Searches for $t\bar{t}H$ at ATLAS

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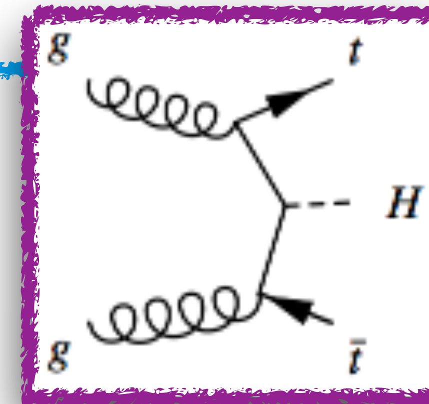
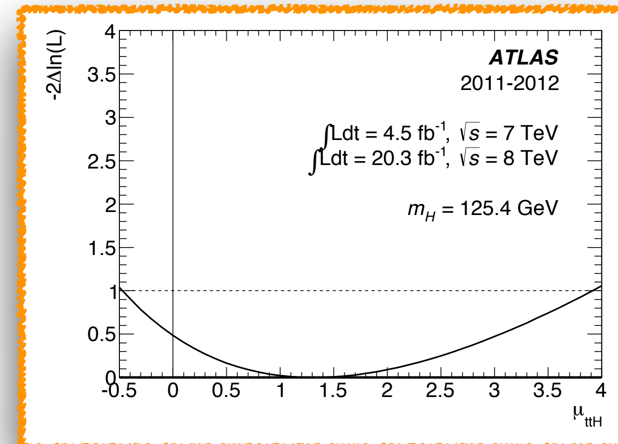
on behalf of the ATLAS collaboration
Albert-Ludwigs-Universitat Freiburg

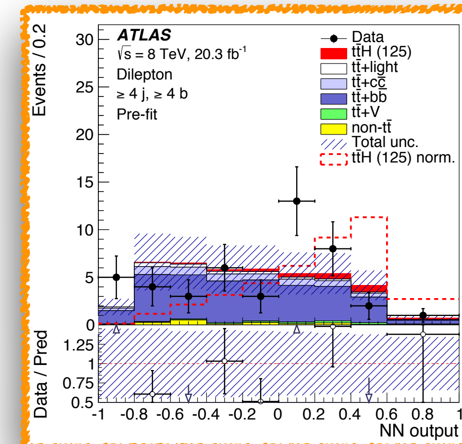
Higgs Couplings workshop
Durham, 12-17 October 2015

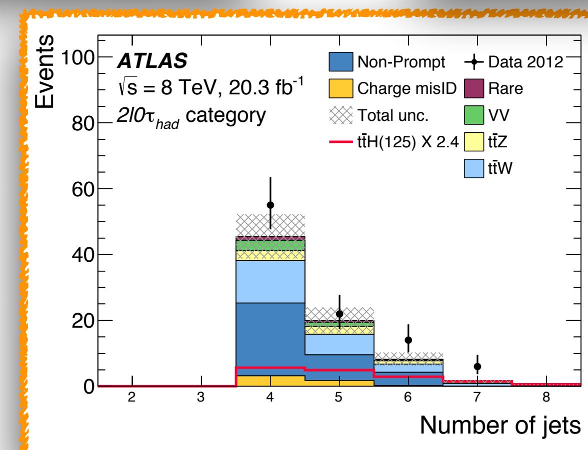
Overview

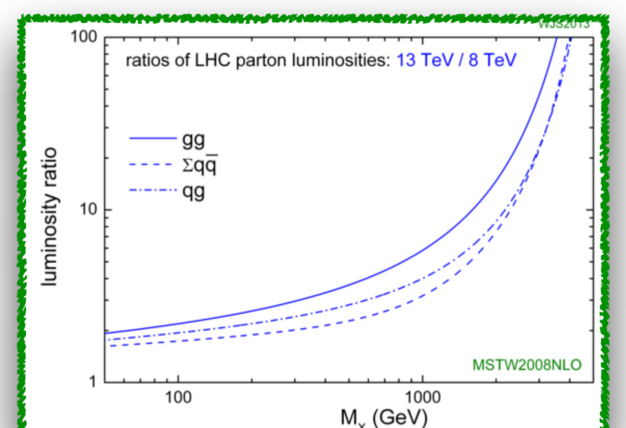


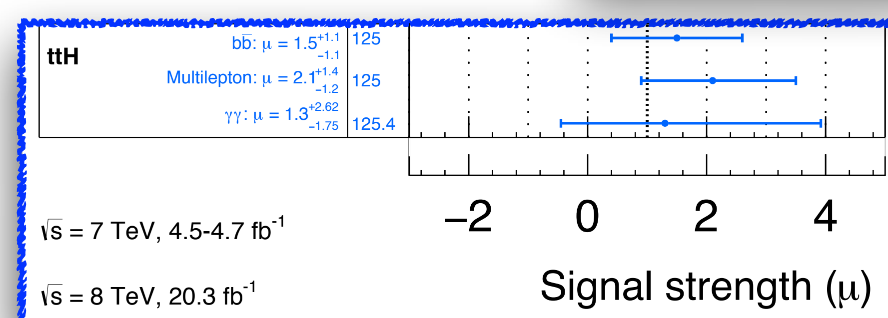
- ✦ *Motivations*
- ✦ *ATLAS Run1 analyses:*
  - ✦ *strategy and results*
- ✦ *Run1 combination*
- ✦ *Run2 prospects*



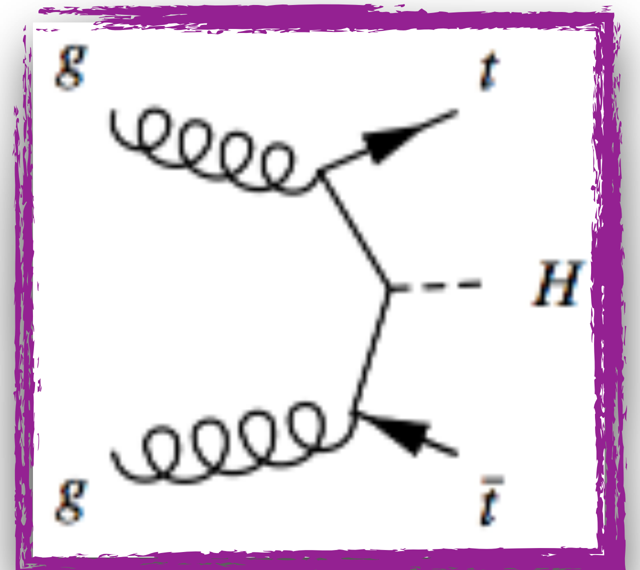






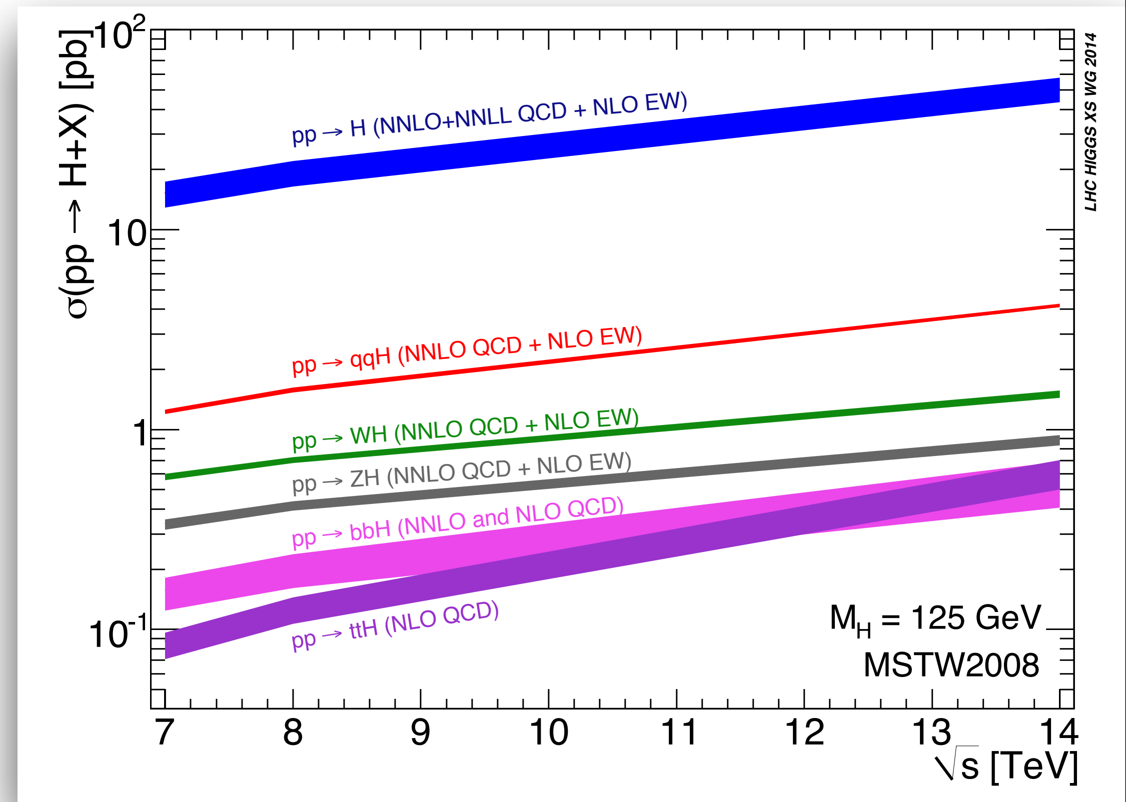


- ***Associated production with top pair ($t\bar{t}H$)*** is the "major" Higgs boson production mechanism with the smallest rate at LHC

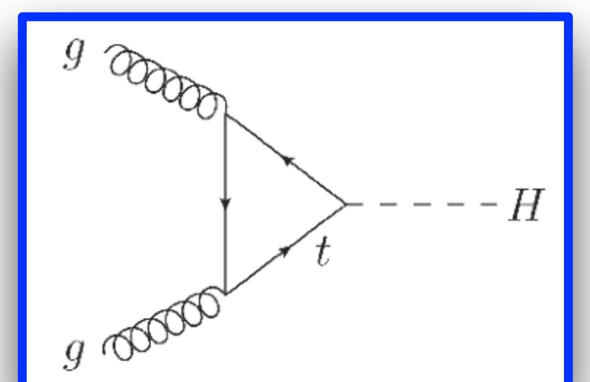


@8TeV: 1/200 of the inclusive Higgs production

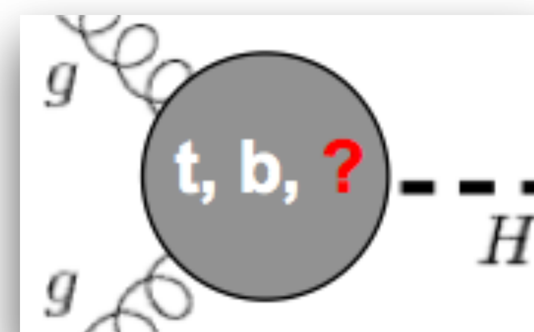
tree level diagram with top-Higgs boson coupling



- While it is not the only production mode sensitive to the top Yukawa coupling ….



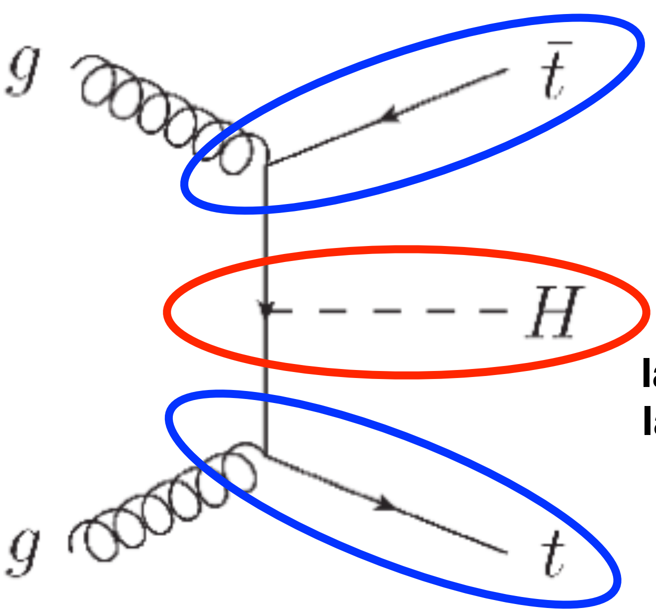
in reality it is :



- … its measurement is a key ingredient in the investigation of the top-Higgs interactions without any assumption of new physics that can enter loop contributions

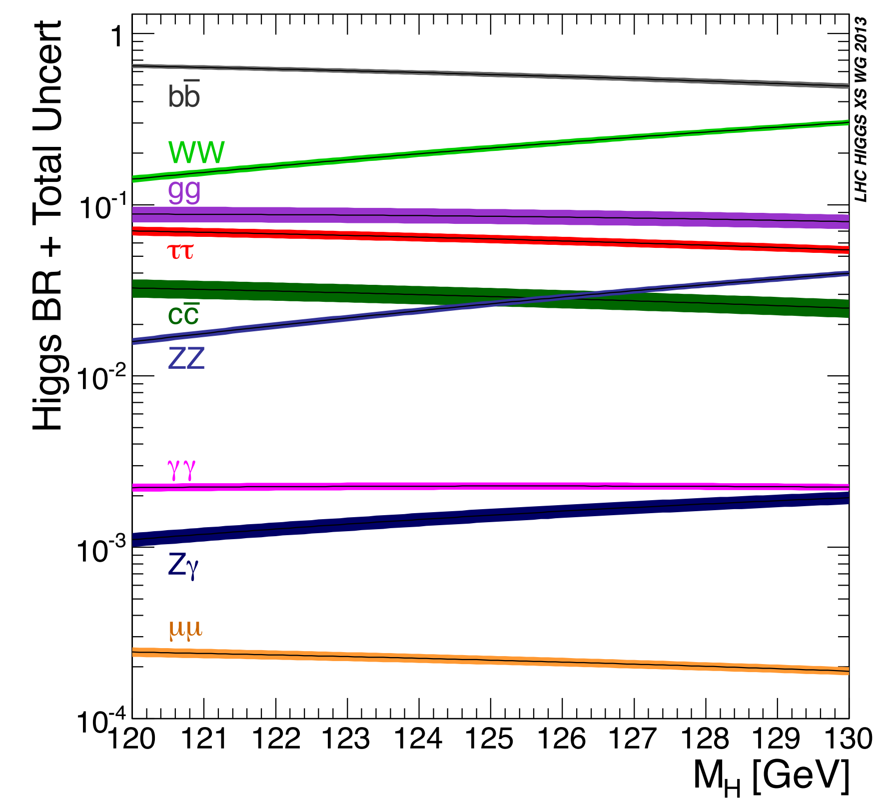
$t\bar{t}H$: which final states?

Higgs boson decay



large BR & large bkgd → purity & precision

- ***$b\bar{b}$*** *(57%)*
- ***ττ*** *(6%)*: use both leptonic and hadronic τ decay modes
- **WW*** *(22%)*: further penalties from leptonic BR decays, no mass peak reconstruction
- **ZZ*** *(2.8%)*: excellent mass resolution, very low branching ratio in fully leptonic channels
- **γγ** *(0.23%)*: excellent mass resolution



$t\bar{t}$ decay

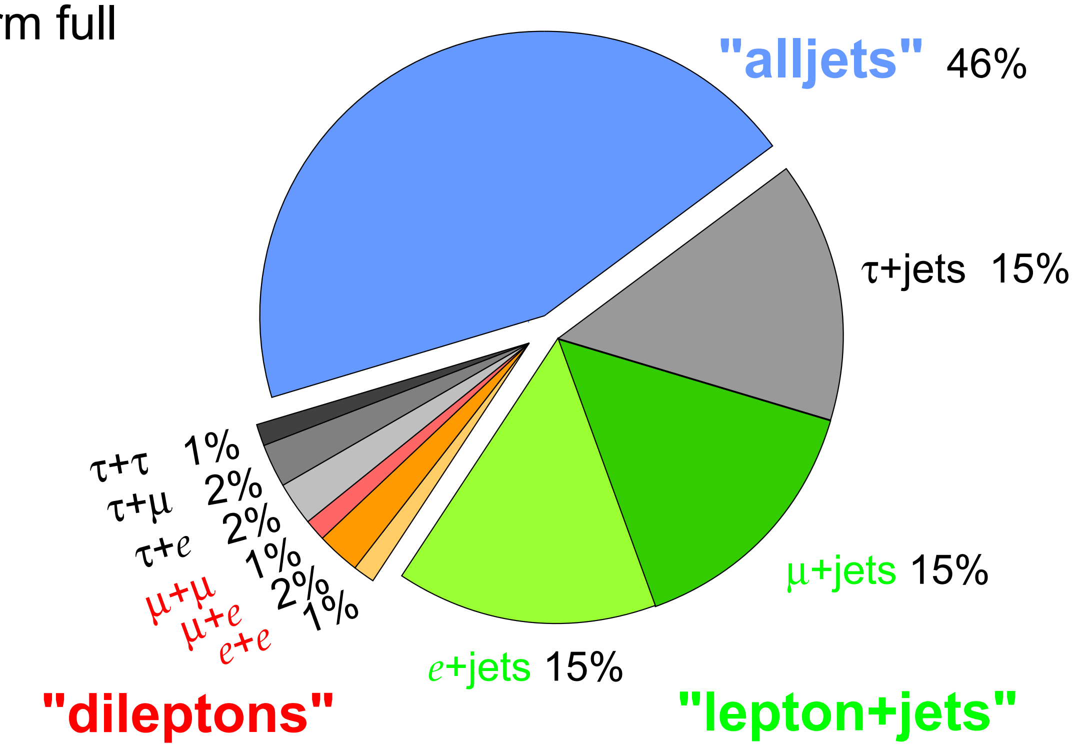
large BR & large bkgd → purity & precision

"all hadronic": possible to perform full ttbar reconstruction.

"lepton+jets": exploit lepton for triggering/background reduction.

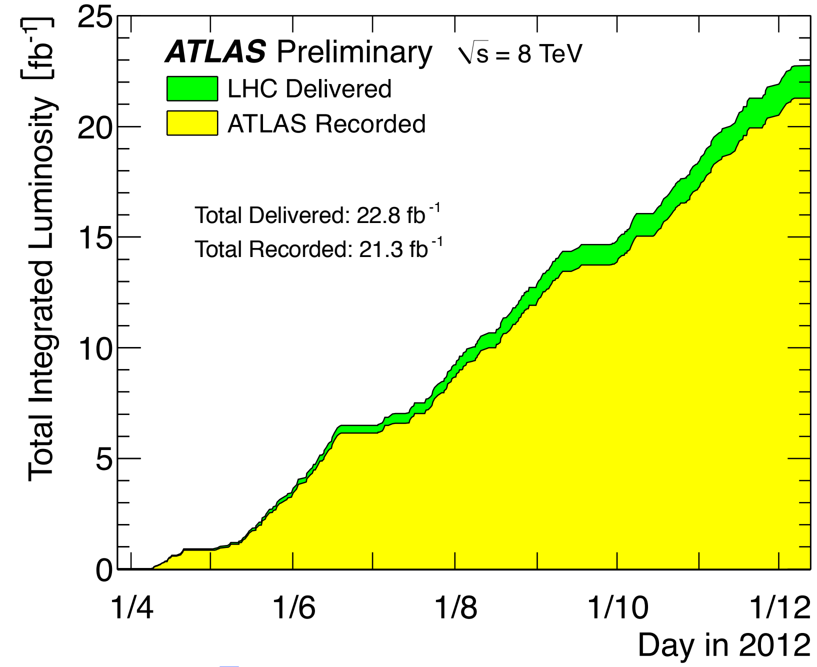
"di-lepton": large penalty from small leptonic BR

[can also consider final states with hadronically decaying τ]



ATLAS Run I analyses

- Broad spectrum of analyses covering multiple final states:
  - combine low BR Higgs decay with high BR $t\bar{t}$ decay and vice-versa
  - $t\bar{t}$ decay products help selection of signal and the reduction of backgrounds. Increased combinatorics when attempting to reconstruct the Higgs boson candidate



Search for $t\bar{t}H$ ($H\to b\bar{b}$): 8 TeV

[Eur. Phys. J. C (2015) 75:349]

Search for $t\bar{t}H$ ($H\to\gamma\gamma$): 7+8 TeV

[Physics Letters B 740 (2015) 222]

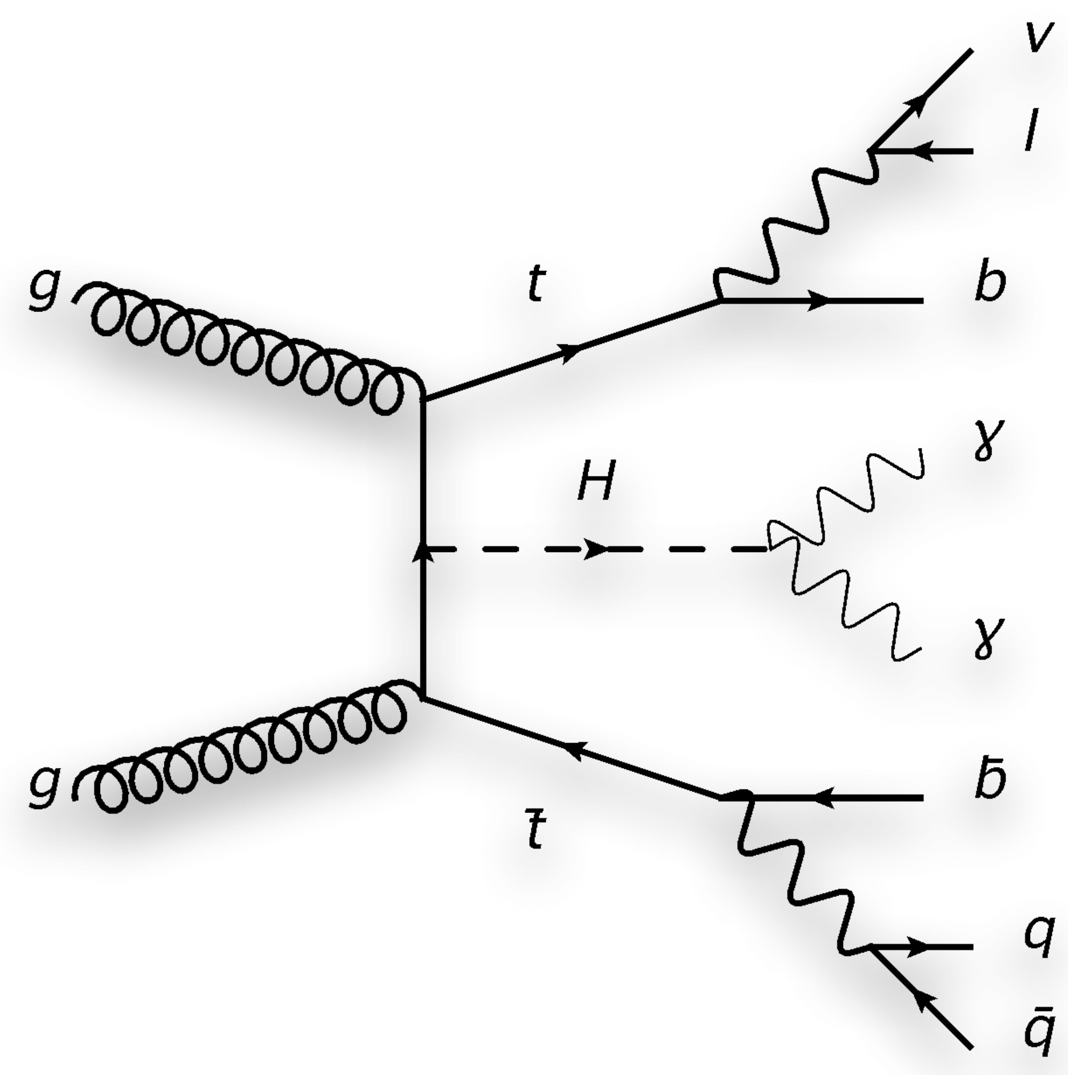
Search for $t\bar{t}H$ multilepton: 8 TeV

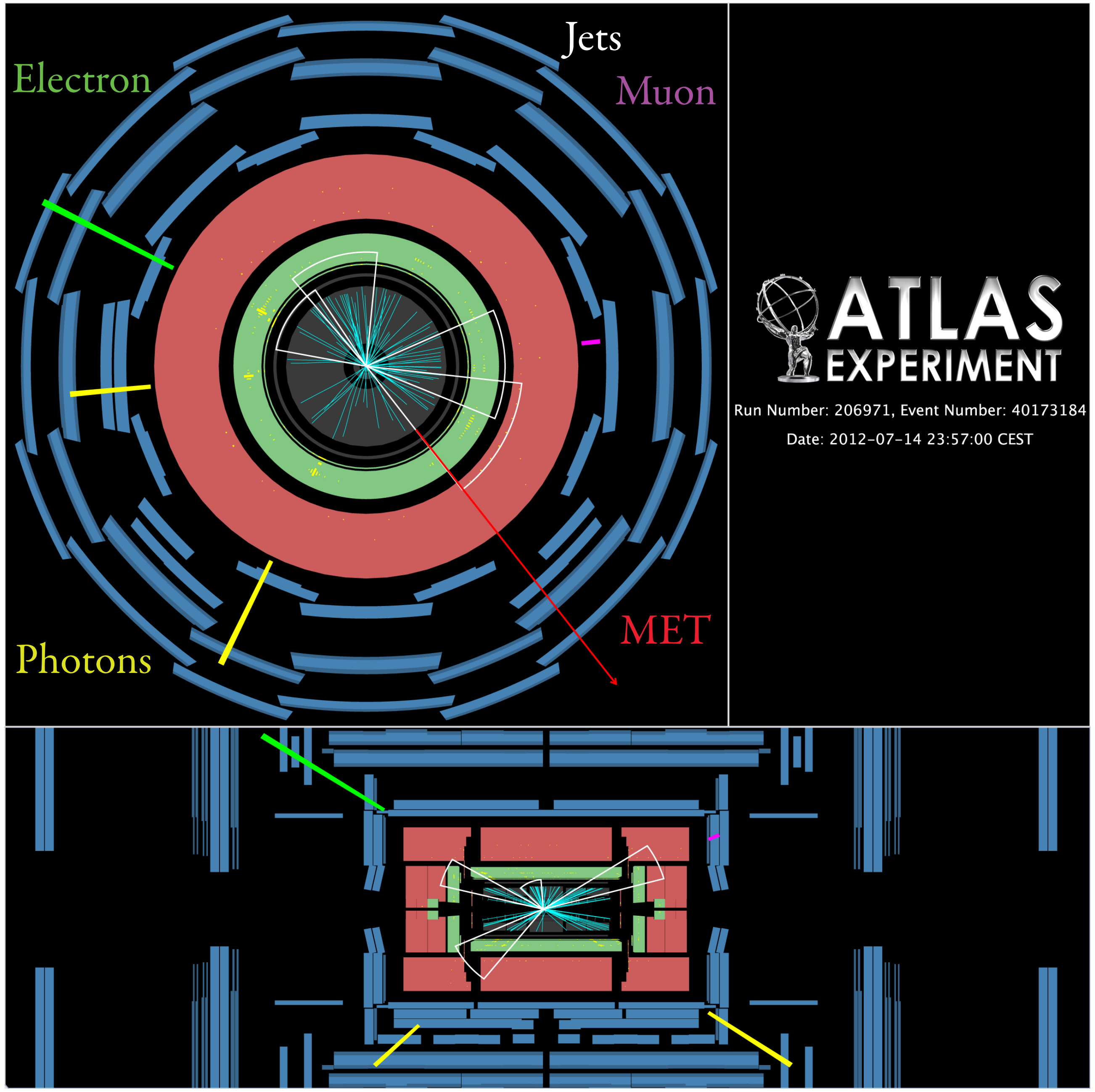
[Physics Letters B 749 (2015) 519-541]

$t\bar{t}$ decay / ***Higgs boson decay***

	$t\bar{t}$ allHad	$t\bar{t}$ l+jets	$t\bar{t}$ di-leptons
$H\to b\bar{b}$			
$H\to\gamma\gamma$			
H->WW*			
H->tautau			
H->ZZ*			

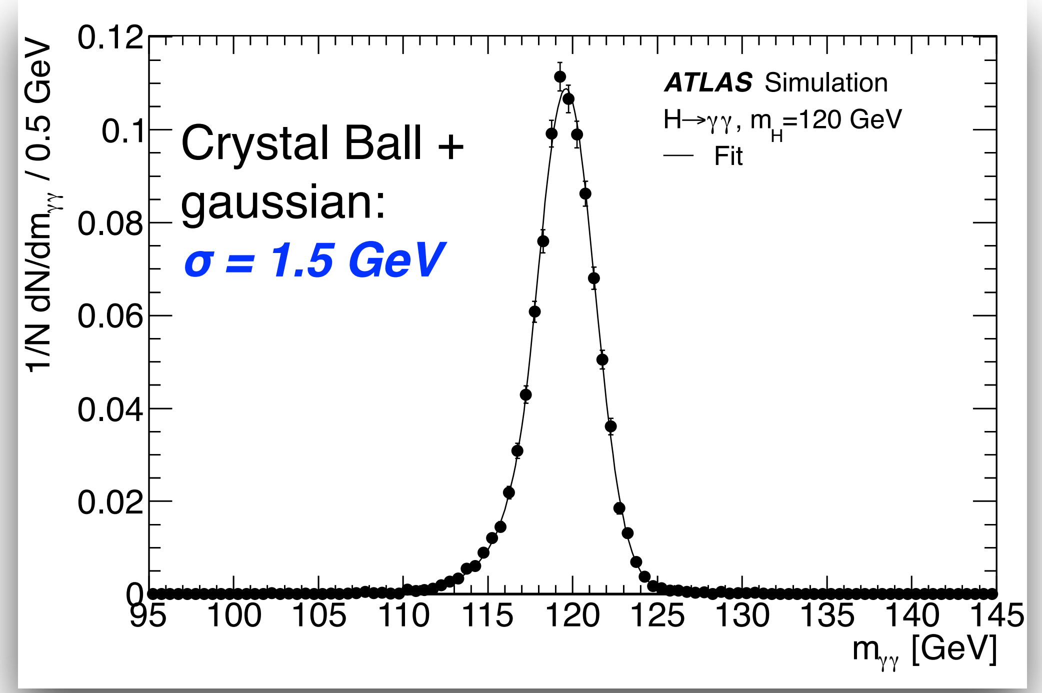
$t\bar{t}H$ ($H \to \gamma\gamma$)





$t\bar{t}H$ ($H\to\gamma\gamma$): event selection

- Following similar approach of the main $H\gamma\gamma$ analysis: ***look for a bump over a smooth background in the di-photon invariant mass spectrum***



- 2 high p_T isolated photons (di-photon trigger):
  - central region of the detector ($|\eta|<2.47$)
  - 'tight' identification criteria
  - $E_T^1>0.35*m_{\gamma\gamma}$, $E_T^2>0.25*m_{\gamma\gamma}$

- Loose topological selection, optimised for $t\bar{t}H$ sensitivity (overall efficiency ~15%):

Hadronic $t\bar{t}$

- no electrons or muons
- OR of jet requirements:
  - ≥6 jets (p_T>25 GeV), ≥2 b-tagged jets (80% b-eff.)
  - ≥5 jets (p_T>30 GeV), ≥1 b-tagged jets (70% b-eff.)
  - ≥6 jets (p_T>30 GeV), ≥1 b-tagged jets (60% b-eff.)

Leptonic $t\bar{t}$

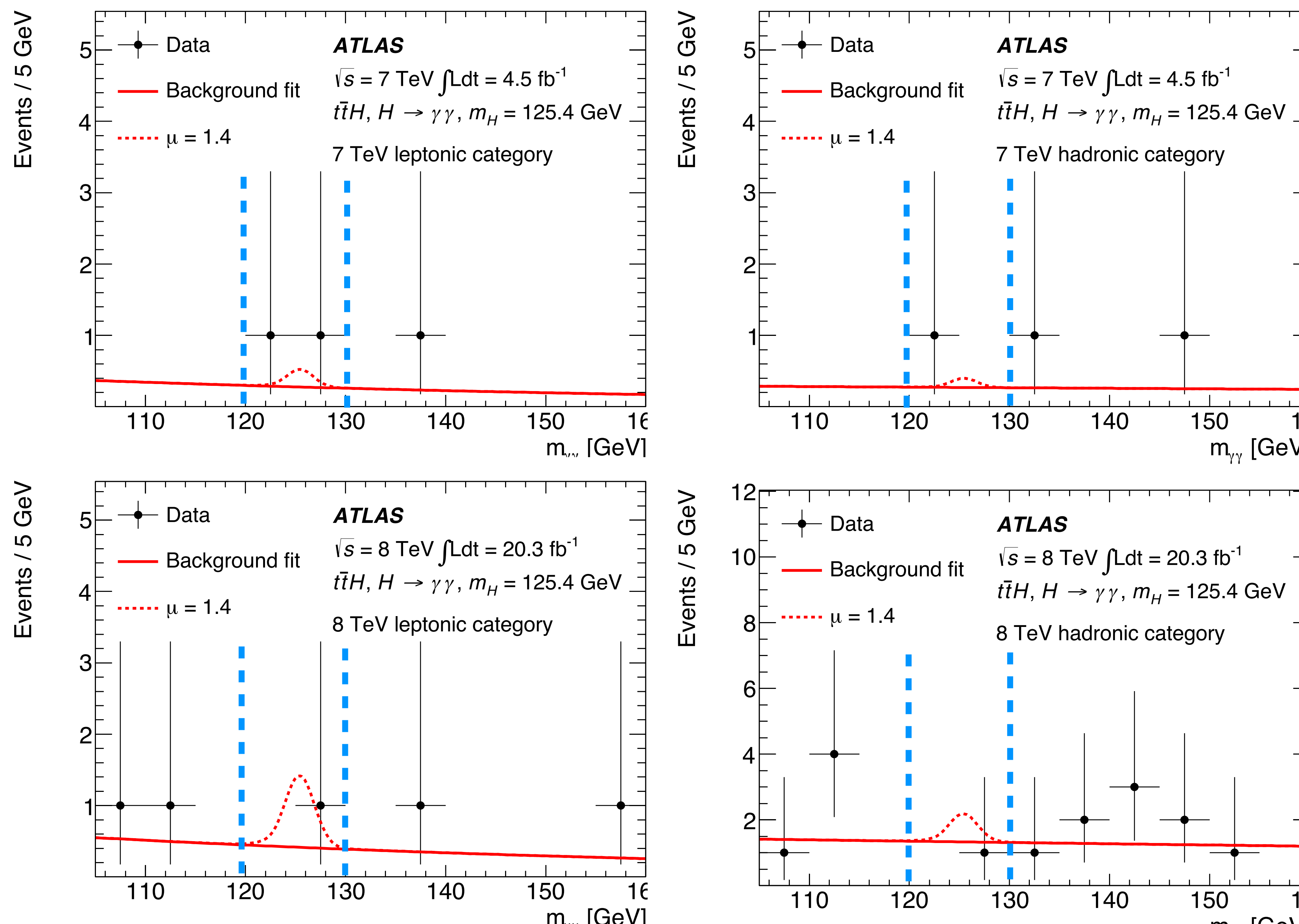
- at least 1 isolated lepton (ele p_T>15 GeV, mu p_T>10 GeV)
- ≥1 b-tagged jet (80% b-eff.)
- veto $m_{e\gamma}$ around Z peak

Event selection (2)

- Selection also optimised to minimise contamination from other Higgs production modes

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B	N_{data}
8 TeV leptonic	0.59	1.0%	0.2%	8.1%	2.3%	80.3%	5.5%	2.7%	$0.9^{+0.6}_{-0.4}$	1
8 TeV hadronic	0.50	7.3%	1.0%	0.7%	1.3%	84.3%	3.4%	2.0%	$2.7^{+0.9}_{-0.7}$	1
7 TeV leptonic	0.10	0.6%	0.1%	14.9%	4.0%	72.8%	5.0%	2.4%	$0.5^{+0.5}_{-0.3}$	2
7 TeV hadronic	0.07	10.5%	1.3%	1.3%	1.4%	81.1%	2.5%	1.8%	$0.5^{+0.5}_{-0.3}$	1

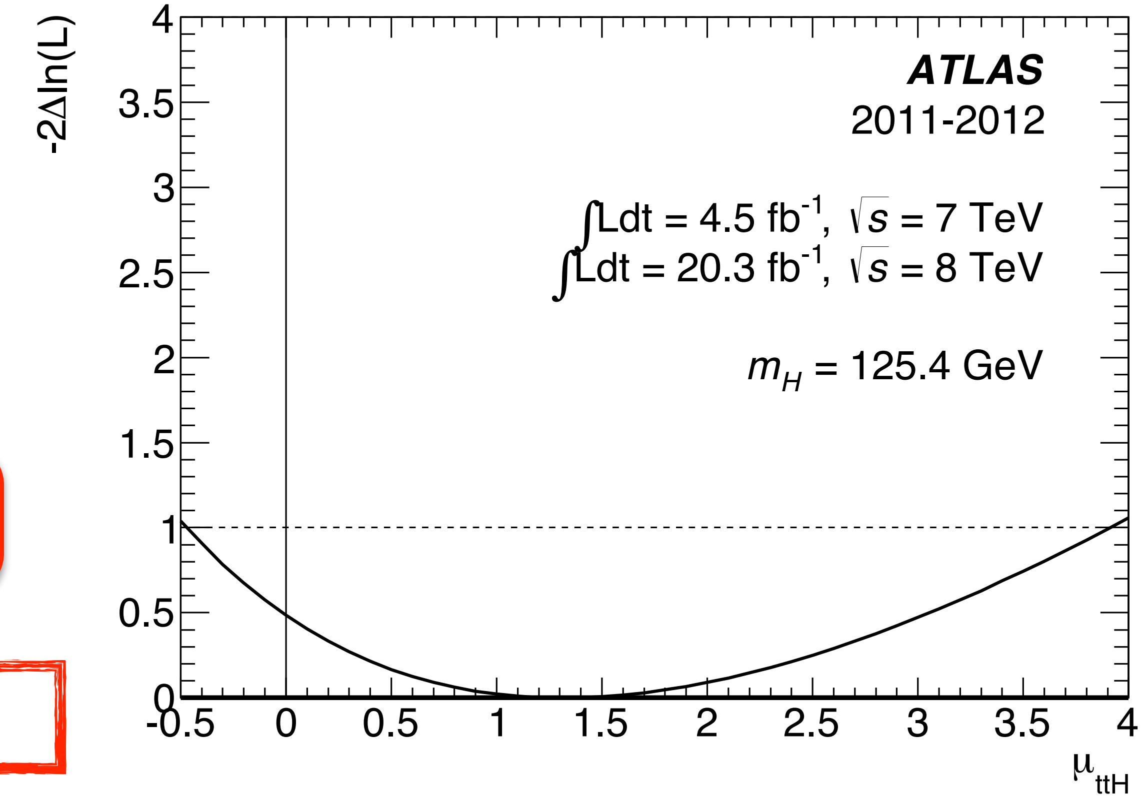
- Background $m_{\gamma\gamma}$ distribution described with *an exponential function*:
  - parameters derived in CR (inverting isolation or photon ID requirements)
  - normalization from sidebands in SR

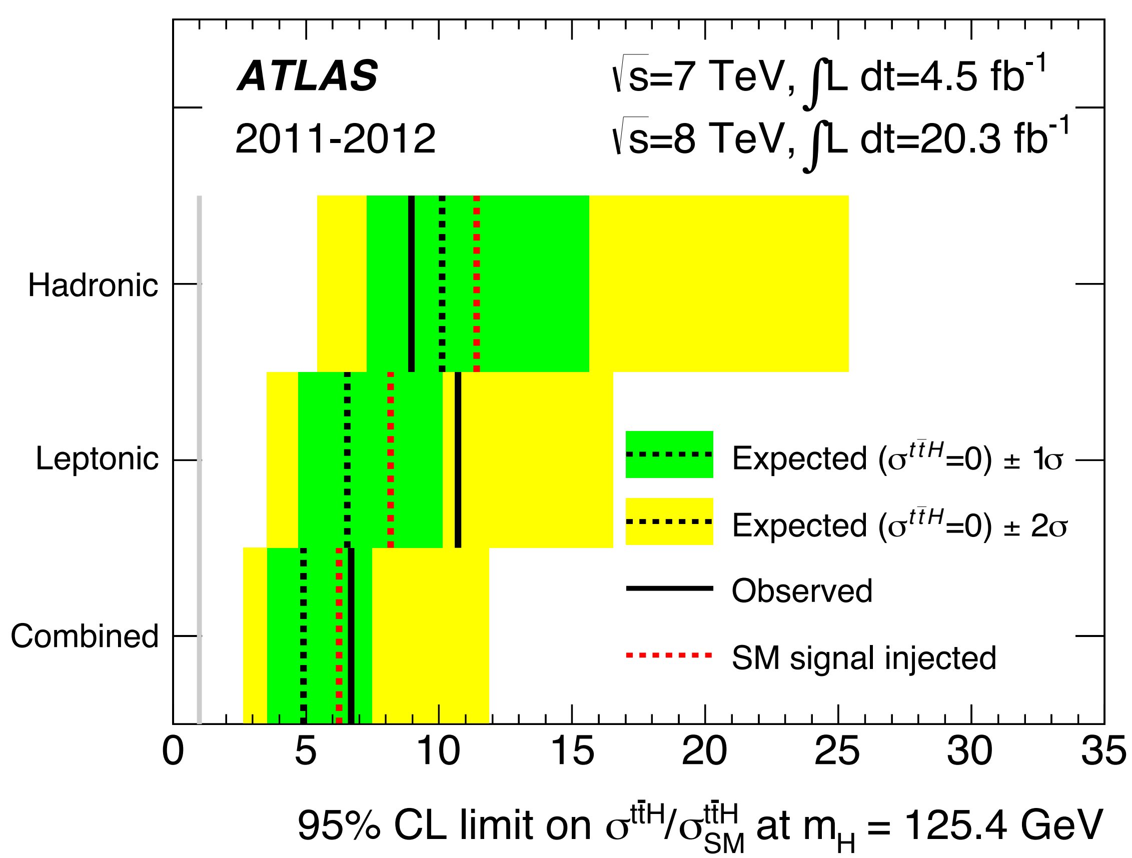


- Results obtained from a unbinned maximum likelihood of $m_{\gamma\gamma}$ distribution in the 4 regions:
  - main parameter: signal strength $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM}$
  - contribution from other Higgs boson production modes set at the SM values (theory uncertainties on normalization)

$$\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM} = 1.3 \ ^{+2.5}_{-1.7}(stat.) \ ^{+0.8}_{-0.4}(sys.)$$

result largely dominated by statistical uncertainty



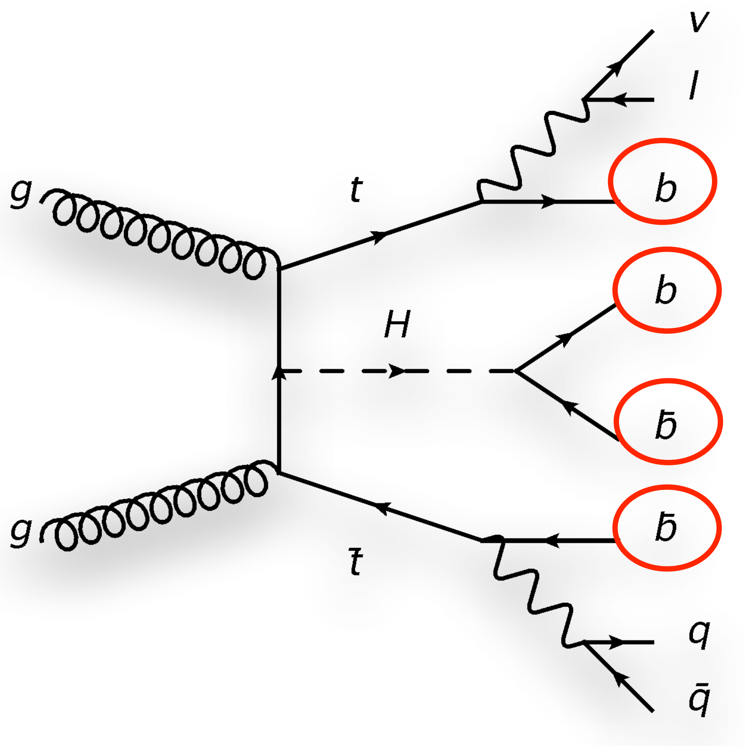


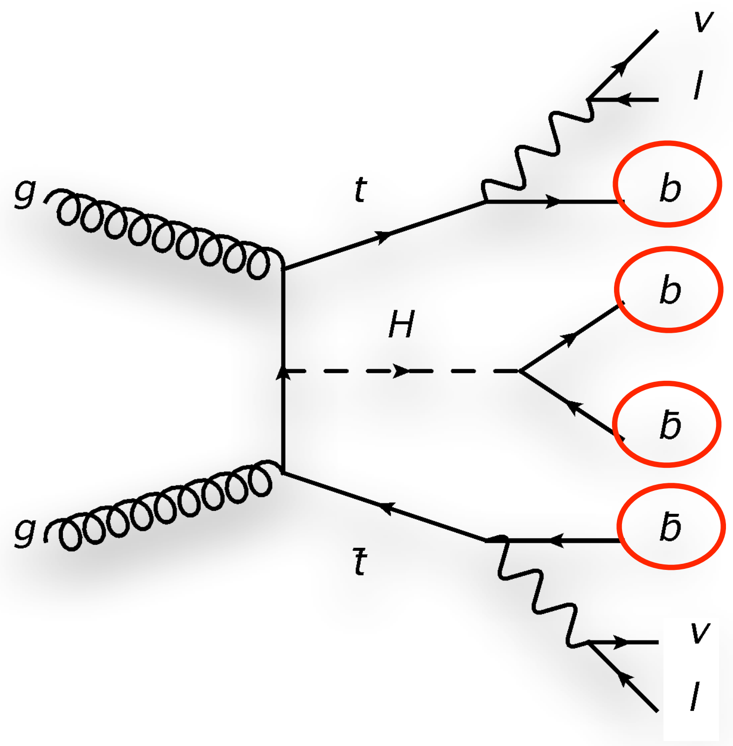
- Negligible contamination from other Higgs boson decay modes:
  - can interpret as upper limit on cross section times H->$\gamma\gamma$ branching ratio
- At 95% CL, for m_H=125.4 GeV:

observed σ*BR/(σ*BR)$_{SM}$ < 6.5

expected σ*BR/(σ*BR)$_{SM}$ < 4.9

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

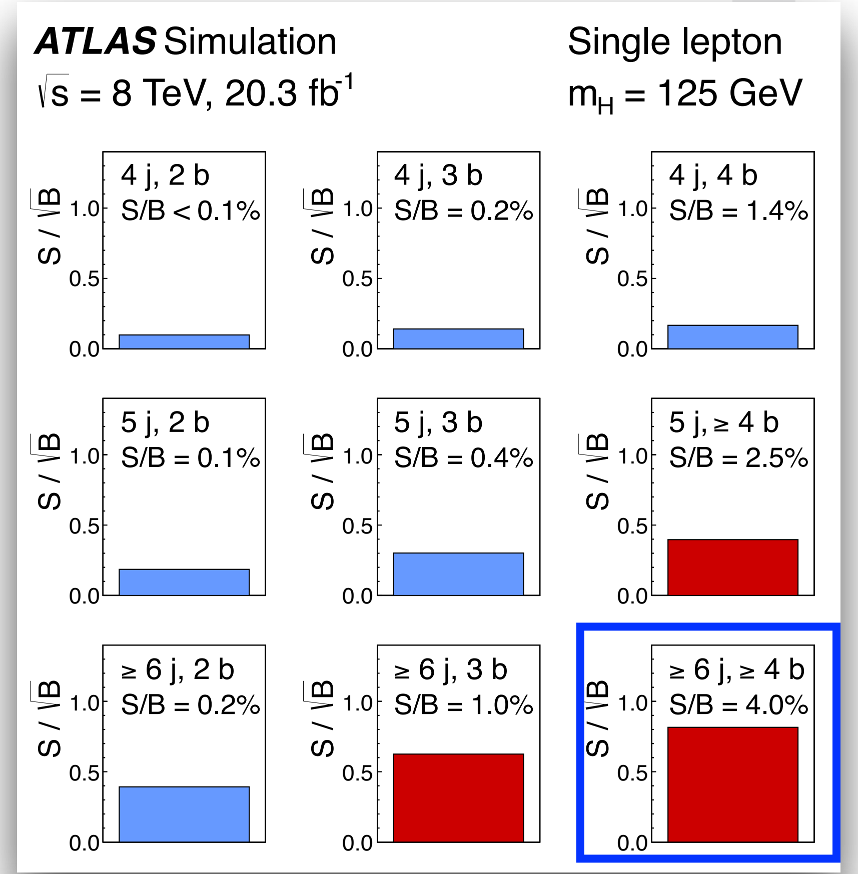


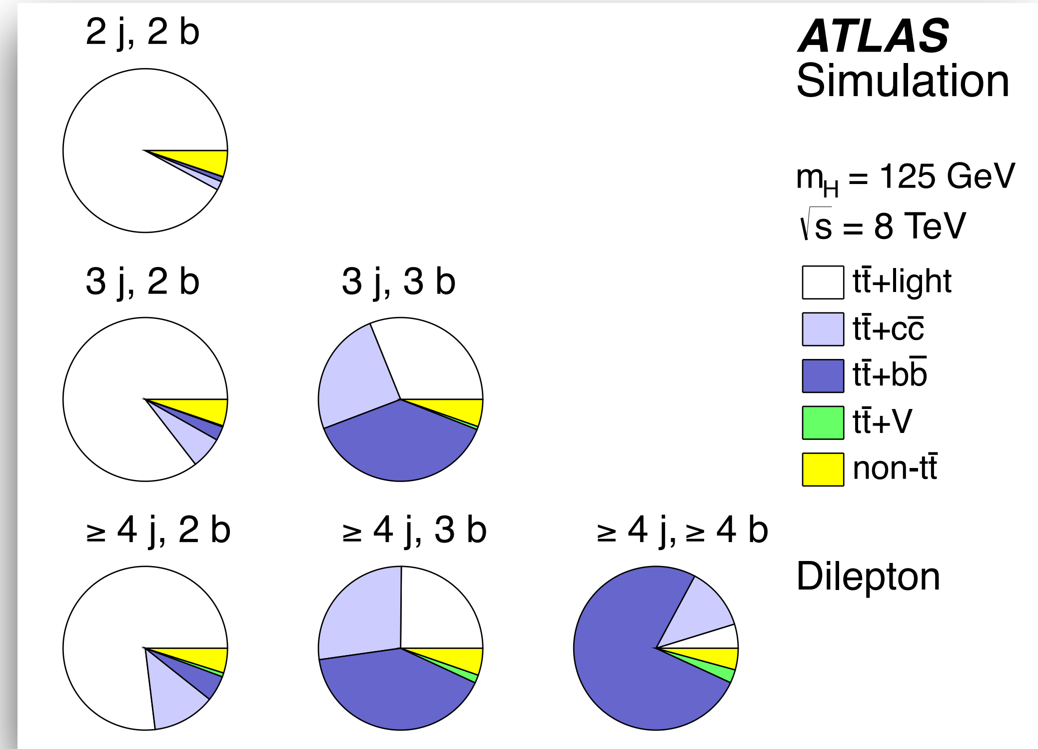


$t\bar{t}H$ ($H \to b\bar{b}$): strategy

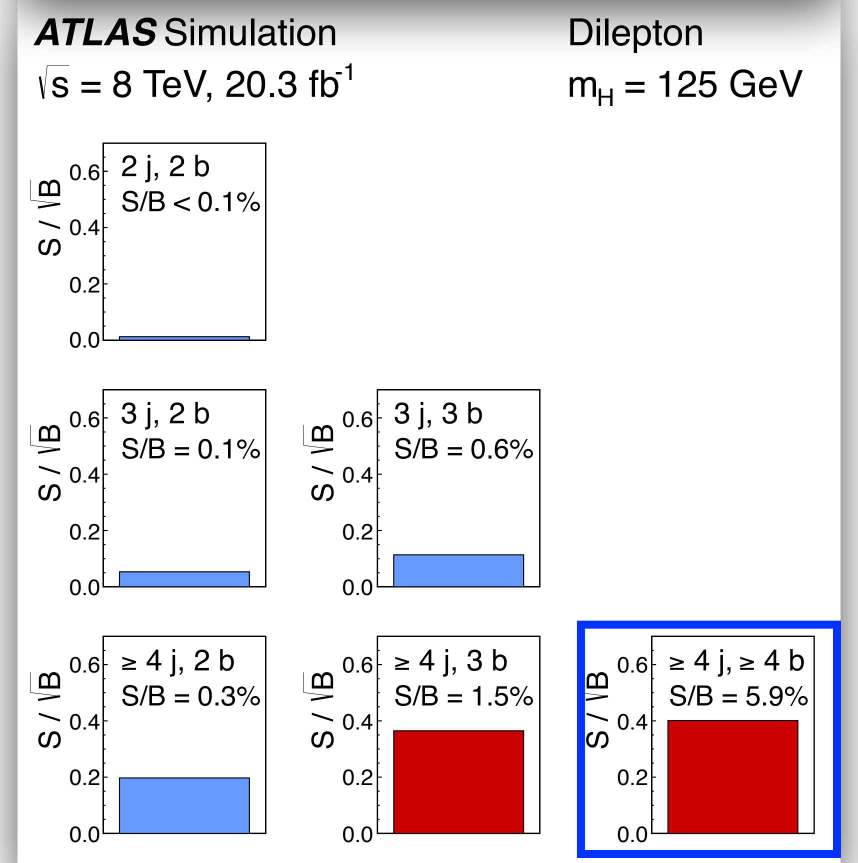
- 2 main channels:
  - *lepton+jets*: 1 lepton (electron or muon) [≥4 jets, ≥2 b-tags]
  - *di-lepton*: opposite sign lepton pair (ee, eμ, μμ) [≥2 jets, ≥2 b-tags]

- *Categorising events* according to the number of jets (p_T>25 GeV) and b-tagged jets (70% b-eff.):
  - *exploiting different S/B [and S/sqrt(B)] in each region*
  - ***signal depleted*** *and* ***signal enriched*** *regions*
  - *best S/B:* ***l+jets 4.0% , di-lepton 5.9%***

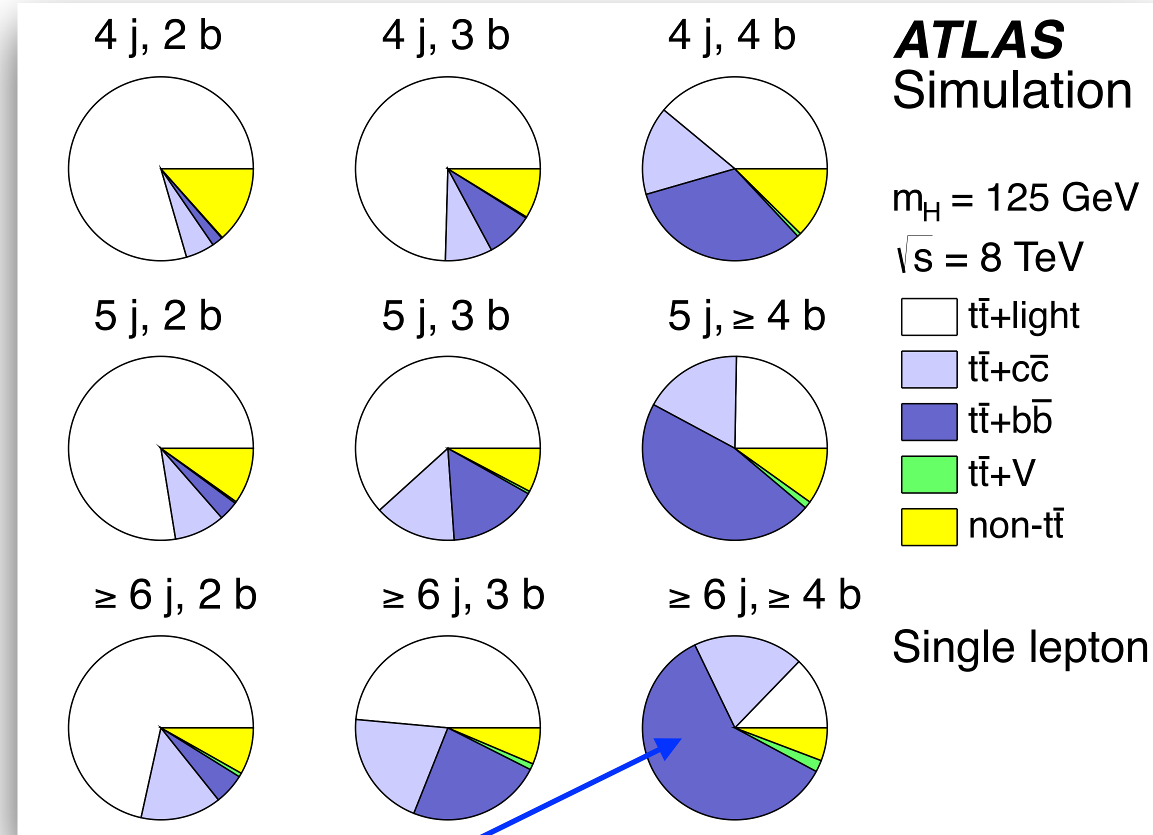




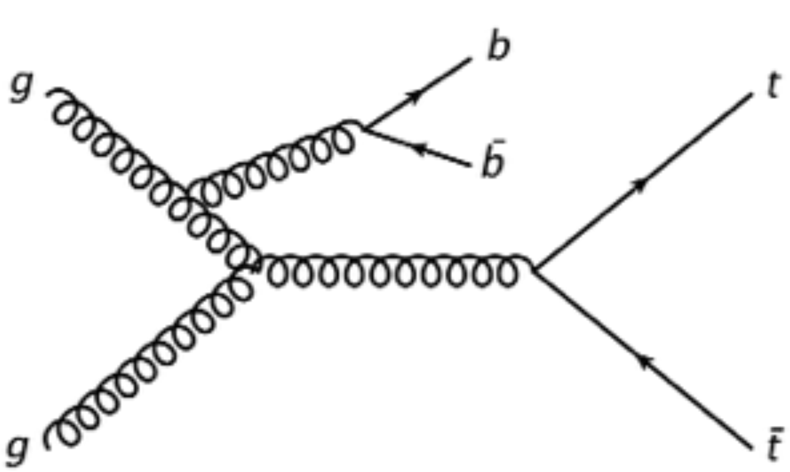
- *Variable background composition* across regions: used to control main background normalisation from data



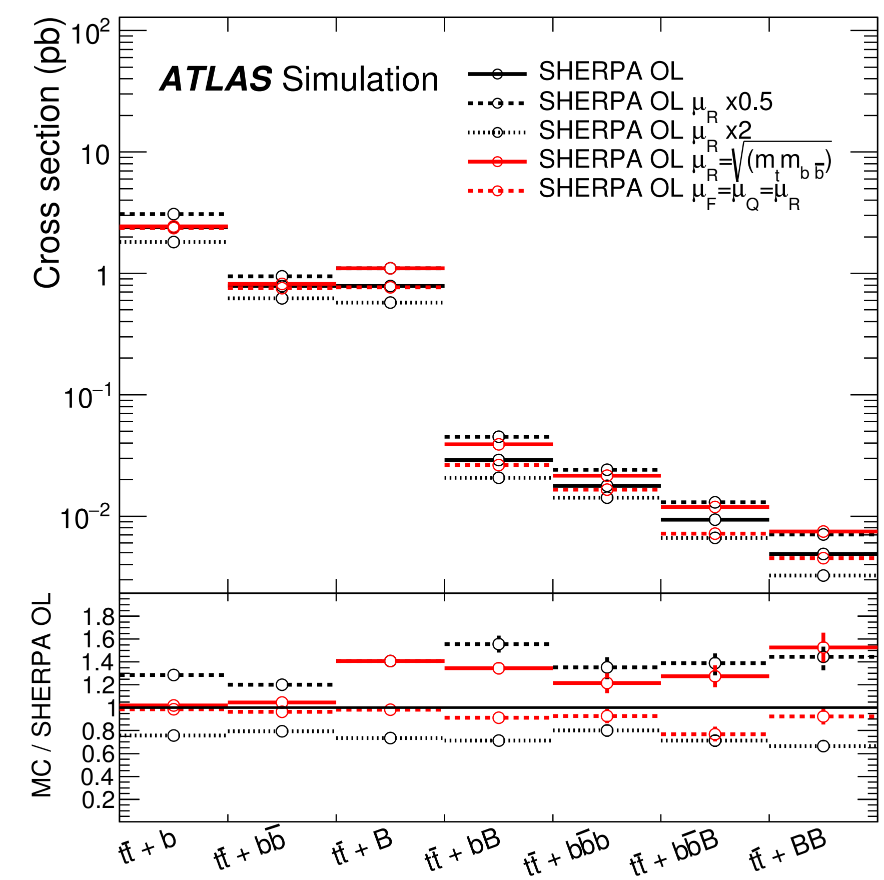
$t\bar{t}H$ (H->$b\bar{b}$): backgrounds



- Reducible backgrounds:
  - ***$t\bar{t}$+light jets / $t\bar{t}$+cc***: can enter signal-enriched regions by mis-tagging of light and c-jets. Predictions from Powheg +Pythia6 (with ttbar/top pt reweighting)
  - ***non-$t\bar{t}$:*** single top (largest), W+jets, Z+jets and di-bosons taken from MC, QCD Multijet fully data-driven.
- ***$t\bar{t}$+V***: partly irreducible ($t\bar{t}$Z Z->$b\bar{b}$) but very small expected contribution (< half of expected signal in 4b-tags regions)
- ***$t\bar{t}$+$b\bar{b}$***: main irreducible background
  - distribution across analysis regions strongly depends on bb kinematic

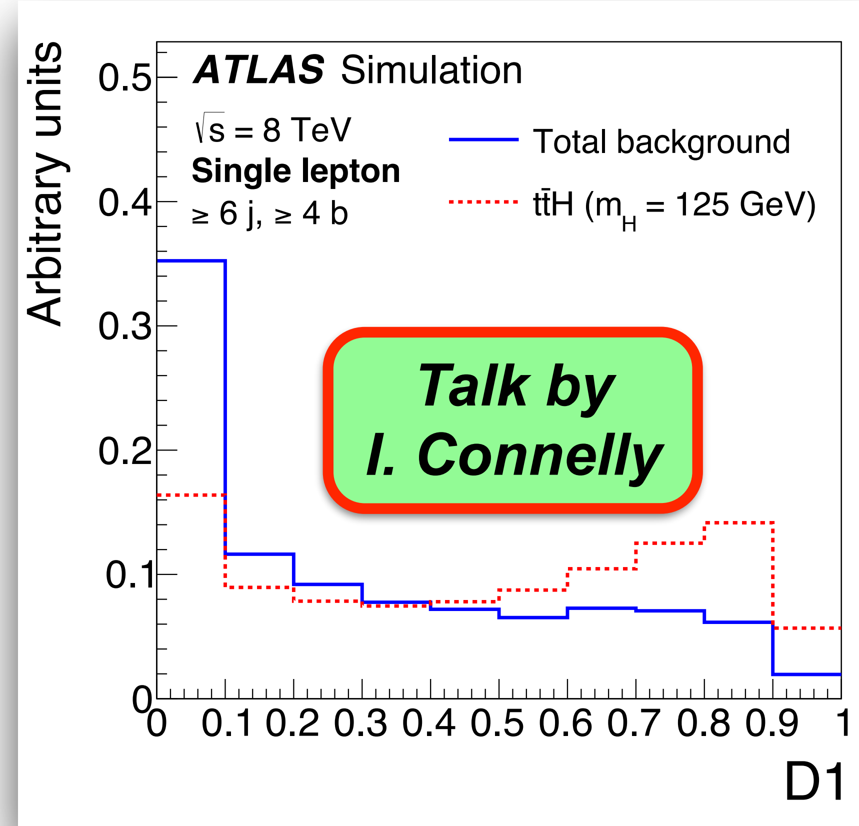


  - Powheg+Pythia6 events reweighted to *Sherpa OpenLoops NLO predictions* (both relative amount of each b-hadron category and kinematic within each category)
  - *50% normalisation uncertainty* + modelling uncertainties from Sherpa OpenLoops generation parameters

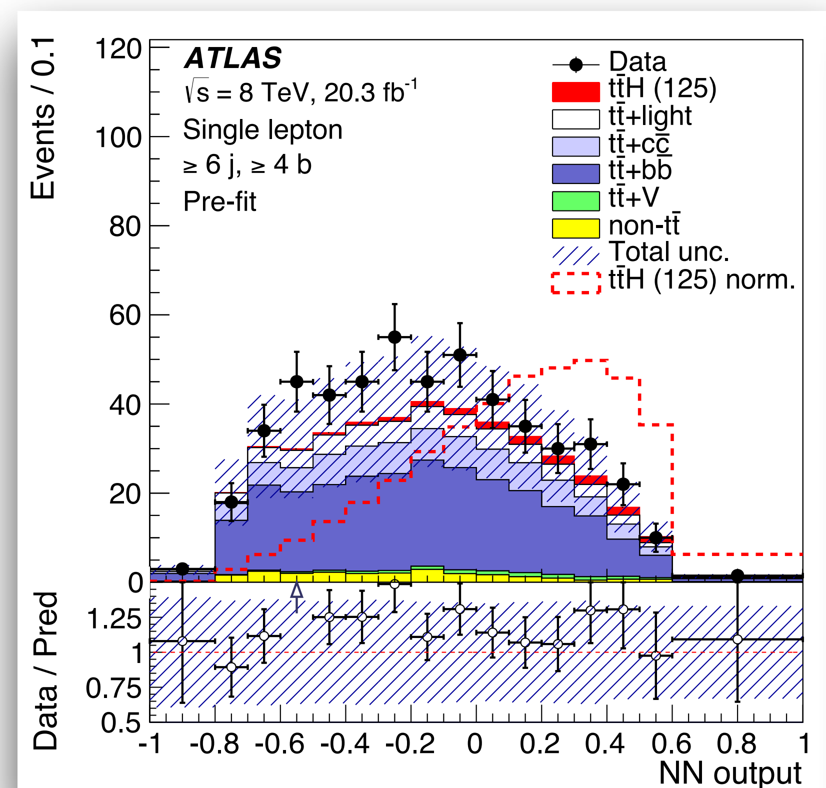


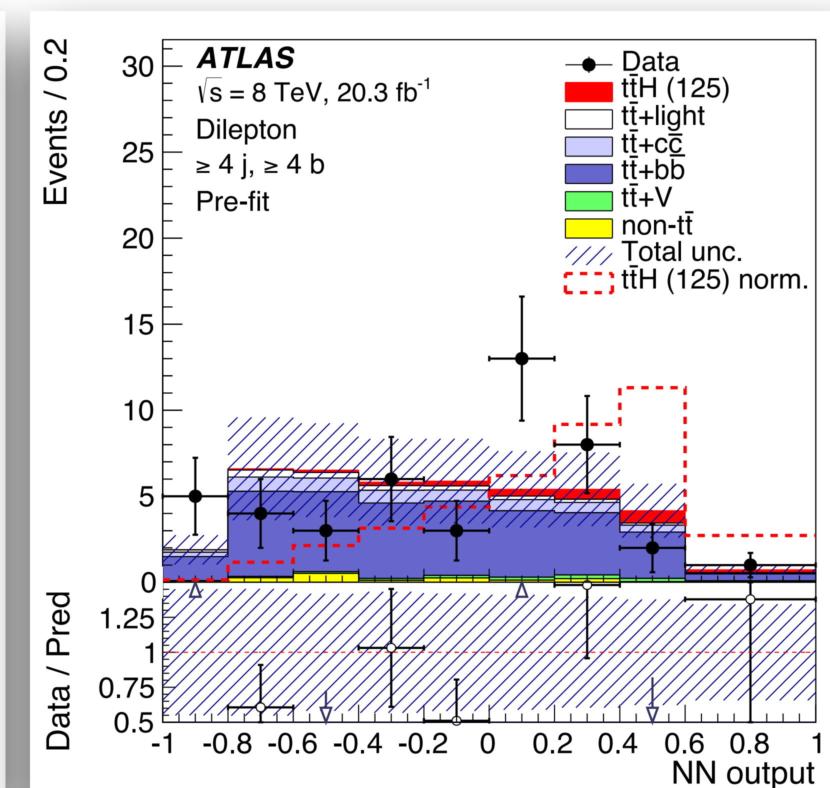
$t\bar{t}H$ ($H \to b\bar{b}$): discriminant

- Fitting a discriminant distribution in each analysis region:
  - *signal-depleted regions*:
    H_T= scalar sum of jet (and lepton) p_Ts for the single lepton (di-lepton) analysis.
  - *signal-enriched regions*:
    ***MVA output**= neural network discriminant* trained for the best separation of signal from background in each region. In *l+jets* (5j, 3b) region the NN is trained to separate ttbar+light from ttbar+HF



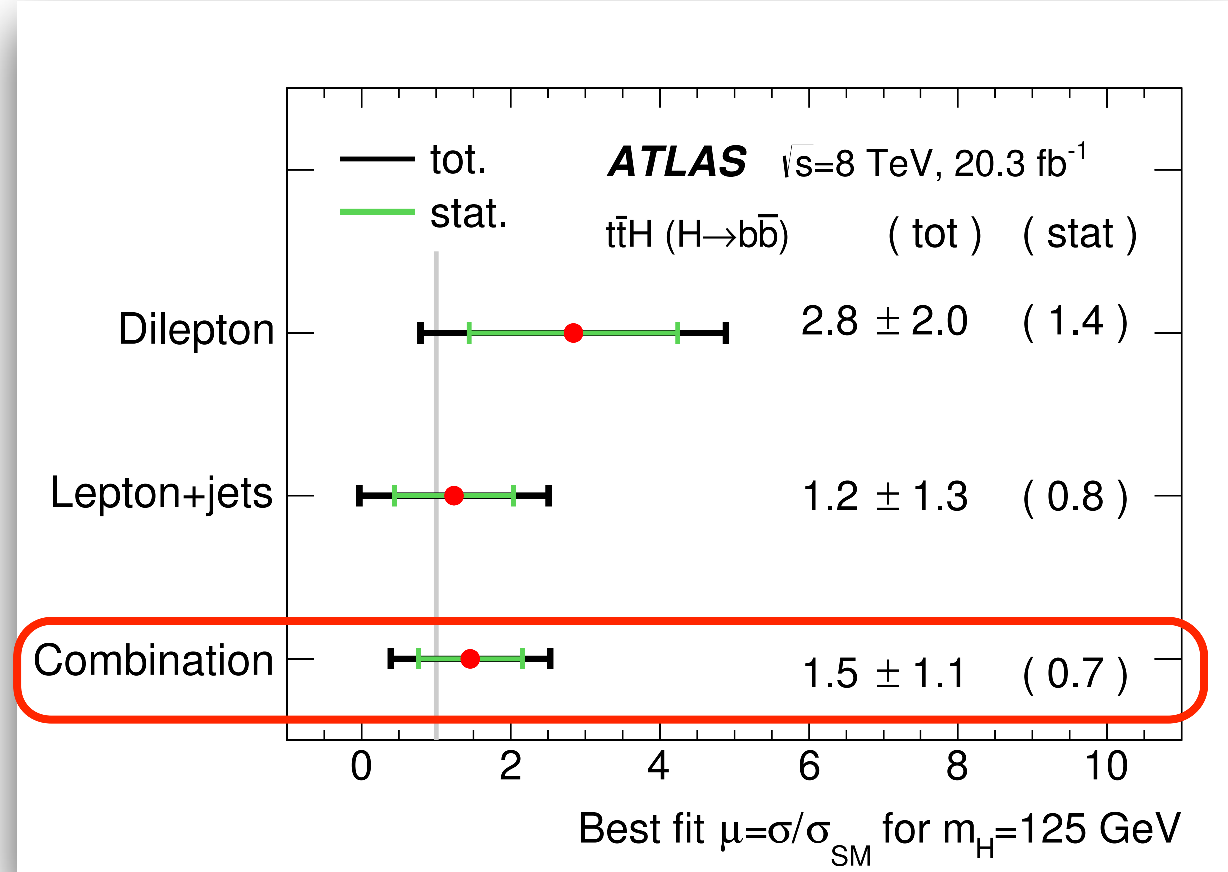
- Large variety of variables considered (list optimised separately in each region):
  - ***single object kinematics***: jet p_Ts
  - ***global event kinematics***: centrality, aplanarity, H_T, ….
  - ***di-jet pair properties***: ΔR_{bb}^{maxpt}, $m_{bb}^{min\Delta R}$ (targeting partial event reconstruction)
  - **(*l+jets* only) matrix element discriminants:** Neyman-Pearson D1, …

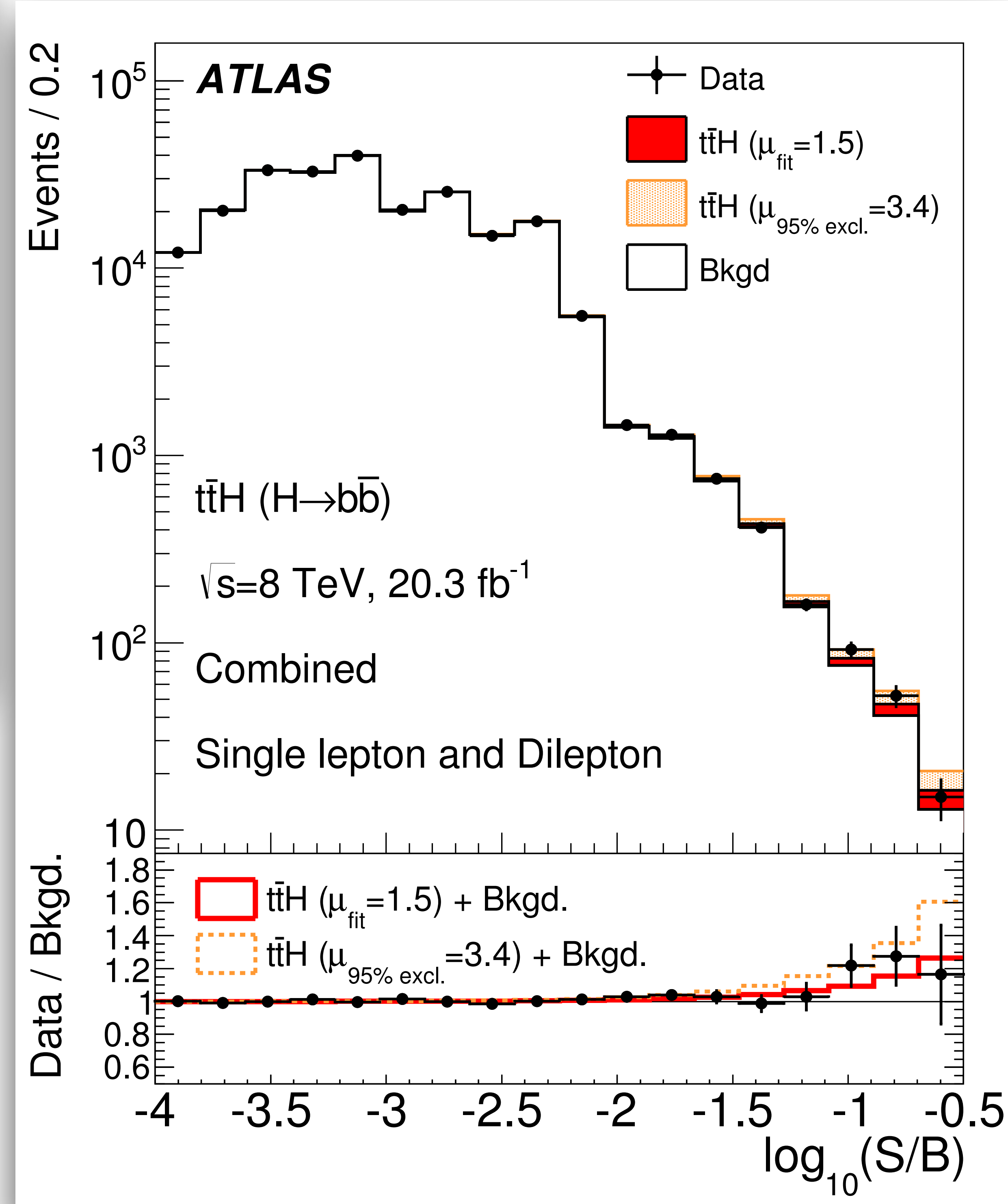




$t\bar{t}H$ ($H \to b\bar{b}$): results

- Performing simultaneous profile likelihood fit to all the 15 regions:





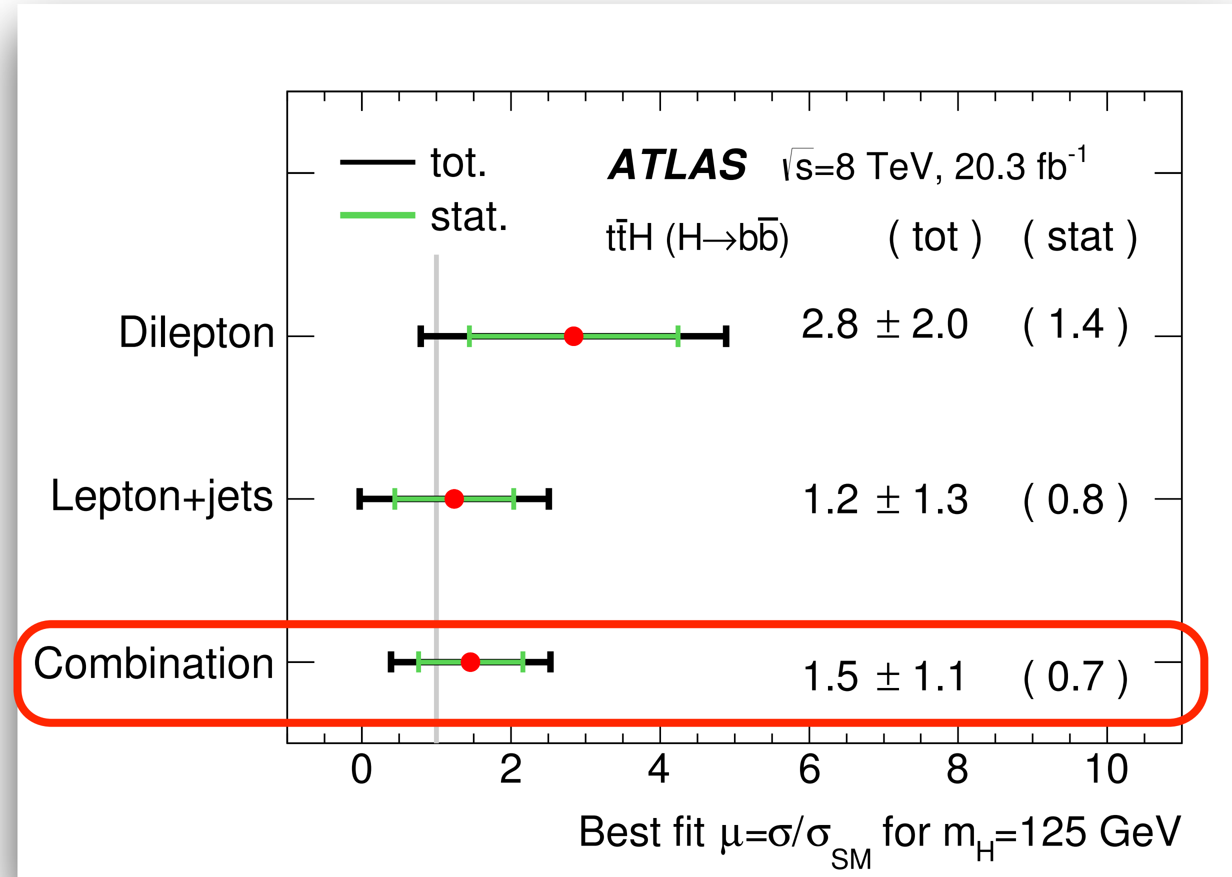
- At 95% CL, for m_H=125 GeV:

observed σ*BR/(σ*BR)$_{SM}$ < 3.4

expected σ*BR/(σ*BR)$_{SM}$ < 2.2

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

- Performing simultaneous profile likelihood fit to all the 15 regions:

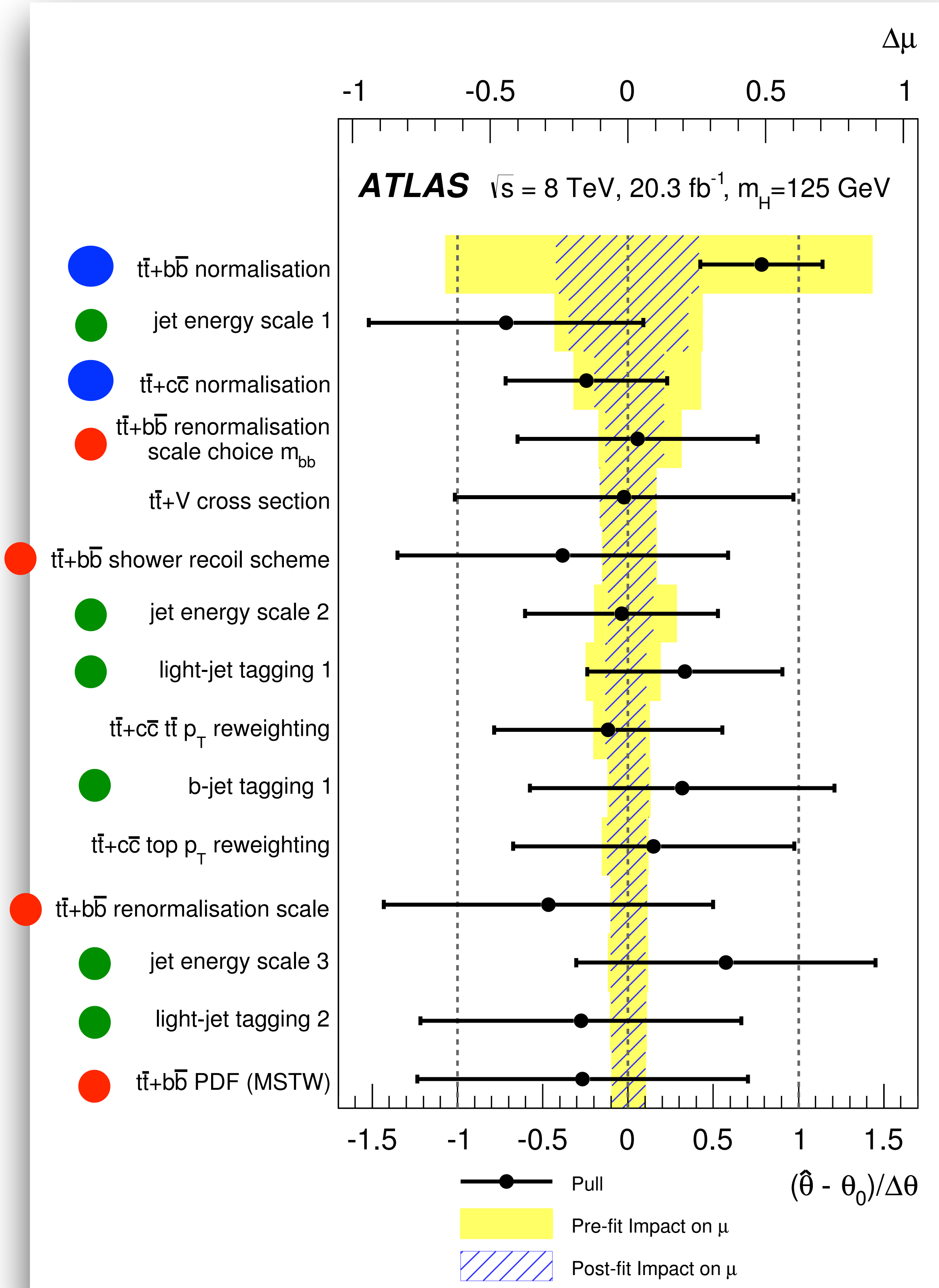


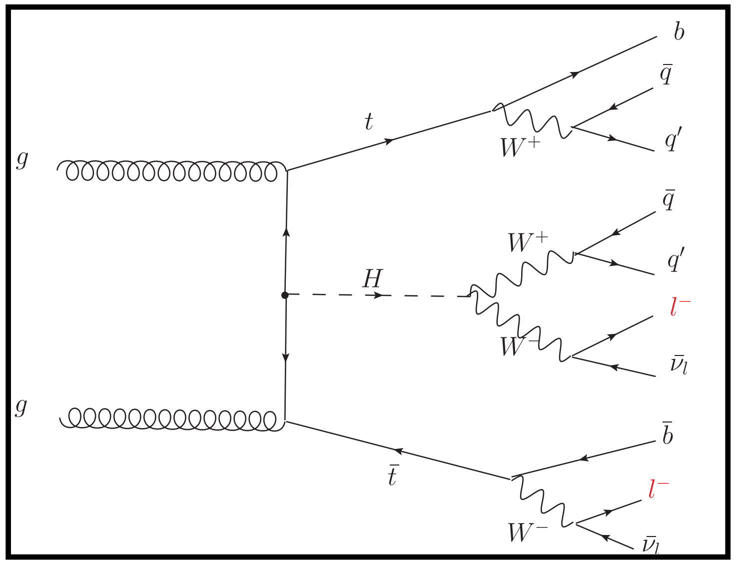
- At 95% CL, for m_H=125 GeV:

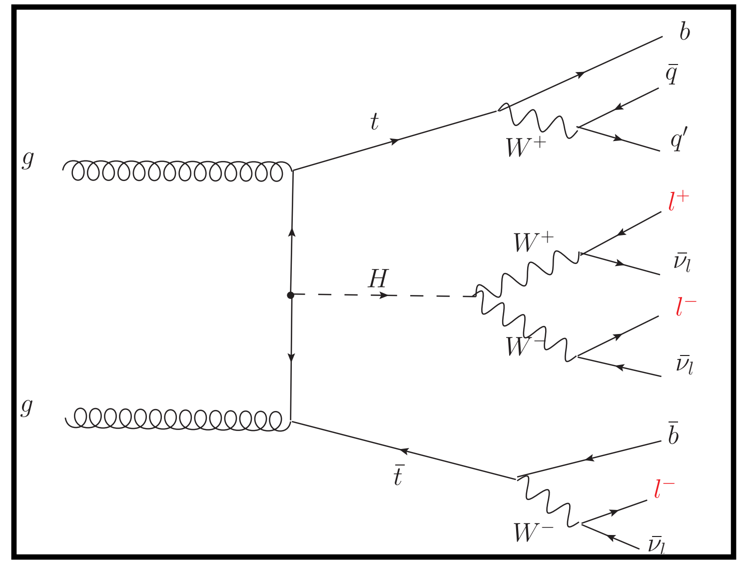
observed σ*BR/(σ*BR)$_{SM}$ < 3.4

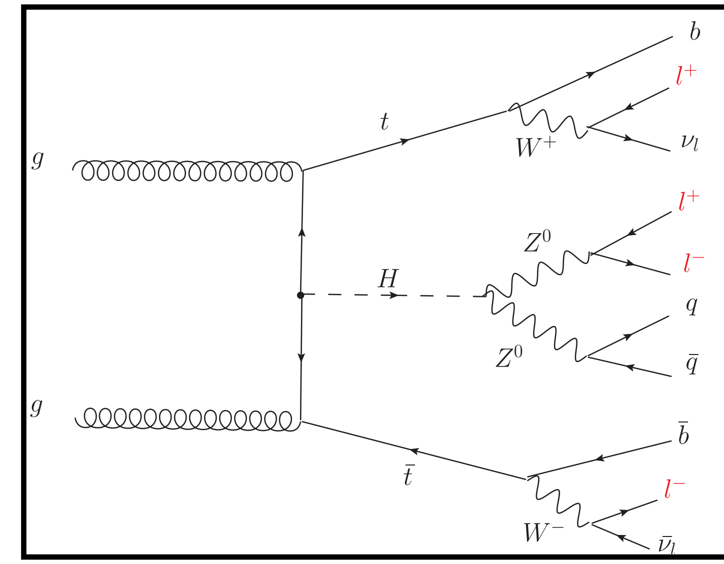
expected σ*BR/(σ*BR)$_{SM}$ < 2.2

- Analysis dominated by systematic uncertainties:
  - *normalisation of tt+bb̄/tt+cc events*, ttbar+bb̄ modelling, *detector effects (jet energy scale, flavour tagging)*

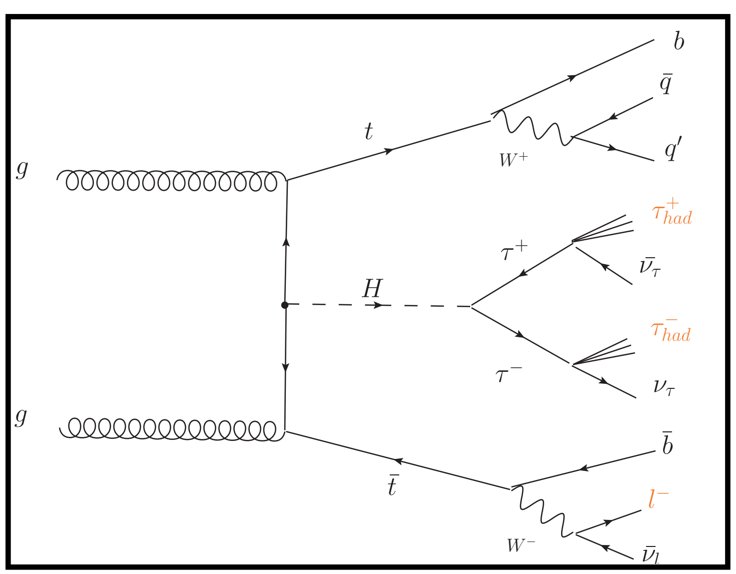


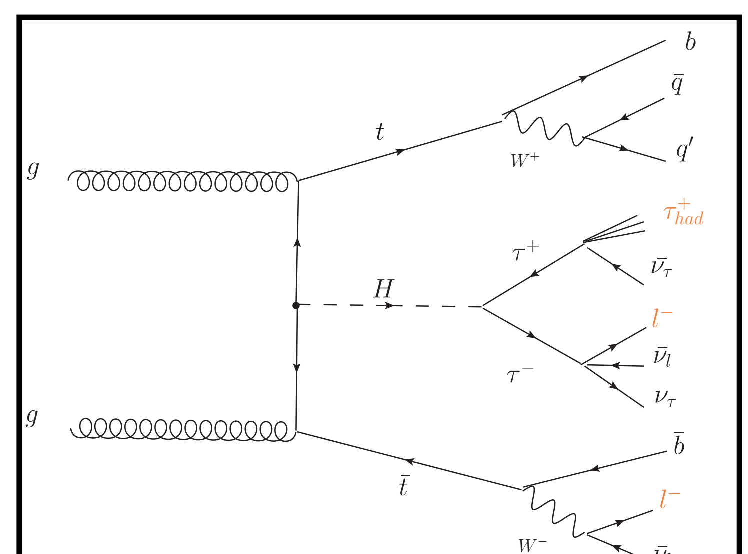






$t\bar{t}H$ multilepton final states





$t\bar{t}H$ multilepton: strategy

- 5 different final states with multiple electrons/muons/ (hadronically decaying tau leptons):
  - consider only combinations that *can not originate from ttbar events* —> reducing the largest background
  - mainly targeting ***H->WW**** and ***H->ττ*** decay modes

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\mathrm{had}}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\mathrm{had}}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\mathrm{had}}$	4%	93%	0%	3%

$2\ell 0\tau_{had}$:
- **same sign (SS)** light lepton pair ($|\eta_{ele}|<1.37$)
- ≥4 jets, ≥1 b-tagged
- *6 SRs*: ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$) ⊗ (4 jets, ≥5 jets)

$1\ell 2\tau_{had}$:
- opposite sign tau pair
- ≥3 jets, ≥1 b-tagged jet
- *1 SR*: 60 GeV < $m_{\tau\tau}$< 120 GeV

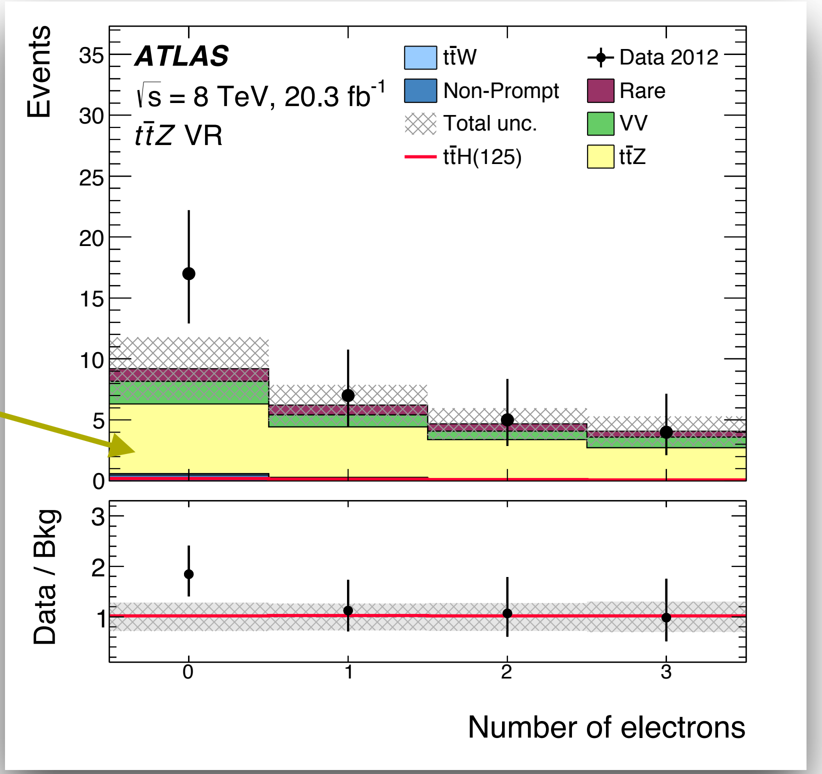
$2\ell 1\tau_{had}$:
- **same sign** ($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$) pair + opposite sign τ_{had}
- Z veto for $e^{\pm}e^{\pm}\tau_{had}$ channel
- *1 SR*: (≥4 jets, ≥1 b-jet)

4ℓ (only electrons and muons):
- Σcharge=0
- ≥2 jets, ≥1 b-tagged jet
- 100 GeV < m_{4l} < 500 GeV
- *2 SRs*: Z-enriched / Z-depleted region with / without opposite sign, same flavour lepton pair

3ℓ (only electrons and muons):
- Σ|charge|=1
- Z veto and m_{ll}>12 GeV for opposite sign same flavour pair
- *2 SRs*: (≥4 jets, ≥1 b-jet) + (3 jets, ≥2 b-jets)

$t\bar{t}$+Z: dominant background in 3ℓ, 4ℓ and $2\ell 1\tau_{had}$ channels

- estimated from MC: 5% - 30% norm uncertainties (generators comparison)
- validation region from 3ℓ selection with on-shell Z

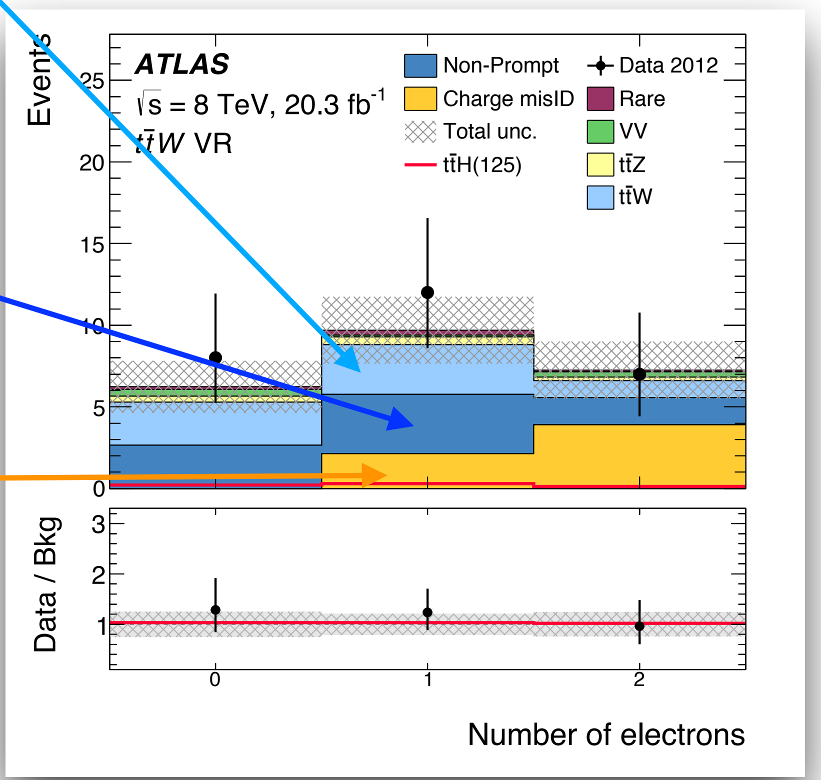


dibosons: subdominant prompt lepton background

- validation from 3 lepton region with 0-1 b-jets (<4jets)
- 100% uncertainty on WZ+b

$t\bar{t}$+W: dominant background in $2\ell 0\tau_{had}$, $2\ell 1\tau_{had}$

- estimated from MC: 5% - 30% norm uncertainties (generators comparison)
- validation from 2l SS (2-3 jets, ≥2 b-jets)



non-prompt (light) leptons: important background in $2\ell 0\tau_{had}$, $2\ell 1\tau_{had}$

- mainly from b-jets in $t\bar{t}$ events
- fake rate estimated from data in control regions

charge mis-ID leptons: only important for SS analyses with electrons

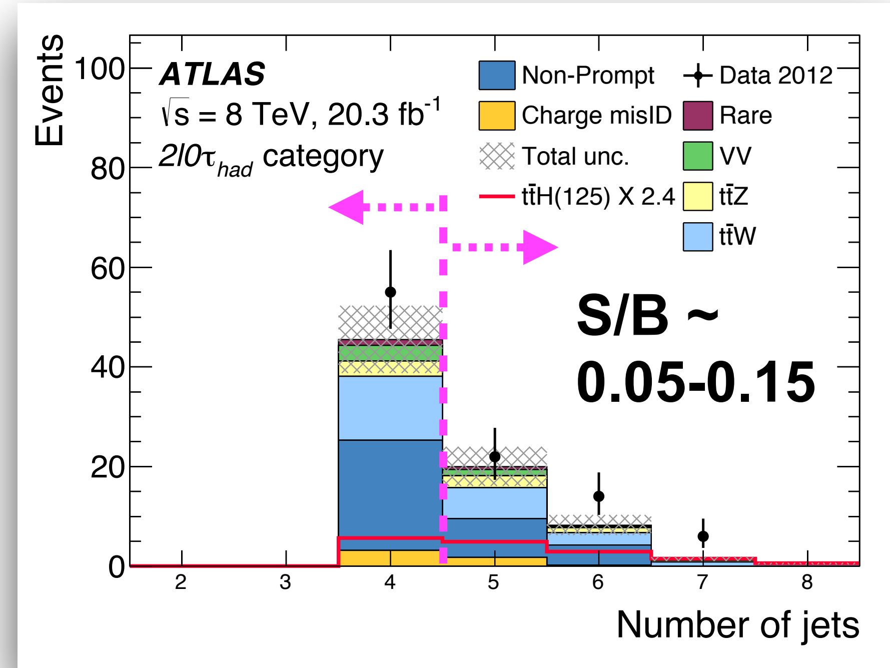
- charge misID rate extracted from same sign events in Z peak

fake taus (from jets): dominant background in $1\ell 2\tau_{had}$ channel

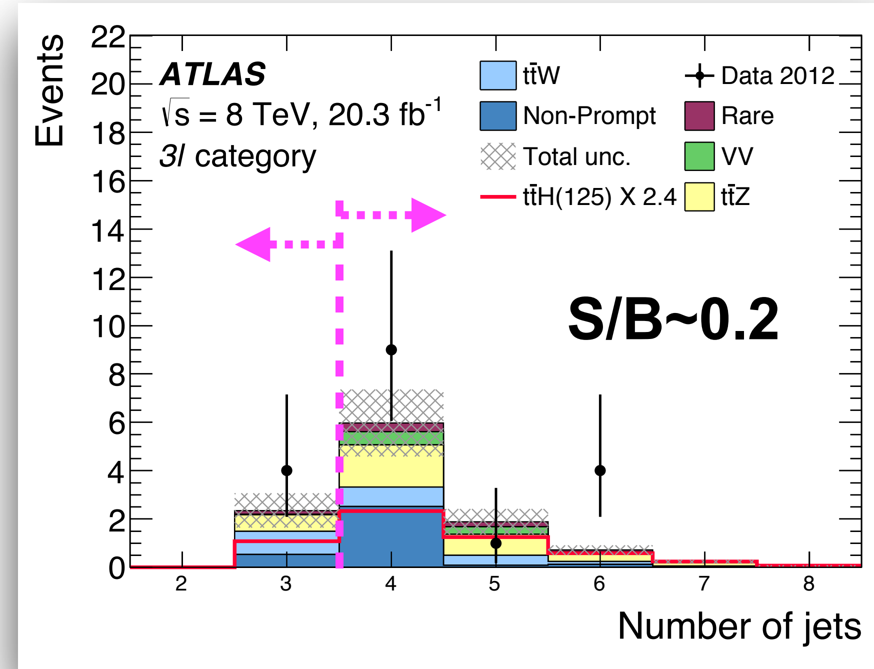
- estimated from MC (mainly $t\bar{t}$ events)
- validated in data (changing charge requirement + looser tau ID)

$t\bar{t}H$ multilepton: signal regions

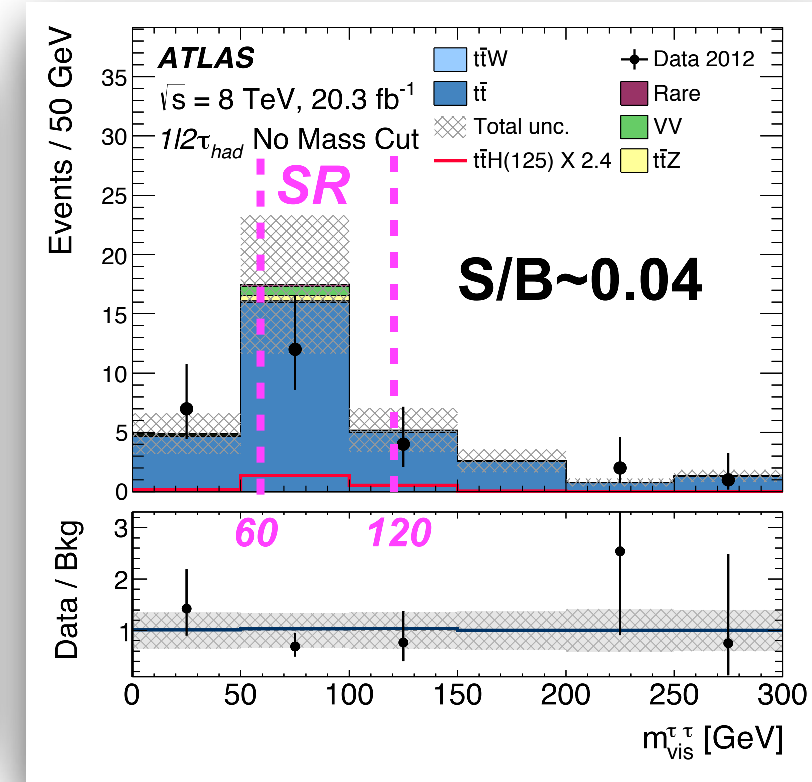
$2\ell 0\tau_{had}$

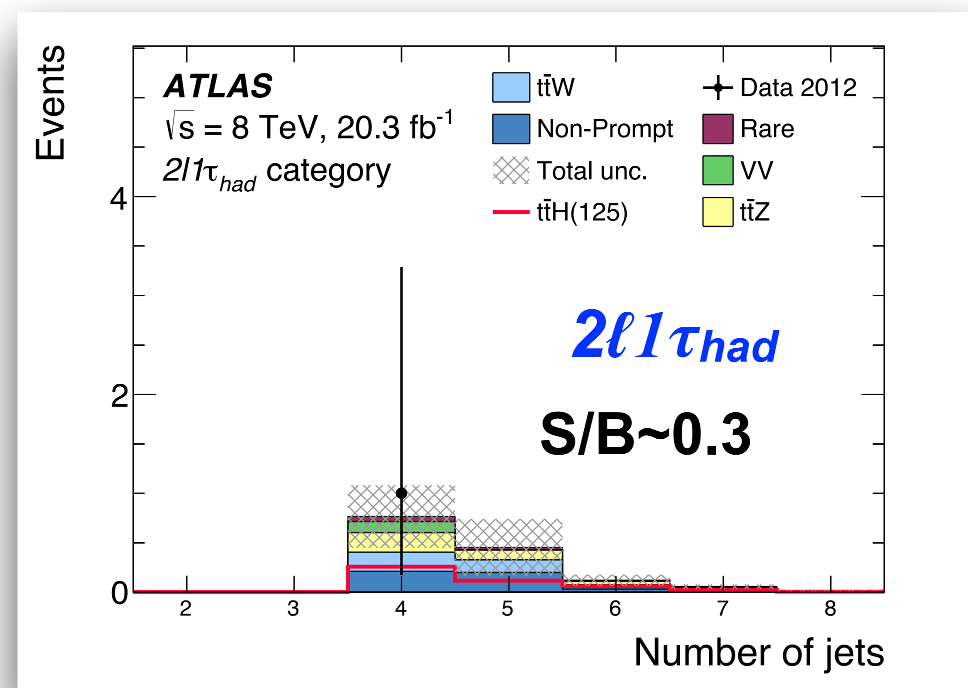


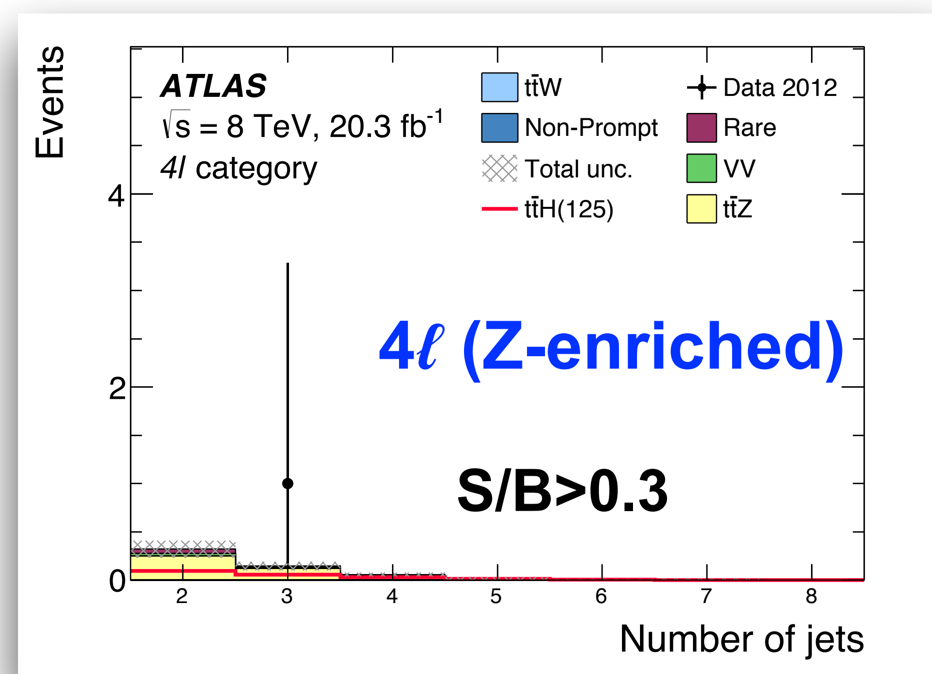
3ℓ



$1\ell 2\tau_{had}$

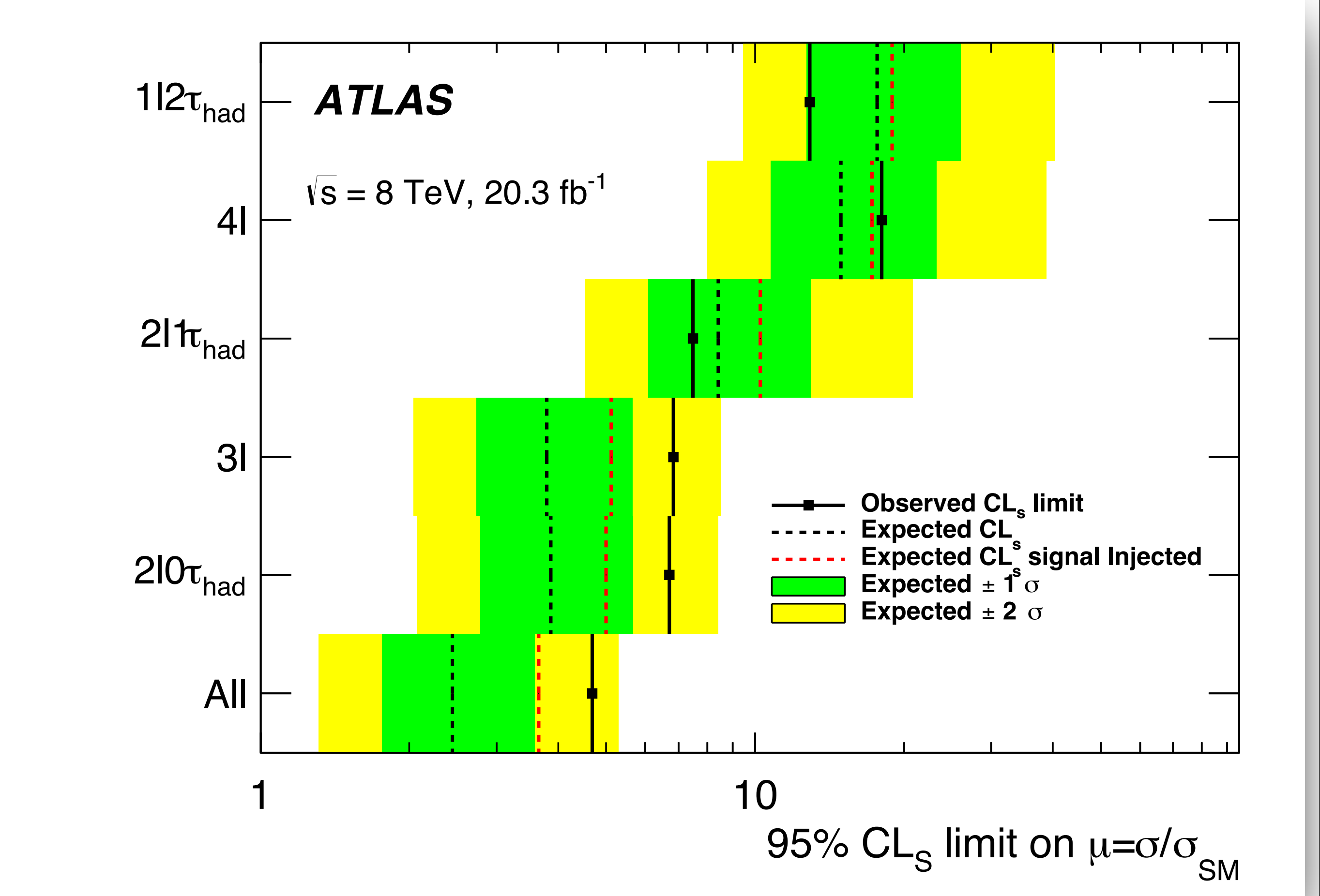






- Results obtained from a simultaneous fit in all the channels (no shape information used):
  - sensitivity dominated by **$2\ell 0\tau_{had}$** and **3ℓ** analyses
  - combination performed assuming SM Higgs boson branching ratios
- Best fit signal strength:

$$\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}^{SM} = 2.1\,^{+1.4}_{-1.2}\,[^{+1.1}_{-1.0}(stat.)]$$



Source	$\Delta\mu$	
$2\ell 0\tau_{\rm had}$ non-prompt muon transfer factor	+0.38	−0.35
$t\bar{t}W$ acceptance	+0.26	−0.21
$t\bar{t}H$ inclusive cross section	+0.28	−0.15
Jet energy scale	+0.24	−0.18
$2\ell 0\tau_{\rm had}$ non-prompt electron transfer factor	+0.26	−0.16
$t\bar{t}H$ acceptance	+0.22	−0.15
$t\bar{t}Z$ inclusive cross section	+0.19	−0.17
$t\bar{t}W$ inclusive cross section	+0.18	−0.15
Muon isolation efficiency	+0.19	−0.14
Luminosity	+0.18	−0.14

- At 95% CL, for m_H=125 GeV:

observed σ/σ_{SM} < 4.7

expected σ/σ_{SM} < 2.4

- **Most analyses are still statistically limited**:
  - *largest systematic uncertainties:* non-prompt contribution in SS analyses and ttW acceptance

$t\bar{t}H$ multilepton: results

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  - sensitivity dominated by **$2\ell0\tau_{had}$** and **3ℓ** analyses
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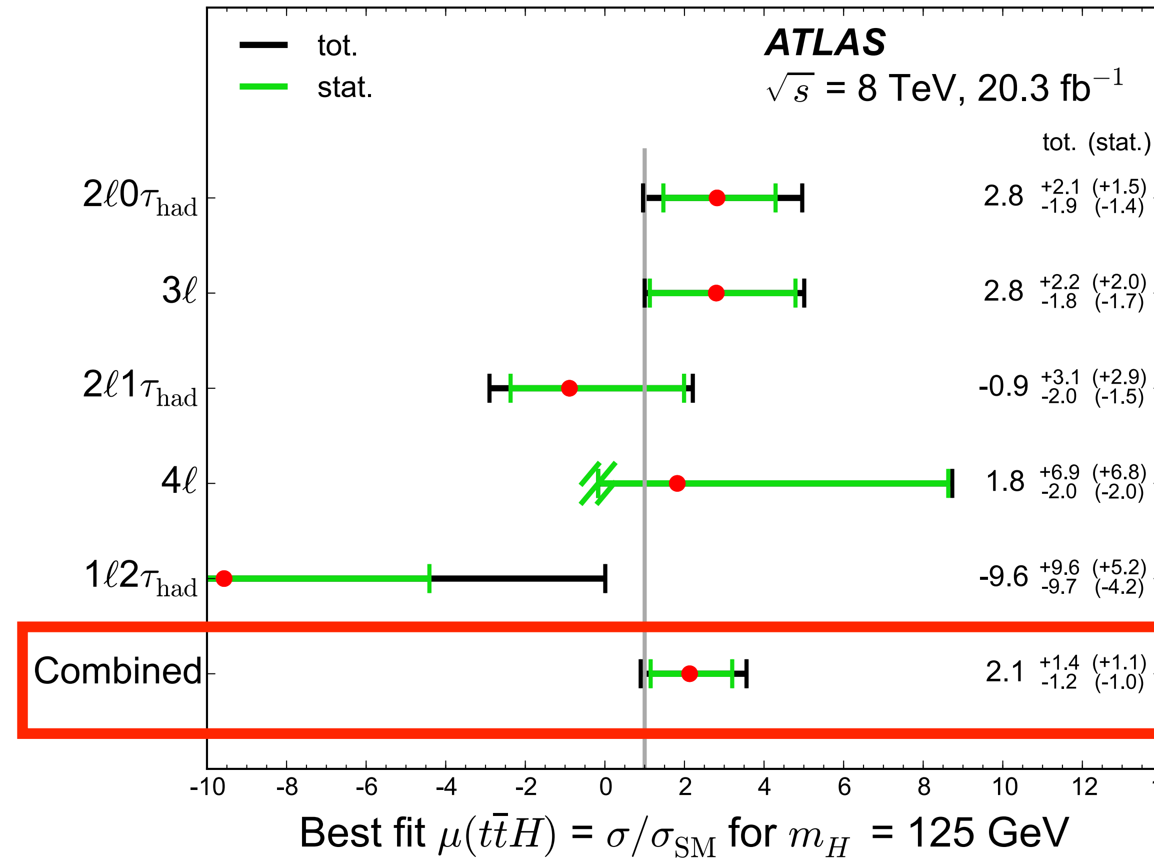
- Best fit signal strength:

$$\sigma_{t\bar{t}H}/\sigma^{SM}_{t\bar{t}H} = 2.1\,^{+1.4}_{-1.2}\,[^{+1.1}_{-1.0}(stat.)]$$

- *1.8 σ excess* (0.9 expected)



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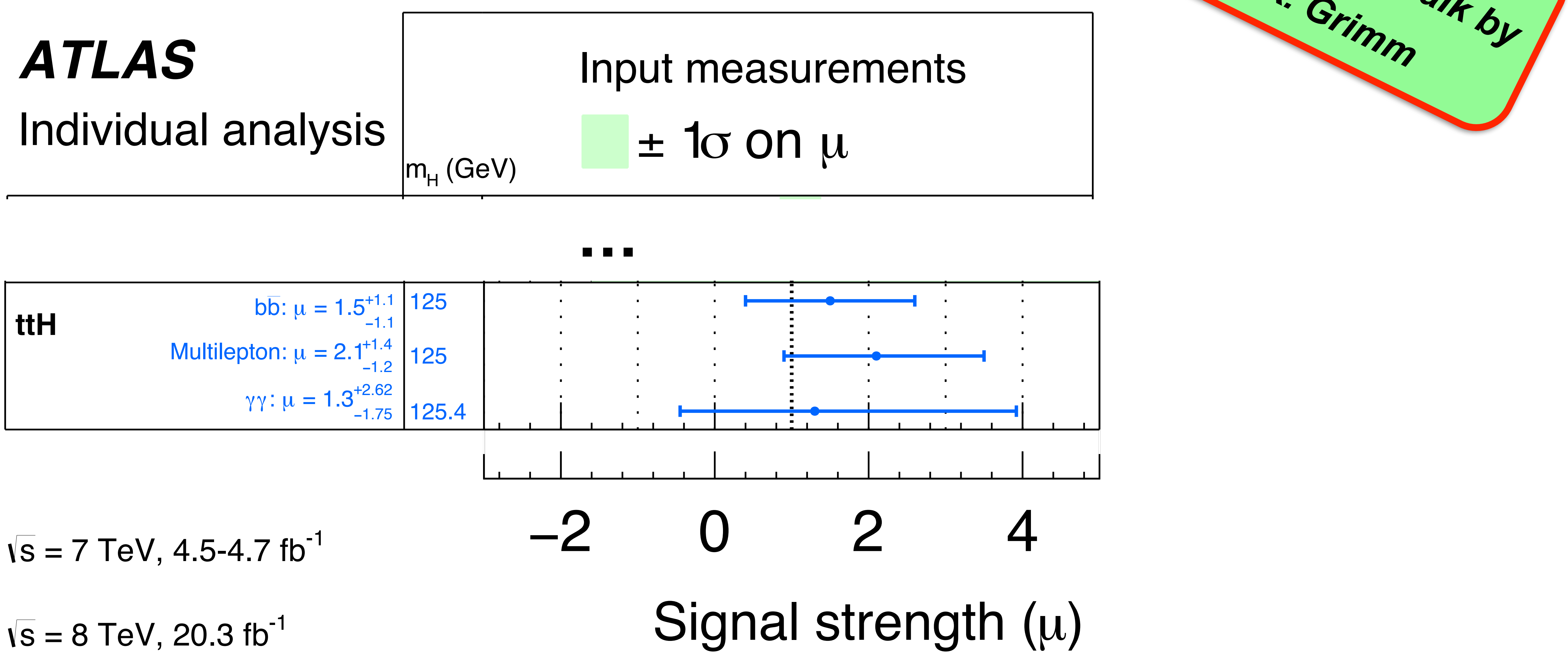
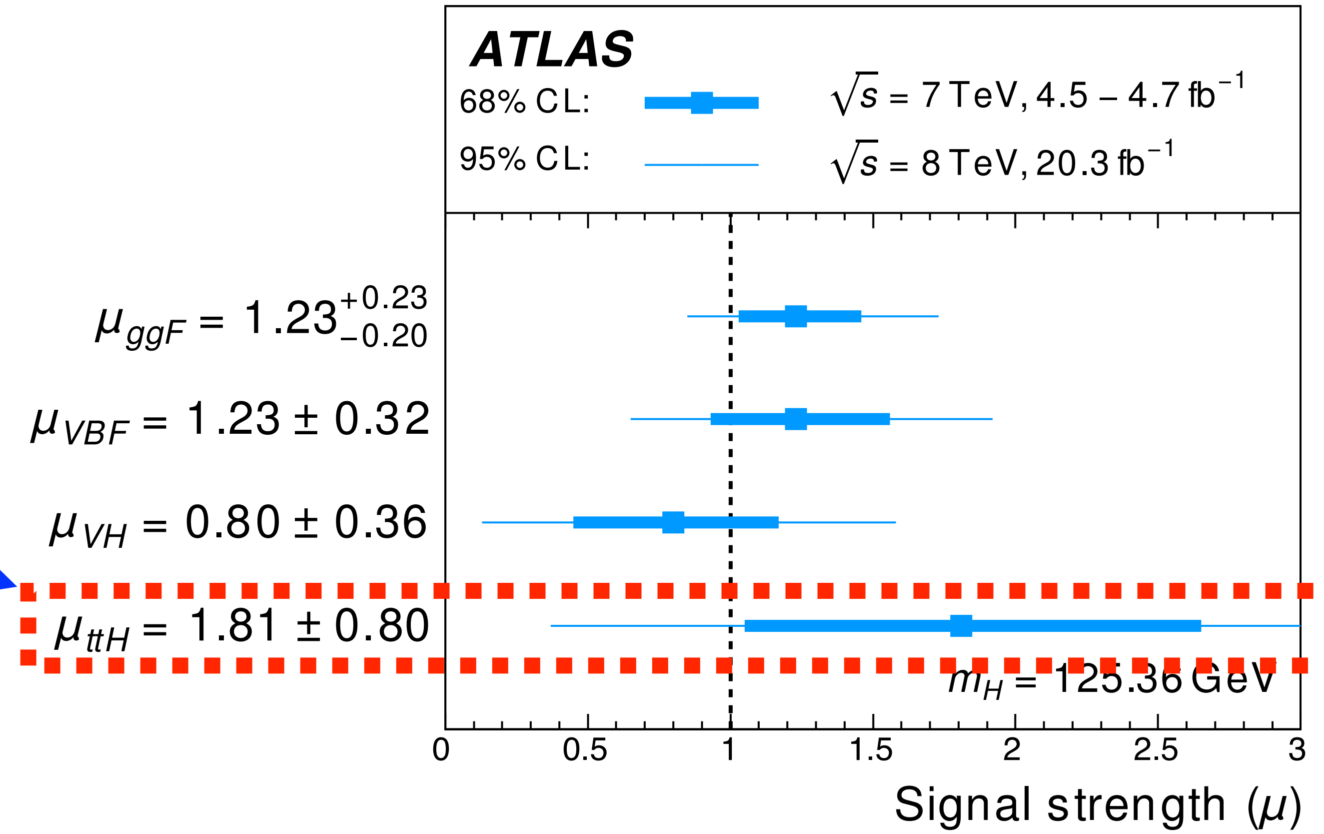


- Results from: arXiv:1507.04548 (submitted to EPJC)

"Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at sqrt(s) = 7 and 8 TeV in the ATLAS experiment"

$t\bar{t}H$ combination

- $t\bar{t}H$ combination as part of the ATLAS Higgs coupling combination:
  - correlation with other Higgs analyses not so large
- Probing different Higgs production modes individually:
  - *assuming SM Higgs boson branching ratios*



	observed	*expected*
signal significance	**2.5 s.d.**	**1.5 s.d.**
95% upper limit on σ	**3.2**	**1.4**

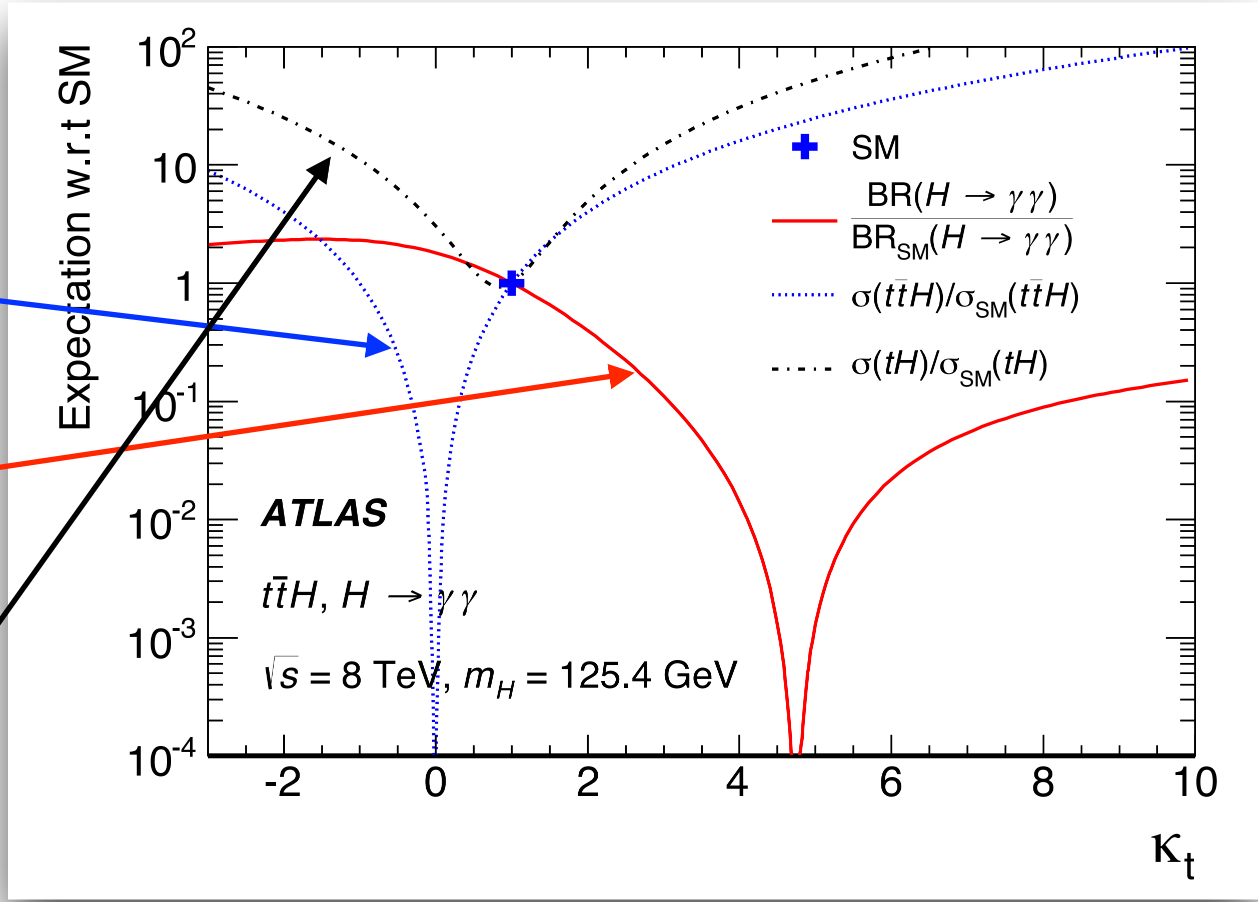
- Good complementarity of the various analyses, very little correlation
- ***Large gain from the combination***: factor 2 better than single most sensitive channel

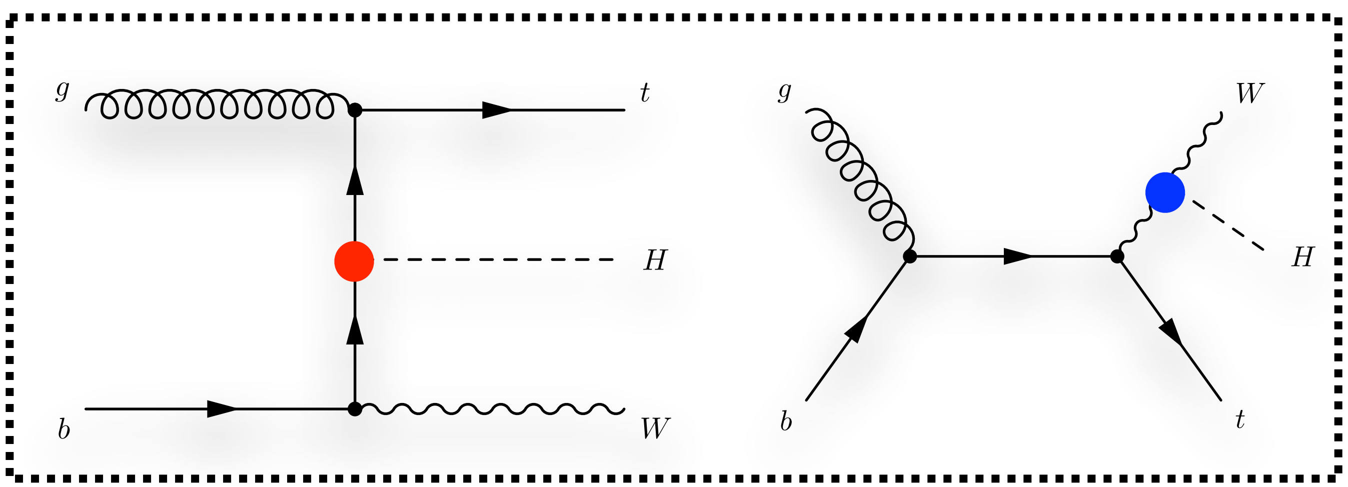
- Very similar result if simultaneously fitting for Higgs BR (mainly determined by other non $t\bar{t}H$ analyses)

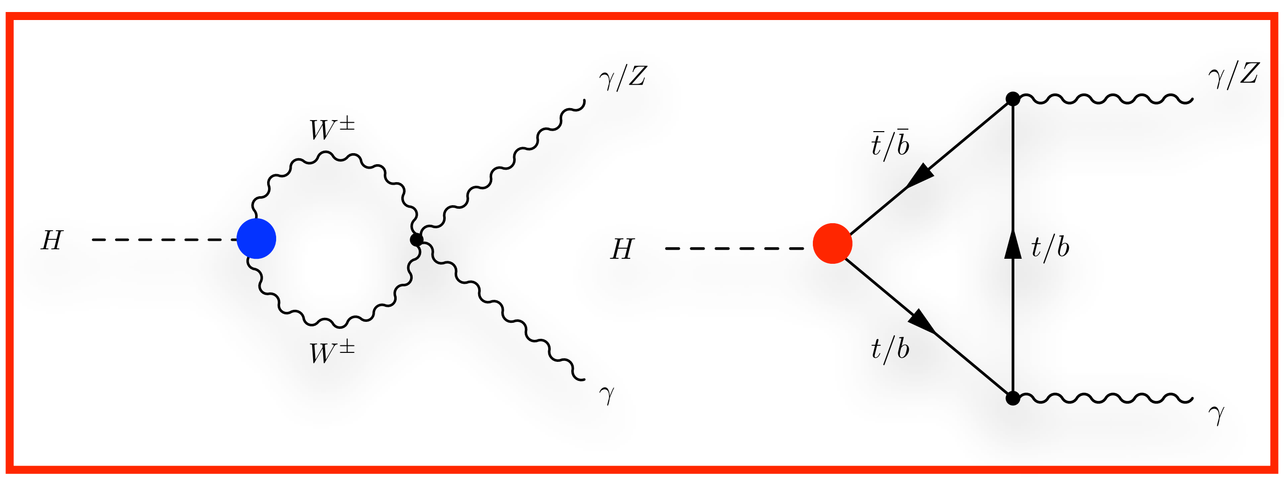
Hunting the top-Yukawa coupling

- **Coupling fit**: assuming coupling to each SM particle can be modified by factor κ_i ($Y_t = \kappa_t Y_t^{SM}$)

- What processes are sensitive to κ_t ?
  - ***$t\bar{t}H$ cross section***: $\propto(\kappa_t)^2$
  - ***ggF cross section***: $\propto(\kappa_t)^2$ (but through loop)
  - ***H->$\gamma\gamma$ decay***: interference between top quark and W-boson contribution in the loop.
  - ***ZH production and H->Zγ***: interference between top quark and W-boson contribution in the loop.
  - **single top +Higgs boson (tH) production**: interference between top-mediated and W-mediated diagrams.



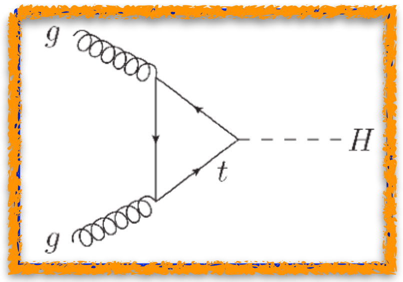




- ttH (H->$\gamma\gamma$) given the relatively large tH contribution has sensitivity to the sign of κ_t

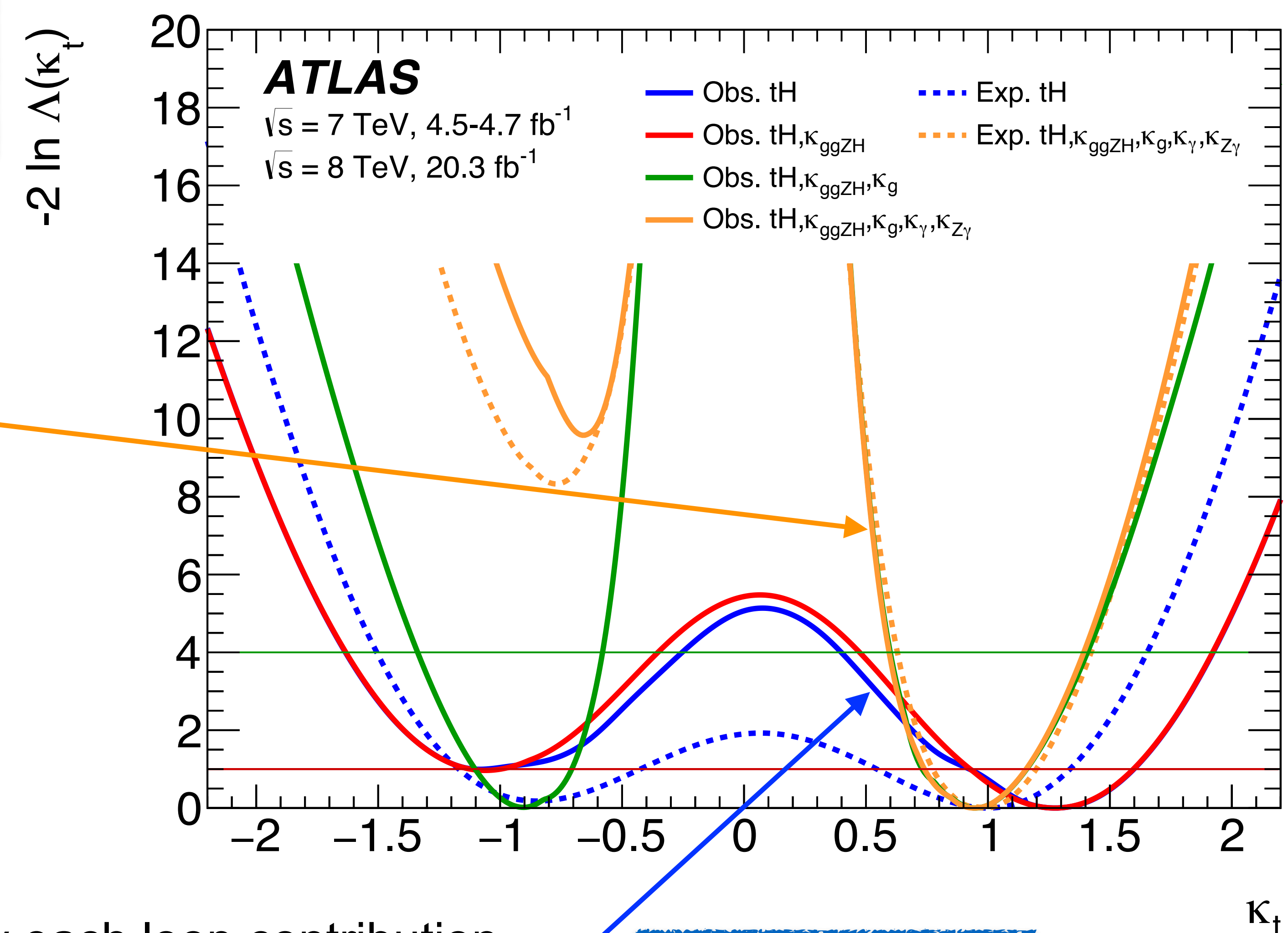
To resolve (the loops) or not to resolve

- *Sensitivity to κ_t strongly depends on the assumptions on the contribution from loop diagrams.*

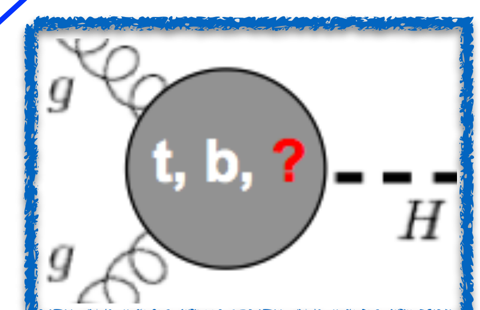


- ***"resolved loops"*** scenario:
  - only SM particles contribute to the loop diagrams
  - no new particles that the Higgs boson can decay into (Br_i=0)
  - ***strong sensitivity on κ_t mainly coming from ggF H->$\gamma\gamma$ analysis***

$$\kappa_t = 0.94 \pm 0.21$$

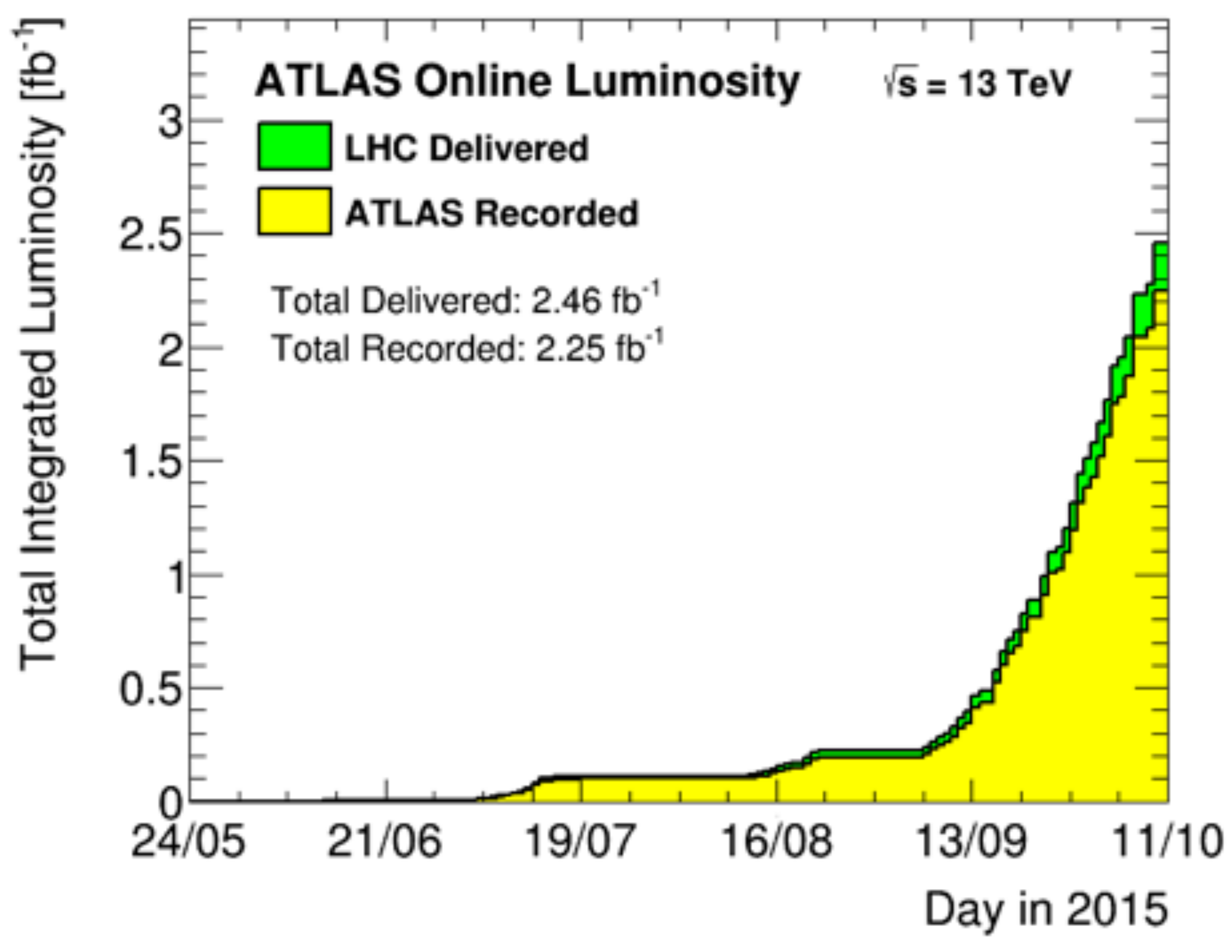


- ***"No resolved loops"*** scenario:
  - allowing BSM effects to modify independently each loop contribution.
  - independent κ-modifier for $\gamma\gamma$, gg, and Zγ vertices)
  - still no new particles the Higgs boson can decay into (Br_i=0)
  - ***sensitivity on κ_t completely dominated by ttH analyses***

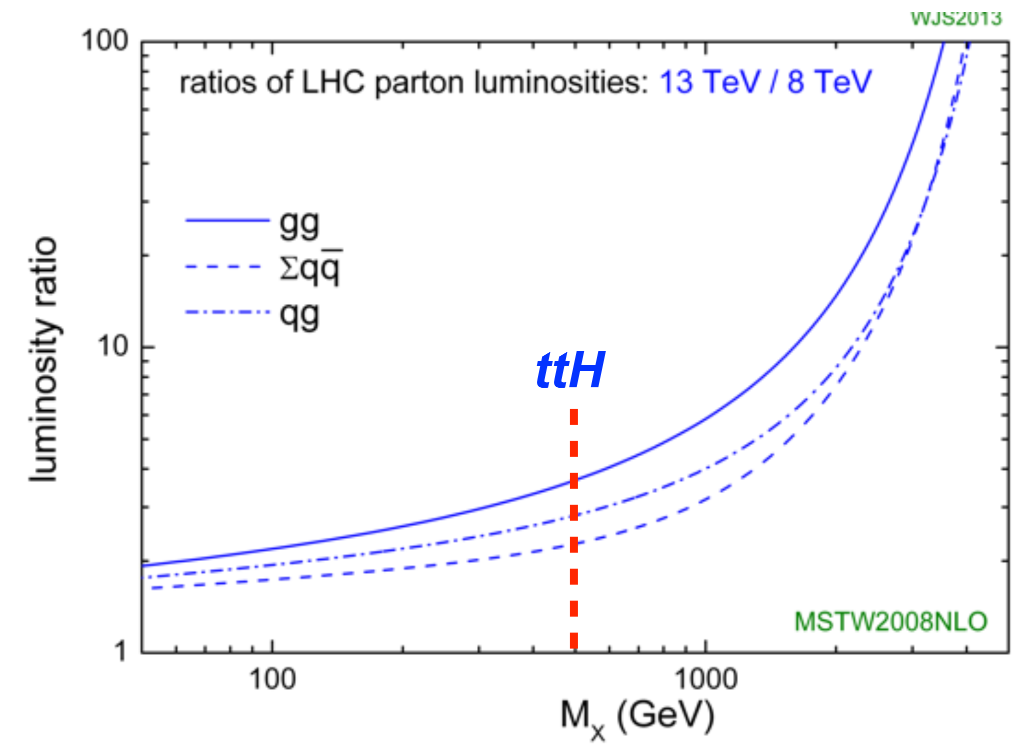


$$\kappa_t \in [-1.12, -1.00] \cup [0.93, 1.60]$$

Run2 prospects

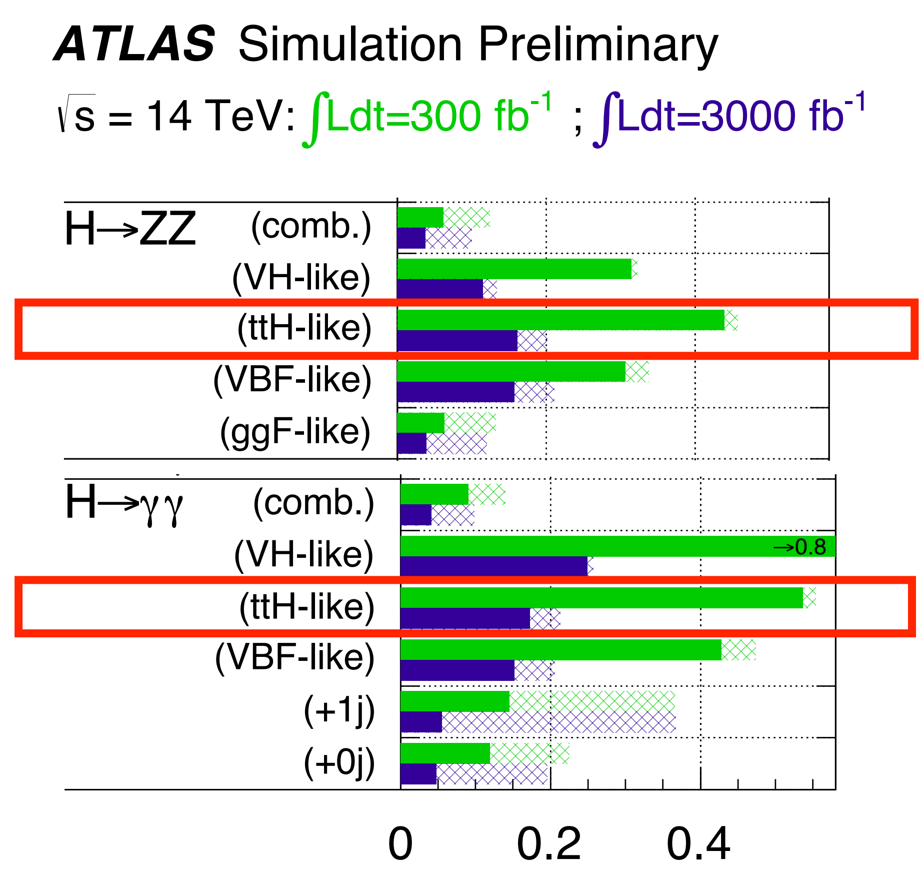


- ***LHC Run2:*** 13 TeV centre of mass energy, up to 4 (30) fb^{-1} collected by the end of 2015 (2016)



- Cross section increase (8TeV -> 13TeV):
  - ***tt̄H: 3.9 . The largest increase of all Higgs boson production modes***
  - *tt̄+X*: \`only' 3.3 but effective S/B will depend on kinematics

- ***Statistically limited*** analyses will directly profit from cross section and luminosity increase:
  - expected 50% (40%) error on σ/σ_{SM} for tt̄H Hγγ (H->ZZ->4l) with 300 fb^{-1}

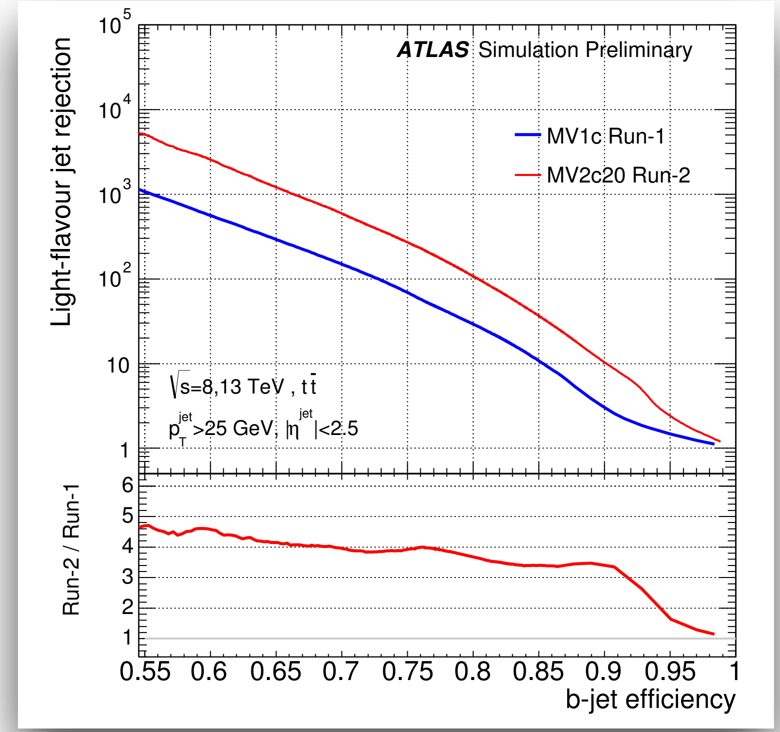


ATL-PHYS-PUB-2014-016

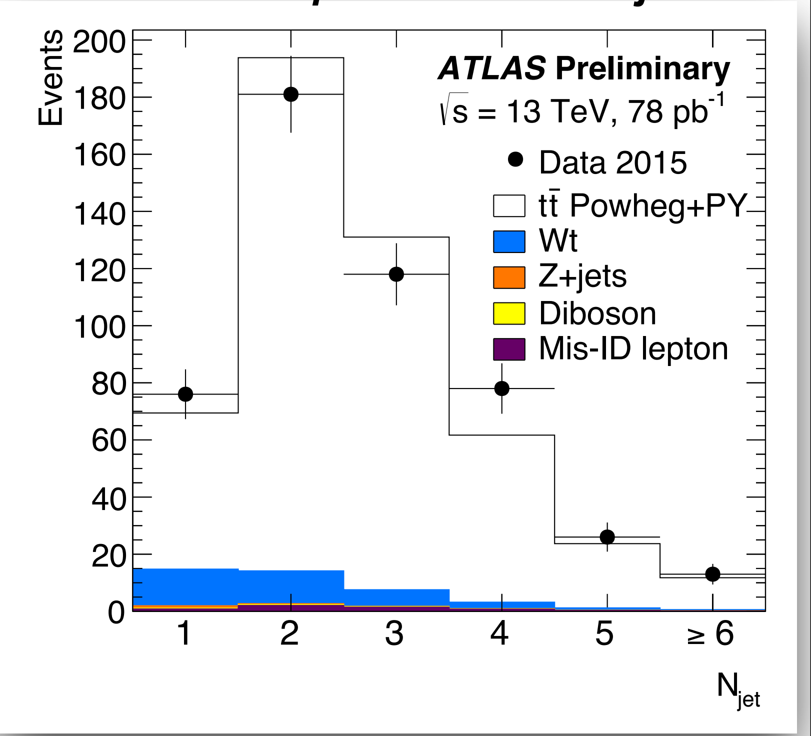
- With more statistics, more sophisticated techniques will be applicable:
  - further categorisation to increase signal sensitivity
  - better handling of backgrounds: recent Run1 measurements of tt̄+bb and tt̄+V
  - MVA techniques in multilepton analyses
  - promising results from boosted scenario in tt̄H (H->bb̄) [arXiv:0910.5472]

Summary and Conclusions

- In Run1, ATLAS has performed the search for $t\bar{t}H$ production in a broad spectrum of final states:
  - all the main Higgs boson decay modes have been considered
  - combination of the analyses is very effective in increasing sensitivity
- ***"No significant excess over background only prediction"***:
  - best fit signal strength: $\mu_{ttH} = 1.81 \pm 0.80$
  - at 95% CL: $\sigma_{ttH}/\sigma_{ttH}^{SM} < 3.2$ (expected <1.2)
  - already providing important information to constrain BSM Higgs properties in generic models
- Excellent prospects for Run2:
  - *x4 cross section increase*
  - *better detector*: additional pixel layer strongly enhance b-tagging performance
  - more than 2 fb^{-1} of 13 TeV data already collected: *understanding of backgrounds* has already started



ttbar eμ selection + 1 b-jet



The observation of ttH is one of the main ATLAS priorities for Run2

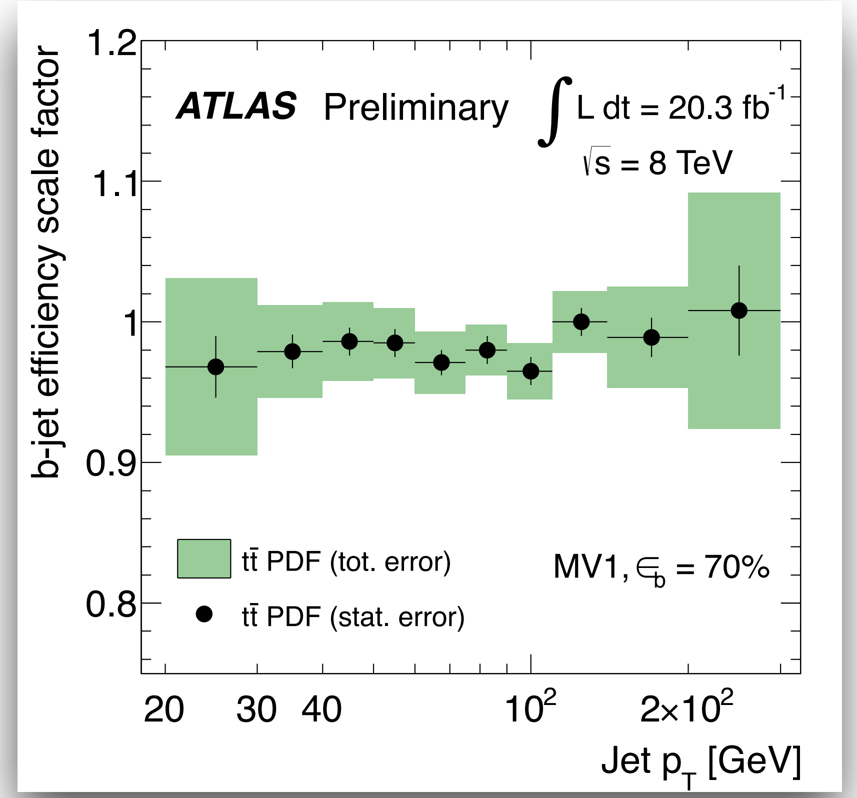
BackUp

ATLAS analyses: common aspects

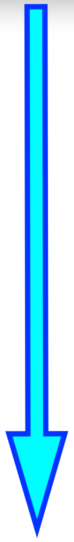
- Good control on leptons and photons reconstruction/identifications

- Generally requiring large number of central (|η|<2.5) jets in the final state

- *b-jets always present in ttbar decay*: very precise understanding of the b-tagging efficiency in data



- ***"Divide et impera"***: using multiple analysis regions:
  - *increasing signal acceptance, exploits different S/B (S/sqrt(B)) in each region*
  - *constrain/validate background estimates*
  - *control/constrain analysis systematic uncertainties*
  - *use shape discriminants so improve signal sensitivity*



- Backgrounds estimations:
  - *irreducible backgrounds*: relying on MC (NLO generators) + data-driven normalisation
  - *reducible backgrounds*: as data-driven as possible (inputs from CR, other analyses, ….)

MC used

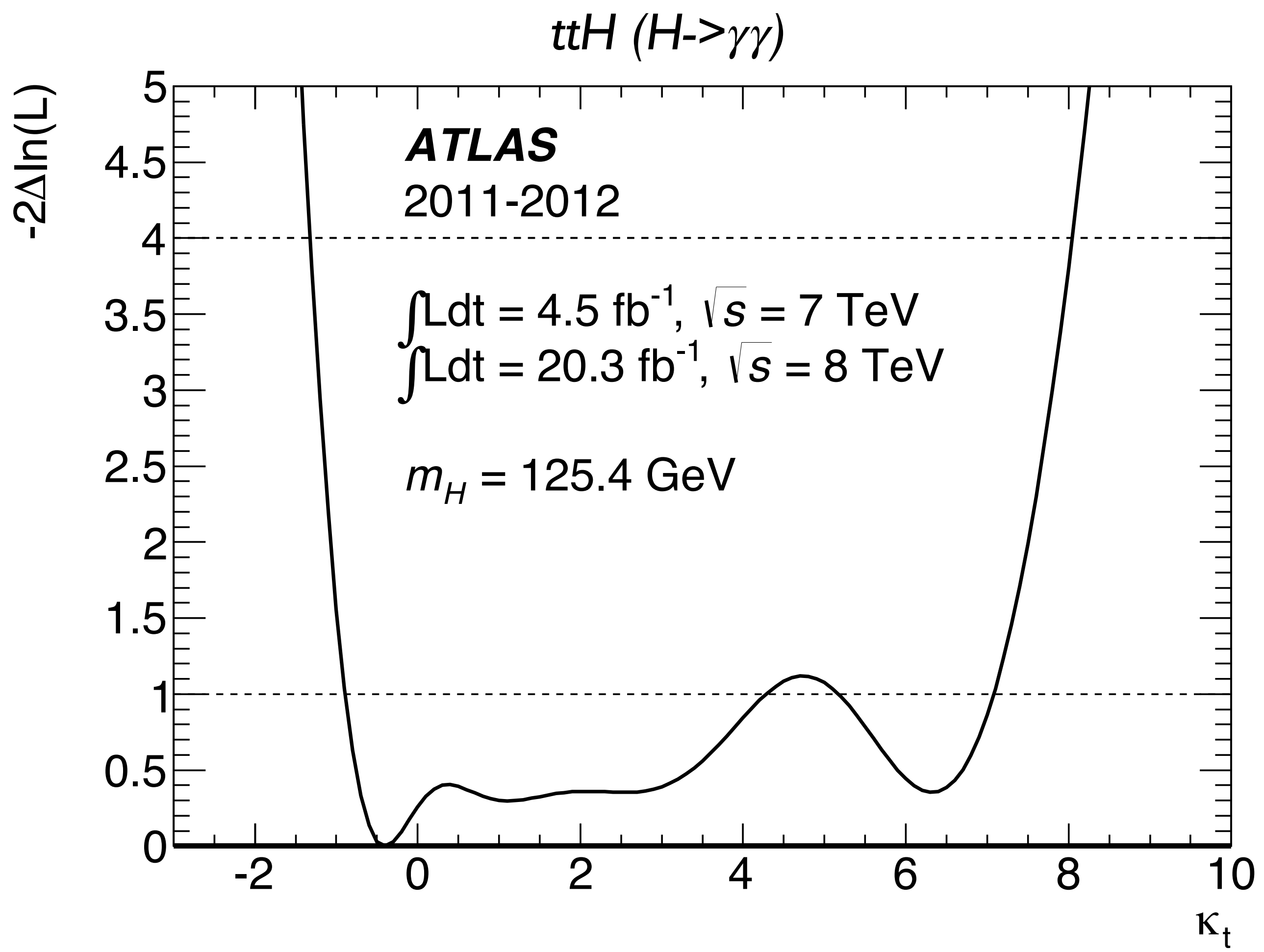
Production process	Event generator	Showering program	PDF set
ggF	Powheg	Pythia6/Pythia8	CT10
VBF	Powheg	Pythia6/Pythia8	CT10
WH	Pythia8	Pythia8	CTEQ6L1
$ZH: q\bar{q} \to ZH$	Pythia8	Pythia8	CTEQ6L1
$ZH: gg \to ZH$	Powheg	Pythia8	CT10
ttH	Powheg	Pythia8	CT10
bbH	MadGraph5_aMC@NLO	Herwig++	CT10
$tH: qb \to tHq'$	MadGraph	Pythia8	CT10
$tH: gb \to WtH$	MadGraph5_aMC@NLO	Herwig++	CT10

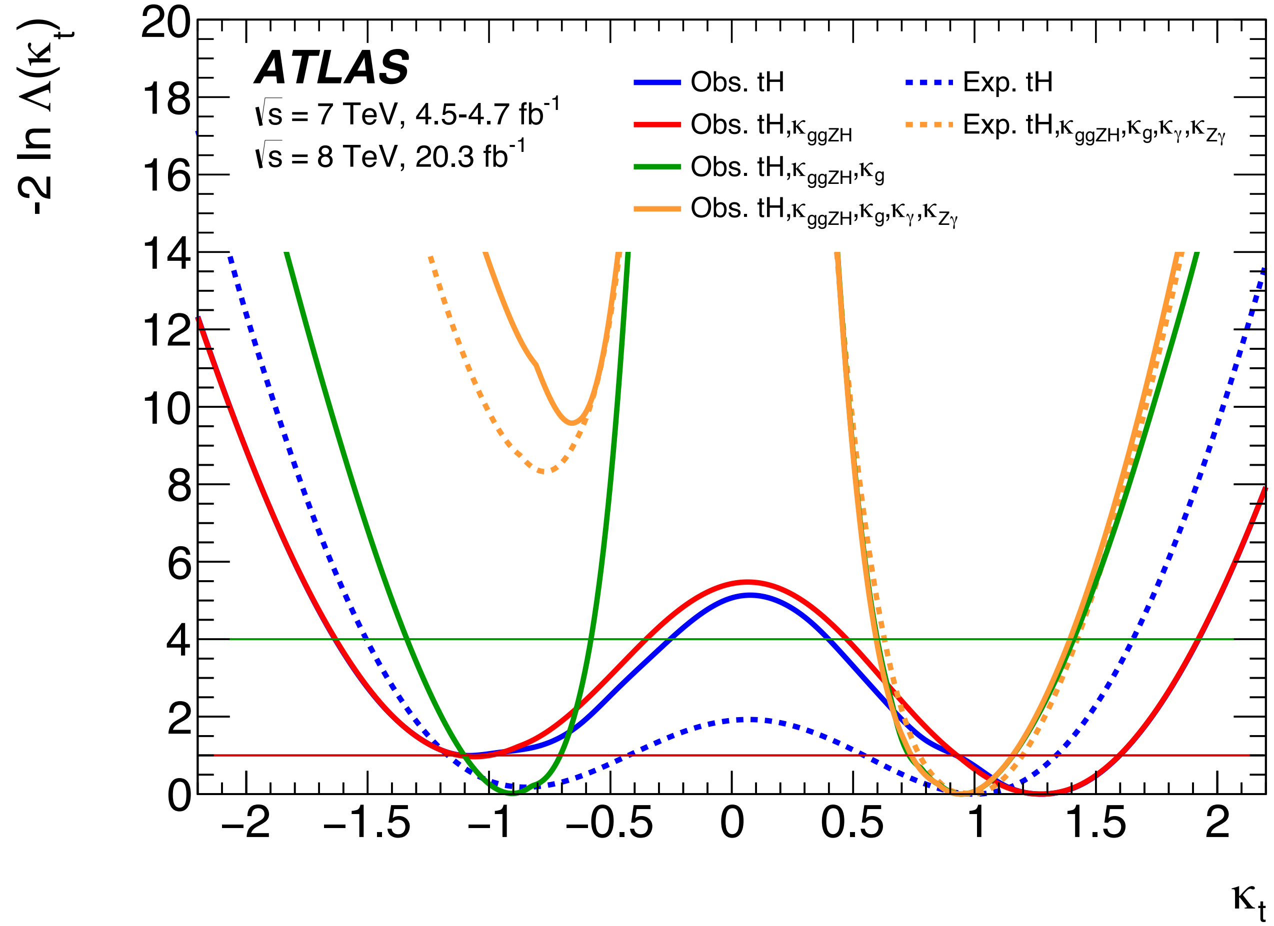
ttH H->$\gamma\gamma$ systematics

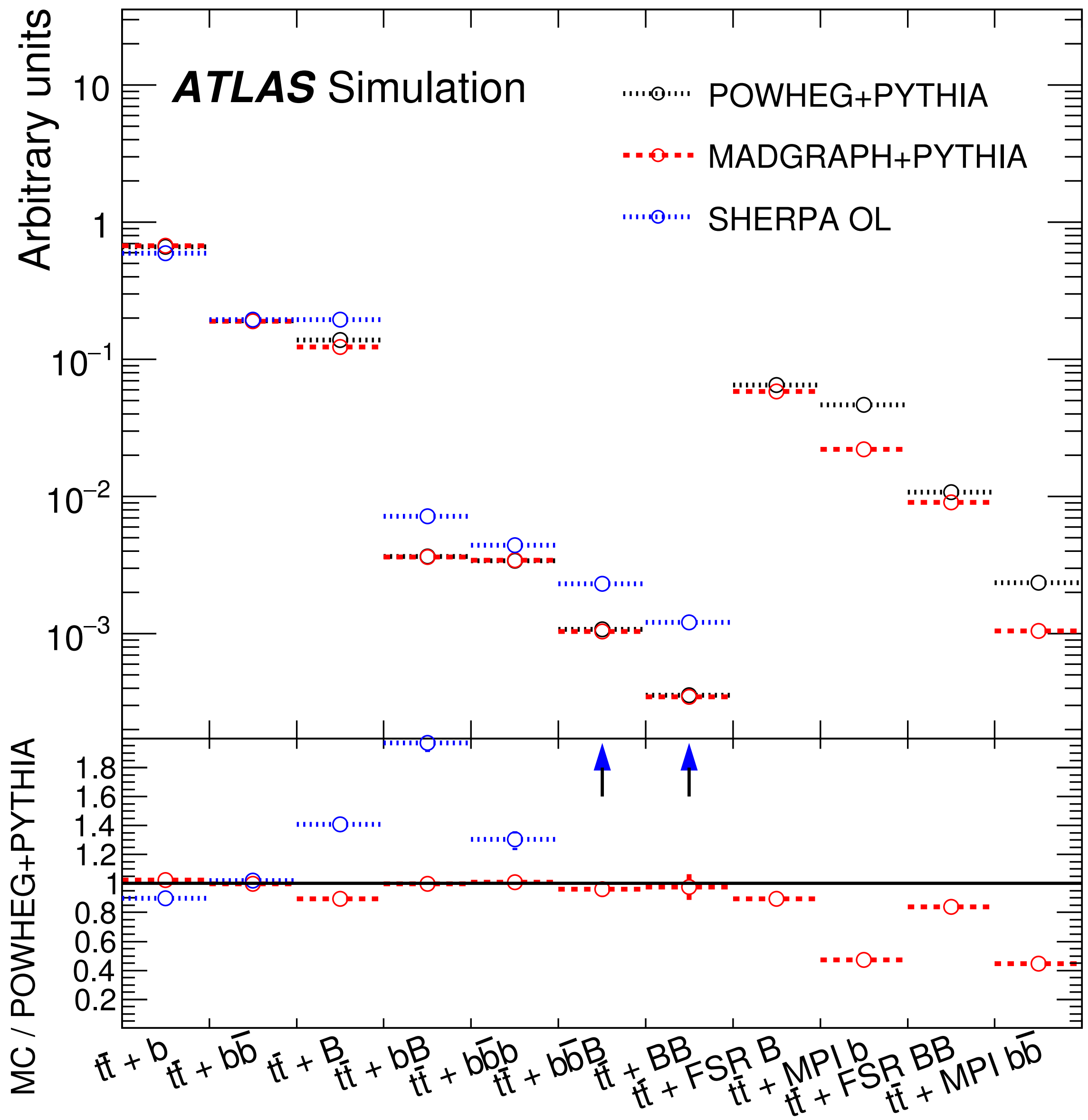
	$t\bar{t}H$ [%]		tHqb [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±1.8							
Photons	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0
Leptons	< 0.1	±0.7	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.7
Jets and E_T^{miss}	±9.1	±1.6	±19	±2.4	±13	±2.9	±30	±10
Bkg. modeling	0.12 evt.	0.01 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,−13		+8,−7		+12,−12		+11,−12	+5.5,−5.5
MC Modeling	±11	±3.3	±12	±4.4	±13	±5.2	±130	±100

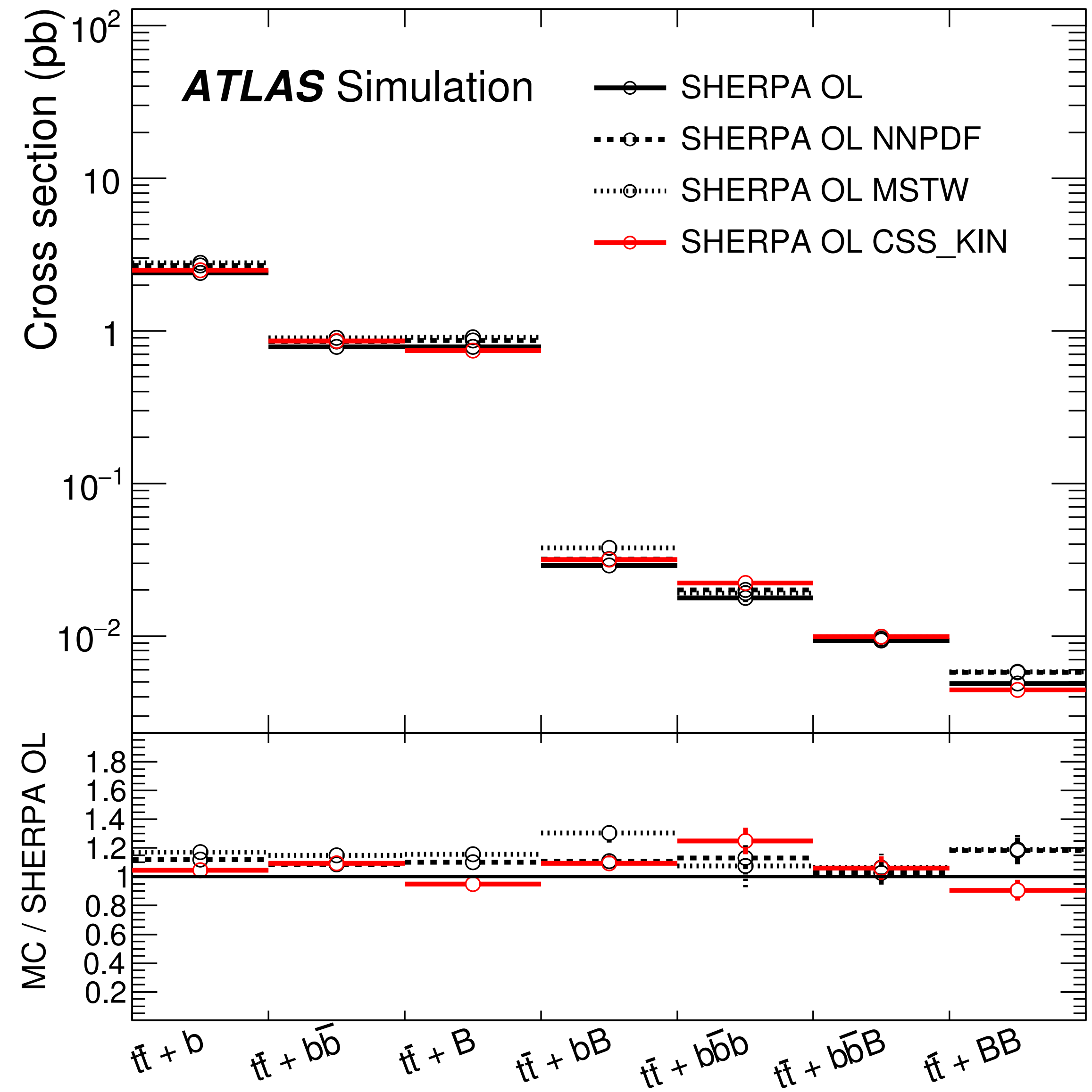
ttH H->$\gamma\gamma$ systematics

- Analysis with unique sensitivity to κ_t









- ***b***: truth jet (p_T>20GeV, |eta|<2.5) matched to a SINGLE b-hadron (not from ttbar decay)
- ***B***: truth jet (p_T>20GeV, |eta|<2.5) matched to multiple b-hadrons (not from ttbar decay). Gluon splitting

ttH H->bb: NN variables

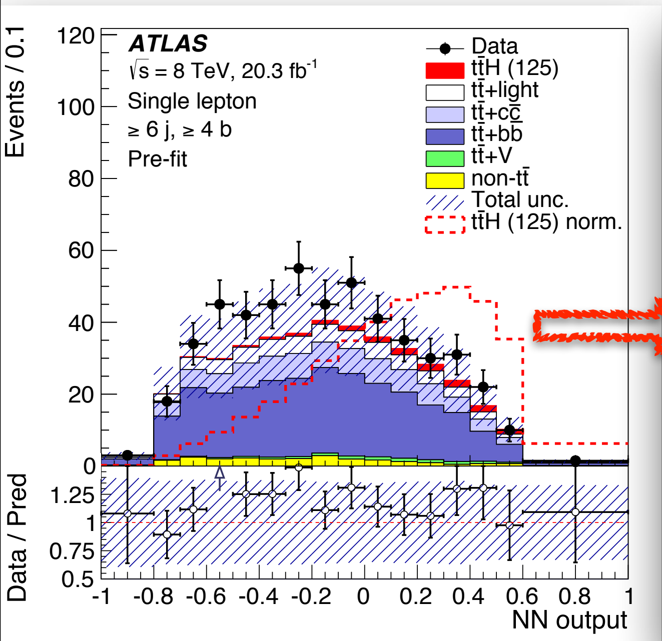
l+jets

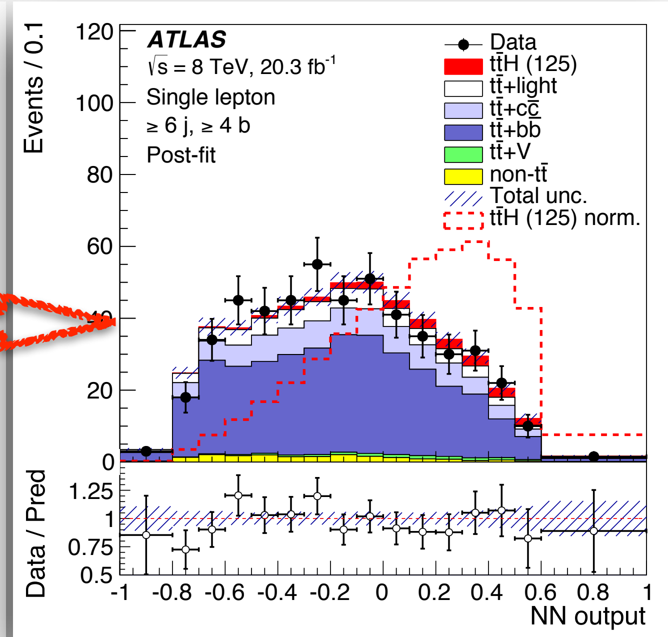
Variable	Definition	NN rank			
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b	5j, 3b
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_{T} divided by sum of the E for all jets and the lepton	2	2	1	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	p_{T} of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	4	3	2	-
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs	5	6	5	-
SSLL	Logarithm of the summed signal likelihoods (Eq. (2))	6	4	-	-
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	8	8	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	9	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$\mathrm{Aplan}_{\mathrm{b-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor[92] built with only b-tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_{\mathrm{T}} \geq 40GeV$	-	1	3	-
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}	-	-	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_{T}	-	-	-	1
$p_{\mathrm{T,uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Scalar sum of the p_{T} of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}	-	-	-	7

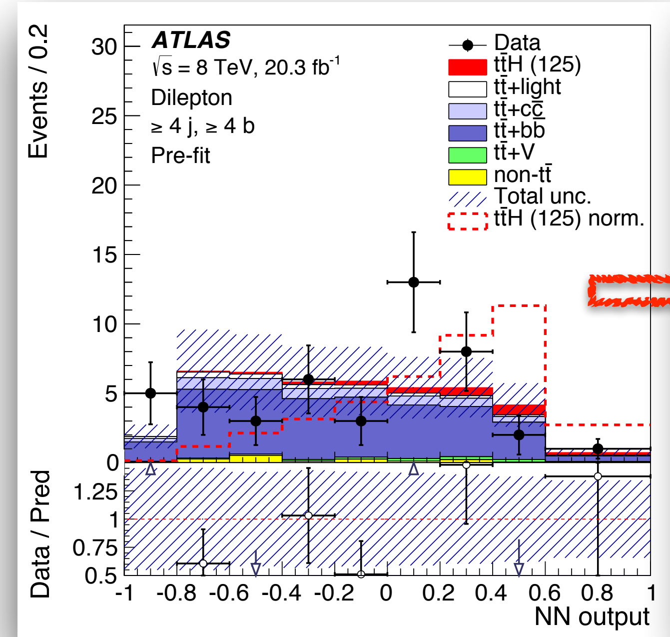
di-lepton

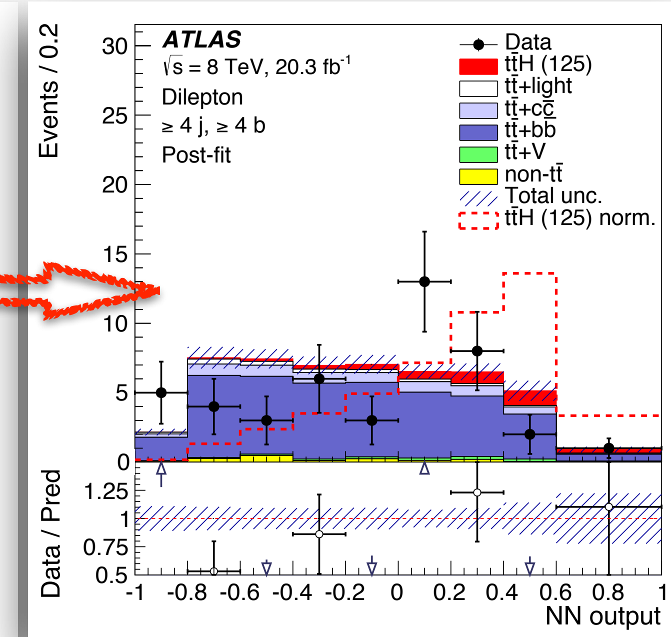
Variable	Definition	NN rank		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event	1	1	1
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	2	8	-
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system	3	-	-
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the closest lepton	4	5	-
$\mathrm{N}_{30}^{\mathrm{Higgs}}$	Number of Higgs candidates within 30 GeV of the Higgs mass of 125 GeV	5	2	5
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	6	4	8
$\mathrm{Aplan}_{\mathrm{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	7	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \mathrm{m}}$	Minimum dijet mass between any two jets	8	3	2
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the furthest lepton	9	-	-
$m_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass between any two jets closest to the Higgs mass of 125 GeV	10	-	10
H_{T}	Scalar sum of jet p_{T} and lepton p_{T} values	-	6	3
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	ΔR between the two b-tagged jets with the largest invariant mass	-	9	-
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between any lepton and jet	-	10	-
Centrality	Sum of the p_{T} divided by sum of the E for all jets and both leptons	-	-	7
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	9
$H4$	Fifth Fox–Wolfram moment computed using all jets and both leptons	-	-	4
$p_{\mathrm{T}}^{\mathrm{jet3}}$	p_{T} of the third leading jet	-	-	6

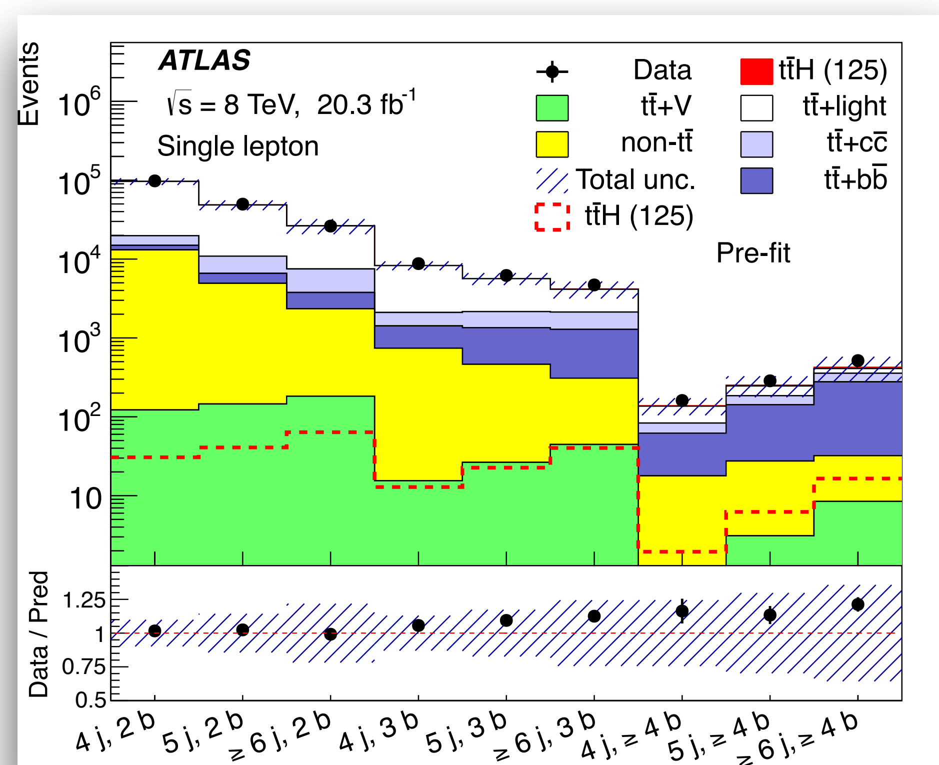
ttH H->bb: pre/post-fit plots

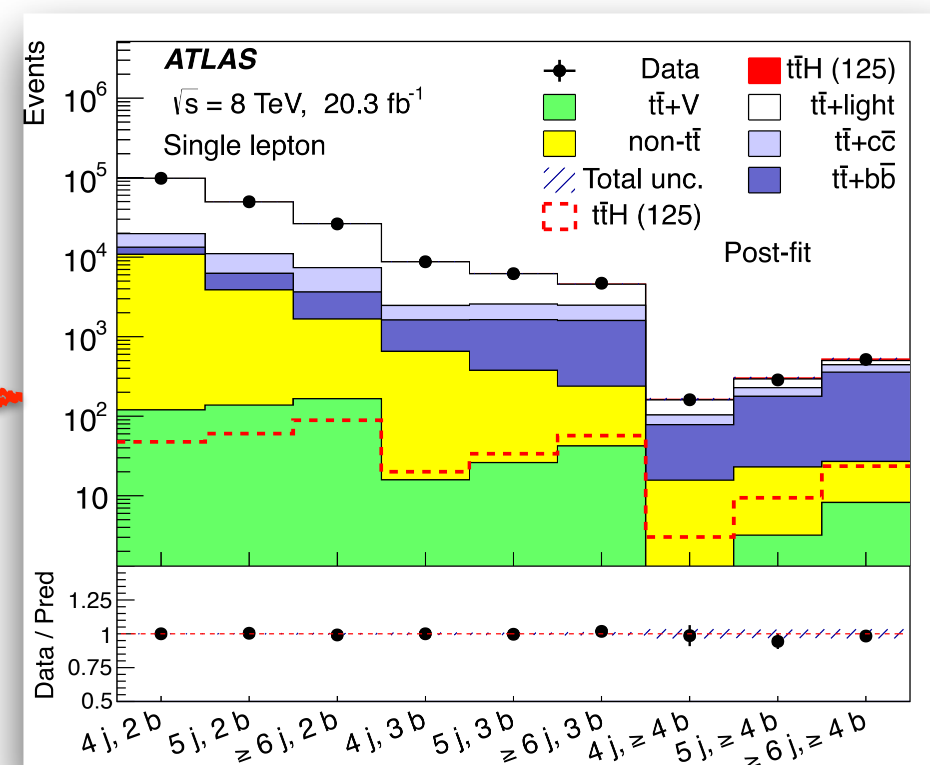


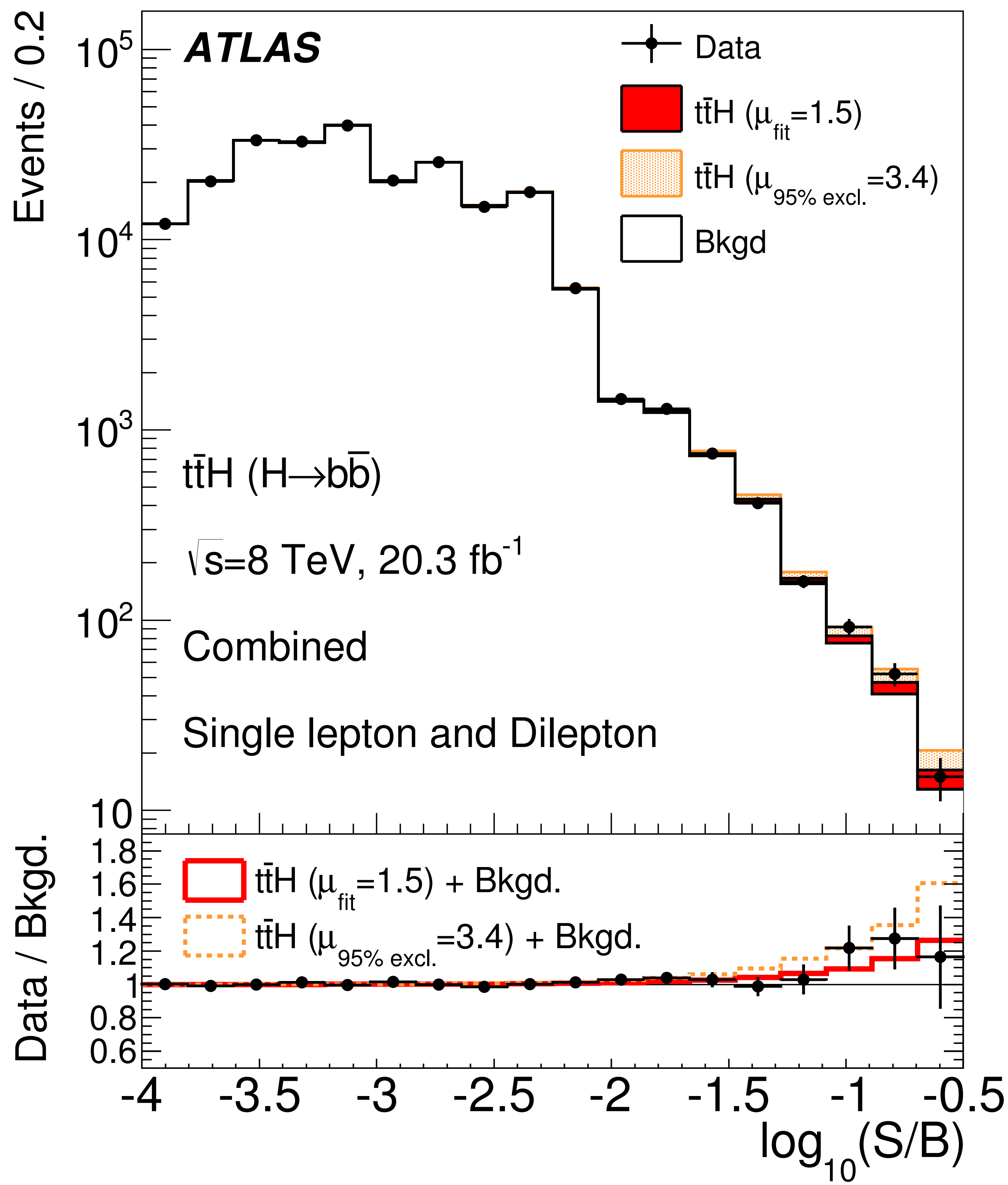












ATLAS
Data
tt̄H (μ_fit=1.5)
tt̄H (μ_95% excl.=3.4)
Bkgd
tt̄H (H→bb̄)
√s=8 TeV, 20.3 fb^-1
Combined
Single lepton and Dilepton
Events / 0.2
Data / Bkgd.
tt̄H (μ_fit=1.5) + Bkgd.
tt̄H (μ_95% excl.=3.4) + Bkgd.
log10(S/B)

ttH H->bb: systematics

≥ 4 j, ≥ 4 b

	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±2.5	±2.5	±2.5	±2.5	±1.8	±1.8	±1.8	±1.8
Jet energy scale	±4.5	±12	±9.4	±7.0	±2.0	±5.5	±4.5	±3.3
Jet efficiencies	–	±5.9	±1.6	±0.9	–	±2.6	±0.7	±0.4
Jet energy resolution	±0.1	±4.5	±1.1	–	±0.1	±2.3	±0.6	–
b-tagging efficiency	±10	±5.5	±5.4	±11	±5.6	±3.1	±3.0	±5.8
c-tagging efficiency	±0.5	–	±12	±0.6	±0.3	–	±10	±0.3
l-tagging efficiency	±0.7	±34	±7.0	±1.6	±0.4	±21	±4.2	±0.9
High p_{T} tagging efficiency	–	–	±0.6	–	–	–	±0.3	–
$t\bar{t}$: p_{T} reweighting	–	±5.8	±6.2	–	–	±5.0	±5.4	–
$t\bar{t}$: parton shower	–	±14	±18	±14	–	±4.8	±11	±8.1
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$+HF: modelling	–	±11	±16	±12	–	±3.8	±10	±10
Theoretical cross sections	–	±6.3	±6.3	±6.2	–	±4.1	±4.1	±4.1
$t\bar{t}H$ modelling	±1.9	–	–	–	±1.8	–	–	–
Total	±12	±40	±59	±55	±6.7	±22	±22	±13

≥ 6 j, ≥ 4 b

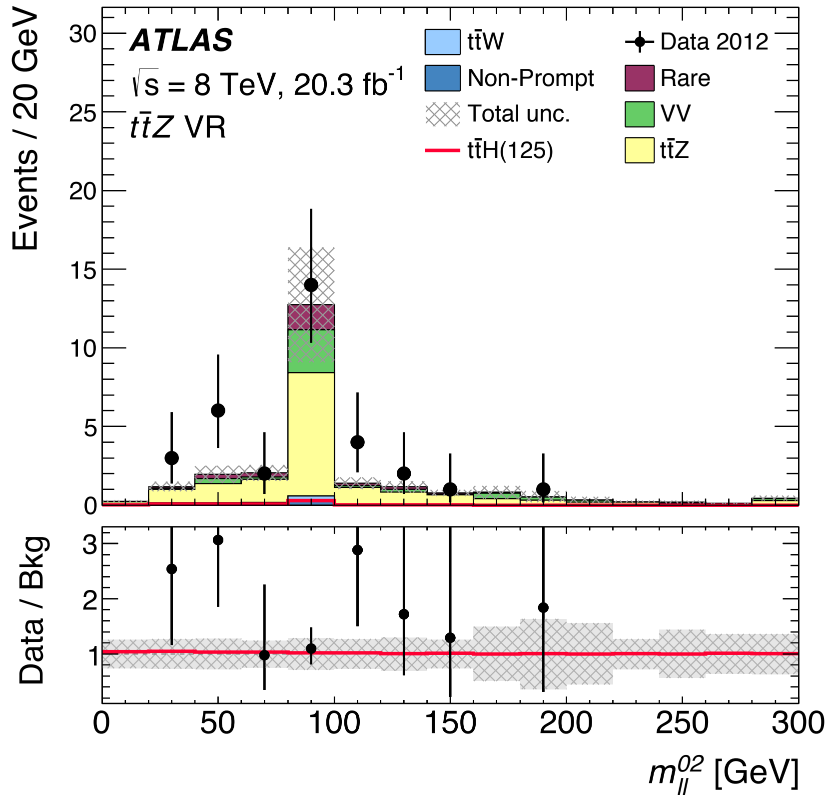
	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±1.4	±1.4	±1.4	±1.5	±1.3	±1.3	±1.3	±1.3
Jet energy scale	±6.4	±13	±11	±9.2	±2.3	±5.3	±4.7	±3.6
Jet efficiencies	±1.7	±5.2	±2.7	±2.5	±0.7	±2.3	±1.2	±1.1
Jet energy resolution	±0.1	±4.4	±2.5	±1.6	±0.1	±2.3	±1.3	±0.8
b-tagging efficiency	±9.2	±5.6	±5.1	±9.3	±5.0	±3.1	±2.9	±5.0
c-tagging efficiency	±1.7	±6.0	±12	±2.4	±1.4	±5.1	±10	±2.1
l-tagging efficiency	±1.0	±19	±5.2	±2.1	±0.6	±11	±3.0	±1.1
High p_{T} tagging efficiency	±0.6	–	±0.7	±0.6	±0.3	–	±0.4	±0.3
$t\bar{t}$: p_{T} reweighting	–	±5.4	±6.1	–	–	±4.7	±5.4	–
$t\bar{t}$: parton shower	–	±13	±16	±11	–	±3.6	±10	±6.0
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$+HF: modelling	–	±11	±16	±8.3	–	±3.6	±9.1	±7.1
Theoretical cross sections	–	±6.3	±6.3	±6.3	–	±4.1	±4.1	±4.1
$t\bar{t}H$ modelling	±2.7	–	–	–	±2.6	–	–	–
Total	±12	±32	±59	±54	±6.9	±9.2	±23	±12

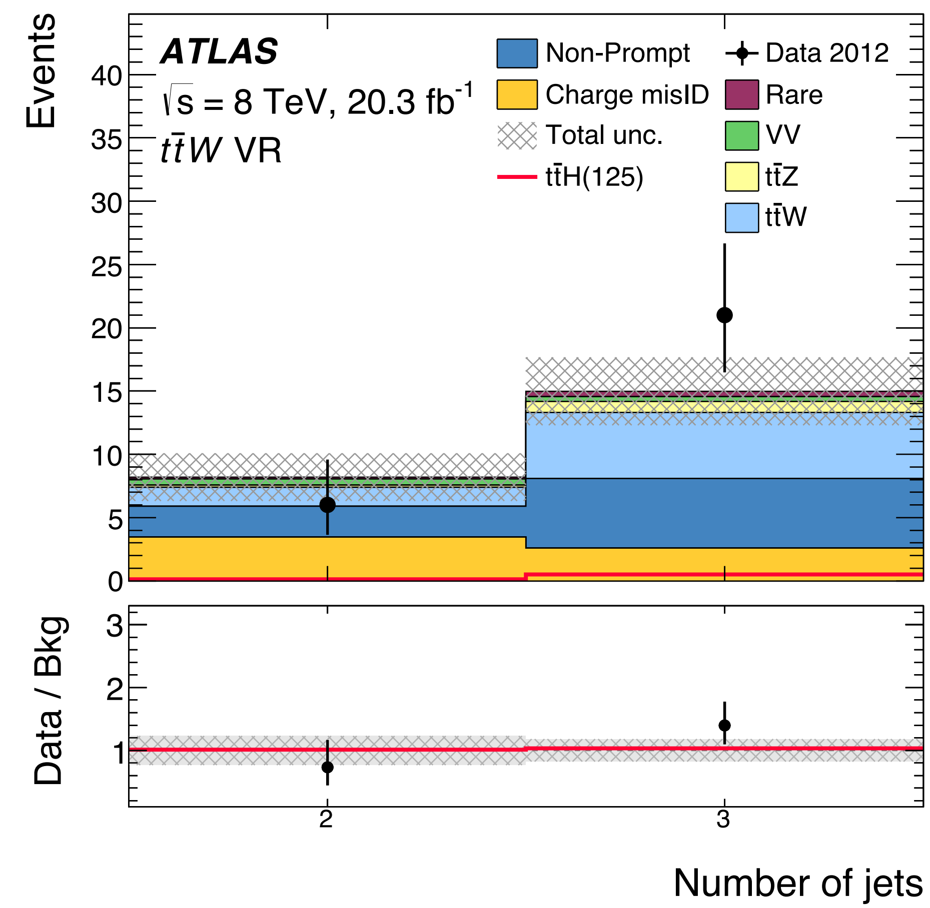
$t\bar{t}H$ multilepton: MonteCarlos

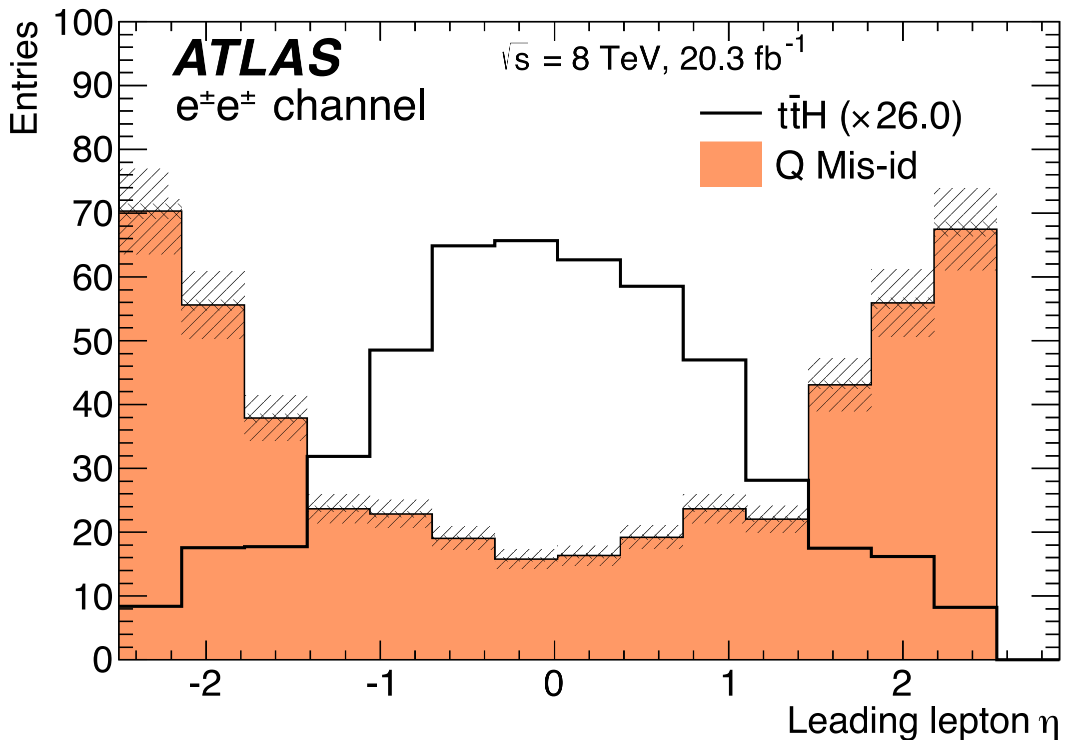
Process	ME Generator	Parton Shower	PDF	Tune
$t\bar{t}H$	HELAC-Oneloop [41, 42] + POWHEG-BOX [48-50]	PYTHIA 8 [43]	CT10 [44]/CTEQ6L1 [45, 46]	AU2 [47]
$tHqb$	MADGRAPH [33]	PYTHIA 8	CT10	AU2
tHW	MG5_aMC@NLO [29]	HERWIG++ [51]	CT10/MRST LO** [52]	UE-EE-4 [53]
$t\bar{t}W$ + $\leq$ 2 partons	MADGRAPH	PYTHIA 6 [54]	CTEQ6L1	AUET2B [55]
$t\bar{t}(Z/\gamma^*)$ + $\leq$ 1 parton	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$t(Z/\gamma^*)$	MADGRAPH	PYTHIA 6	CTEQ6L1	AUET2B
$q\bar{q}, gg \to WW, WZ$	SHERPA [56]	SHERPA	CT10	SHERPA default
$qq \to qqWW, qqWZ, qqZZ$	SHERPA	SHERPA	CT10	SHERPA default
$q\bar{q}, gg \to ZZ$	POWHEG-BOX [57]	PYTHIA 8	CT10	AU2
$gg \to ZZ$	GG2ZZ [58]	HERWIG [59]	CT10	AUET2 [60]
$t\bar{t}$	POWHEG-BOX [61]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C [62]
s-, t-channel, Wt single top	POWHEG-BOX [63, 64]	PYTHIA 6	CT10/CTEQ6L1	Perugia2011C
$Z \to \ell^+\ell^- + \leq 5$ partons	ALPGEN [65]	PYTHIA 6	CTEQ6L1	Perugia2011C
$W \to \ell\nu + \leq 5$ partons	ALPGEN	PYTHIA 6	CTEQ6L1	Perugia2011C

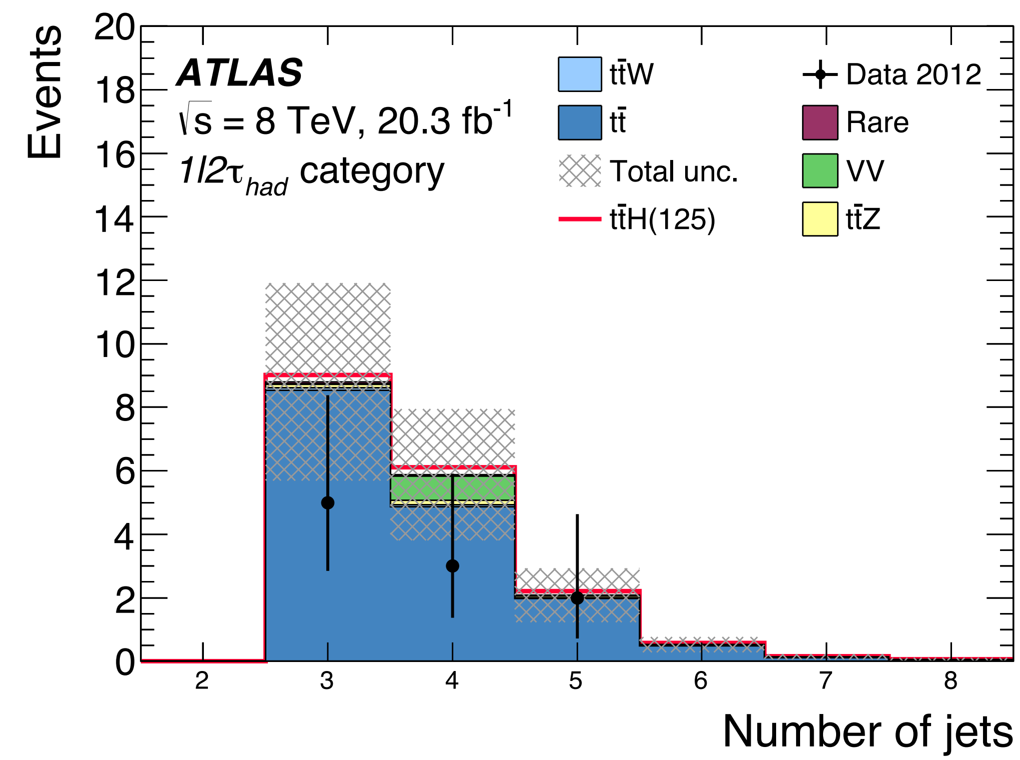
- Precise table with all the cuts

Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected bkg.	$t\bar{t}H$ $(\mu = 1)$	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.26	0.47 ± 0.29	6.5 ± 1.8	0.73 ± 0.14	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.2	2.1 ± 0.5	0.38 ± 0.30	15 ± 3	2.13 ± 0.41	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 0.9	0.95 ± 0.25	0.69 ± 0.39	8.6 ± 2.2	1.41 ± 0.28	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.20	0.74 ± 0.42	9.1 ± 2.1	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 1.0	1.5 ± 0.3	1.9 ± 1.0	24 ± 5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.22	0.53 ± 0.30	12.7 ± 2.9	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.7	3.9 ± 0.8	0.86 ± 0.55	11.4 ± 2.3	2.34 ± 0.35	18
$2\ell 1\tau_{\mathrm{had}}$	–	$0.4\ ^{+0.6}_{-0.4}$	0.38 ± 0.12	0.37 ± 0.08	0.12 ± 0.11	1.4 ± 0.6	0.47 ± 0.08	1
$1\ell 2\tau_{\mathrm{had}}$	–	15 ± 5	0.17 ± 0.06	0.37 ± 0.09	0.41 ± 0.42	16 ± 5	0.68 ± 0.13	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.12	0.05 ± 0.02	0.55 ± 0.15	0.17 ± 0.02	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.025 ± 0.003	0

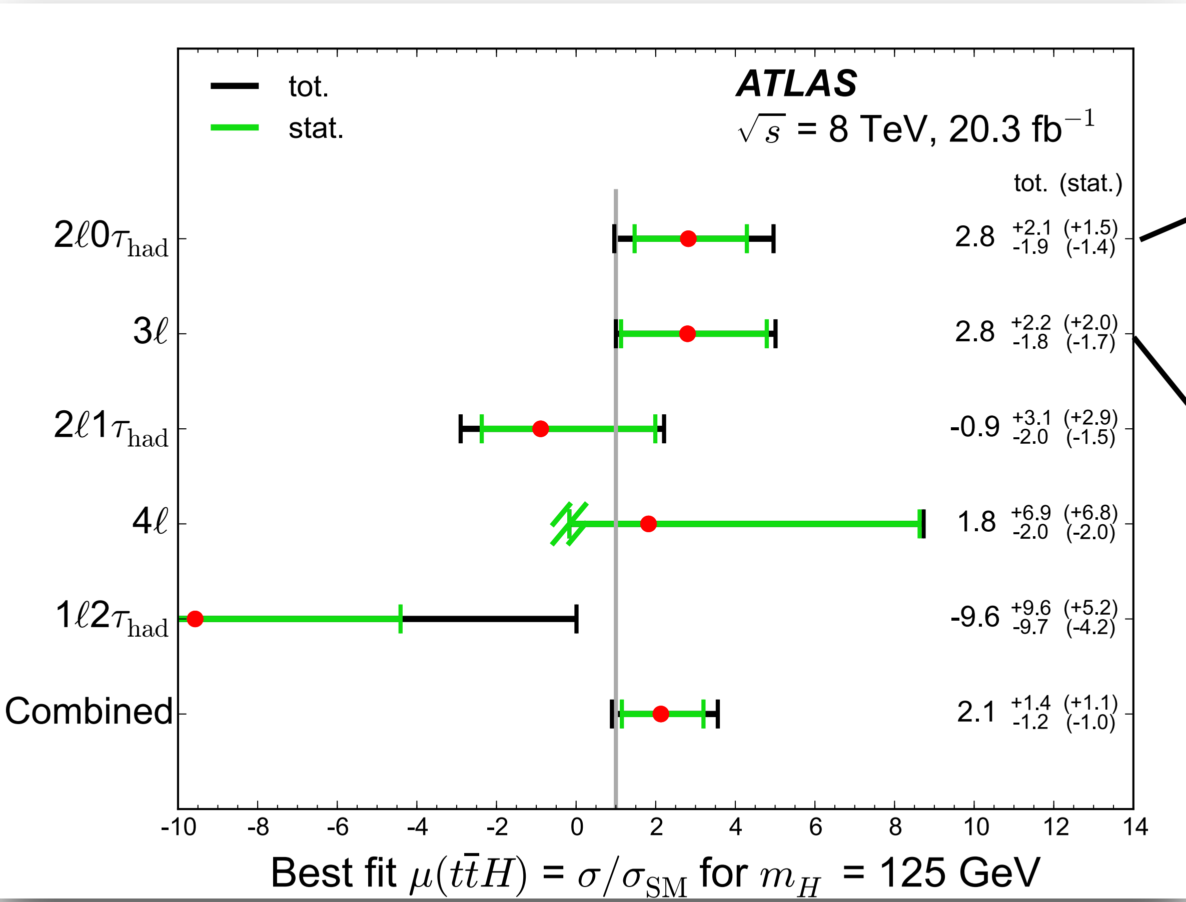

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$t\bar{t}Z$ VR
tt̄W
Non-Prompt
Total unc.
tt̄H(125)
Data 2012
Rare
VV
tt̄Z
Events / 20 GeV
Data / Bkg
m_{ll}^{02} [GeV]

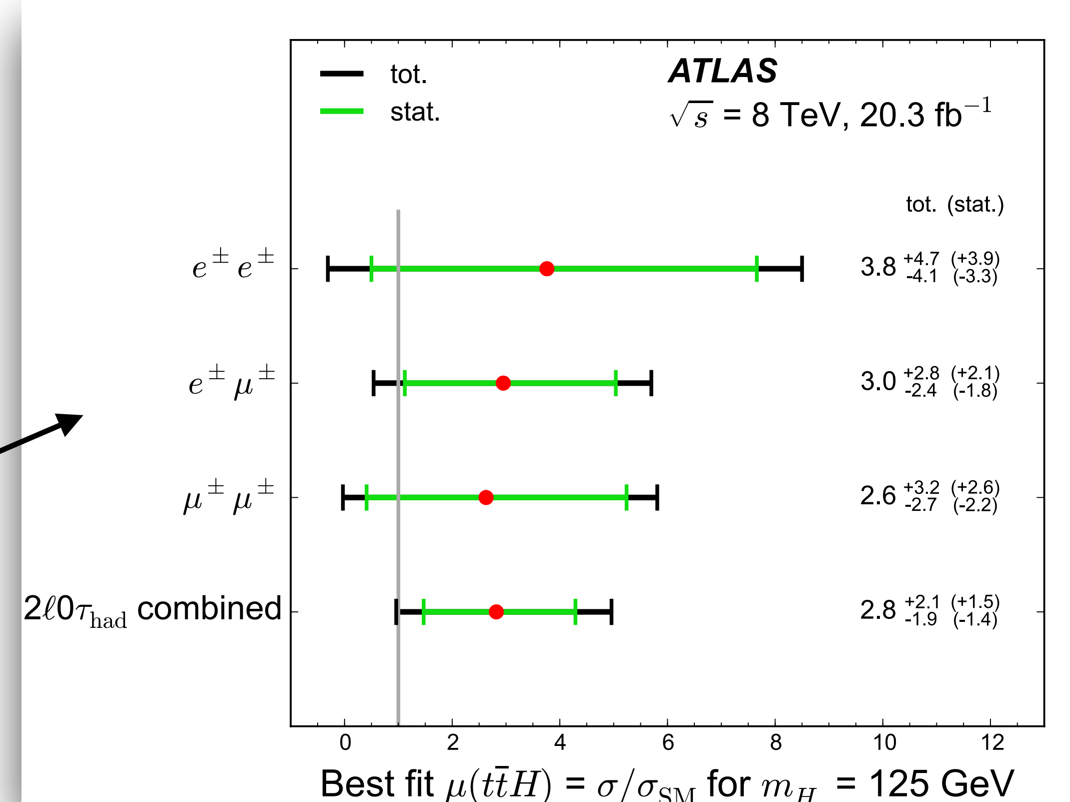

ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$t\bar{t}W$ VR
Non-Prompt
Charge misID
Total unc.
tt̄H(125)
Data 2012
Rare
VV
tt̄Z
tt̄W
Events
Data / Bkg
Number of jets

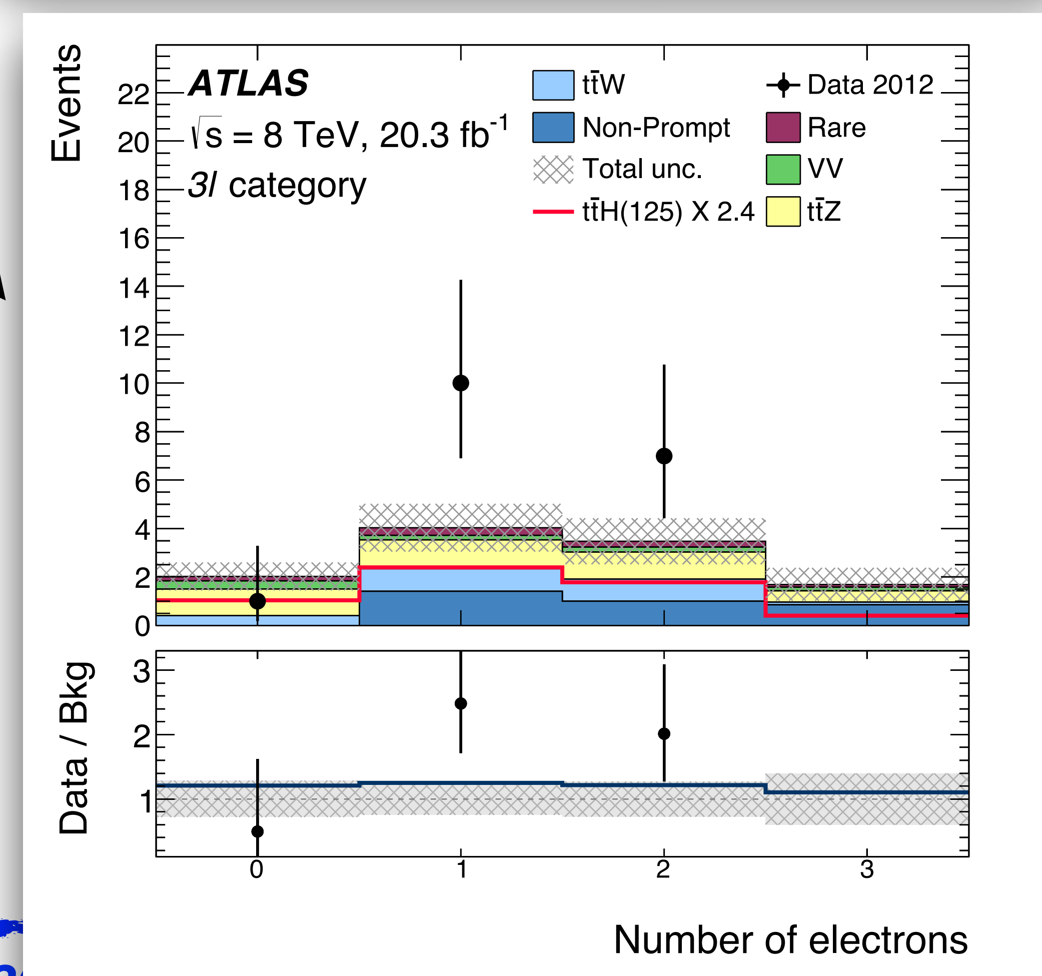

ATLAS
e±e± channel
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
tt̄H (×26.0)
Q Mis-id
Entries
Leading lepton η


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$1l2\tau_{had}$ category
tt̄W
tt̄
Total unc.
tt̄H(125)
Data 2012
Rare
VV
tt̄Z
Events
Number of jets

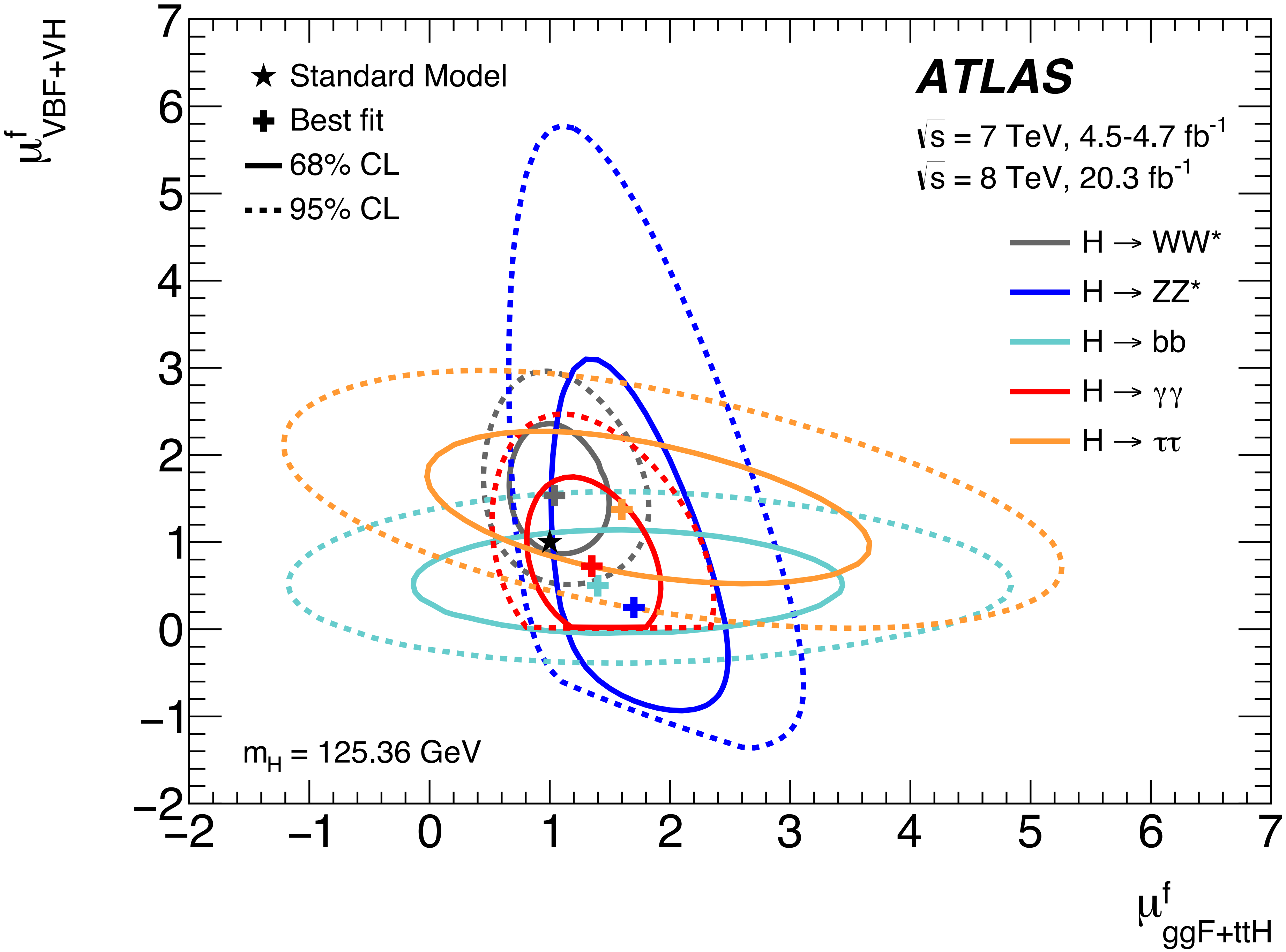
$t\bar{t}H$ multilepton: results







- This shows the role of various analyses



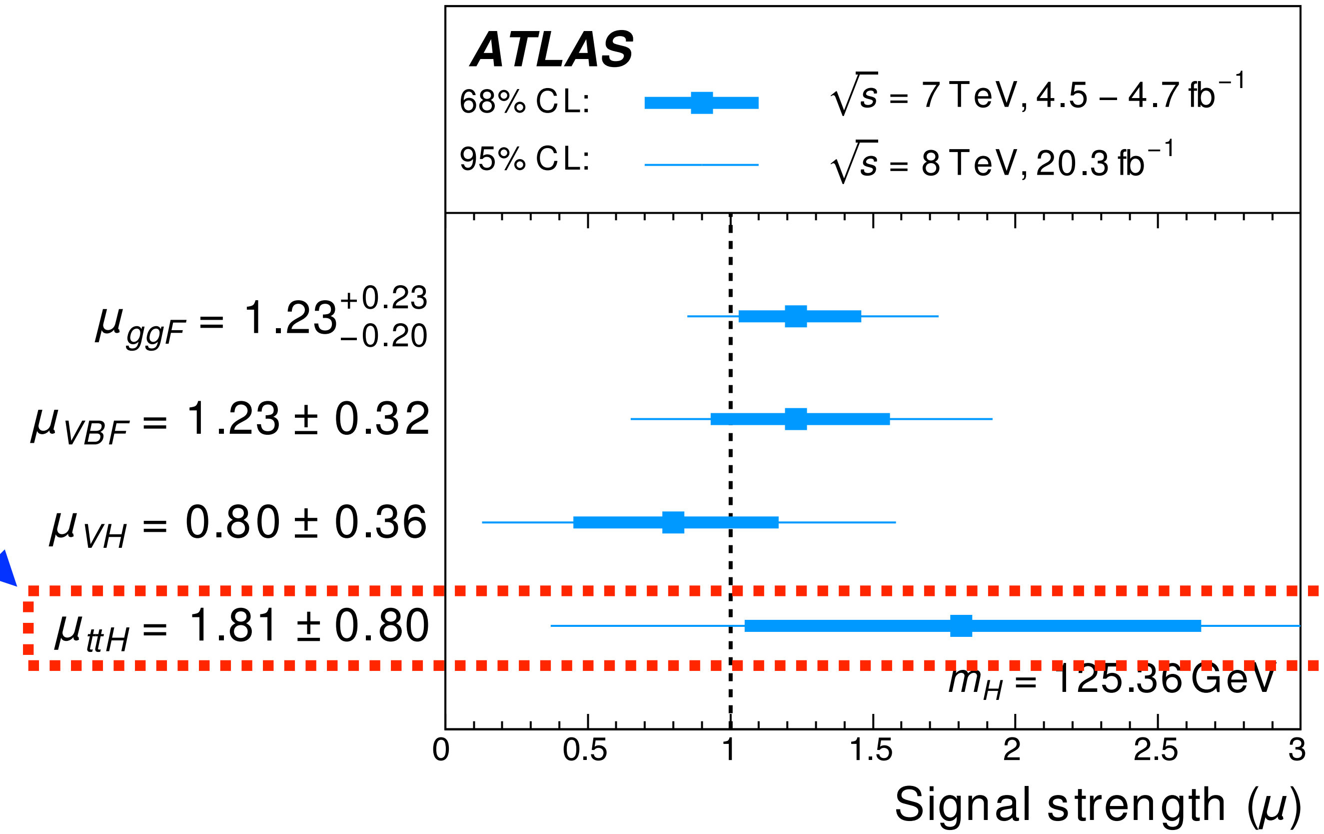
- The horizontal constraints on the H->bb line comes from the ttH (bb) analysis

Full couplings parameterisation

Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\text{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	W–t	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	W–t	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

ttH combination

- ttH combination as part of the ATLAS Higgs coupling combination:
  - correlation with other Higgs analyses not so large
- Probing different Higgs production modes individually:
  - *assuming SM Higgs boson branching ratios*



	observed	*expected*
signal significance	**2.5 s.d.**	**1.5 s.d.**
95% upper limit on σ	**3.2**	**1.4**

- Good complementarity of the various analyses, very little correlation
- ***Large gain from the combination***: 50% better than single most sensitive analysis

- A more complex case:
  - *using best fit values* for branching ratios (mainly determined by other Higgs analyses)

$$\sigma_{ttH}/\sigma_{\text{ggF}}$$

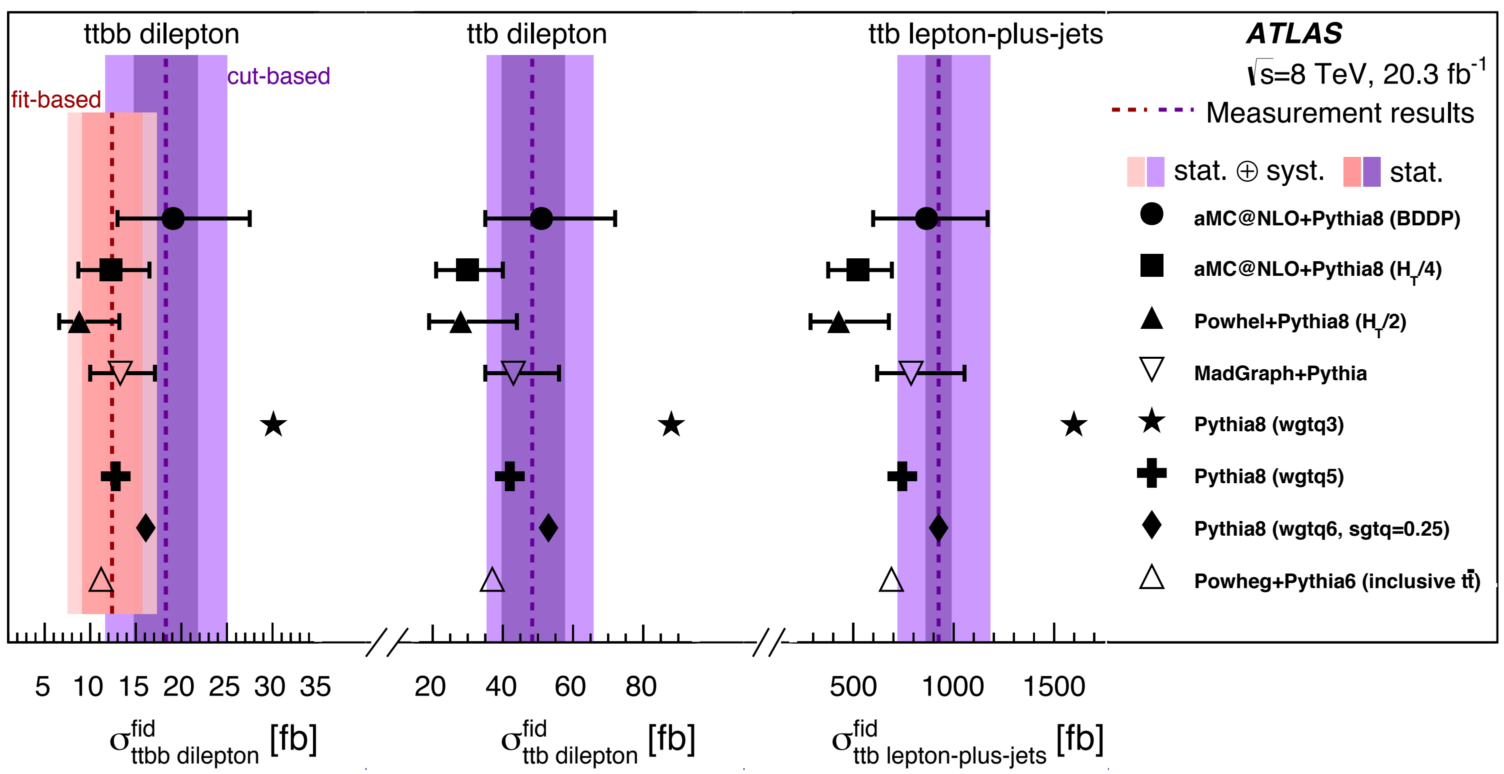
obs.= $0.012\,^{+0.007}_{-0.005}$ $\left[\begin{matrix}+0.005 & +0.004 & +0.0014\\ -0.004 & -0.003 & -0.0005\end{matrix}\right]$ (*stat.*, *sys.*, *th.*)

exp.(*)= 0.007 ± 0.001

(*)= arXiv:1307.1347

Recent SM measurements

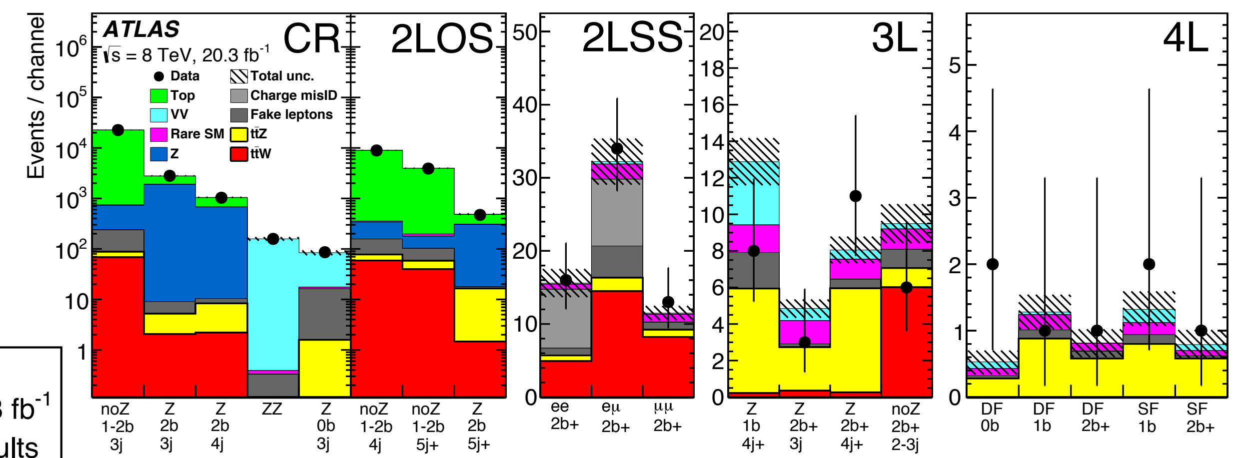
✦ ttbar+b(b)

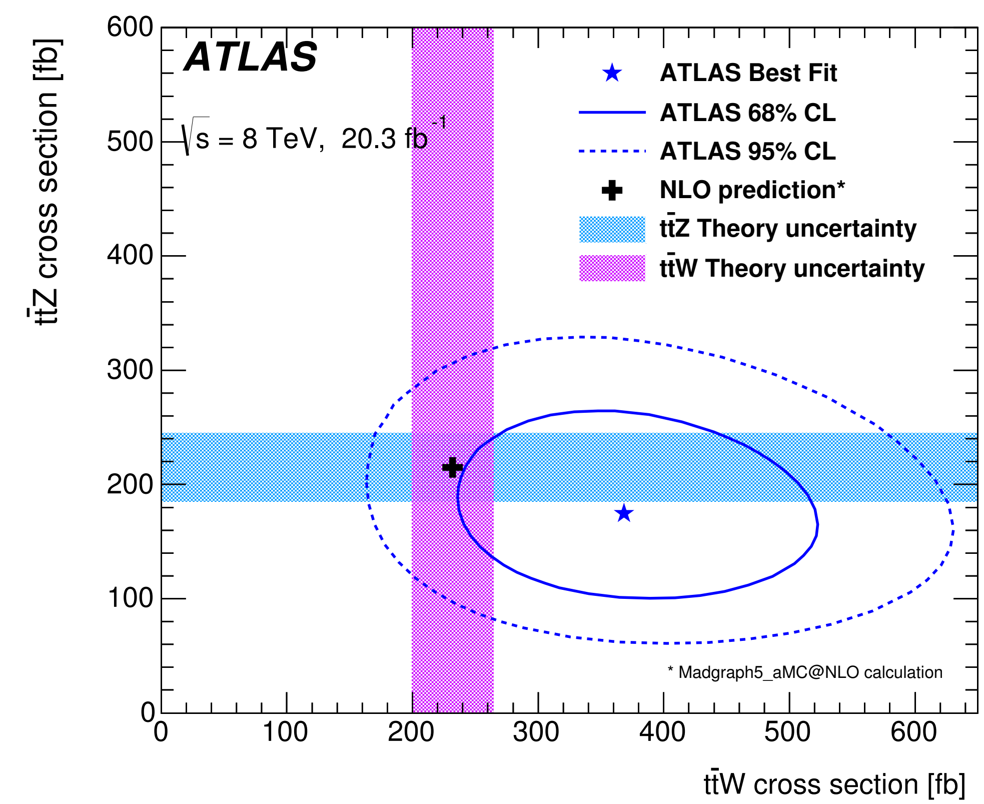


http://arxiv.org/abs/1508.06868

submitted to EPJC

✦ ttbar+W/Z





http://arxiv.org/abs/1509.05276

submitted to JHEP