HEFT 2017, Durham May 22th-24th

Top results from ATLAS and CMS

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On behalf of the ATLAS and CMS collaboration

HELMHOLTZ GEMEINSCHAFT

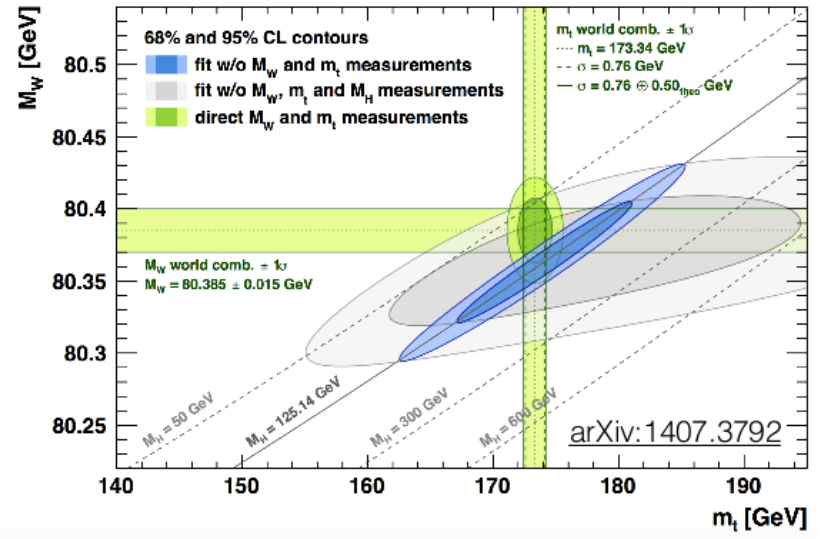
DESY

Introduction

Why looking for top quarks?

Top is very heavy:

- Only standard model particle with mass at about VEV → $y_t \sim 1$
- Big correction to higgs mass → testing the standard model



Top decays before hadronisation

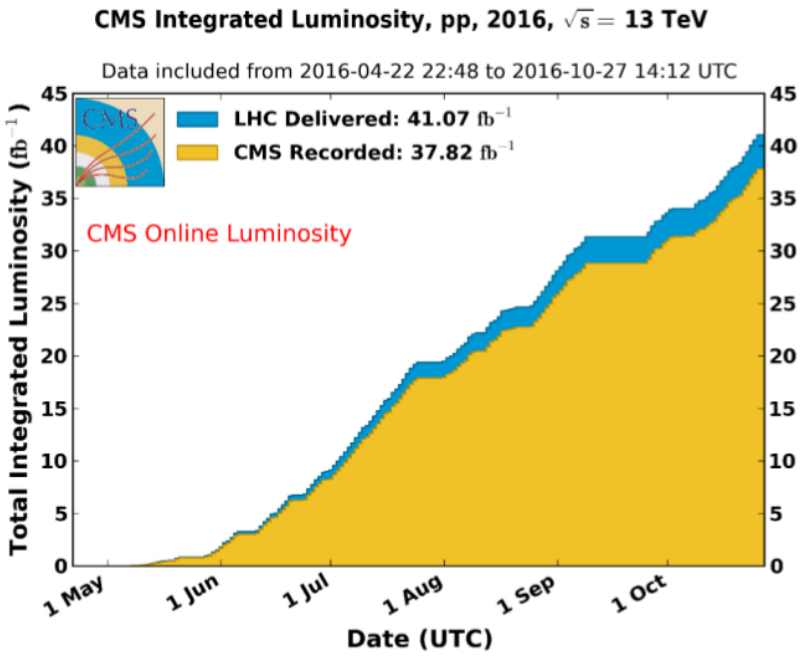
- Only place to study a bare quark

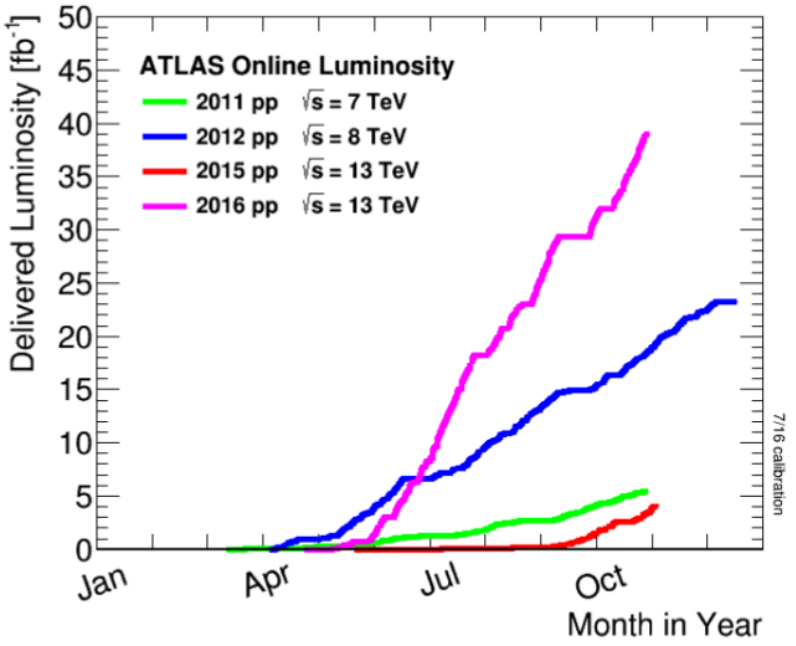
$$\tau_{had} \approx 2 \times 10^{-24} s$$

$$\tau_{top} \approx 5 \times 10^{-25} s$$

Top could be a place to find new physics

Introduction





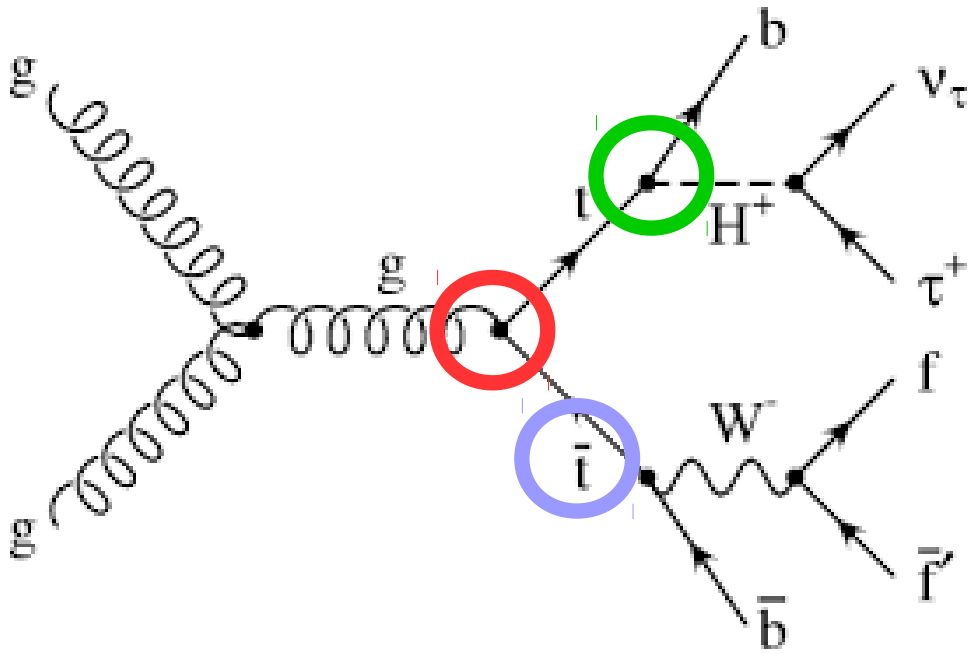
- Top factory: more then 30 Million top pairs produced at E_{CM}=13 TeV
- Most analyses use only parts of the data sets:
  - $t\bar{t}V$ searches use about 1/3 of the 13 TeV data
  - Cross sections available for up to 3.2 fb^{-1} @ 13 TeV (2015 dataset)
  - FCNC use only data from 7/8 TeV
- Many analyses are modelling or experimental (JES) systematic dominated and improvements need time

Introduction

> **Production**:
- **Cross section**
- Mechanism
- Spin correlation

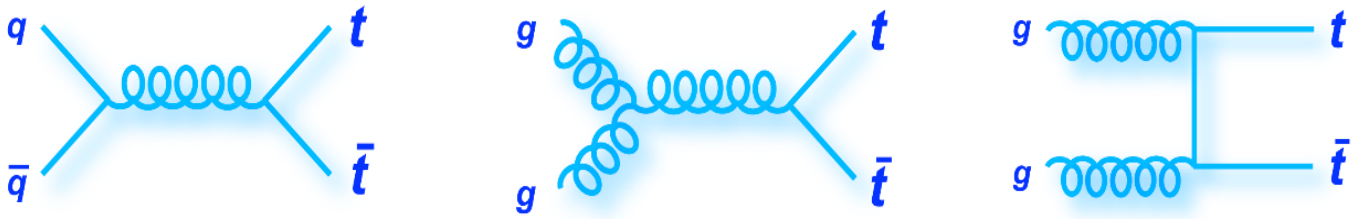
> **Top Properties**:
- **Mass**
- Width
- Spin
- Charge
- **Polarisation**

> **Decay**:
- **Branching ratios/rare decays**
- **W polarisation**
- Decay vertex structure



Inclusive cross sections

Production and decay



$q\bar{q}$ annihilation (~10%) gg fusion (~90%)

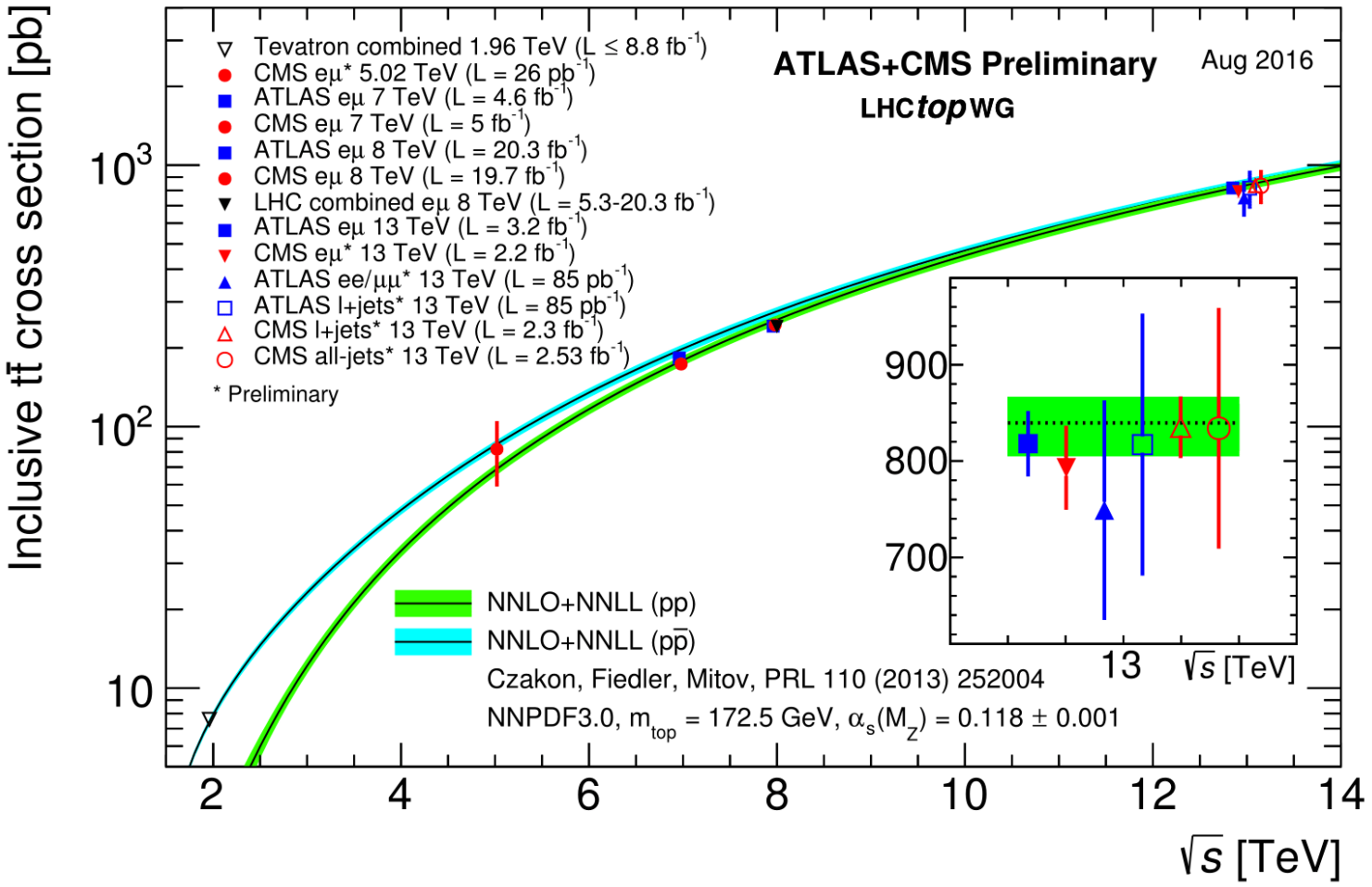
- Dominate production via gluon fusion
  - Constrain gluon PDF
  - Extract α_s and m_{top}
- Probe pQCD at higher orders
- Soft radiation in initial and final state
  - Differential distributions
  - Constrain models for parton shower
- Natural probes for new physics
  - Highly boosted events
- Measurements in channels categorized by W decays

Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

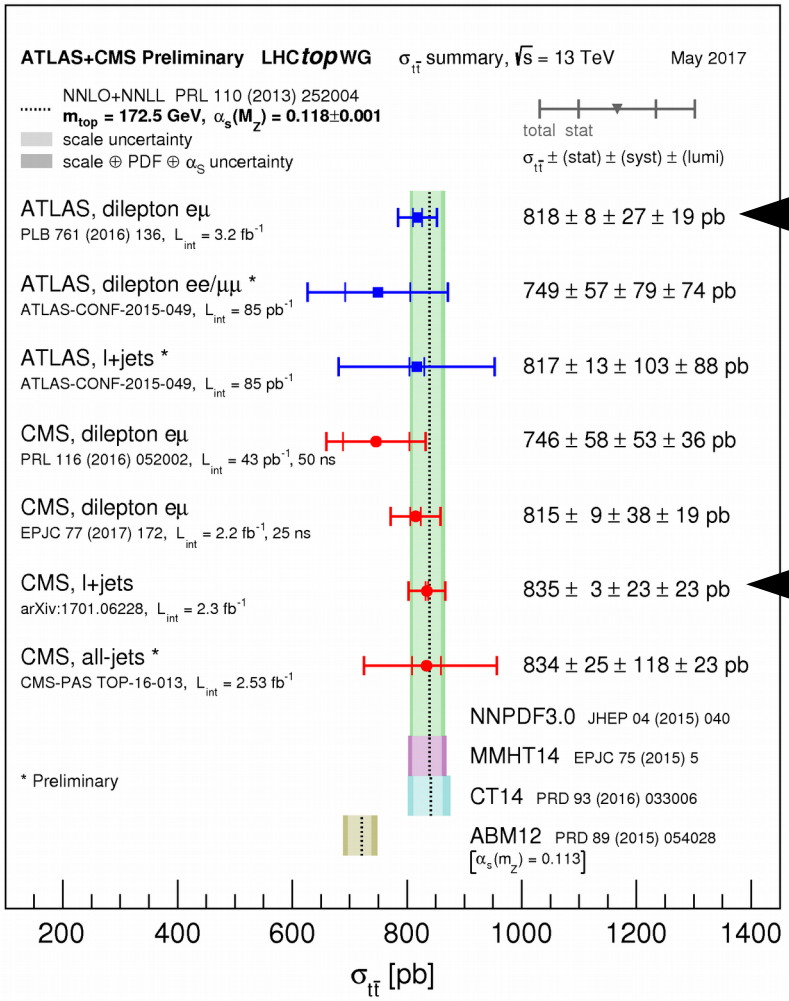
dileptons

Total cross section



> Evolution versus centre of mass energy well understood

Total cross section (II)



- Results are dominated by systematics
- ATLAS di-leptonic:
  - b-tagging systematics constrained using tagged jets distribution

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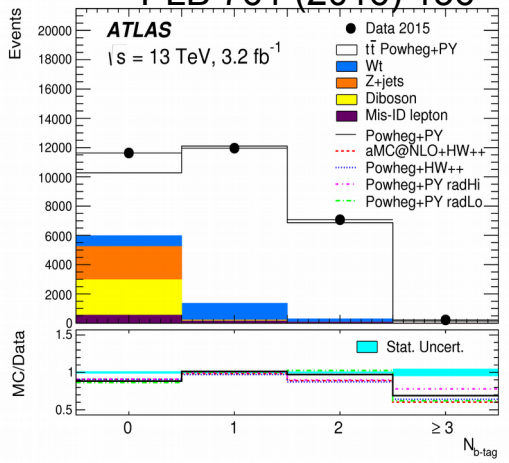
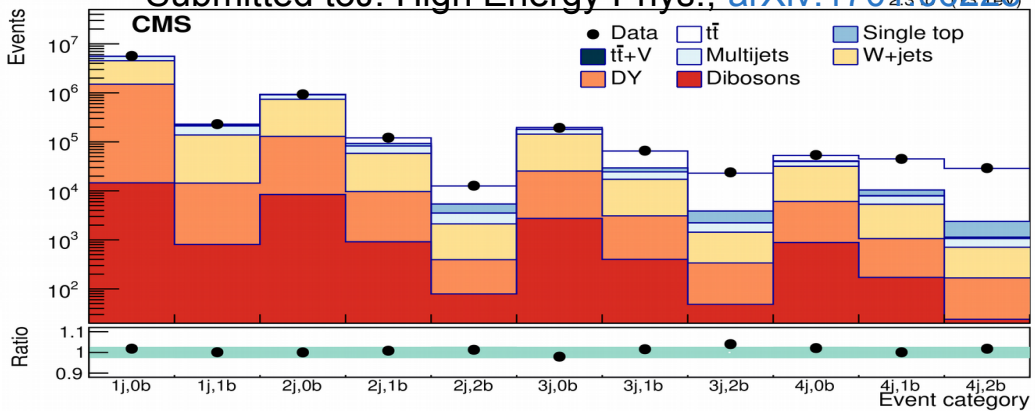


- CMS lepton+jets:
  - many categories in number of jets and b-tags to constrain backgrounds

Submitted toJ. High Energy Phys., arXiv:1701.06228

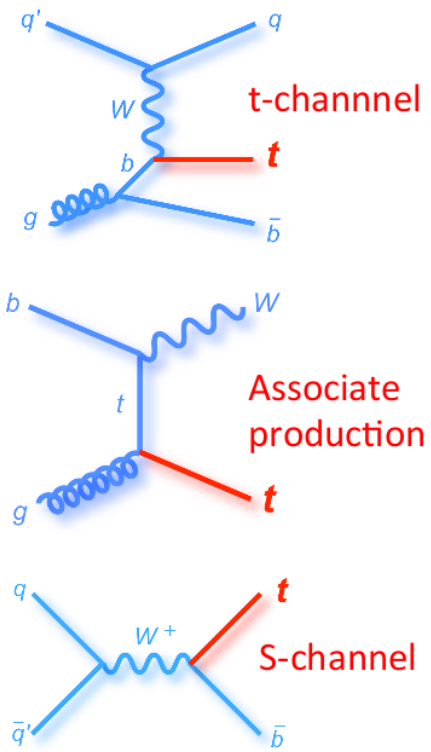


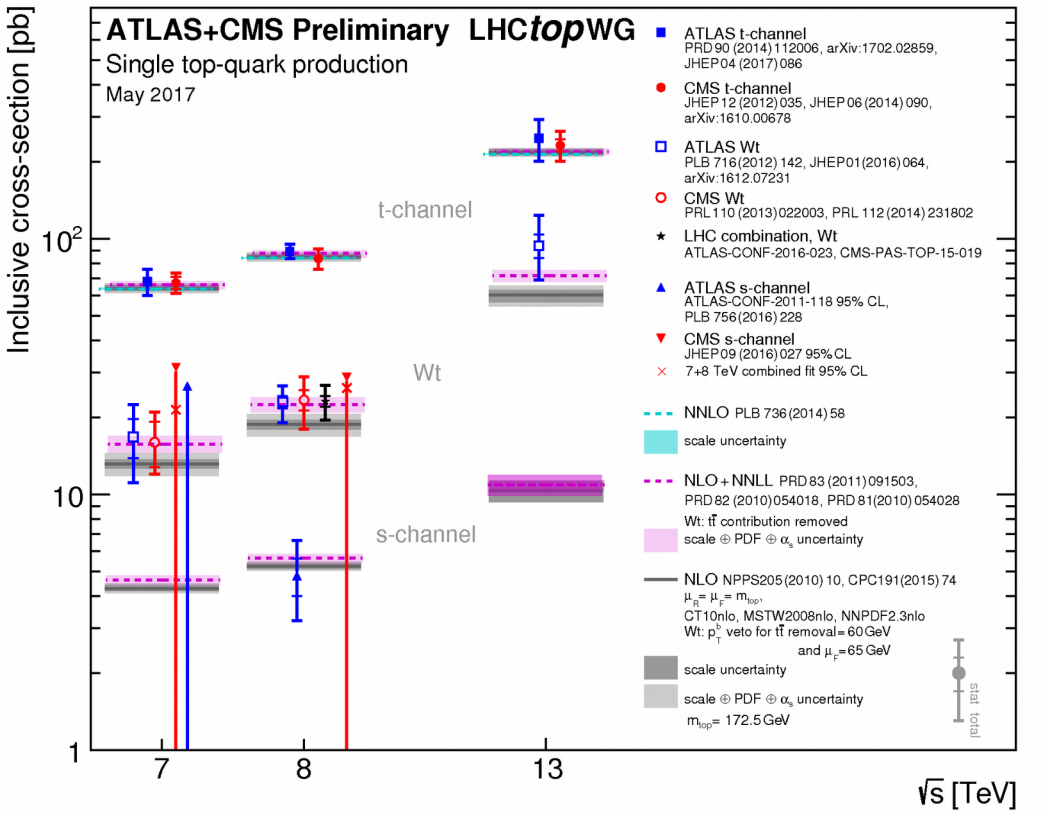
Relative uncertainty of best measurements ~3%

Single top inclusive cross section

> EWK production : smaller cross sections

- Measurement for t-channel and Wt, evidence for s-channel





> First results at 13 TeV for t-channel and Wt

- Excellent agreement at all energies and production channels

Differential cross sections

Differential cross section: additional jets in top

> Top as tool to study QCD radiation:

- Tag the event with a two lepton (eμ), two b-tag selection → very clean top sample
- Look for additional jets in events

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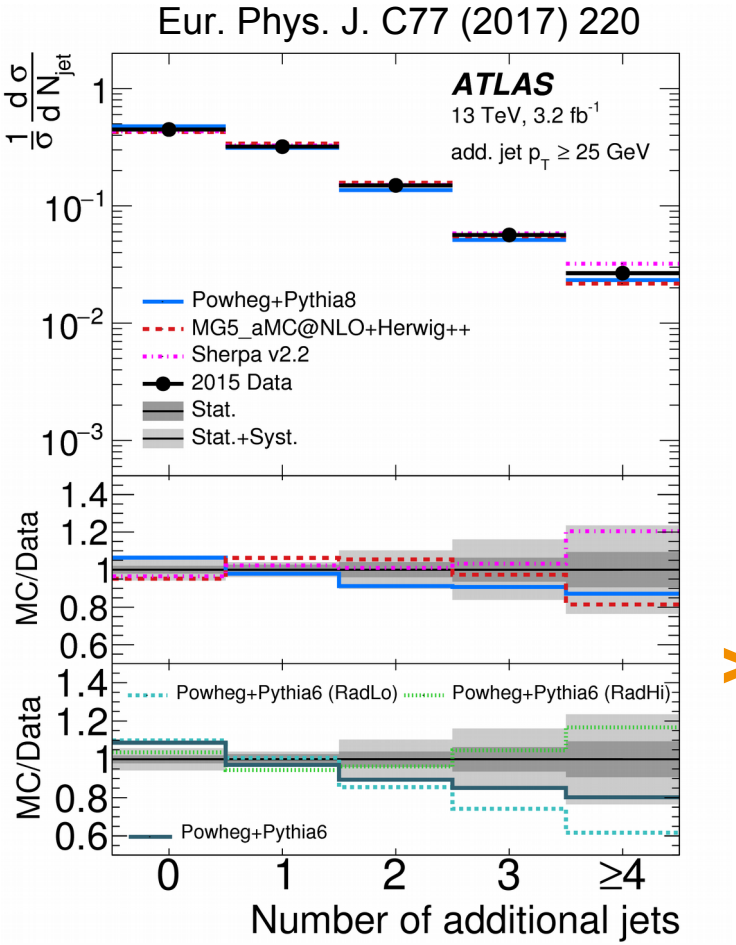
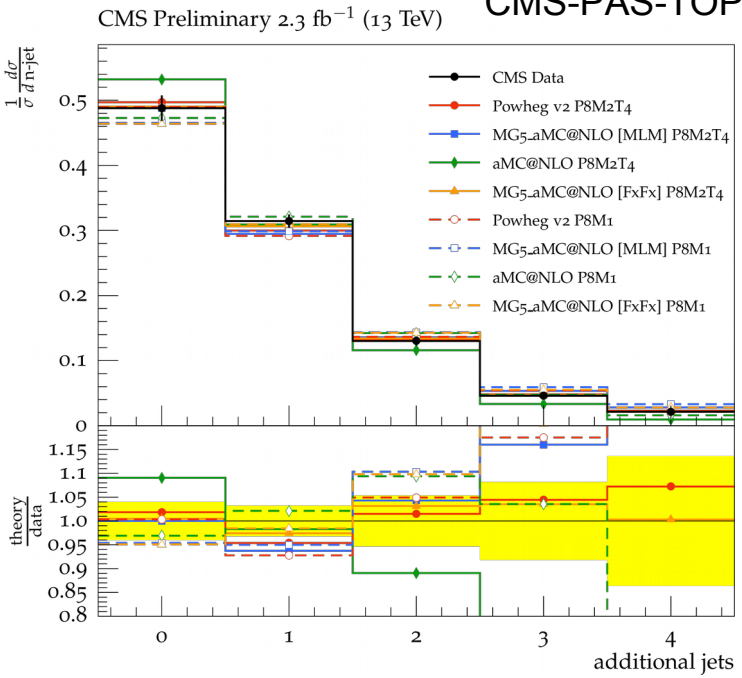


CMS-PAS-TOP-16-021



> Important for generator development:

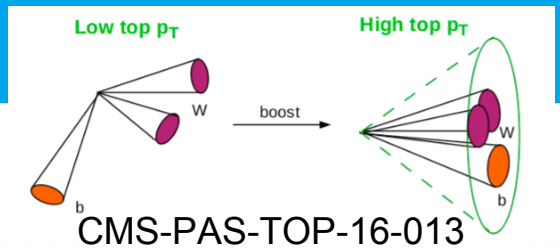
- ttbar kinematics to fix shower α_s

  then derive an UE tune using fixed α_s
- Commissioning/understanding of new matched/merged NLO multi-parton (scale, α_s)

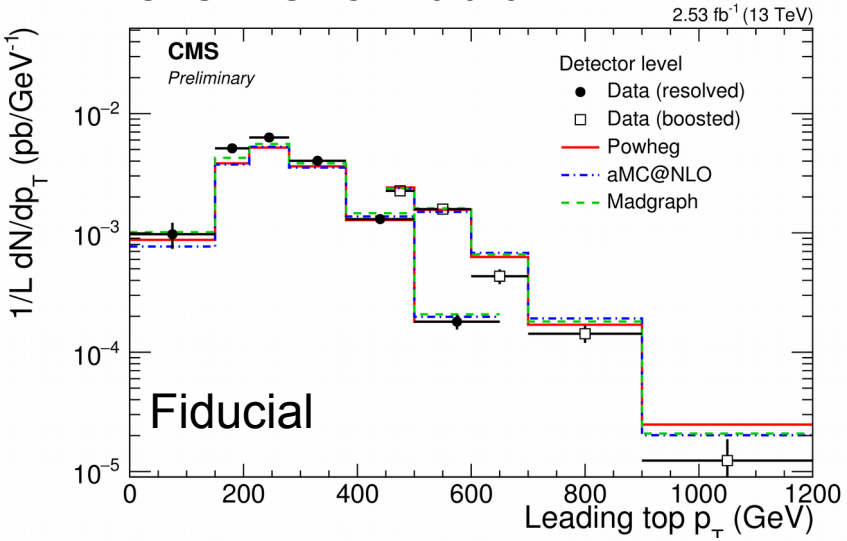
Qualitative χ^2 statements in the paper

Partonic top cross sections

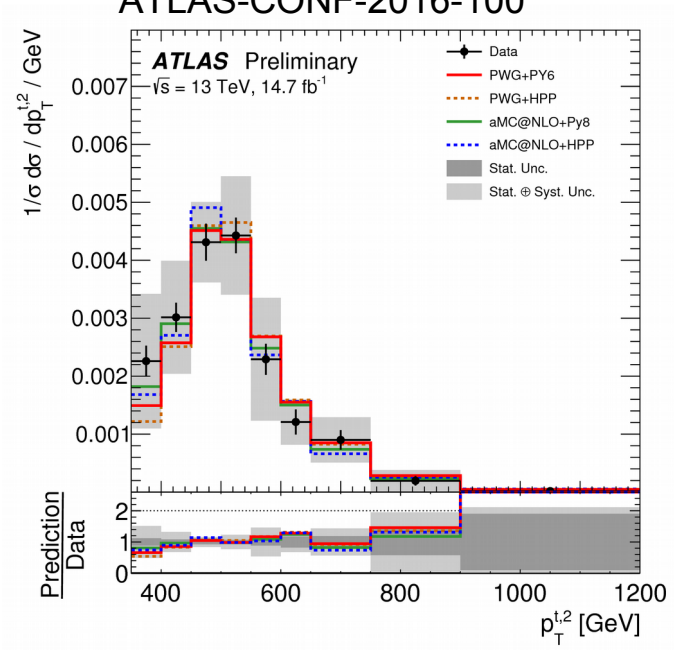
- CMS measurement in the all hadronic channel
  - Boosted: background estimation using templates from 0-btag selection and normalisation to the top mass distribution
- The discrepancy between MC and data remain at high p_T as well
  - Depends on ME plus shower combinatior

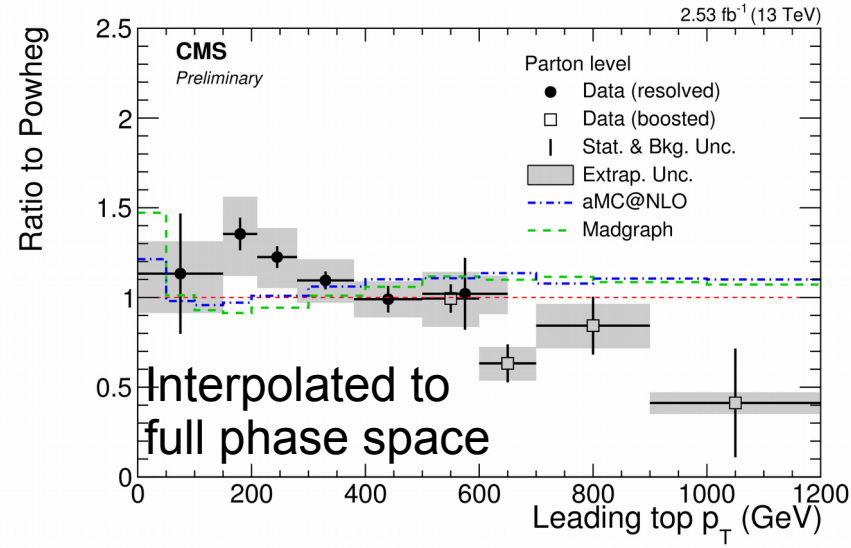


CMS-PAS-TOP-16-013



ATLAS-CONF-2016-100

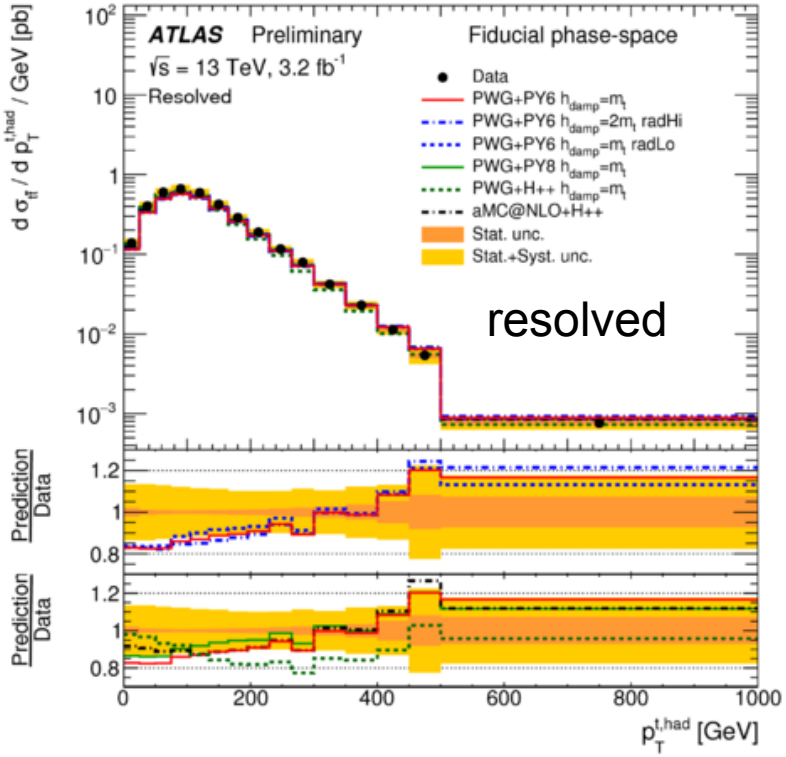


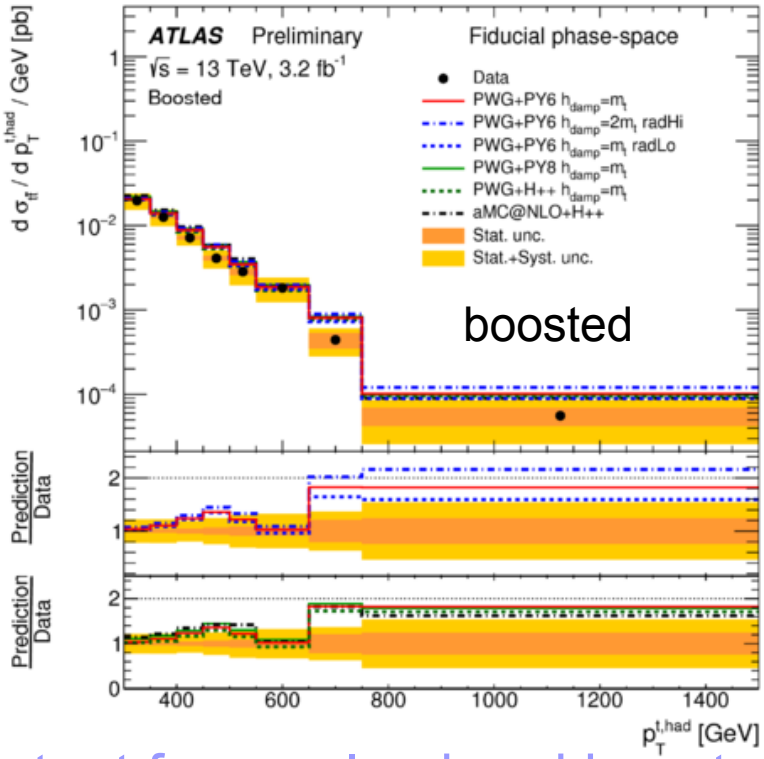


Differential top cross sections

- New measurement combining information from low and high p_T tops (using jet substructure)
  - multiple variables investigated $m(t\bar{t})$, p_T(top), $y(t\bar{t})$, $p_T(t\bar{t})$ (from pure ME to very ISR/FSR dependent)
- ATLAS l+jet measurement:

ATL-CONF-2016-040

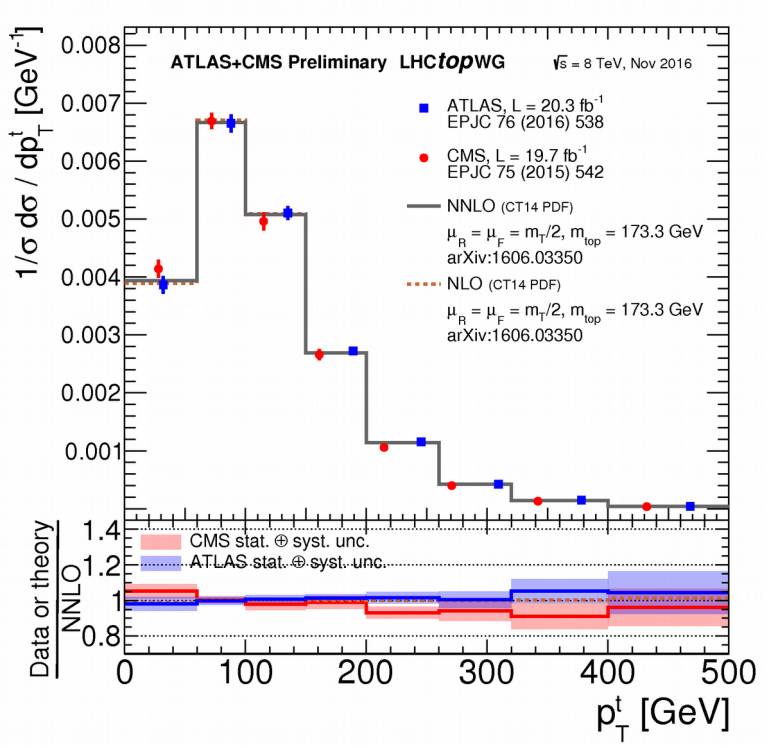


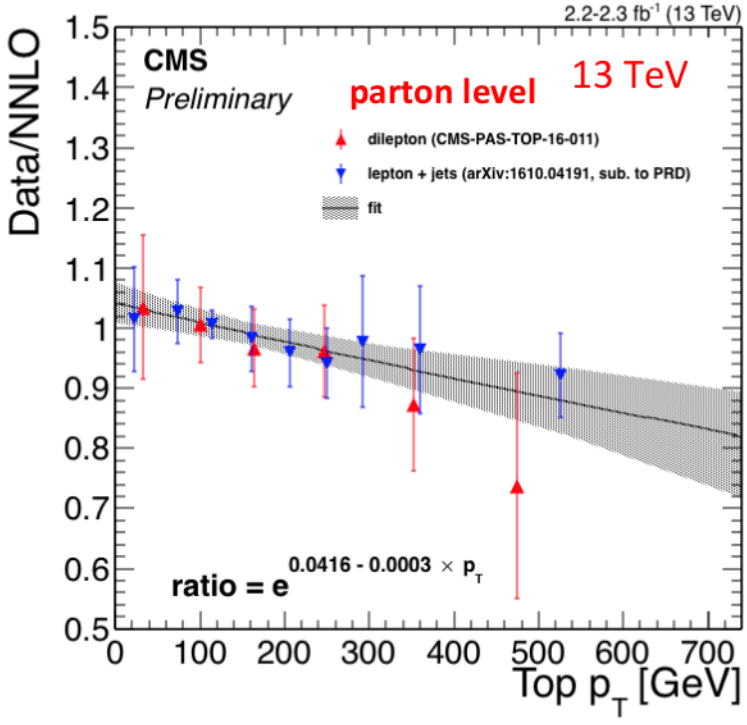


- top p_T not modelled at high p_T, consistent for resolved and boosted

Problems @NLO: top quark p_T

- Top p_T comparison of NNLO with data @ 8 TeV
  - Theory and data of both experiments agree within errors, not very conclusive



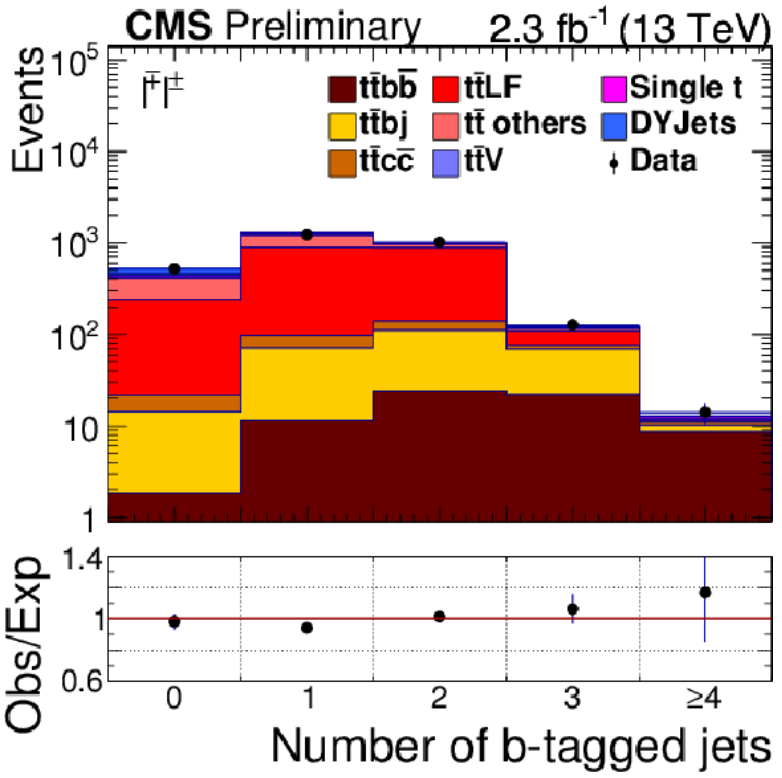


- CMS sees a much bigger and significant slope @ 13 TeV:
  - Missing higher order, EWK-corrections?
  - Need more data, more qualitative, confirmation from ATLAS
  - Other generator+shower cobination look better (Powheg+Herwig7)

$t\bar{t}$+X (X=bb,W,Z) production

$t\bar{t}b\bar{b}$ cross section @ 13 TeV

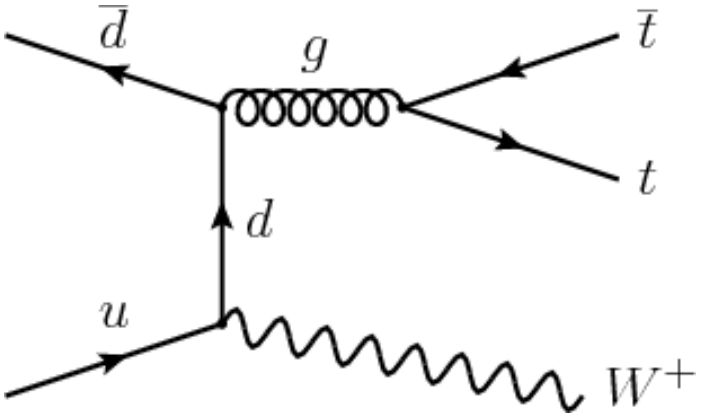
- Important background for searches
  - Measurement of the $t\bar{t}H$ coupling
- CMS: first inclusive $t\bar{t}b\bar{b}$ cross section at 13 TeV
- Comparison with Powheg+Pythia8
  - Bigger fraction of $t\bar{t}b\bar{b}$ measured then simulated (but most b from parton shower)

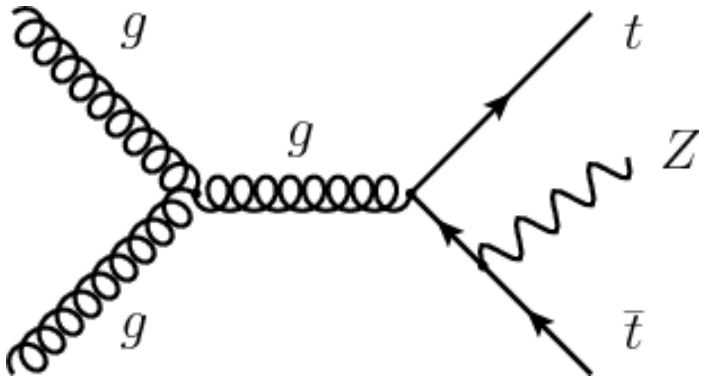


Phase Space	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Measurement			
Visible	$0.085 \pm 0.012 \pm 0.029$	$3.5 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
Full	$3.9 \pm 0.6 \pm 1.3$	$176 \pm 5 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
Simulation (POWHEG)			
Visible	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

$t\bar{t}V$ production

- Large dataset gives access to the rare $t\bar{t}W$ and $t\bar{t}Z$ processes

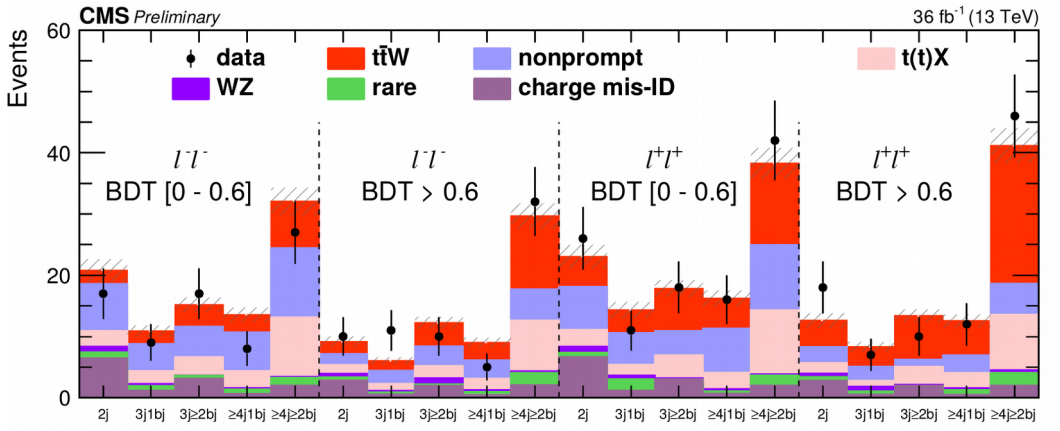




- Direct probe of the $t\bar{t}Z$ coupling (new physics ?)
- Studying important background for searches
- Searches using many leptons to suppress backgrounds:
  - 2 leptons with the same charge
  - 3 or 4 lepton final state

ttV cross section

- CMS result using full 2016 data set (~36 fb^{-1})
  - Using 2 same sign leptons or >=3 leptons
  - Split sample according number of b-jet
  - Control regions to check WZ and ZZ backgrounds
  - $t\bar{t}W$ use multivariate method in addition



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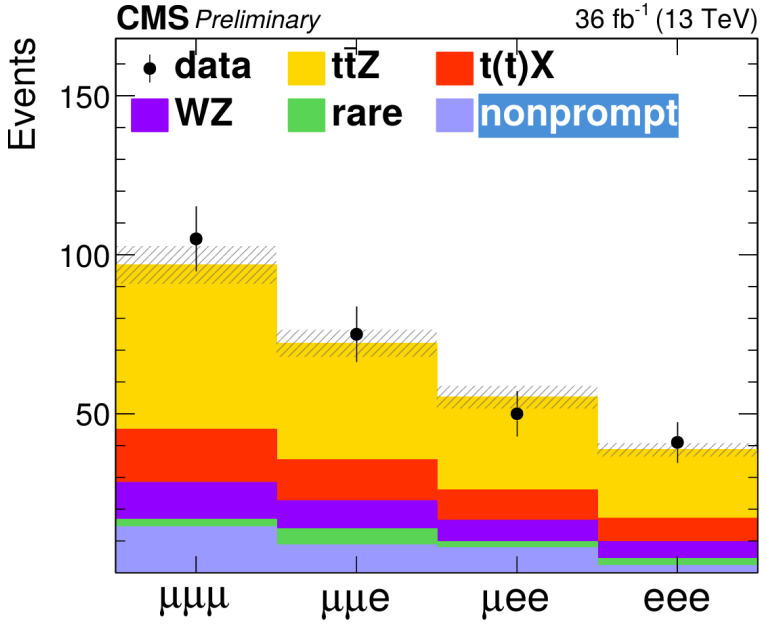
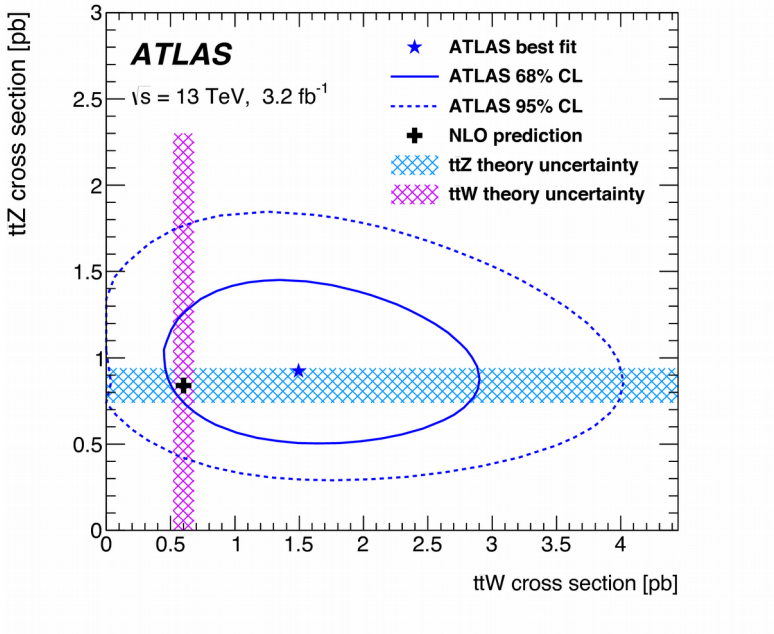


$t\bar{t}V$ cross section

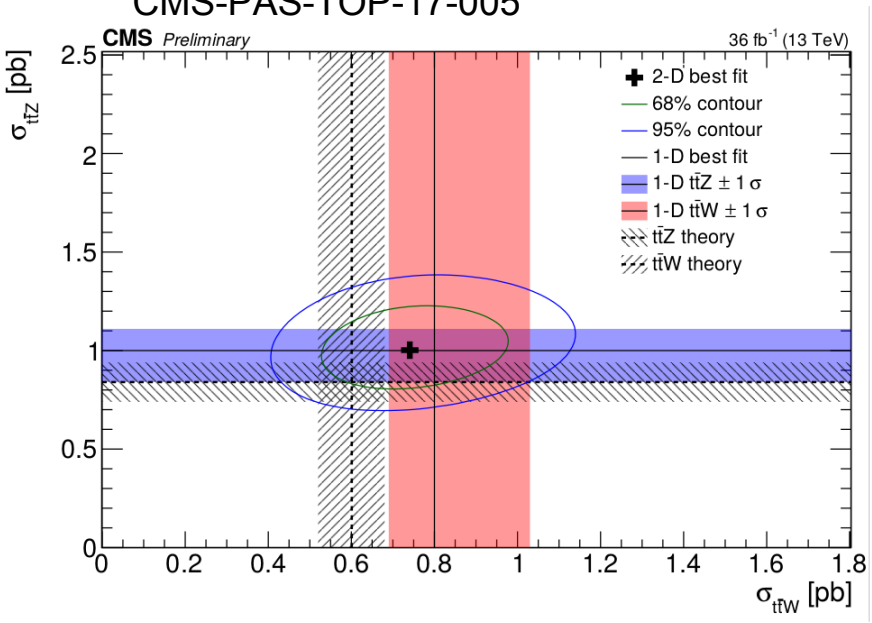
- Fit to many signal region/topologies:
  - Simultaneous extraction of $t\bar{t}W$ and $t\bar{t}Z$
  - Take into account overlap of both signals in selection

arXiv:1609.01599



$t\bar{t}W$: 2.2σ (expected : 1.0σ)
$t\bar{t}Z$: 3.9σ (expected : 3.4σ)

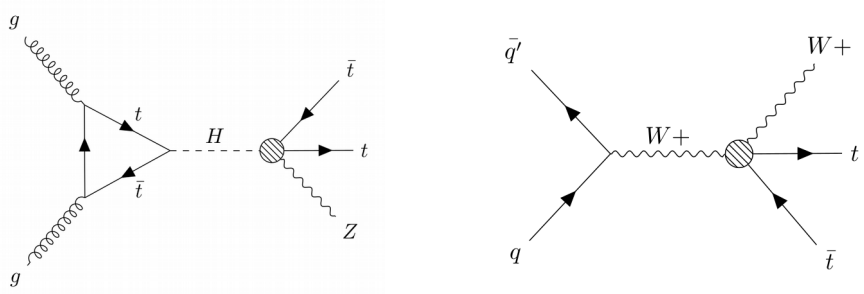
CMS-PAS-TOP-17-005



$t\bar{t}W$: 4.6σ (expected : 5.5σ)
$t\bar{t}Z$: 9.5σ (expected : 9.9σ)

- Results still statistically dominated
  - need to analyse more data and increase precision

$t\bar{t}V$ cross section: EFT theory interpretation



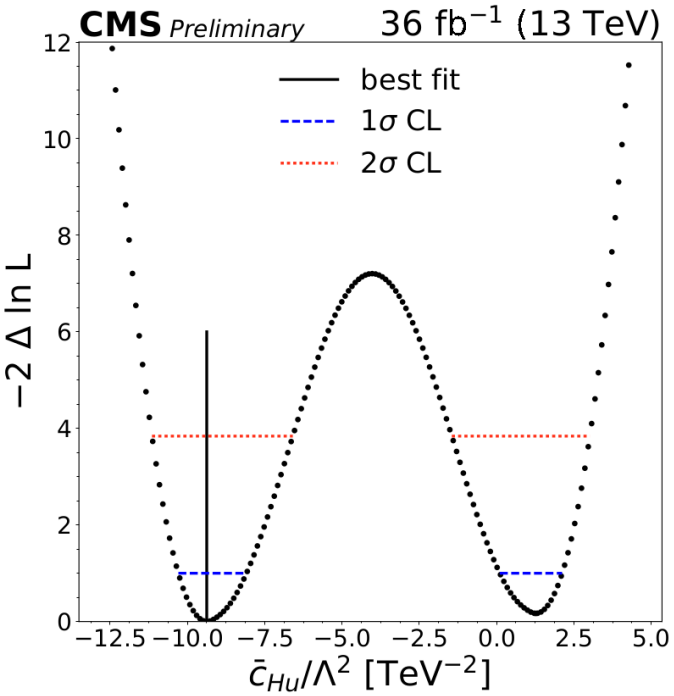
- Effective Lagrangian:

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

  - Add additional production mechanism to $t\bar{t}W$ and $t\bar{t}Z$ production

- Limits on effective couplings with W/Z/H in final state:

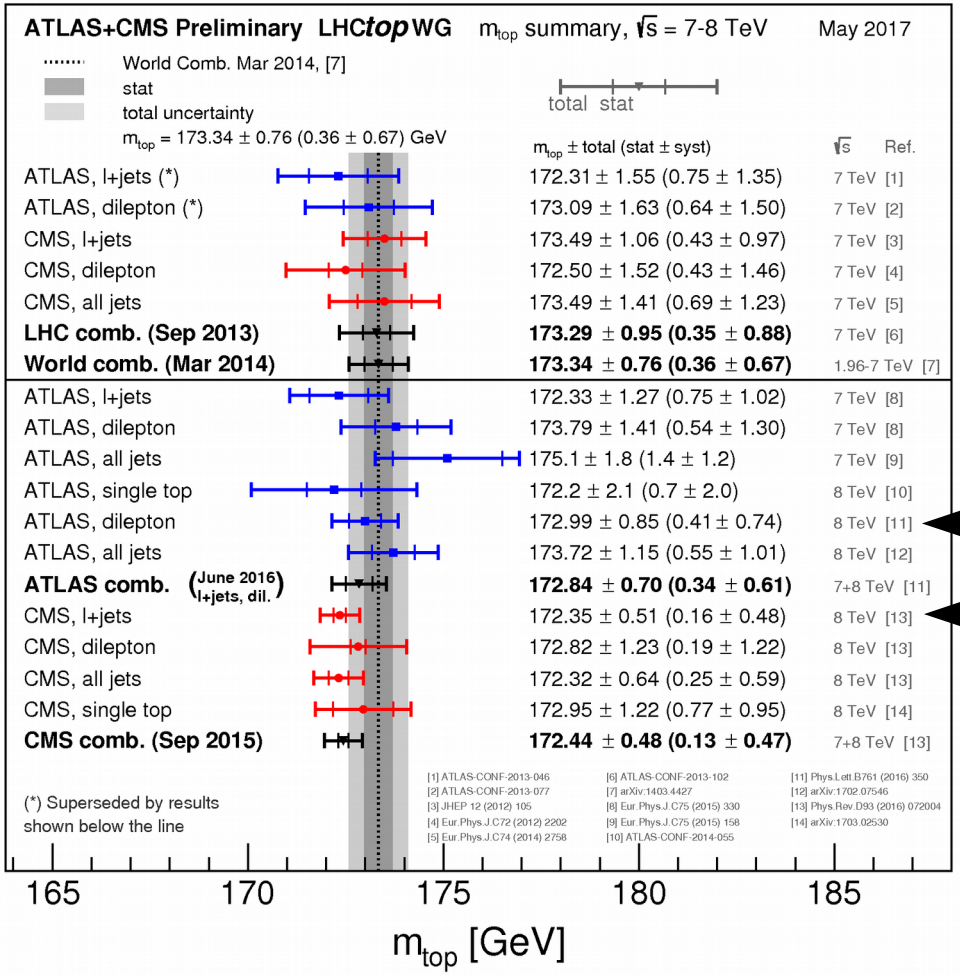
CMS-PAS-TOP-17-005



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]

Top quark properties

Top quark mass: 7/8 TeV summary



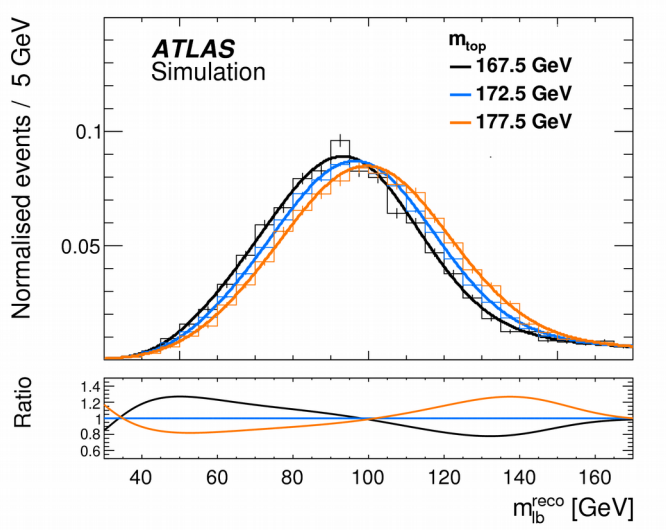
> Run-1 measurements almost completed (ATLAS l+jet missing)

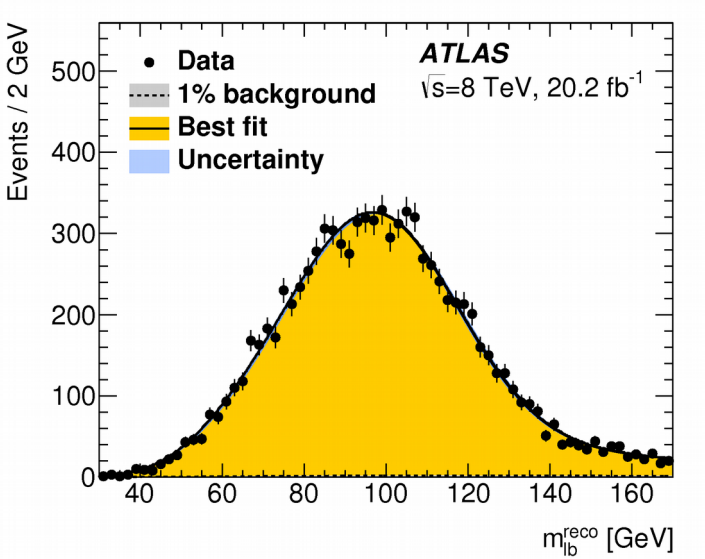
- combination has to exploit new measurements

Top quark mass: ATLAS di-leptons @ 8 TeV

- Di-lepton channel, two neutrinos in final state → system not fully reconstructed
  - Optimise selection on p_T(lb) to reduce systematics
  - Use m(lb) as sensitive variable

Phys. Lett. B761 (2016) 350





- Most precise di-leptonic measurement (0.5% rel. precision):

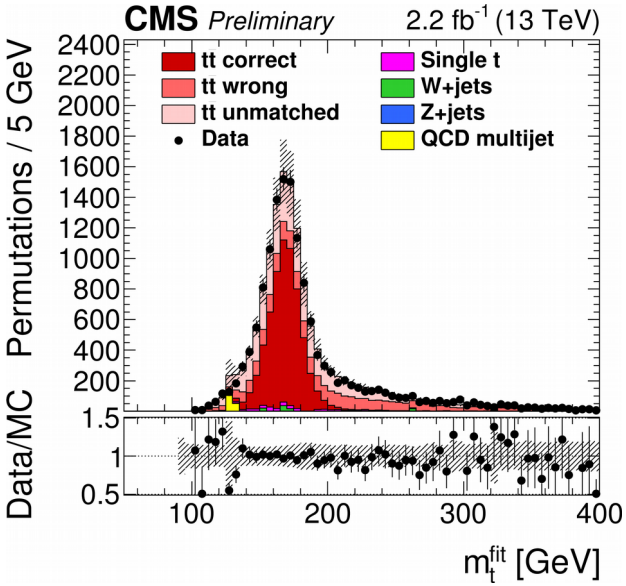
$$m_{top} = 172.99 \pm 0.41\ (stat) \pm 0.74\ (syst)\ GeV$$

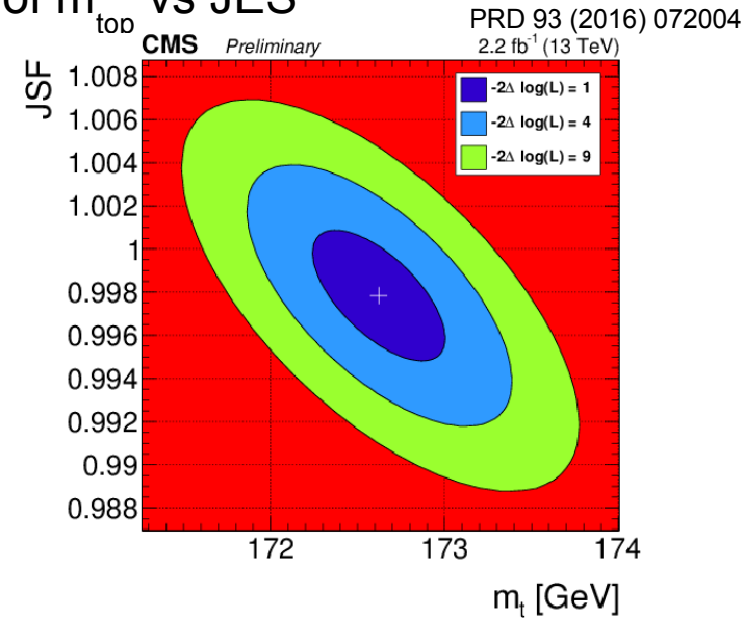
- New CMS measurement: arXiv:1704.06142

$$m_{top} = 172.22 \pm 0.18\ (stat) \pm 0.91\ (syst)\ GeV$$

Top mass: CMS lepton+jets @ 13 TeV

- First result at 13 TeV using recipe from 8 TeV
  - Fully reconstructed di-top system, 2-D fit of m_{top} vs JES





- Result @ 13TeV: CMS-PAS-TOP-16-022

  m_{top} = 172.62 ± 0.38 (stat+JES) ± 0.70 (syst) GeV

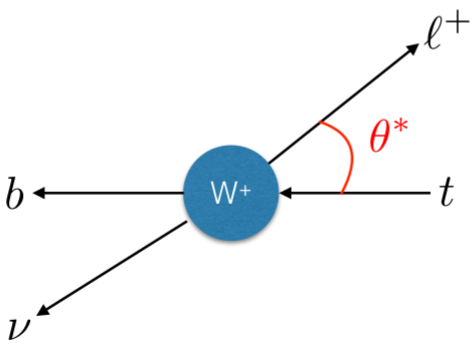
- Result @ 8TeV: Phys. Rev. D 93 (2016)

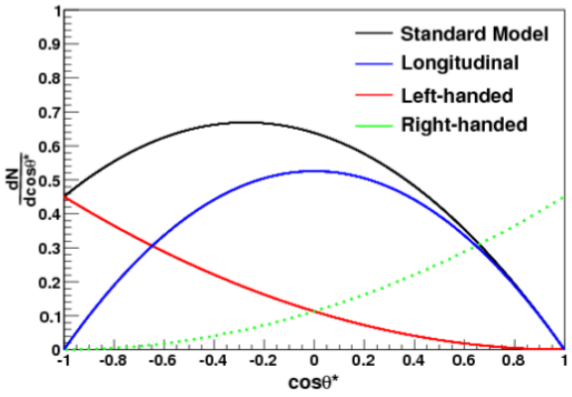
  m_{top} = 172.35 ± 0.16 (stat+JES) ± 0.48 (syst) GeV (about 0.3% precision)

- Excellent agreement with run-1 results but precision not yet reached
  - Limitation: flavor composition, b-fragmentation

W boson polarisation

- W boson can have three different polarisation states:
  - Left-handed
  - Right-handed
  - Longitudinal
- W_{tb} vertex in top decay is characterised by SM (V-A)-structure
  - Fractions of three polarisation states well predicted (NNLO) PRD 81 (2010) 111503
  - Can be probed by measuring top decay angles
  - Single top: vertex accessible in production

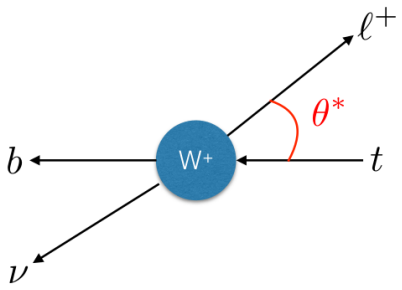


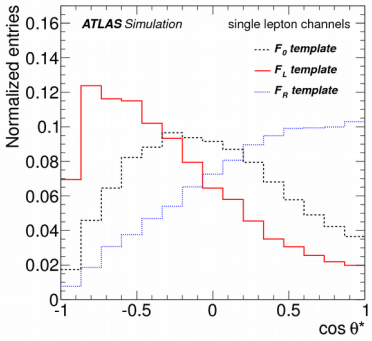


- New physics in vertex would change measured polarisation

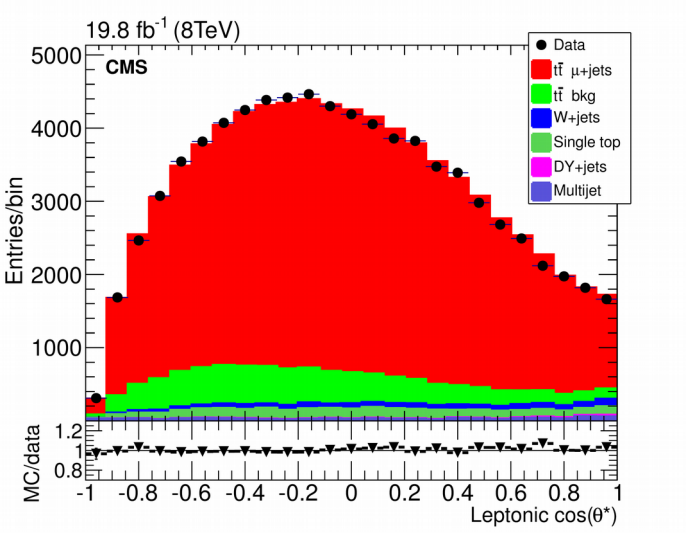
W boson polarisation

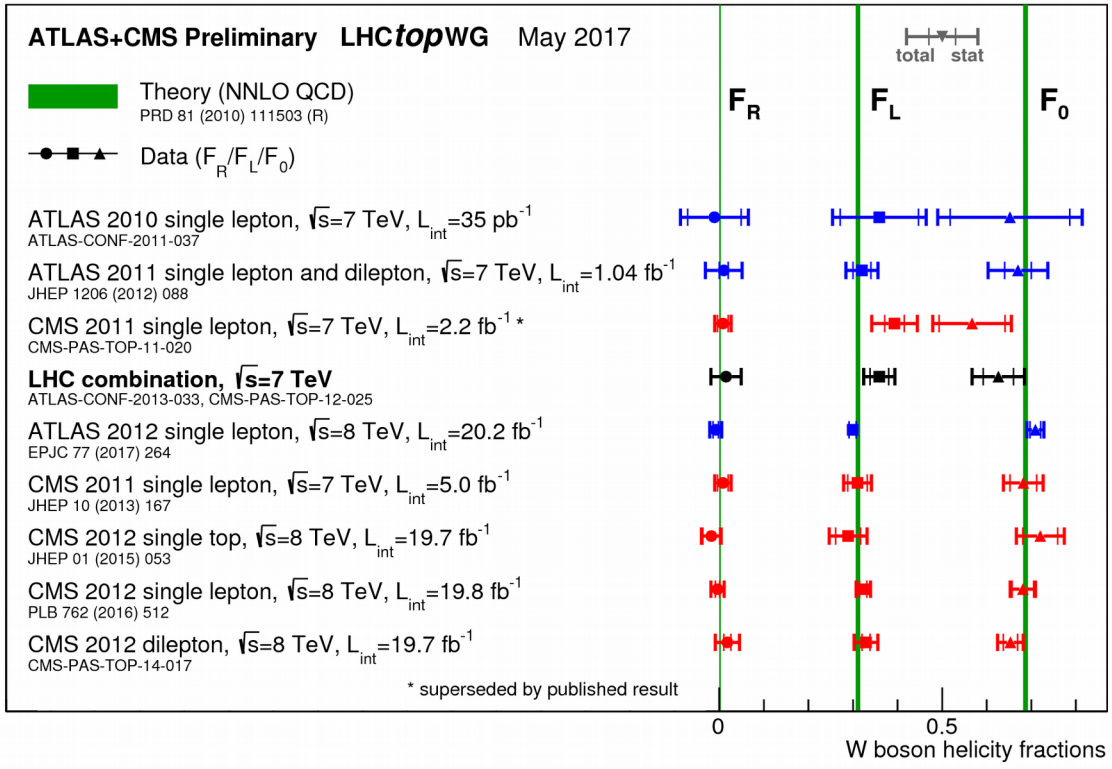
- In di-top: most precise lepton plus jet channel
  - Reconstruct full system
  - Fit templates to reconstructed data





CMS-PAS-TOP-14-017





Polarisation in single top

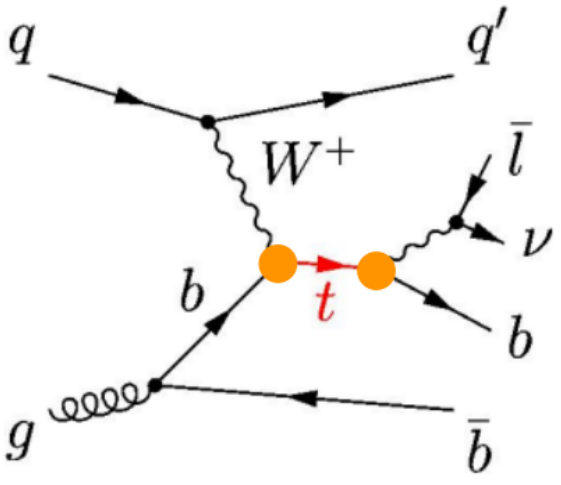
> Single top t-channel:

- Wtb vertex is present in production and decay of the top quark
  Superposition of two vertex structures
- Top is polarized
- Full system can be parametrize in one parameter for top polarisation plus 6 W polarisation observables:

Nucl.Phys.B840:349-378,2010

Phys. Rev. D 93, 011301 (2016)

JHEP04 (2017) 124

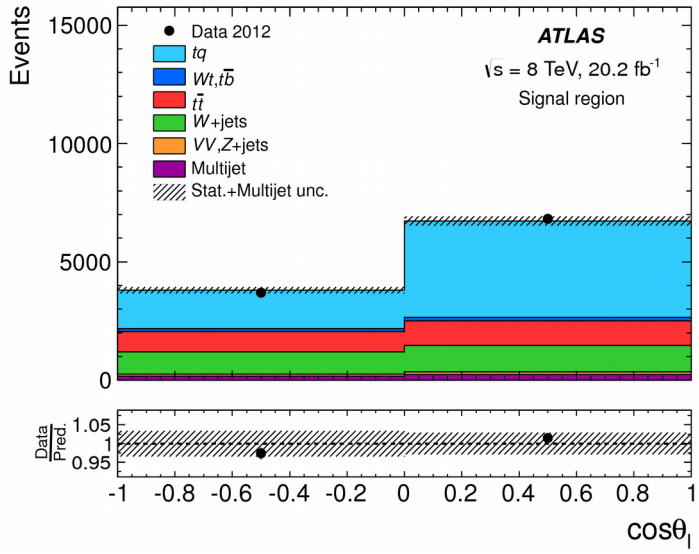


Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P(F_R + F_L)$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_R - F_L)$	−0.23
A_{EC}	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1 - 3F_0)$	−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

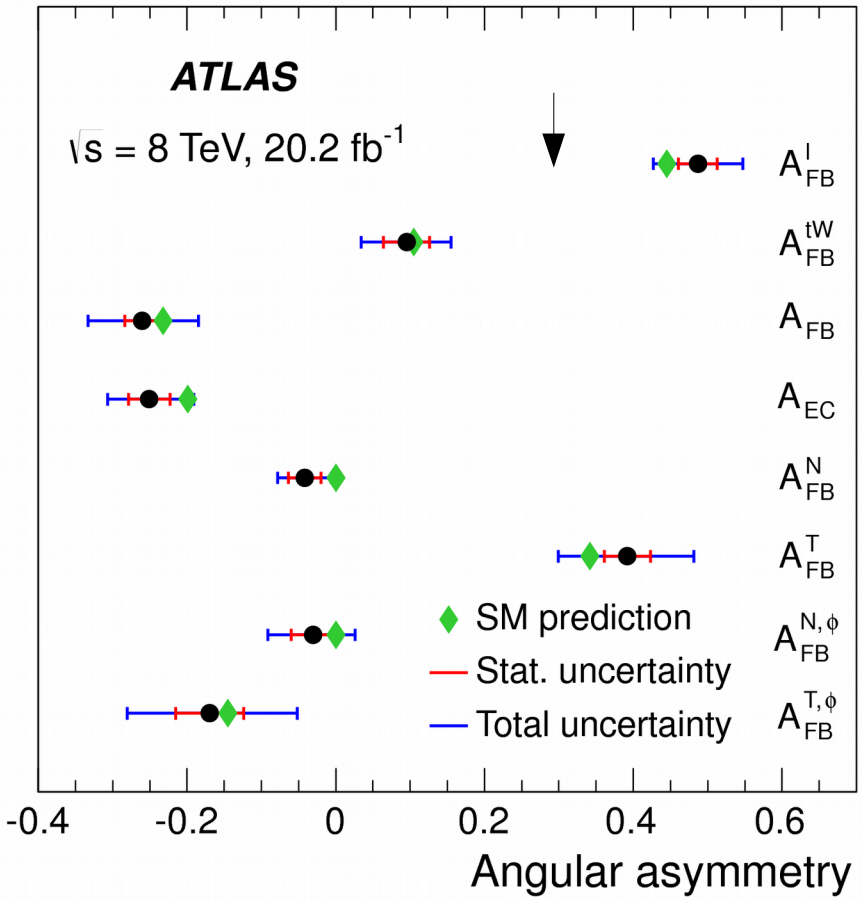
> New ATLAS publication measuring full set of asymmetries

Polarisation in single top

- Kinematic signal selection
  - To reject top-pair background
- Extract all asymmetries (example top polarisation)



JHEP04 (2017) 124



- For comparison: CMS measure $P = 2*A^{l}_{FB} = 0.52 \pm 0.22$

JHEP 04 (2016) 073

W_{tb} vertex constrains

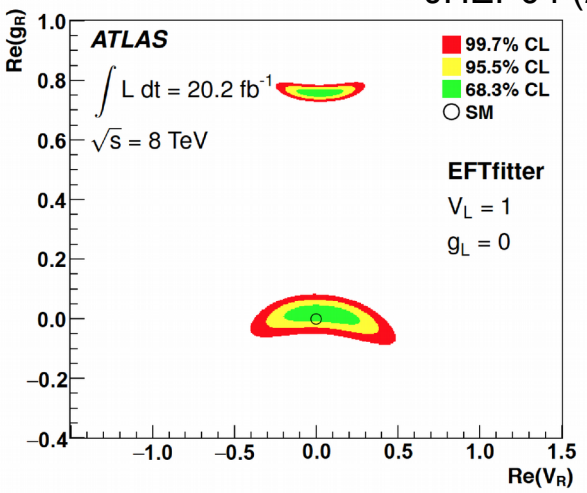
- Interpretation of the measurements using the general expression for the W_{tb} vertex:

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

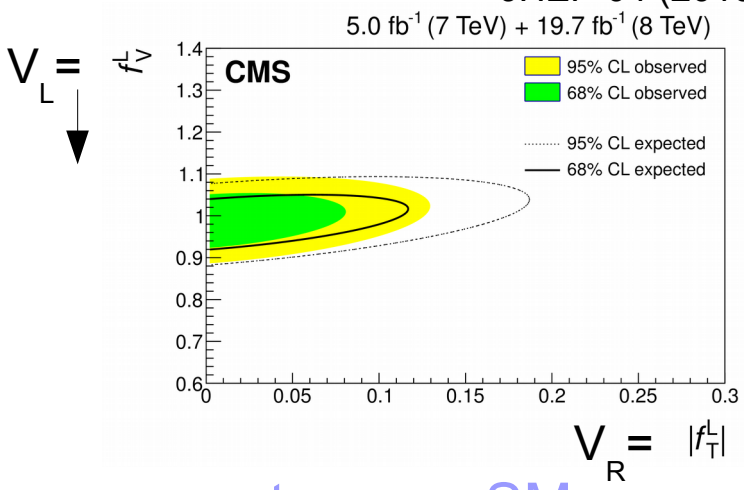
SM: $V_L = V_{tb}$ $V_R = 0$ $g_L = 0$ $g_R = 0$

- Interpretations :

ATLAS W polarisation JHEP04 (2017) 124



CMS single top JHEP 04 (2016) 073



- All interpretations assume the other parameters are SM

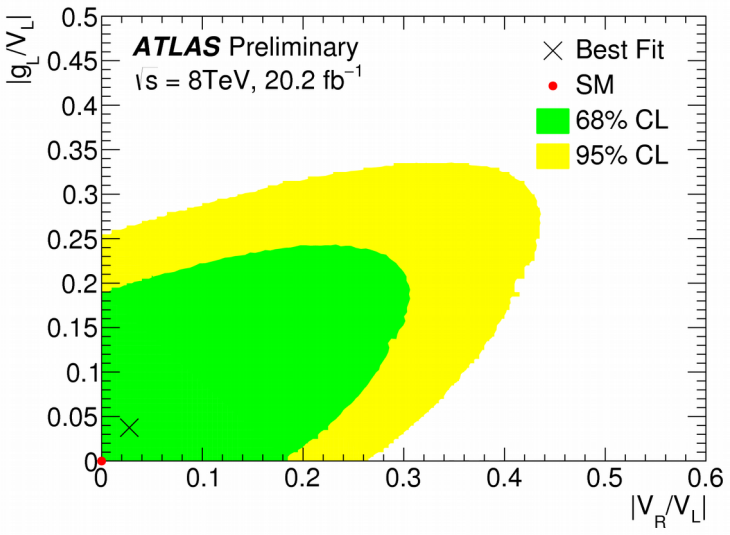
W_{tb} vertex constrains

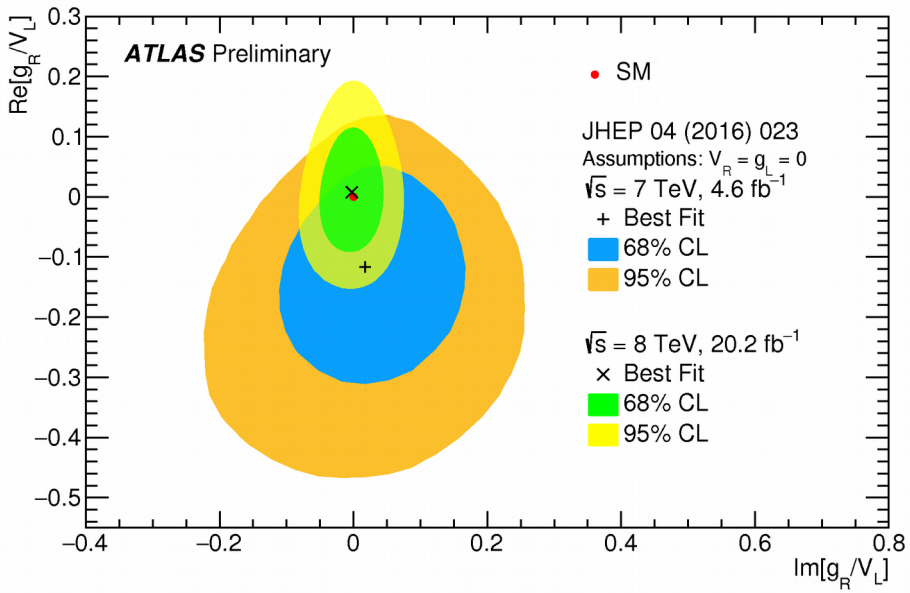
- Interpretation of the measurements using the general expression for the W_{tb} vertex:

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

SM: $V_L = V_{tb}$ $V_R = 0$ $g_L = 0$ $g_R = 0$

- New ATLAS single top interpretation:
  - Triple-differential angular decay rates of single top

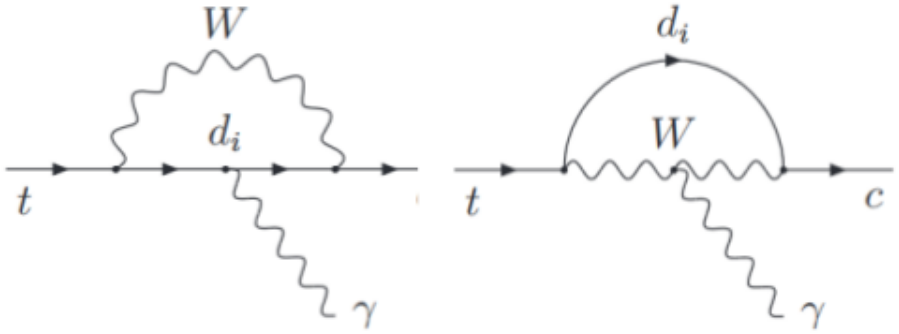




Rare decays & FCNC

FCNC in Standard model

- SM: flavour changing neutral currents (FCNC) are forbidden tree level
  - GIM mechanism
- Existing on loop level
  - Penguin diagram:



arXiv:0409342 arxiv:1311.2026

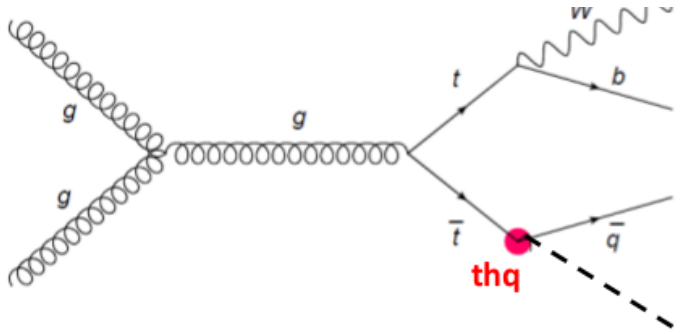
- Still highly suppressed:
  - Tiny branching ratios:

Standard Model (branching ratio)			
$t \to uZ$	8×10^{-17}	$t \to cZ$	1×10^{-14}
$t \to u\gamma$	3.7×10^{-16}	$t \to c\gamma$	4.6×10^{-14}
$t \to ug$	3.7×10^{-14}	$t \to cg$	4.6×10^{-12}
$t \to uH$	2×10^{-17}	$t \to cH$	3×10^{-15}

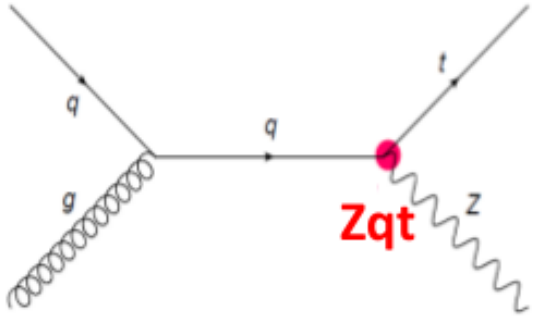
- Beyond the Standard Model these signatures can be enhanced
  → interesting signature to search for new phenomena

FCNC search strategies

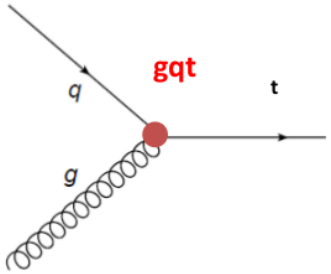
- 3 ways to search for FCNC:
  - Decay of top quarks:
    - sensitivity similar for t→uX and t→cX (X = γ, Z, g, H)



  - Associated production in single top
    - sensitivity for tXu > tXc (PDF)



  - s-channel top production
    - only gut and gct
    - only SM top decays taken into consideration



- Most Analyses using full 7 and 8 TeV dataset

FCNC: Search strategies

- Results are usually interpreted
  - Branching Ratio limit (model independent)
  - Framework of anomalous couplings:

[arXiv:0803.3810, 0811.3842, 0904.2387]

$$\mathcal{L}_{FCNC} = \sum_{q=u,c} \Bigg[\frac{\sqrt{2}}{2} g_s \frac{\kappa_{gqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{gq}^L P_L + f_{gq}^R P_R\right) q G_{\mu\nu}^a + \frac{\sqrt{2}}{2} e \frac{\kappa_{\gamma qt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{\gamma q}^L P_L + f_{\gamma q}^R P_R\right) q A_{\mu\nu} + \frac{1}{\sqrt{2}} \eta_{hqt} \cdot \bar{t} \left(f_{hq}^L P_L + f_{hq}^R P_R\right) q H + \frac{\sqrt{2}}{4} \frac{g}{\cos\theta_W} \frac{\kappa_{zqt}}{\Lambda} \cdot \bar{t}\sigma^{\mu\nu} \left(f_{zq}^L P_L + f_{zq}^R P_R\right) q Z_{\mu\nu} + \frac{1}{4} \frac{g}{\cos\theta_W} \zeta_{zqt} \cdot \bar{t}\gamma^{\mu} \left(\tilde{f}_{zq}^L P_L + \tilde{f}_{zq}^R P_R\right) q Z_{\mu} \Bigg] + h.c$$

$$\text{with } \sigma^{\mu\nu} = \frac{i}{2}[\gamma^{\mu}, \gamma^{\nu}]$$

- some simplifications:
  - no 4-fermion contact interactions
  - $|f^L_i|^2 + |f^R_i| = 1$ and coupling > 0 (independent-convention)
  - Analyses often do not distinguish L and R

FCNC search example: tgq

- ATLAS: search in initial state
  - Looking for only the decay products of one single top in the detector (1 lepton, 1 b-jet, MET)

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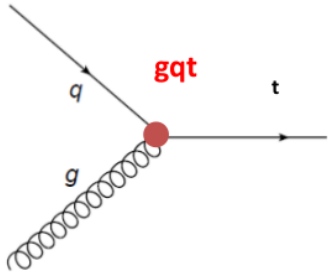
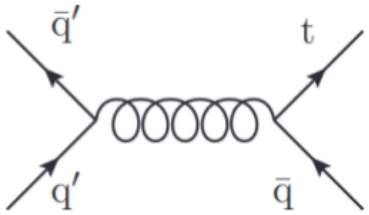
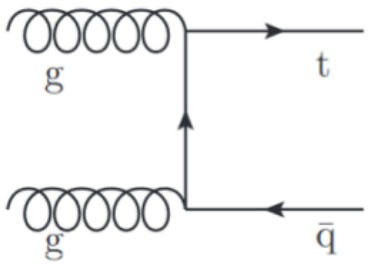


- CMS: search in the final state
  - Same selection for Wt
  - Looking for top plus jet (1 lepton, 1 b-jet, 1 add. jet, ME

JHEP 02 (2017) 028





- Neural networks are used to separate signal from backgrounds using shape informations

FCNC search example: tgq

- Results are presented as limits inside the anomalous coupling coupling framework or im limits on branching fractions t → gX
  - (axes are twisted between ATLAS and CMS)

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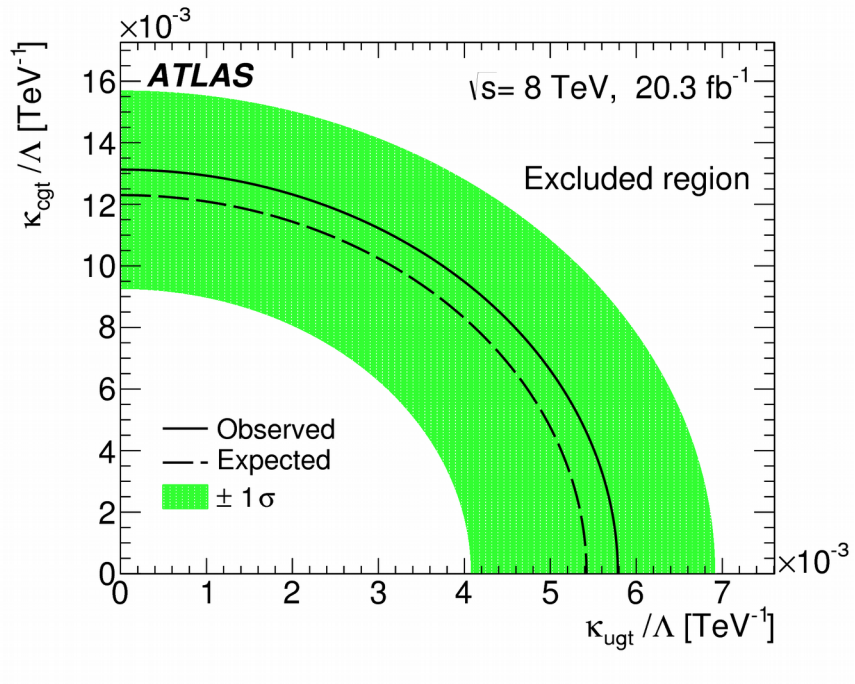

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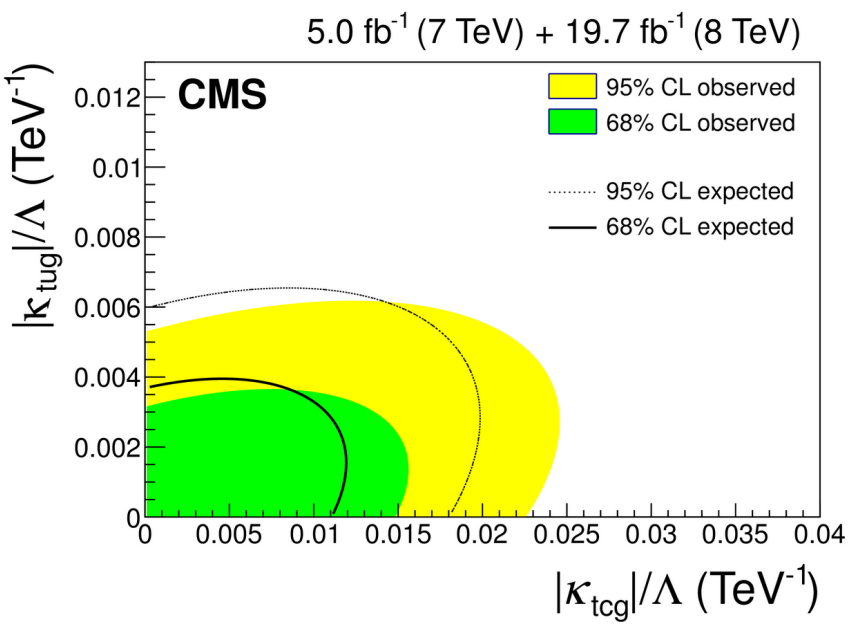
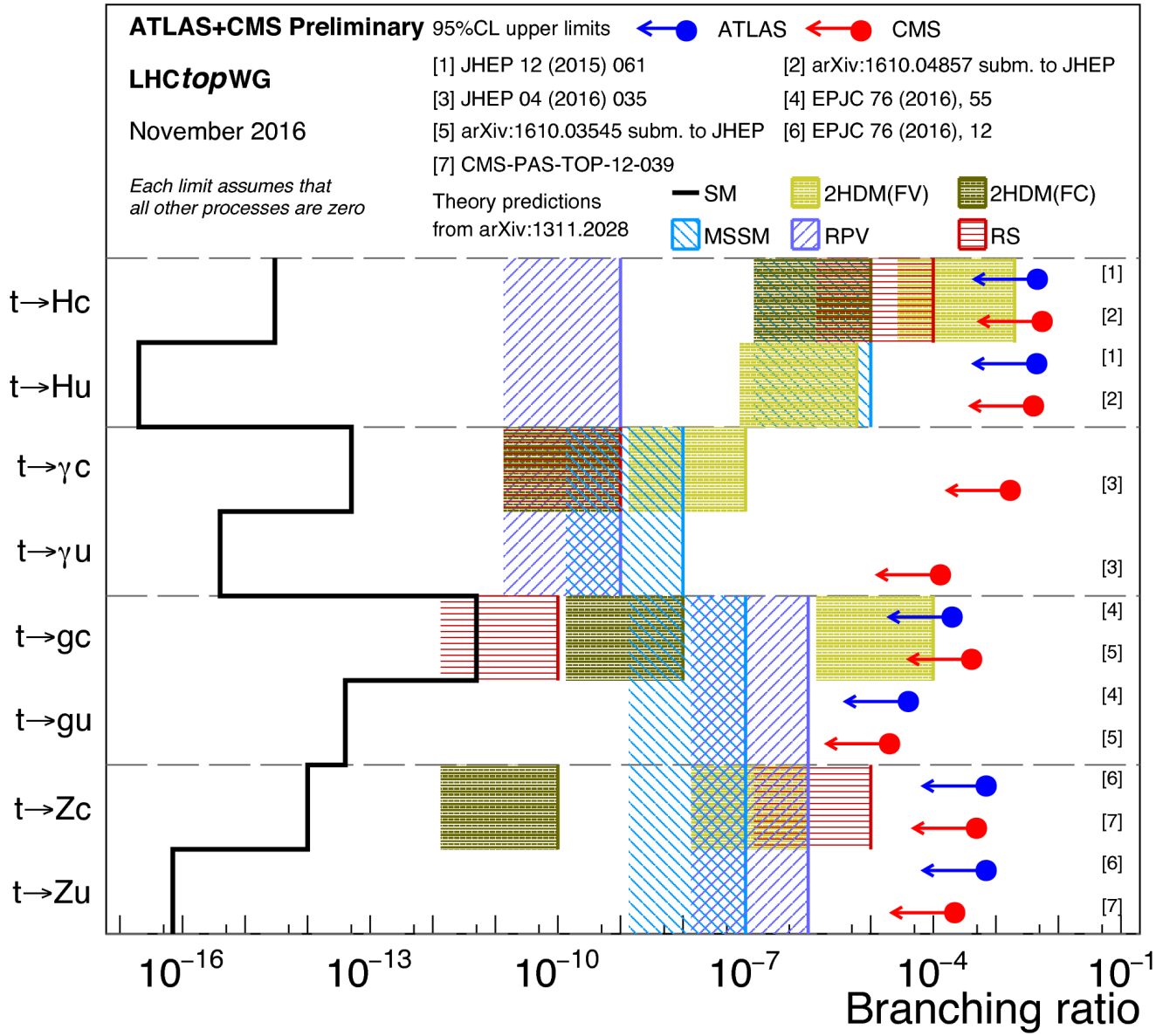


Upper limits @ CL= 95%:
BR(t → gu < 0.4×10^{-4})
BR(t → gc < 2.0×10^{-4})

Upper limits @ CL= 95%:
BR(t → gu < 0.2×10^{-4})
BR(t → gc < 4.1×10^{-4})

Results: FCNC searches



Summary

- LHC is an exciting place to do top physics:
  - Big production cross section (top factory), more data coming in 2017
- Inclusive production is well understood
  - agrees with NNLO calculation
- Differential cross section
  - Matched merged Multileg@NLO needed for hard radiation but it is still in commissioning
- Top Properties:
  - Top mass measurements with 2011/12 data nearly finished and need combination, first measurement at 13 TeV shown
  - W polarisation results are shown for di-top and single-top and interpreted
- FCNC:
  - Limits are shown, no significant deviation seen
- Most measurements dominated by modelling systematics, need active discussion between experiments and theory community