Higgs boson production via ttH

ATLAS and CMS results

Judith Katzy on behalf of the ATLAS and CMS collaborations

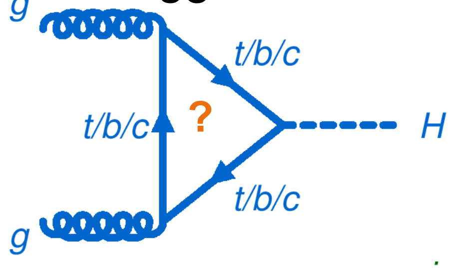
Motivation

top-Higgs coupling largest in SM

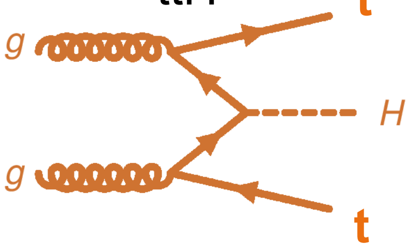
$y_t \sim m_t / v$

$\sigma_{ttH} \sim |y_t|^2$

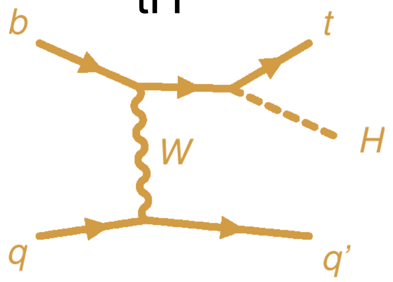
ggF



ttH



tH



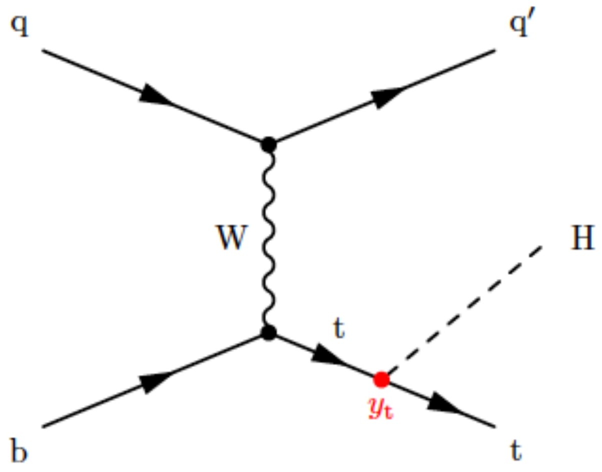
pp@13 TeV

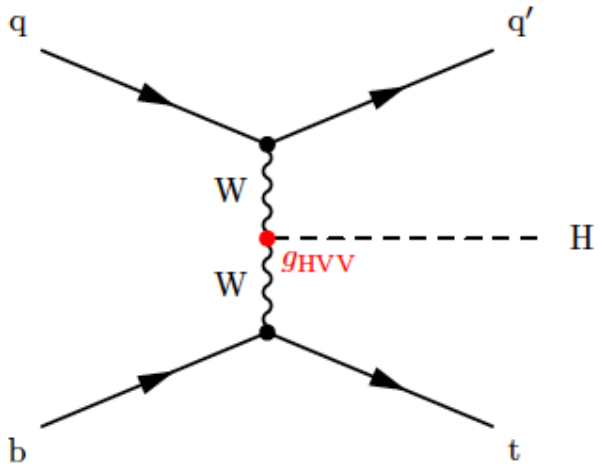
SM ($y_t \sim 1$): 44 pb | 507 fb | 74 fb

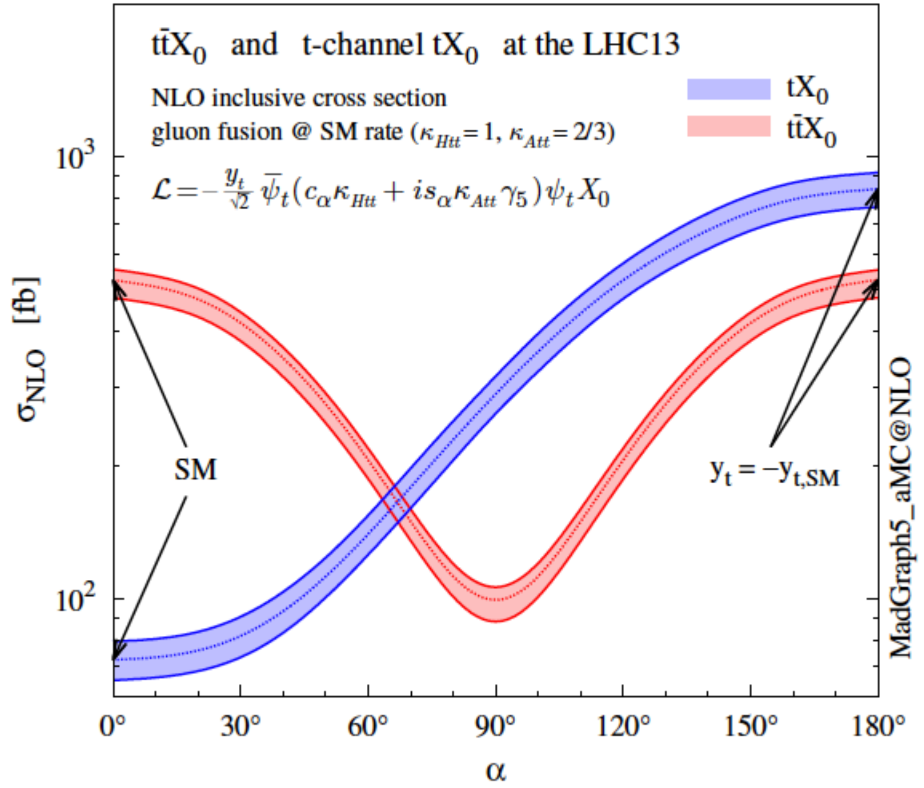
ttH+tH: direct probe of top-Higgs coupling

Motivation

Sign of y_t & CP structure of fermionic Higgs couplings







t-channel tHq production
SM: $y_t \sim$ 1, destructive interference: $\sigma_{tH} \sim$ 74 pb
BSM: $y_t \sim$ -1, constructive interference $\sigma_{tH} \sim$850 pb

CP properties talk by Ahmed

tH sensitive to sign of y_t

Motivation

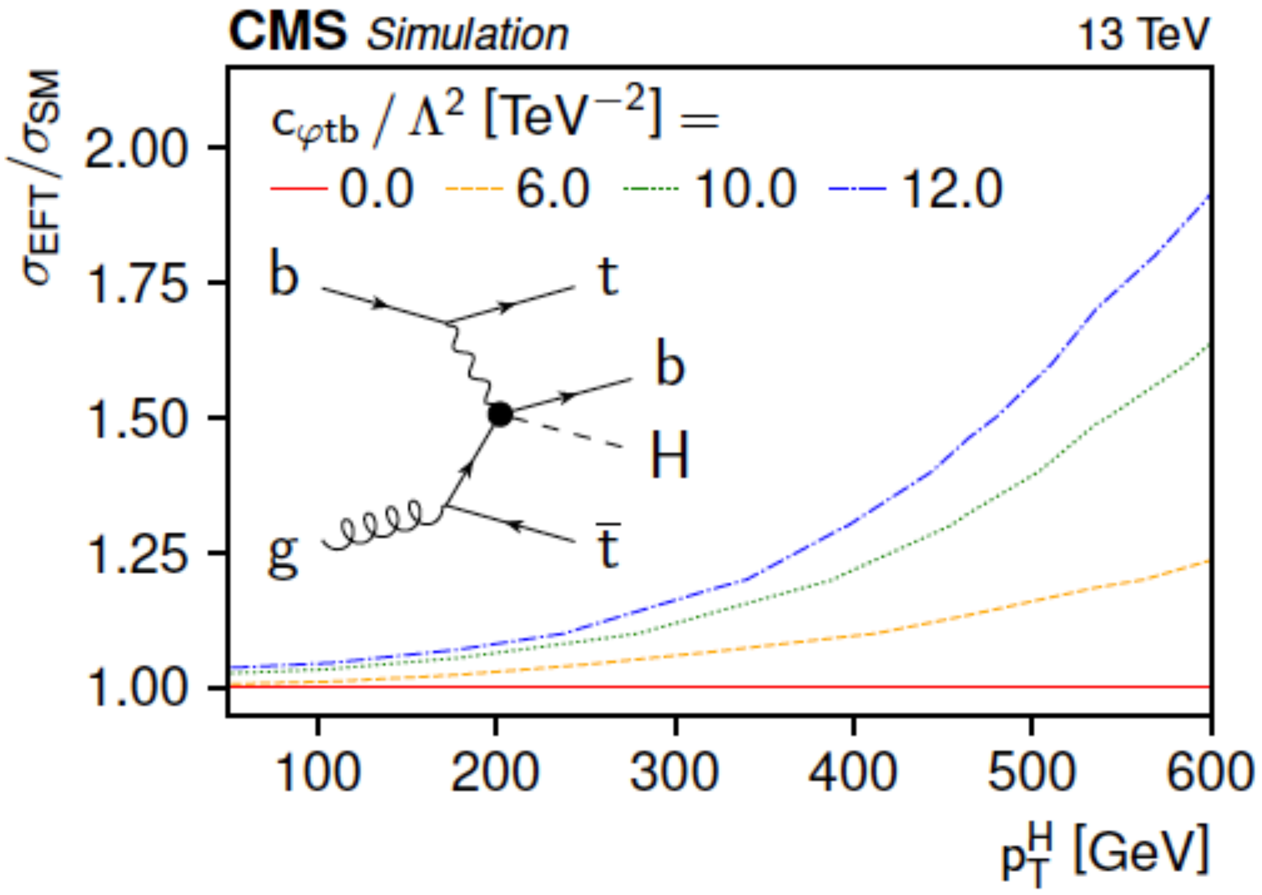
Unique opportunities to probe Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,\text{i}} \frac{c_{\text{i}}^{(d)}}{\Lambda^{d-4}} \mathcal{O}_{\text{i}}^{(d)}$$

Study dimension six operators affecting ttH and tH production

Probe Wilson coefficients in ttH production as a function of Higgs pT

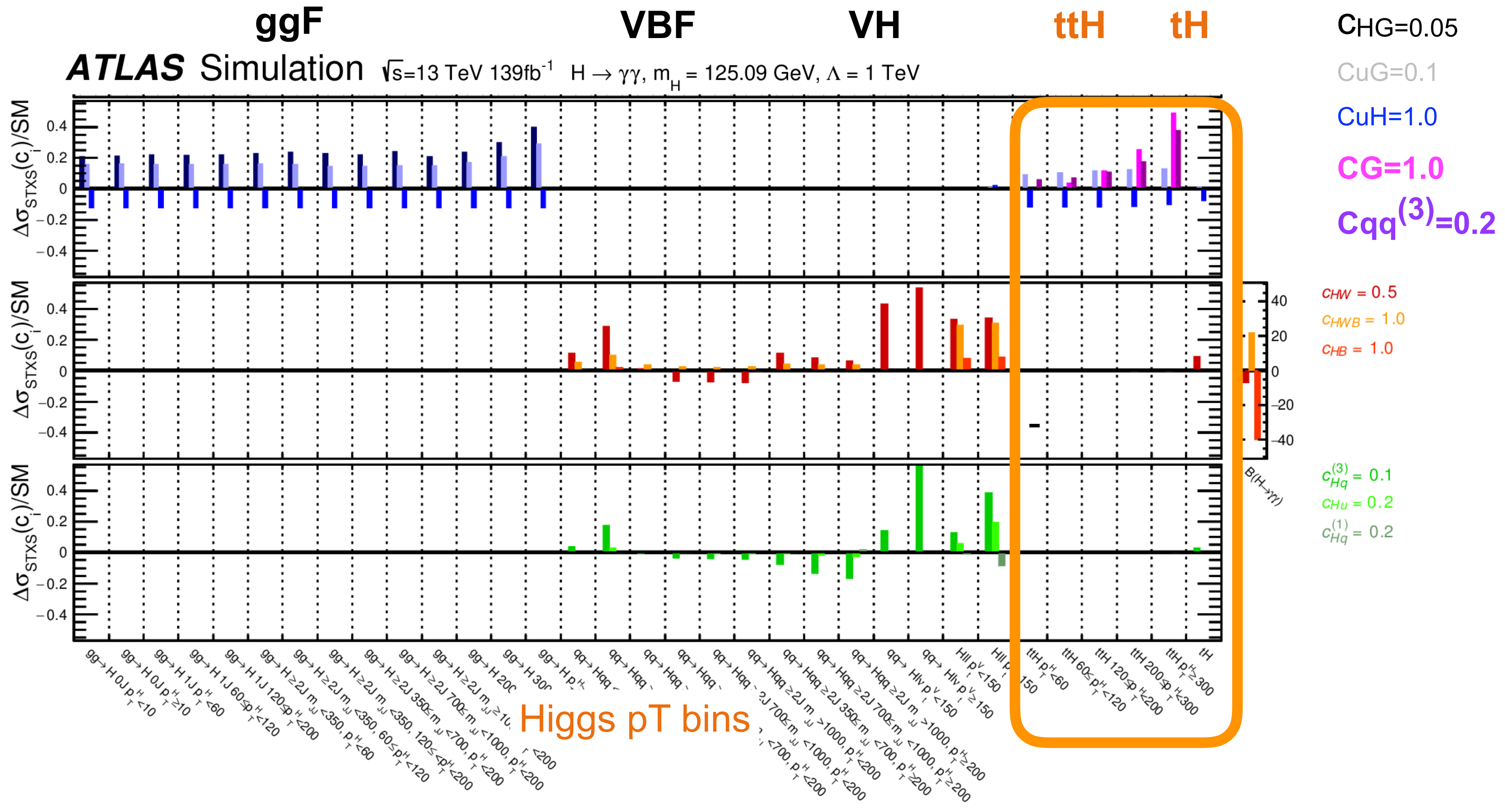
Use STXS bins in Higgs pT



EFT talk by Giacinto

Motivation

Unique opportunities to probe Effective Field Theory



Unique sensitivity to some operators

Measurements

Rare process in different Higgs decay modes

σ_{ttH} ~ 530 fb
σ_{tH} ~ 74 fb

$$N_{events} = L \cdot \sigma_{ttH} \cdot \mathcal{B}(H) \cdot \mathcal{B}(ttbar) \cdot \varepsilon \cdot A$$

Higgs decay mode	B. ratio
H->bb	58.1 %
H->WW	21.5 %
H->$\tau\tau$	6.3 %
H->ZZ -> qq, ll	
H->$\gamma\gamma$	0.23 %
H->ZZ ->4 leptons (e,μ)	0.0124 %

"ML" (H->WW, H->$\tau\tau$, H->ZZ -> qq, ll)

ttbar decay mode	B.Ratio
Di-lepton (e,μ)	4%
Single lepton (e,μ) + jets	30%
All jets	44%

Measurements

ATLAS and CMS ttH and tH measurements at 13 TeV

	H->bb	H->WW, $\tau\tau$, ZZ	H->$\gamma\gamma$	HZZ->4l
ATLAS	Full Run2 σ_{ttH} pT(H)	80 ifb σ_{ttH} Full Run2 σ_{ttH} 0l H->$\tau_{had}\tau_{had}$	Full Run2 σ_{ttH} σ_{tH} $p_T(H)$	Full Run2 σ_{ttH}
CMS	36 ifb σ_{ttH} Full Run 2 boosted σ_{ttH}, $p_T(H)$ >200 GeV	Full Run2 σ_{ttH} σ_{tH}	Full Run2 σ_{ttH} σ_{tH} $p_T(H)$	Full Run2 σ_{ttH}

$\mu = \sigma_{meas}/\sigma_{SM}$

ttH H->bb

Measurement advantages and challenges

H->bb has largest branching ratio (58%)

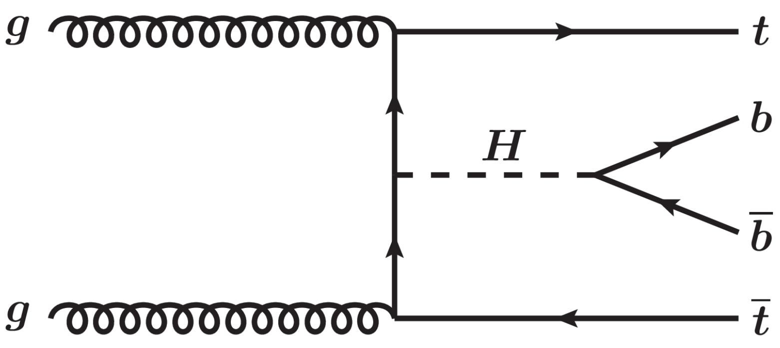
Due to large combinatorics of 4 b-jets no Higgs mass peak

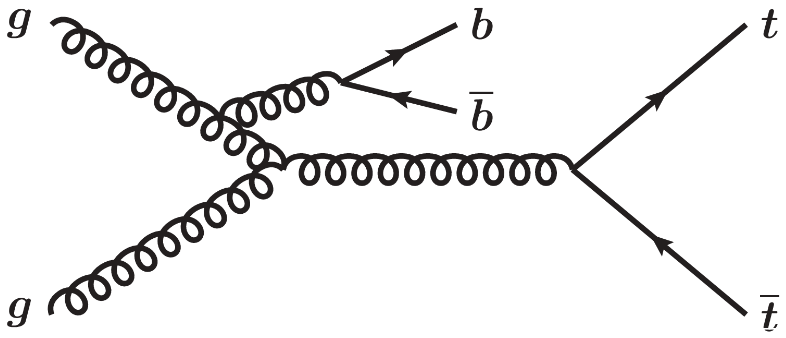
Use leptonic top decays to avoid QCD multi-jet background
- Fully hadronic top decays have been tried but yield poor resolution

Typically signal / background below 10% even in most sensitive signal regions

Large irreducible background ttbb
- Various codes of ttbb@NLO 4FS calculations matched to PS available and used by recent analyses in ATLAS and CMS for tt + ≥1b
- Different philosophy of estimating modelling uncertainties in ATLAS and CMS

See talk by Ana Cueto Gomez on background modelling



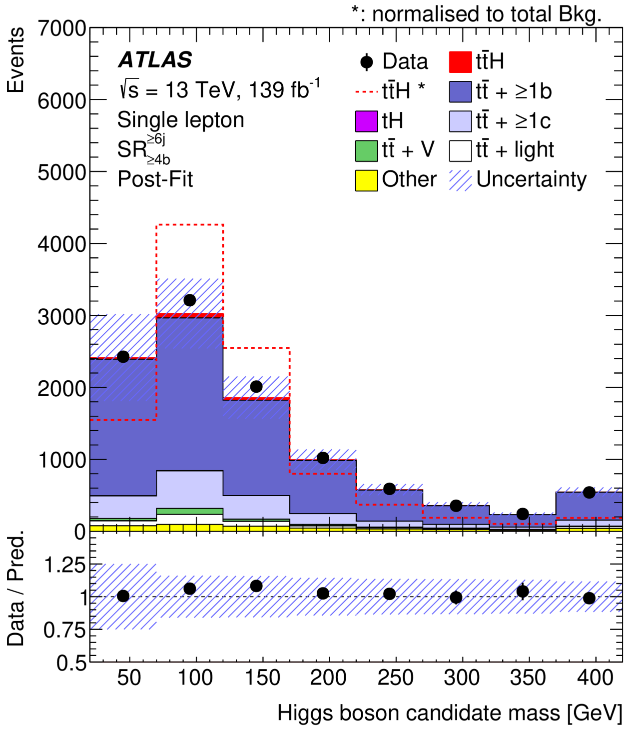


ttH H->bb

ATLAS full Run-2 analysis 139 fb^{-1}

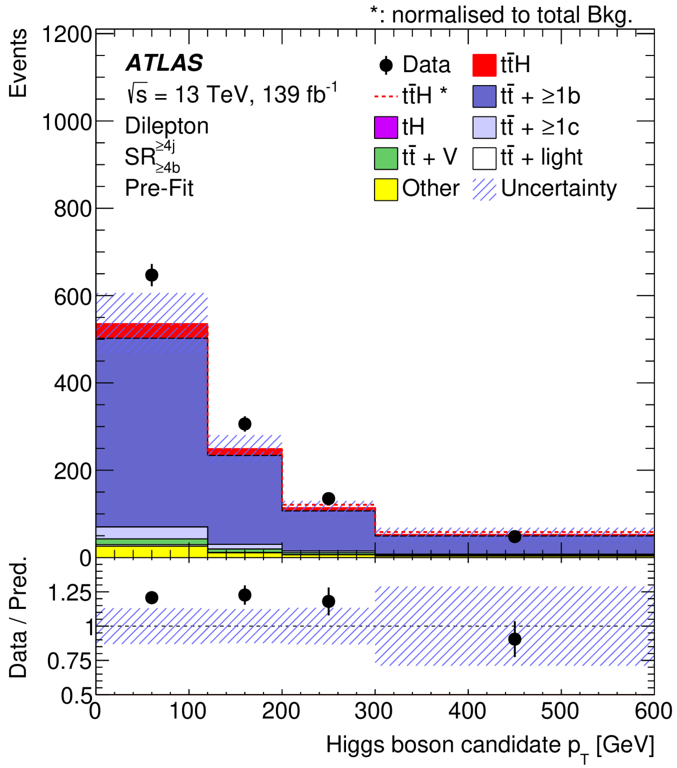
Strategy: Measure in pure phase space to minimise problems with modelling of various tt+jets backgrounds:

- Require ≥ 1 lepton, light jets and 4 well identified b-jets in the signal region
- Measure in resolved and boosted channel



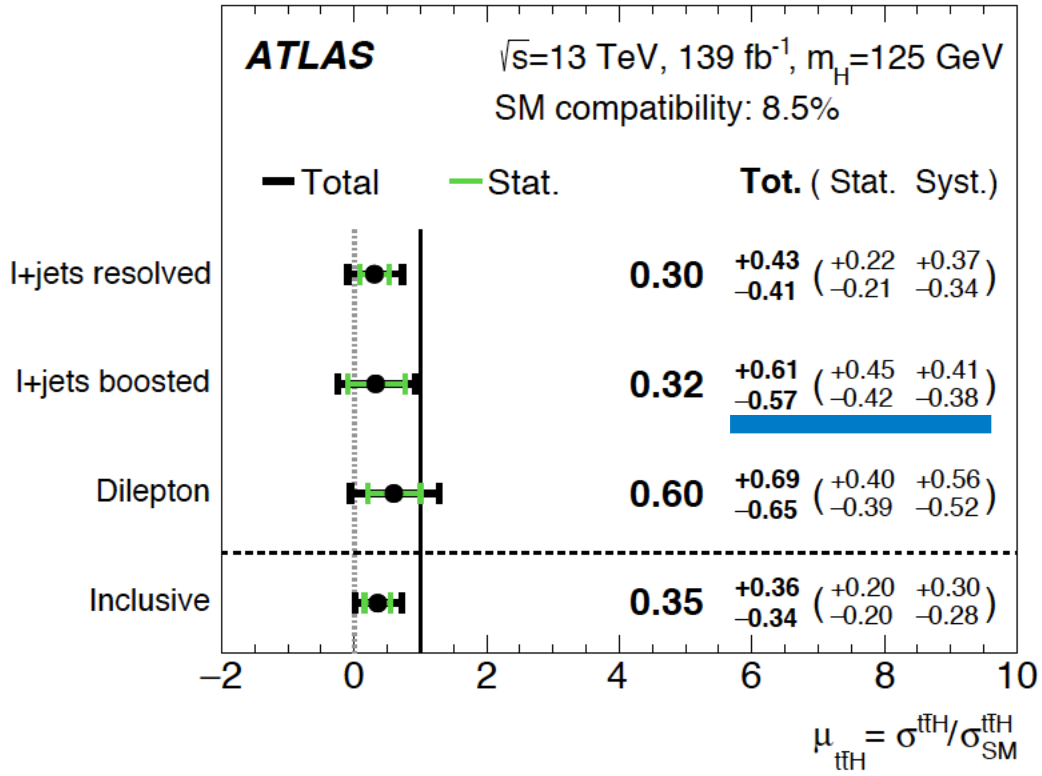
Analysis chain:

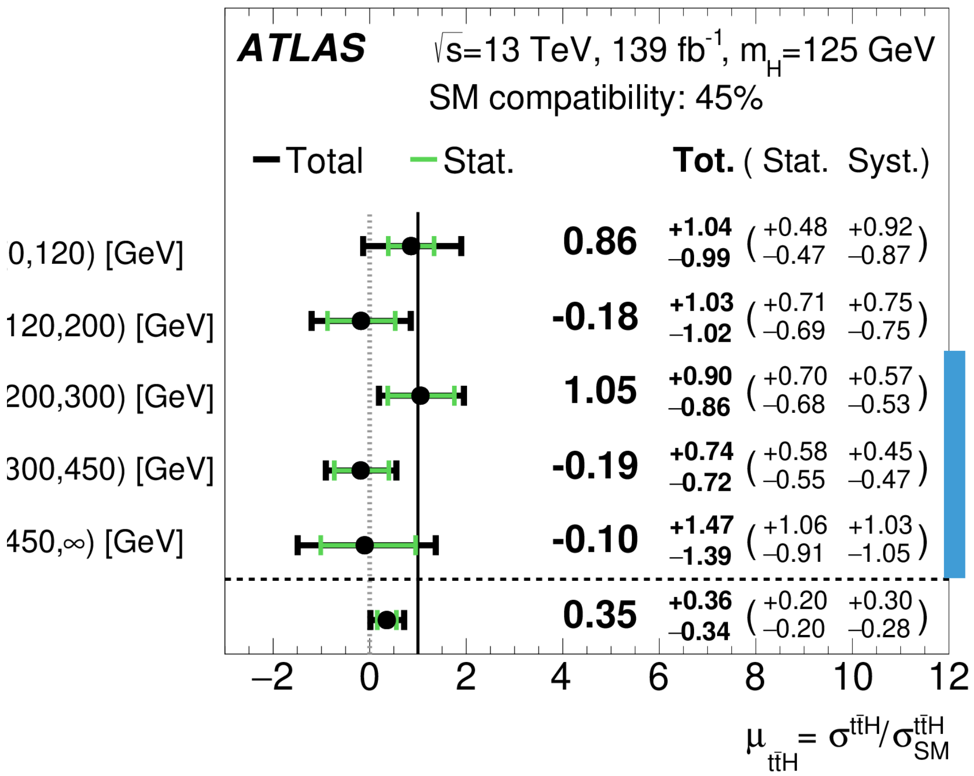
- Reconstructed Higgs candidate and split into p_T H
- Separate signal vs background with MVA based on Higgs candidate and event properties
- Perform Maximum Likelihood fit to signal and control regions to extract μ_{ttH}



ttH H->bb

ATLAS full Run2



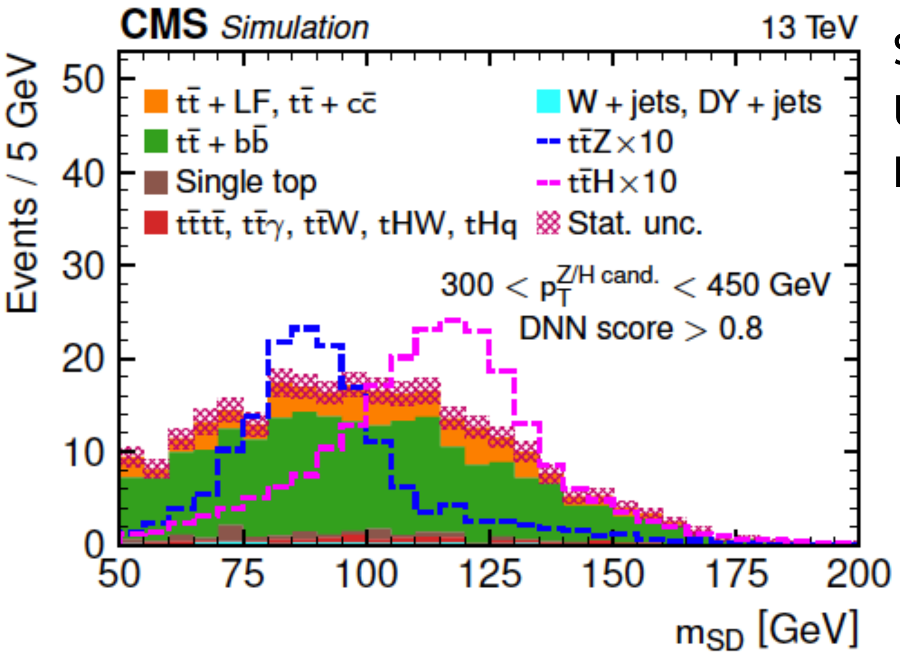


Inclusive μ_{ttH} systematics limited; μ_{ttH} @ high Higgs pT stats limited

Dominant Uncertainty: Modelling of ttbb background

ttH H->bb, boosted Higgs

Probe μ_{ttH} at high pT and probe EFT



Single lepton+2 resolved b-jets, boosted object with pT>200 GeV containing bb

Use ttbb@NLO 4FS as background MC for ttbb

Higgs pT bins [200,300][300,450][450,∞[

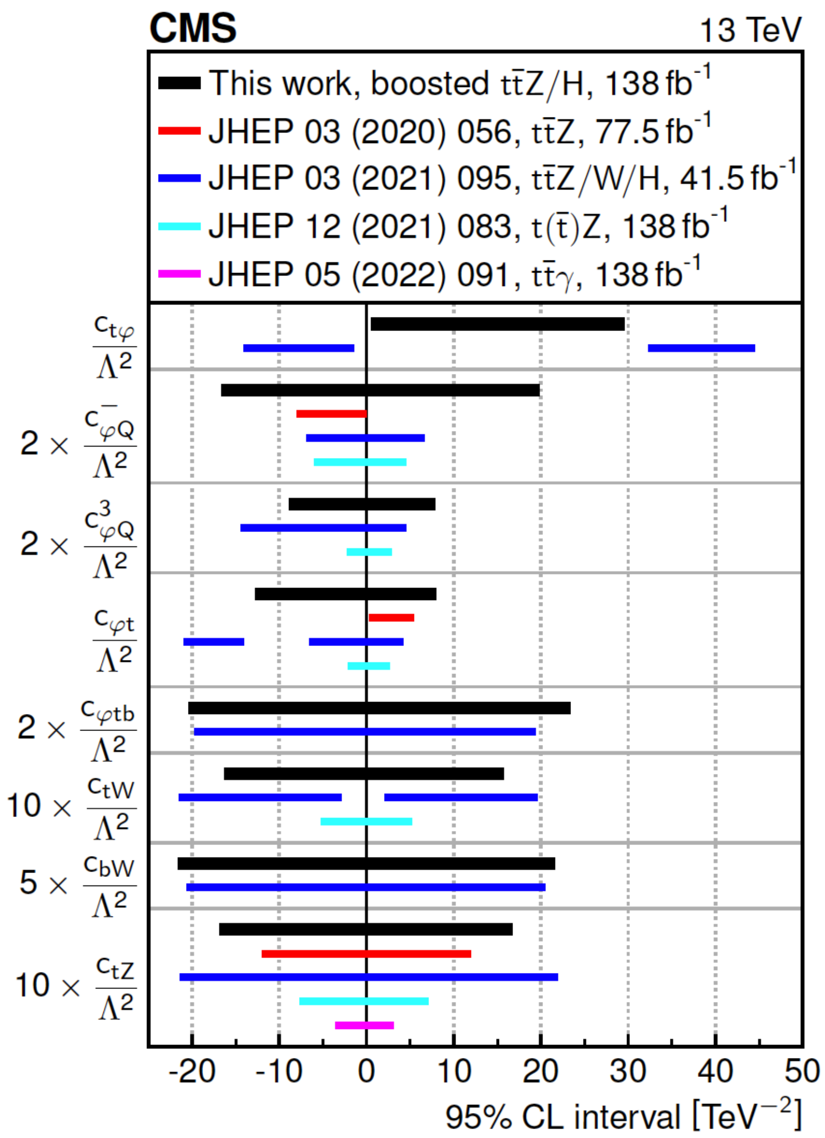
μ_{ttH} for pT(Higgs) > 200 GeV

Signal strength	Observed	Stat.	MC stat.	Exp. syst.	Theo. syst.	Expected
$\mu_{t\bar{t}Z}$	$0.65^{+1.04}_{-0.98}$	$^{+0.80}_{-0.75}$	$^{+0.36}_{-0.38}$	$^{+0.38}_{-0.31}$	$^{+0.43}_{-0.38}$	$1.00^{+0.91}_{-0.84}$
$\mu_{t\bar{t}H}$	$-0.27^{+0.86}_{-0.83}$	$^{+0.72}_{-0.65}$	$^{+0.31}_{-0.33}$	$^{+0.19}_{-0.19}$	$^{+0.28}_{-0.35}$	$1.00^{+0.79}_{-0.72}$

Source of uncertainty	$\Delta\mu_{t\bar{t}Z}$	$\Delta\mu_{t\bar{t}H}$
$t\bar{t}+c\bar{c}$ cross section	$^{+0.27}_{-0.23}$	$^{+0.14}_{-0.13}$
$t\bar{t}+b\bar{b}$ cross section	$^{+0.18}_{-0.24}$	$^{+0.16}_{-0.22}$
$t\bar{t}+2b$ cross section	$^{+0.03}_{-0.03}$	±0.09
μ_R and μ_F scales	$^{+0.12}_{-0.14}$	$^{+0.11}_{-0.15}$
Parton shower	$^{+0.16}_{-0.17}$	$^{+0.07}_{-0.06}$
b tagging efficiency	$^{+0.25}_{-0.13}$	±0.10
$b\bar{b}$ tagging efficiency	$^{+0.18}_{-0.13}$	$^{+0.07}_{-0.04}$
Jet energy scale and resolution	±0.11	$^{+0.11}_{-0.12}$
Jet mass scale and resolution	±0.10	±0.08

ttH H->bb, boosted Higgs

Probe μ_{ttH} at high Higgs pT and Wilson Coefficients



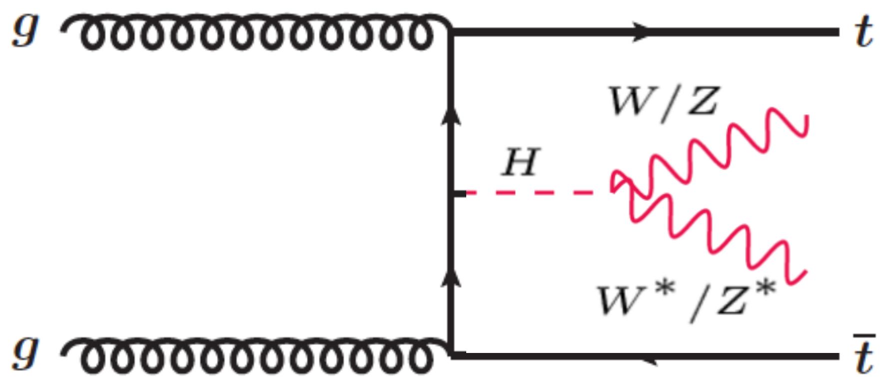
Observed confidence intervals constrained by ttH

ttH + tH in ML

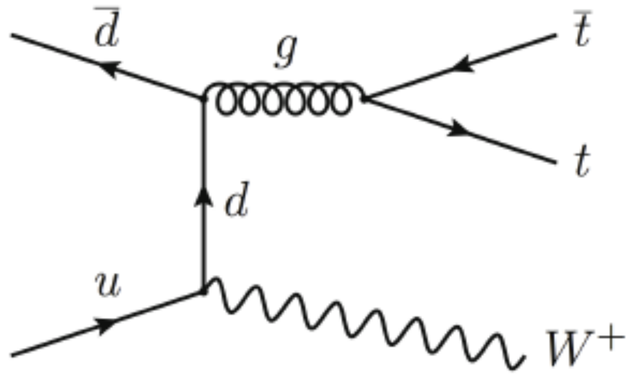
ATLAS + CMS

Various analysis channels depending on #leptons (e,μ) and relative sign, #hadronic τ

ttH: 10 channels
Most sensitive:
2l SS 0τ
3l 0τ
2l 2τ



tH: 3 channels
2lSS+0τ, 2lSS+1τ, 3l



Key issues:
Large irreducible ttW background
- Large uncertainties in NLO predictions
- Different philosophy of estimating modelling uncertainties in ATLAS and CMS

Leptonic backgrounds of various sources

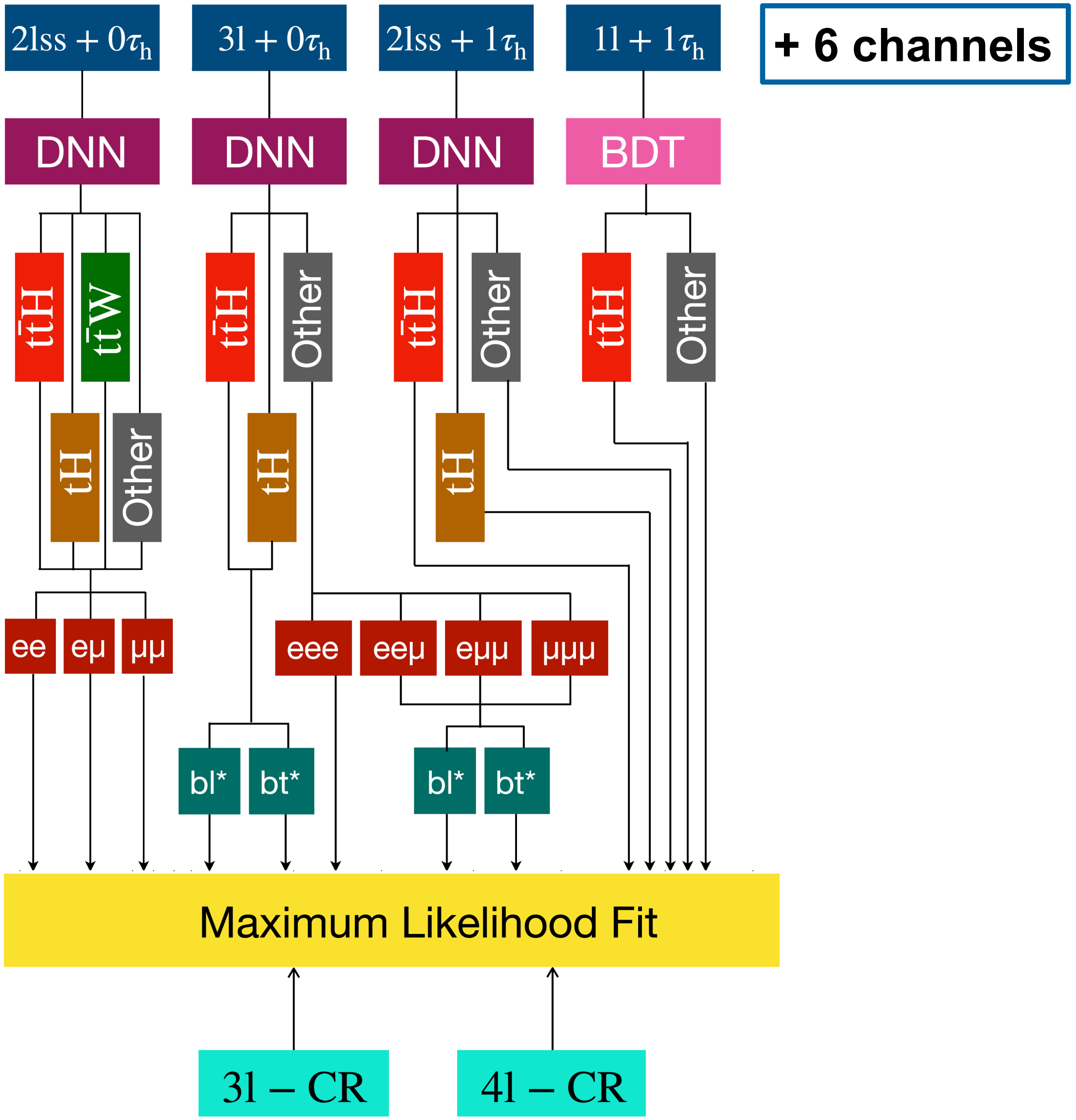
ttH+tH in ML

CMS full Run2 137 fb^{-1}

S/B for ttH up to 35% tH up to 3.3%

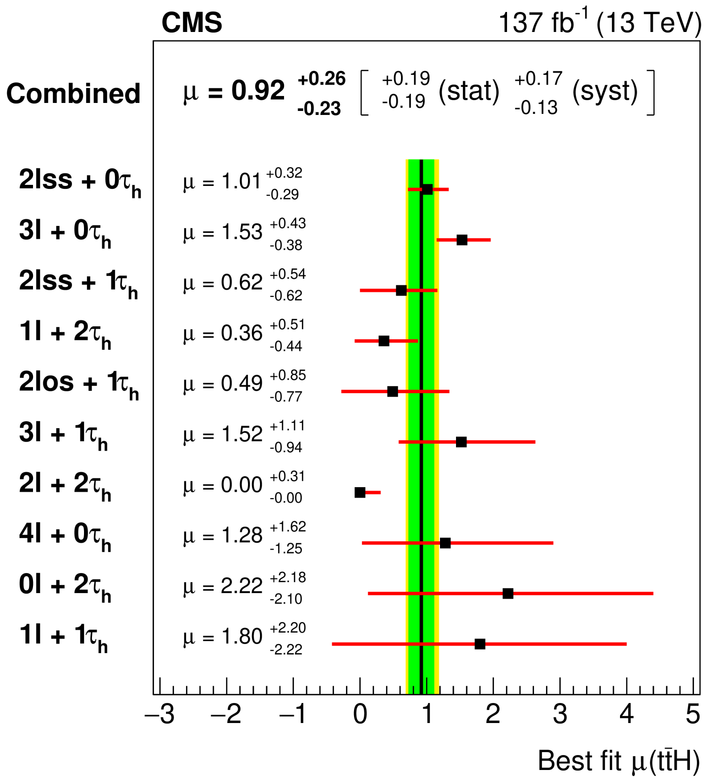
Separate regions for ttH, tH, ttW, other backgrounds, CR (ttZ,ZZ,WZ)

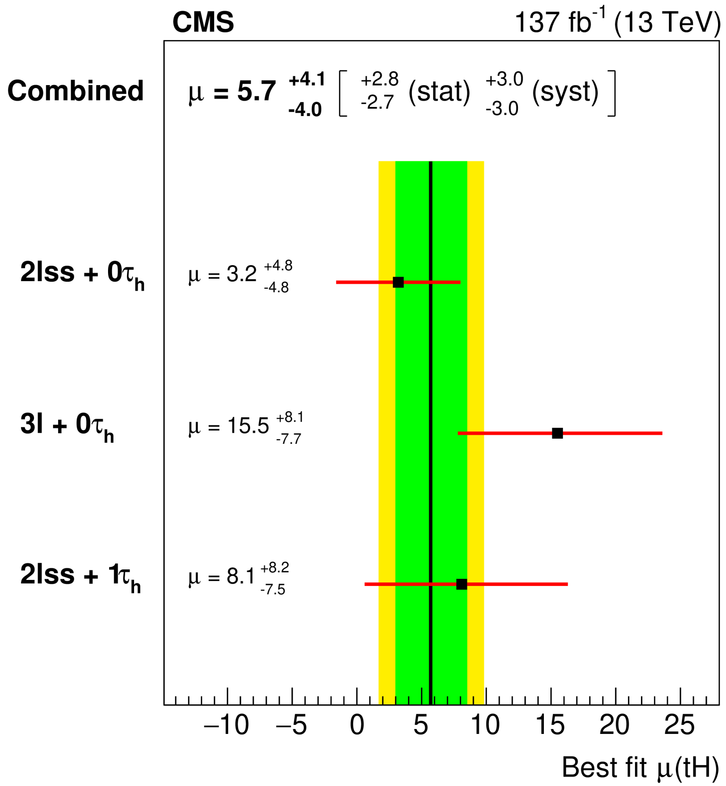
Maximum likelihood Fit:
Extract **ttH** and **tH**
and normalisation of ttW and ttZ

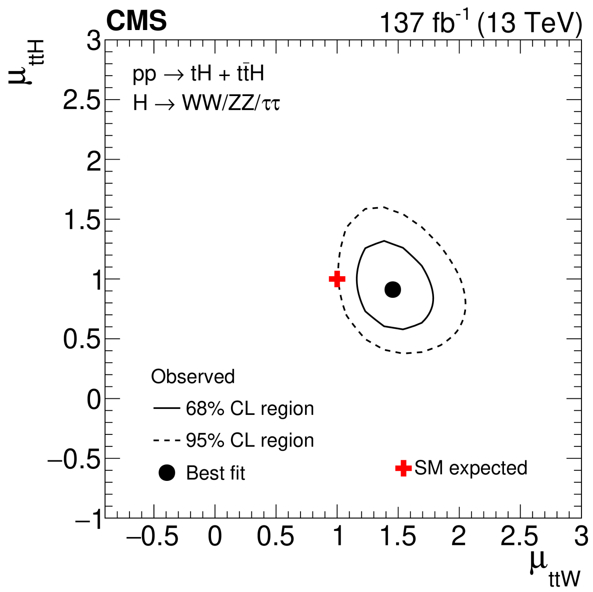


ttH+tH in ML

CMS full Run2 137 fb^{-1} - ttH and tH cross section assuming SM kinematics







μ_{ttH}=0.92 ±0.19(stat)$^{+0.17}_{-0.13}$(syst)

μ_{tH}= 5.7 ± 2.7(stat) ± 3.0(syst)

$\mu_{ttW} \sim 1.5\ \mu_{SM}$

Dominant systematic uncertainty:
normalisation of MC estimated processes

Dominant systematic uncertainty:
Misidentified leptons + flips

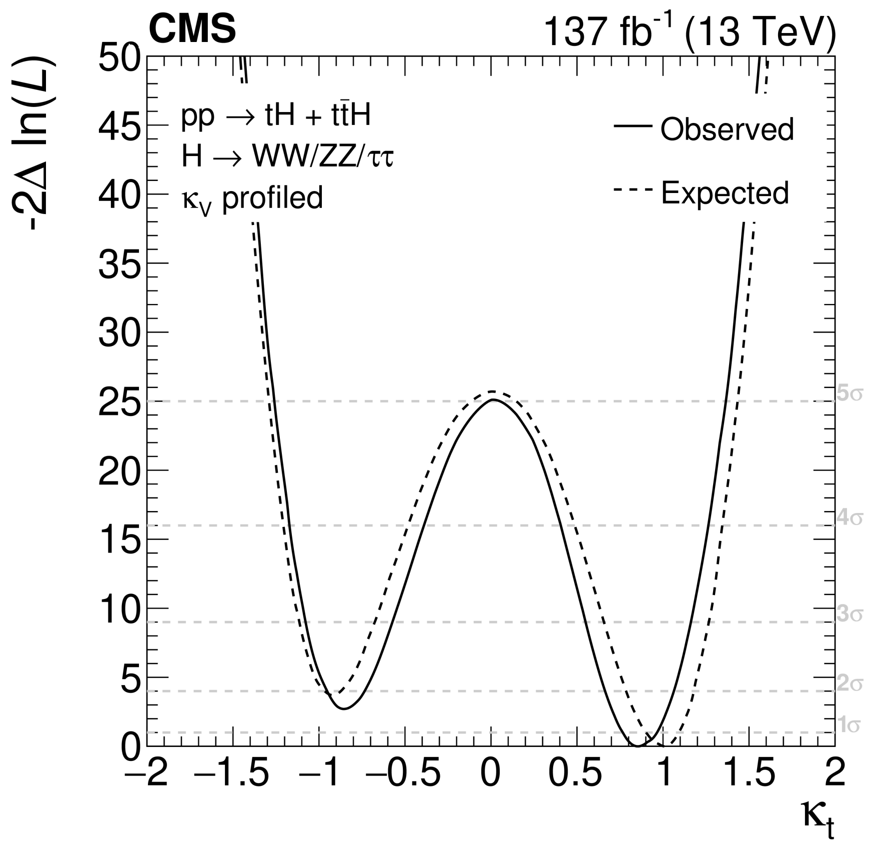
ttH+tH in ML

Extract y_t without SM assumptions

Take interference effects in tHq on kinematic observables into account

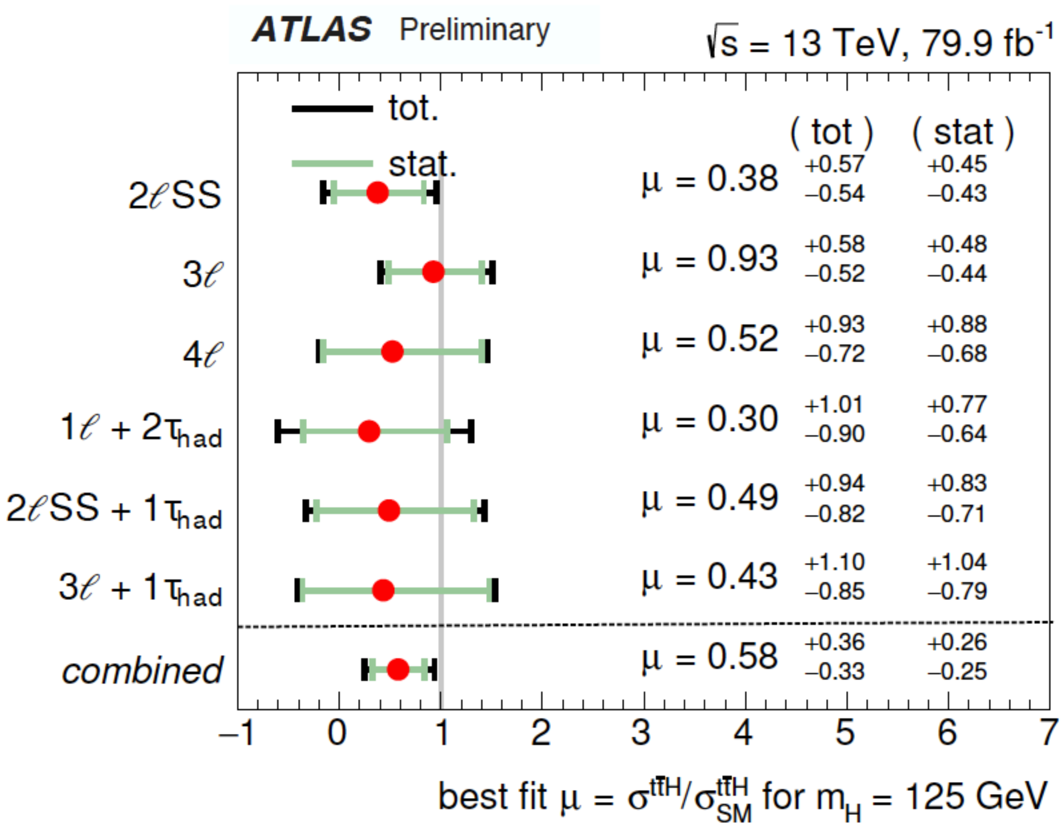
extract $\kappa_t = y_t(\text{meas}) / y_t(\text{SM})$

-0.7 < κ_t < -0.9 or 0.7 < κ_t < 1.1 at 95% CL



ttH in ML

ATLAS preliminary 80 fb^{-1}

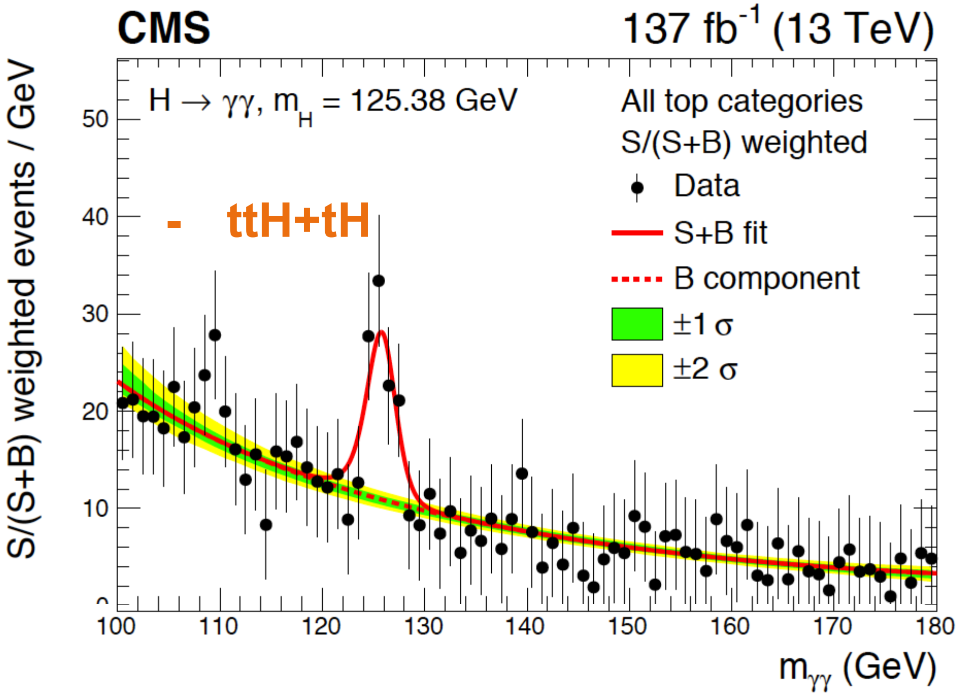


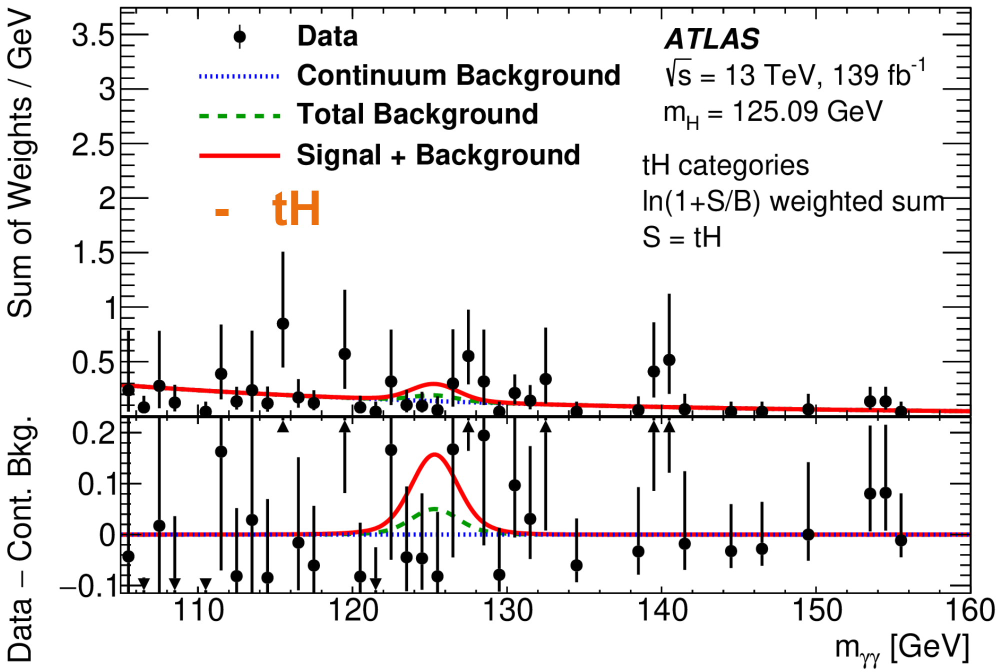
$$\hat{\lambda}_{t\bar{t}W}^{2\ell\mathrm{LJ}} = 1.56^{+0.30}_{-0.28},\ \hat{\lambda}_{t\bar{t}W}^{2\ell\mathrm{HJ}} = 1.26^{+0.19}_{-0.18},\ \text{and}\ \hat{\lambda}_{t\bar{t}W}^{3\ell} = 1.68^{+0.30}_{-0.28}$$

ttH H->$\gamma\gamma$

ATLAS+CMS full Run2: inclusive ttH + tH cross sections

Talk by Pascal





CMS

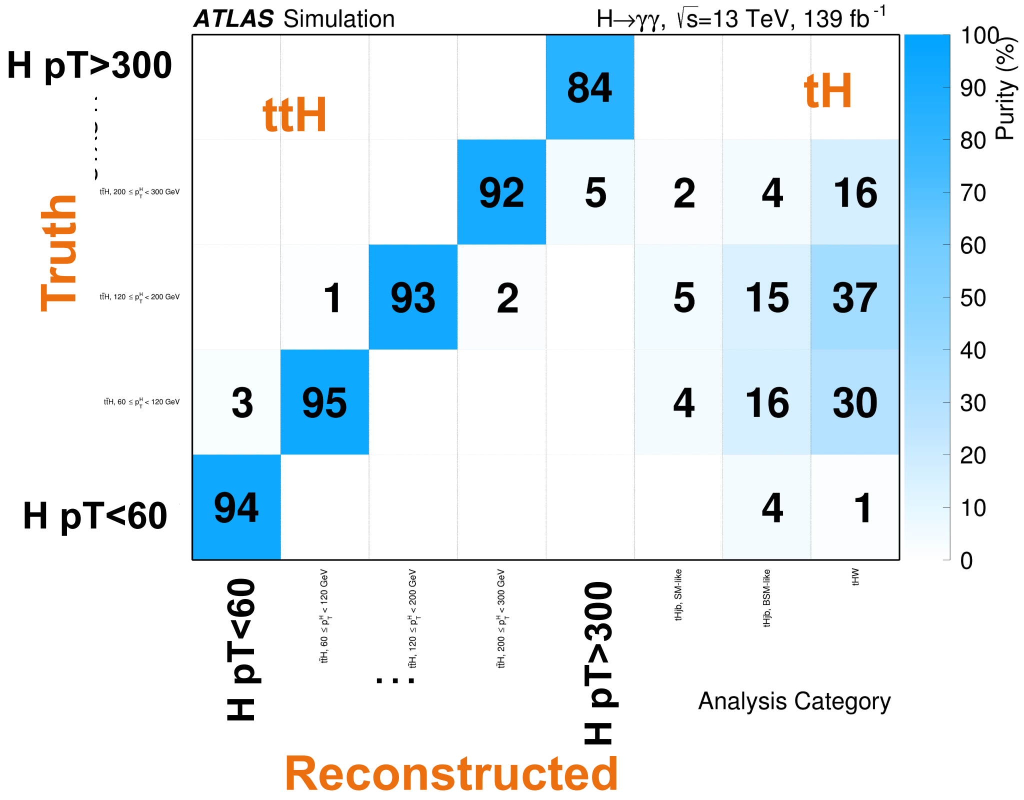
		Th.	Exp.	Stat.
μ_{ttH+tH}	$1.35^{+0.34}_{-0.28}$	$^{+0.17}_{-0.10}$	$^{+0.08}_{-0.05}$	$^{+0.28}_{-0.25}$

ATLAS

		Tot.	Stat.	Syst.
μ_{ttH}	0.89	$^{+0.32}_{-0.30}$	($^{+0.31}_{-0.29}$	$^{+0.08}_{-0.05}$)
μ_{tH}	3	$^{+4}_{-3}$	($^{+4}_{-3}$	$^{+1}_{-1}$)

ttH H->$\gamma\gamma$

ATLAS and CMS differential in Higgs pT

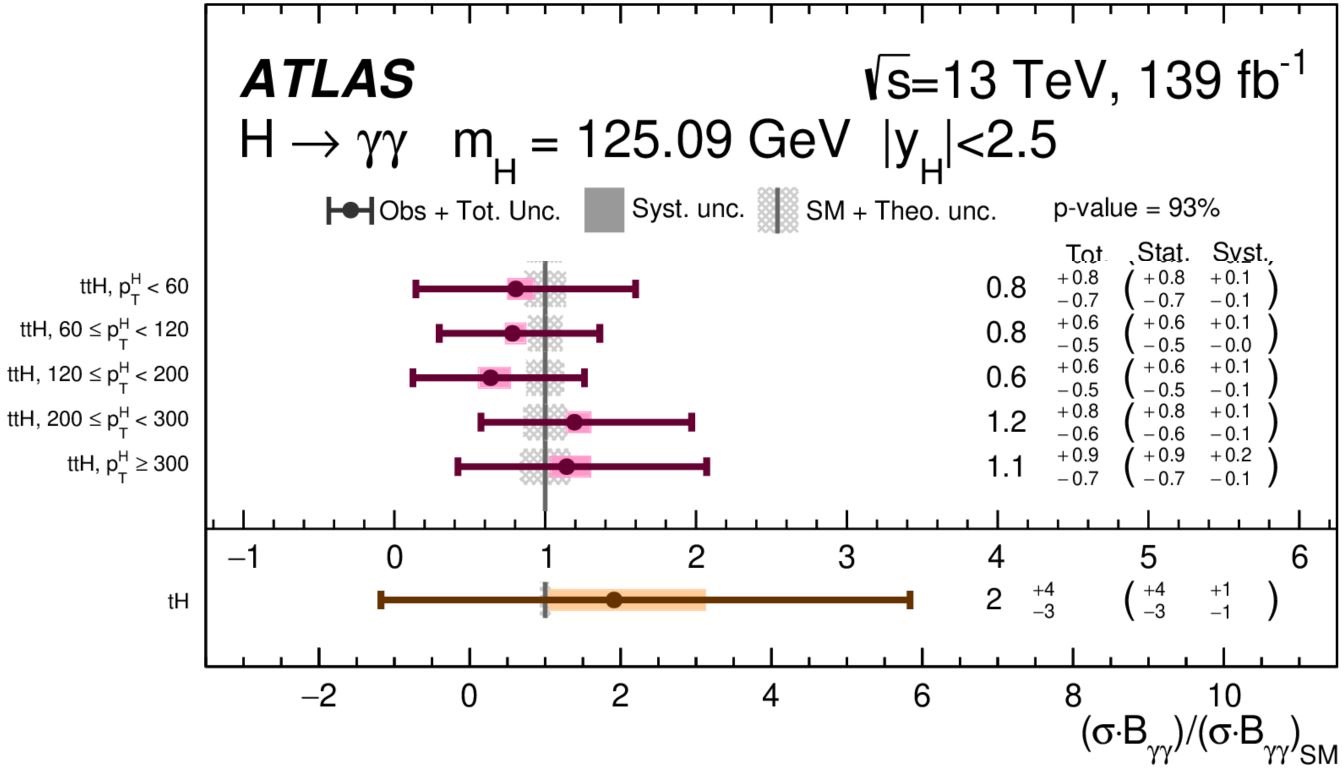


Event yields in full Run 2

$t\bar{t}H$	S	B	S/B
p_T^H < 60 GeV, High-purity	3.04	4.01	0.75
p_T^H < 60 GeV, Med-purity	2.78	13.3	0.20
$60 \leq p_T^H$ < 120 GeV, High-purity	4.30	4.09	1.05
$60 \leq p_T^H$ < 120 GeV, Med-purity	2.99	8.61	0.35
$120 \leq p_T^H$ < 200 GeV, High-purity	4.65	3.52	1.32
$120 \leq p_T^H$ < 200 GeV, Med-purity	1.66	4.16	0.39
$200 \leq p_T^H$ < 300 GeV	3.39	2.26	1.50
$p_T^H \geq$ 300 GeV	2.73	1.66	1.64
tH			
$tHqb$, High-purity	0.55	2.16	0.25
$tHqb$, Med-purity	0.14	2.78	0.05
$tHqb$, BSM ($\kappa_t = -1$)	0.12	1.86	0.06
tHW	0.16	6.91	0.02

ttH H->$\gamma\gamma$

ATLAS + CMS full Run2 differential in Higgs pT



CMS

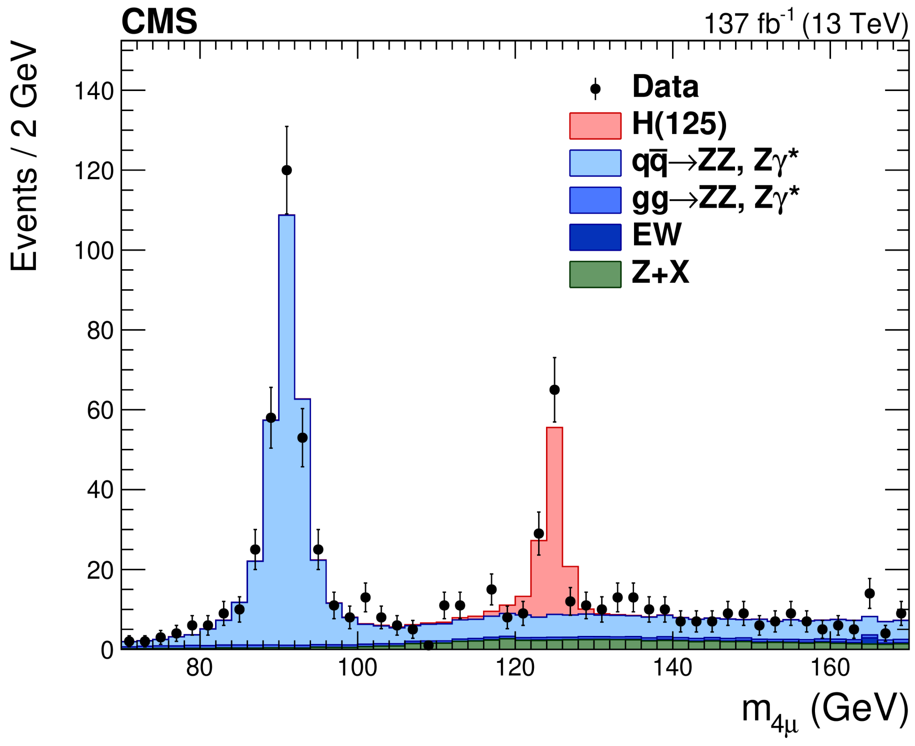
Parameters	$\sigma\mathcal{B}/(\sigma\mathcal{B})_{SM}$ Observed (Expected) Best fit
$t\bar{t}H\ p_T^H < 60$	$0.73^{+0.92}_{-0.73}\left(^{+0.89}_{-0.75}\right)$
$t\bar{t}H\ 60 < p_T^H < 120$	$1.25^{+0.65}_{-0.55}\left(^{+0.72}_{-0.55}\right)$
$t\bar{t}H\ 120 < p_T^H < 200$	$0.80^{+0.58}_{-0.49}\left(^{+0.58}_{-0.53}\right)$
$t\bar{t}H\ 200 < p_T^H < 300$	$0.92^{+0.89}_{-0.73}\left(^{+0.81}_{-0.75}\right)$
$t\bar{t}H\ p_T^H > 300$	$0.00^{+1.34}_{-0.00}\left(^{+1.21}_{-1.00}\right)$
tH	$8.38^{+3.48}_{-4.55}\left(^{+4.93}_{-1.00}\right)$

Measurements have very small systematic and large statistical uncertainties

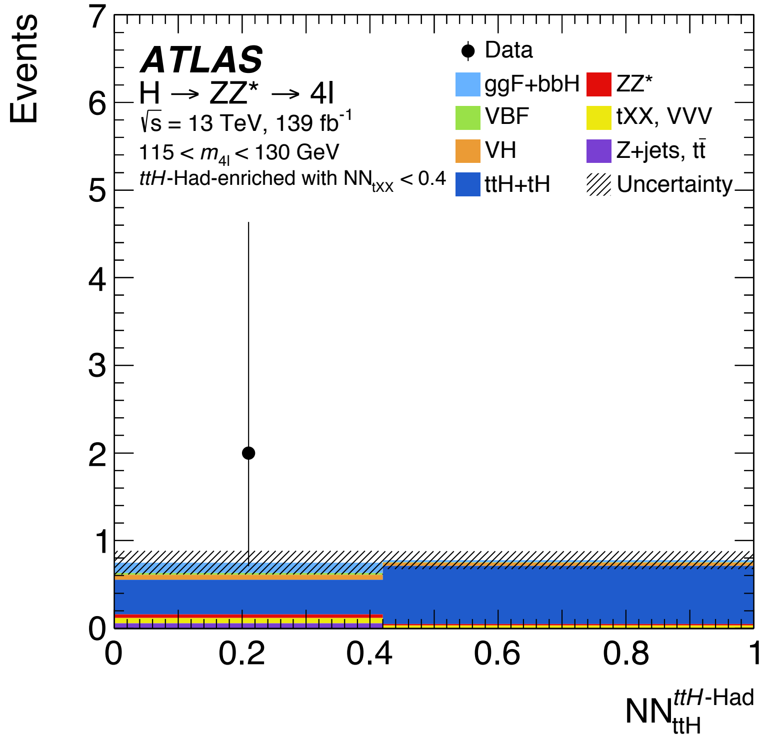
ttH H->ZZ->4l

ATLAS + CMS full Run2 data

Inclusive H->4μ



ttH H->4l

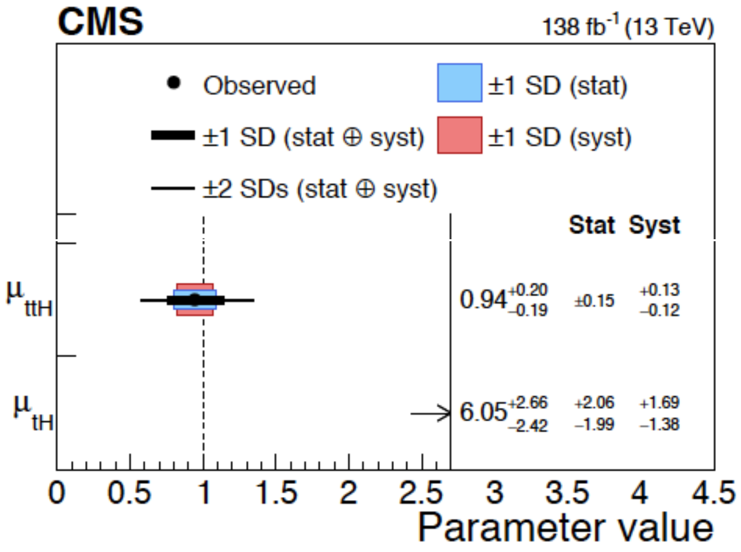


$(\sigma_{ttH}B)_{meas}/(\sigma_{ttH}B)_{SM}$ CMS: 3^{+16}_{-3} ATLAS: $1.6 \pm 1.7^{+0.3}_{-0.2}$

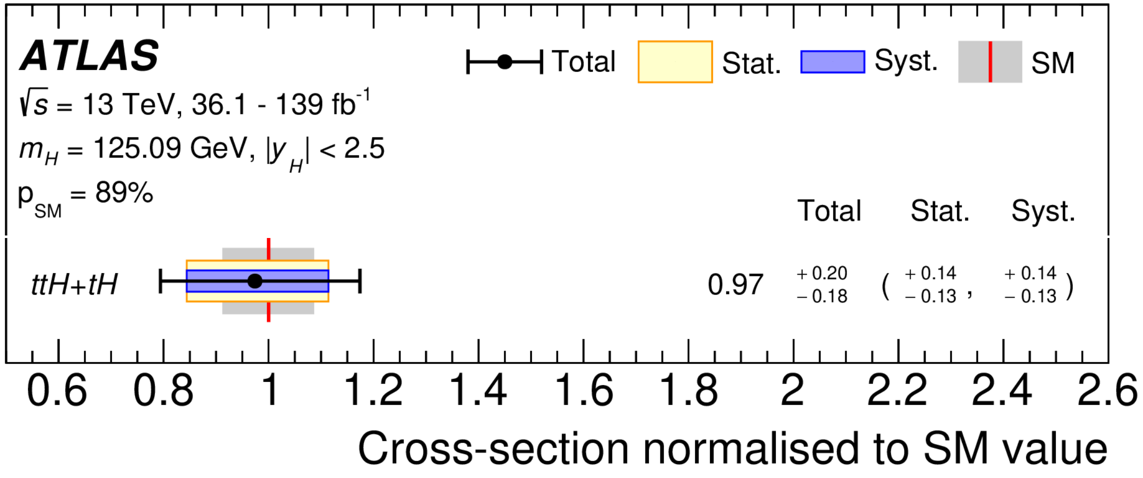
Combined Results for each experiment

Combination of ttH results in different channels

H->$\gamma\gamma$, 4l, ML 139 fb^{-1}
H->bb 36 fb^{-1}



ttH+tH, H->$\gamma\gamma$, 4l, bb 139 fb^{-1}
ttH, H->WW,ZZ, $\tau\tau$ 36 fb^{-1}



statistical and systematic uncertainties of similar size

μ_{ttH} known at ~20%

$\sigma_{tH.}$ not yet observed

Summary & Outlook

Measurements of ttH and tH performed on full Run2 data set in many channels, few are still in preparation

Measurements of ttH in differential Higgs pT are statistics limited in most of the phase space

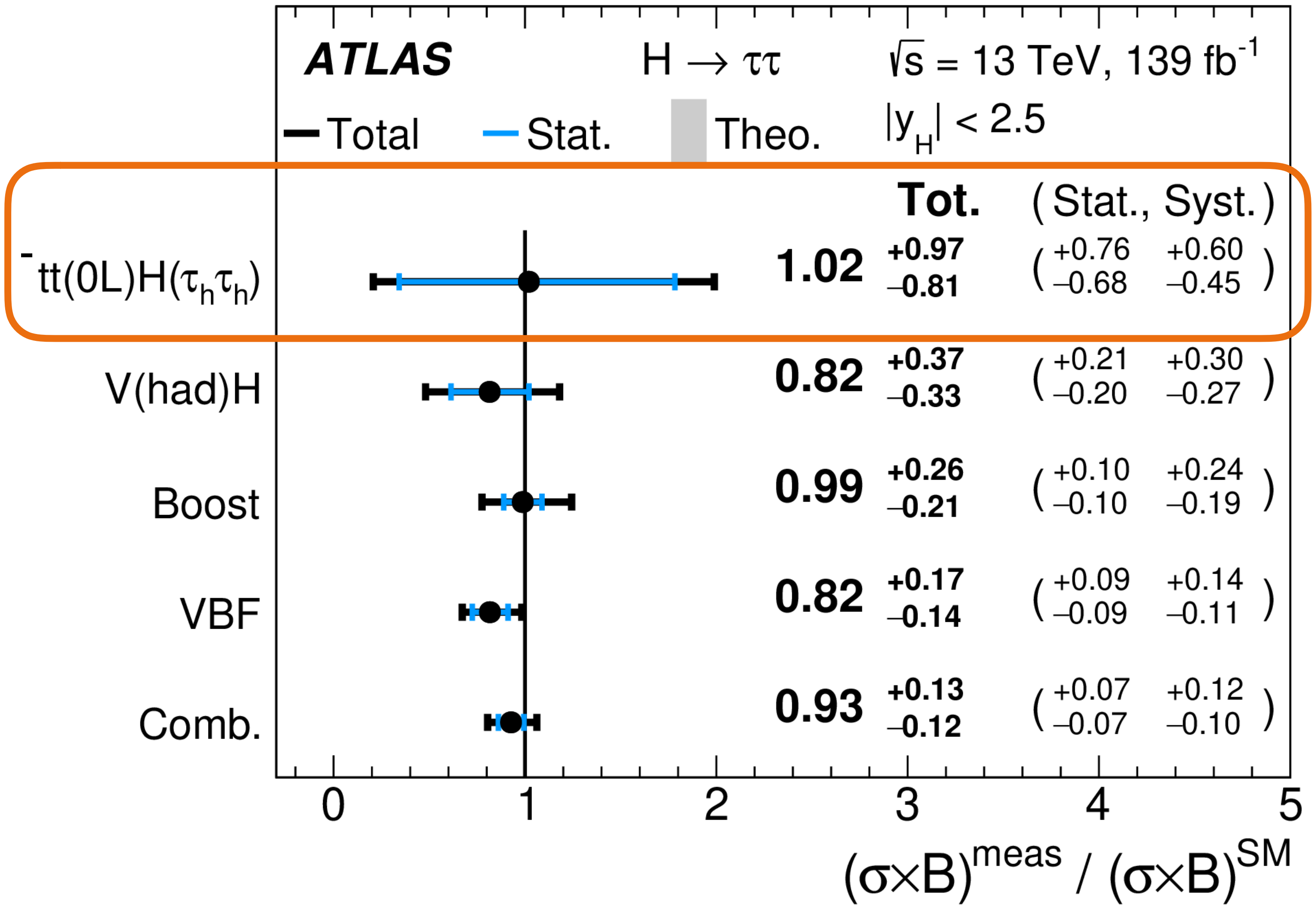
Combination of Run2 results of ATLAS and CMS would be beneficial
- Need to overcome significant differences in treatment of systematic uncertainties in ttHML and ttHbb
- LHC Higgs WG note on theory uncertainty treatment in cds; to appear on arXiv soon

13.6 TeV: increase of ttH and tH cross section by 12%

Thank you

ttH 0 lepton, H->$\tau_{had}\tau_{had}$

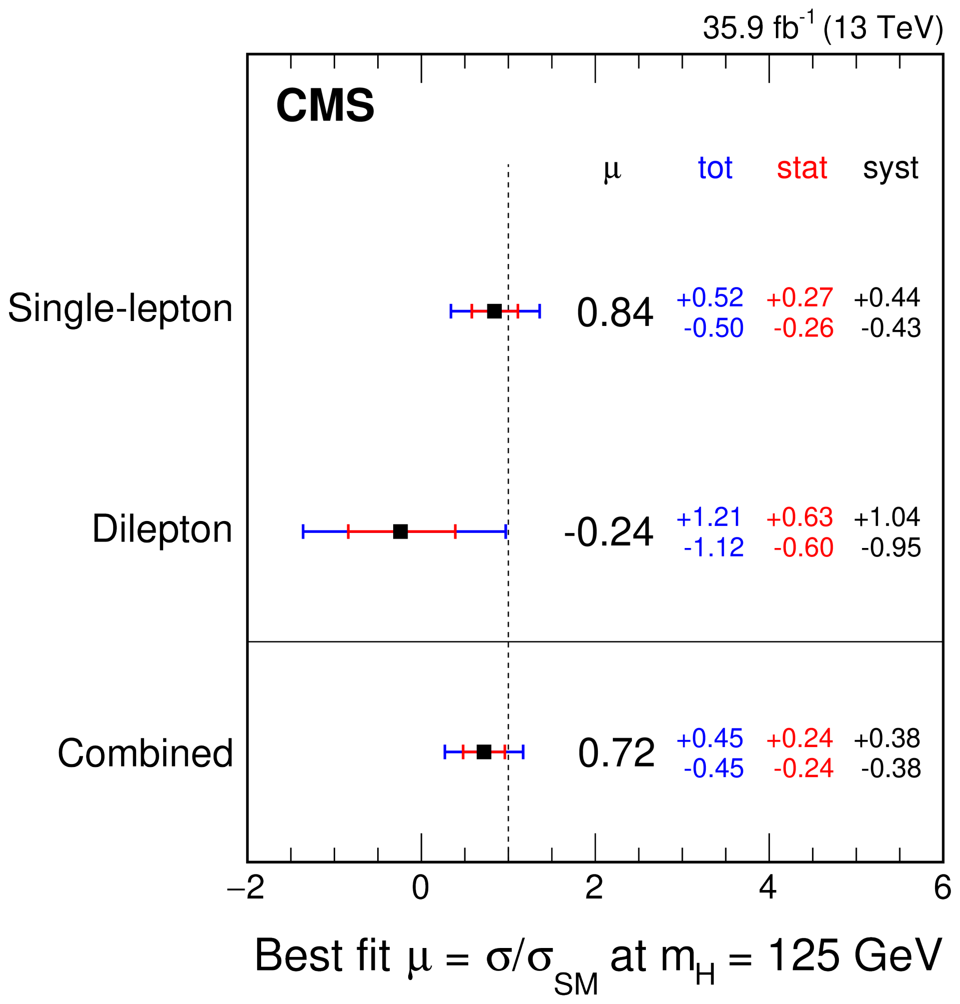
ATLAS full Run2



ttH H->bb

CMS 36 fb^{-1}

- **>= 1 leptonic top decay**



- Measurement performed in phase space starting with 3b
- Use of MVA techniques to separate signal from background and different background categories
- Use tt@NLO 5FS as background MC also for ttbb
- **Systematic limited**
- **Dominant uncertainty:**
- - uncertainty on tt+heavy flavour rate
-

STXS binning ttH + tH

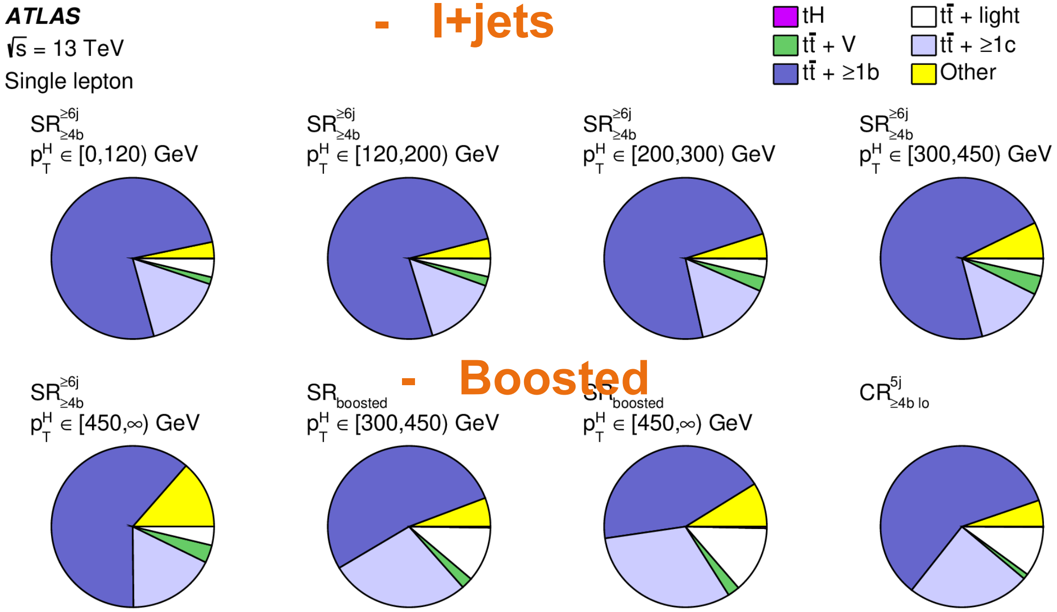
Including Higgs pT

- **$t\bar{t}H$** [$pp \to t\bar{t}H$]
  - $p_T^H < 60\,GeV$
  - $60 \leq p_T^H < 120\,GeV$
  - $120 \leq p_T^H < 200\,GeV$
  - $200 \leq p_T^H < 300\,GeV$
  - $300 \leq p_T^H < 450\,GeV$
  - $p_T^H \geq 450\,GeV$
- **tH** [$pp \to tH + X$]

ttHbb SR background composition

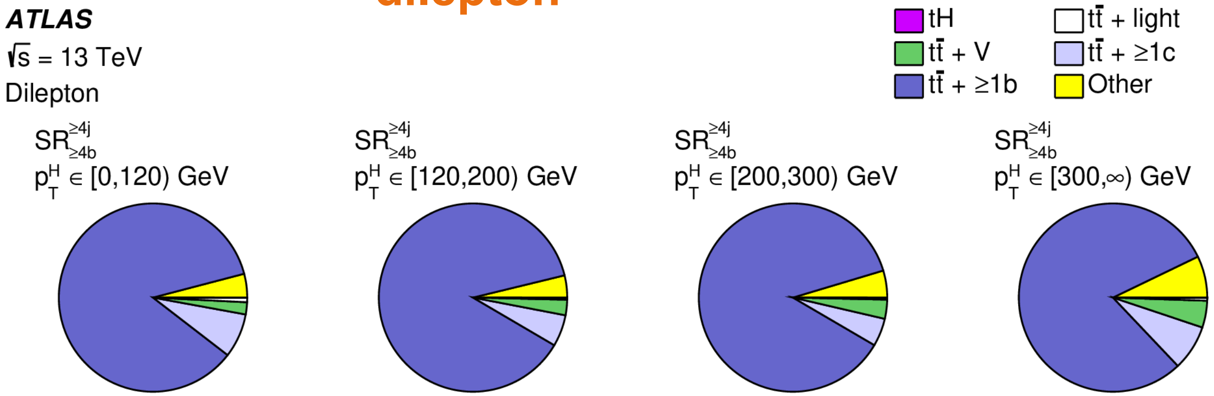
ATLAS full Run2

- l+jets



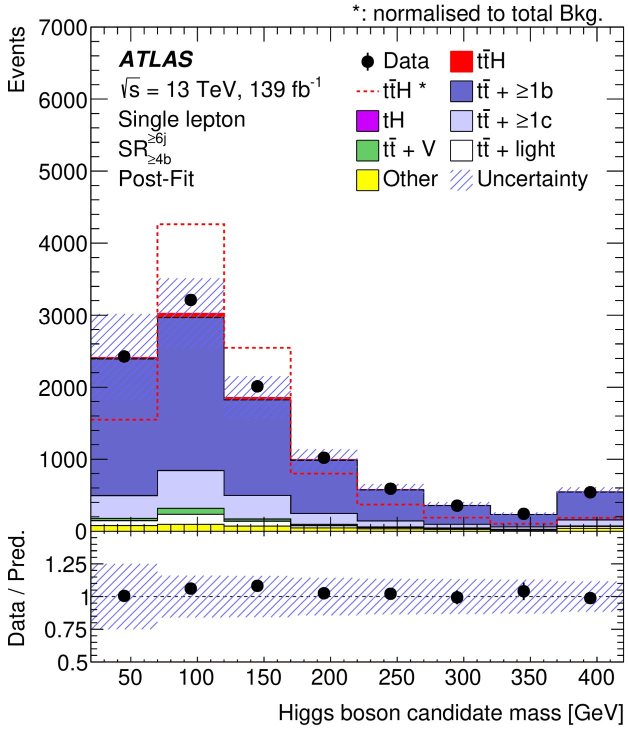
- Boosted

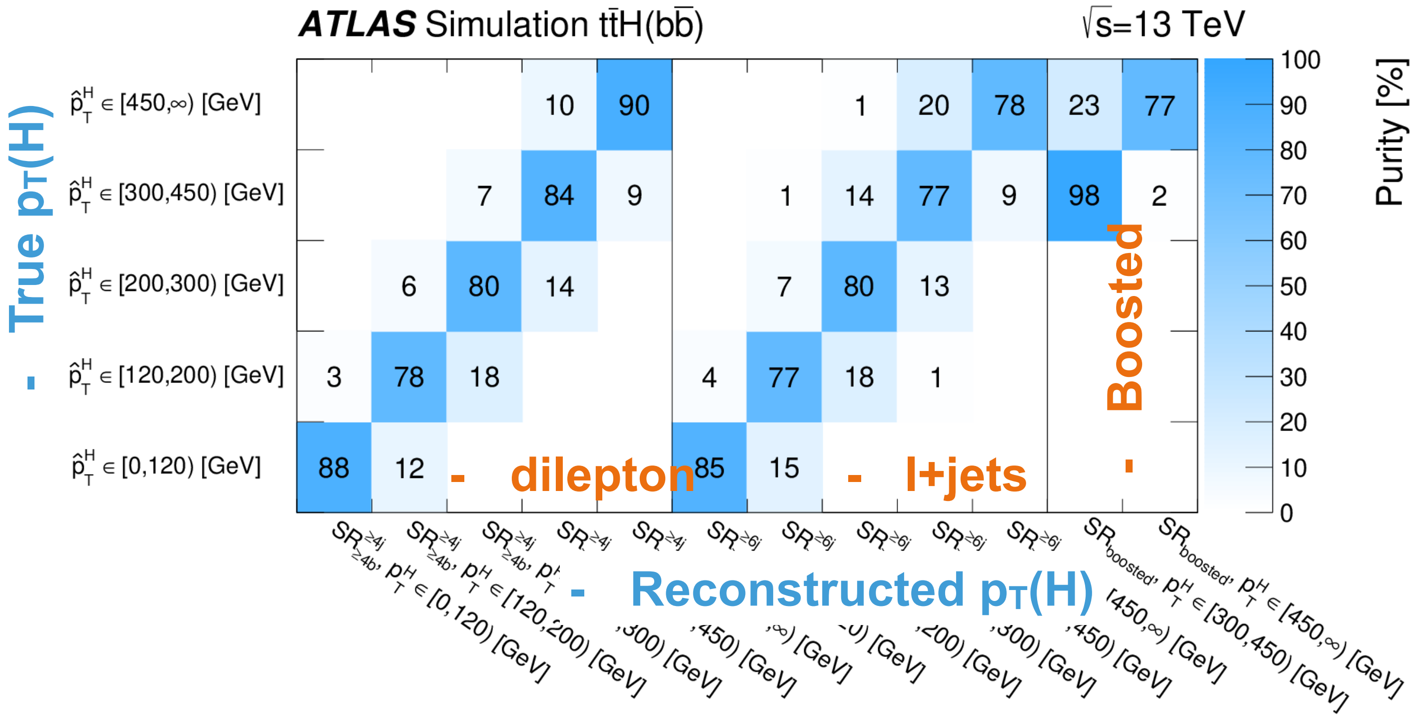
- dilepton



ttH H->bb

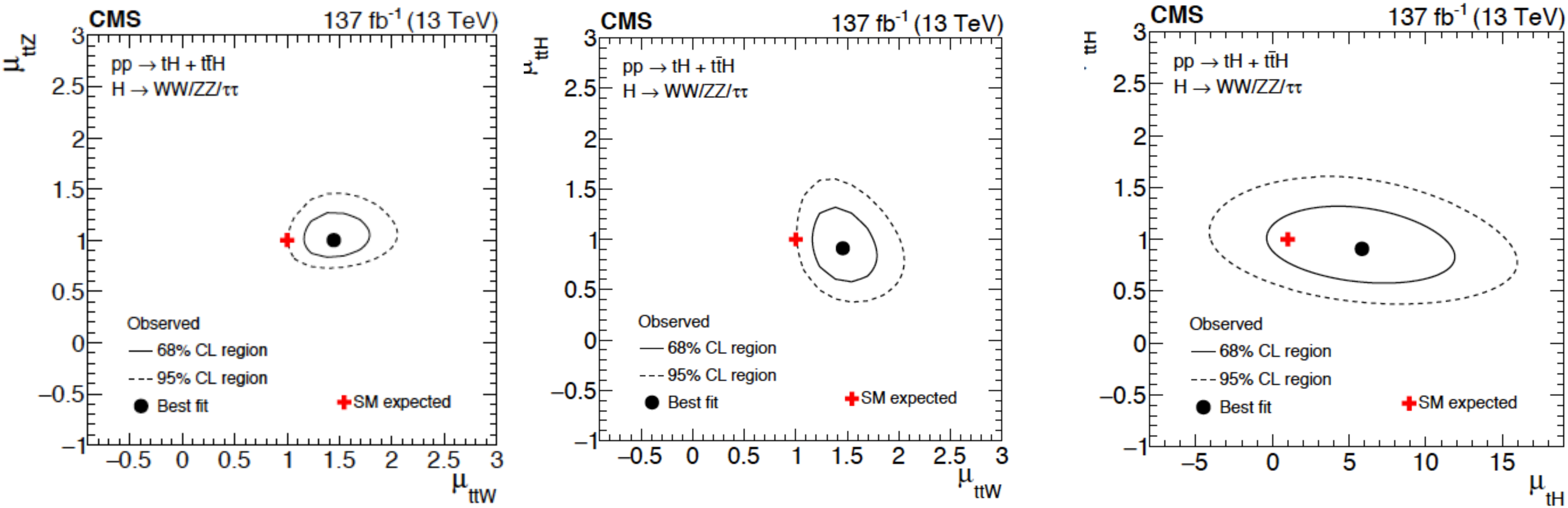
ATLAS full Run-2 analysis 139 fb^{-1}





ttHML

CMS full Run2 139 ifb

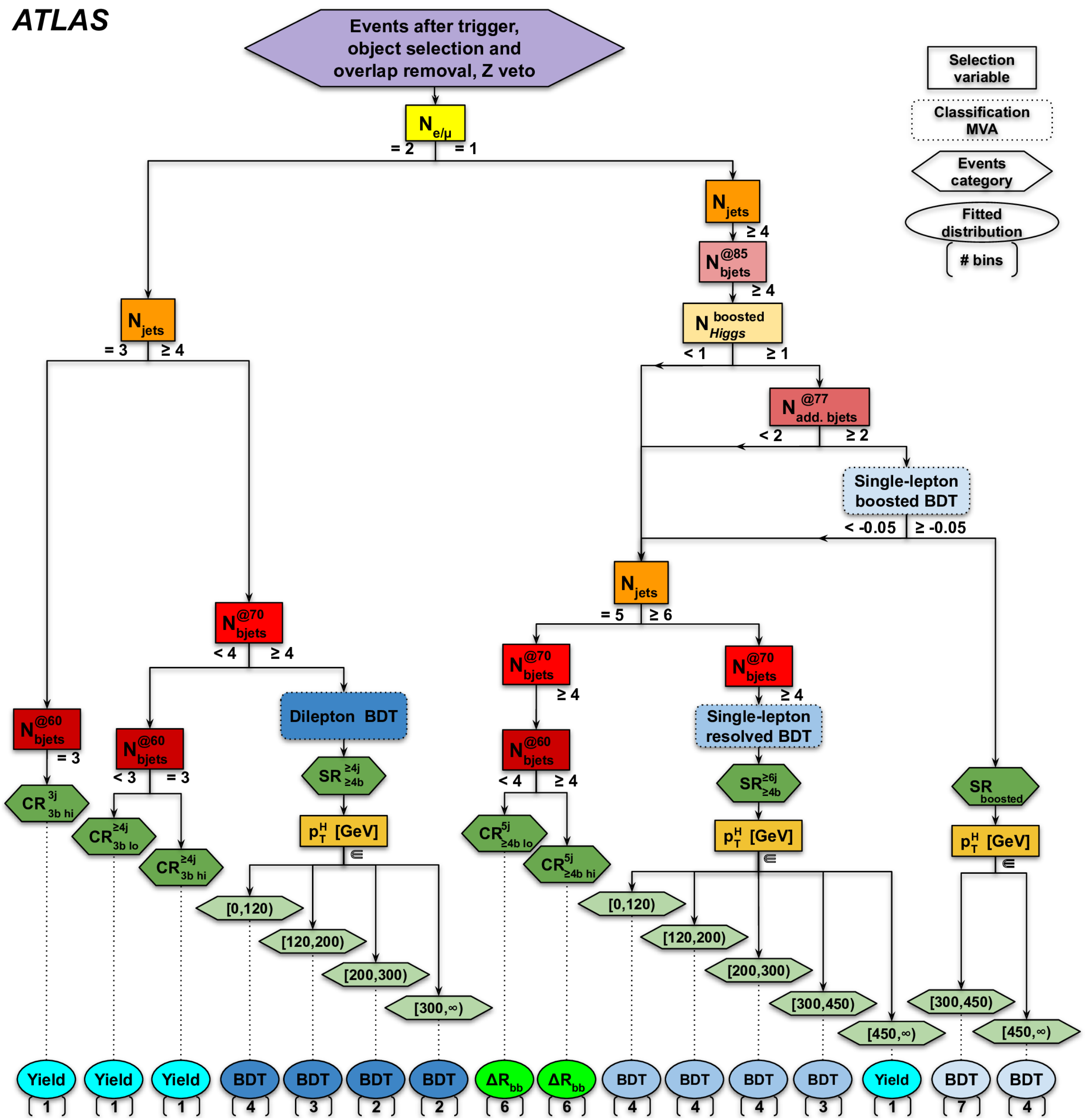


- ttW ~1.5 times higher in data

- $\kappa_t = y_t(\text{meas}) / y_t(\text{SM})$
- **$-0.7 < \kappa_t < -0.9$ or $0.7 < \kappa_t < 1.1$ at 95% CL**

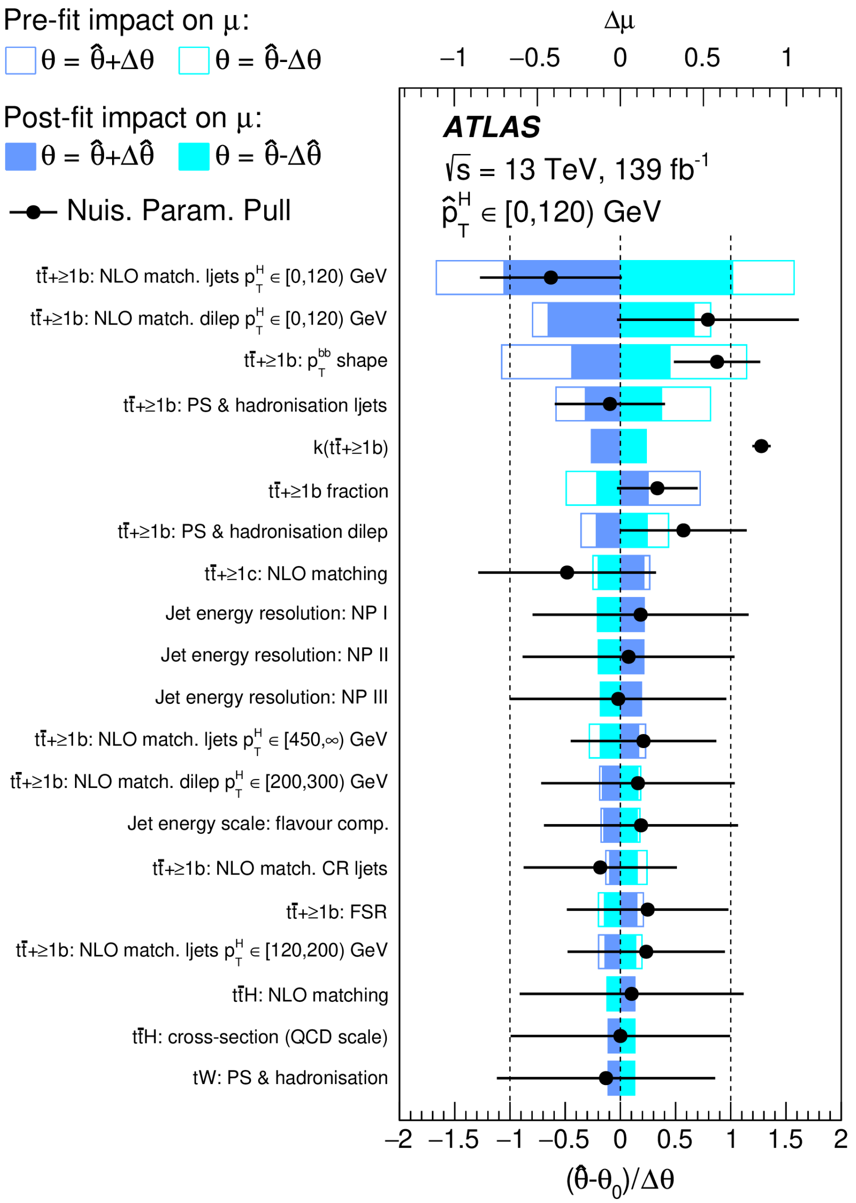
ttHbb

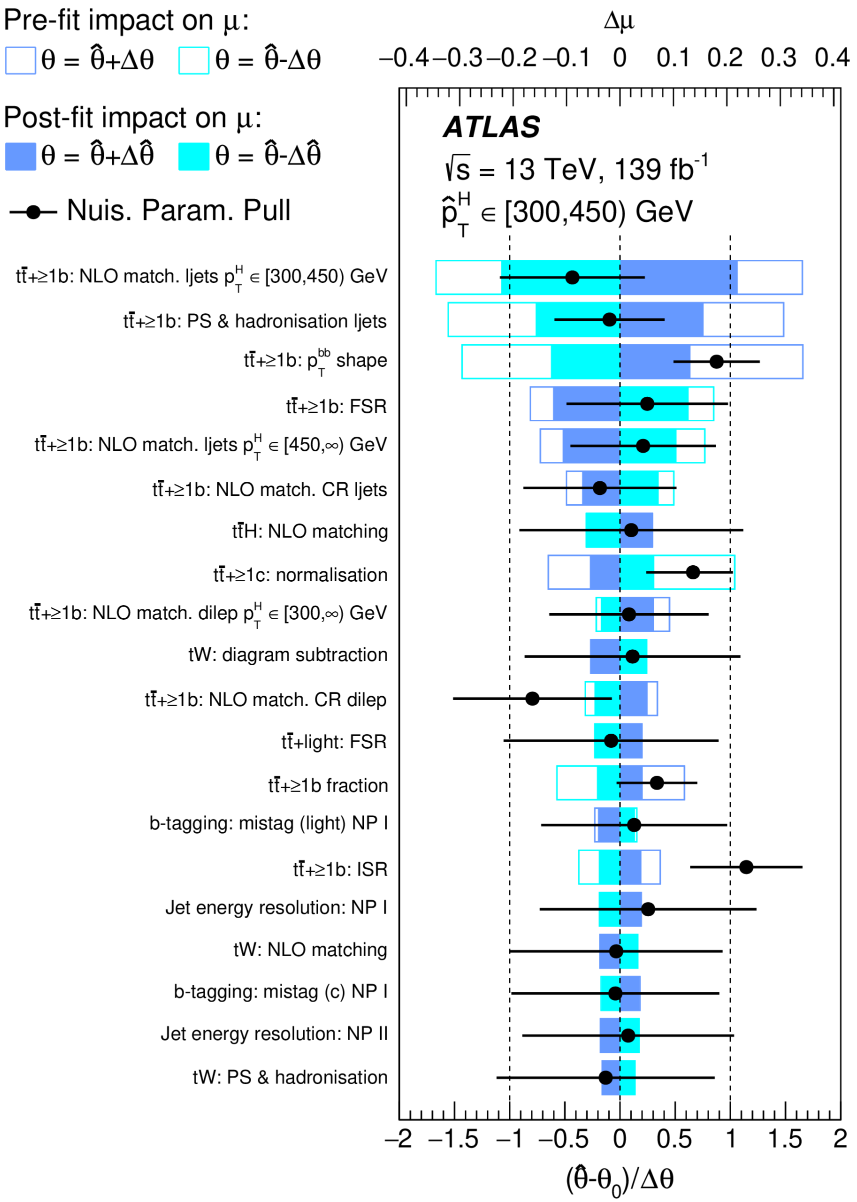
ATLAS 139 ifb



ttHbb

ATLAS 139 ifb



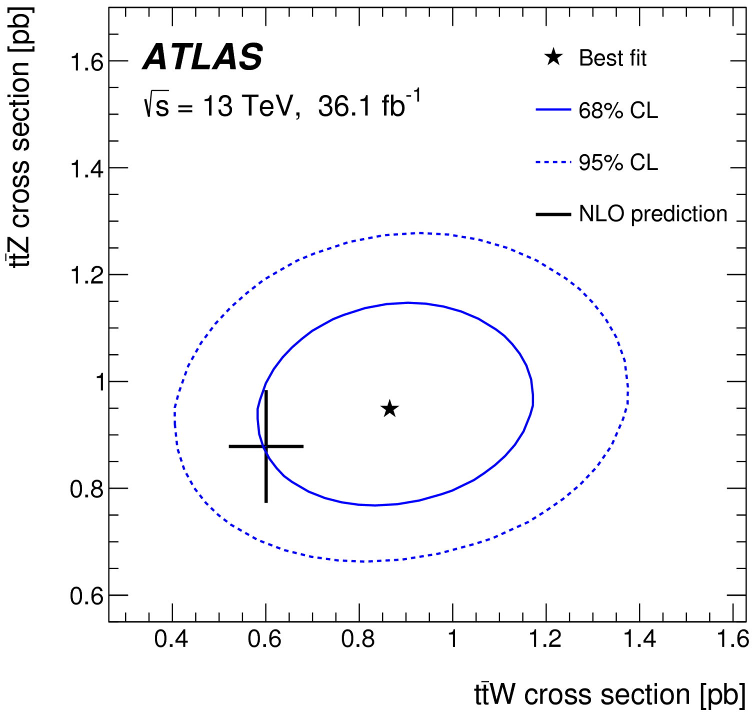


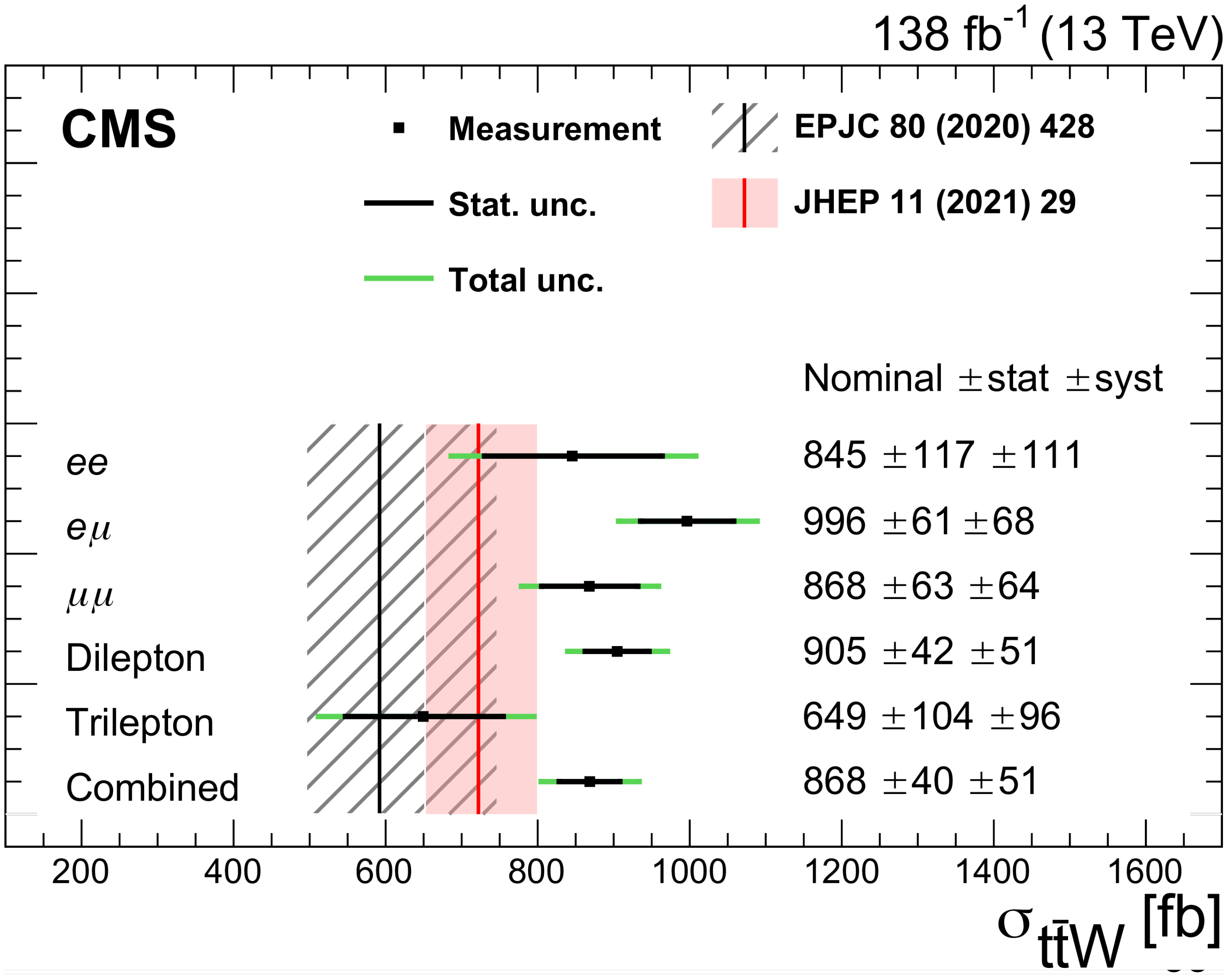
ttW

Measurements

- ATLAS: Phys. Rev. D 99 (2019) 072009
- CMS: arXiv:2208.0648

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	–
3ℓ $t\bar{t}Z$	1.08 ± 0.18	–
2ℓ-SS and 3ℓ $t\bar{t}W$	–	1.41 ± 0.33
4ℓ	1.21 ± 0.29	–

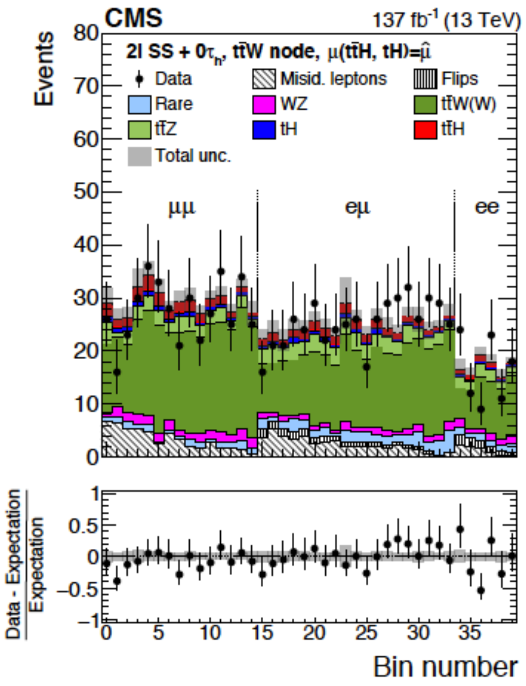




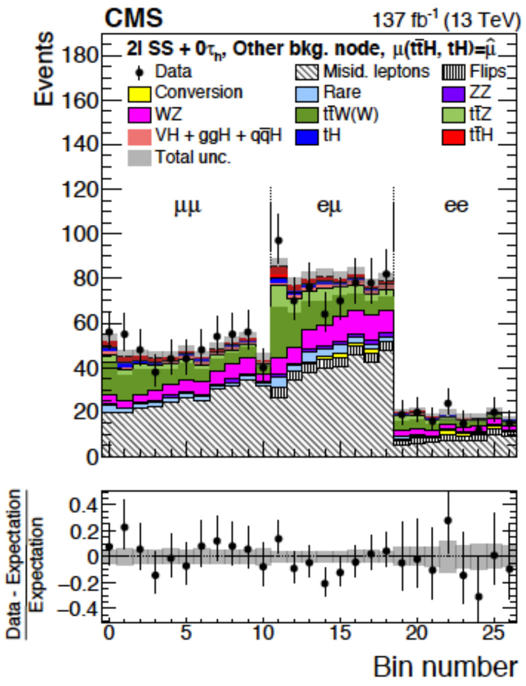
ttH+tH in ML

Example: nodes of 2lSS+0τ

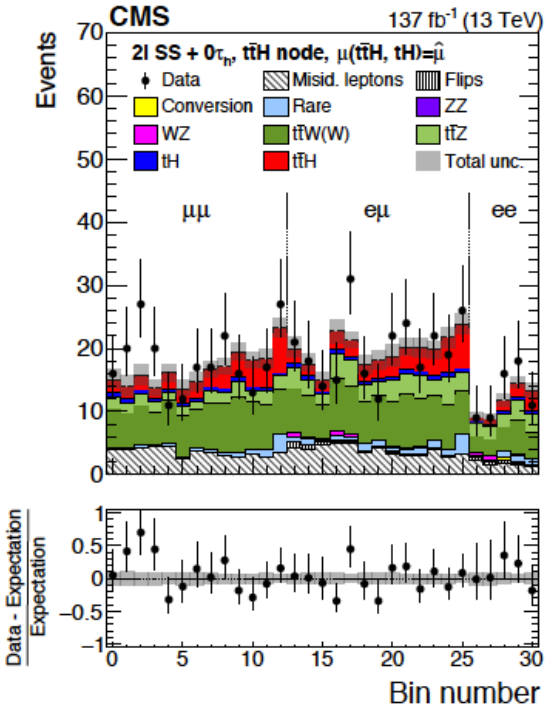
- ttW



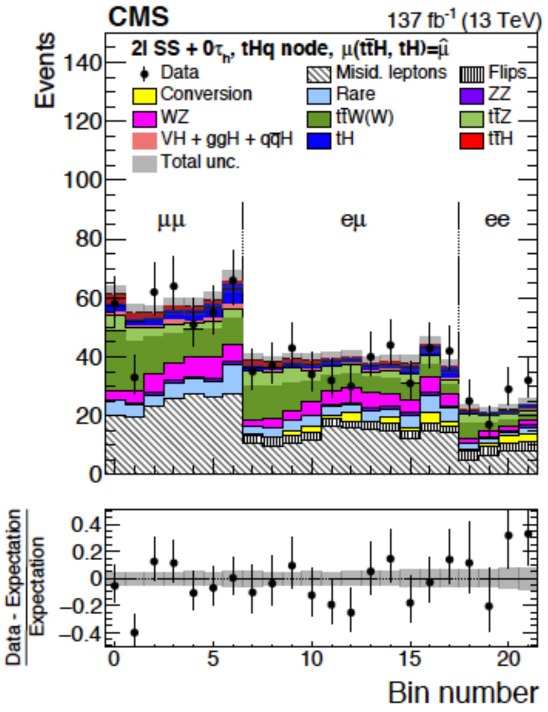
- Misidentified leptons



- ttH

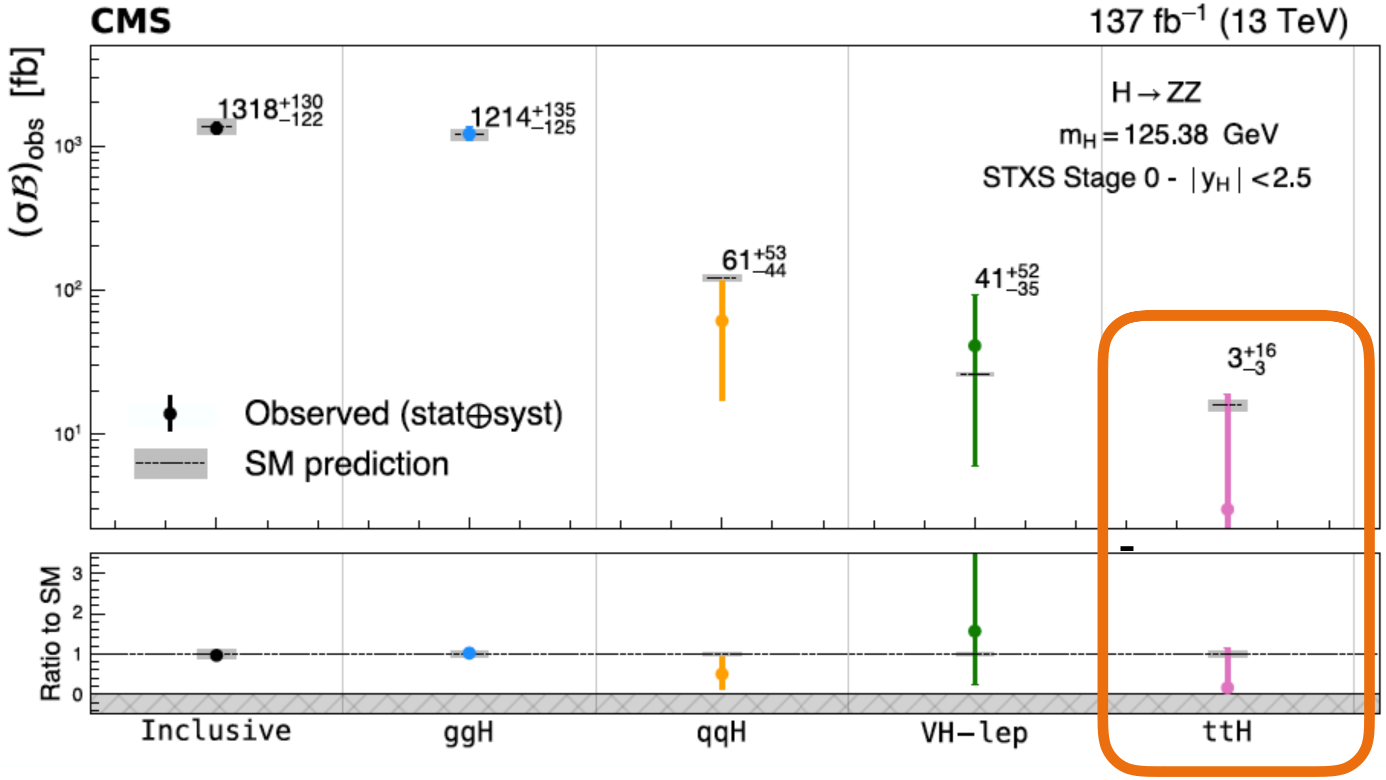


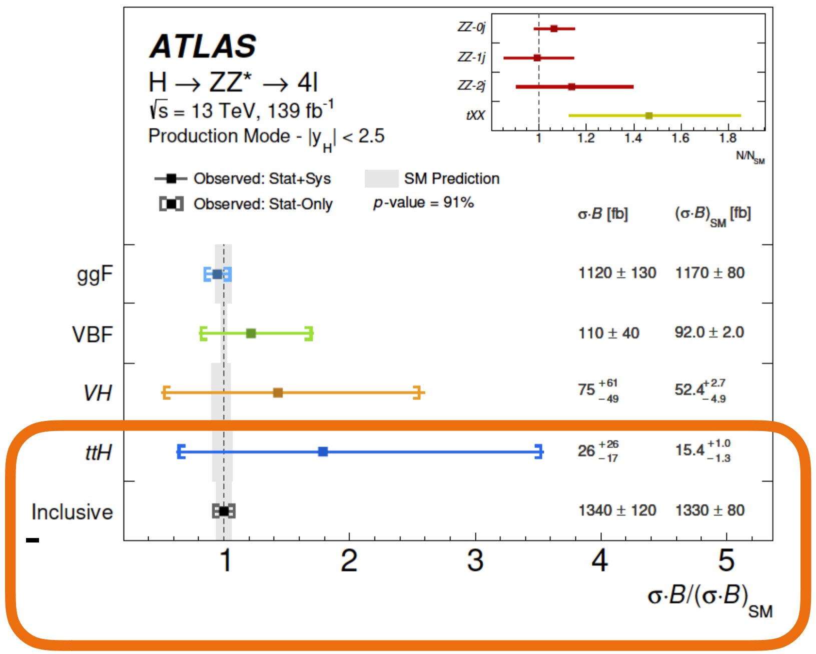
- tH



ttH H->ZZ->4l

ATLAS + CMS full Run2 data





Combinations

Differential in Higgs pT