinsic:
- mass, charge, width, spin

see talk given by Simon Spannagel:
Top quark mass measurements with CMS



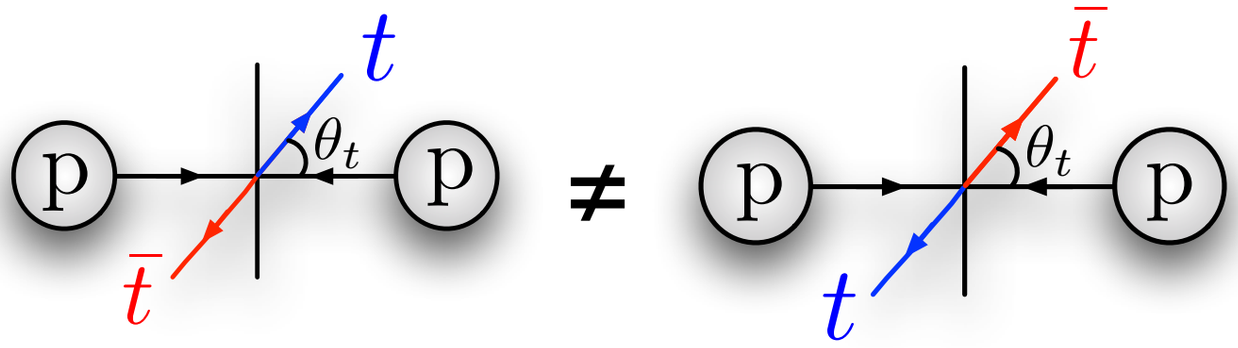
decay:
- FCNC
- W helicity
- CP violation

production:
- charge asymmetry
- spin correlation
- polarization
- ttV

top properties CMS results:
- charge asymmetry
- spin correlations
- CP violation
- ttV

charge asymmetry

SM predicts a charge asymmetry in $t\bar{t}$ production:

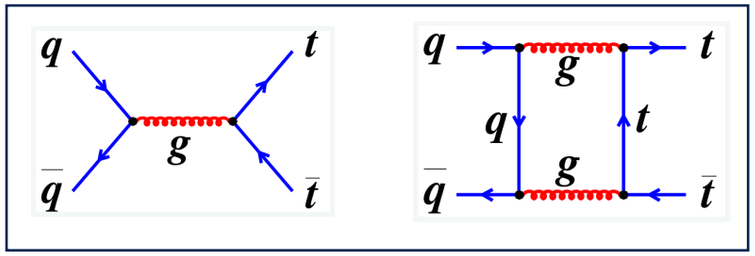


$$\frac{d\sigma_A}{d\cos\theta_t} = \frac{d\sigma_{t\bar{t}}}{d\cos\theta_t} - \frac{d\sigma_{\bar{t}t}}{d\cos\theta_t}$$

Large asymmetry would indicate new physics: additional axial couplings, W'…

- LO no asymmetry
- NLO: interferences of the $q\bar{q}$ diagrams

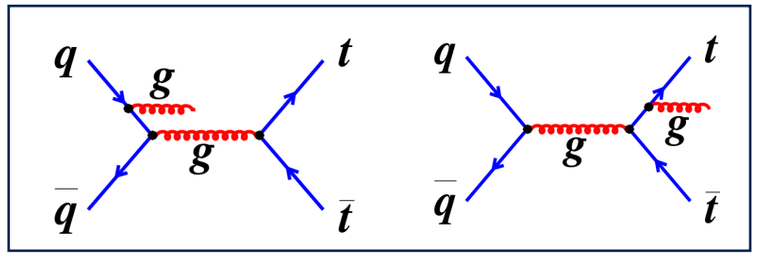
Born and box diagrams



positive asymmetry

ISR/FSR

+

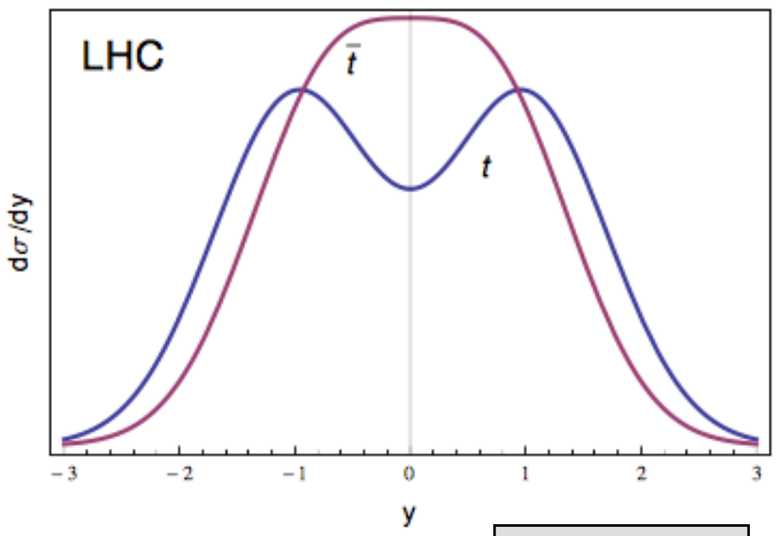


negative asymmetry

- LHC has a symmetric initial state (pp)
- $\bar{q}$ is mostly from sea quarks: q carry more momentum
- tops are more forward than anti-quarks

asymmetry in terms of top rapidity differences:

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



German Rodrigo
arXiv:1207.0331

charge asymmetry

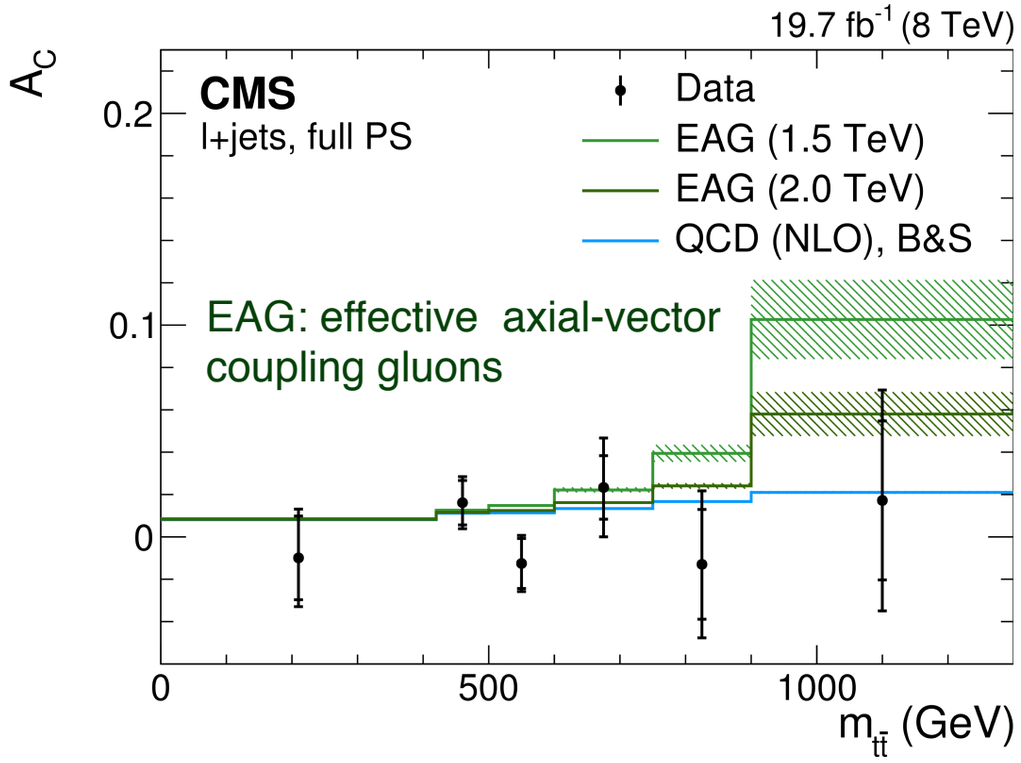
lepton + jets events 8 TeV 19.7 fb^{-1}

arXiv:1507.03119, accepted by PLB

- fully reconstructed $t\bar{t}$ in each event
- differential and inclusive measurements
- data unfolded to parton level

A_C = [0.10 ± 0.68(stat) ± 0.37(syst)]%
NLO [Kuhn, Rodrigo] = [1.02 ± 0.05]%
NLO [Bernreuther,Si] = [1.11 ± 0.04]%

- dominant systematic uncertainties: JES and unfolding



Werner Bernreuther and Zong-Guo Si [Phys. Rev. D 86, 034026]
Johann H. Kühn, Germán Rodrigo [10.1007/JHEP01(2012)063]
E. Gabrielli, M. Raidal, and A. Racioppi [Phys. Rev. D 85, 074021]
Emidio Gabrielli and Martti Raidal [Phys. Rev. D 84, 054017]

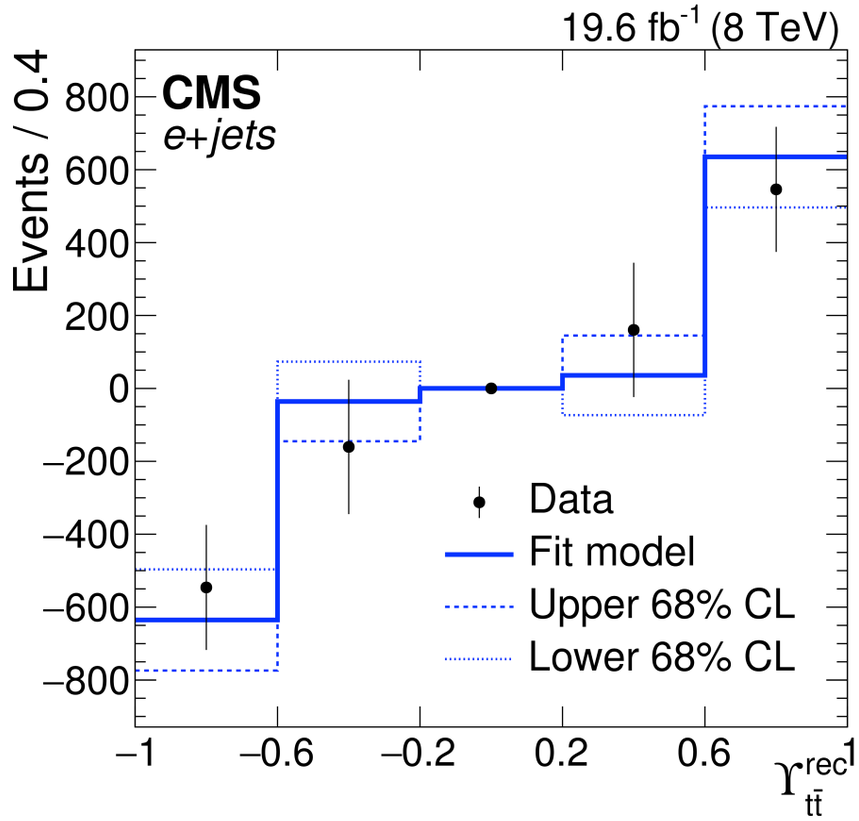
lepton + jets events 8 TeV 19.7 fb^{-1} template measurement

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

- sensitive variable: $Y_{t\bar{t}} = \tanh(\Delta|y|_{t\bar{t}})$
- symmetric and anti-symmetric templates of $Y_{t\bar{t}}$

most precise inclusive measurement

A_C = [0.33 ± 0.26(stat) ± 0.33(syst)]%



- dominant systematic uncertainties:
  Data sideband and simulation stat. unc.,
  JES, renormalization and factorization scales

charge asymmetry

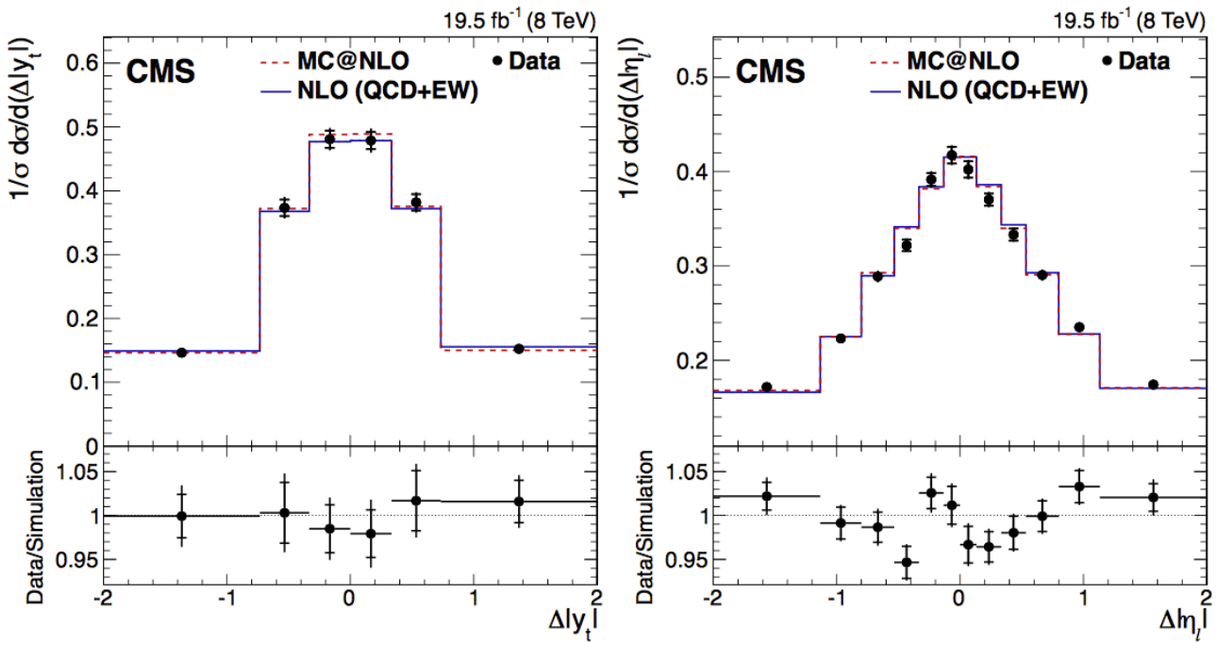
dilepton + jets events 8 TeV 19.7 fb^{-1}

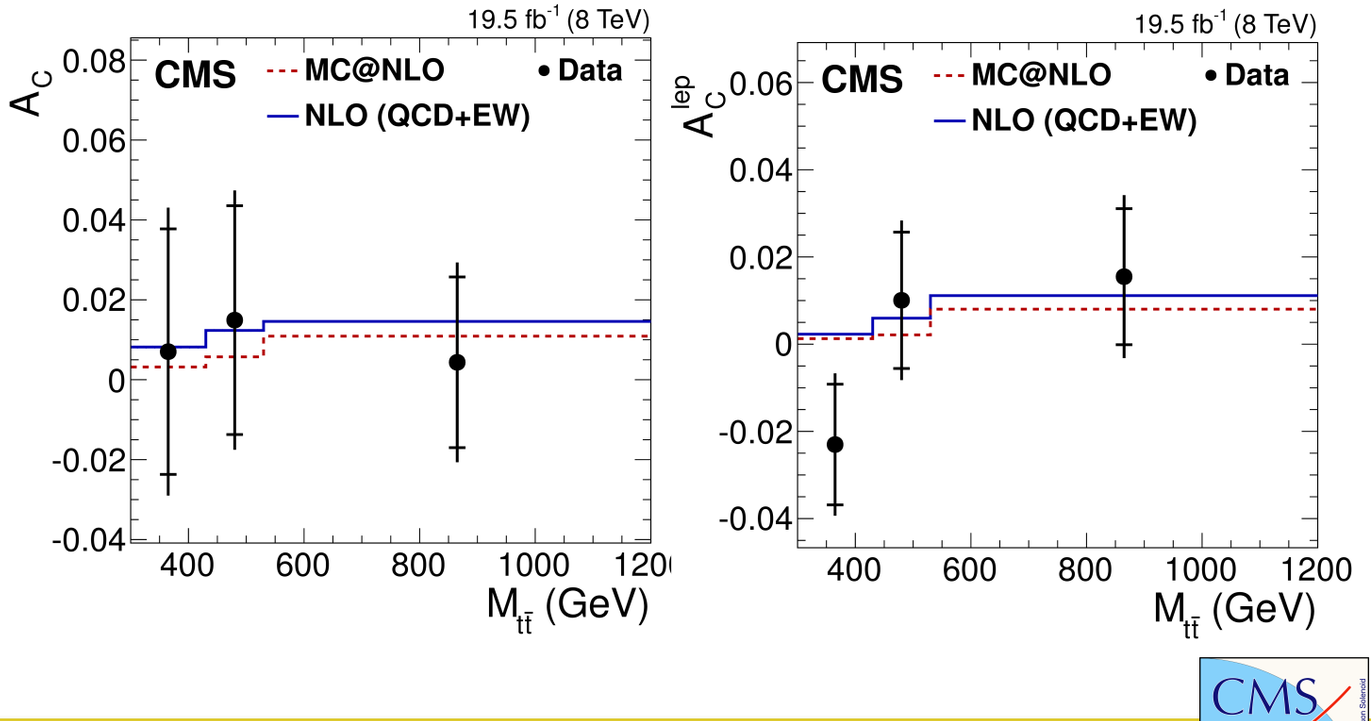
arXiv:1603.06221 , submitted to PLB

- asymmetry of the reconstructed $t\bar{t}$ and leptons
- differential measurements in $m_{t\bar{t}}$, $p_{t\bar{t}}$, $|y|_{t\bar{t}}$
- data unfolded to parton level

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

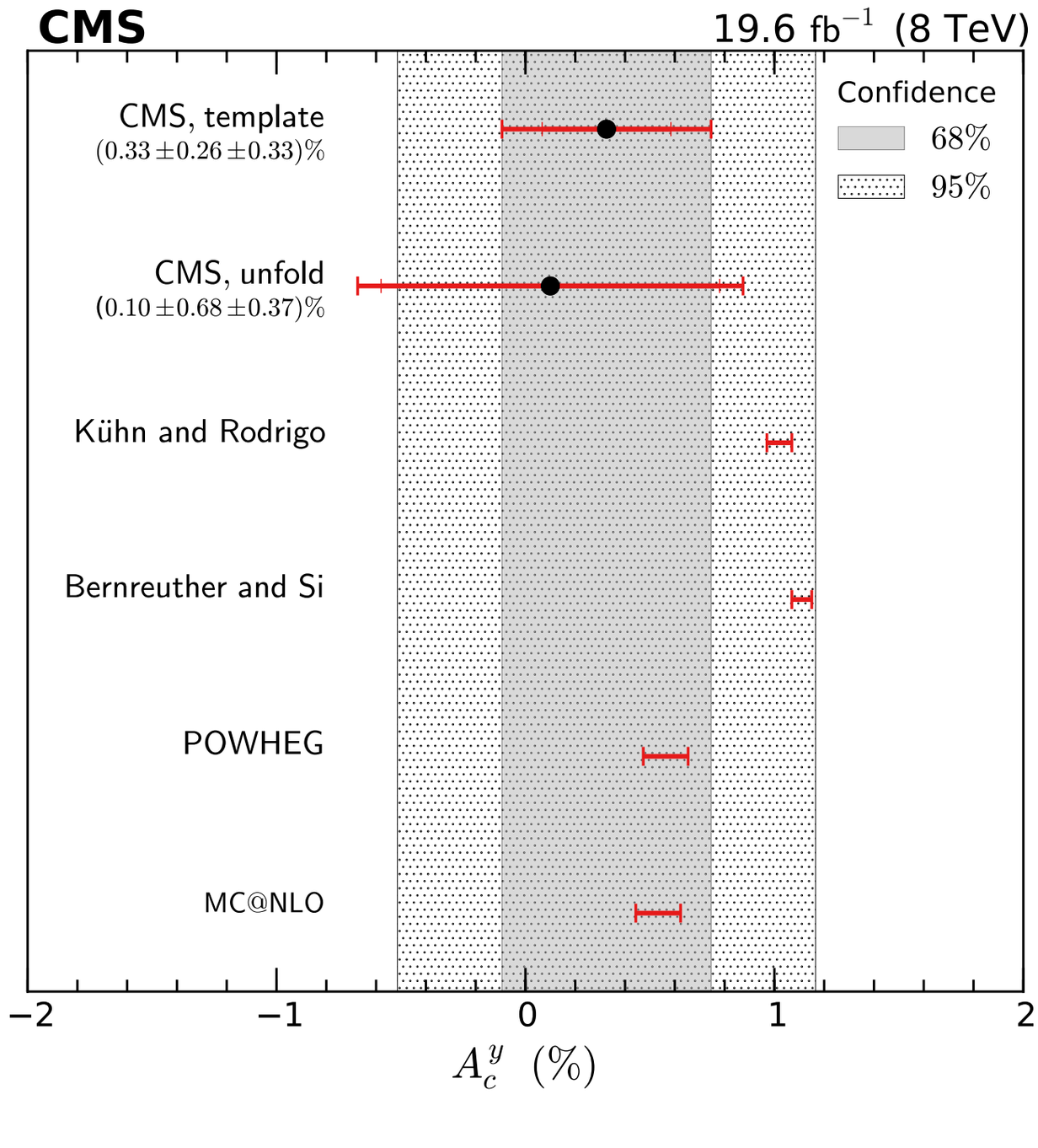
A_C(lep) = [0.3 ± 0.6(stat) ± 0.3(syst)]%
NLO(lep) = [0.64 ± 0.03]%
A_C = [1.1 ± 1.1(stat) ± 0.7(syst)]%
NLO = [1.11 ± 0.04]%





- dominant systematic uncertainties:
  A_C: Unfolding,hadronization, renormalization and factorization scales
  A_C(lep): Unfolding, renormalization and factorization scales

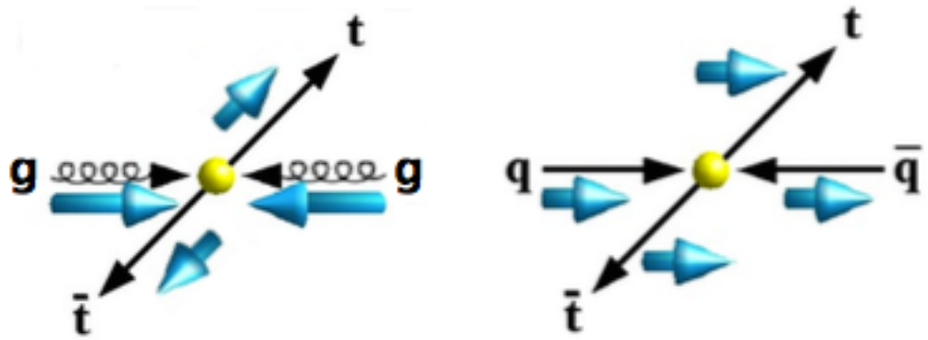
charge asymmetry



spin correlations

- top quarks decay before their spin de-correlate

$$1/\Gamma_t \;<\; 1/\Lambda \;<\; m_t/\Lambda^2$$



- spin correlation properties propagate to the decay products

- in SM spins are correlated

- spin correlation strength: $A = \dfrac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$

$A = A^{SM} \cdot f$ $\qquad f = \dfrac{N^{t\bar{t}}_{SM}}{N^{t\bar{t}}_{SM} + N^{t\bar{t}}_{uncor}}$

in helicity basis: $A^{SM} = 0.31$

spin correlations

muon + jets events 8 TeV 19.7 fb^{-1}

arXiv:1511.06170, submitted to PLB

- matrix element method to calculate event and sample likelihoods

discriminating variable:

$$\lambda_{event} = \frac{P(H_{uncor})}{P(H_{cor})}$$

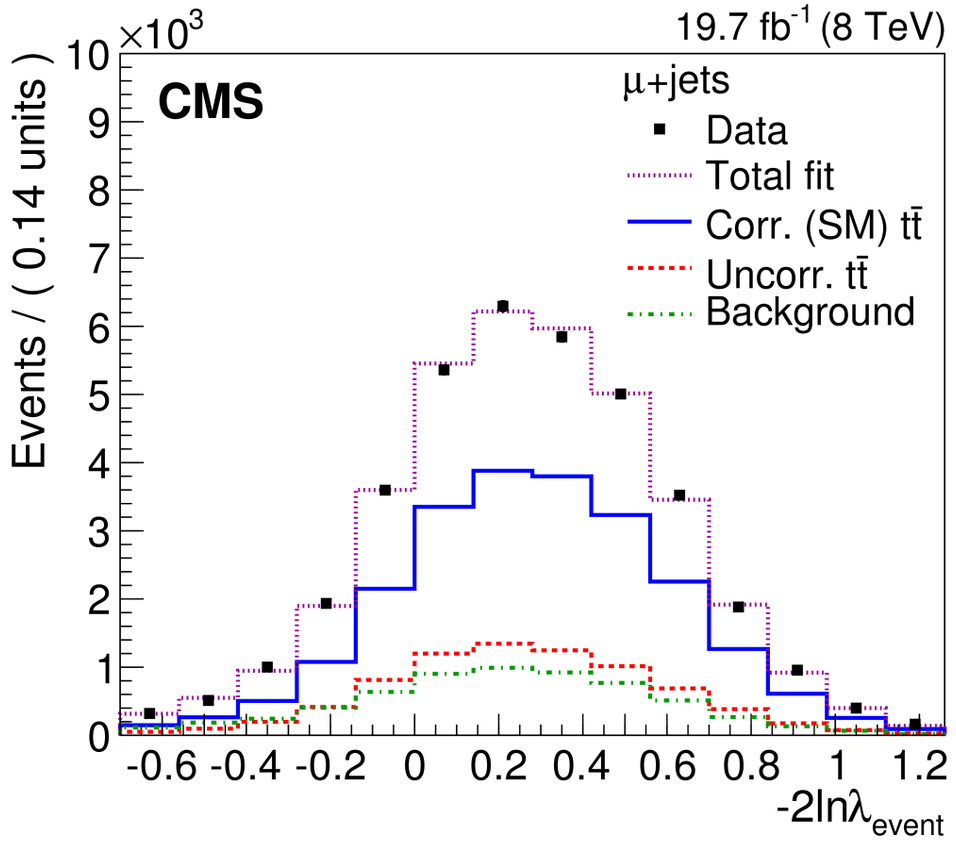
fit event likelihood ratio:

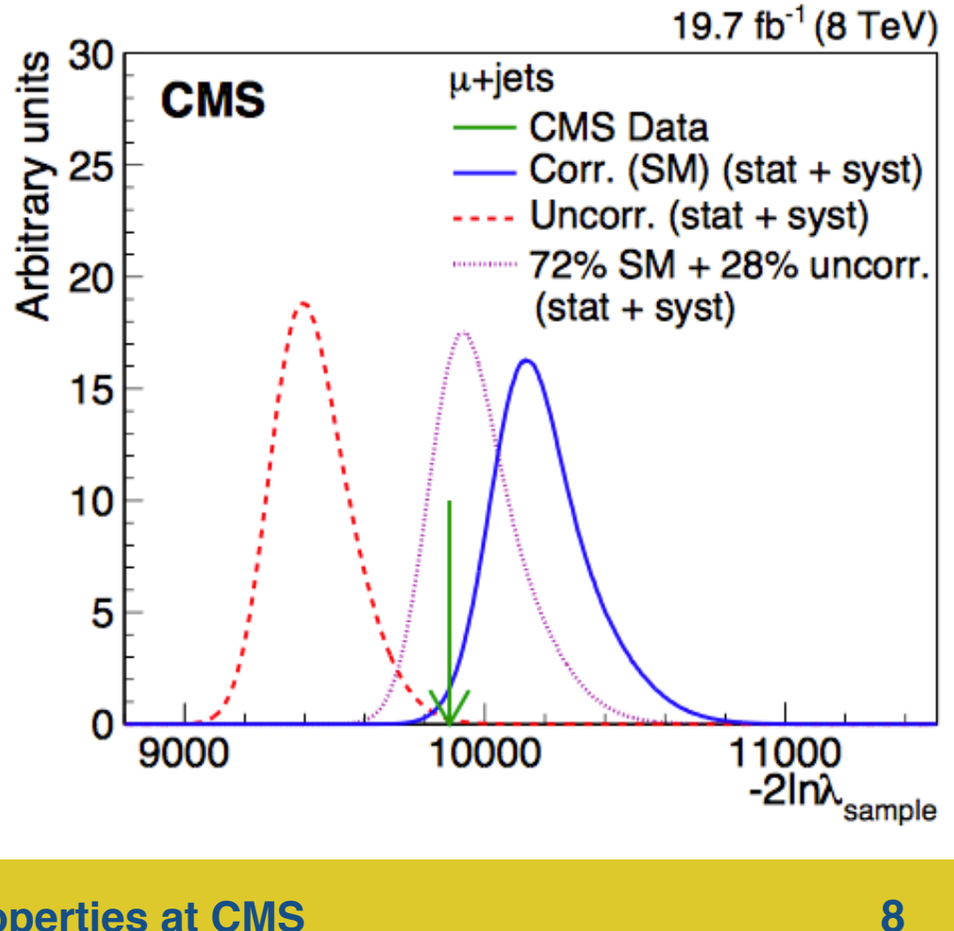
-2 ln λ_{event}

$$A^{measured} = 0.22 \pm (0.03)(\text{stat.})^{+0.05}_{-0.04}(\text{sys.})$$

$$f = 0.72 \pm (0.08)(\text{stat.})^{+0.15}_{-0.13}(\text{sys.})$$

- dominant systematic uncertainties: scale, JES





spin correlations

dilepton + jets events 8 TeV 19.7 fb^{-1}

Phys. Rev. D 93, 052007

- direct measurement of correlation coefficient using angular distribution and asymmetries:
  $A_{\Delta\phi}$, A_{c1c2}, $A_{\cos\phi}$

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

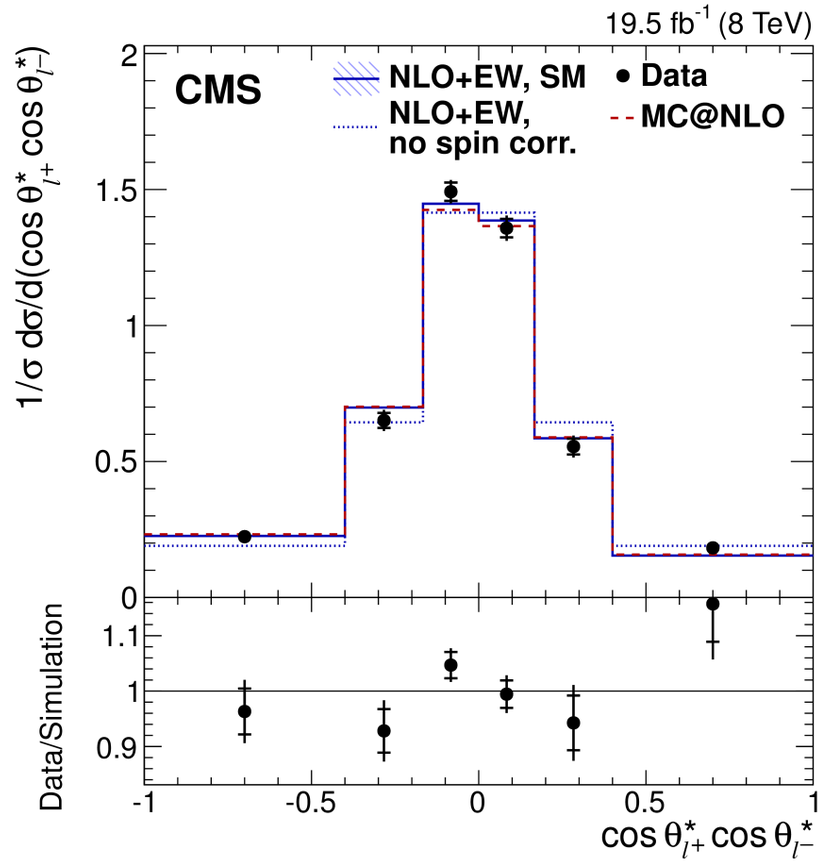
$$c_1c_2 = \cos\theta^*_{l^+}\cos\theta^*_{l^-} \qquad A_{hel.} = -4A_{c_1c_2}$$

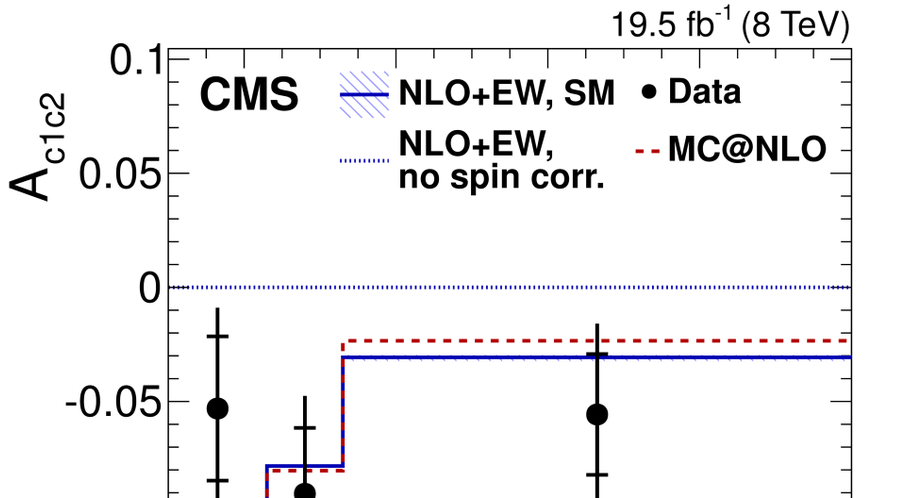
Variable	$f_{SM} \pm (stat) \pm (syst) \pm (theor)$	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13\,^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08\,^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

$$A_{c_1c_2} = -0.069 \pm 0.013(\text{stat.}) \pm 0.016(\text{sys.})$$

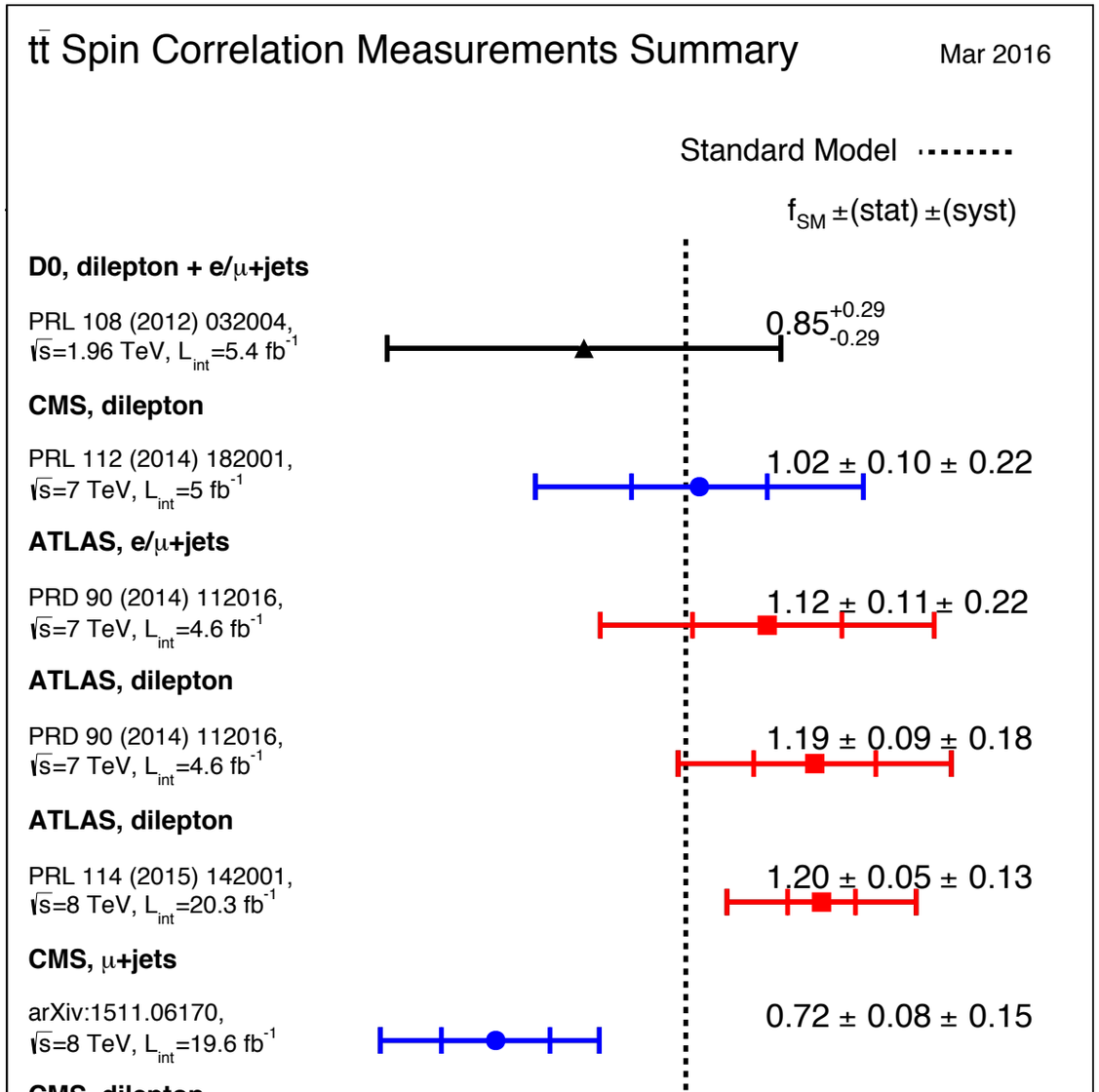
$$A_{hel.} = 0.278 \pm 0.084$$

- dominant systematic uncertainties:
  top quark p_T, top quark mass, Unfolding (simulation stat.), JES





spin correlations



CP violation

first measurement in $t\bar{t}$ production

- no observable CP violation in $t\bar{t}$ production in SM
- CP violation sign of new physics
- search with effective asymmetric parameter A_{CP} based on T-odd triple product observables

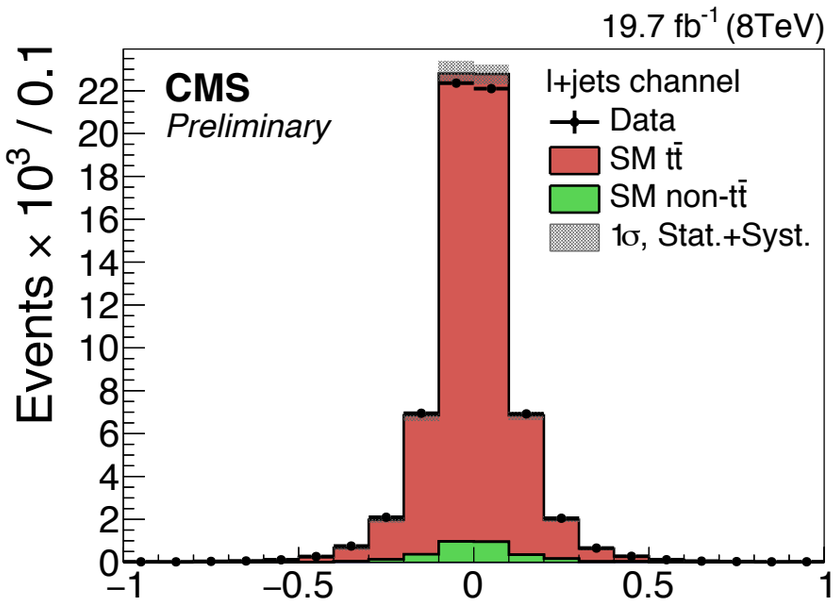
$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$$

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{b\bar{b}\ CM} \propto Q_\ell \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_4 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j1}) \xrightarrow{lab} \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1})$$

$$O_7 = q \cdot (p_b - p_{\bar{b}})\, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{lab} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z$$



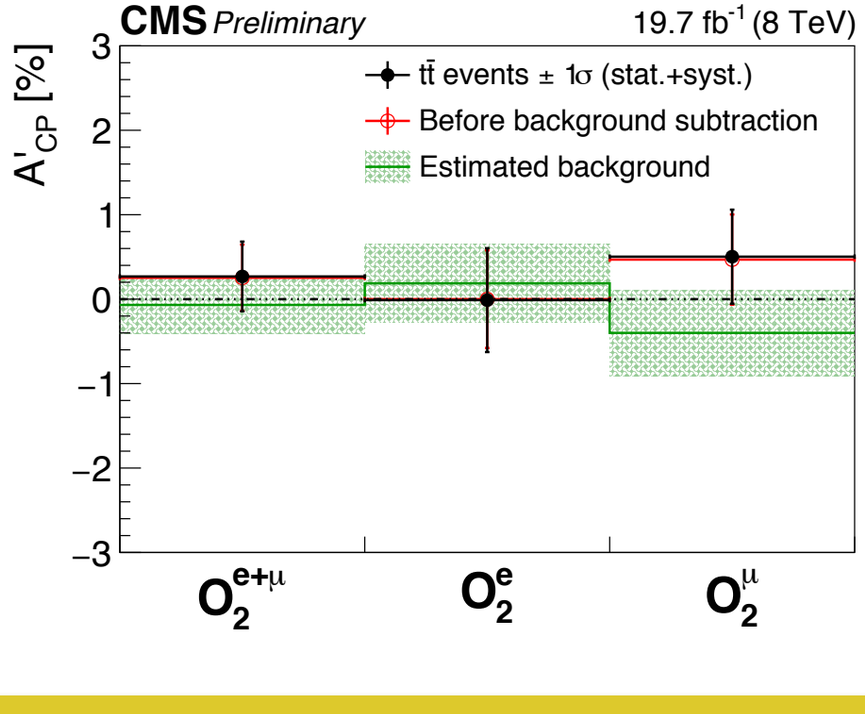
8 TeV 19.7 fb^{-1} **TOP-16-001**

$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

- dominant systematic uncertainties: theoretical

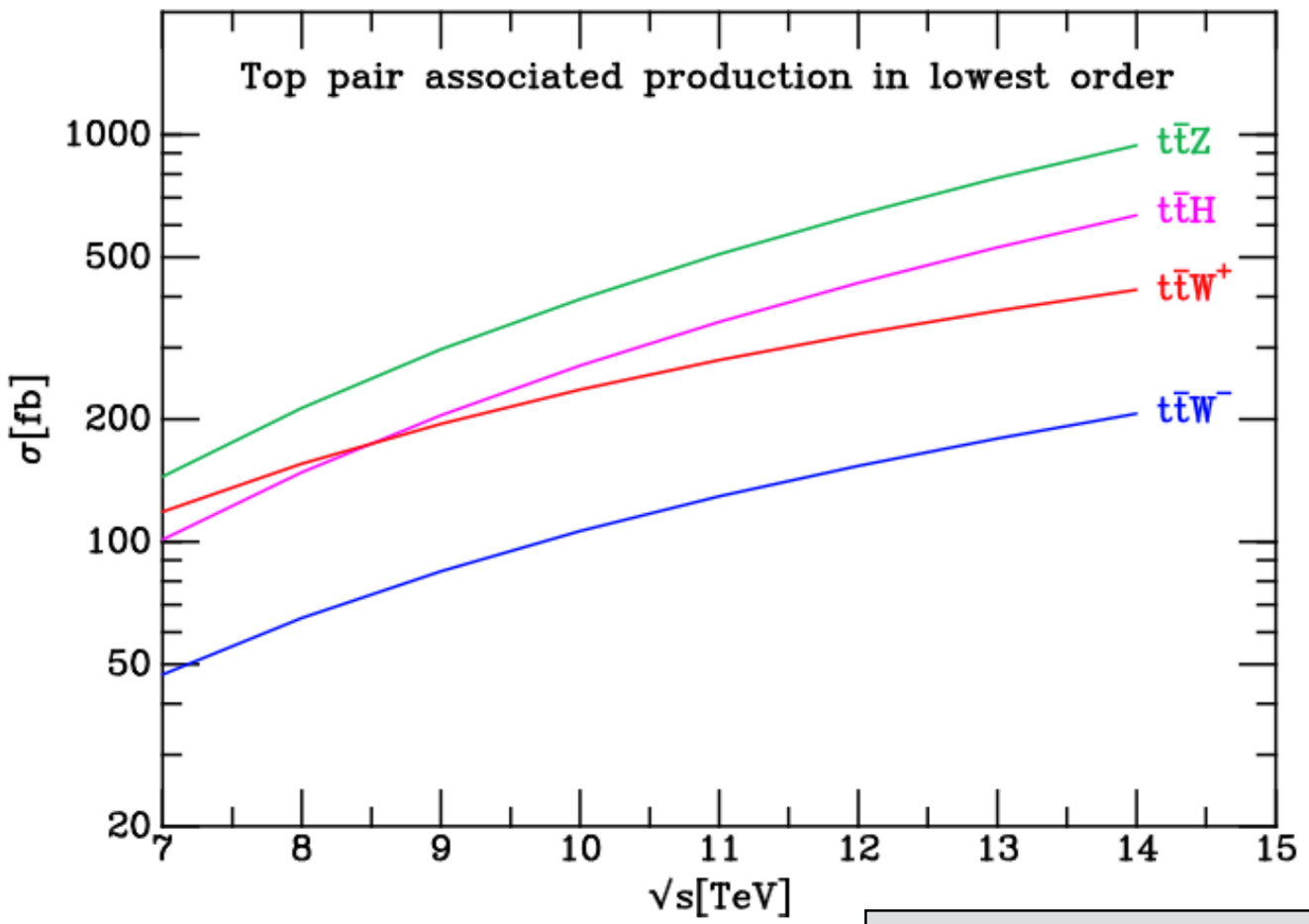
in agreement with SM

O_3

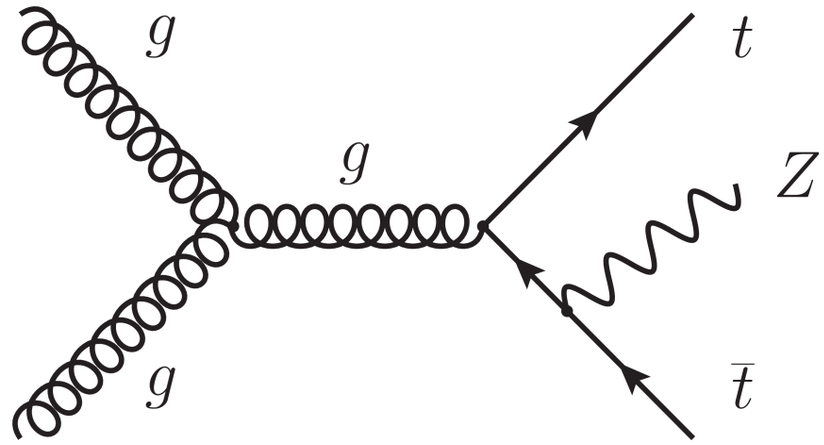


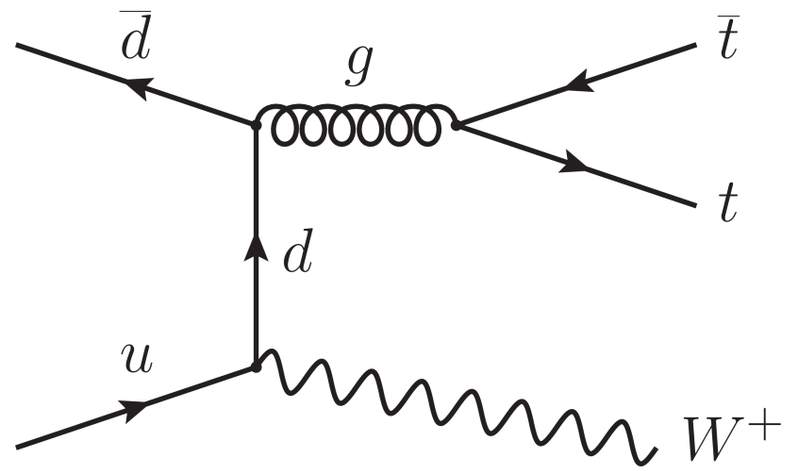
$t\bar{t}V$

- top quark coupling with EW bosons
- extension of SM modifies the couplings
- background for $t\bar{t}H$ and many BSM processes
- $t\bar{t}Z$: direct measurement of the top quark coupling to Z
- $t\bar{t}V$: limits to dimension-six operators



Campbell, Ellis
10.1007/JHEP07(2012)052





$t\bar{t}V$

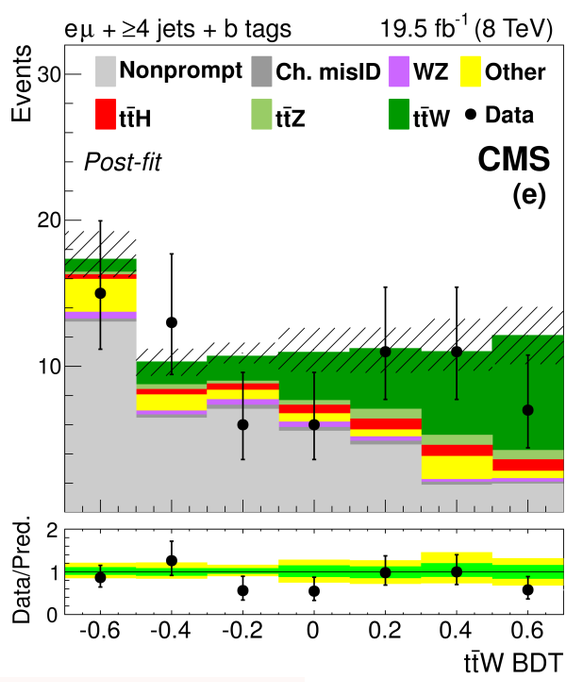
8 TeV 19.7 fb^{-1} 10.1007/JHEP01(2016)096

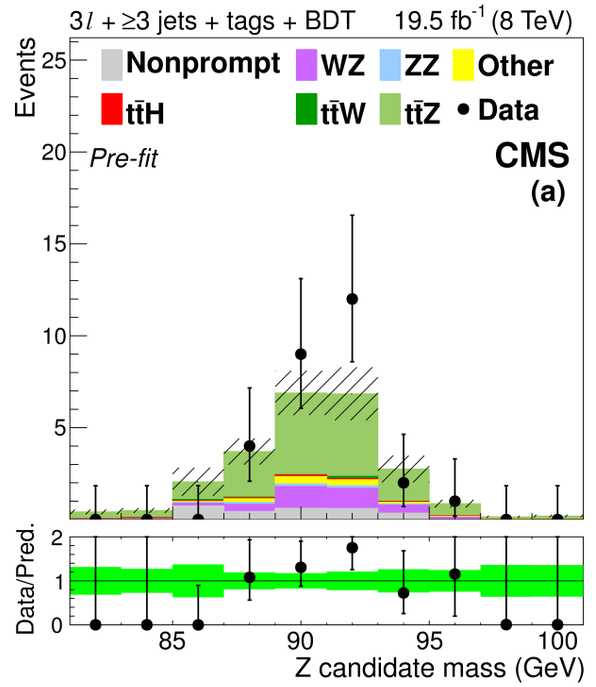
- full-event reconstruction by using Matching Linear Discriminant as input to BDT
  - $t\bar{t}W$: SS, 3l final states
  - $t\bar{t}Z$: OS, 3l, 4l final states

first observation of $t\bar{t}Z$!

$$\sigma_{t\bar{t}W} = 382^{+117}_{-102} \text{ fb with } 4.8\sigma$$

$$\sigma_{t\bar{t}Z} = 242^{+65}_{-55} \text{ fb with } 6.4\sigma$$



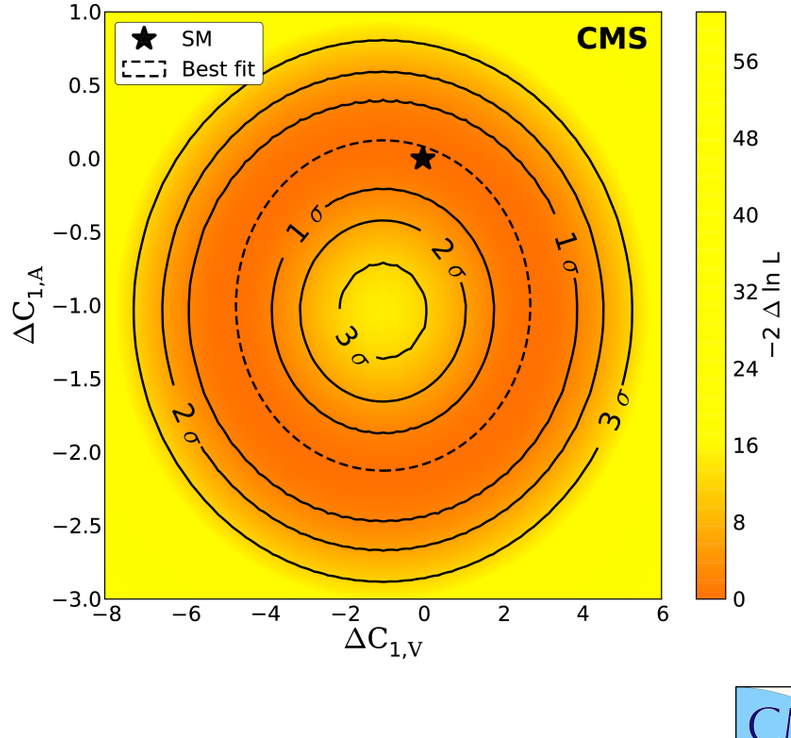


- dominant systematic uncertainties: signal modelling, b-tagging efficiency

Constraints on new physics:

- Constraints on the axial and vector components of the tZ coupling
- Constraints on dimension-six operators

Operator	Best fit point(s)	1 standard deviation CL	2 standard deviation CL
$\bar{c}_{uB}$	−0.07 and 0.07	[−0.11, 0.11]	[−0.14, 0.14]
$\bar{c}_{3W}$	−0.28 and 0.28	[−0.36, −0.18] and [0.18, 0.36]	[−0.43, 0.43]
$\bar{c}'_{HQ}$	0.12	[−0.07, 0.18]	[−0.33, −0.24] and [−0.02, 0.23]
$\bar{c}_{Hu}$	−0.47 and 0.13	[−0.60, −0.23] and [−0.11, 0.26]	[−0.71, 0.37]
$\bar{c}_{HQ}$	−0.09 and 0.41	[−0.22, 0.08] and [0.24, 0.54]	[−0.31, 0.63]



ttV

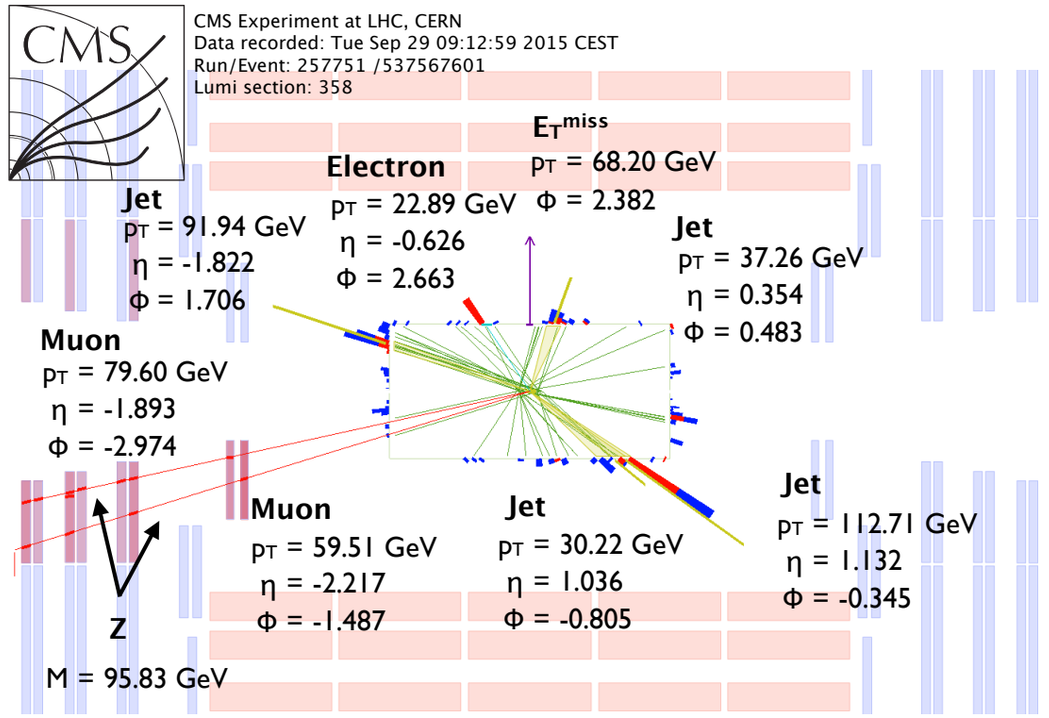
13 TeV 2.7 fb^{-1} TOP-16-009

- ttZ: 3lepton, 4lepton final states
- 8 + 2 signal regions to extract signal
- data driven estimates for the non-prompt leptons
- binned likelihood fit to all categories

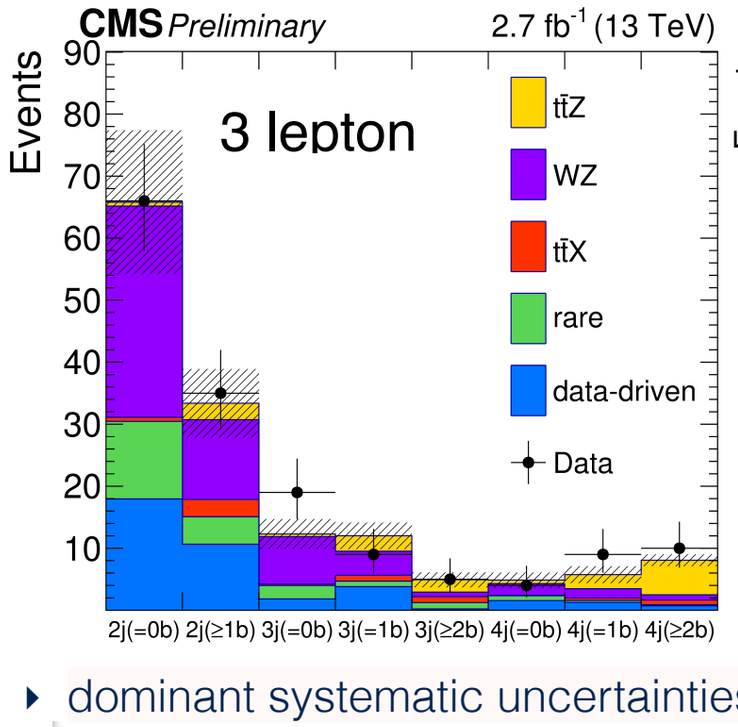
Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.5
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.1	3.6

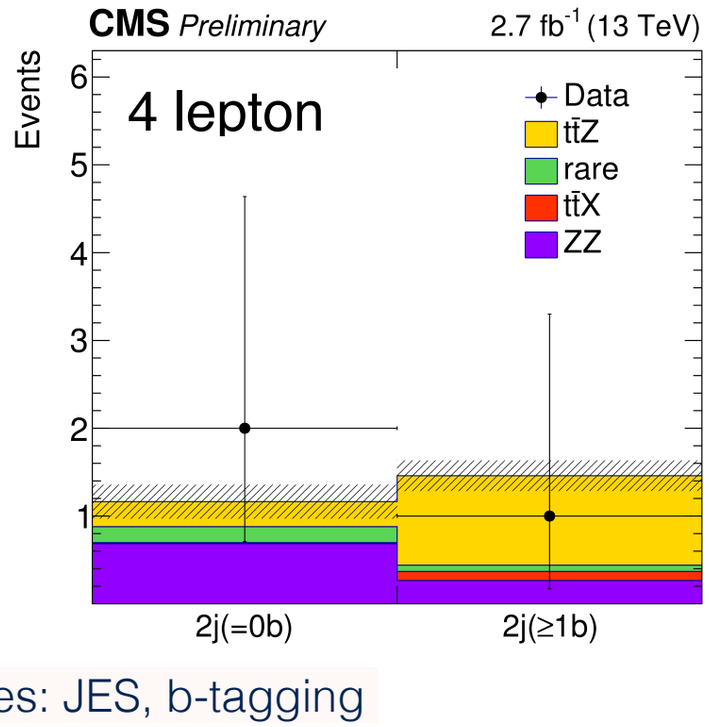
$$\sigma_{t\bar{t}Z} = 1065^{+352}_{-313}(\text{stat.})^{+168}_{-142}(\text{sys.})\ \text{fb}$$

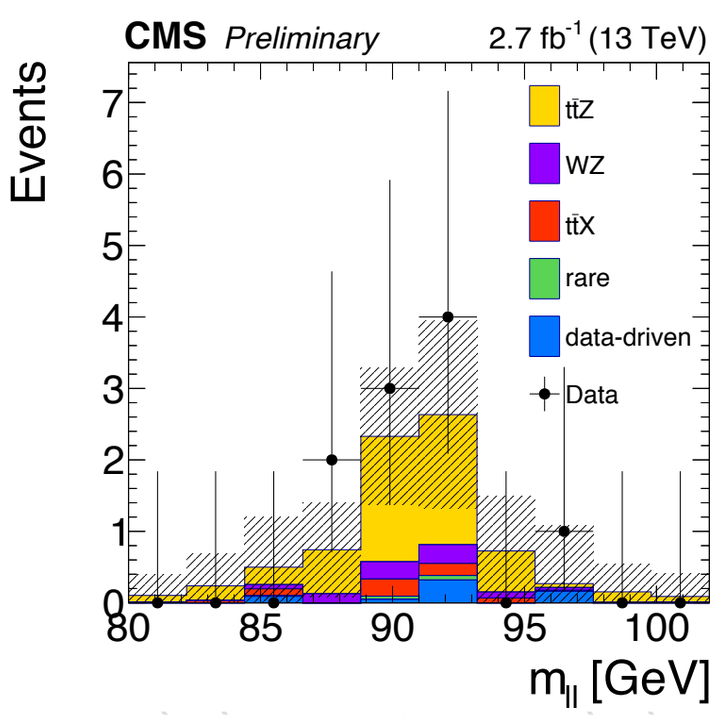
$$\text{aMCatNLO} = 839.3^{+80}_{-92}(\text{scale})^{+25}_{-25}(\text{pdf})^{+25}_{-25}(\alpha_s)\ \text{fb}$$



evidence of ttZ at 13 TeV







- dominant systematic uncertainties: JES, b-tagging

conclusions

- many interesting top properties measurements from Run1
  - all results are in good agreement with SM
  - first observation of $t\bar{t}Z$ at 8 TeV
  - uncertainties mostly systematically dominated

- Run2 at 13 TeV: higher precision, higher energy, higher statistics!!
  - already some Run 2 top measurements
  - $t\bar{t}Z$ measurement at 13 TeV
  - new exciting top properties measurements will arrive very soon!

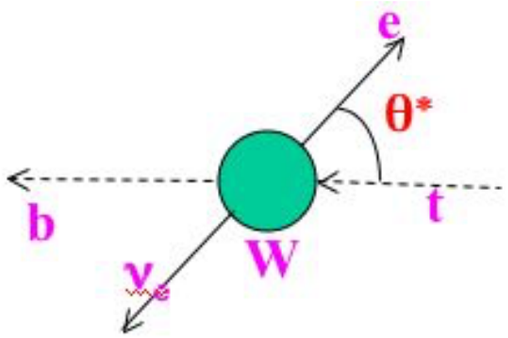
For more:

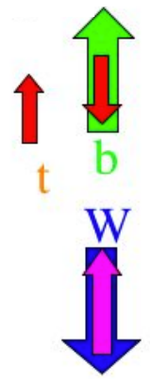
CMS Top publications page
CMS Top preliminary results page

backup slides

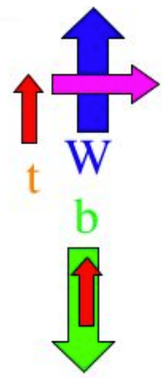
W helicity

- the tWb coupling can be studied in $t\bar{t}$ $V_{tb} \sim 1$
- no right-handed W in the b-quark massless limit

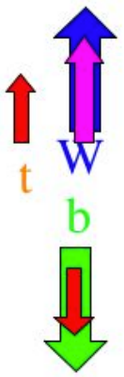




$F_L = 0.31$



$F_0 = 0.68$

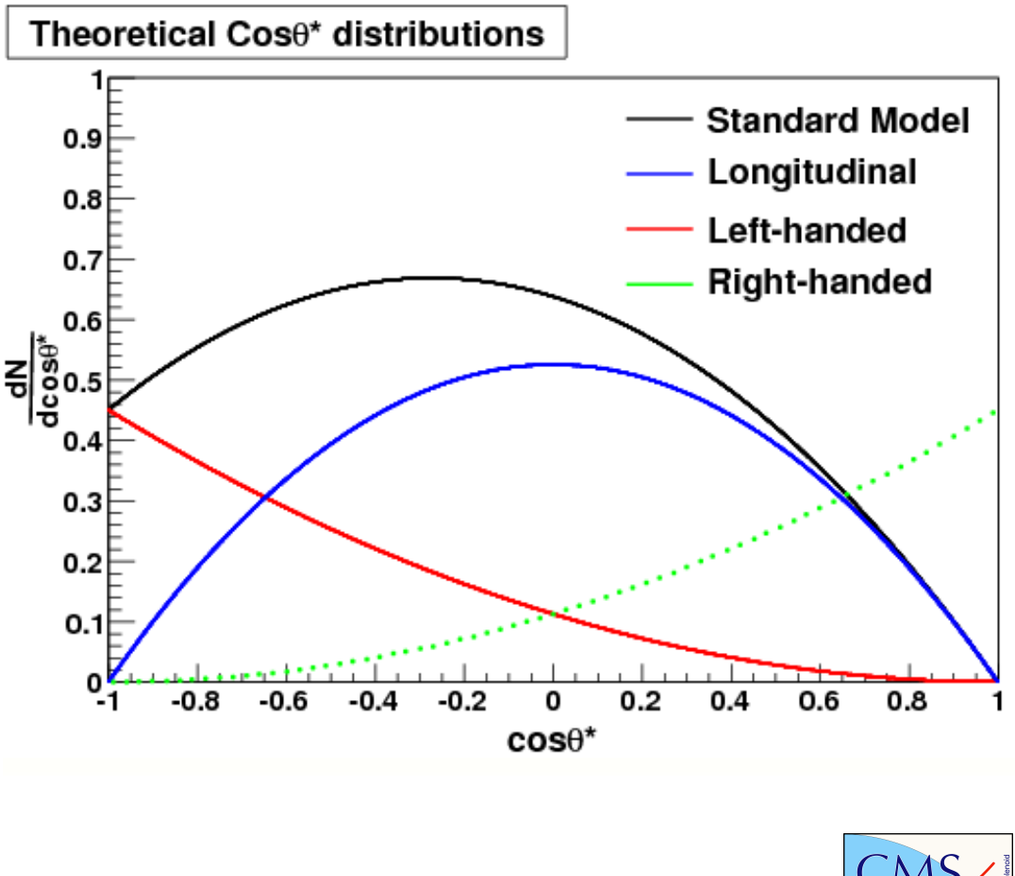


$F_R < 0.01$

- helicity states are extracted fitting the cosθ*

$$F_L + F_{R+} F_0 = 1$$

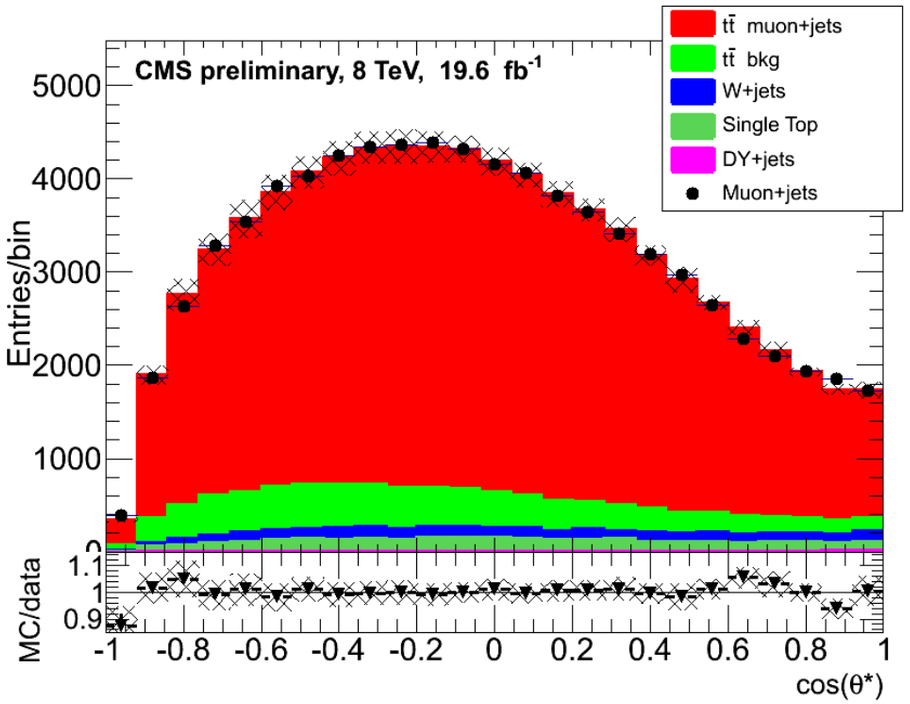
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}(\sin\theta^*)^2 F_0$$



W helicity

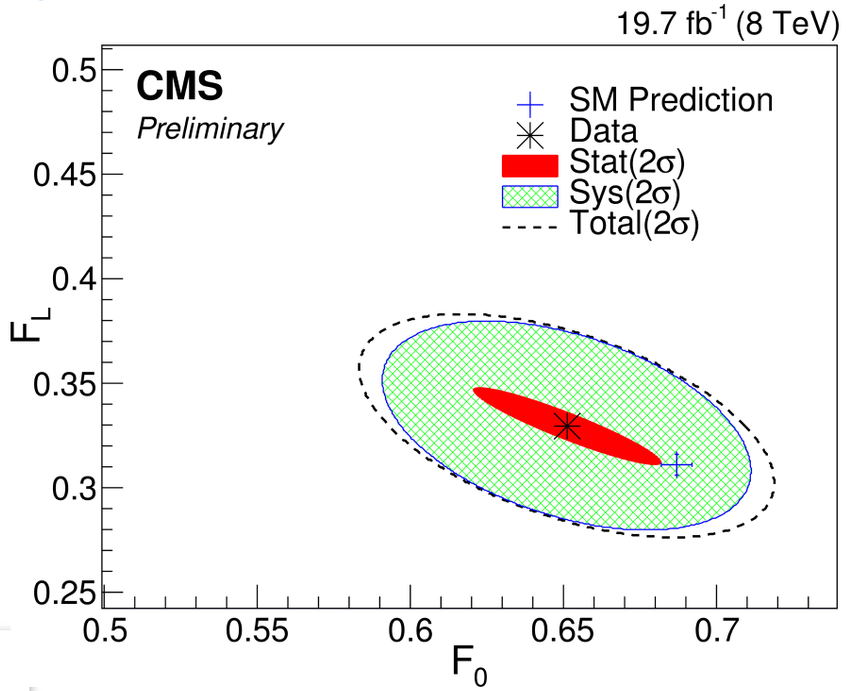
muon + jets events 8 TeV 19.7 fb^{-1}

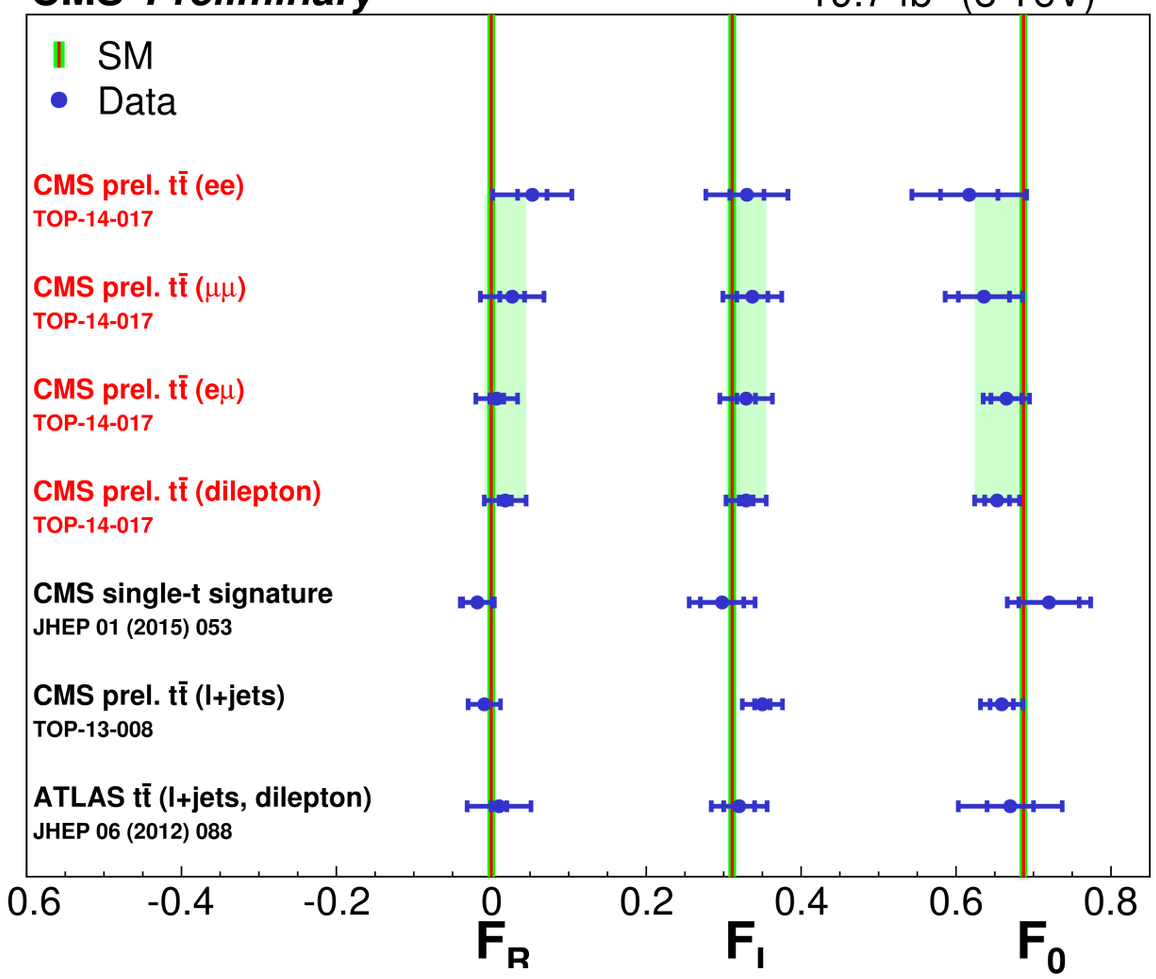
TOP-13-008



dilepton + jets events 8 TeV 19.7 fb^{-1}

TOP-14-017





Agreement with SM!

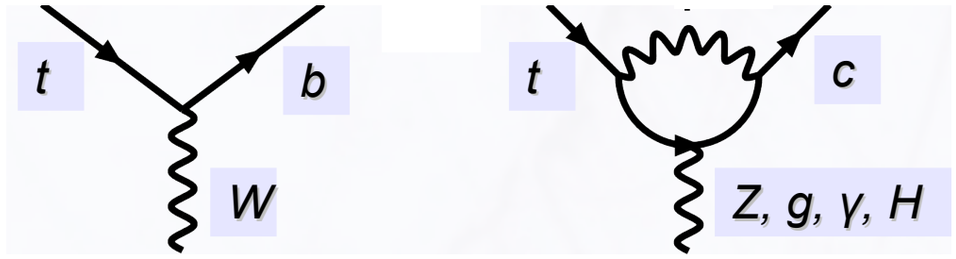
TOP-13-008 $F_R = -0.009 \pm 0.006(stat.) \pm 0.020(syst.)$

TOP-14-017 $F_R = 0.018 \pm 0.008(stat.) \pm 0.026(syst.)$

- dominant systematic uncertainties:
  top-quark mass, tt̄ scales, tt̄ matching scales

FCNC

- Flavour changing currents are suppressed in SM
- in BSM enhanced by many order of magnitude



CC FCN

	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

ACTA Phys. Pol. B 35 (2004)

8 TeV 19.7 fb^{-1}

TOP-14-020

$t \to qH, H \to b\bar{b}$

TOP-14-019

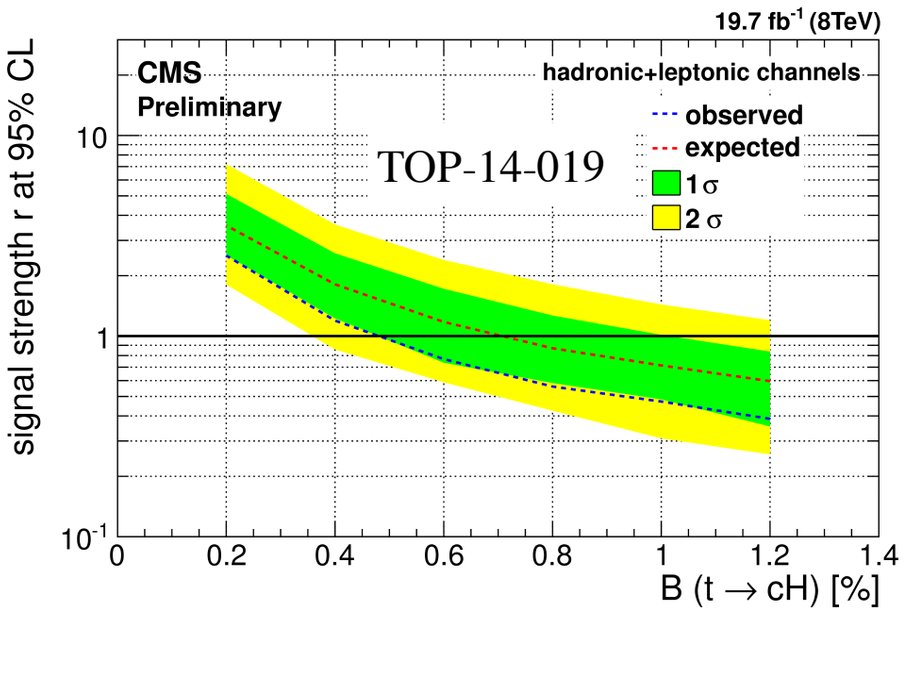
$t \to qH, H \to \gamma\gamma$

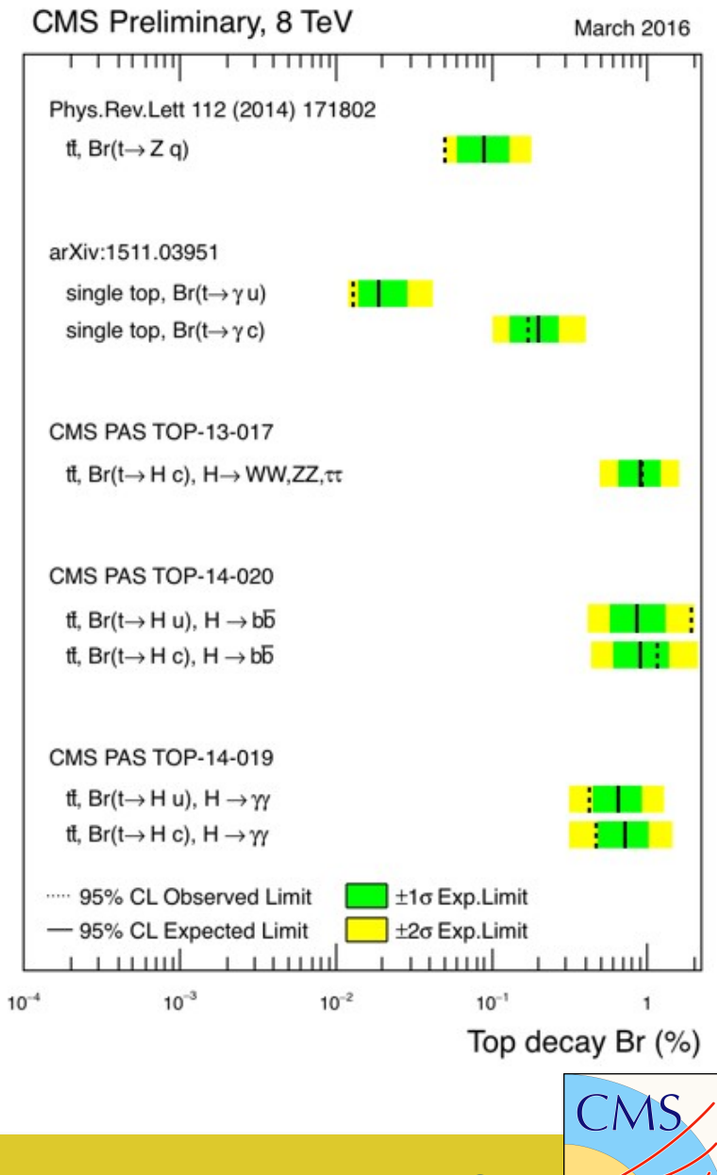
10.1103/PhysRevLett.112.171802

$t \to qZ$

TOP-13-017

$t \to qH, H \to VV, \tau\tau$





- Sensitivity to some BSM
- No significant excess of events over the SM background

charge asymmetry

lepton + jets events 8 TeV 19.7 fb^{-1}

arXiv:1507.03119, accepted by PLB