$t\bar{t}H$ / tH Experimental Status
LHC Higgs XS WG General Assembly

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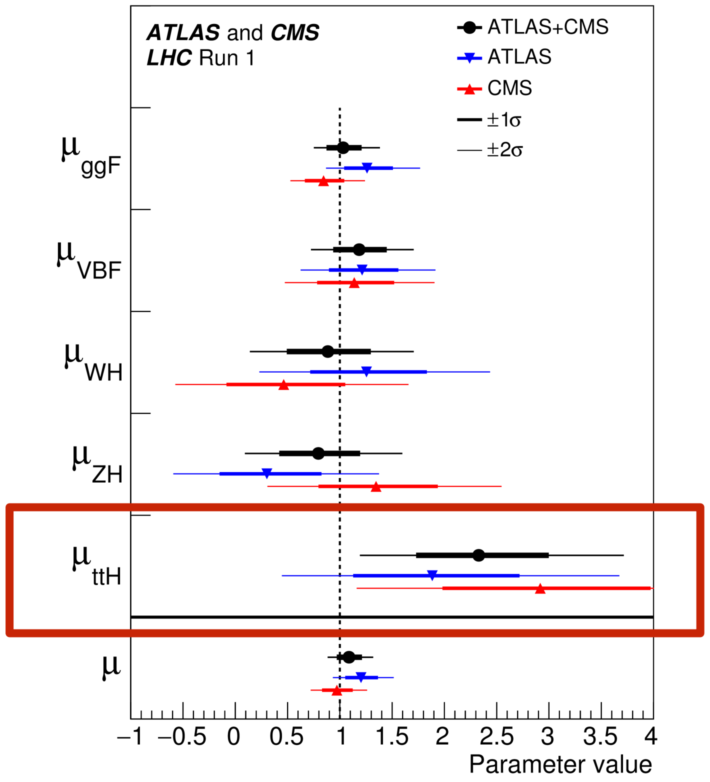
$t\bar{t}H$ / tH Overview

- ATLAS $t\bar{t}H$ results at ICHEP16:
  - $t\bar{t}H$ ($H \to b\bar{b}$): ATLAS-CONF-2016-080 2015+2016 (13.2/fb)
  - $t\bar{t}H$ (multilepton): ATLAS-CONF-2016-058 2015+2016 (13.2/fb)
  - $t\bar{t}H$ ($H \to \gamma\gamma$): ATLAS-CONF-2016-067 2015+2016 (13.3/fb)
  - $t\bar{t}H$ combination: ATLAS-CONF-2016-068 2015+2016

- CMS $t\bar{t}H$/tH results at ICHEP16 and Moriond16:
  - $t\bar{t}H$ ($H \to b\bar{b}$): HIG-16-004 2015 (2.3/fb)
  - $t\bar{t}H$ (multilepton): HIG-16-022 2015+2016 (15.2/fb)
  - $t\bar{t}H$ ($H \to \gamma\gamma$): HIG-16-020 2016 (12.9/fb)
  - tH ($H \to b\bar{b}$): HIG-16-019 2015 (2.3/fb)

- Full set of analyses released at Winter and Summer conferences from both collaborations
  - *Focus on aspects which are important for each analysis from an experimental point of view*

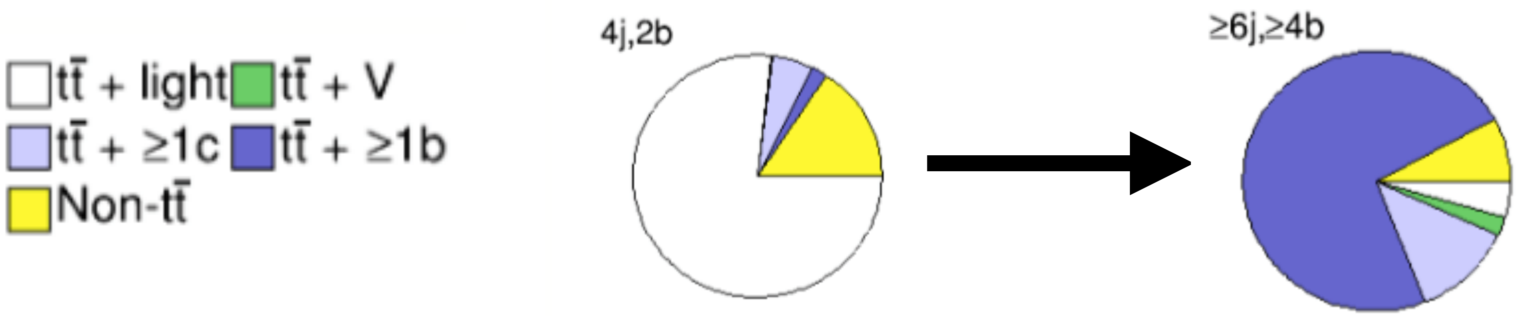
- **Reminder of Run-1 results:**
  - Significance of 4.4 σ (2.0 σ expected)

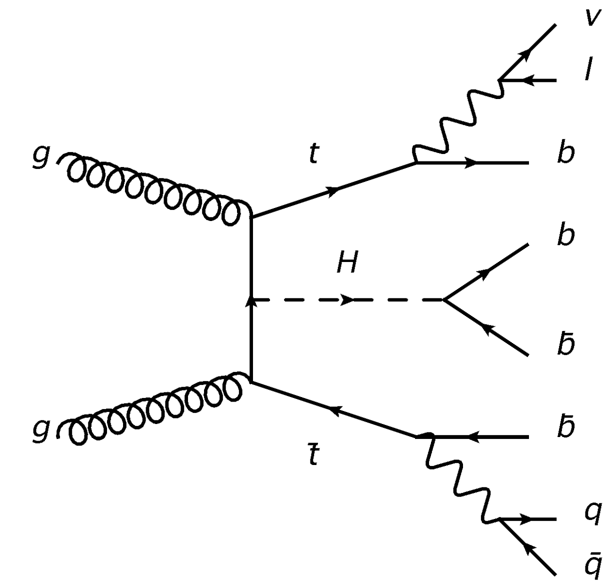


ATLAS: 10.0 (2016) + 3.2 (2015) = 13.2/fb
CMS: 12.9 (2016) + 2.3 (2015) = 15.2/fb

$t\bar{t}H(bb)$ Analysis Overview

- **Very complex final state:**
  - l+jets: 4 b's, 2 q's and 1 lepton
  - dilepton: 4 b's and 2 leptons
- **Background modelling is very important: tt+HF, tt+light**

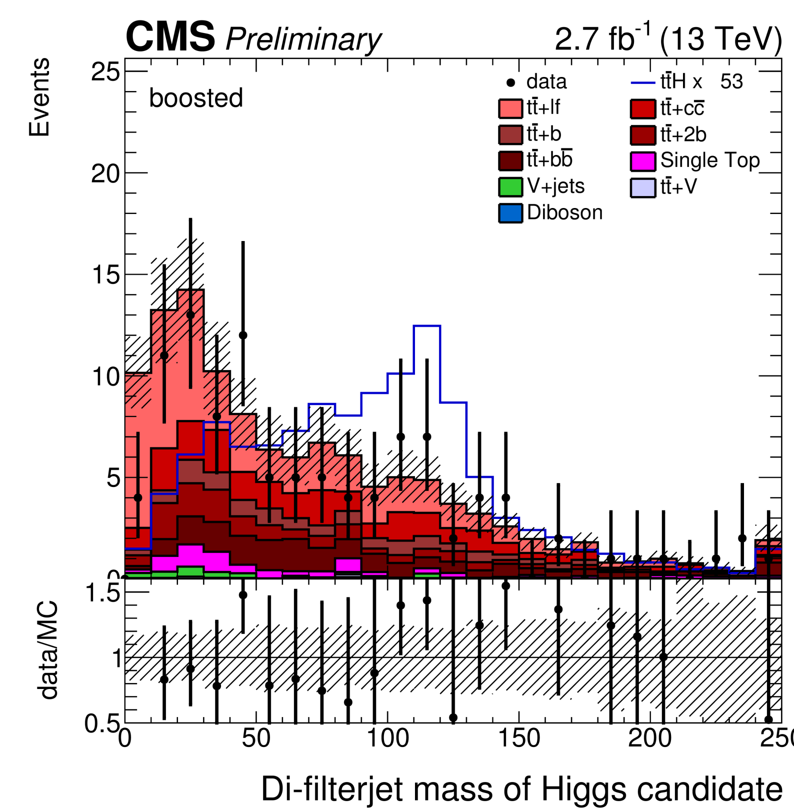




- **Fit CR and SRs simultaneously**
  - BDT designed to separate ttH(bb) from tt+bb
  - Reconstruction BDT, MEM techniques for ttH reconstruction

(CMS)

l+jets	2 b-tags	3 b-tags	4 b-tags
4 jets	inclusive boosted	BDT	MEM
5 jets		BDT	MEM
6 jets	BDT	BDT	MEM



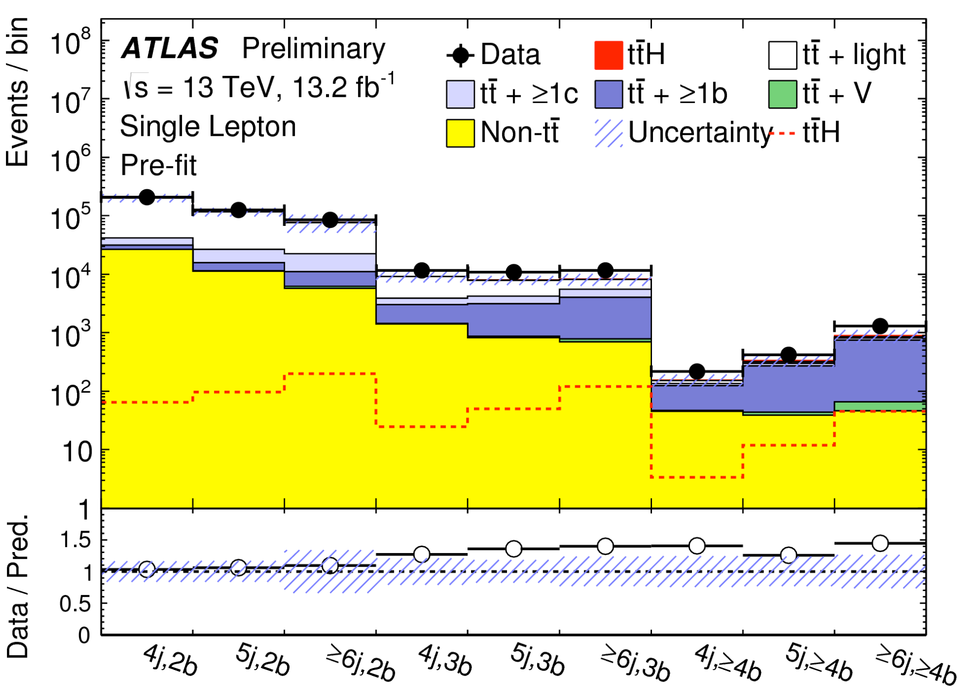
- **Additionally CMS has a boosted technique in the l+jets channel**
  - Require both hadronic top and Higgs tags (pT > 200 GeV)
  - High S/B with reduced combinatorial background

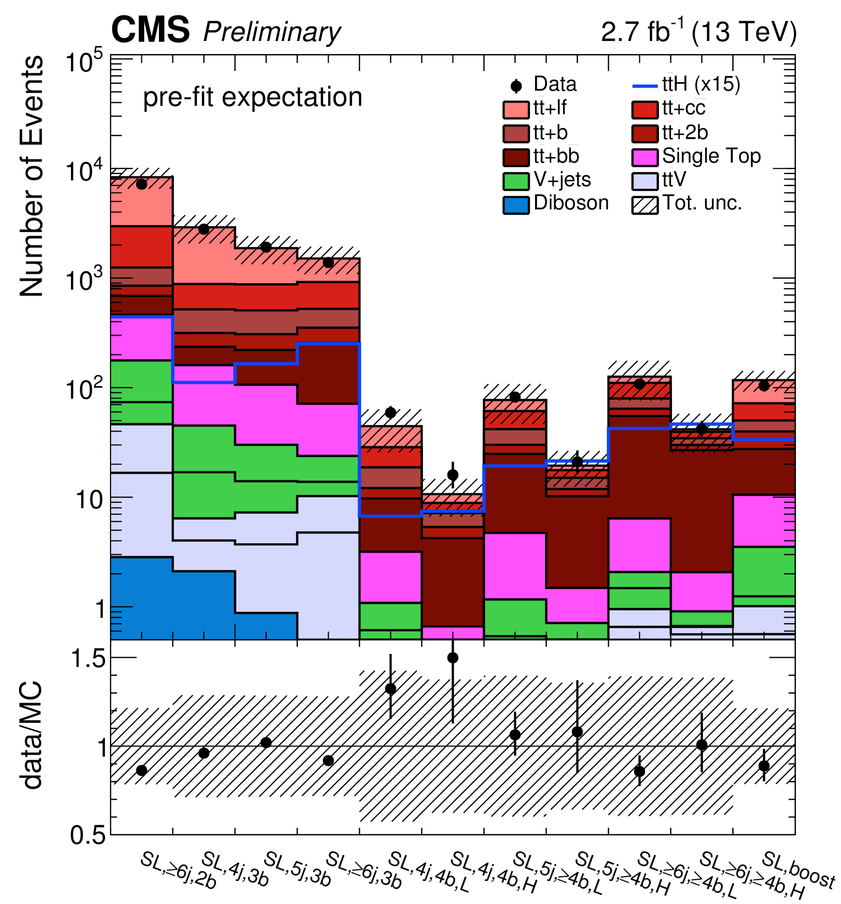
- Modelling of the tt+jets background is crucial with advanced reconstruction techniques
  - Understanding of the uncertainties on this background vital

$t\bar{t}H(bb)$ Common Items

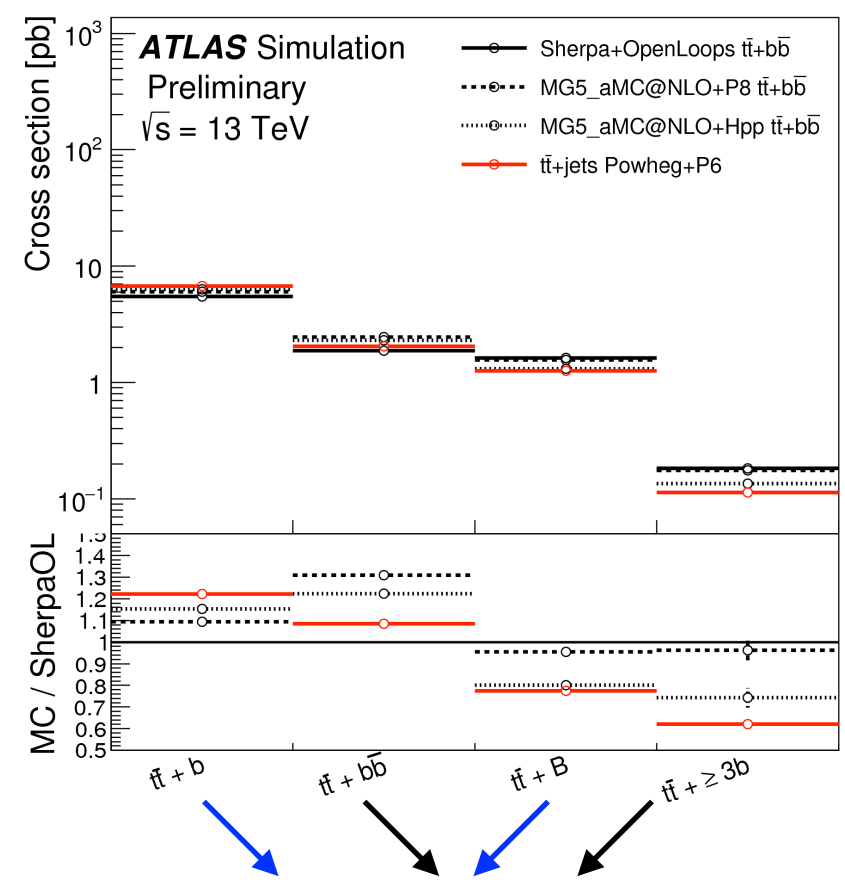
- $t\bar{t}$+jets modelling:
  - ATLAS: Powheg+Pythia6, CT10 PDF, hdamp=m_{top}, Perugia2012 tune
    - $t\bar{t}$+light and $t\bar{t}$+≥1c corrected to match NNLO QCD top quark p_T and $t\bar{t}$ p_T
    - $t\bar{t}$+≥1b kinematics re-weighted to Sherpa+OL (inclusive $t\bar{t}$+≥1b normalization still P+P6)
  - CMS: Powheg+Pythia8, CT10 PDF, hdamp=m_{top}, CUETP8M1 tune

- ATLAS: Deficit observed in (high jet, high b-jet) regions
- CMS: fairly good agreement in all pre-fit regions





ATLAS: kinematic RW (top pT, $t\bar{t}$ pT) per category to match SherpaOL NLO $t\bar{t}+b\bar{b}$



additionally: 2D RW of dR(b-jets) and pT of b-jet system (B or b-jet pT and η)

$t\bar{t}$H(bb) Systematics

- $t\bar{t}$+jets breakdown in the fit:
  - ATLAS: $t\bar{t}$+light, $t\bar{t}$+≥1b, $t\bar{t}$+≥1c
  - CMS: $t\bar{t}$+light, $t\bar{t}$+b, $t\bar{t}$+2b(B), $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+$c\bar{c}$
- CMS: 50% rate uncertainty on all $t\bar{t}$+HF backgrounds (uncorrelated)
  - largest uncertainty
- ATLAS: free-floating normalisation factors for $t\bar{t}$+≥1b and $t\bar{t}$+≥1c
  - Fit results for factors
    - **1.33 +/- 0.18** and **1.31 +0.53 -0.40**
- ATLAS: including comparison of different calculations for $t\bar{t}$+$b\bar{b}$
  - Largest uncertainties come from $t\bar{t}$+$b\bar{b}$ modelling
  - 5F vs 4F Sherpa+OL vs P+P6, comparisons of 4F calculations of Sherpa+OL and MG5_aMC@NLO

CMS

QCD scale ($t\bar{t}$)	rate	Scale uncertainty of NLO $t\bar{t}$ prediction
QCD scale ($t\bar{t}$+hf)	rate	Additional scale uncertainty of NLO $t\bar{t}$+hf predictions
pdf (gg)	rate	Pdf uncertainty for gg initiated processes except $t\bar{t}H$
Q^2 scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the $t\bar{t}$ ME generator, independent for additional jet flavors
PS Scale ($t\bar{t}$)	shape	Renormalization and factorization scale uncertainties of the parton shower (for $t\bar{t}$ events), independent for additional jet flavors

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	$\pm 6\%$	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

ATLAS

$t\bar{t}H(bb)$ Importance of LHC HXS WG

- Largest uncertainties in the analysis come from $t\bar{t}+b\bar{b}$ normalization and modelling
  - Experimental measurements still in progress (CMS @ 8 TeV)

- **Modelling of this background is critical to sensitivity of analysis**
- A lot of progress made in understanding differences in both 4F and 5F calculations within a coordinated LHC HXS WG effort
  - Hugely beneficial to experimental understanding of this important background

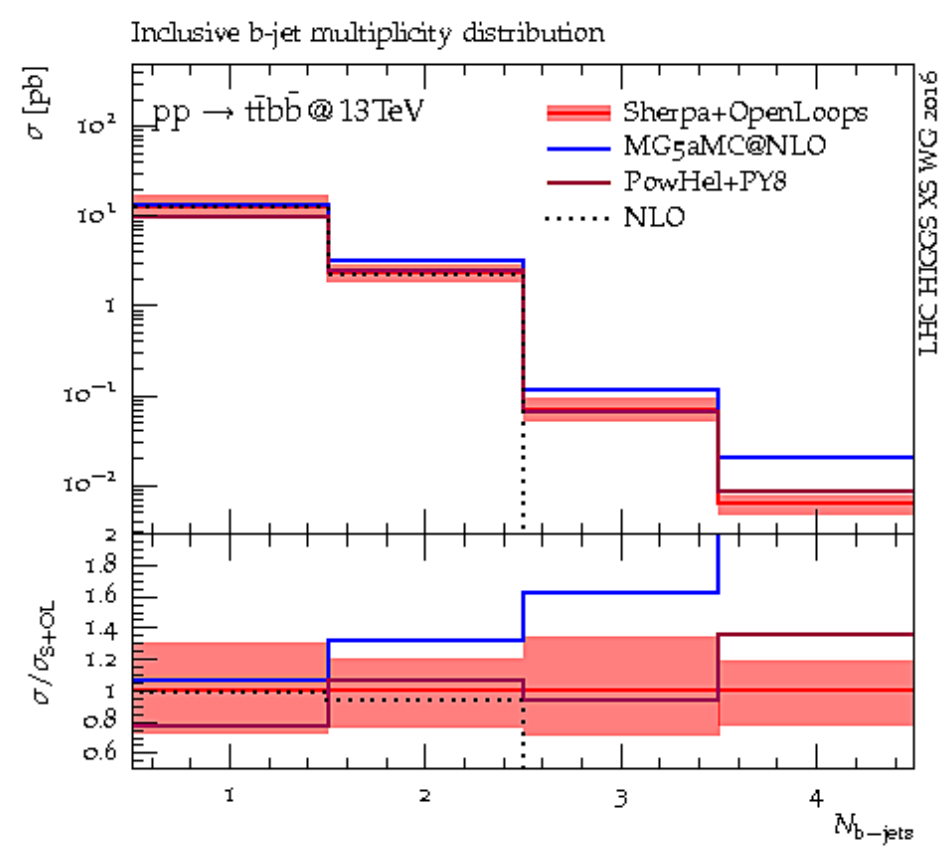
- **Strongly encourage this continued coordinated effort throughout the short/medium/long term**

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

Inclusive b-jets not from top quarks
parton level pT > 25 GeV, Iηl<2.5

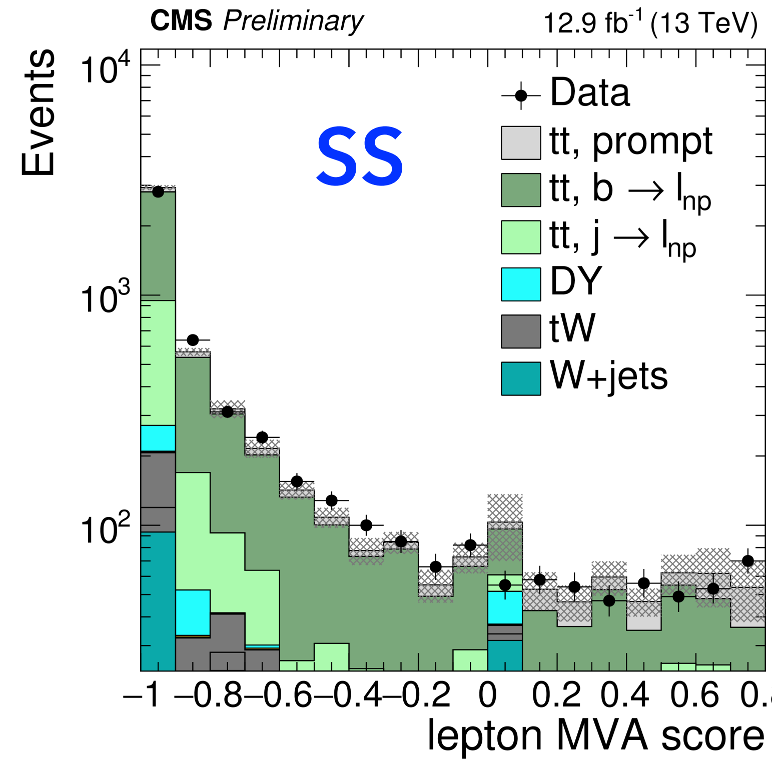
parton shower	on
hadronisation	off
UE	off
top decays	off

Selection	Tool	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NLO+PS}$ [fb]	$\sigma_{\rm NLO+PS}/\sigma_{\rm NLO}$
$n_b \geq 1$	SHERPA+OPENLOOPS	$12820^{+35\%}_{-28\%}$	$12939^{+30\%}_{-27\%}$	1.01
	MADGRAPH5_AMC@NLO		$13833^{+37\%}_{-29\%}$	1.08
	POWHEL		$10073^{+45\%}_{-29\%}$	0.79
$n_b \geq 2$	SHERPA+OPENLOOPS	$2268^{+30\%}_{-27\%}$	$2413^{+21\%}_{-24\%}$	1.06
	MADGRAPH5_AMC@NLO		$3192^{+38\%}_{-29\%}$	1.41
	POWHEL		$2570^{+35\%}_{-28\%}$	1.13



$t\bar{t}H$(ML) Analysis Overview

- ATLAS: tight lepton cuts on lepton variables
  - *Counting experiment*
- CMS: lepton-BDT (prompt-vs-nonprompt leptons) and loose pT cuts
  - Input variables: isolation, impact parameter, ID lepton
  - *2 MVAs to separate $t\bar{t}H$ from $t\bar{t}$ and $t\bar{t}V$*



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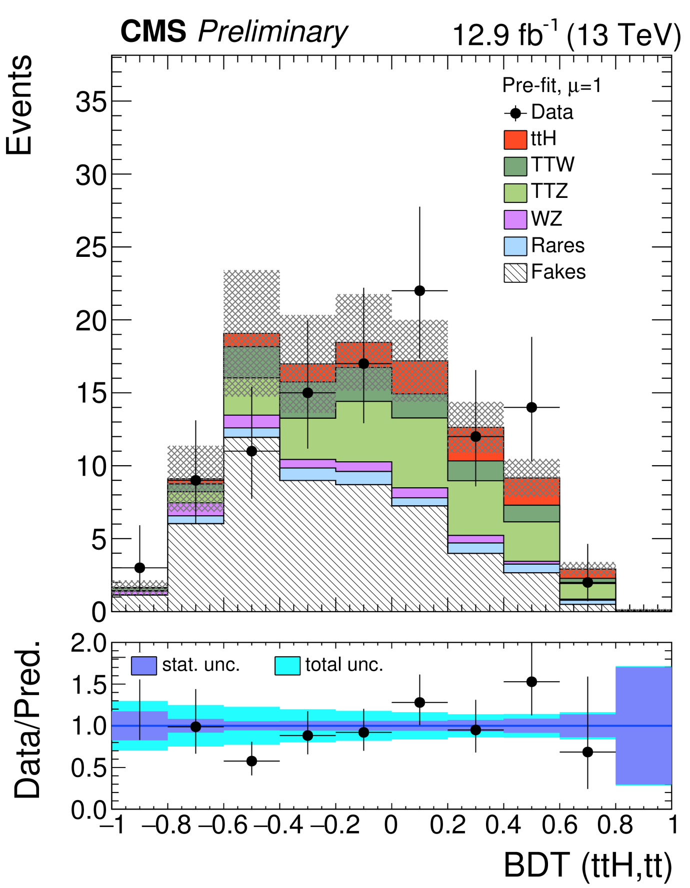
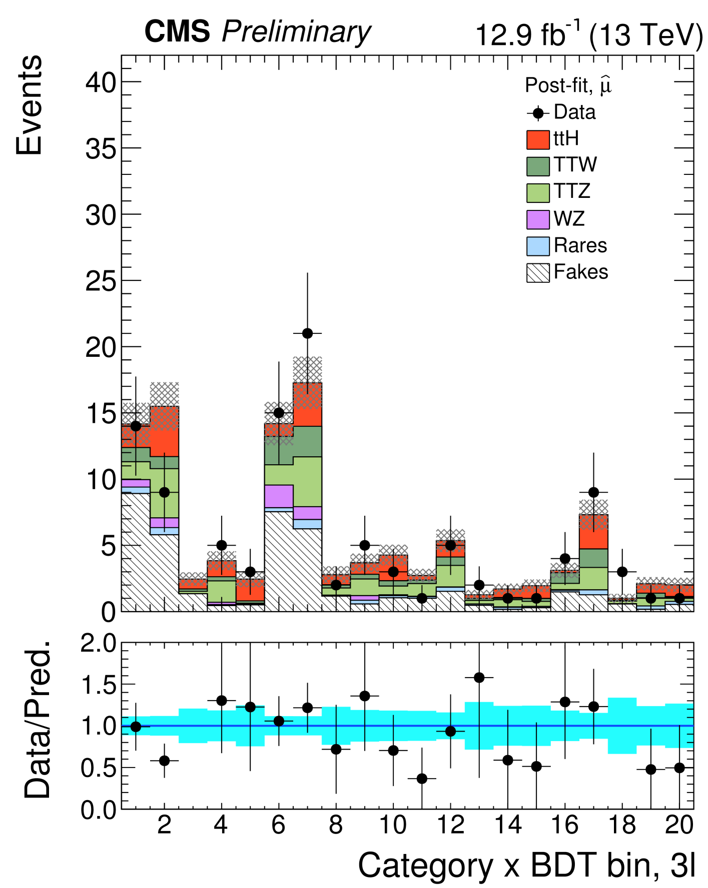
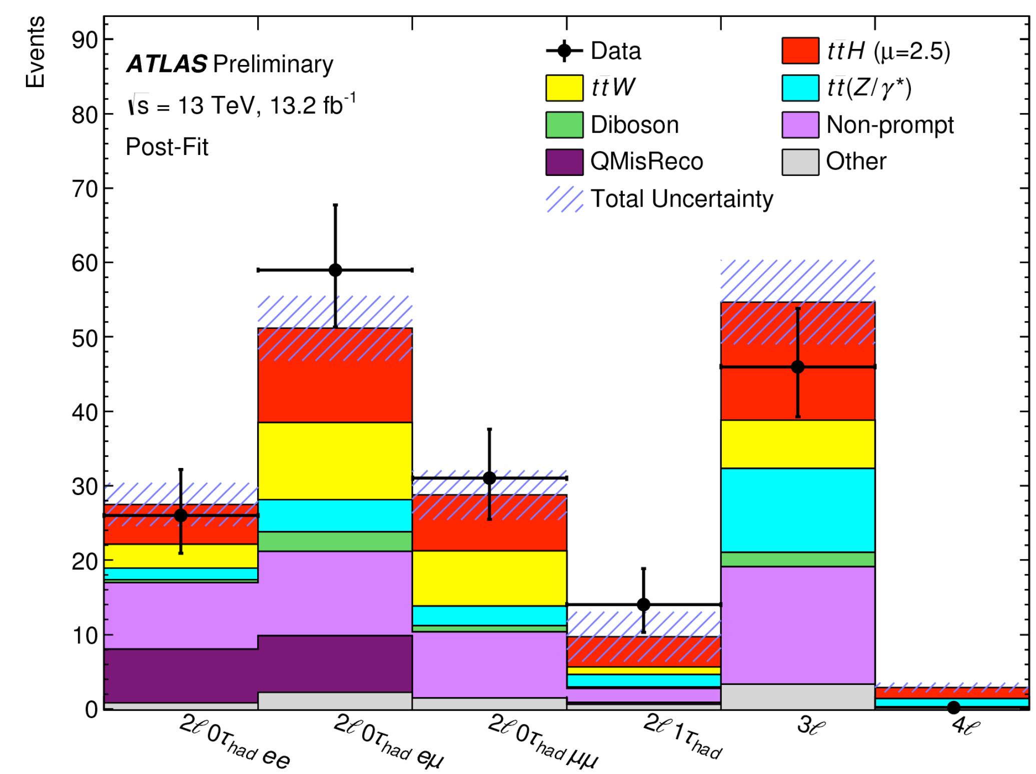
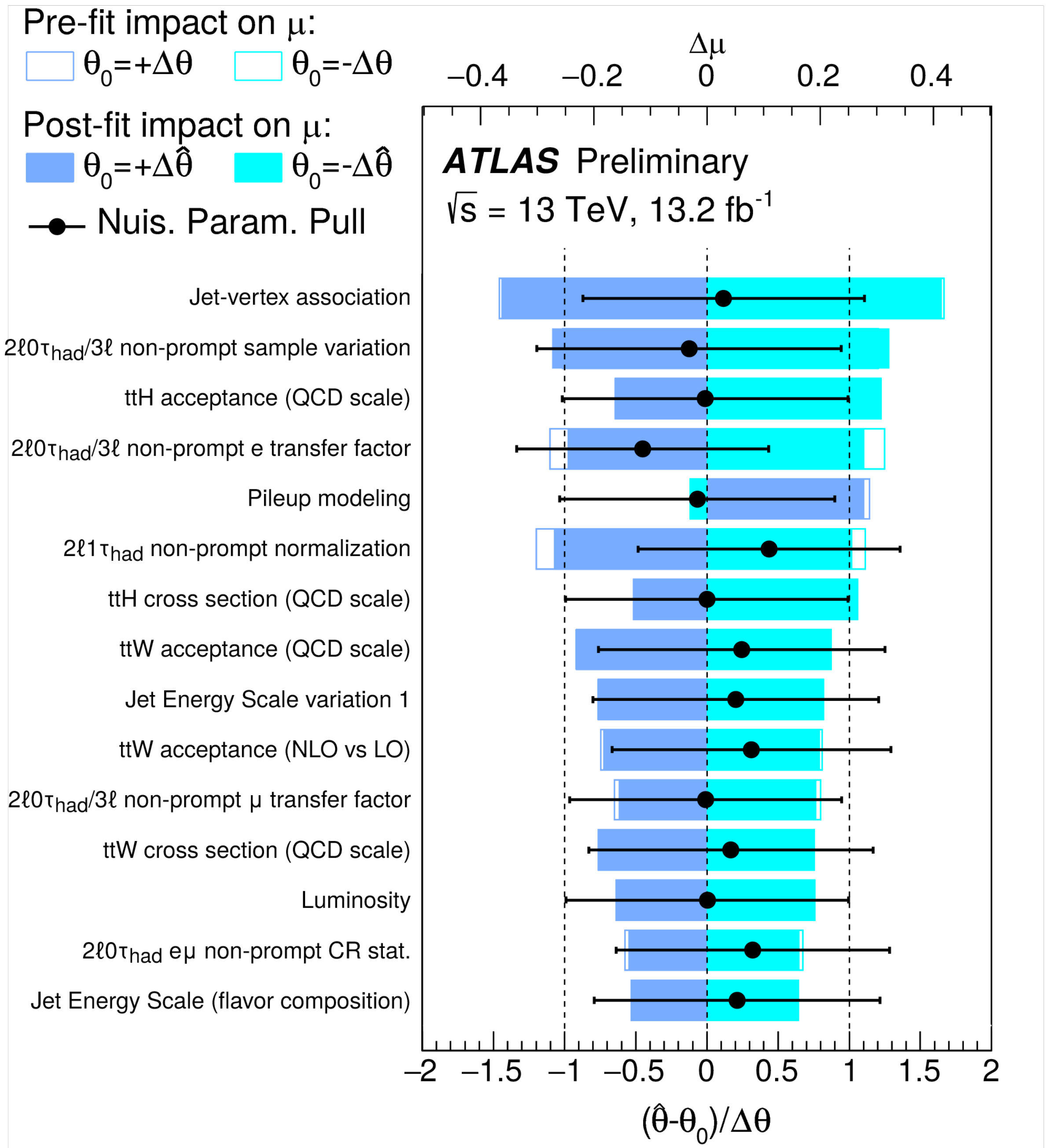


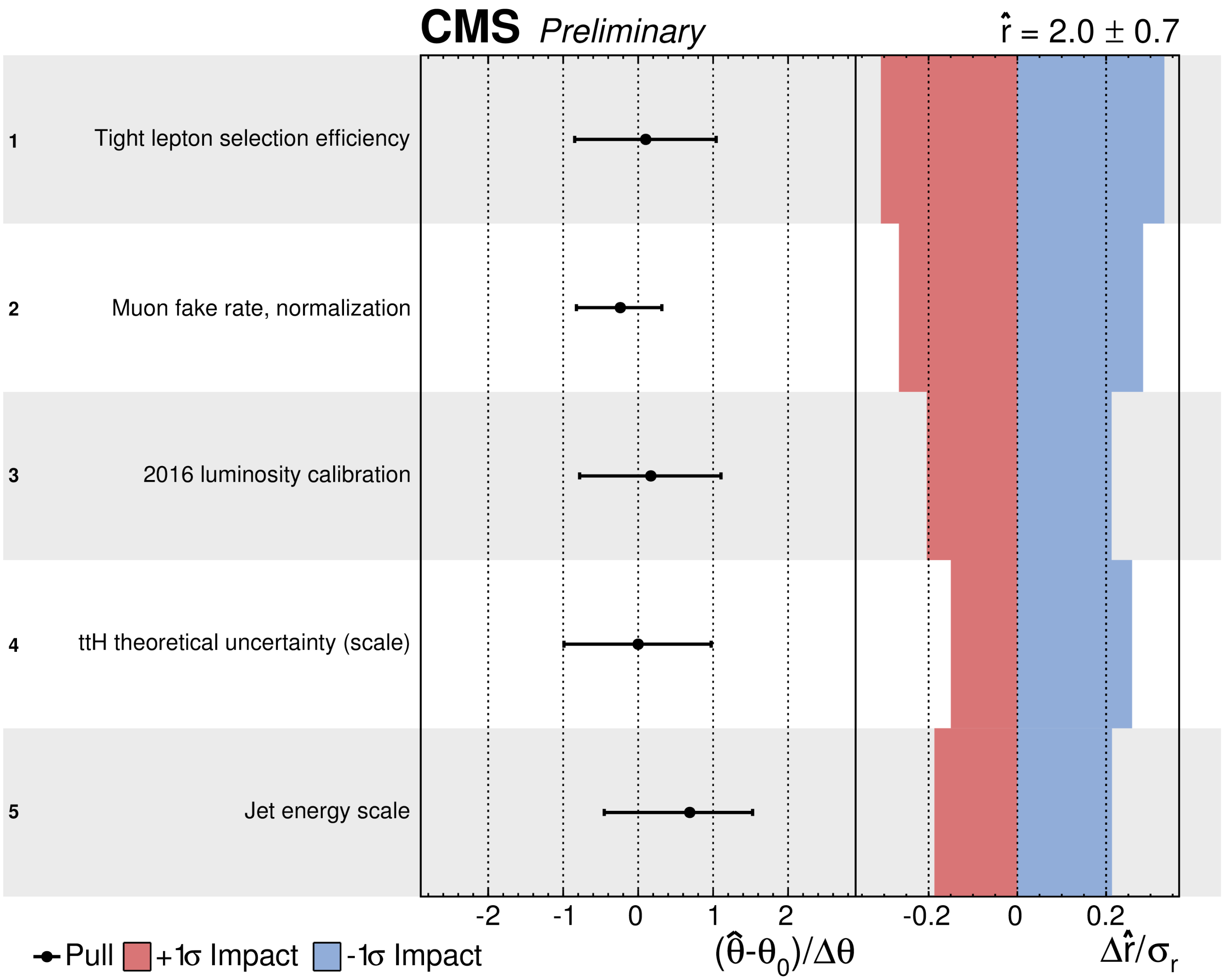




$t\bar{t}H$(ML) Systematics

- Many experimental related uncertainties due pile-up and fake leptons
  - Channel dependent uncertainties (lepton related uncertainties)
- Important uncertainties from $t\bar{t}H/V$ modelling and acceptance
  - Correlated across all channels





$t\bar{t}H$(ML) Common Items

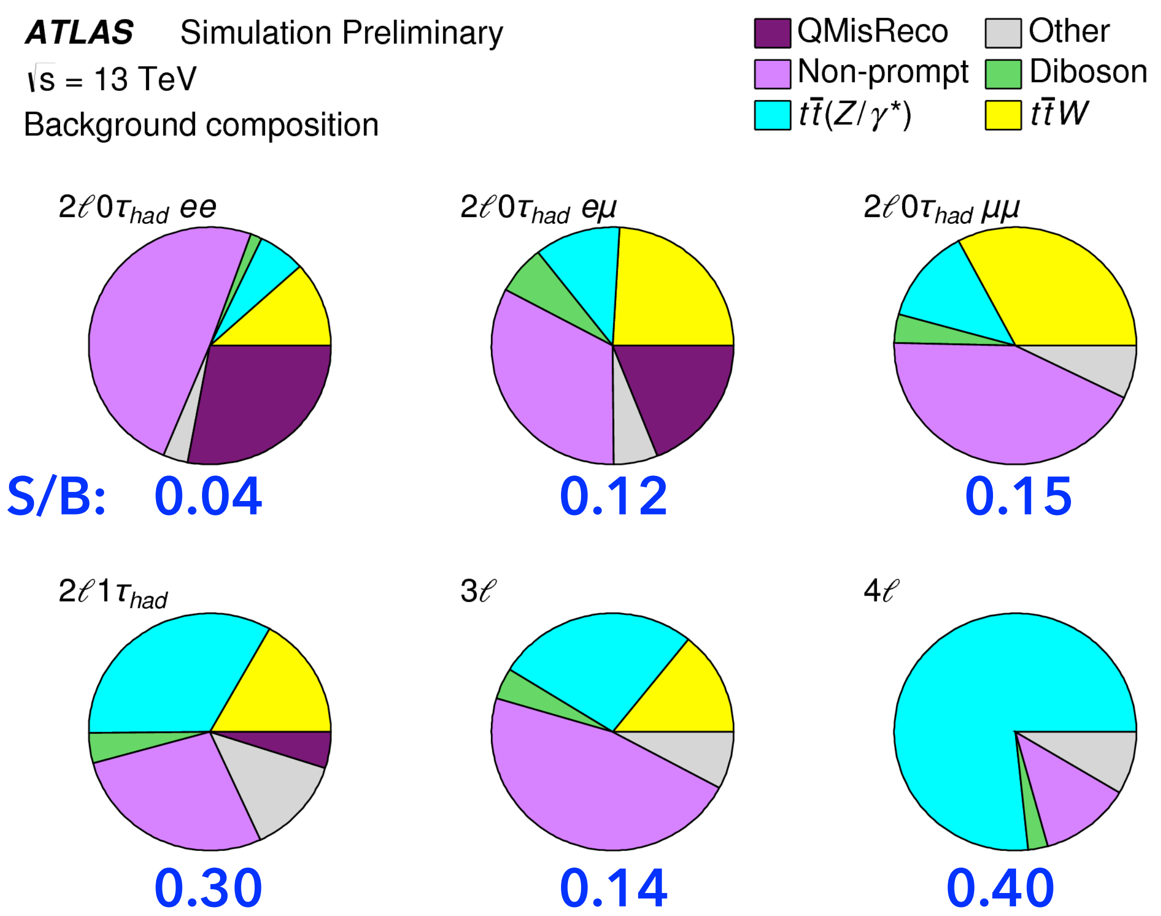
- **Main limiting factor is understanding of fake lepton backgrounds**
  - Charge mis-ID (2L SS electron channels) and non-prompt fake leptons

- Still important uncertainties from $t\bar{t}V$ - especially scale uncertainties
  - NLO QCD+EW XS numbers used by both experiments (coordinated in the YR4)
  - **$t\bar{t}W$ -> 0 additional jets (2L) -> 2 additional jets (3L) , $t\bar{t}Z$ -> 0 additional jets in SR**

- $t\bar{t}H$ uncertainties become larger with higher sensitivity
  - Especially in cases where signal strength is higher than SM expectation
  - *Correlated across all channels and fit regions*

All ML Channels

Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9



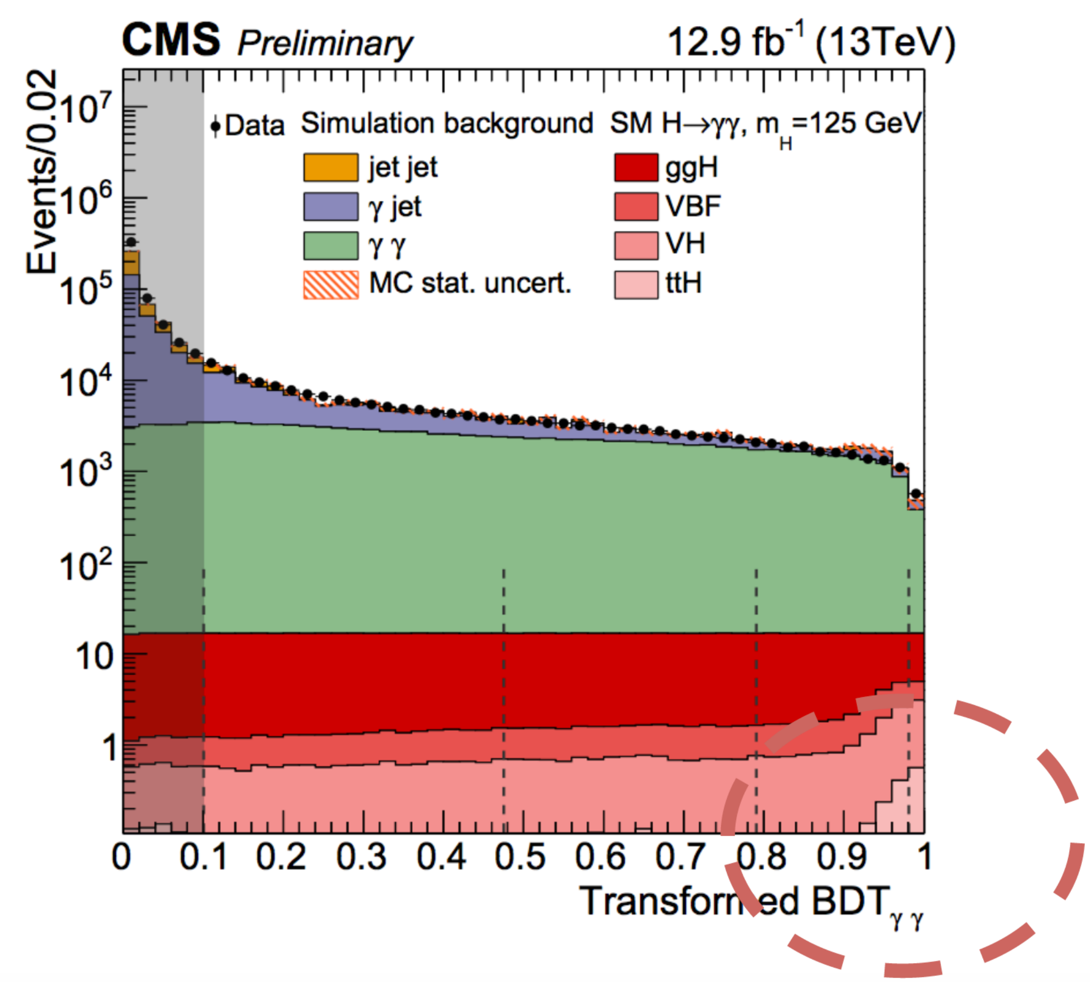
$t\bar{t}H(\gamma\gamma)$ Event Categorization

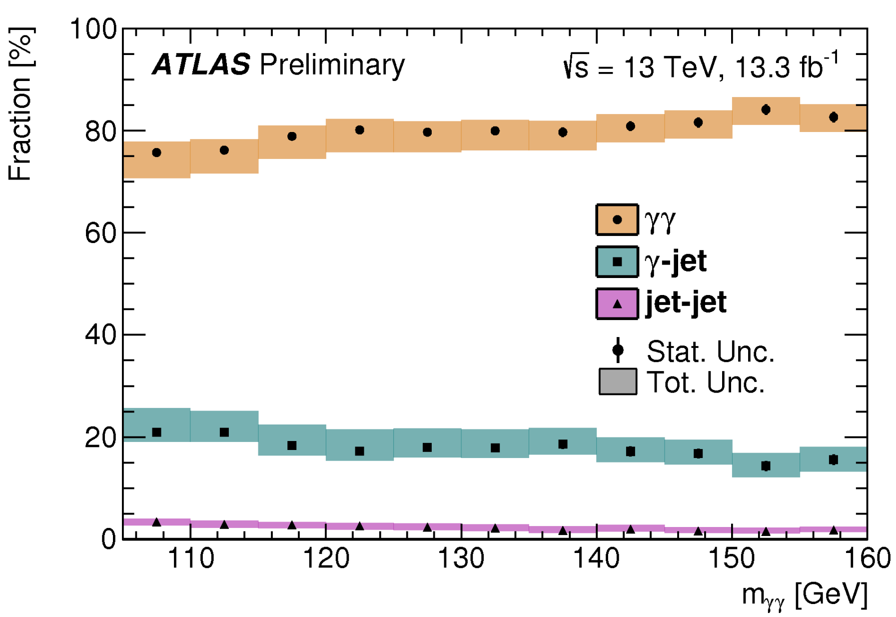
- Event categorization to improve analysis sensitivity

hadronic category (0 ℓ)	
ATLAS	**CMS**
≥ 5 jets, pT> 30 GeV	≥ 5 jets, pT> 25 GeV
≥ 1 b-jet	
cut-based γγ selection	**cut on BDTγγ**

leptonic category (≥ 1 ℓ)	
ATLAS	**CMS**
pT(ℓ) >10 GeV	pT(ℓ) >**20** GeV
≥ 2 jets pT>25 GeV, ≥ 1 b-jet	
Z veto ($m_{\ell\ell}$ and $m_{e\gamma}$)	
cut-based γγ selection MET > 20 GeV (for 1bjet events)	**cut on BDTγγ**

- CMS
  - BDTγγ discriminate H→γγ from diphoton background
  - Built to be mass independent



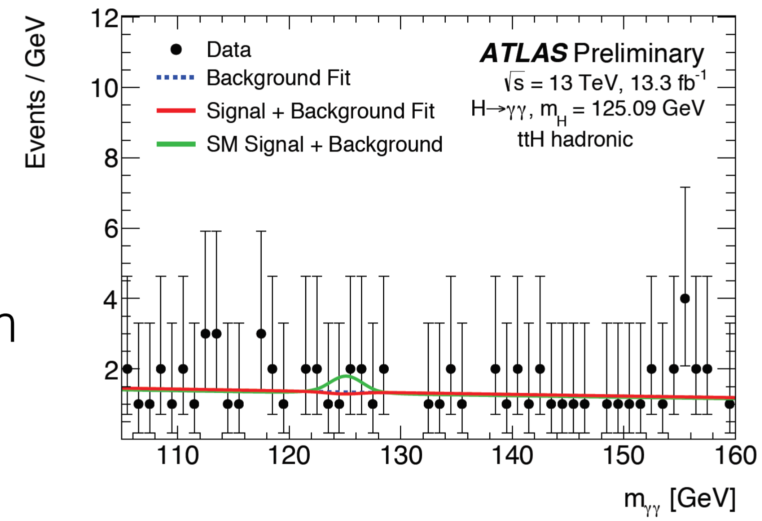


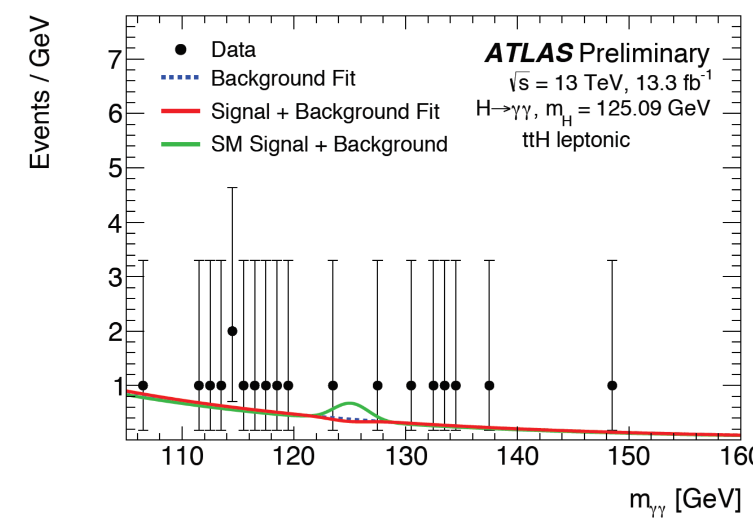
- ATLAS
  - Inclusive background modelling around the Higgs mass of 125 GeV

$t\bar{t}H(yy)$ Results

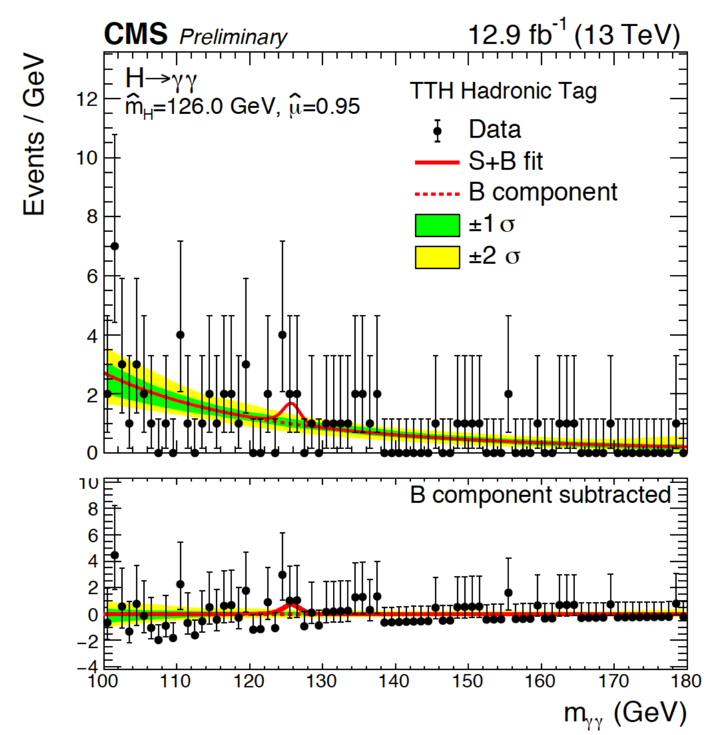
- **Both analyses statistically limited**
  - Background composition important to understand background model
    - More important with increased statistics
    - **Study background composition from $t\bar{t}$+γ / $t\bar{t}$+γγ**
  - Higgs+HF systematics

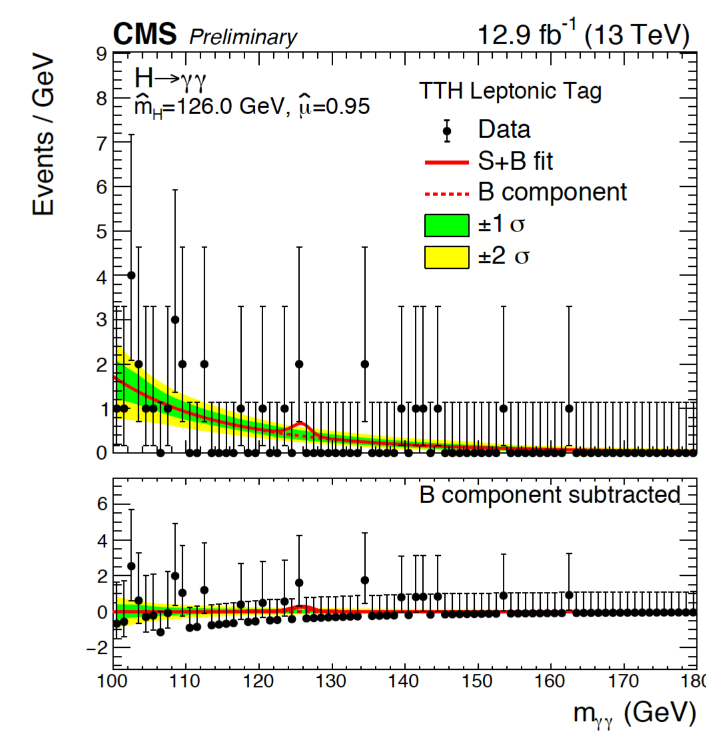
- ATLAS
- $\mu(t\bar{t}H) = -0.25 + 1.26 - 0.99$
  - Dominant systematic uncertainty from photon energy scale/resolution





- CMS
- $\mu(t\bar{t}H) = 1.91 + 1.5 - 1.2$

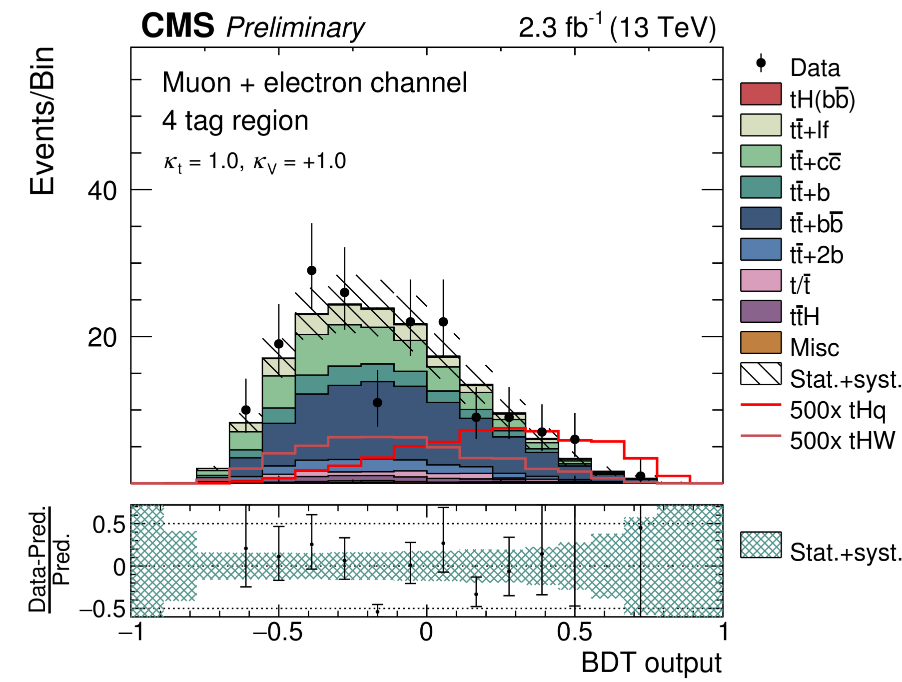




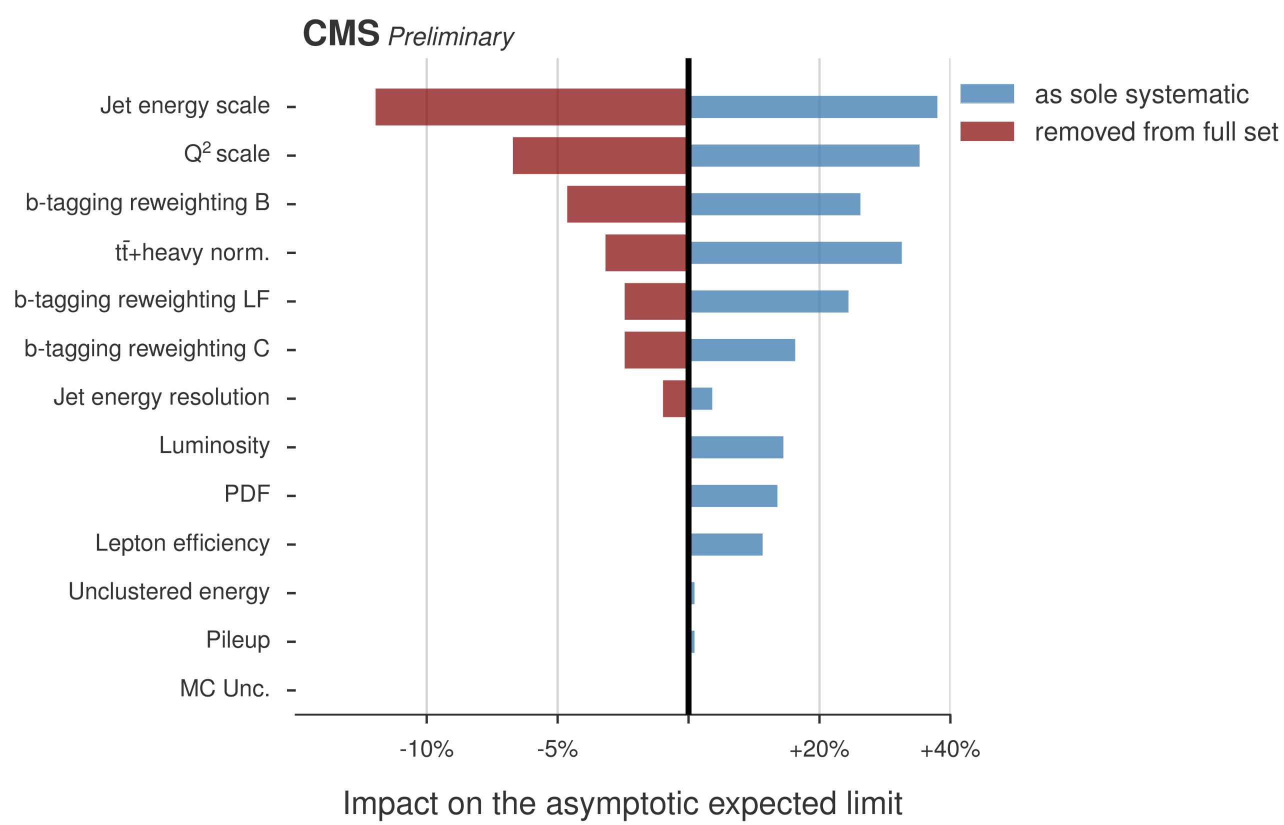
- Similar sensitivity from both ATLAS and CMS

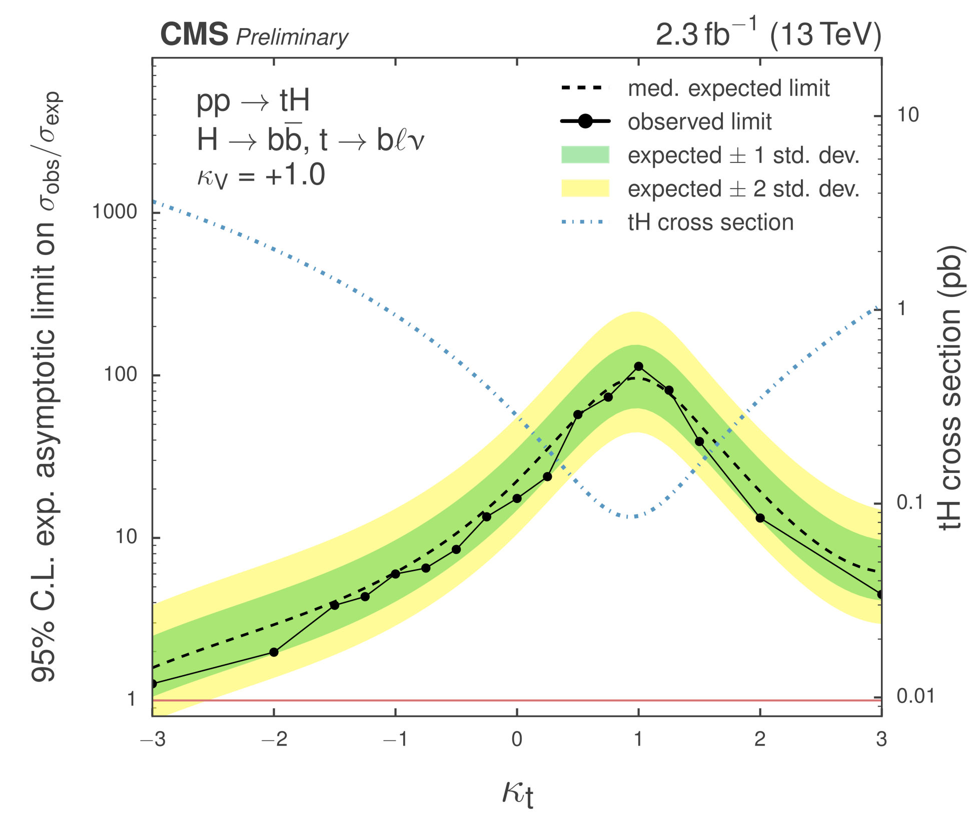
tH(bb) - CMS

- Limits on the cross section of tH production as a function of the coupling strength factors κ_t and κ_V
- 2 reconstruction BDTs (tHq and $t\bar{t}$ hypothesis) + kinematics
- Classification performed separately for each point in the κ_t -κ_V plane



- Similar $t\bar{t}$+HF systematic treatment as CMS $t\bar{t}$H(bb)
- Systematic uncertainty with largest impact: JES, Q^2 scale
    - *NLO WtH with WtH-ttH LO interference*





- *Obs (exp) 95% CL upper limit for SM = 113.7 (98.6) x σ_{SM}*
- *Obs (exp) 95% CL upper limit for the inverted top coupling scenario = 6.0 (6.4) x σ_{ITC}*

Outlook and Conclusions

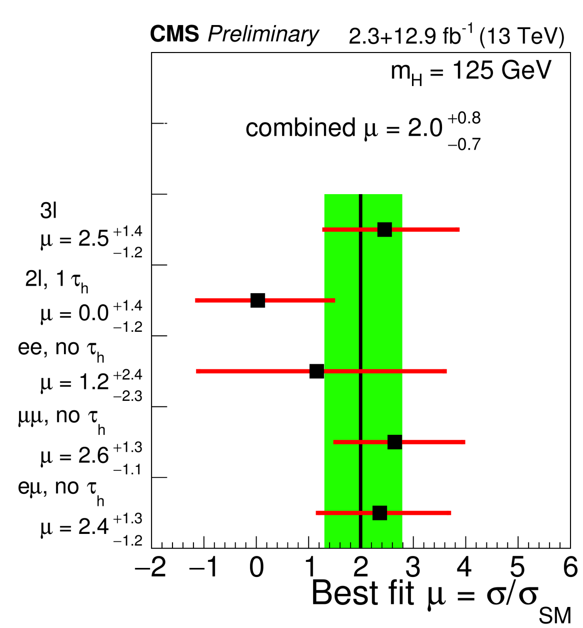
- First Run-2 analyses from both collaborations released at Moriond and ICHEP 2016 conferences
  - Still important modelling uncertainties which are vital for improving the sensitivity of $t\bar{t}H$/tH results with Run-2 data (~ 150 / fb)
  - Getting closer to *expected* evidence of ttH from the experiments
  - Run-2 already surpassed expected Run-1 sensitivity reach

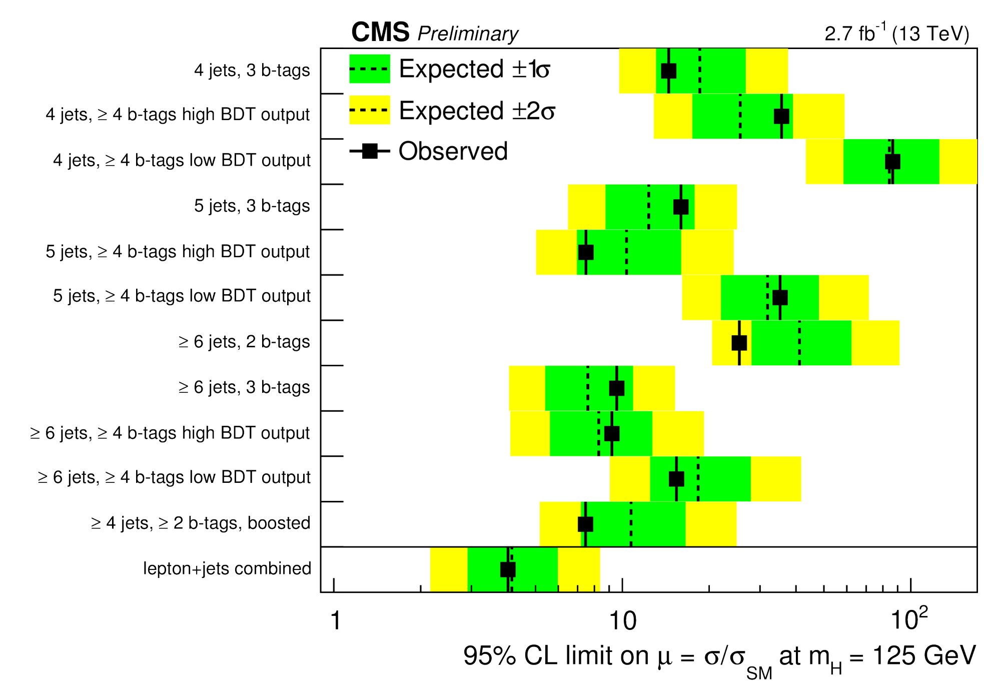
- **Strongly advocate for a continued coordinated effort between experiments and theory to tackle limited understanding of main backgrounds and signal modelling**
  - Very important to improve our understanding of proper uncertainties on these backgrounds
  - *Experimental measurements of these backgrounds are also vital*
    - Correlated phase-space

- Important to have a common understanding of modelling uncertainties between the experiments
  - Especially important regarding combination

ATLAS

Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H,\ H \to \gamma\gamma$	-0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8





Back-up