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Evidence for Higgs boson production in association with a $t\bar{t}$ pair

Jannik Geisen on behalf of the ***ATLAS*** collaboration
Supervised by Arnulf Quadt

II. Physikalisches Institut, Georg-August-Universität Göttingen

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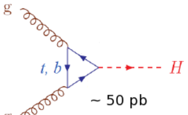
Bundesministerium
für Bildung
und Forschung

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103
ATLAS

Introduction

Higgs production at the LHC

- Higgs boson discovery in 2012 by ATLAS & CMS
- Is it "the expected" Higgs boson? → potential door to BSM
- $t\bar{t}H$: special production process → low XS → not yet observed by ATLAS



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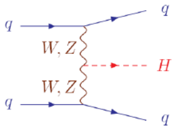

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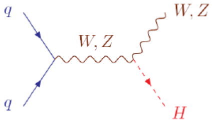

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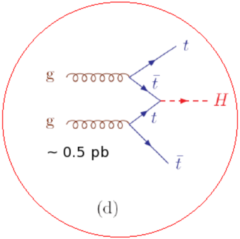

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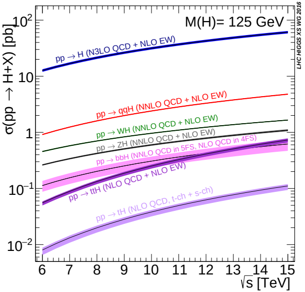

Introduction
The top Yukawa coupling

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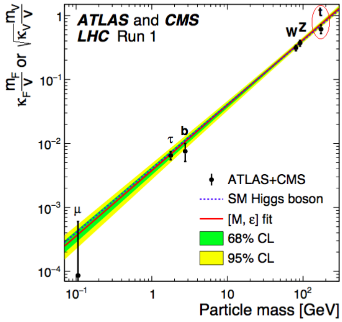
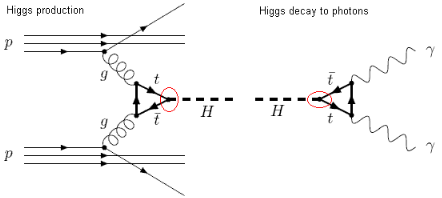
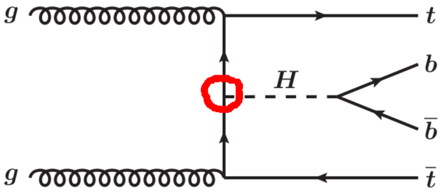
- Yukawa coupling $y_f \propto m_f$
- For top quark: $y_t \approx 1$
  $\Rightarrow$ sensitive to new physics



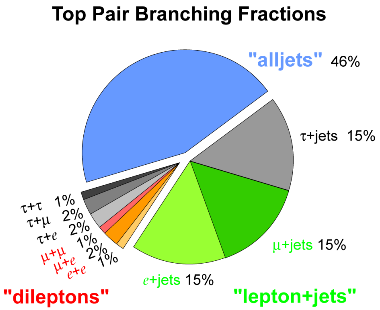




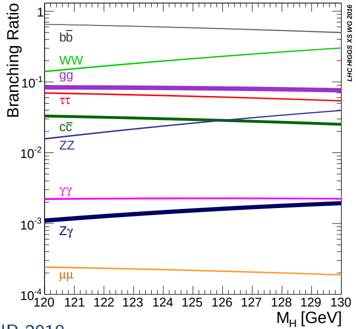
- gg fusion and $H \rightarrow \gamma\gamma$ decay
  $\Rightarrow$ only indirect measurement
- $t\bar{t}H$ allows direct measurement

Introduction
Top and Higgs decays

- $\sigma_{\mathrm{SM}}^{t\bar{t}H} = 507^{+35}_{-50}$ fb $\rightarrow$ only $\approx 1\%$ of Higgs produced at the LHC
  $\Rightarrow$ Upside: additional $t\bar{t}$ pair improves signal purity significantly
- Different top & Higgs decays $\rightarrow$ many different event topologies
  $\Rightarrow$ Four main analyses in ATLAS, studying different Higgs decays:
  $\Rightarrow H \rightarrow b\bar{b}, H \rightarrow$ ML (multi-leptons), $H \rightarrow ZZ^* \rightarrow 4l$ (resonant), $H \rightarrow \gamma\gamma$



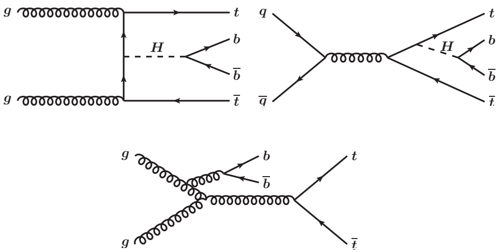
Higgs branching ratios:

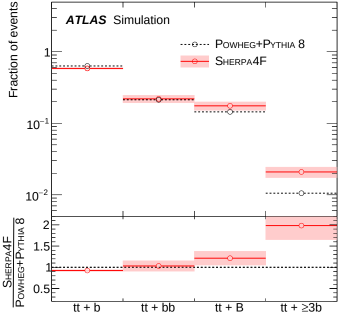


$t\bar{t}H(H \rightarrow b\bar{b})$

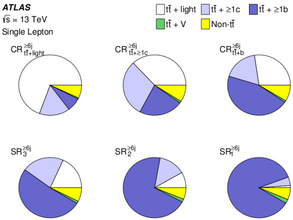
Phys. Rev. D 97, 072016 (2018)

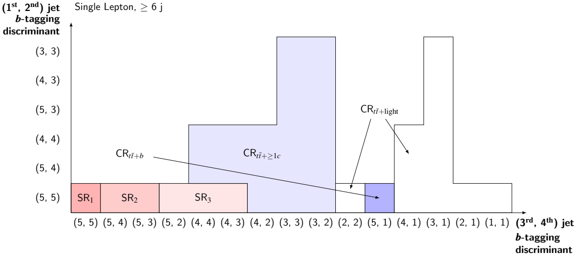
- Complex final state → semileptonic/dileptonic $t\bar{t}$ decay (allhad only Run I)
  ⇒ 4 or 6 jets & 4 b-jets at LO!
- Systematic impact of objects: jets, b-tagging, leptons, MET
- Largest background: $t\bar{t}$ + jets (light flavour, $c\bar{c}$, $b\bar{b}$ = “irreducible”)
  ⇒ $t\bar{t} + b\bar{b}$ cross-section ≈ 30 times higher than signal
  ⇒ Analysis depends on discriminating $t\bar{t}H(H \to b\bar{b})$ from $t\bar{t} + b\bar{b}$





- Split channel using N_{jets} & $N_{b-\text{jets}}$ (different b-tagging working points)
  $\Rightarrow$ Regions enriched in $t\bar{t}$ + lf/$c\bar{c}$/$b\bar{b}$/Higgs
- High values of N_{jets} & $N_{b-\text{jets}}$: phase-space closer to signal region (SR)
  $\Rightarrow$ Other regions are control regions (CR): constrain & estimate background





Single lepton regions with $N_{\text{jets}} \geq 6$
Highest signal purity: select 4 (very) tight b-tagged jets $\to$ "SR1"

$t\bar{t}H(H \to b\bar{b})$

MVA and fit

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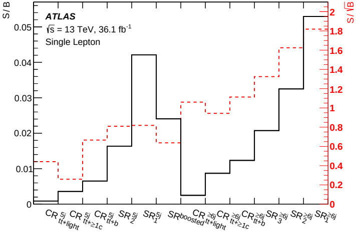
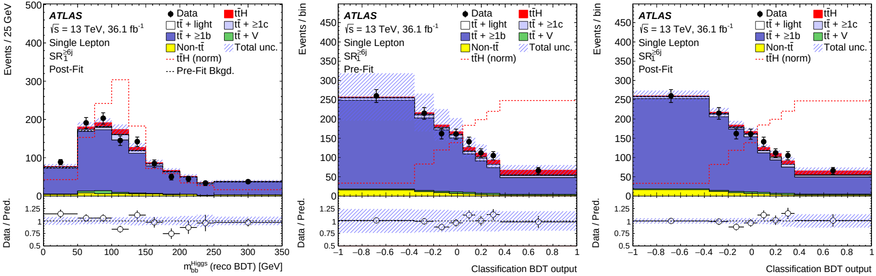
- Final state reconstructed by BDT
  $\Rightarrow$ finds $b\bar{b}$ from Higgs
- Then fed into classification BDT
  $\Rightarrow$ discriminate $t\bar{t}H(H \to b\bar{b})$ vs. $t\bar{t} + b\bar{b}$





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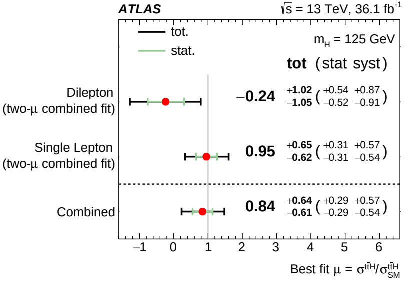
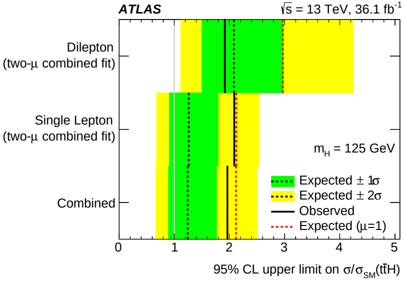
- Parameter of interest: signal strength $\mu = \sigma^{t\bar{t}H}/\sigma^{t\bar{t}H}_{\text{SM}}$
- Systematically limited by MC modelling + background modelling stats
  $\Rightarrow$ Estimating $t\bar{t} + b\bar{b}$ by comparing different MC generators
- Also: b-tagging, JES/JER
- No significant gain from more data $\rightarrow$ need to improve modelling

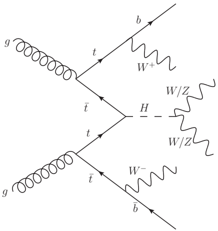


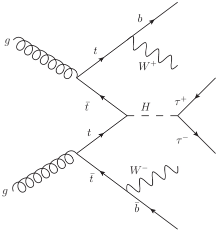


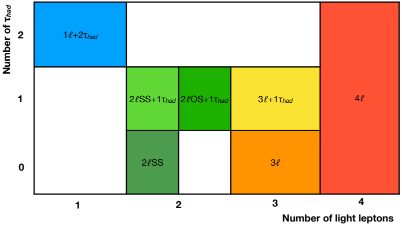
$t\bar{t}H(H \to \mathrm{ML})$

Phys. Rev. D 97, 072003 (2018)

- Includes $H \to WW^*/ZZ^*/\tau\tau$; complex final state $\Rightarrow$ 1-4 leptons, 0-2 taus
- Split into 7 channels using N_{leptons}, $N_{\tau_{\text{had}}}$, lepton charge
- Many different event topologies $\Rightarrow$ optimisation on many objects
- Systematic impact: leptons (prompt & non-prompt/fakes), MET, b-tagging, jets
- Veto $t\bar{t}H(H \to ZZ^* \to 4l) \to$ individual analysis







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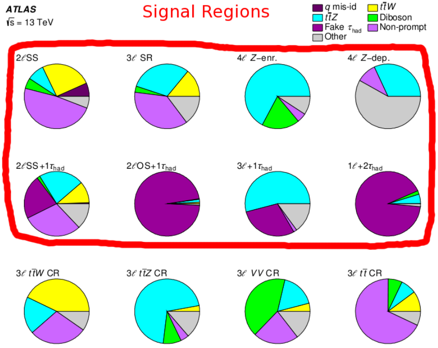
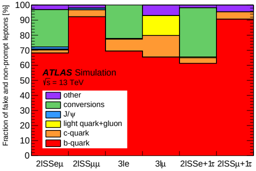
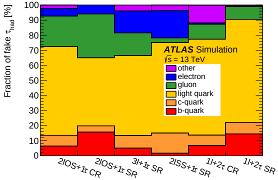
Two main background components:

- Prompt leptons $\rightarrow$ estimate via MC: $t\bar{t}W, t\bar{t}Z$, Diboson
- Fake τ_{had}; fake & non-prompt (light) leptons; charge mis-ID (electrons) $\Rightarrow$ data-driven estimate







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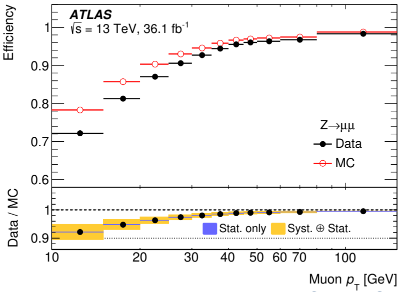
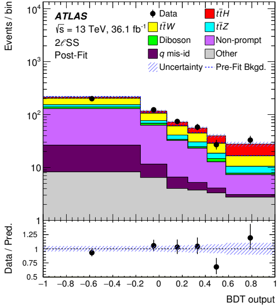
Two MVA stages:

- Object level BDTs → remove bad leptons
  - Non-prompt leptons via isolation-like BDT
  - Charge mis-ID via BDT
- Event level MVA → discriminate $t\bar{t}H(H \to \text{ML})$ vs. backgrounds
  - Combine multiple BDTs with multi-dimensional binning

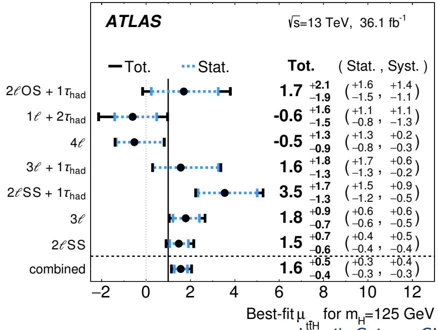


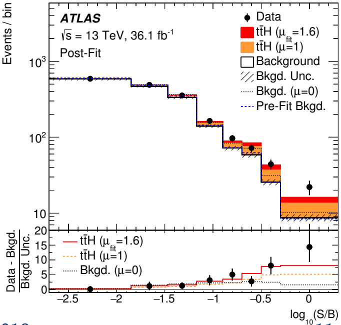


$t\bar{t}H(H \rightarrow \mathbf{ML})$

Results

- 2 same-sign (light) leptons "2lSS" and 3 (light) leptons "3l"
  $\Rightarrow$ Most sensitive channels
- Dominant systematics: signal & background modelling, JES & JER, non-prompt light-lepton estimate, flavour-tagging, τ_{had}-ID
- Visible signal above background after combining channels
  $\Rightarrow$ Significance: 4.1σ observed, 2.8σ expected





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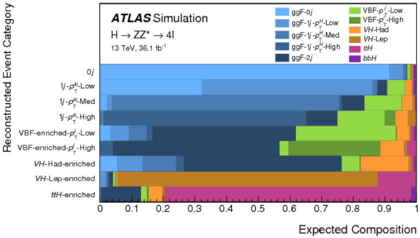
$t\bar{t}H(H \rightarrow \mathrm{ZZ}^* \rightarrow 4\mathrm{l})$

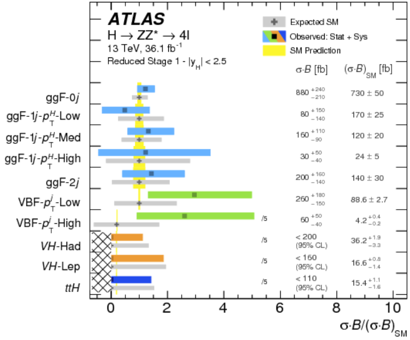
JHEP 03 (2018) 095

$t\bar{t}H(H \to \mathbf{ZZ}^* \to 4\mathbf{l})$

Overview and results

- Part of $H \to ZZ^* \to 4l$ analysis; inclusive $H \to ZZ^* \to 4l$ selection
- Get $t\bar{t}H$ via N_{jets}, $N_{b-\text{jets}}$ $\to$ very pure channel: S/B $\approx$ 125-300%
- **BUT:** very low statistics $\sigma \times \text{BR} = 0.507 \text{ pb} \times 0.0001251$
- No data event found in signal region $\to$ more data needed $\to$ set limits: $\Rightarrow \sigma \times \text{BR} < 1.9\ (7.1)$ times SM @ 68% (95%) CL



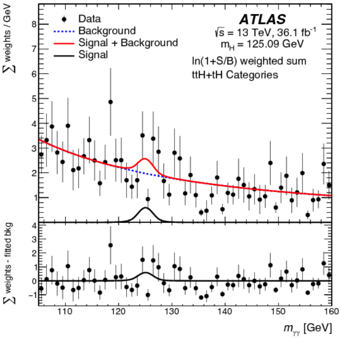


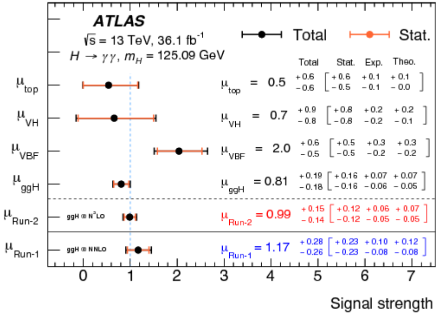
$t\bar{t}H(H \rightarrow \gamma\gamma)$

arXiv:1802.04146 [hep-ex]

$t\bar{t}H(H \to \gamma\gamma)$
Overview and results

- Part of $H \to \gamma\gamma$ analysis, inclusive $H \to \gamma\gamma$ selection
- Again channel with low statistics: $\sigma \times \text{BR} = 0.507\ \text{pb} \times 0.00227$
- Get $t\bar{t}H$ via N_{jets}, $N_{b-\text{jets}}$ $\to$ hadronic and leptonic categories
- Use excellent resolution on $m_{\gamma\gamma}$ to discriminate signal vs. background
- $t\bar{t}H + tH$ result: $\mu_{\text{top}} = 0.5\ ^{+0.6}_{-0.5}(\text{stat}) \pm 0.1(\text{syst})$ $\to$ limited by statistics





$t\bar{t}H$ combination

Phys. Rev. D 97, 072003 (2018)

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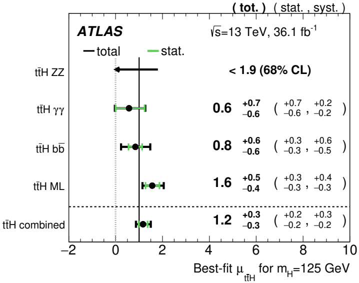
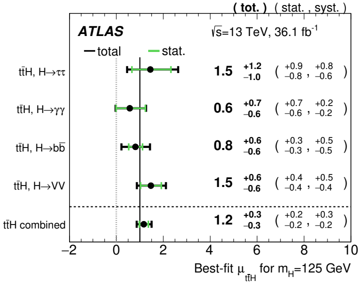




Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ

- Evidence for $t\bar{t}H$ in ATLAS
- Measured cross-sections compatible with SM

What you can take away

- $t\bar{t}H$ search is very challenging
- Individual analyses have their own challenges and limitations
  $\Rightarrow t\bar{t}H(H \rightarrow \text{ML})$ highest sensitivity on μ
- ATLAS found evidence for $t\bar{t}H \rightarrow$ compatible with SM
- Next steps:
  - Current results use 2015 + 2016 data (36.1 fb^{-1}) $\rightarrow$ include more data
    $\Rightarrow$ 79.7 fb^{-1} when including 2017 data
    $\Rightarrow \approx$ 140 fb^{-1} expected with full Run II
  - Develop improved analyses techniques to decrease systematics on couplings

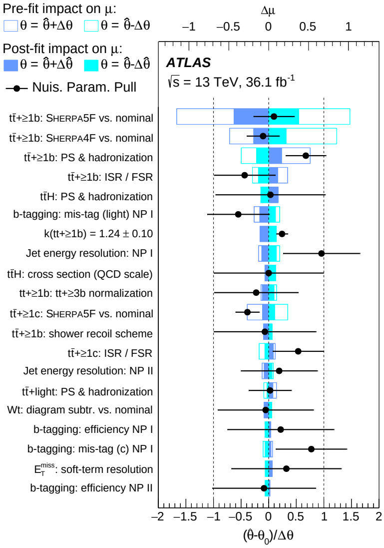
Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\,^{+0.5}_{-0.4}$	$1.0\,^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	$0.8\,^{+0.6}_{-0.6}$	$1.0\,^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \rightarrow \gamma\gamma$	$0.6\,^{+0.7}_{-0.6}$	$1.0\,^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \rightarrow 4\ell$	< 1.9	$1.0\,^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\,^{+0.3}_{-0.3}$	$1.0\,^{+0.3}_{-0.3}$	4.2σ	3.8σ

Thank you for your attention!

Backup

$t\bar{t}H(H \rightarrow b\bar{b})$

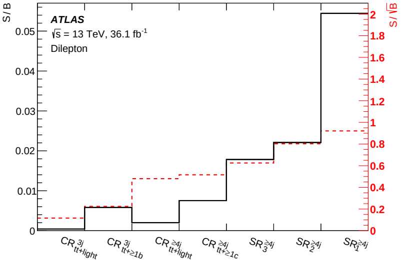
Systematics ranking

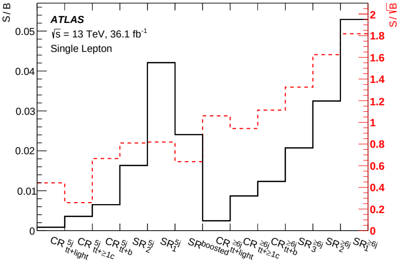


Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	$+0.46$	-0.46
Background-model stat. unc.	$+0.29$	-0.31
b-tagging efficiency and mis-tag rates	$+0.16$	-0.16
Jet energy scale and resolution	$+0.14$	-0.14
$t\bar{t}H$ modeling	$+0.22$	-0.05
$t\bar{t} + \geq 1c$ modeling	$+0.09$	-0.11
JVT, pileup modeling	$+0.03$	-0.05
Other background modeling	$+0.08$	-0.08
$t\bar{t}$ + light modeling	$+0.06$	-0.03
Luminosity	$+0.03$	-0.02
Light lepton (e, μ) id., isolation, trigger	$+0.03$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t} + \geq 1b$ normalization	$+0.09$	-0.10
$t\bar{t} + \geq 1c$ normalization	$+0.02$	-0.03
Intrinsic statistical uncertainty	$+0.21$	-0.20
Total statistical uncertainty	$+0.29$	-0.29
Total uncertainty	$+0.64$	-0.61

$t\bar{t}H(H \to b\bar{b})$

S/B and $S/\sqrt{B}$

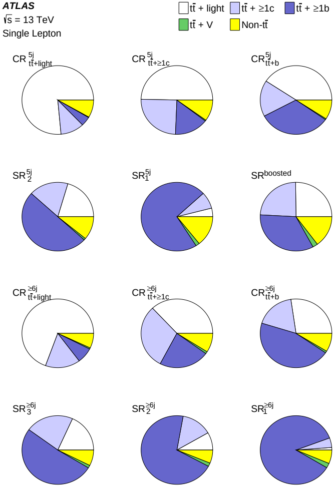


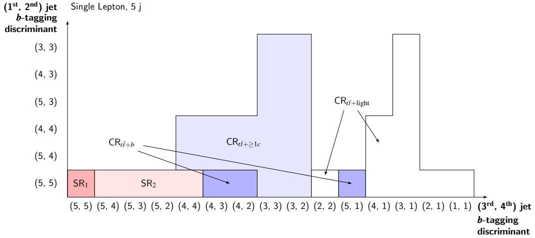


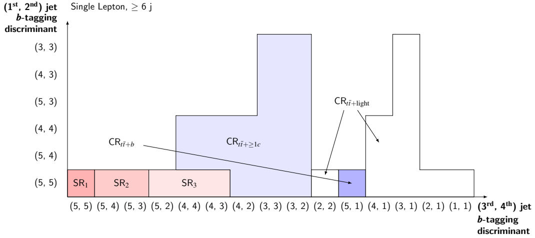
- $S/B > 5\%$ and $S/\sqrt{B} \approx 2$ in purest signal region!

$t\bar{t}H(H \rightarrow b\bar{b})$

Singlelepton regions







$t\bar{t}H(H \to b\bar{b})$
Dilepton regions

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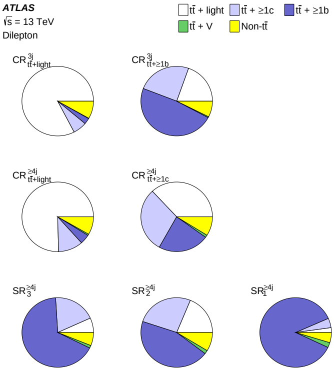

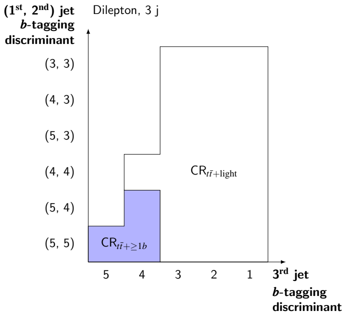

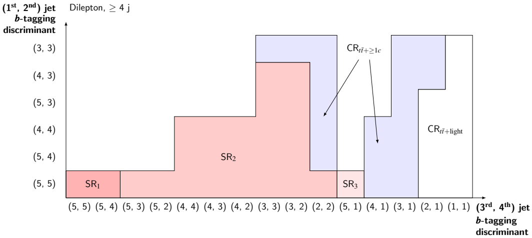

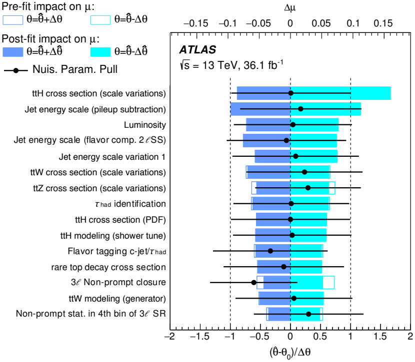

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

- $t\bar{t}$ modelling in $t\bar{t}H(H \to b\bar{b})$ = leading uncertainty in full combination!

$t\bar{t}H$ combination

$t\bar{t}H(H \rightarrow b\bar{b})$ difference ATLAS vs CMS

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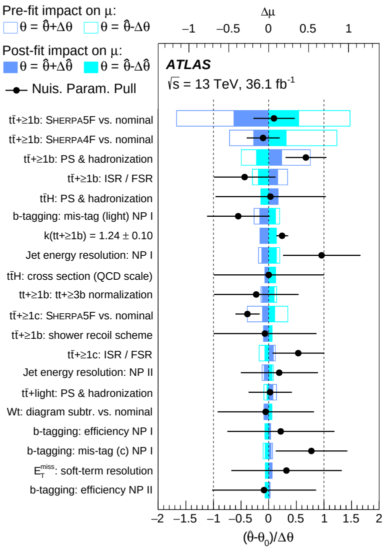
ATLAS



CMS

Source	Type	Remarks
Luminosity	rate	Signal and all backgrounds
Lepton ID/Iso	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet energy scale	shape	Signal and all backgrounds
Jet energy resolution	shape	Signal and all backgrounds
b-tag HF fraction	shape	Signal and all backgrounds
b-tag HF stats (linear)	shape	Signal and all backgrounds
b-tag HF stats (quadratic)	shape	Signal and all backgrounds
b-tag LF fraction	shape	Signal and all backgrounds
b-tag LF stats (linear)	shape	Signal and all backgrounds
b-tag LF stats (quadratic)	shape	Signal and all backgrounds
b-tag charm (linear)	shape	Signal and all backgrounds
b-tag charm (quadratic)	shape	Signal and all backgrounds
QCD scale (tt̄H)	rate	Scale uncertainty of NLO tt̄H prediction
QCD scale (tt̄)	rate	Scale uncertainty of NLO tt̄ prediction
QCD scale (tt̄+hf)	rate	Additional 50% rate uncertainty of tt̄+hf predictions
QCD scale (t)	rate	Scale uncertainty of NLO single t prediction
QCD scale (V)	rate	Scale uncertainty of NNLO W and Z prediction
QCD scale (VV)	rate	Scale uncertainty of NLO diboson prediction
PDF (gg)	rate	PDF uncertainty for gg initiated processes except tt̄H
PDF (gg tt̄H)	rate	PDF uncertainty for tt̄H
PDF (qq̄)	rate	PDF uncertainty of qq̄ initiated processes (tt̄ W, W, Z)
PDF (qg)	rate	PDF uncertainty of qg initiated processes (single t)
μ_R scale (tt̄)	shape	Renormalization scale uncertainty of the tt̄ ME generator, independent for additional jet flavors
μ_F scale (tt̄)	shape	Factorization scale uncertainty of the tt̄ ME generator, independent for additional jet flavors
PS Scale: ISR (tt̄)	rate	Initial state radiation uncertainty of the parton shower (for tt̄ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavors
PS Scale: FSR (tt̄)	rate	Final state radiation uncertainty (for tt̄ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavors
ME-PS matching (tt̄)	rate	NLO parton-shower matching, *hdamp* (for tt̄ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavors
Underlying Event (tt̄)	rate	Underlying event (for tt̄ events), jet multiplicity dependent rate uncertainty, independent for additional jet flavors
NNPDF3.0NLO (tt̄H,tt̄)	shape	Variation of the NNPDF sub-PDF, same for tt̄H and additional jet flavors
Bin-by-bin statistics	shape	statistical uncertainty of the signal and background prediction due to the limited sample size