Anomalous top quark couplings, FCNC, and EFT interpretations in CMS

30^{th} Rencontres de Blois

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on behalf of the CMS Collaboration

Blois, France
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

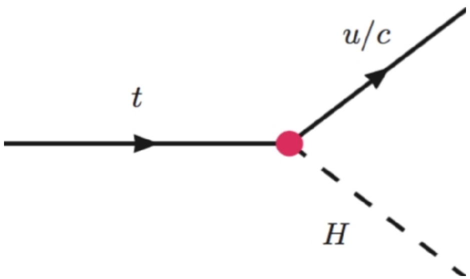
Evidence for new physics may appear in top quark measurements

Top quark heaviest elementary particle → **enhanced sensitivity to new physics?**

Decay t→bW by far **dominant**

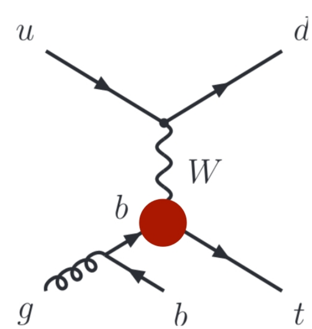
Precision measurements of production and decay probe for new physics

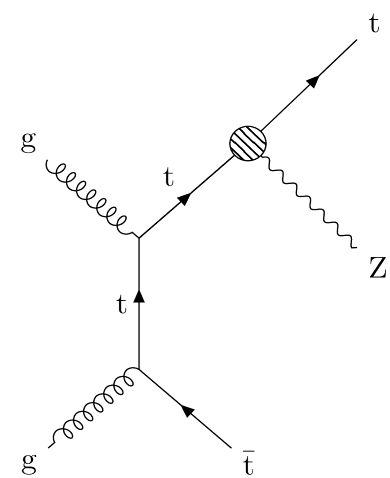
Physics beyond the standard model



Search for extremely rare top quark decay or production modes via **Flavor-changing neutral currents (FCNC)**

Study **nature of Wtb vertex and $t\bar{t}g$ coupling** via properties of top quark production and decay products





Interpret measurements in **Effective Field Theory (EFT) framework** parameterizing new physics

Flavor-Changing Neutral Currents

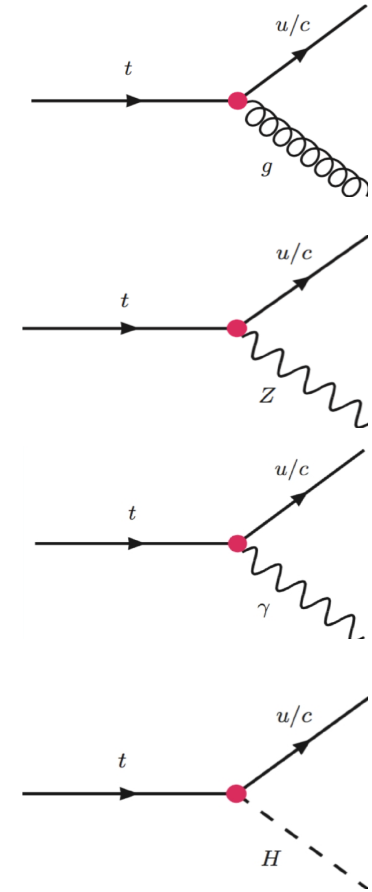
FCNC forbidden at tree level in SM,
suppressed by GIM mechanism at higher orders

Top quark **coupling** (κ) with up/charm quark via g, Z, γ, H may appear in top quark **production or decay**

$$\mathcal{L} = \sum_{q=u,c} \Big[\sqrt{2}\, g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R)\, q\, G^a_{\mu\nu}$$
$$+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R)\, q\, Z_{\mu\nu}$$
$$- e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t}\, \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R)\, q\, A_{\mu\nu}$$
$$+ \frac{g}{\sqrt{2}} \bar{t}\, \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R)\, q\, H \Big] + \text{h.c.}$$

BSM models predict sizable FCNC branching fractions

	SM	2HDM	MSSM	RS
BF(t→cg)	10^{-12}	$10^{-8} – 10^{-4}$	$10^{-7} – 10^{-6}$	10^{-10}
BF(t→cZ)	10^{-14}	$10^{-10} – 10^{-6}$	$10^{-7} – 10^{-6}$	10^{-5}
BF(t→cγ)	10^{-14}	$10^{-9} – 10^{-7}$	$10^{-9} – 10^{-8}$	10^{-9}
BF(t→cH)	10^{-15}	$10^{-5} – 10^{-3}$	$10^{-9} – 10^{-5}$	10^{-4}



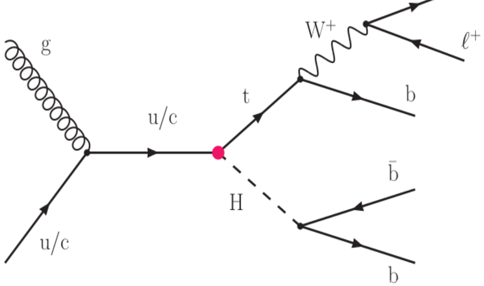
arXiv:1311.2028

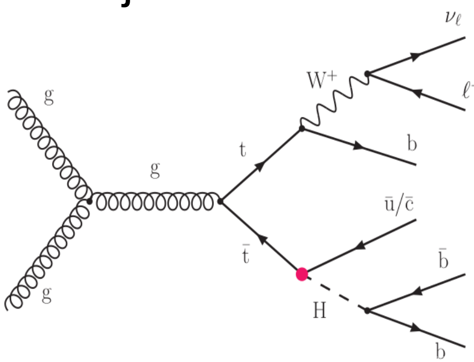
FCNC t→qH in $t\bar{t}$ and single top

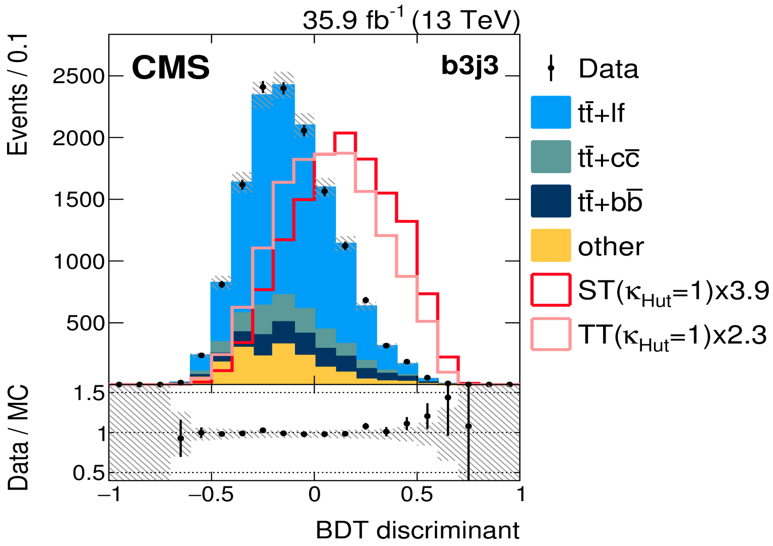
CMS-TOP-17-003
arXiv:1712.02399
36 fb^{-1}, 13 TeV

First t→qH search to include single top process

Targeting **H→$b\bar{b}$ decay** in ℓ+jets channel



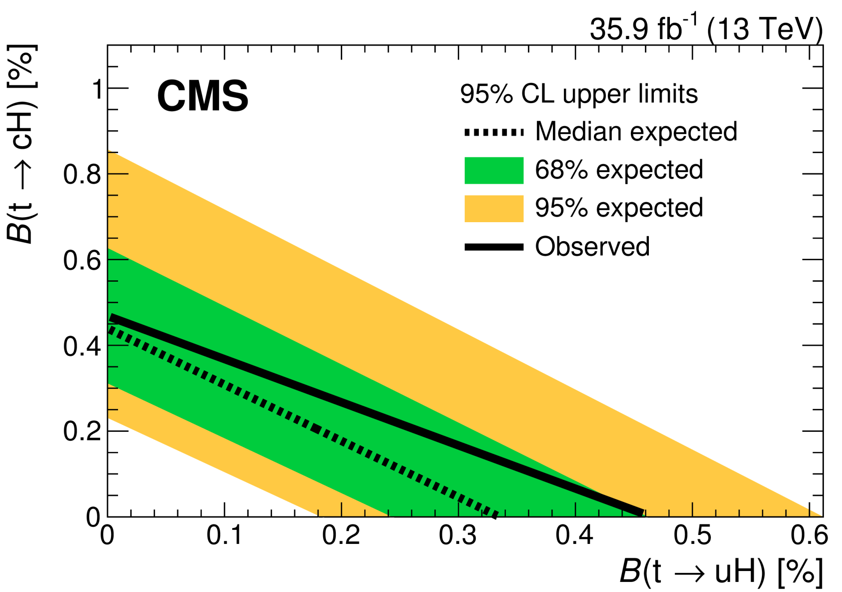




Five **event categories** based on number of jets and b jets

Discriminating variables e.g. lepton charge, b tag discriminant of jet associated to H, $m_{b\bar{b}}$

→ input for **BDTs trained in each category** to separate signal events, with either Hut or Hct coupling, from SM background

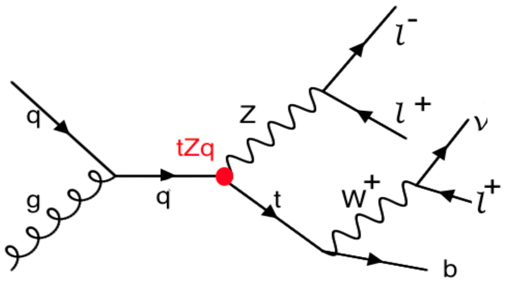


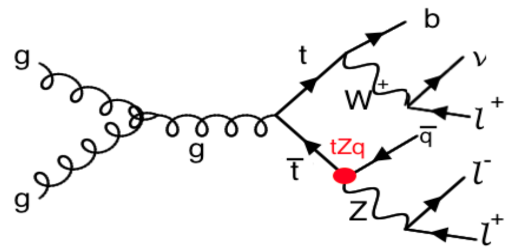
CMS-PAS-TOP-17-017

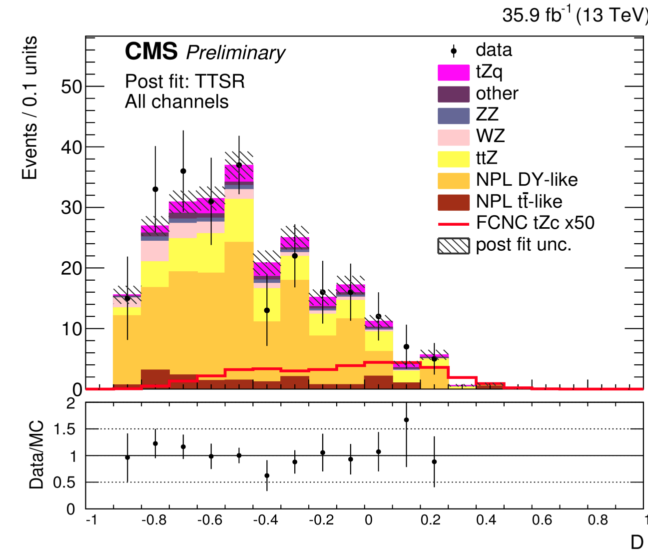
36 fb^{-1}, 13 TeV

FCNC $t \to qZ$ in $t\bar{t}$ and single top

Targeting **3-lepton final state** (OSSF dilepton pair)

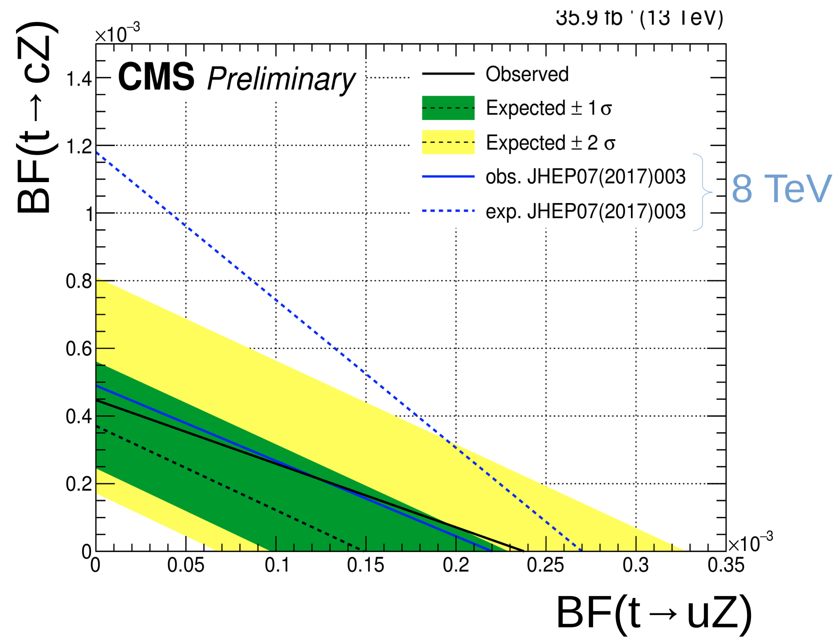






4 lepton channels, and **3 control regions** (for WZ and non-prompt backgrounds) and **2 signal regions** (for single top and $t\bar{t}$ FCNC)

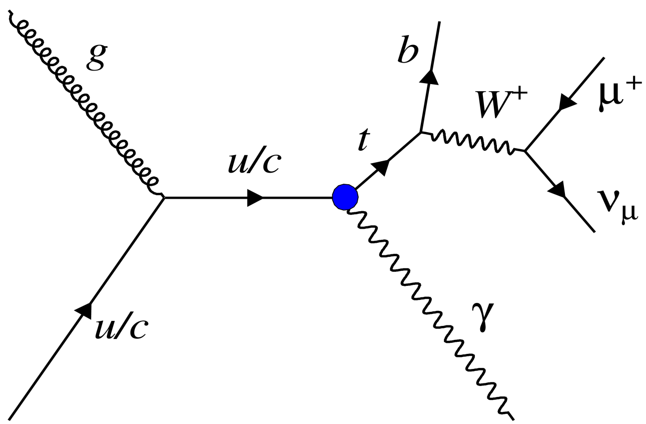
Discriminating variables using angular distances, masses and b tag information → input for **BDTs trained in each signal region** and lepton channel to separate either single top or $t\bar{t}$ FCNC signal from SM background

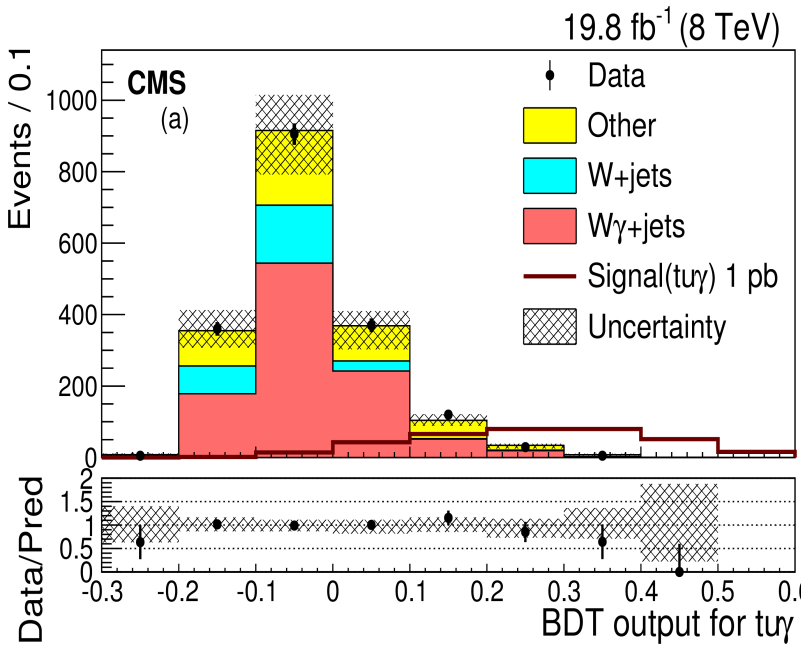


FCNC t→qγ in single top

CMS-TOP-14-003
JHEP 04 (2016) 035
20 fb^{-1}, 8TeV

Targeting **single top tγ with t→bW** in muon channel





Main **W(+γ) backgrounds estimated** from fit of neural network discriminants to data

Discriminating variables
e.g. photon p_T, b tag discriminant, ΔR(γ,b)
→ **input for BDTs** trained to discriminate signal against these backgrounds

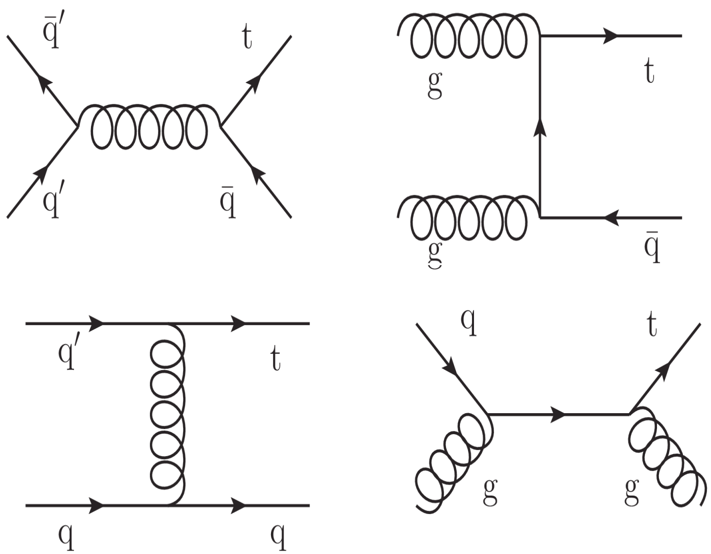
Upper limits on anomalous couplings and branching fractions

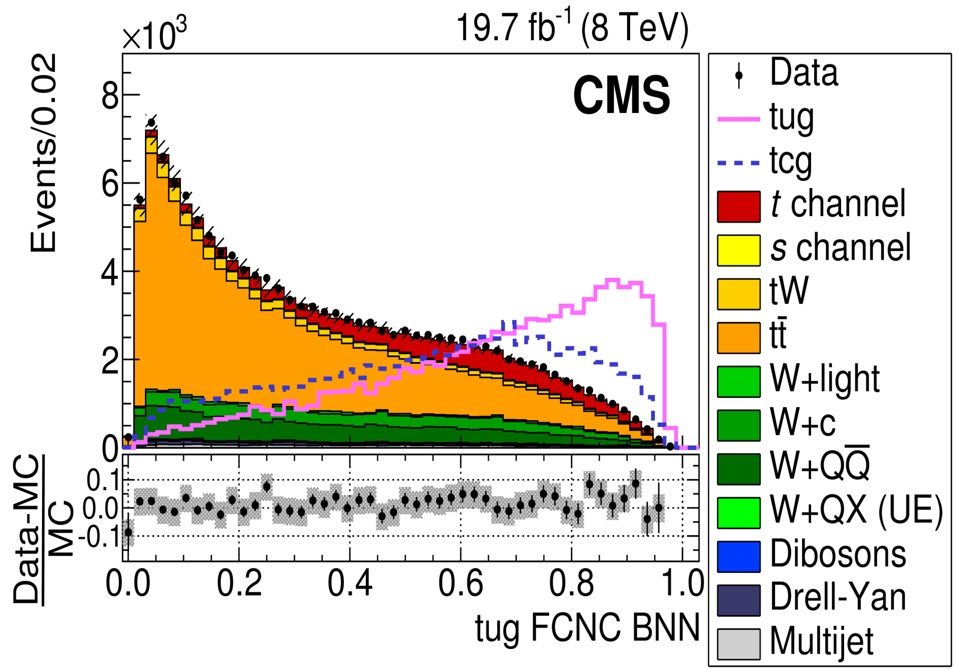
BF(t→uγ) < 0.013 % (obs)
< 0.019 % (exp)
BF(t→cγ) < 0.170 % (obs)
< 0.200 % (exp)

at 95% CL

CMS-TOP-14-007
JHEP 02 (2017) 028
5+20 fb^{-1}, 7+8 TeV

FCNC t→qg in single top





Targeting **muon channel**

Control regions to validate W+jets and tt̄ modeling; neural network to suppress multijet

Bayesian neural networks, discriminate
- single top *t* channel vs background
- FCNC signal vs SM background

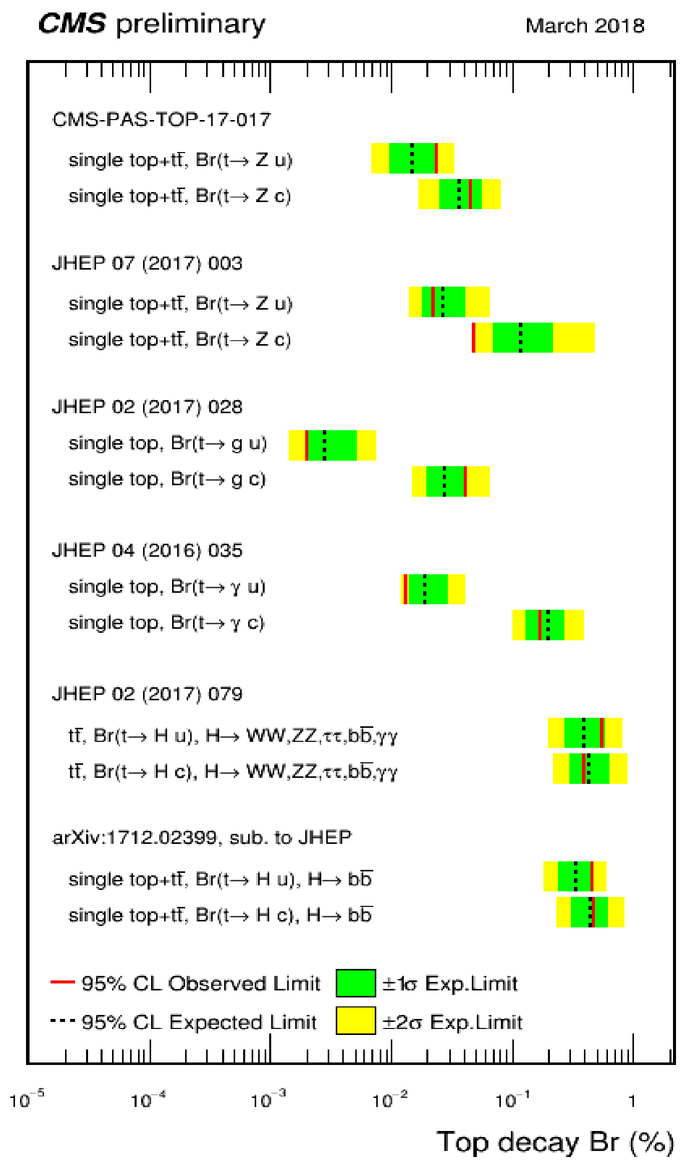
variables: e.g. light-flavor jet p_T, muon charge

→ signal extraction via **fits to data**

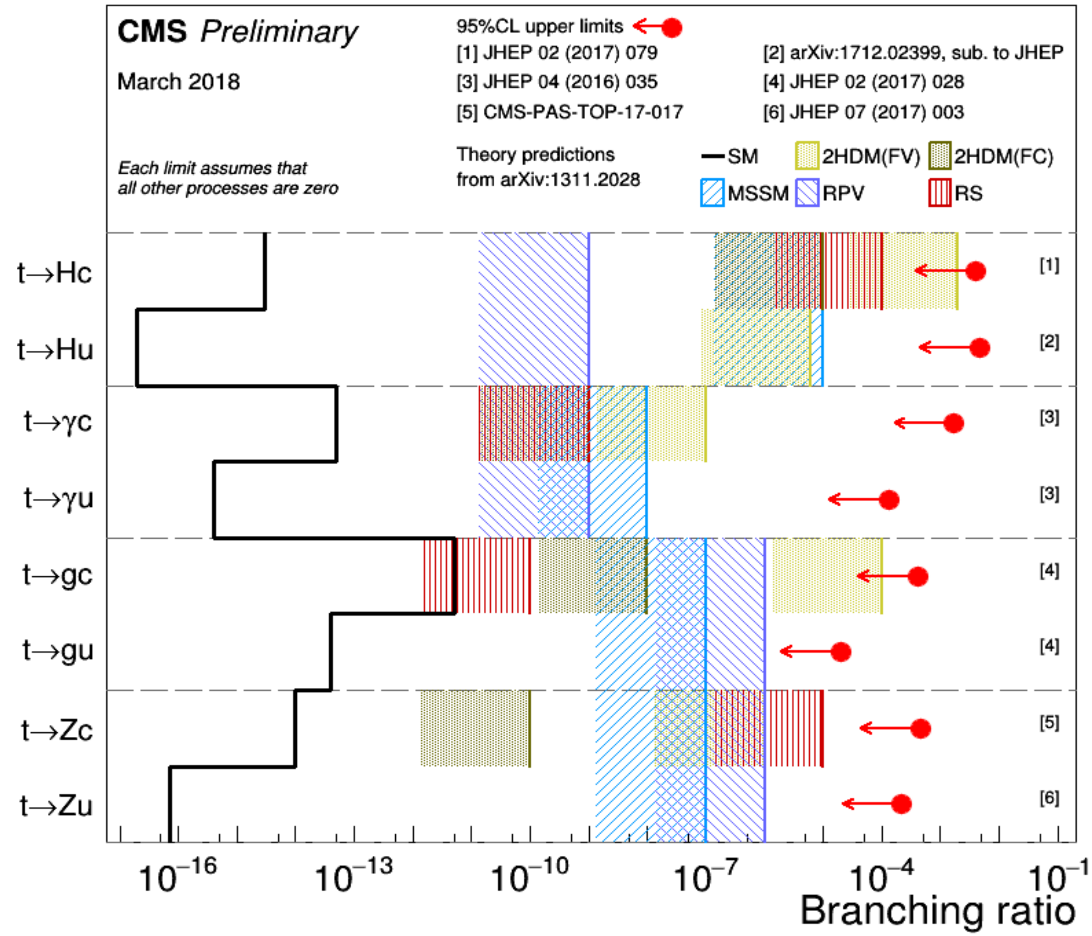
BF(t→ug) < 0.0020 % (obs)
< 0.0028 % (exp)
BF(t→cg) < 0.041 % (obs)
< 0.028 % (exp)

at 95% CL

Summary of FCNC searches in CMS

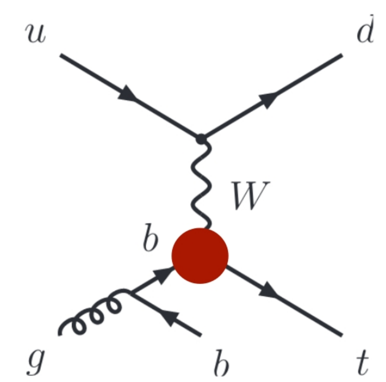


Still long way to probe bulk of the BSM models with enhanced FCNC, but **models predicting highest branching fractions within reach**



Nucl. Phys. B 812:181-204 (2009)

The Wtb vertex structure and W boson helicity



Single top production cross section
proportional to strength of Wtb interaction

Anomalous vector **and tensor couplings**

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

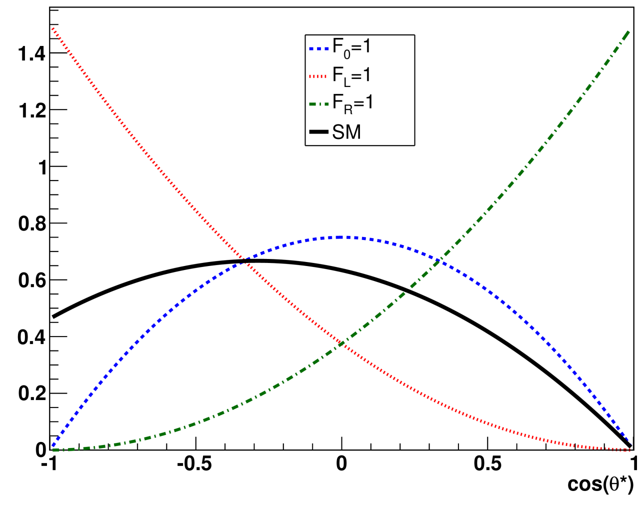
Left-handed vector
In SM: $V_{\mathrm{L}} = V_{\mathrm{tb}} \approx 1$

Right-handed vector

Left- and right-handed tensor

In SM: $V_{\mathrm{R}} = g_{\mathrm{L}} = g_{\mathrm{R}} = 0$ at tree level

Couplings can be probed by measuring:
- single top production cross section and (angular) decay observables
- W boson polarization (helicity fractions F_0, F_L, F_R)



See talk of H. Liao

Constraining anomalous Wtb couplings

CMS-TOP-14-007, JHEP 02 (2017) 028
5+20 fb^{-1}, 7+8 TeV

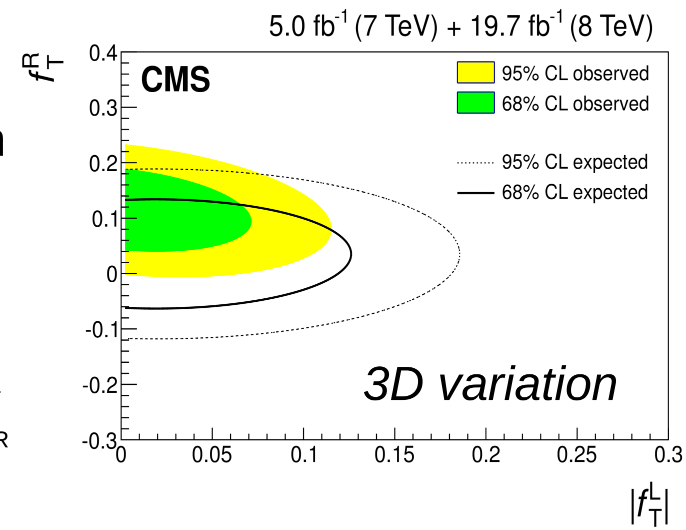
In single top

Bayesian neural networks for coupling extraction
- single top vs backgrounds
- anomalous coupling scenarios vs SM

3D variation results consistent with SM

$f_V^L > 0.98$, $|f_V^R| < 0.16$
$|f_T^L| < 0.057$, $-0.049 < f_T^R < 0.048$

$f_V^L = V_L$
$f_V^R = V_R$
$f_T^R = g_L$
$f_T^R = g_R$

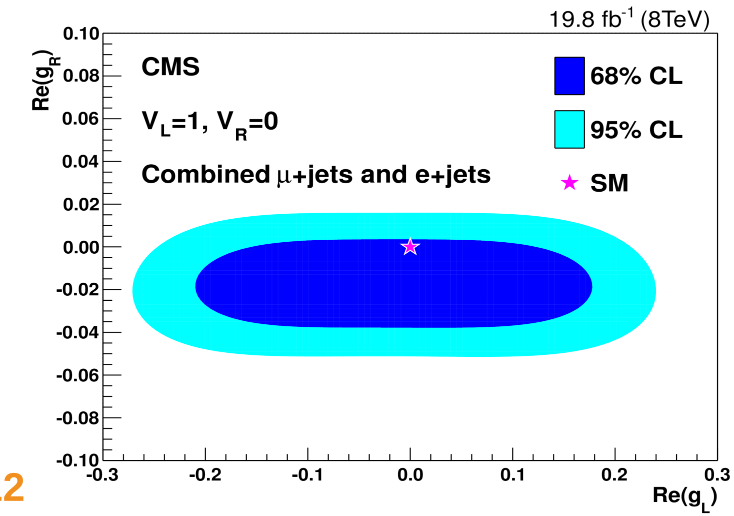


In $t\bar{t}$ via W boson helicity

$t\bar{t}$ reconstruction followed by kinematic fit

Helicity fractions extracted from cos θ* distribution
→ **consistent with SM predictions**

CMS-TOP-13-008, PLB 762 (2016) 512
20 fb^{-1}, 8 TeV



See talk of H. Liao

CMS-TOP-14-023
PRD 93, 052007 (2016)
20 fb^{-1}, 8 TeV

Anomalous $t\bar{t}g$ couplings affecting polarization, spin correlations in $t\bar{t}$

In the SM top quarks **in $t\bar{t}$** produced with **small amount of polarization**, and with **correlated spins**

Probed with **asymmetries of angular observables**,
e.g. ΔΦ between leptons in lab frame,
or angles in helicity frames

Sensitive to polarization

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

Sensitive to spin correlations, e.g.

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

opening angle between leptons in their helicity frames

Anomalous $t\bar{t}g$ couplings might affect top quark polarization and spin correlation in $t\bar{t}$

Effective model of
chromo-magnetic (CMDM) and
chromo-electric (CEDM) dipole moments

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

$$\hat{\mu}_{\mathrm{t}} \equiv \frac{m_{\mathrm{t}}}{g_s}\widetilde{\mu}_{\mathrm{t}}, \quad \hat{d}_{\mathrm{t}} \equiv \frac{m_{\mathrm{t}}}{g_s}\widetilde{d}_{\mathrm{t}},$$

Real part of CMDM affects several spin correlation observables

Imaginary part of CEDM affects CP-violating component of polarization

Anomalous $t\bar{t}g$ couplings affecting polarization, spin correlations in $t\bar{t}$

CMS-TOP-14-023
PRD 93, 052007 (2016)
20 fb^{-1}, 8 TeV

Unfolded data to parton level **agrees with SM predictions** of asymmetry variables, as a function of M, |y|, p_T of $t\bar{t}$ system

See talk of H. Liao

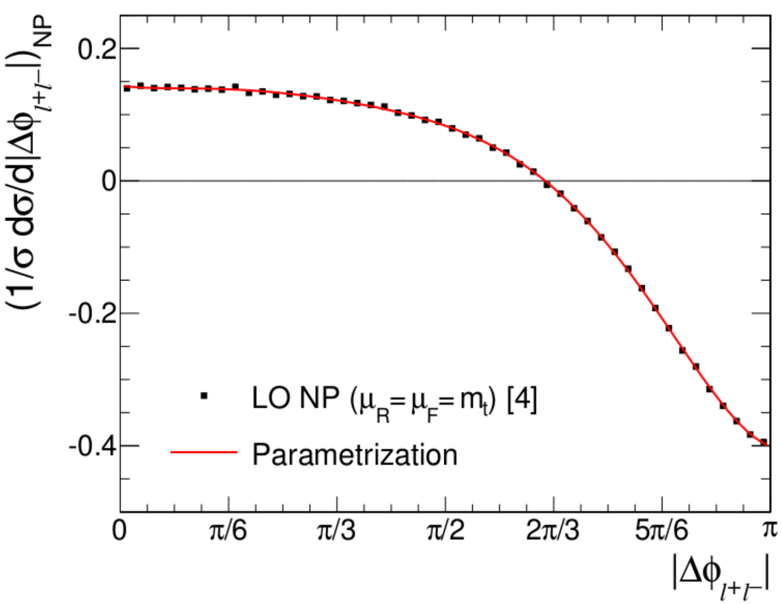
Limits on CMDM and CEDM dipole moments

$$-0.053 < \mathrm{Re}(\hat{\mu}_t) < 0.026$$
$$-0.068 < \mathrm{Im}(\hat{d}_t) < 0.067$$

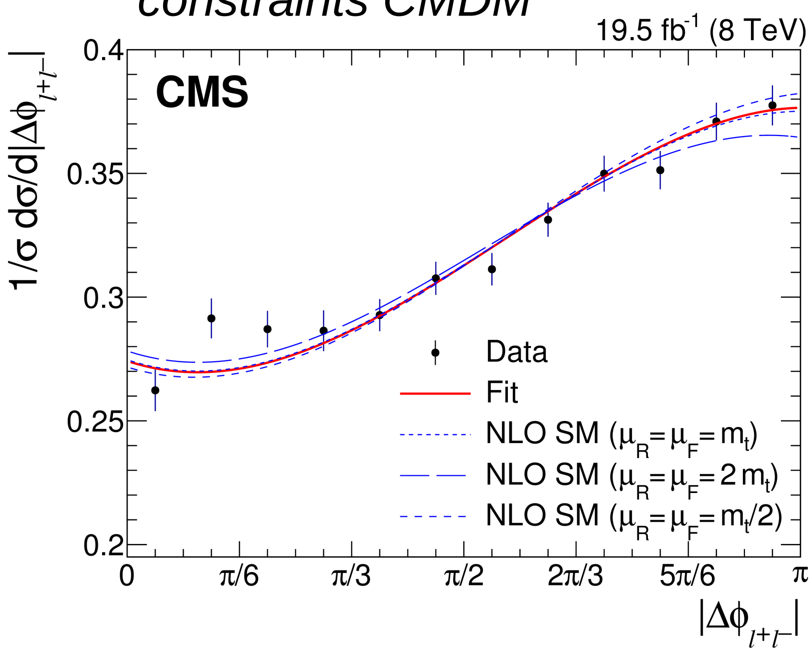
at 95% CL

Contribution to normalized ΔΦ distribution from CMDM

PLB 725 (2013) 115



Fit to ΔΦ distribution constraints CMDM

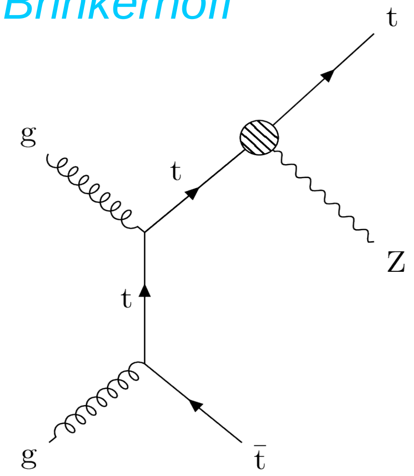


CMS-TOP-17-005
arXiv:1711.02547
36 fb^{-1}, 13 TeV

EFT interpretations in $t\bar{t}V$

Cross section measurement of $t\bar{t}W$ (same-sign dilepton) **and $t\bar{t}Z$** (3 or 4 leptons including OSSF pair)

See talk of A. Brinkerhoff



BSM physics at energy scale Λ **may alter cross sections**

Parametrization as function of **dimension-6 operators**

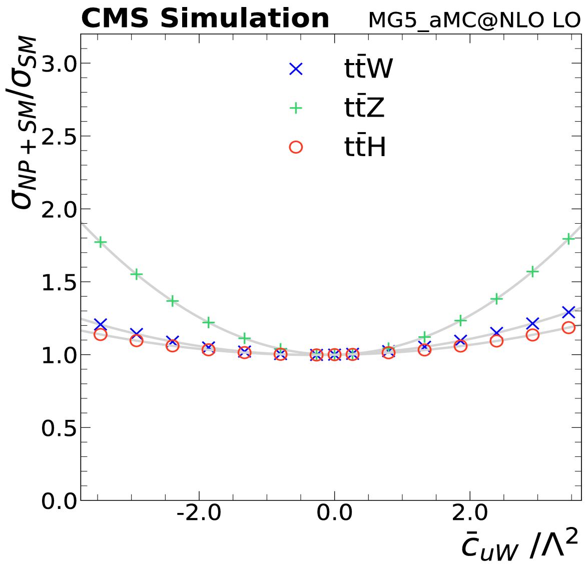
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

Identified **8 Wilson coefficients c_i** that affect $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$ cross sections without impacting expected background yields

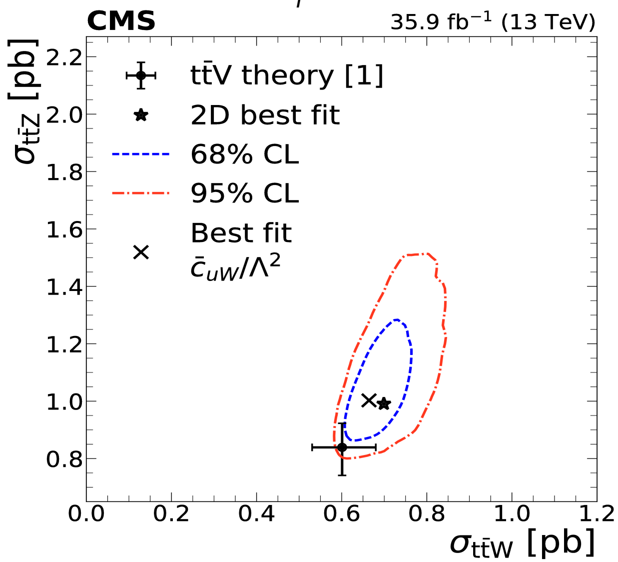
Fitting one c_i at a time

Example: $\bar{c}_{uW}$ affecting mostly $t\bar{t}Z$ cross section

Signal strength varies with size of c_i



$t\bar{t}Z$, $t\bar{t}W$ cross sections corresponding to best-fit c_i and its contours



EFT interpretations in $t\bar{t}$ differential cross sections

NEW

Targeting **opposite-sign dilepton** final state

BSM physics may alter differential cross sections

Anomalous CMDM implemented
at NLO in QCD in EFT framework:
operator O_{tG} corresponding to coefficient c_{tG} / Λ^2

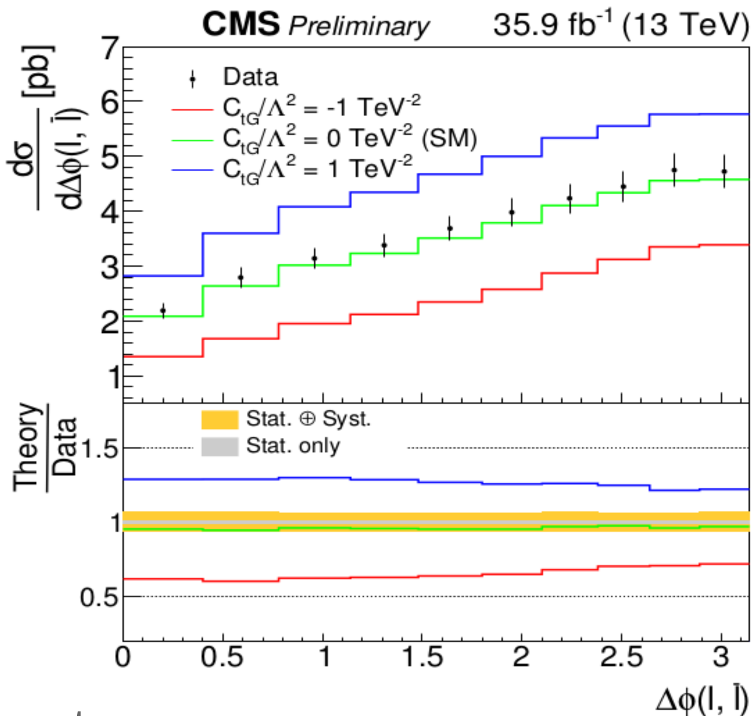
Constrained via χ^2 method
using $\Delta\Phi$ between leptons in lab frame

$-0.06 < c_{tG} / \Lambda^2 < 0.41$ at 95% CL

Consistent with, and improve upon, existing constraints

e.g. using 8 TeV CMS cross section measurement
$-0.42 < c_{tG} / \Lambda^2 < 0.30$ PRD 91 (2015) 114010

Unfolded at particle level
in fiducial phase space



Summary

The LHC as top quark factory enables **precise measurements of top quark production and decay properties**

This opens a **gateway to new physics**, by searching for rare events or subtle deviations from the SM prediction

- Searching for FCNC interactions
- Studying structure of Wtb vertex and $t\bar{t}g$ coupling
- Interpreting in EFT framework

No sign of new physics yet, but **more top quark data being analyzed (and produced)** creates exciting prospects!

Backup

Bibliography

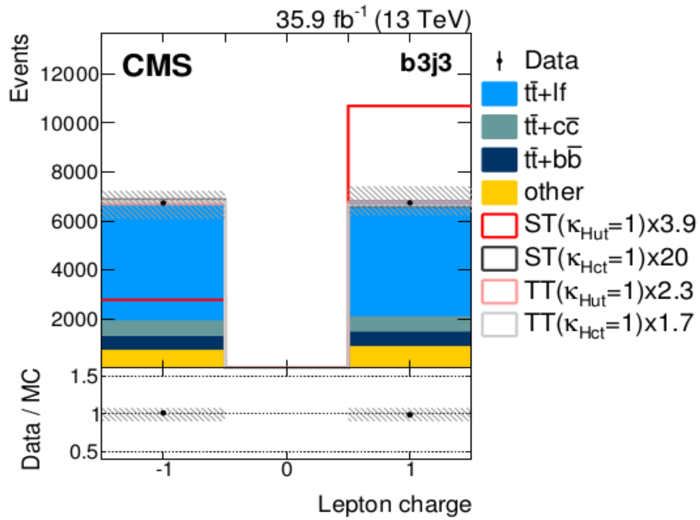
All **CMS top quark physics** results via **this link**

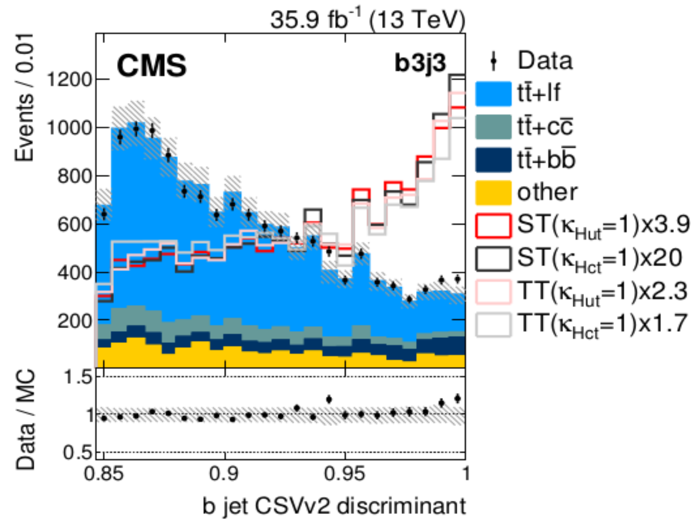
Relevant but not in main body of talk:

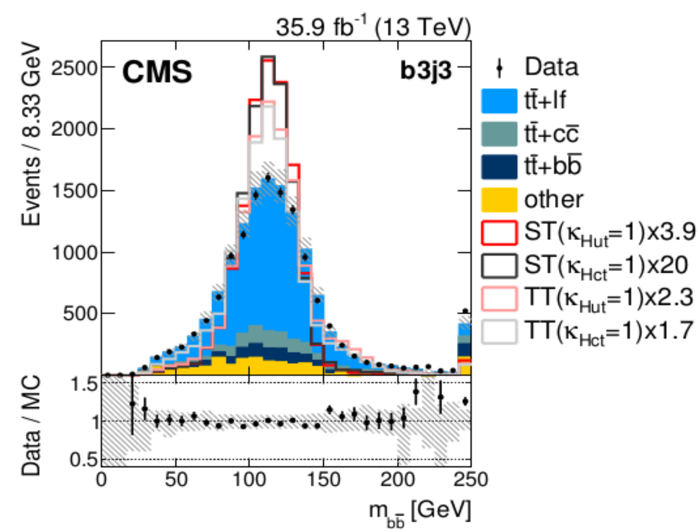
- FCNC $t\to qH$ in $t\bar{t}$, **CMS-TOP-13-017, JHEP 02 (2017) 079**, 20 fb^{-1}, 8 TeV
- FCNC $t\to qZ$ in single top, **CMS-TOP-12-039, JHEP 07 (2017) 003**, 20 fb^{-1}, 8 TeV
- W helicity in single top, **CMS-TOP-12-020, JHEP 01 (2017) 053**, 20 fb^{-1}, 8 TeV
- CP violation in $t\bar{t}$, **CMS-TOP-16-001, JHEP 03 (2017) 101**, 20 fb^{-1}, 8 TeV

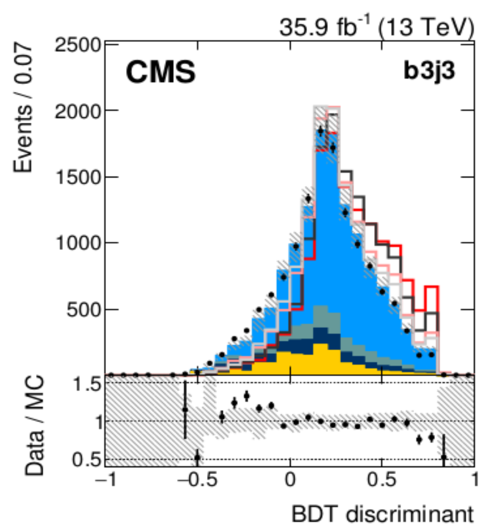
FCNC t→qH in t$\bar{t}$ and single top

Selection of the **most discriminating BDT variables**







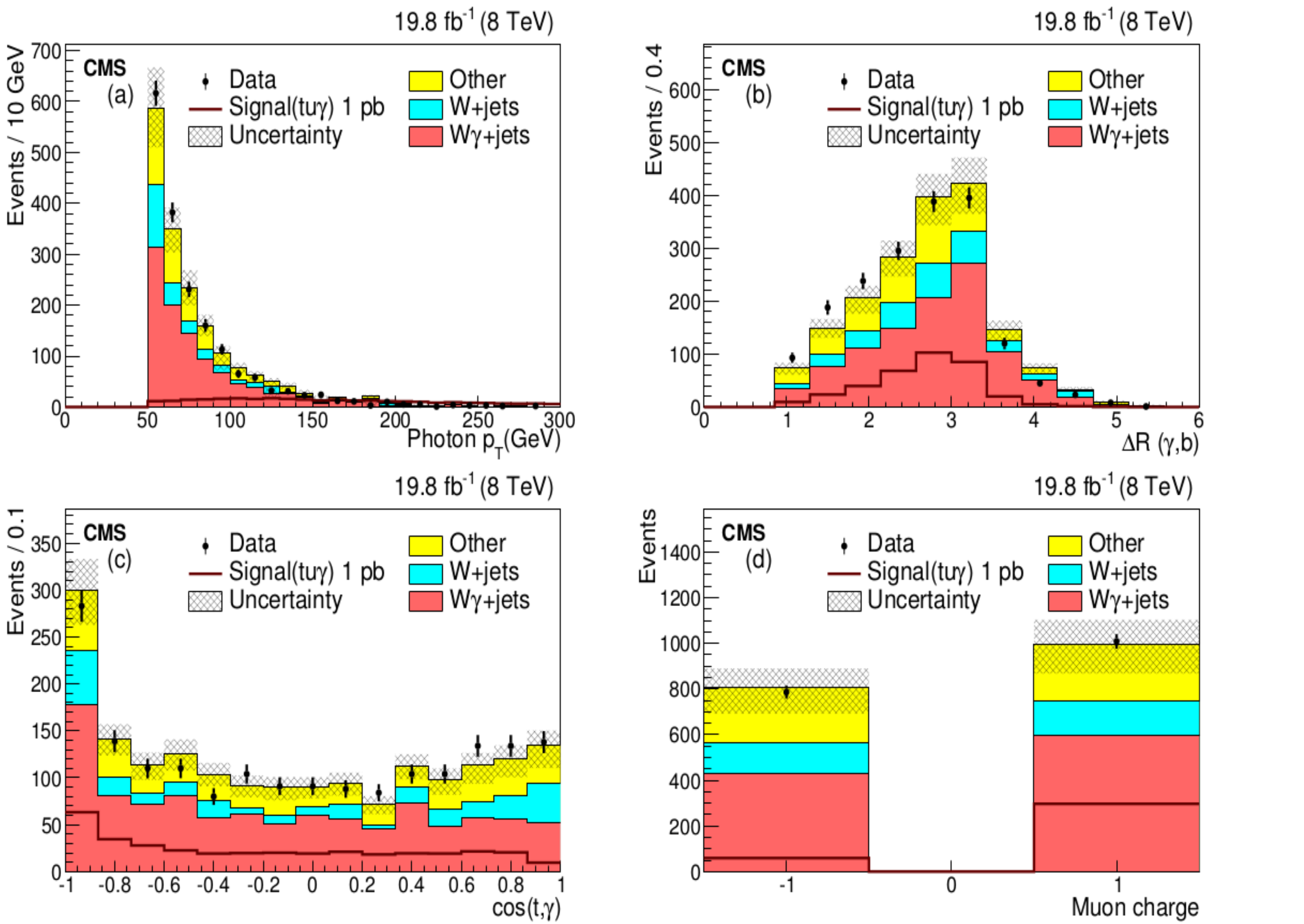


Maximum BDT discriminant value from jet assignment procedure

FCNC t→qγ in single top

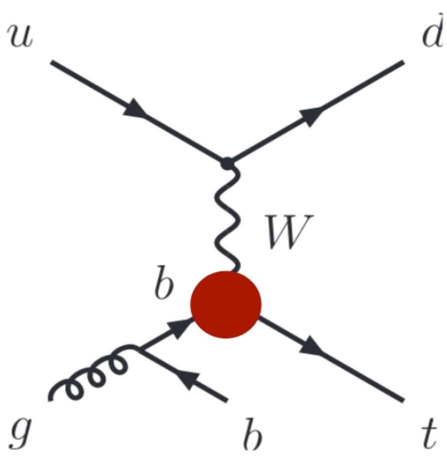
CMS-TOP-14-003
JHEP 04 (2016) 035
20 fb^{-1}, 8TeV

Selection of the **most discriminating BDT variables**



Nucl. Phys. B 812:181-204 (2009)

The Wtb vertex structure



Single top production cross section proportional to strength of Wtb interaction

In SM, V-A structure of Wtb vertex

Anomalous **vector and tensor couplings**

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

Left-handed vector
In SM: $V_L = V_{tb} \approx 1$

Right-handed vector

Left- and right-handed tensor

In SM: $V_R = g_L = g_R = 0$ at tree level

Couplings can be probed by measuring:
- single top production cross section and (angular) decay observables
- W boson polarization (helicity fractions)

CMS-TOP-14-007
JHEP 02 (2017) 028
5+20 fb^{-1}, 7+8 TeV

Anomalous Wtb in single top

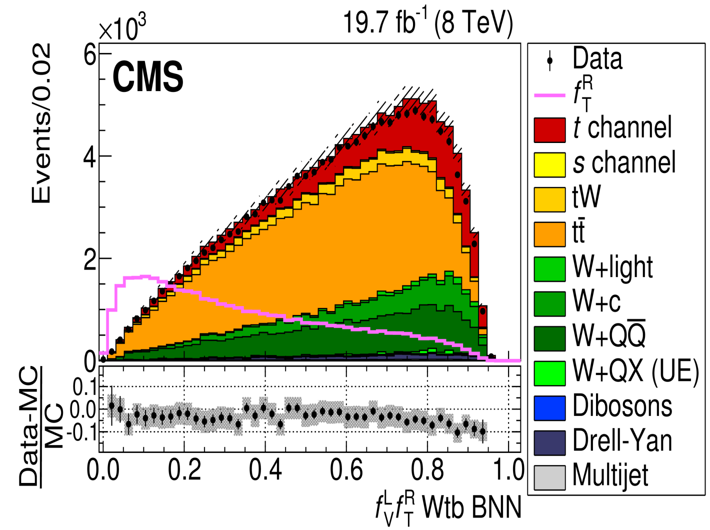
Probe Wtb vertex structure in single top *t*-channel

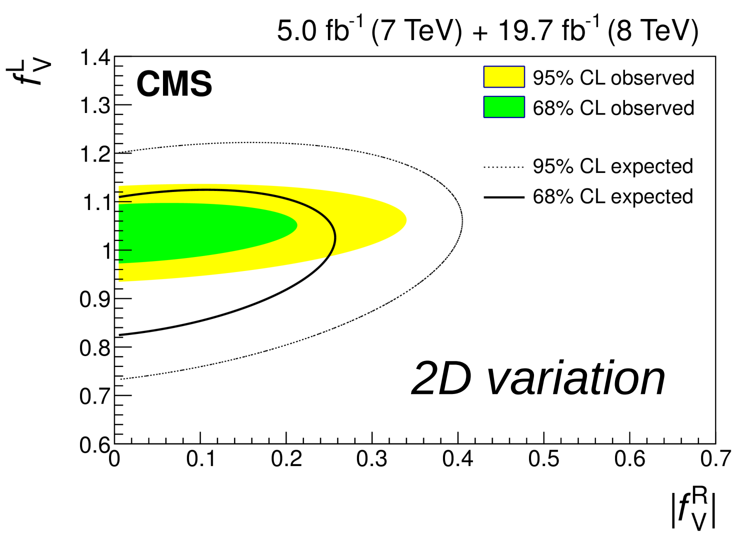
Bayesian neural networks for coupling extraction
- single top vs backgrounds
- SM vs anomalous coupling scenarios

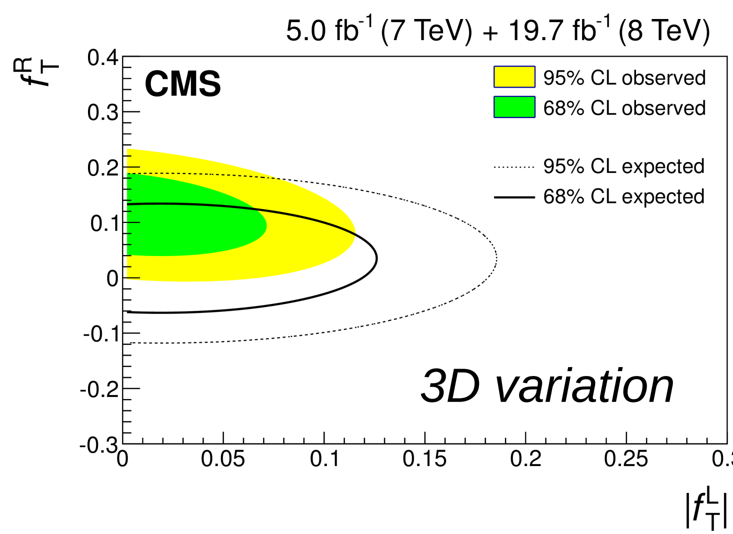
Different combinations of couplings considered

3D variation results consistent with SM

$f_V^L > 0.98$, $|f_V^R| < 0.16$
$|f_T^L| < 0.057$, $-0.049 < f_T^R < 0.048$







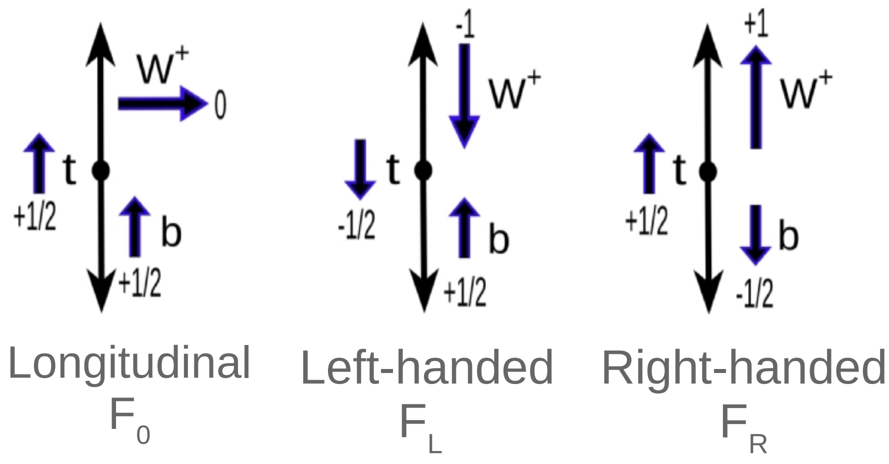
$f_V^L = V_L$
$f_V^R = V_R$
$f_T^R = g_L$
$f_T^R = g_R$

W boson helicity

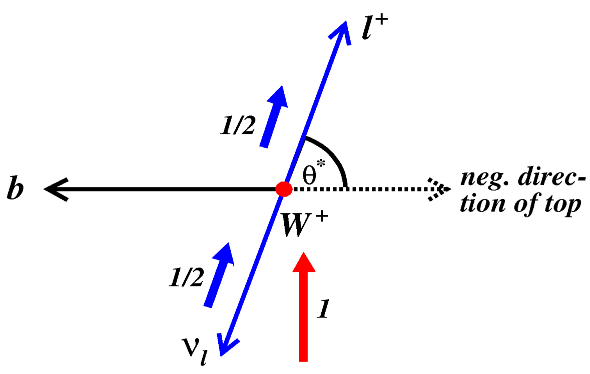
W helicity: projection of spin of W boson on its momentum

Helicity fractions $F_{L,R,0}$ sum to 1

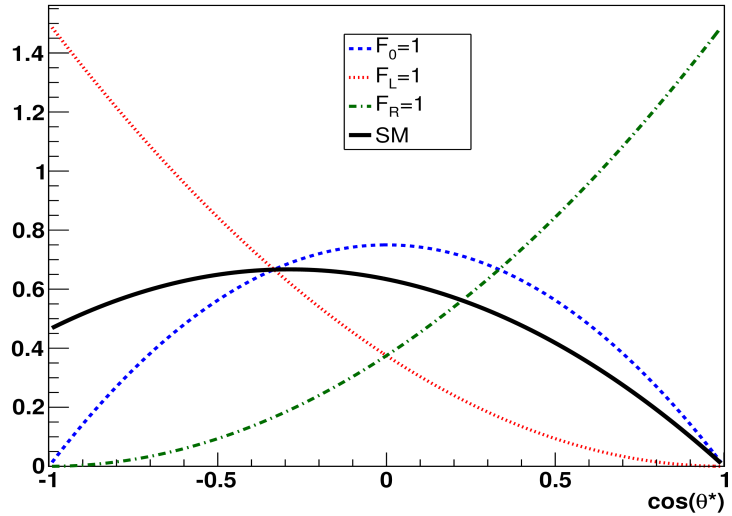
Measurement via angular distributions of top quark decay products, e.g. cos θ^*



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



In W boson rest frame



SM at NNLO:

$F_0 = 0.687 \pm 0.005$

$F_L = 0.311 \pm 0.005$

$F_R = 0.0017 \pm 0.0001$

PRD 81 (2010) 111503

W boson helicity in $t\bar{t}$

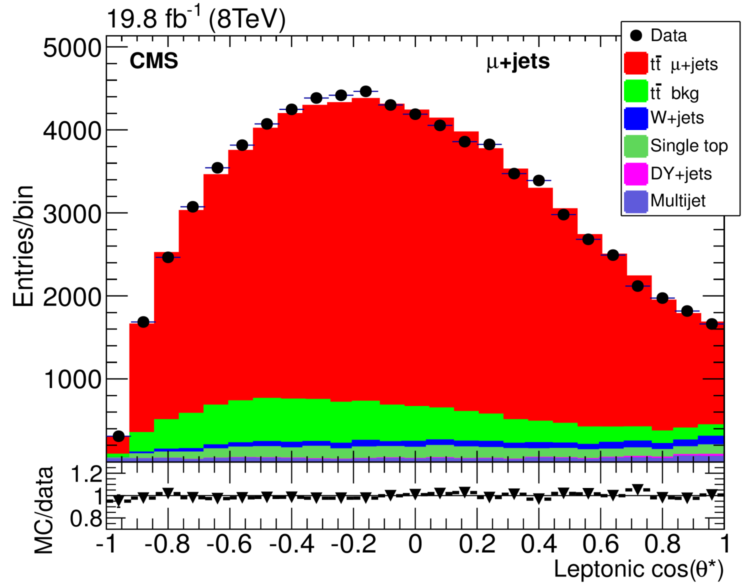
CMS-TOP-13-008,
PLB 762 (2016) 512
20 fb^{-1}, 8 TeV

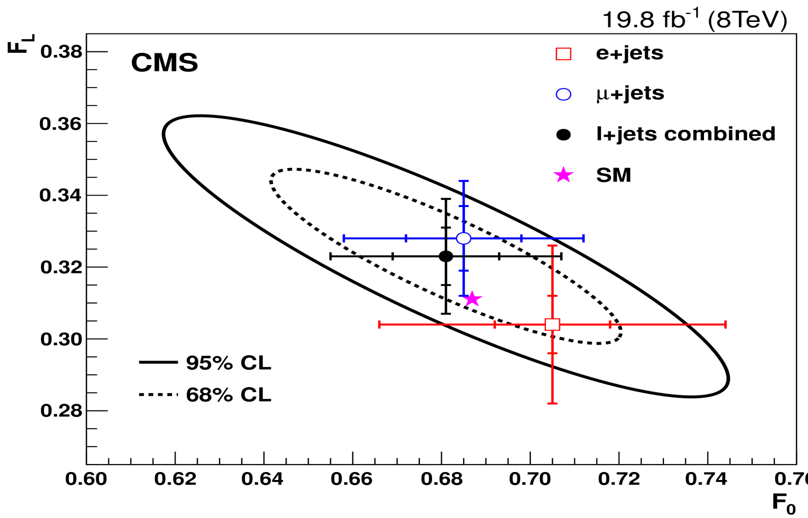
Event topology

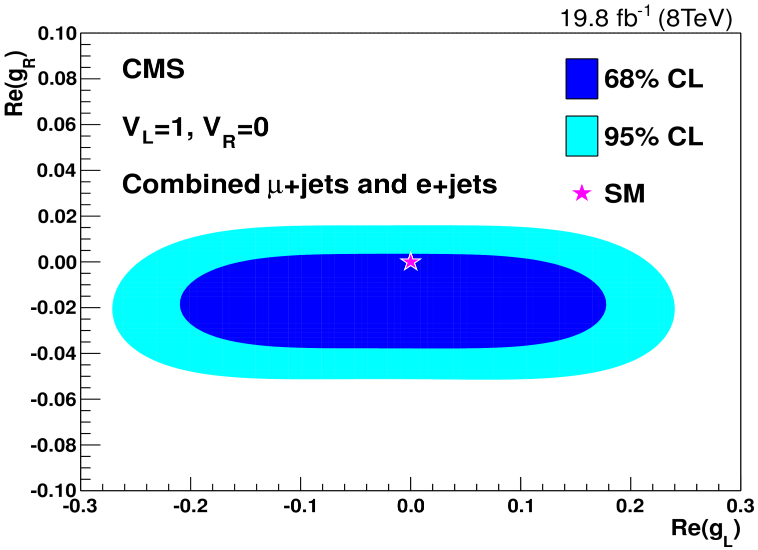
1 isolated muon or electron
≥ 4 jets of which ≥ 2 b jets
$30 < m_T(W) < 200$ GeV

$t\bar{t}$ reconstruction followed by kinematic fit to improve reconstruction acccuracy

W boson helicity fractions extracted from **cos θ* distribution** (leptonic branch)
→ consistent with SM predictions







Unitarity constraint $F_L + F_0 + F_R = 1$

Anomalous ttg couplings affecting polarization, spin correlations in tt

CMS-TOP-14-023
PRD 93, 052007 (2016)
20 fb^{-1}, 8 TeV

In the SM top quarks **in t$\bar{\text{t}}$** produced with **small amount of polarization**, and with **correlated spins**

Probed with **asymmetries of angular observables**, e.g. ΔΦ between leptons in lab frame, or angles in helicity frames

Anomalous ttg couplings might affect top quark polarization and spin correlation in t$\bar{\text{t}}$

Effective model of **chromo-magnetic (CMDM)** and **chromo-electric (CEDM)** dipole moments

Sensitive to polarization

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

Sensitive to spin correlations

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

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

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

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

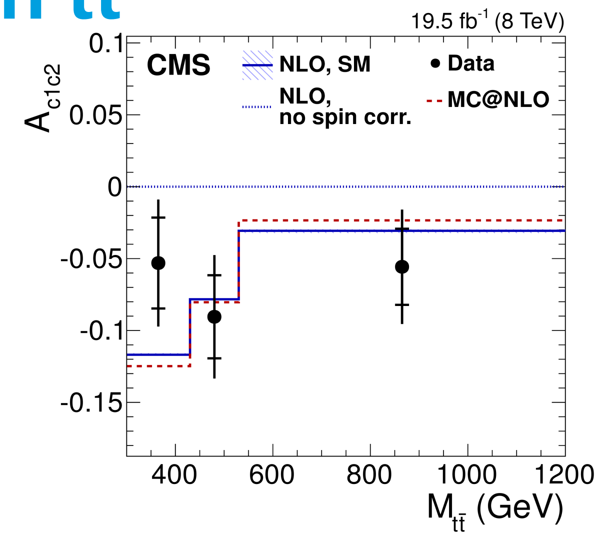
$$\hat{\mu}_{\rm t} \equiv \frac{m_{\rm t}}{g_s}\tilde{\mu}_{\rm t}, \quad \hat{d}_{\rm t} \equiv \frac{m_{\rm t}}{g_s}\tilde{d}_{\rm t},$$

Real part of CMDM affects several spin correlation observables

Imaginary part of CEDM affects CP-violating component of polarization

CMS-TOP-14-023
PRD 93, 052007 (2016)
20 fb^{-1}, 8 TeV

Anomalous ttg couplings affecting polarization, spin correlations in tt

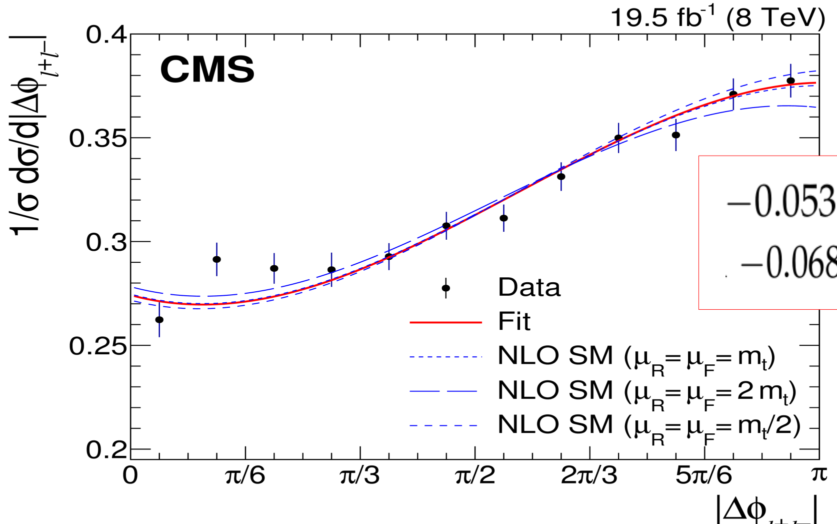


Event topology

2 opposite-sign muons or electrons
≥ 2 jets of which ≥ 1 b jets
missing p_T in same-flavor lepton channels

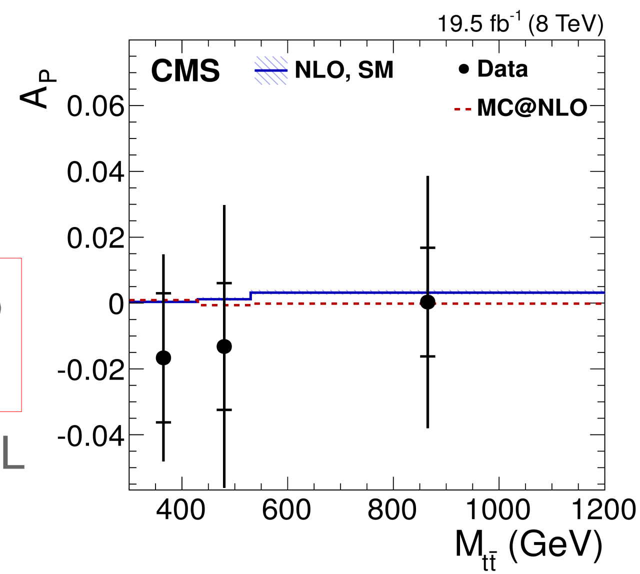
Unfolded data to parton level **agrees with SM predictions** of asymmetry variables
as a function of M, |y|, p_T of $t\bar{t}$ system

Limits on CMDM and CEDM dipole moments



$$-0.053 < \mathrm{Re}(\hat{\mu}_t) < 0.026$$
$$-0.068 < \mathrm{Im}(\hat{d}_t) < 0.067$$

at 95% CL



CP violation in $t\bar{t}$

CMS-TOP-16-001
JHEP 03 (2017) 101
20 fb^{-1}, 8 TeV

Probing asymmetry of T-odd triple-product correlation **observables O_i** CP(O_i) = –O_i

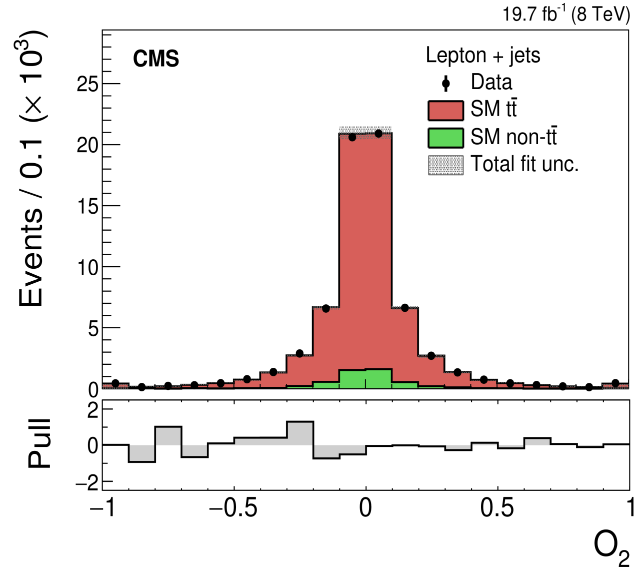
$$A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$$

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_3 = Q_\ell\, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{b\bar{b}\,\text{CM}} \propto Q_\ell\, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_4 = Q_\ell\, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell\, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

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



Event topology

1 isolated muon or electron

≥ 4 jets of which ≥ 2 b jets

$M_{\ell b}$ fit → signal and background events yields

Asymmetries calculated for T-odd observables

A_{CP} (A'_{CP}) = (un)corrected for detector effects

→ **consistent with SM**