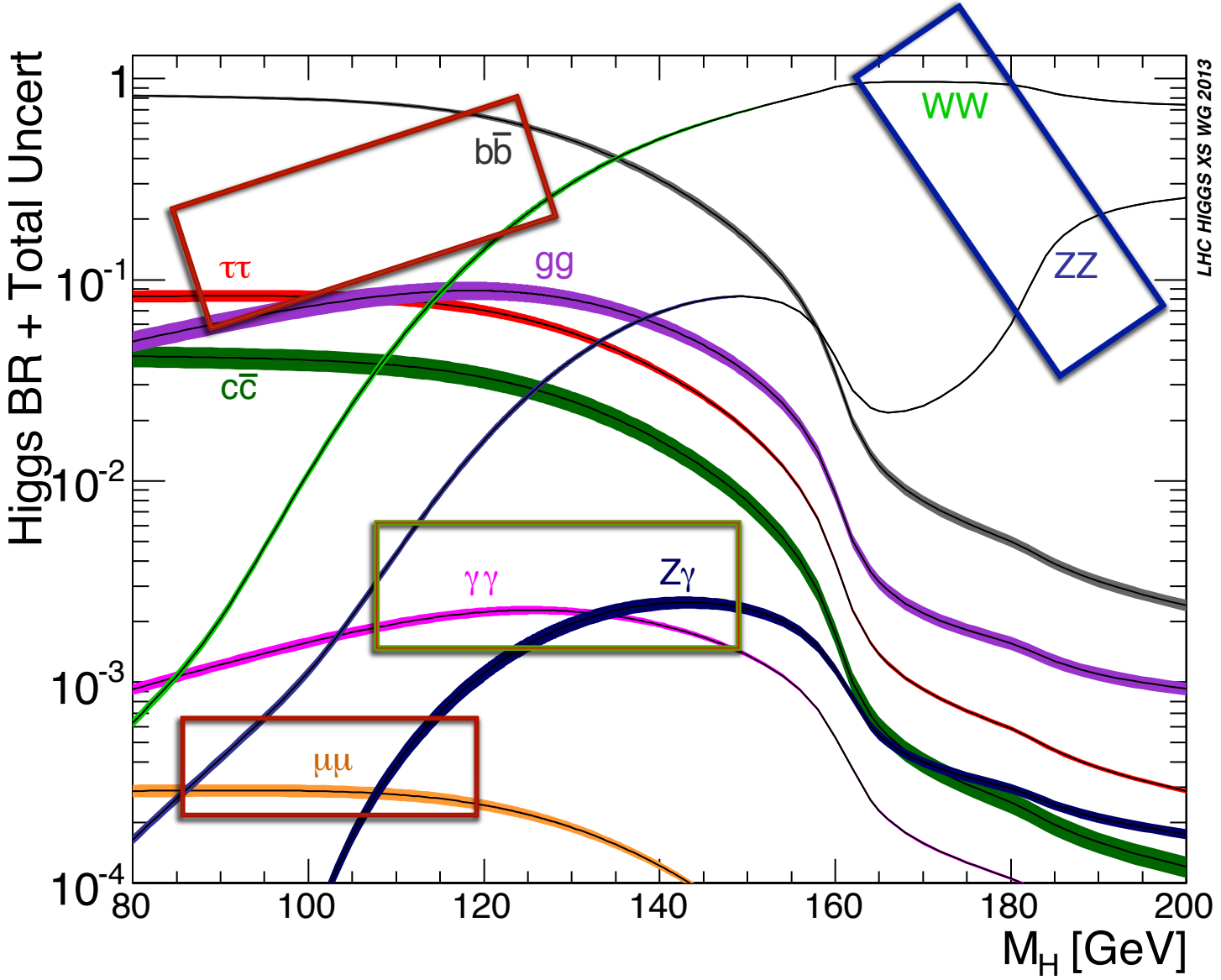
Standard Model Higgs at the LHC

Tongguang Cheng
on behalf of ATLAS and CMS

BF2017: In Search of New Paradigms
Oct 11-13, 2017, Brookhaven National Lab

PURDUE UNIVERSITY NORTHWEST

Decay BR of SM Higgs



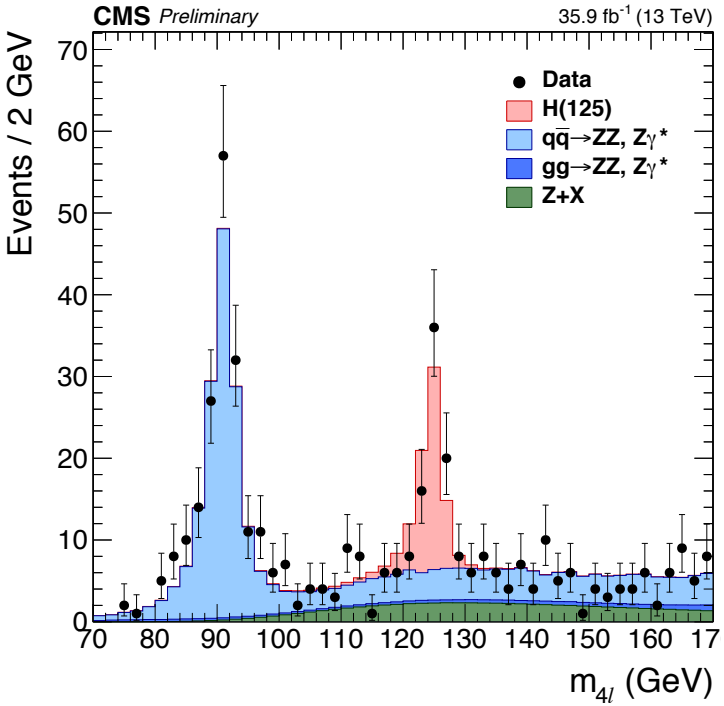
Higgs Bosonic Decay :

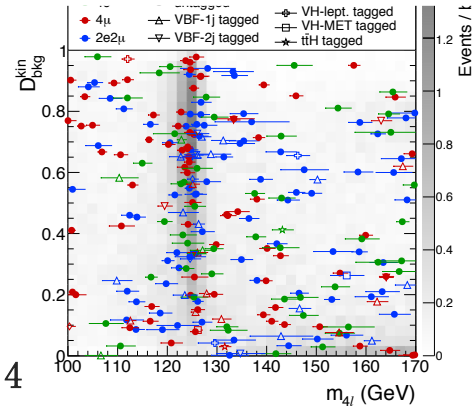
H->ZZ*->4l	Publication	Coverage	Dataset
ATLAS	ATLAS-CONF-2017-032	Mass, couplings	2016 35.9 fb^{-1}
CMS	HIG-16-041	Properties	2016 35.9 fb^{-1}
CMS	HIG-16-033	Width	2016 35.9 fb^{-1}

H->γγ	Publication	Coverage	Dataset
ATLAS	ATLAS-CONF-2017-045	Properties	2016 35.9 fb^{-1}
CMS	HIG-16-040	Properties	2016 35.9 fb^{-1}
CMS	HIG-17-015	Cross section	2016 35.9 fb^{-1}

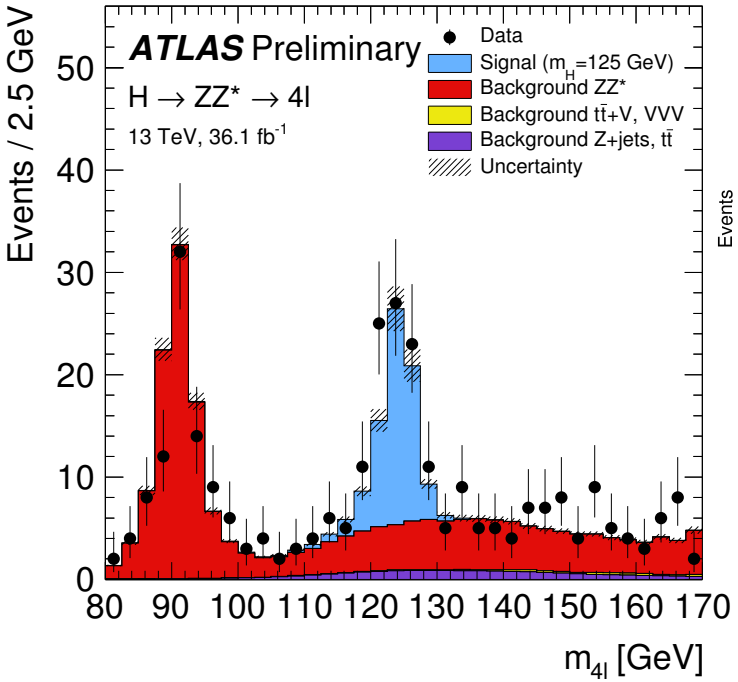
H->γγ + H->ZZ*->4l	Publication	Coverage	Dataset
ATLAS	ATLAS-CONF-2017-046	Mass	2016 35.9 fb^{-1}

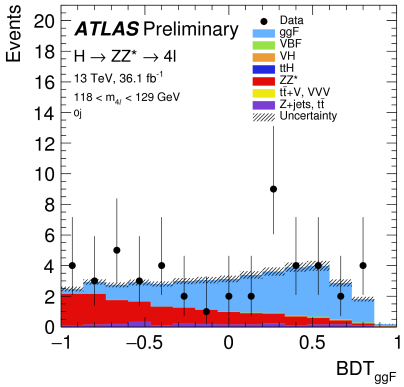
Higgs Bosonic Decay : H->ZZ*->4l





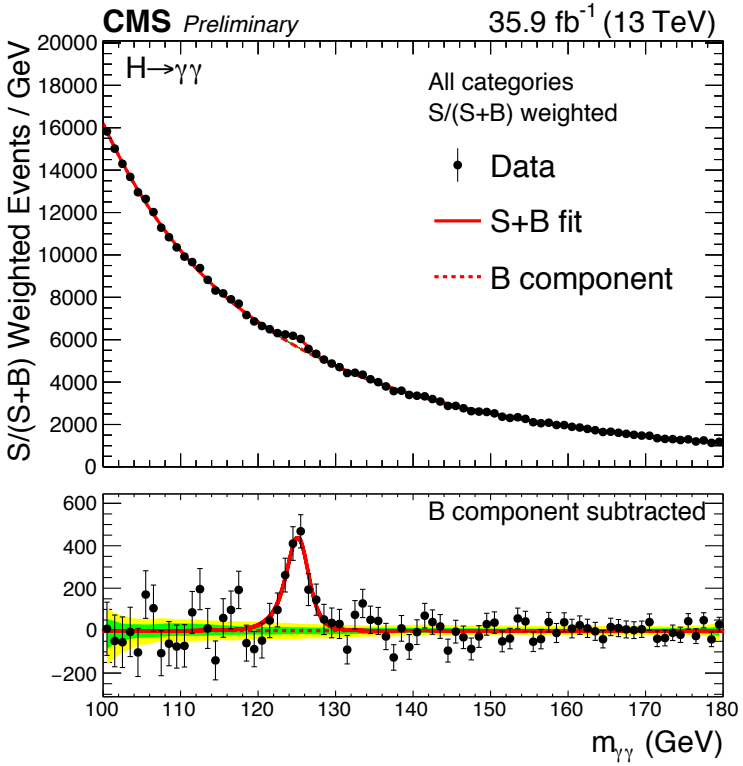
- Signal is reconstructed using four-lepton
- Large signal V.S. bkg ratio
- Kinematic information to further S/B separation in terms of BDT (ATLAS), Matrix-Element Kinematic Discriminant(KD) (CMS)
- Z->4l as standard candle

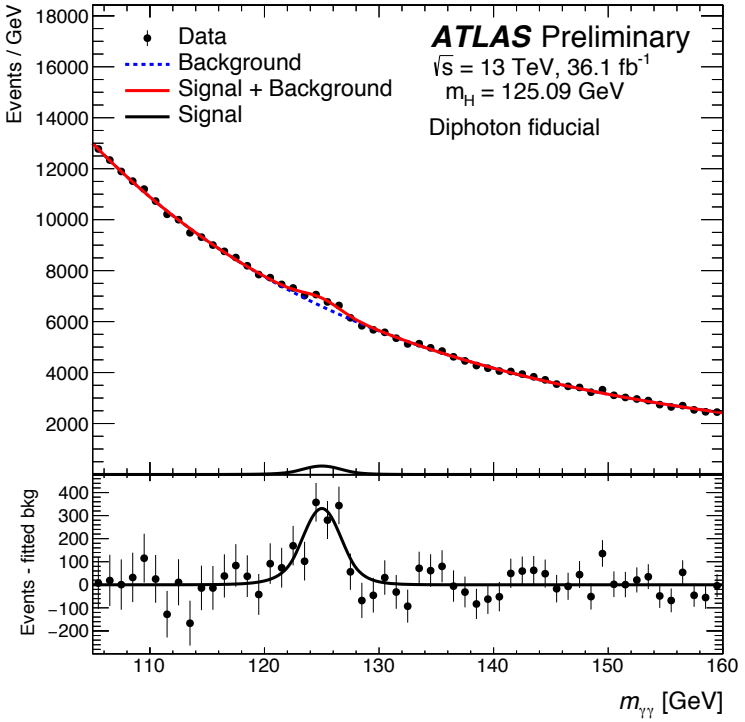




Higgs Bosonic Decay : H->γγ

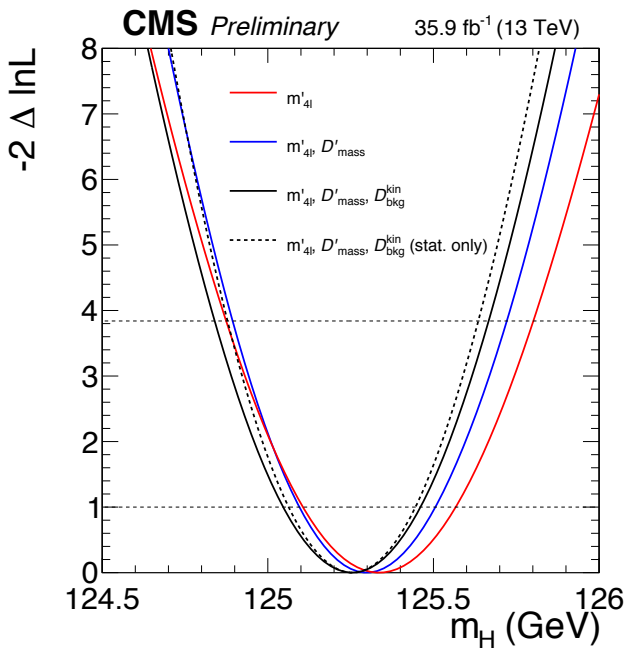
- Signal is reconstructed by two energetic photons
- Events are categorized for cross sections and mass measurements
- Signal is extracted by fitting the di-photon mass spectrum

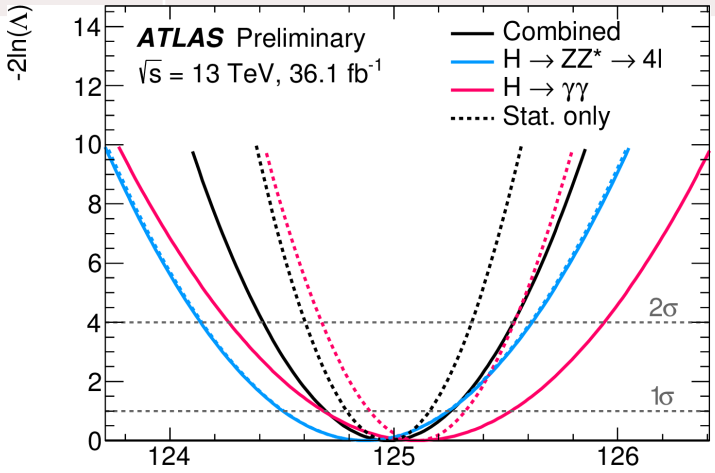


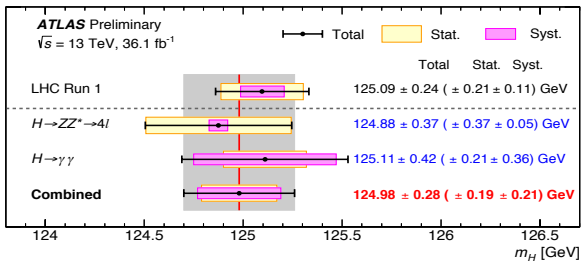


Higgs Bosonic Decay :
mass measurements

	H->ZZ*->4l	H->γγ
ATLAS	Bin in BDT + Z mass constraint, resolution in signal model comes for per-event mass resolution	Signal model is a DCB function; Bkg is parameterized for each category
CMS	3D fit (KD, per-event mass resolution, m_{4l}) + Z mass contraint	NA





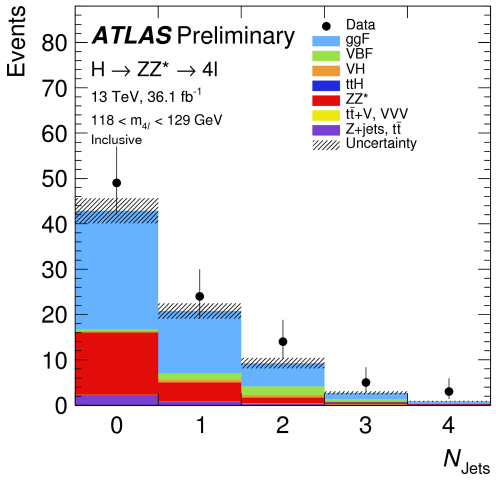


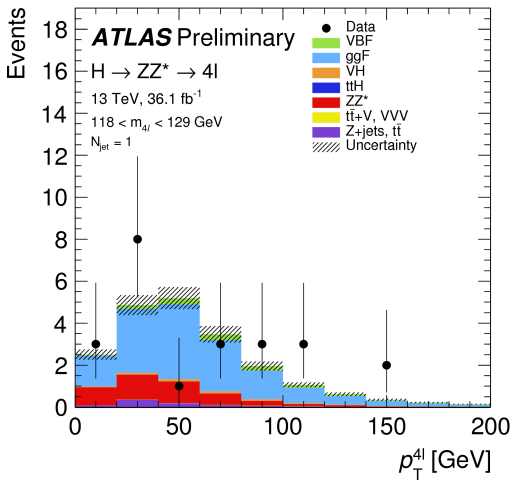
m_H =125.26±0.20 (stat.)±0.08(syst.) GeV

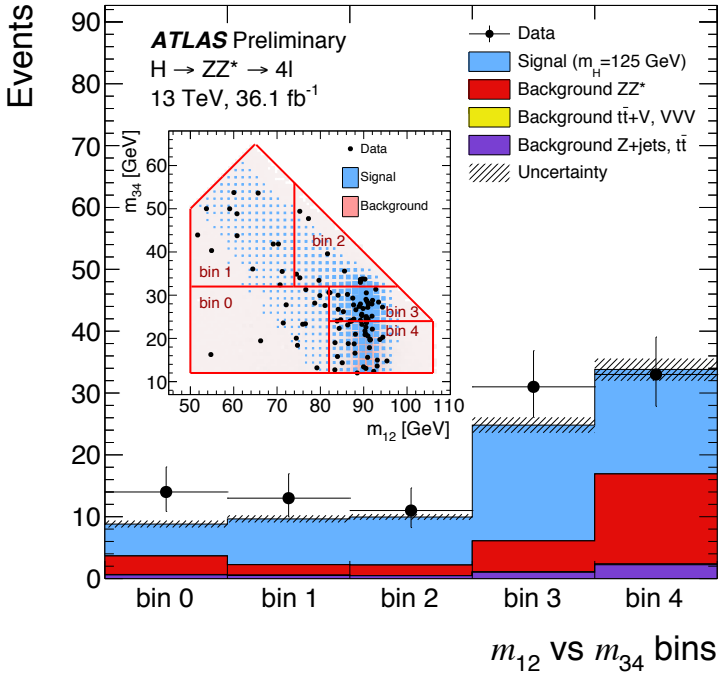
Higgs Bosonic Decay : fiducial cross section

- **Fiducial** phase space is introduced to minimize the model dependence
- For 1D/2D differential **fiducial** cross sections, the signal is extracted from the bins defined by the reconstructed observables

Number of events for each bin defined by reconstructed observables

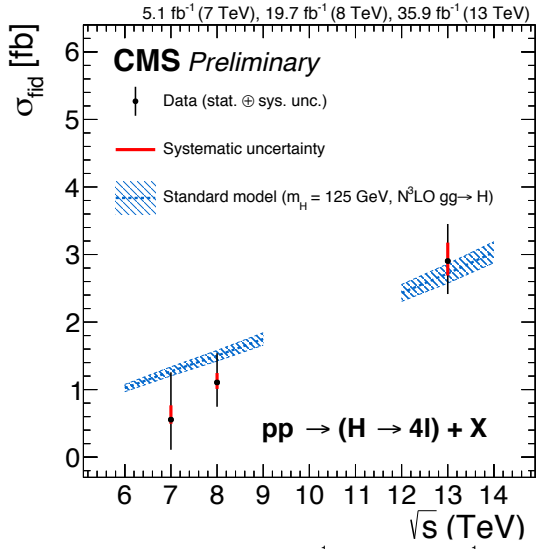


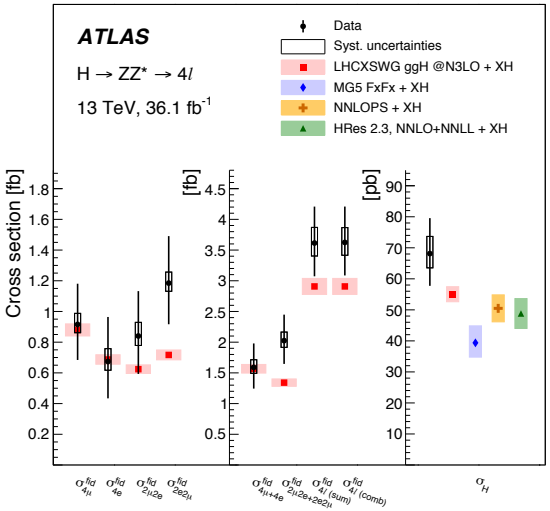


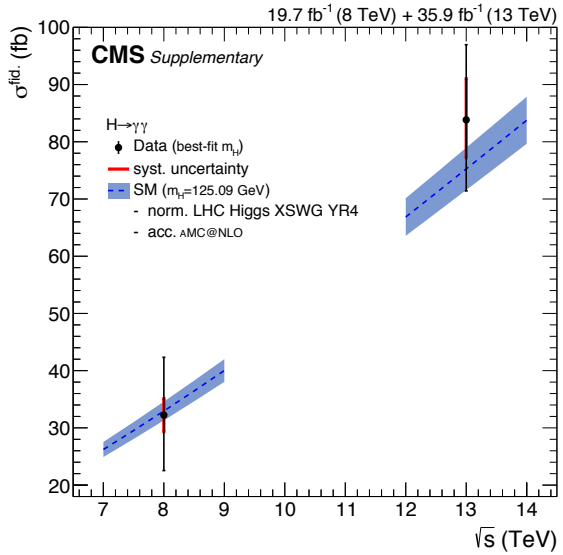


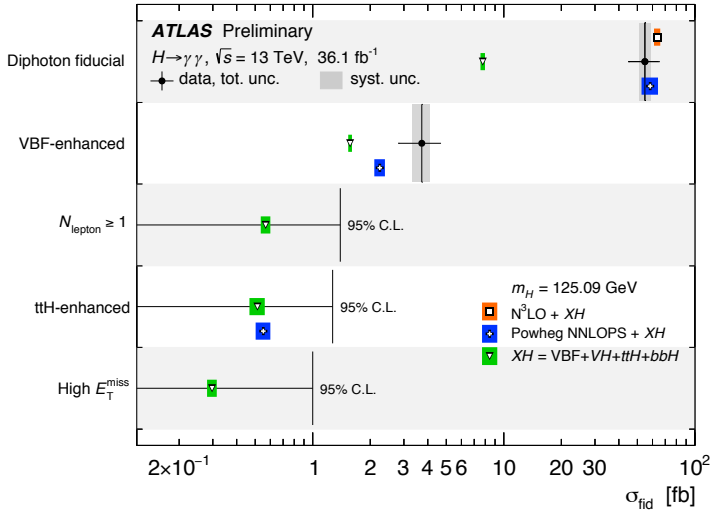
m_{12} vs m_{34} bins

Higgs Bosonic Decay :
fiducial cross section – inclusive cross section



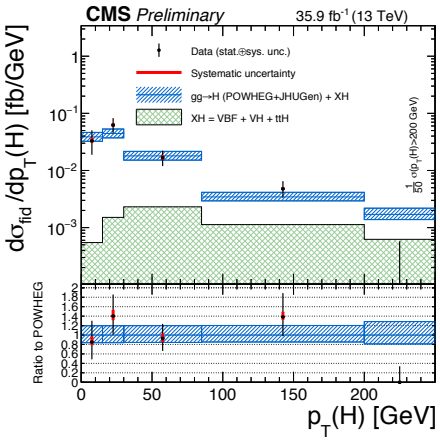


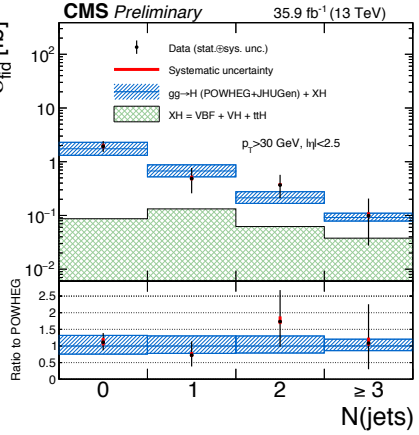


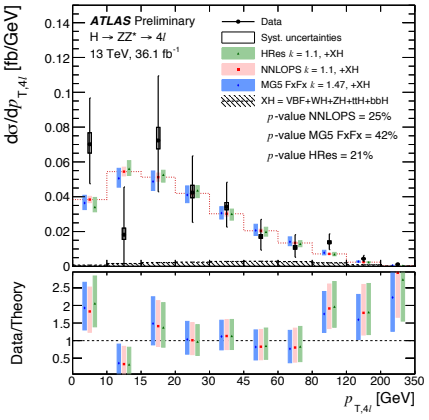


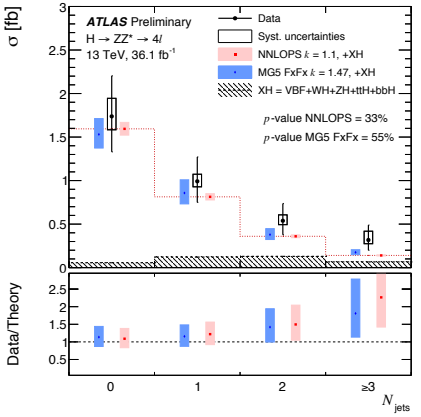
Inclusive cross sections are compatible with LHCXSWG N^{3}LO

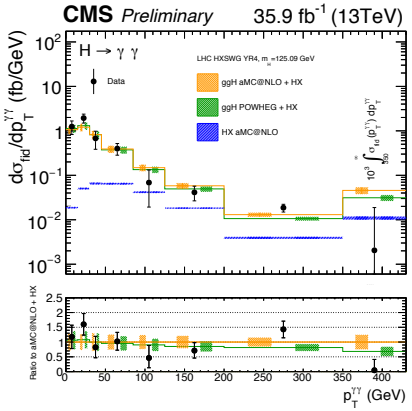
Higgs Bosonic Decay :
fiducial cross section – differential cross section

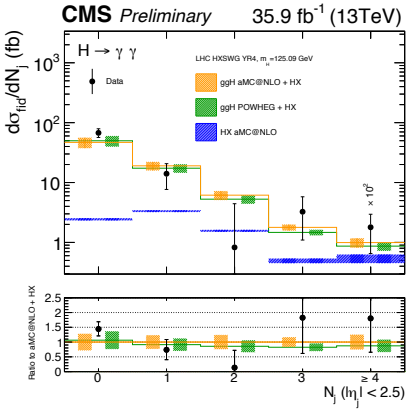


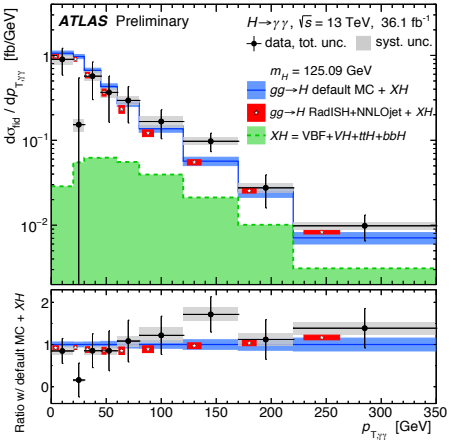








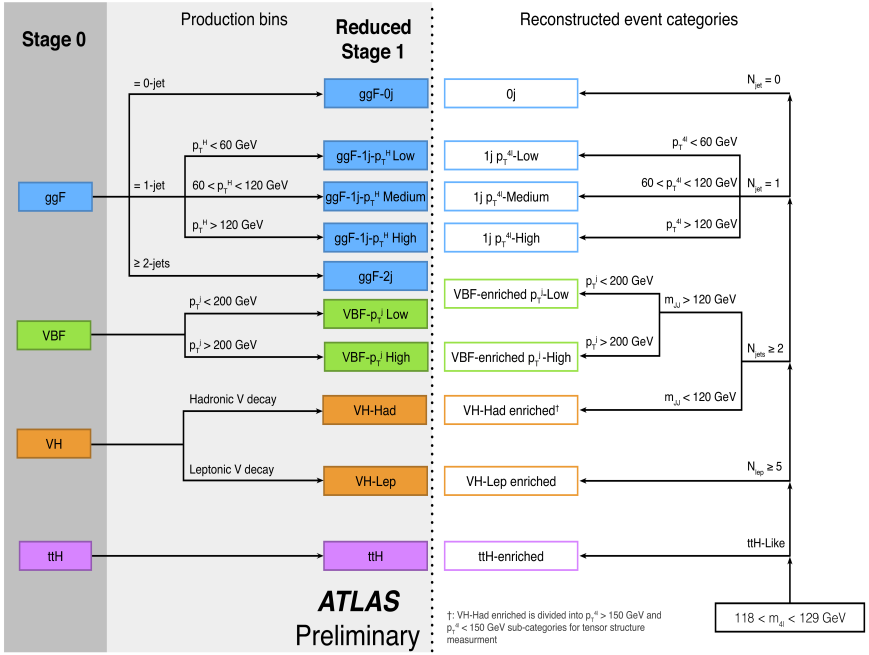




Differential cross sections are compatible with SM Higgs.

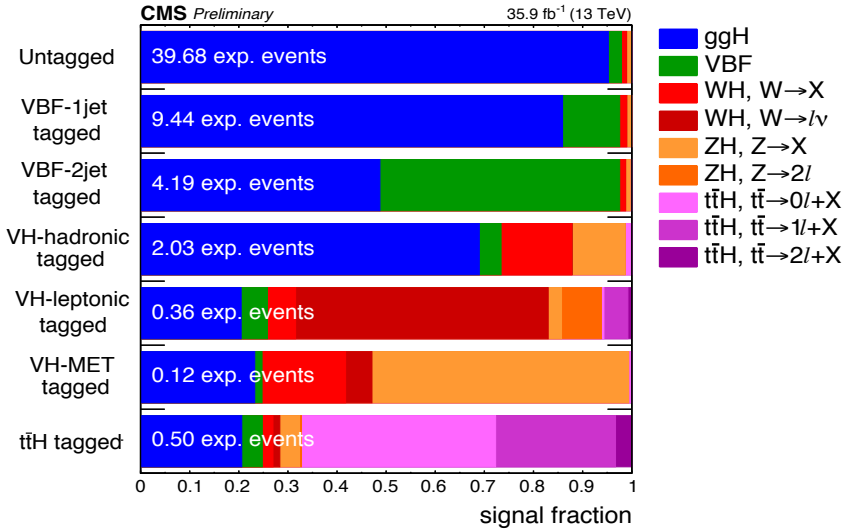
Higgs Bosonic Decay : (simplified) template cross section

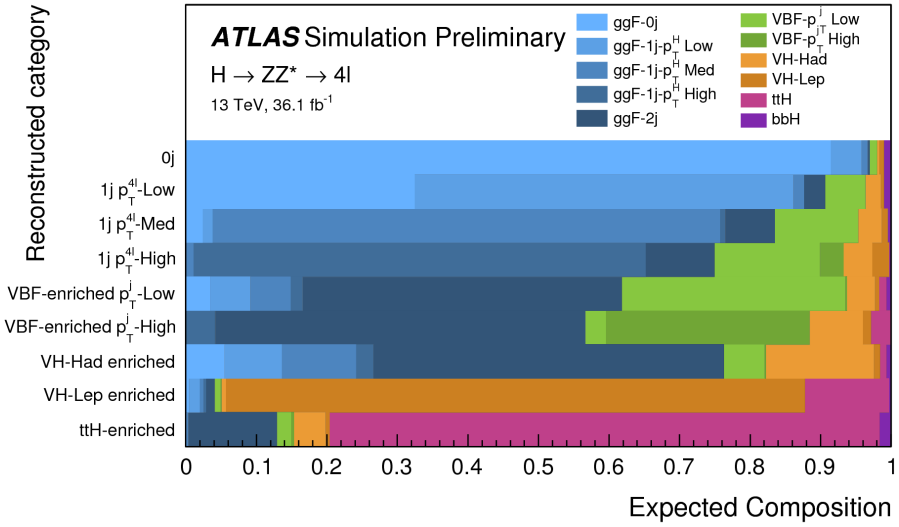
- Simplified template cross section
  Handbook of LHC Higgs Cross Sections:
  4. Deciphering the Nature of the Higgs Sector (arXiv:1610.07922)
  - measurement of **cross sections** instead of signal strengths, in mutually exclusive regions of phase space
  - cross sections are measured for specific production modes



Higgs Bosonic Decay : (simplified) template cross section H->ZZ*->4l

- Simplified template cross section
  - measured exclusive regions of phase space are specific to the different production modes

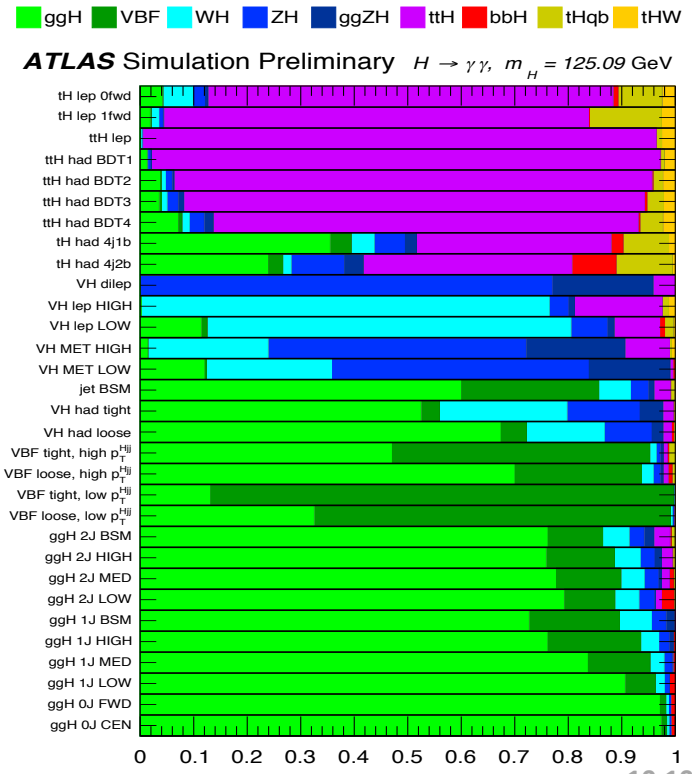




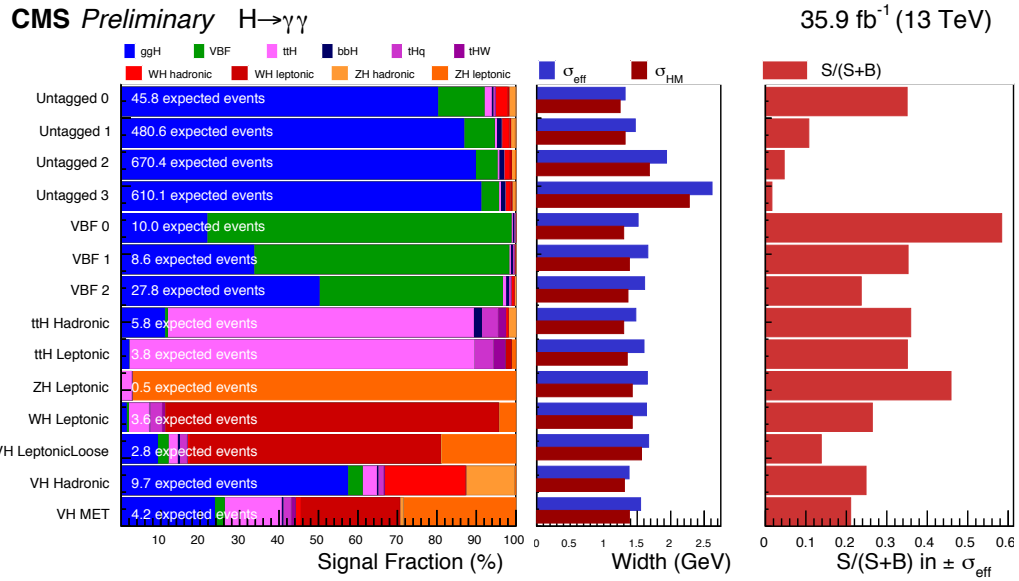
Higgs Bosonic Decay : (simplified) template cross section H->γγ

- Simplified template cross section
  - measured exclusive regions of phase space are specific to the different production modes

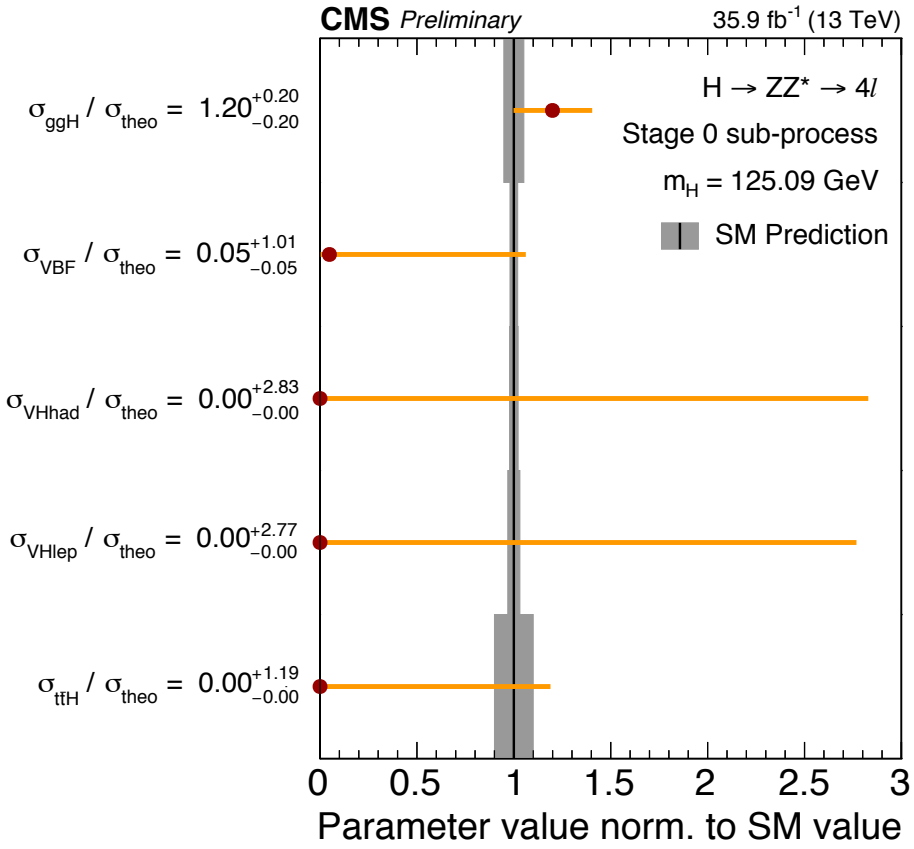
31 exclusive categories each enriched in one of the production mechanisms

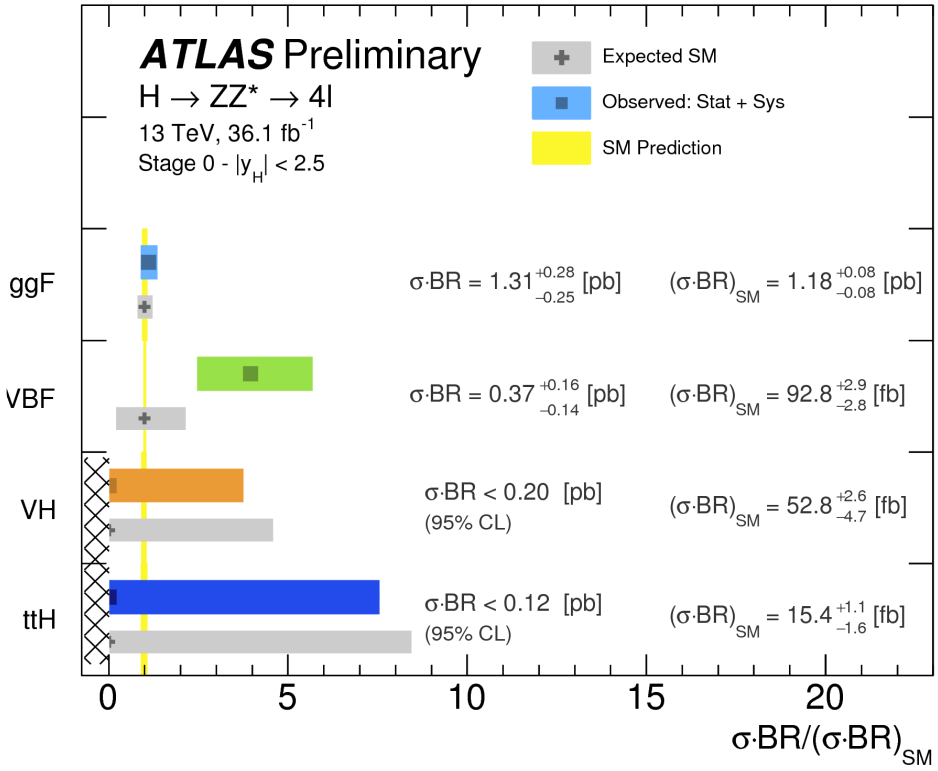


Events are further classified according to σ_m , S/B

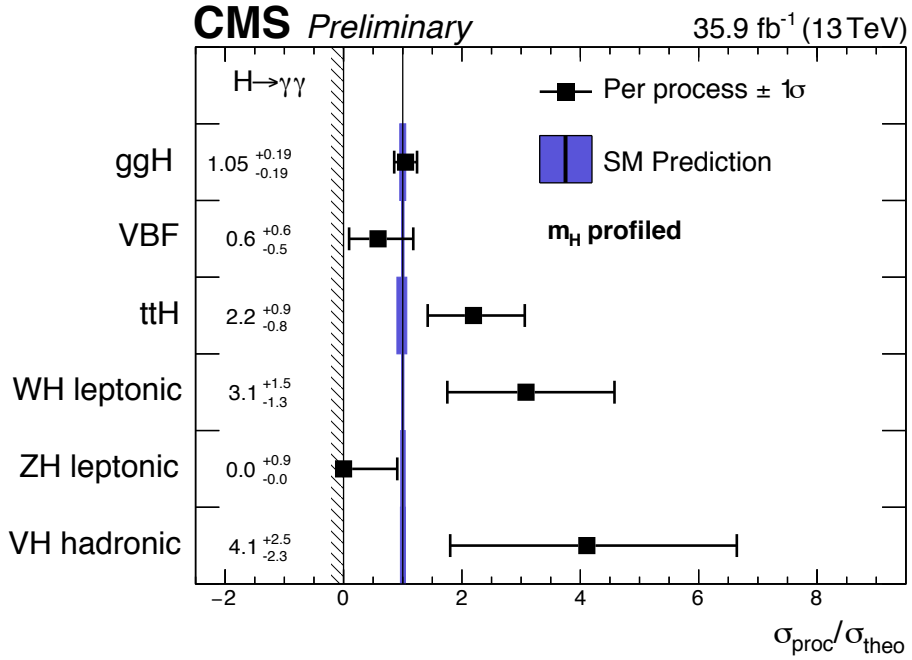


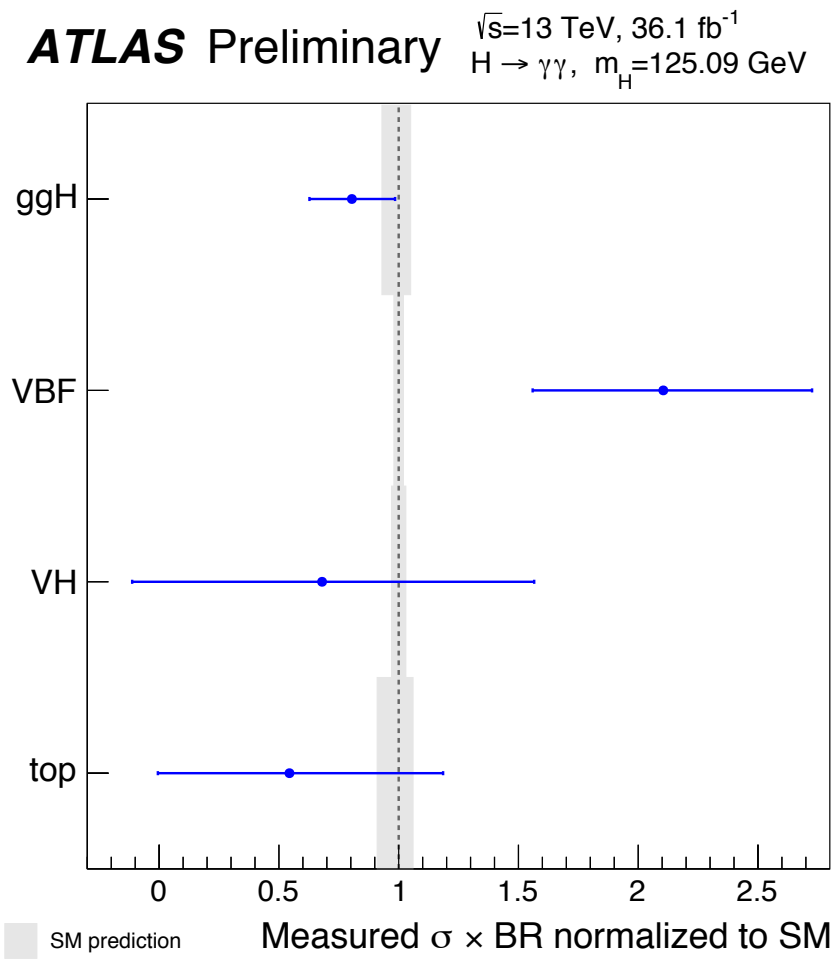
Higgs Bosonic Decay :
template cross section - H->ZZ*->4l results



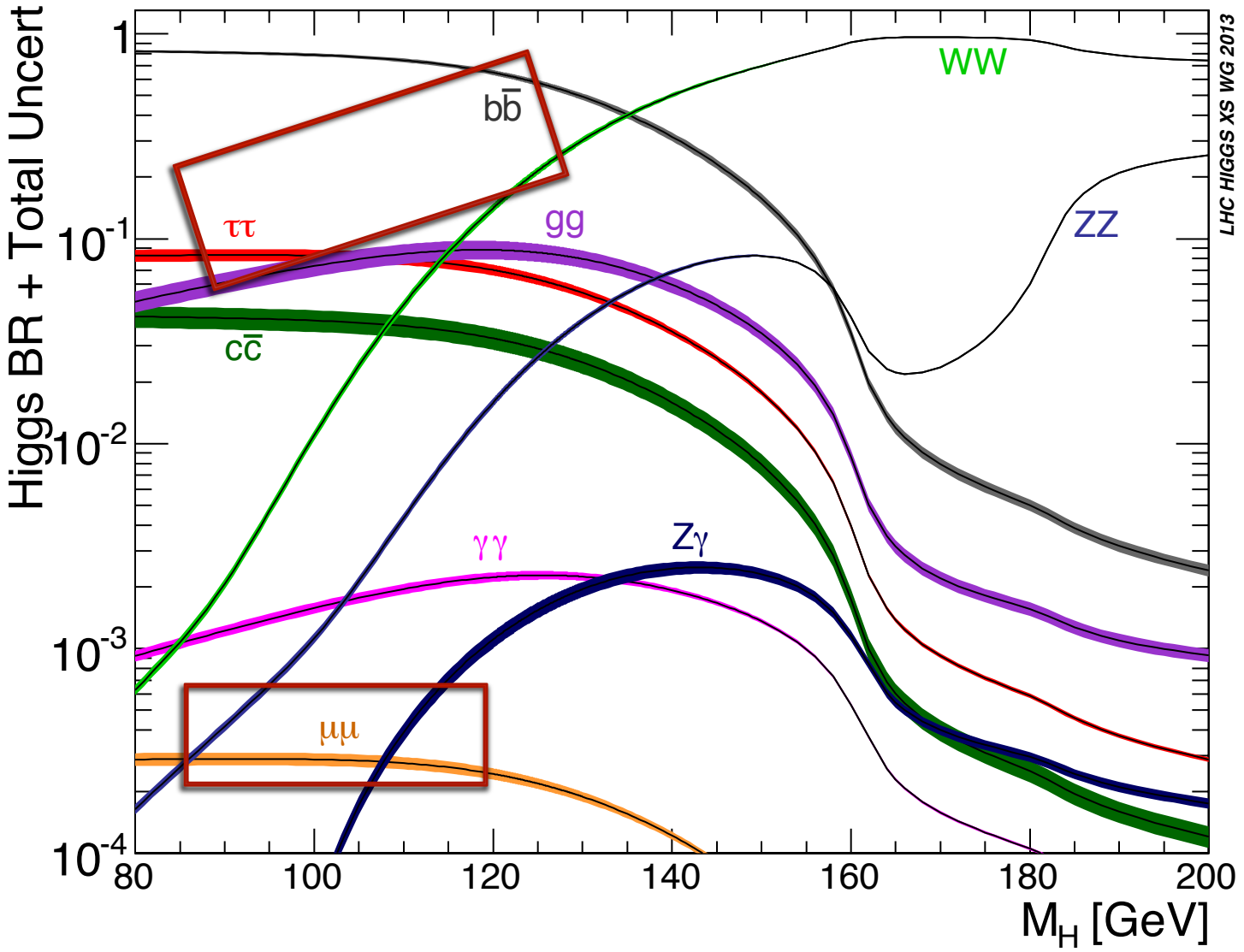


Higgs Bosonic Decay :
template cross section - H->γγ results





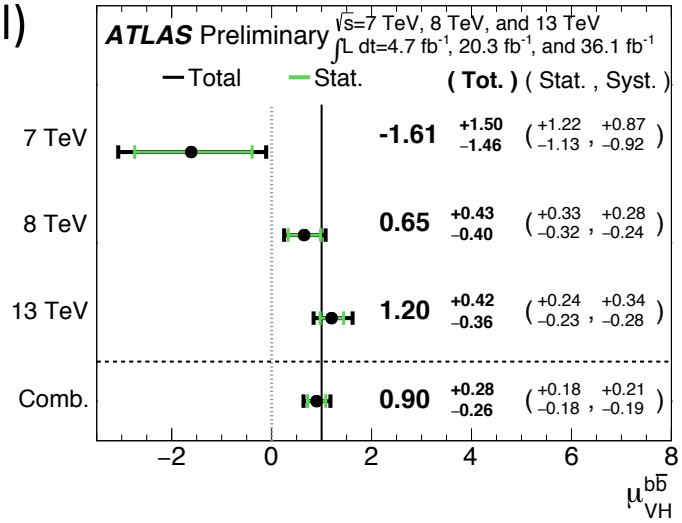
Higgs Fermionic Decay

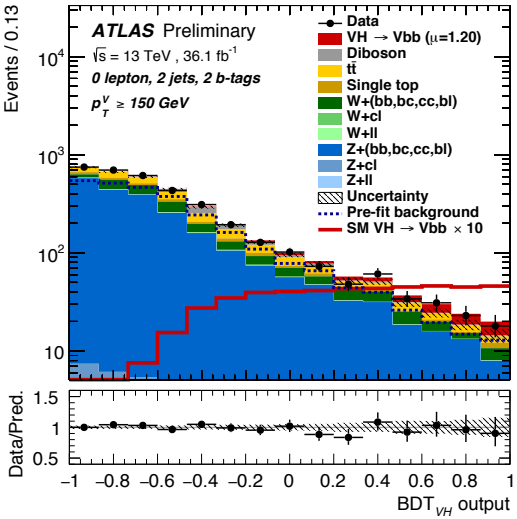


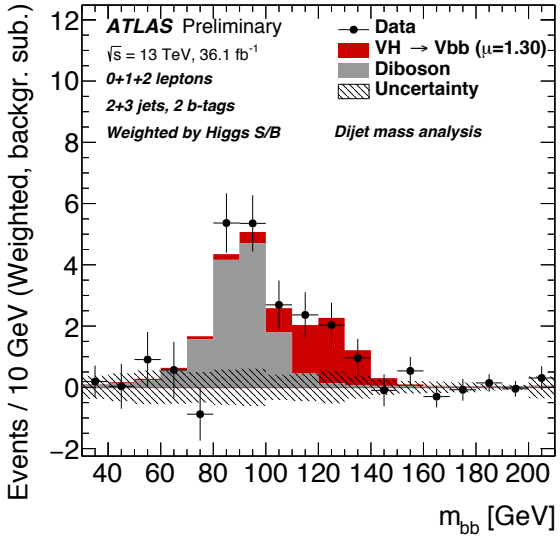
Higgs Fermionic Decay : VH, H->bb

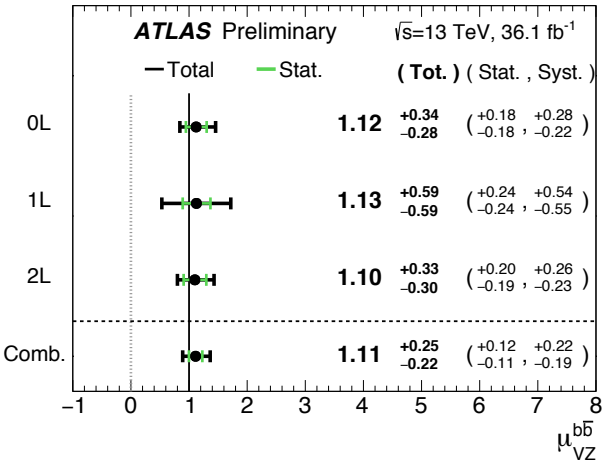
ATLAS-CONF-2017-014

- Events are categorized into 0/1/2-lepton (Zvv,Wlv,Zll) + number of additional jets
- Nominal analysis uses BDT validated by VZ, Z(bb)
  - Alternatively using cut based m_{bb}
- **13TeV data shows 3.5σ (3.0σ expected)**
- **Run-I/II combination gives 3.6σ (4.0σ expected)**





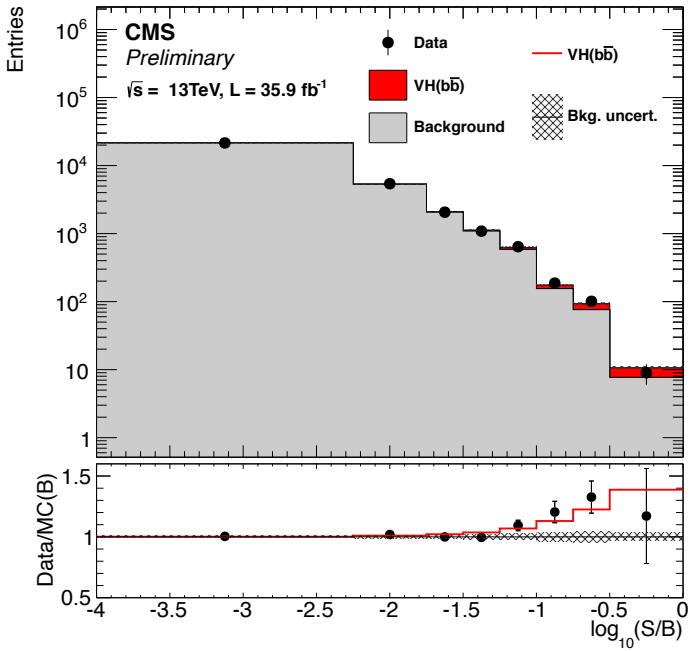


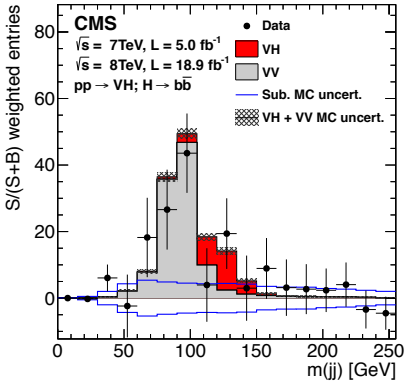


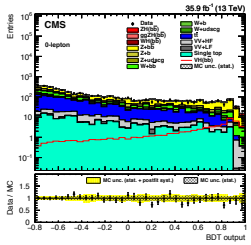
Higgs Fermionic Decay : VH, H->bb

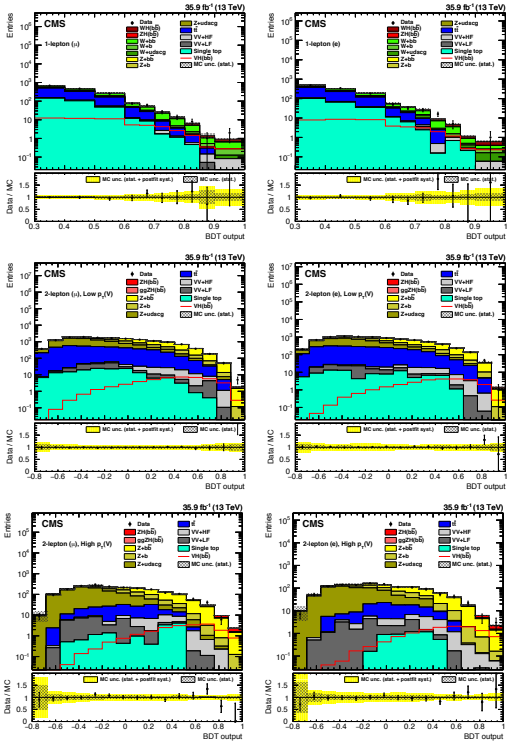
CMS-PAS-HIG-16-044

- Events are categorized into 0/1/2-lepton (Zvv,Wlv,Zll) + number of additional jets
- BDT based MVA analysis as the nominal analysis
- Jet regression applied on b-jets to improve sensitivity
- **7+8TeV data give 2.1σ/(2.1σ expected)**
- **13TeV data give 3.8σ/(3.8σ expected)**



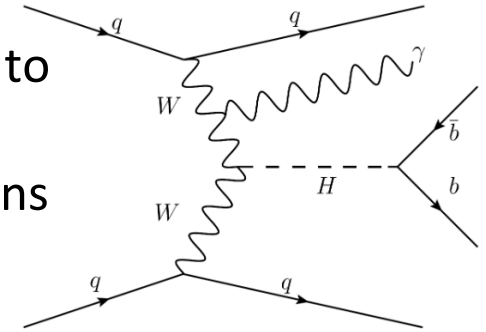






Higgs Fermionic Decay : VBF, H->bb

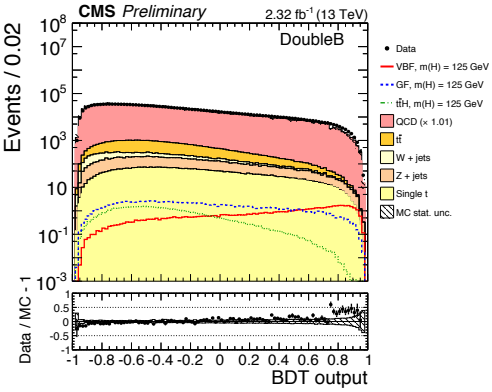
ATLAS-CONF-2016-063



- Add photon as extra handle for trigger and to suppress multi-jet background
- BDT are used to define three analysis regions
- Fit m_{bb} in 3 BDT regions to extract signal

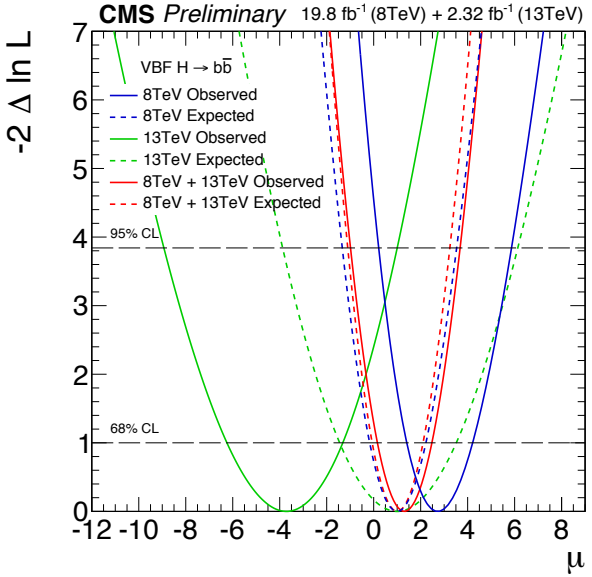
CMS-PAS-HIG-16-003

- Special triggers designed to suppress QCD bkg
  - VBF topology (m_{jj} $\Delta\eta_{jj}$)
  - Online btaging and $\Delta\Phi_{bb}$
- B-jet regression and hard gluon-jet recovery to improve m_{bb} resolution
- Simultaneous fit in all(7) BDT-based categories extract signal on m_{bb} spectrum



Higgs Fermionic Decay :
VBF, H->bb

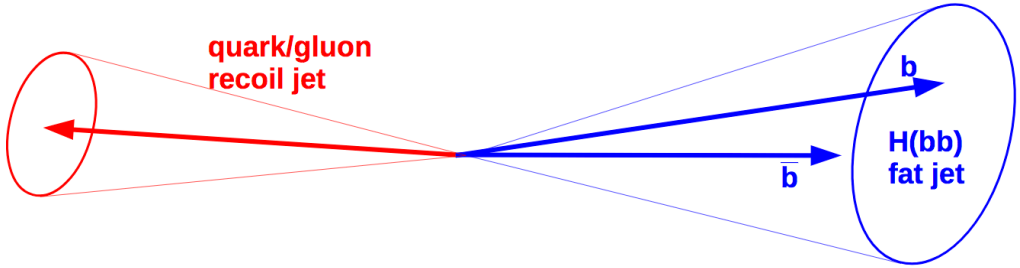
Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0\ ^{+2.3}_{-1.7}$	$1.8\ ^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9\ ^{+2.8}_{-2.7}$	$0.3\ \pm 0.8$



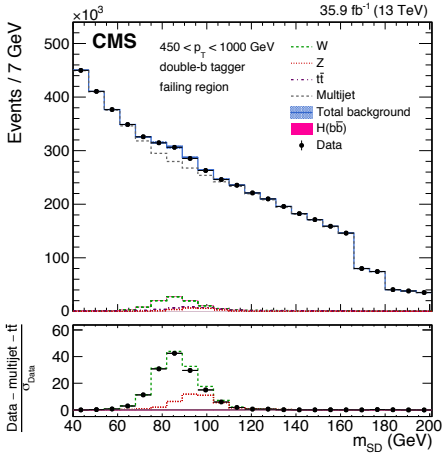
- Combination of 13TeV(2015) and 8TeV data gives
- $\mu = 1.3\ ^{+1.2}_{-1.1}$
- Significance 1.2**σ**

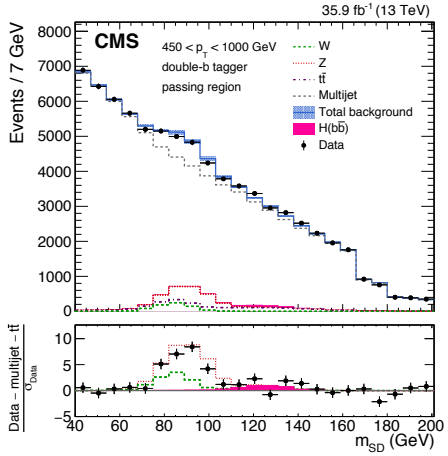
Higgs Fermionic Decay : H->bb – boosted Higgs

CMS-PAS-HIG-17-010



- Use boost topology as the handle to suppress QCD background in inclusive H->bb search
- Double b tagging improves b tagging wrt single merged jet / two subjet b-tagging
- Major QCD background estimation uses anti-btagging CR





	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

Higgs Fermionic Decay : observation of H->ττ

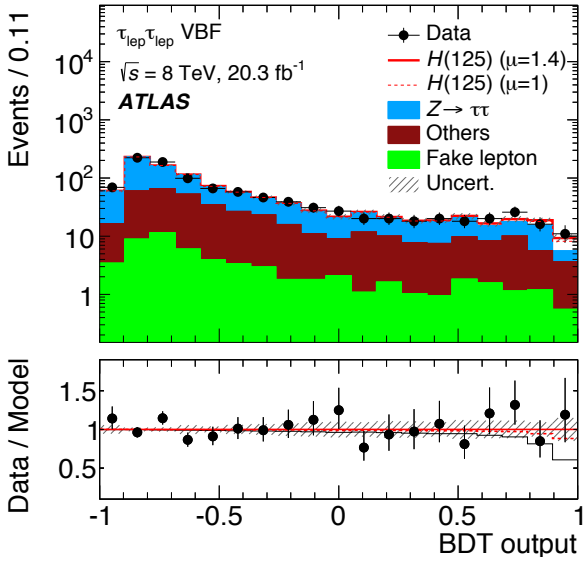
- Events are classified according to τ decay mode

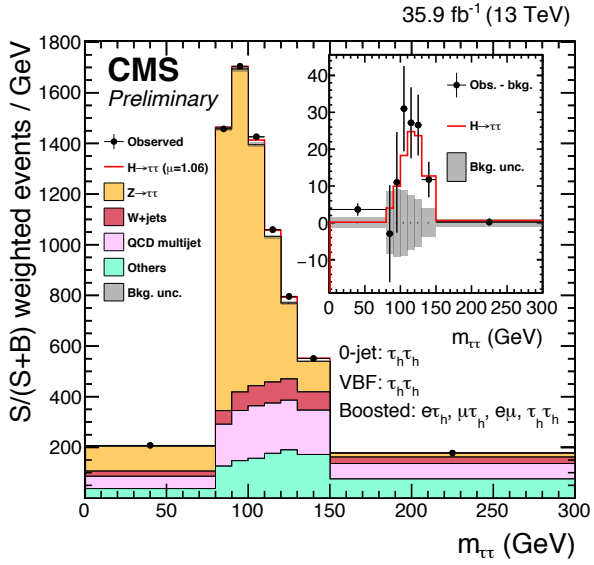
ATLAS - JHEP 04 (2015) 117

- Two categories : boost, VBF; separate BDT training for each
- Z->ττ is estimated by embedding τ into Z->μμ data
- Signal extracted by fitting BDT shape with signal and background templates

CMS-PAS-HIG-16-043

- Reconstruction of $m_{\tau\tau}$ with dynamic likelihood algorithm
- 3 event categories 0-jet, VBF, Boosted
- Z->ττ is estimated from MC with correction derived in Z->μμ control region



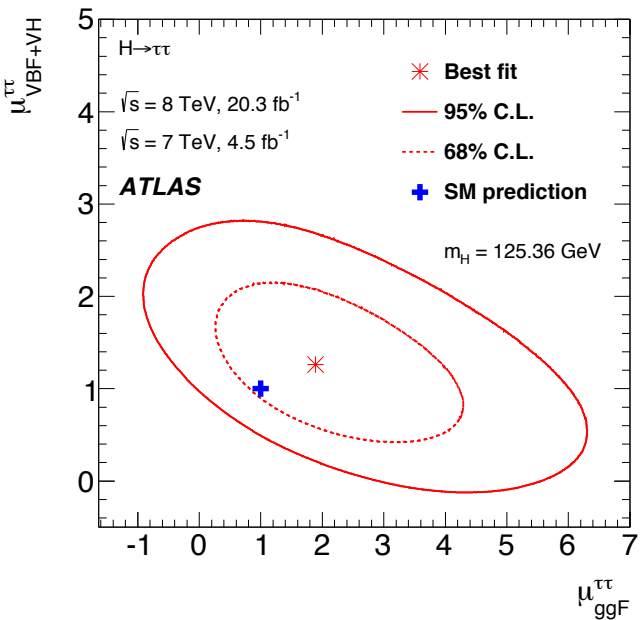


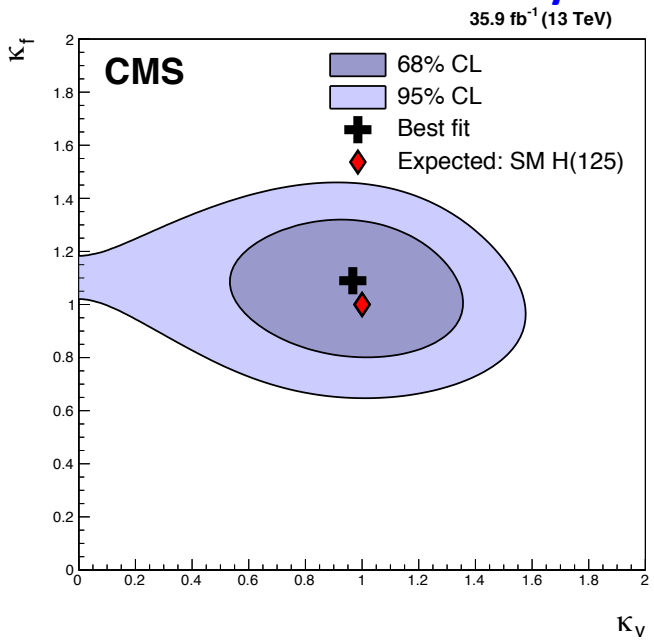
Higgs Fermionic Decay : observation of H->ττ

H->ττ is observed at the LHC.

Data	Experiment(s)	Significance obs(exp)
Run-I	ATLAS	4.5(3.4) σ
Run-II	CMS	4.9(4.7) σ
Run-I+Run-II	CMS	5.9(5.9) σ

Coupling/signal strength measurements show consistency with SM Higgs.

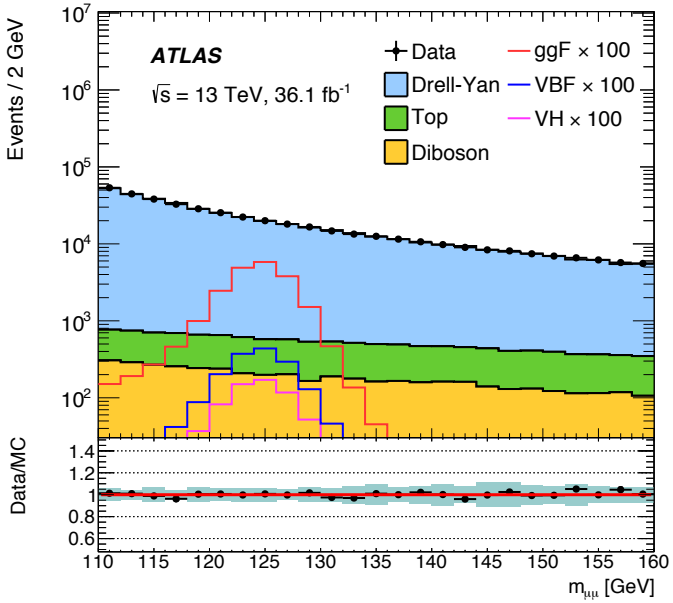




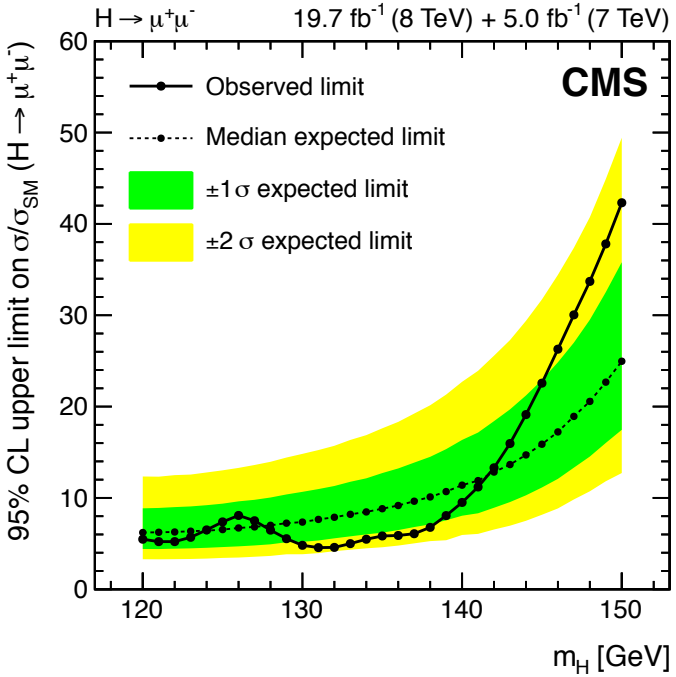
Higgs Fermionic Decay : search for H->μμ

Data	Experiment(s)	Upper limit
Run-II	ATLAS	3.0(3.1) x σ_{SM}
Run-I+Run=II	ATLAS	2.8(2.9) x σ_{SM}
Run-I	CMS	7.4(6.5) x σ_{SM}

Phys. Rev. Lett. 119, 051802 (2017)



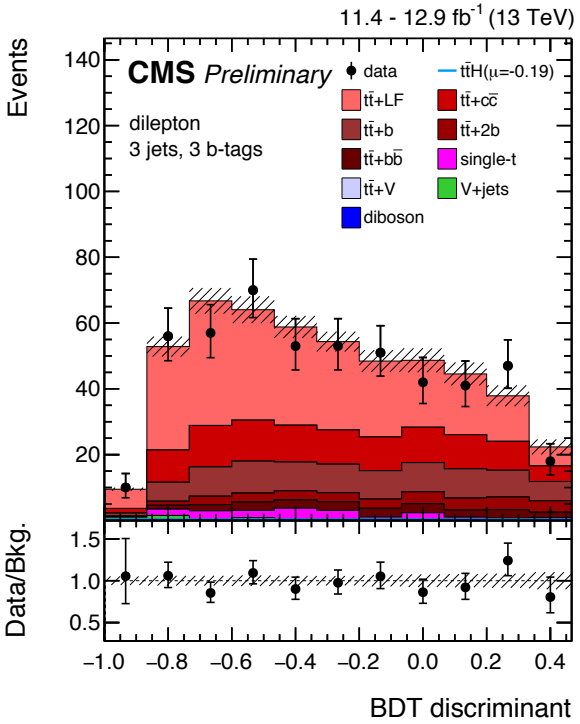
Phys. Lett. B 744 (2015) 184



Top Yukawa coupling : ttH
ttH, H->bb

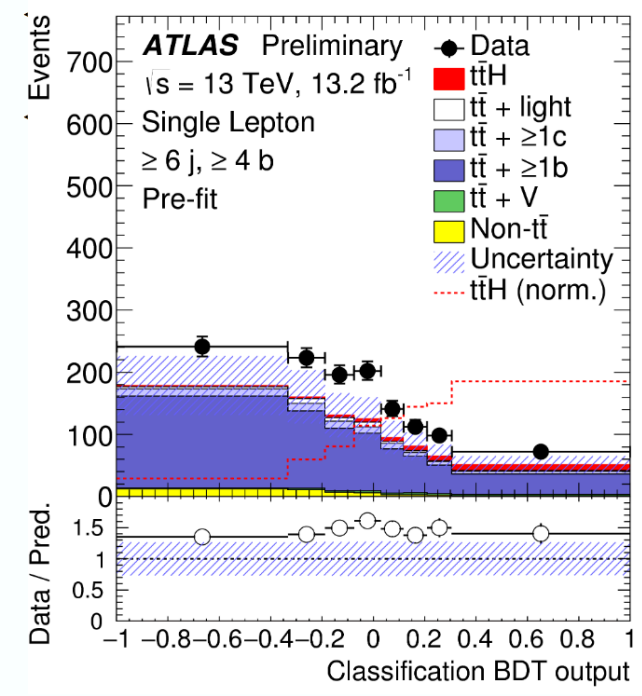
CMS-PAG-HIG-16-038

- Events are categorized with number of leptons and jets
- BDT and matrix-element(ME) is used in each category to improve S/B
- Extracting limit by combined fit to data in all categories

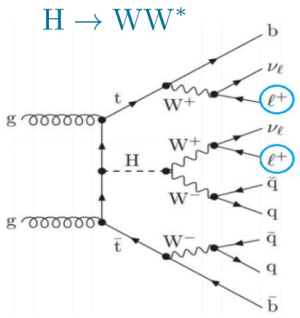


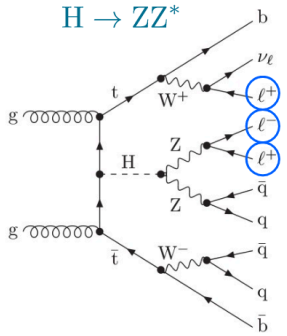
ATLAS-CONF-2016-080

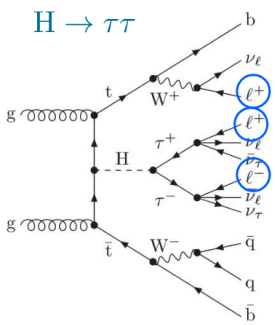
- Event categorization according to number of jets and number of b-tagged jets.
- MVA NN/BDT applied for each category



Top Yukawa coupling : ttH multi-lepton

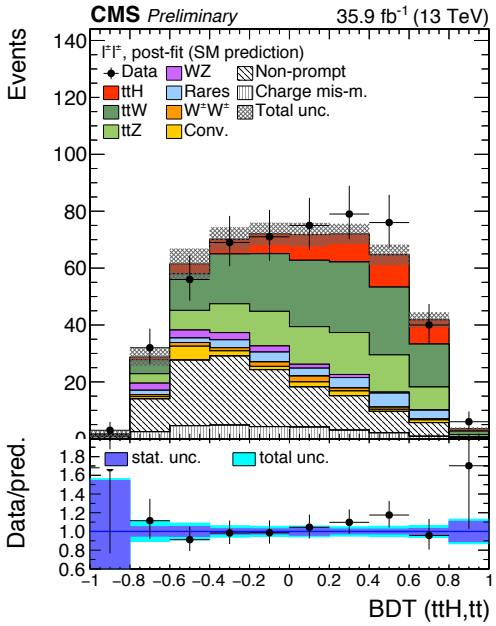






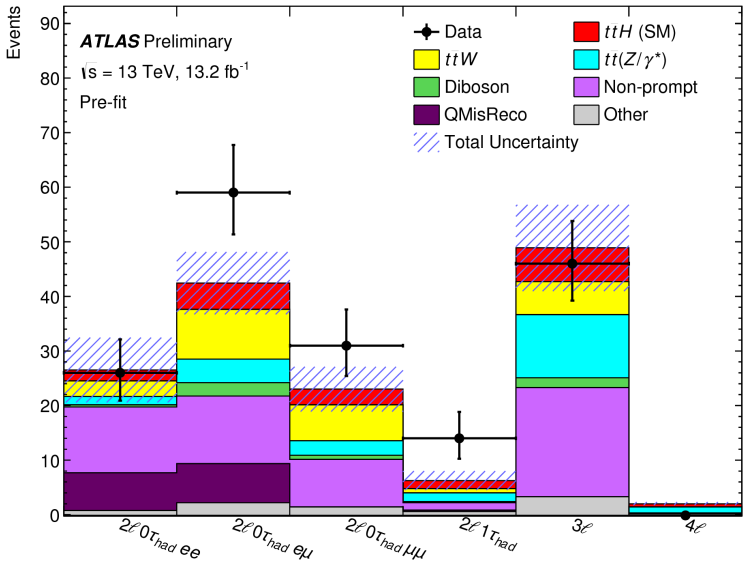
CMS-PAG-HIG-17-004

- Events are classified according to lepton charge/flavor, presence of hadronic tau or >=2 b-tags
- Two BDTs to separate signal from ttbar and ttbarV.



ATLAS-CONF-2016-085

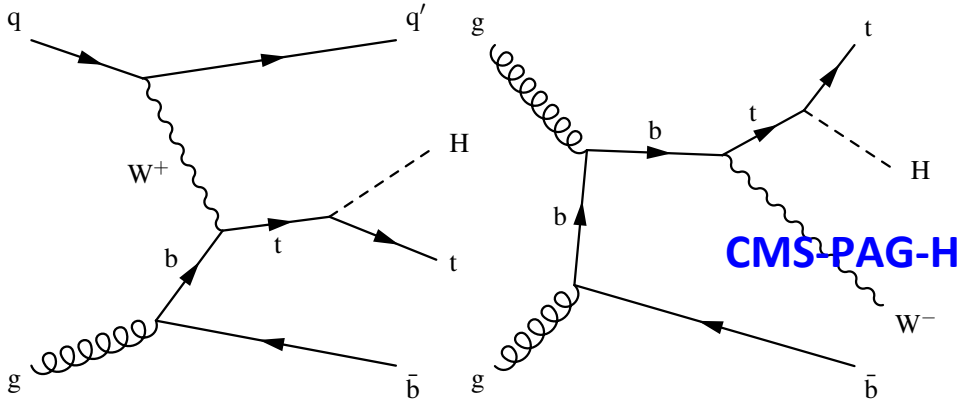
- 4 categories (6 bins) according to number of leptons and hadronic-taus.



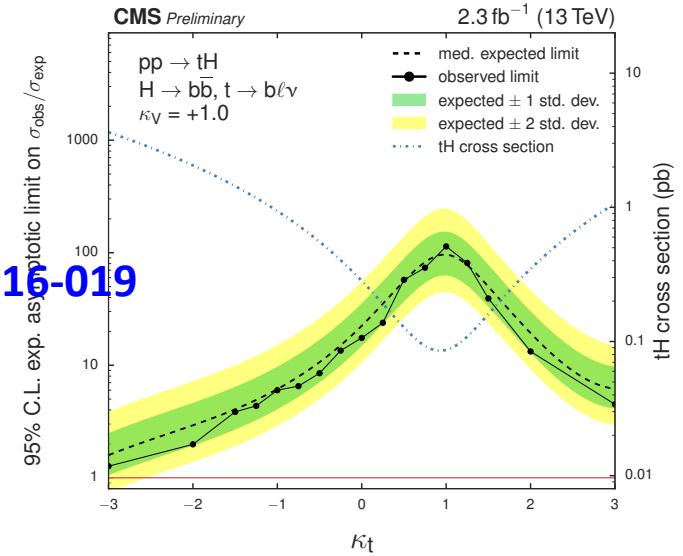
Top Yukawa coupling : ttH
summary

Channel	Dataset	Signal strength		Significance/Limit obs(exp)	
		ATLAS		CMS	
bb	13fb^{-1} 2016	$2.1^{+1.0}_{-0.9}$	2.4(1.2)σ	$-0.2^{+0.8}_{-0.8}$	μ<1.5(1.7)
Multi-lepton	2016 13fb^{-1} (ATLAS), 36fb^{-1} (CMS)	$2.5^{+1.3}_{-1.1}$	2.2(1.0) σ	$1.5^{+0.5}_{-0.5}$	3.3(2.4) σ
τ_{had} +X	36fb^{-1} (CMS)			$0.7^{+0.6}_{-0.5}$	1.4(1.8) σ
γγ	36fb^{-1} 2016	$0.5^{+0.6}_{-0.6}$	1.0(1.8) σ	$2.2^{+0.9}_{-0.8}$	3.3(1.5) σ
ZZ*->4l	36fb^{-1} 2016		μ<7.7	$0.0^{+1.2}_{-0.0}$	

Top Yukawa coupling : tH
sign of Yukawa coupling

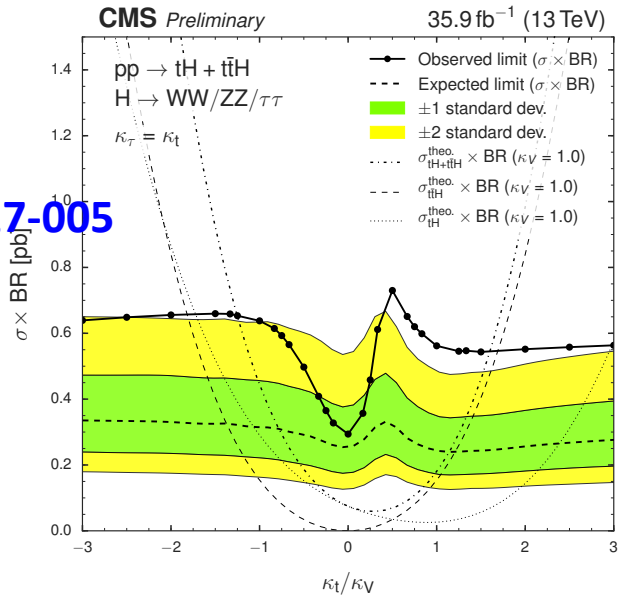


CMS-PAG-HIG-16-019



- tHq/tHW cross sections sensitive to the sign of top Yukawa couping
- With κ_t = +1/-1
  - σ(tHq) = 71/739 fb
  - σ(tHW) = 16/147 fb
- 2016 data in multi-lepton final state

CMS-PAS-HIG-17-005



	$\hat{\mu}$	significance
$\kappa_t/\kappa_V = 1$	$1.8 \pm 0.3\ (stat.) \pm 0.6\ (syst.)$	$\mathbf{2.7}\sigma(1.5\sigma)$
$\kappa_t/\kappa_V = -1$	0.7 ± 0.4	$\mathbf{1.7}\sigma(2.5\sigma)$

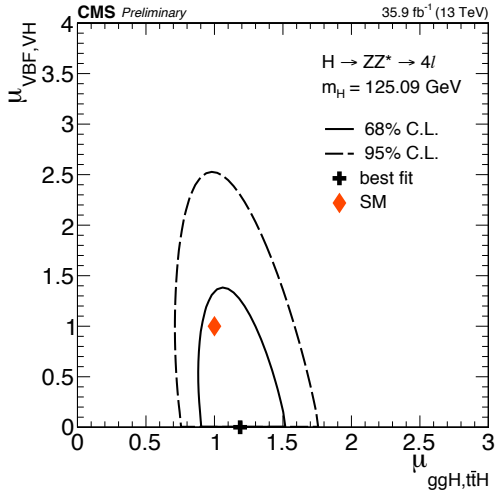
Summary

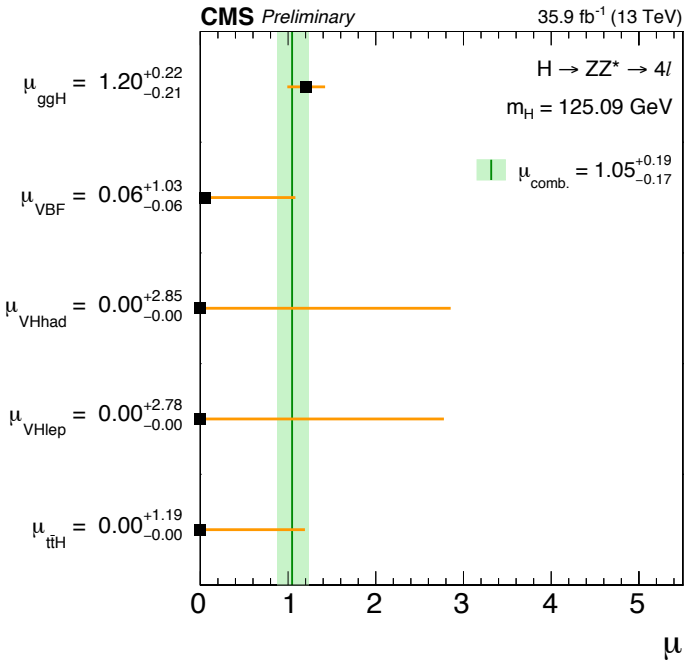
- Standard Model shows compatibility with the data collected in 2016
  - Property measurements in Higgs bosonic decay shows consistency with Standard Model;
    fiducial cross section is updated with 2016 data
    and results **of template cross section** are presented at first time.
  - For Higgs decay to fermions, the evidence is shown in H->bb decay;
    the observation of H->ττ + no evidence in H->μμ
    -> **non-universal couplings to lepton**s
  - **ttbarH, tHq(W)** results are updated using 2016 data
- On the other hand, with data accretion, we will have more Higgs property measurements using its decay to fermions, better precision with Higgs decay to bosons and more consolidate results in **ttbarH/tH**.

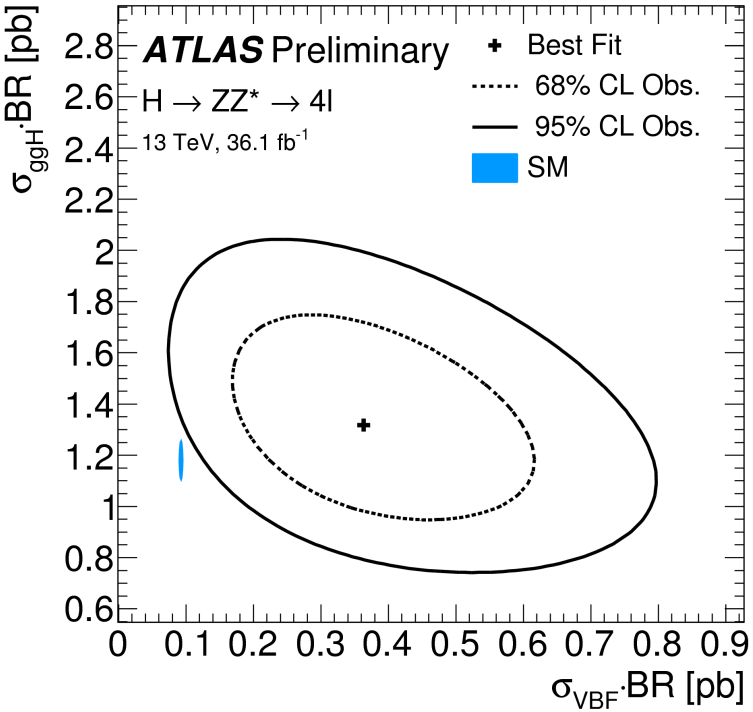
Stay tuned!

Backup slides

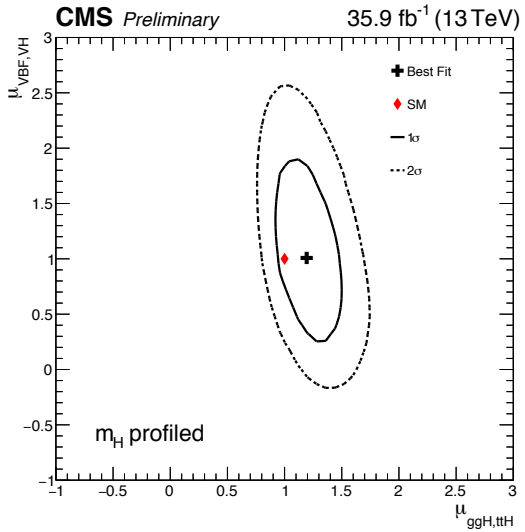
H->ZZ*->4l signal strength

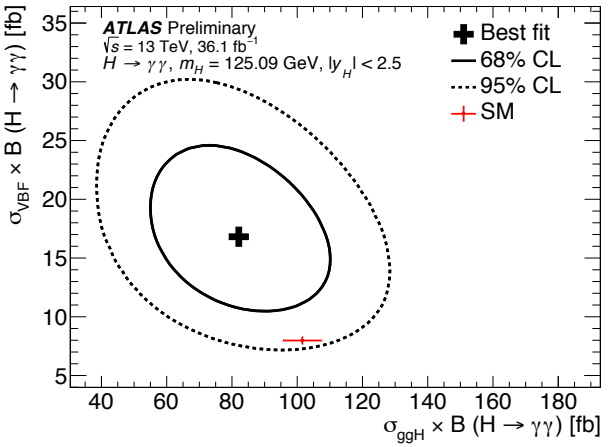


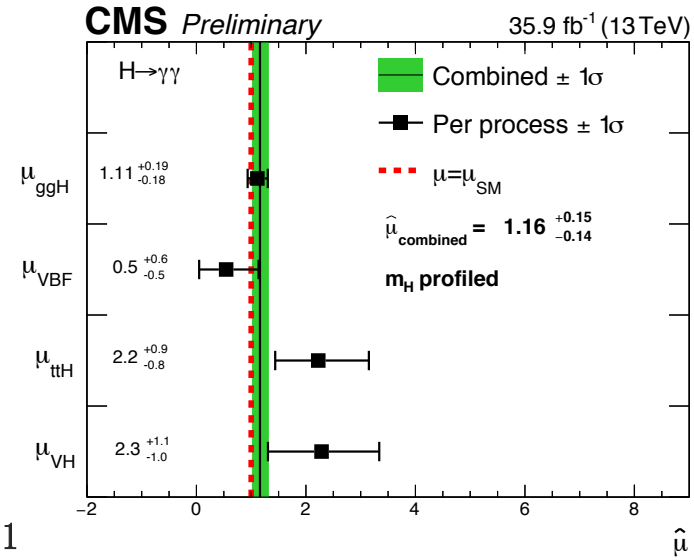


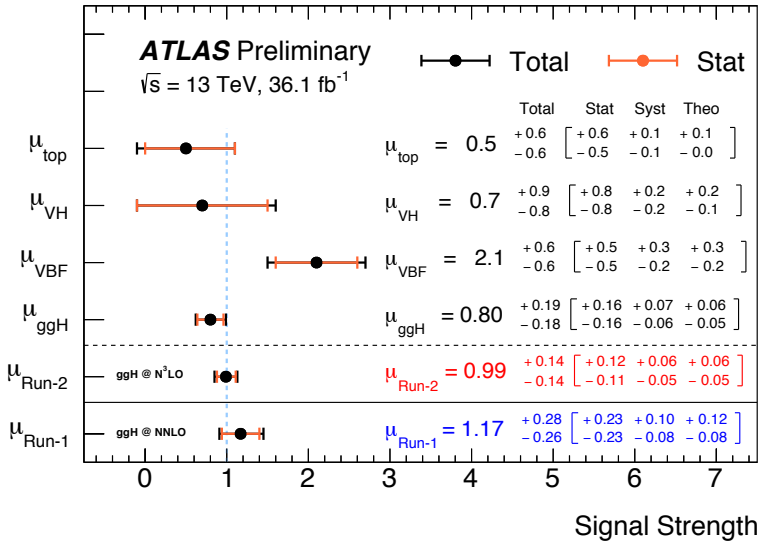


H->γγ signal strength

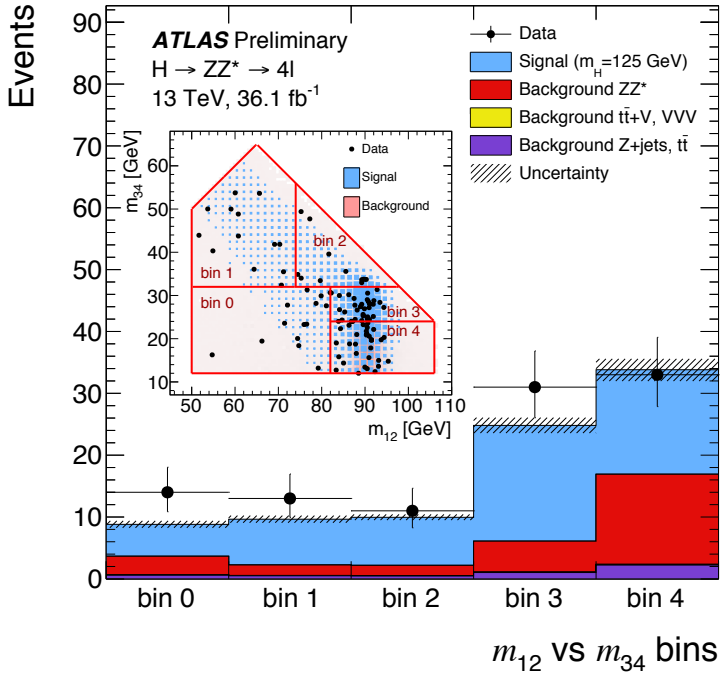


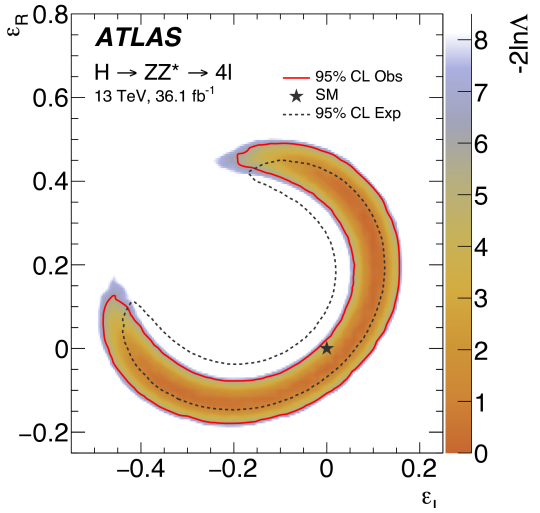


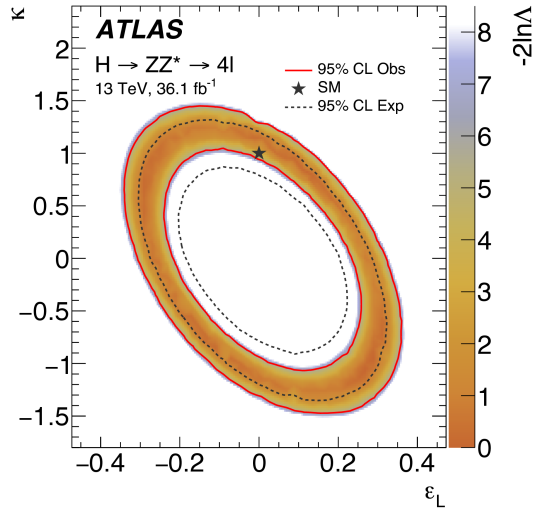




H->ZZ*->4l fiducial cross section



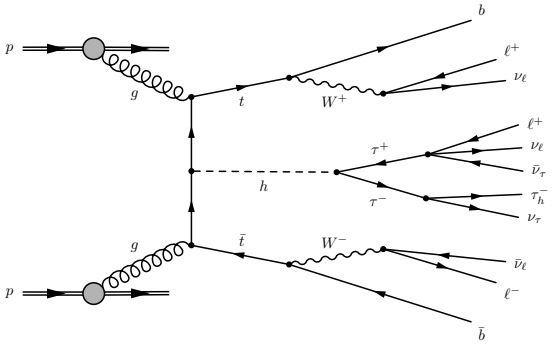


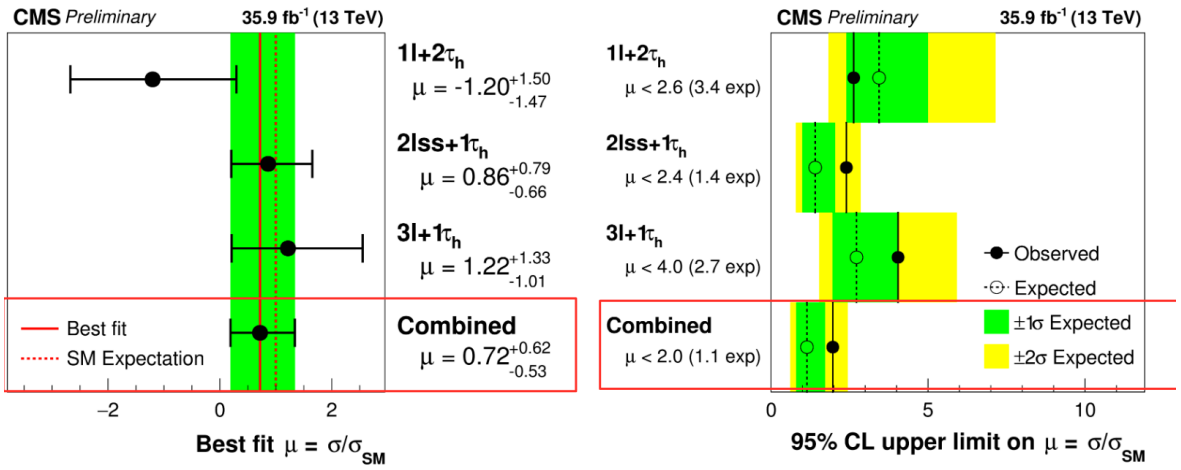


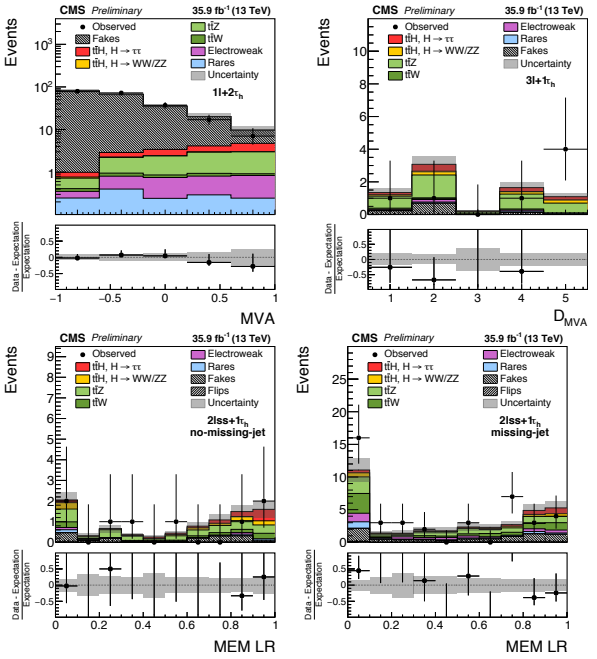
ttH : hadronic τ

HIG-17-003

- MVA method for hadronic τ ID
- Categories: 1lep+2$\tau_{had,}$ 2 ss-lep+1τ_{had}, 3lep+1τ_{had}
- Discriminants to separate signal from ttbarV, ttbar backgrounds in each category





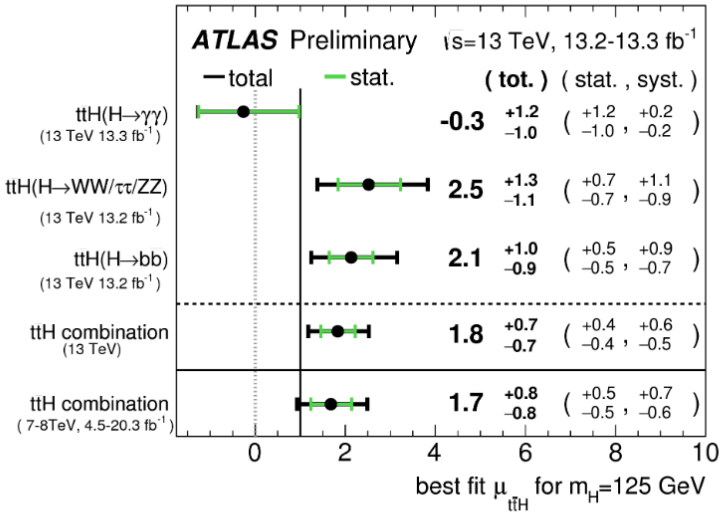


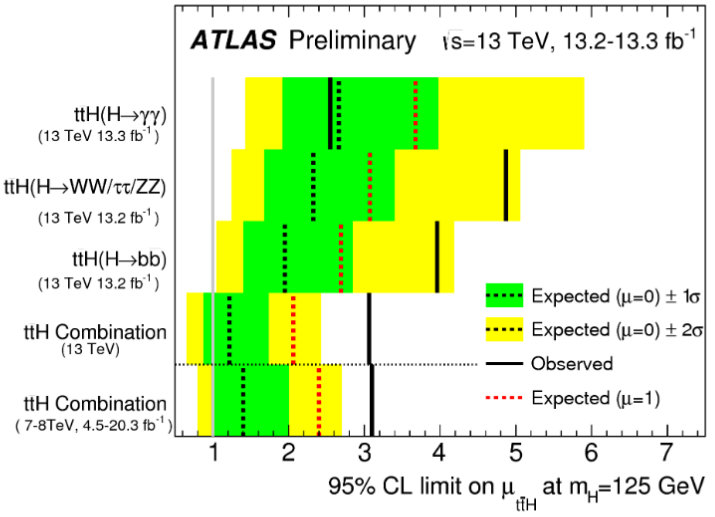
ttH : 13.f fb^{-1} combination

K. Liu, ATLAS tth, Higgs Hunting 2017

ATLAS-CONF-2016-068,

✦ Summary of the ttH signal strength measurements (left) and upper limits (right).





Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H$, $H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H$, $H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H$, $H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

ttH : 36fb^{-1} combination 4l + γγ

ATLAS-CONF-2017-047