$t\bar{t}$H and tH at ATLAS and CMS: Status, Prospects, and Questions

Workshop on the physics of HL-LHC and perspectives at HE-LHC, 30 Oct – 1 Nov 2017 (CERN)

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on behalf of the ATLAS and CMS Collaborations | October 31, 2017

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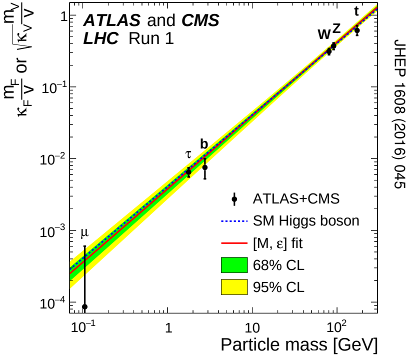
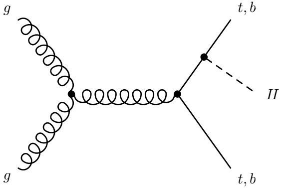
Measuring the Top-Higgs Yukawa Coupling

- Higgs-boson Yukawa coupling λ_t to top quark especially interesting
  - Large ($\approx$ 1): important in loop processes
  - Strong impacts on SM and BSM physics
- Indirect constraints from gluon-fusion production and H $\rightarrow \gamma\gamma$-decays
  - Dominate current value
  - Model-dependent: need to make assumptions on loop contributions

$t\bar{t}$- and t-associated H production:
direct access to top-Higgs coupling





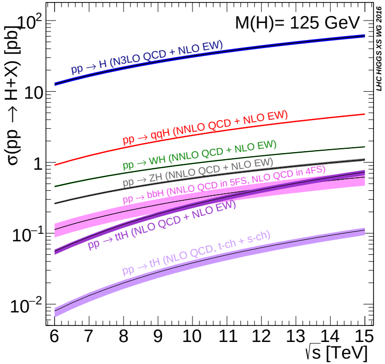
Outline

- Not very many dedicated projections on $\mathrm{t\bar{t}H}$ and tH available yet
- This presentation:

1) **Review of current measurements** (personal selection)
   - What methods are used and what precision is reached?
   - Which uncertainties dominate?
2) **Prospects for higher luminosities**
   - Projections of direct $\mathrm{t\bar{t}H}(\gamma\gamma)$, $\mathrm{t\bar{t}H}(\mu\mu)$, and $\mathrm{H} \rightarrow \mathrm{ZZ}^{*} \rightarrow 4l$ measurements
   - Projections of the indirect coupling measurements
3) **Thoughts on further studies**
   - What additional studies are needed?
   - What theoretical input is needed?

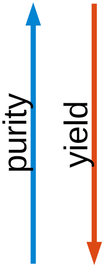
$t\bar{t}H$ and tH Production at the LHC

- **Small $t\bar{t}H$ production cross-section** of $\approx$ 0.5 pb at 13 TeV
  - **Large dependence on $\sqrt{s}$** compared to other channels, e. g. factor $\approx$ 4 increase from 8 TeV
  - Uncertainty dominated by missing higher orders (QCD scales)
- **Yet smaller tH production** cross-section of $\approx$ 0.1 pb



- Combination of $t\bar{t}$/t and H decays: **multitude of possible final states with many objects**
  - Jets and b jets
  - Light leptons and hadronic τs
  - Photons

Searches for $t\bar{t}H$ Production at the LHC



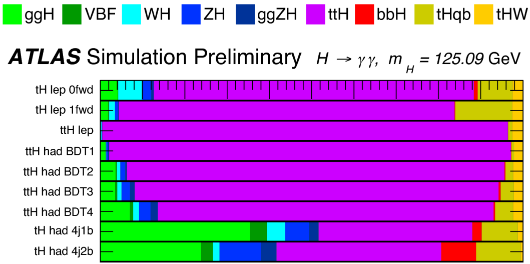
Latest LHC Run-II results on $\mu = \sigma/\sigma_{SM}$

	ATLAS	(ATLAS-CONF)	CMS	(CMS-PAS)
$t\bar{t}H(ZZ^* \rightarrow 4l)$	< 7.7	(2017-043)	< 1.2	(HIG-16-041)
$t\bar{t}H(\gamma\gamma)$	$0.5^{+0.6}_{-0.6}$	(2017-045)	$2.2^{+0.9}_{-0.8}$	(HIG-16-040)
$t\bar{t}H$(multi-leptons)	$1.6^{+0.5}_{-0.4}$	(2017-077)	$1.5^{+0.5}_{-0.5}$ (l)	(HIG-17-004)
			$0.7^{+0.6}_{-0.5}$ (τ_h)	(HIG-17-003)
$t\bar{t}H(b\bar{b})$	$0.8^{+0.6}_{-0.6}$	(2017-076)	$-0.2^{+0.8}_{-0.8}$	(HIG-16-038)
combination	$1.2^{+0.3}_{-0.3}$	(2017-077)		

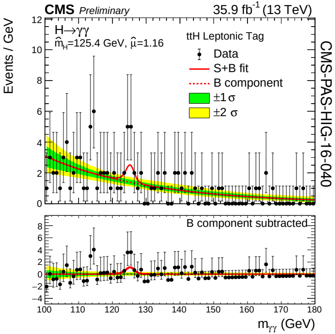
- In general: similar analysis strategies and sensitivity by ATLAS & CMS

$t\bar{t}$H, H $\rightarrow \gamma\gamma$ & 4l

- H $\rightarrow \gamma\gamma$ and H $\rightarrow$ ZZ* $\rightarrow$ 4l **cleanest channels**: high purity
  - $t\bar{t}$ and H systems of event can be cleanly separated and identified
- Challenge: **small signal yield** of $\sigma \times \mathcal{B} \approx$ 1 fb ($\gamma\gamma$), $\approx$ 0.14 fb (4l)
- Several categories **targeting $t\bar{t}$H and tH** production
  - $\gamma\gamma$ ATLAS: $t\bar{t}$/t leptonic (2 $t\bar{t}$H, 1 tH) and hadronic (4 $t\bar{t}$H, 2 tH) channels
  - $\gamma\gamma$ CMS: $t\bar{t}$/t leptonic (1 $t\bar{t}$H), hadronic (1 $t\bar{t}$H) channels
  - 4l ATLAS+CMS: incl. $t\bar{t}$H category
- **Empirical bkg. model** from sidebands



ATLAS-CONF-2017-045



$t\bar{t}H$, $H \to \gamma\gamma$ & 4l: Results

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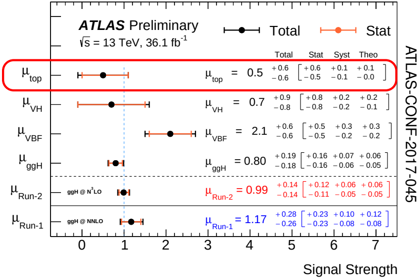
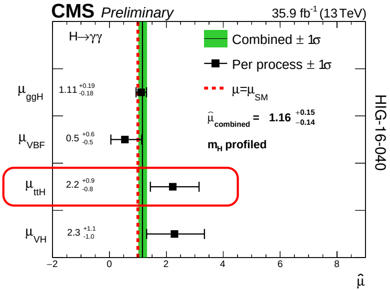
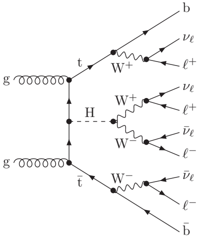


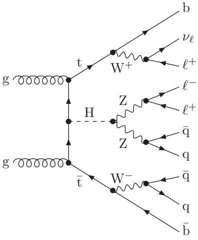


- $H \to \gamma\gamma$ channel: precision of $\Delta\mu = 0.6$–0.9
  - Results compatible with SM expectation
  - **Entirely dominated by statistical uncertainty**
  - Systematic uncertainties dominated by **signal modelling**
- $H \to ZZ^* \to 4l$: no events observed, only upper limits

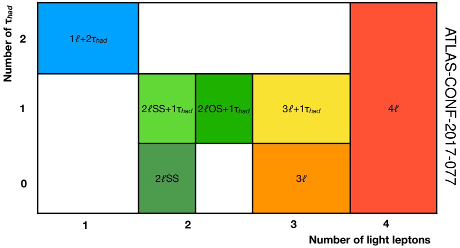
$t\bar{t}$H, H $\rightarrow$ multi-leptons

- Targeting **H $\rightarrow$ WW*, ZZ*, $\tau\tau$** and ≥ 1 **leptonically decaying t** quark
  - Event selection: $l^{\pm}l^{\pm}$ or $\geq 3l$, jets, and b tags
  - **Several categories** to enhance different channels
  - Excl. H $\rightarrow 4l$, CMS: excl. τ_{had} (dedicated analyses)
- Main backgrounds (composition depends strongly on category)
  - **Irreducible $t\bar{t}$ + V production: from theory** with $\mathcal{O}(10\,\%)$ uncertainty
  - **Fake and non-prompt leptons, lepton charge mis-ID: estimated from data** with $\mathcal{O}(30\,\%)$ uncertainty





Example: ATLAS categorisation



$t\bar{t}H$, $H \to$ multi-leptons: Results

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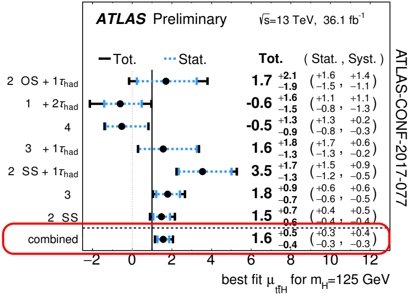
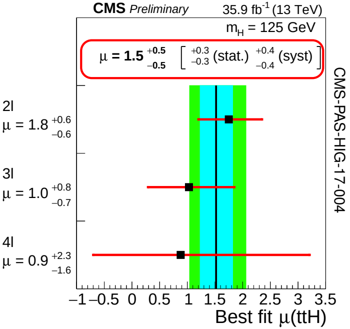
- ATLAS and CMS: **sensitivity enhanced using MVA methods**
  - e. g. 2*lSS*: two BDTs to separate $t\bar{t}H$ vs. $t\bar{t}$ and $t\bar{t}H$ vs. $t\bar{t}+V$

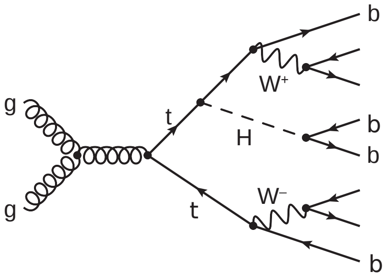


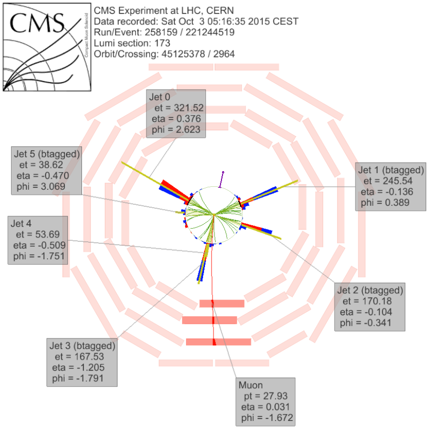


- $H \to$ multi-leptons channel: similar precision of $\Delta\mu = 0.5$
  - Results compatible with SM expectation
  - **Statistical and systematic uncertainty at same size**
  - Dominating: **signal & $t\bar{t}+V$ modelling (theory), non-prompt *l*, JEC**

$t\bar{t}H$, $H \to b\bar{b}$

- Largest H branching ratio: $\sigma \times \mathcal{B} \approx 0.3\,\text{pb}$





single-lepton-channel candidate event

CMS-PAS-HIG-16-004 (suppl. material)

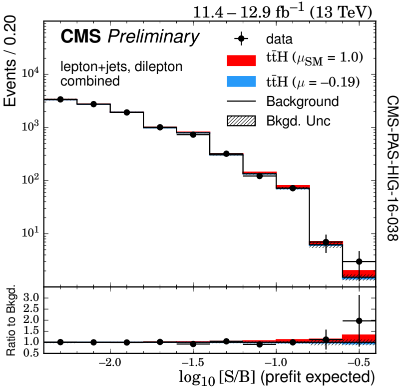
- Challenging final state
  - **Huge combinatorics** in event reconstruction
  - Large $t\bar{t} + b\bar{b}$ background $\mathcal{O}(10)$pb with associated **large theory uncertainties**

$t\bar{t}H$, $H \rightarrow b\bar{b}$: Strategy

- Selection of **semi- and dileptonic $t\bar{t}$** decays

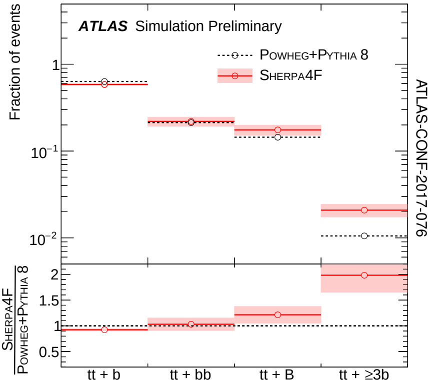
  All-hadronic final state analysed at 8 TeV, e. g. ATLAS J. High Energ. Phys. (2016) 160

- Events **categorised by number of jets and b-tagging information** (in some cases also boosted-object category)
  - First separation of signal and $t\bar{t} + X$ backgrounds
- Final discriminants exploiting **BDT and Matrix Element Method** (MEM)
  - Details differ, e. g. ATLAS using a reconstruction BDT, CMS using a 2D discriminant from BDT and MEM
- Simultaneous fit across all categories



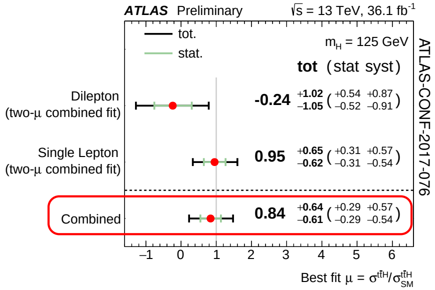
$t\bar{t}H$, $H \to b\bar{b}$: Background Modelling

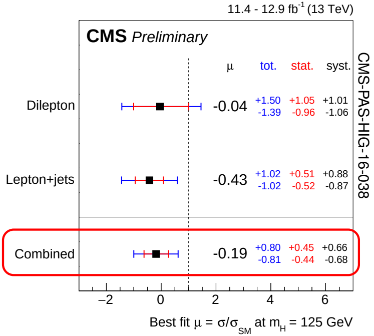
- $t\bar{t}$ + HF: **Powheg+Pythia8**, normalised to **NNLO+NNLL** prediction
- Approach by ATLAS
  - **$t\bar{t}+\geq 1$b** fractions corrected to **Sherpa+OpenLoops NLO 4-flavour-scheme** calculation
  - Normalisation of **$t\bar{t}+\geq 1$b/c freely floating** in final fit
  - Add. uncertainties include choice of generator, PDF, QCD scales, ISR/FSR



- Approach by CMS
  - Separate templates for $t\bar{t}+b$, $t\bar{t}+b\bar{b}$, $t\bar{t}+2b$, $t\bar{t}+c\bar{c}$, $t\bar{t}+$LF
  - **50% rate uncertainty per process**, uncorrelated in final fit
  - Add. uncertainties include PDF, QCD scales, ISR/FSR

$t\bar{t}H$, $H \to b\bar{b}$: Results





- $H \to b\bar{b}$ channel: precision of $\Delta\mu = 0.6$–0.8

  (results with equal luminosity: similar sensitivity of experiments)
  - Results compatible with SM expectation (CMS: 1.5 σ below SM)
  - **Systematic uncertainties dominate** (already at 13 fb^{-1})
  - Theory **$t\bar{t}$ + HF modelling uncertainty** dominates, other: b tagging, JEC
    - Also: limited MC sample size in background modelling

Status: $t\bar{t}$H LHC Run-II Results

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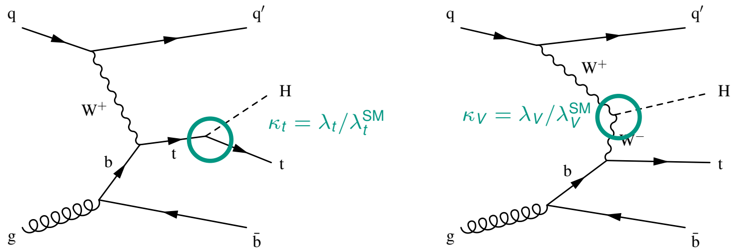
combination	$1.2^{+0.3}_{-0.3}$	(2017-077)		

- With 36 fb^{-1}: **evidence for $t\bar{t}$H production**
  - Combination: 4.2 σ obs., 3.8 σ exp. (ATLAS)
  - Multi-leptons obs.: 4.1 σ (ATLAS), 3.3 σ (CMS)
- Very **different uncertainties** depending on channel
  - Strongly statistics limited channels
  - Channels with large & theoretically difficult backgrounds

$\rightarrow$ **different strategies to gain from higher luminosities**

tH Production at the LHC

- **t-channel and tW-channel** production contribute (s channel negligible)
  - Dominating contributions depend on κ_t and κ_V

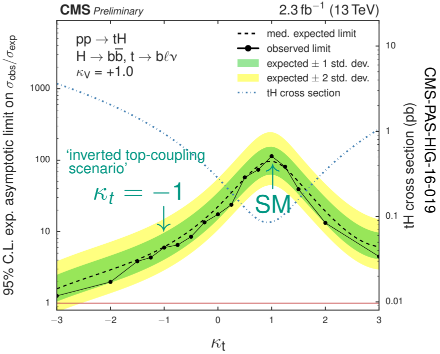


- Interference: $\boxed{\mathcal{A} \propto (\kappa_V - \kappa_t)} \rightarrow \sigma \propto \kappa_V^2 + \kappa_t^2 - 2\kappa_V\kappa_t$
- **Destructive interference** in SM $\rightarrow$ **small cross section** of $\approx$ 90 fb
  - But strong dependence on κ_t (also sign!)

tH production sensitive to magnitude and sign of top-Yukawa coupling

Searches for tH Production

- Dedicated tH searches in **H $\to$ b$\bar{\text{b}}$ and H $\to$ leptons final states**
  - Similar strategies and uncertainties as for t$\bar{\text{t}}$H
- E.g. CMS upper limits (obs.) on tH cross-section in H $\to$ b$\bar{\text{b}}$ channel
  - SM: 113.7 $\times\ \sigma_{\text{SM}}$
  - $\kappa_t = -1$: 6.0 $\times\ \sigma_{\text{ITC}}$
    - Not excluded by coupling measurements if BSM contributions allowed in loops
  - **Statistical uncertainties** dominate
  - Systematics: **JEC, QCD scales**

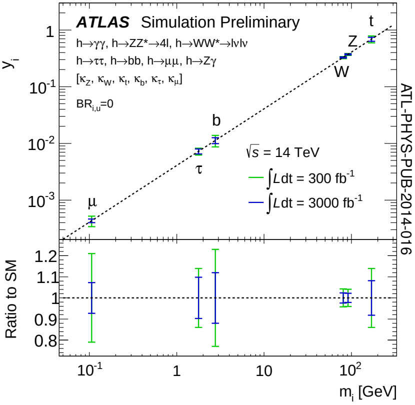


- Also: both tH and t$\bar{\text{t}}$H contributions considered in H $\to \gamma\gamma$

(ATLAS-CONF-2017-045, CMS-PAS-HIG-16-040)

Prospects at 300 and 3000 fb^{-1}

Indirect Constraints

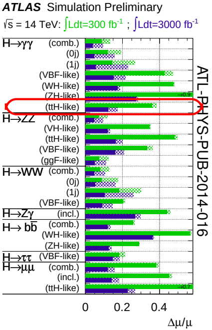


- Projected sensitivity of combined coupling measurement assuming a SM Higgs-boson

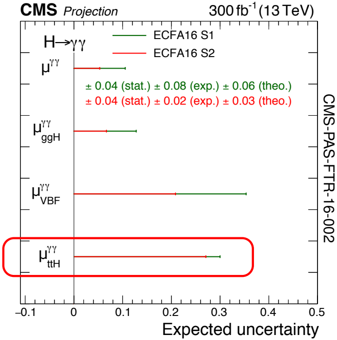
Relative uncertainty on λ_t of 14 % (300 fb^{-1}) and 8.2 % (3000 fb^{-1})

$t\bar{t}H(\gamma\gamma)$ at 300 fb^{-1}

projection by "smearing"



projection by "extrapolation"



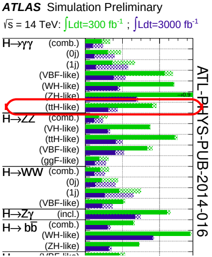
- Uncertainty on μ (Run-II with 36 fb^{-1}: $\mu = 0.5 \pm 0.6$)

ATLAS (14 TeV)	0.38 (all unc.)	0.36 (no theory unc.)
CMS (13 TeV)	0.30 ($\approx$ Run-II unc.)	0.27 ($\frac{1}{2}$ theory, $\frac{1}{\sqrt{L}}$ exp. unc.)

@300 fb^{-1}: $t\bar{t}H(\gamma\gamma)$ entirely dominated by statistical uncertainty

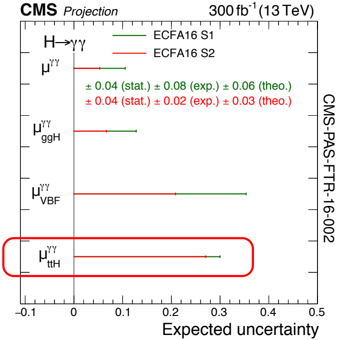
$t\bar{t}H(\gamma\gamma)$ at 300 fb^{-1}

projection by “smearing”



Based on Run-I analysis:
sign. reduction of theory unc.
$\approx$ 0.1 (Run I) $\rightarrow \approx$ 0.06 (Run II)

projection by “extrapolation”



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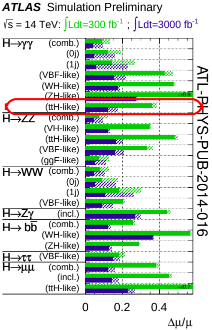
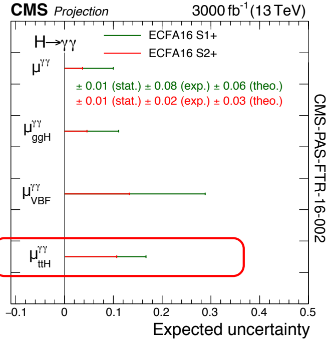
@300 fb^{-1}: $t\bar{t}H(\gamma\gamma)$ entirely dominated by statistical uncertainty

$t\bar{t}H(\gamma\gamma)$ at $3000\,fb^{-1}$

projection by “smearing”



projection by “extrapolation”



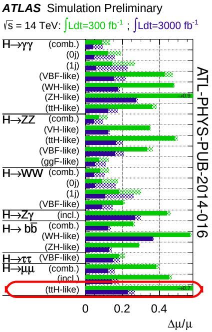
- Uncertainty on μ (Run-II with $36\,fb^{-1}$: $\mu = 0.5 \pm 0.6$)

ATLAS (14 TeV)	0.17 (all unc.)	0.12 (no theory unc.)
CMS (13 TeV)	0.17 (HL-LHC unc.)	0.11 ($\frac{1}{2}$ theory, $\frac{1}{\sqrt{L}}$ exp. unc.)

@$3000\,fb^{-1}$: theory uncertainties play a role

$t\bar{t}$H($\mu\mu$)

projection by “smearing”

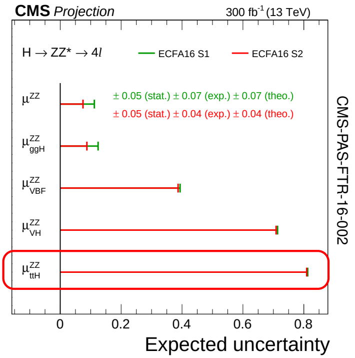


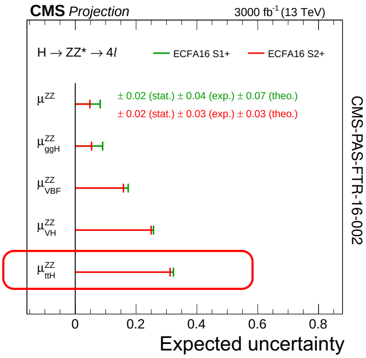
- Uncertainty on μ (ATLAS)

300 fb^{-1}	0.74 (all unc.)	0.72 (no theory unc.)
3000 fb^{-1}	0.27 (all unc.)	0.23 (no theory unc.)

Some sensitivity (30% level) @3000 fb^{-1}, dominated by stat. uncertainty

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





- Uncertainty on μ (CMS)

$300\,\text{fb}^{-1}$	0.81 ($\approx$ Run-II unc.)	0.81 ($\frac{1}{2}$ theory, $\frac{1}{\sqrt{L}}$ exp. unc.)
$3000\,\text{fb}^{-1}$	0.32 (HL-LHC unc.)	0.31 ($\frac{1}{2}$ theory, $\frac{1}{\sqrt{L}}$ exp. unc.)

Entirely dominated by statistical uncertainty even at @$3000\,\text{fb}^{-1}$

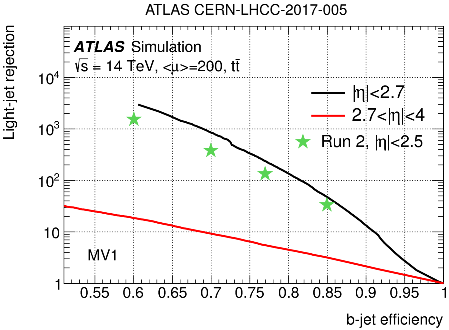
Thoughts on Further Studies

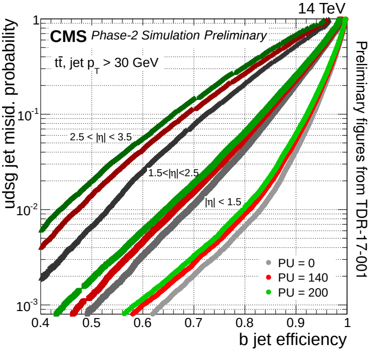
What to Study?

Dedicated projections for other $t\bar{t}H$ channels and for tH production:
what to expect with more data? (personal list of questions)

- Implications on **scope of measurements**?
  - Ultimate precision of inclusive $t\bar{t}H$ cross-section measurements in different channels and combination
  - Prospects for differential $t\bar{t}H$ measurements
  - Prospects for dedicated tH cross-section measurements
- Implications on **systematic uncertainties**?
  - Impact of reduced statistical component in systematic uncertainties, in particular: b-tagging, non-prompt / contributions, JEC
  - Do additional theory modelling uncertainties become important?
- Implications on **experimental techniques and constraints**?
  - Limitations by trigger constraints?
  - Limitations by realistic size of MC samples?
  - Gain by boosted-object reconstruction?

Example: b-Tagging





- Similar b-tagging performance expected between ATLAS and CMS
  - Dependence on PU scenario
- Expect any **change in b-tagging performance to significantly impact $t\bar{t}H(b\bar{b})$** measurement
  - Impact in **other channels**?
- Can uncertainties be reduced by **larger control-sample size**?

Theory Uncertainties

- $t\bar{t}H(b\bar{b})$, $t\bar{t}H$(multi-leptons): **background modelled using simulation**
- Modelling uncertainties (among) dominant: **direct impact on ultimate precision**
  - Single **largest impact: $\mathbf{t\bar{t} + b\bar{b}}$ cross-section uncertainty** limits $t\bar{t}H(b\bar{b})$
  - $t\bar{t} + V$ cross-section uncertainty impacts $t\bar{t}H$(multi-leptons)
- Prospects for improvements?
  - What can be expected from **control regions and dedicated separate measurements?**
- Related: **practical aspects of MC sample size**
  - Can $t\bar{t} + X$ phase-space be efficiently enhanced?
  - In particular relevant for MVA-based methods: require additional training samples
  - Can systematic variations be incorporated via event weights?

Summary & Conclusions

- $t\bar{t}$H and tH production: **direct access to top-Higgs Yukawa coupling**
  - Challenging final states with many objects and different uncertainties
  - Status: evidence for $t\bar{t}$H production
- The hunt is still at the beginning: **rich and exciting programme ahead**
- Increase in luminosity will directly help in some channels
  - Precision channels H $\to \gamma\gamma$ and H $\to$ ZZ* $\to 4l$: $\lesssim$ **10% feasible** ($\gamma\gamma$) (to some extent H $\to$ multi-leptons)
  - Other channels: **improvement of experimental uncertainties?**
- Most required inputs from theory side
  - **Reduction of $t\bar{t} + b\bar{b}$ uncertainty?** (dominating uncertainty H $\to b\bar{b}$)
  - Reduction of $t\bar{t}$ + V uncertainty?
- **Further dedicated projections for tH and $t\bar{t}$H analyses required to better understand gain and limitations**