FPCP 2017
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Top quark production and properties

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for the

ATLAS and CMS collaborations

FPCP in Prague, June 2017

UNIVERSITÄT BONN

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ATLAS EXPERIMENT

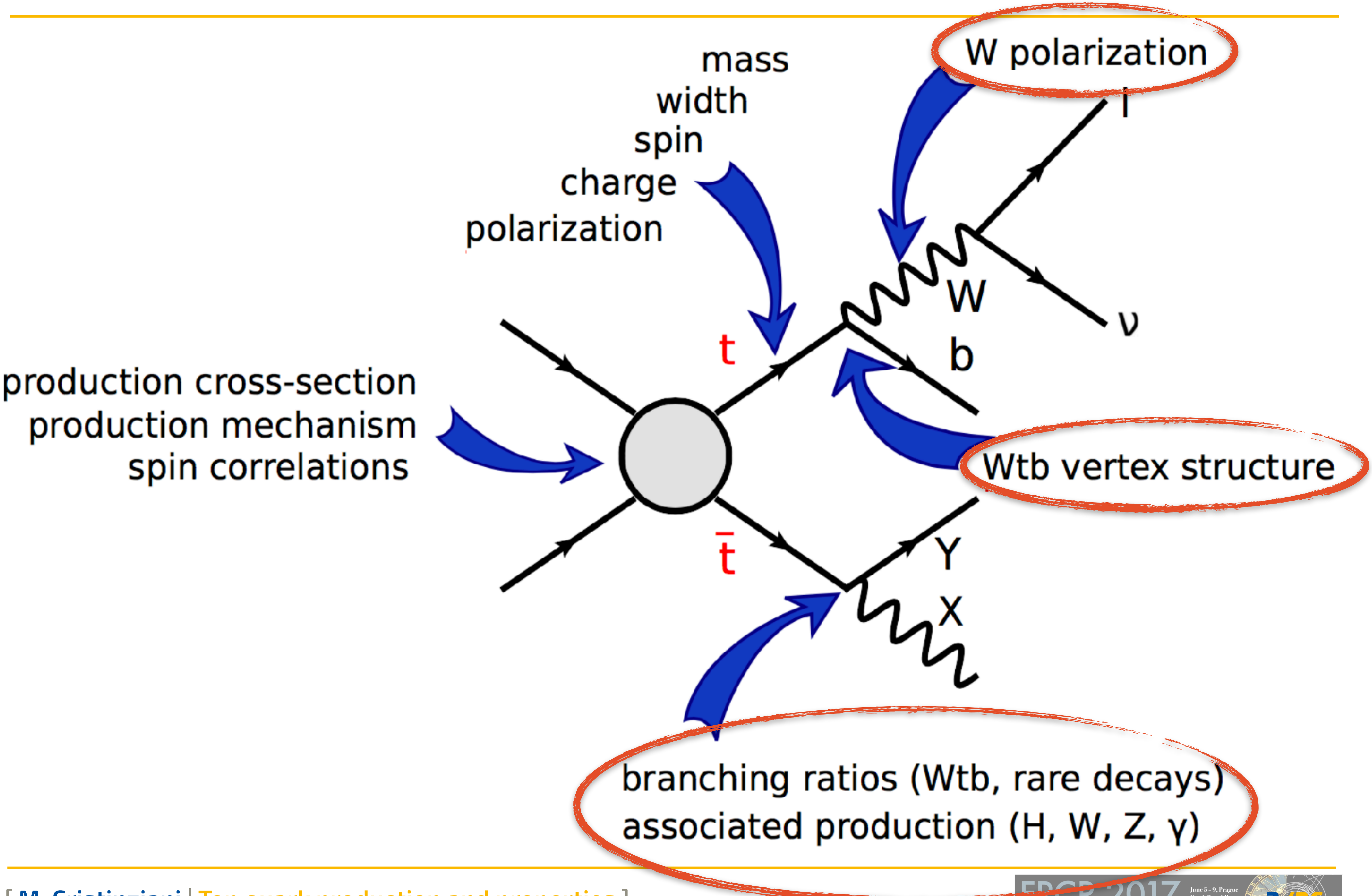
CMS

The top quark

Top quark is unique in many ways

- heaviest, of course … but also:
- it's a bare quark, decaying before hadronising
  - $\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}\,s$
  - $\tau_{flip} \approx h\, m_t / \Lambda_{QCD}^2 \gg \tau_{had}$
  - $\tau_{top} \approx h/\Gamma_{top} \sim G_F^{-1} m_t^{-3} = 5 \cdot 10^{-25} s$
- Top Yukawa is the largest SM coupling
  - $m_{top} = y_t\, v/\sqrt{2} \approx 174\ \mathrm{GeV} \rightarrow y_t \approx 1$
- and hence largest Higgs mass correction
- There are many of them
  - 6 million in Run-1
  - ~2 orders of magnitude to go

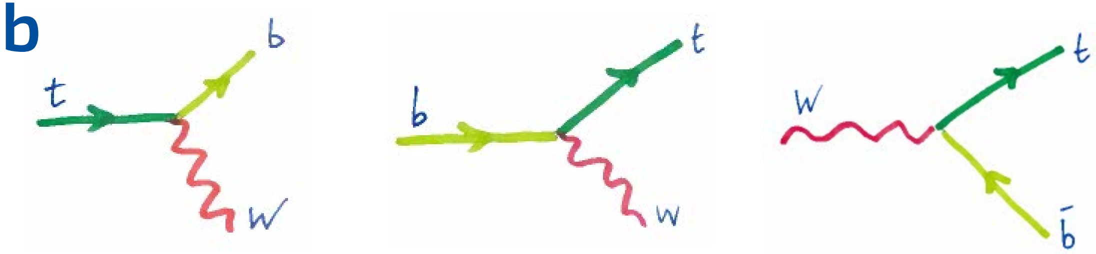
Outline


mass
width
spin
charge
polarization
W polarization
l
W
ν
b
t
t̄
production cross-section
production mechanism
spin correlations
Wtb vertex structure
Y
X
branching ratios (Wtb, rare decays)
associated production (H, W, Z, γ)

Top couplings

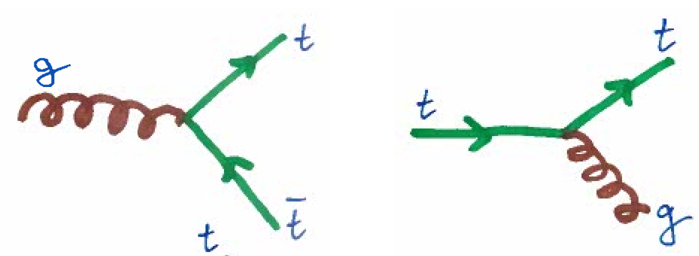
Flavour changing charged current

- Wtb

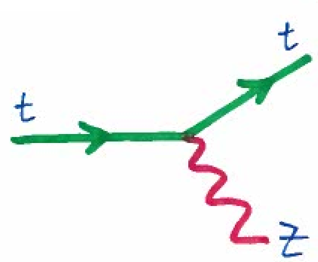


Flavour conserving neutral current

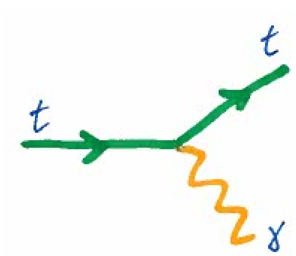
- tgt



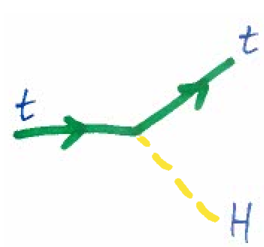
- tZt



- tγt

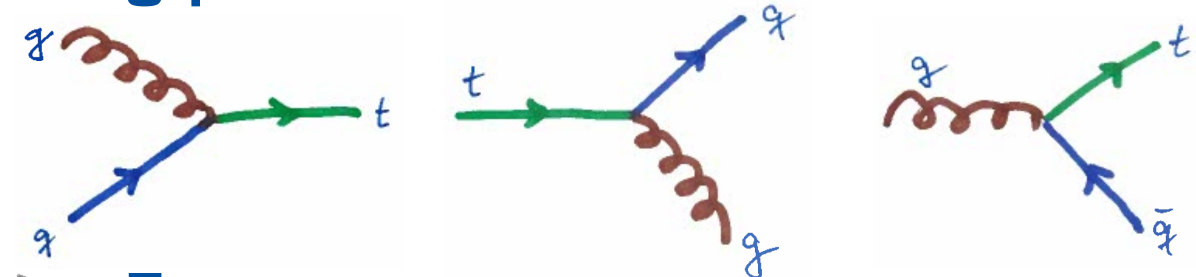


- tHt

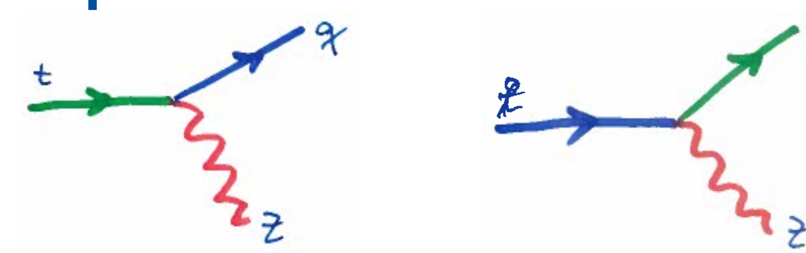


… and neutral current

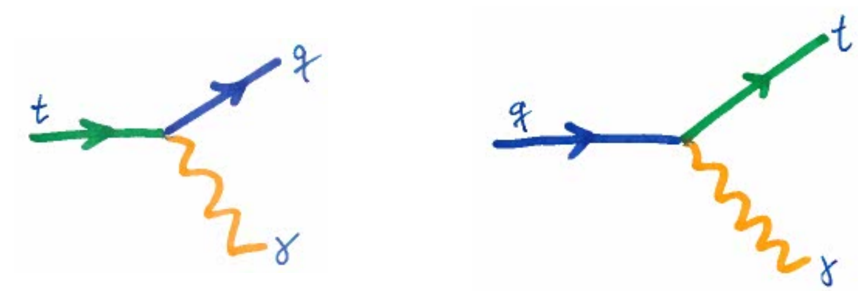
- tgq



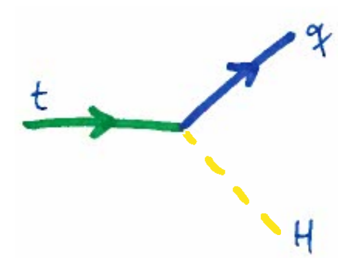
- tZq



- tγq



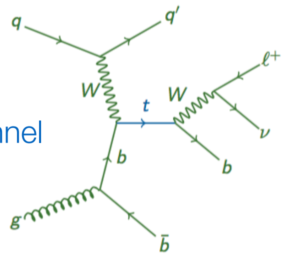
- tHq



Wtb vertex structure
Single top production and decay

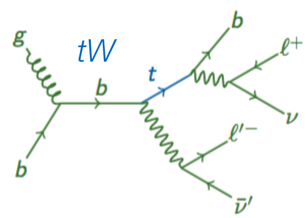
Three mechanisms (@ LO)

t-channel



$\sigma_{t\text{-}ch}$ (8 TeV) = $87.7^{+3.4}_{-1.9}$ pb
$\sigma_{t\text{-}ch}$ (13 TeV) = $217.0^{+9.1}_{-7.7}$ pb

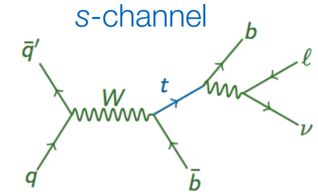
Golden channel



σ_{Wt} (8 TeV) = 22.4 ± 1.5 pb
σ_{Wt} (13 TeV) = 71.7 ± 3.8 pb

Observed at the LHC

s-channel



$\sigma_{s\text{-}ch}$ (8 TeV) = 5.6 ± 0.2 pb
$\sigma_{s\text{-}ch}$ (13 TeV) = 10.3 ± 0.4 pb

Challenging at the LHC

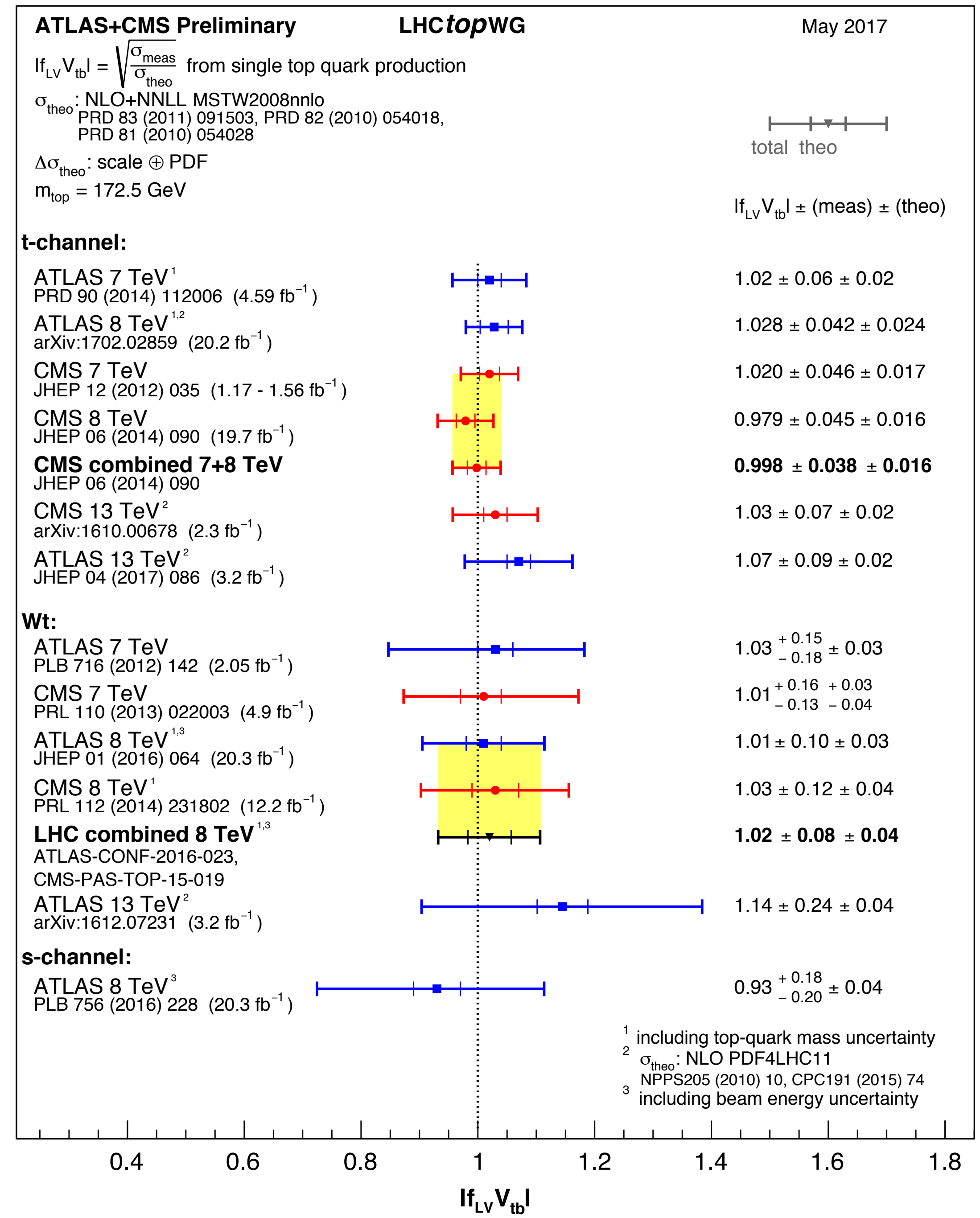
Can extract $|V_{tb}|$ with

- $\sigma_{meas.} / \sigma_{theo.} = |f_{LV} \cdot V_{tb}|^2$
- f_{LV} left-handed FF including new physics
- independent of $N_{generations}$ or CKM unitarity

Assumptions

- Wtb SM-like, left-handed, weak coupling
- $|V_{tb}| >> |V_{ts}|, |V_{td}|$

Agreement in all 3 processes with SM



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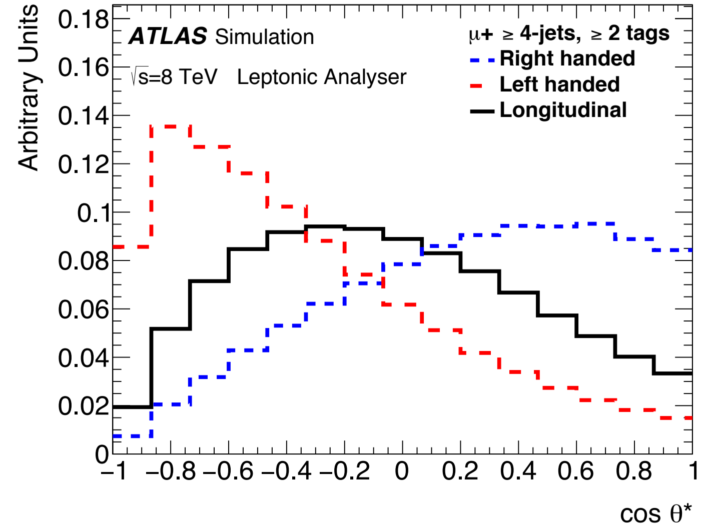
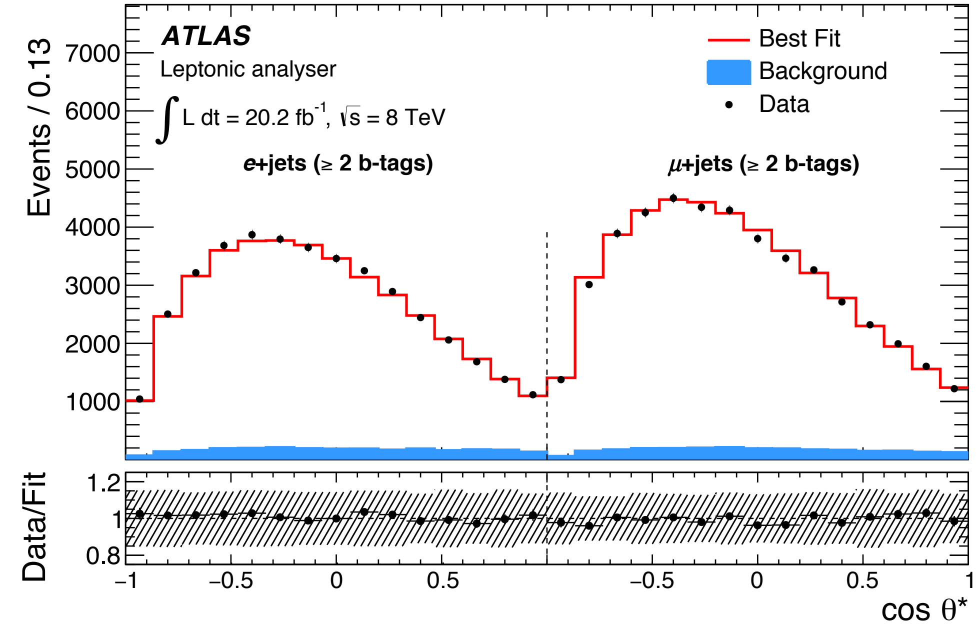
Wtb vertex structure
W polarisation in $t\bar{t}$ events

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

$$F_L = 0.311 \pm 0.005,\ F_R = 0.0017 \pm 0.0001,$$
$$F_0 = 0.687 \pm 0.005$$





Structure of Wtb vertex

- angular distribution of W decay products
- kinematic reconstruction of the $t\bar{t}$ system
- analysers: charged lepton (d-type quark) from W
- template fit used to extract helicity fractions

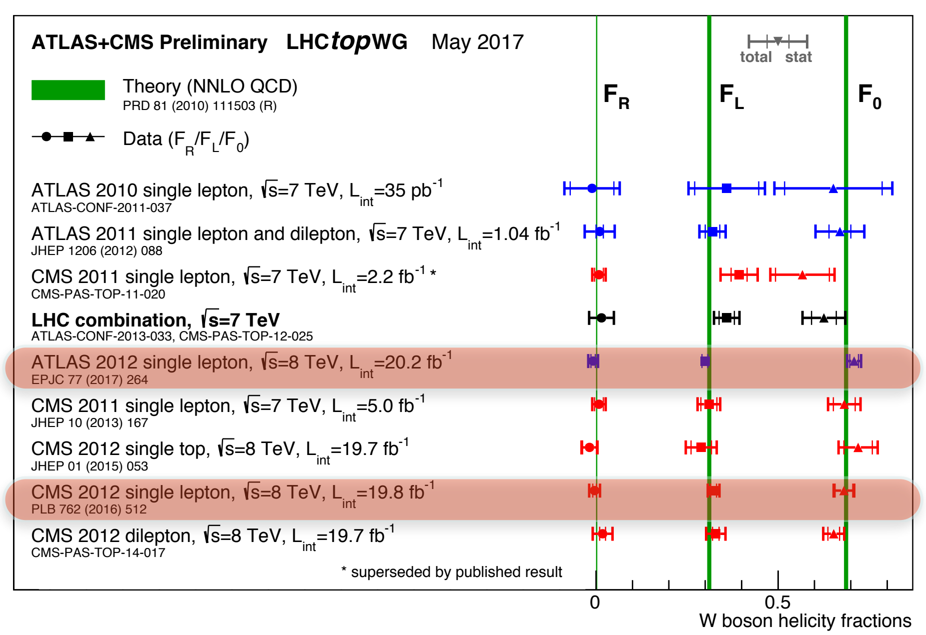
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_L P_L + g_R P_R)tW_{\mu}^{-}$$

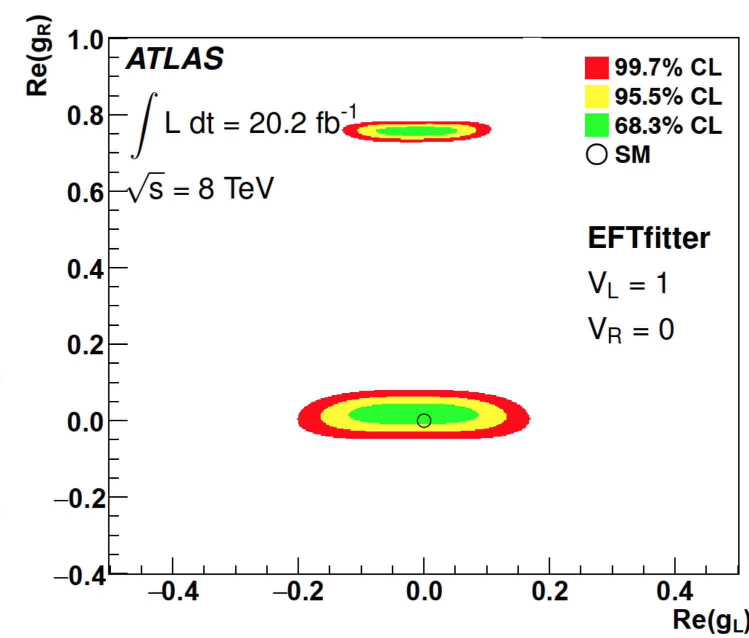
Result using leptonic analyser

$$F_0 = 0.709 \pm 0.012\ (\text{stat.+bkg. norm.})\ ^{+0.015}_{-0.014}\ (\text{syst.})$$
$$F_L = 0.299 \pm 0.008\ (\text{stat.+bkg. norm.})\ ^{+0.013}_{-0.012}\ (\text{syst.})$$
$$F_R = -0.008 \pm 0.006\ (\text{stat.+bkg. norm.}) \pm 0.012\ (\text{syst.})$$

Dominant uncertainty

Jet energy scale and resolution





JHEP 02 (2017) 028

Wtb vertex structure
Search for anomalous couplings

Single top t-channel

- using 7+8TeV, μ+jets only

Strategy

- Bayesian NN (BNN) for S/B separation
- dedicated anom. Wtb BNNs for each scenario

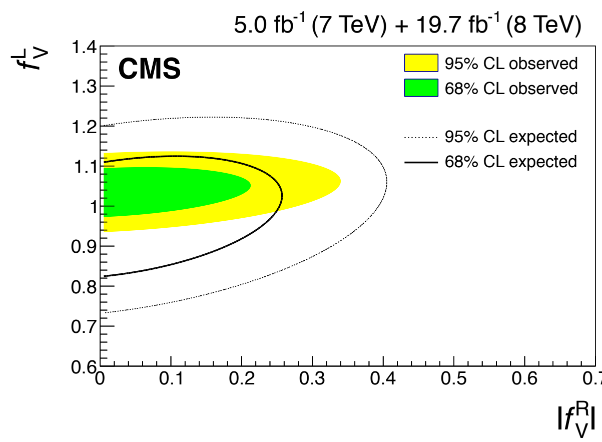
Limit extraction

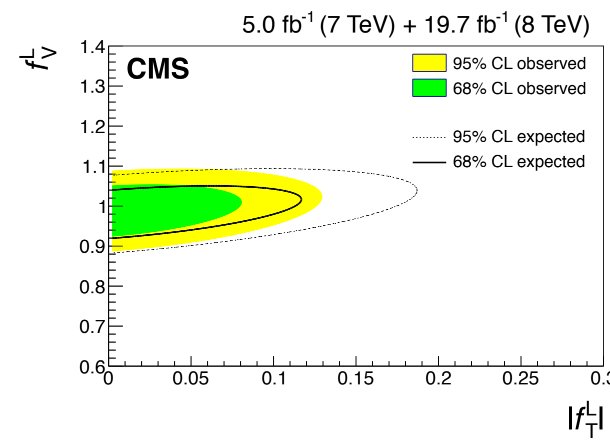
- simultaneous 2- or 3-dim fit to SM BNN
  - and anomalous Wtb BNN outputs
  - remaining couplings assumed as SM

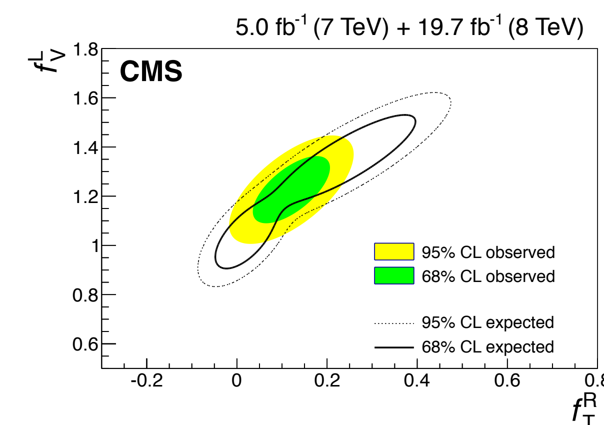
Results @ 95% C.L.

- $|f_V^R| < 0.16$
- $|f_T^L| < 0.057$
- $-0.049 < f_T^R < +0.048$

Two-dimensional fit

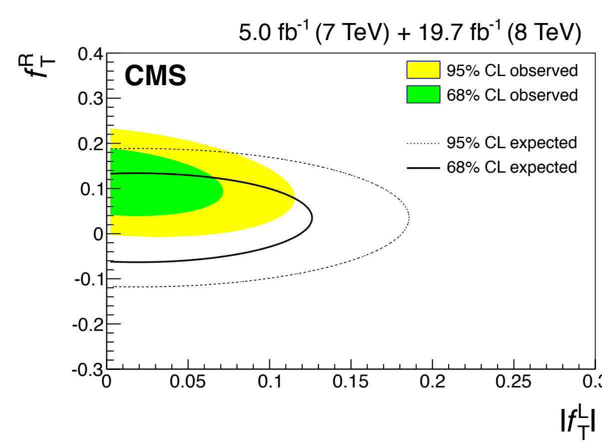


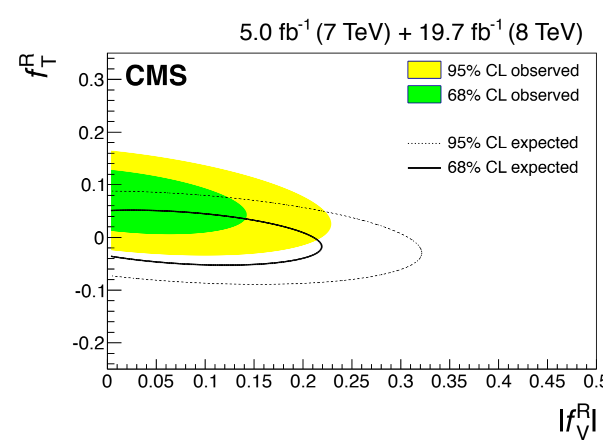




$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right)\mathrm{t}W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)\mathrm{t}$$

Three-dimensional fit





Wtb vertex structure t-channel angular analysis

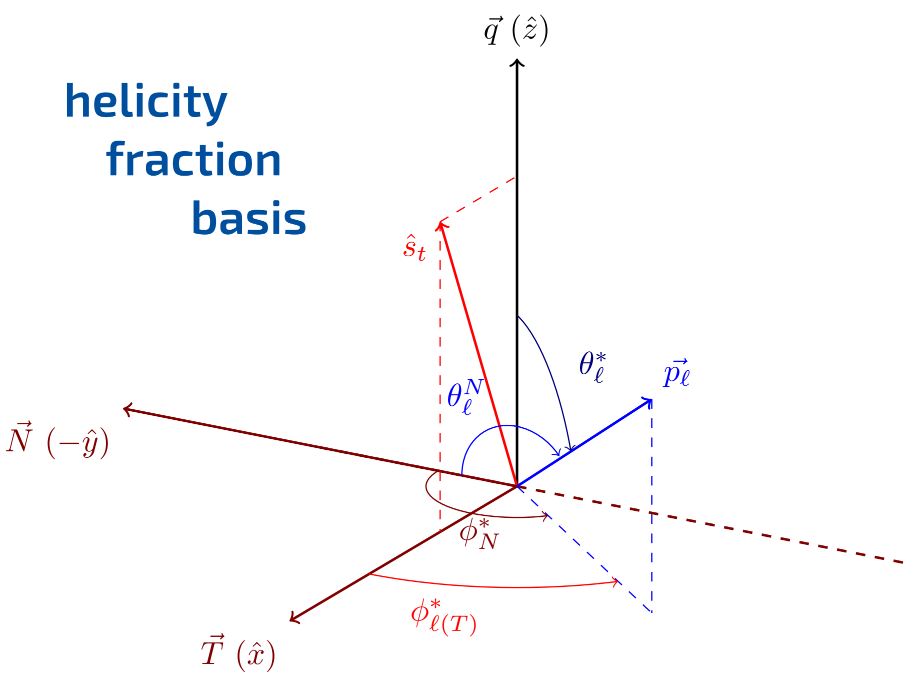
Angular asymmetries

- top-quark polarisation

W boson spin observables

- unfolded at parton level

helicity fraction basis



Extract limits on a.couplings

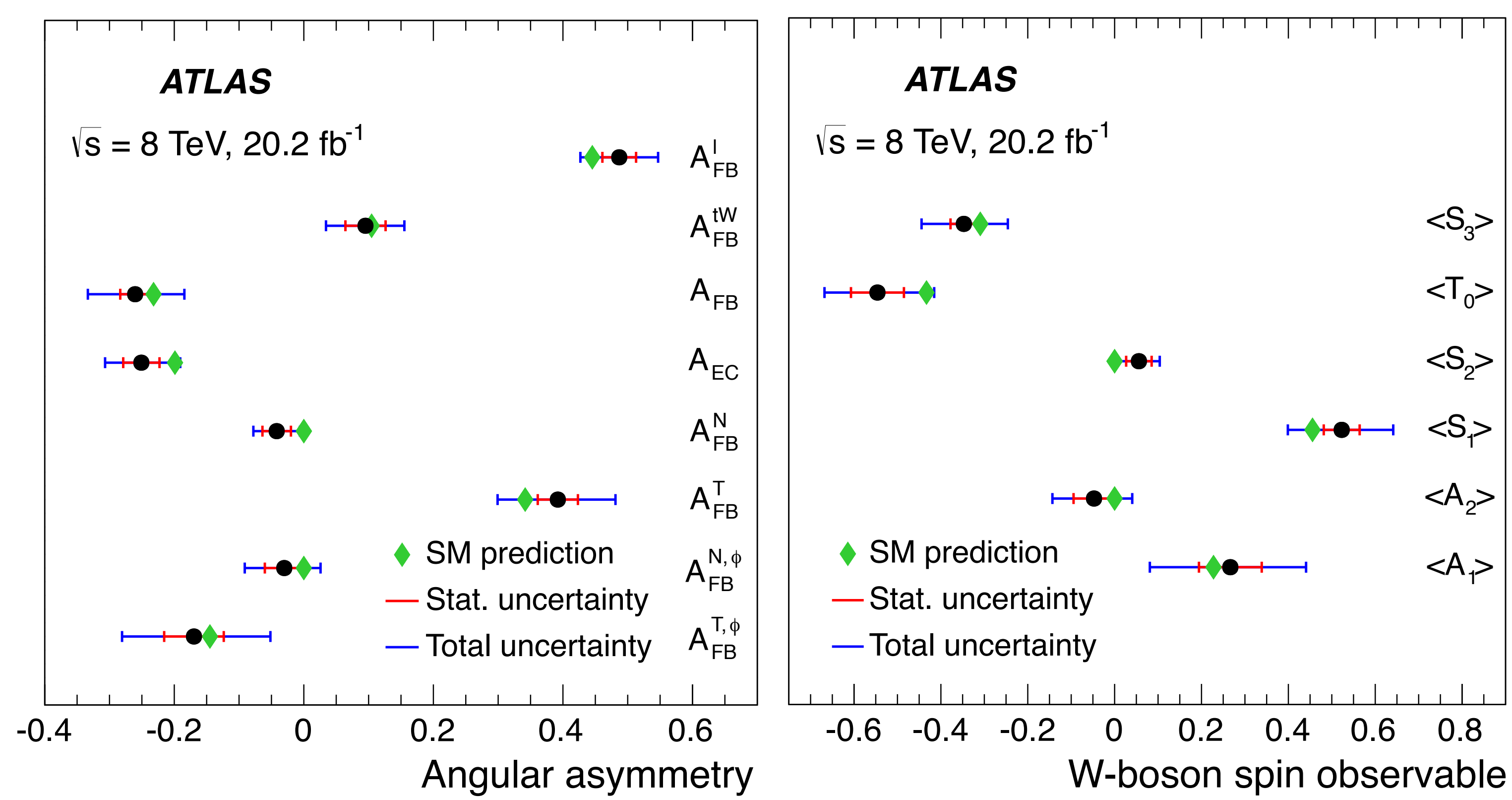
- -0.18 < Im[g_R] < 0.06 @ 95% C.L.

CMS measures top quark asymmetry smaller then predicted (2σ)

Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R + F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R - F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1 - 3F_0)$	−0.20
A_{FB}^{T}	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
A_{FB}^{N}	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1 + \alpha_X P \cos\theta_X)$$

$\alpha_l P = 0.97 \pm 0.12$



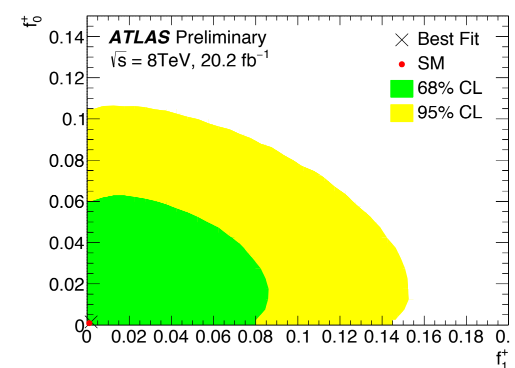
ATLAS-TOPQ-2015-11

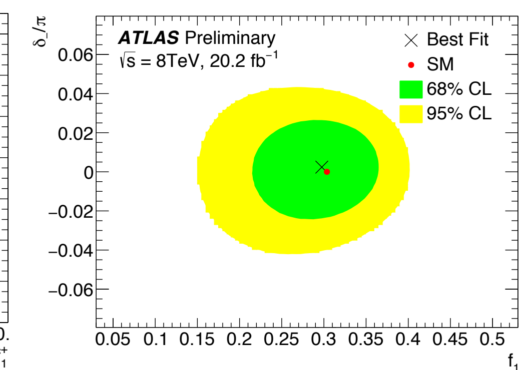
Wtb vertex structure
Triple differential decay rates

Normalised triple-differential $(\theta,\theta^*,\varphi^*)$ decay rate of top quarks

- complete description of anomalous couplings in Wtb + top polarisation
- relate to helicity amplitudes in $t\to Wb$

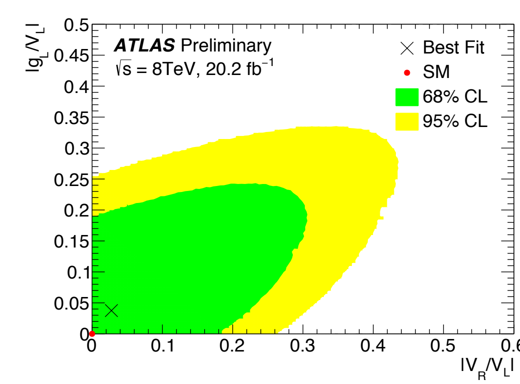
$$\frac{1}{N}\frac{d^3N}{d(\cos\theta)d\Omega^*} = \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}\sqrt{2\pi}Y_k^m(\theta,0)Y_l^m(\theta^*,\phi^*).$$

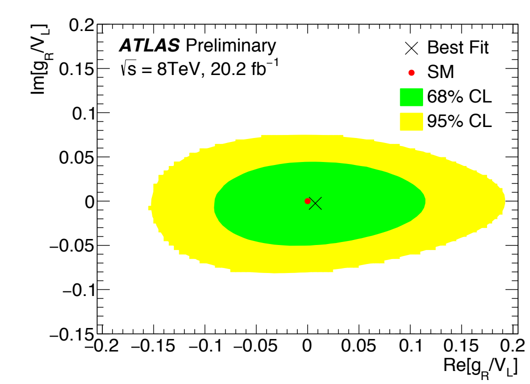




9 $a_{k,l,m}$ = 0, parameterised by

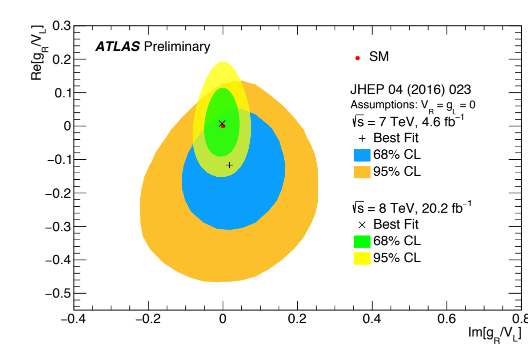
- 3 amplitude fractions f_1, f_1^+, f_0^+
- 2 phases δ_- : can imply CP violation, δ_+ not observable
- a nuisance parameter





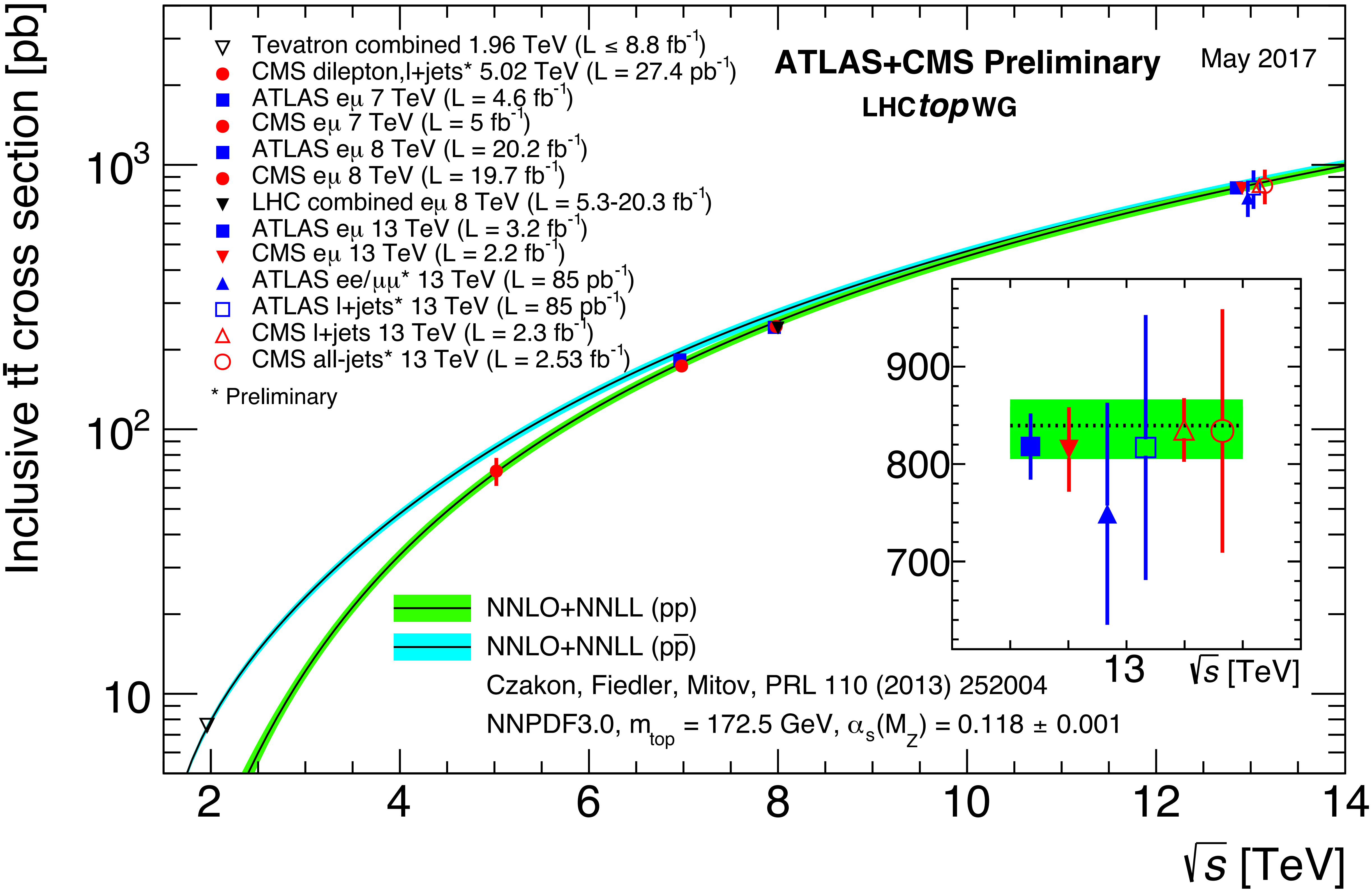
Strategy and results

- global fit with all correlations
- extraction of limits on anomalous couplings
- no assumptions on values of the other couplings



In agreement with SM

Inclusive $t\bar{t}$ production



CMS-PAS-TOP-16-021

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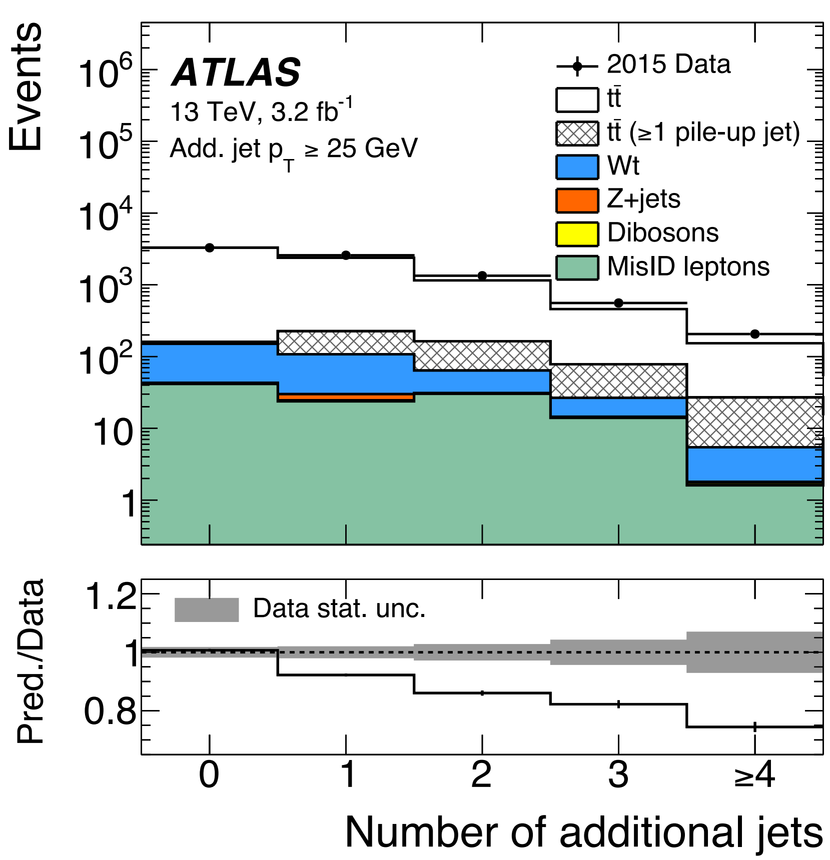
Measurement of $t\bar{t}$+jets

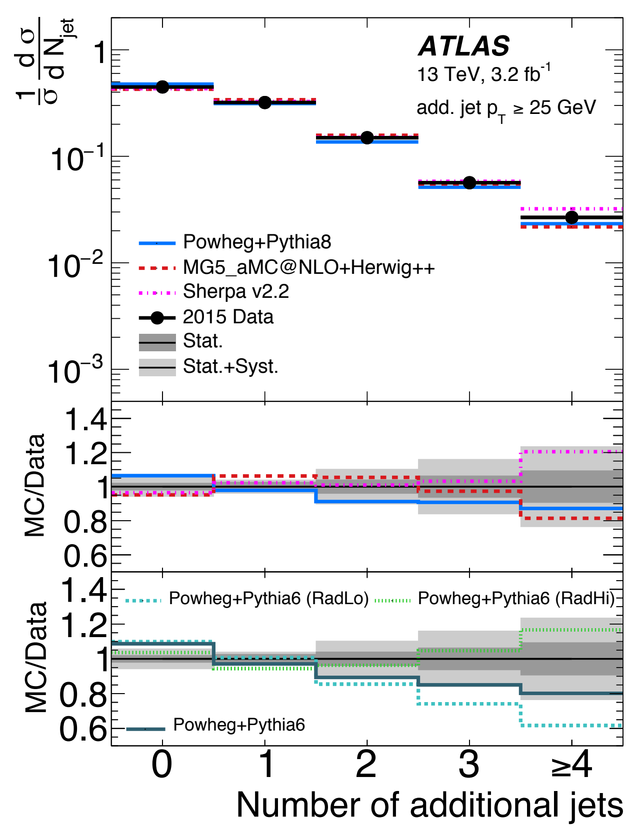
Differential distributions in N_{jets}

- extensive measurements in Run-1
- including events with veto on extra jets
  → improve modelling in simulation

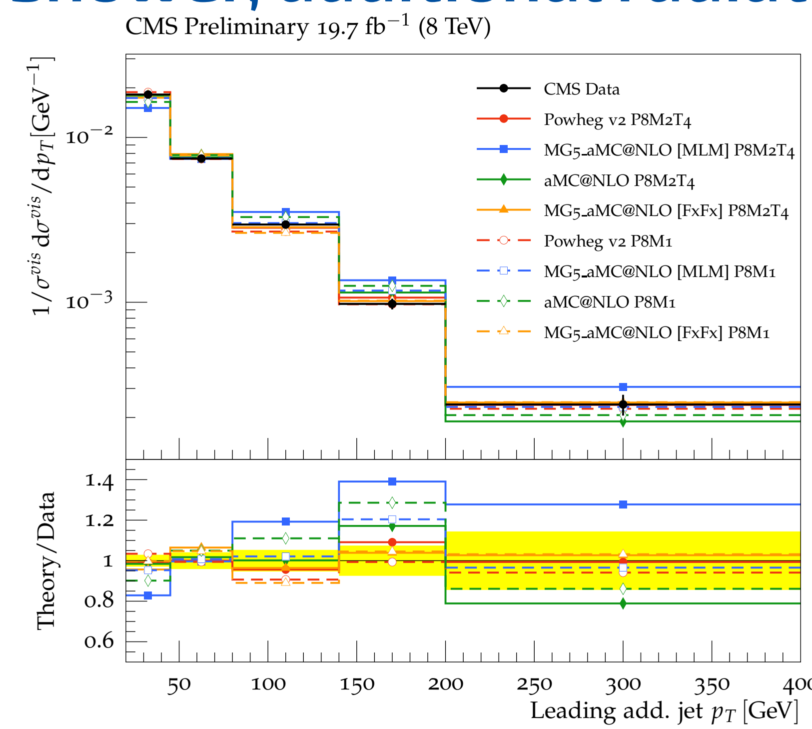
Latest results at 13 TeV

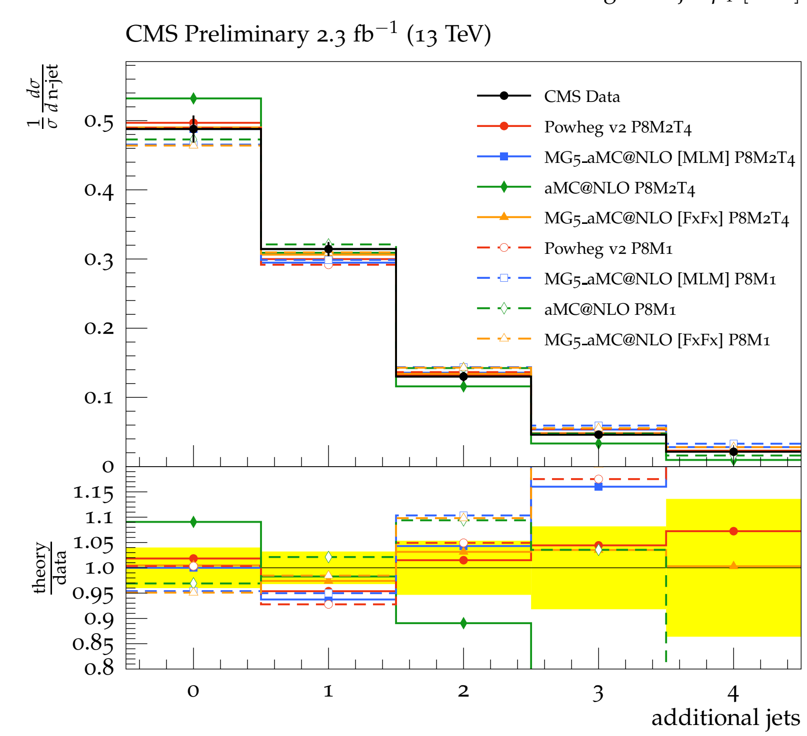
- $t\bar{t}$+jets in dilepton channel





Tuning parameters in matrix-element, parton-shower, additional radiation





Measurement of $t\bar{t}+b\bar{b}$

Important test of QCD

- $t\bar{t}$+jets and $t\bar{t}+b\bar{b}$ irreducible background for difficult analyses like $t\bar{t}H$

Measurements

- several at 7 and 8 TeV
- new result at 13 TeV using dilepton channel 2.3 fb^{-1}
- also in visible phase space and as ratio

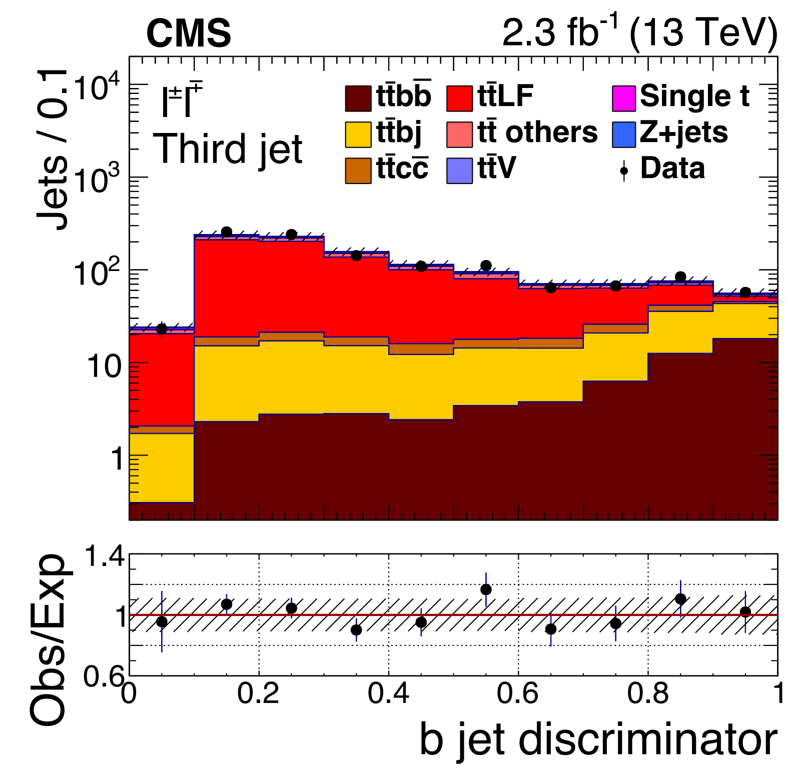
$$(\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj})^{\text{vis}} = 0.024 \pm 0.003\,(\text{stat}) \pm 0.007\,(\text{syst}).$$

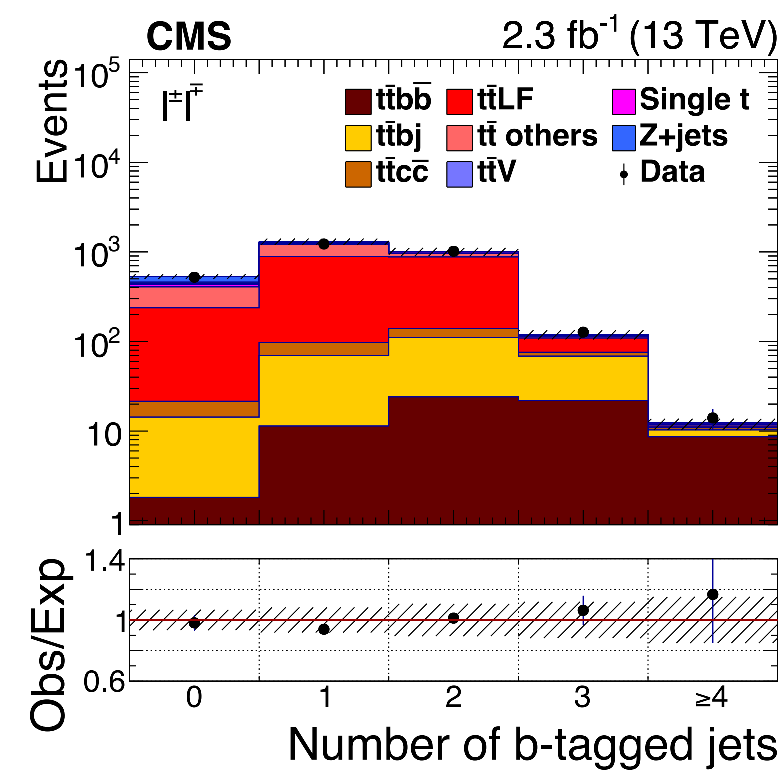
$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003\,(\text{stat}) \pm 0.006\,(\text{syst}).$$

- good agreement with expectation

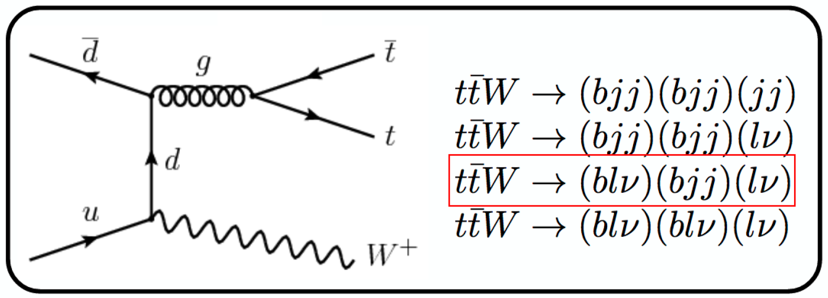
Systematic uncertainties dominate

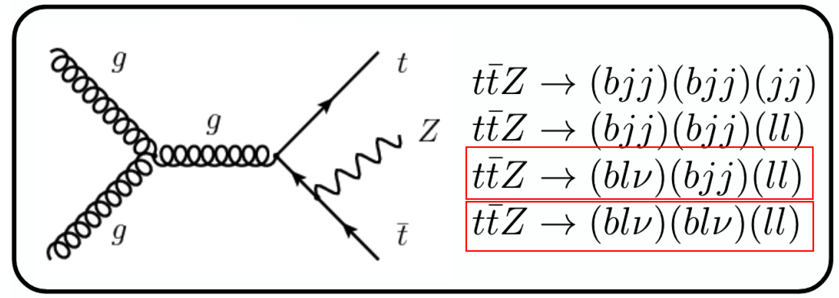
- largest contribution from b-tagging and mis-tagging of c- and light jets

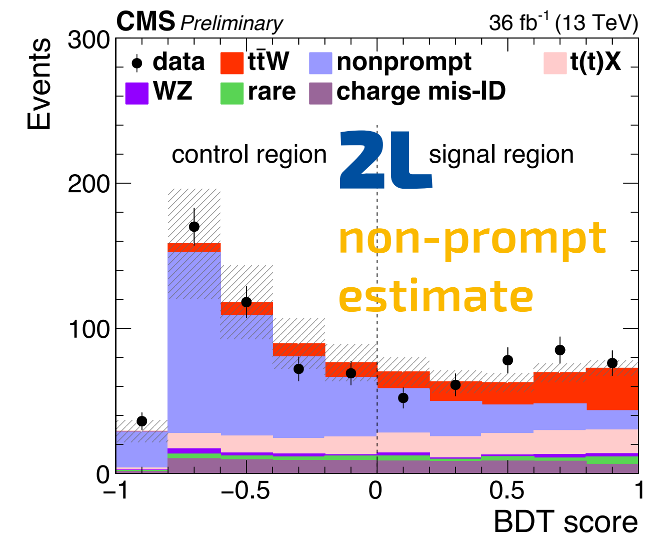




tZt
Measurement of $t\bar{t}W$ & $t\bar{t}Z$

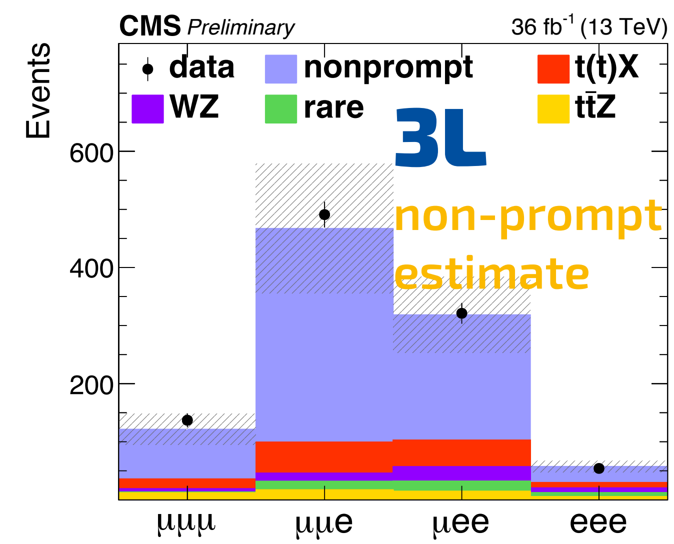






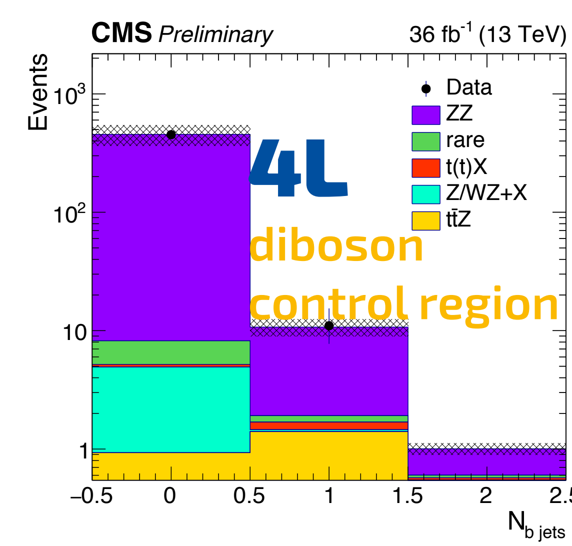
New: analysis of full 2015/16 13 TeV data

- 2 same-sign lepton → $t\bar{t}W$, BDT
- 3 or 4 leptons → $t\bar{t}Z$, cut & count
- several signal regions based on N_{jets} and $N_{b\text{-}jets}$



SS 2L

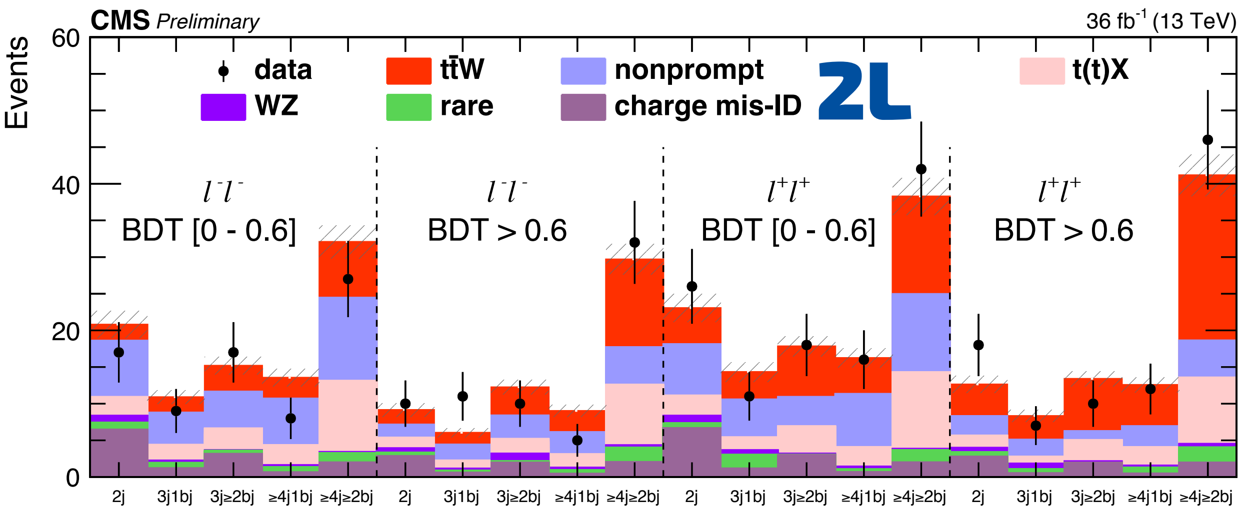
- further split in + + and - -
- non-prompt background from low BDT score region

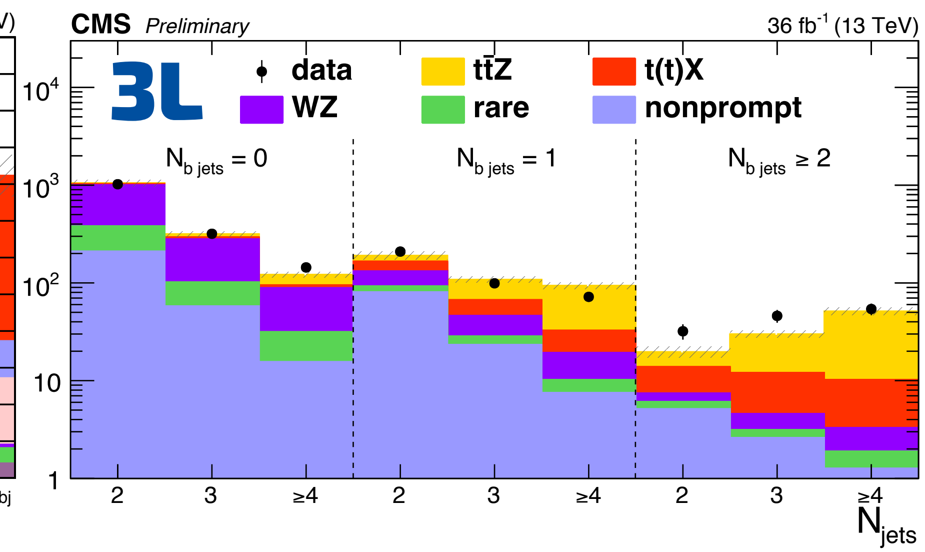


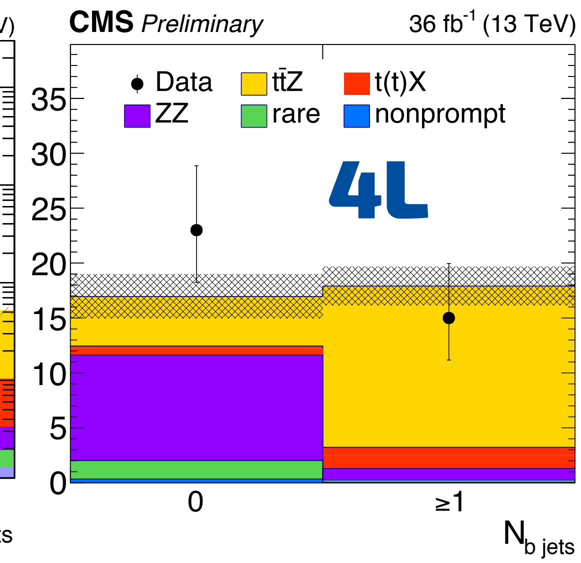
3L and 4L

- non-prompt lepton background from control regions
- WZ/ZZ from simulation, validated in control regions

Results and EFT interpretation



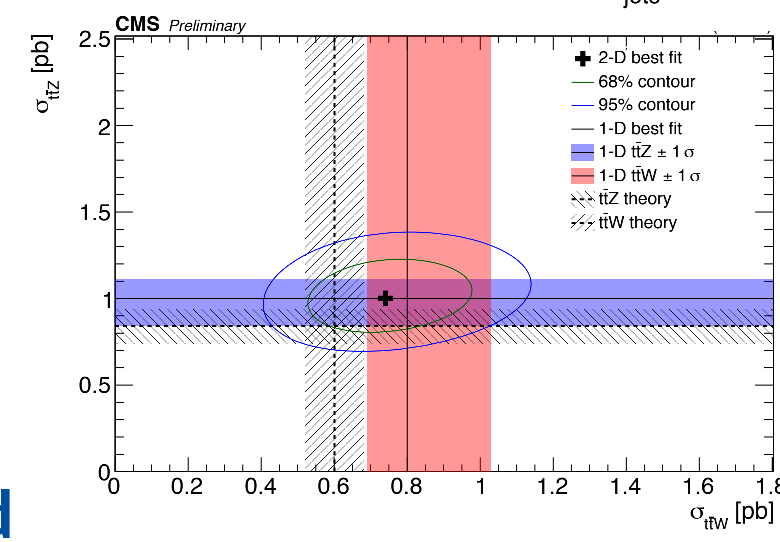




Measured cross section at 13 TeV

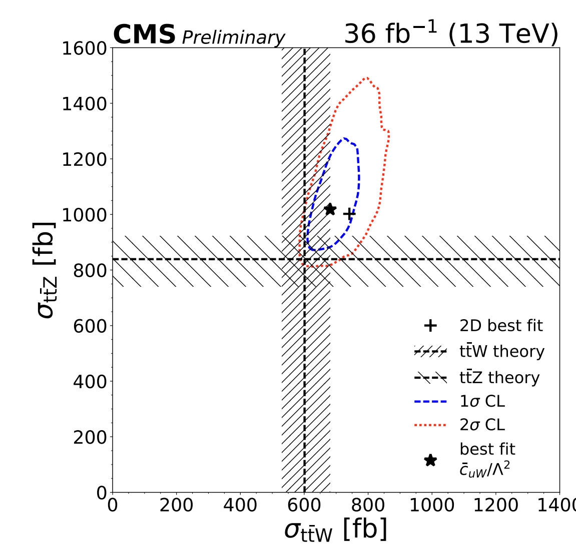
$$\sigma(t\bar{t}Z) = 1.00^{+0.09}_{-0.08}(\text{stat.})\ ^{+0.12}_{-0.10}(\text{sys.})\ \text{pb}$$

$$\sigma(t\bar{t}W) = 0.80\ ^{+0.12}_{-0.11}(\text{stat.})\ ^{+0.13}_{-0.12}(\text{sys.})\ \text{pb}$$



EFT Lagrangian

- do not consider NP couplings to first and second generation or affecting $t\bar{t}$, H, or diboson
- consider NP effects on $t\bar{t}H$, $t\bar{t}W$ and $t\bar{t}Z$

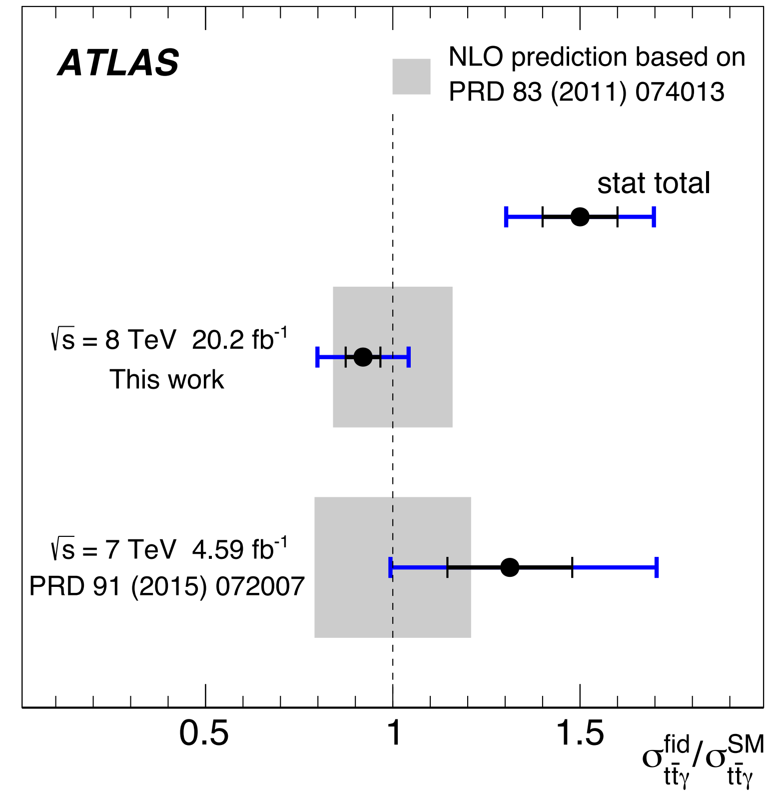


Wilson coefficient	Best fit [TeV^{-2}]	1σ CL [TeV^{-2}]	2σ CL [TeV^{-2}]
$\lvert\bar{c}_{uB}/\Lambda^2 + 0.1\ \text{TeV}^{-2}\rvert$	3.2	[0.0, 4.4]	[0.0, 5.4]
$\lvert\bar{c}_{u}/\Lambda^2 + 18.5\ \text{TeV}^{-2}\rvert$	19.1	[5.0, 26.4]	[0.0, 32.5]
$\bar{c}_{uW}/\Lambda^2$	3.0	[-4.1, -1.5] and [1.2, 4.1]	[-5.1, 5.0]
$\bar{c}_{Hu}/\Lambda^2$	-9.4	[-10.3, -8.1] and [0.1, 2.1]	[-11.1, -6.6] and [-1.4, 3.0]

Measurement of $t\bar{t}\gamma$ production

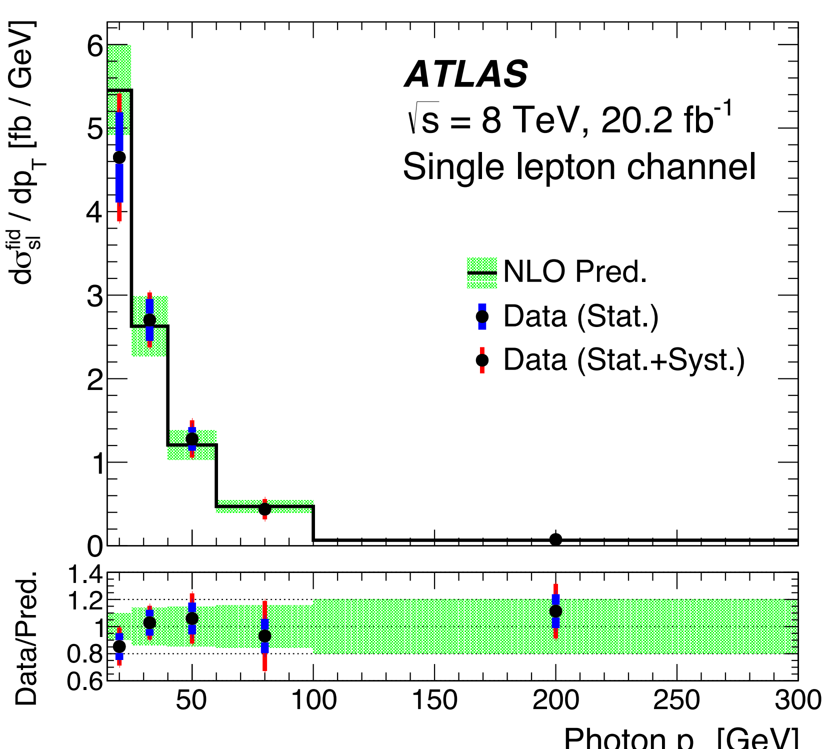
First observation (5.3σ) with 7 TeV data

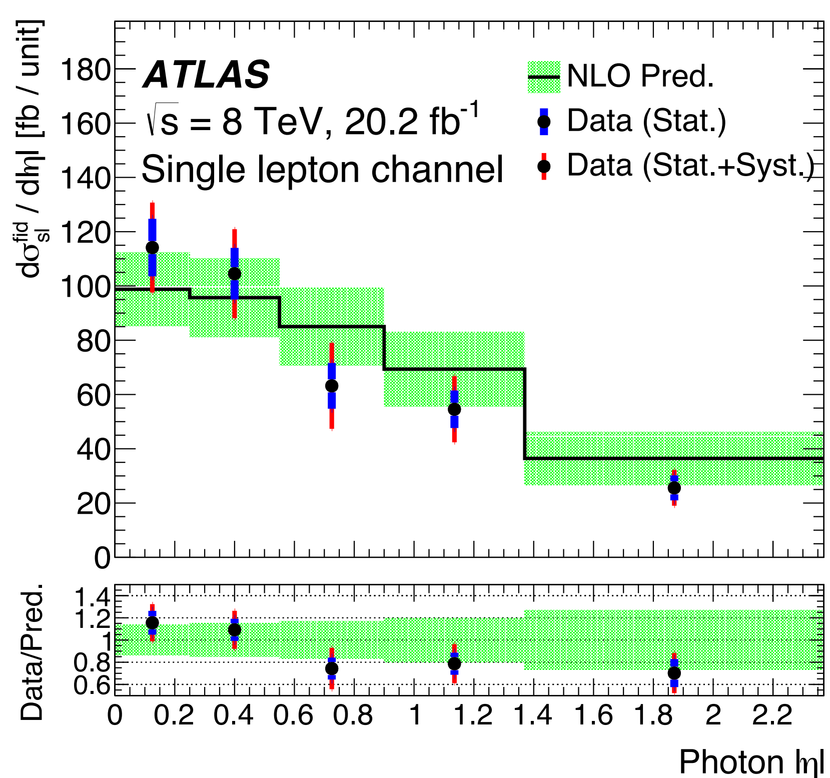
- measurement in a fiducial volume, $E_T(\gamma)$ > 20 GeV
- non-prompt photon contributions data-driven
- template fit to track isolation variable

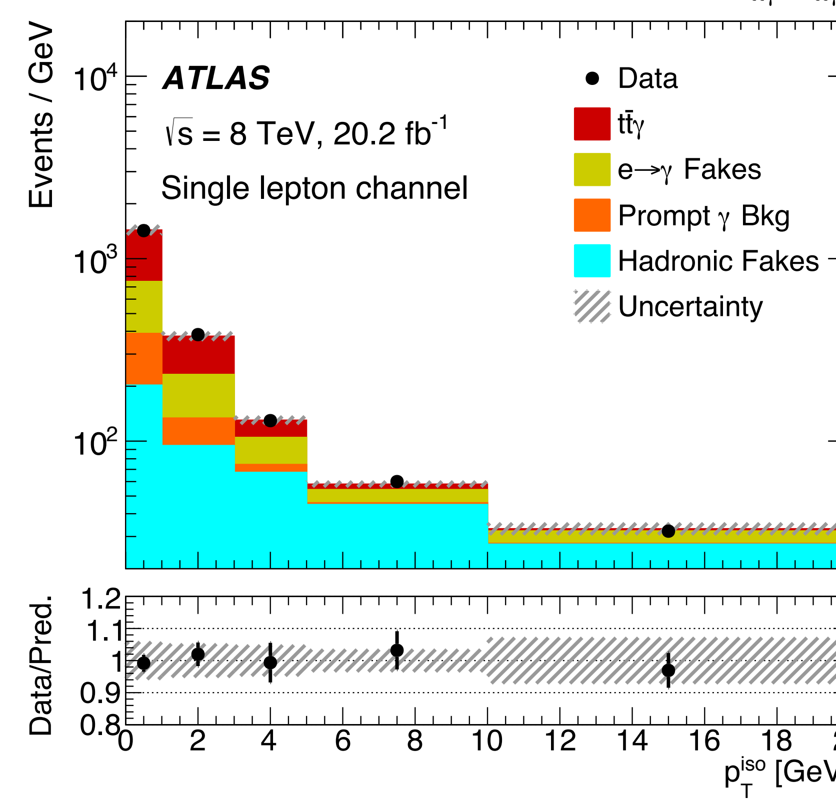


New for FPCP2017 paper with 8 TeV data

- also differential in photon p_T and |η|



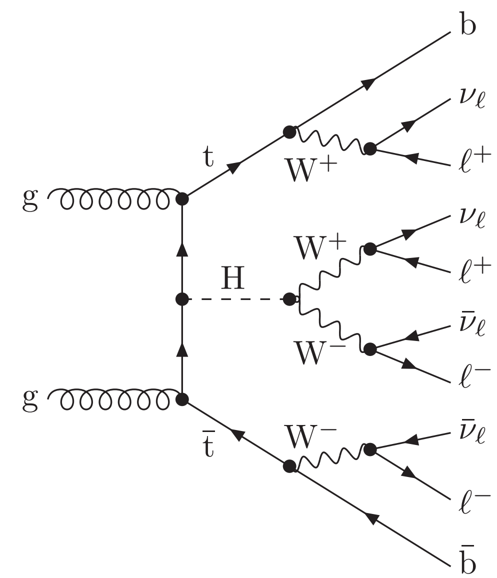


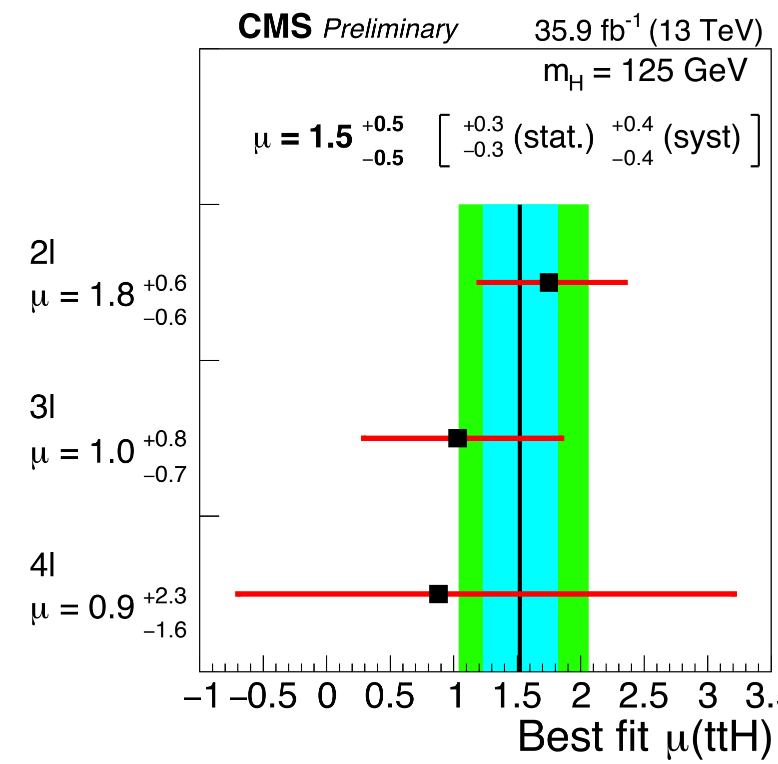


tHt
$t\bar{t}H$ production

Run-1 ATLAS+CMS combination

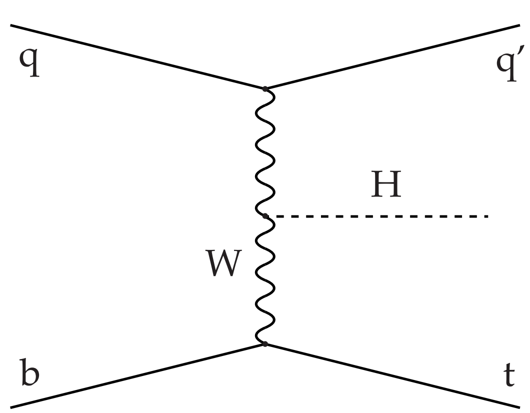
- $\mu = \sigma_{\text{meas.}}/\sigma_{\text{theo.}} = 2.3^{+0.7}_{-0.6}$
- 4.4σ (2.0σ expected)

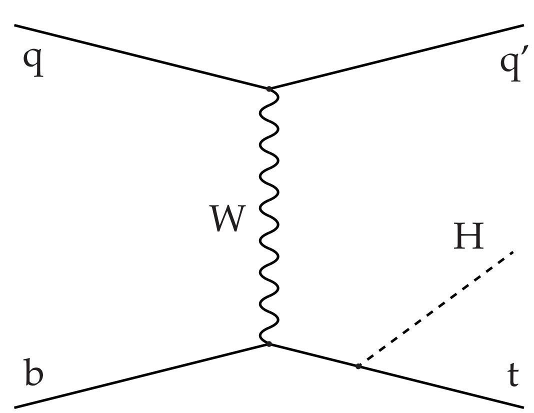


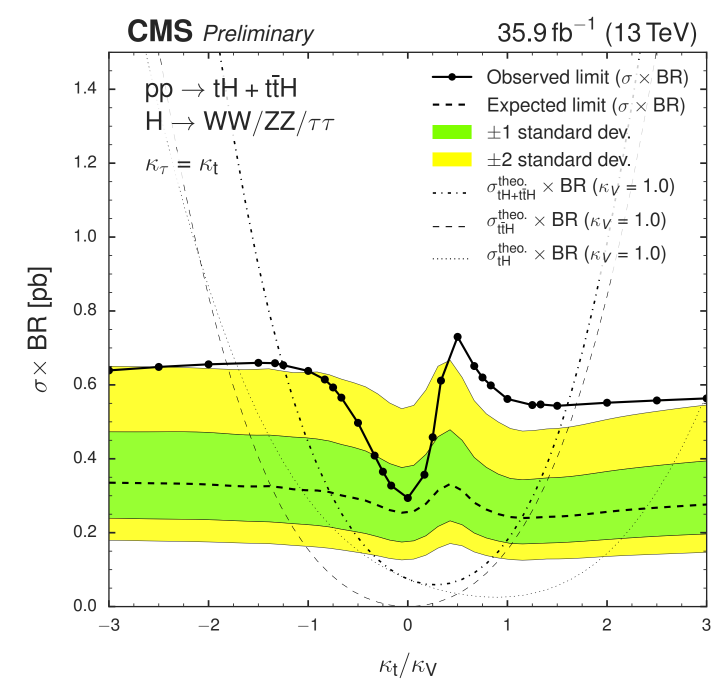


Latest Run-2 results (CMS)

- multilepton: 3.3σ (2.5σ)
- tau-lepton channels: 1.4σ (1.8σ)
- search for tH





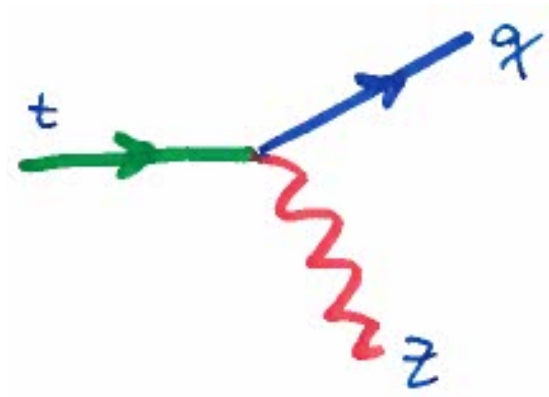


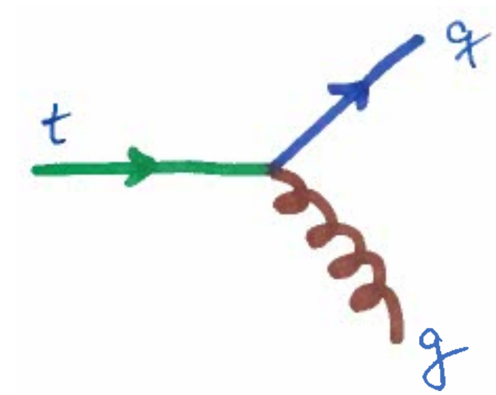
Charged current decays

- BR(t→Wb) = 99.8%, BR(t→Ws) = 0.2%, BR(t→Wd) = 0.01%

Flavour changing neutral current decays

- forbidden at tree level in SM
- strongly suppressed higher orders
- some BSM predict large enhancement



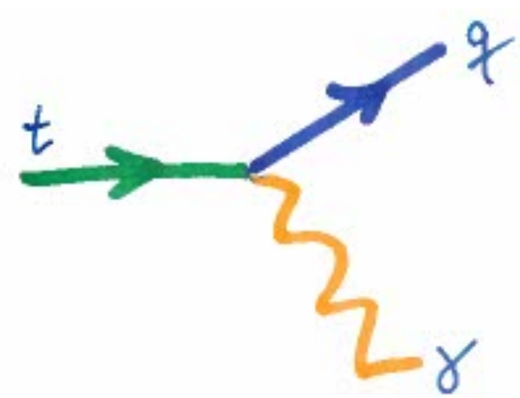


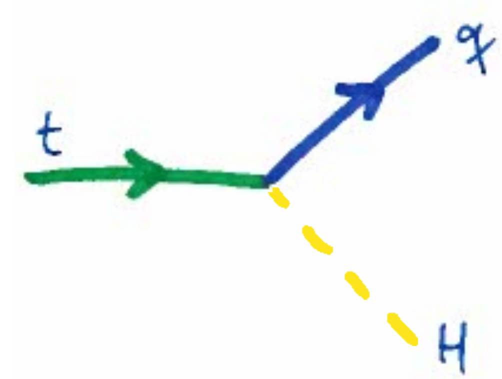
Look at

- Higgs, γ, Z or gluon

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

arXiv:1311.2028 [hep-ph] (2013)





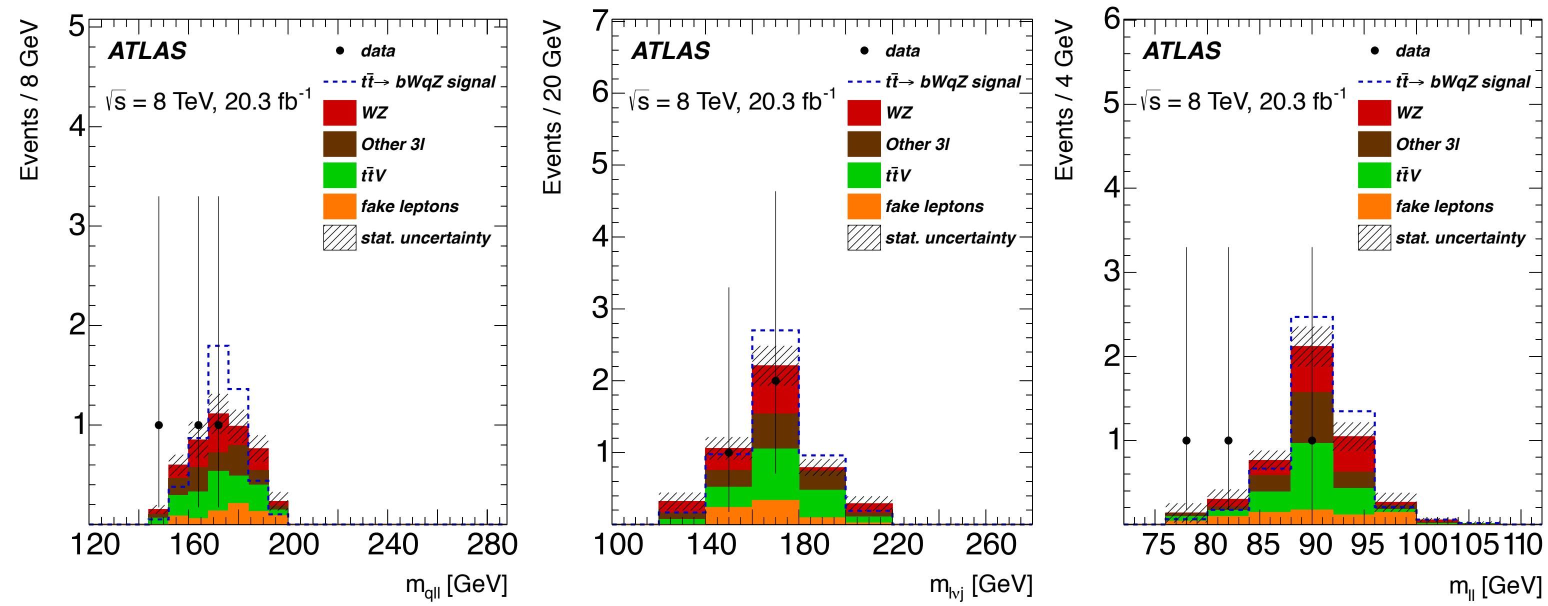
FCNC tZq

Search for $t\bar{t} \rightarrow ZqWb$

- three lepton final state
- pair objects and minimise χ^2

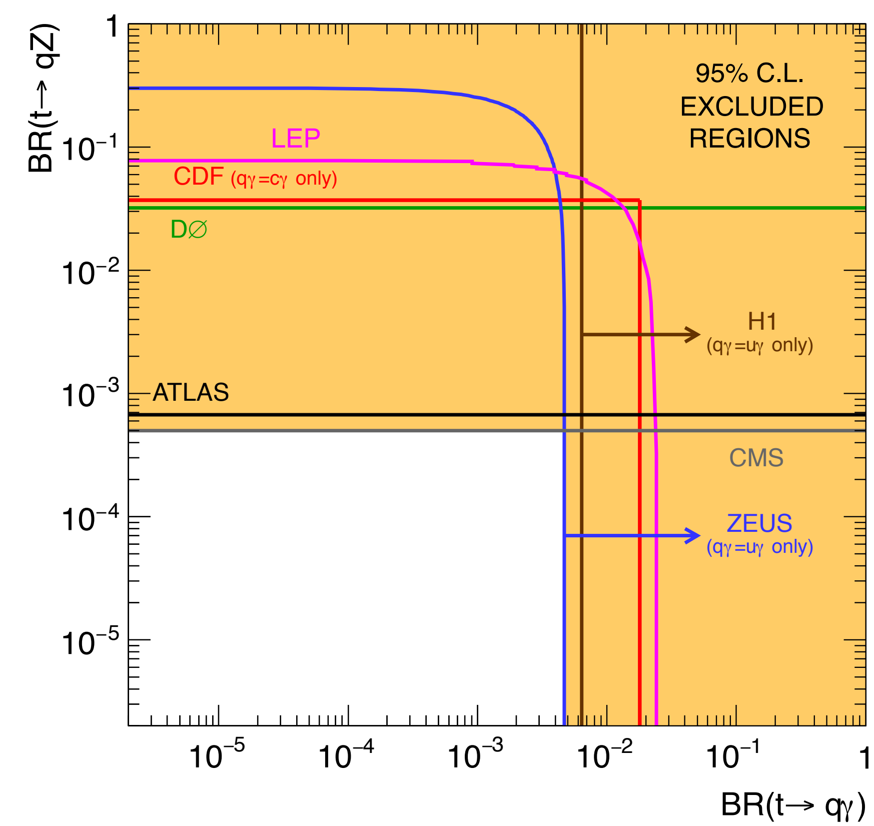
$$\mathcal{L}_{Ztu} = -\frac{g}{2c_W}\bar{u}\gamma^{\mu}\left(X^{\mathrm{L}}_{ut}P_{\mathrm{L}} + X^{\mathrm{R}}_{ut}P_{\mathrm{R}}\right)tZ_{\mu} - \frac{g}{2c_W}\bar{u}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_Z}\left(\kappa^{\mathrm{L}}_{ut}P_{\mathrm{L}} + \kappa^{\mathrm{R}}_{ut}P_{\mathrm{R}}\right)tZ_{\mu}$$

$$\chi^2 = \frac{\left(m^{\mathrm{reco}}_{j_a\ell_a\ell_b} - m_{t\mathrm{FCNC}}\right)^2}{\sigma^2_{t\mathrm{FCNC}}} + \frac{\left(m^{\mathrm{reco}}_{j_b\ell_c\nu} - m_{t\mathrm{SM}}\right)^2}{\sigma^2_{t\mathrm{SM}}} + \frac{\left(m^{\mathrm{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W}$$



Results

- BR(t→Zq) < 0.07% (0.08%)



Extrapolation

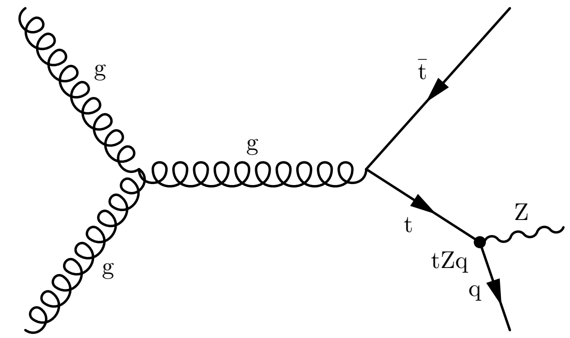
- sensitivity increase at HL-LHC, 3ab^{-1}

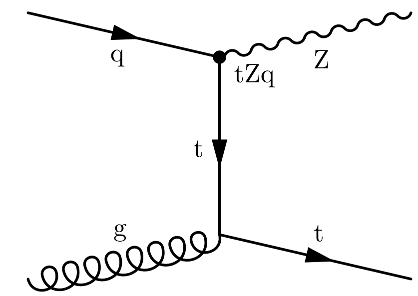
"γ" $t\to Zu$	"σ" $t\to Zu$	"γ" $t\to Zc$	"σ" $t\to Zc$	"γ" $t\to Zu+Zc$	"σ" $t\to Zu+Zc$
$4.3\cdot10^{-5}$	$4.3\cdot10^{-5}$	$5.6\cdot10^{-5}$	$5.8\cdot10^{-5}$	$2.4\cdot10^{-5}$	$2.5\cdot10^{-5}$

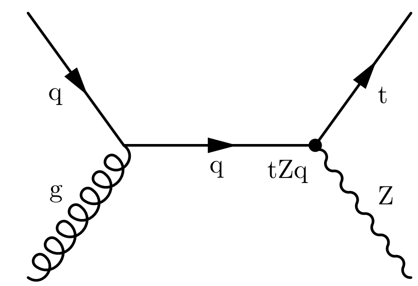
FCNC tZq

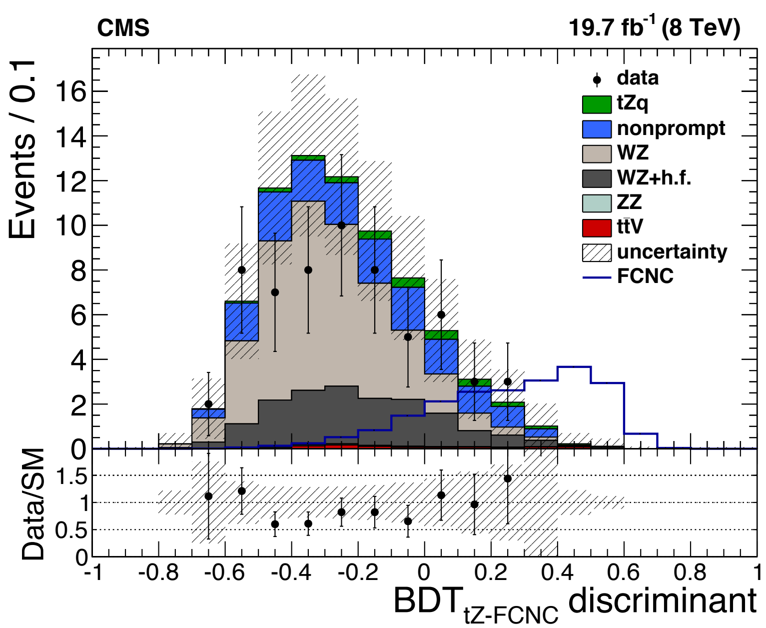
Production and decay vertices

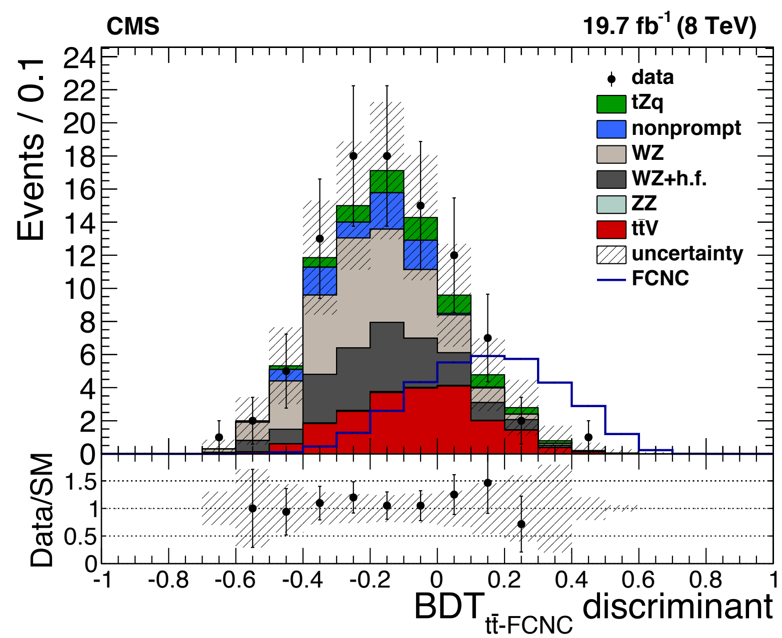
- three lepton signature
- training two BDTs: BDT-tZ and BDT-$t\bar{t}$





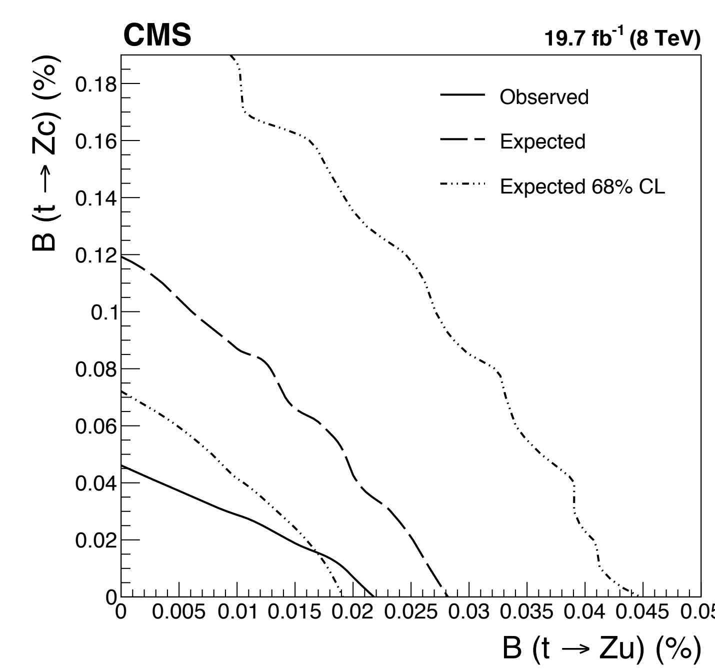






Results

- BR(t→Zu) < 0.022% (0.027%)
- BR(t→Zc) < 0.049% (0.118%)



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ATLAS-HIGG-2016-26

FCNC tHq

H→leptons

- aiming at H→ WW, ττ,ZZ
- reinterpreting $t\bar{t}H$ searches

H→$b\bar{b}$

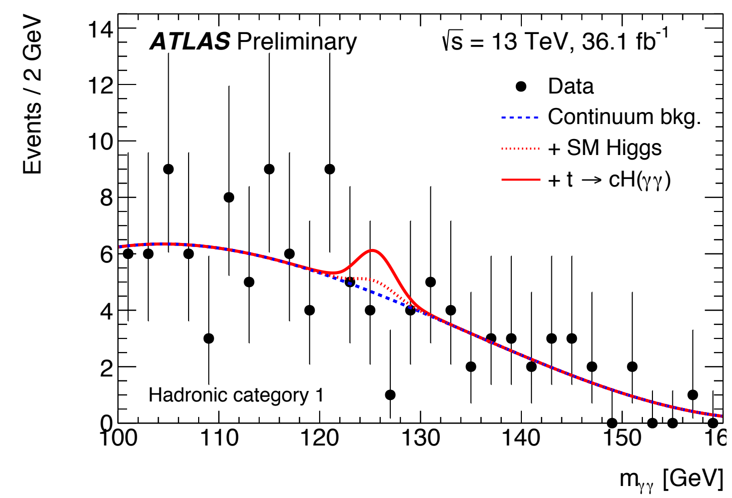
- dedicated analysis
- split in regions (N_{jets}, $N_{b\text{-}tags}$)

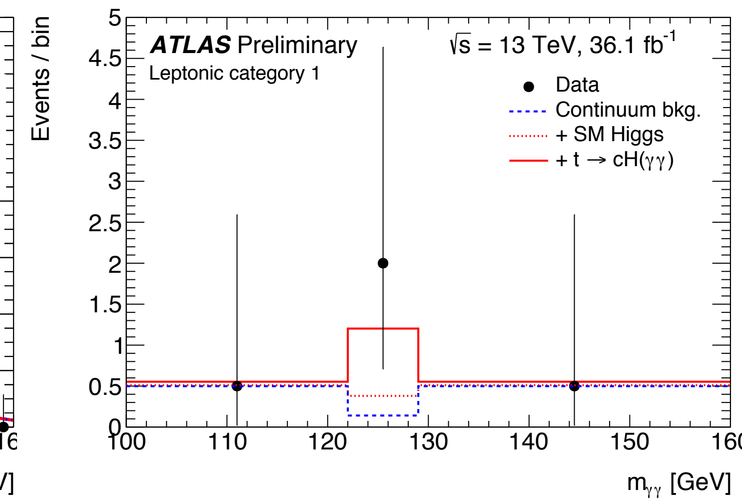
H→γγ

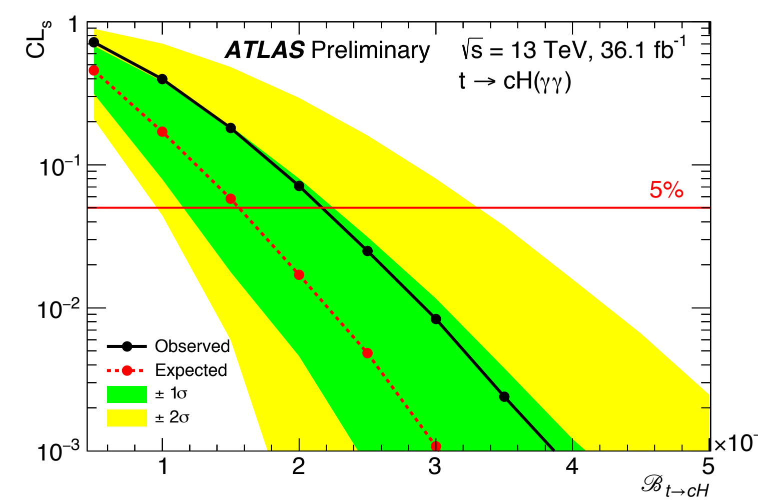
- limited by statistics

New for FPCP2017

- First Run-2 FCNC search: H→ γγ (36/fb)
- Use leptonic and hadronic top (split into two categories each)







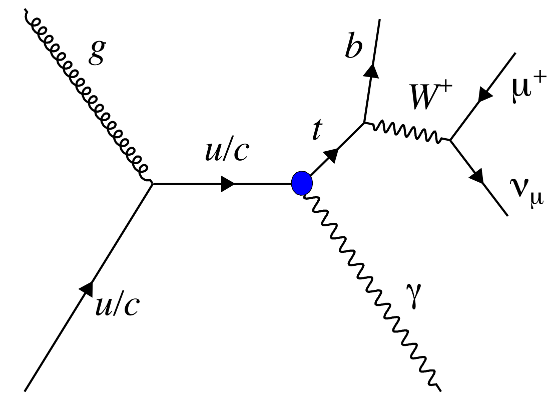
Result

- BR (t→Hc) < 0.22% (0.16%)
- BR (t→Hu) < 0.24% (0.17%)

Run-1 ATLAS combination

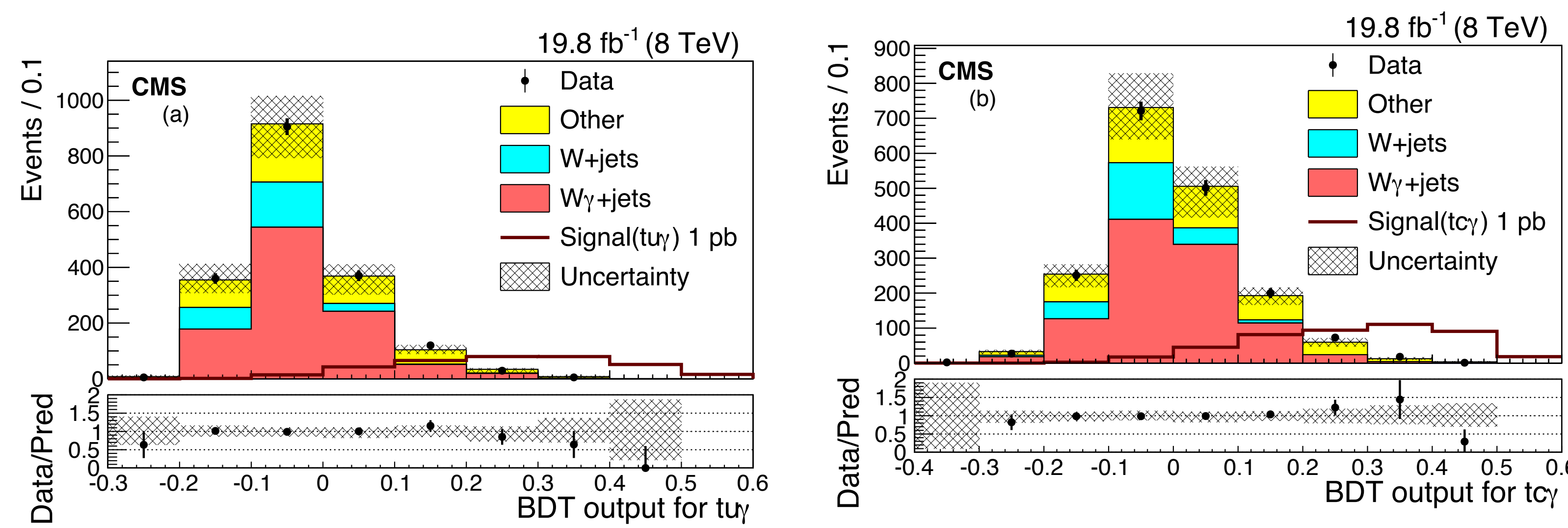
- BR (t→Hc) < 0.46% (0.25%)
- BR (t→Hu) < 0.45% (0.29%)

FCNC tγq



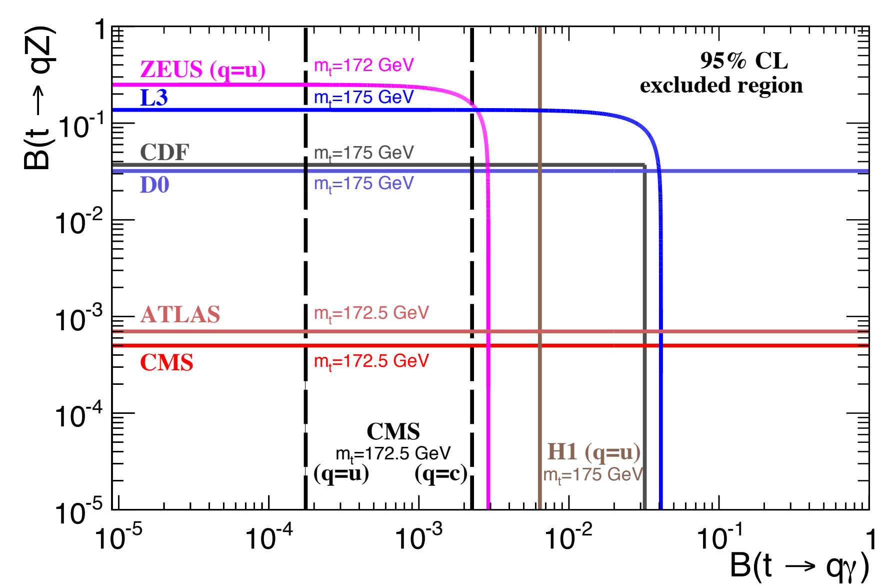
Associated tγ production

- BDT training



Results

- BR $(t \to u\gamma) < 1.3 \cdot 10^{-4}$
- BR $(t \to c\gamma) < 1.7 \cdot 10^{-4}$



Anomalous couplings

- $\kappa_{tu\gamma} < 0.025$ and $\kappa_{tc\gamma} < 0.091$ using NLO

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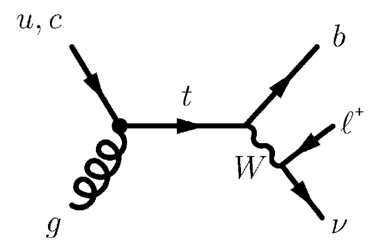
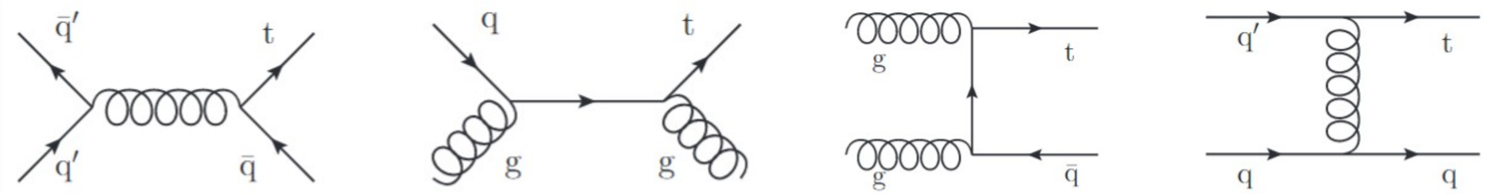
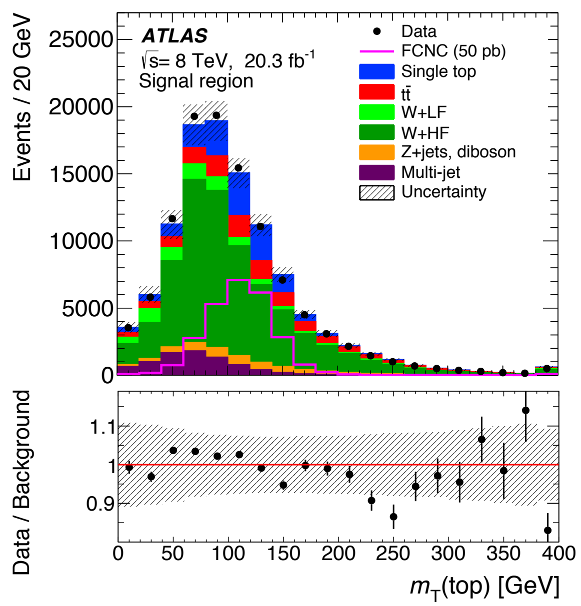
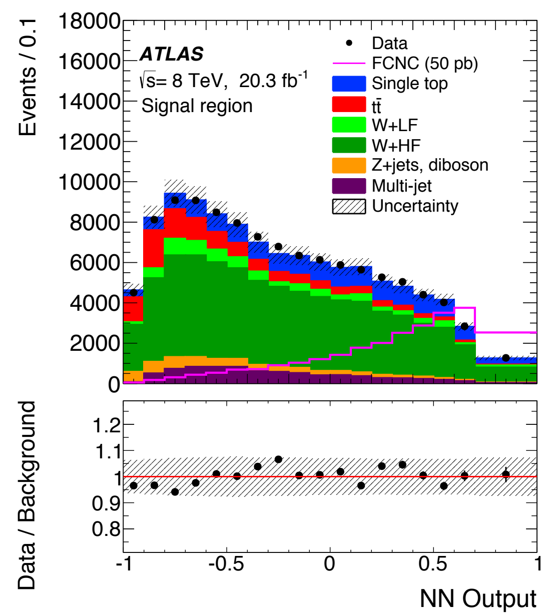
FCNC tgq

tgq vertex can be probed in single top production

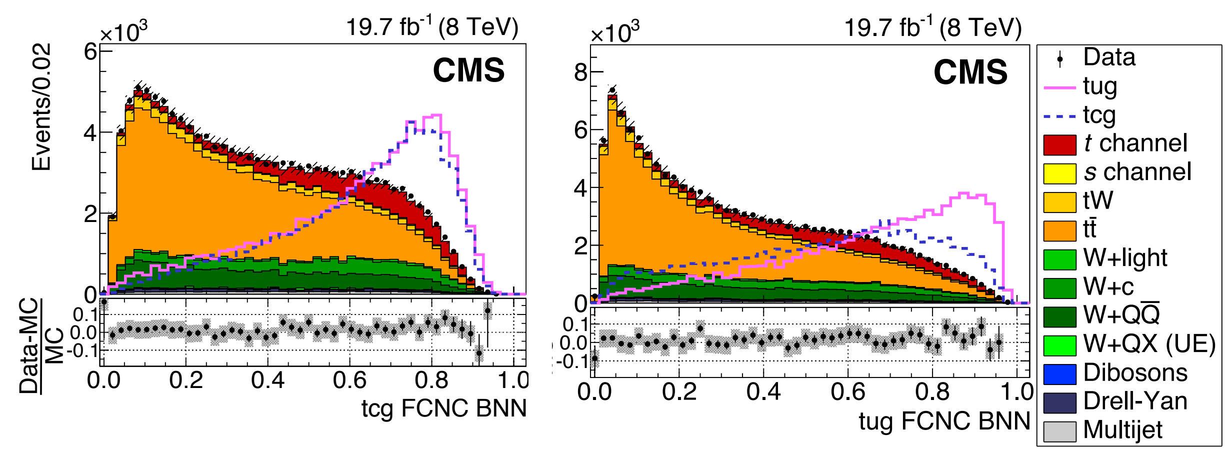
- Wb  or Wbj 

- top-quark softer than in SM, large $p_T(W)$, different charge asymmetry→ NN
- multijet BNN, SM BNN + two dedicated BNN





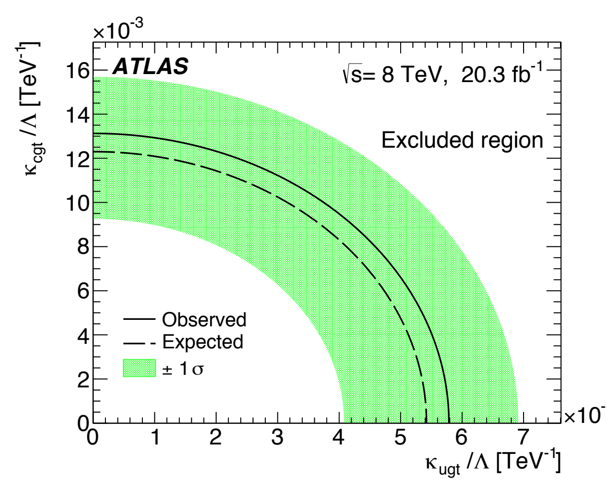
BR(t→gu) < 0.004%   BR(t→gc) < 0.020%

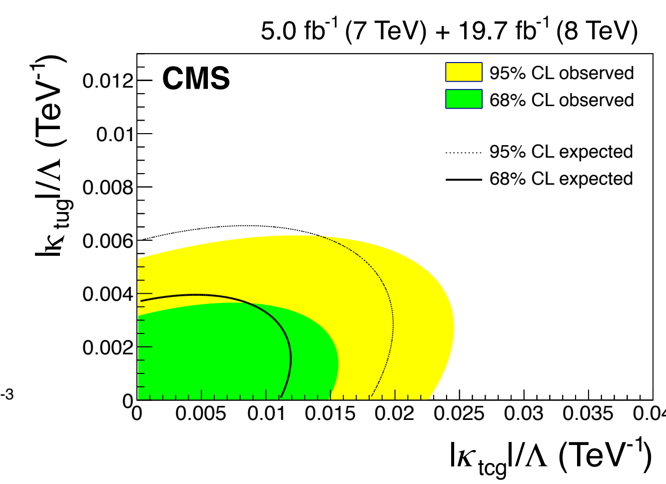


BR(t→gu) < 0.002%   BR(t→gc) < 0.041%

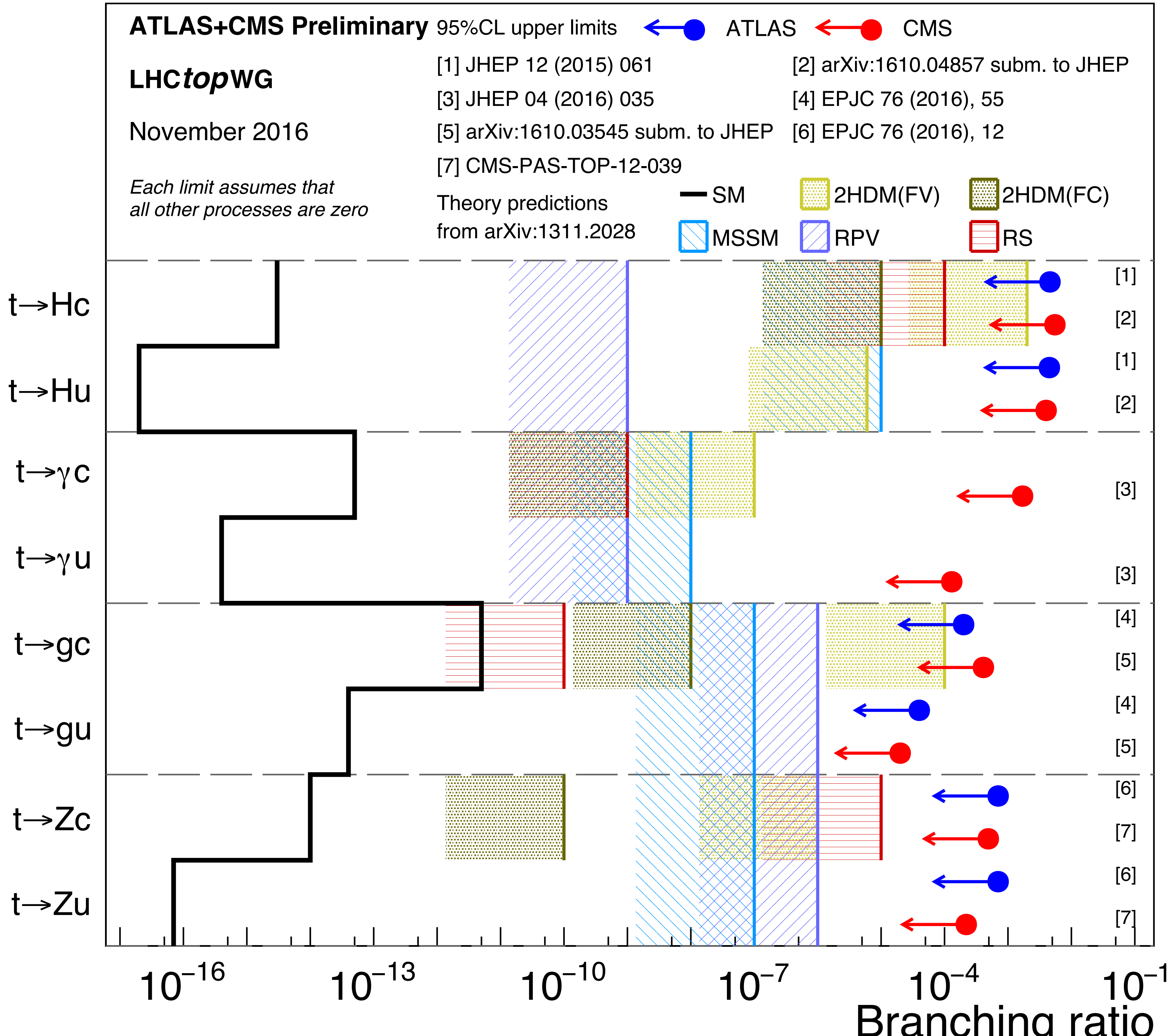
- also interpreted in terms of κ_{tqg} or BR

$$\mathfrak{L} = \frac{\kappa_{\rm tqg}}{\Lambda} g_s \overline{\rm q} \sigma^{\mu\nu} \frac{\lambda^{\rm a}}{2} {\rm t} G^{\rm a}_{\mu\nu}$$





FCNC summary

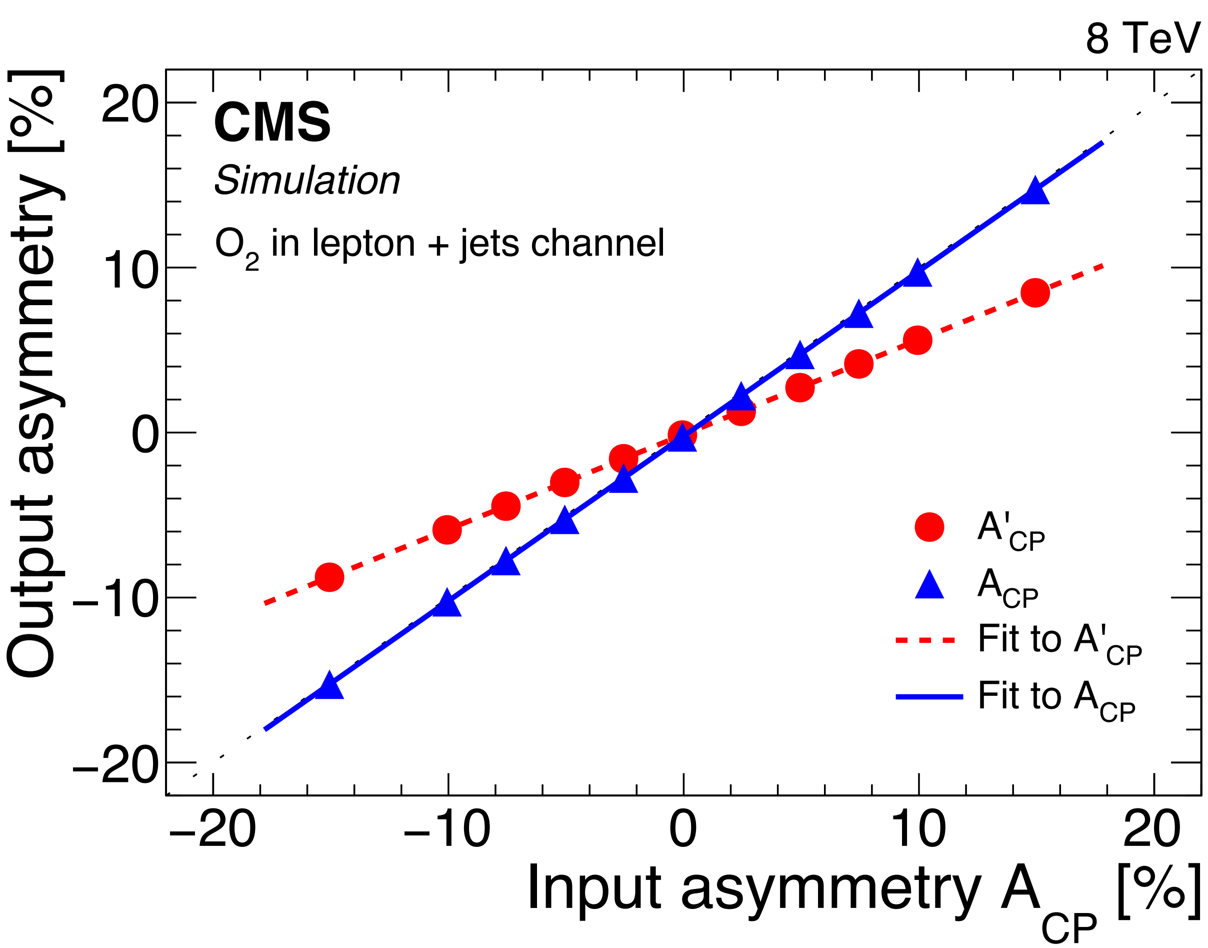


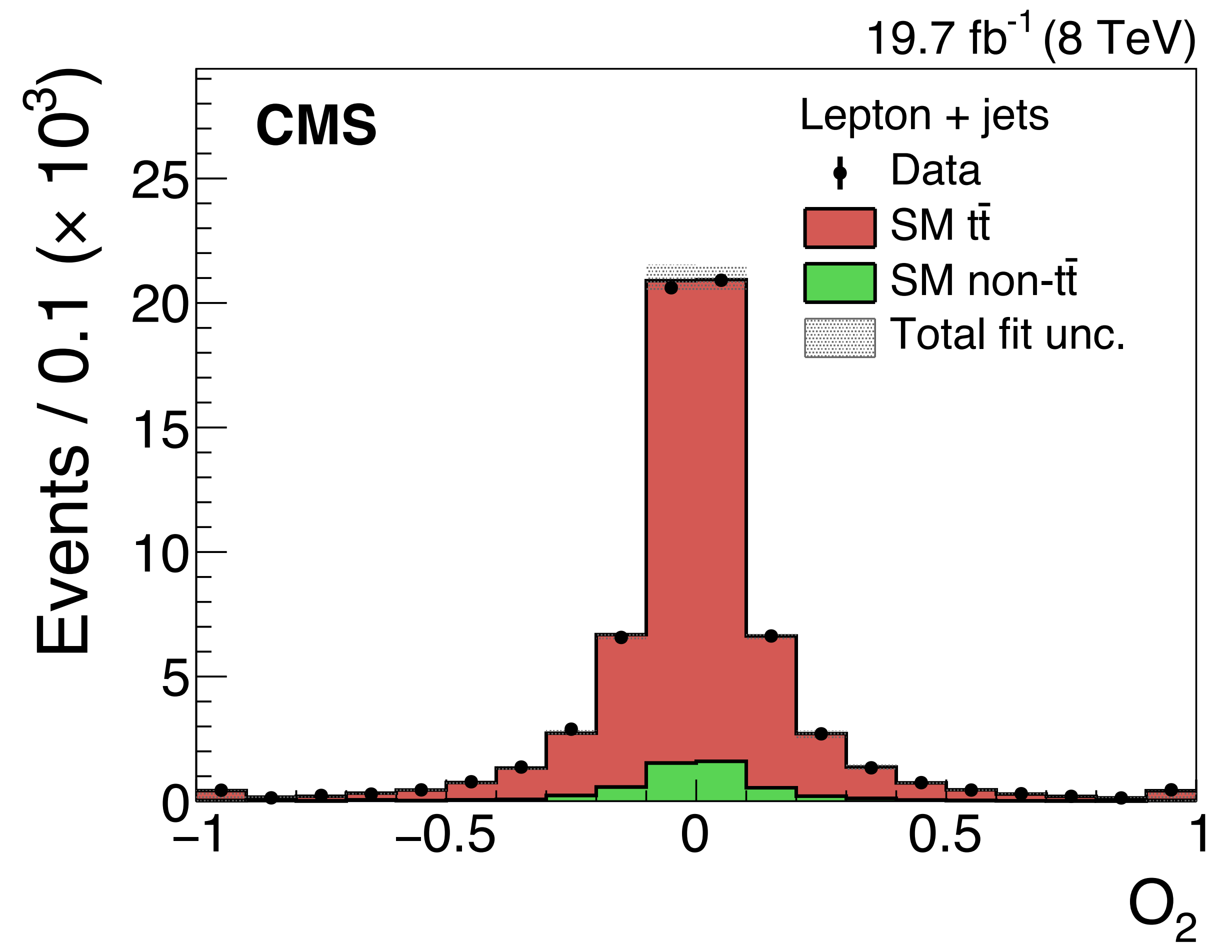
Best limits

BR (10^{-4})	κ,λ(10^{-3}) (/Λ)
22	90
24	94
17	91
1.3	25
2.0	13/TeV
0.2	4.1/TeV
4.9	
2.2	

CP violation in $t\bar{t}$ production and decay

- construct T-odd observables of the form **v₁** · (**v₂** x **v₃**) from momentum and spin vectors
  - e.g. $(\vec{p}_{\mathrm{b}} + \vec{p}_{\bar{\mathrm{b}}}) \cdot (\vec{p}_{\ell} \times \vec{p}_{j_1})$ and $Q_{\ell}\, \vec{p}_{\mathrm{b}} \cdot (\vec{p}_{\ell} \times \vec{p}_{j_1})$
- CP violation manifests as an asymmetry in O_i (>0 vs. <0)
- diluted by 35 — 73 %, mainly due to incorrectly assigned b-jets





- measured values consistent with 0, with %-level uncertainties

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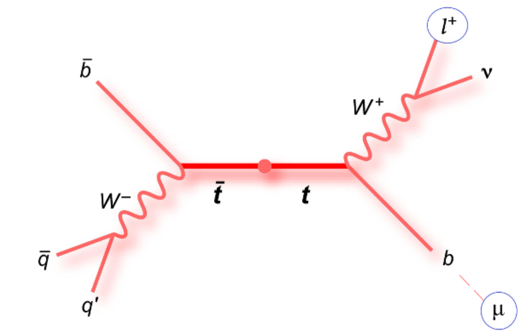
CP asymmetries in b-hadron decays using $t\bar{t}$ events

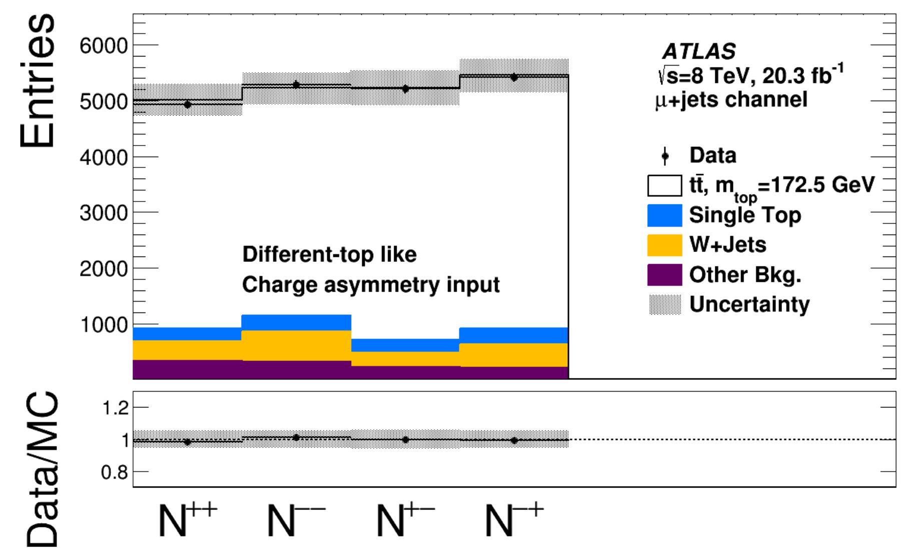
Top-quark pair excellent source of b-hadrons[1]

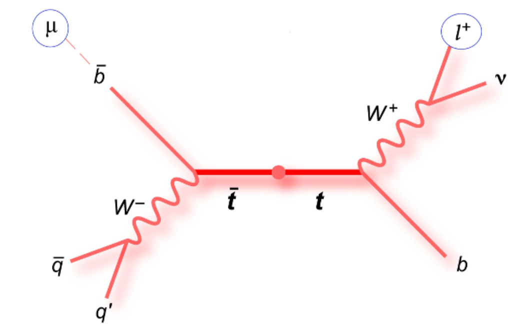
- hadron charge can be measured at production and decay
- soft muon tagging (SMT) to reconstruct the charge at decay



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

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





	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]
mixing CP → A^{b}_{mix}	-2.5 ± 2.8	0.2 ± 0.7	< 0.1	[95]	$< 10^{-3}$	[95, 96]
direct CP: $A^{b\ell}_{\mathrm{dir}}$	0.5 ± 0.5	-0.03 ± 0.14	< 1.2	[94]	$< 10^{-5}$	[19, 94]
direct CP: $A^{c\ell}_{\mathrm{dir}}$	1.0 ± 1.0	-0.06 ± 0.25	< 6.0	[94]	$< 10^{-9}$	[19, 94]
direct CP: A^{bc}_{dir}	-1.0 ± 1.1	0.07 ± 0.29	-		$< 10^{-7}$	[97]

- dominated by stat. uncertainties → will improve with 13 TeV data
- first constraint on A_{dir}^{bc} and improved limit on A_{dir}^{cl}

[1] see PRL 110 (2013) 232002

Summary

Search for CP violation

- in top quark decay
- in single top quark production
- in b-hadrons from $t\bar{t}$

Characterisation of top quark production and decay

- Wtb structure through inclusive and differential single top
- couplings to neutral bosons through $t\bar{t}$+X measurements
- search for very rare FCNC couplings

Interpretations

- in terms of anomalous couplings in Wtb
- in terms of EFT coefficients (single or multiple analyses)