Measurements of top-antitop production in association with a boson: $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, $t\bar{t}H$

SM @ LHC

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Galileo Galilei Institute - Florence

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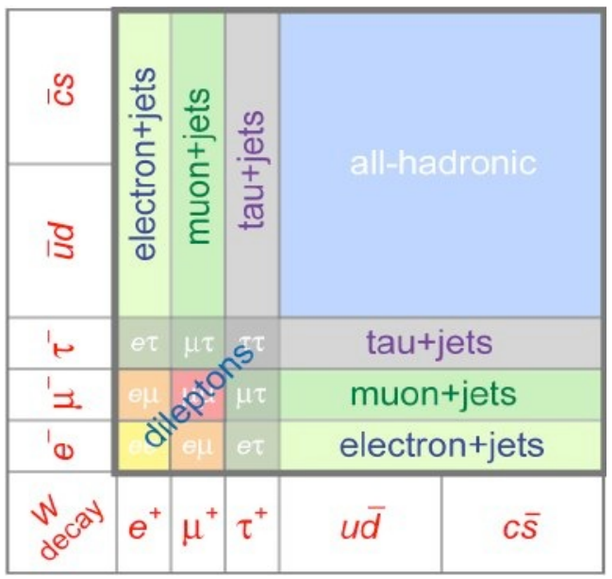
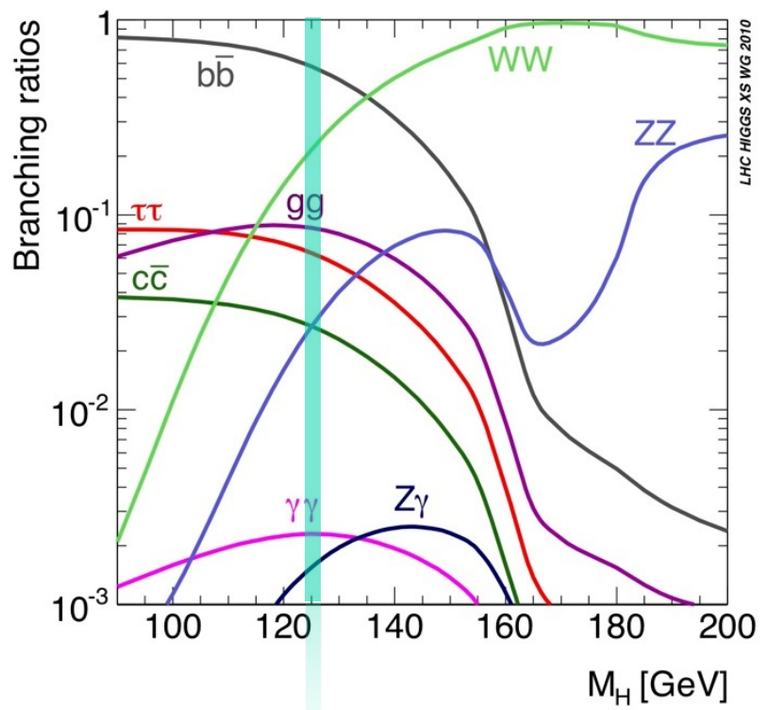
on behalf of the **ATLAS** and **CMS** collaborations

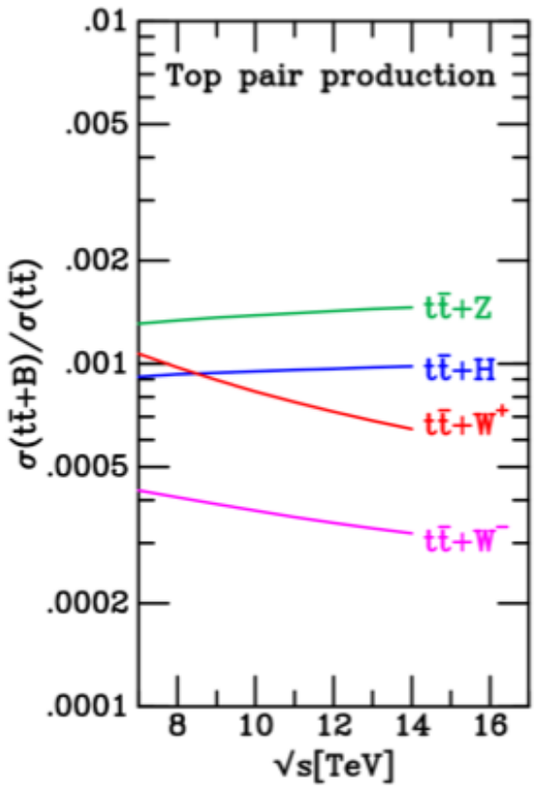
Introduction

- The top quark couples to bosons through its gauge and Yukawa interactions
- Top-quark couplings are revealed without dilution from hadronisation
- Final states characterized through top and bosons decay modes





Associated production becomes observable at LHC !

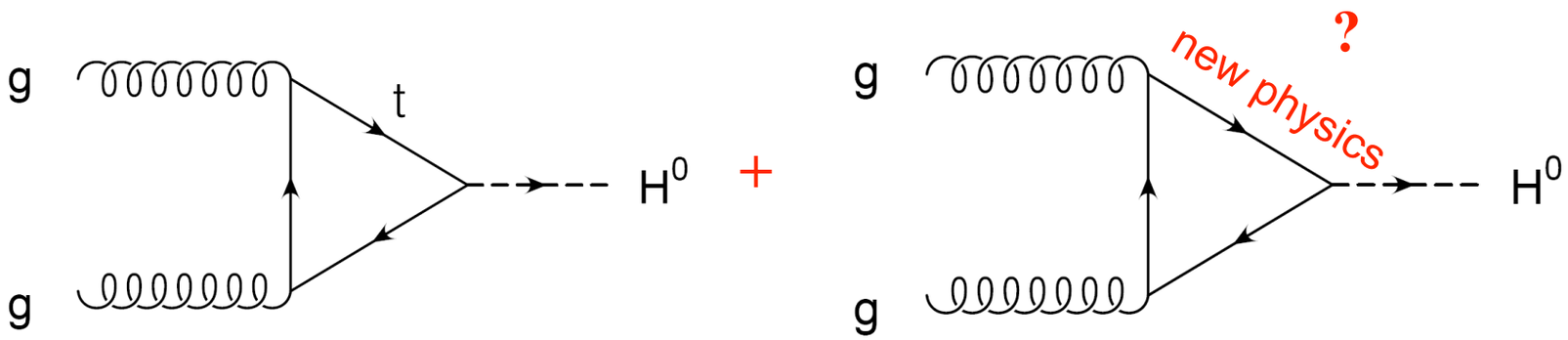


arXiv:1309.1947

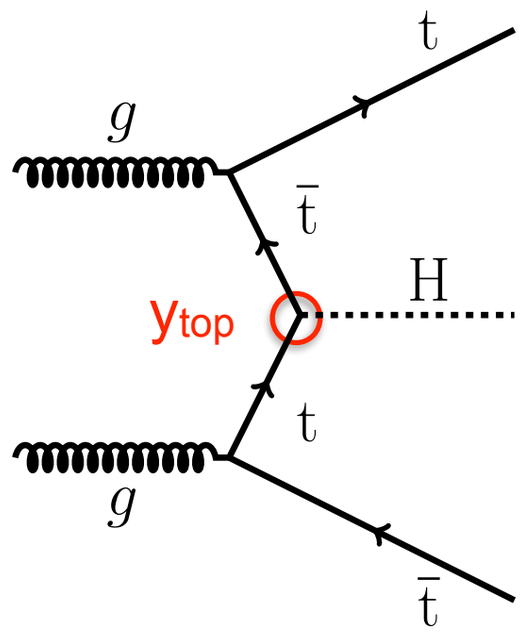
Introduction

- Measurement of electroweak couplings allows to probe V-A and A structure of electroweak theory

- Higgs production at the LHC already implies top-Higgs coupling



- $t\bar{t}H$ production mechanism allows direct measurement of the coupling!
- SM predicts $y_{top} = \sqrt{2}\, m_{top} \sim 1$
- Needs to be verified!

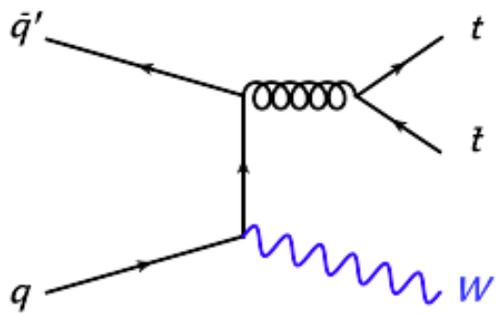


$t\bar{t}Z$ and $t\bar{t}W$

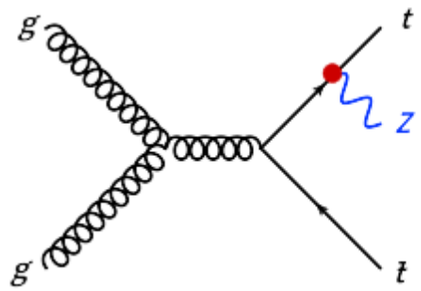
$t\bar{t}Z$ and $t\bar{t}W$ - introduction

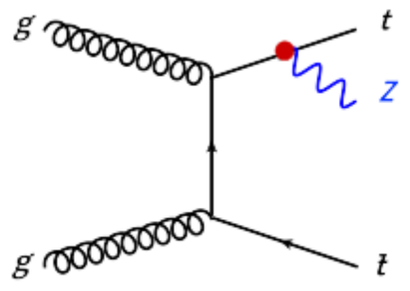
- LHC allows to measure $t\bar{t}\gamma$ and $t\bar{t}Z$ separately
- $t\bar{t}W$ process doesn't allow to probe the top-W coupling (ISR process)

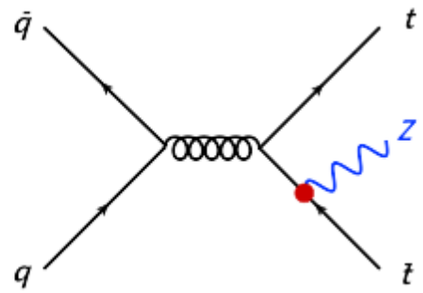
$t\bar{t}W$ (ISR)



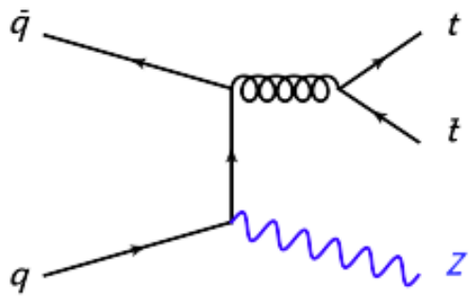
$t\bar{t}Z$ (FSR)







(dominant process)



$t\bar{t}Z$ (ISR)

- $t\bar{t}Z$ and $t\bar{t}W$ are (irreducible) backgrounds to $t\bar{t}H$!

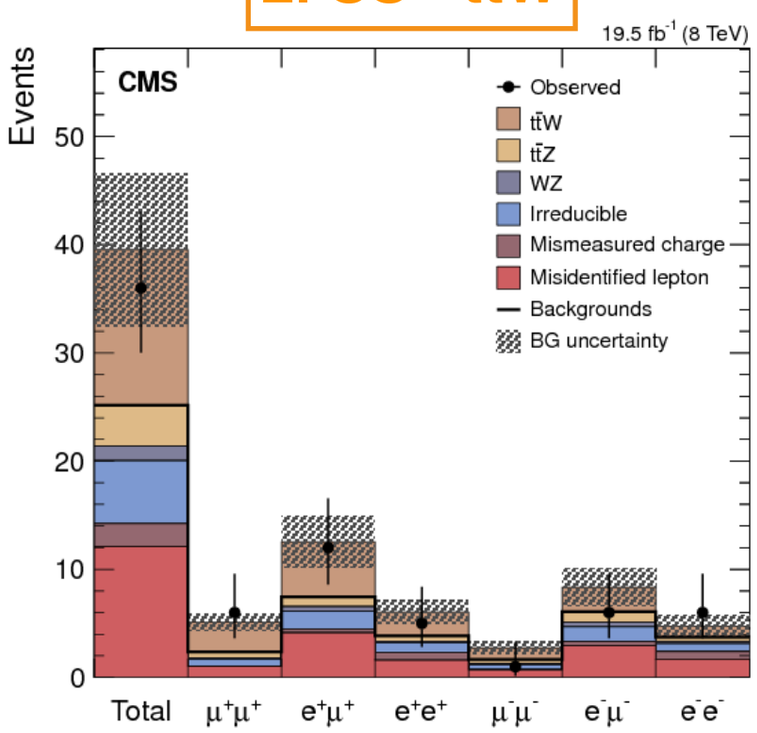
$t\bar{t}Z$ and $t\bar{t}W$

Cut and count in 2l SS, 3l and 4l:

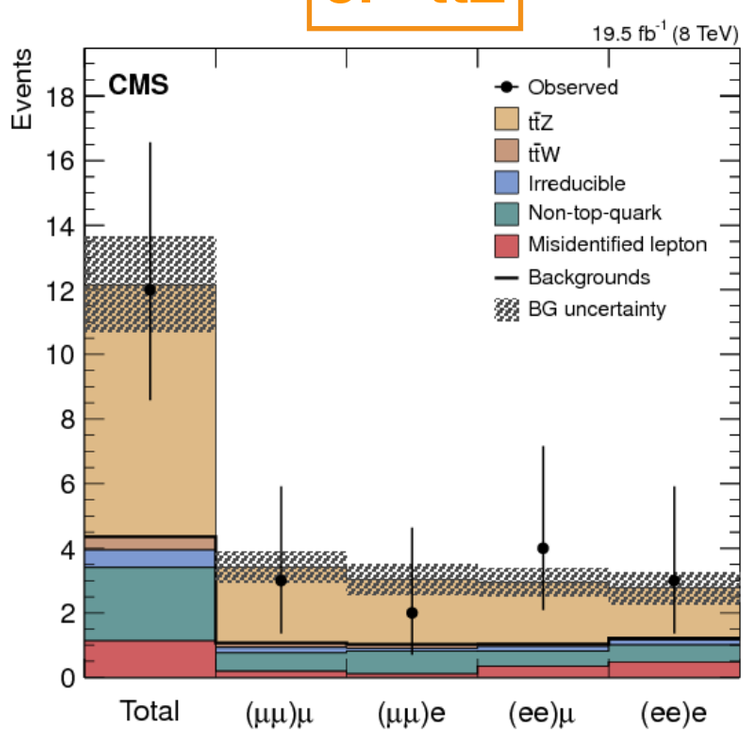
- **$t\bar{t}W$:** 2l SS, splits by charge (- -,++) and flavour (>=3j, >=1b, Z mass veto, HT>155)
  Misidentified-lepton background ($t\bar{t}$, Z+jets) estimated from sideband using the tight-to-loose lepton ID ratio
- **$t\bar{t}Z$:** 3l (Z mass, >=4j, >= 2b) and 4l (Z mass, 1 tight b, 1 loose b)
  WZ (3l) and ZZ (4l) backgrounds estimated from sidebands in data w/ no b-jet.
  Rate of b-tagged jets from Z+jets events.
  Irreducible backgrounds with at least one top from simulation (tbZ, $t\bar{t}H$, $t\bar{t}W$).

1D and 2D ($\sigma(t\bar{t}W)$ & $\sigma(t\bar{t}Z)$) fit using profile likelihood ratio

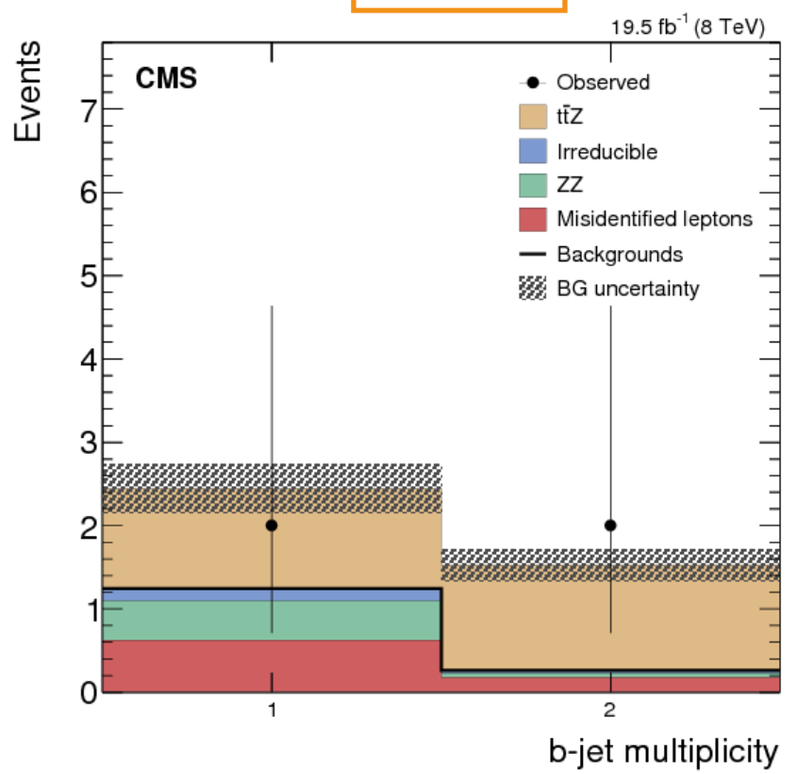
2l SS - $t\bar{t}W$



3l - $t\bar{t}Z$



4l - $t\bar{t}Z$



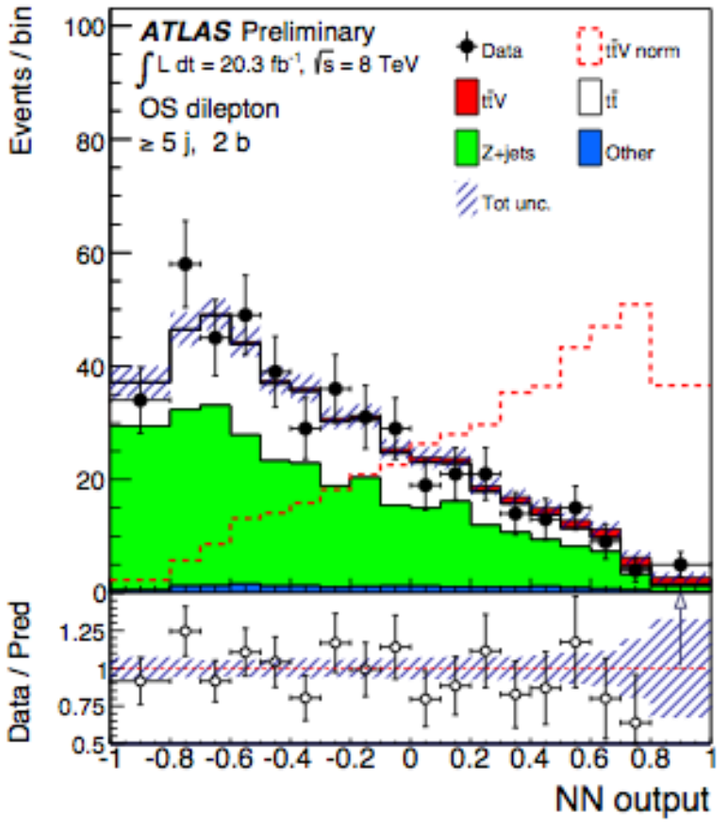
$t\bar{t}Z$ and $t\bar{t}W$

2l OS, μμ SS and 3l

- **2l OS and 3l:** multiple categories w/ different jet and b-jet multiplicities w/ or w/o Z mass
- **μμ SS:** Met> 40, HT> 240, >=2j, >=2 b

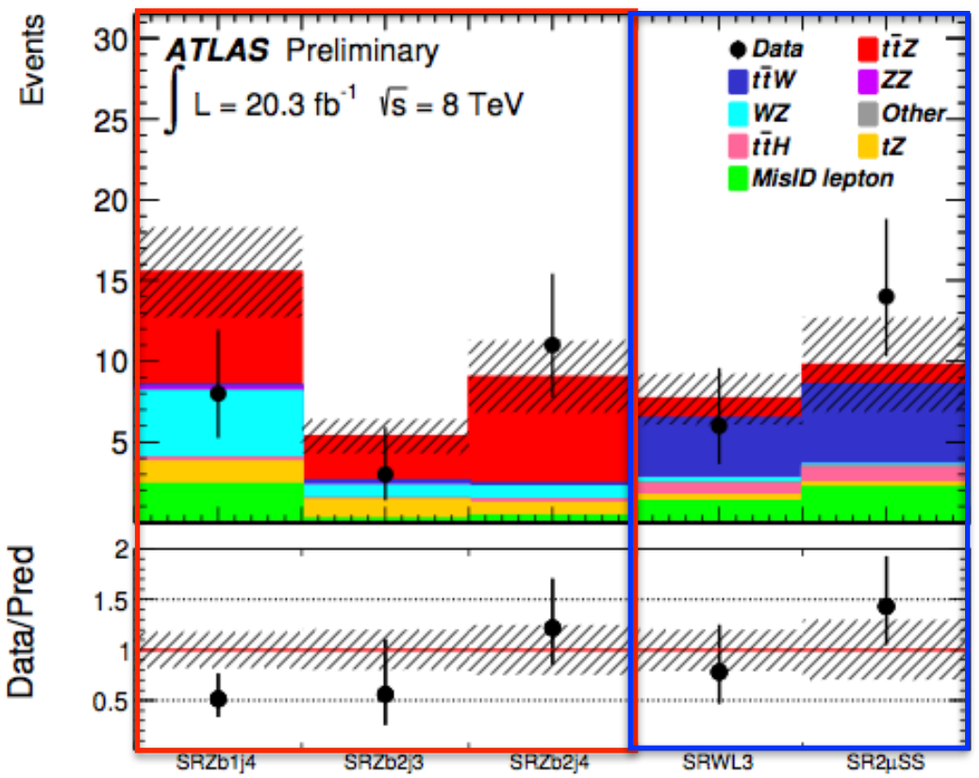
- Simultaneous fit to all three channels (11 categories) to extract $t\bar{t}Z$ and $t\bar{t}W$

2l OS (mainly - $t\bar{t}Z$)



In 2l OS large bkg from $t\bar{t}$ and Z+jets:

NN to separate $t\bar{t}V$ (hadronic W, jet centrality..)

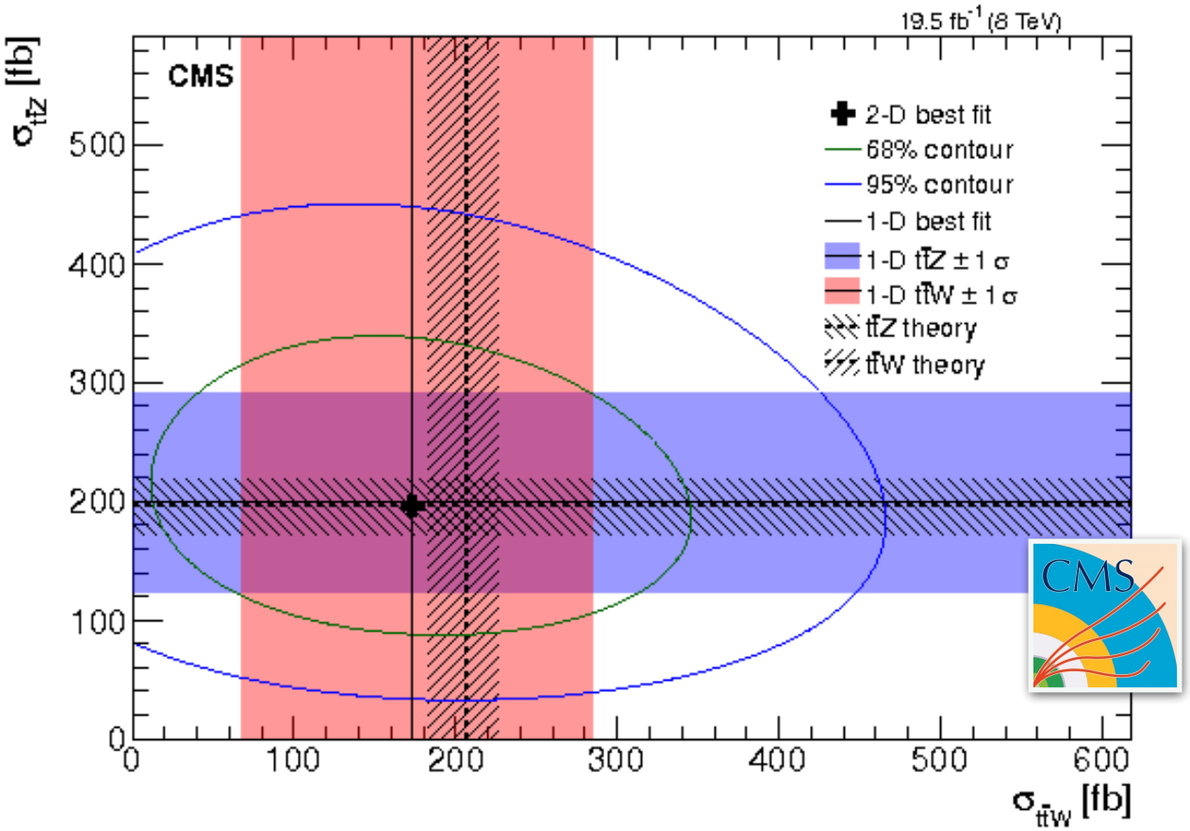


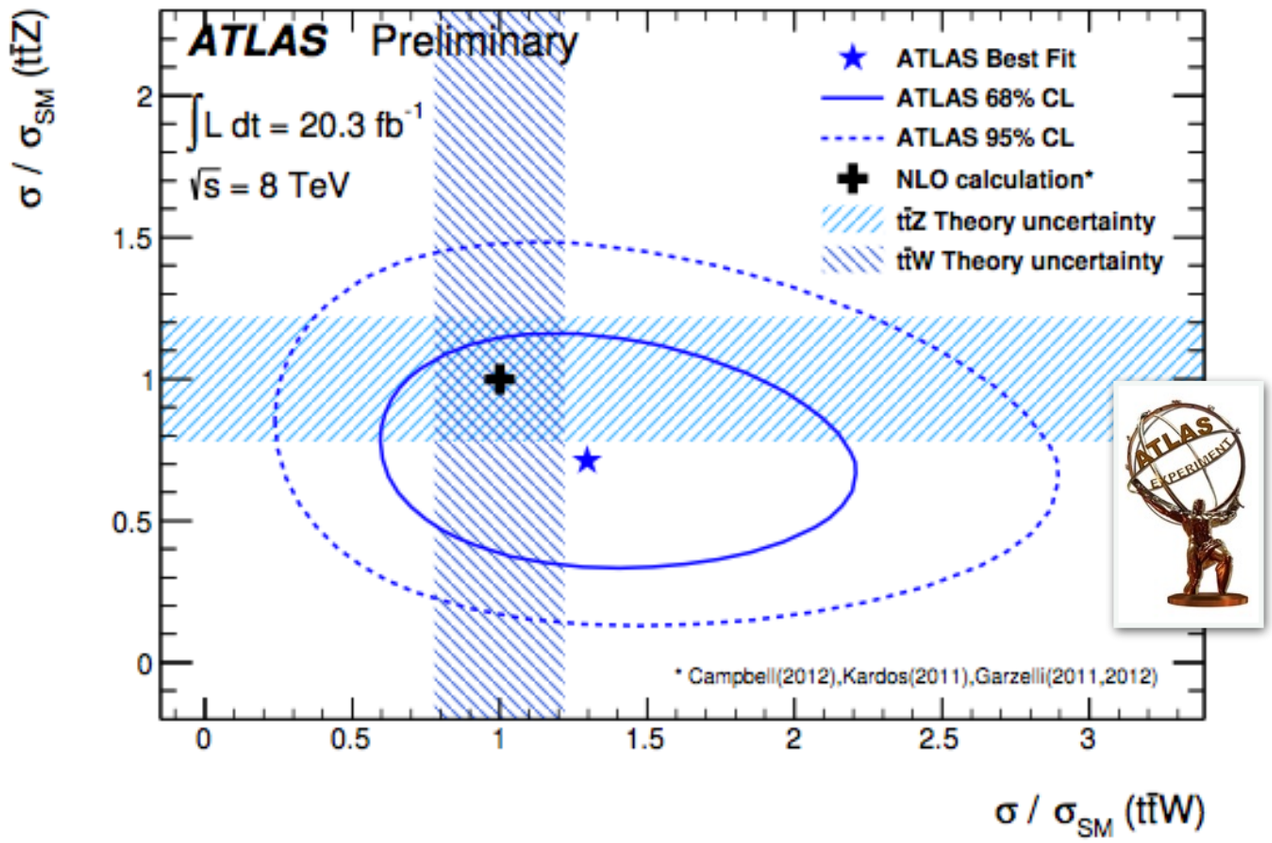
$t\bar{t}Z$ (3l) **$t\bar{t}W$ (3l w/o Z and μμ SS**

$t\bar{t}Z$ and $t\bar{t}W$

Evidence for **$t\bar{t}Z$** (ATLAS, CMS) and **$t\bar{t}W$** (ATLAS)!

8 TeV NLO cross sections: $\sigma(t\bar{t}Z) = 206 \pm 45$ fb, $\sigma(t\bar{t}W) = 232 \pm 51$ fb





Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
3ℓ+4ℓ	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

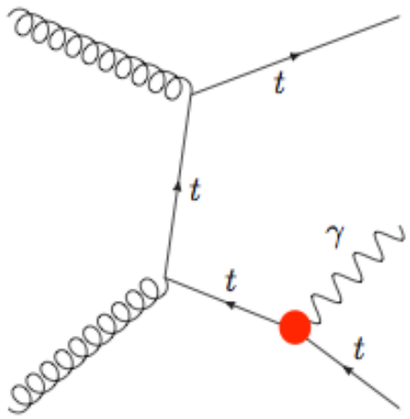
	Summary of combined simultaneous fit results		
Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) $\pm$ 21(syst.) fb	3.1	3.7
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1	2.3

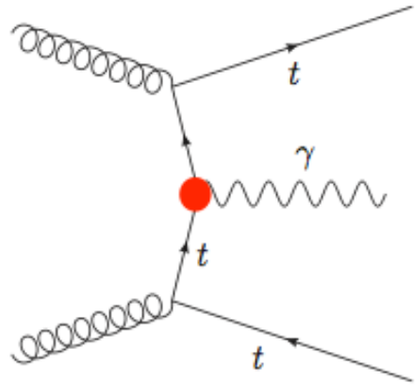
$t\bar{t}\gamma$ - introduction

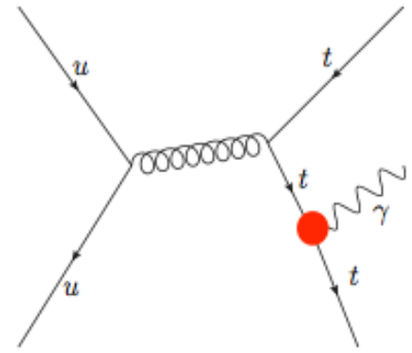
- Goal of $t\bar{t}\gamma$ measurement: measure the top-quark charge, **magnetic** and **electric dipole moments** as well as the coupling

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\gamma^\mu t\,A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d_V^\gamma + id_A^\gamma\gamma_5\right)t\,A_\mu$$

possible contributions from new phenomena

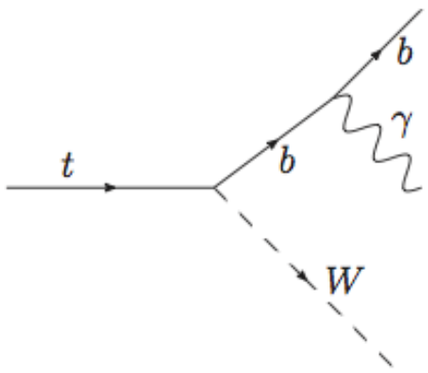


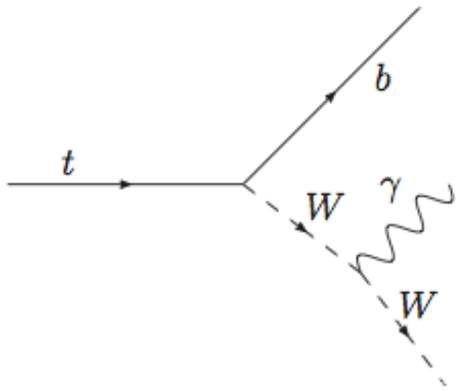


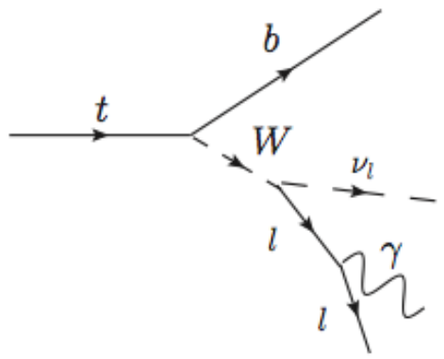


- Current datasets allow to measure the cross-section with large uncertainties
- Large irreducible background of photons radiated from other charged particles

simulation with WHIZARD to take into account interferences







- **$t\bar{t}$ in μ/e+jets**
  $E_T(\gamma)>20$ GeV, $|\eta|<2.37$, $\notin$ (1.37,1.52)
  $\Delta R(\gamma, l/jet) > 0.7/0.5$
  $|M(e,\gamma)-M(Z)| > 5$ GeV

- **Template fit to track isolation**
  (not used in γ identification)

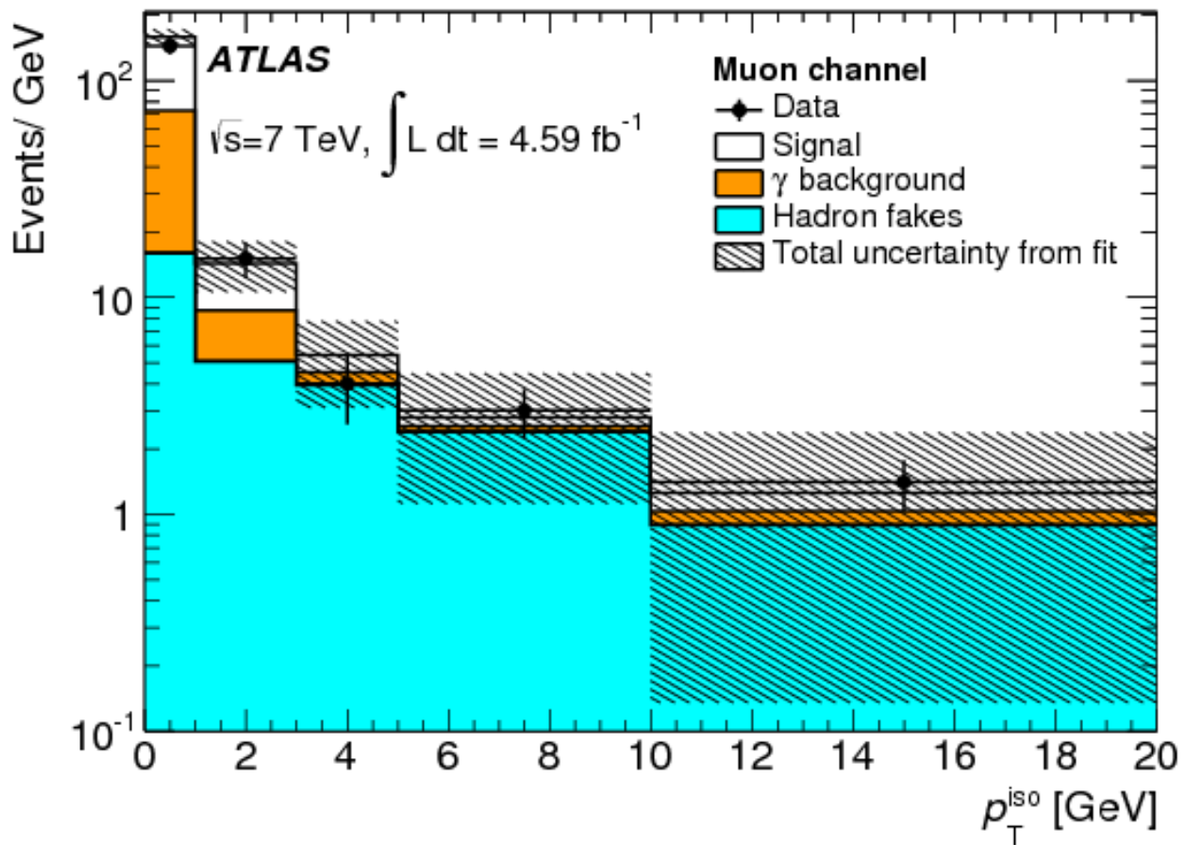
- **Fiducial cross section result**

$$\sigma^{\text{fid}}_{t\bar{t}\gamma} = N_s/(\epsilon \cdot \mathcal{L}_{\text{int}})$$
$$= 63 \pm 8(\text{stat.})\,^{+17}_{-13}(\text{syst.}) \pm 1\,(\text{lumi.})\ \text{fb}$$

In agreement with NLO 48 ± 10

Main systematic: jet modeling (17%)

7 TeV - 4.59 fb^{-1}

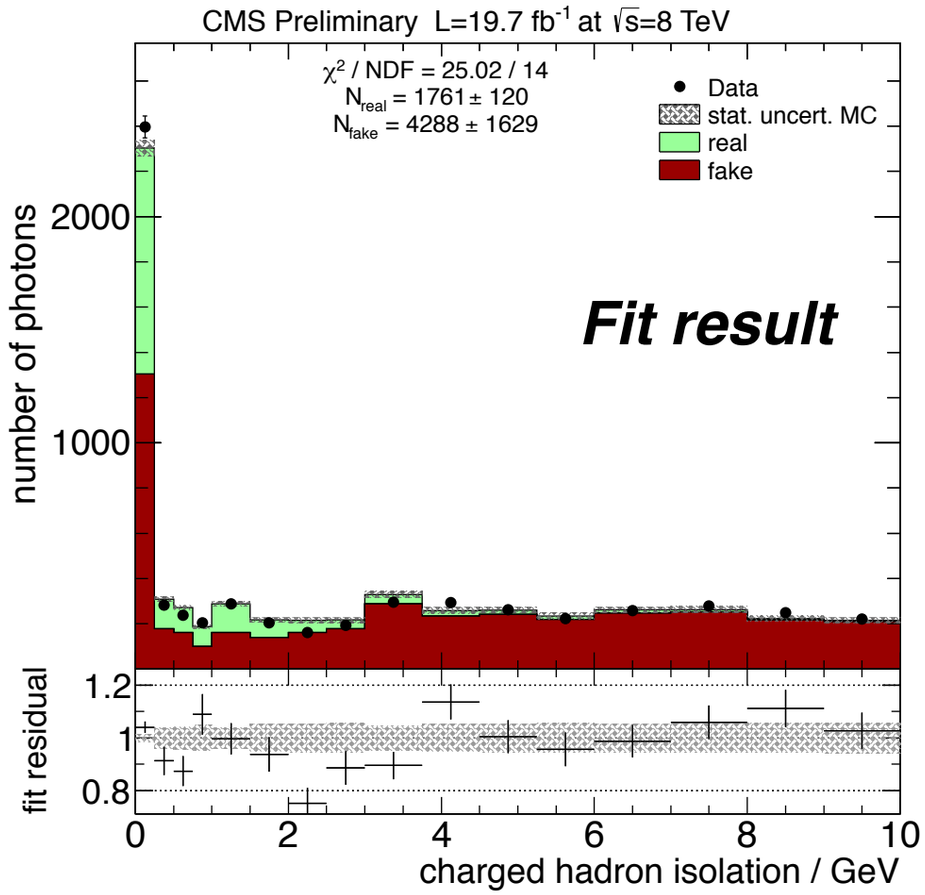


Templates for **prompt γ** and **hadron fakes** from data.

- **tt̄ in μ+jets**
  γ with E_T>25 GeV, |η|<1.44
  ΔR (γ,μ/jet) > 0.7, ΔR (γ,b) > 0.1

- **Template fit of charged hadron isolation**
  (not used in γ identification)

- Purity of selected tt̄ sample and
  γ efficiency from simulation



$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t}$$
$$= (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma_{\bar{t}t}^{\text{CMS}}$$
$$= 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\,\text{pb}$$

(tt̄ in di-leptons at 8 TeV TOP-12-007)

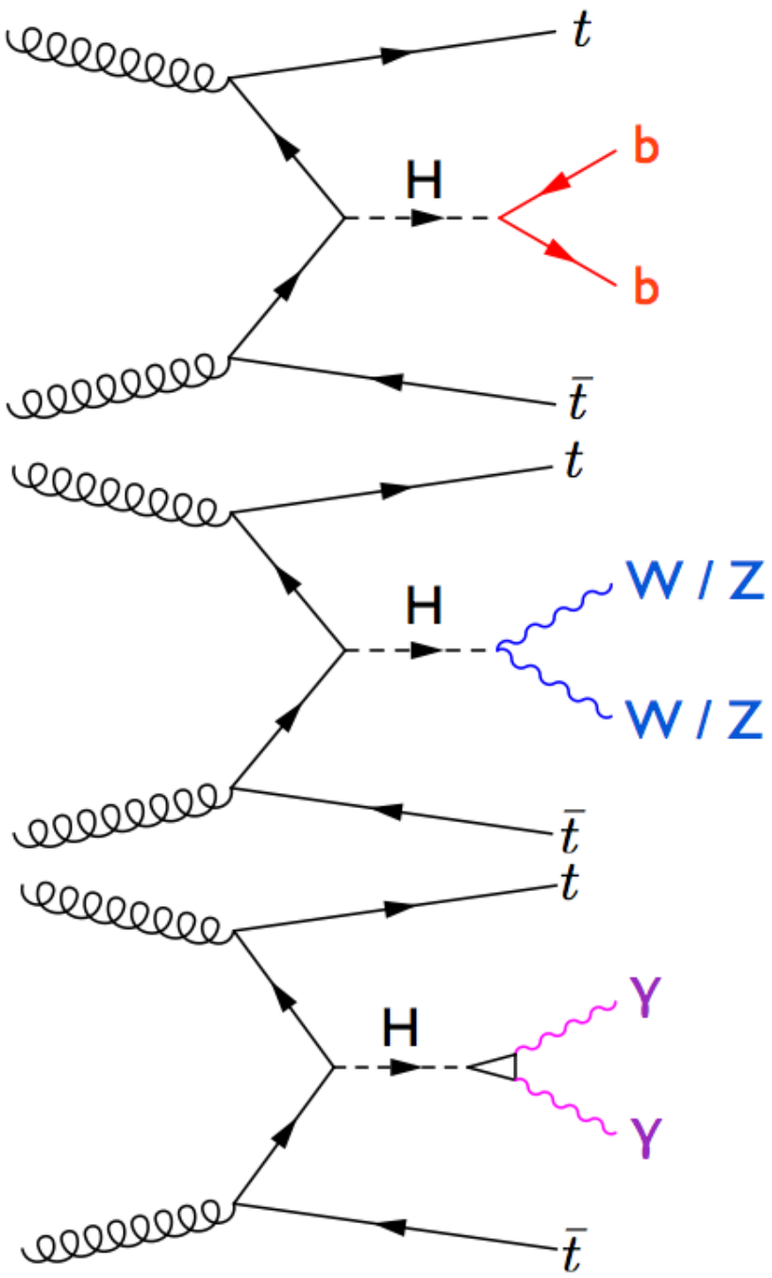
In agreement with NLO 1.8 ± 0.5 pb

Signal template: from simulation

Background template: from data, combining distributions from three sidebands of photon-ID variables - 23% syst. on final result

$t\bar{t}H$

$t\bar{t}H$ - introduction



Largest BR: 58%

- 4 b-quarks in the final state, challenging Higgs mass reconstruction
- Main background: $t\bar{t}$+jets

H→WW BR: 22 %

- Multi-leptons signatures from W, Z bosons and tau decays
- Main background: $t\bar{t}V$ and non-prompt leptons

H→ γγ BR: ~0.2 %

- Precise Higgs mass reconstruction
- Main backgrounds: $t\bar{t}$+γ and QCD multi-photon/jets

H→$\tau_h\tau_h$ (not covered today)

$t\bar{t}H$, H→ bb

- **Strategy** - consider single-lepton and di-lepton $t\bar{t}$ final states
  - further categorisation in N(jets) and N(b-jets)
  - S/B increases with N(jets) and N(b-jets)
  - categories w/ low S/B used to constrain backgrounds and systematics
  - 15 (16) categories for ATLAS (CMS), best S/B~7%

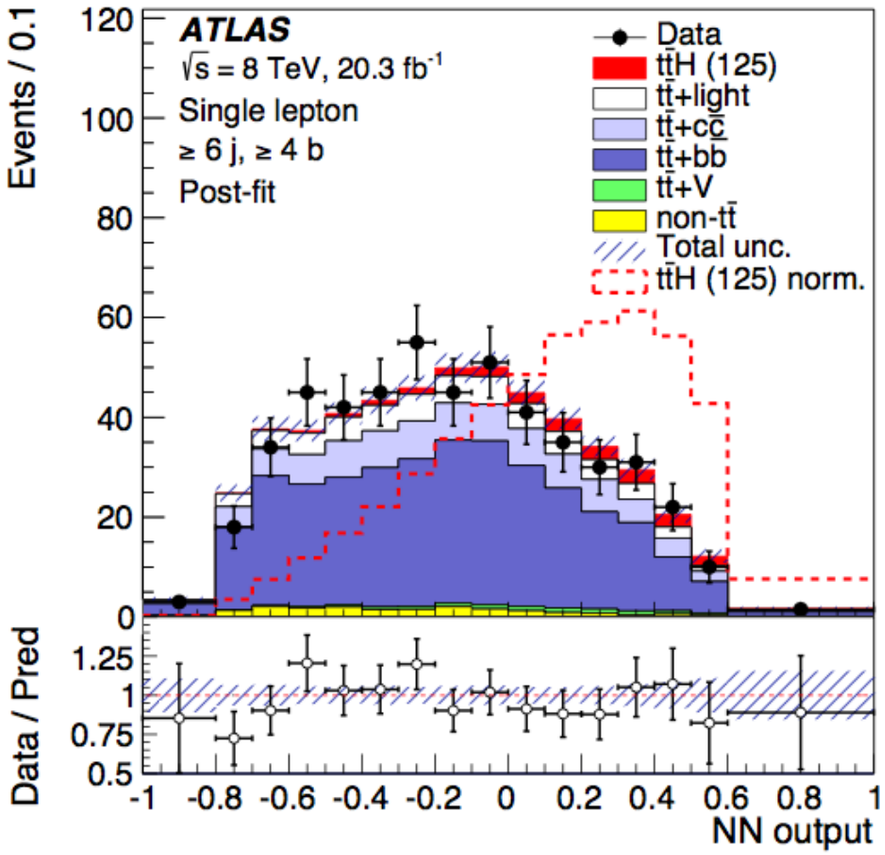
- **Main background: $t\bar{t}$+jets**
  - modeled from simulation (POWHEG+PYTHIA (ATLAS) - MADGRAPH+3 extra partons (CMS))
  - corrected to match differential measurements (pT of $t\bar{t}$, top quark pT)
  - different classification using truth information
    - $t\bar{t}$+b(b) $t\bar{t}$+c(c) $t\bar{t}$+light (ATLAS)
    - $t\bar{t}$+bb $t\bar{t}$+b $t\bar{t}$+c(c) $t\bar{t}$+light (CMS)
  - main systematic: $t\bar{t}$+bb normalisation (~50% prior to the fit)

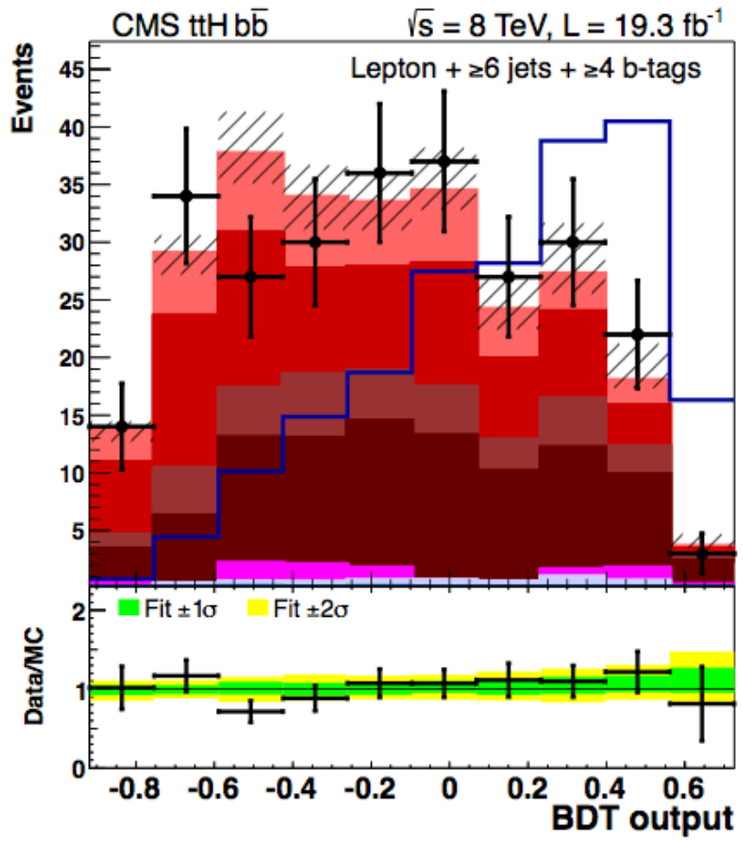
$t\bar{t}H$, $H \rightarrow b\bar{b}$

Multivariate analyses to further constrain sensitivity in signal dominated categories

- NN for ATLAS, BDTs for CMS
- kinematic variables for ATLAS, b-tagging variables in addition for CMS

Combined fit to all channels:





ATLAS: $\mu = \sigma/\sigma_{SM} = 1.5 \pm 1.1$
expected(observed) UL @ 95% CL: 2.2(3.4)

CMS: $\mu = \sigma/\sigma_{SM} = 0.7 \pm 1.9$
expected(observed) UL @ 95% CL: 3.5(4.1)

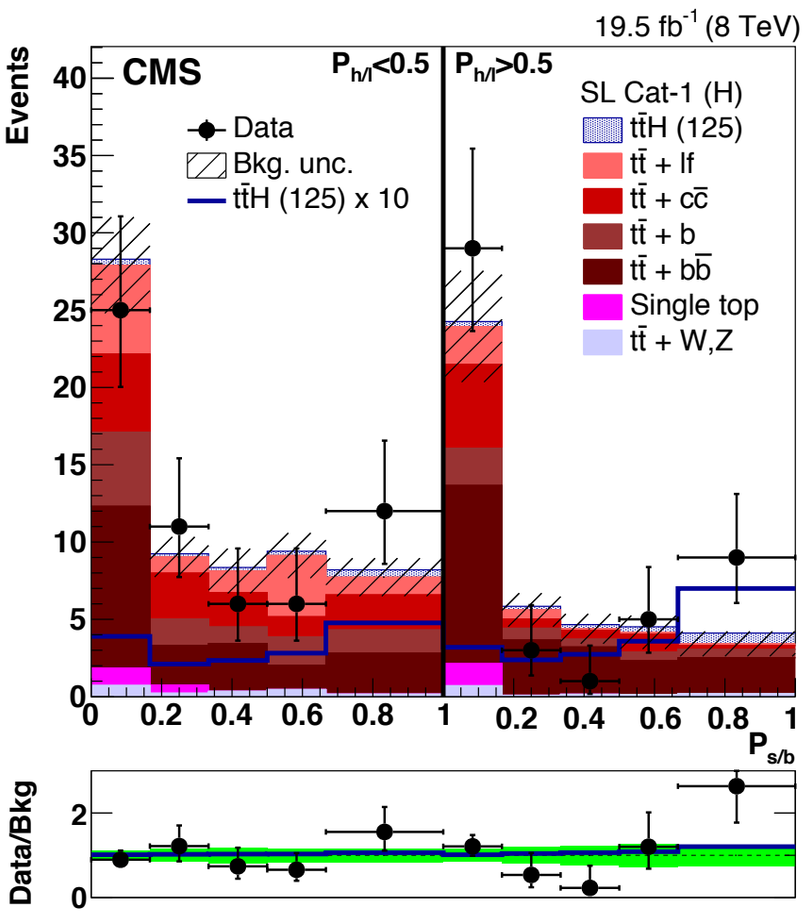
$t\bar{t}H$, H→ bb Matrix Element Method

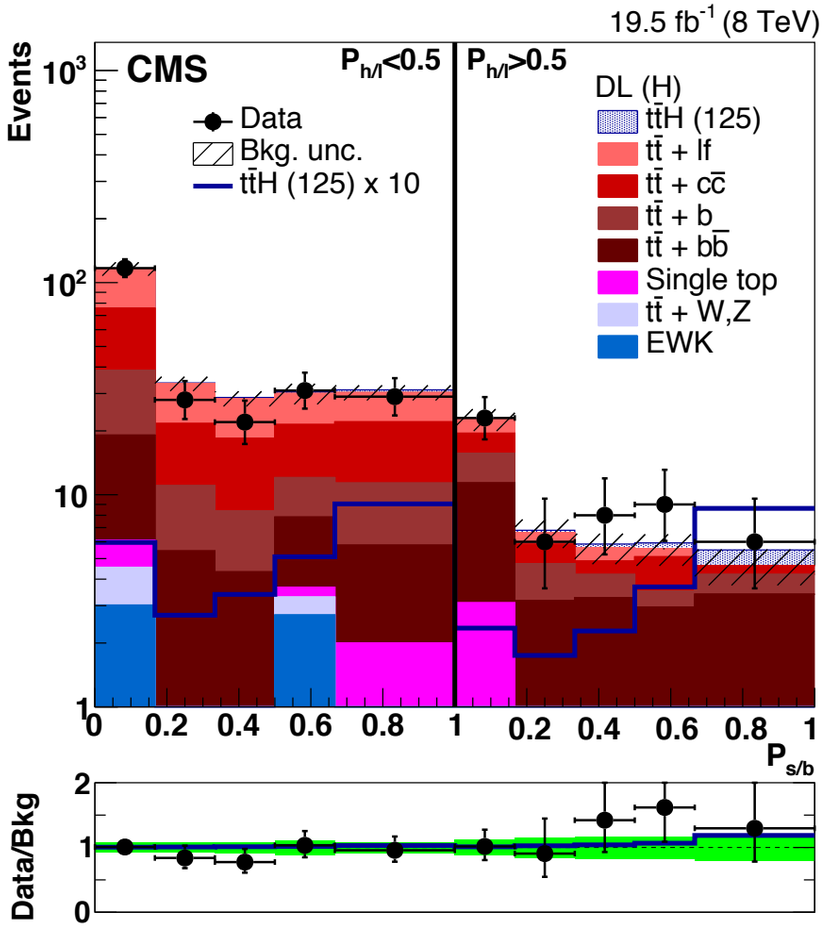
Matrix Element Method (MEM):

- method calculates likelihood for an event to be consistent with a given physics process
- links full kinematic information of an event with LO calculation
- discrimination against irreducible $t\bar{t}$+bb background

CMS (standalone analysis):

- two categories: single lepton (SL), >=5 jets or two opposite sign leptons (DL), >=4 jets
- discriminant (Ps/b) defined by likelihood ratios of MEM for $t\bar{t}H$ and $t\bar{t}$+bb





CMS: $\mu = \sigma/\sigma_{SM} = 1.2^{+1.6}_{-1.5}$ expected(observed) UL @ 95% CL: 3.3(4.2)

Comparable results w/ standard analysis

Promising strategy to control $t\bar{t}$+bb

ATLAS: variables using MEM included in NN (single-lepton channel)

$t\bar{t}H$, H→ γγ

- **Strategy** - reconstruct M(γγ) and use loose selection for $t\bar{t}$
- Check that contributions from H production mode not sensitive to top Yukawa coupling are minor

- **Two categories**:

  Hadronic: >= 4 jets 1 b-tag (CMS), >= 5(6) jets 2(1) b-tag (ATLAS)

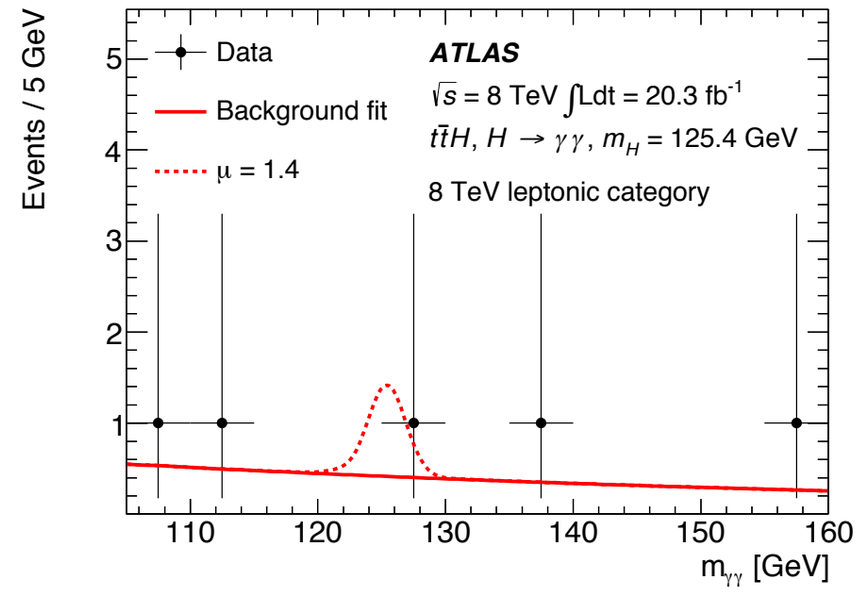
  Leptonic: >= 2 jets 1 b-tag (CMS), >= 1 jet 1 b-tag (ATLAS)

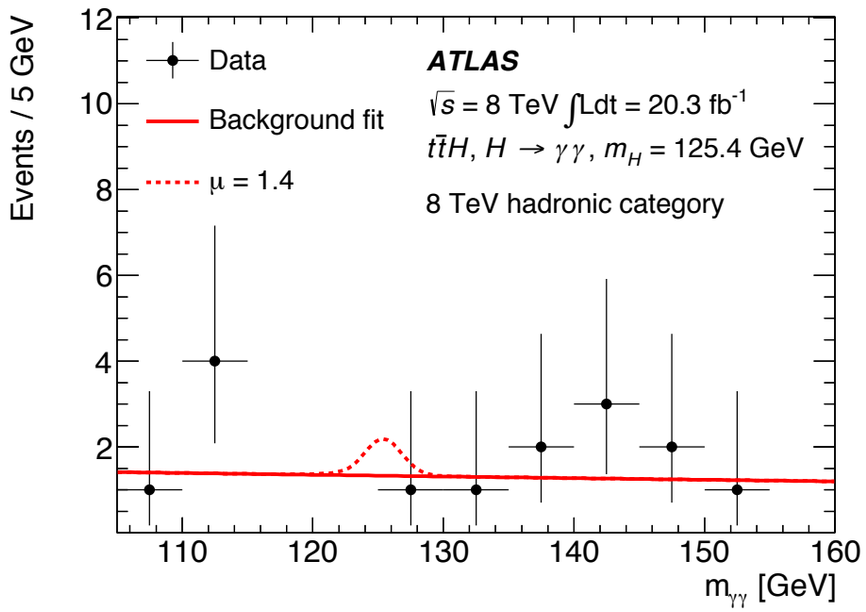
- **Fit M(γγ) distribution** as in inclusive γγ analysis
  - falling background: ATLAS uses exponential, CMS fit can use exponential, power-law, polynomial or Laurent series - tested in fit

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

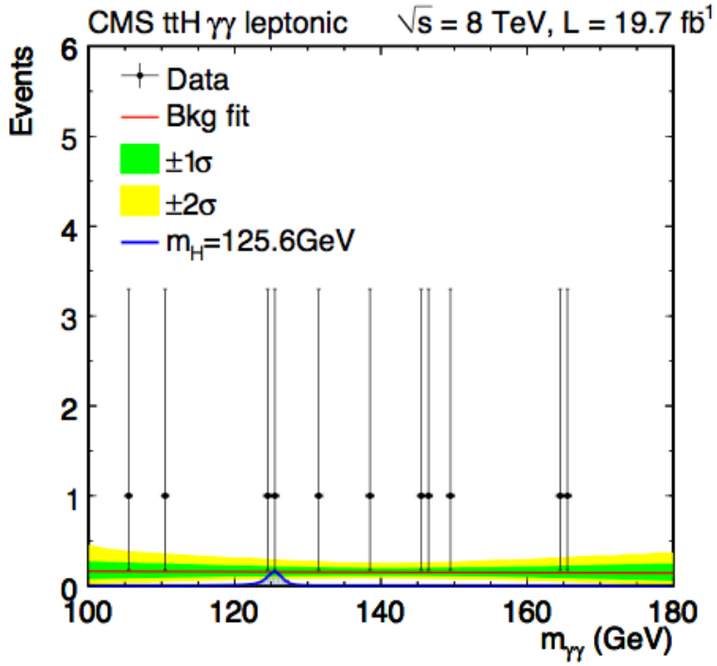
- A few candidate events, analysis statistically limited
- Fitted signal consistent with SM

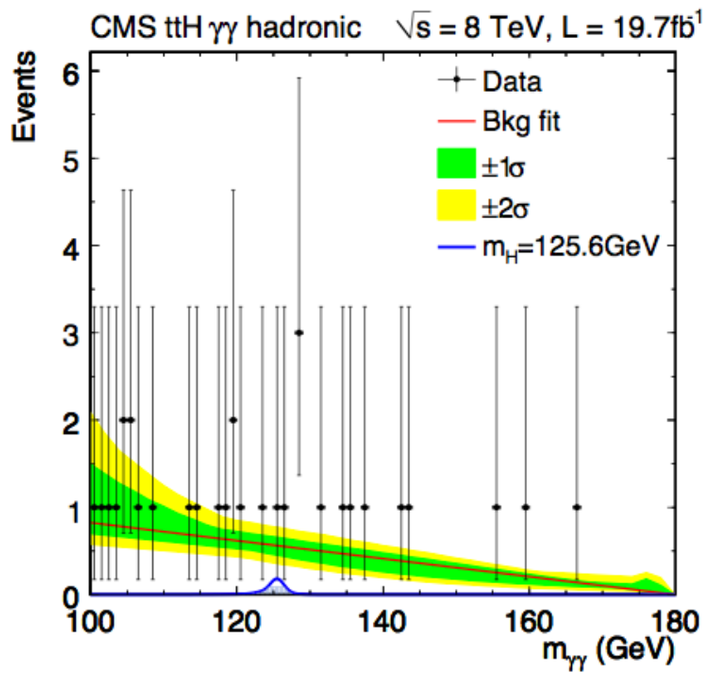
ATLAS: $\mu = \sigma/\sigma_{SM} = 1.4^{+2.2}_{-1.4}$
expected(observed) UL @ 95% CL: 4.9 (6.7)





CMS: $\mu = \sigma/\sigma_{SM} = 2.7^{+2.6}_{-1.8}$
expected(observed) UL @ 95% CL: 4.7 (7.4)





$t\bar{t}H$, H→multileptons

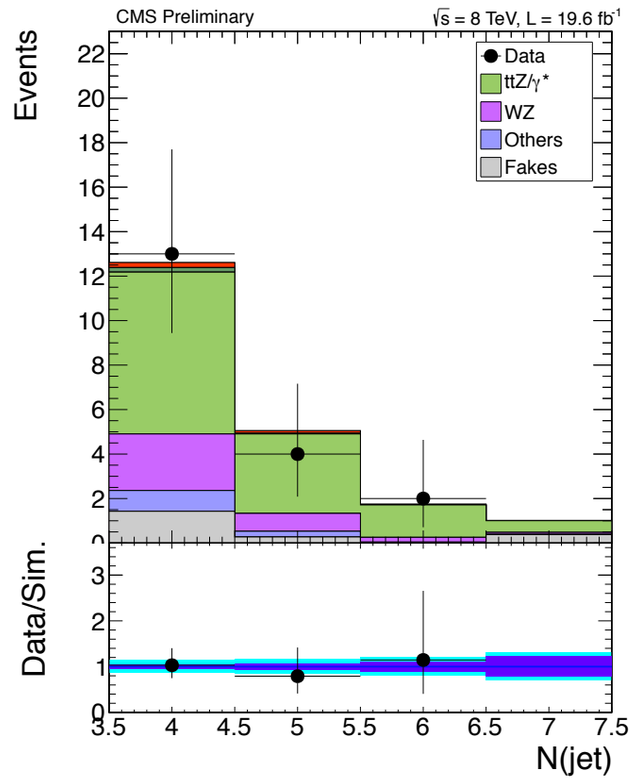
- **Strategy** - take advantage of final states not reachable from $t\bar{t}$ production
  - **2l SS, 3l, 4l**
  - **2l SS 1τ** and **1l 2τ** for **H→$\tau\tau$ (ATLAS)**

- **Main reducible background: $t\bar{t}$ with fake l from b-jet**
  - dedicated lepton id (BDT) - CMS
  - calorimeter and tracking isolation variables, IP requirements - ATLAS
  - data driven estimates - ATLAS & CMS

- **$t\bar{t}V$** estimated from simulation using NLO x-sec
  - acceptance effects comparing different generators (ATLAS)
  - $t\bar{t}Z$ tested in tri-lepton region in data: stat. uncertainty ~35% (CMS)

- **WZ, ZZ** normalised/validated using control region w/o b-jets (~50% uncertainty)

- Charge misidentification in 2l SS



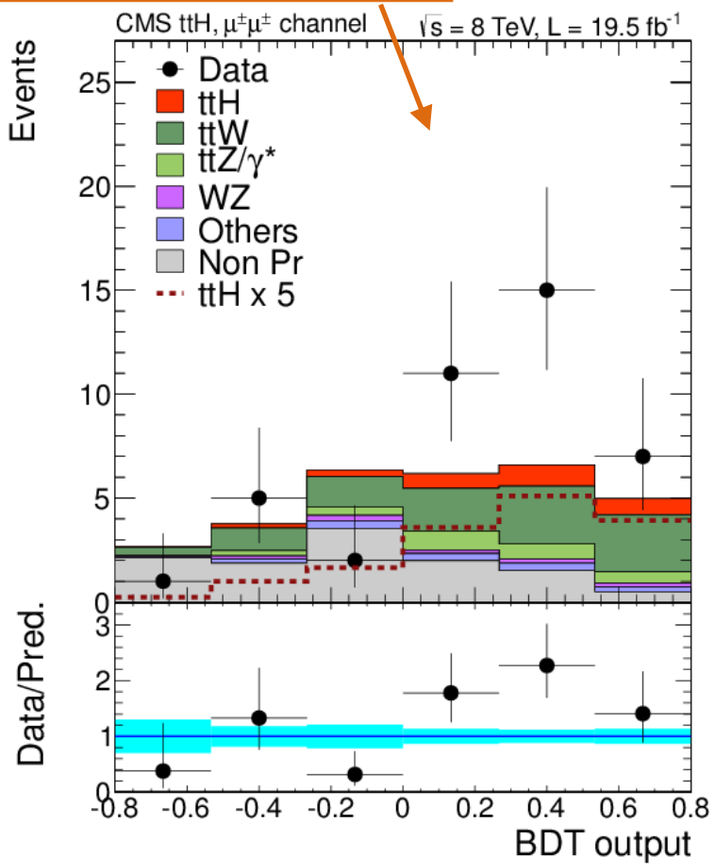
$t\bar{t}Z$ validation region

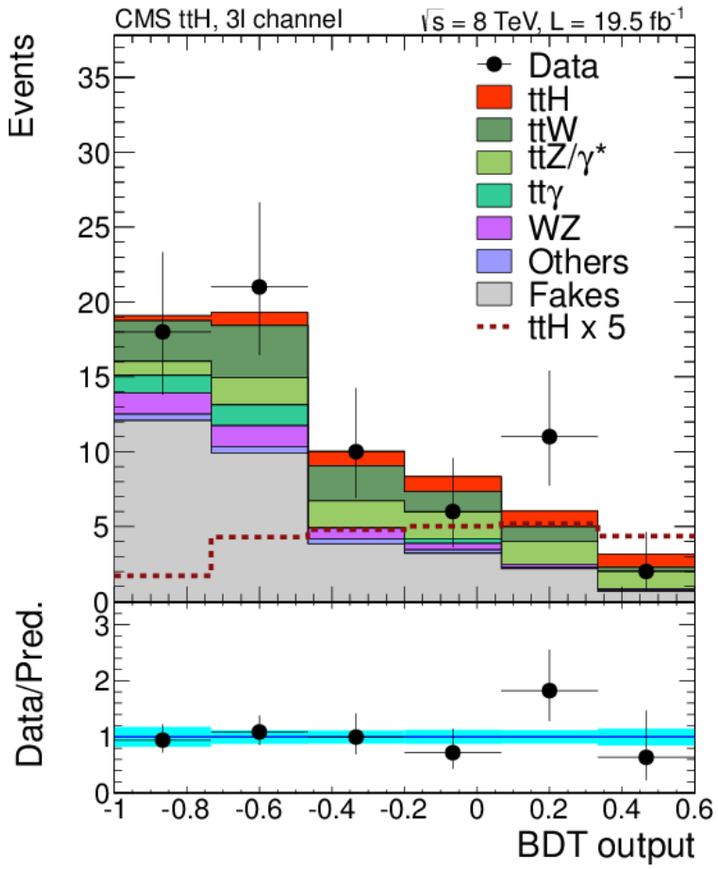
$t\bar{t}H$, H→multileptons

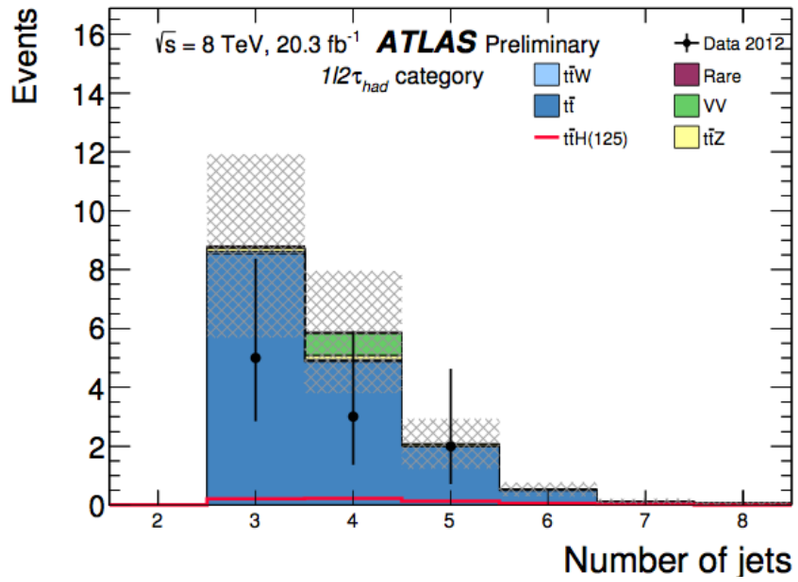
- **Event categorisation**:
  - ATLAS: by jet multiplicity (4j, >=5j) in 2l SS and Z enriched/depleted in 4l
  - CMS: by sum of charge in 2l SS and 3l ($t\bar{t}W$, WZ and Wjets are asymmetric) - 5% gain in sensitivity

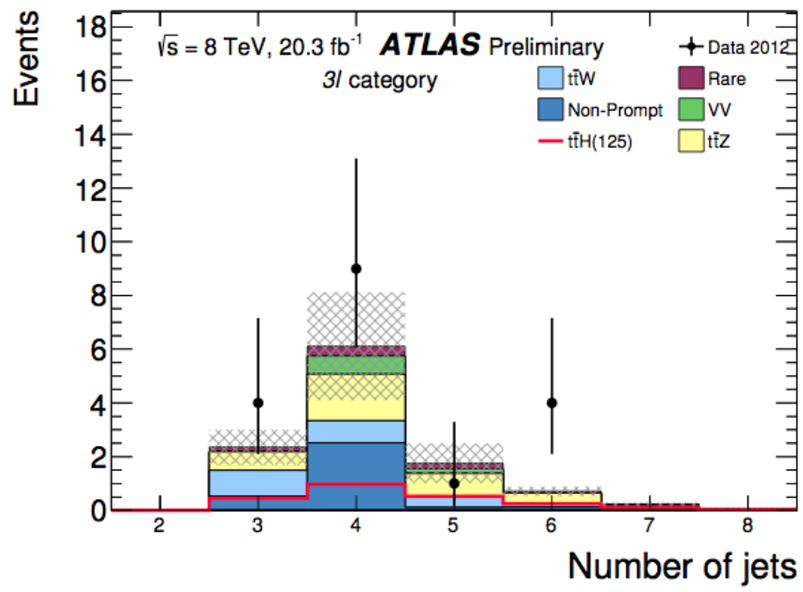
- **Signal extraction**:
  - ATLAS: maximum likelihood fit to the the data yields
  - CMS: fit to discriminating variables
    BDTs exploiting kinematical variables for 2l and 3l, N(jets) for 4l

Excess in $\mu^{\pm}\mu^{\pm}$!

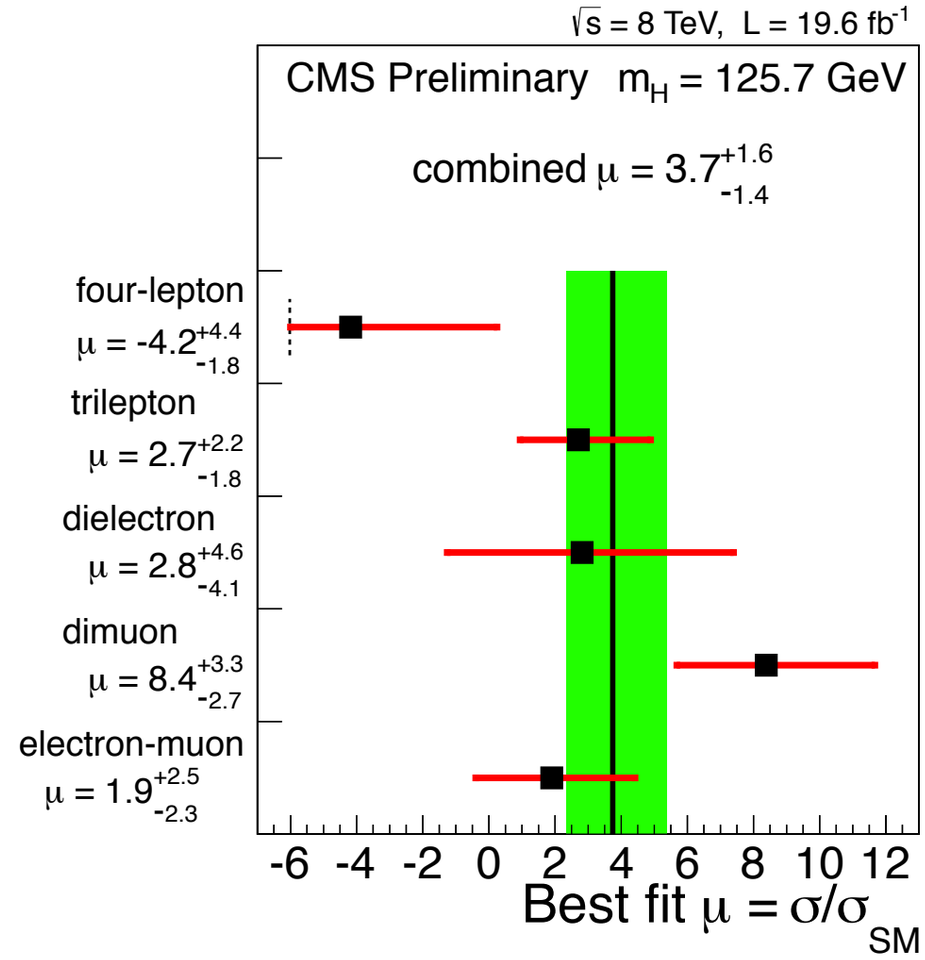


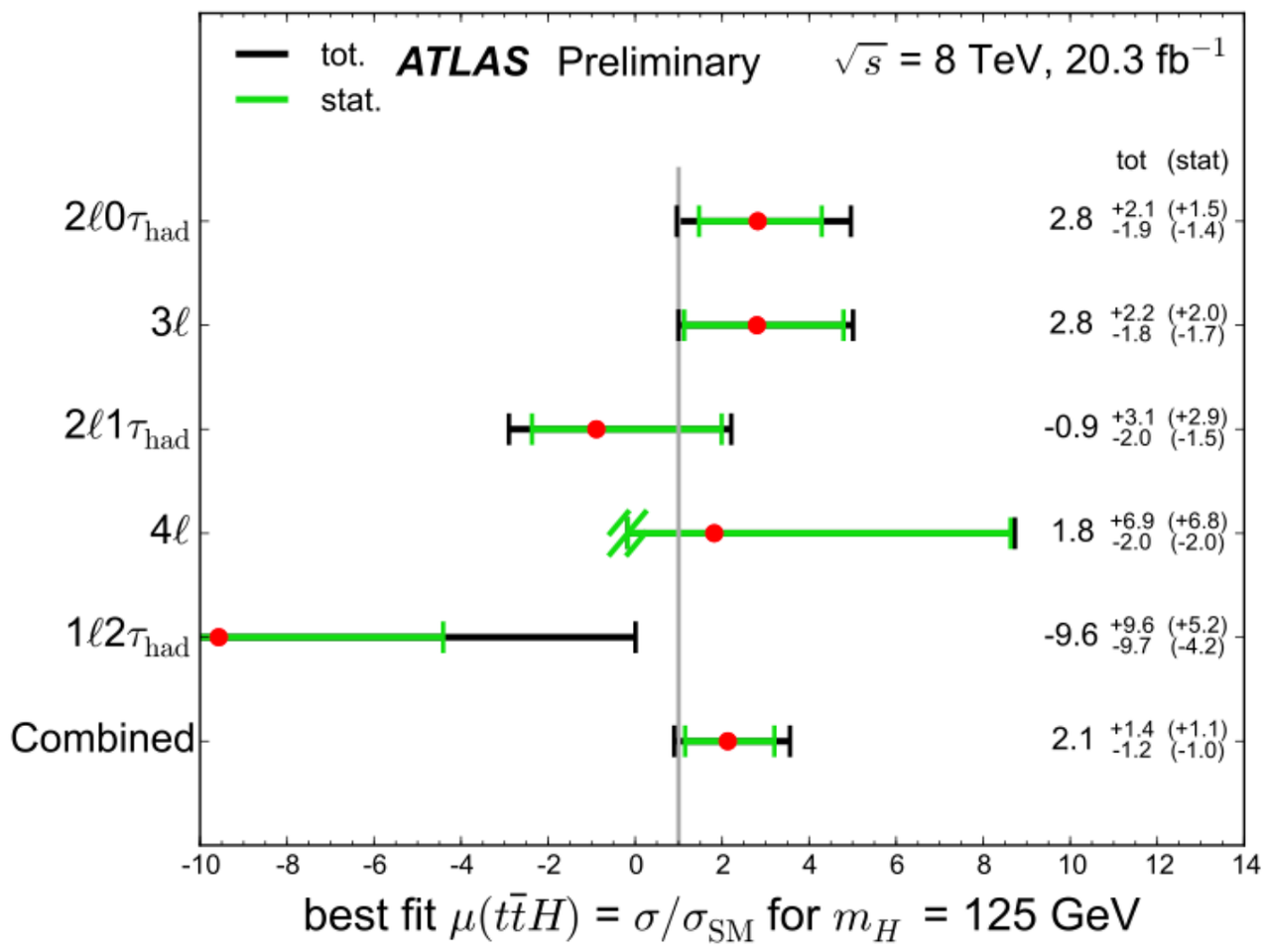






$t\bar{t}H$, H→multileptons



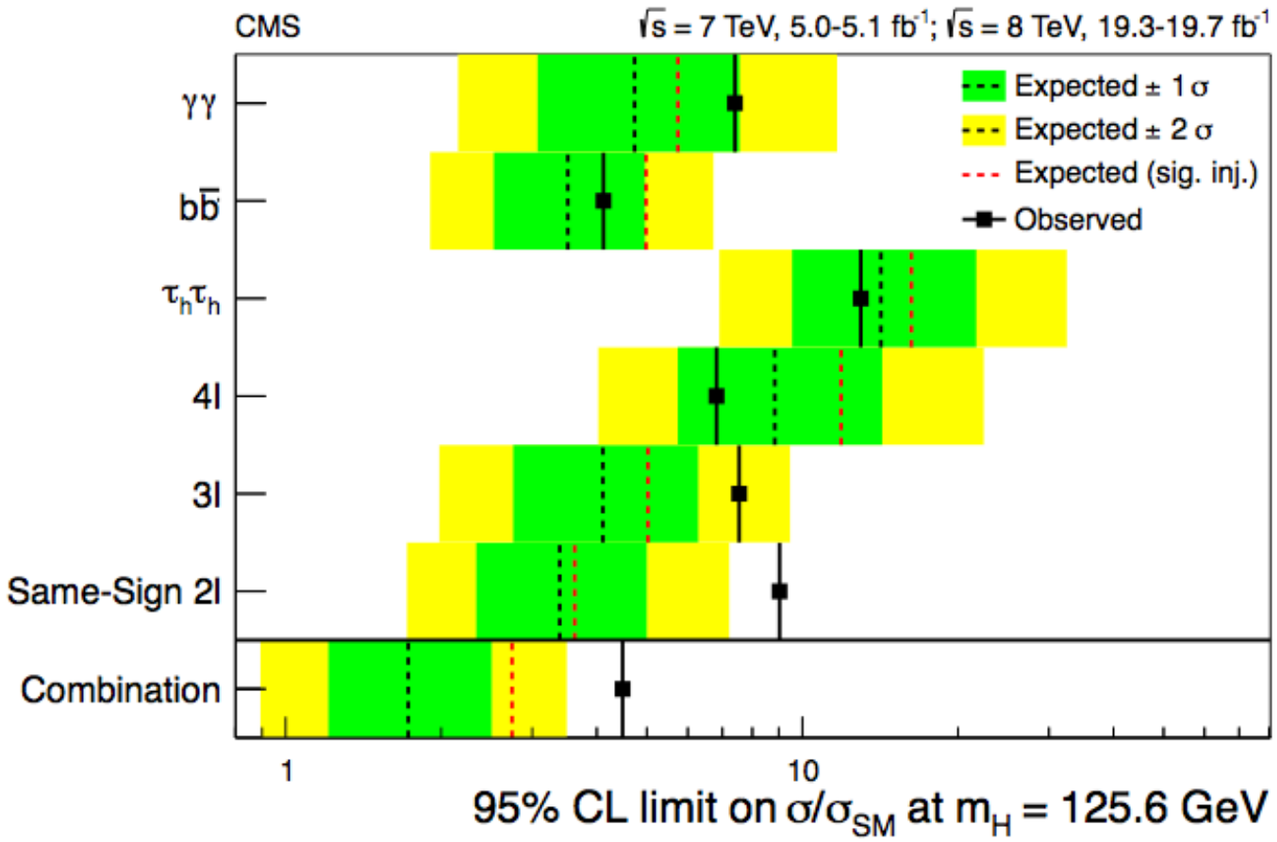


CMS: $\mu = \sigma/\sigma_{SM} = 3.7^{+1.6}_{-1.4}$
$\mu^{\pm}\mu^{\pm}$ only: $\mu = \sigma/\sigma_{SM} = 8.5^{+3.3}_{-2.7}$
expected(observed) UL @ 95% CL: 2.4(6.6)

ATLAS: $\mu = \sigma/\sigma_{SM} = 2.1^{+1.4}_{-1.2}$
expected(observed) UL @ 95% CL: 4.7(2.4)

$t\bar{t}H$ - combination

- CMS makes a combined fit of the bb BDT, multi lepton, $\tau\tau$ and $\gamma\gamma$ final discriminants
- SM Higgs branching ratios assumed, free parameter is the $t\bar{t}H$ signal strength μ
- Upper limit on $t\bar{t}H$ production useful to constrain possible enhanced rate due to BSM



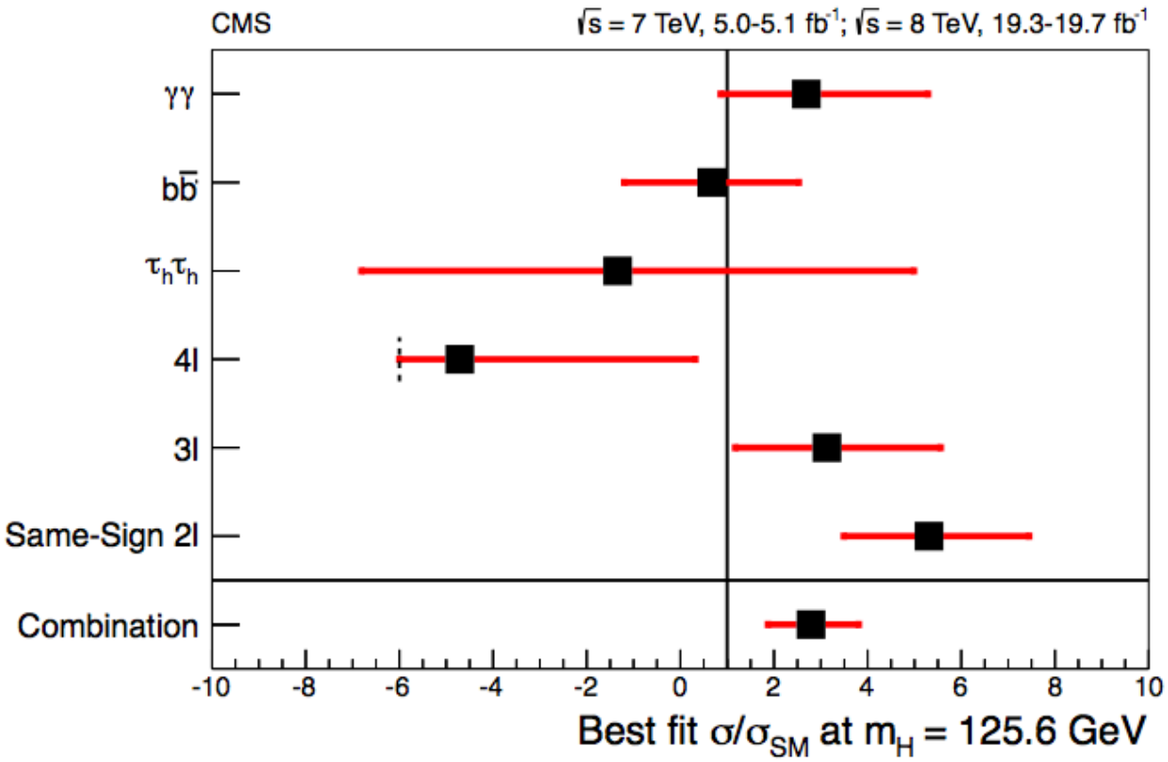
expected(observed) UL @ 95% CL: 1.8 (4.3)

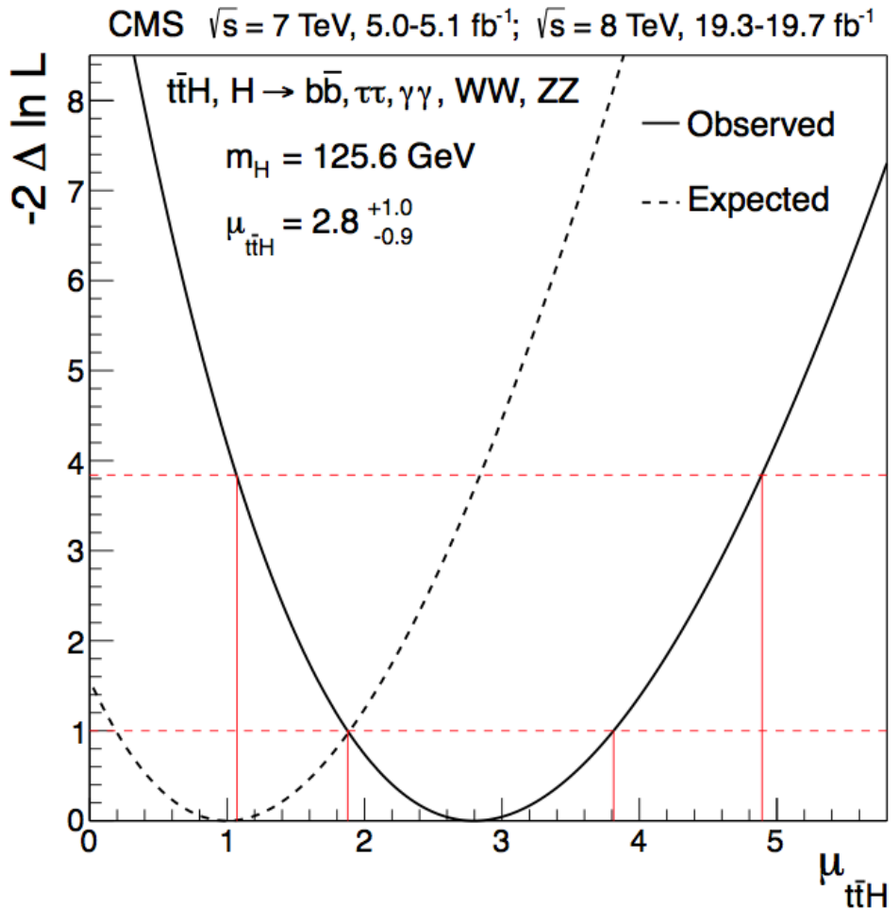
expected UL @ 95% CL (signal injected): 2.9

observed limit driven by the excess in the $\mu^{\pm}\,\mu^{\pm}$

($t\bar{t}H$, $H \rightarrow bb$ MEM not included)

$t\bar{t}H$, H→combination





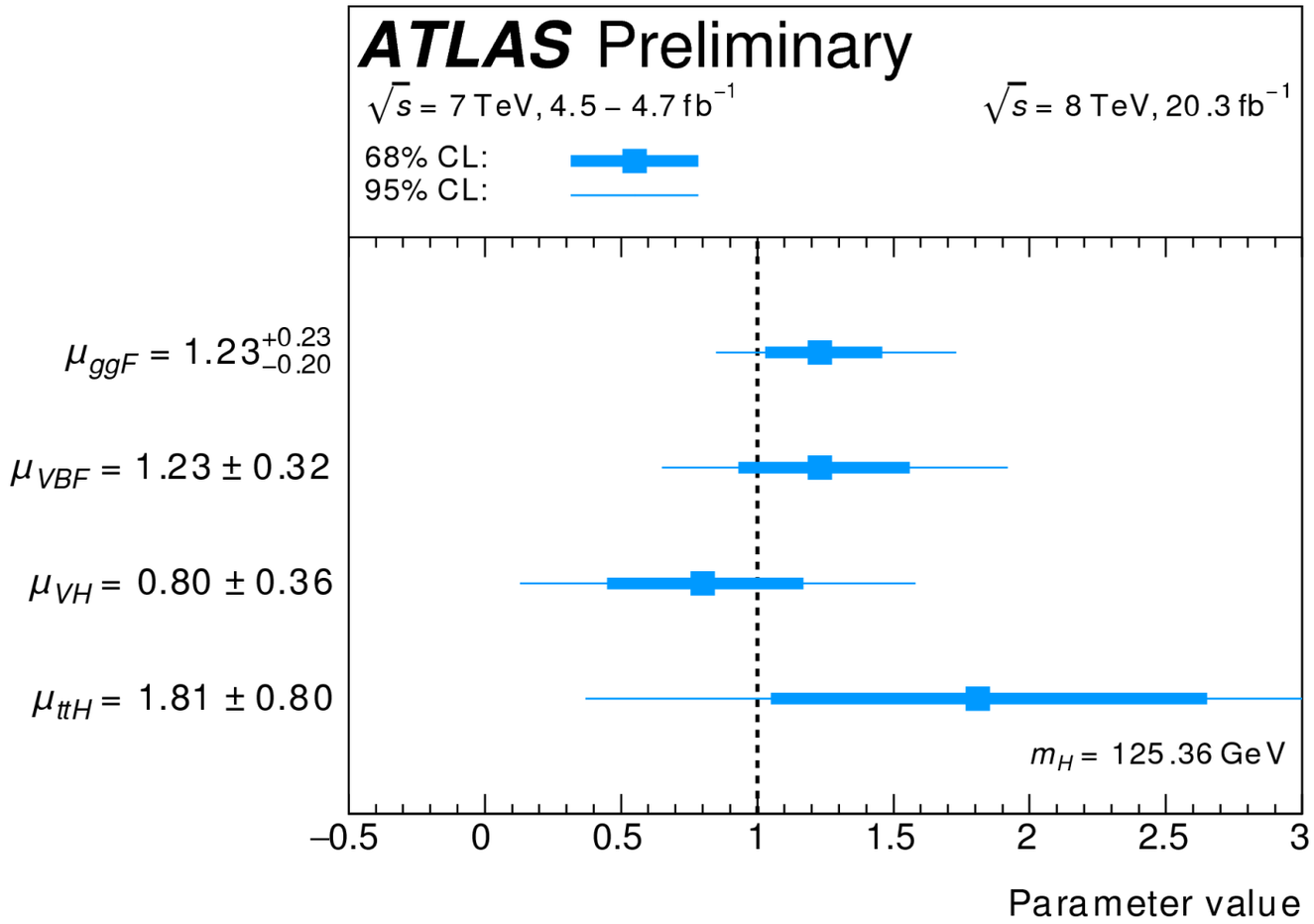
Internal consistency with common signal strength: 29%

Best fit on μ = σ/σSM = 2.8 ± 1.0
Equivalent to a 2 standard deviation upward fluctuation compared to SM including $t\bar{t}H$

Best fit on μ = σ/σSM w/o μ± μ± channel = 1.9 ± 1.0

$t\bar{t}H$, H→combination

- Combination of analyses in several decay modes & production modes, including $t\bar{t}H$ and off-shell Higgs production
- Production modes probed by four signal strength parameters: μ_{ggF}, μ_{VH}, μ_{VBF} and $\mu_{t\bar{t}H}$

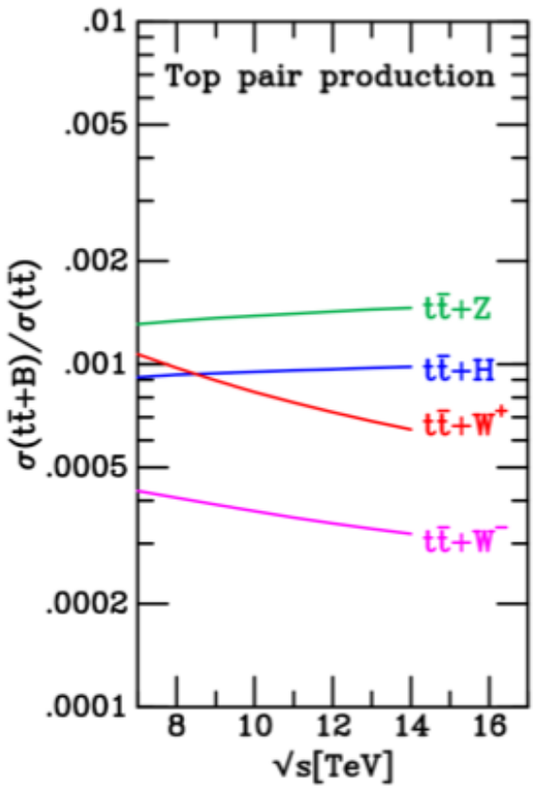


$\mu_{t\bar{t}H} = \sigma/\sigma_{SM} = 1.81 \pm 08$
expected(observed) UL @ 95% CL: 1.4 (3.2)

Conclusion

- ATLAS and CMS have analyzed the full 8 TeV datasets
- First evidence for rare SM processes $t\bar{t}Z$ and $t\bar{t}W$!
- Several $t\bar{t}H$ signatures considered: $t\bar{t}$+bb, $t\bar{t}+\tau_h\tau_h$, $t\bar{t}+\gamma\gamma$, $t\bar{t}$+leptons
  - Sophisticated analysis techniques used
  - O(SM) sensitivity on $\mu(t\bar{t}H)$ reached!
  - Some excess seen in CMS $\mu^{\pm}\mu^{\pm}$ analysis, no significant excess in bb or $\gamma\gamma$ channels
- $t\bar{t}H$ and $t\bar{t}Z$ cross section will increase by a factor ~4 at 13 TeV !

Looking forward for Run II!



References

- ttW/Z : ATLAS-CONF-2014-038, Eur. Phys. J. C (2014) 3060, (CMS-TOP-12-036)
- ttγ: arXiv:1502.00586 (CERN-PH-EP-2014-284), CMS-TOP-13-011
- ttH in bb : arXiv.1503.05066v1 (CERN-PH-EP-2015-047), HIG-12-035, HIG-13-019 ,arXiv:1502.02485(CMS-HIG-14-010)
- ttH in γγ: arXiv:1409.3122, CMS-PAS-HIG-13-015
- ttH in multileptons : ATLAS-CONF-2015-006, CMS-HIG-13-020
- ttH combination : ATLAS-CONF-2015-007, arXiv:1408.1682v2 (CMS-HIG-13-029)

ttH multilepton - ATLAS

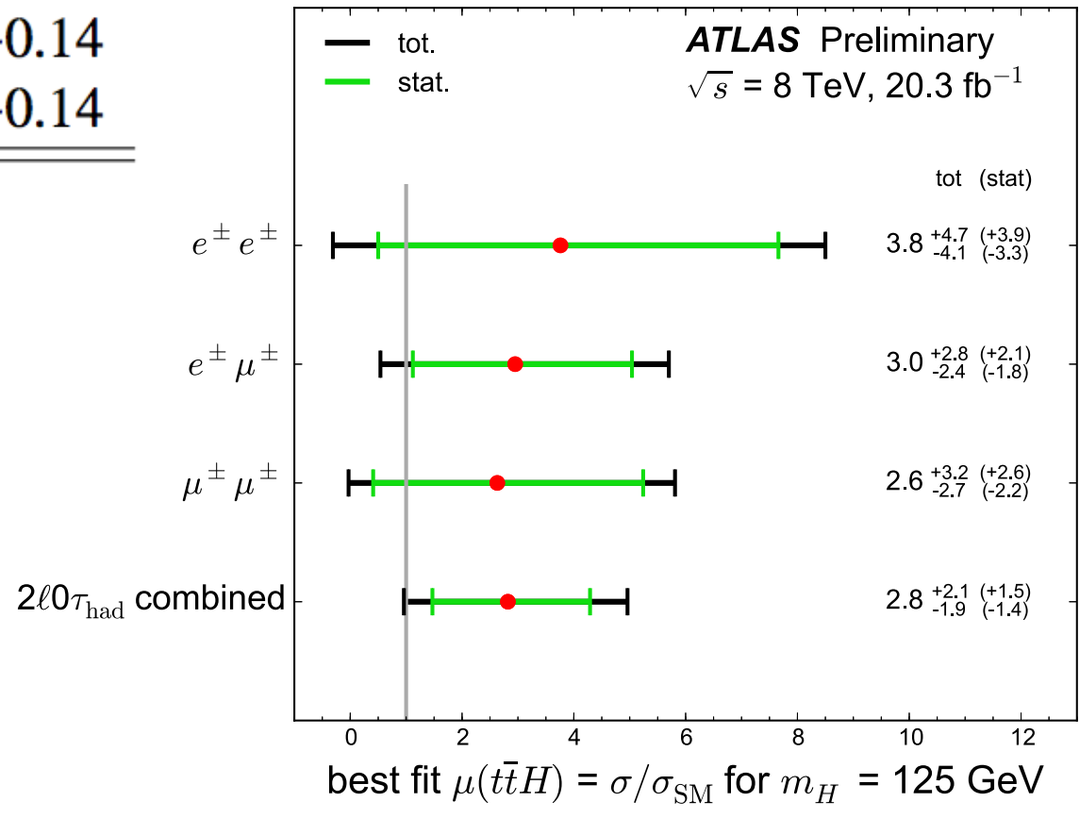
	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\text{had}}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\text{had}}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\text{had}}$	4%	93%	0%	3%

2l0$\boldsymbol{\tau}$: |η(e)|< 1.37 to reduce charge misID

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 ± 0.32	0.47 ± 0.42	6.5 ± 2.0	0.73 ± 0.11	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.4	2.1 ± 0.7	0.38 ± 0.32	15 ± 4	2.13 ± 0.31	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 1.1	0.95 ± 0.31	0.69 ± 0.63	8.6 ± 2.5	1.41 ± 0.21	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.25	0.74 ± 0.58	9.1 ± 2.3	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 0.9	1.5 ± 0.2	1.9 ± 1.2	24.0 ± 4.5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.26	0.53 ± 0.30	12.7 ± 3.0	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.9	3.9 ± 0.9	0.86 ± 0.59	11.4 ± 3.1	2.34 ± 0.32	18
$2\ell 1\tau_{\text{had}}$	–	$0.4\ ^{+0.6}_{-0.4}$	0.38 ± 0.15	0.37 ± 0.09	0.12 ± 0.15	1.4 ± 0.6	0.47 ± 0.02	1
$1\ell 2\tau_{\text{had}}$	–	15 ± 5	0.17 ± 0.07	0.37 ± 0.10	0.41 ± 0.42	16 ± 6	0.68 ± 0.07	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.13	0.05 ± 0.02	0.55 ± 0.17	0.17 ± 0.01	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.03 ± 0.00	0

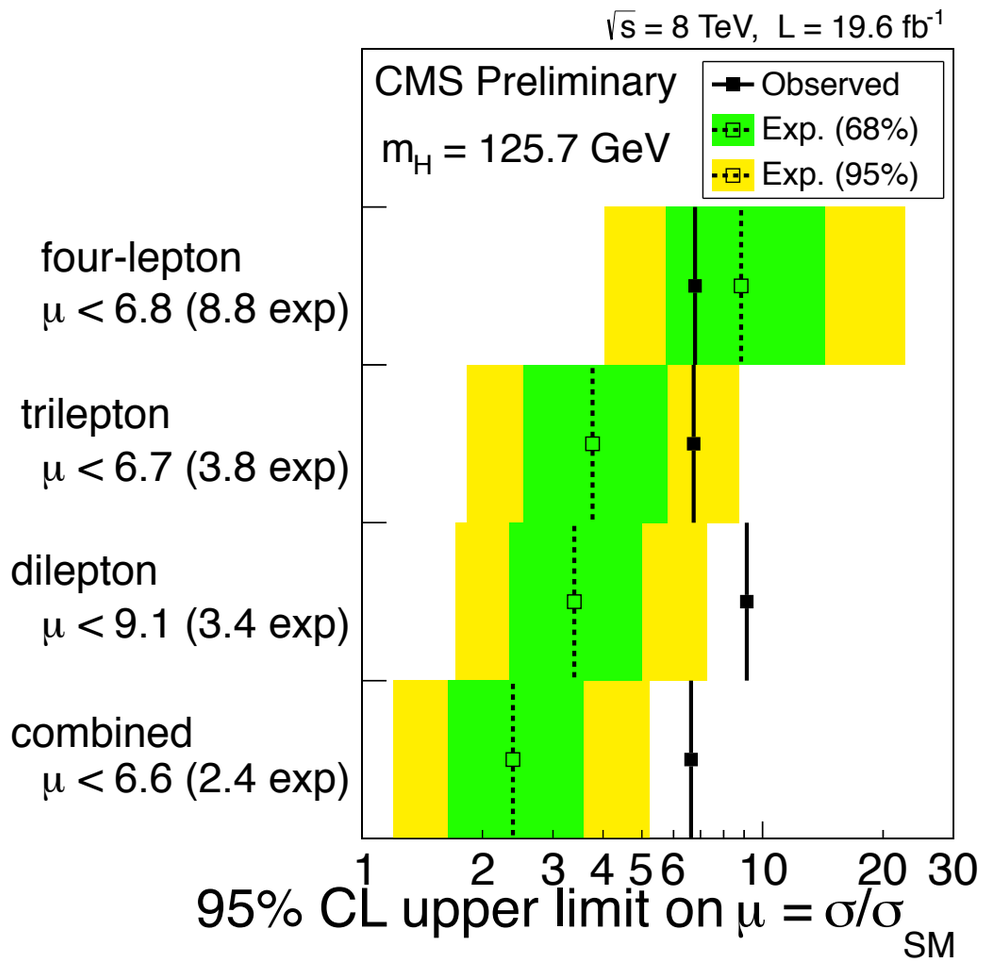
ttH multilepton - ATLAS

Source	$\Delta\mu$	
$2\ell 0\tau_{\text{had}}$ 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
$2\ell 0\tau_{\text{had}}$ 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

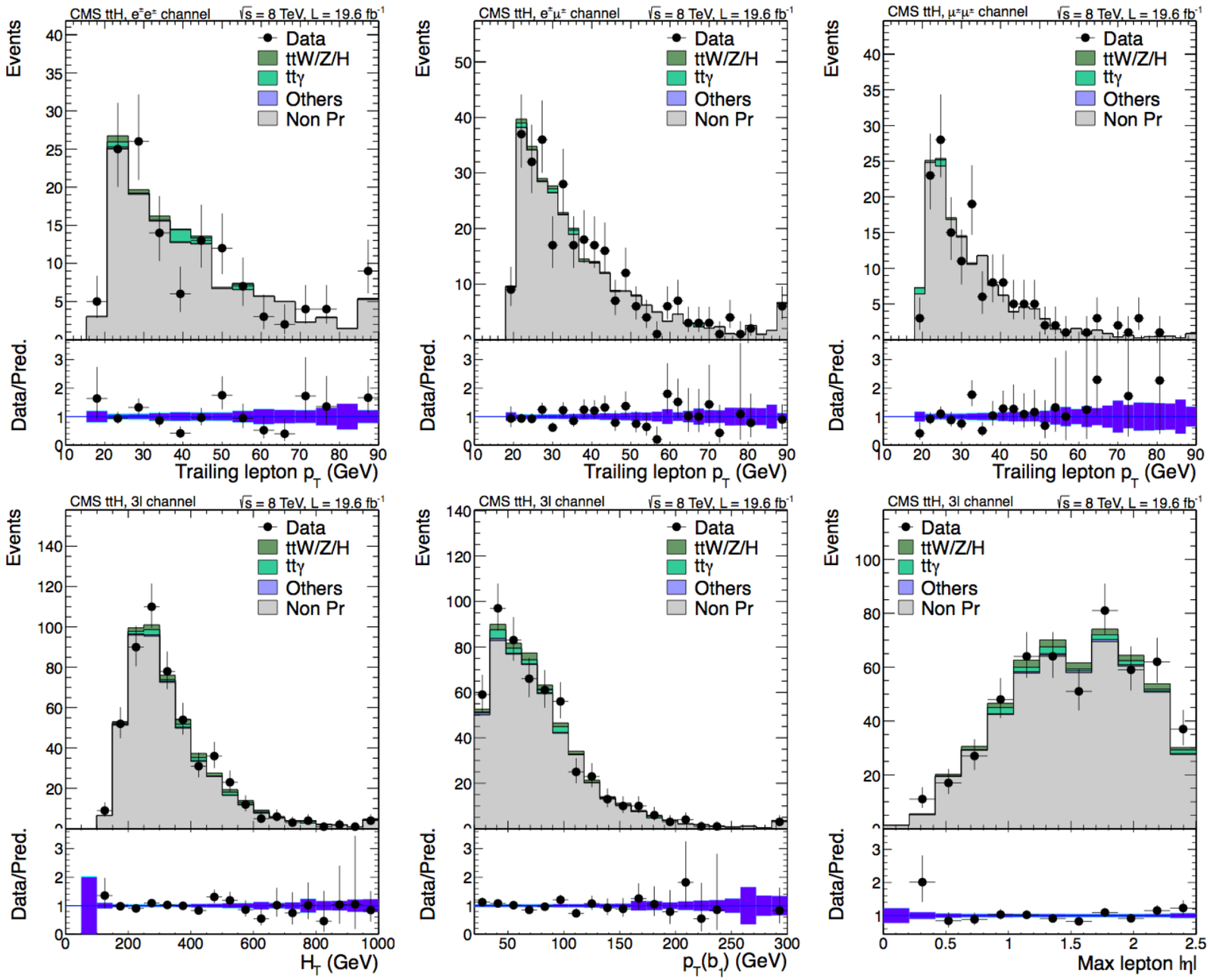


ttH multilepton - CMS

	ee	eμ	μμ	3ℓ	4ℓ
$t\bar{t}H, H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H, H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

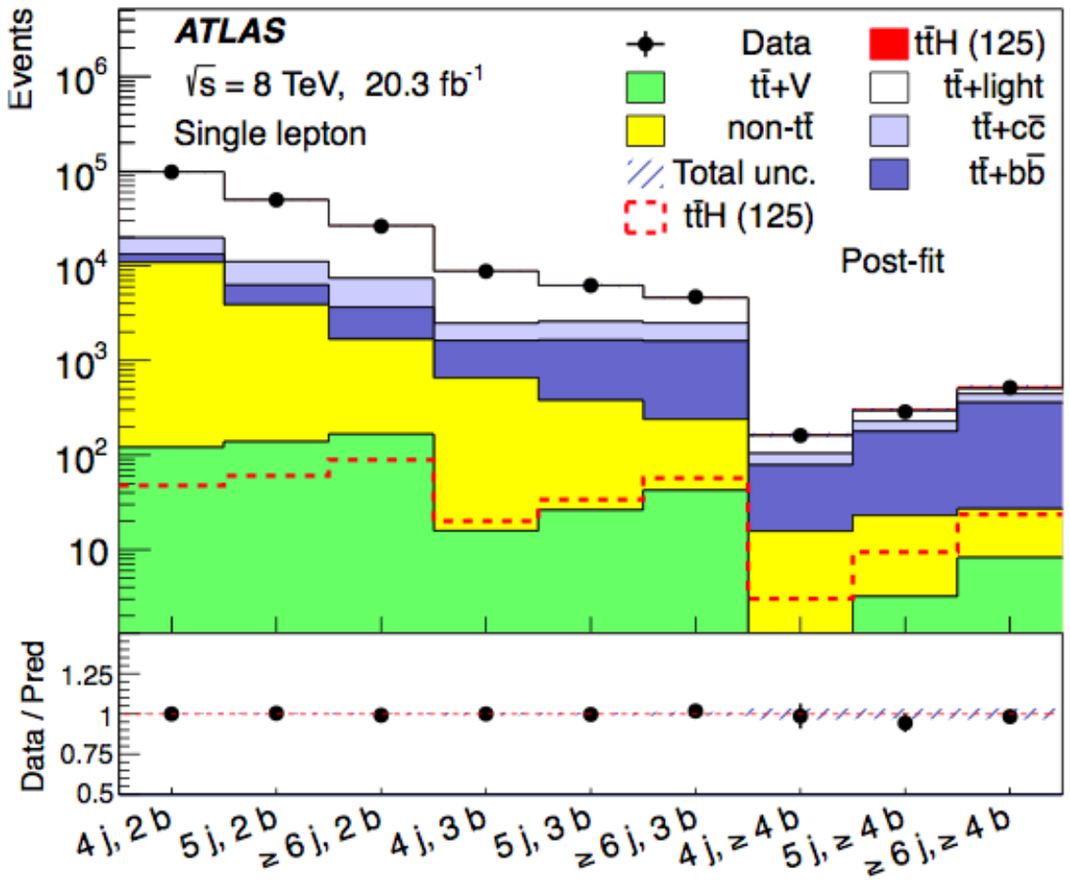


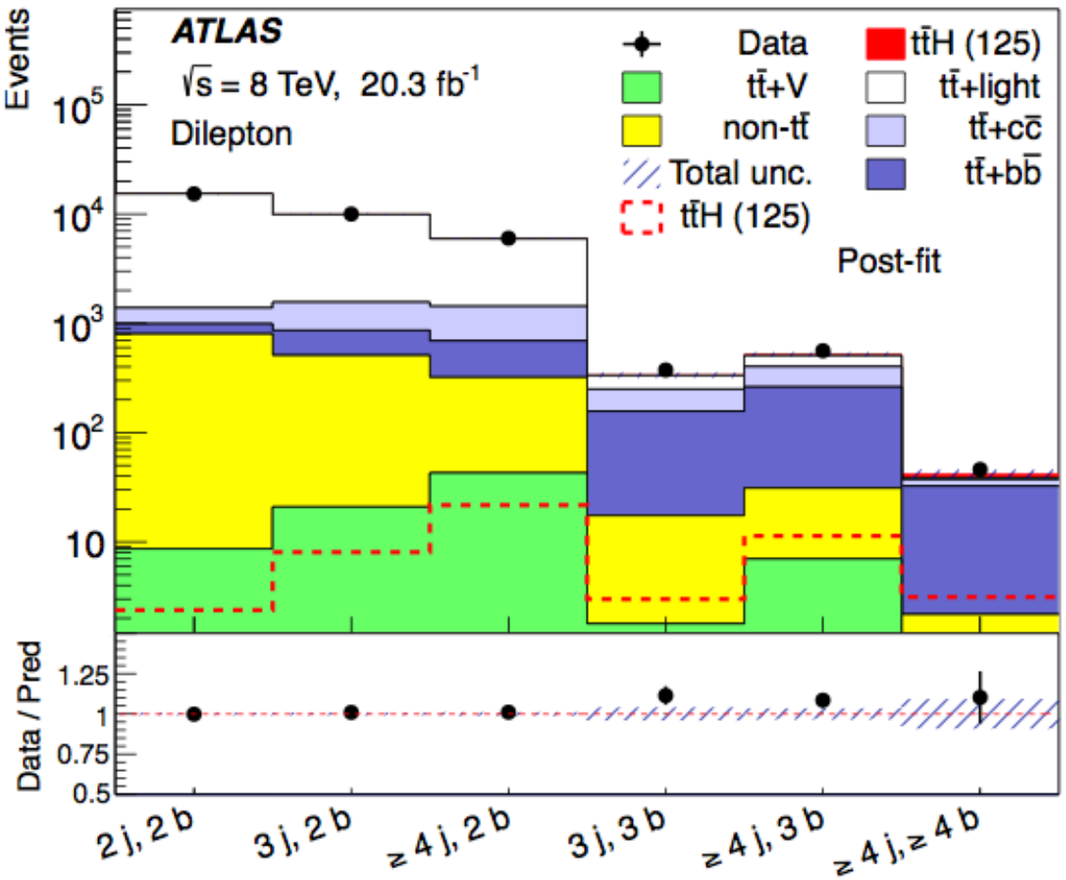
ttH multilepton - CMS



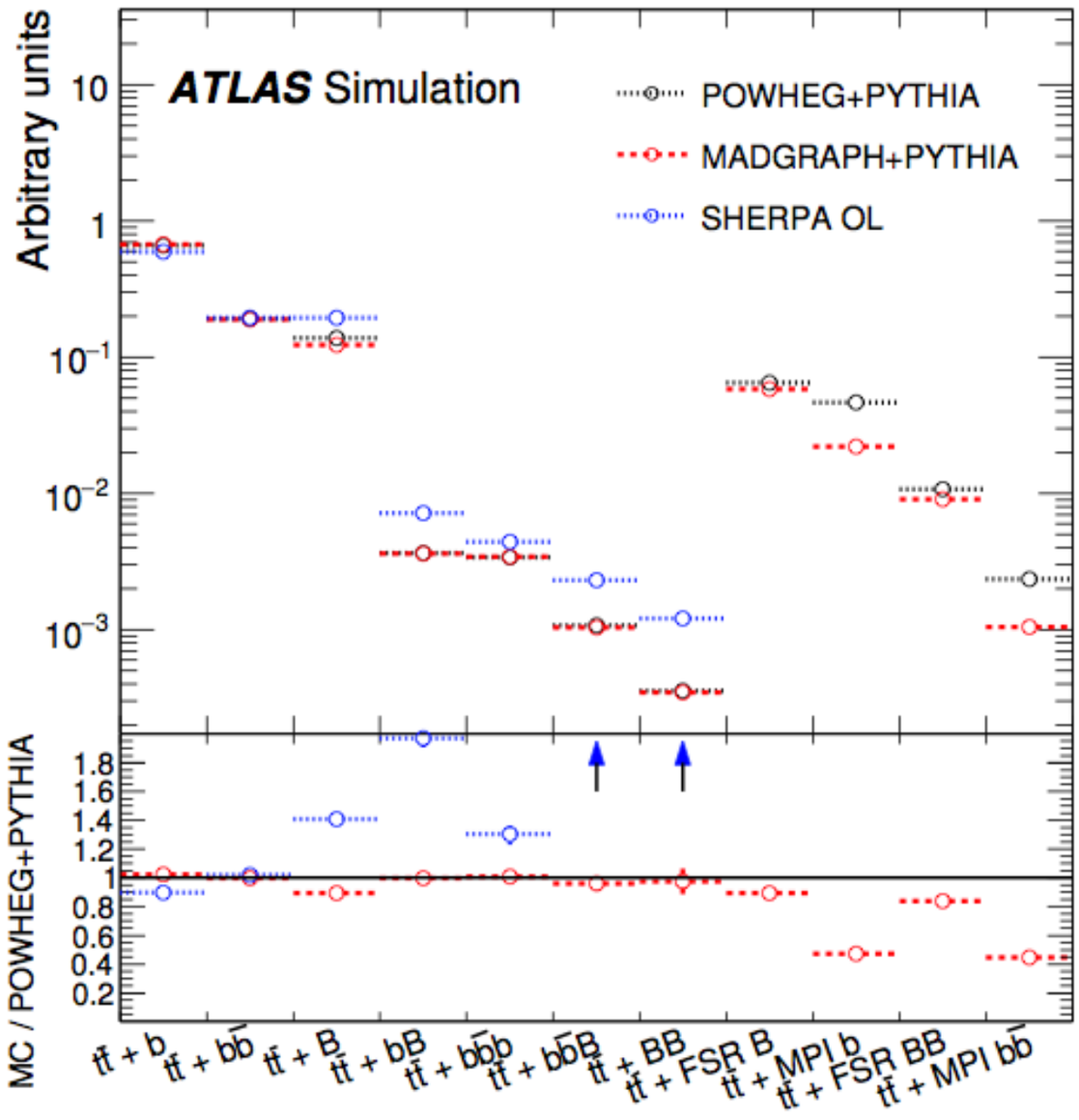
kinematical distributions of one lepton failing the MVA designed to reject fake leptons from b-jets.

ttH, H→bb - ATLAS

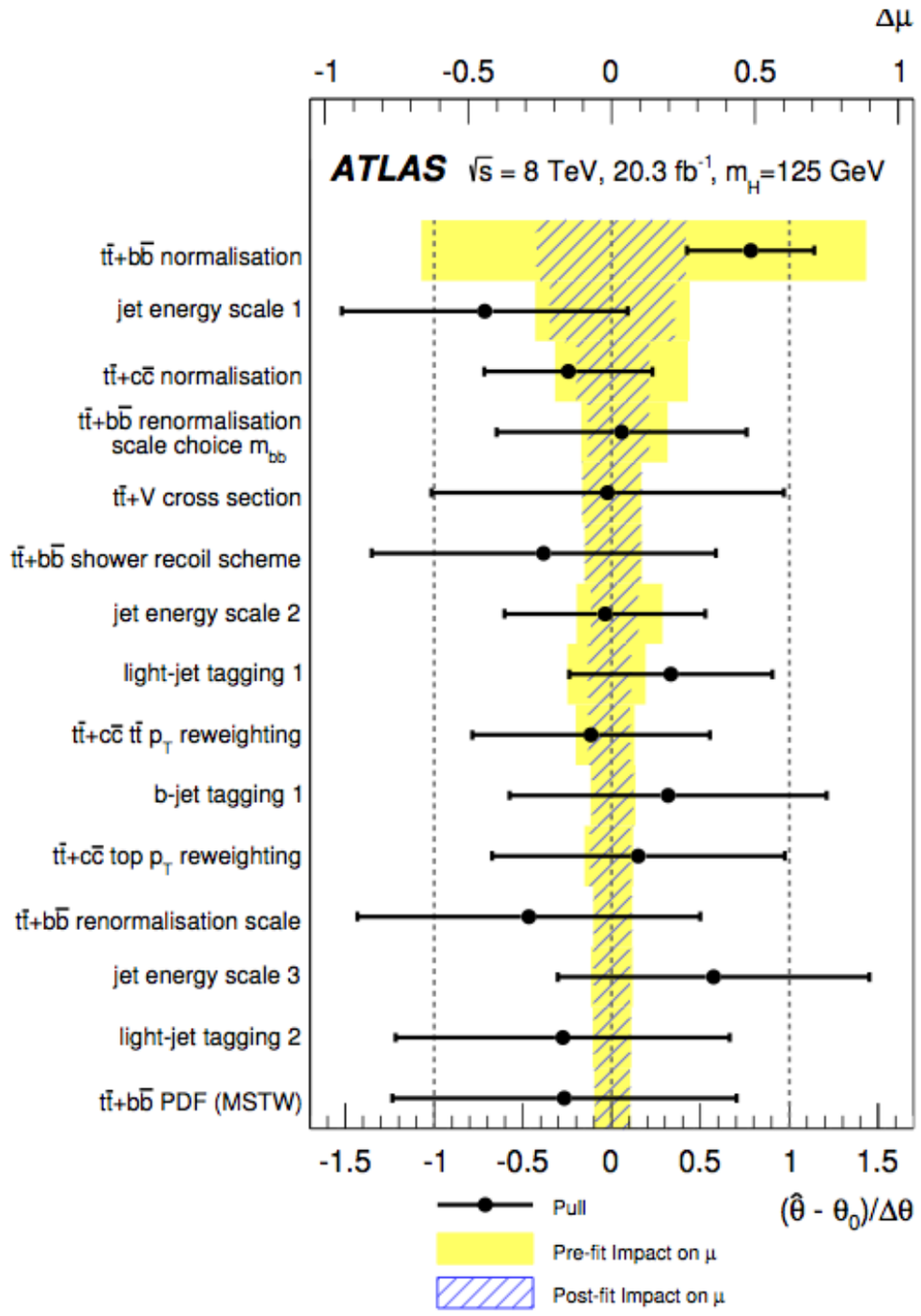




ttH → bb - ATLAS



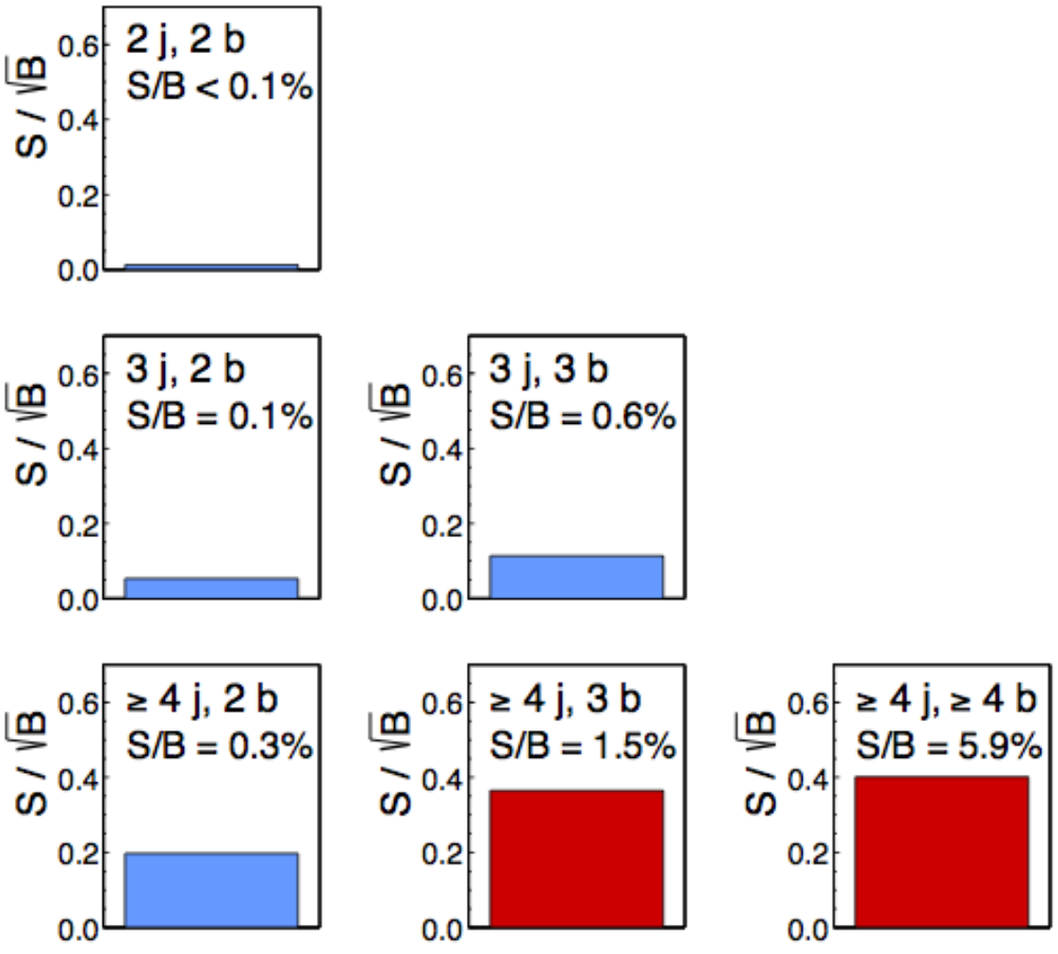
POWHEG+PYTHIA reweighted to model NLO tt+bb prediction from SHERPA+OpenLoops

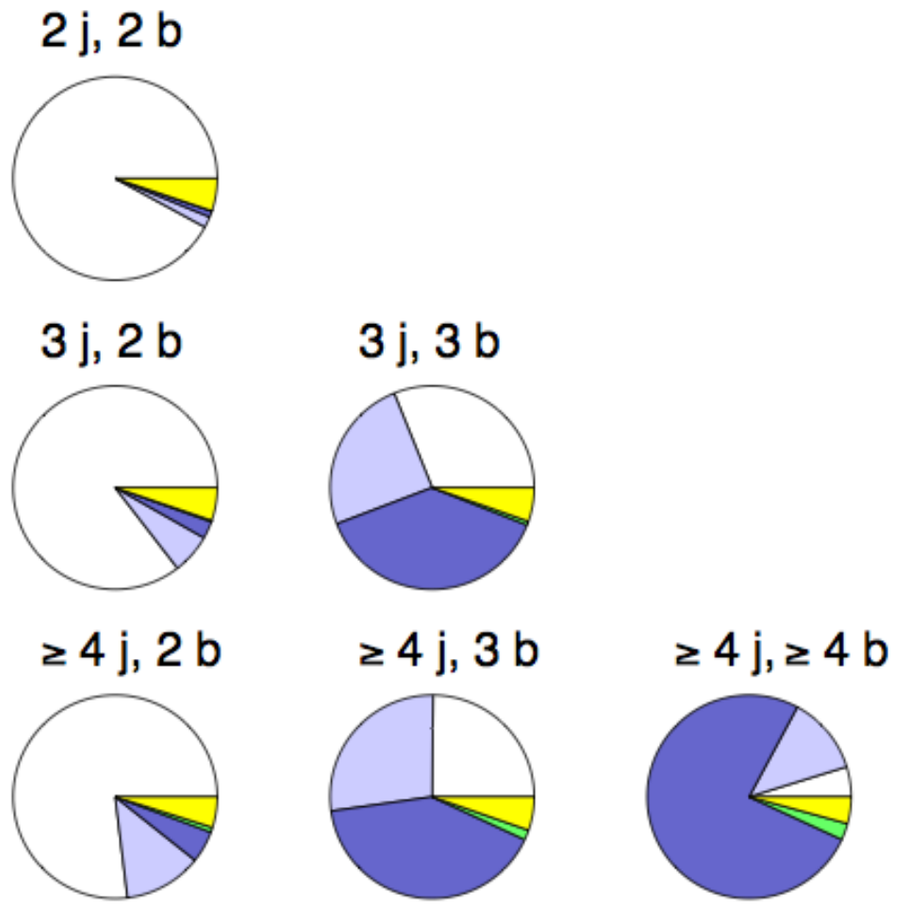


ttH, H → bb - ATLAS

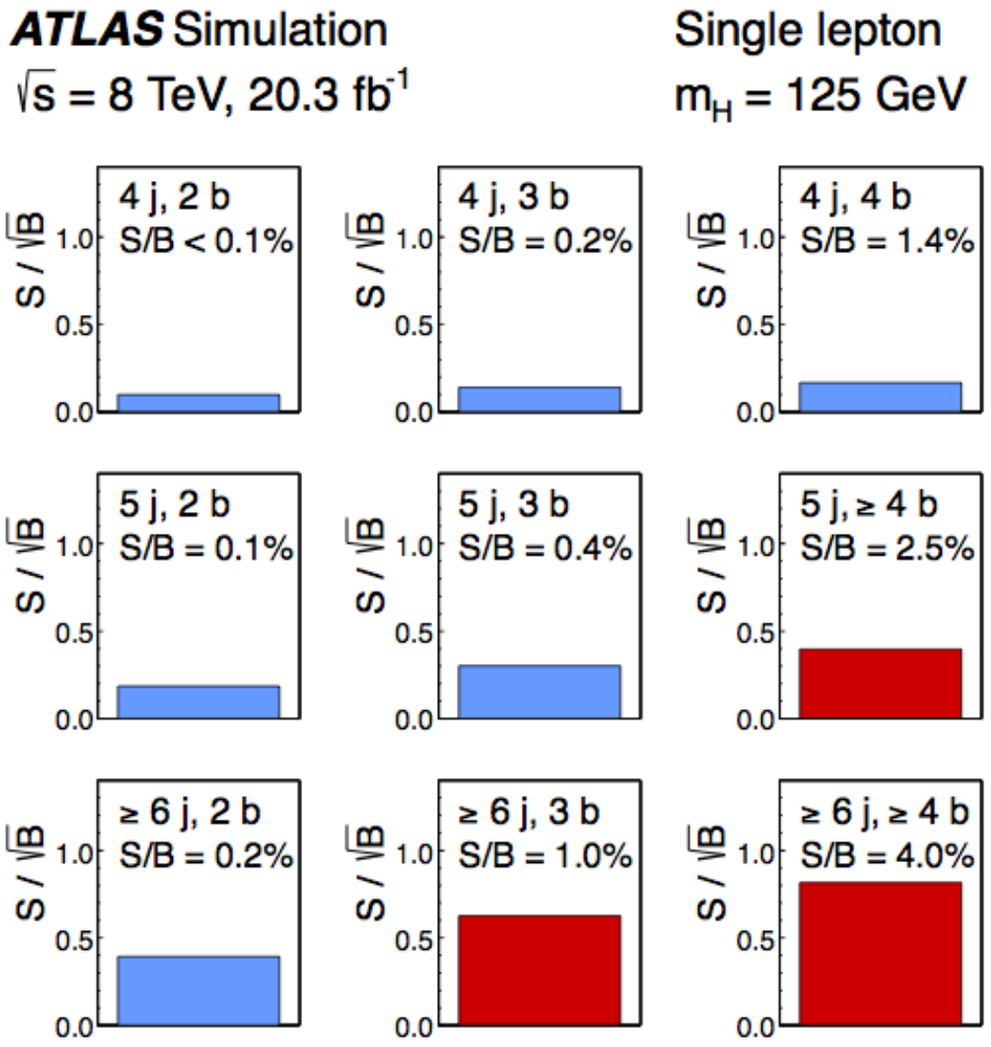
ATLAS Simulation
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}

Dilepton
m_H = 125 GeV

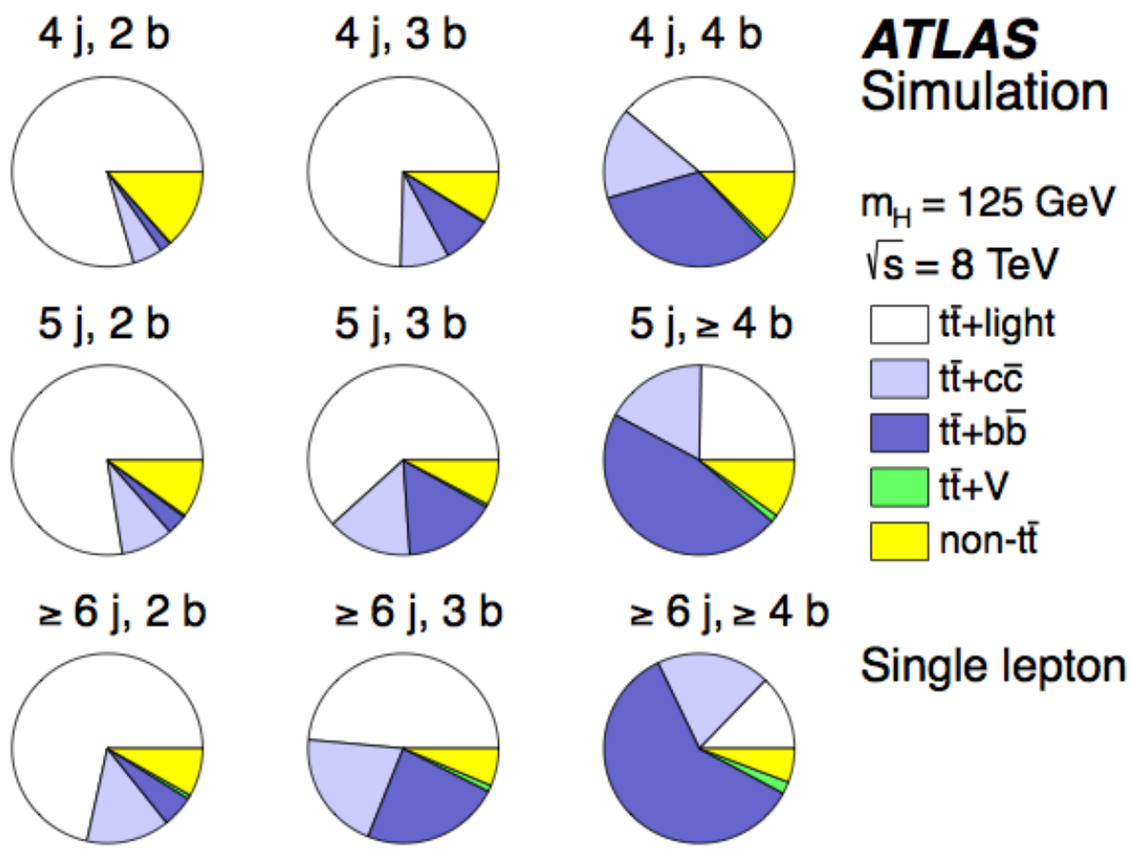




ttH, H →bb - ATLAS



(a)



(b)

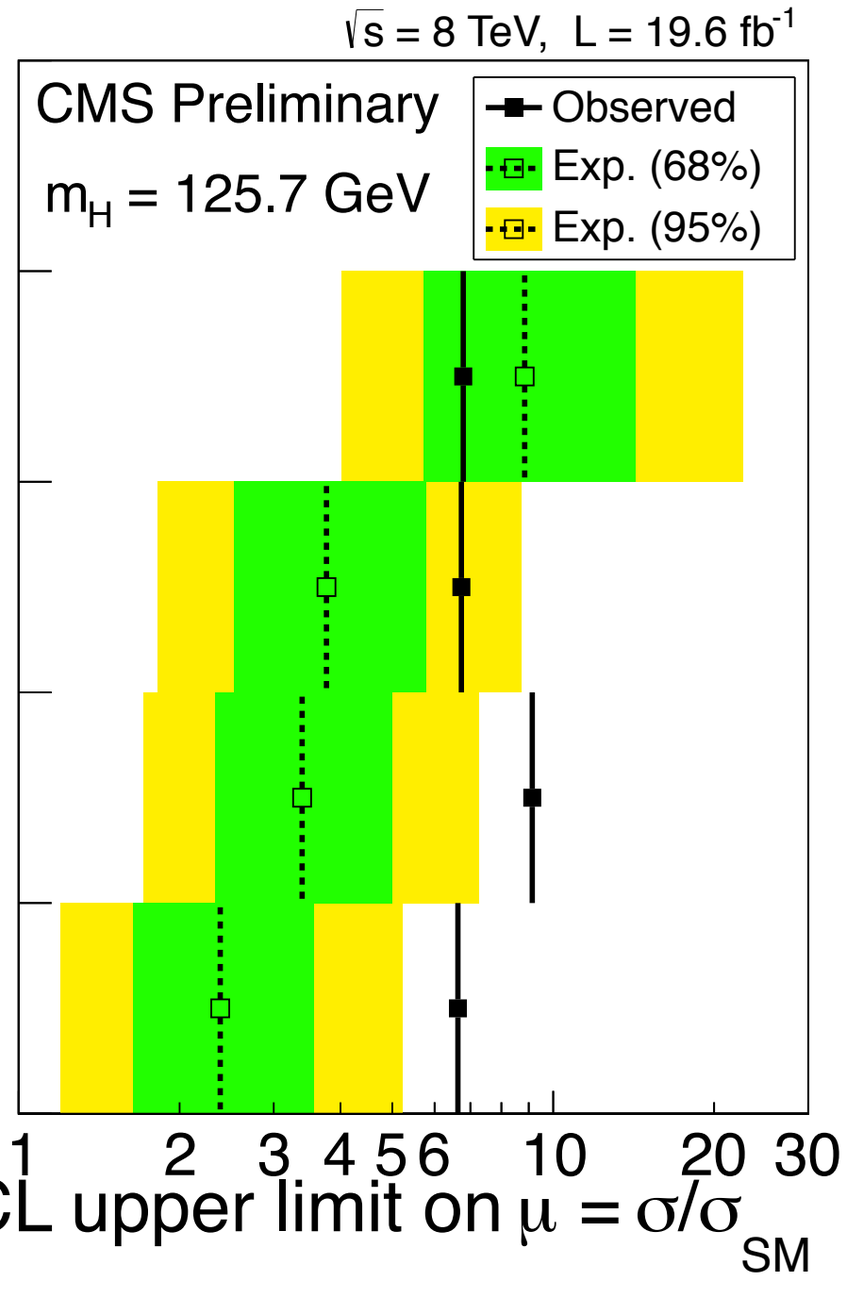
ttH, H → bb, H → γγ - ATLAS

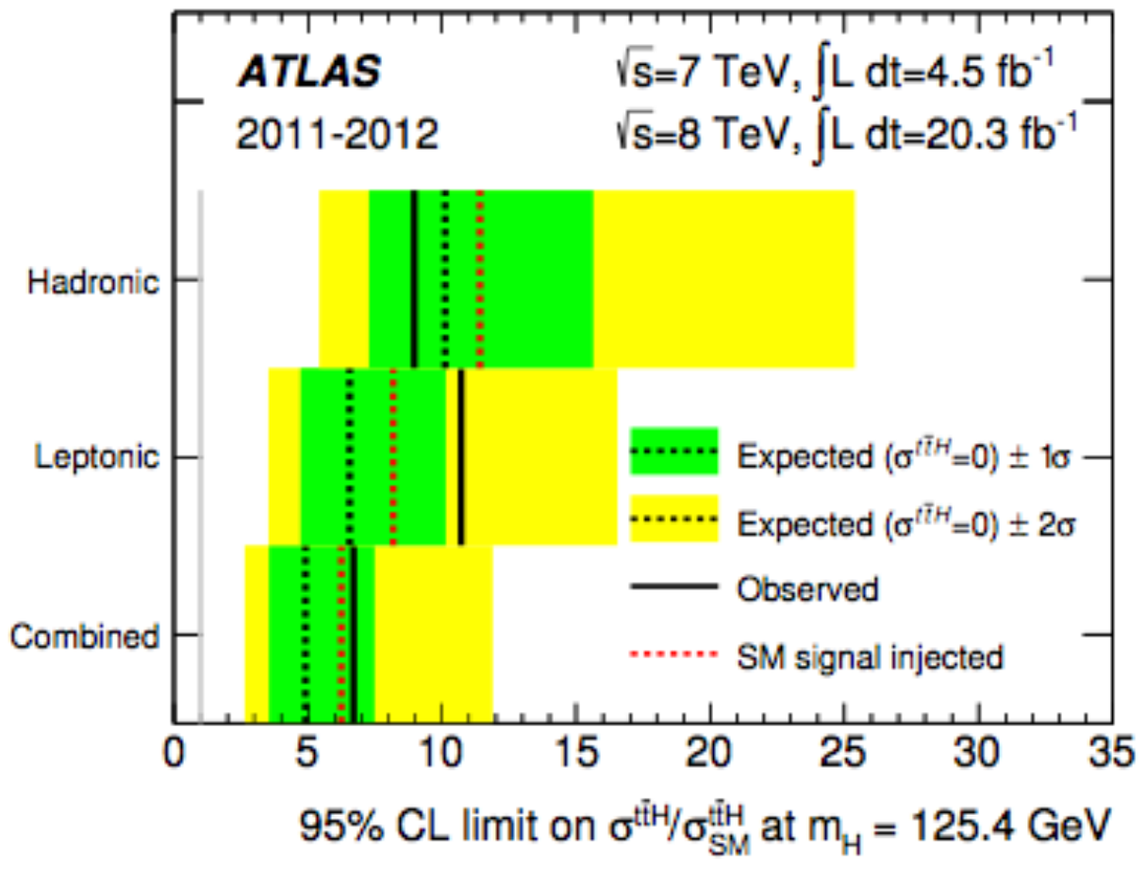
four-lepton
$\mu < 6.8$ (8.8 exp)

trilepton
$\mu < 6.7$ (3.8 exp)

dilepton
$\mu < 9.1$ (3.4 exp)

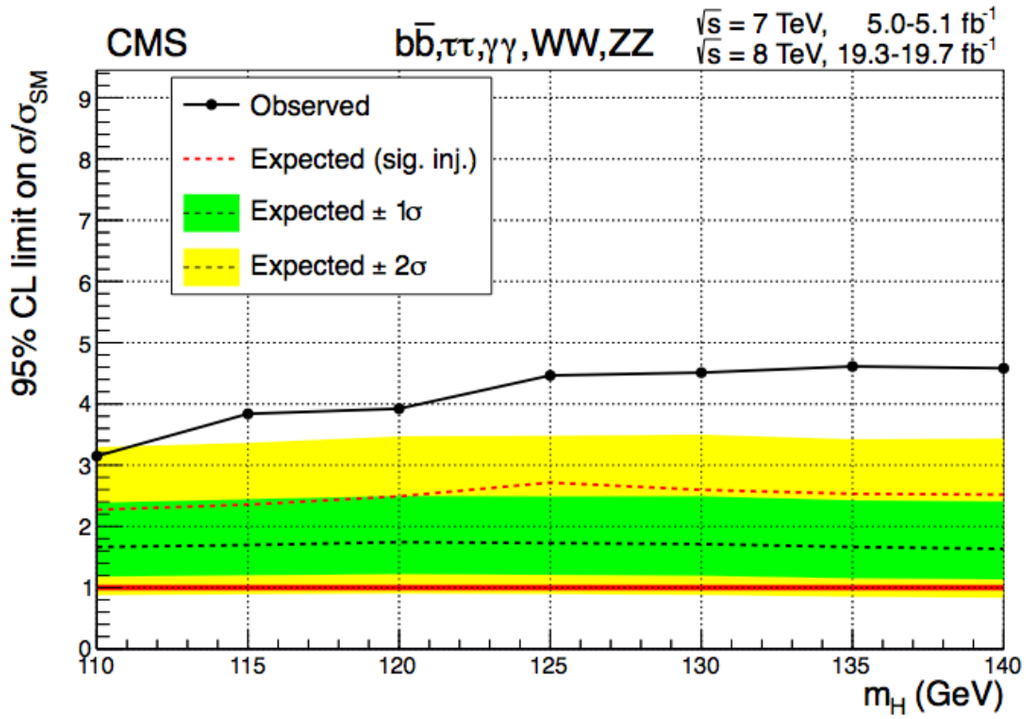
combined
$\mu < 6.6$ (2.4 exp)





ttH combination - CMS

$t\bar{t}H$ channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$\gamma\gamma$	$+2.7^{+2.6}_{-1.8}$	7.4	5.7	4.7	[3.1, 7.6]	[2.2, 11.7]
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	5.0	3.5	[2.5, 5.0]	[1.9, 6.7]
$\tau_h\tau_h$	$-1.3^{+6.3}_{-5.5}$	13.0	16.2	14.2	[9.5, 21.7]	[6.9, 32.5]
4l	$-4.7^{+5.0}_{-1.3}$	6.8	11.9	8.8	[5.7, 14.3]	[4.0, 22.5]
3l	$+3.1^{+2.4}_{-2.0}$	7.5	5.0	4.1	[2.8, 6.3]	[2.0, 9.5]
Same-sign 2l	$+5.3^{+2.1}_{-1.8}$	9.0	3.6	3.4	[2.3, 5.0]	[1.7, 7.2]
Combined	$+2.8^{+1.0}_{-0.9}$	4.5	2.7	1.7	[1.2, 2.5]	[0.9, 3.5]



ttH combination - CMS

Source	Rate uncertainty		Shape
	Signal	Backgrounds	
Experimental			
Integrated luminosity	2.2–2.6%	2.2–2.6%	No
Jet energy scale	0.0–8.4%	0.1–11.5%	Yes
CSV b-tagging	0.9–21.7%	3.0–29.0%	Yes
Lepton reco. and ID	0.3–14.0%	1.4–14.0%	No
Lepton misidentification rate (H $\rightarrow$ leptons)	—	35.1–45.7%	Yes
Tau reco. and ID (H $\rightarrow$ hadrons)	11.3–14.3%	24.1–28.8%	Yes
Photon reco. and ID (H $\rightarrow$ photons)	1.6–3.2%	—	Yes
MC statistics	—	0.2–7.0%	Yes
Theoretical			
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_{T}	—	1.4–6.9%	Yes
Additional hf uncertainty (H $\rightarrow$ hadrons)	—	50%	No
H contamination (H $\rightarrow$ photons)	36.7–41.2%		No
WZ (ZZ) uncertainty (H $\rightarrow$ leptons)	—	22% (19%)	No

ttWZ - ATLAS

	Trilepton and same-sign dilepton			Opposite-sign dilepton	
Analysis strategy	comparable signal and background: cut and count			small signal in huge background multivariate techniques	
	3ℓZ	3ℓZveto	2μSS	2ℓOSZveto	2ℓOSZ
Z-mass selection	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	-	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
Additional selection			$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV $H_{\mathrm{T}} > 240$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV$_{(ee,\,\mu\mu)}$ $H_{\mathrm{T}} > 130$ GeV$_{(e\mu)}$ $\Delta R_{\mathrm{ave}}^{\mathrm{jj}} > 0.75$	$\Delta R_{\mathrm{ave}}^{\mathrm{jj}} > 0.75$
Lepton flavour Signal Main background	all trilepton $t\bar{t}Z$ tZ, WZ and fakes	all trilepton $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	$\mu\mu$ $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	all dilepton $t\bar{t}Z$ and $t\bar{t}W$ $t\bar{t}$+jets	ee, $\mu\mu$ $t\bar{t}Z$ dominated Z+jets
Validation regions	(3j + 2j + 1j, 1b) (CRZ)	(1b) (CRW)	$E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV		
Regions in the fit (**Signal region**, control region)	**(≥ 4j, 1b) (SRB1J4)** **(3j, ≥ 2b) (SRB2J3)** **(≥ 4j, ≥ 2b) (SRB2J4)**	**(3j + 2j, ≥ 2b) (SRW3ℓ)**	**(≥ 2j, ≥ 2b) (SR2μSS)**	(3j, 1b + 2b) **(4j, 1b + 2b)** **(≥ 5j, 1b + 2b)**	(3j, 2b) (4j, 2b) **(≥ 5j, 2b)**

ttW/Z - CMS

	$\mu^+\mu^+$	$e^+\mu^+$	e^+e^+	$\mu^-\mu^-$	$e^-\mu^-$	e^-e^-
$t\bar{t}W$ (expected)	2.8 ± 0.4	5.1 ± 0.5	2.2 ± 0.3	1.1 ± 0.2	2.3 ± 0.3	1.0 ± 0.2
Misidentified lepton	1.0 ± 0.6	4.1 ± 2.1	1.6 ± 0.9	0.7 ± 0.4	3.0 ± 1.5	1.7 ± 0.9
Mismeasured charge	–	0.4 ± 0.1	0.7 ± 0.2	–	0.4 ± 0.1	0.7 ± 0.2
Irreducible	0.7 ± 0.4	1.6 ± 0.9	0.9 ± 0.5	0.5 ± 0.3	1.4 ± 0.7	0.7 ± 0.4
WZ	0.1 ± 0.1	0.4 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.1	0.2 ± 0.1
$t\bar{t}Z$	0.6 ± 0.3	0.9 ± 0.5	0.5 ± 0.3	0.4 ± 0.2	1.0 ± 0.5	0.5 ± 0.3
Total background	2.4 ± 0.7	7.4 ± 2.3	3.9 ± 1.1	1.7 ± 0.5	6.1 ± 1.8	3.7 ± 1.1
Total expected	5.2 ± 0.8	12.5 ± 2.4	6.1 ± 1.1	2.8 ± 0.5	8.4 ± 1.8	4.7 ± 1.1
Observed	6	12	5	1	6	6

	Yield
$t\bar{t}Z$ (expected)	7.8 ± 0.9
Irreducible	0.8 ± 0.4
$t\bar{t}W$	0.2 ± 0.1
Non-top-quark	2.3 ± 1.2
Misidentified lepton	1.1 ± 0.8
Total background	4.4 ± 1.6
Total expected	12.2 ± 1.8
Observed	12

	2 b Jets required	1 b Jet required
$t\bar{t}Z$ (expected)	1.3 ± 0.2	1.3 ± 0.2
Misidentified lepton	0.1 ± 0.1	0.5 ± 0.2
ZZ	0.05 ± 0.01	0.47 ± 0.02
Irreducible	0.04 ± 0.03	0.14 ± 0.04
Total background	0.2 ± 0.1	1.1 ± 0.2
Total expected	1.5 ± 0.2	2.4 ± 0.3
Observed	2	2

ttW/Z - CMS

Source of uncertainty	Channels		
	2ℓ	3ℓ	4ℓ
	Uncertainty (%)		
Modelling of trigger eff.	3	1	1
Modelling of lepton sel. (ID/isolation)	4	6	8
Jet energy scale and resolution	4	5	4
Identification of b jets	2	3	3
Pileup modelling	1	1	1
Choice of parton distribution functions	1.5	1.5	1.5
Signal model	5	5	5
Total	8	10	11

ttγ - ATLAS - fiducial x-sec definition

- Final state particles with a lifetime > 10 ps

- Photons from non-hadron parent, pT> 20 GeV, |η|< 2.37
- Lepton p4 defined by combination of lepton + photons (DeltaR<0.1), pT>20 GeV, |η|< 2.5
- Jets from particles w/ lifetime > 10 ps, muon/electrons are discarded, anti-kT w/ distance parameter 0.4, pT> 25 GeV, |η|< 2.5

- Jets w/ DeltaR(e,j)<0.2, DeltaR(j,γ)< 0.1, DeltaR(j,μ) are discarded
- Photons w/ DeltaR(l,γ)<0.7 are discarded

- $t\bar{t}$ dilepton final states and $\tau \rightarrow$ lνν are discarded
- Exactly one lepton, at least one photon, four or more jets, one jet matched to a b-hadron (pT>5 GeV, DeltaR(j,b-hadron)<0.4)

$t\bar{t}$+bbar background in ttH, H→bb

ATLAS : matching procedure using DeltaR<0.4, clustering of stable particles excluding muons and neutrinos

tt+b(b) : at least one jet matched to b-quark not originating from top

tt+c(c) : at least one jet matched to c-quark, not originating from W decay

tt+lights : none of the above condition is verified

CMS :

tt+bb : 2 jets are matched in DeltaR<0.5 to b-quark not originating from top

tt+b : arises if one b-jet is too soft or forward or if the 2 b-jets merge

tt+c(c) : one or two jets matched to c-quark

tt+lights : none of the above condition is verified