Review of ttH searches at ATLAS and CMS

GDR Terascale, LPNHE - 25/11/2016

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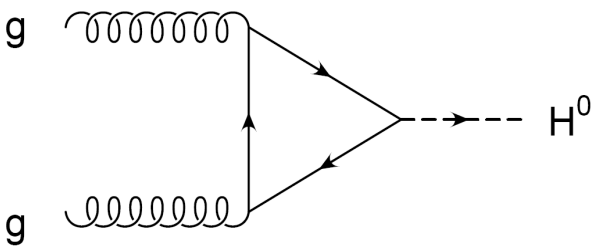
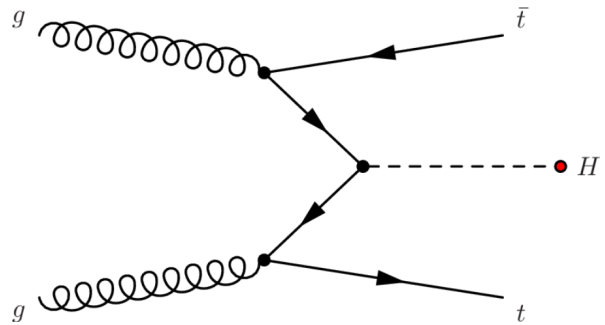
for the ATLAS and CMS Collaboration

ttH production at 13 TeV



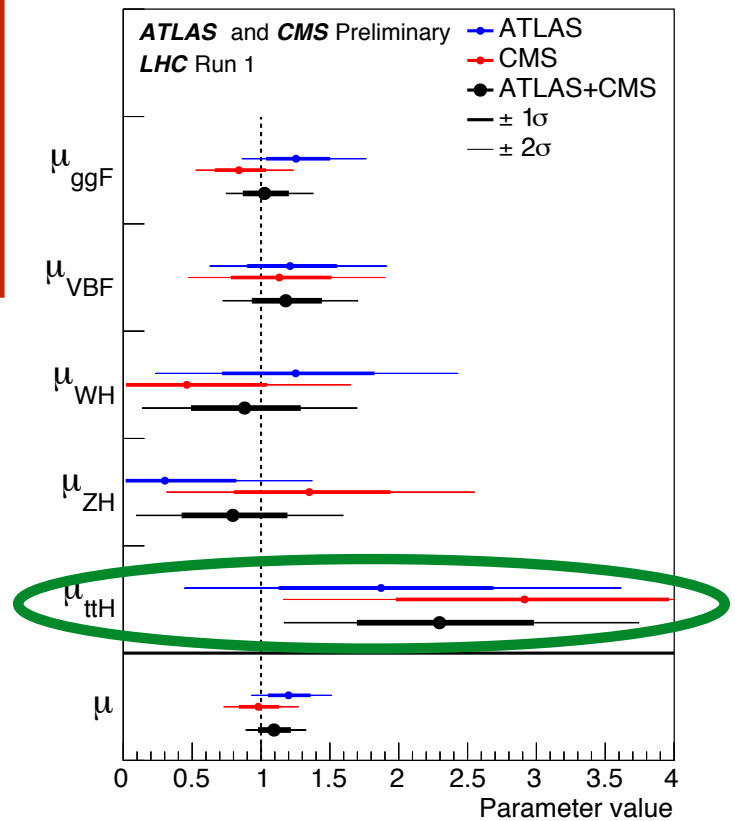
Indirect (loop level) probe of top Yukawa coupling

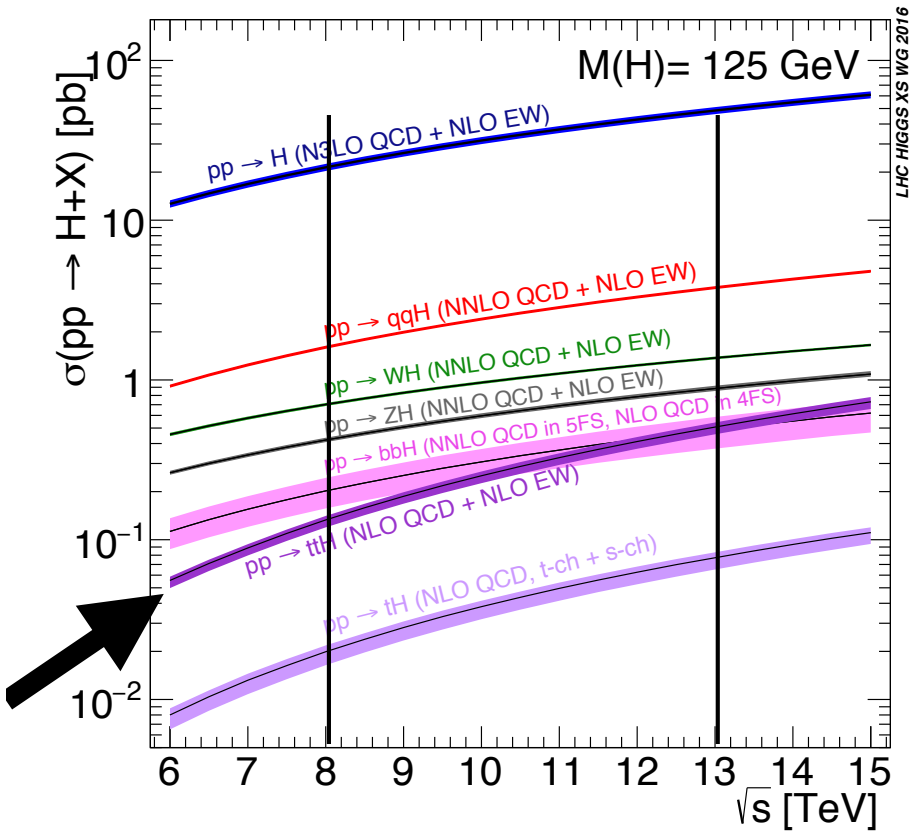


Direct (tree level) **probe of top Yukawa coupling**

Summary of Run I Higgs couplings

LHC 8 TeV: observation at **4.4σ** (2.0σ expected)





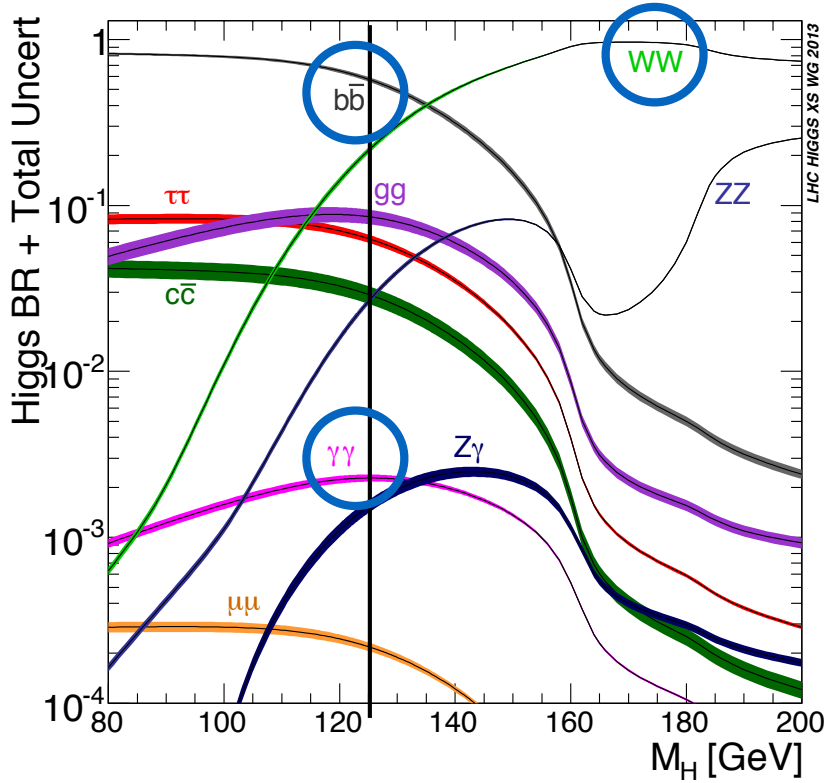
- ttH ~1% of total Higgs boson cross section
- Large **increase of ttH cross section from 8 TeV to 13 TeV: x3.8** (ttbar x3.3, ttZ x3.7, ttW x2.4)

Searches for ttH production at the LHC

ttH,H→bb: 58.1%
- High cross section x BR, but multi-jet background
- Difficult tt+bb modeling
- ATLAS : 2015 + 2016 data
- CMS : 2015, 2016 data

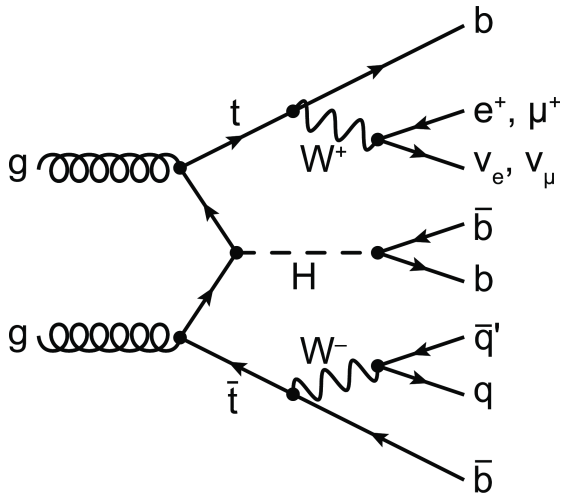
ttH,H→γγ : 0.23%
- Clean signature thanks to excellent mass resolution, but small branching ratio
- Background from mass fit in data
- ATLAS : 2015 + 2016 data
- CMS : 2015, 2016 data

ttH multilepton : H→WW (21.5%)**, H→ZZ** (2.6%) **and H→ ττ** (6.3%)
- H→WW, H→ZZ semi-leptonic and leptonic decays
- Lower rate than H→bb, but low background final state (better handle on irreducible backgrounds)
- ATLAS : 2015 + 2016 data
- CMS : 2015 + 2016 data



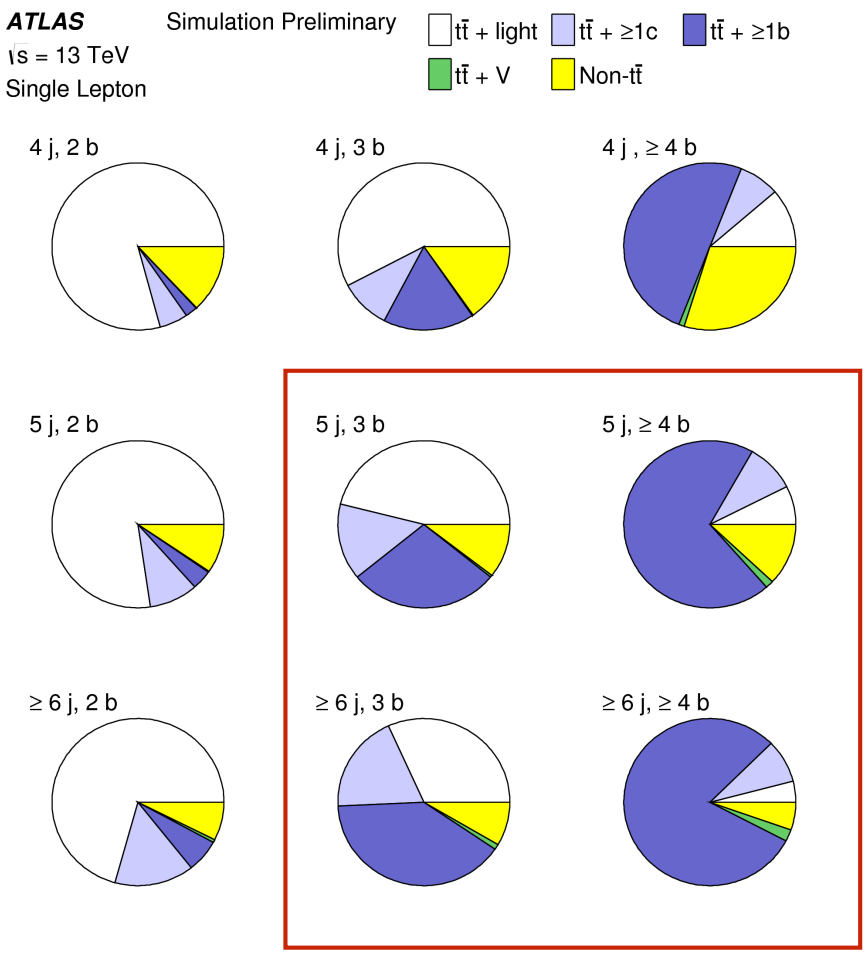
ATLAS ttH,H→bb

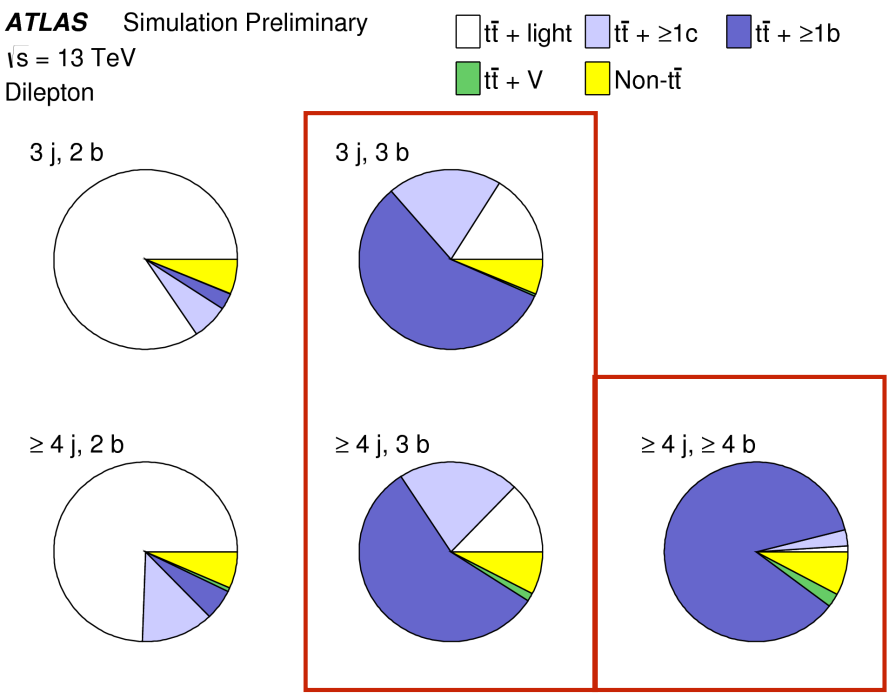
ATLAS-CONF-2016-080



Selection targeting lepton+jets and dileptons

- **l+jets:** =1 lepton, ≥5 jets, ≥3 b-tag
- **2l:** 2 opposite sign lepton, ≥3 jets, ≥3 b-tag
- Mass resolution ~10%, jet combinatorics: use **multivariate methods** in jet/b-jet categories





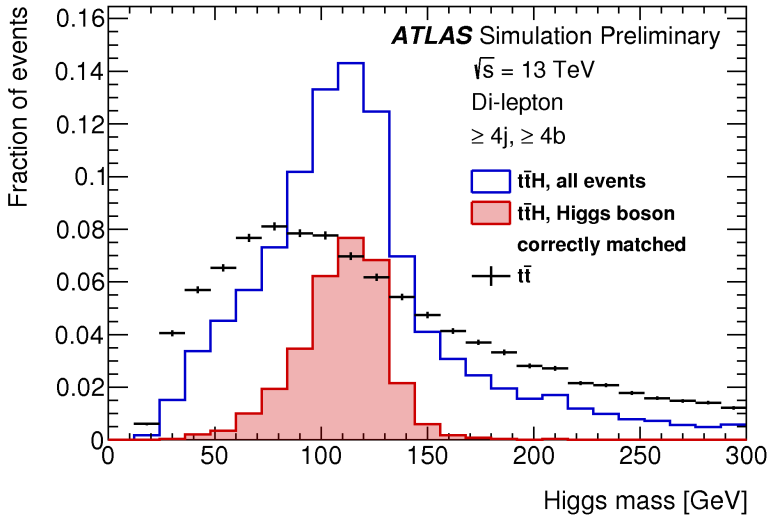
- **ttbar + ≥1b**: major background in signal regions
- **HT** HT distribution used as a discriminant in the background control regions

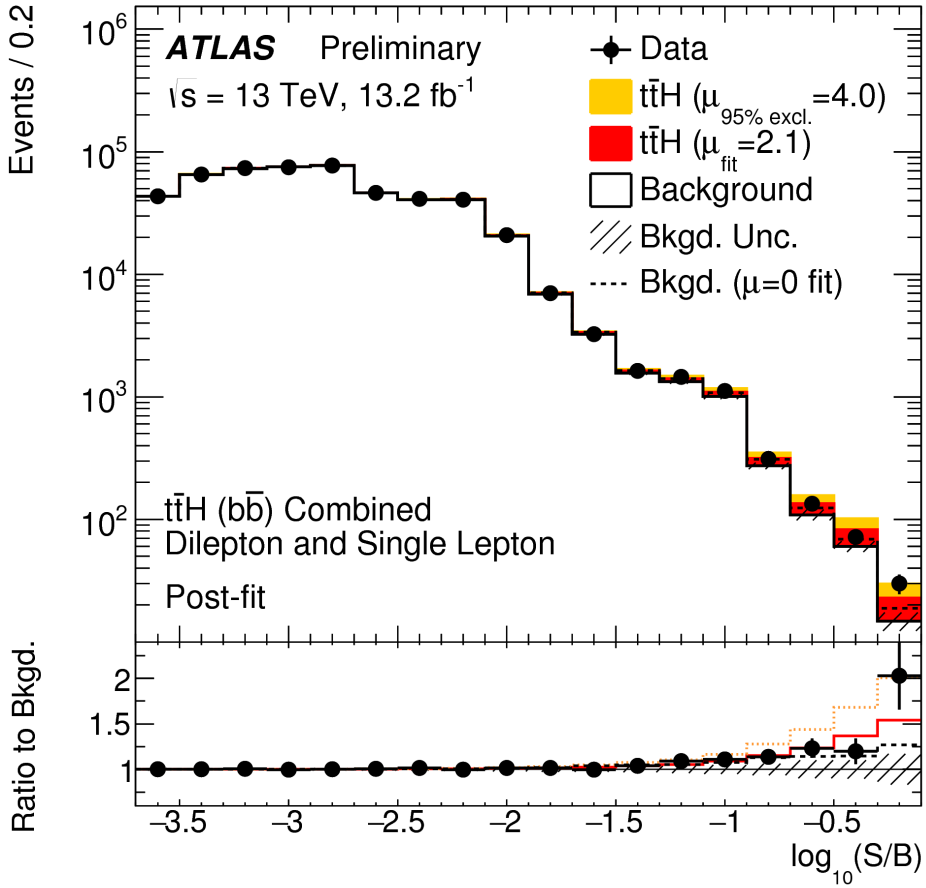
ATLAS ttH,H→bb

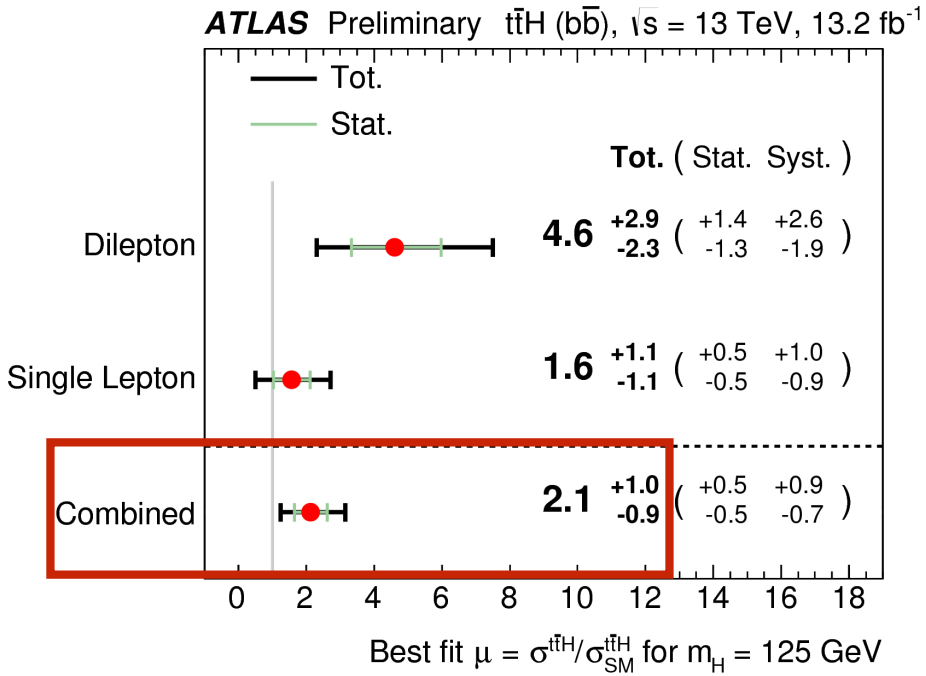
ATLAS-CONF-2016-080

Analysis strategy: two-step multivariate technique

- **Reconstruction BDT :** Match reconstructed jets to Higgs and top quark jets
- **NN/BDT output :** includes previous BDT + kinematic variables, in signal region only
- All regions included in final likelihood fit
- tt+≥1b, tt+≥1c normalisations: free param. in the fit





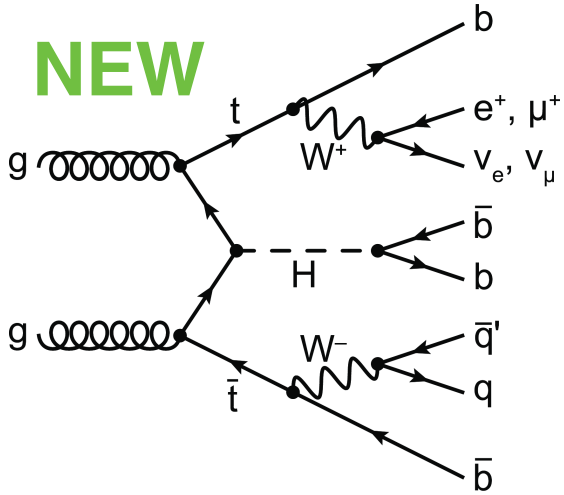


Theory uncertainties on ttbar + ≥1b is Δμ~0.5, already dominates the measurement

CMS ttH,H→bb

CMS HIG-16-038

NEW

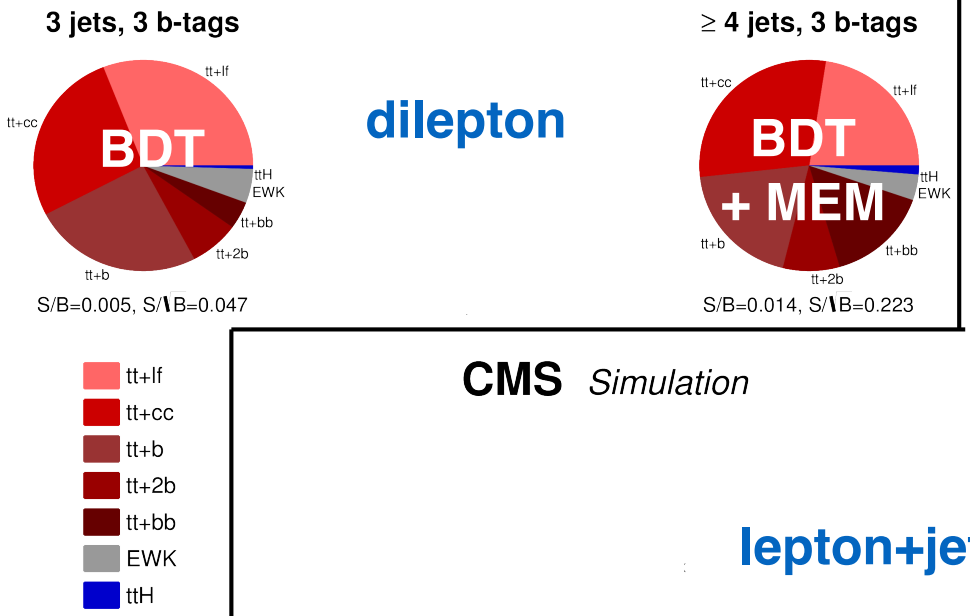


Analysis targeting lepton+jets and dileptons

- **l+jets:** =1 lepton, ≥4 jets, ≥3 b-tag
- **2l:** 2 opposite sign lepton, ≥3 jets, ≥3 b-tag

CMS *Simulation*

dilepton



Change relative to Moriond 2016 (2.3 fb-1):

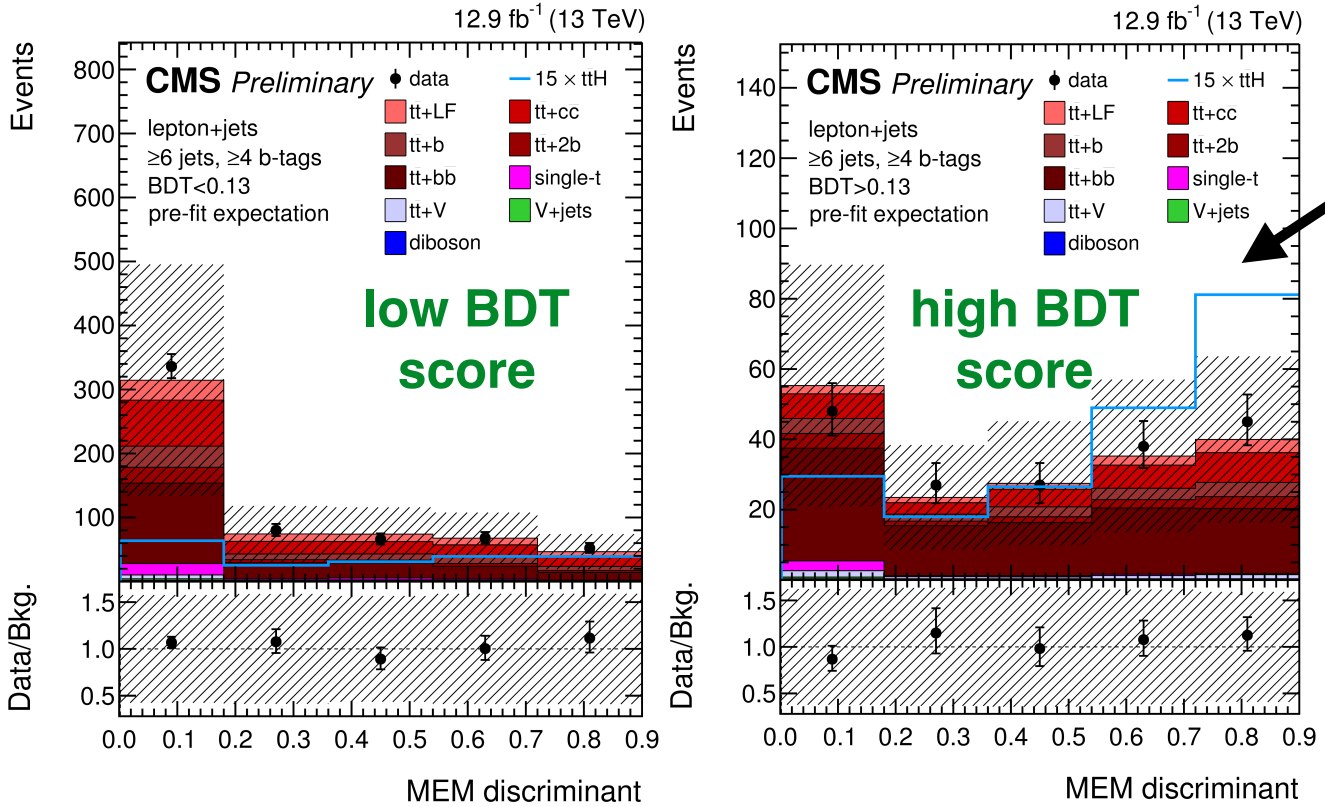
- Remove low significance categories
- Use **Matrix Element Method** (MEM) as final discriminant in **low/high BDT** score categories

CMS *Simulation*

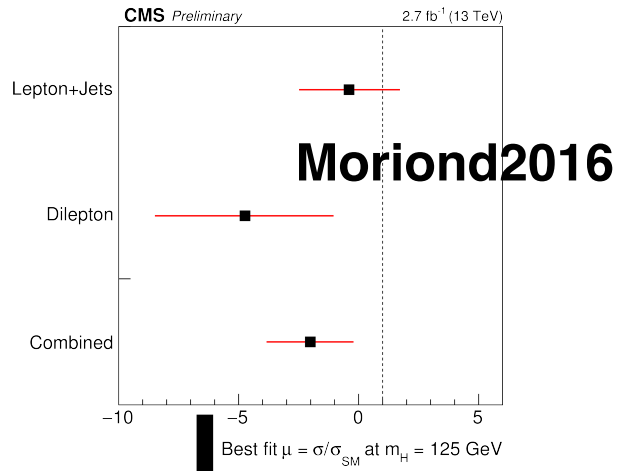
lepton+jets

CMS ttH,H→bb NEW

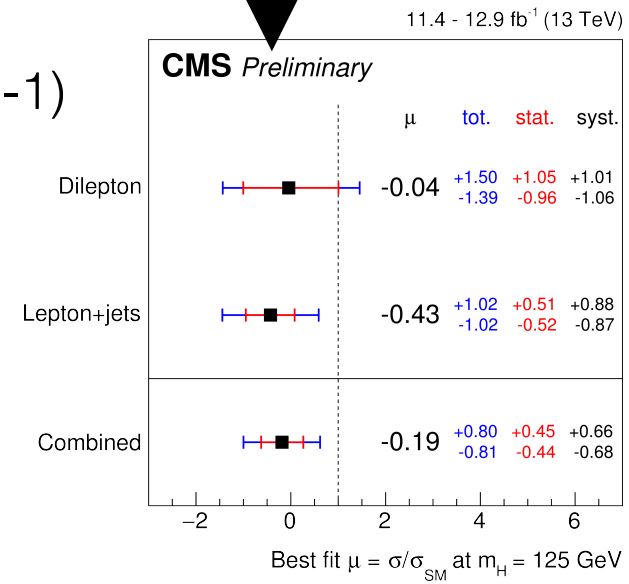
CMS HIG-16-038



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



This analysis:

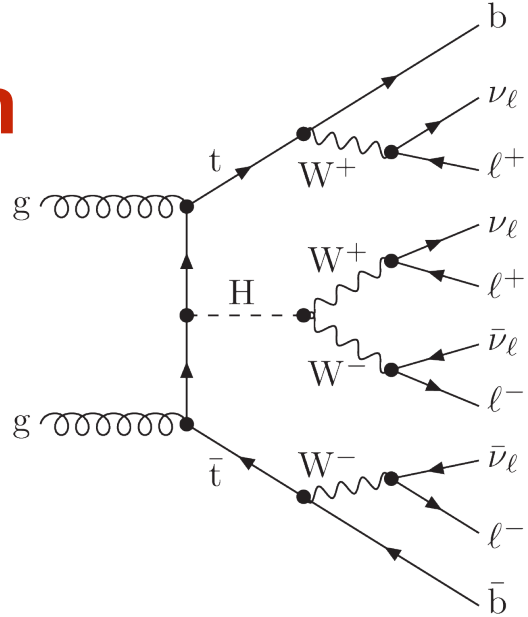


- **Expected limit** : 3.6 x SM (3.2 fb-1) => **1.7 x SM** (12.9 fb-1)
- Systematics dominated (50% on tt+HF)

Channel	Observed UL	Expected UL	Best-fit μ
Dilepton	3.2	$3.4^{+1.5}_{-1.0}$	$-0.04^{+1.50}_{-1.39}(\text{tot.})\ ^{+1.05}_{-0.96}(\text{stat.})\ ^{+1.01}_{-1.06}(\text{syst.})$
Lepton+jets	1.8	$2.1^{+1.0}_{-0.6}$	$-0.43^{+1.02}_{-1.02}(\text{tot.})\ ^{+0.51}_{-0.52}(\text{stat.})\ ^{+0.88}_{-0.87}(\text{syst.})$
Combined	1.5	$1.7^{+0.7}_{-0.5}$	$-0.19^{+0.80}_{-0.81}(\text{tot.})\ ^{+0.45}_{-0.44}(\text{stat.})\ ^{+0.66}_{-0.68}(\text{syst.})$

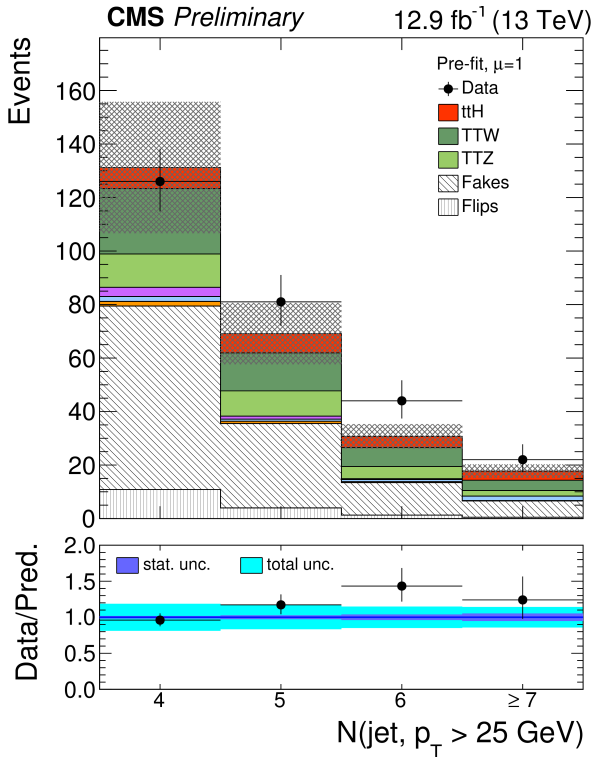
CMS ttH multilepton

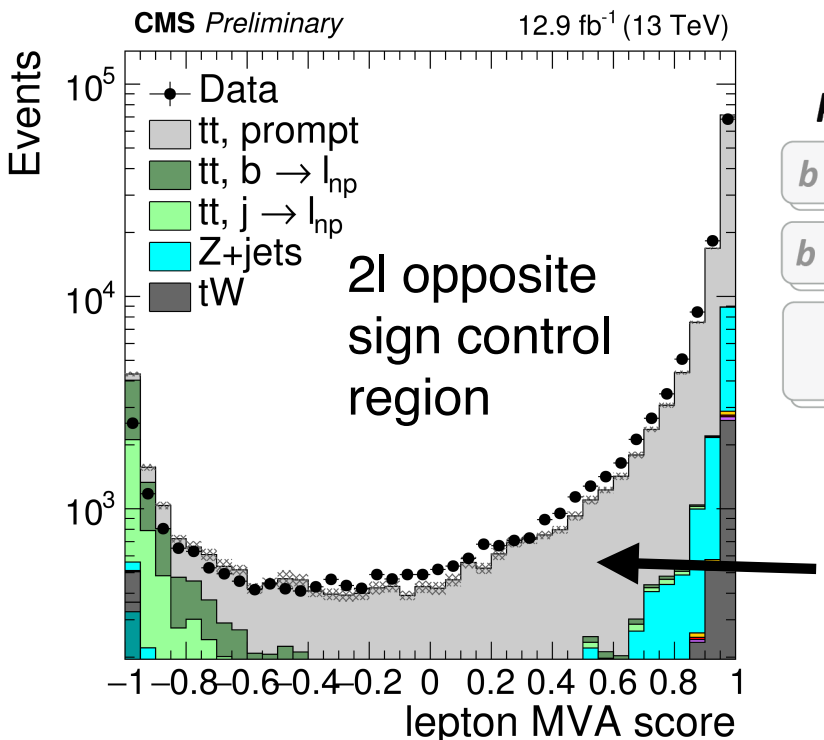
CMS HIG-16-022



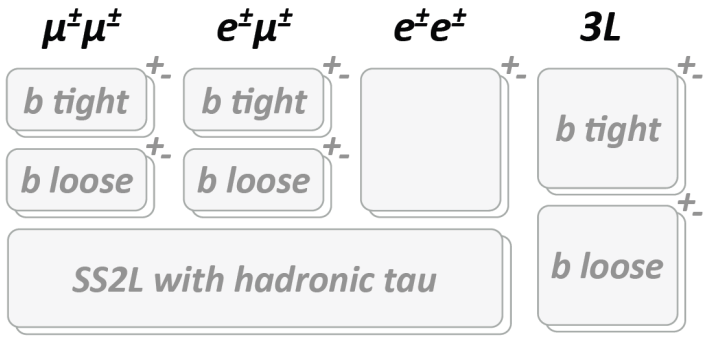
Targeting 2 lepton same-sign (2lss) and ≥3 leptons (3l)

- **2 same sign leptons:** ≥4 jets, ≥1 b-tag
- **3 leptons:** ≥2 jets, ≥1 b-tag
- **Backrounds:** tt+W/Z, tt+jets (same-sign required to reduce Drell-Yan and ttZ)
- **Background normalisation** from control region: loosened identification (**fakes**), Z→ll (mis-charge = "**flips**", 2lss only)





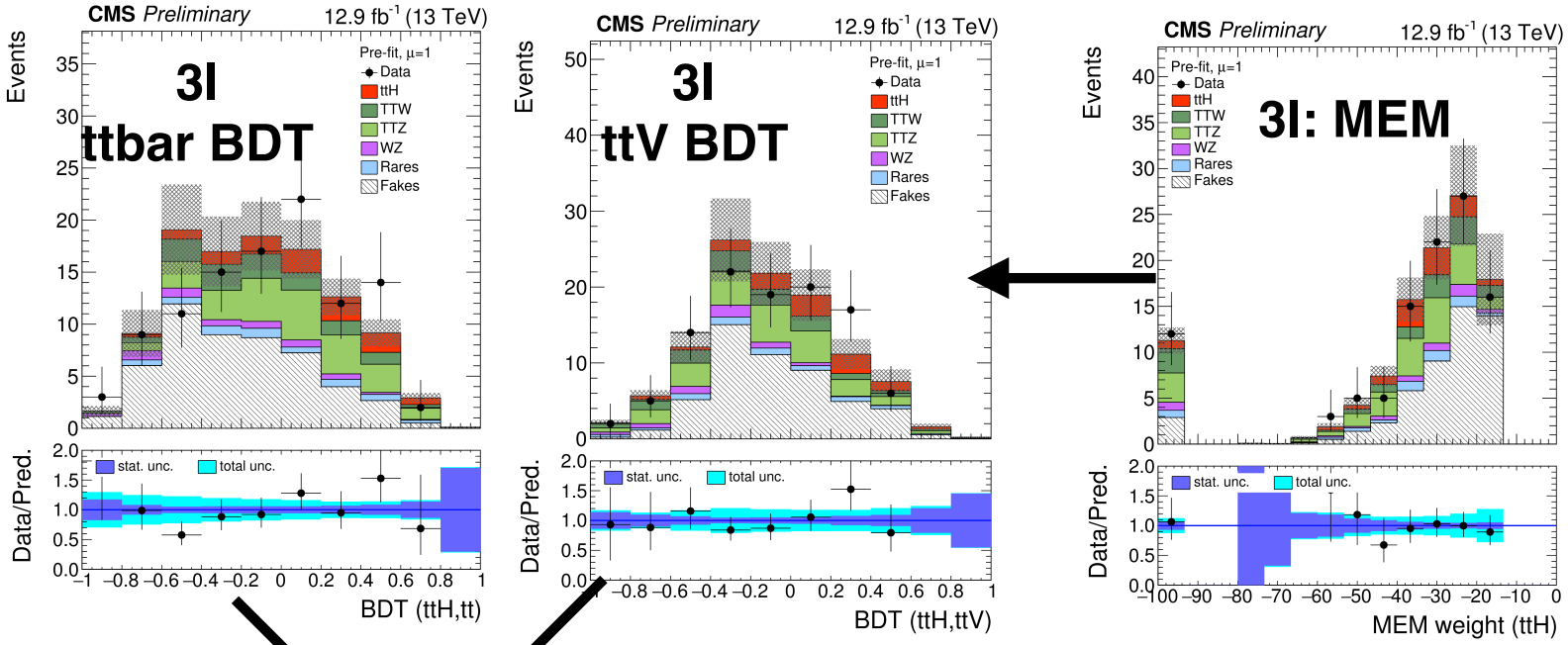
Analysis categories:

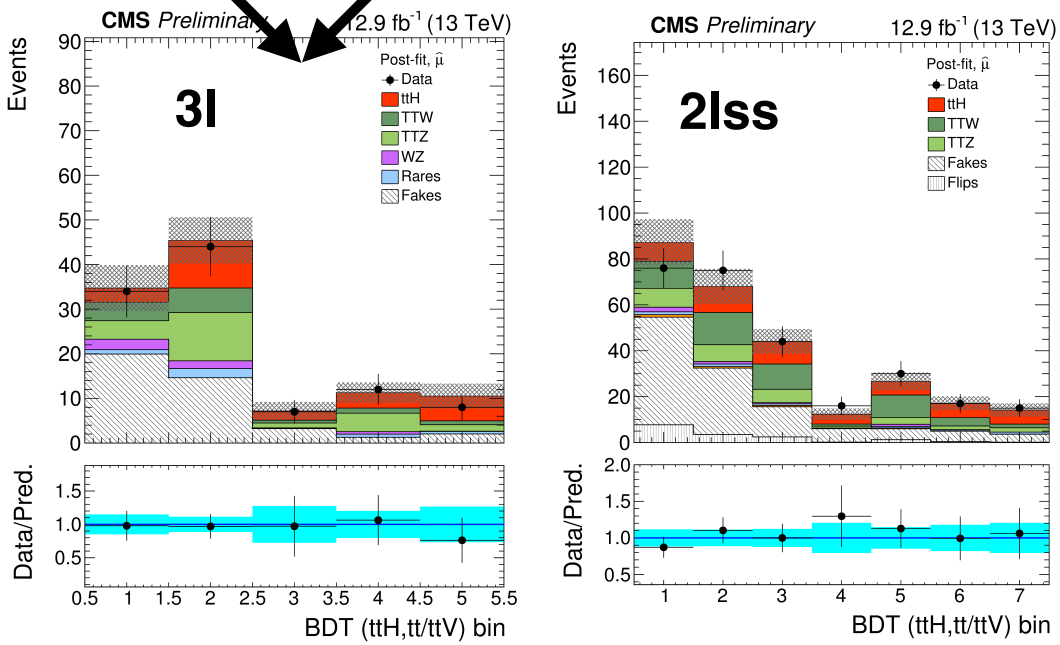


- **Lepton identification** with BDT using shape, isolation and overlapping jet information

CMS ttH multilepton

CMS HIG-16-022



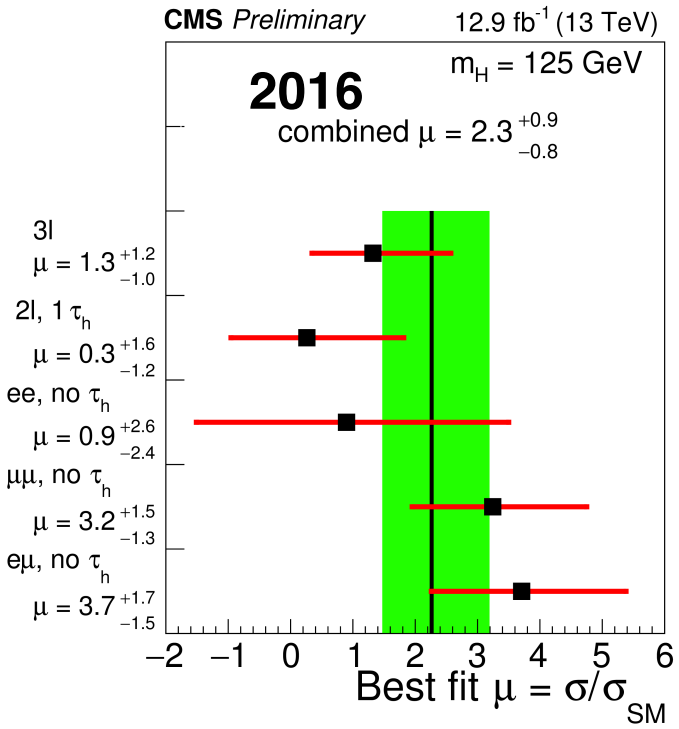


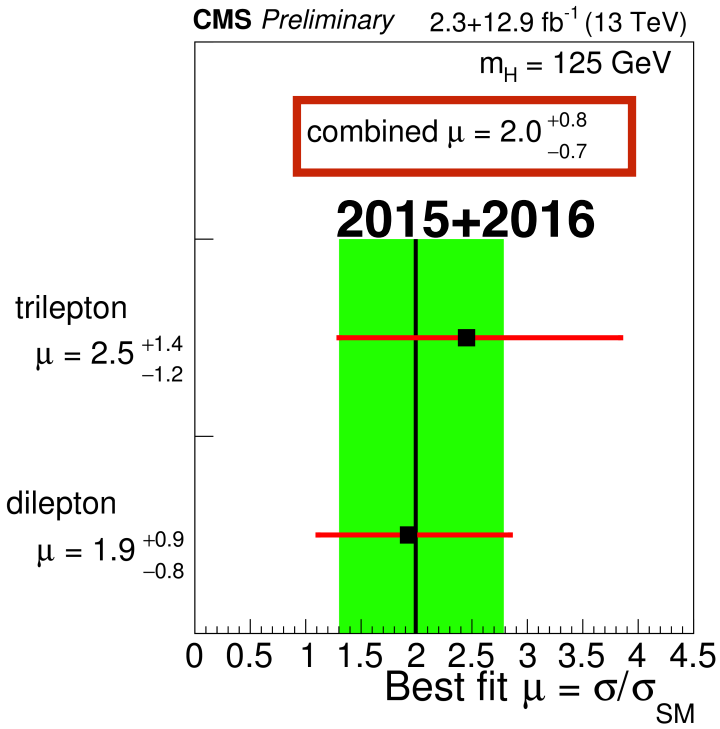
Analysis sensitivity:

- 2lss and 3l categories: Train **2 BDTs, against ttbar and ttW/Z**
- Unroll 2D distributions
- **3l category** : include log of **MEM** weights for ttH, ttW and ttZ as ttV BDT input

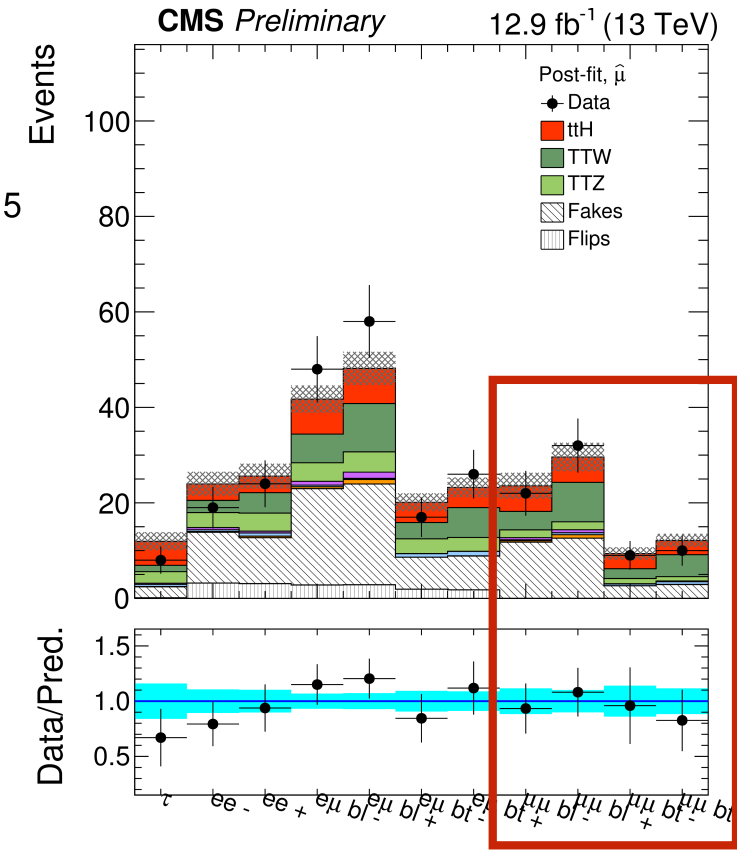
CMS ttH multilepton

CMS HIG-16-022





- Post-fit distribution of yields per categories shows no excess in dimuon



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

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit μ $\pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

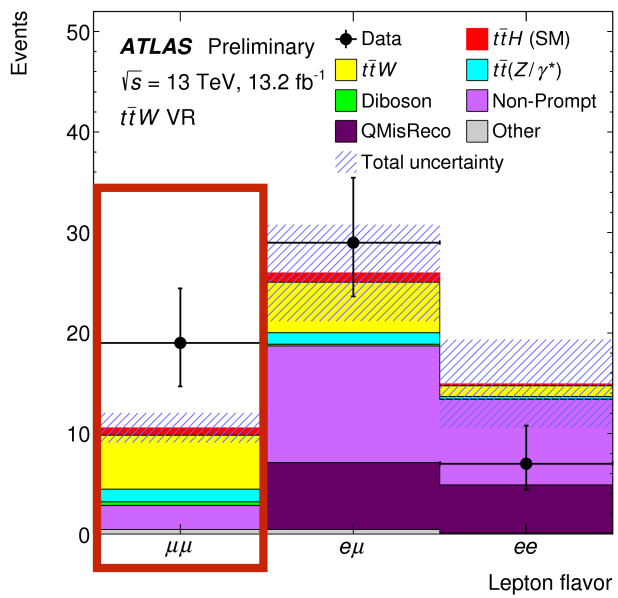
ATLAS ttH multilepton

ATLAS-CONF-2016-058

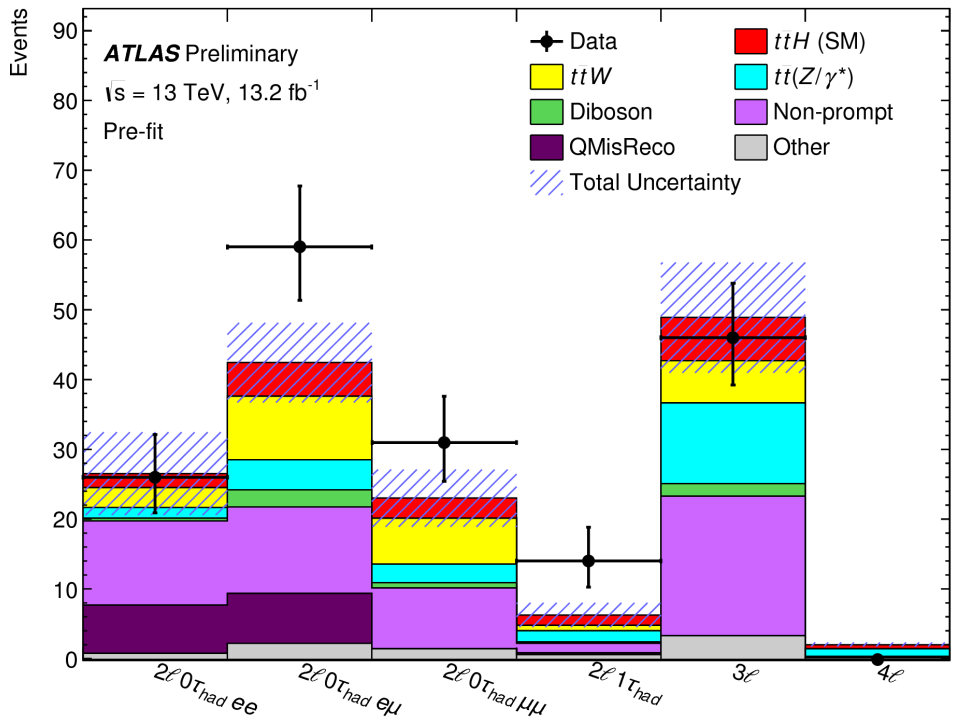
ATLAS analysis: 4 channels

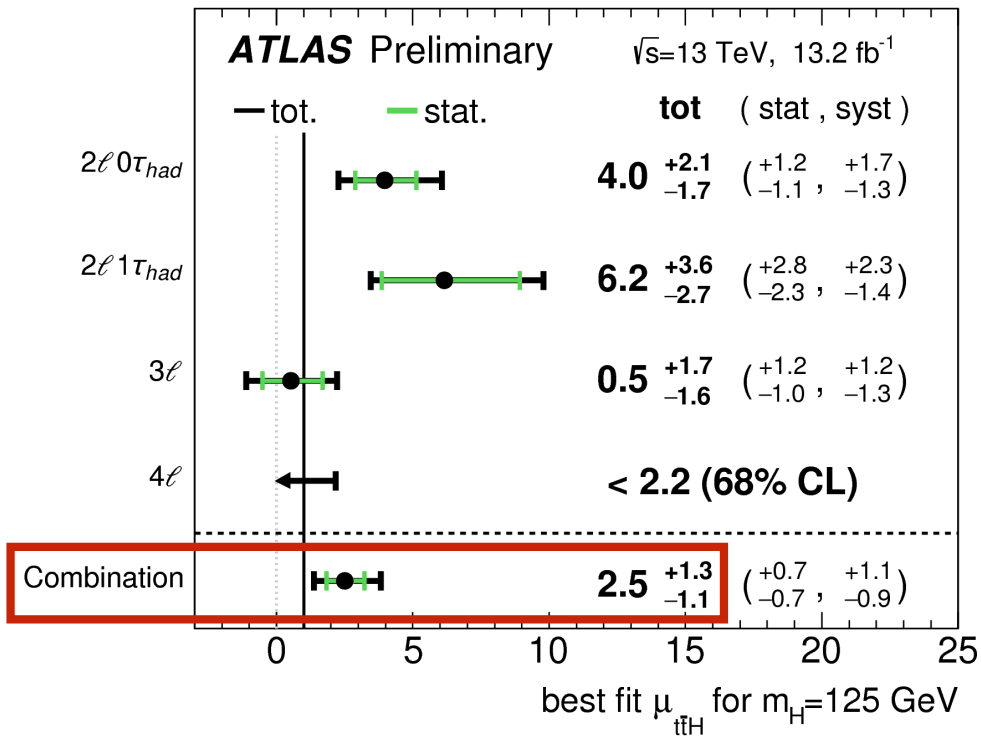
- **2l same sign (ee, eμ, μμ), no τ had:** ≥5 jets, ≥1 b-tag
- **2l same sign, 1 τ had :** ≥4 jets, ≥1 b-tag
- **3l:** ≥4 jets, ≥1 b-tag ; or ≥3 jets, ≥2 b-tag
- **4l:** ≥2 jets, ≥1 b-tag

- Similar method to CMS for background measurement
- Fake τ from simulation, normalised to control region
- Main systematic uncertainties : Fakes and flips Δμ~0.6



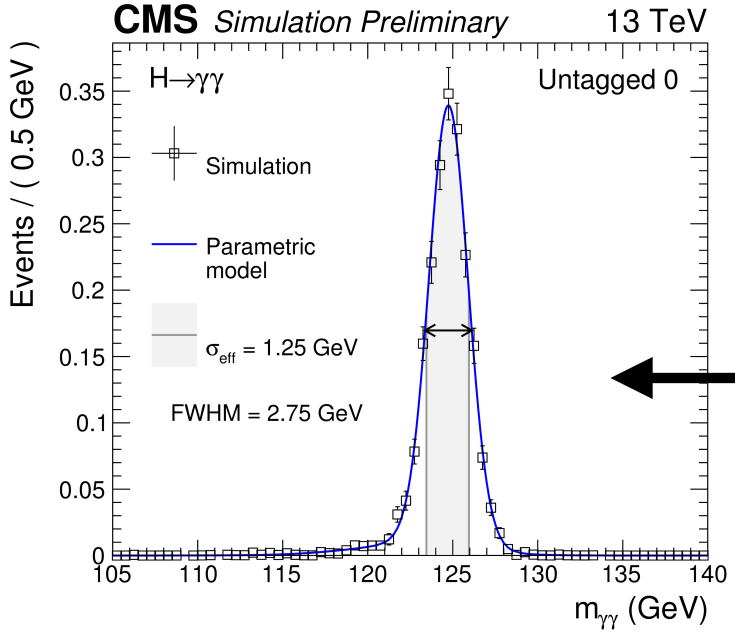
Cut and count analysis in 6 categories



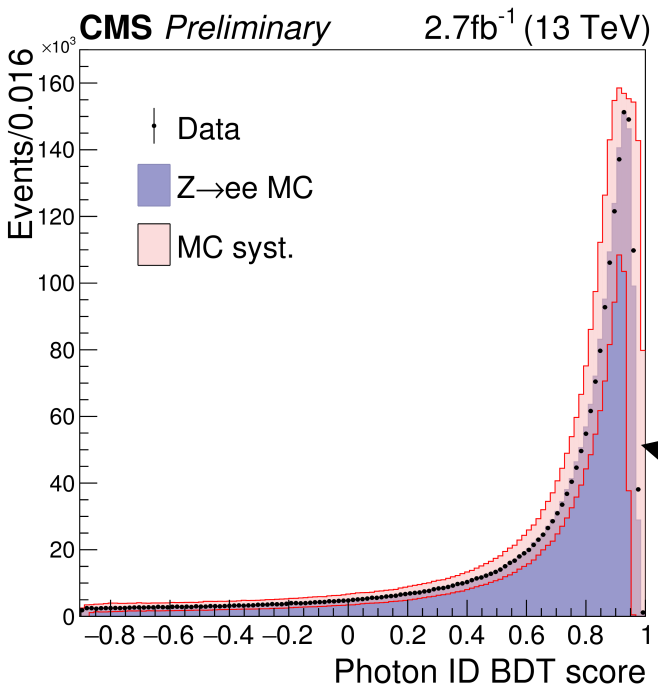


ATLAS, CMS H→γγ analysis

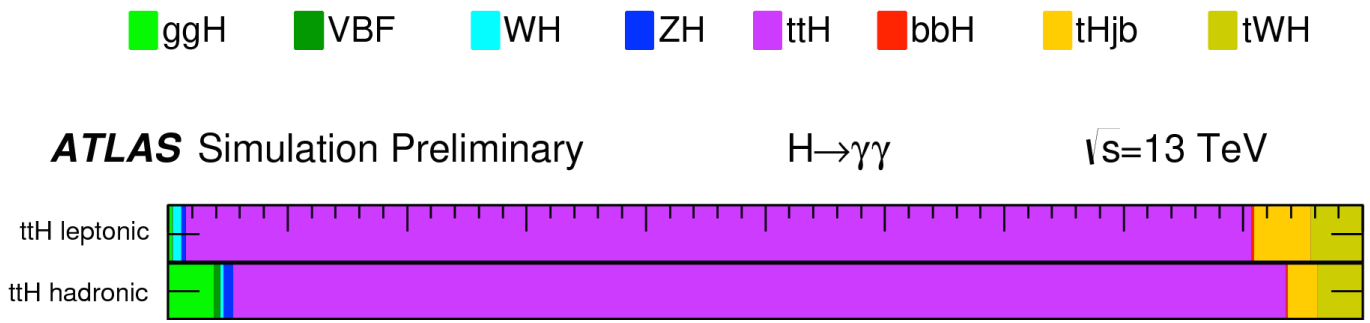
ATLAS-CONF-2016-067, CMS HIG-16-020



- Look for **small signal peak (BR~0.2%) over large background**
- **Photon energy resolution** ~1% depending on categories: calibration is crucial



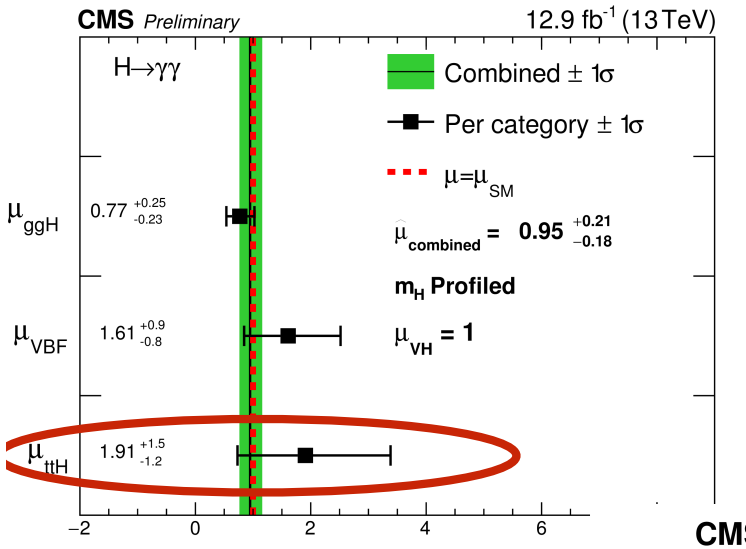
Very **pure ttH categories**



- **Photon identification:** reject jets faking photons with shower shape and isolation: BDT (CMS), cut-based (ATLAS)

CMS ttH,H→γγ

CMS HIG-16-020



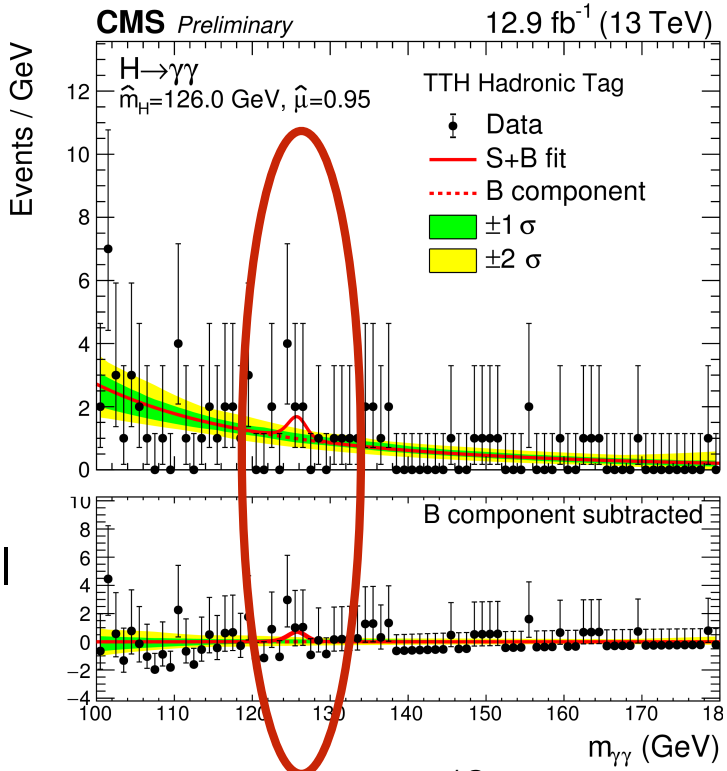
2 ttH categories: hadronic and leptonic

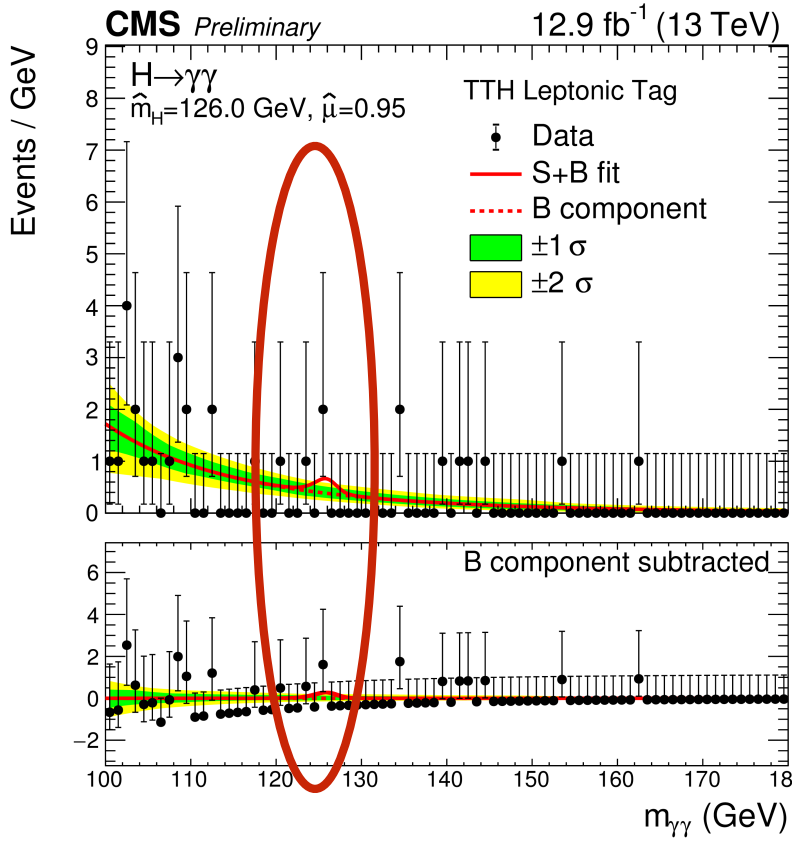
- Tighten photon pT/m requirement relative to inclusive categories (targeting ggh production)
- Control region with inverted photonId is used to predict expected background for optimisation

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

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

- **ttH** hadronic/leptonic combined: **$\mu=1.9^{+1.5}_{-1.2}$** measured simultaneously with other production mechanisms
- Measurement is dominated by statistical uncertainties



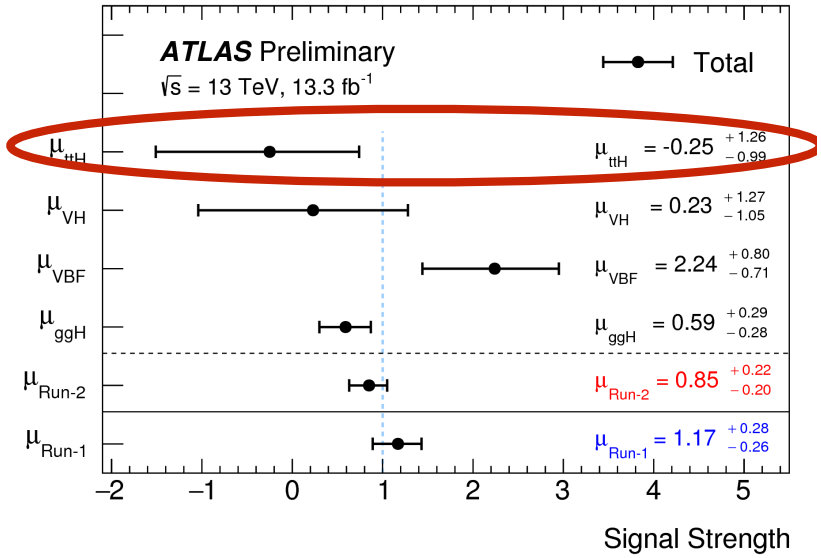


ATLAS ttH,H→γγ

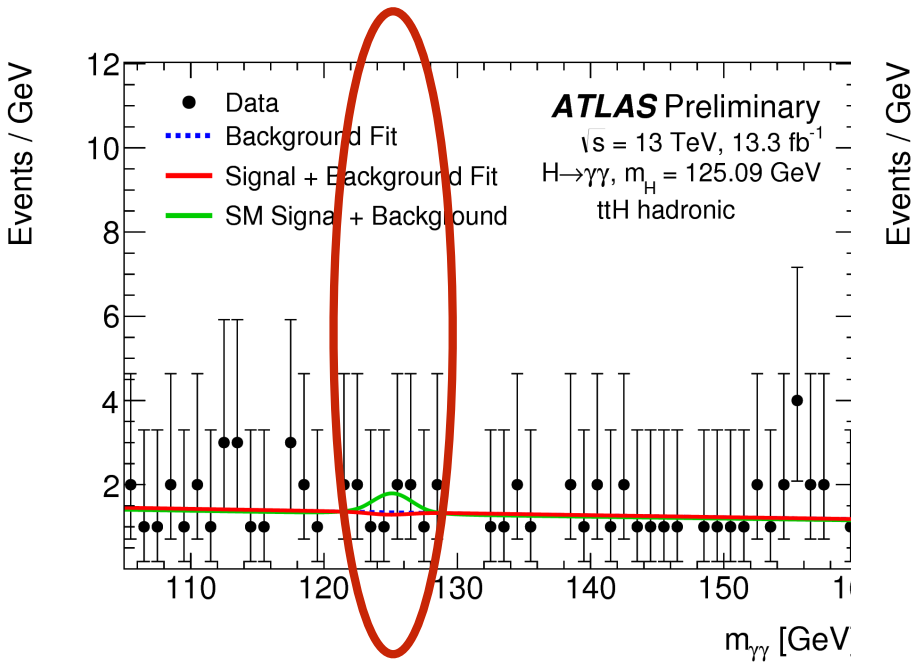
ATLAS-CONF-2016-067

2 ttH categories: hadronic and leptonic

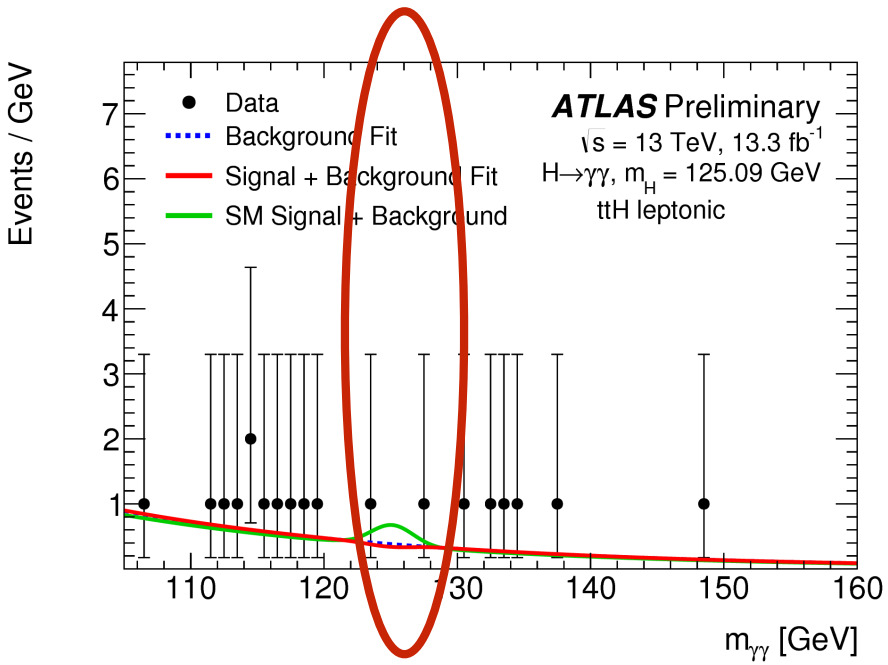
- Control region with inverted photonId
  - **ttH** hadronic/leptonic combined: **μ=-0.25$^{+1.26}_{-0.99}$** measured simultaneously with other production mechanisms (ratio WH/ZH assumed as SM)
  - Measurement is dominated by statistical uncertainties



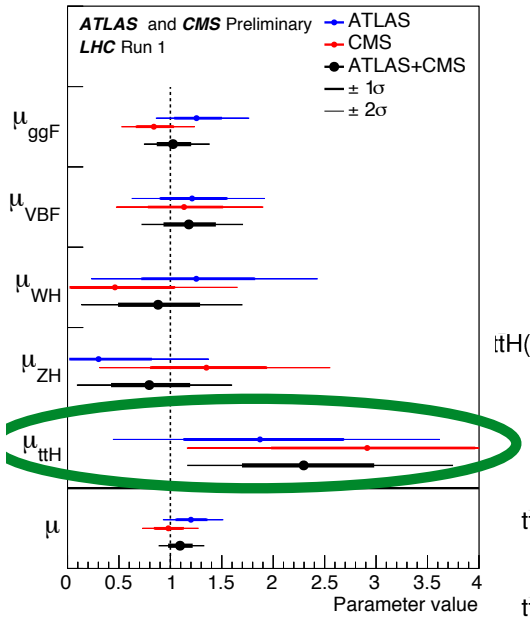
ttH hadronic tag: 0 lepton, ≥5 jets, ≥1 b-tag



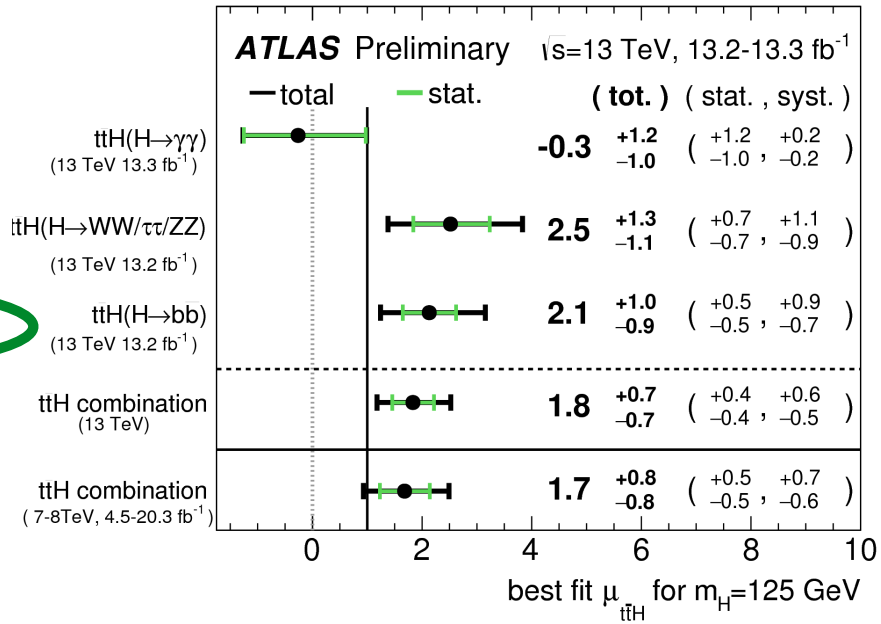
ttH leptonic tag: ≥1 lepton, ≥2 jets, ≥1 b-tag



ttH summary and projections



Run I: $\mu=2.3^{+0.7}_{-0.6}$



CMS

- ttH, **H→bb** (2016): **$\mu=-0.19^{+0.8}_{-0.8}$**

- ttH **multilepton** (2015+2016): **$\mu=2.0^{+0.8}_{-0.7}$**

- ttH, **H→γγ** (2016): **$\mu=1.9^{+1.5}_{-1.2}$**

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

CMS-NOTE-13-002

- Extrapolated from 8 TeV first measurements, same syst.
- **$\Delta\kappa_t/\kappa_t$:** from H→γγ and H→bb: **10%** (7% if half theory uncert.)

CMS expected precision on top - Higgs coupling (%)

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

ATLAS PHYS-PUB-2014-012

- ttH,H→γγ 1l,2l only, same extrapolation
- Similar experimental sensitivity

ATLAS expected precision on ttH signal strength (%)

$\Delta\mu/\mu \propto 2\Delta\kappa_t/\kappa_t$

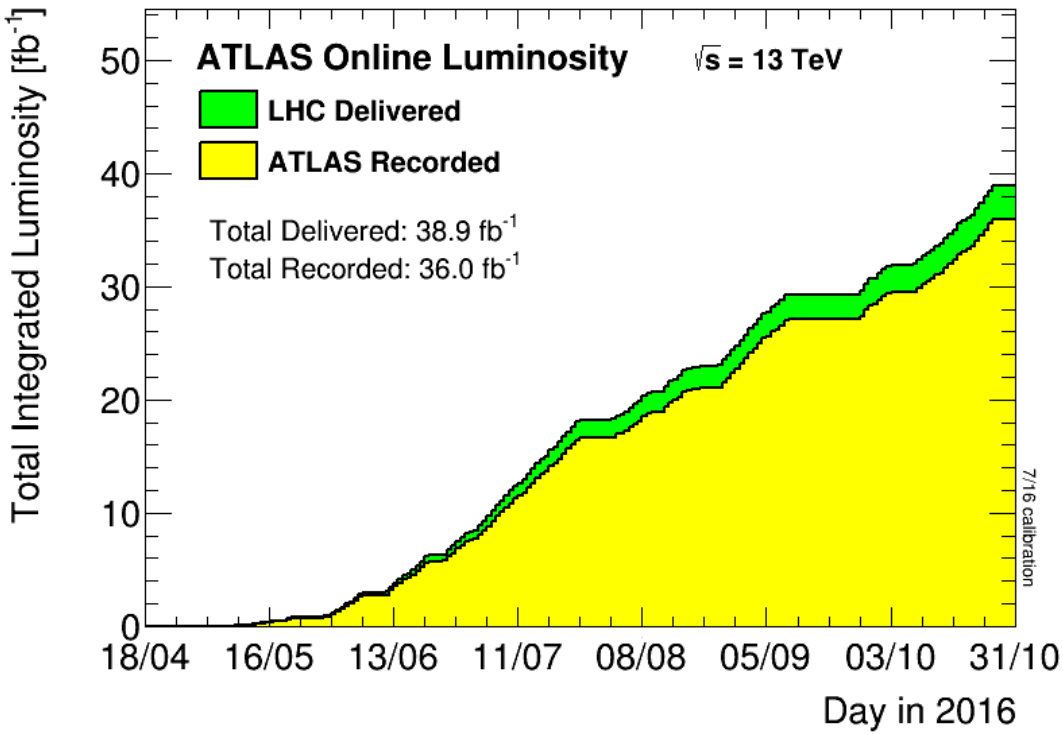
Production mode	$\Delta\hat{\mu}/\hat{\mu}$ (%) Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$

Conclusions

ttH production

- Results are consistent with Run I
- Sensitivity is already comparable or slightly better than Run I
- Able to reach ~40% precision on ttH signal strength with ATLAS and CMS 2015+2016 data,
- More data is needed to evaluate if the Run I "μ~2 excess" (though compatible with SM) is not a fluctuation.

We analyzed ~13 fb-1 : still ~23 fb-1 of 2016 data to be analyzed



Back-up slides

CMS ttH,H→bb

CMS HIG-16-038

Category	Observed	Expected
4 jets, 4 b-tags (low BDT)	46.9	$53.0^{+26.0}_{-17.0}$
4 jets, 4 b-tags (high BDT)	12.8	$13.9^{+6.6}_{-4.1}$
5 jets, $\geq$ 4 b-tags (low BDT)	20.0	$17.2^{+8.3}_{-5.3}$
5 jets, $\geq$ 4 b-tags (high BDT)	6.0	$6.1^{+3.0}_{-1.8}$
$\geq$ 6 jets, 3 b-tags (low BDT)	12.1	$18.1^{+8.0}_{-5.2}$
$\geq$ 6 jets, 3 b-tags (high BDT)	5.8	$7.7^{+3.5}_{-2.3}$
$\geq$ 6 jets, $\geq$ 4 b-tags (low BDT)	9.6	$9.4^{+4.5}_{-2.9}$
$\geq$ 6 jets, $\geq$ 4 b-tags (high BDT)	6.1	$4.3^{+2.1}_{-1.3}$
lepton+jets combined	1.8	$2.1^{+1.0}_{-0.6}$

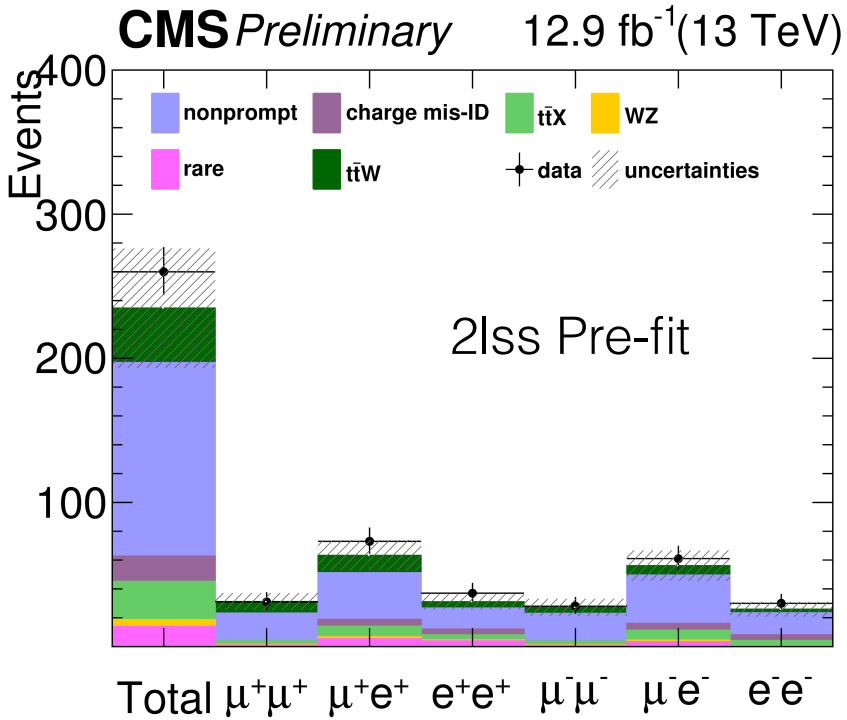
Most sensitive channel : 6 jets, 3 b

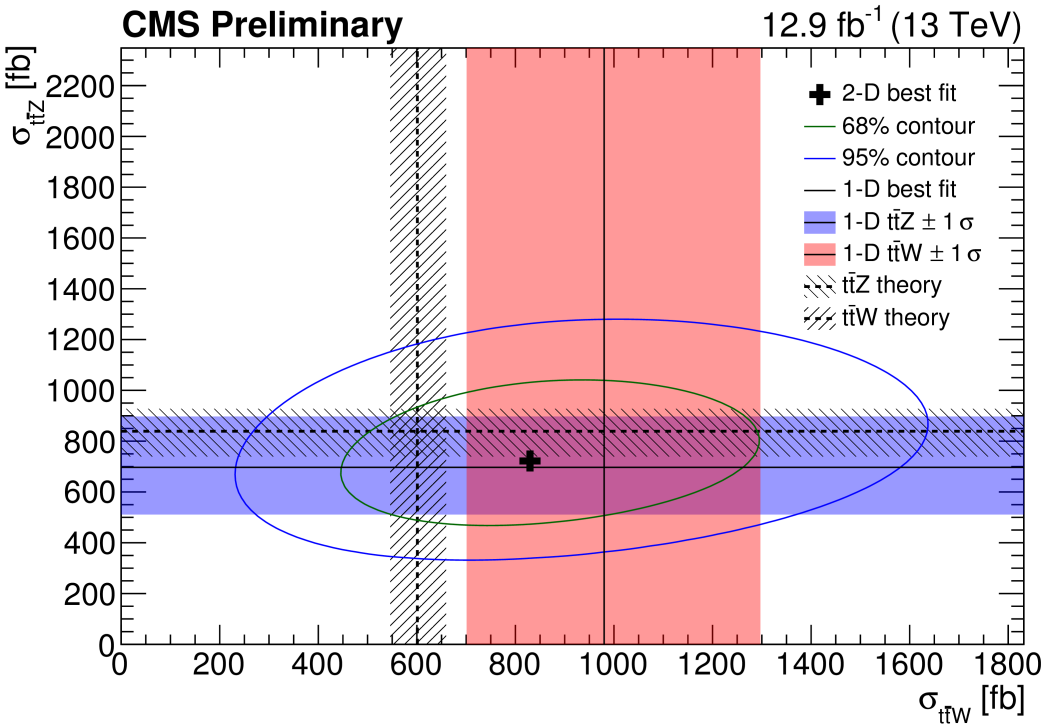
Process	$t\bar{t}$ rate up/down [%]	$t\bar{t}H$ rate up/down [%]
Jet energy scale	$+12.6/-11.8$	$+8.4/-8.0$
Jet energy resolution	$+0.2/-0.3$	$-0.0/-0.1$
Pile-up	$+0.1/-0.1$	$-0.2/+0.1$
Electron efficiency	$+0.5/-0.5$	$+0.5/-0.5$
Muon efficiency	$+0.4/-0.4$	$+0.4/-0.4$
Electron trigger efficiency	$+1.2/-1.2$	$+1.3/-1.3$
Muon trigger efficiency	$+0.8/-0.8$	$+0.9/-0.9$
b-Tag HF contamination	$-9.4/+9.8$	$-2.6/+2.8$
b-Tag HF stats (linear)	$-3.1/+3.3$	$-2.5/+2.7$
b-Tag HF stats (quadratic)	$+2.6/-2.4$	$+2.4/-2.2$
b-Tag LF contamination	$+7.1/-5.2$	$+5.8/-4.5$
b-Tag LF stats (linear)	$-2.0/+4.4$	$+0.5/+1.5$
b-Tag LF stats (quadratic)	$+2.1/+0.2$	$+1.5/+0.5$
b-Tag charm Uncertainty (linear)	$-11.1/+14.9$	$-3.1/+4.1$
b-Tag charm Uncertainty (quadratic)	$+0.5/-0.5$	$-0.0/+0.0$
Q^2 scale ($t\bar{t}$+LF)	$-6.2/+7.5$	–
Q^2 scale ($t\bar{t}$+b)	$-1.7/+2.0$	–
Q^2 scale ($t\bar{t}$+2b)	$-1.1/+1.4$	–
Q^2 scale ($t\bar{t}$+$b\bar{b}$)	$-2.0/+2.5$	–
Q^2 scale ($t\bar{t}$+$c\bar{c}$)	$-4.3/+5.4$	–
PS scale ($t\bar{t}$+LF)	$+4.8/-9.0$	–
PS scale ($t\bar{t}$+b)	$-0.9/+0.7$	–
PS scale ($t\bar{t}$+2b)	$-0.8/+0.9$	–
PS scale ($t\bar{t}$+$b\bar{b}$)	$-1.5/+2.7$	–
PS scale ($t\bar{t}$+$c\bar{c}$)	$-3.9/+3.0$	–

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)