Recherche de la production associée du boson de Higgs et de quarks top au LHC

Congrès de la SFP 2017 - 04/07/2017, Orsay

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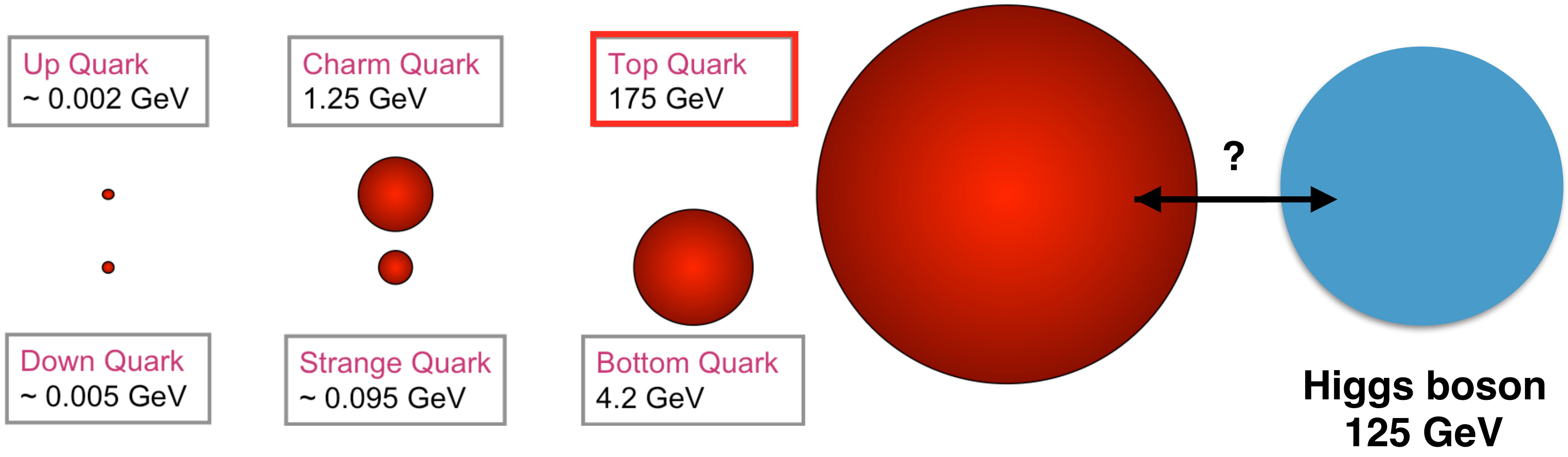
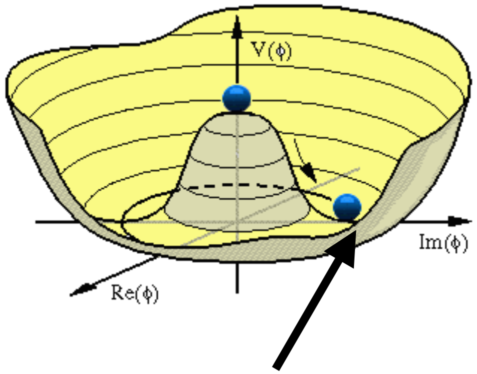
Top quark - Higgs boson coupling





v is breaking the EW symmetry

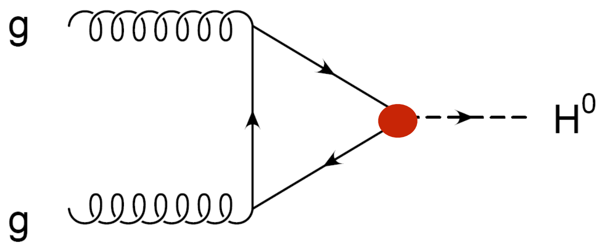
The Higgs boson generates fermion mass via its vacuum expectation value v (Yukawa coupling).

$$\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

Mass term in the SM Lagrangian

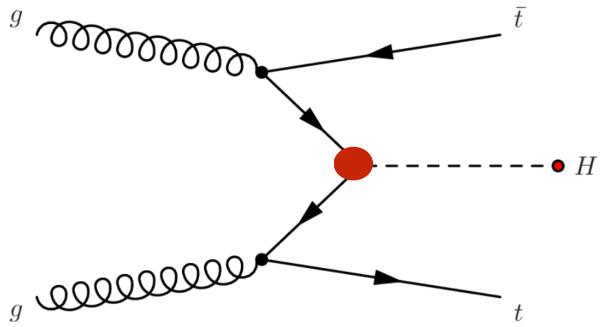
$$-\lambda_f \bar{\psi}_L \phi \psi_R$$

- Top Yukawa coupling $\lambda_t = \sqrt{2}.\, m_t/v \sim 1$
- The top quark plays a special role in many extensions beyond the SM
- Measuring accurately λ_t is one of the priorities of the LHC



Gluon fusion (ggF): Indirect (loop level) probe of top Yukawa coupling

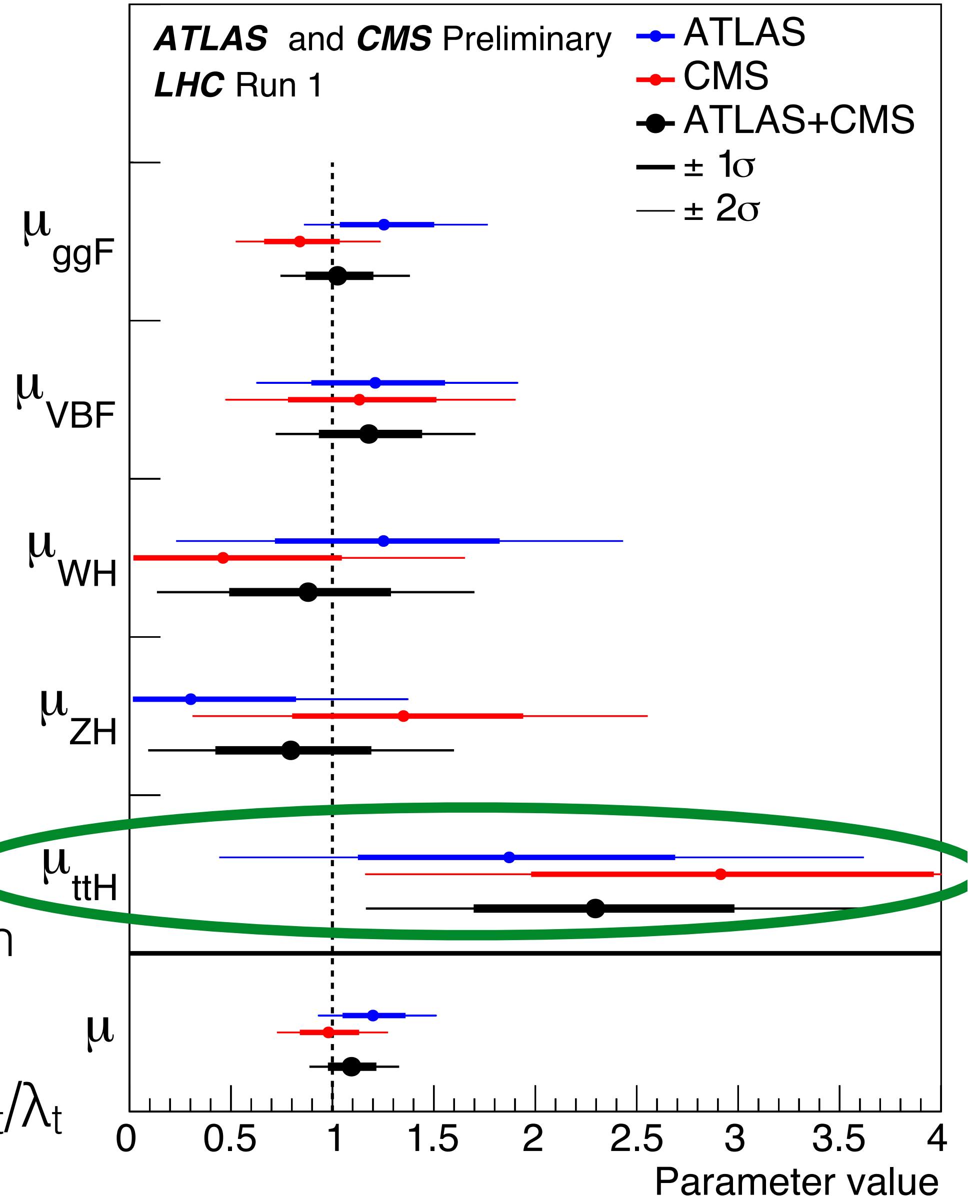
~**1%** of total Higgs boson cross section at the LHC



ttH: Direct (tree level) **probe of top Yukawa coupling**

JHEP 08(2016) 045

LHC Run I (8 TeV): ttH significance 4.4σ observed (2.3σ expected)

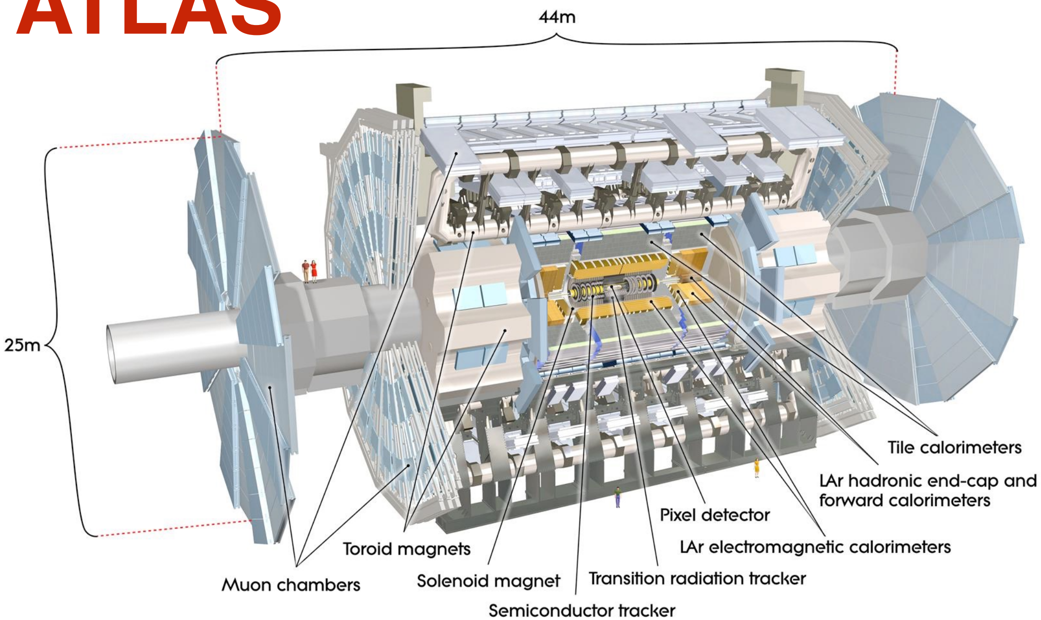


Signal strength $\mu = \sigma / \sigma_{SM}$

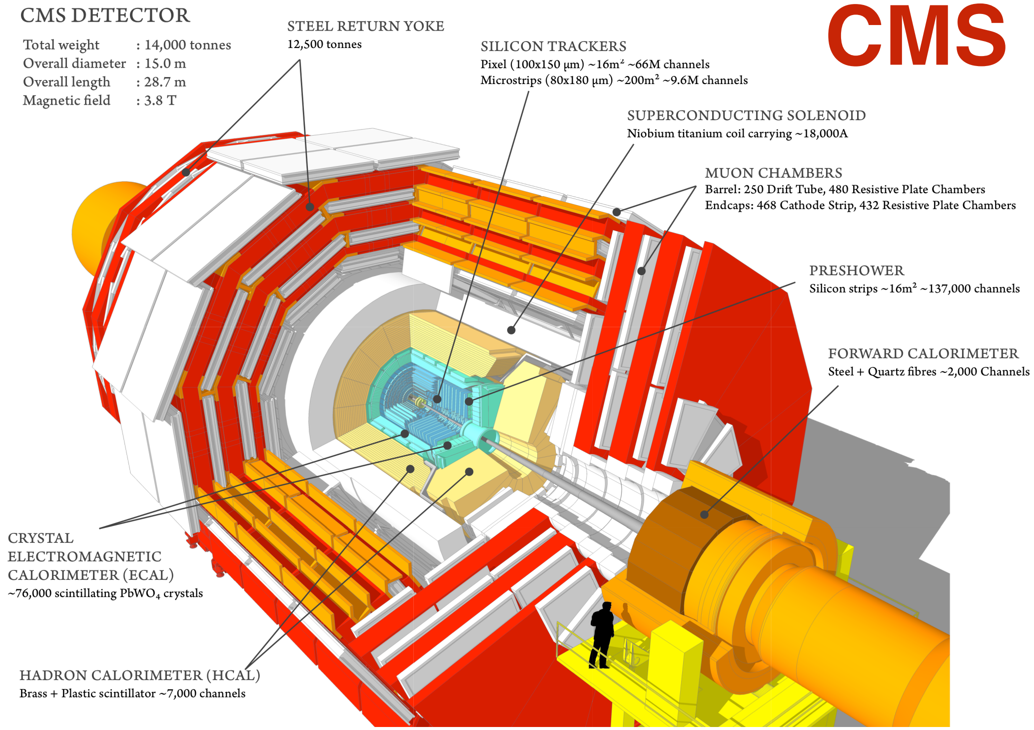
$\Delta\mu_{ttH} / \mu_{ttH} \propto 2 \Delta\lambda_t / \lambda_t$

ATLAS and CMS detectors at the LHC

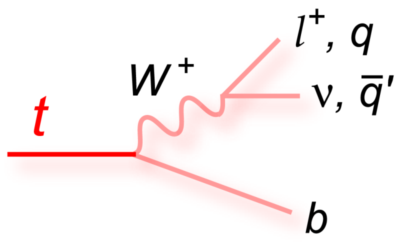
ATLAS



CMS

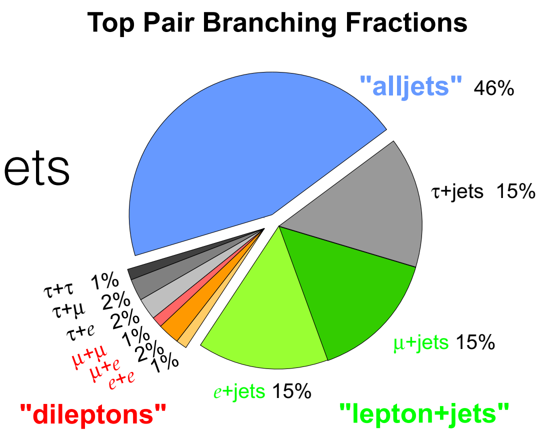


Higgs boson and Top quark decay



Top quark decay

- Both tops can decay to b + leptons or jets



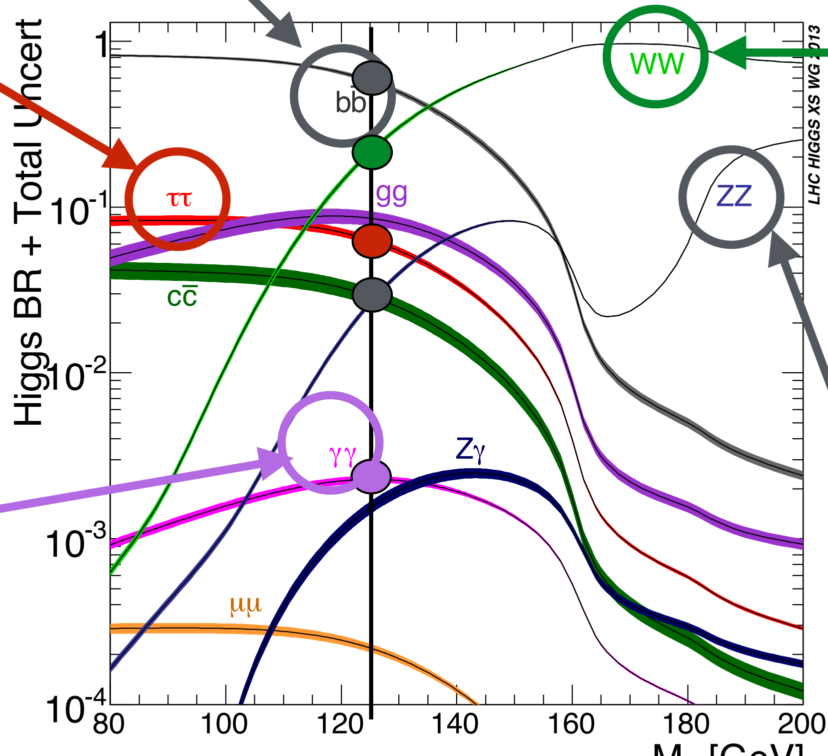
Higgs boson decay

H→bb (57.7%)

- Large branching ratio
- But large jets background

H→ττ (6.3%)

- Hadronic or leptonic τ decay



H→WW (21.5%)

H→WW, H→ZZ, semi-leptonic and leptonic decays:

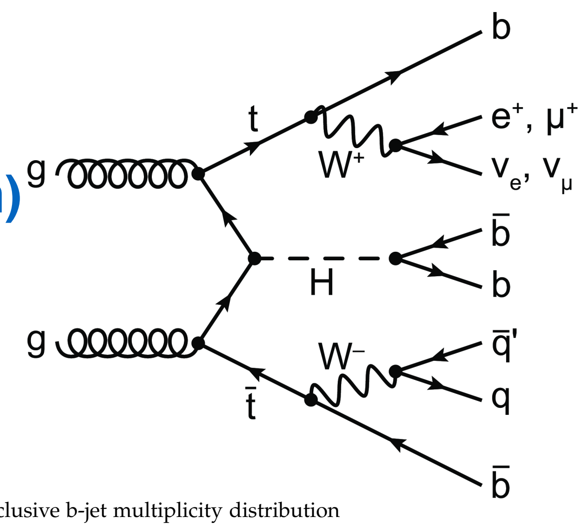
- clean lepton signature
- ZZ→4l: excellent mass resolution

H→γγ (~0.2%)

- Excellent mass resolution,
- But low branching ratio

H→ZZ (2.6%)

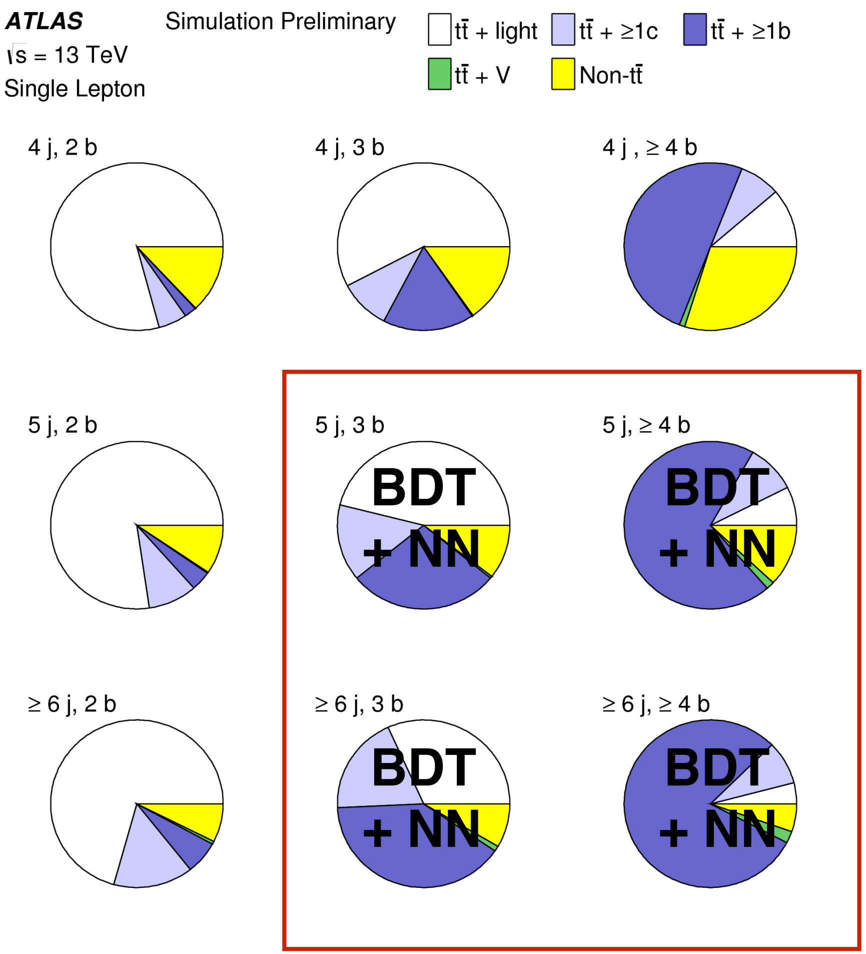
$t\bar{t}H, H \rightarrow b\bar{b}$



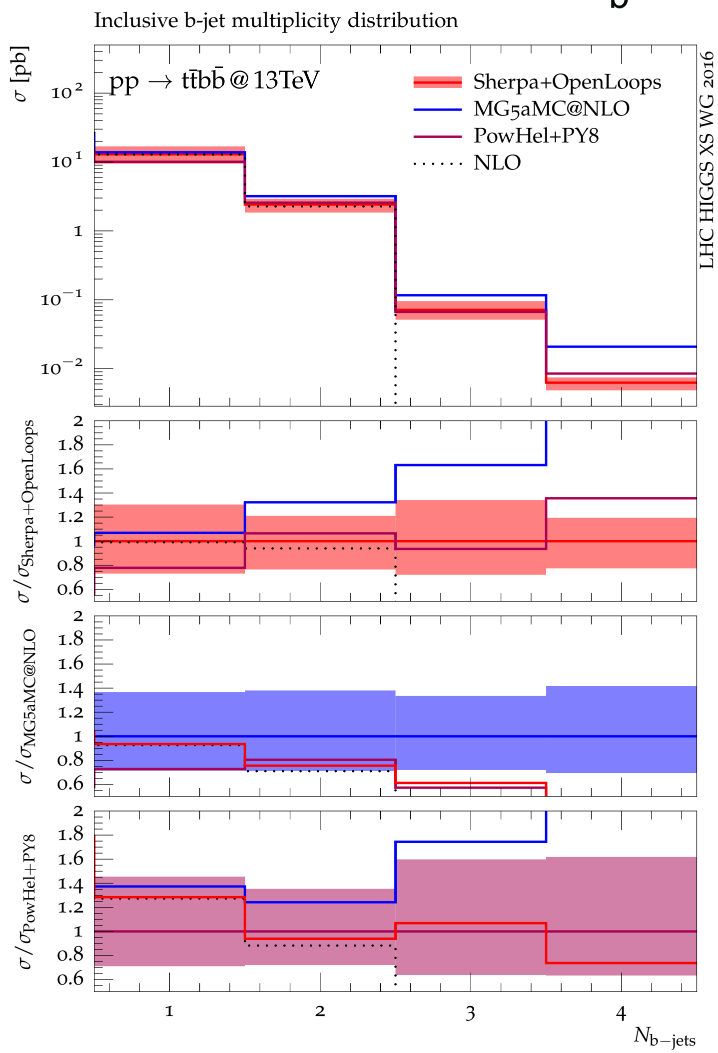
Selection targeting lepton+jets and dileptons (opposite sign)

- H→bb mass resolution ~10%, jet combinatorics
- Use **multivariate methods:** Boosted decision tree (BDT), Neural Network (NN), Matrix Element Method (MEM)

Classify with the number of jets and b-tagged jets



- **ttbar + ≥1b: major background** in signal regions
- Difficult to model in Monte-Carlo simulation: 30-50% uncertainties

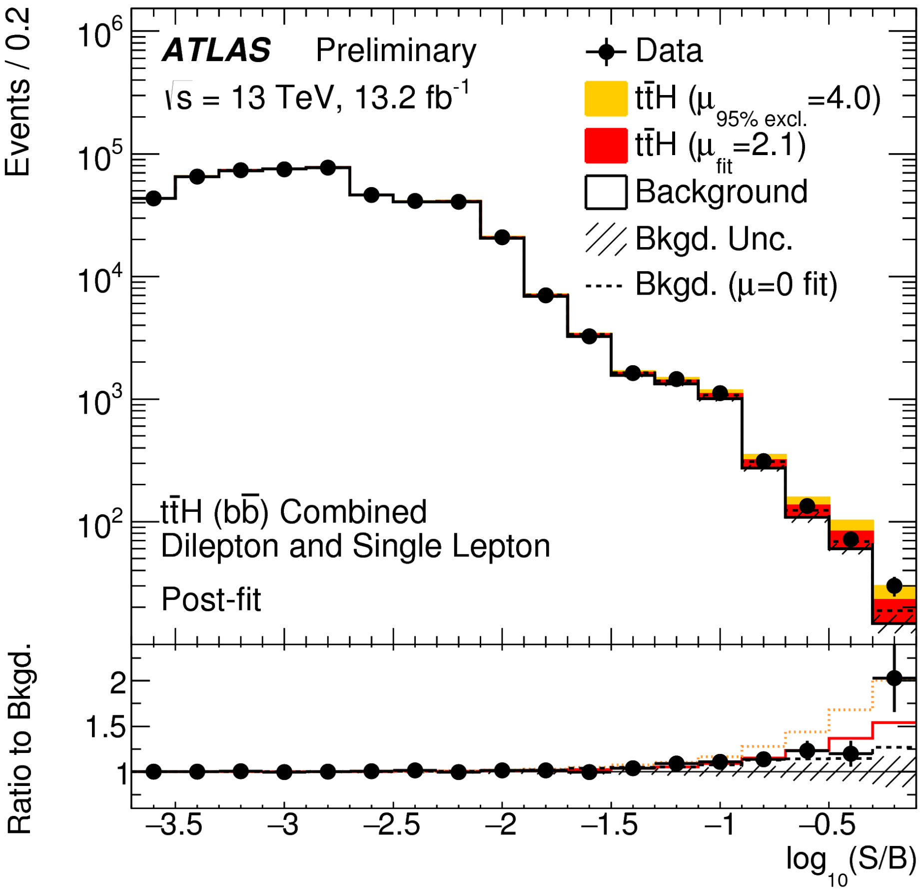


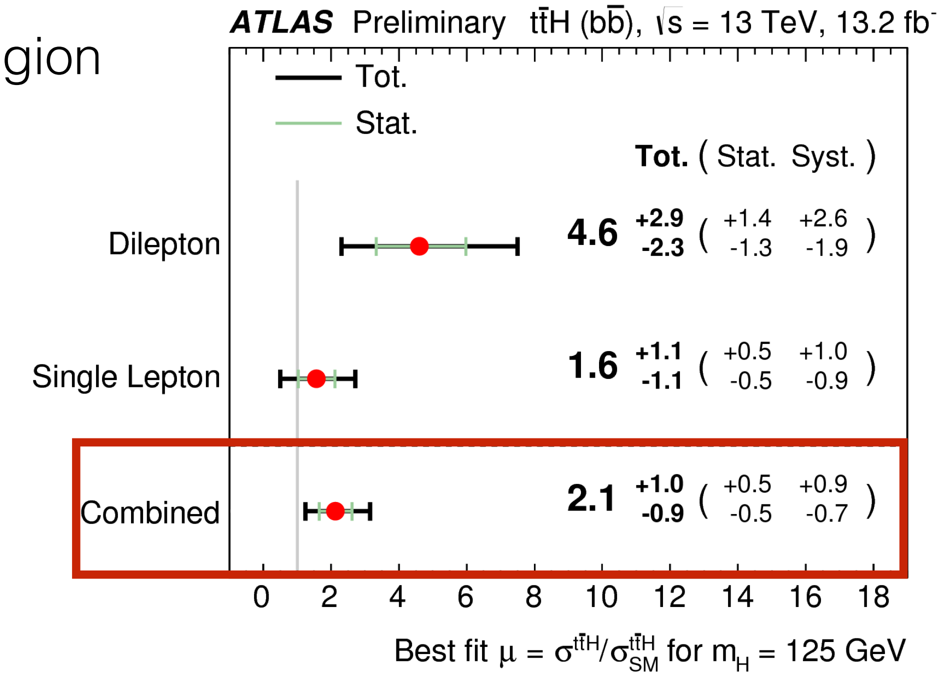
ATLAS $t\bar{t}H, H\to b\bar{b}$

ATLAS-CONF-2016-080

Analysis strategy: two-step multivariate technique

- **Reconstruction BDT** to improve H→bb mass
- **NN/BDT against backgrounds:** includes reconstruction + kinematic variables in signal region
- tt+≥1b, tt+≥1c normalisations are free in the fit





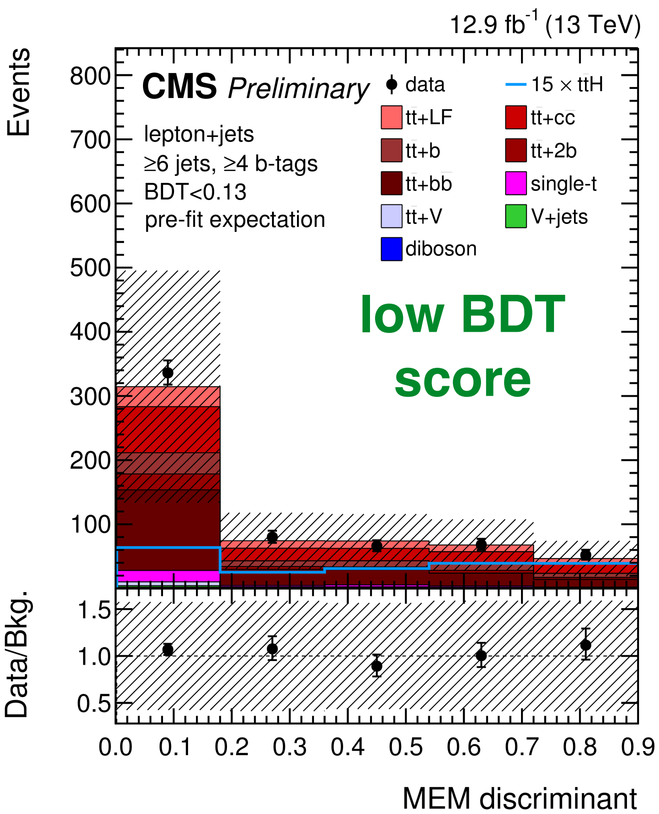
Theory uncertainties on ttbar + ≥1b is Δμ~0.5, already dominates the measurement

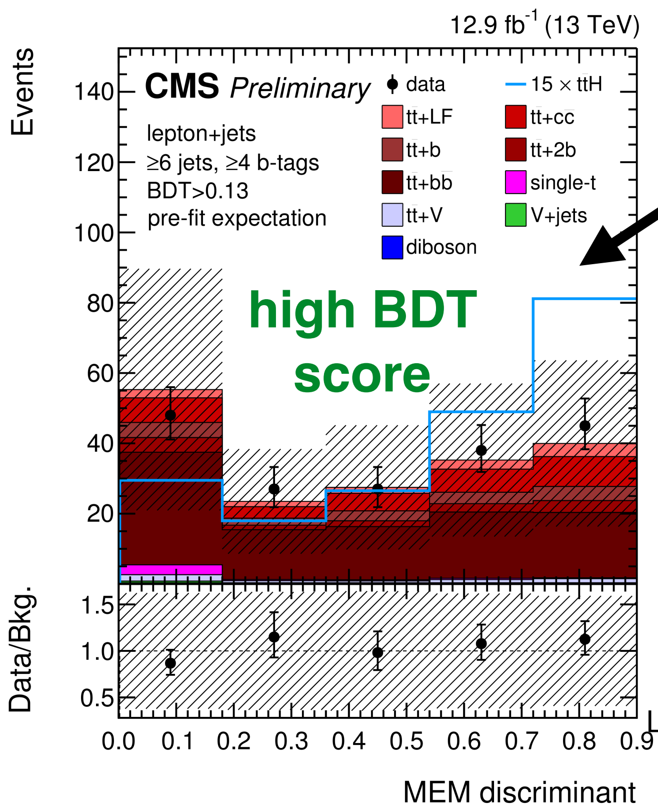
CMS $t\bar{t}H, H \to b\bar{b}$

CMS HIG-16-038

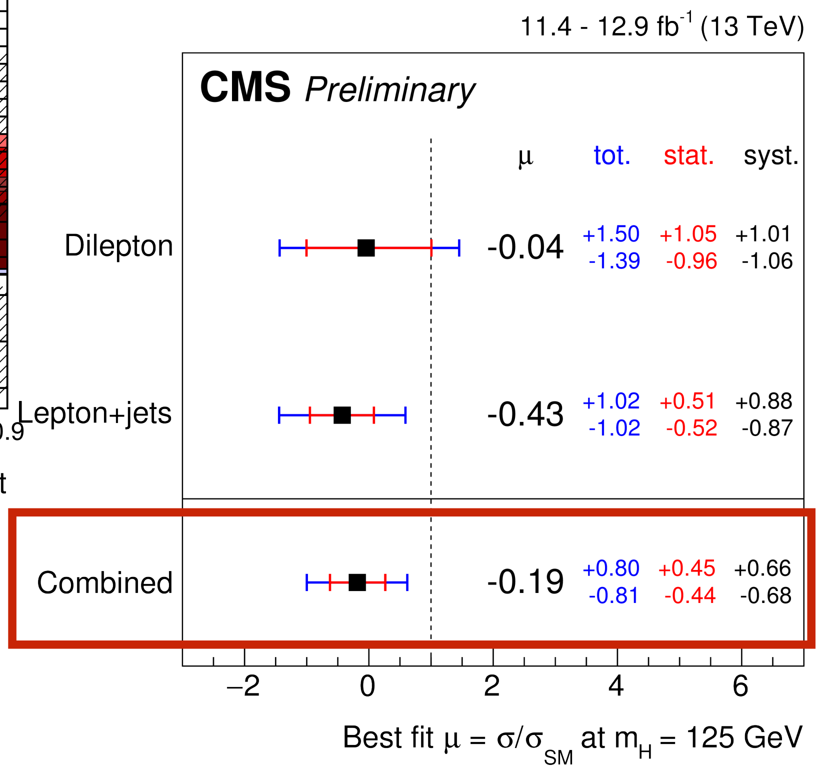
Analysis strategy:

- Split signal regions in low/high BDT parts
- Use Matrix Element Method as discriminant





Example of discriminants for 6j, 4b category (most discriminant among l+jets)

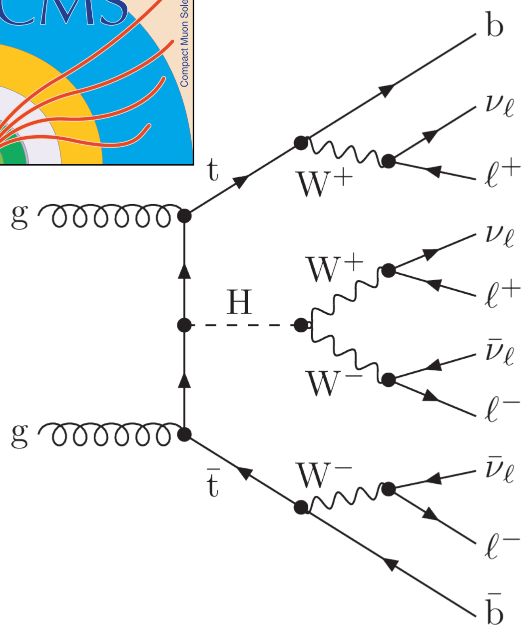


Systematics dominated:

50% uncertainty on ttbar+heavy flavour

CMS $t\bar{t}H$ multilepton

CMS HIG-17-004

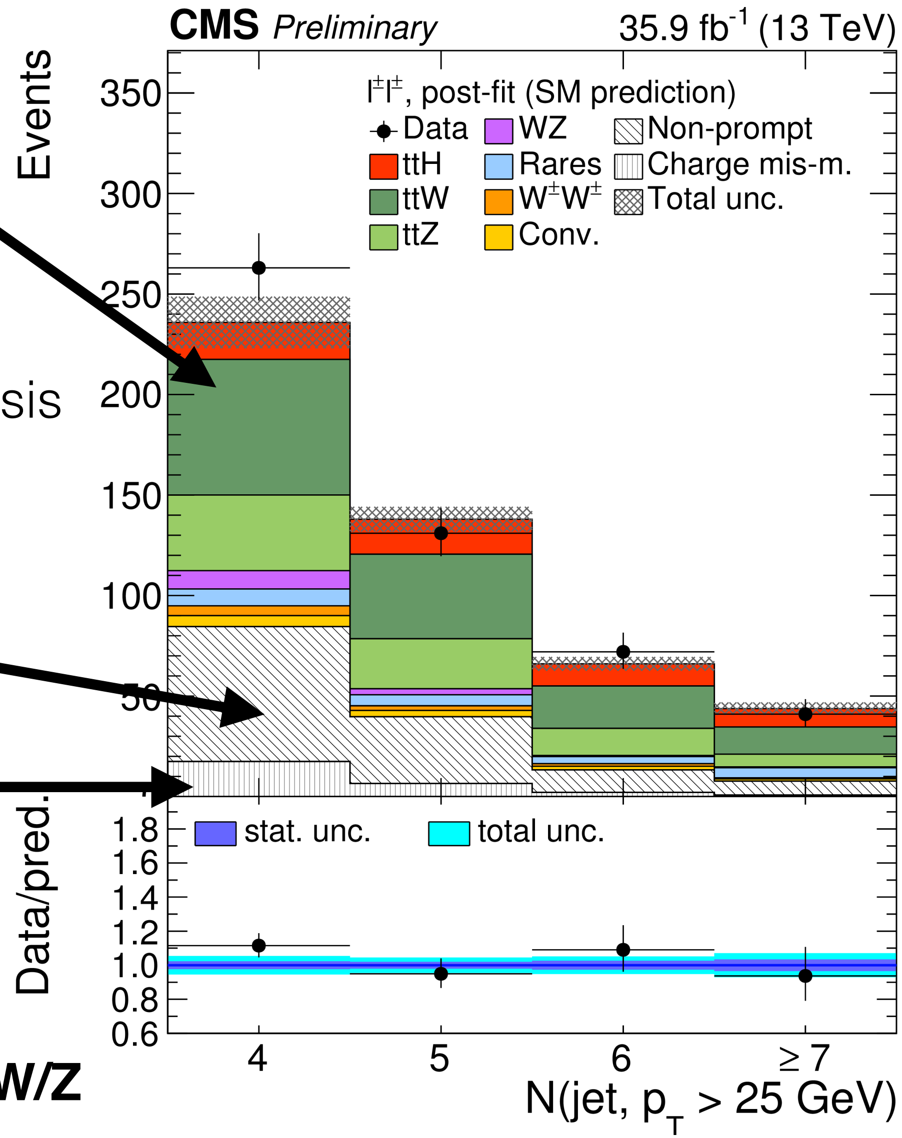


leptons = electrons, muons (veto τ_h)

Irreducible: tt+W/Z/γ*
- from Monte Carlo,
- O(10%) uncertainty

Reducible: mainly tt+jets,
- Lepton identification optimised for this analysis
- measured in data,
- O(30%) uncertainty

- **Jets faking leptons:** fake rate computed from jets control region with loosened identification
- **Charge mis-assignment** (2ℓss only)**:** flip rate from $Z \to \ell^\pm \ell^\pm$ data



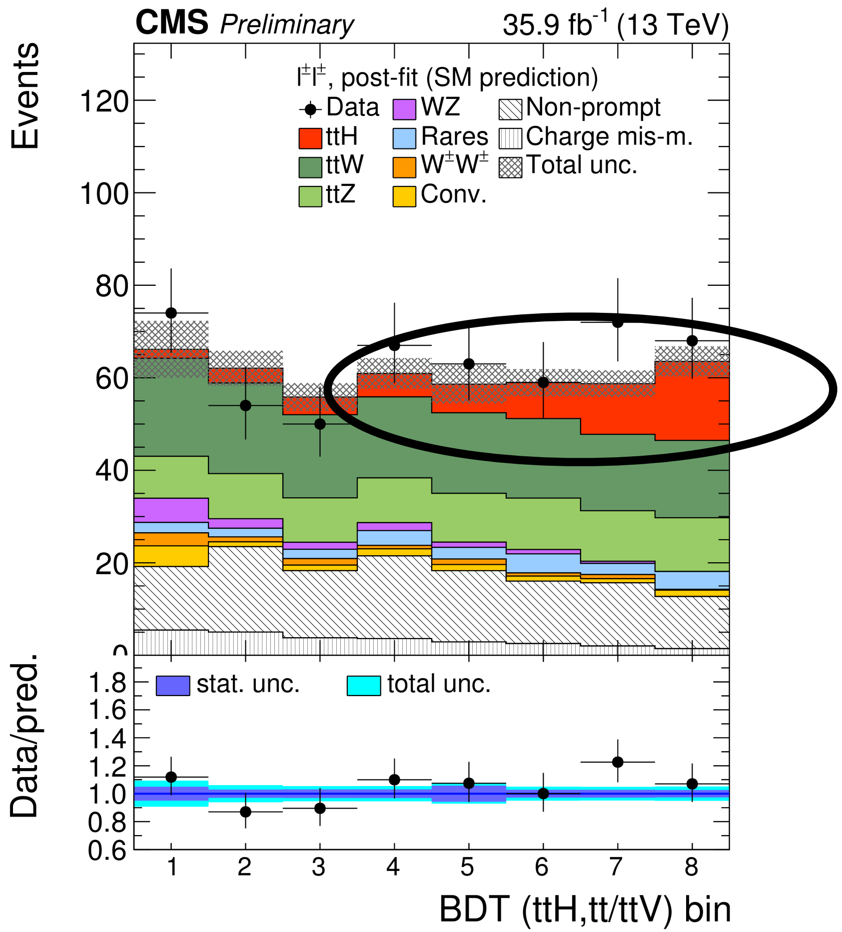
Strategy in 2ℓss and 3ℓ categories:
- Train **2 kinematic BDTs, against tt+jets and ttW/Z**

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

CMS HIG-17-004

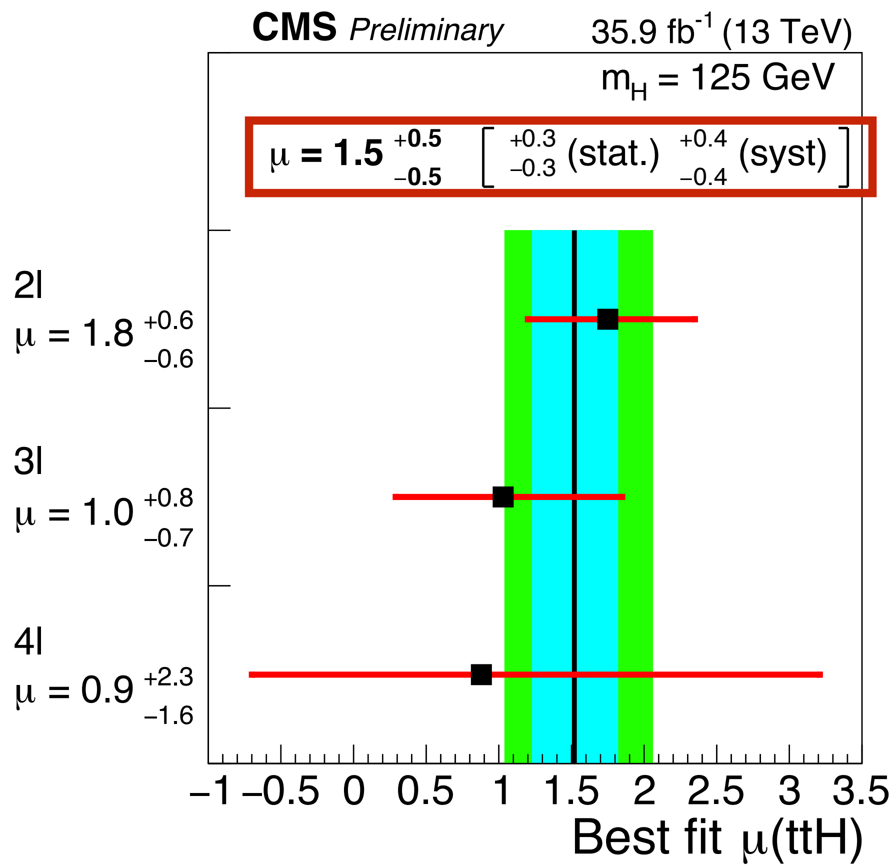
Analysis sensitivity:

- Map 2D BDT into 1D (group into bins with similar s/b)



Significance :

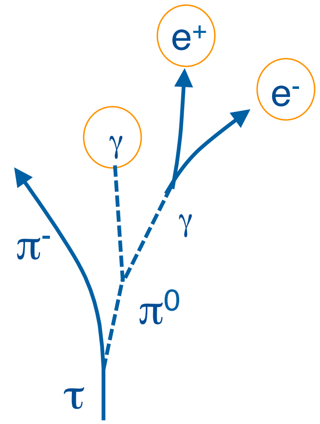
- **3.3σ observed (2.5σ expected)**
- Combining with 2015 data: 3.3σ
- Check fit with floating ttW/Z: 3σ



- **Main systematics** uncertainties : **tight lepton selection** and **fakes**

CMS $t\bar{t}H, H\rightarrow\tau\tau$

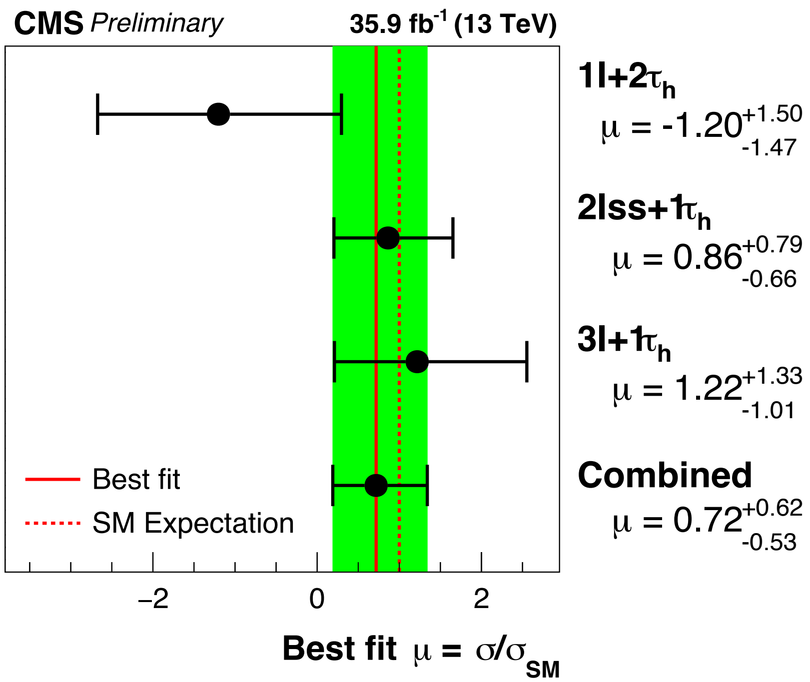
CMS HIG-17-003



τ_h reconstruction:

- Finds the tau decay mode
- MVA against jets faking tau: using tau isolation, optimised for ttH busy hadronic environment

Signal strengths $\mu=\sigma/\sigma_{SM}$



Similar strategy as in multilepton analysis:

- for background estimate
- and analysis sensitivity (BDT, MEM)

- **$1\ell+2\tau_h$:** Additional difficulty from jets faking τ_h background
- **$2\ell ss+1\tau_h$:** most sensitive

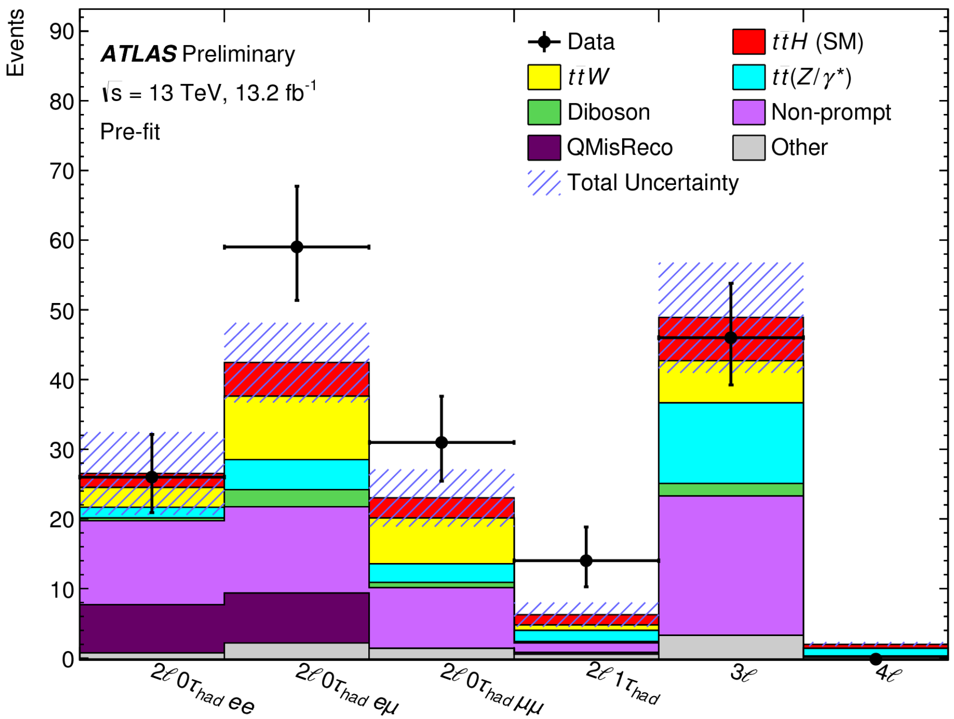
- **Main systematics** uncertainties : tight lepton selection, τ_h identification and jets fake τ_h

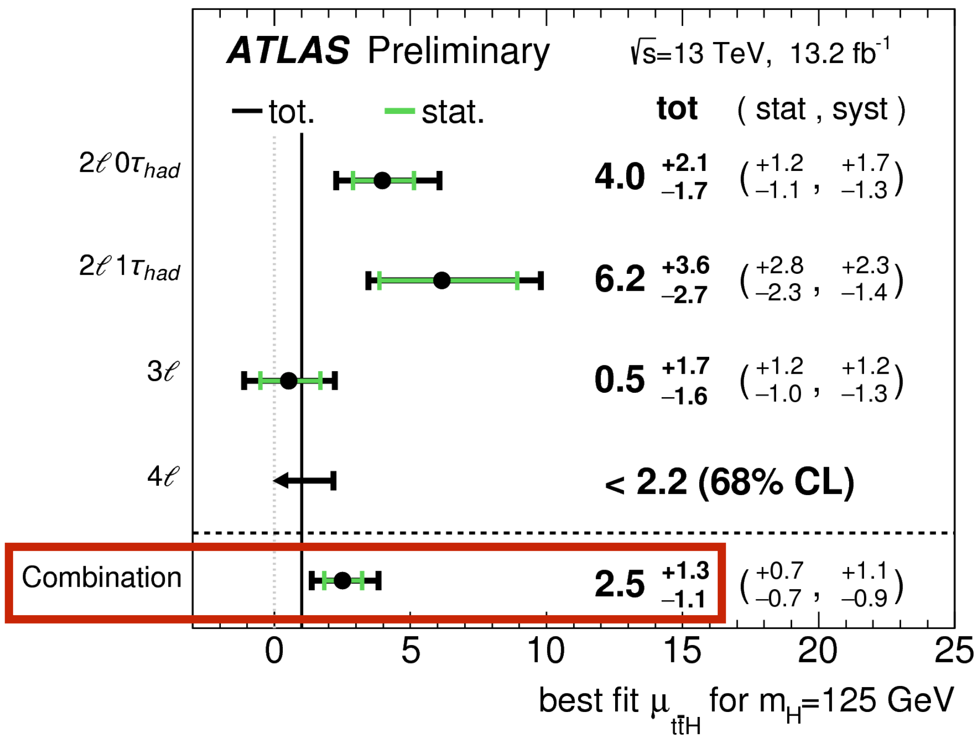
ATLAS $t\bar{t}H$ multilepton

ATLAS-CONF-2016-058

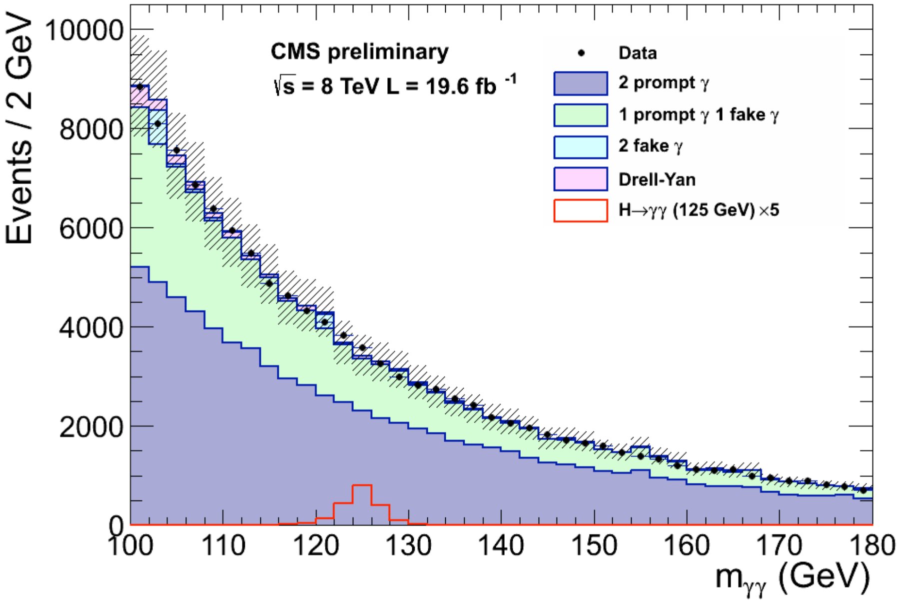
- Similar method to CMS for background measurement
- **Main systematic** uncertainties : Fakes and charge mis-assignment $\Delta\mu$~0.6

Cut and count analysis in 6 categories

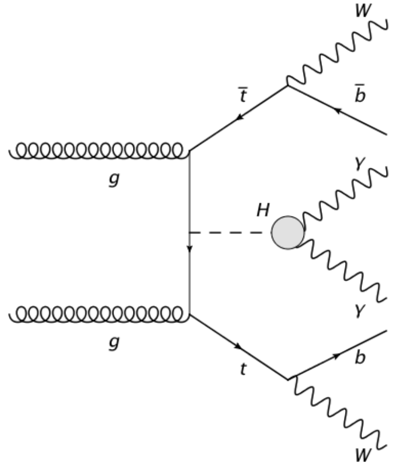


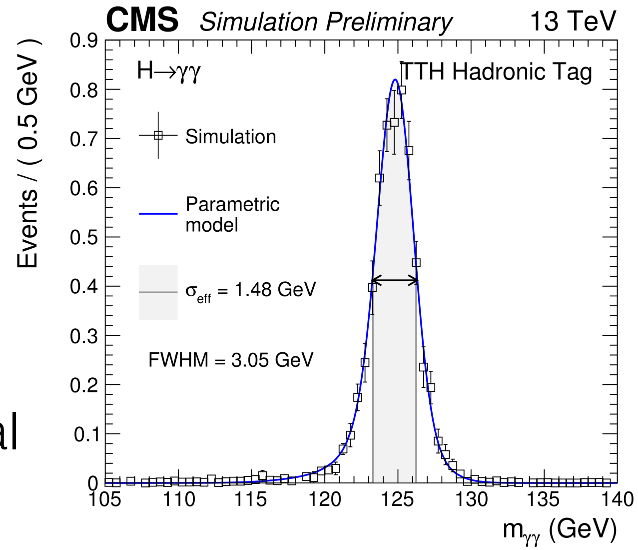


$t\bar{t}H, H\rightarrow\gamma\gamma$ analysis



- Look for **small signal peak (BR~0.2%) over large background**
- **Photon identification:** reject jets faking photons with shower shape and isolation: BDT (CMS), cut-based (ATLAS)

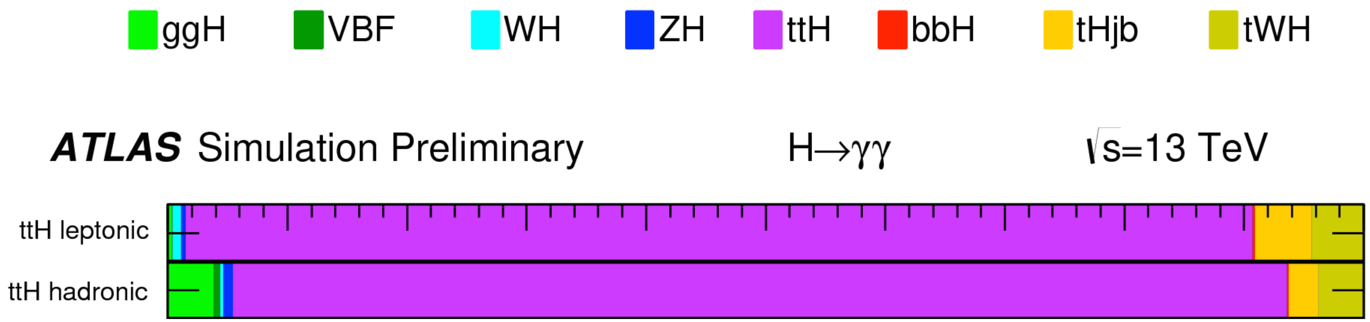




- **Photon energy resolution ~1-2%** depending on categories: calibration is crucial

Two high purity ttH categories

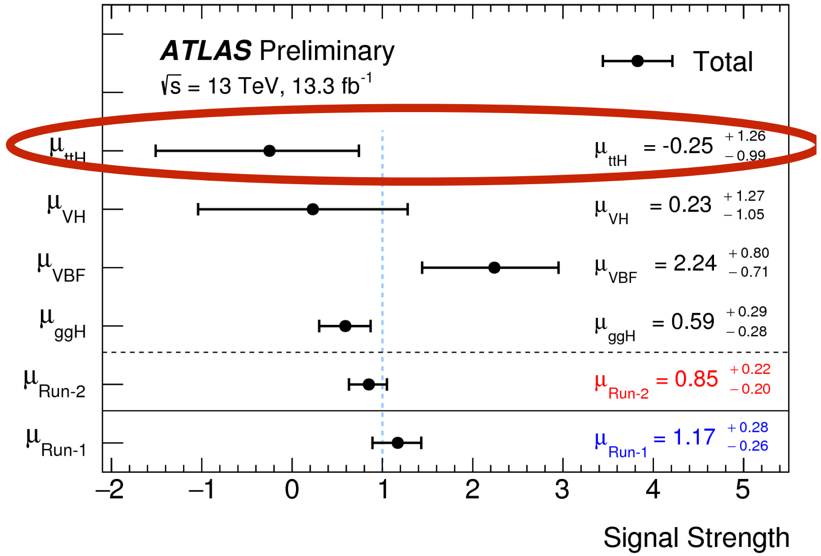
- Requiring 0 or 1 lepton, jets and b-jets



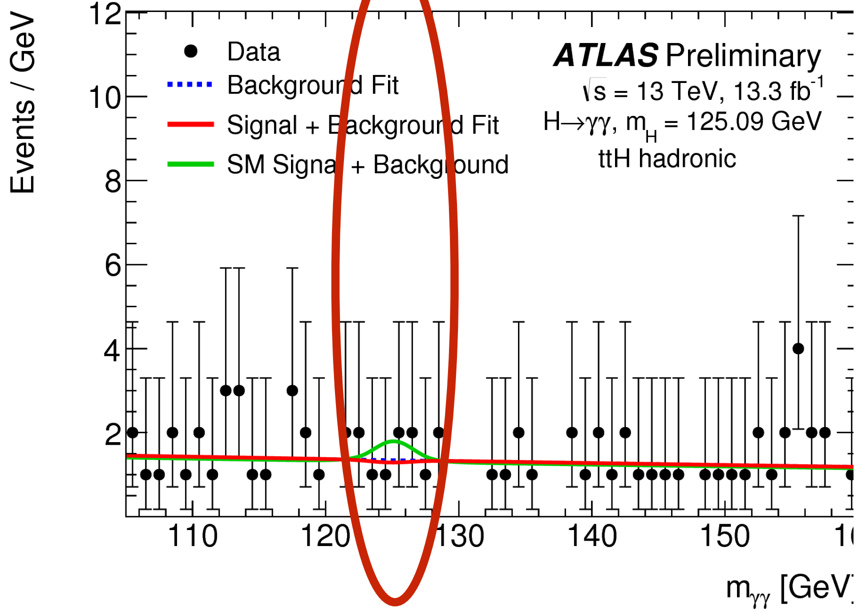
ATLAS $t\bar{t}H, H\rightarrow\gamma\gamma$

ATLAS-CONF-2016-067

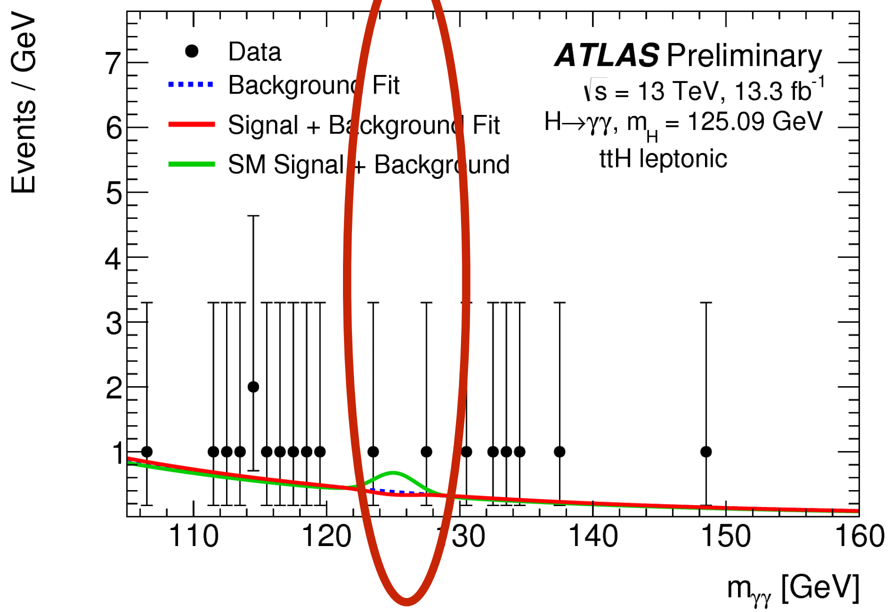
- **ttH** hadronic/leptonic combined: **μ=-0.25$^{+1.26}_{-0.99}$** measured simultaneously with other production mechanisms
- Dominated by statistical uncertainties



ttH hadronic tag: 0 lepton, ≥5 jets, ≥1 b-tag

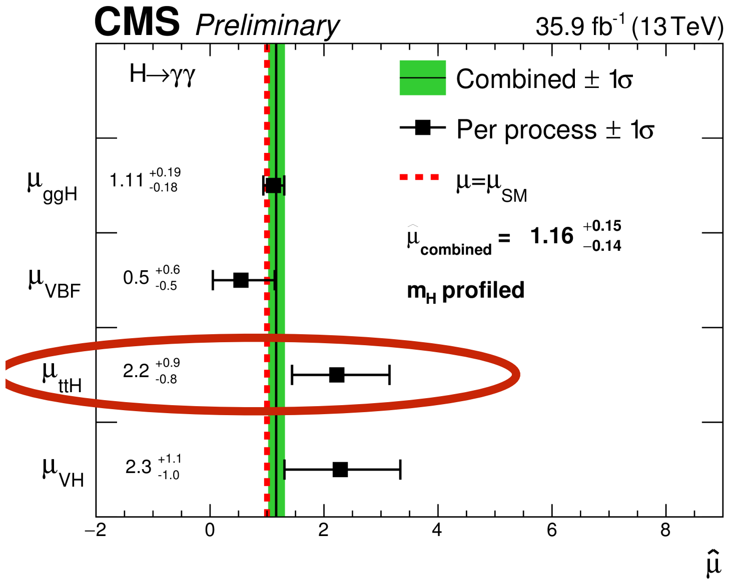


ttH leptonic tag: ≥1 lepton, ≥2 jets, ≥1 b-tag



CMS $t\bar{t}H, H\rightarrow\gamma\gamma$

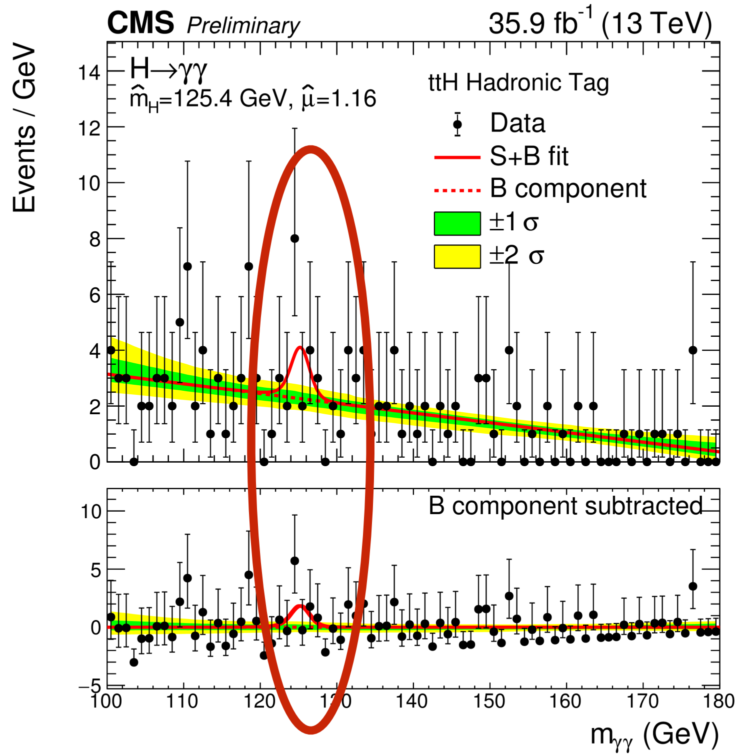
CMS HIG-16-040



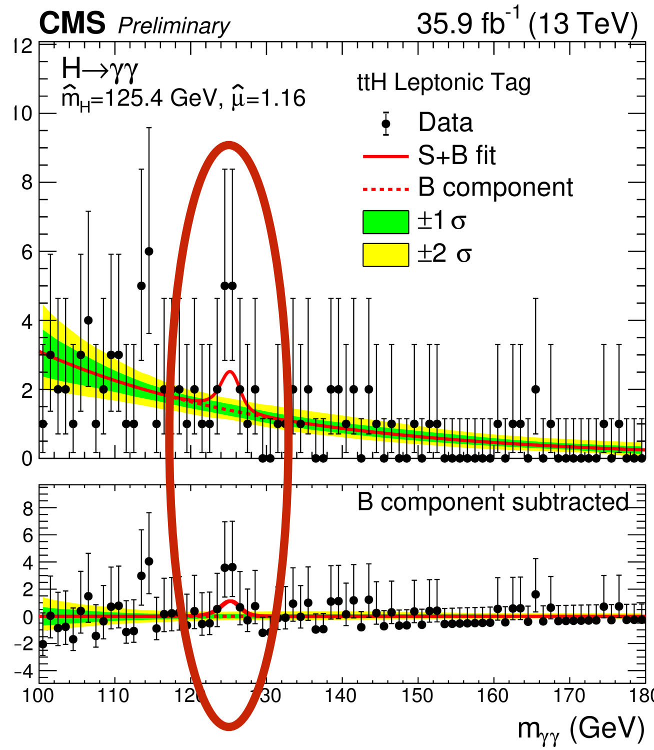
- New: a BDT is used in Hadronic category
- Signal strength measured simultaneously with other production mechanisms
- Dominated by statistical uncertainties

Significance: 3.3σ observed (1.5σ expected)

ttH hadronic tag: 0 lepton, ≥5 jets, ≥1 b-tag



ttH leptonic tag: ≥1 lepton, ≥2 jets, ≥1 b-tag



$t\bar{t}H$ summary

CMS HIG-16-038, HIG-17-004, HIG-17-003, HIG-16-040, HIG-16-041
ATLAS-CONF-2016-068, JHEP 08(2016) 045

Signal strength $\mu=\sigma/\sigma_{SM}$

Run 1 LHC combination	$2.3^{+0.7}_{-0.6}$	
	ATLAS Run 2	**CMS Run 2**
$H\to bb$	$2.1^{+1.0}_{-0.9}$	$-0.2^{+0.8}_{-0.8}$
Multilepton	$2.5^{+1.3}_{-1.1}$	$1.5^{+0.5}_{-0.5}$
$H\to\tau\tau$		$0.7^{+0.6}_{-0.5}$
$H\to\gamma\gamma$	$-0.3^{+1.2}_{-1.0}$	$2.2^{+0.9}_{-0.8}$
$H\to 4l$	-	$0.0^{+1.2}_{-0.0}$
Combination	$1.8^{+1.2}_{-1.0}$	-

Full 2016 dataset (CMS Run 2: Multilepton, $H\to\tau\tau$, $H\to\gamma\gamma$, $H\to 4l$)

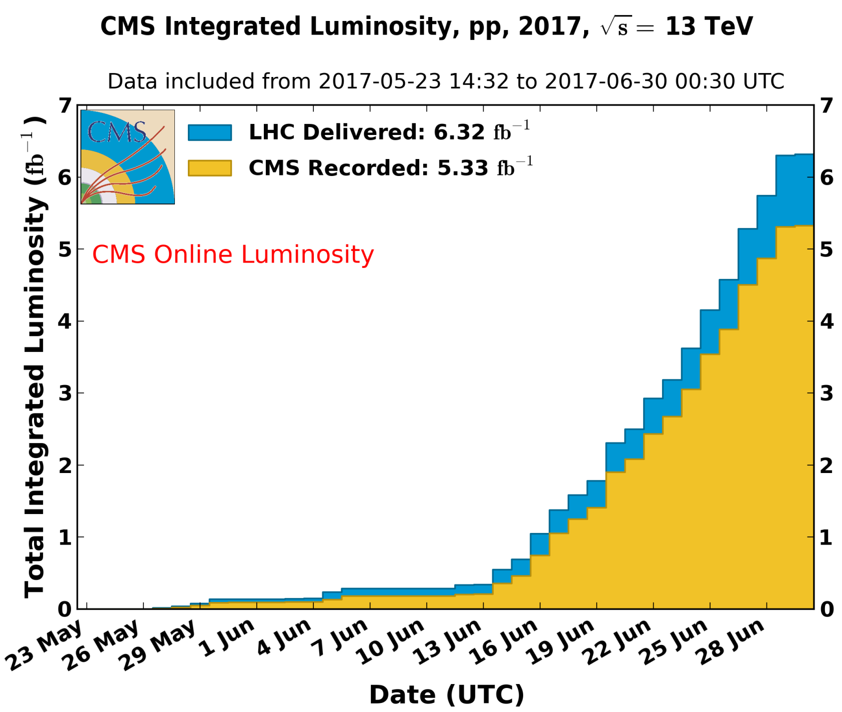
Conclusions

Direct measurement of Top - Higgs coupling with ttH searches

- **Observation** of ttH signal with a combined analysis of all channels at **Run 1 LHC (ATLAS+CMS)**: **4.4σ** (2.3σ expected)
- Observation in single analyses at Run 2 by CMS: **multilepton final state at 3.3σ** (2.5σ expected), and **H→γγ final state at 3.3σ** (1.5σ expected)
- **ATLAS Run 2 combination** with 1/3rd of 2016 dataset is not far: **2.8σ** (1.8σ expected)

More to come: analysis of full 2016 dataset by ATLAS and CMS H→bb to be completed

2017 data acquisition just started: more data will be analyzed soon



Back-up slides

ATLAS $t\bar{t}H \rightarrow bb$

ATLAS-CONF-2016-080

Systematic uncertainties break down

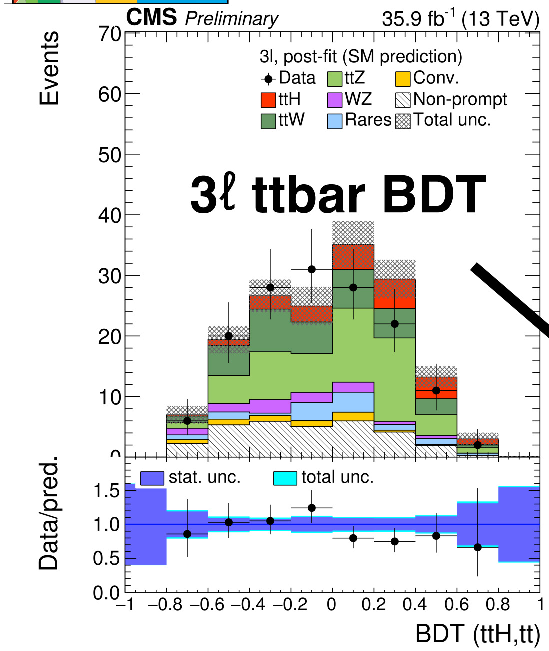
Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

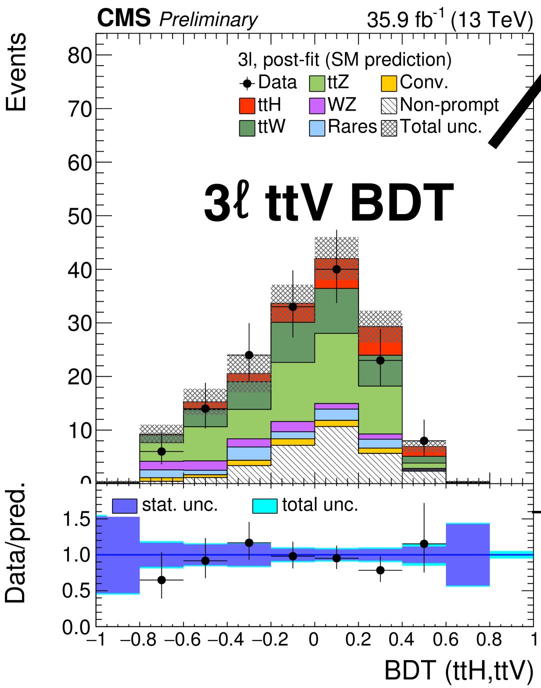
tt+b systematic uncertainties

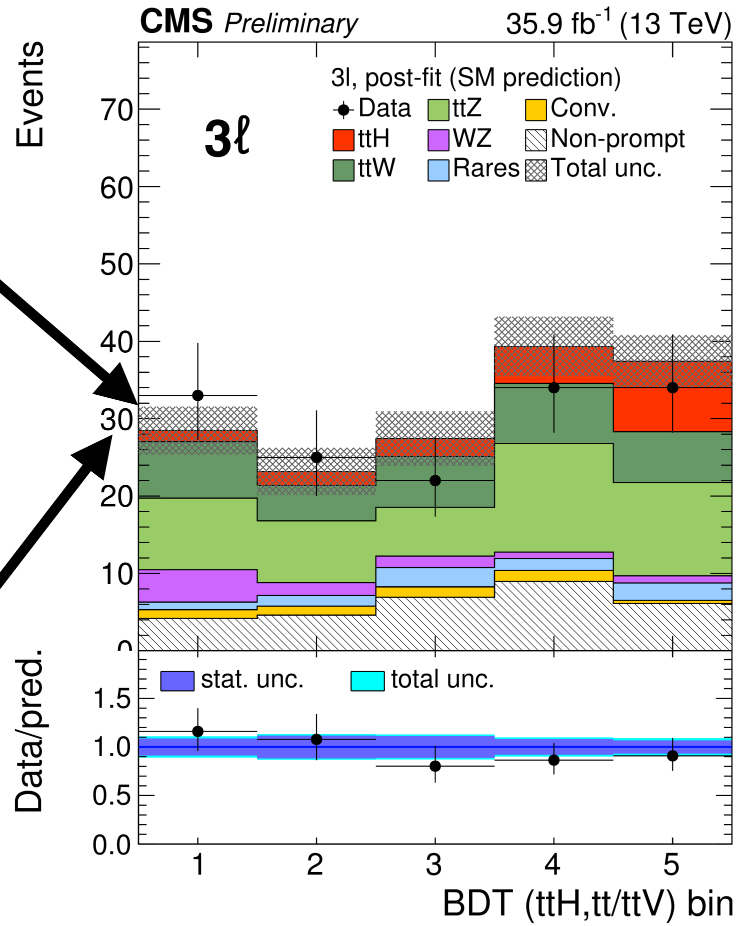
Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

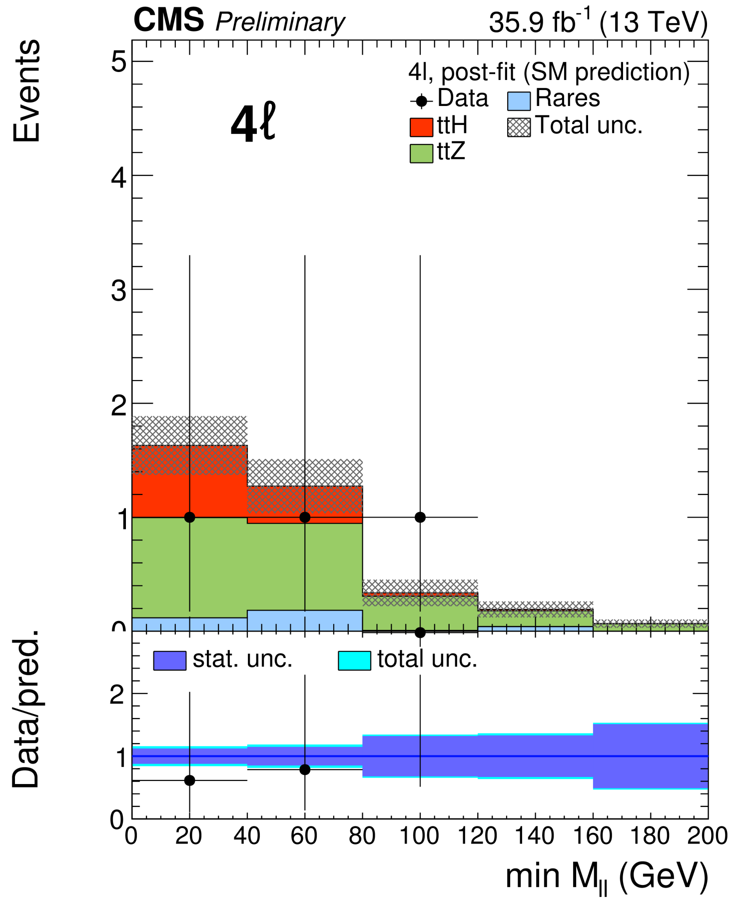
$t\bar{t}H$ multilepton discriminants

CMS HIG-17-004









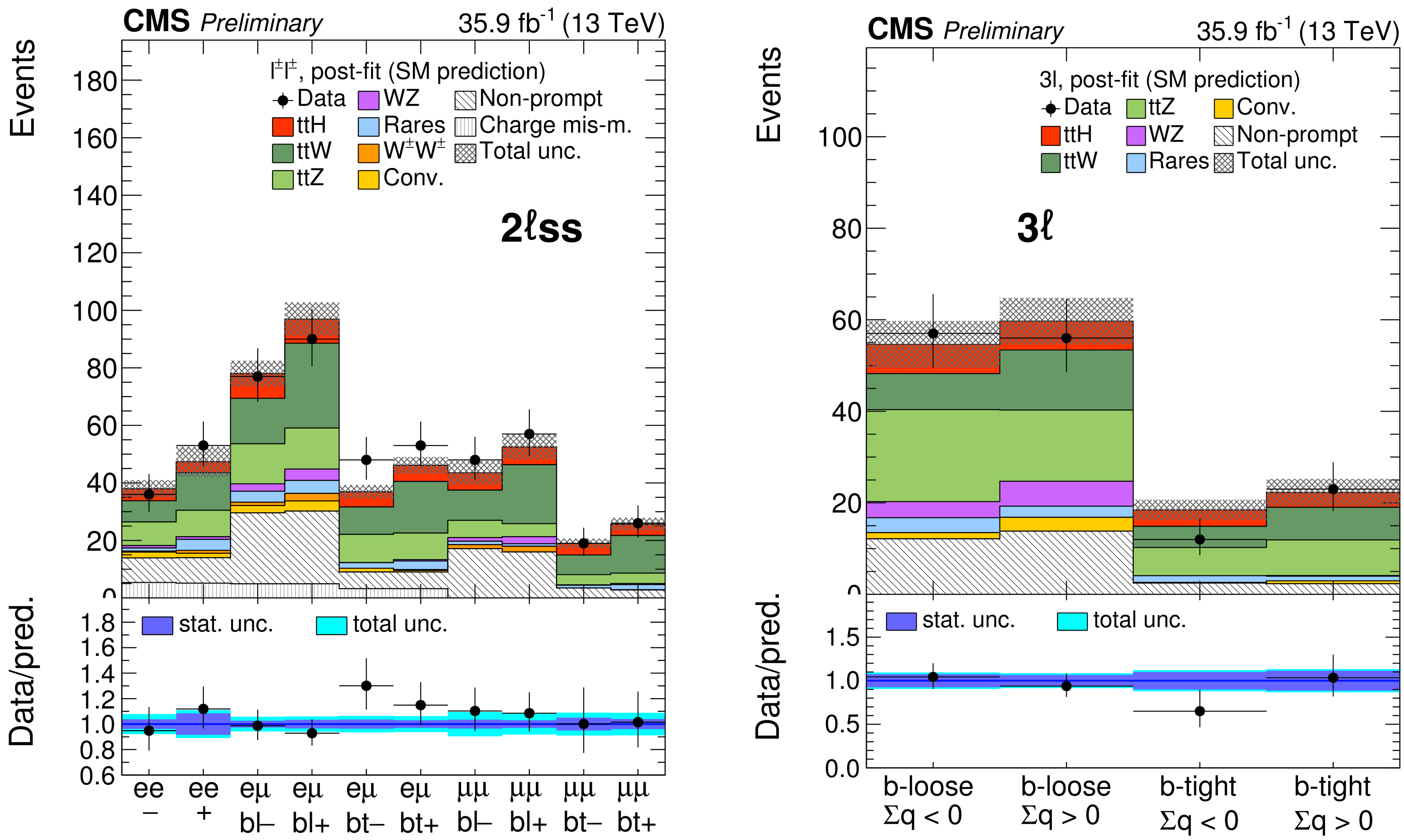
- **4ℓ** category : counting experiment

- 3ℓ vs ttW/Z: Includes **Matrix Element Method** likelihood ratio of ttH vs ttW+ttZ

$t\bar{t}H$ multilepton results

CMS HIG-17-004

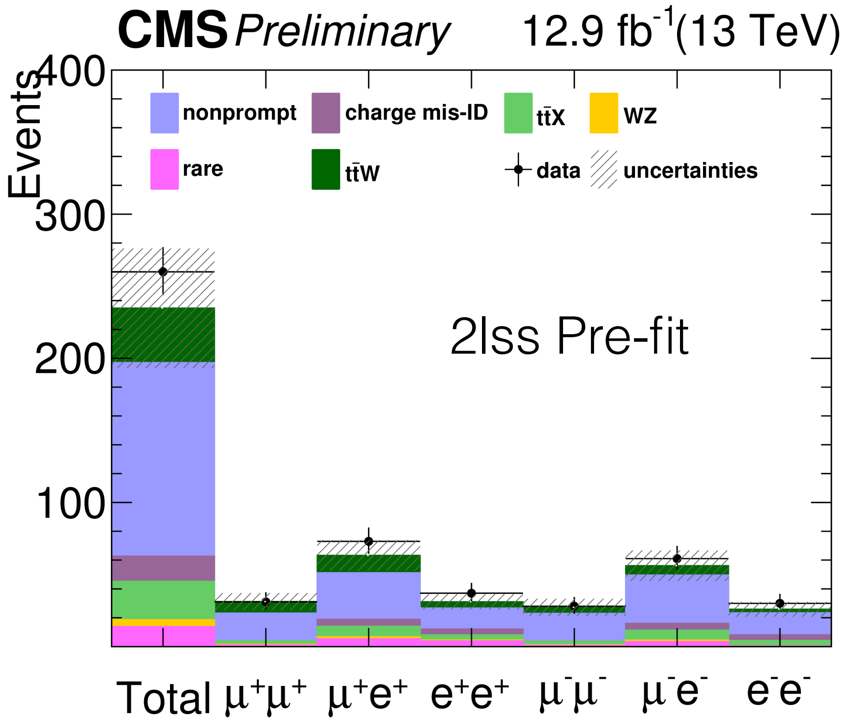
Categories per flavour/charge

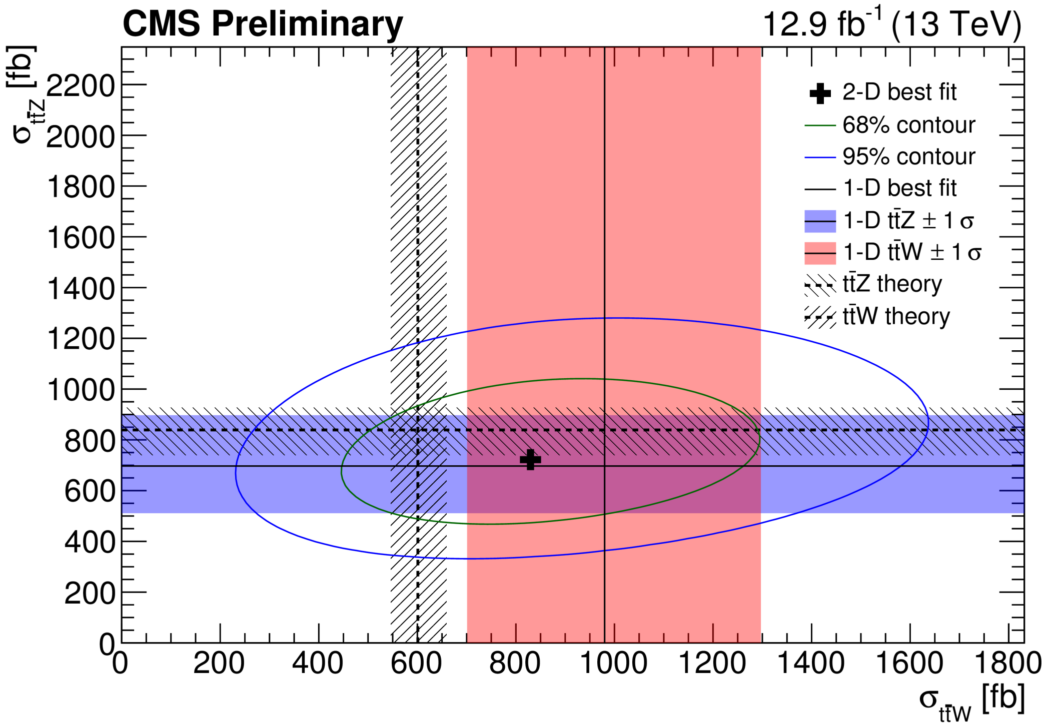


CMS ttbar+W/Z with ICHEP dataset

CMS TOP-16-017

- Background to ttH multi lepton searches
- At 13 TeV, **cross section ~x4** relative to 8 TeV
- ttW with 2lss: BDT using event kinematics: **3.9σ** (2.6σ) observed (expected)
- ttZ with 3l,4l : counting events classified by jets/b-jets multiplicity: **4.6σ** (5.8σ)

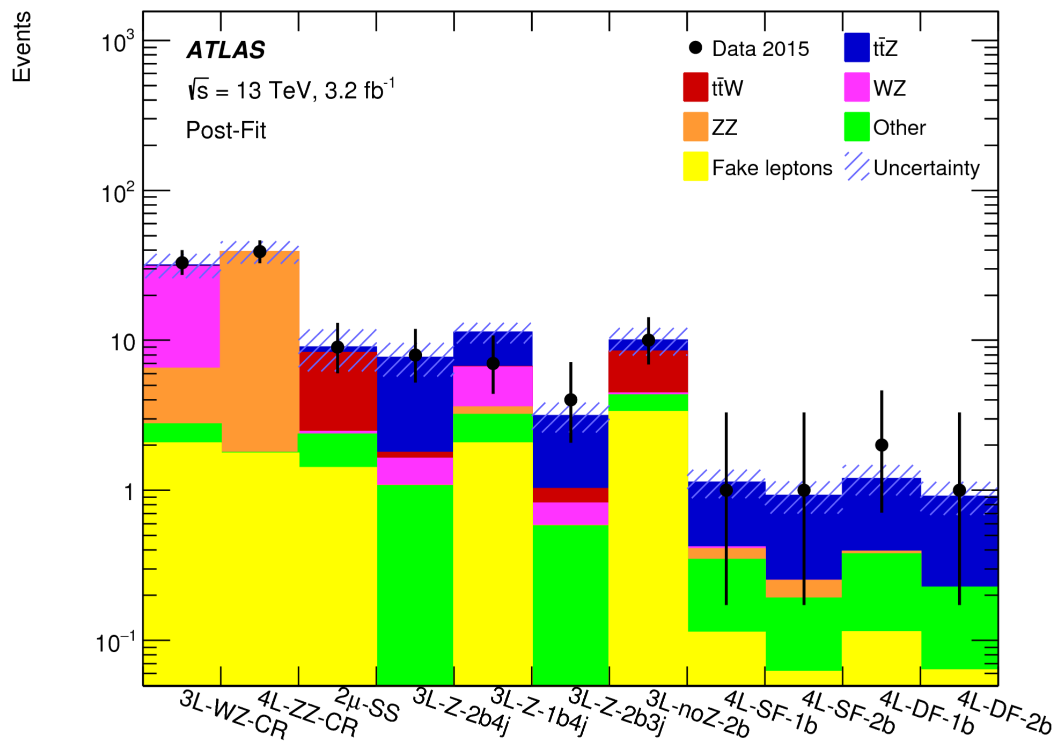


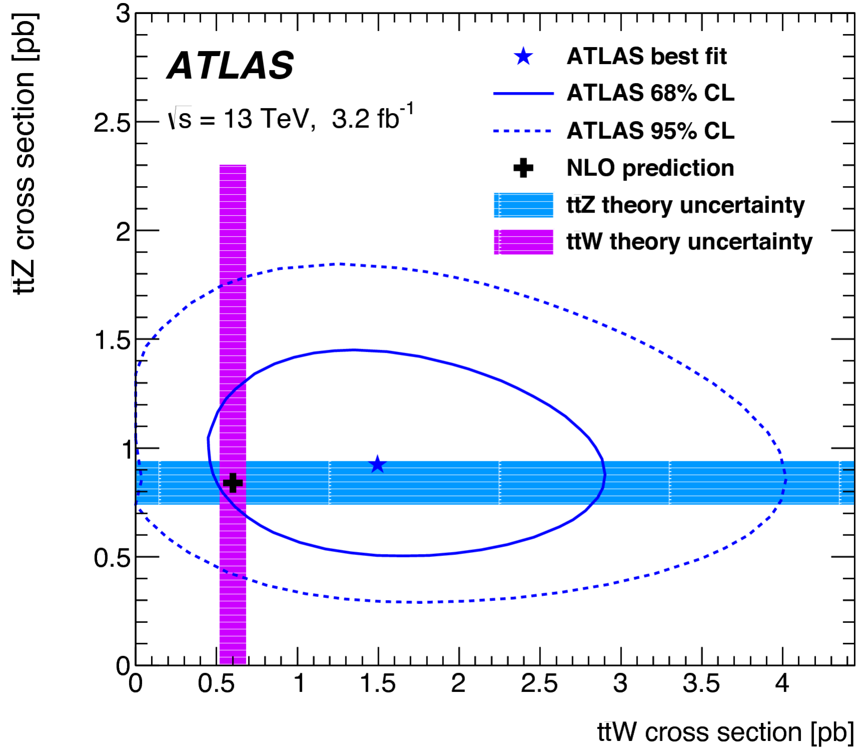


ATLAS ttbar+W/Z production at 13 TeV

ATLAS arXiv:1609.01599

- ttW with 2lss (dimuon only), 3l: **2.2σ** (1.0σ) observed (expected)
- ttZ with 3l (on-Z region included),4l : counting events classified by jets/b-jets multiplicity: **3.9σ** (3.4σ)





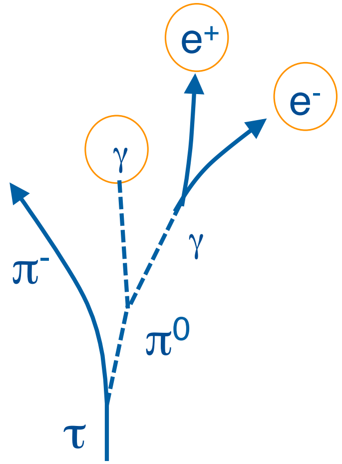
Hadronic τ reconstruction and identification

CMS TAU-16-002

Hadron + strip (HPS) algorithm

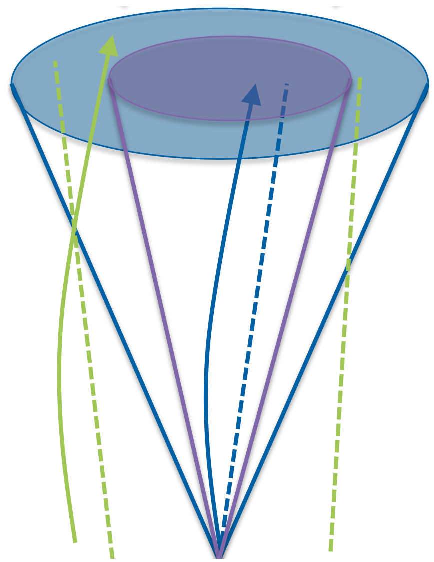
- Seeded by reconstructed PF jets
- Neutral pions : strips 0.05 x 0.020 in η-Φ
- Look into jet constituents, decay mode finding

- a single charged particle without any strips: $h^{\pm}$;
- combination of one charged particle and one strip: $h^{\pm}\pi^{0}$;
- combination of a single charged particle with two strips: $h^{\pm}\pi^{0}\pi^{0}$;
- combination of three charged particles: $h^{\pm}h^{\mp}h^{\pm}$.



Dynamic strip reconstruction

- Widen strip size in the case of bremsstrahlung or τ_h nuclear interaction, depends on pT

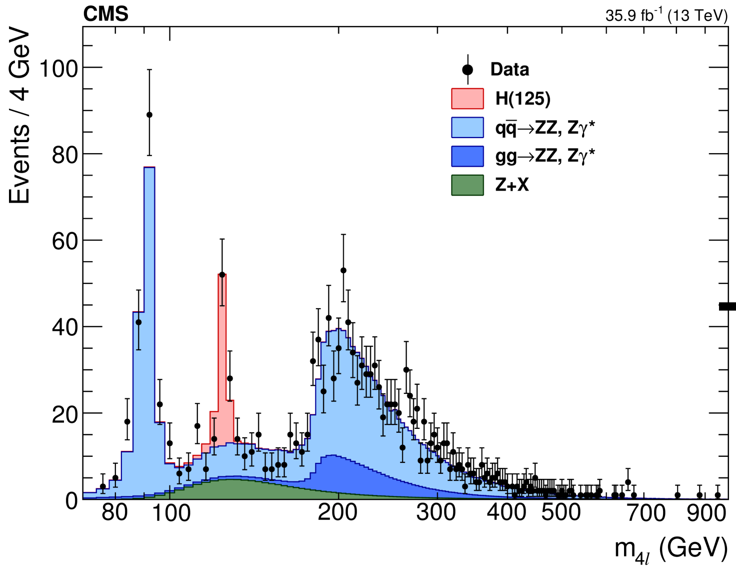


MVA based discriminator against jets

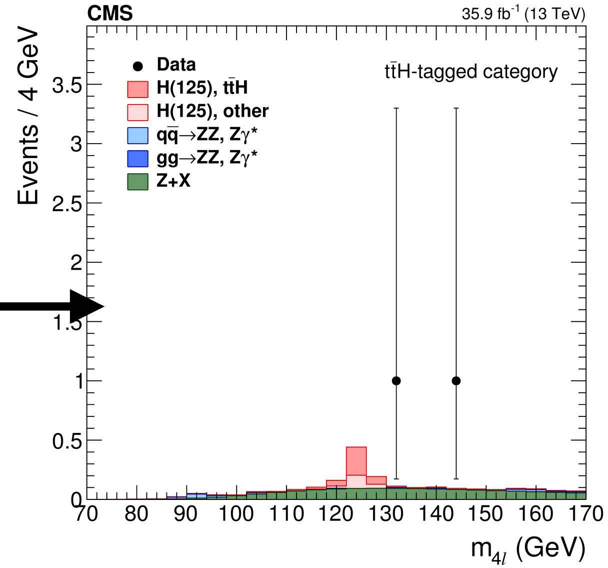
- Use isolation sums computed within a cone of 0.3, optimised for ttH busy hadronic environment

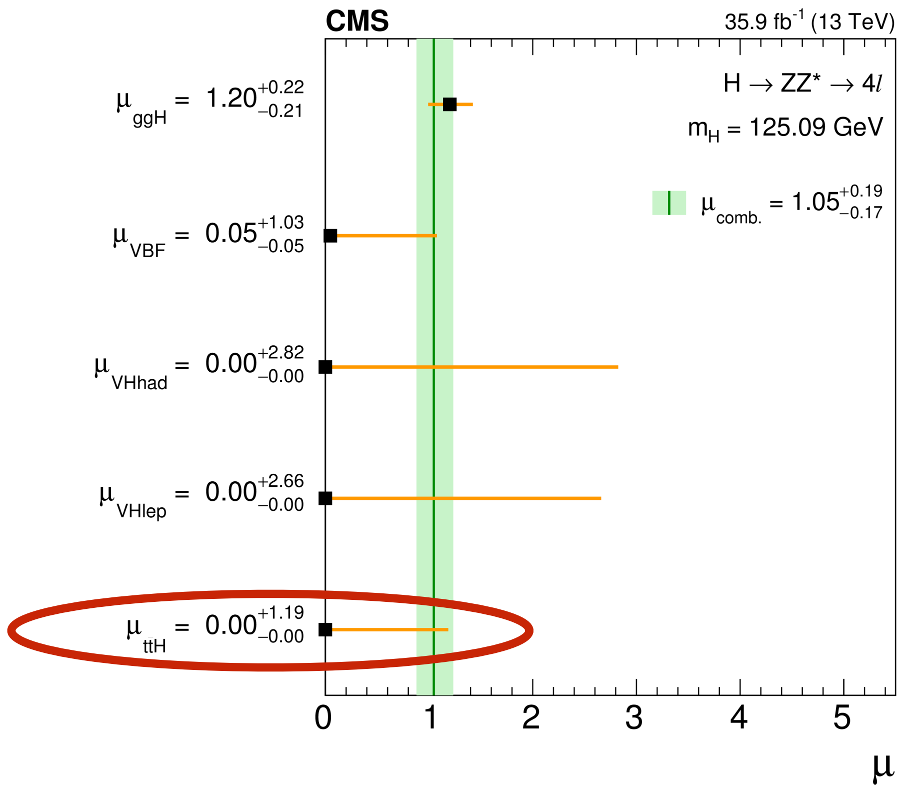
CMS $t\bar{t}H, H\to ZZ^*\to 4l$

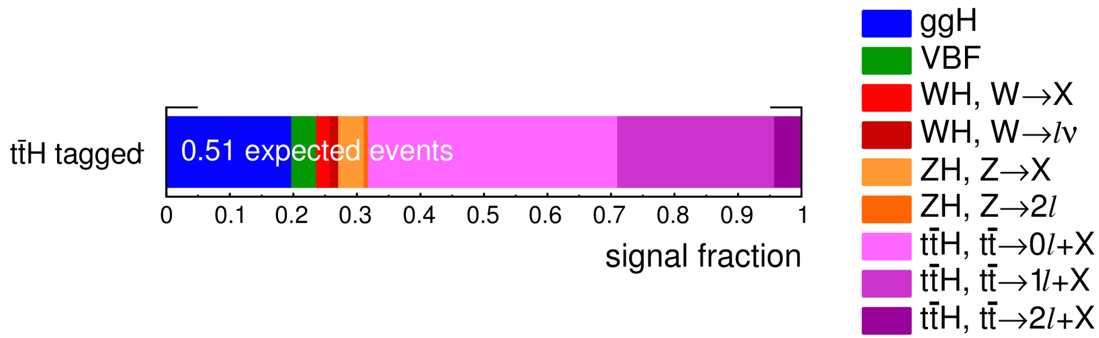
CMS HIG-16-041 (submitted to JHEP)



ttH selection







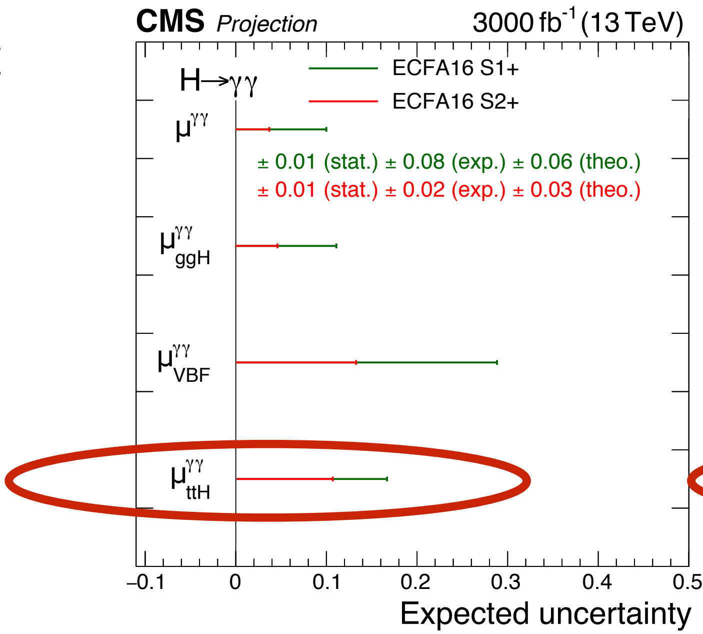
$t\bar{t}H$ projections

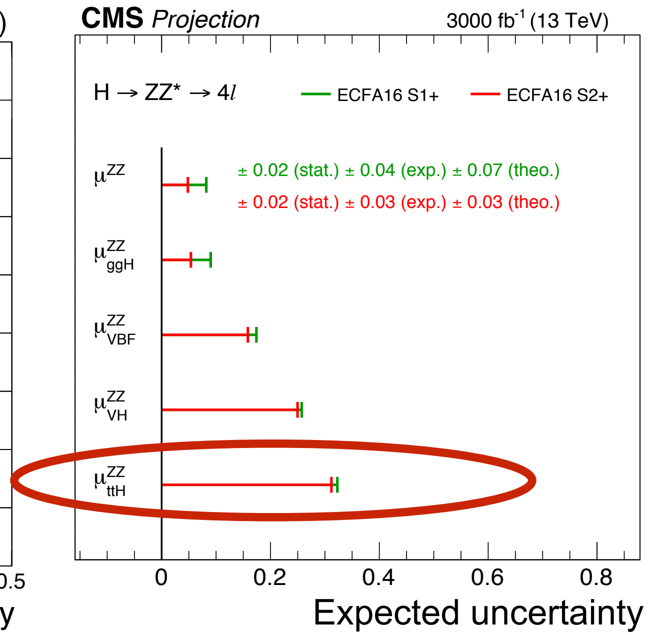
Projections at HL-LHC L=3000 fb^{-1}

CMS FTR-16-002

- Extrapolated from 13 TeV first measurements,
- Same syst (S1+), and scaled with luminosity (S2+)
- Effect of higher pile-up and detector upgrade included
- ttH,H→γγ: 0l, 1l ~ 10-17%
- ttH,H→ZZ*→4l ~ 32%

CMS expected precision on ttH signal strength (%)





ATLAS PHYS-PUB-2014-012

- Extrapolated from 8 TeV first measurements, same syst.
- ttH,H→γγ 1l,2l only
- Similar experimental sensitivity

ATLAS expected precision on ttH signal strength (%)

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$