

ETH zürich

Fermionic SM Higgs decays at CMS and ATLAS

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On behalf of the CMS and ATLAS collaborations

QCD @ LHC,
22-26 August, 2016



★ Higgs boson production and decay

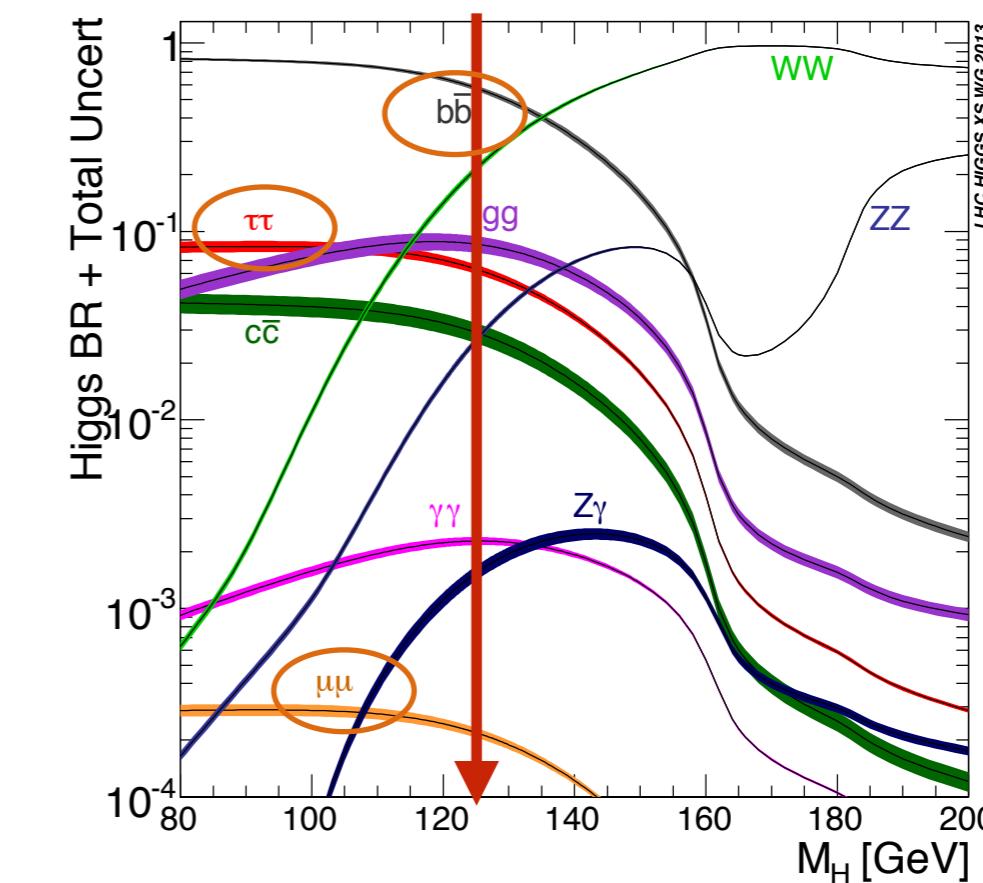
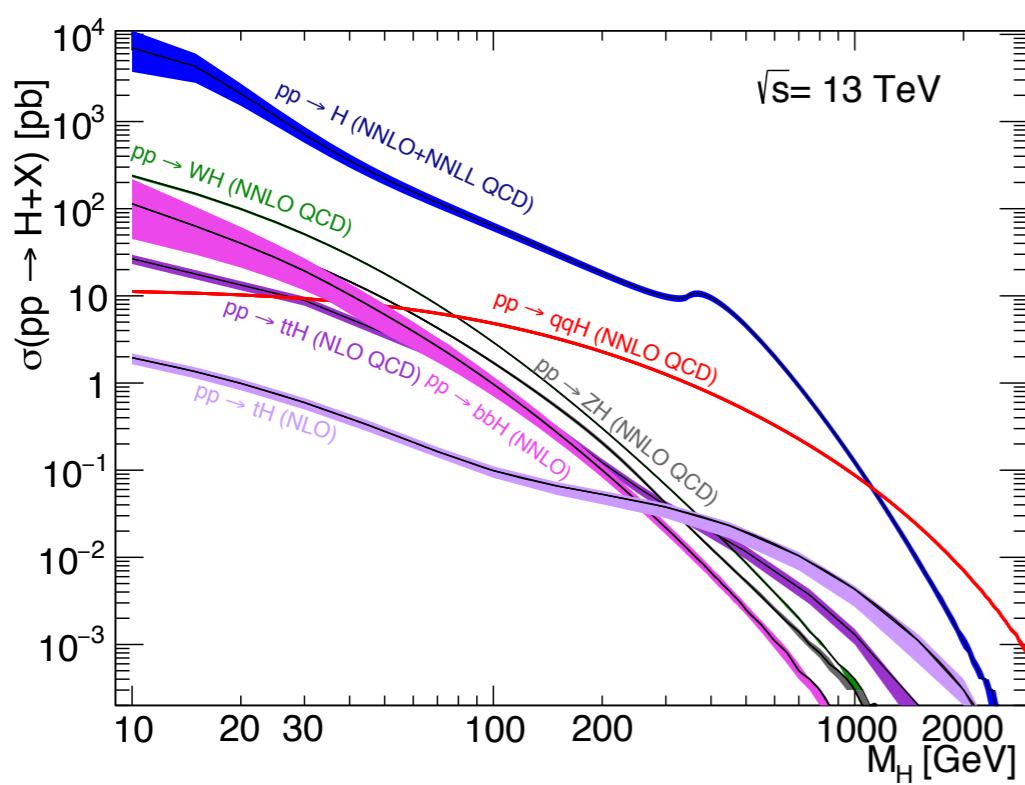
★ $H \rightarrow bb$

- $VH, H \rightarrow bb$ (ATLAS Run II[**NEW**])
- $VBF, H \rightarrow bb$ (CMS Run II[**NEW**])
- $VBF + \gamma, H \rightarrow bb$ (ATLAS Run II[**NEW**])
- $t\bar{t}H, H \rightarrow bb$ (ATLAS Run II[**NEW**], CMS Run II)

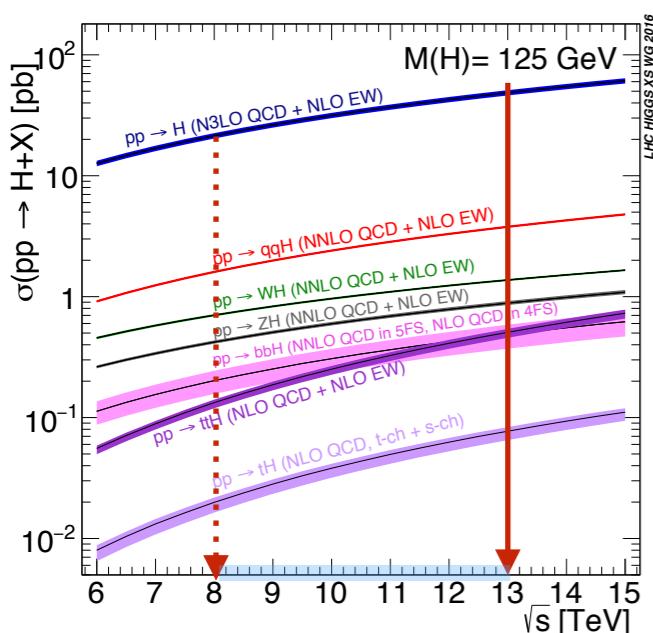
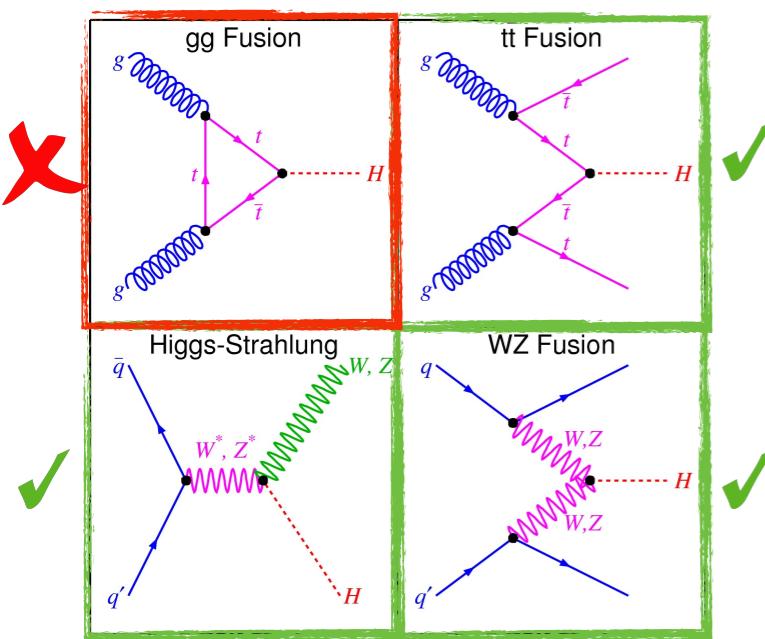
★ $H \rightarrow \tau\tau$ (ATLAS, CMS Run I)

★ $H \rightarrow \mu\mu$ (ATLAS Run II[**NEW**])

- ★ Higgs boson was discovered by ATLAS & CMS
 - Decays to $\gamma\gamma$, ZZ, WW
 - The properties measured so far are consistent with Standard Model
- ★ Large branching ratios for bb & $\tau\tau$
 - Analysis less sensitive due to overwhelming background
 - Observation in fermionic final state will be a test of Yukawa coupling



- ★ The highest decay BR in SM : $\text{BR}(H \rightarrow b\bar{b}) \approx 58\%$
- ★ Important to establish coupling of Higgs to down-type quarks
- ★ Inclusive search is not feasible at LHC due to overwhelming BG
- ★ Focus on more distinctive production modes : VH, VBF, ttH



Results from Run I :

CMS

Channel	H → $b\bar{b}$	Best fit (68% CL) Observed $\sigma/\sigma_{\text{SM}}$
VH		0.89 ± 0.43
$t\bar{t}H$		0.7 ± 1.8
VBF		$2.8^{+1.6}_{-1.4}$
Combined		$1.03^{+0.44}_{-0.42}$

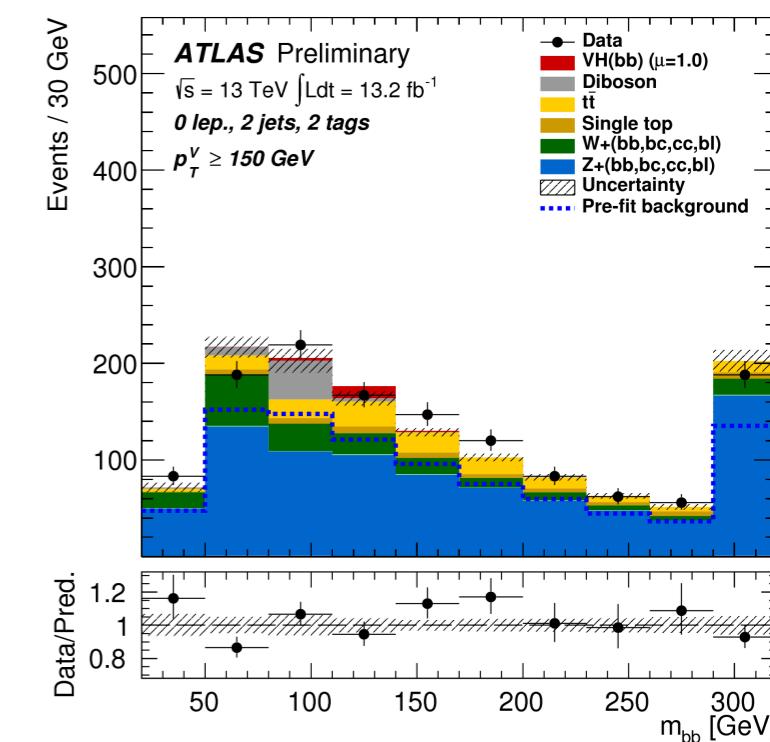
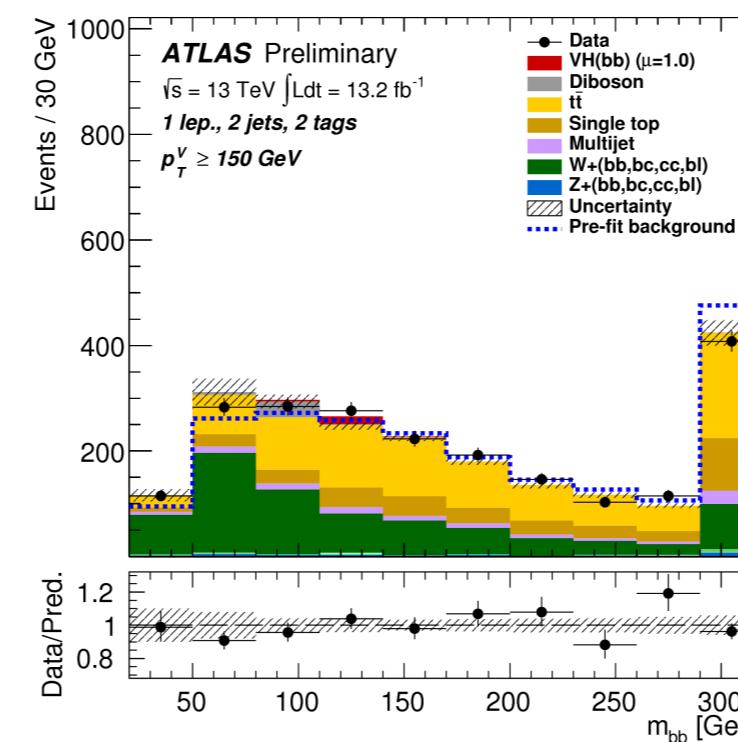
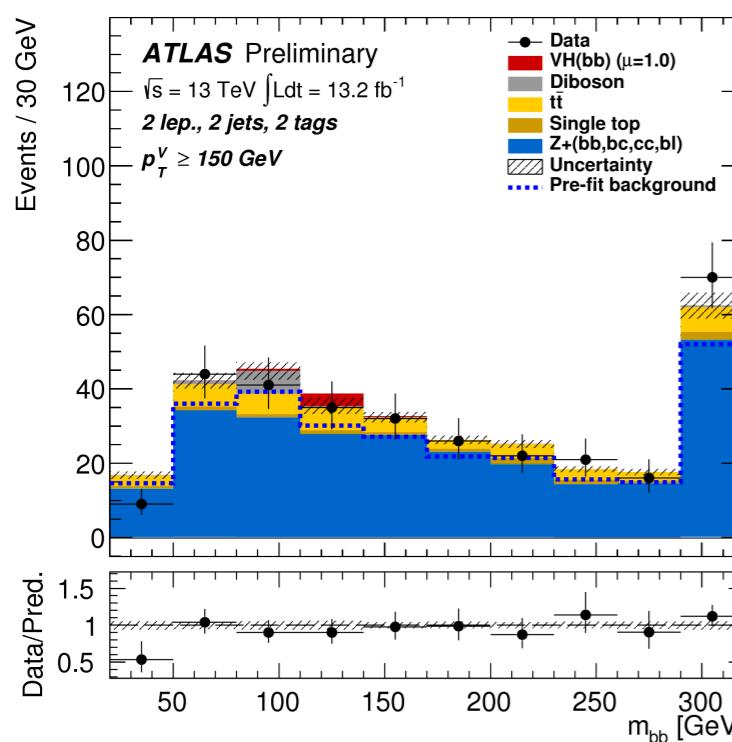
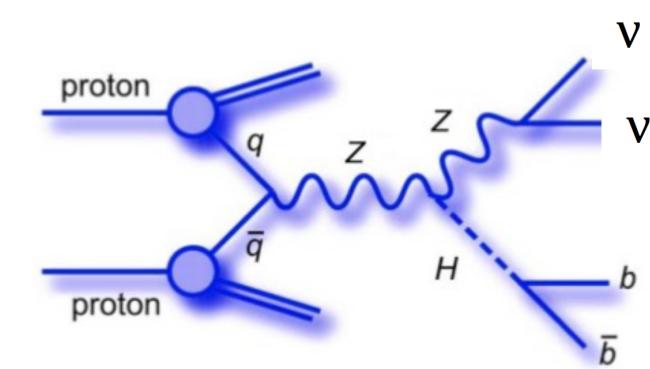
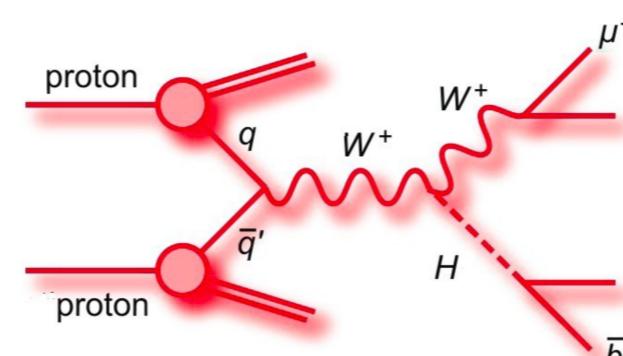
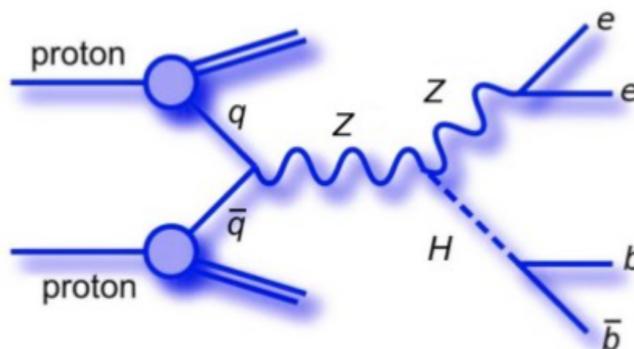
ATLAS

Channel	H → $b\bar{b}$	Best fit Observed $\sigma/\sigma_{\text{SM}}$
VH		$0.51^{+0.40}_{-0.37}$
$t\bar{t}H$		$1.4^{+1.0}_{-1.0}$
VBF		$-0.8^{+2.3}_{-2.3}$

Increased $\sqrt{s} = 13 \text{ TeV} \rightarrow$ increased cross section for both signal and BG. Most significant gain for ttH (~3.8 times compared to 8 TeV)

ATLAS-CONF-2016-091**NEW****13 TeV****Analysis strategy:**

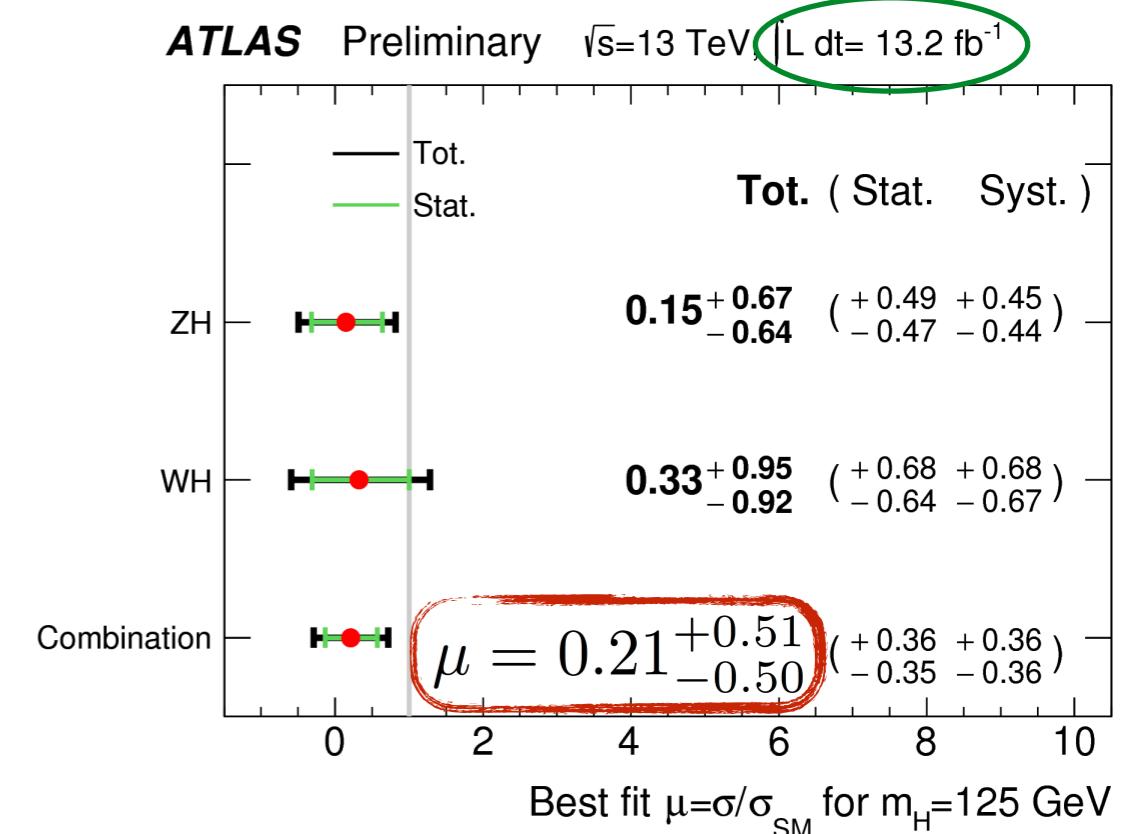
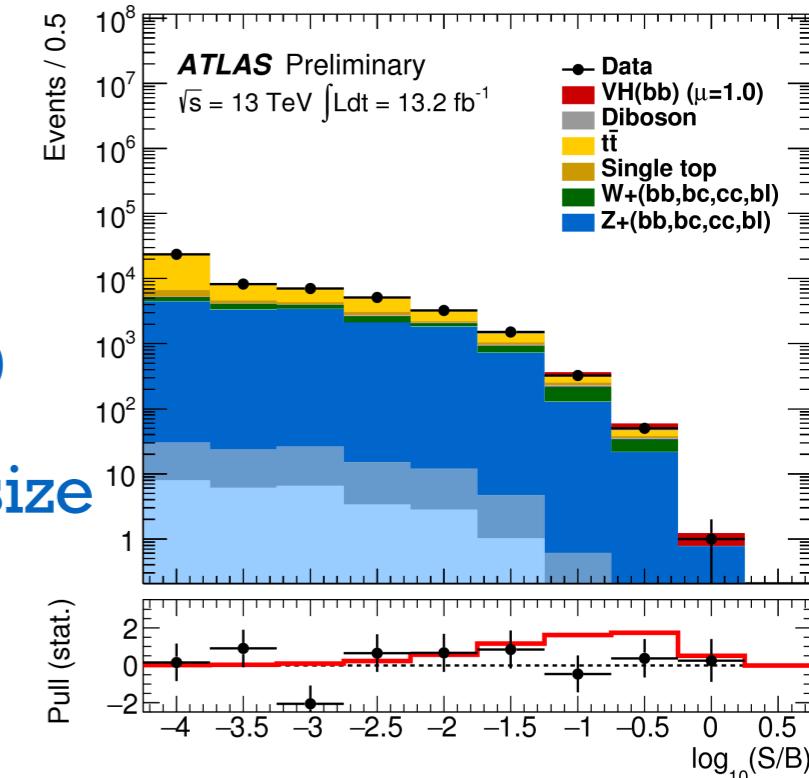
- Leptonic decays of Z/W events $\rightarrow 0, 1, 2$ leptons final state
- Use multivariate techniques(BDT) to achieve good S²/B
- Main backgrounds vary by channel: Z+b ($0, 2$ l); tt and W+jets ($1l$)
- Most discrimination from m_{bb} and ΔR(b₁,b₂)



VH, H \rightarrow bb. Results

- ★ Signal strength is extracted using profile likelihood fit
- ★ Use BDT discriminant as fitted shape
- ★ Cross check with di-boson signal (WZ+ZZ with Z \rightarrow bb).
Observed significance: 3.2σ . $\mu_{VZ} = 0.91 \pm 0.17(\text{stat})^{+0.32}_{-0.23}(\text{sys})$
- ★ Systematic and statistical uncertainties are of the same size
- ★ Systematic unc. is mainly from BG normalization (\downarrow with more data)

Significance (expected) μ		
ATLAS 13 TeV	$0.4\sigma(1.94\sigma)$	$0.21^{+0.51}_{-0.50}$
ATLAS 8 TeV	$1.4\sigma(2.6\sigma)$	$0.51^{+0.40}_{-0.37}$
CMS 8 TeV	$2.1\sigma(2.5\sigma)$	0.89 ± 0.43
ATLAS+CMS 7+8 TeV	$2.6\sigma(3.7\sigma)$	$0.70^{+0.29}_{-0.27}$



VBF H \rightarrow bb signature:

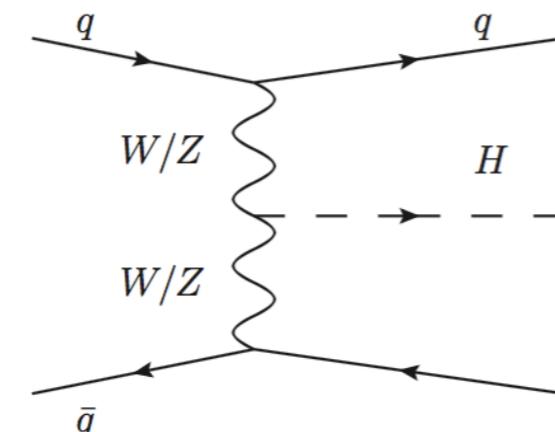
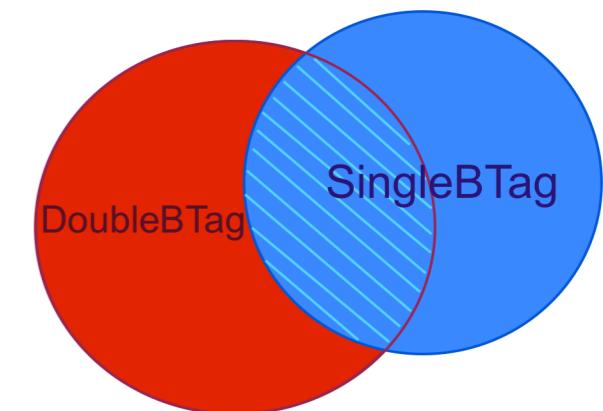
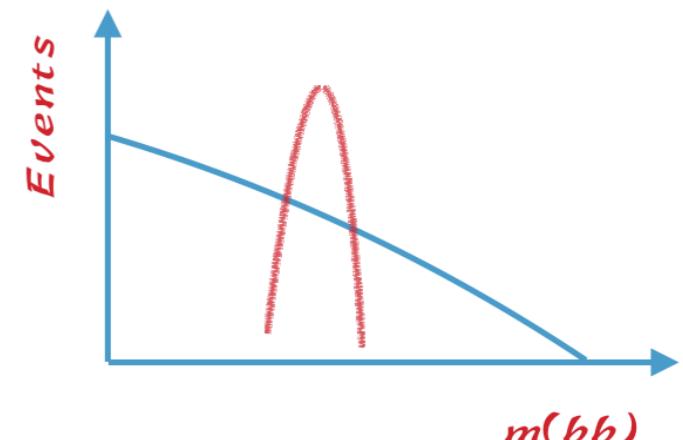
- 2 central b-jets
- 2 **light q-jets** with large $\Delta\eta$ and $m(jj)$
- suppressed colour-flow between VBF jets

Analysis strategy:

- topological triggers
- use MVA to exploit the differences between signal and QCD. **BDT is orthogonal to b-jet kinematics.**
- Perform fits of $m(bb)$ spectra in different MVA categories
- Search for a $m(bb)$ bump on a smoothly falling BG

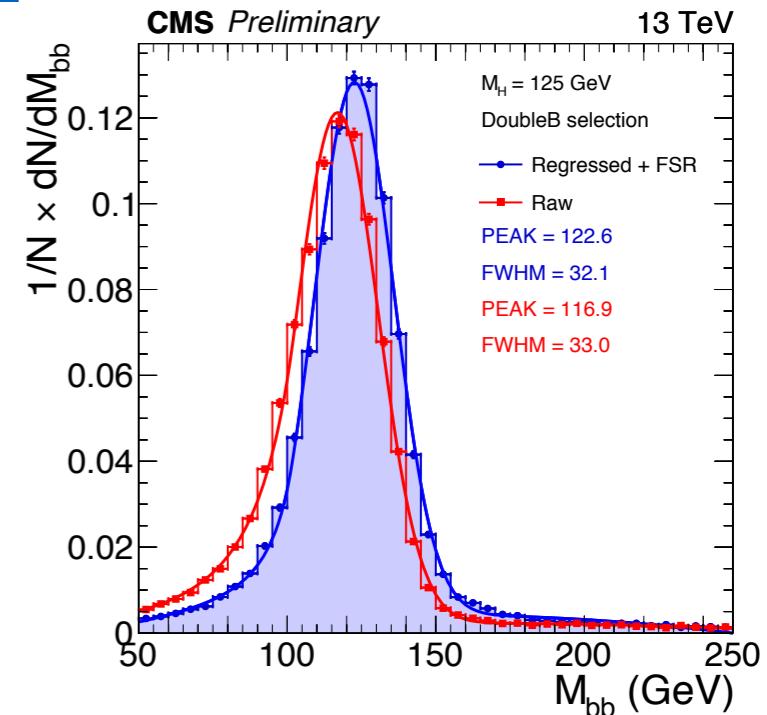
Offline selection:

- Offline selection follows trigger requirements
- Analysis is split into two parts from complementary trigger strategies : **SingleB** and **DoubleB**

CMS-HIG-16-003**NEW CMS****13 TeV**

To improve $m(bb)$ resolution the regression trained to correct jet pT. $m(bb)$ resolution is improved by 7%

- Targets semileptonic b decays that lead to mismeasurement due to undetected neutrino
- Trained using $t\bar{t}$ events, validated with $Z+jets$

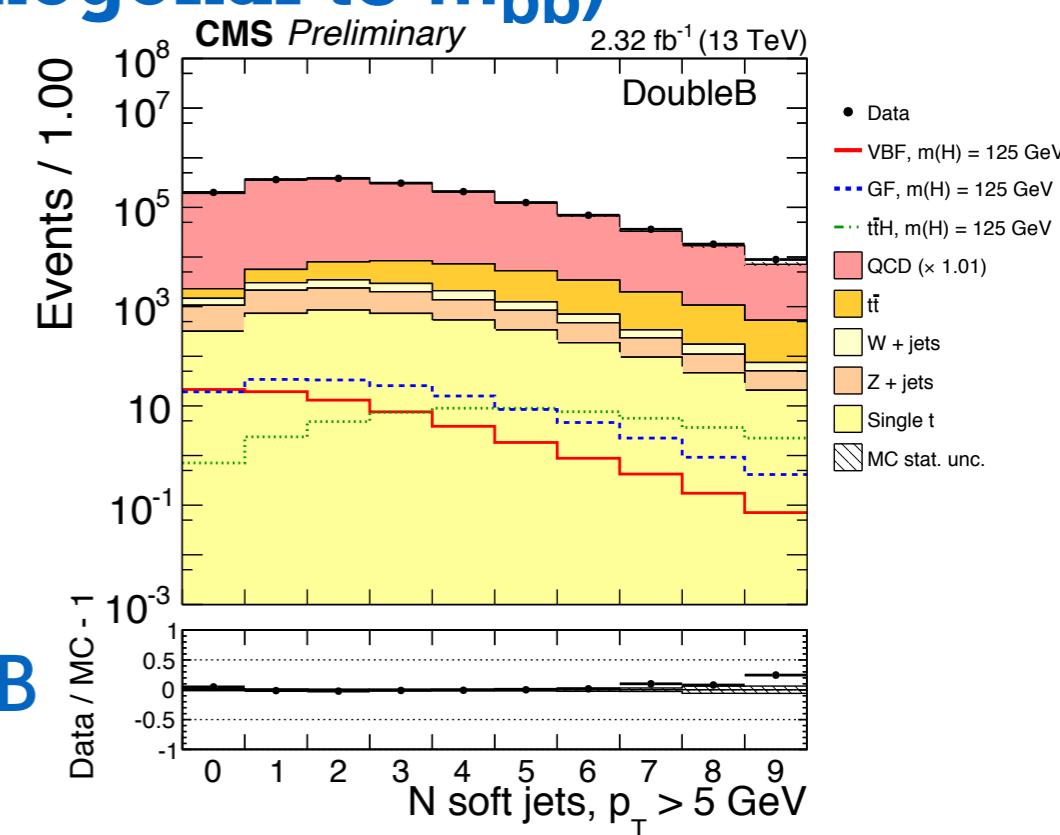


★ Event categorization based on BDT (orthogonal to m_{bb})

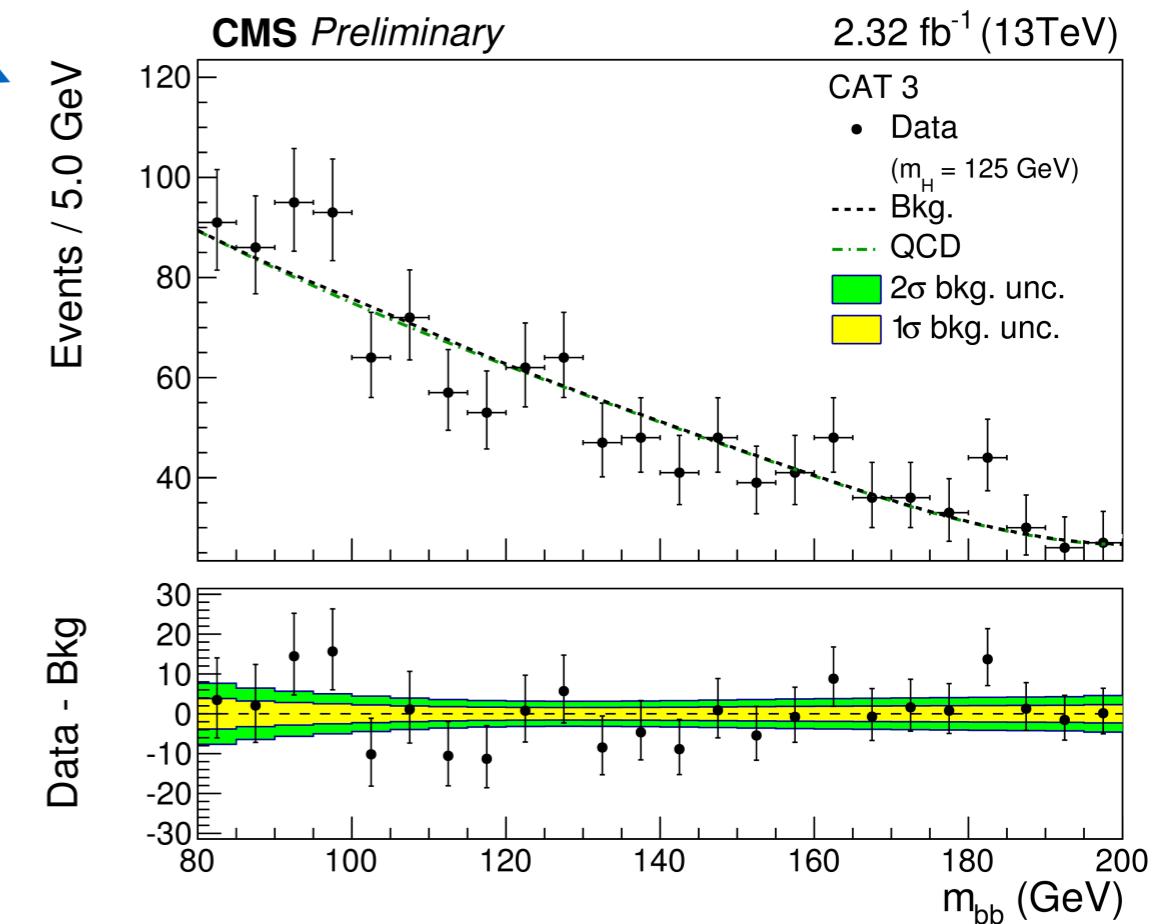
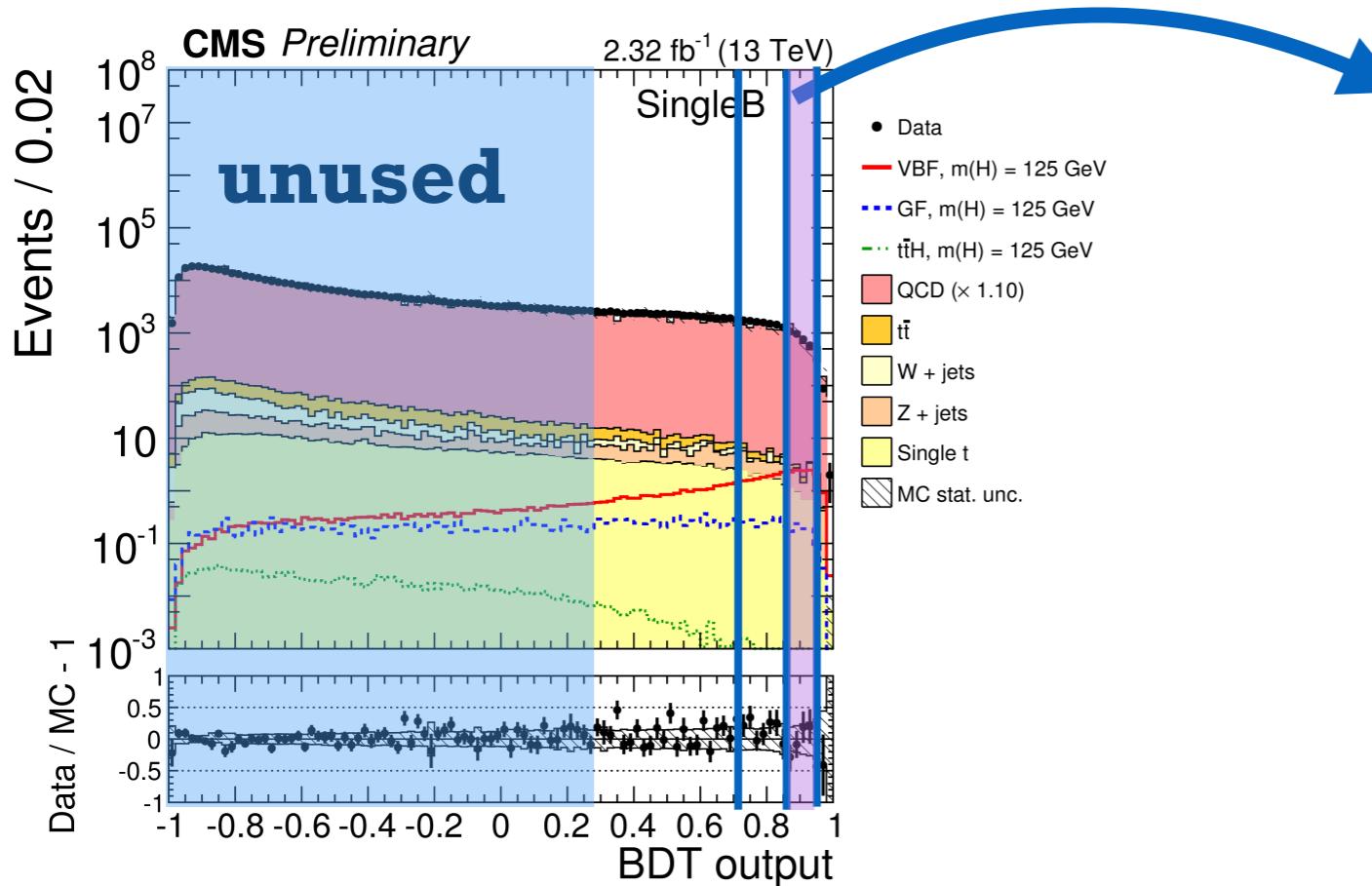
★ Discriminating variables like :

- color flow: soft track-jet multiplicity
- q/g discrimination: minor RMS of jet constituents in the η - ϕ plane
- VBF di-jet signature
- b-tag

★ Separate trainings for DoubleB & SingleB

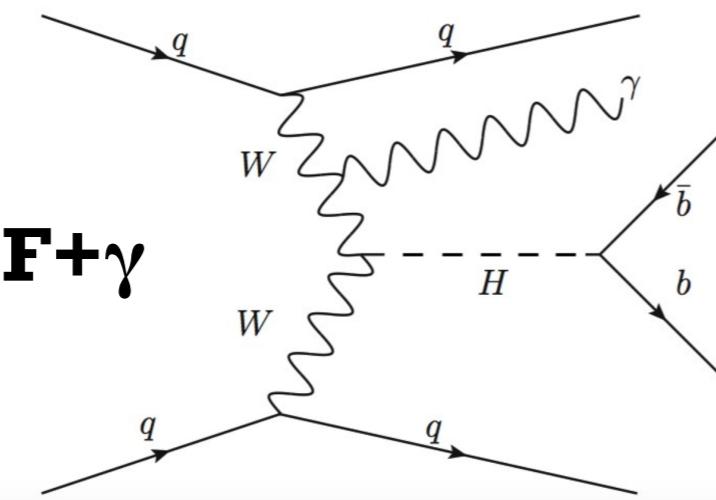


- ★ Events are divided in 7 BDT output categories to maximise the signal sensitivity
- ★ QCD MC is **NOT** used in the fit, data from signal-free category is used to model BG and then «transferred» to the signal categories
- ★ top & Z+jets are modelled from MC, normalization floating
- ★ Simultaneous fit in 7 signal categories

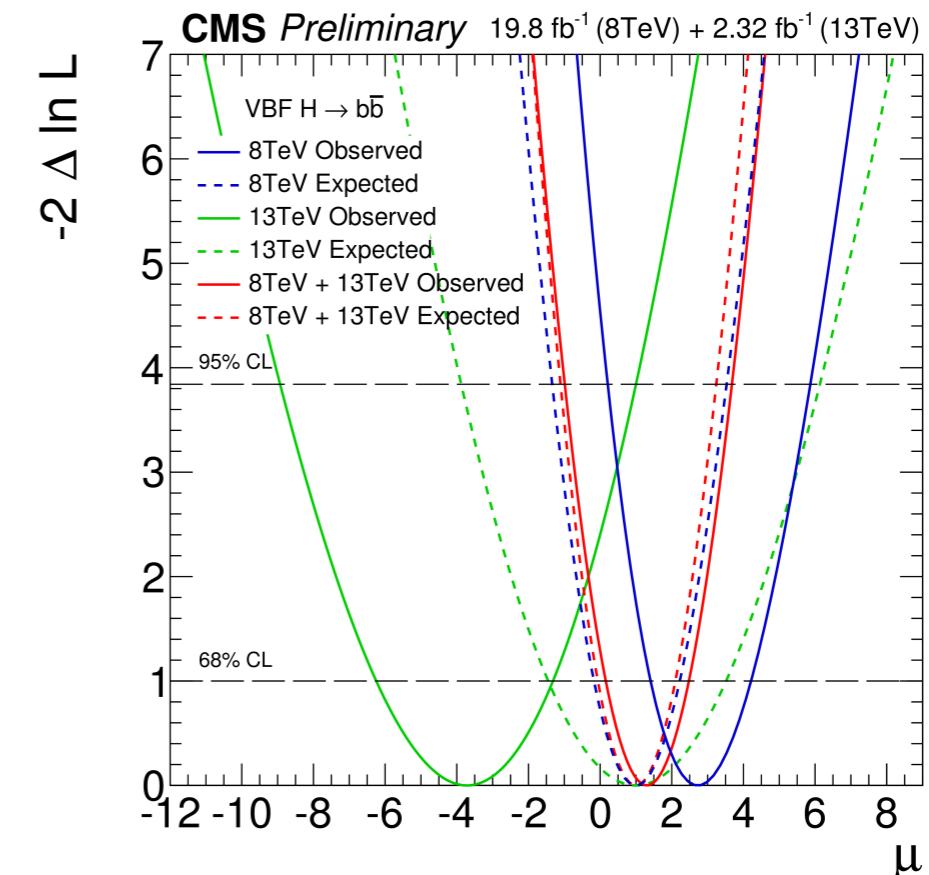
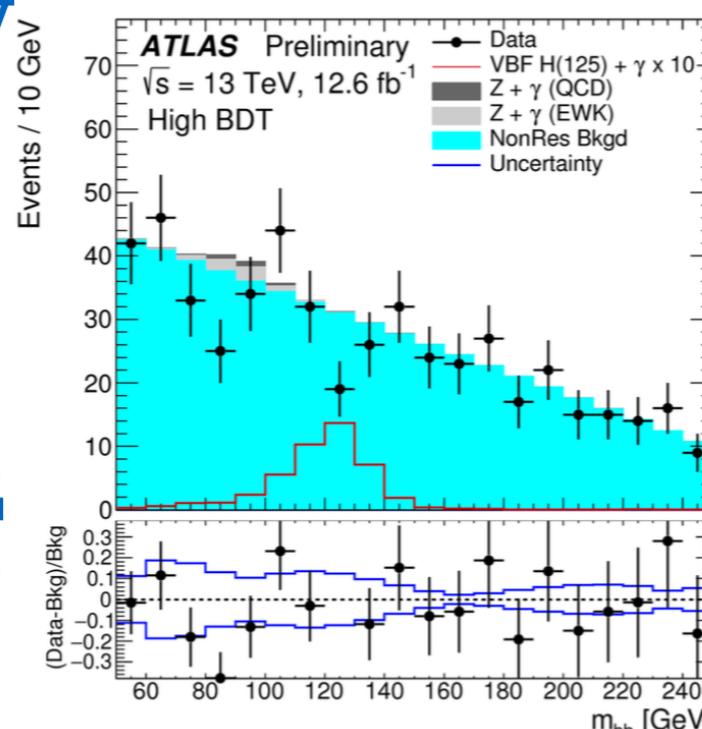


13 TeV

$\mu = -3.72^{+2.39}_{-2.51}$
U.L. @ 95% CL (expected) : 3.0(5.0)

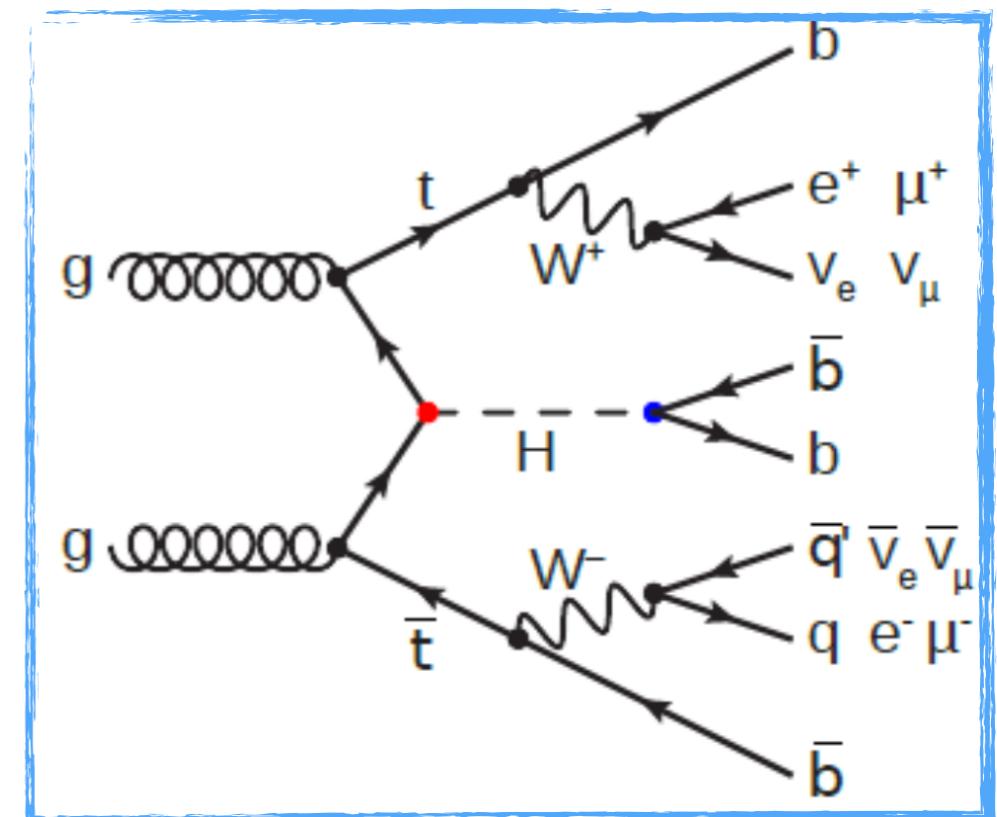
ATLAS-CONF-2016-063**NEW ATLAS****VBF+ γ** **13 TeV**

- ★ Triggers: L1 single photon, 4 jets at HLT
- ★ Selection : tight γ id, vbf signature, $m(jj) > 800$ GeV
- ★ BDT $\perp m(bb)$
- ★ Fit $m(bb)$ in 3 categories
- ★ $\mu = -3.9^{+2.8}_{-2.7}$
- ★ U.L. @ 95% CL (expected): 4.0(6.0)



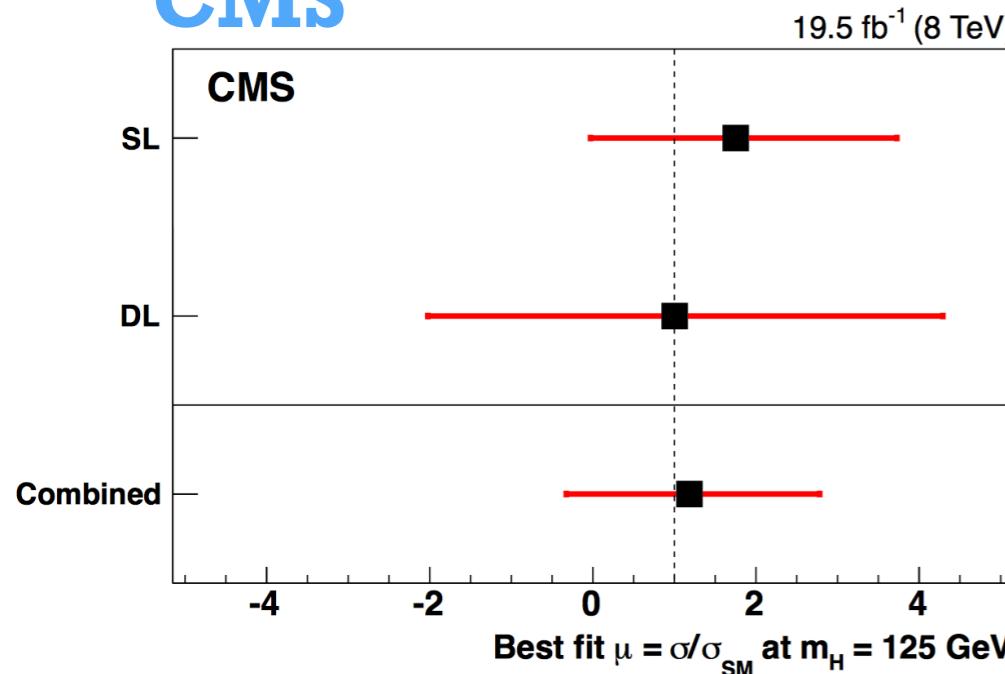
	U.L. @ 95% CL (expected)	μ
CMS 13 TeV	3.0(5.0)	$-3.7^{+2.4}_{-2.5}$
CMS 8 TeV	5.5(2.5)	$2.8^{+1.6}_{-1.4}$
CMS 8 TeV+13 TeV	3.4(2.2)	$1.3^{+1.2}_{-1.1}$
ATLAS 8 TeV	4.4(5.4)	-0.8 ± 2.3
ATLAS VBF+ γ 13 TeV	4.0(6.0)	$-3.9^{+2.8}_{-2.7}$

- ★ $t\bar{t}H$ is the only possibility to measure top-Higgs Yukawa coupling directly
- ★ Large increase of x-sec with \sqrt{s}
- ★ **high cross section x BR**, but complex multi-jet final state
- ★ **Rich experimental signature**, varies by the decay of the top quarks(1 ℓ , 2 ℓ , fully hadronic)
- ★ **Critical** to model the $t\bar{t}$ +jets BG

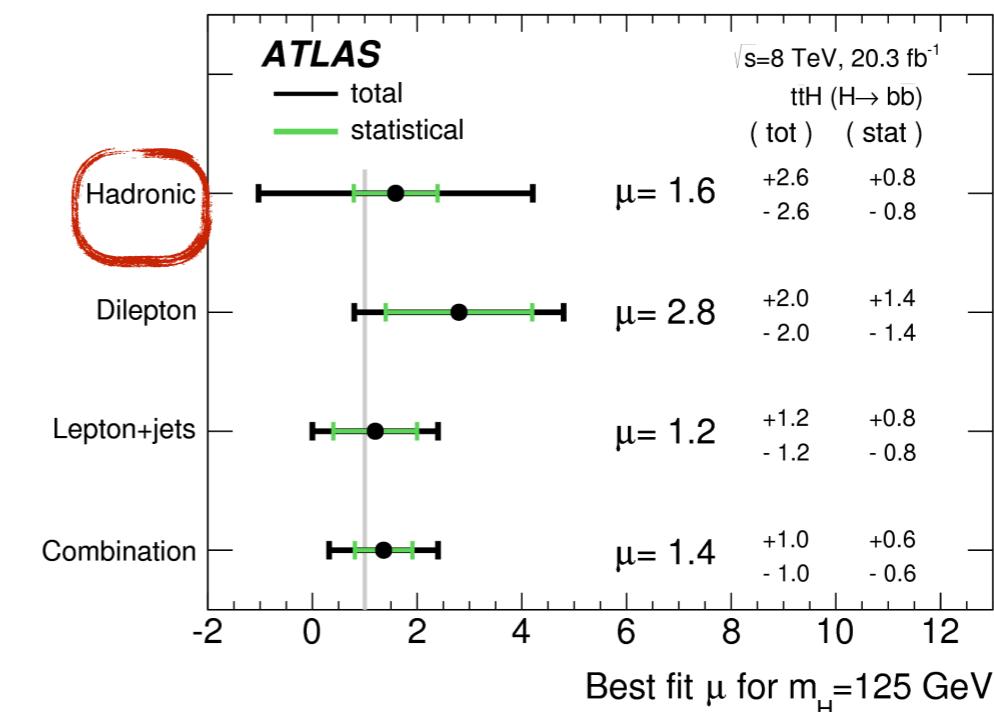


Results from Run I :

CMS



ATLAS



★ Analysis strategy:

- 2 categories: lepton+jets & dileptons
- Lepton triggers and offline event selection
- =1, =2 opposite sign leptons
- $\geq 4, \geq 3$ jets
- ≥ 2 b-tags
- ♦ lepton+jets: high statistics
- ♦ dileptons: minimal non tt BG, minimal jet combinatorics

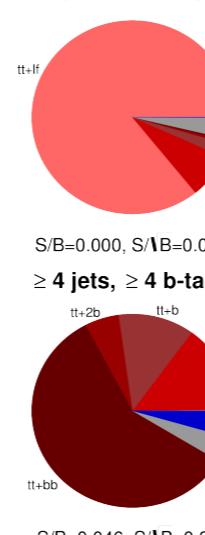
★ Events are further categorised by jets, b-tag multiplicities and for CMS boosted jets($l+jets$)

★ $tt+\geq 1$ bjet, $tt+\geq 1$ cjet, tt +light jets are dominant BG

CMS-HIG-16-004

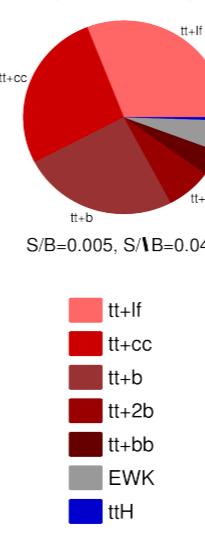
CMS Simulation

3 jets, 2 b-tags



S/B=0.000, S/B=0.026

3 jets, 3 b-tags



S/B=0.005, S/B=0.047

ATLAS-CONF-2016-080

NEW

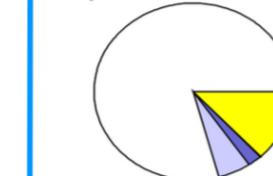
13 TeV

dilepton

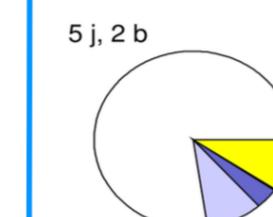
ATLAS

Simulation Preliminary
 $\sqrt{s} = 13$ TeV
Single Lepton

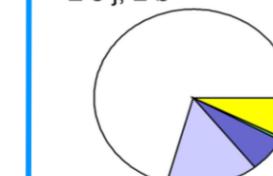
4 j, 2 b



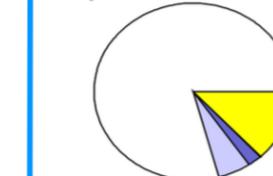
5 j, 2 b



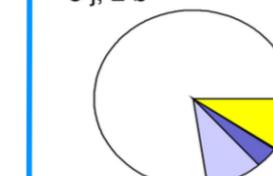
≥ 6 j, 2 b



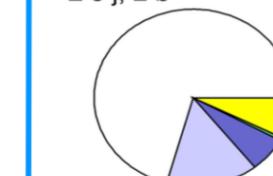
4 j, 3 b



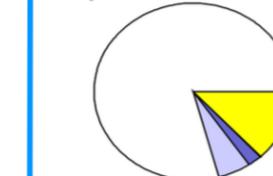
5 j, 3 b



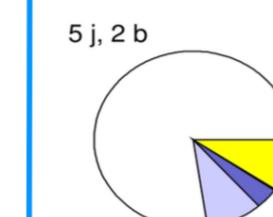
≥ 6 j, 3 b



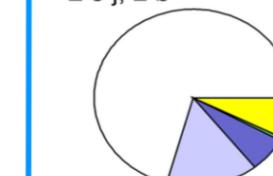
4 j, ≥ 4 b



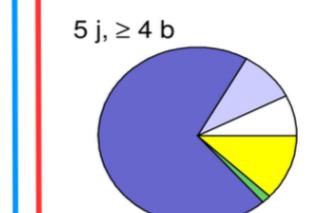
5 j, ≥ 4 b



≥ 6 j, ≥ 4 b



Control Region



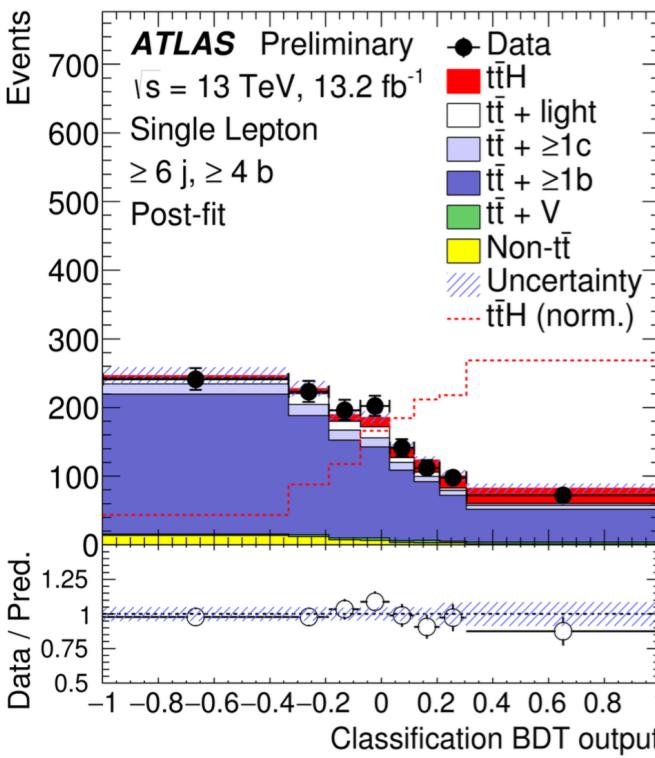
Signal Region

Exploit different background compositions in simultaneous fit of all regions to reduce uncertainties.

lepton+jets

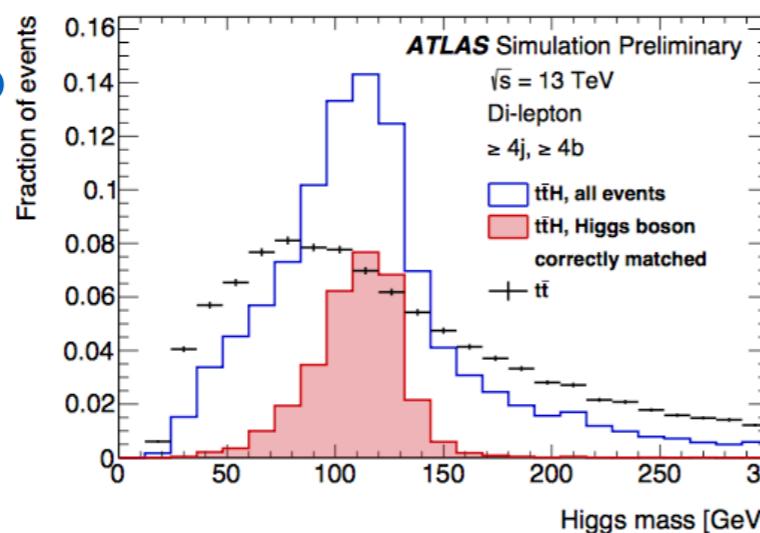
ATLAS uses 2-stage multivariate technique in **signal regions**:

'Reconstruction BDT' is trained to match jets to partons from top and Higgs using ttH simulation.
Matching ε for Higgs jets ~ 30%



2nd stage - 'Classification BDT' to classify events as Signal and BG. BDT output shape fitted to data.

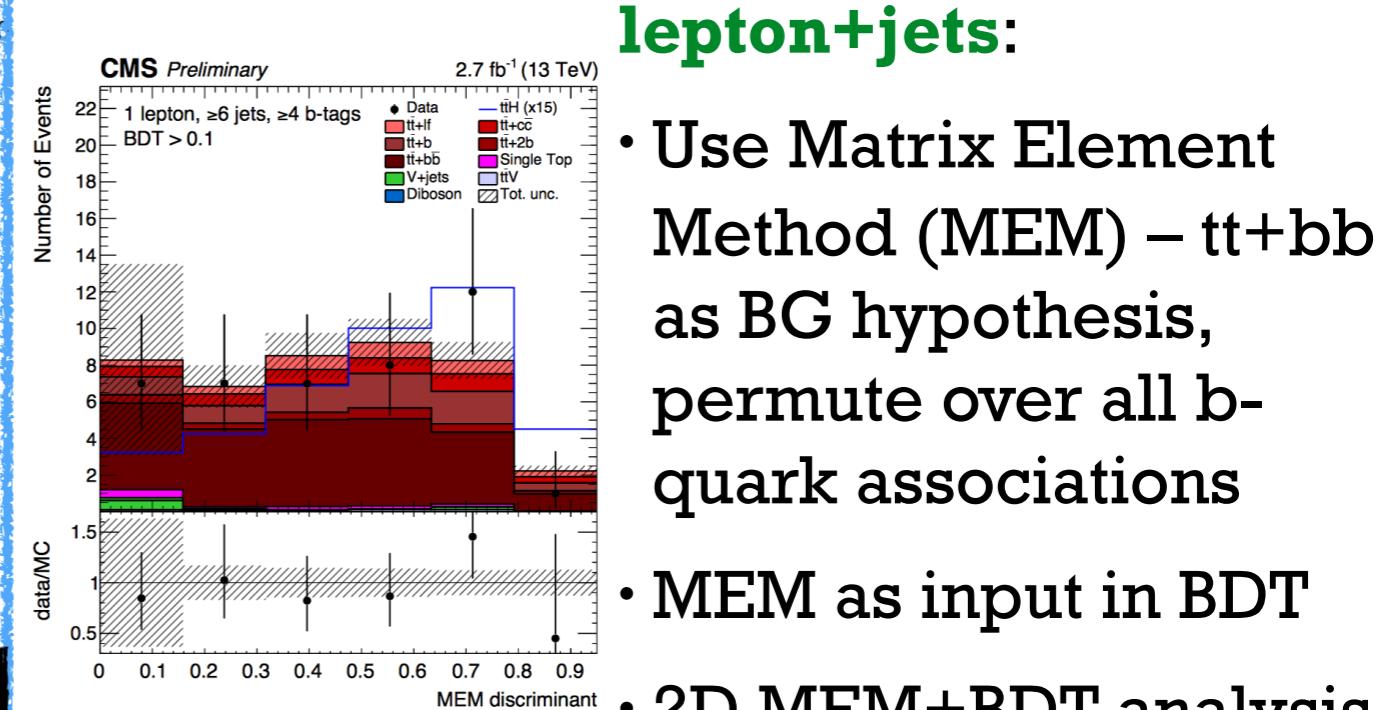
In **control regions** $H_T^{\text{all}}(H_T^{\text{had}})$ is used as discriminating variable.



CMS includes a boosted category, uses BDT and MEM as input in BDT for some categories.

dileptons, lepton+jets:

- Use Boosted Decision Tree (BDT)
- Good separation against inclusive tt BG

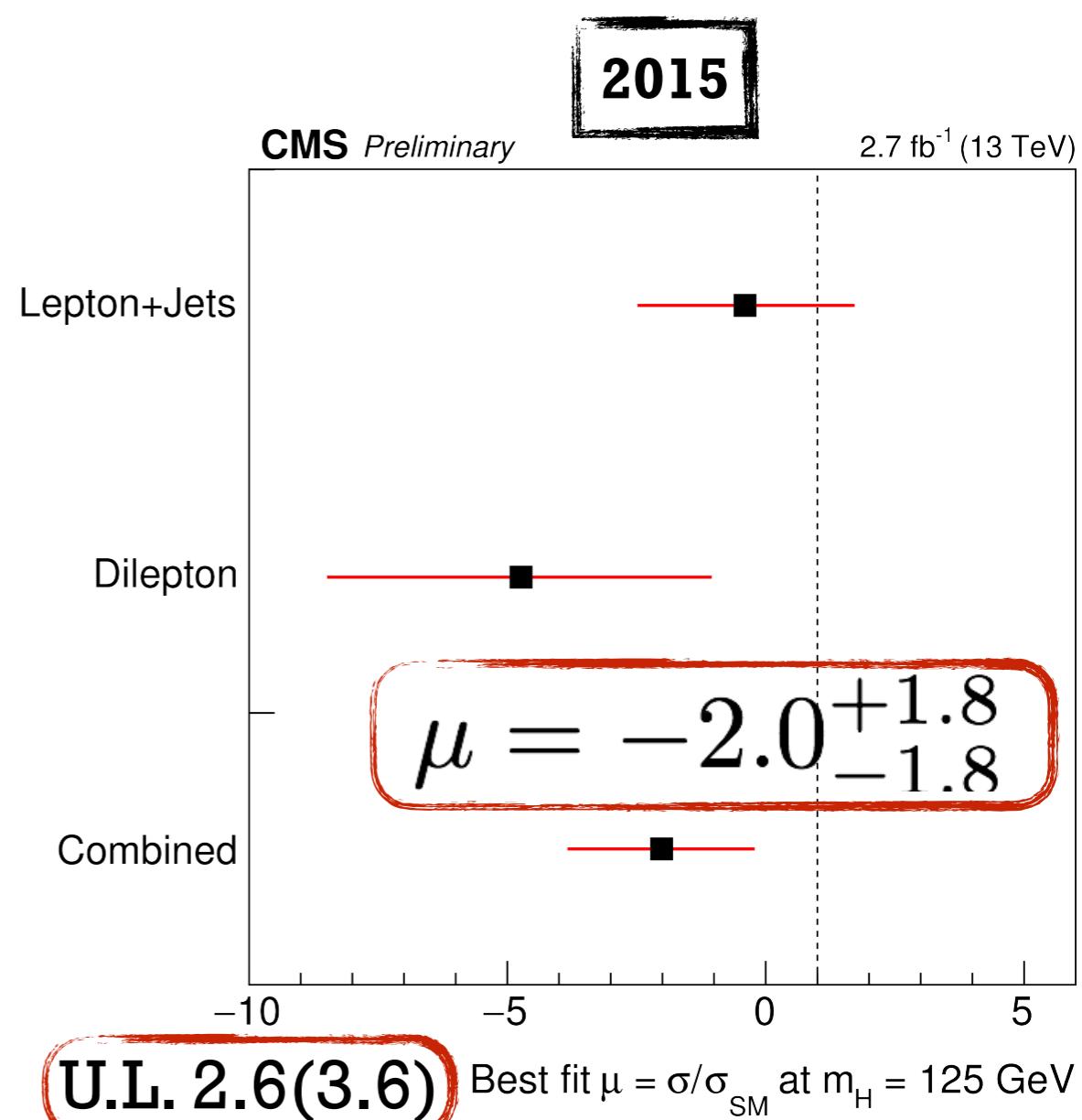
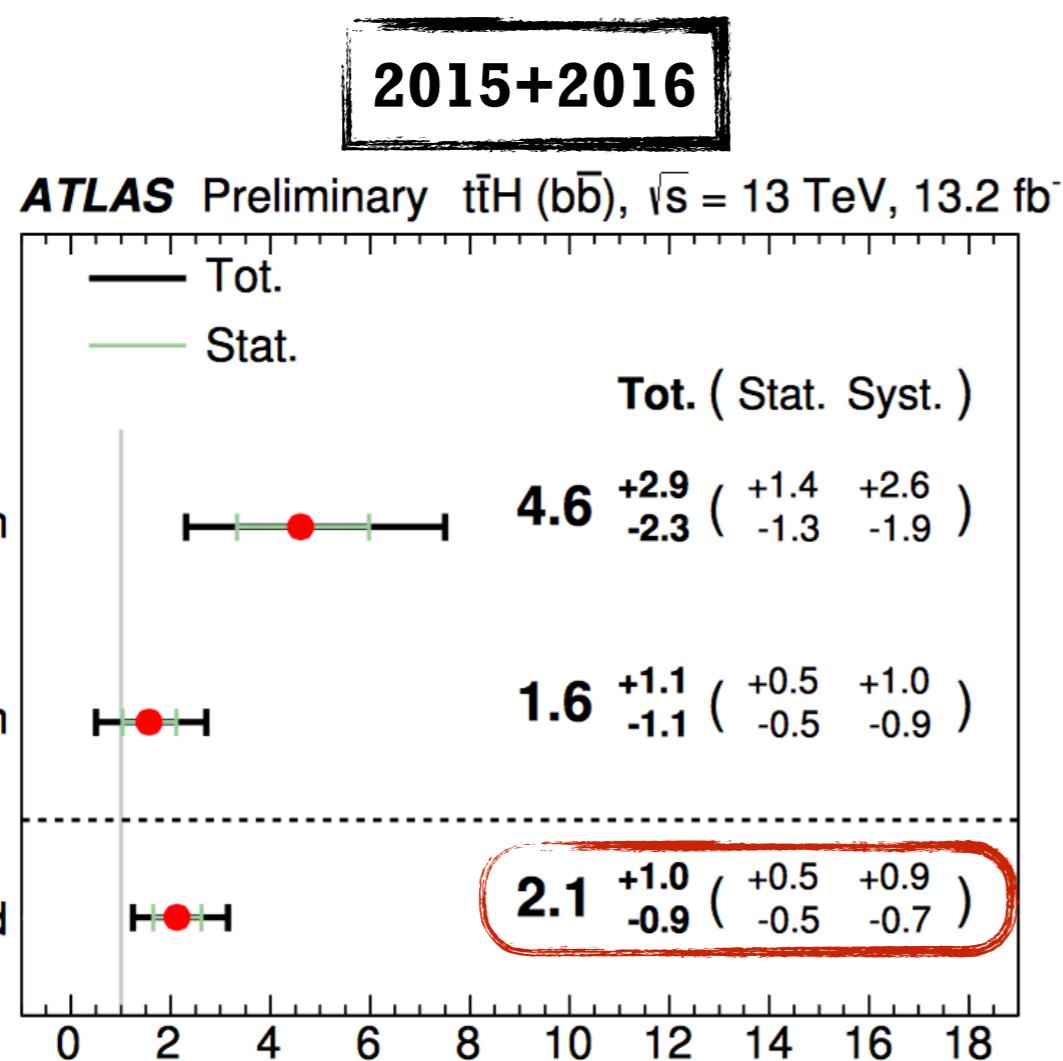


lepton+jets:

- Use Matrix Element Method (MEM) – tt+bb as BG hypothesis, permute over all b-quark associations
- MEM as input in BDT
- 2D MEM+BDT analysis

Final discriminant is fit to data

- ★ CMS 2.7 fb^{-1} 2015 data, ATLAS 13.2 fb^{-1} 2015+2016 data
- ★ Simultaneous binned maximum likelihood fit across all categories
- ★ Uncertainty of the measurement is dominated by normalization and modelling of $t\bar{t} + b/c$ jet BGs. Systematics dominated.

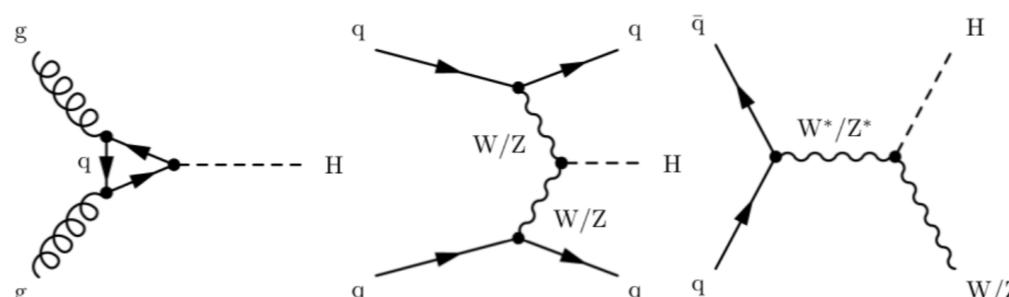
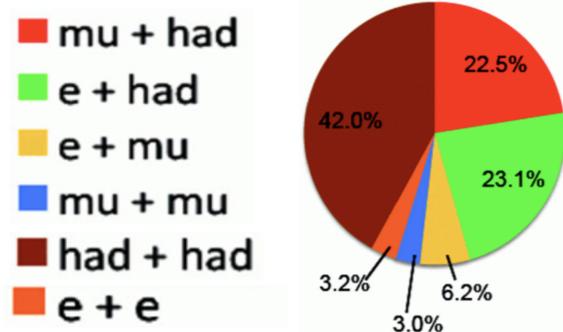


★ **BR = 6.3 %**

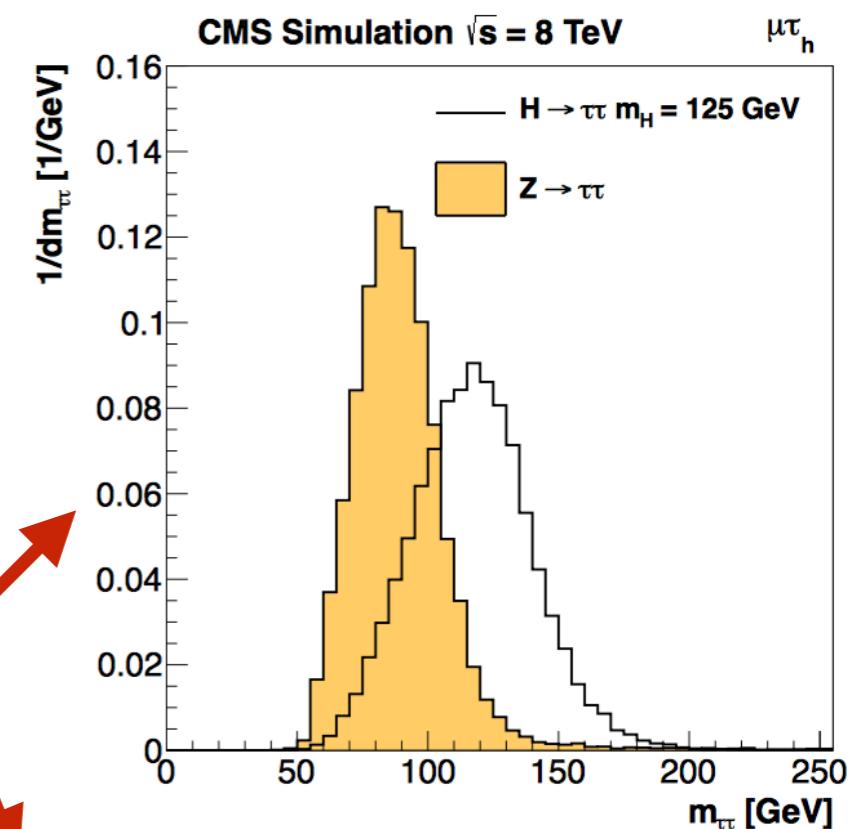
★ **Production Process:**
GF, VBF, VH

★ **Channels:**

$ee, \mu\mu, e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$

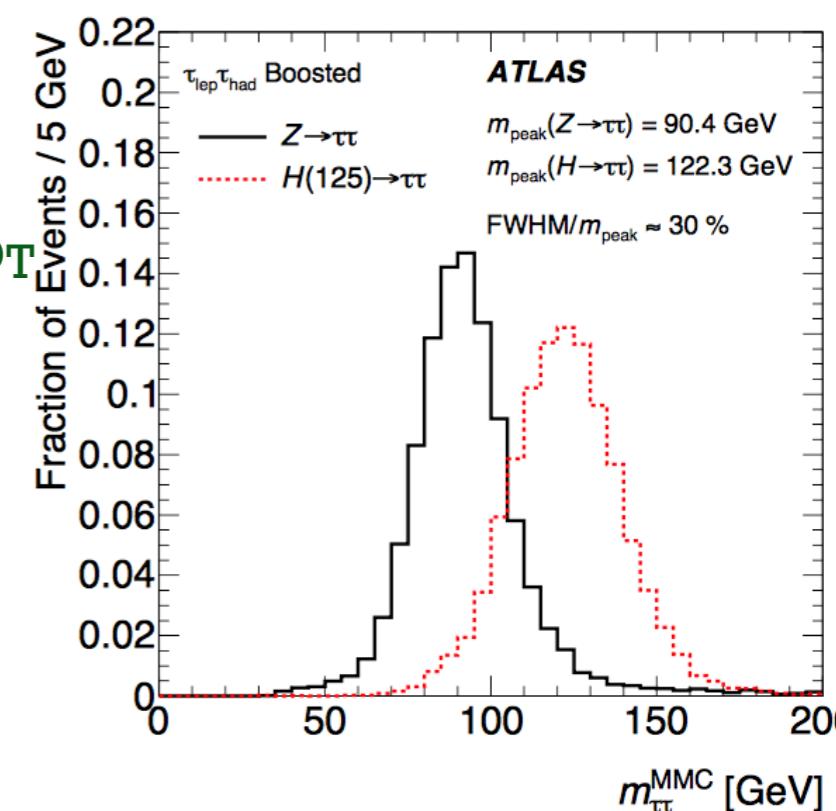


Both experiments use likelihood techniques to reconstruct full di- τ mass
M $\tau\tau$ resolution: 10 - 20%



Analysis:

- Main challenges: mass resolution, triggering
- Events are categorized based on jet multiplicity and p_T
- 0-jet: ~signal-free, constrain BGs
- 1-jet (“boost”): sensitive to GF, in CMS further divided using p_T(τ) and p_T(H)
- 2-jets : sensitive to VBF, in CMS further divided in Loose&Tight categories



Signal Extraction

★ ATLAS: BDT discriminant

- Combining event kinematics and $M_{\tau\tau}$
- BDT trained separately in each channel and category

★ CMS: cut based with fit of $M_{\tau\tau}$

- Events divided into many sub-categories (previous slide)

Background

★ Major backgrounds: $Z \rightarrow \tau\tau$, $W + \text{jets}$, QCD, $t\bar{t}$

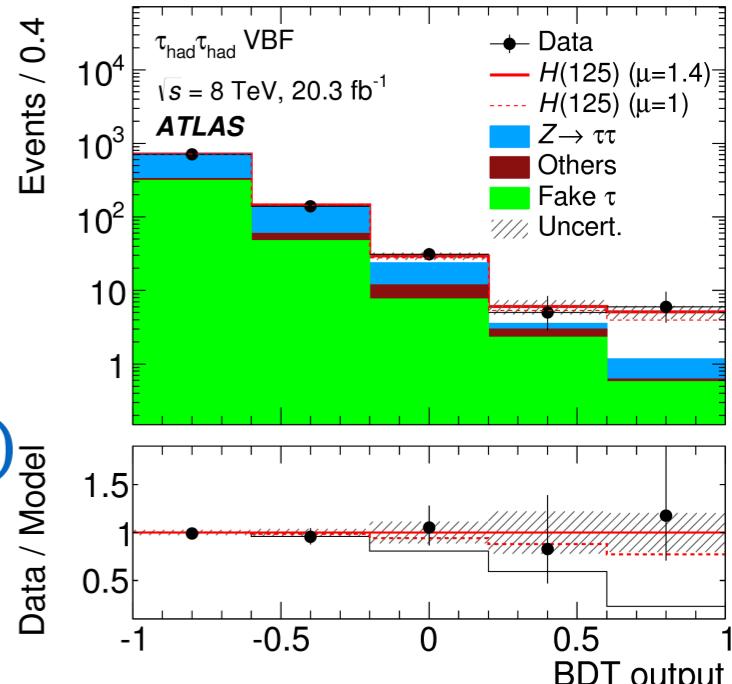
★ Estimation from data using embedding method ($Z \rightarrow \tau\tau$) and fake rate method ($W + \text{jets}$, QCD)

Results

	μ	Significance (expected)
CMS 8 TeV	$0.89^{+0.31}_{-0.28}$	3.4(3.7)
ATLAS 8 TeV	$1.41^{+0.40}_{-0.35}$	4.4(3.3)
CMS+ATLAS	$1.12^{+0.25}_{-0.23}$	5.5(5.0)

CMS : JHEP 05 (2014) 104

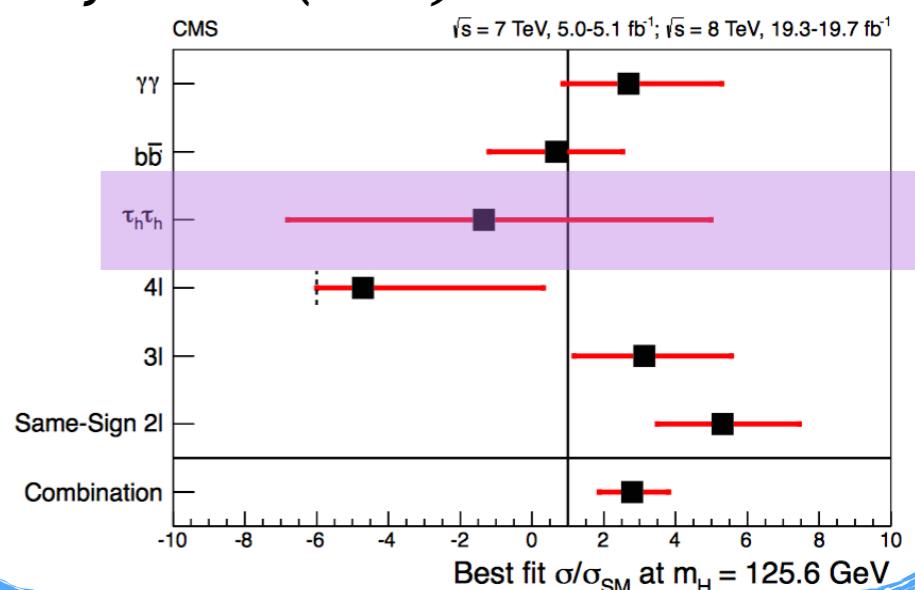
ATLAS : JHEP 04 (2015) 117



another production mode: $t\bar{t}H$

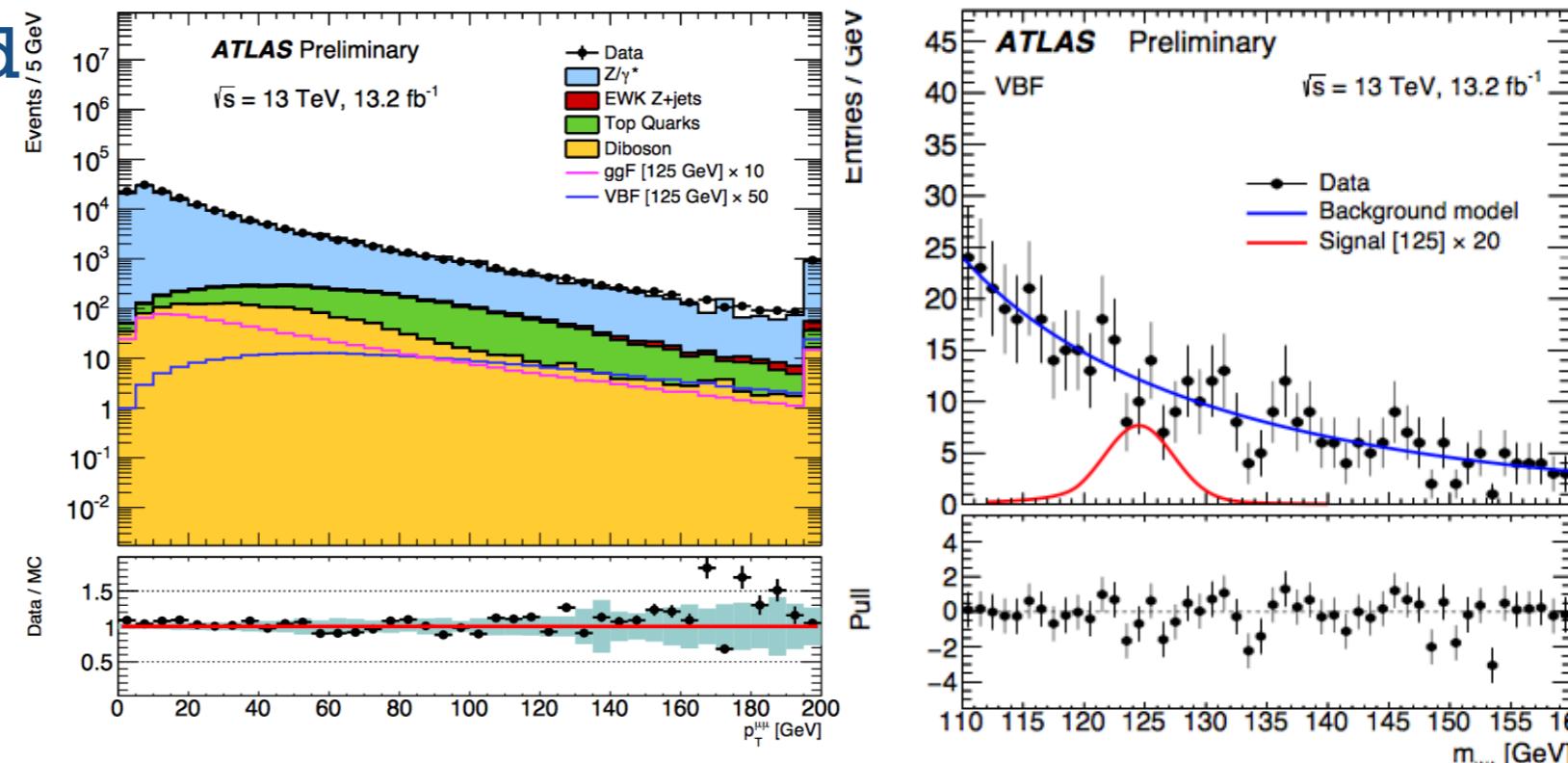
ATLAS : Phys.Lett. B 749 (2015) 519

CMS: JHEP 09 (2014) 087



- ★ Very rare decay BR = 0.022%
- ★ Higgs boson coupling to 2nd generation fermions
- ★ **Signature:**
clean final state, but **small BR** and **overwhelming** $Z/\gamma^* \rightarrow \mu\mu$ **background**.
- ★ **Analysis strategy:**
Search for peak in $m_{\mu\mu}$ spectrum over smoothly falling background
- ★ Events categorization according to VBF and GF signature enriched. 1 cat for VBF and 6 for GF based on $p_T(\mu\mu)$ and $\eta(\mu\mu)$

ATLAS-CONF-2016-041



	U.L. @ 95% CL (expected)
ATLAS 13 TeV	4.4(5.5)
ATLAS 7+8 TeV	7.1(7.2)
ATLAS 7+8+13 TeV	3.5(4.5)
CMS 8 TeV	7.4(6.5)

Summary

- ★ Lots of progress in Higgs fermionic searches from both CMS and ATLAS
- ★ $H \rightarrow \tau\tau$ decays have been observed in Run I
- ★ New results for $H \rightarrow bb$ produced in VH, VBF and ttH with 13 TeV data
- ★ New result for $H \rightarrow \mu\mu$ with 13 TeV data but more data is needed for an observation

Thank you!

- ★ CERN-EP-2016-100, arXiv:1606.02266 - Run I LHC Combination(ATLAS +CMS)
- ★ ATLAS-CONF-2016-091 - Run II $VH \rightarrow bb$ result by ATLAS
- ★ CMS-HIG-14-004 - Run 1 VBF $H \rightarrow bb$ with final $H \rightarrow bb$ combination by CMS
- ★ CERN-EP-2016-076, arXiv:1606.02181 - Run I VBF $H \rightarrow bb$ result by ATLAS
- ★ CMS-HIG-16-003 - Run II VBF $H \rightarrow bb$ result by CMS
- ★ ATLAS-CONF-2016-063 - Run II VBF + γ Hbb result by ATLAS
- ★ CMS-HIG-16-004 - Run II ttH $H \rightarrow bb$ result by CMS
- ★ ATLAS-CONF-2016-080 - Run II ttH $H \rightarrow bb$ result by ATLAS
- ★ JHEP 04 (2015) 117 - Run I $H \rightarrow \tau\tau$ result by ATLAS
- ★ JHEP05(2014)104 - Run I $H \rightarrow \tau\tau$ result by CMS
- ★ Phys. Lett. B 738 (2014) 68 - Run I $H \rightarrow \mu\mu$ result by ATLAS
- ★ Phys. Lett. B 744 (2015) 184 - Run I $H \rightarrow \mu\mu$ result by CMS
- ★ ATLAS-CONF-2016-041 - Run II $H \rightarrow \mu\mu$ result by ATLAS