Associated production of top quarks with the Higgs boson

Precision2016, Quy Nhon (Viet Nam) - 29/09/2016

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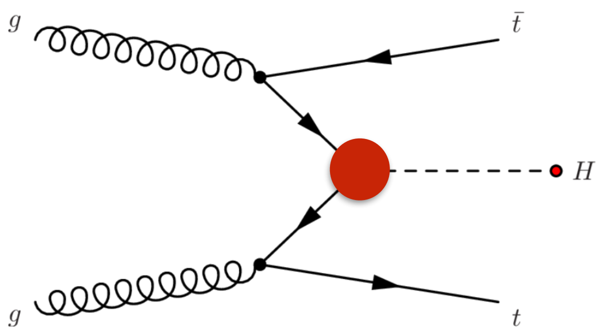
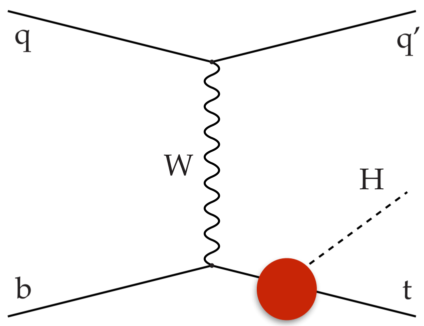
Outline

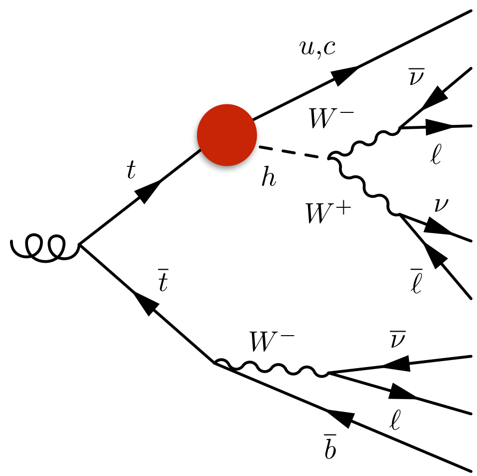
ttH production : direct probe of top Yukawa coupling



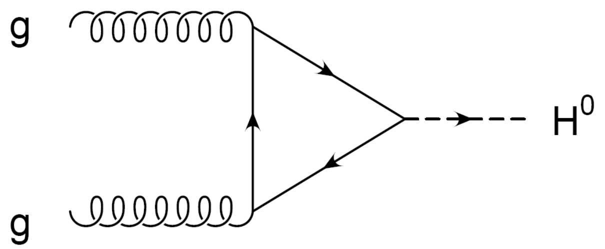
tHq production : probing the sign of top Yukawa coupling



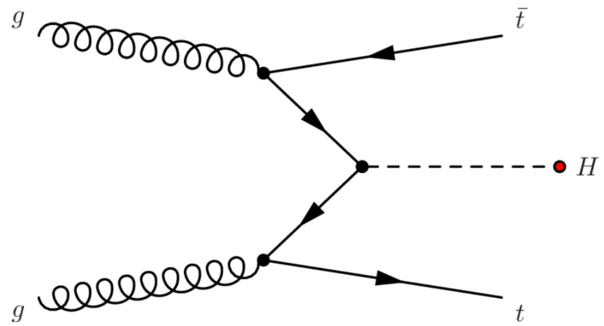
Flavour changing neutral current (FCNC) **tH coupling**



ttH production at 13 TeV



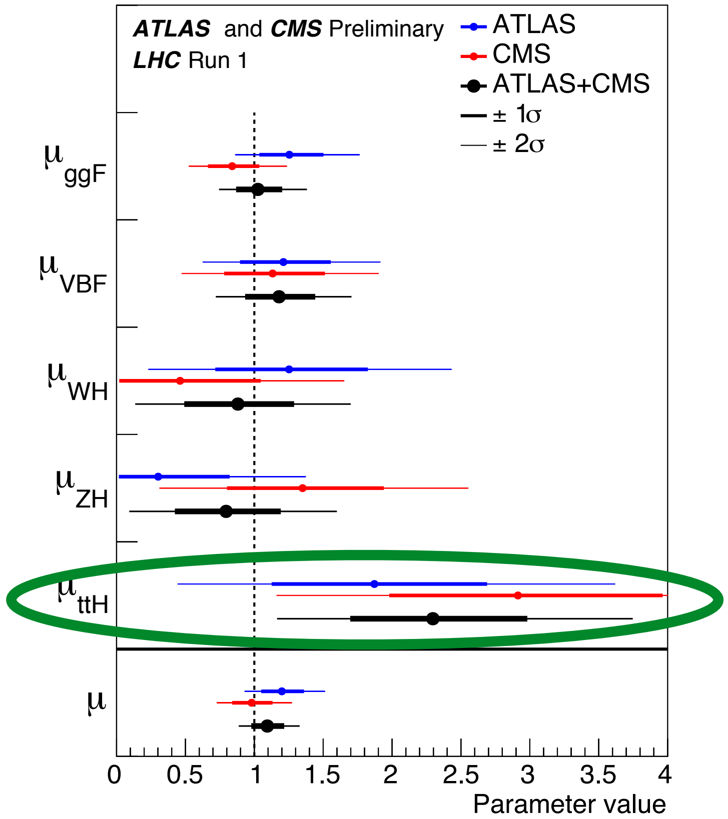
Indirect (loop level) probe of top Yukawa coupling

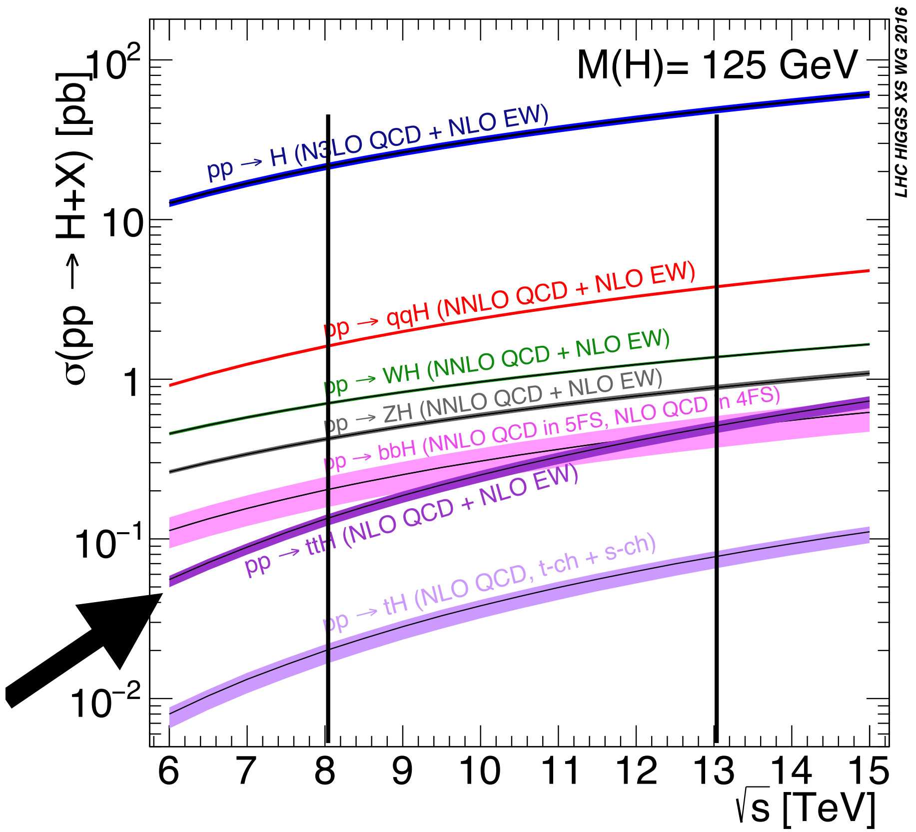


Direct (tree level) probe of top Yukawa coupling

Summary of Run I Higgs couplings

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





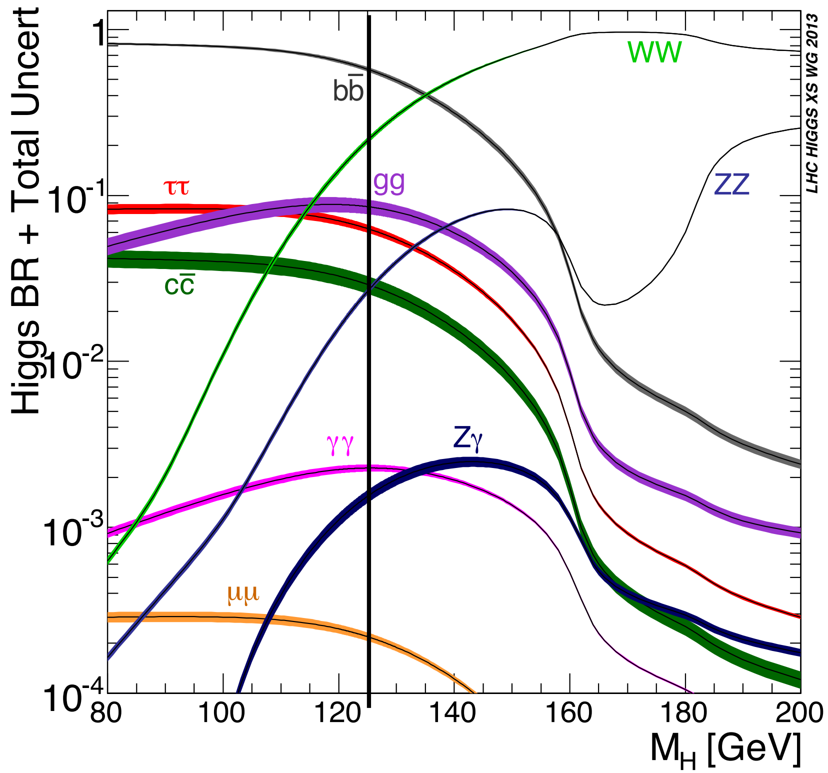
- ttH ~1% of total Higgs boson cross section
- Large **increase of ttH cross section from 8 TeV to 13 TeV: x3.8** (ttbar x3.3, ttZ x3.7, ttW x2.4)

Searches for ttH production

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

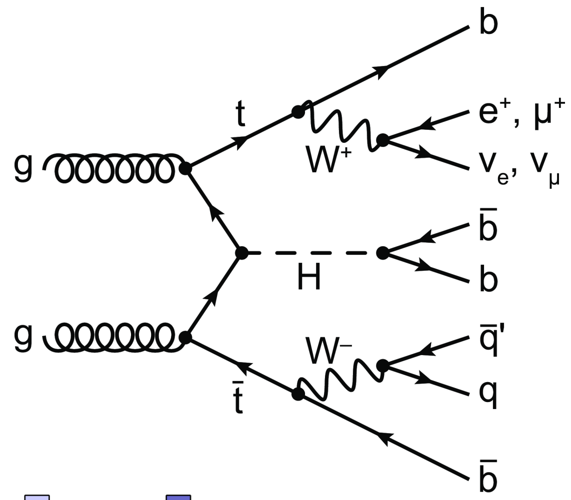
ttH,H→γγ : 0.23%
- Clean signature thanks to excellent mass resolution, but small branching ratio
- ATLAS : 2015 + 2016 data
- CMS : 2015, 2016 data

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, low background final state
- ATLAS : 2015 + 2016 data
- CMS : 2015 + 2016 data



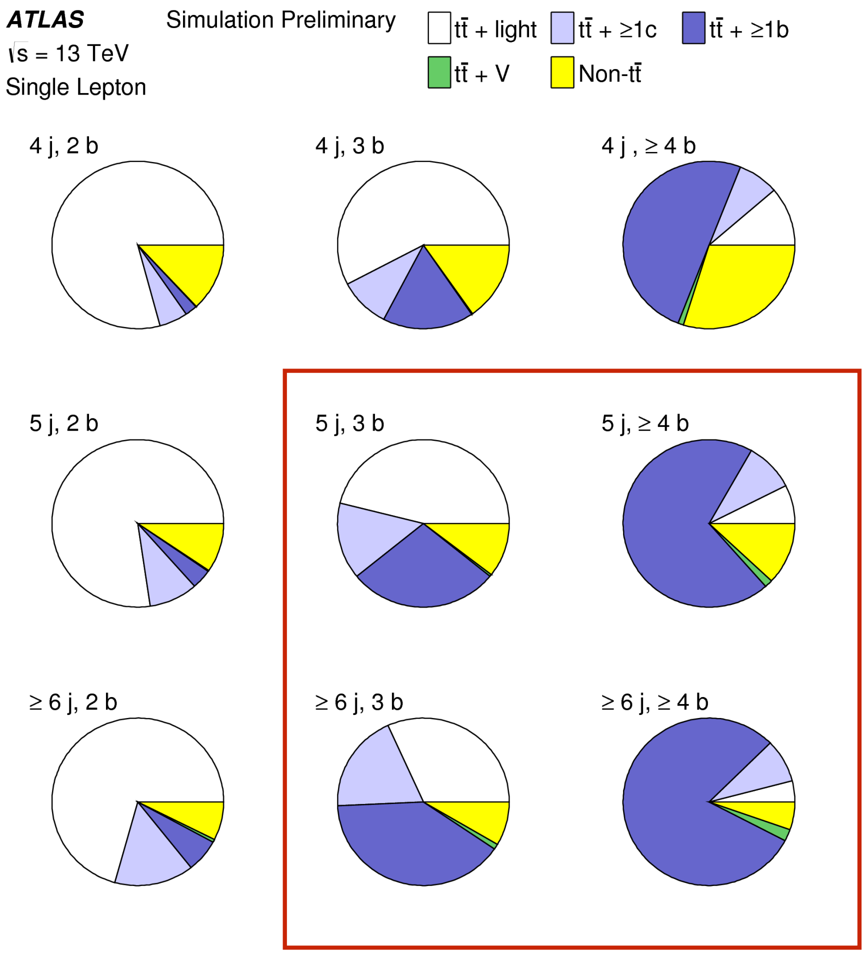
ATLAS ttH,H→bb

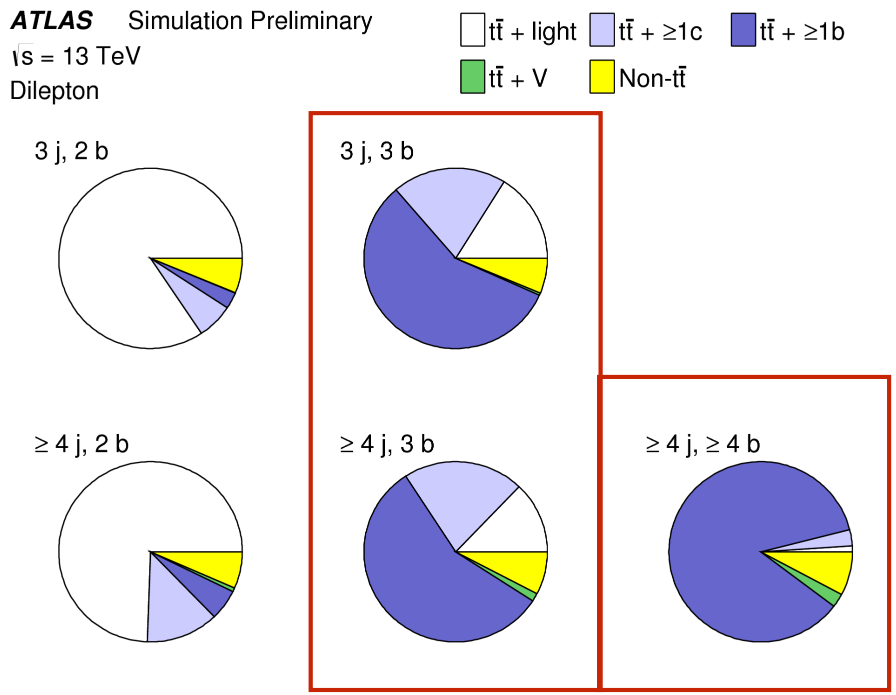
ATLAS-CONF-2016-080



Signal region targeting lepton+jets and dileptons

- **l+jets:** =1 lepton, ≥4 jets, ≥3 b-tag
- **2l:** 2 opposite sign lepton, ≥3 jets, ≥3 b-tag
- Categorize events in number of jets and b-jets





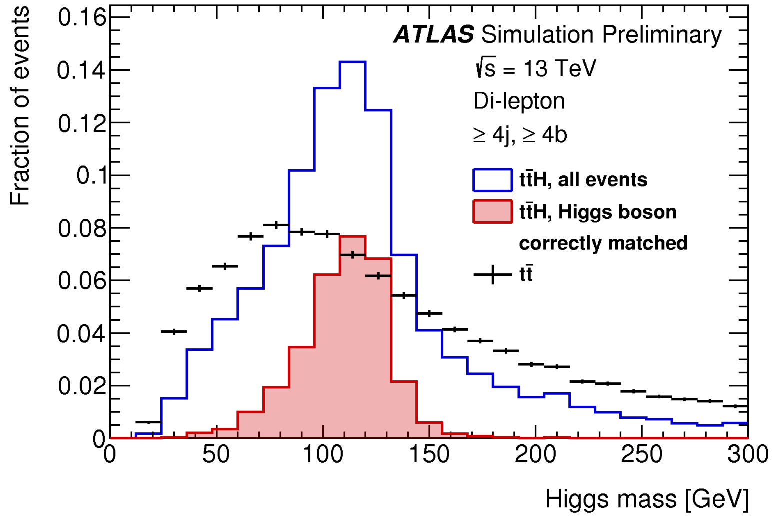
- **ttbar + ≥1b**: major background in signal regions
- **HT** distribution used to normalise backgrounds in control regions

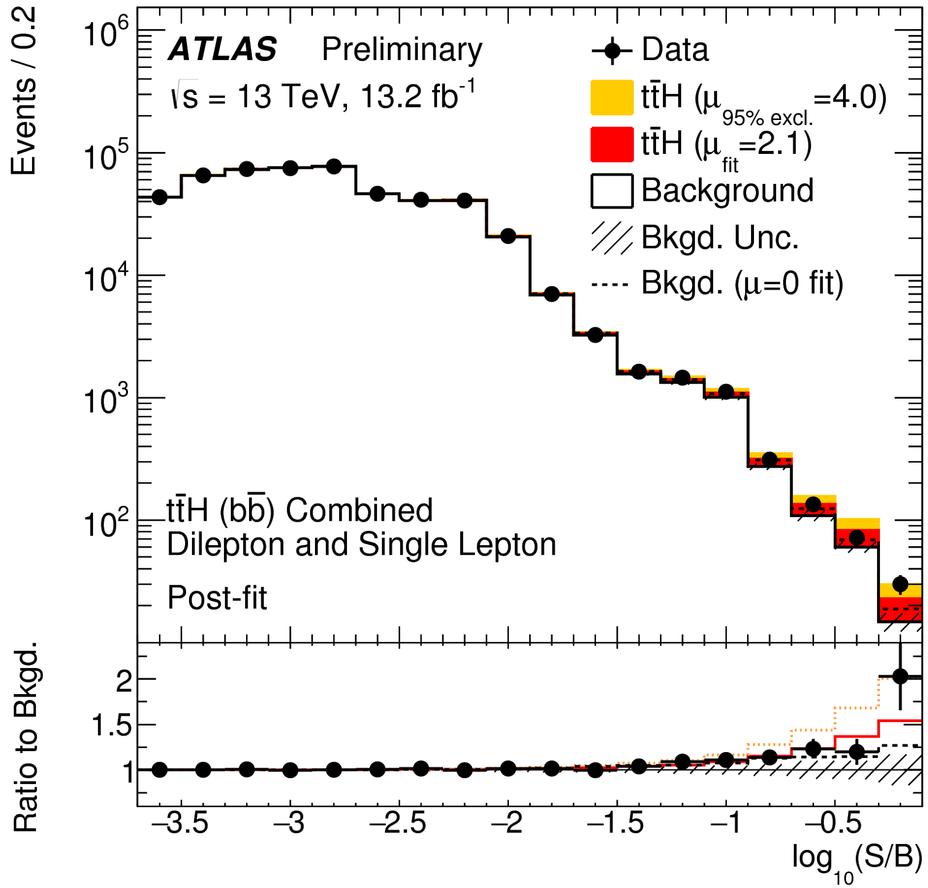
ATLAS ttH,H→bb

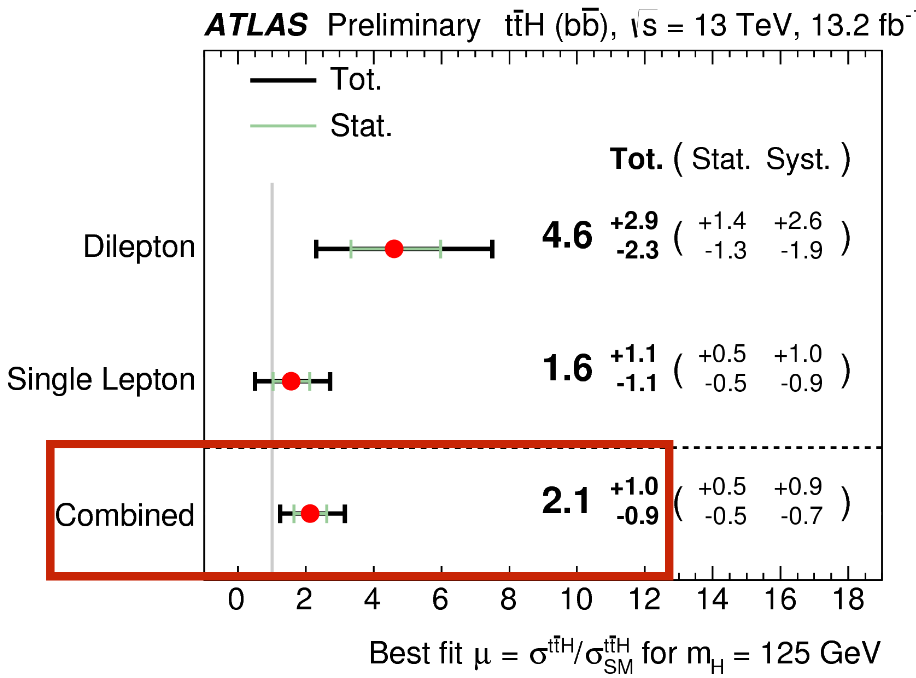
ATLAS-CONF-2016-080

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
- All regions included in final likelihood fit



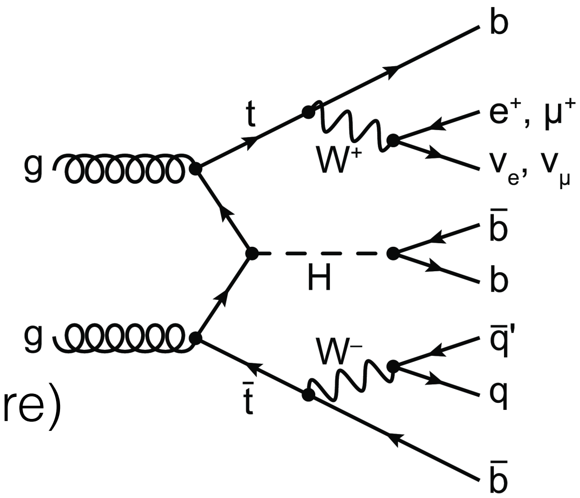




Theory uncertainties on ttbar + ≥1b is $\Delta\mu$~0.5, already dominates the measurement

CMS ttH,H→bb

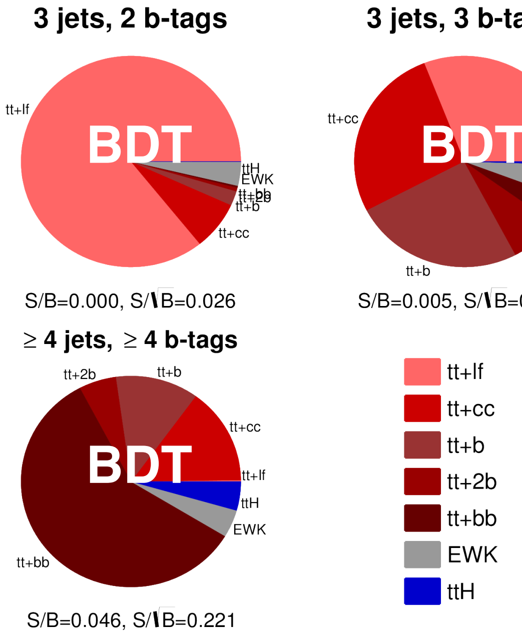
CMS HIG-16-004



Analysis targeting lepton+jets and dileptons

- **l+jets:** =1 lepton, ≥4 jets, ≥3 b-tag (4j 2b not in the fit)
    - Includes **boosted jets** for the first time (fat jet substructure)
- **2l:** 2 opposite sign lepton, ≥3 jets, ≥2 b-tag

CMS *Simulation* - **dilepton**



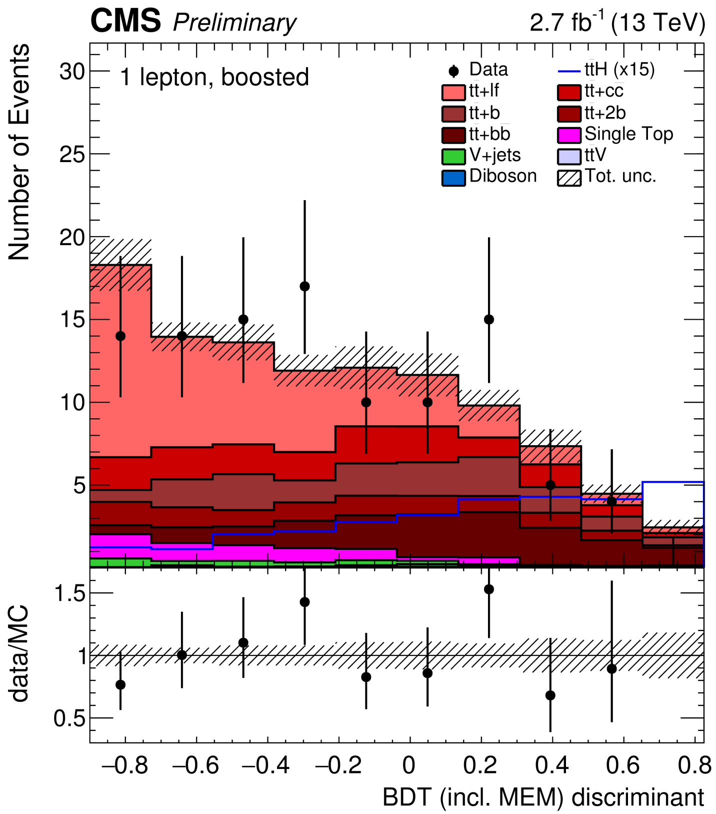
Mass resolution ~10%, jet combinatorics: use **multivariate methods** in jet/b-jet categories

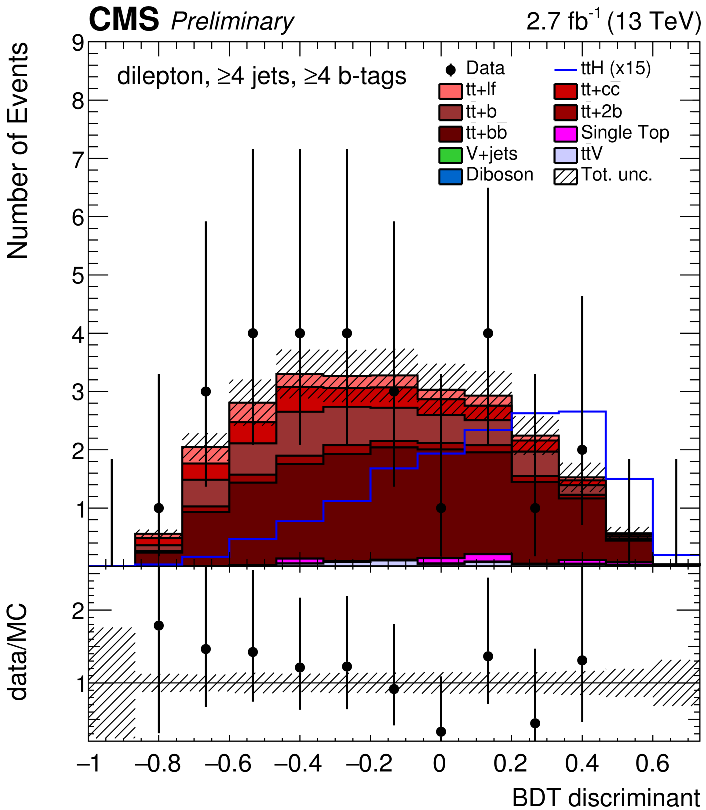
- **BDT**
- **Matrix Element Method** (MEM)

CMS *Simulation* - **lepton+jets**

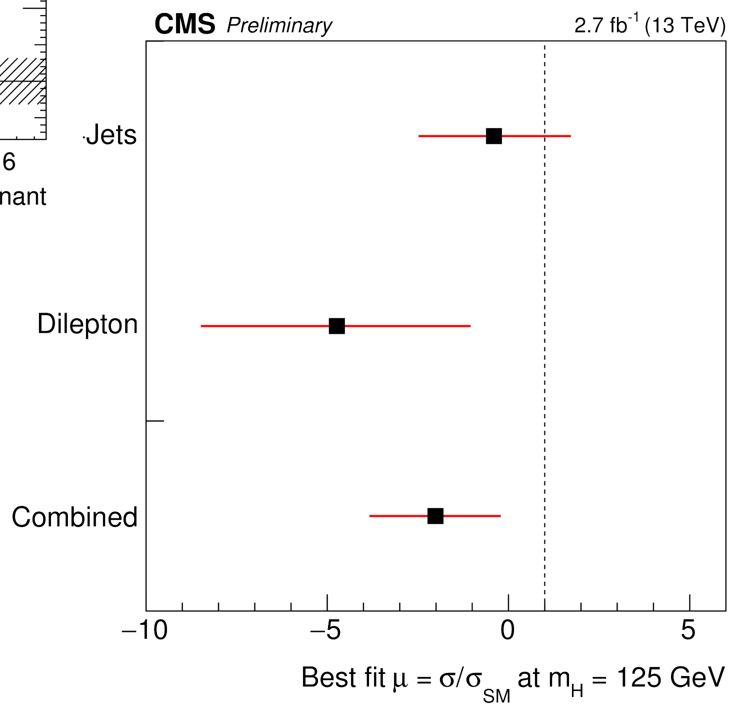
CMS ttH,H→bb

CMS HIG-16-004





Example of discriminants for two categories

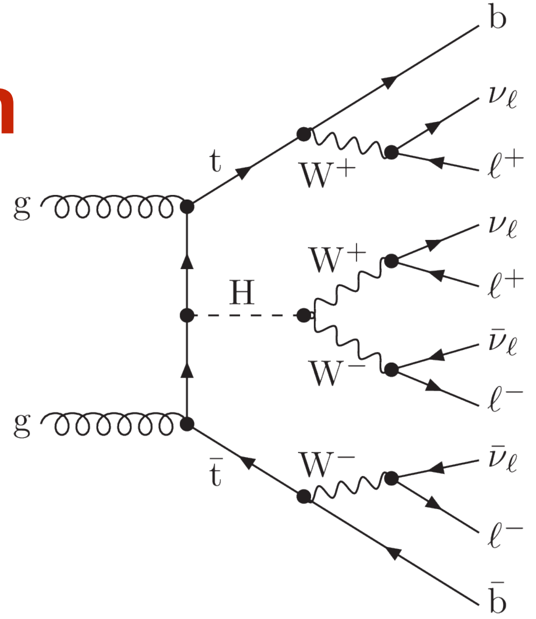


More data is needed for an observation at ATLAS or CMS

Channel	Best-fit μ	Observed UL	Expected UL
Lepton+jets	$-0.4^{+2.1}_{-2.1}$	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	$-4.7^{+3.7}_{-3.8}$	5.2	$7.7^{+3.6}_{-2.3}$
Combined	$-2.0^{+1.8}_{-1.8}$	2.6	$3.6^{+1.6}_{-1.1}$

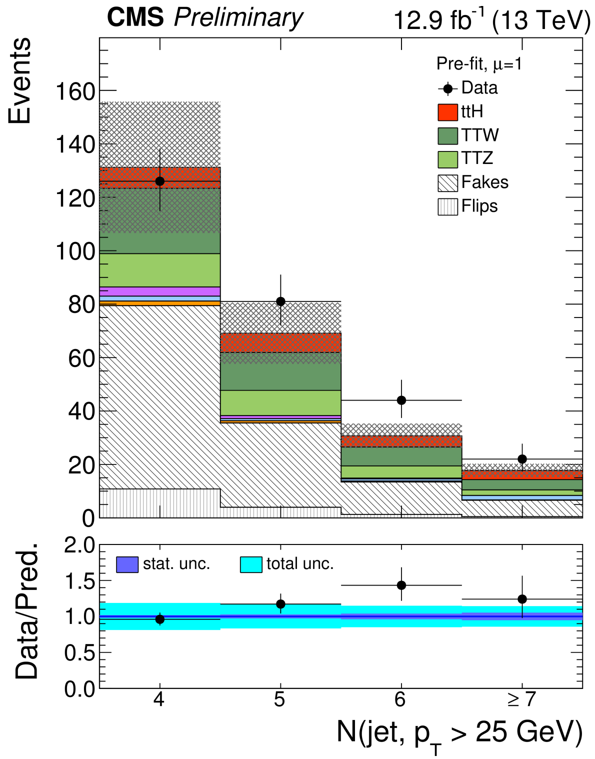
CMS ttH multilepton

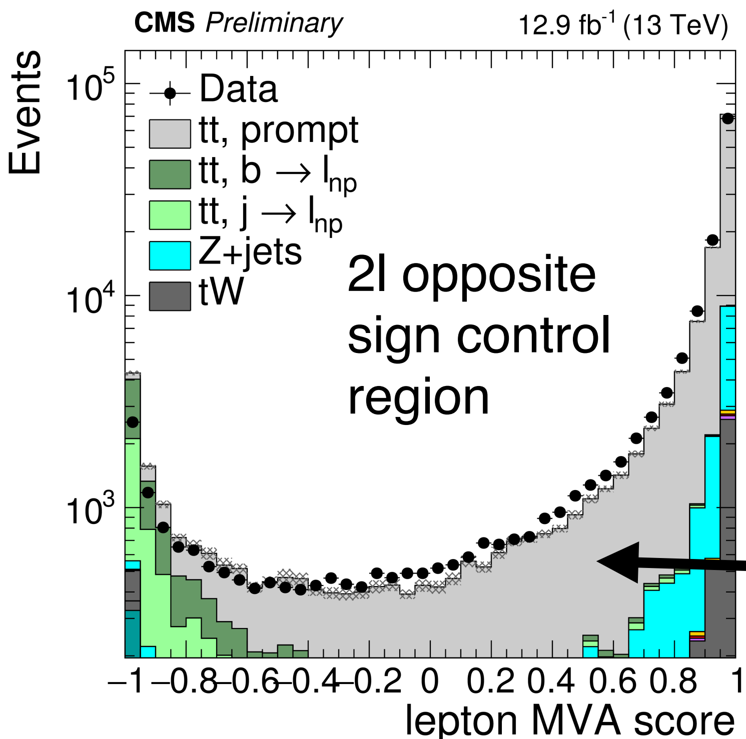
CMS HIG-16-022



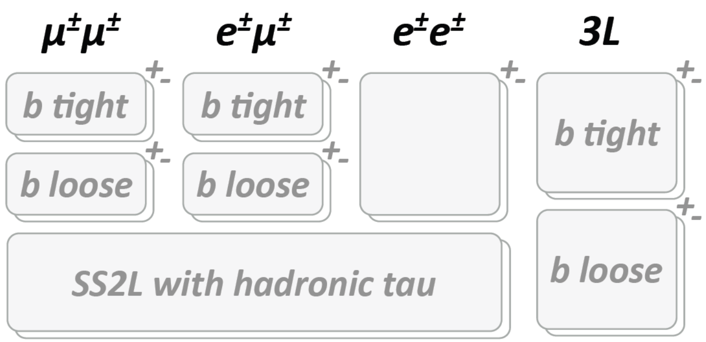
Targeting 2 lepton same-sign (2lss) and ≥3 leptons (3l)

- **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)





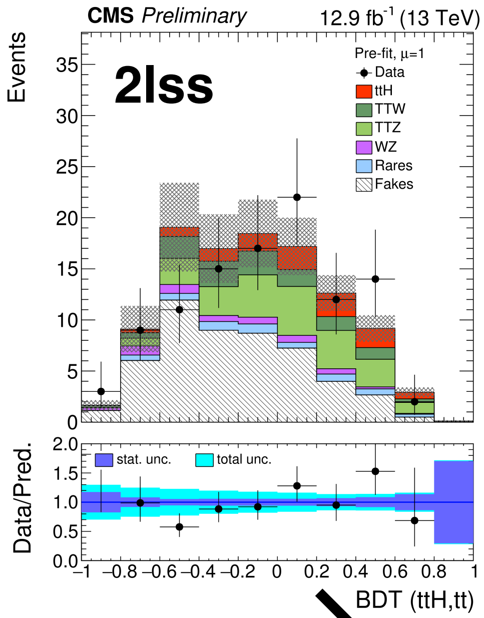
Analysis categories:

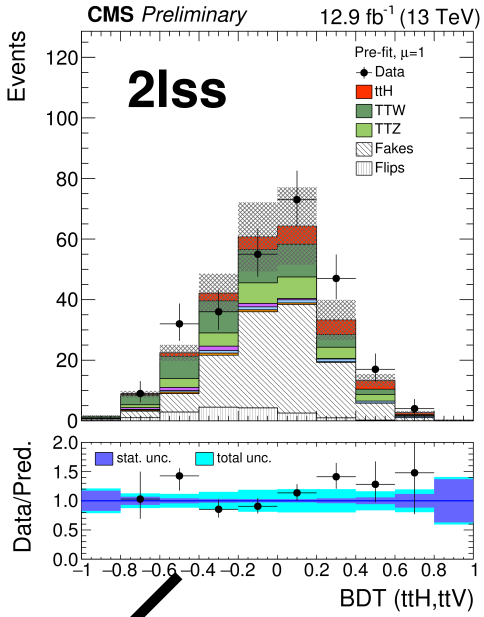


- **Lepton identification** with a BDT using shape, isolation and overlapping jet information

CMS ttH multilepton

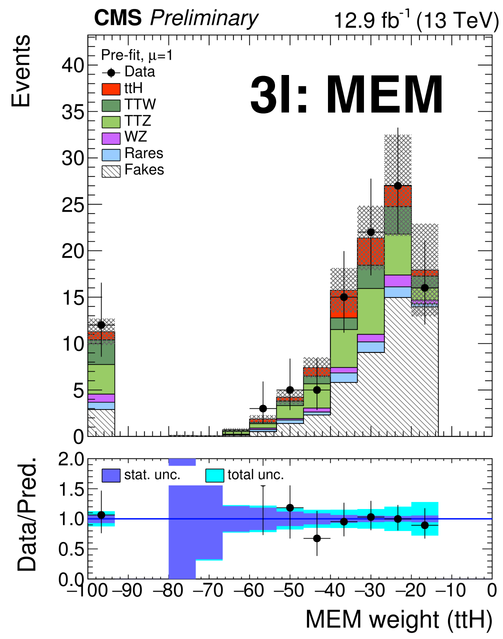
CMS HIG-16-022

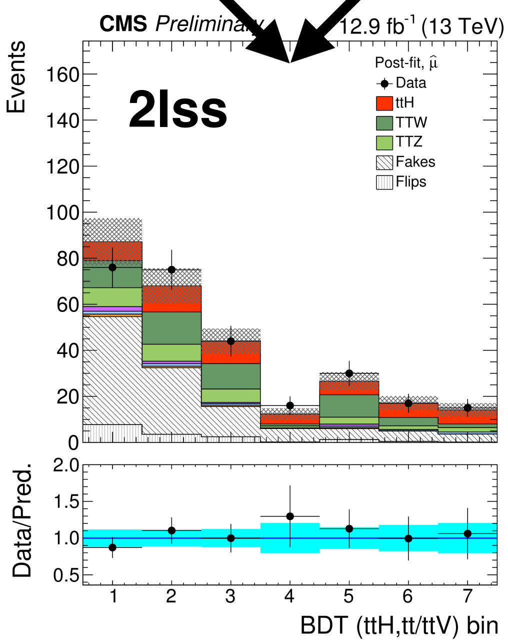


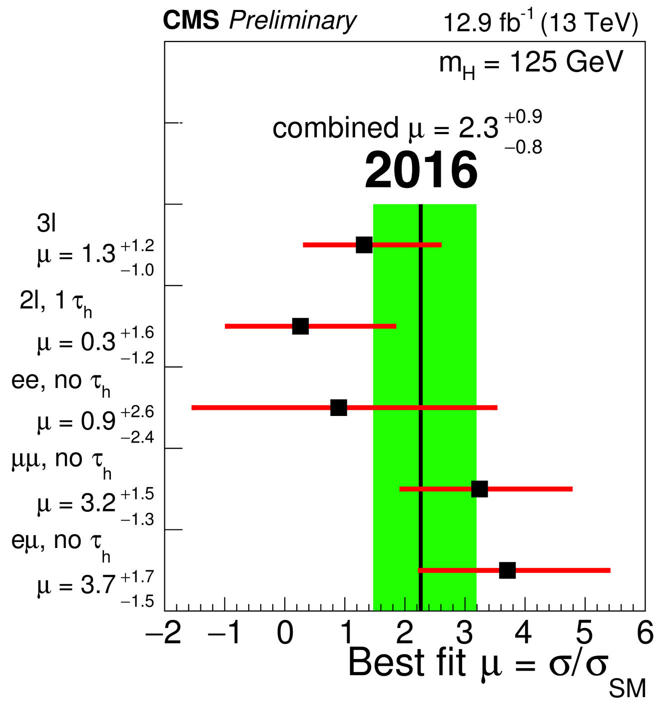


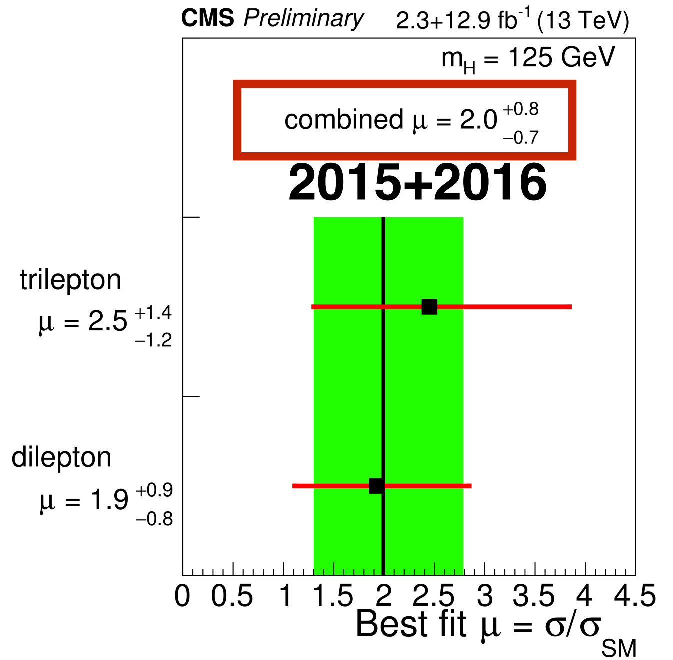
Analysis sensitivity:

- Train **2 BDTs, against ttbar and ttW/Z**
- **3l category** : include **MEM** as BDT input (new)
- Main syst. uncert. : tight lepton selection and fakes







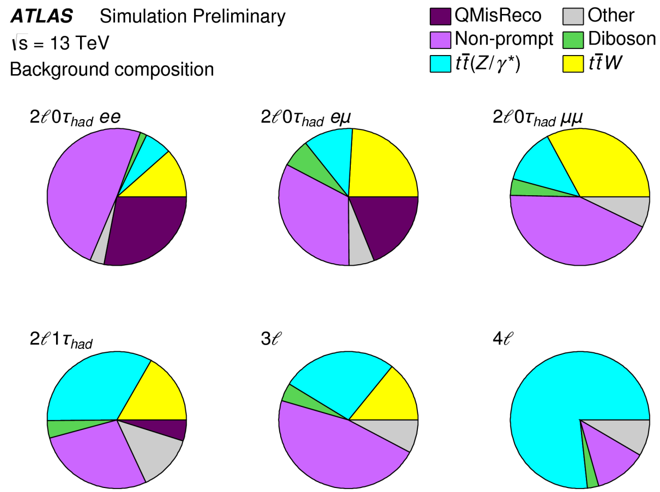


ATLAS ttH multilepton

ATLAS-CONF-2016-058

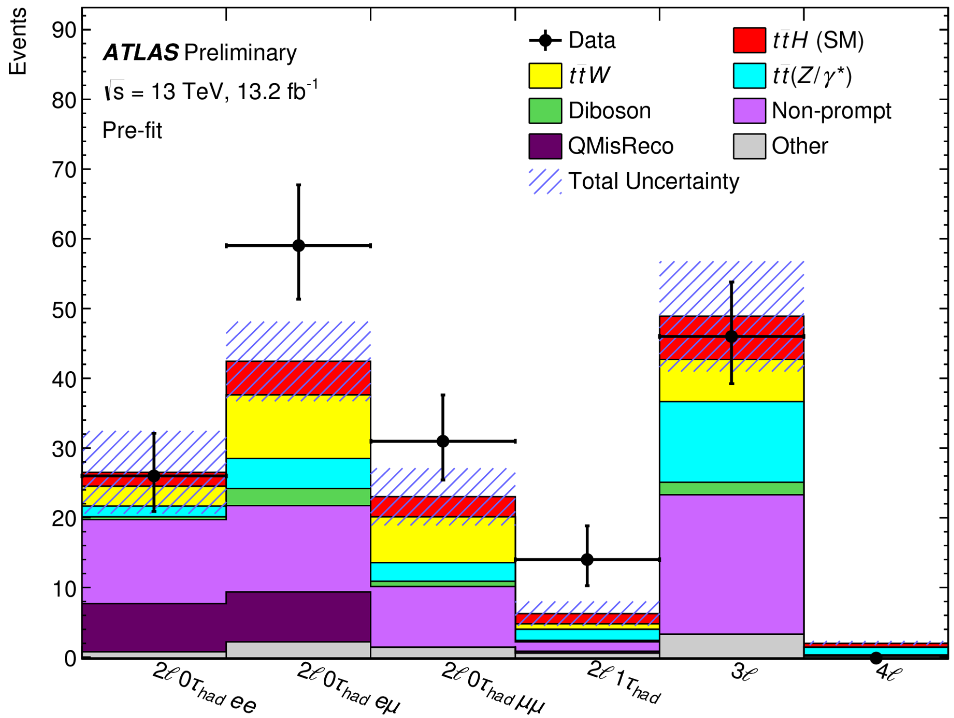
ATLAS analysis: 4 channels

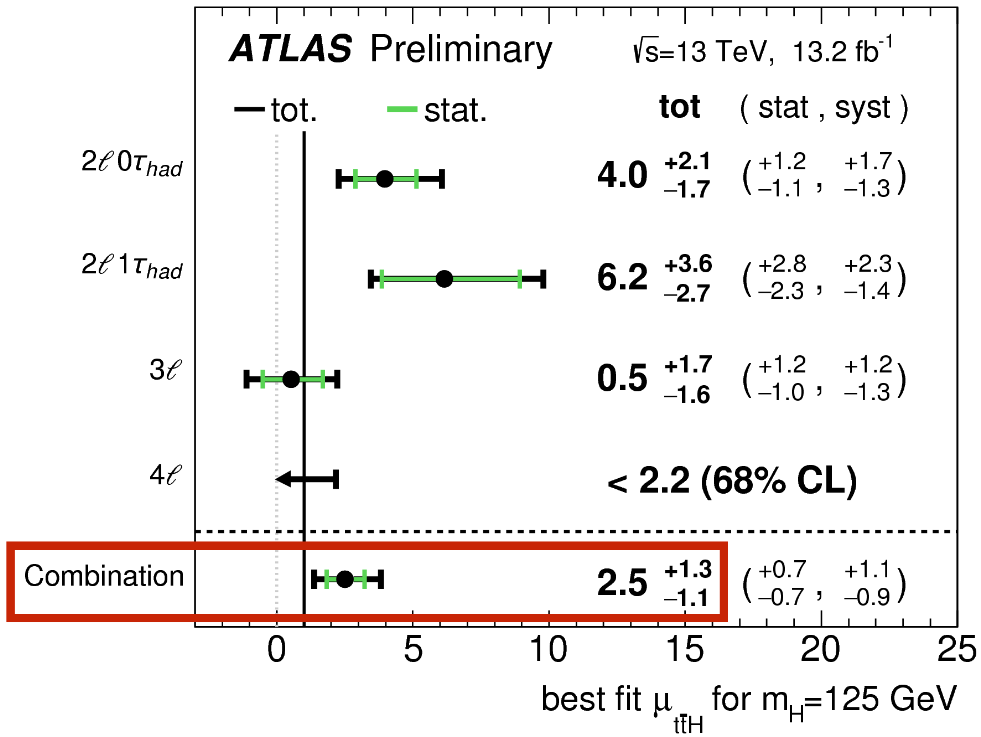
- **2l same sign (ee, eμ, μμ), no τ had:** ≥5 jets, ≥1 b-tag
- **2l same sign, 1 τ had :** ≥4 jets, ≥1 b-tag
- **3l:** ≥4 jets, ≥1 b-tag ; or ≥3 jets, ≥2 b-tag
- **4l:** ≥2 jets, ≥1 b-tag



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

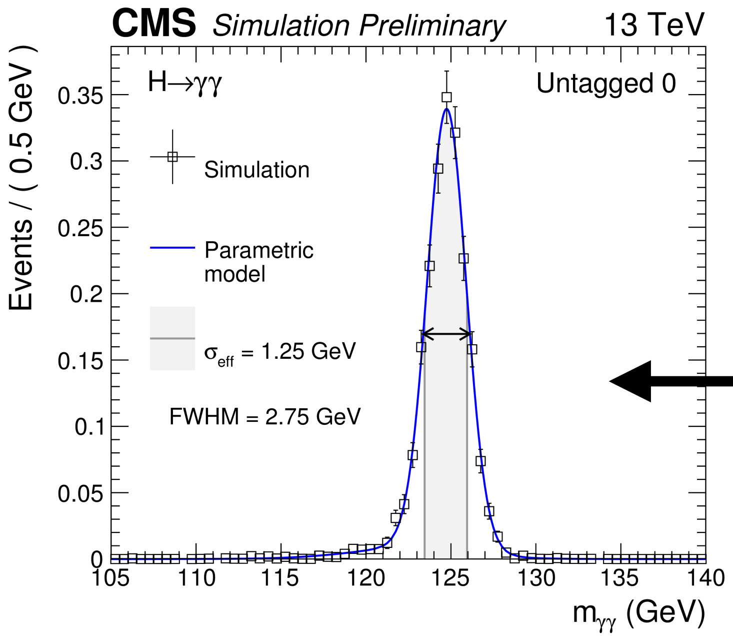
Cut and count analysis in 6 categories





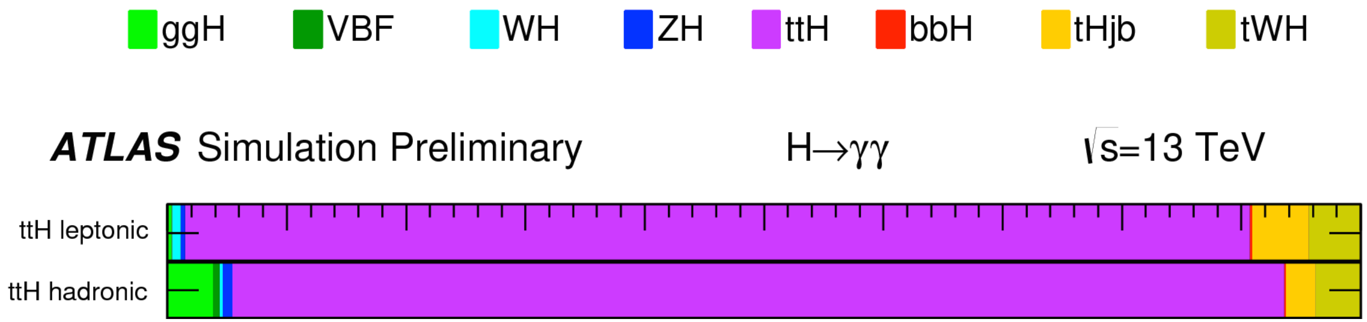
ATLAS, CMS H→γγ analysis

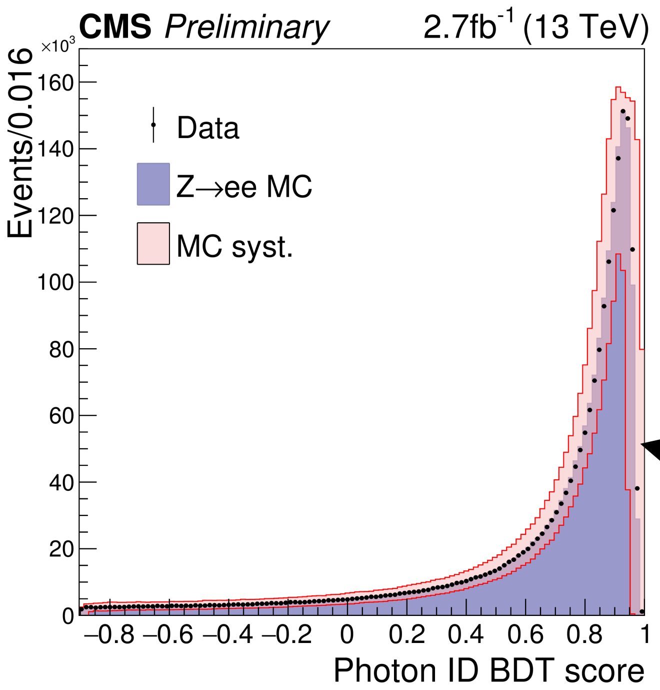
ATLAS-CONF-2016-067, CMS HIG-16-020



- 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**

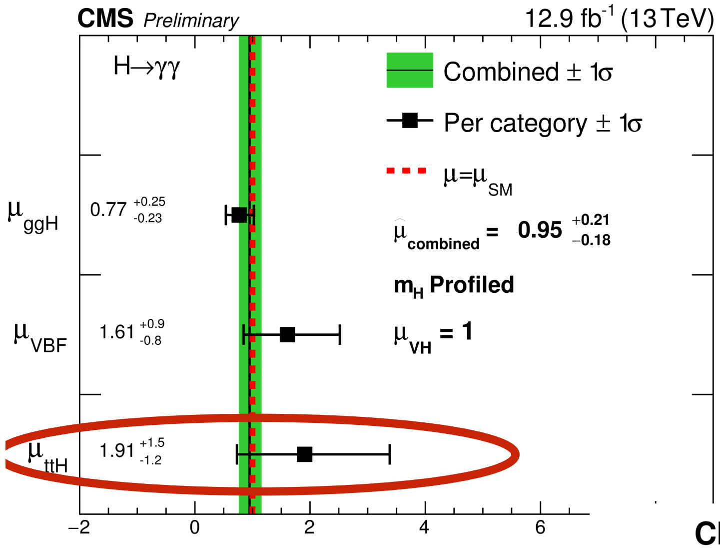




- **Photon identification:** reject jets faking photons with shower shape and isolation: BDT (CMS), cut-based (ATLAS)

CMS ttH,H→γγ

CMS HIG-16-020



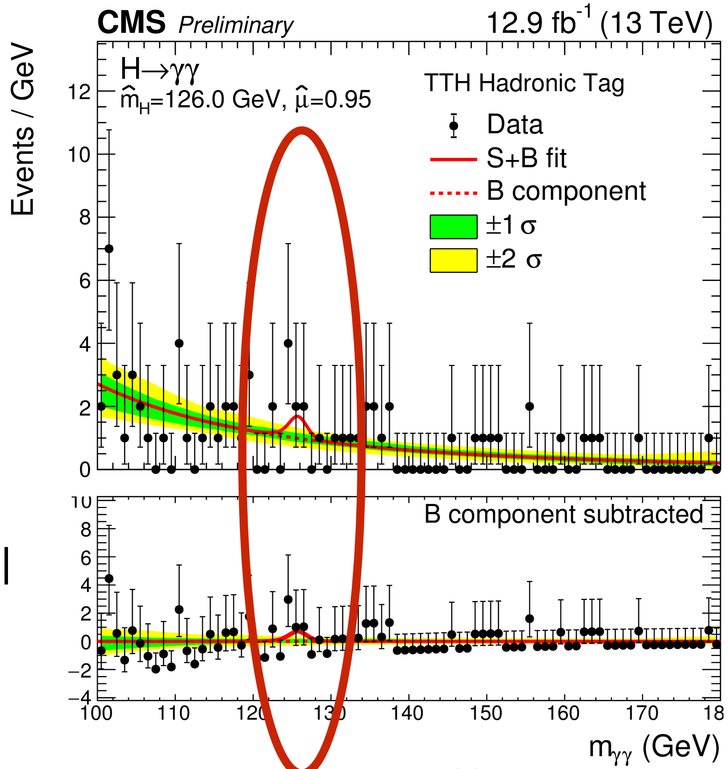
2 ttH categories: hadronic and leptonic

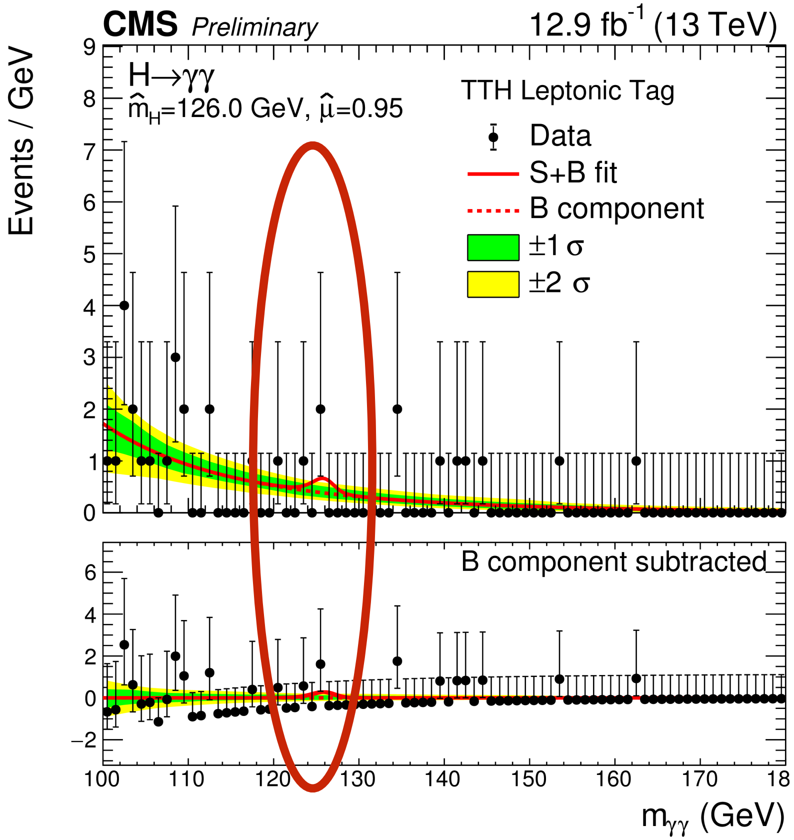
- Tighten photon pT/m requirement relative to inclusive categories (targeting ggh production)
- Control region with inverted photonId is used to predict expected background for optimisation

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

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

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



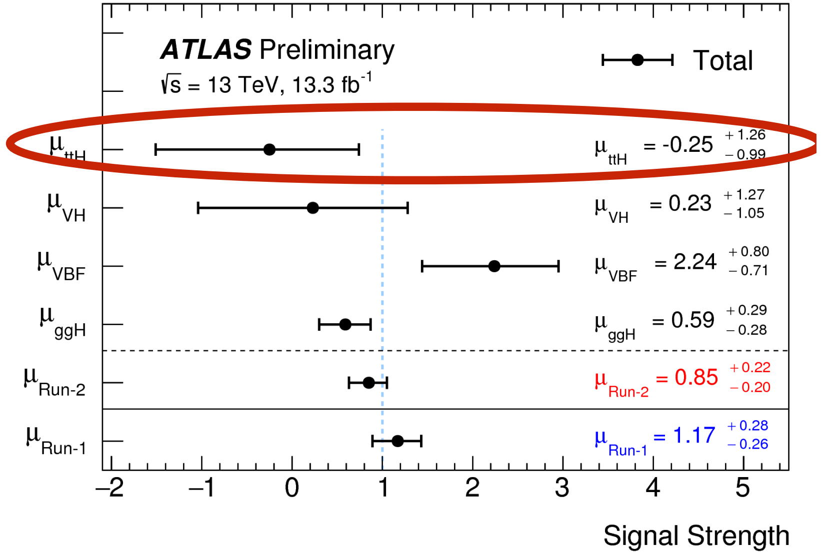


ATLAS ttH,H→γγ

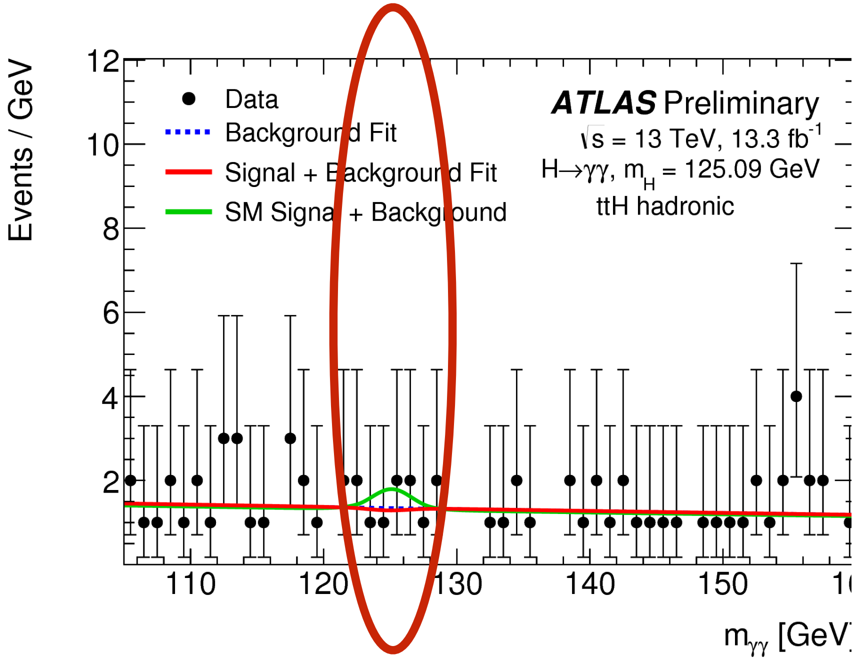
ATLAS-CONF-2016-067

2 ttH categories: hadronic and leptonic

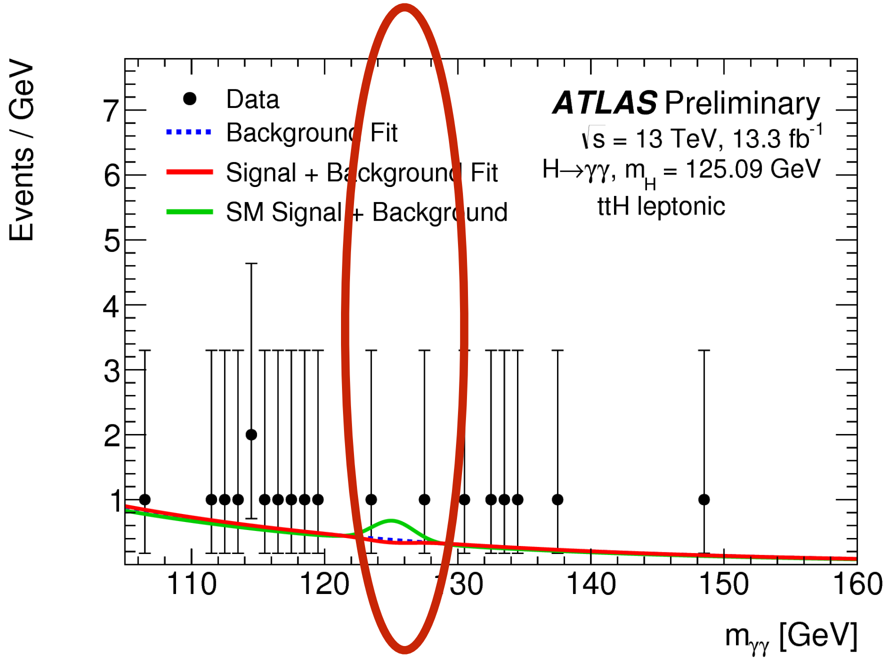
- Control region with inverted photonId
  - **ttH** hadronic/leptonic combined: **μ=-0.25$^{+1.26}_{-0.99}$** measured simultaneously with other production mechanisms (ratio WH/ZH assumed as SM)
  - Measurement is dominated by statistical uncertainties



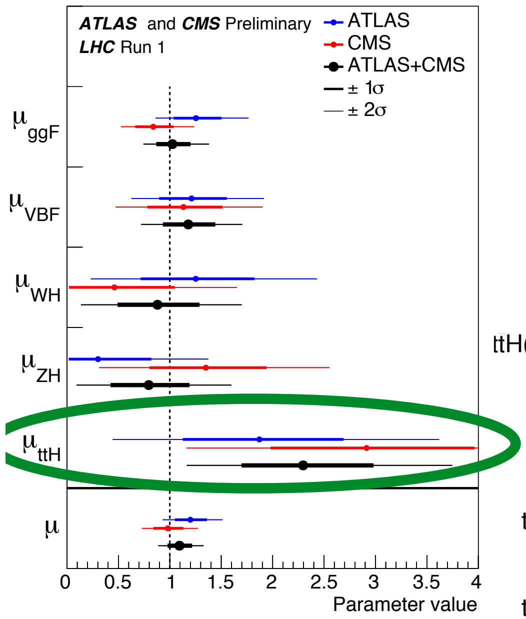
ttH hadronic tag: 0 lepton, ≥5 jets, ≥1 b-tag



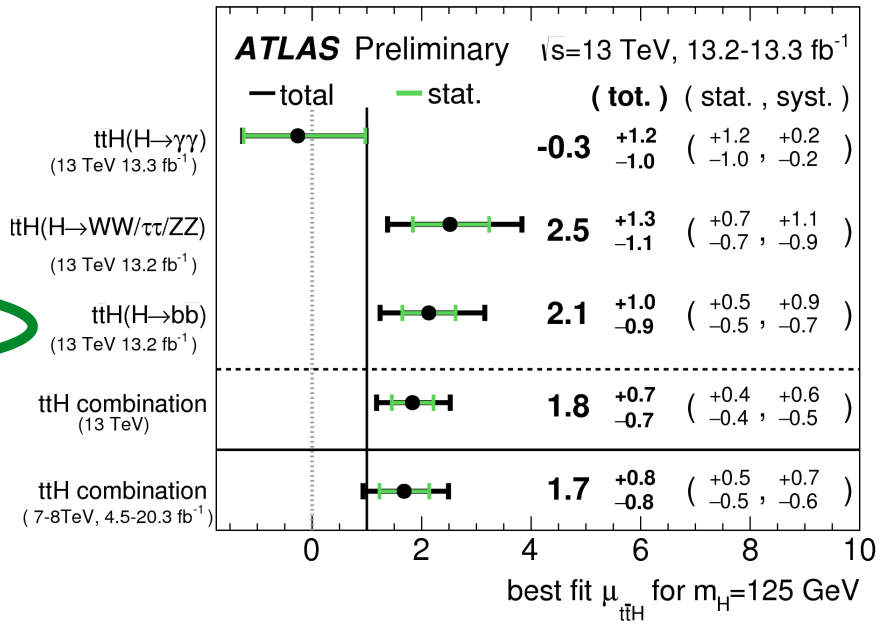
ttH leptonic tag: ≥1 lepton, ≥2 jets, ≥1 b-tag



ttH summary and projections



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



CMS

- ttH, **H→bb** (2015): **$\mu=-2.0^{+1.8}_{-1.8}$**

- 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.
- **$\Delta\kappa_t$:** from H→γγ and H→bb: **10%** (7% if half theory uncert.)

ATLAS PHYS-PUB-2014-012

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

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 expected precision on ttH signal strength (%)

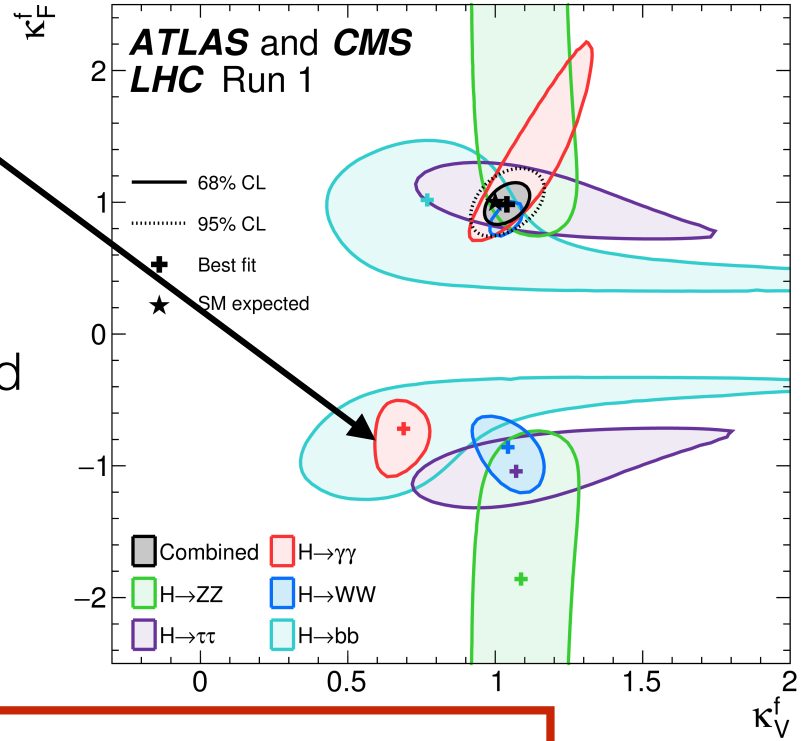
$\mu \propto K_t$

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

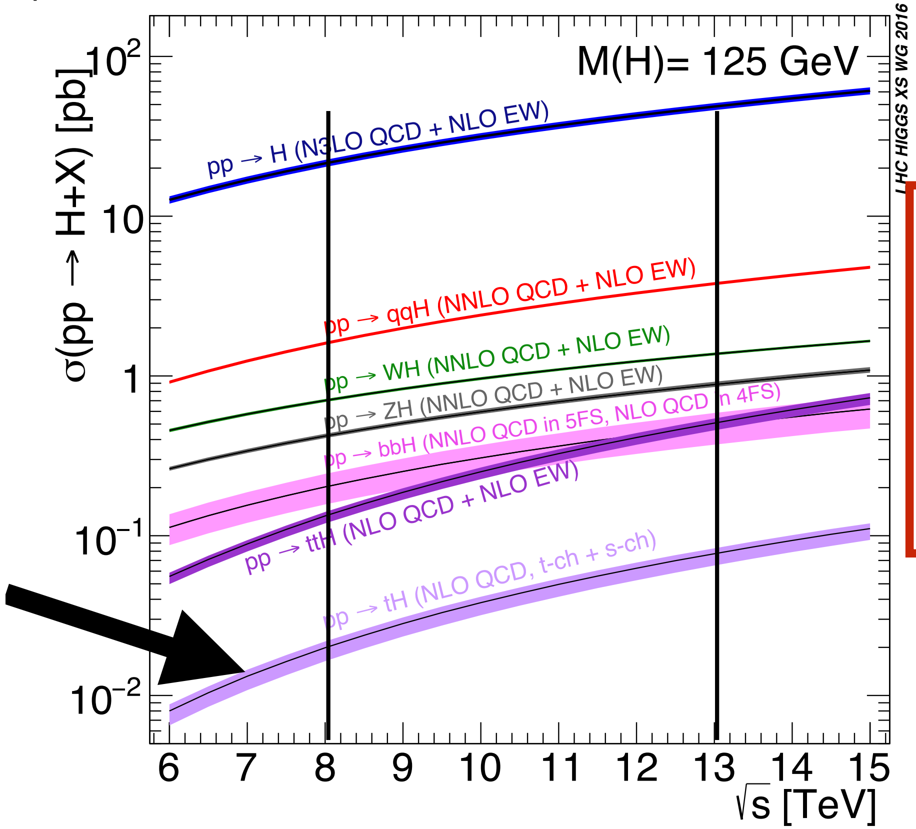
tHq production and negative coupling

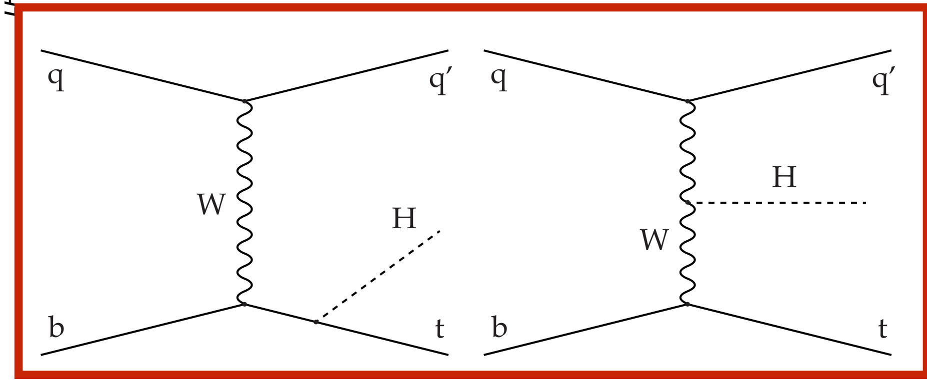
H→γγ sensitive to the sign of top-Higgs coupling

$$\Gamma(H \to \gamma\gamma) \propto \left|\kappa_F A_t + \kappa_V A_W\right|^2$$



On top of ttH production, can **search for tHq production** to lift the degeneracy
- Destructive interference between coupling to top and W : tHq has a 30 smaller cross section than ttH predicted in the SM





Signature : tH + **forward jet**

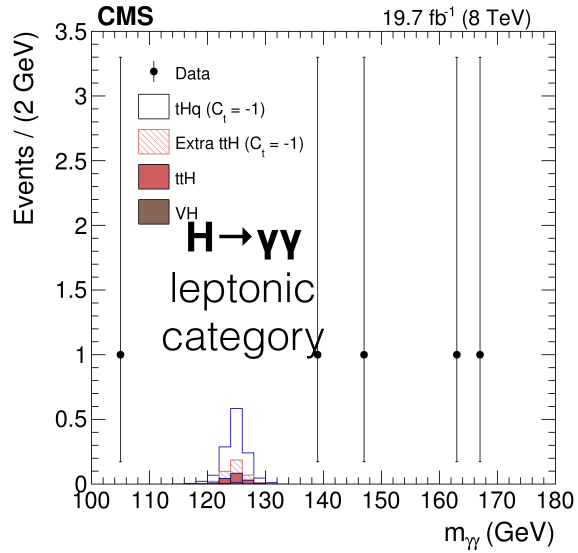
Negative top-Higgs coupling
- can **increase** a lot (~x15) the **tHq cross section**
- and induce BR(H→γγ) ~x2

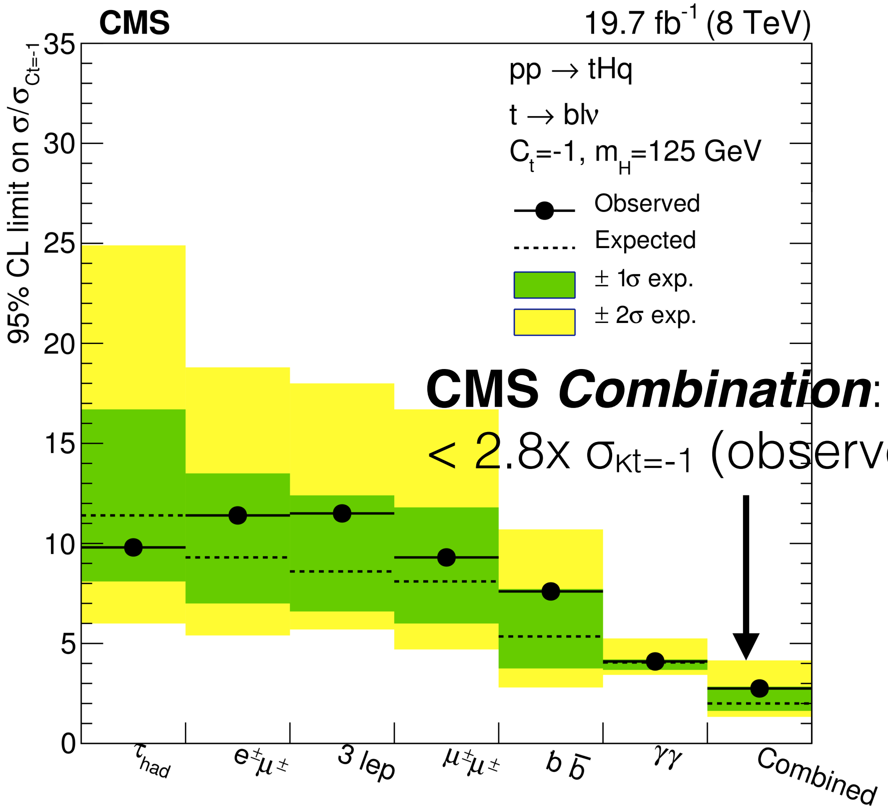
tHq at Run I

CMS JHEP 06 (2016) 177, ATLAS Phys. Lett. B 740 (2015) 222-242

CMS tHq 8 analyses carried out in same final states as ttH:

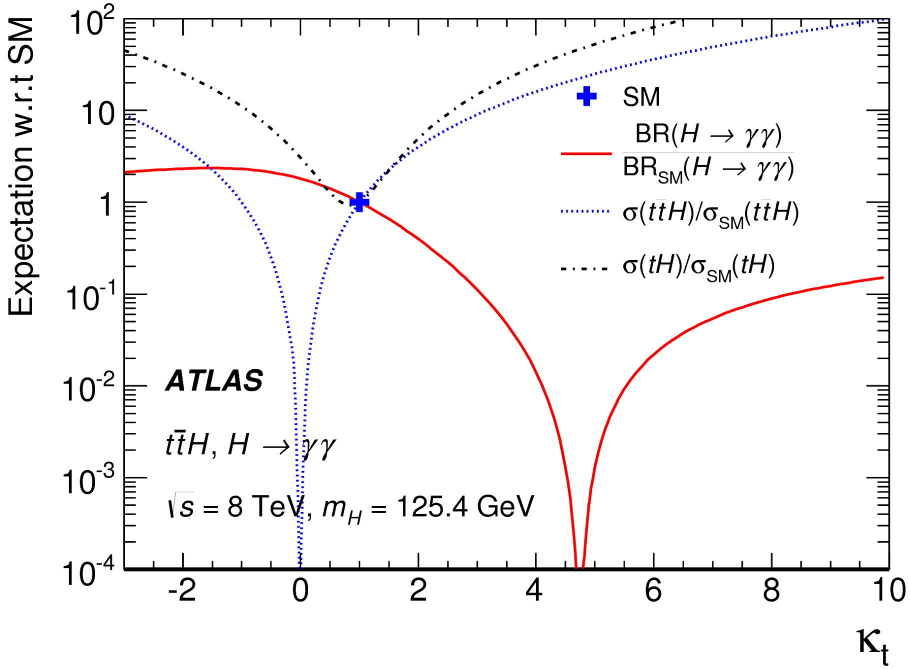
- **H→γγ:** background fit in leptonic channels, also done at ATLAS
- **H→bb**: Use NN as discriminant in 3b/4b, e/μ categories
- **Multilepton**: Bayes classifier in 3l, eμ, μμ categories
- **H→ττ:** Fisher discriminant in eμτ, μμτ categories





CMS *Combination*: Exclude σ < 2.8x $\sigma_{\kappa t=-1}$ (observed limit)

ATLAS: $\kappa_t \in [-1.3, 8.0]$



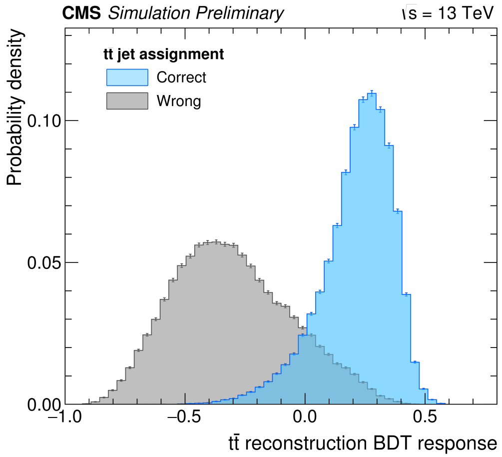
tHq, H→bb at 13 TeV

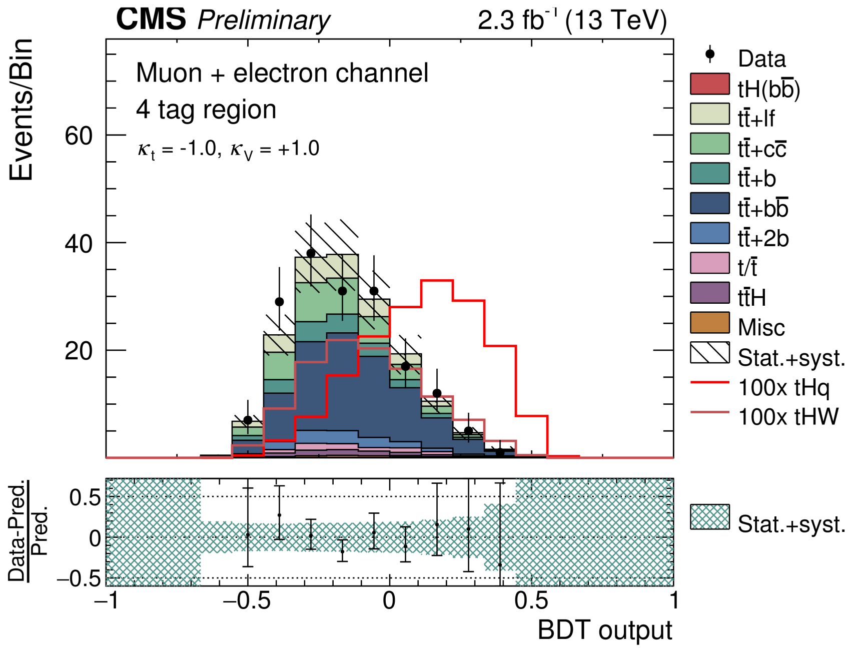
CMS HIG-16-019

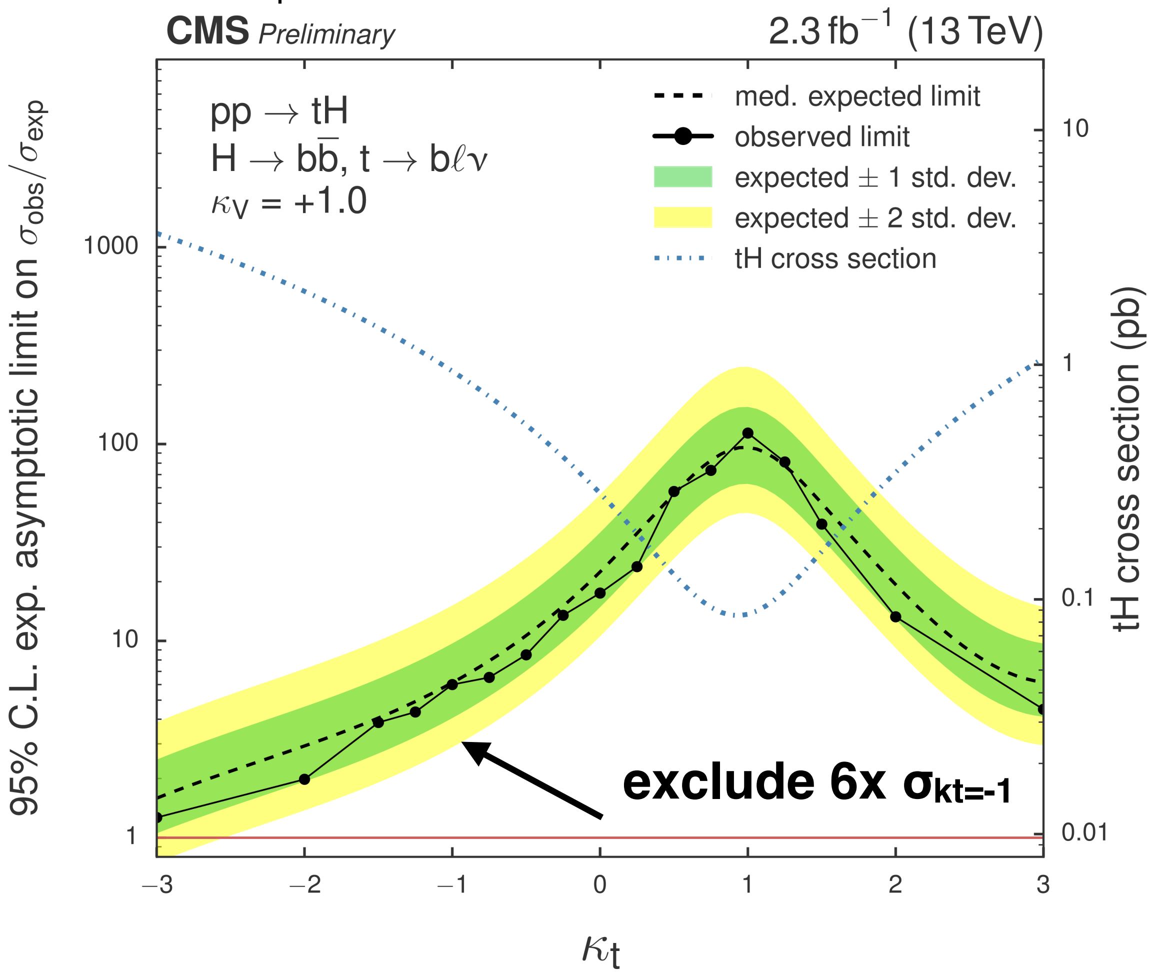
Analysis performed with 2015 data:

- **Jet assignment** with a **reconstruction BDT** under tHq and ttbar hypotheses
- Signal / background **discrimination with a classification BDT**

=> Done for each benchmark point in the κ_t / κ_V plane







- Similar sensitivity to Run 1 despite 1/7 of the statistics: analysis improved

Top-Higgs coupling with FCNC

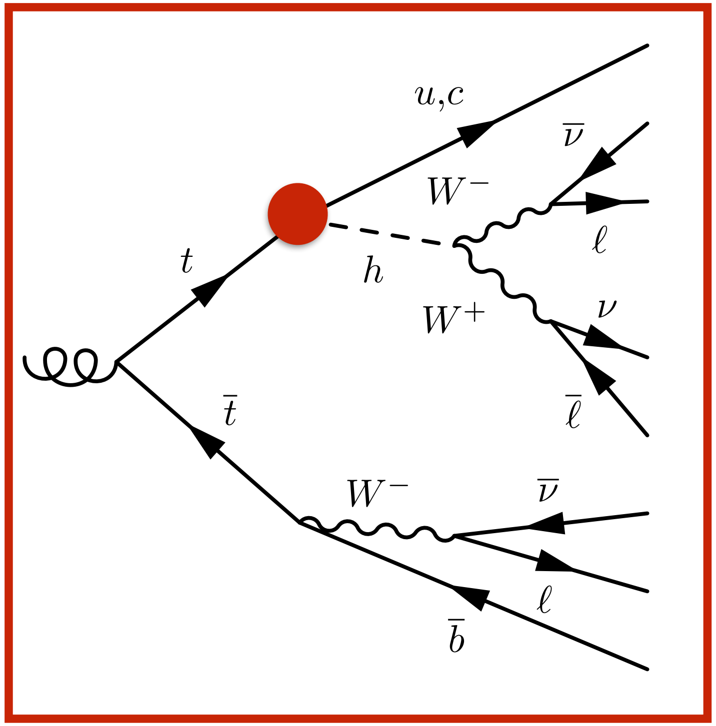
Searching for flavor changing neutral currents with t→(u)cH

- Process arising only at the loop level in the standard model (forbidden by GIM mechanism)
- Very small branching ratio: any excess would be a clear sign of new physics

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

Searches in ttbar production, followed by top FCNC decay with a Higgs boson

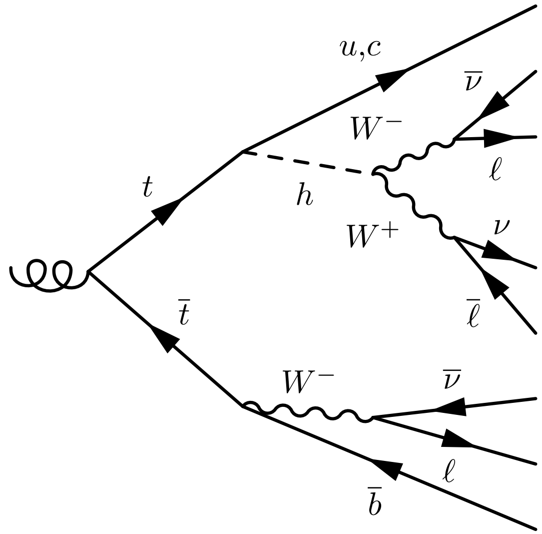
Anomalous tH FCNC production not pursued yet.



CMS tH FCNC, Run I

CMS TOP-13-017, TOP-14-019, TOP-14-020 (paper to appear soon)

CMS tH FCNC analyses :
- **H→γγ:** background fit in hadronic and leptonic channels
- **H→bb**: Reconstruction BDT, use NN as discriminant
- **Multilepton**: Cut based analysis



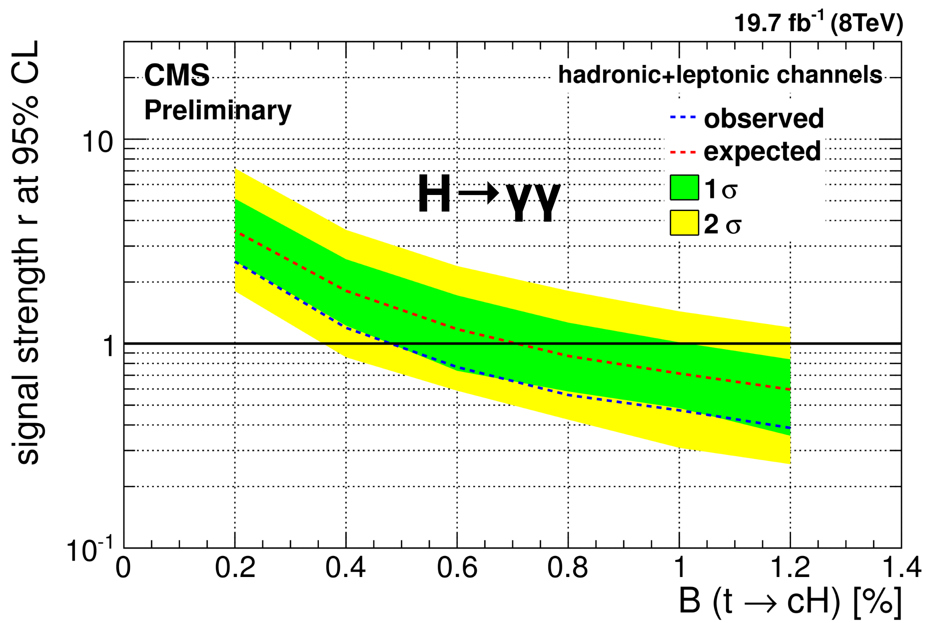
Limits of BR(t→(u)cH) at the 1% level or less (still orders of magnitude above MSSM predictions)

Multilepton

	$-\sigma$	$BR_{exp}(t \to Hc)$	$+\sigma$	$BR_{obs}(t \to Hc)$
trilepton	0.95	1.33	1.87	1.26
same-sign dilepton	0.68	0.93	1.26	0.99
combined	0.65	0.89	1.22	0.93

H→bb

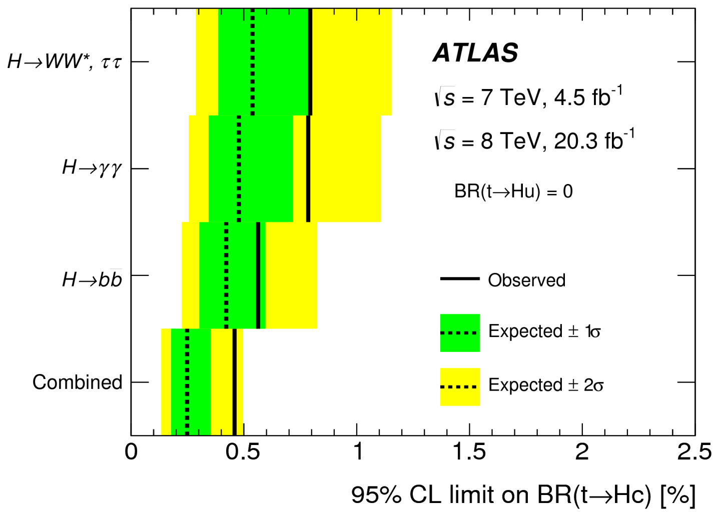
	$t \to cH$ channel	$t \to uH$ channel
Signal	73.9 ± 108.7(stat.)± 24.4(syst.)	196.9 ± 87.3(stat.)± 59.1(syst.)
Total background	6766 ± 136.0(stat.)± 947.2(syst.)	6636 ± 118.6(stat.)± 796.3(syst.)
Observed events	6840	6840
Expected limit	0.89%	0.85%
Observed limit	1.16%	1.92%

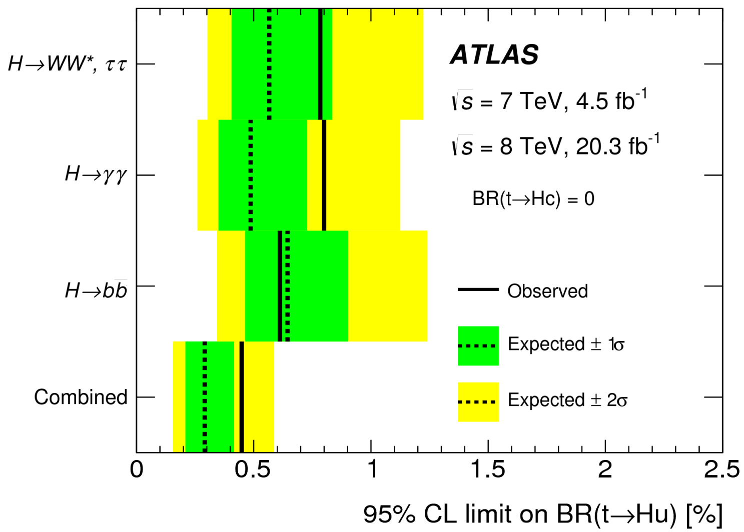


ATLAS tH FCNC Run I and projections

JHEP 12 (2015) 061

- Similar analyses performed at ATLAS
- **Exclusion limits BR(t→(u)cH) < 0.45%**





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

ATLAS-PHYS-PUB-2016-019

- Semi-leptonic ttbar decay, H→bb
- Reference scenario: tracker, muon |η|<4
- Limits 50x better than at 8 TeV
- Approaching the range of 2HDM/MSSM predictions

	$t\to Hu$	$t\to Hc$	$t\to Hu+Hc$
Reference scenario	$1.2\cdot10^{-4}$	$1.0\cdot10^{-4}$	$0.55\cdot10^{-4}$

- Similar results BR(t→cH)~1,5.10^{-4} with H→γγ from extrapolated 8 TeV results (ATLAS-PHYS-PUB-2013-012)

Conclusions

ttH production

- 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), and results are consistent with Run I
- More data is needed to evaluate if the Run I “excess” (though compatible with SM) is not a fluctuation.

tHq searches with negative top-Higgs coupling

- Run I tHq sensitivity was able to exclude <~3 the tHq cross section for Ct=-1
- First 13 TeV measurements are being made available. $H \rightarrow bb$ sensitivity already comparable Run I dataset with 2015 data

Top quark FCNC decay with Higgs

- Analyses performed at 8 TeV reach BR < 0.4%.
- Run II analyses are ongoing.

2016 data taking period is still ongoing !

Back-up slides

CMS ttH,H→bb

CMS HIG-16-004

Most sensitive channel : 6 jets, 3 b

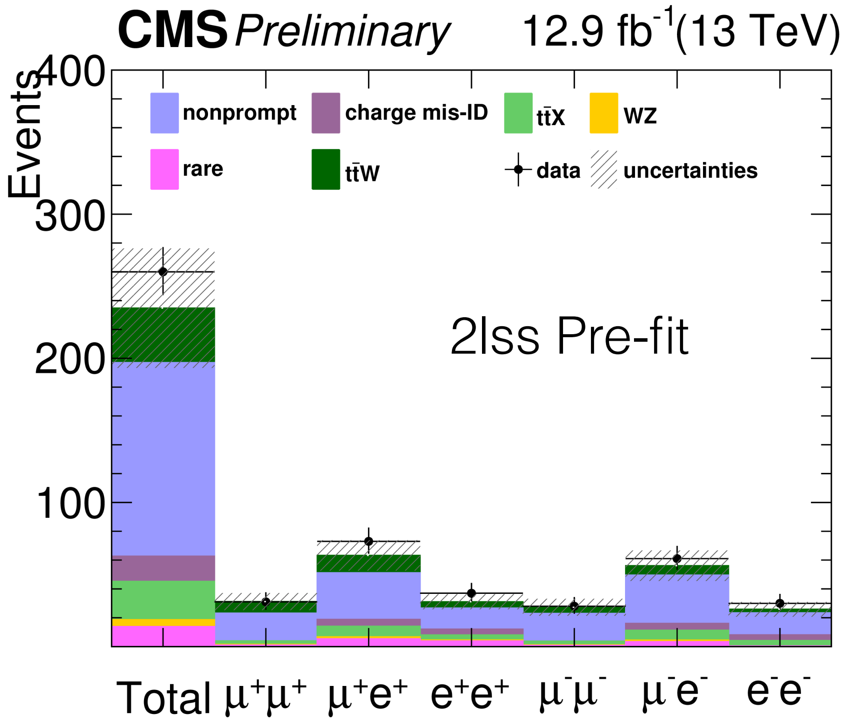
Category	Observed	Expected
4 jets, 3 b-tags	14.5	$18.6^{+8.2}_{-5.5}$
4 jets, $\geq$ 4 b-tags high BDT output	35.7	$25.6^{+13.4}_{-8.1}$
4 jets, $\geq$ 4 b-tags low BDT output	86.6	$84.2^{+41.3}_{-25.8}$
5 jets, 3 b-tags	16.0	$12.3^{+5.5}_{-3.6}$
5 jets, $\geq$ 4 b-tags high BDT output	7.5	$10.3^{+5.6}_{-3.4}$
5 jets, $\geq$ 4 b-tags low BDT output	35.2	$31.9^{+16.1}_{-9.9}$
$\geq$ 6 jets, 2 b-tags	25.4	$41.1^{+21.1}_{-13.1}$
$\geq$ 6 jets, 3 b-tags	9.6	$7.6^{+3.3}_{-2.2}$
$\geq$ 6 jets, $\geq$ 4 b-tags high BDT output	9.2	$8.3^{+4.4}_{-2.7}$
$\geq$ 6 jets, $\geq$ 4 b-tags low BDT output	15.4	$18.3^{+9.6}_{-5.8}$
$\geq$ 4 jets, $\geq$ 2 b-tags, boosted	7.5	$10.7^{+5.9}_{-3.5}$
lepton+jets combined	4.0	$4.1^{+1.8}_{-1.2}$

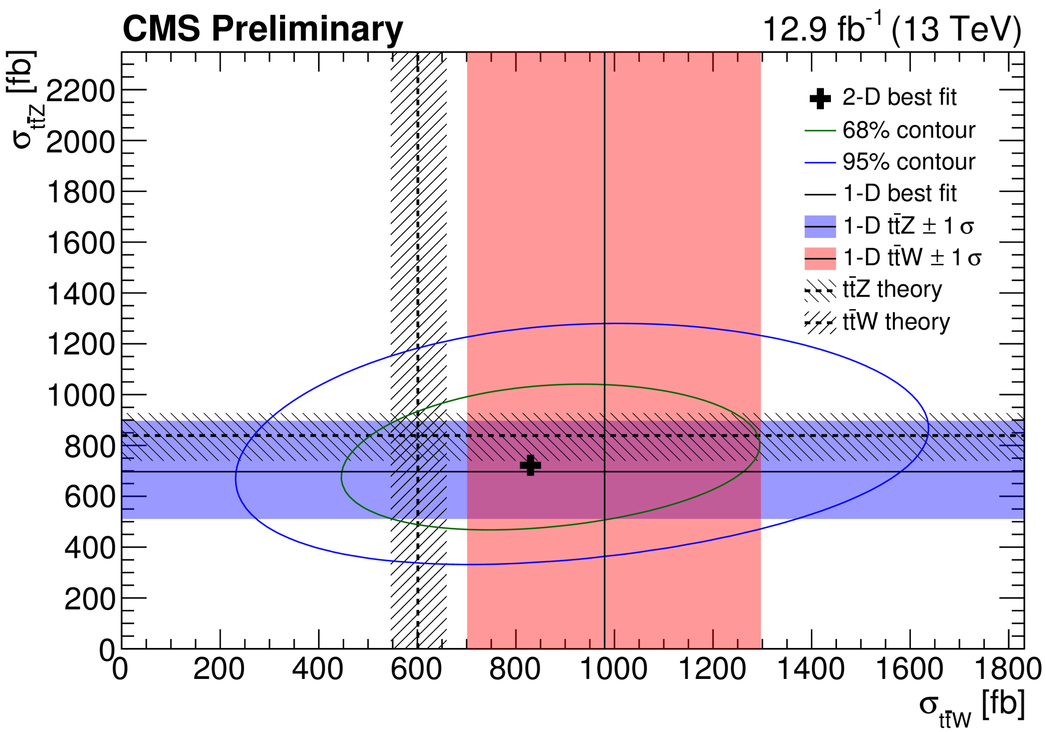
Process	$t\bar{t}$ rate up/down [%]	$t\bar{t}H$ rate up/down [%]
Jet energy Scale	$+11.3/-10.1$	$+7.7/-7.0$
Jet energy Resolution	$-0.1/+0.1$	$-0.1/+0.1$
Pile-Up	$-0.1/+0.0$	$+0.1/-0.2$
Electron Efficiency	$+1.6/-1.6$	$+1.6/-1.6$
Muon Efficiency	$+1.2/-1.2$	$+1.2/-1.2$
b-Tag HF contamination	$-3.5/+8.4$	$+0.2/+0.6$
b-Tag HF stats (linear)	$-6.4/+6.2$	$-5.3/+4.9$
b-Tag HF stats (quadratic)	$+4.2/-4.4$	$+3.3/-3.6$
b-Tag LF contamination	$+7.1/-5.1$	$+5.5/-4.2$
b-Tag LF stats (linear)	$-3.2/+6.5$	$-0.6/+1.1$
b-Tag LF stats (quadratic)	$+0.5/+1.2$	$-0.8/+1.1$
b-Tag charm Uncertainty (linear)	$-12.6/+16.9$	$-0.6/+0.7$
b-Tag charm Uncertainty (quadratic)	$+1.4/-1.4$	$+0.0/-0.0$
Q2 scale ($t\bar{t}$+lf)	$-1.9/+2.8$	–
Q2 scale ($t\bar{t}$+b)	$-0.6/+0.9$	–
Q2 scale ($t\bar{t}$+2b)	$-0.5/+0.8$	–
Q2 scale ($t\bar{t}$+$b\bar{b}$)	$-0.9/+1.3$	–
Q2 scale ($t\bar{t}$+$c\bar{c}$)	$-1.6/+2.4$	–
PS scale ($t\bar{t}$+lf)	$4.4/-8.7$	–
PS scale ($t\bar{t}$+b)	$-1.3/+0.8$	–
PS scale ($t\bar{t}$+2b)	$-1.0/+0.4$	–
PS scale ($t\bar{t}$+$b\bar{b}$)	$-2.0/+1.3$	–
PS scale ($t\bar{t}$+$c\bar{c}$)	$-4.3/+2.3$	–

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)

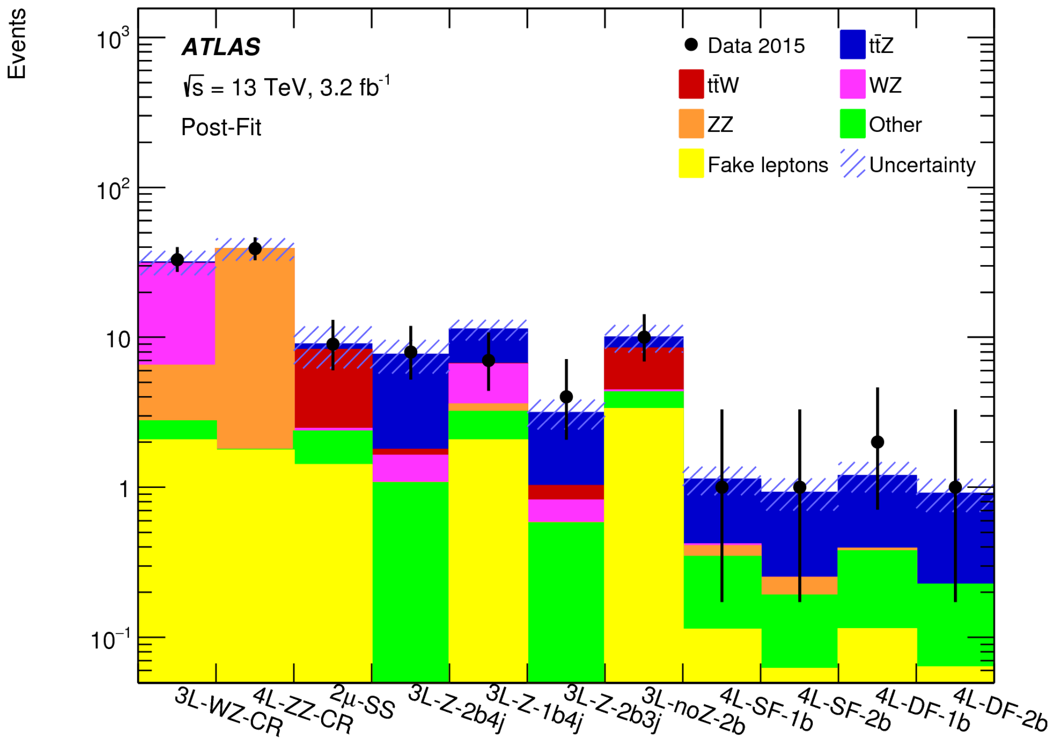


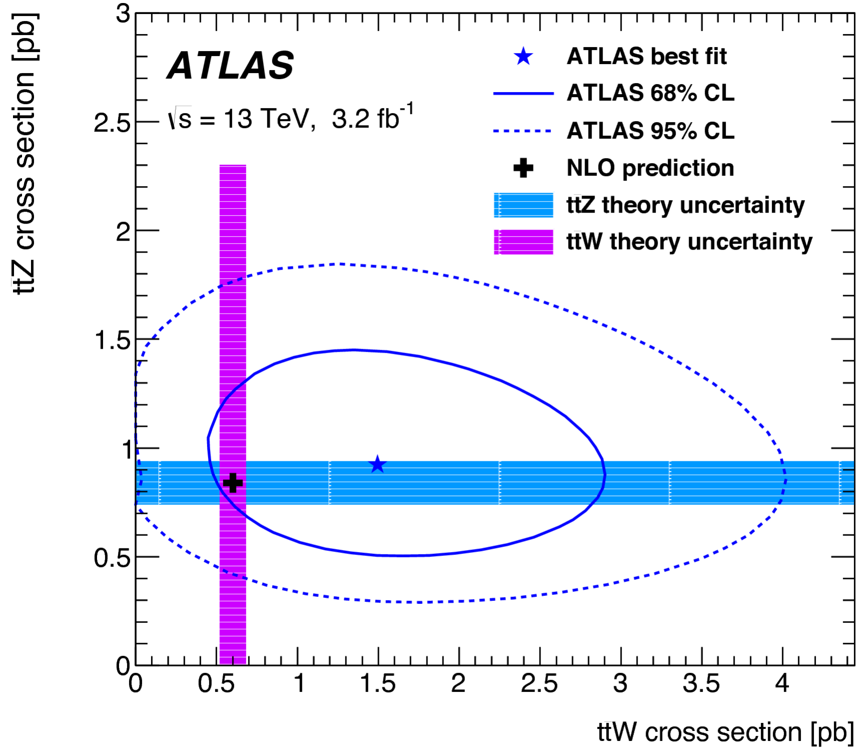


ATLAS ttbar+W/Z production at 13 TeV

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)





ttH multilepton : dimuon ?

ATLAS-CONF-2016-058, CMS HIG-16-022