Top properties measurements with the CMS detector at the LHC

Jui-Fa Tsai (National Taiwan University)

on behalf of the CMS Collaboration

38th International Conference on High Energy Physics

August, 2016 @ Chicago

About Top Quark at LHC

★ **The most massive elementary particle in standard model (SM)**

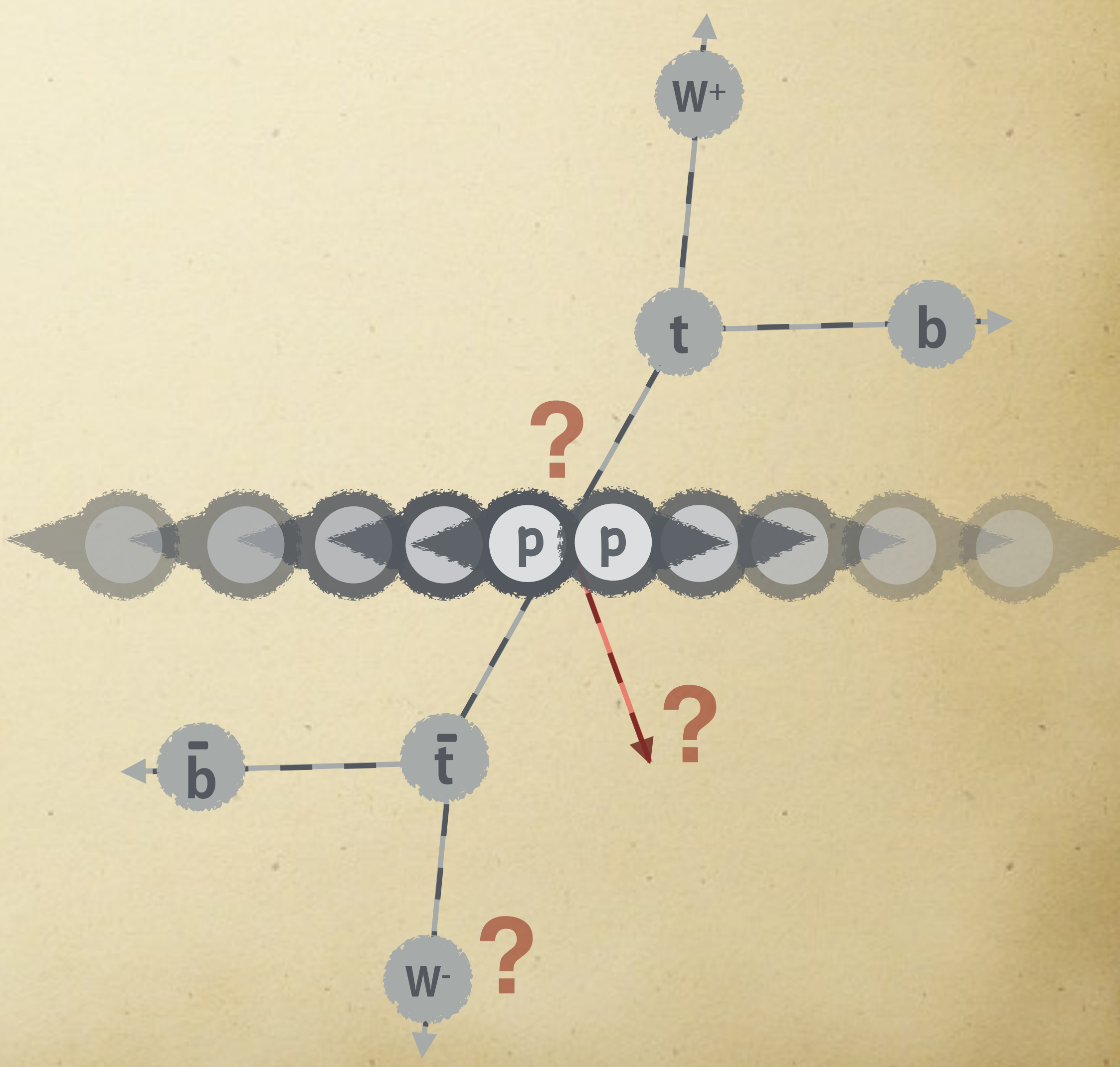
- ★ M_{top} ~ 172.5 GeV.
- ★ Play an essential role in electroweak symmetry break (EWSB).
- ★ Good source to test SM.

★ **Many properties of top quark can be measured**

- ★ Spin, charge asymmetry, CPV and $t\bar{t}$+Z/W.

★ **LHC is a top-quark factory**

- ★ Most of top quarks come from top-quark pair ($t\bar{t}$) production
  - — Dominated by gluon-gluon fusion process.
- ★ Large production cross sections
  - — $\sigma(t\bar{t})$ ~ 252.89 pb @ 8 TeV
  - — $\sigma(t\bar{t})$ ~ 831.76 pb @ 13 TeV



Latest News on Top Properties from CMS

★ Related to $t\bar{t}$ production

★ Spin correlations

* TOP-14-023 : Dilepton @ 8TeV .... PRD 93, 052007 (2016)
* TOP-13-015 : Lepton+jets (matrix element method) @ 7 & 8 TeV .... PLB 758 (2016) 321

★ Charge asymmetry

* TOP-12-033 : Lepton+jets @ 8 TeV .... PLB 757 (2016) 154
* TOP-13-013 : Lepton+jets (template method) @ 8 TeV .... PRD 93, 034014 (2016)
* TOP-15-009 : Dilepton @ 8 TeV .... arXiv:1603.06221 (PLB accepted)

★ Associated production with vector boson

* TOP-16-017 : $t\bar{t}$+Z/W @ 13 TeV NEW !!!

★ Related to $t\bar{t}$ coupling

★ CP violation

* TOP-16-001 : Lepton+jets @ 8 TeV

★ W Helicity fraction

* TOP-13-008 : Lepton+jets @ 8 TeV NEW !!! .... arXiv:1605.09047 (PLB accepted)

★ Search for top FCNC

Properties related to top-quark pair production

* Spin correlations
* Charge asymmetry
* Associated production with vector boson

Spin correlations

★ **In QCD, the spin of heavy quarks is correlated at production.**

★ **Very short life time**

G. Mahlon & S. J. Parke - PRD 81, 074024 (2010)
W. Bernreuther & Z.-G. Si - PLB 725, 115 (2013)

- ★ τ_t < τ(hadronization) < τ(spin-decorrelation) << τ_b
- ★ No hadronic bound state, i.e behavior as a bare quark.
- ★ Information of spin propagates to the daughter particles.
  - — Direct measurement with charged leptons
  - — Can be studied with or without reconstruction of the tt.

★ **Spin correlation strength**

- ★ Dependent on the observables, production mechanism and energy.

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

D. Krohn, T. Liu, J. Shelton, & L.-T. Wang - PRD 84, 074034 (2011)
S. Fajfer, J.F. Kamenik & B. Melic - JHEP 08 (2012) 114
J.A. Aguilar-Saavedra & M. Perez-Victoria - JPCS 447, 012015 (2013)
A. Brandenburg, Z.-G. Si & P. Uwer - PLB 539, 235 (2002)

★ **Coefficient *f***

- ★ Gives the degree of spin correlation relative to the SM.

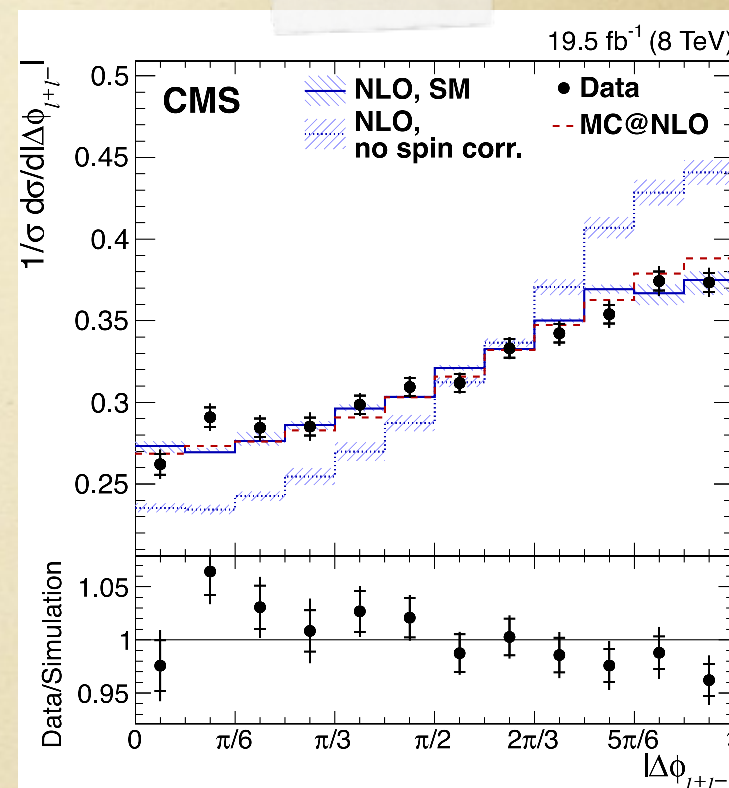
$$A_{\text{obs}}^{\text{means}} = A_{\text{obs}}^{\text{SM}} \cdot f$$

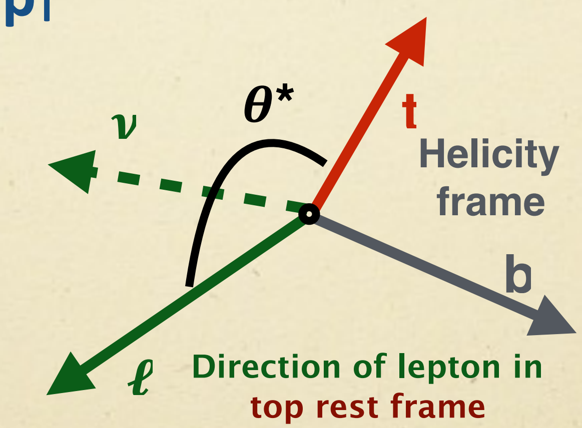
Spin correlations - dilepton

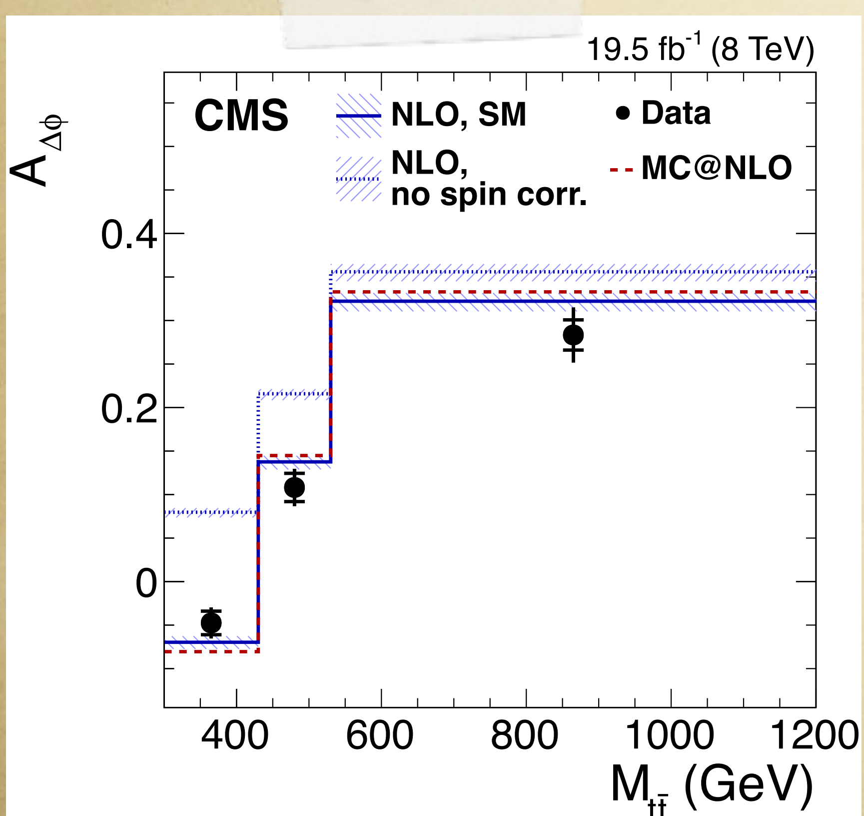
PRD 93, 052007 (2016)

- ★ **Observables formed by the angles between the 2 leptons**
  - ★ $\Delta\phi(\ell^+,\ell^-)$: Difference in azimuthal angles in the lab frame.
  - ★ φ : Open angle between 2 leptons' momenta wrt. the mother top.
  - ★ $\cos\theta^*_+ \cos\theta^*_-$: Product of the cosine of the helicity angles of 2 leptons

- ★ **Bkg-subtracted data is unfolded (TUnfold).**
- ★ **Inclusive and differential measurements**
  - ★ As functions of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$







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. $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08 ^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

Spin correlations - lepton+jets

PLB 758 (2016) 321

★ **Muon+jets channel**

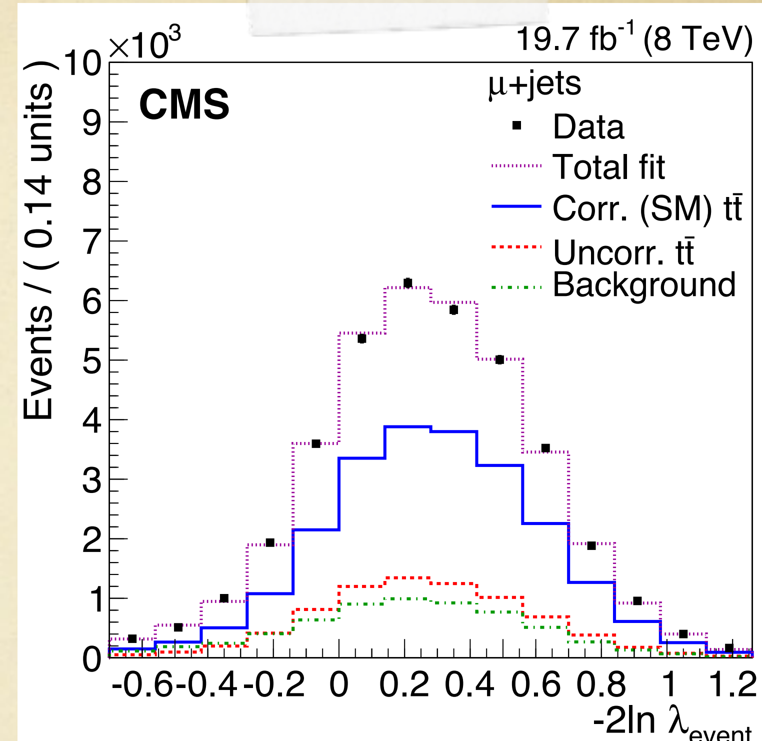
★ **LO Matrix element method (MEM)**

$$P(x_i|H) = \frac{1}{\sigma_{obs}(H)} \int f_{PDF}(q_1) f_{PDF}(q_2) dq_1 dq_2 \frac{(2\pi)^4 |M(y,H)|^2}{q_1 q_2 s} W(x_i, y) d\Phi_6$$

Initial parton kinematics

Transfer function relates observed kinematics x to parton level kinematics y

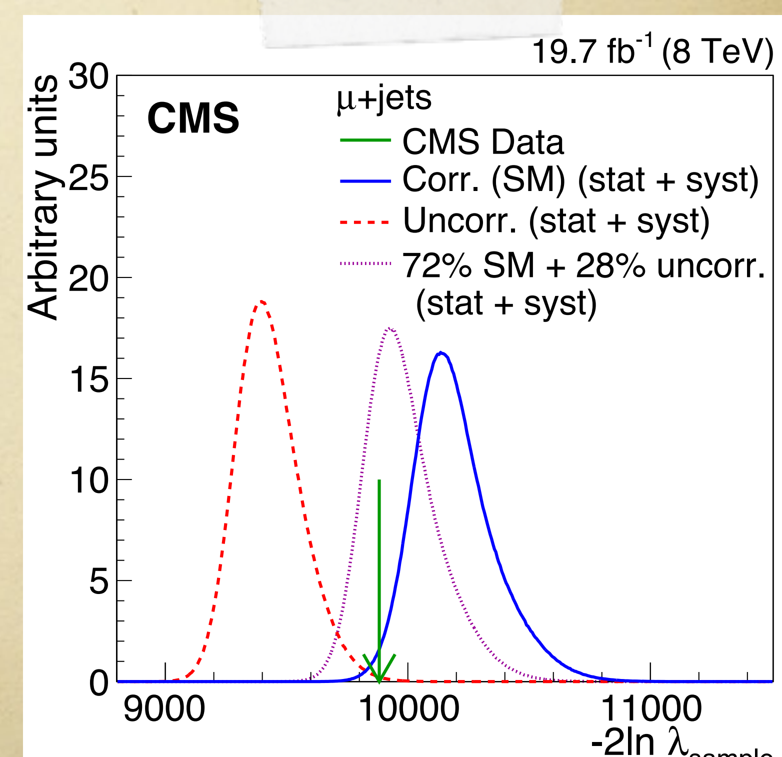
$H = H_{corr}$ or H_{uncorr}



★ **Calculate sample likelihood and event probability for 2 hypotheses**

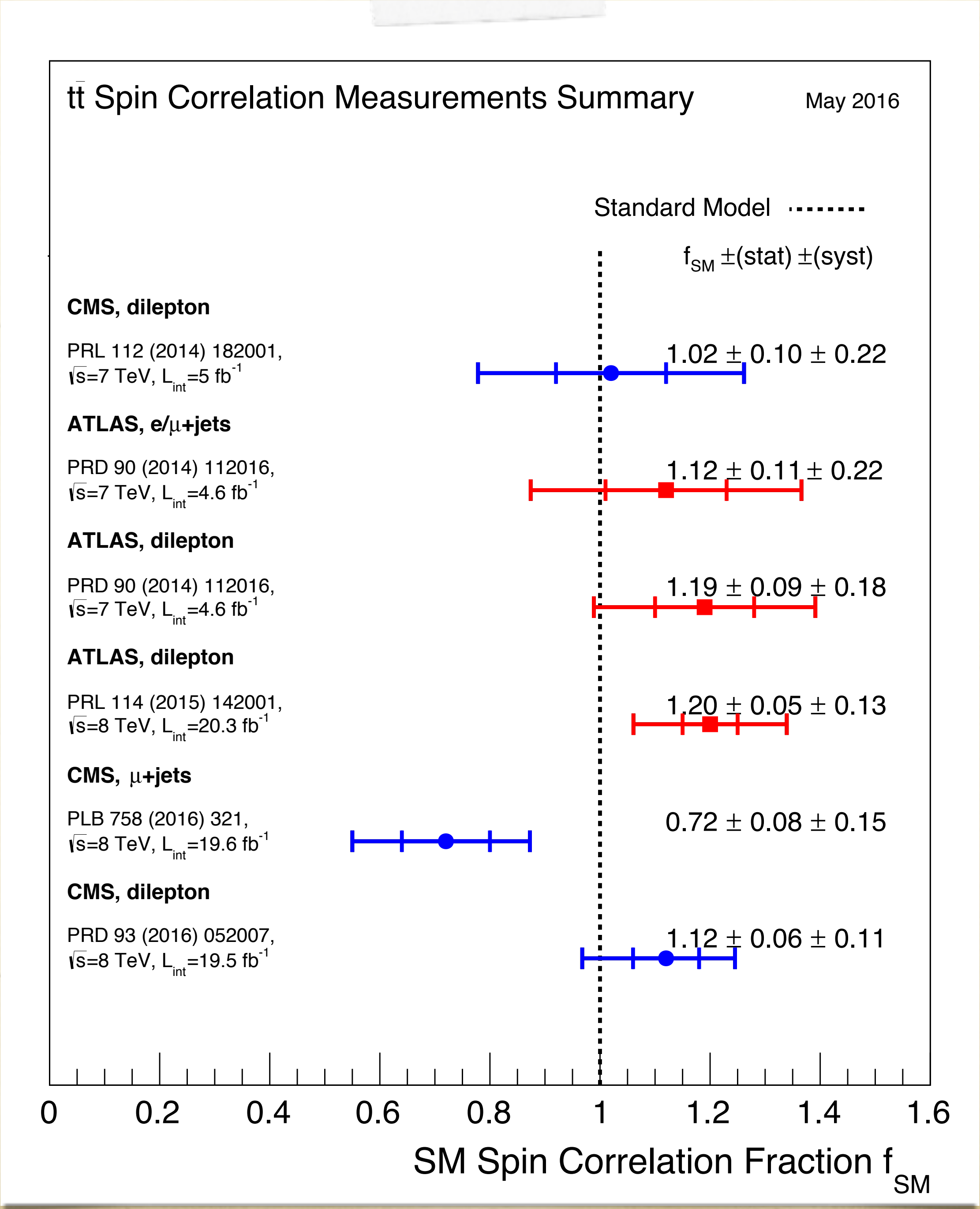
★ **Template fit to extract bkg. fraction and *f***

- ★ $f = 0.72 \pm 0.08 (stat.)^{+0.15}_{-0.13} (syst.)$
- ★ 2.2σ agreement with correlated hypothesis (SM)
- ★ 2.9σ agreement with uncorrelated hypothesis



Spin correlations

- ★ **Summary of spin correlation with f_{SM}**
  - ★ **In agreement with SM predictions.**



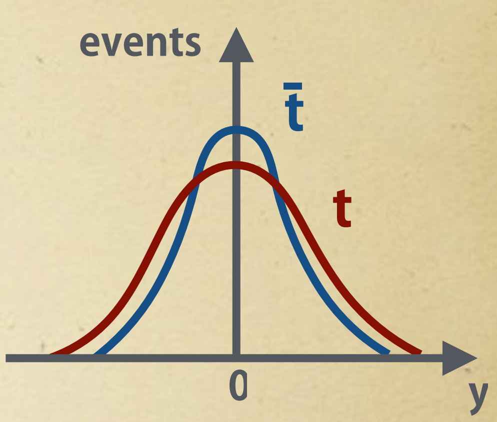
Charge asymmetry

★ **Non-zero charge asymmetry from quark anti-quark interaction.**

★ **LHC has symmetric state with proton-proton collision**

— PDF is not symmetry, i.e. quarks carry more momentum than anti-quarks.

— Rapidity (y) distribution of top is boarder then anti-top

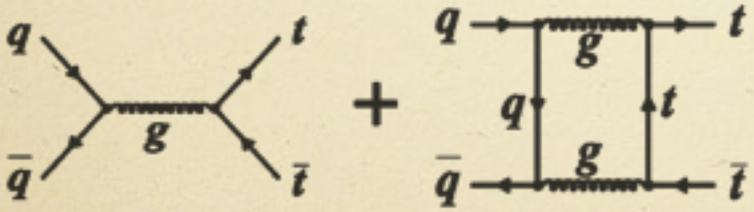


★ **Observable and asymmetry parameter**

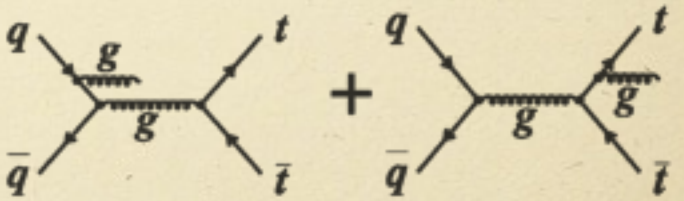
$$\Delta|y| = |y_{\mathrm{t}}| - |y_{\bar{\mathrm{t}}}|$$

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

★ **Only in $q\bar{q}$-initial state, not for gg (symmetry)**



Tree–level & box : asymmetry (+)



ISR & FSR : asymmetry (–)

★ **Relatively small effect in the SM**

— A_C = +0.0102 ± 0.0005 [Kühn, Rodrigo]

A_C = +0.0111 ± 0.0004 [Bernreuther, Si]

J.H.Kühn & G.Rodrigo - JHEP 01 (2012) 063

A. Brandenburg, Z.-G. Si & P. Uwer - PRD 86 (2012) 034026

★ **Can be enhanced in some BSM scenarios**

— Axigluons, Z' bosons, axial couplings of the gluon.

Charge asymmetry - lepton+jets

★ Unfolding method

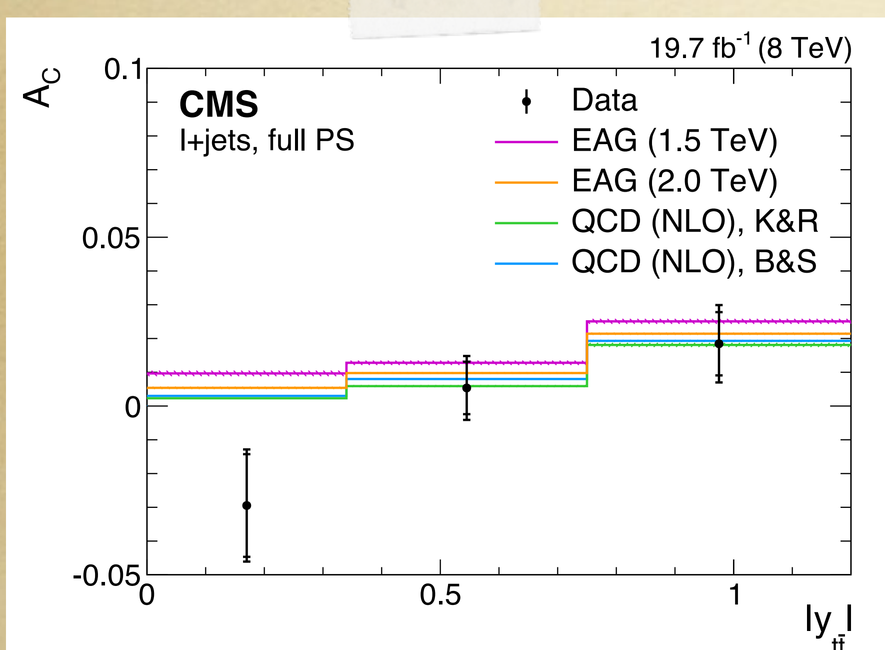
PLB 757 (2016) 154

- ★ Background subtracted distributions of $\Delta|y|$ are unfolded (TUnfold)
  - — Correction to fiducial volume and full phase space
- ★ Extract A_C from unfolded spectra as functions of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$

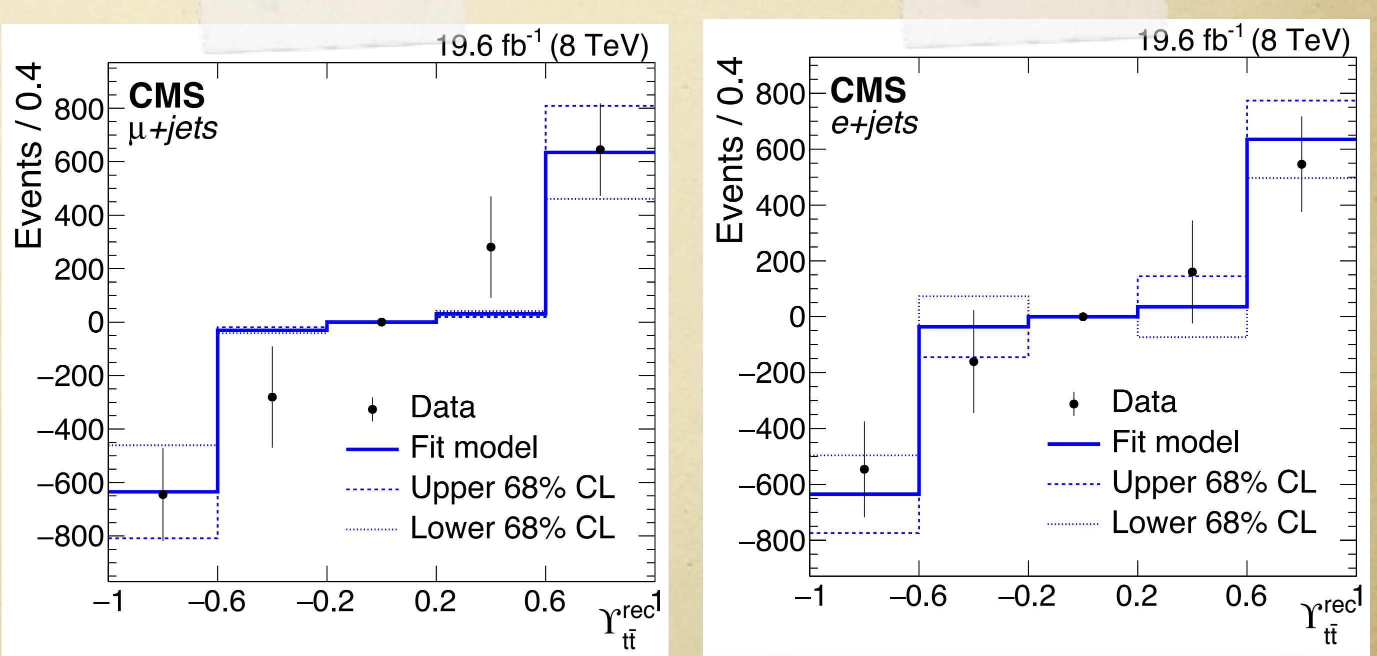
★ Template method

PRD 93, 034014 (2016)

- ★ Observable $Y_{t\bar{t}}$ (changes sign under the exchange $t \leftrightarrow \bar{t}$) $\quad Y_{t\bar{t}} = \tanh(\Delta|y|)$
- ★ Template fit to reconstructed $Y_{t\bar{t}}$ distribution to extract asymmetry parameter
  - — Use Probability density of symmetric and anti-symmetric components



Unfolding method

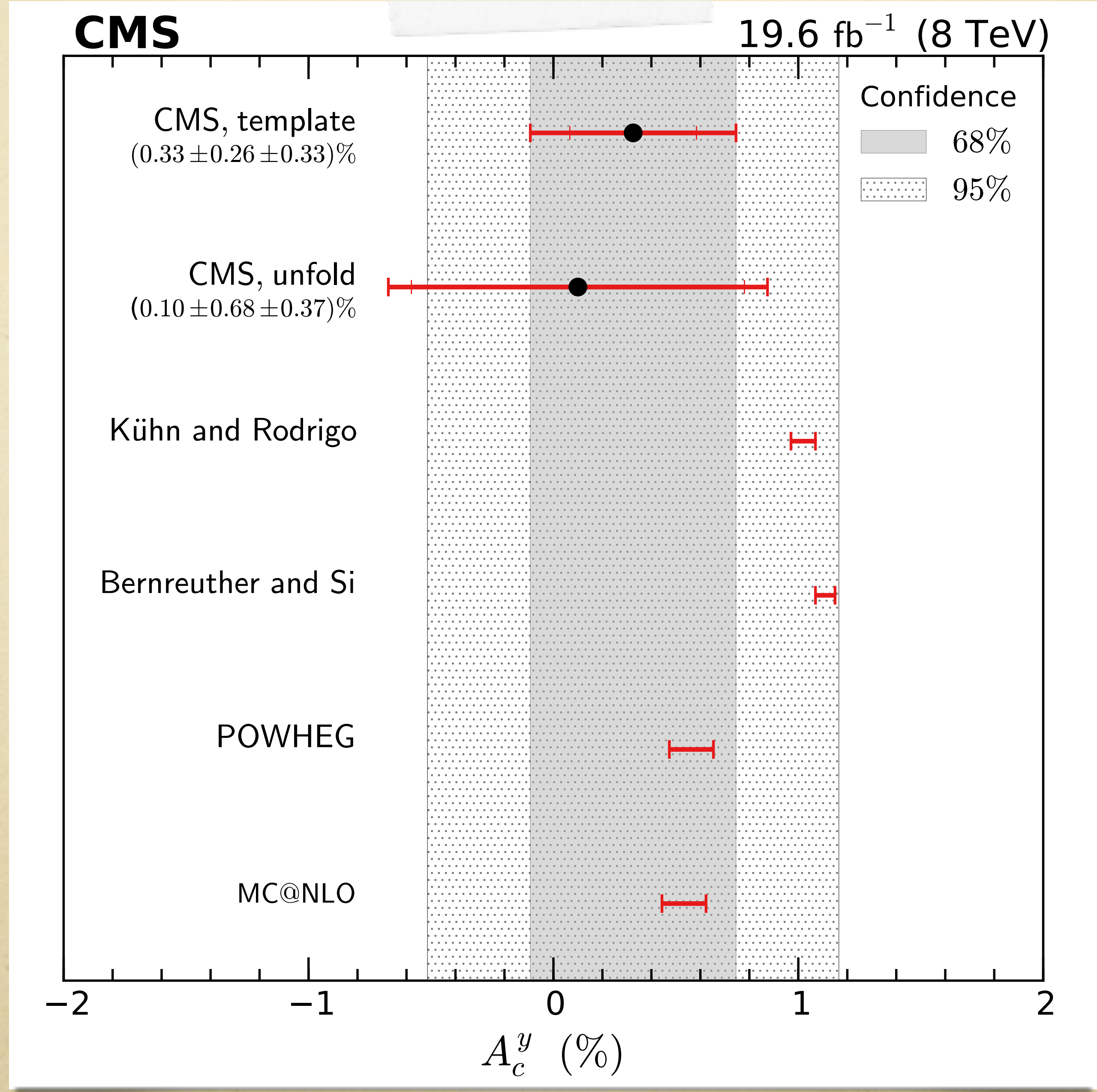


Template method

Charge asymmetry - lepton+jets

★ **Summary of charge asymmetry with lepton+jets channel in CMS**

★ **In agreement with SM predictions.**



Charge asymmetry - dilepton

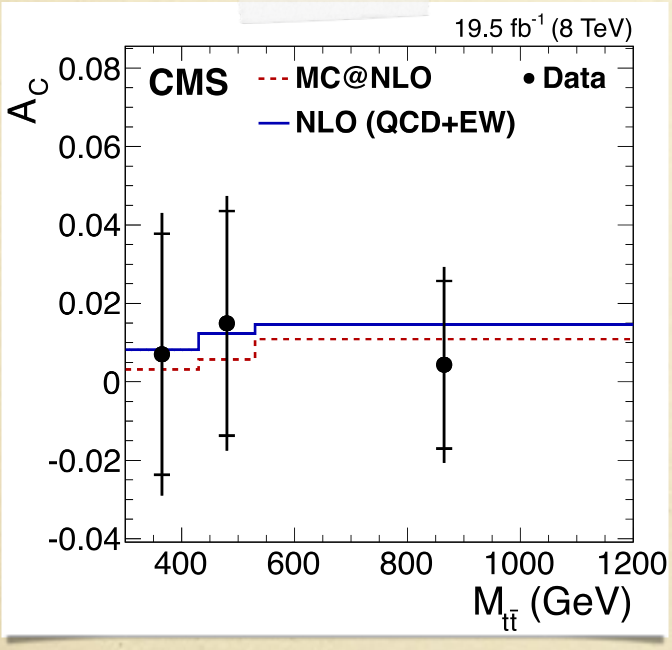
arXiv:1603.06221 (PLB accepted)

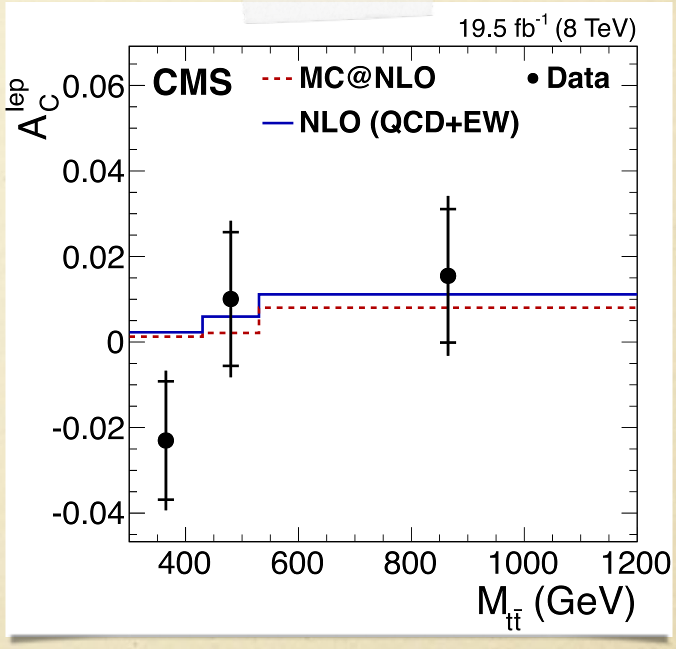
★ Unfolding method

- ★ Additional observable for A_C^{Lep} included
  - — Leptonic charge asymmetry (free from $t\bar{t}$ reconstruction)

$$\Delta(|\eta|) = |\eta^+| - |\eta^-|$$

- ★ Background subtracted distributions of Δ|y| are unfolded (TUnfold)
- ★ Extract A_C and A_C^{Lep} from unfolded spectra as functions of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$





- ★ In agreement with predictions

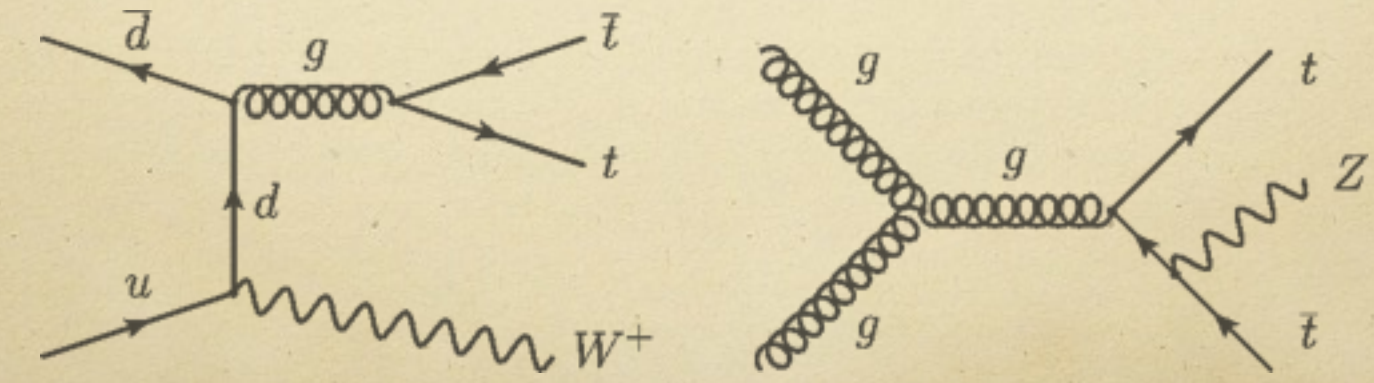
Variable	Data	MC@NLO	NLO (QCD+EW)
A_C	$0.011 \pm 0.011 \pm 0.007$	0.006 ± 0.001	0.0111 ± 0.0004
A_C^{lep}	$0.003 \pm 0.006 \pm 0.003$	0.004 ± 0.001	0.0064 ± 0.0003

Associated production with vector boson

- ★ **Measure couplings of top and vector boson**
  - ★ Important backgrounds for top-Higgs coupling measurements

B. Mellado Garcia, P. Musella, M. Grazzini, & R. Harlander - "CERN Report 4: Part I Standard Model Predictions"

- ★ **$t\bar{t}$+Z/W measurement at 13 TeV** NEW !!! CMS-TOP-16-017
  - ★ 3 analyses with final states of leptons
    - — Same signed 2 leptons : $t\bar{t}$+W
    - — 3 leptons (2 SFOC): $t\bar{t}$+Z
    - — 4 leptons (2 SFOC): $t\bar{t}$+Z [SFOC : Same-Flavor Opposite Charge]
  - ★ Data-driven bkg. estimated for non-prompt leptons, WZ/ZZ (control regions)
  - ★ Boosted Decision Tree (BDT) is used for multivariate analysis in $t\bar{t}$+W
    - — To suppress the mis-reconstruction of $t\bar{t}$
    - — Trained $t\bar{t}$+W and $t\bar{t}$ events as signal and background, respectively.
  - ★ Categorized the observed regions
    - — The number of jets and b jets

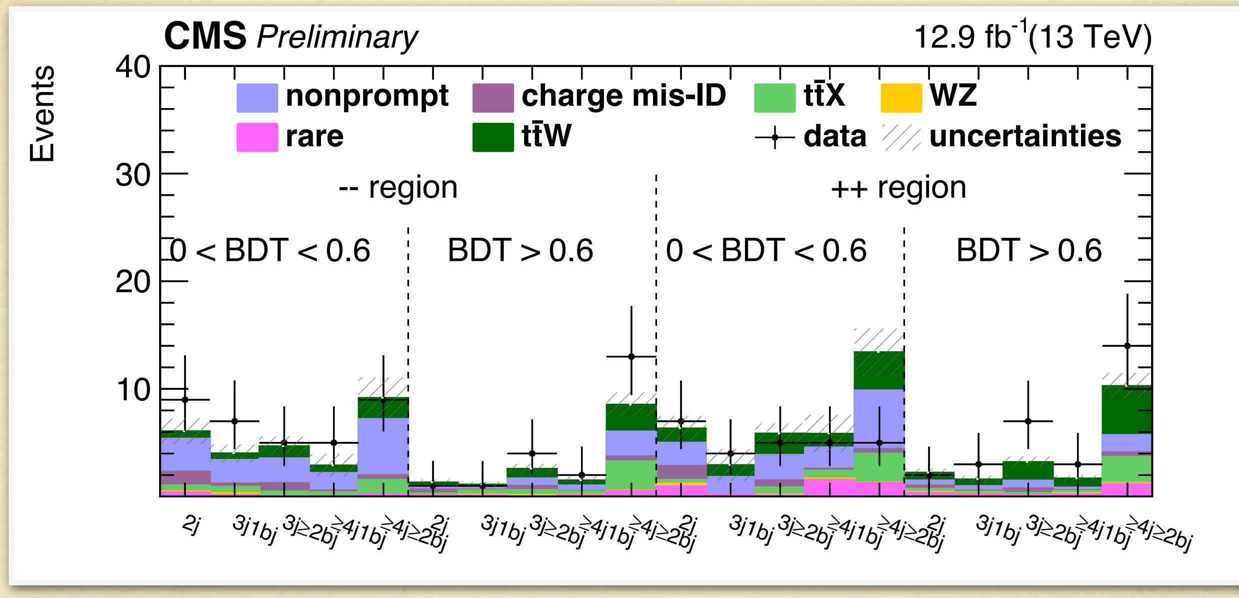


Associated production with vector boson

CMS-TOP-16-017

★ $t\bar{t}$+Z/W measurement at 13 TeV

★ Binned likelihood fit to all categories, including nuisance parameters

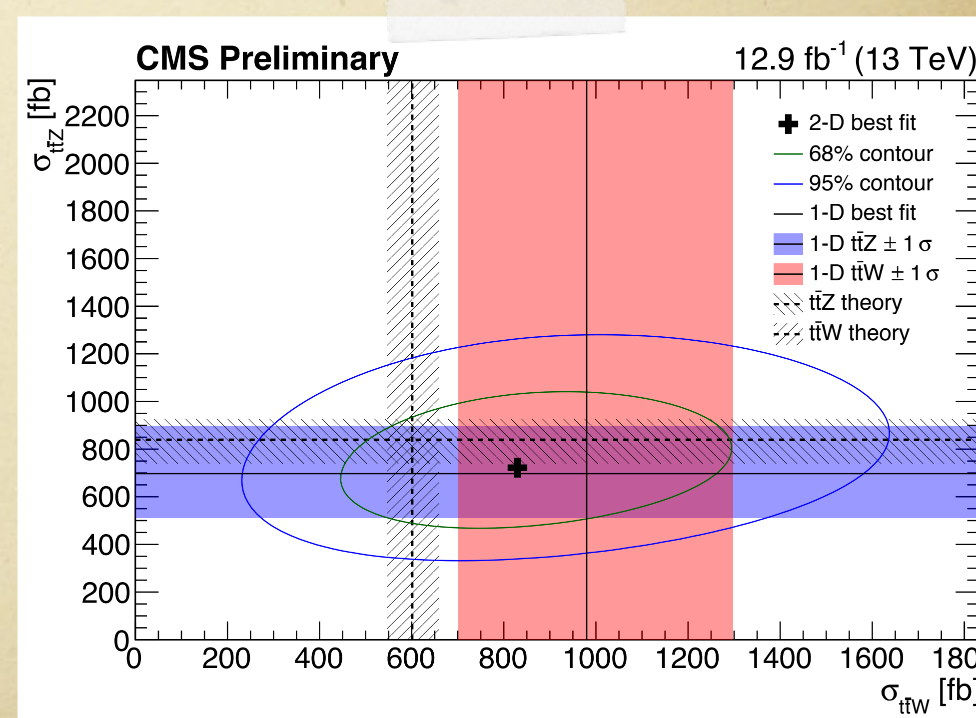


★ In agreement with the SM predictions.

Channel	Expected significance	Observed significance
$2\ell ss$ analysis ($t\bar{t}W$)	2.6	3.9
3ℓ analysis ($t\bar{t}Z$)	5.4	3.8
4ℓ analysis ($t\bar{t}Z$)	2.4	2.8
3ℓ and 4ℓ combined ($t\bar{t}Z$)	5.8	4.6

$$\sigma(\mathrm{pp} \to t\bar{t}Z) = 0.7^{+0.16}_{-0.15}(\mathrm{stat.})^{+0.14}_{-0.12}(\mathrm{syst.})\ \mathrm{pb}$$

$$\sigma(\mathrm{pp} \to t\bar{t}W) = 0.98^{+0.23}_{-0.22}(\mathrm{stat.})^{+0.22}_{-0.18}(\mathrm{syst.})\ \mathrm{pb}$$



Properties related to top-quark pair coupling

* CP violation in $t\bar{t}$
* W-boson helicity fraction
* FCNC

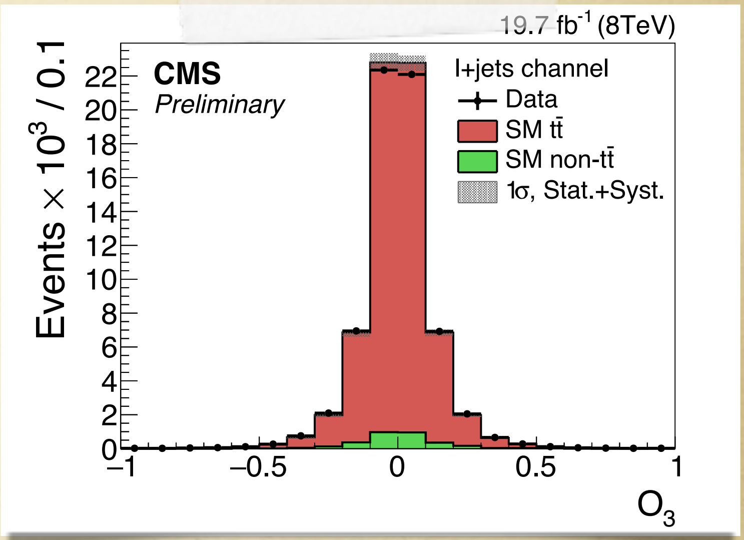
CP Violation in $t\bar{t}$

- ★ **Tiny in the SM, but new physics can enhance CPV**
  - ★ Anomalous couplings in $t\bar{t}$ production and W decays.
  - ★ Measure with 4 T-odd triple-product observables (O_i)
    - — Assume CPT conservation
    - — Observables are calculated by the composition of decays' momenta of $t\bar{t}$ lepton+jets final state.
    - — Present with asymmetry parameter A_{CP}

A. Hayreter & G. Valencia - PLD 93 (2016) 014020
S. K. Gupta, A. S. Mete, and G. Valencia - PLD 80 (2009) 034013

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

CMS-TOP-16-001



- ★ **Results are consistent with SM**
  - ★ No basis in the background.
  - ★ Final A_{CP} after bkg. subtraction are **zero** as in SM.
  - ★ Systematic uncertainties are mostly canceled.

$A'_{CP}(O_i)$	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	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

* The numbers in table are present in % with statistical and systematic uncertainty separately.

W-boson helicity fraction

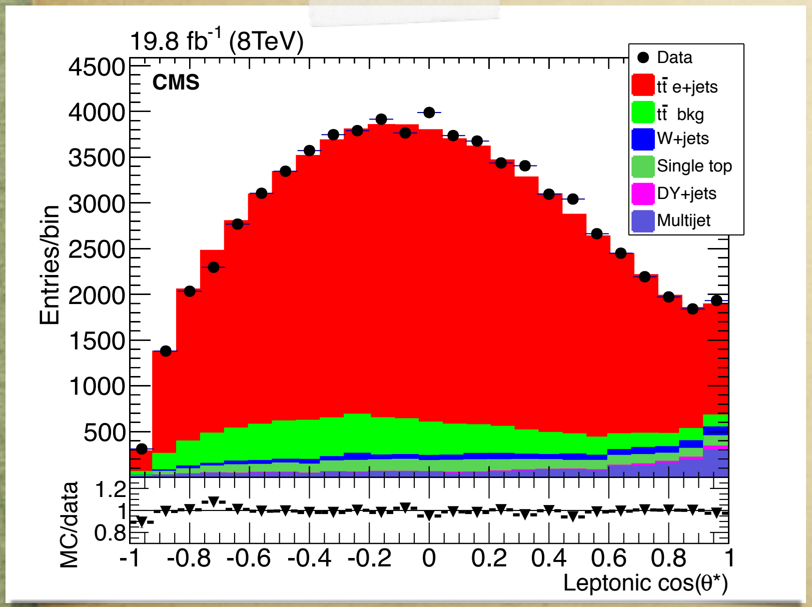
★ **W helicity fractions (F_x) are sensitive to the Wtb vertex structure.**

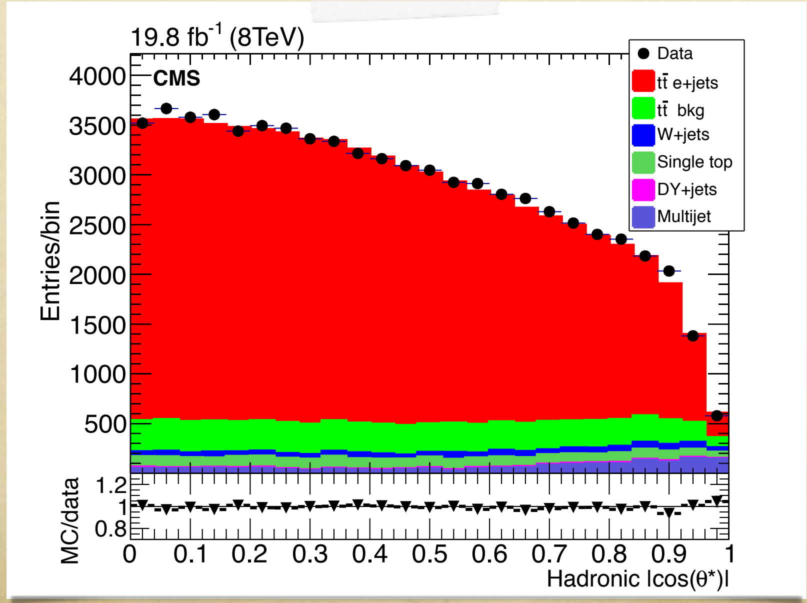
- ★ F_X is the ratio of decay rates ($F_0+F_R+F_L=1$) A. Czarnecki, J. G. Korner & J. H. Piclum - PLD 81 (2010) 111503
  - — F_0 = 0.687 ± 0.005, F_L = 0.311 ± 0.005, F_R = 0.0017 ± 0.0001 (NNLO, $m_b \neq 0$)
- ★ New physics (anomalous Wtb couplings) can alter these values.
- ★ The angle (θ^*) between the **down-type fermion and top boost in W rest-frame.**

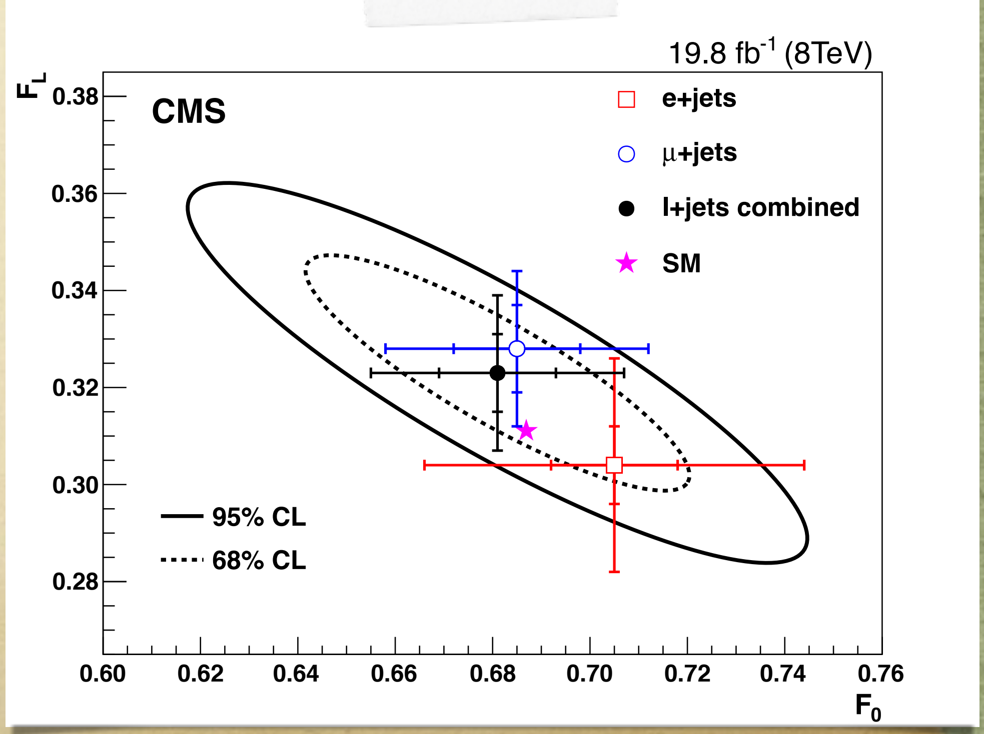
$$\frac{d\sigma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

★ **e/μ + 4 jets (2 b-tagged)** NEW !!! arXiv:1605.09047 (PLB accepted)

- ★ Most precise measurement of helicity fractions to date.
  - — F_0 = 0.681 ± 0.012 (stat) ± 0.023 (syst)
  - F_L = 0.323 ± 0.008 (stat) ± 0.014 (syst)
  - F_R = -0.004 ± 0.005 (stat) ± 0.014 (syst)

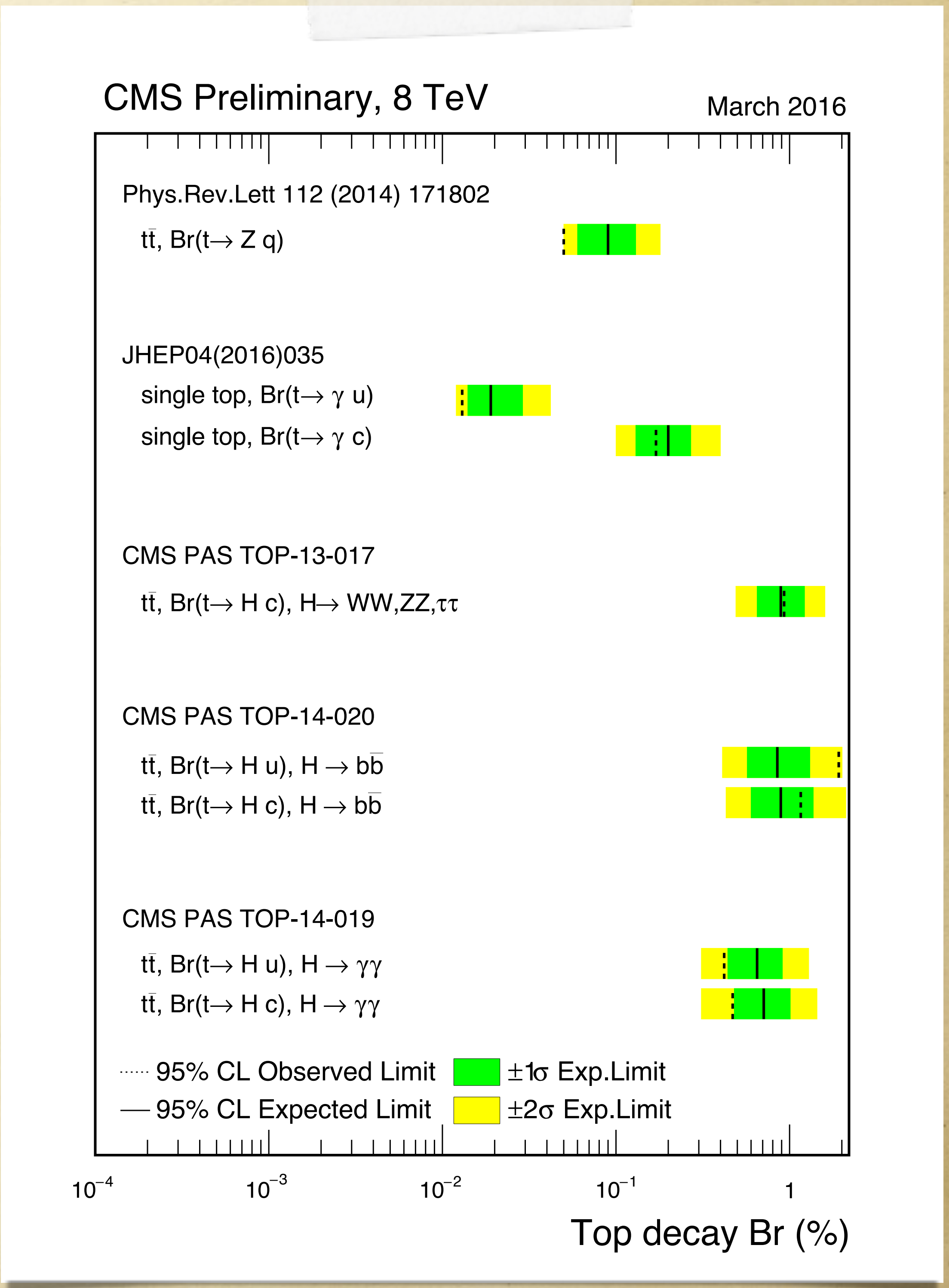




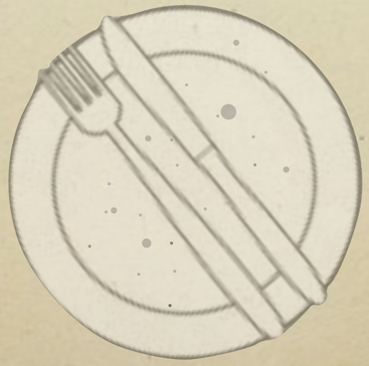


FCNC

- ★ **Summary of top flavor-changing neutral current (FCNC) in CMS**
  - ★ **The rare decay processes are only allowed in higher order diagrams in SM.**
    - — **Tiny branching fractions.**
    - — **New physics can enhance the decay rate.**
  - ★ **Current observed/expected limits for FCNC of top quark in CMS.**
    - — **Measured with $t\bar{t}$ and single top production.**
    - — **New for this conference!**
    - — **Detail in next talk by Abideh Jafari.**



Summary



Summary

★ **Several the top properties have been tested in CMS**
  - ★ Results are in agreement with SM, no hint of new physics.

★ **Related to $t\bar{t}$ production**
  - ★ Spin correlation
    — measure in two different method : unfolding and MEM
  - ★ Charge asymmetry
    — measure in two different method : unfolding and templates fit
  - ★ Associated production with vector boson is studied at 13 TeV data.

★ **Related to $t\bar{t}$ coupling**
  - ★ CP violation
    — No hint of the asymmetry
  - ★ W Helicity fraction.
  - ★ Top FCNC decay
    — Summary of the current limits.

Backup

Spin correlation - dilepton

Sample	ee	$\mu\mu$	eμ	Total
Single top quark (tW, 2 leptons)	298.0 ± 1.6	425.9 ± 1.9	1161.9 ± 3.1	1885.8 ± 4.0
Single top quark (other)	2.6 ± 0.6	4.6 ± 0.9	18.8 ± 1.6	26.1 ± 1.9
$t\bar{t} \to \ell +$ jets	107.1 ± 7.7	62.2 ± 5.4	327 ± 13	497 ± 16
W + jets	7.3 ± 3.6	1.8 ± 1.8	10.0 ± 3.5	19.1 ± 5.3
$Z/\gamma^\star(\to ee/\mu\mu) +$ jets	211 ± 16	368 ± 23	1.6 ± 0.5	581 ± 28
$Z/\gamma^\star(\to \tau\tau) +$ jets	33.9 ± 2.5	51.5 ± 3.0	137.6 ± 5.1	223.0 ± 6.4
WW/WZ/ZZ	27.6 ± 1.4	40.7 ± 1.4	89.3 ± 2.3	157.5 ± 3.0
Triboson	1.5 ± 0.1	2.3 ± 0.2	5.2 ± 0.3	9.0 ± 0.4
$t\bar{t}W/t\bar{t}Z/t\bar{t}\gamma$	86.4 ± 6.5	141.3 ± 8.2	332 ± 13	559 ± 17
Total background	775 ± 20	1098 ± 25	2083 ± 20	3957 ± 38
Data	7089	10074	26735	43898
Signal yield (data − background)	6314 ± 86	8980 ± 100	24650 ± 160	39940 ± 210

Reconstructed asymmetry	Simulation	Data
$A_{\Delta\phi}$	0.188 ± 0.002	0.170 ± 0.005
$A_{\cos\varphi}$	0.114 ± 0.003	0.109 ± 0.005
$A_{c_1c_2}$	-0.050 ± 0.003	-0.049 ± 0.005
A_{P+}	-0.026 ± 0.003	-0.032 ± 0.005
A_{P-}	-0.022 ± 0.003	-0.028 ± 0.005

Asymmetry variable	$A_{\Delta\phi}$	$A_{\cos\varphi}$	$A_{c_1c_2}$	A_P	A_P^{CPV}
Experimental systematic uncertainties					
Jet energy scale	0.001	0.005	0.007	0.018	0.001
Jet energy resolution	<0.001	0.001	0.002	0.003	0.002
Lepton energy scale	0.001	0.002	0.005	0.003	<0.001
Background	0.001	0.001	0.001	0.002	<0.001
Pileup	<0.001	<0.001	<0.001	<0.001	<0.001
b tagging efficiency	<0.001	0.001	0.001	0.001	0.001
Lepton selection	0.001	<0.001	<0.001	0.002	<0.001
$t\bar{t}$ modeling uncertainties					
Parton distribution functions	0.004	0.005	0.005	0.001	<0.001
Top quark p_T	0.011	0.006	0.006	0.004	<0.001
Fact. and renorm. scales	0.002	0.003	0.005	0.002	0.002
Top quark mass	0.001	0.001	0.007	0.008	0.001
Hadronization	0.001	0.004	0.005	0.019	0.003
Unfolding (simulation statistical)	0.002	0.005	0.006	0.003	0.003
Unfolding (regularization)	<0.001	<0.001	<0.001	<0.001	<0.001
Total systematic uncertainty	0.012	0.012	0.016	0.028	0.005

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	—

Spin correlation - lepton+jets

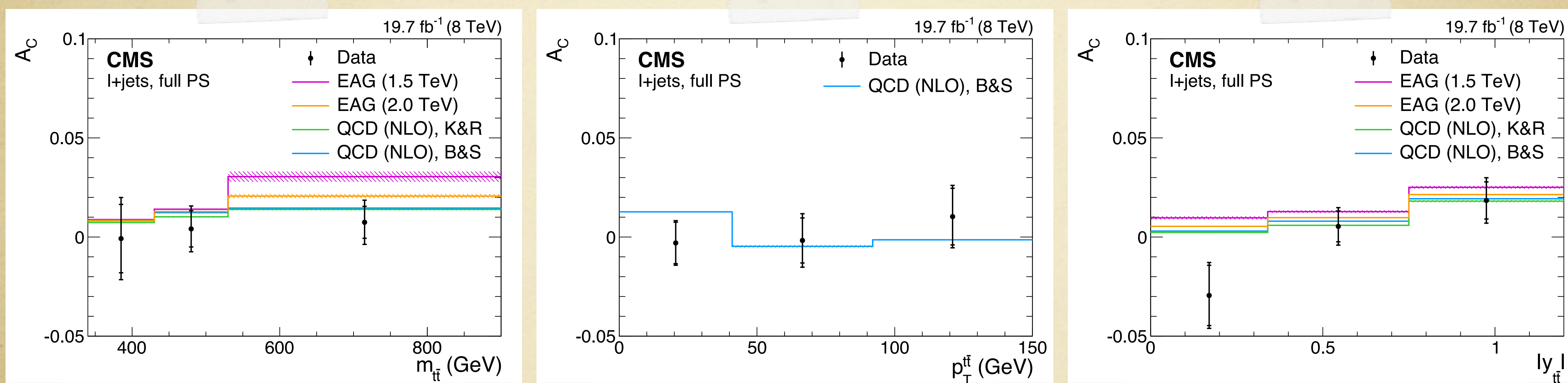
Source of syst. uncer.	Up variation	Down variation
Simulation stat.	0.042	−0.042
Scale	−0.068	0.124
JES	0.051	−0.090
JER	−0.023	−0.004
PDF	0.018	0.045
m_{t}	0.001	−0.034
top quark $p_{\mathrm{T}}^{\mathrm{t}}$ modeling	0.023	—
Background modeling	0.017	−0.016
Pileup	0.012	−0.015
b tagging efficiency	−0.001	0.001
Mistag rate	0.005	−0.006
Trigger	<0.001	<0.001
Lepton ID/Iso	<0.001	<0.001
Calibration	0.003	−0.003
Total syst. uncer.	$^{+0.15}_{-0.13}$	

Process	Yield
W+jets	722 ± 20
Z/γ^*+jets	139 ± 18
$\mathrm{t}, \bar{\mathrm{t}}$ (s channel)	41 ± 3
$\mathrm{t}, \bar{\mathrm{t}}$ (t channel)	314 ± 10
$\mathrm{t}, \bar{\mathrm{t}}$ (tW)	935 ± 20
$\mathrm{t}\bar{\mathrm{t}}$ other	$3\,896 \pm 24$
$\mathrm{t}\bar{\mathrm{t}}$ μ+jets	$31\,992 \pm 69$
Total simulation	$38\,039 \pm 81$
Data	37 775

Charge asymmetry - lepton+jets

★ Unfolding method

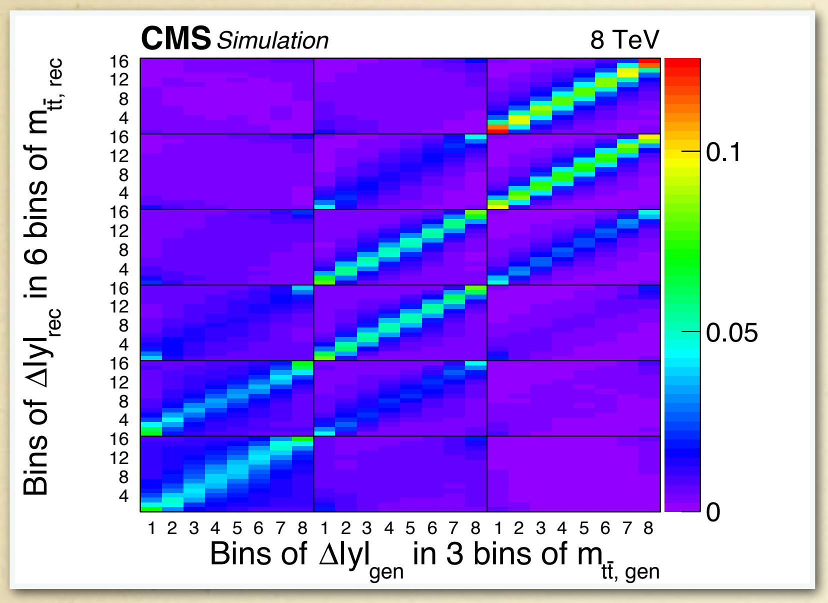
- ★ Background subtracted distributions of Δ|y| are unfolded (TUnfold)
  - — Correction to fiducial volume and full phase space
- ★ Extract A_C from unfolded spectra as functions of $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, and $p_T^{t\bar{t}}$

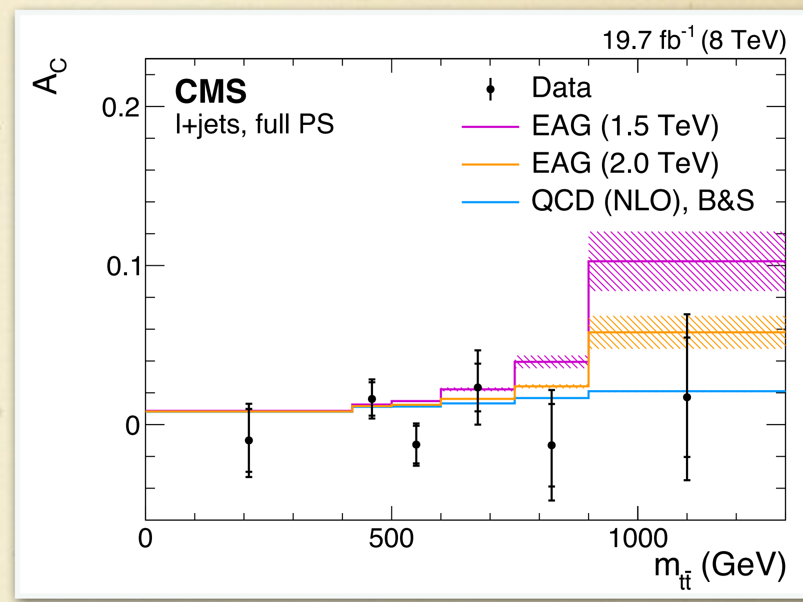


- ★ In agreement with predictions

	Asymmetry (A_C)
Reconstructed	0.0036 ± 0.0017 (stat)
Background-subtracted	0.0008 ± 0.0023 (stat)
Corrected for migration effects	-0.0042 ± 0.0072 (stat)
Fiducial phase space	-0.0035 ± 0.0072 (stat) ± 0.0031 (syst)
Theoretical prediction [Bernreuther, Si] [11, 49]	0.0101 ± 0.0010
Full phase space	0.0010 ± 0.0068 (stat) ± 0.0037 (syst)
Theoretical prediction [Kühn, Rodrigo] [10]	0.0102 ± 0.0005
Theoretical prediction [Bernreuther, Si] [11, 49]	0.0111 ± 0.0004

Charge asymmetry - lepton+jets





Uncertainty source	Inclusive A_C uncertainty		Differential A_C uncertainty	
	fid. PS	full PS	fid. PS	full PS
Jet energy scale	0.0020	0.0018	0.0009–0.0066	0.0008–0.0063
Jet energy resolution	0.0003	0.0003	0.0005–0.0020	0.0005–0.0020
Pileup	0.0006	0.0006	0.0002–0.0027	0.0003–0.0027
b tagging	0.0009	0.0008	0.0002–0.0033	0.0002–0.0032
Lepton selection efficiency	0.0009	0.0009	0.0005–0.0016	0.0005–0.0017
W +jets background	0.0005	0.0007	0.0003–0.0030	0.0005–0.0025
QCD multijet background	0.0010	0.0009	0.0008–0.0030	0.0011–0.0028
Unfolding	0.0012	0.0022	0.0004–0.0023	0.0011–0.0033
Generator	0.0002	0.0005	0.0008–0.0058	0.0007–0.0043
Hadronization	0.0010	0.0011	0.0007–0.0046	0.0008–0.0040
Top quark p_T reweighting	0.0000	0.0002	0.0000–0.0014	0.0001–0.0015
μ_R and μ_F scales	0.0002	0.0007	0.0008–0.0057	0.0009–0.0064
PDF	0.0002	0.0003	0.0004–0.0014	0.0004–0.0012
Total syst. uncertainty	0.0031	0.0037	0.0043–0.0120	0.0041–0.0115
Statistical uncertainty	0.0072	0.0068	0.0078–0.0181	0.0078–0.0172
Total uncertainty	0.0078	0.0077	0.0094–0.0217	0.0094–0.0207

Charge asymmetry - lepton+jets

★ Template method

- ★ **Observable $Y_{t\bar{t}}$ (changes sign under the exchange t ↔ $\bar{t}$)** $Y_{t\bar{t}} = \tanh(\Delta|y|)$
- ★ **Template fit to reconstructed $Y_{t\bar{t}}$ distribution to extract α**
  - — **Probability density of symmetric and anti-symmetric components**

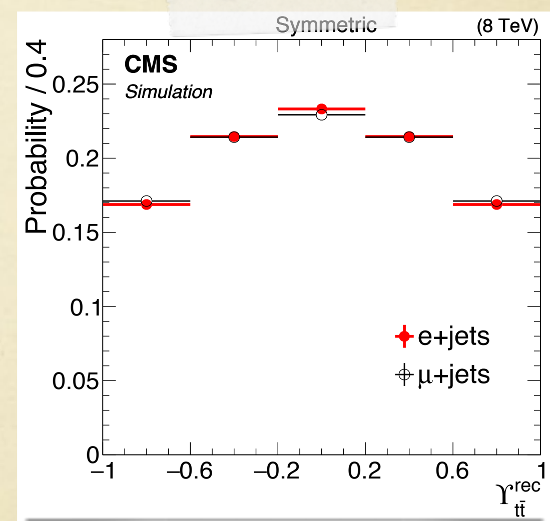
$$\rho(Y_{t\bar{t}}) = \frac{1}{\sigma}\frac{d\sigma}{dY} \longrightarrow \rho^{\pm}(Y_{t\bar{t}}) = [\rho(Y_{t\bar{t}}) \pm \rho(-Y_{t\bar{t}})]/2 \longrightarrow \hat{A}_C^Y = 2\int \rho^{-}\,dY$$

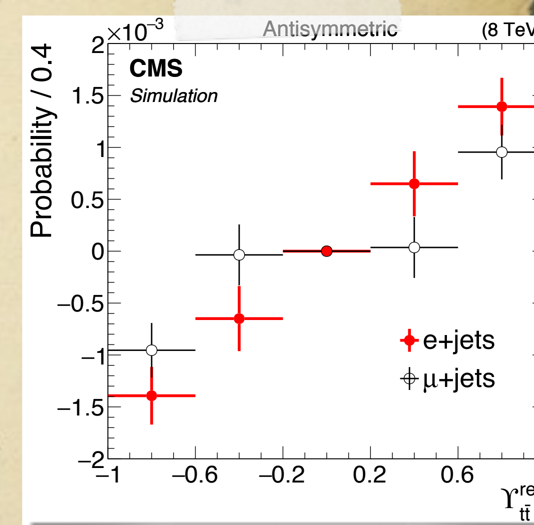
  - — **Fit with these two components to determine α**

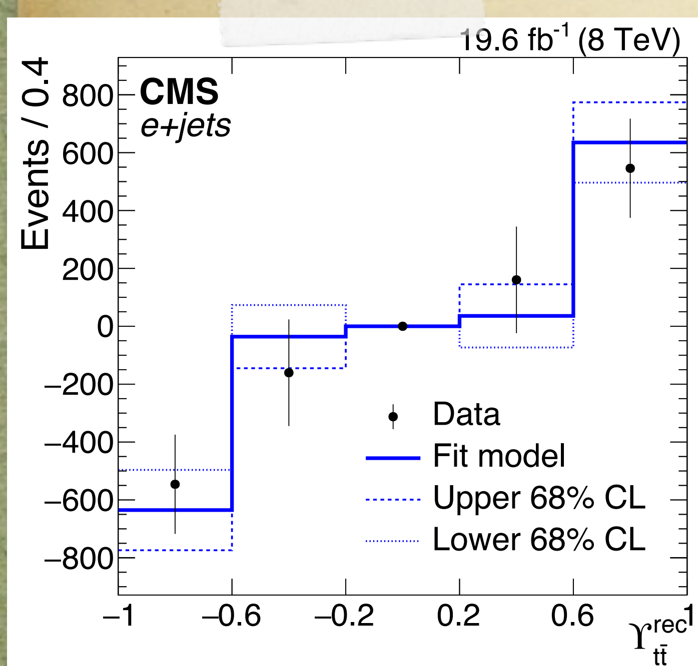
$$\rho(\alpha) = \rho^{+} + \alpha\rho^{-}$$

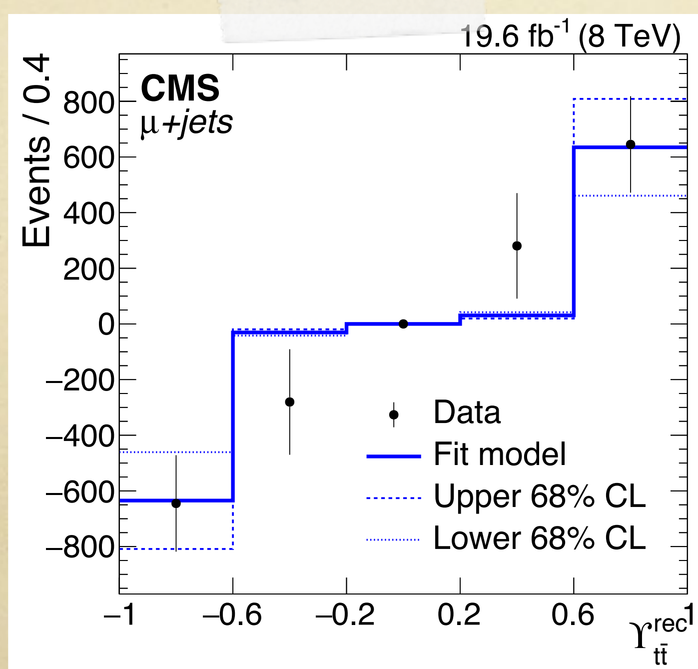
$$A_C^Y = \alpha \hat{A}_C^Y$$

- ★ **In agreement with predictions**





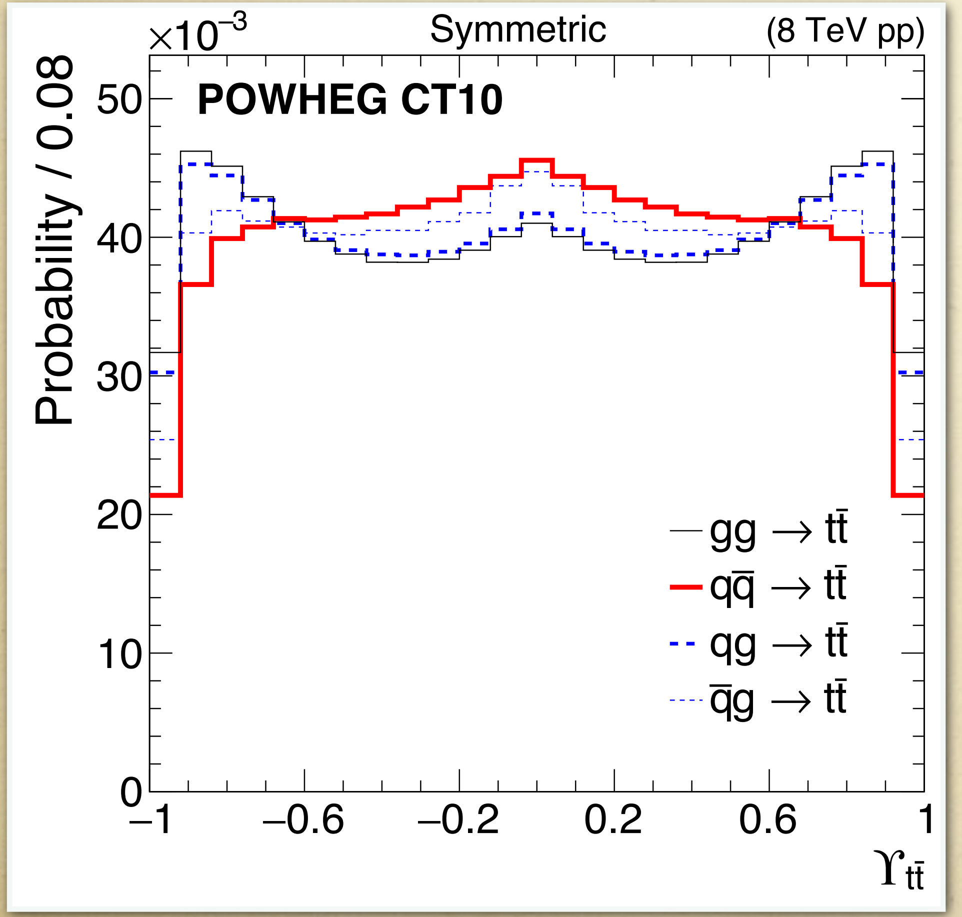


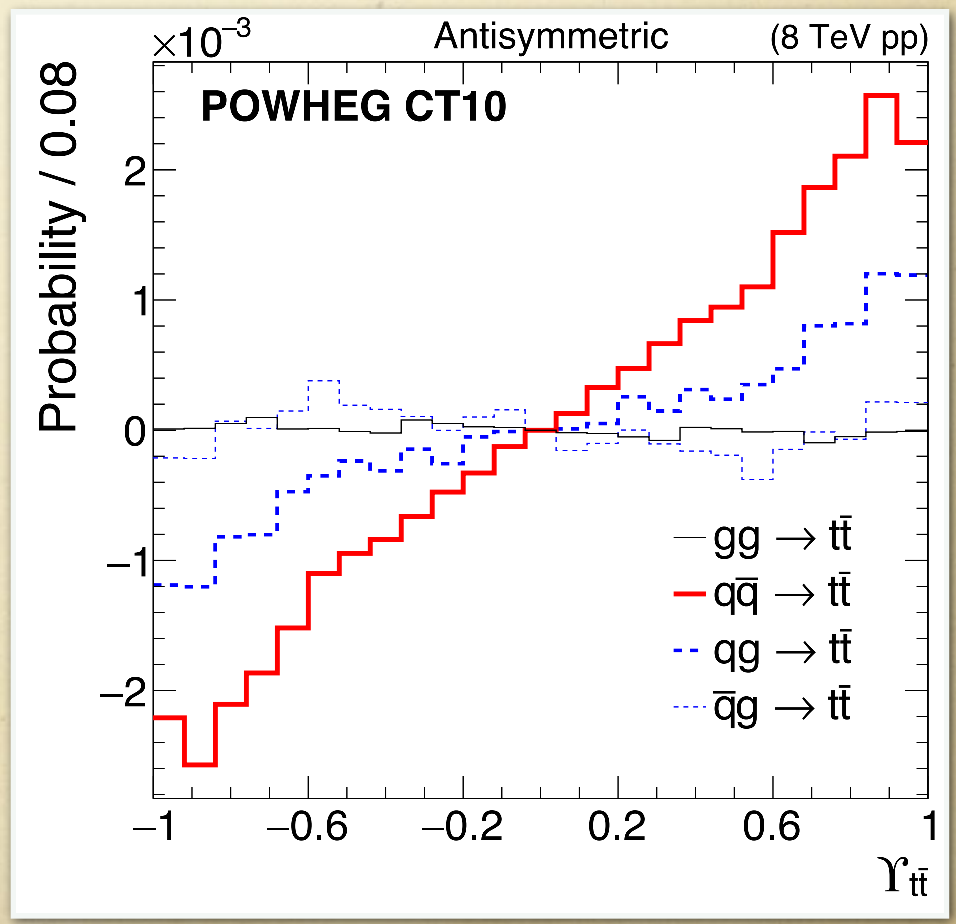


Source	A_c^y (%)
e+jets	0.09 ± 0.34 (stat)
μ+jets	0.68 ± 0.41 (stat)
Combined	0.33 ± 0.26 (stat) ± 0.33 (syst)
POWHEG CT10	0.56 ± 0.09
MC@NLO	0.53 ± 0.09
Kühn and Rodrigo [8]	1.02 ± 0.05
Bernreuther and Si [9]	1.11 ± 0.04

Charge asymmetry - lepton+jets

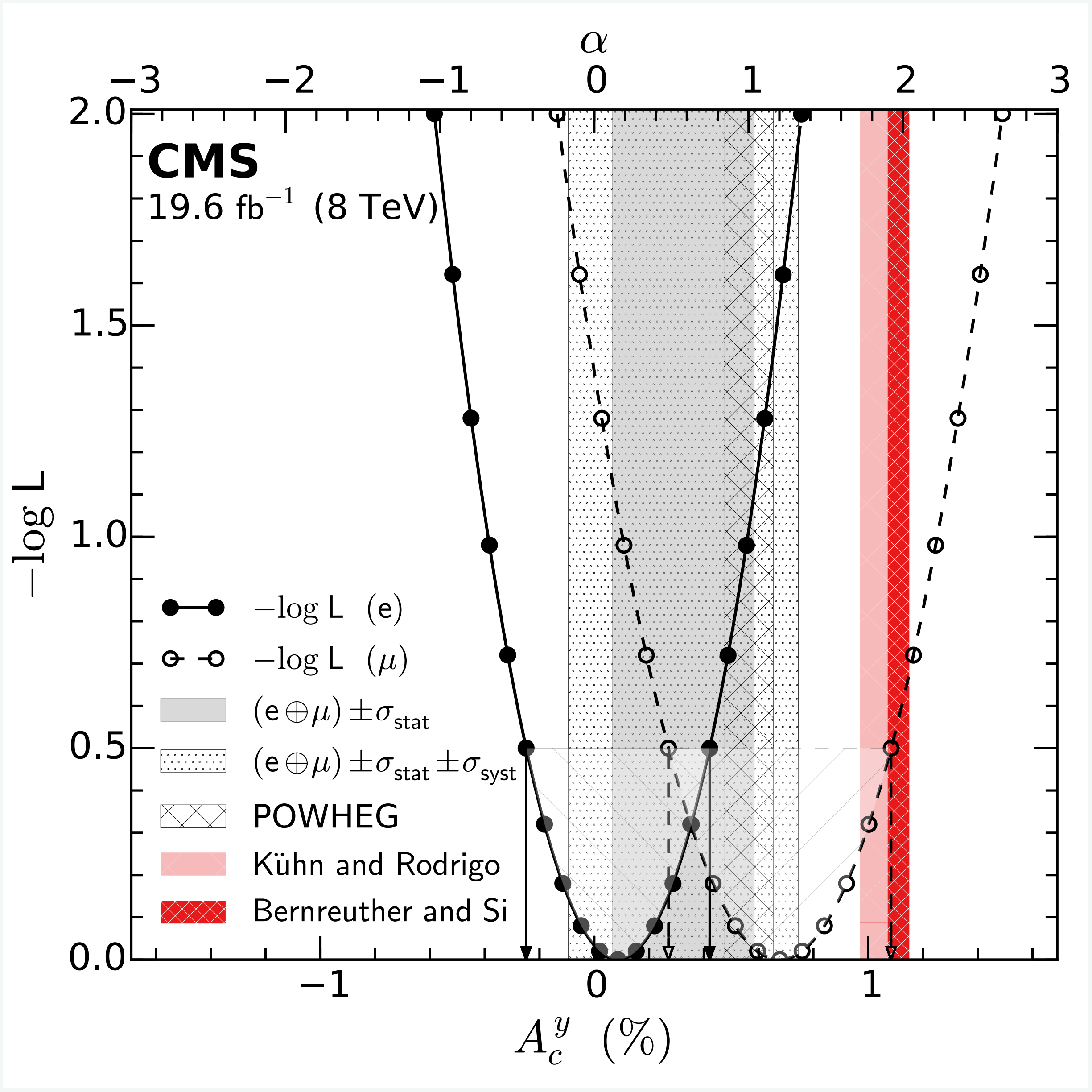
Initial state	Fraction (%)	$\hat{A}_c^y$ (%)
gg	65.2	−0.06(3)
$q\bar{q}$	13.4	2.95(6)
qg	18.2	1.17(5)
$\bar{q}g$	3.2	−0.2(1)
pp	100.0	0.56(2)



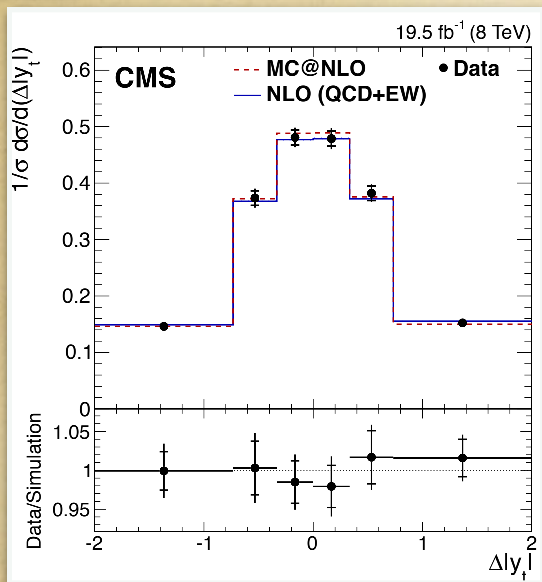


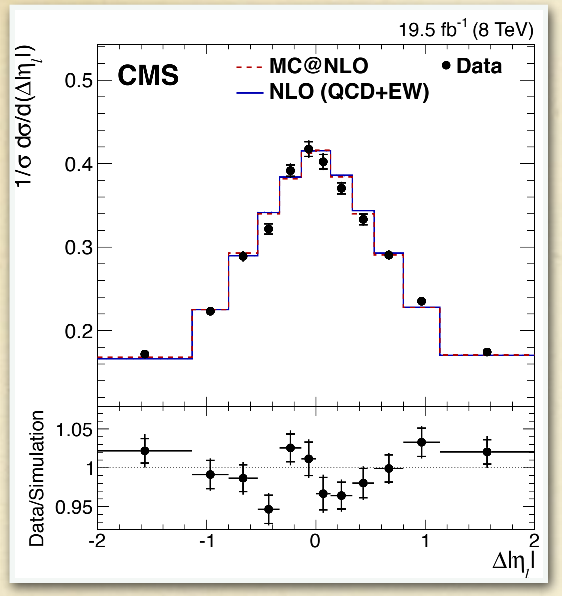
Charge asymmetry - lepton+jets

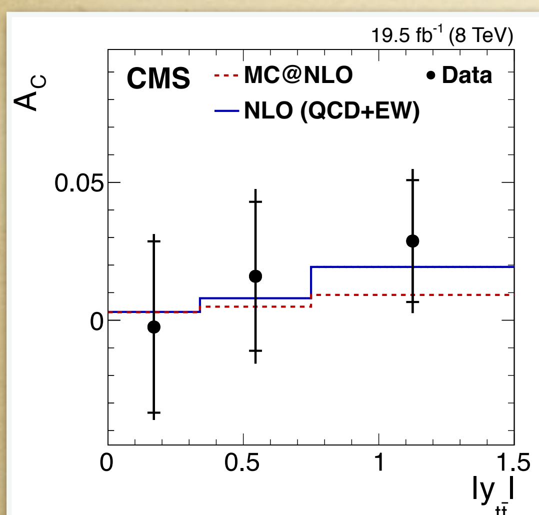
(%)	Source of systematic uncertainty in A_c^y
0.18	Data sideband statistical uncertainty
0.15	Simulation statistical uncertainty
0.14	Jet energy scale
0.14	Renormalization and factorization scales
0.073	Modeling of b tagging
0.037	σ_{St} $(\sigma_{\mathrm{t}} + \sigma_{\bar{\mathrm{t}}})$
0.035	Jet energy resolution
0.026	Modeling of pileup
0.023	W$\mathrm{b\bar{b}}$ content
0.021	Ratio of St cross sections, $\sigma_{\mathrm{t}}/\sigma_{\bar{\mathrm{t}}}$
0.021	Modeling of $\mathrm{t\bar{t}}$ production
0.018	PDFs
$<$0.010	$\mathcal{L}$, σ_{DY}, δ_{Wj}, trigger ϵ_μ, $F^{\mathrm{e}}_{\mathrm{Mj}}$, $\delta_{\mathrm{t\bar{t}}}$, α_s
$<$0.001	Trigger ϵ_{e}, $p_{\mathrm{T}}^{\mathrm{t}}$, $\mathrm{ID_e}$, ID_μ, F^{μ}_{Mj}
0.33	Total

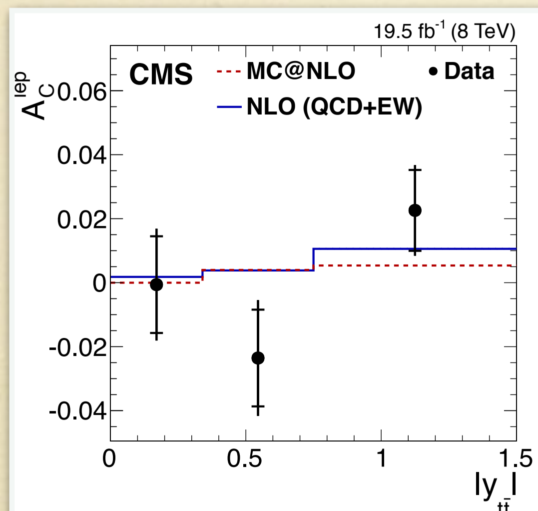


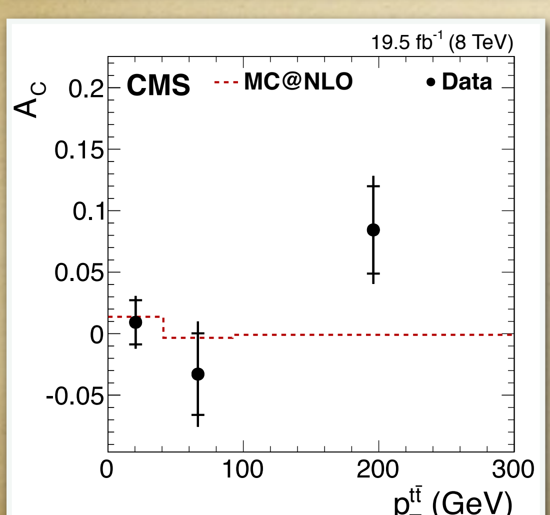
Charge asymmetry - dilepton

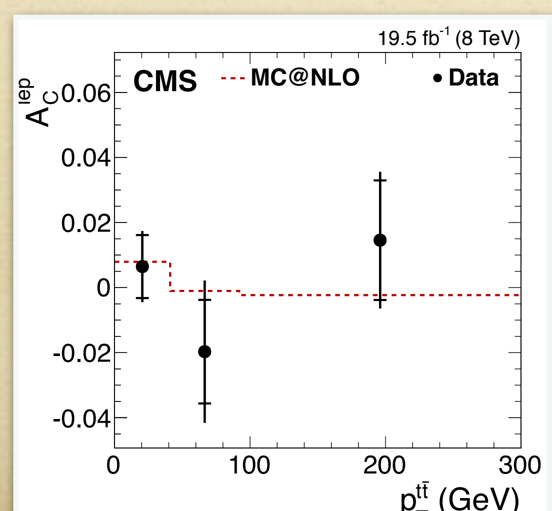








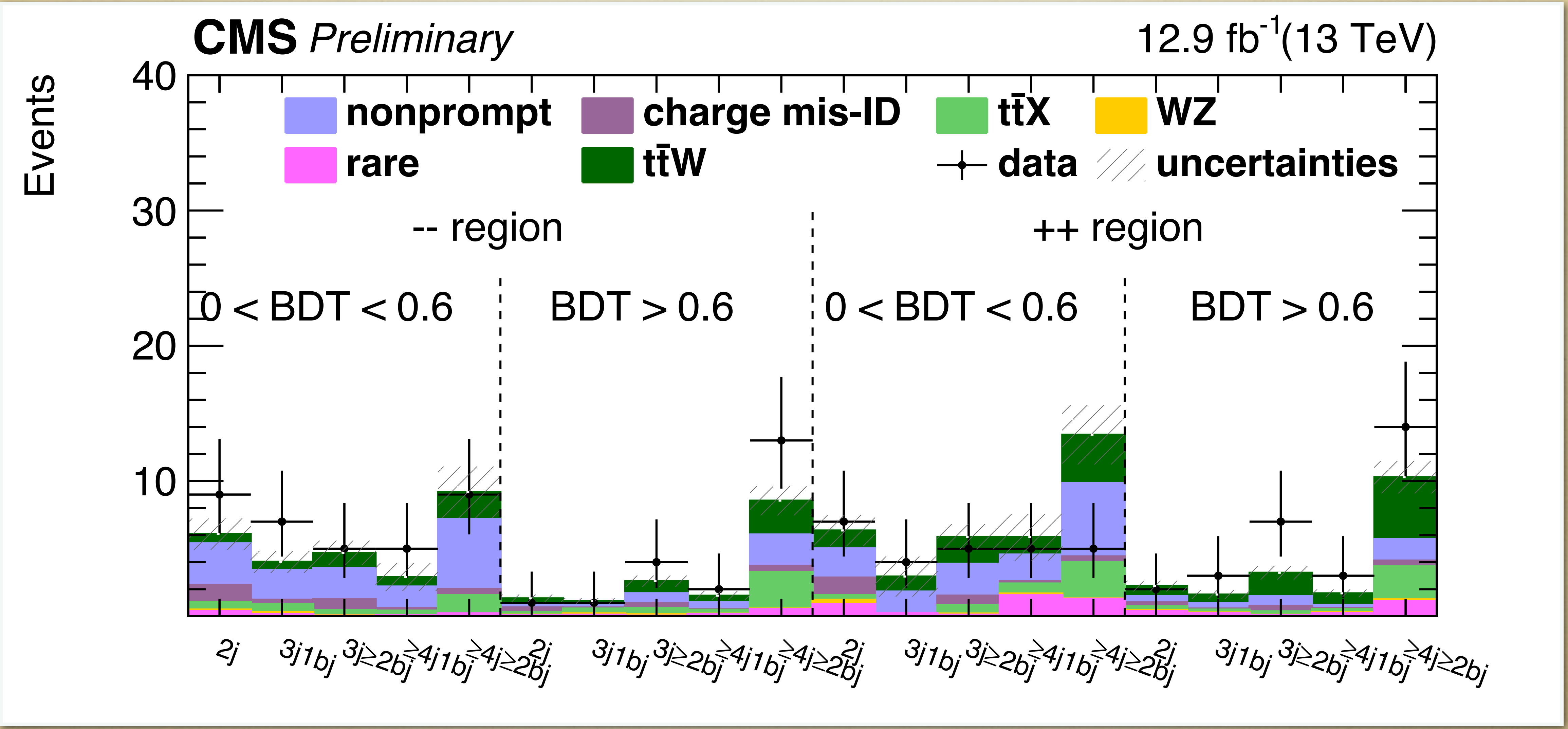




Charge asymmetry variable	A_C	A_C^{lep}
Experimental systematic uncertainties		
Jet energy scale	0.001	<0.001
Jet energy resolution	0.002	<0.001
Lepton energy scale	0.001	<0.001
Background	0.001	0.001
Pileup	<0.001	<0.001
b tagging efficiency	0.001	<0.001
Lepton selection	<0.001	<0.001
$t\bar{t}$ modeling uncertainties		
Parton distribution functions	0.001	0.001
Top quark p_T	0.001	<0.001
Renormalization and factorization scales	0.003	0.002
Top quark mass	0.001	0.001
Hadronization	0.003	<0.001
Unfolding (simulation statistical)	0.005	0.002
Unfolding (regularization)	<0.001	<0.001
Total systematic uncertainty	0.007	0.003

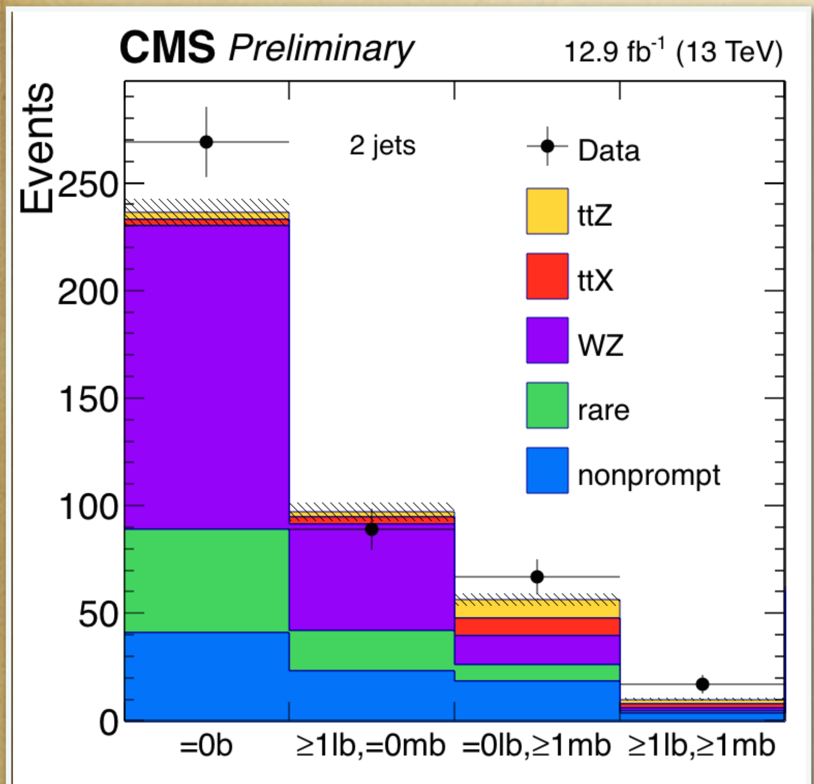
Associated production with vector boson

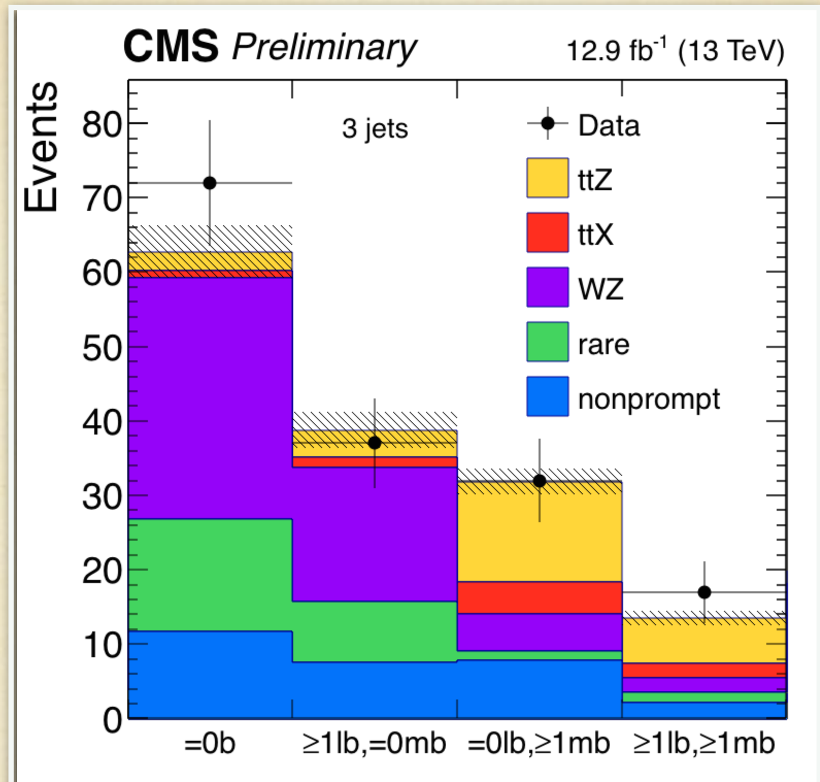
2 leptons

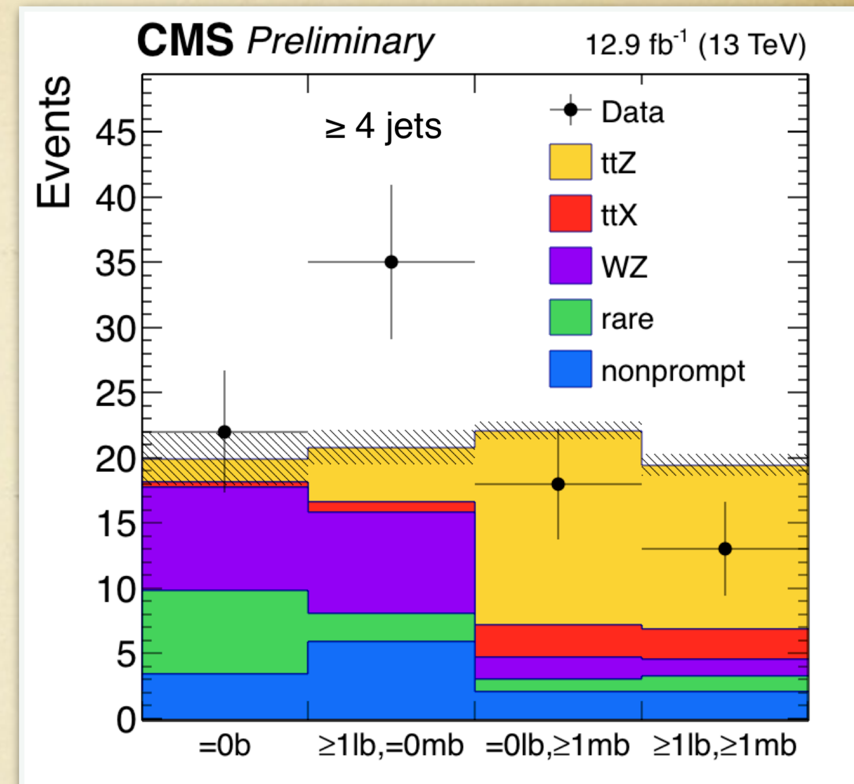


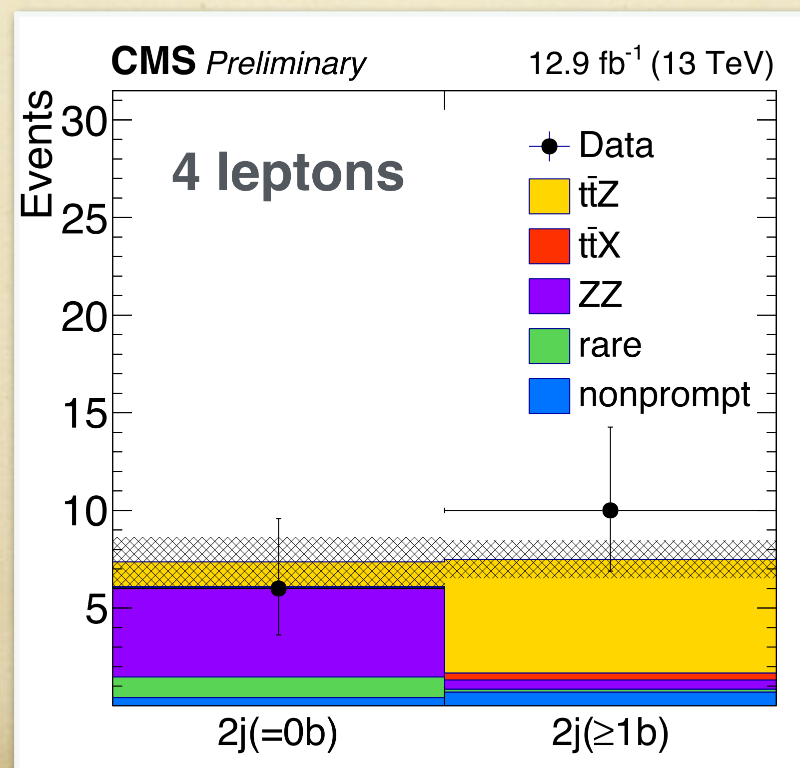
Associated production with vector boson

3 leptons









CP Violation

★ 4 observables

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

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

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

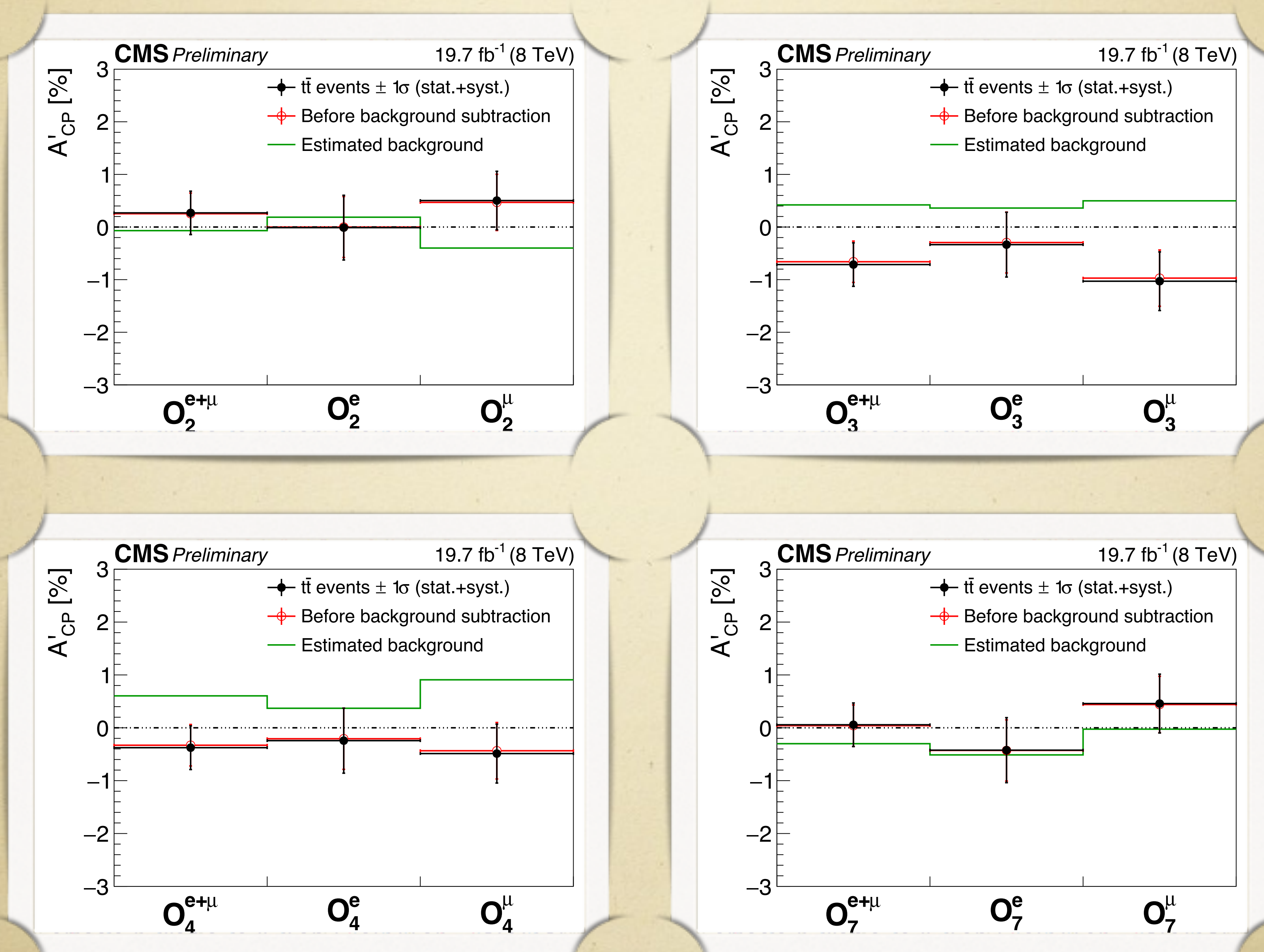
$$O_7 = q \cdot \left(p_b - p_{\bar{b}}\right) \epsilon\left(P, q, p_b, p_{\bar{b}}\right) \xrightarrow{\text{lab}} \propto \left(\vec{p}_b - \vec{p}_{\bar{b}}\right)_z \left(\vec{p}_b \times \vec{p}_{\bar{b}}\right)_z$$

★ No asymmetries in background (data control sample)

$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$+0.19 \pm 0.47$	-0.40 ± 0.51	-0.08 ± 0.34
O_3	$+0.36 \pm 0.47$	$+0.50 \pm 0.51$	$+0.42 \pm 0.34$
O_4	$+0.37 \pm 0.47$	$+0.91 \pm 0.51$	$+0.61 \pm 0.34$
O_7	-0.51 ± 0.47	-0.03 ± 0.51	-0.29 ± 0.34

CP Violation

★ 4 observables are consistent with SM



W-boson helicity fraction

* Systematic uncertainties and coefficient factor

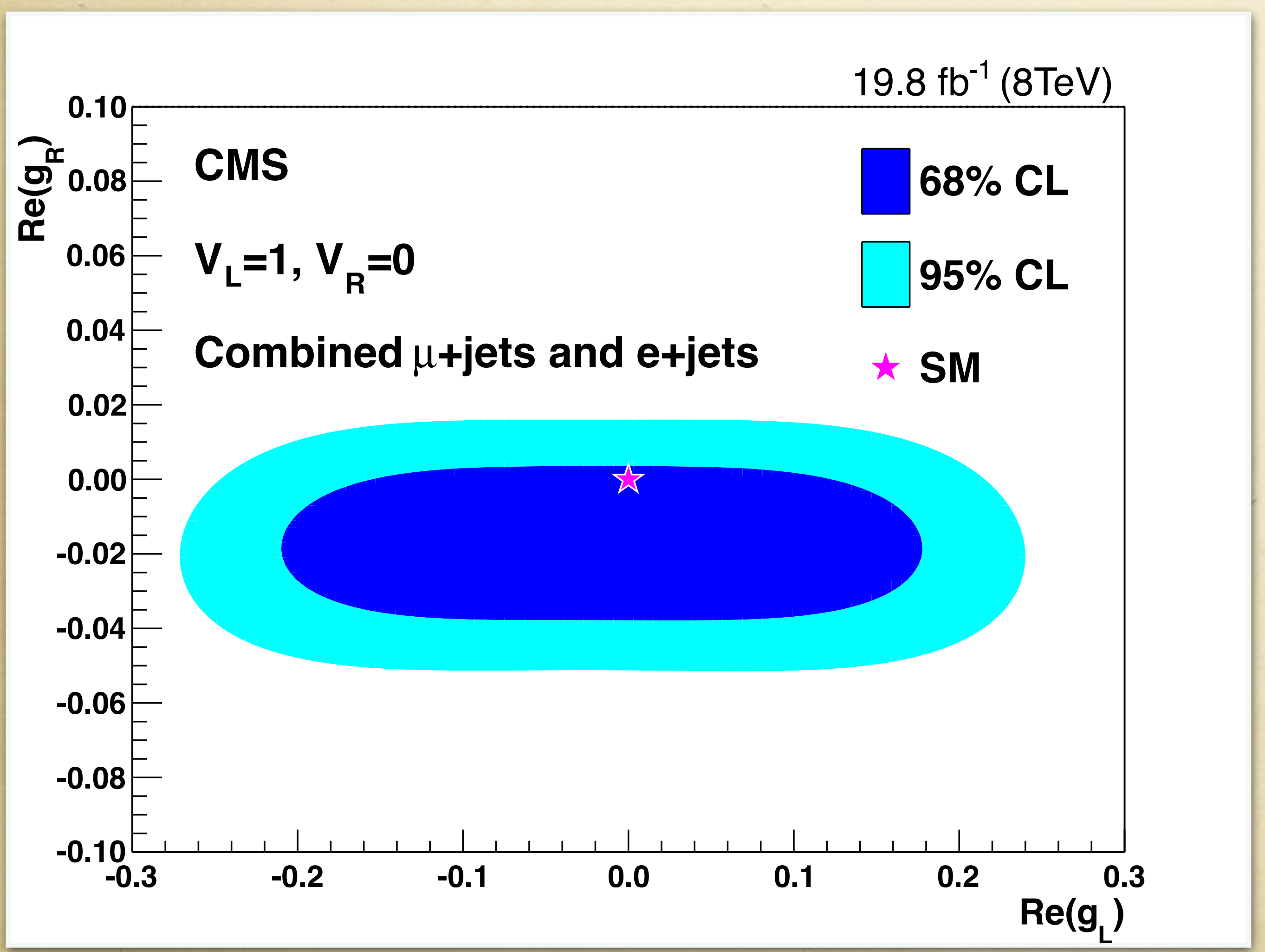
	e+jets			μ+jets			ℓ+jets		
	W boson helicity fractions								
	F_0	F_L	F_R	F_0	F_L	F_R	F_0	F_L	F_R
Value	0.705	0.304	−0.009	0.685	0.328	−0.013	0.681	0.323	−0.004
$\rho_{0,L}$	−0.950			−0.957			−0.959		
	Uncertainties								
	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_R$	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_R$	$\pm\Delta F_0$	$\pm\Delta F_L$	$\pm\Delta F_R$
Statistical	0.013	0.009	0.005	0.013	0.009	0.005	0.012	0.008	0.005
Systematic	0.037	0.020	0.021	0.024	0.014	0.017	0.023	0.014	0.014
Total	0.039	0.022	0.022	0.027	0.016	0.017	0.026	0.016	0.014
	Breakdown of systematic uncertainties								
	$\pm\Delta F_0$	$\pm\Delta F_L$		$\pm\Delta F_0$	$\pm\Delta F_L$		$\pm\Delta F_0$	$\pm\Delta F_L$	
JES	0.004	0.003		0.005	0.003		0.005	0.003	
JER	0.001	0.002		0.004	0.003		0.003	0.003	
b tagging eff.	0.001	$<10^{-3}$		0.001	$<10^{-3}$		0.001	$<10^{-3}$	
Lepton eff.	0.001	0.002		0.001	0.001		0.001	0.001	
Single top normal.	0.002	$<10^{-3}$		0.003	0.001		0.003	0.001	
W +jets bkg.	0.008	0.001		0.007	0.001		0.007	0.001	
DY+jets bkg.	0.002	$<10^{-3}$		0.001	$<10^{-3}$		0.001	$<10^{-3}$	
Multijet bkg.	0.023	0.007		0.007	0.003		0.008	0.001	
Top quark mass	0.012	0.008		0.010	0.008		0.010	0.007	
$t\bar{t}$ scales	0.011	0.008		0.014	0.007		0.012	0.007	
$t\bar{t}$ match. scale	0.011	0.007		0.010	0.007		0.009	0.007	
Hadronisation	0.015	0.009		0.005	0.003		0.006	0.004	
Limited MC size	0.002	0.001		0.002	0.001		0.002	0.001	
Pileup	0.001	0.001		$<10^{-3}$	$<10^{-3}$		0.001	$<10^{-3}$	
$t\bar{t}$ p_T reweight	0.011	0.010		$<10^{-3}$	0.001		$<10^{-3}$	0.002	
PDF	0.004	0.001		0.002	0.001		0.002	0.001	

W-boson helicity fraction

★ **BSM contributions to Wtb vertex modify helicity fraction**

★ **In the effective operative framework Wtb vertex can be parametrized**

$$\mathcal{L}_{\mathrm{Wtb}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\,t\,W_{\mu}^{-} + \mathrm{h.c.},$$



$SM: V_L = V_{tb} \approx 1$

$V_R = g_L = g_R = 0$