H→μμ and other rare decays at LHC

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Motivation

In July 2012, the ATLAS and CMS Collaborations discovered at LHC a new particle with a mass of 125 GeV

Further measurements indicated that this particle is consistent with the Standard Model (SM) Higgs boson

Please follow talks on Higgs Boson studies!

H → μ+μ− probes the Yukawa coupling of the Higgs boson to second-generation fermions, important in understanding the mechanism of electroweak symmetry breaking in SM

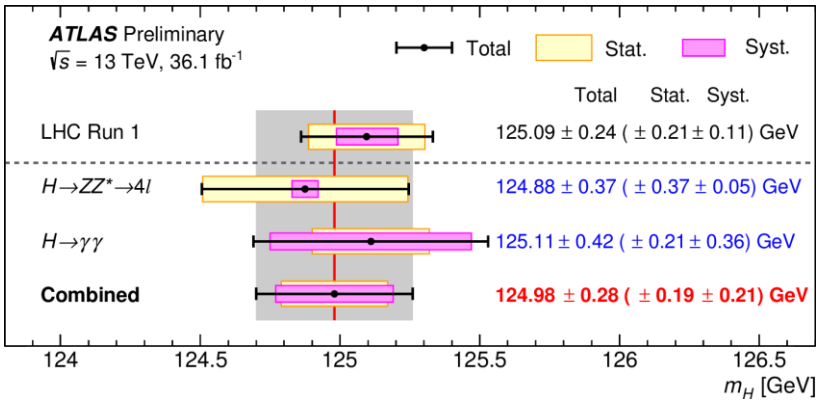
Several Beyond Standard Model (BSM) scenarios predict a higher branching ratio

Deviations from SM could be a sign for new physics

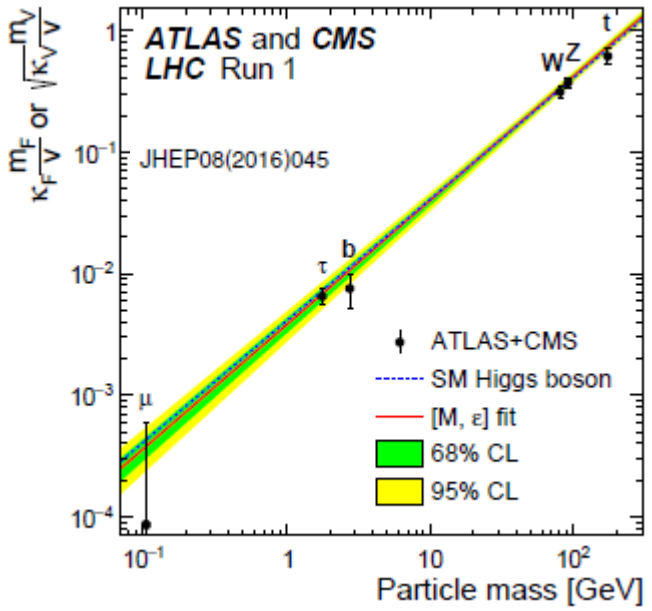
Presented here searches performed using pp collision data recorded with the ATLAS detector in 2015 and 2016 at 13 TeV.

The data set corresponds to an integrated luminosity of 36.1 fb−1 ± 0.8 fb-1

ATLAS-CONF-2017-046

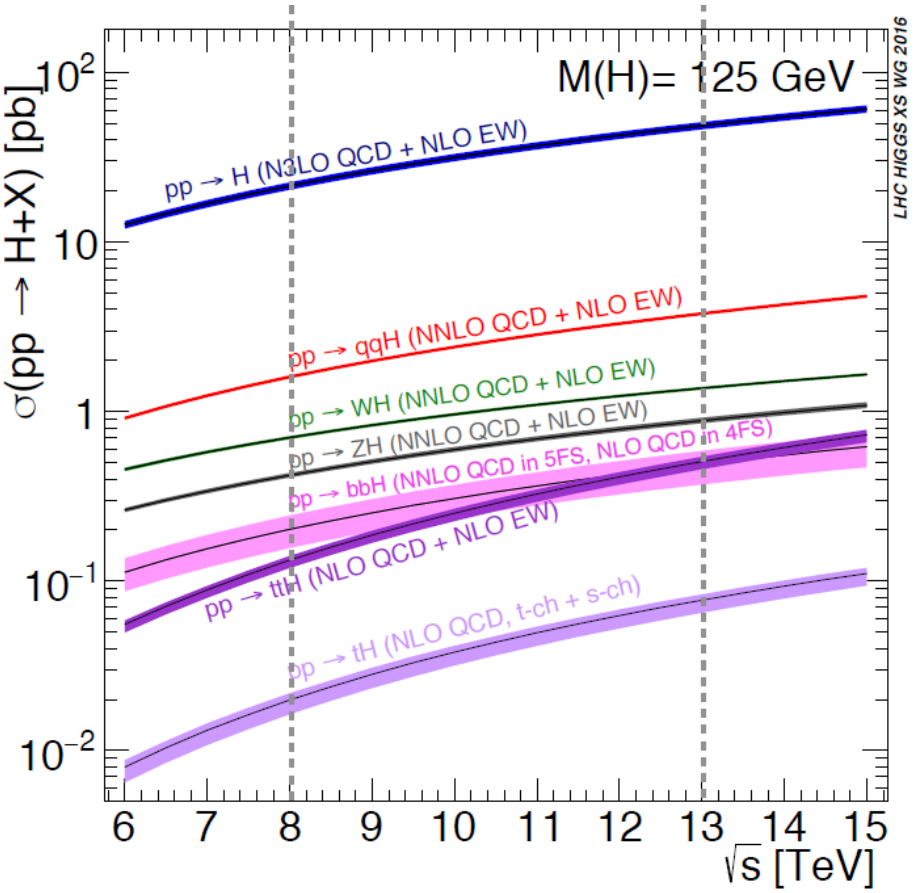


Coupling modifiers



Higgs production at LHC

Large cross section increase from 8 to 13 TeV:



2.6

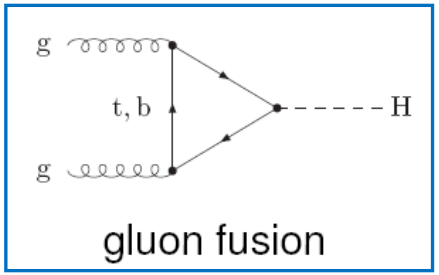
2.7

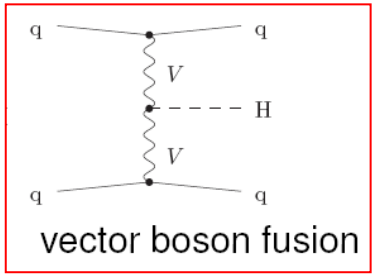
2.2

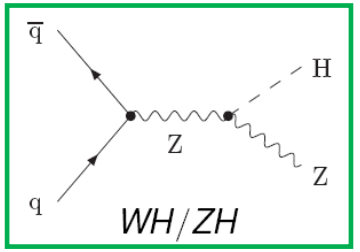
4.6

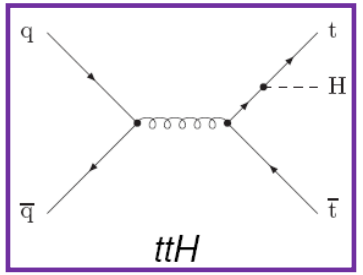
2.7

4.8



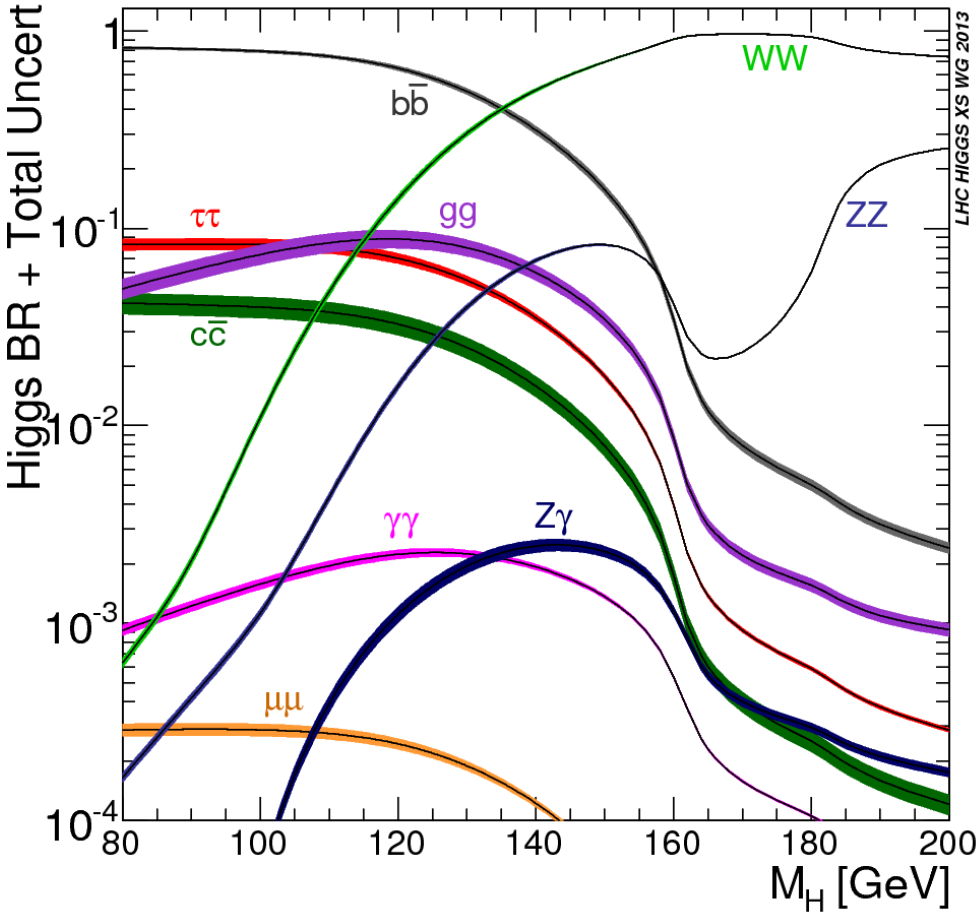






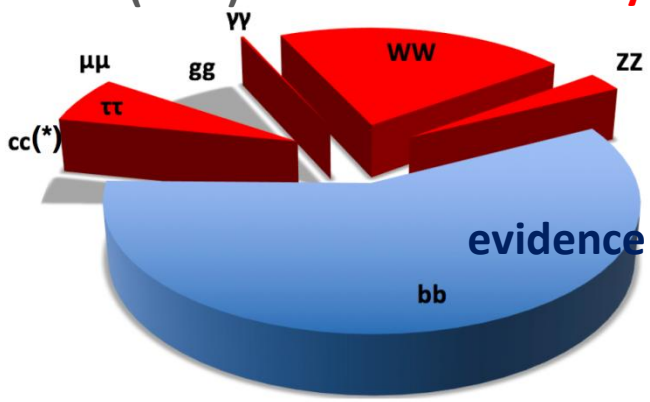
Gluon fusion has the largest production rate, order of magnitude higher than VBF or VH

Higgs Boson decays at LHC



'tough' modes (11%)

observed decays (31%)



Decay	Branching [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	**2.90 ± 0.35**
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	**0.155 ± 0.014**
$H \to \mu\mu$	**0.0218 ± 0.001**

Higgs coupling to 2nd generation fermions (cc, μμ)

H → μμ Monte-Carlo simulation vs. data

PRL 119 (2017) 051802

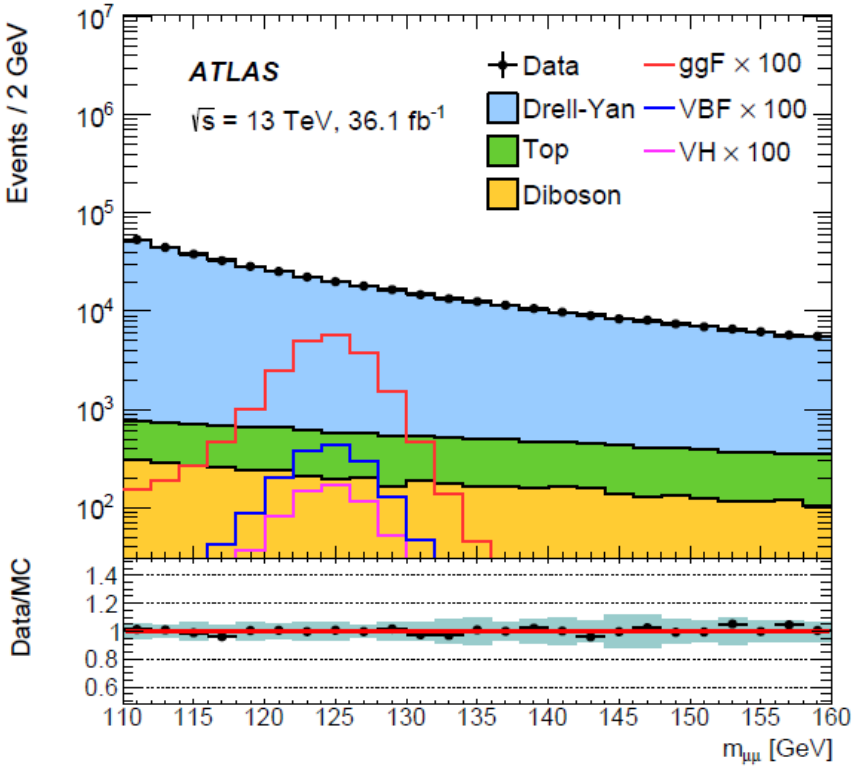
Monte Carlo used:
- to model analytic function for signal processes
- to optimize the event selection
- analytic functions to model $m_{\mu\mu}$ distributions for the total background

ggF and ***VBF*** generated with ***POWHEGBOX*** at ***NLO QCD*** using ***CT10*** pdf

PYTHIA8 for parton showering and hadronization and ***H → μμ*** events produced in ***VH***

Hadronization and underlying event parameters set according to ***AZNLO*** tuned on the ***Z*** boson p_T distribution measurement in ***7 TeV*** pp collisions

Higgs boson ***pT*** spectrum for the ***ggF*** process to reweighted to match **HRes** predictions



Pile-up: mean number of interactions per crossing ~25

Full detector simulation with Geant 4

Analysis strategy

- Single-muon triggers with the transverse momentum
  $p_T > 26$ GeV for isolated muons or
  $p_T > 50$ GeV for muons without any isolation
- The trigger efficiency is about ***95%*** for the signal processes
- Select events with exactly two opposite-charge muons and classify them into eight categories
- Muons reconstruction done based on Inner detector and Muon Spectrometer
- Cuts:
  - ✓ Leading muon $p_T > 27$ GeV
  - ✓ $p_T > 15$ GeV and $|\eta| < 2.5$
  - ✓ $110 < m_{\mu\mu} < 160$ GeV - fitting range chosen to avoid the Z boson mass peak
  - ✓ MET< 80 GeV
  - ✓ Veto events with *b*-jets

Categorization: VBF

To select VBF events use a BDT trained by 14 variables :

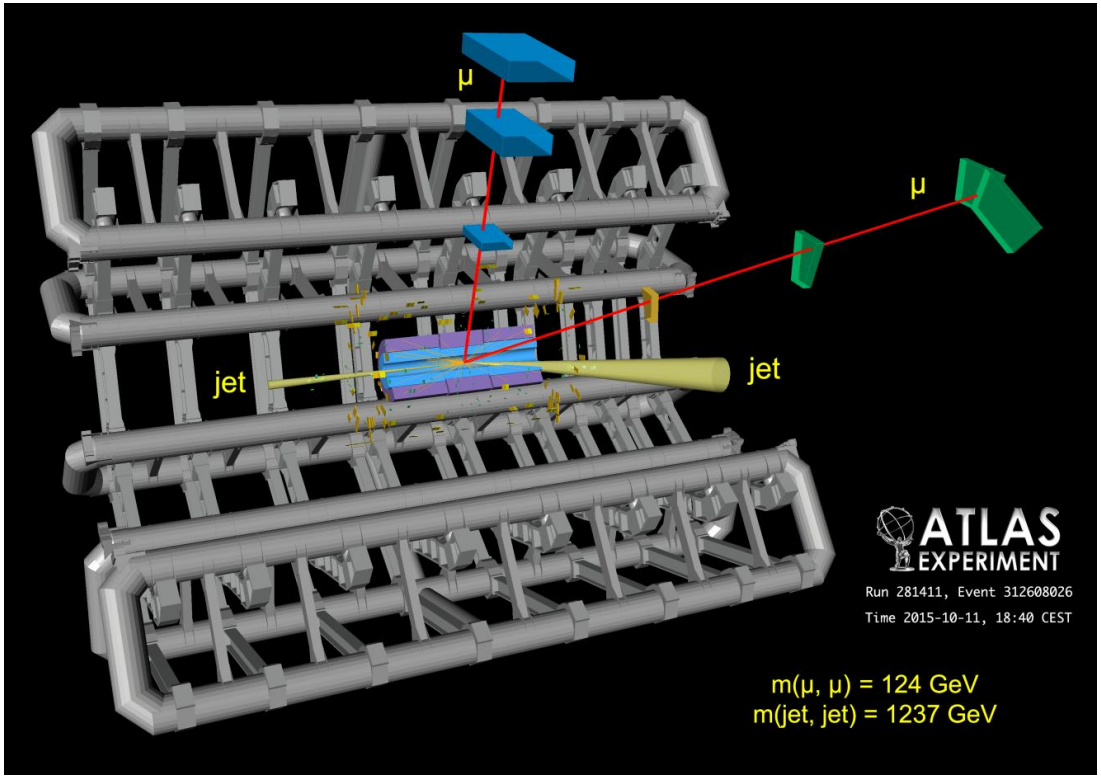
- dijet invariant mass m_{JJ}
- $\Delta\eta_{JJ}$
- angular distance ΔR_{JJ} between two jets
- transverse momentum of dijet system p_T^{JJ}
- E_{miss}^{T}

Categories tend to use $S/\sqrt{B} \sim 1/\sqrt{\sigma}$ ratio at different regions

Two categories defined using MVA to provide good sensitivity to the vector-boson fusion (VBF):

VBF_loose: *0.7<BDT<0.9,*

VBF_tight: BDT>0.9

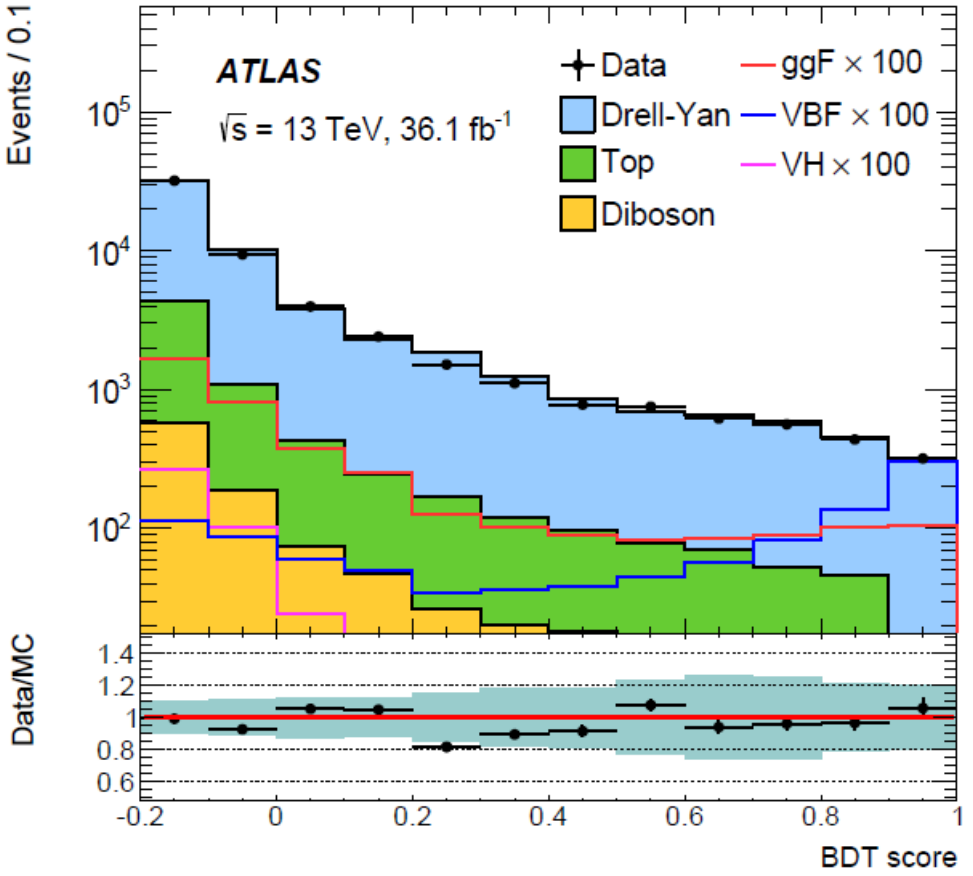


Signal events produced in VBF process likely to have two high-pT forward jets in opposite detector hemispheres and hadronic activity between them

ggF categorization and BDT score distribution in signal region

Other 6 categories sensitive to signal events produced in the gluon–gluon fusion (ggF) at different muon η and the transverse momentum of the dimuon system $p_T^{\mu\mu}$:

$\lvert\eta_{1,2}\rvert < 1$	**rest** η	
Low Central	**Low Non-central**	$p_T^{\mu\mu} < 15GeV$
Medium Central	**Medium Non-central**	$15GeV < p_T^{\mu\mu} < 50GeV$
High Central	**High Non-Central**	$p_T^{\mu\mu} > 50GeV$



Clear signal separation from background and good description by MC

Event yields

	S	B	S/√B	FWHM, GeV	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7	6585
***Non-central medium $p_T^{\mu\mu}$**	66	31000	**0.37**	7.1	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3	3160
Non-central high	40	13000	0.35	7.7	12829
VBF loose	3.4	260	0.21	7.6	274
***VBF tight**	3.4	78	**0.38**	7.5	79

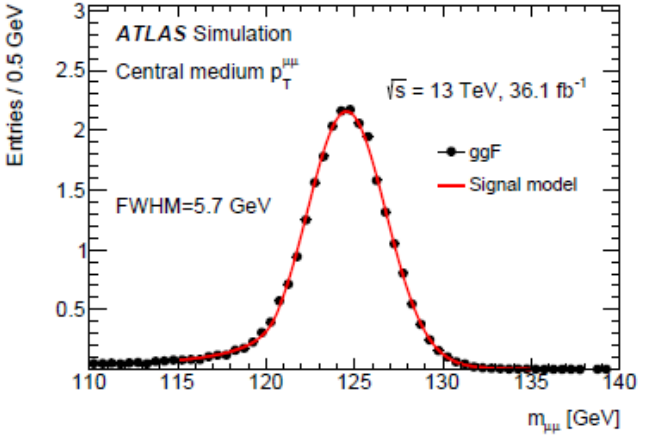
*** Categories with higher sensitivities**

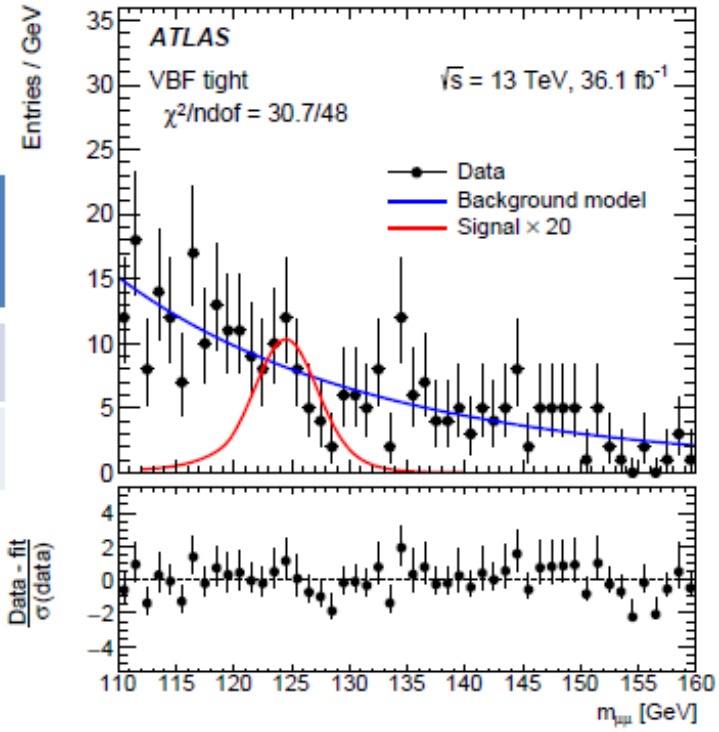
$H \to \mu\mu$ signal and background modeling

Signal $m_{\mu\mu}$ are shaped with a convolution of Cristal Ball ⊗ Gauss

Background $m_{\mu\mu}$ modeled by

$$P_B(m_{\mu\mu}) = f \times \left[BW(m_{BW}, \Gamma_{BW}) \otimes Gauss(\sigma_{GS}^B) \right] + (1-f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^3$$





Data set	Upper limit @95% observed (expected)		Signal strength
Run2	3.0	3.1	-0.07±1.5
Run1+Run2	2.7	2.8	-0.13±1.4

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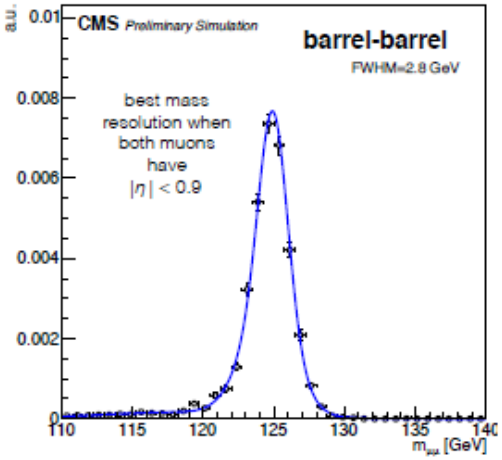
SM $H\to\mu\mu$ in pp collisions at $\sqrt{s}$= 13 TeV with CMS

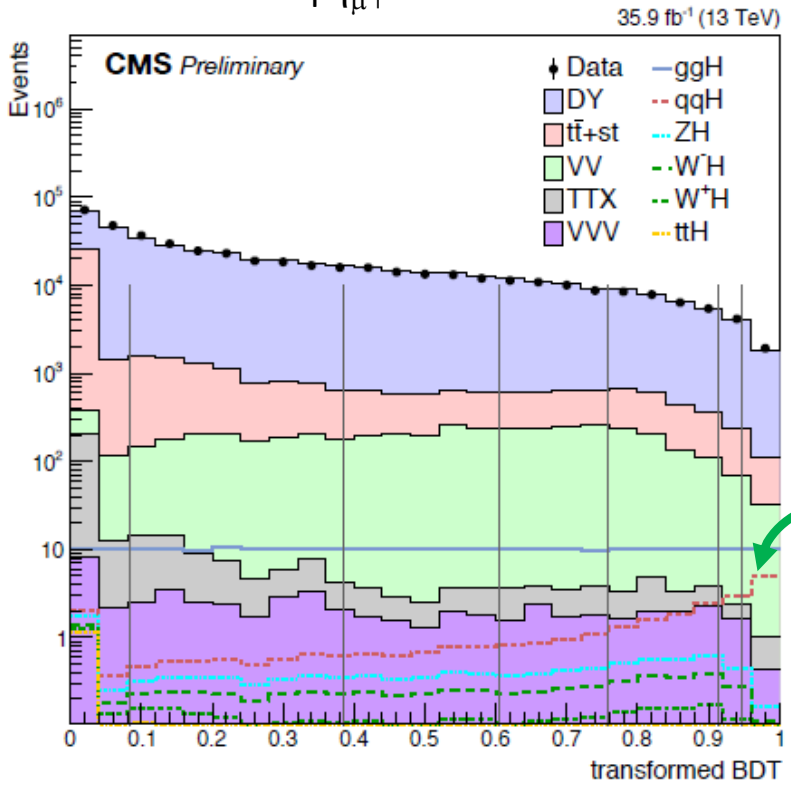
BDT to enhance S/B
BDT loosely correlated with VBF
BDT categories shown as separated by vertical lines

The left most category and last two categories have only one η category
The rest regions have three η categories:

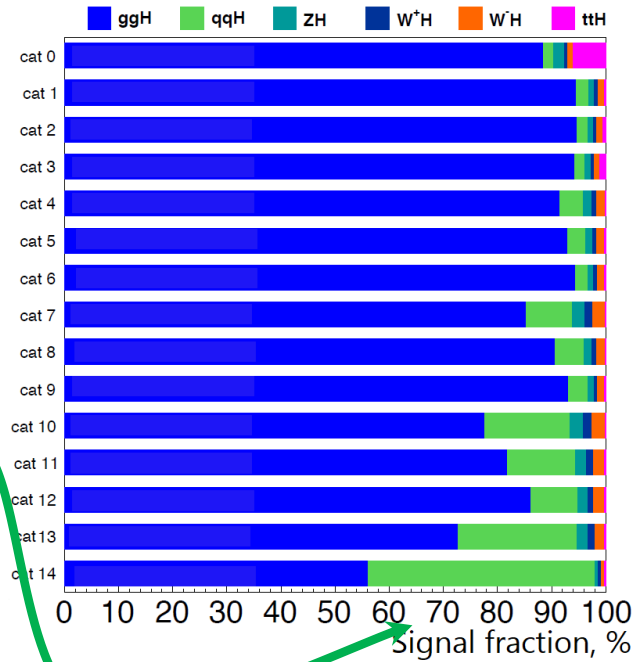
- Both muons are at $|\eta_\mu| < 0.9$
- Max. muon $0.9 < |\eta_\mu| < 1.9$
- Max. muon $1.9 < |\eta_\mu| < 2.4$

CMS-PAS-HIG-17-019



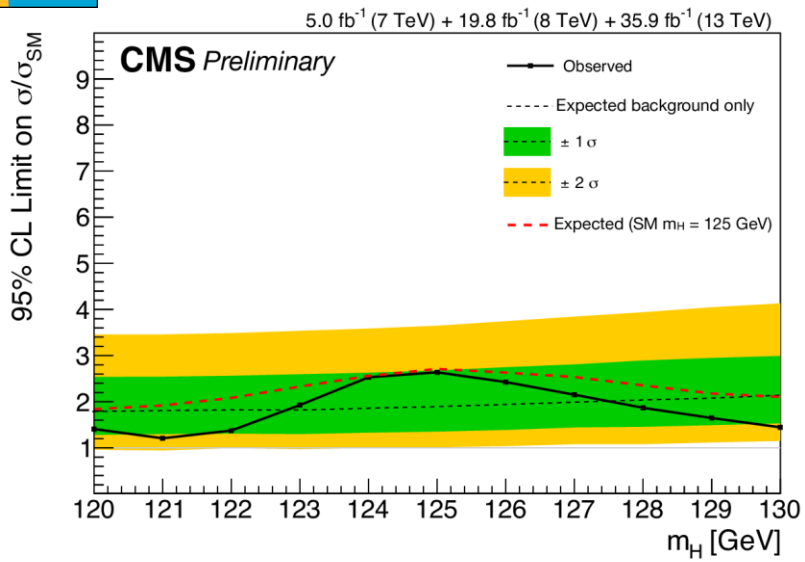


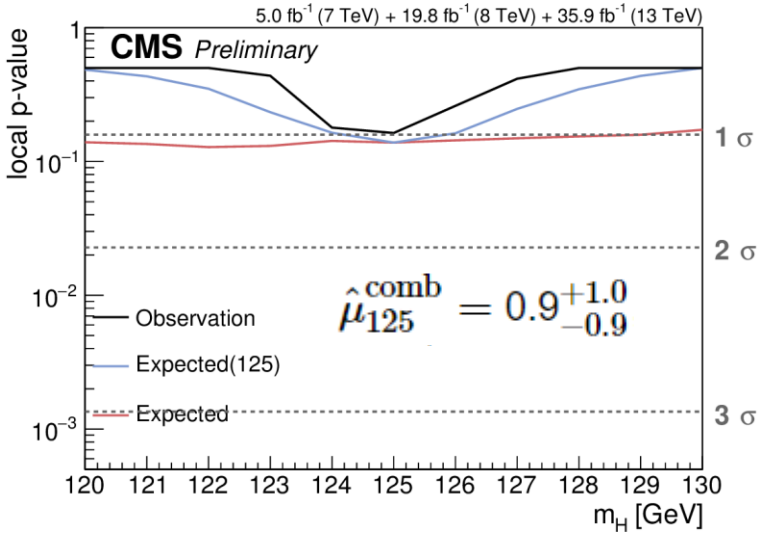
qqH



SM H→μμ in pp collisions at √s= 13 TeV with CMS

CMS PAS HIG-17-019





Combined local p-value and significance as a function of the SM Higgs boson mass

Data set	Upper limit 95% observed(expected)	Signal strength
13TeV **@35.9 fb^{-1}**	2.64(2.08)	0.74 (0.98)
7TeV+8TeV+13TeV	2.64(1.89)	0.98 (1.09)

Search for the $Z\gamma$ decay mode of the Higgs Boson

This analysis searches for the $Z\gamma$ decay of the Higgs boson exploiting $Z \rightarrow ee$ or $\mu\mu$.

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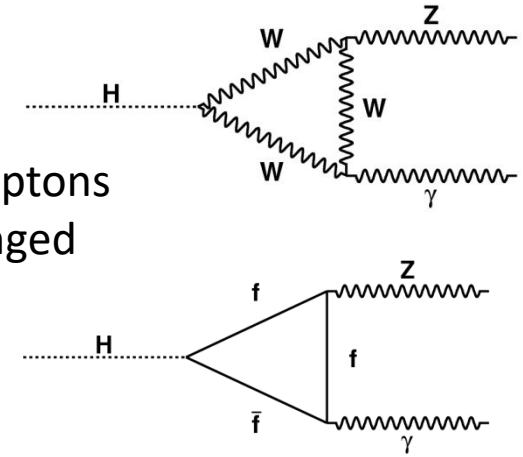
Difference in branching ratio with SM prediction IF:

- H is a composite state
- in models with additional colourless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the $\boldsymbol{H \rightarrow Z\gamma}$ loop



Dataset 36.1 fb−1 of pp collisions at √ s=13 TeV.

The branching ratio for the $H \rightarrow Z\gamma$ predicted by the SM
$B(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$ for mH=125.09 GeV

$H \rightarrow ZZ$	2.67 ± 0.11
$H \rightarrow \gamma\gamma$	0.228 ± 0.011

Search for $H \to Z\gamma$: Categorization

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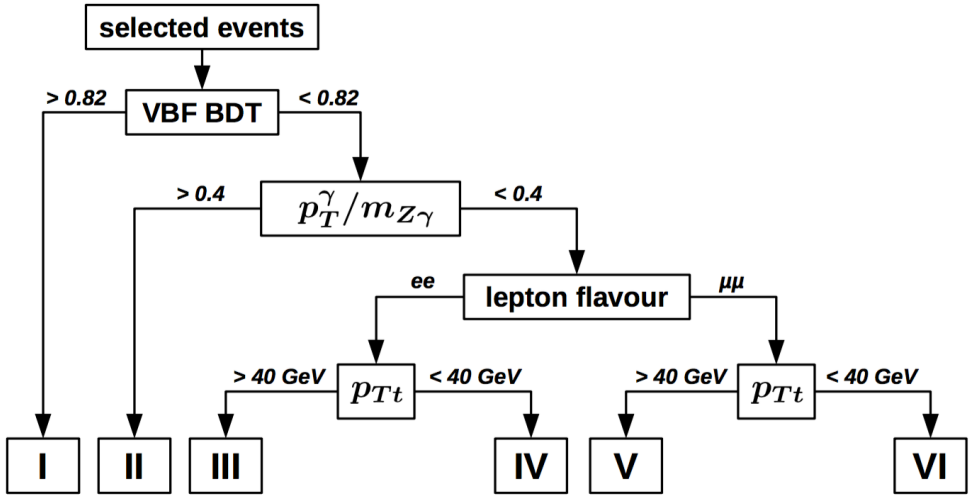
- Events split into 6 exclusive categories
  - I VBF enriched
  - II High relative p^{γ}_{T}
  - III *ee* high p_{Tt}
  - IV *ee* low p_{Tt}
  - V $\mu\mu$ high p_{Tt}
  - VI $\mu\mu$ low p_{Tt}



- Provide 20% improvement in sensitivity with respect to the Run1 categories PLB 732(2014)8

- Analysis benefits from larger dataset

- Increased production cross section from 7TeV+8TeV to 13 TeV

Dominant background: Non-resonant Z+γ production
smaller contribution from Z+jets (jet mis-identified as a γ)

H→Zγ

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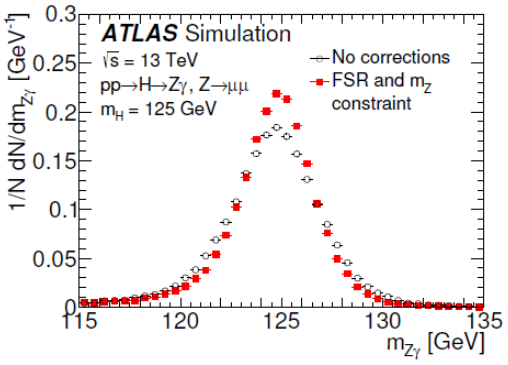
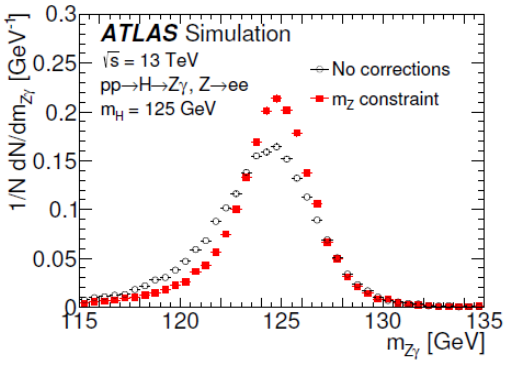
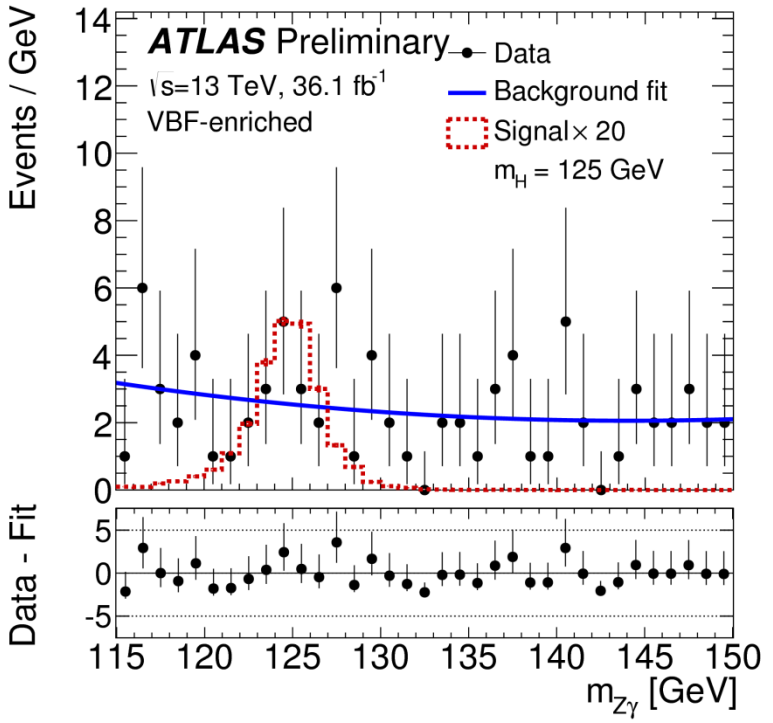
- Signal model extracted by fit to ***m(Zγ)***
- Relies on good mass resolution
- Kinematic fit on Z to improve

  $m_{\mu\mu\gamma}$ ($m_{ee\gamma}$) resolution by ***7% (13%)***





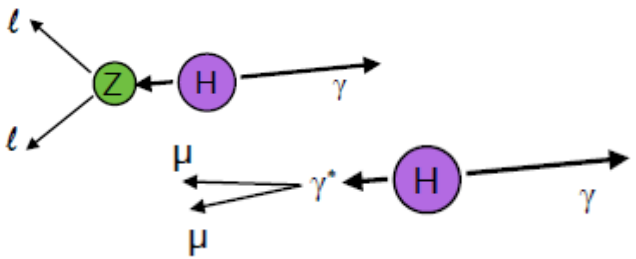


No evidence of localized excess visible near the anticipated Higgs mass

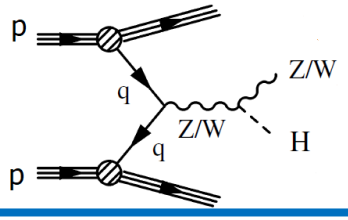
95% CL Upper limit	Expected without Higgs boson decays	Expected with SM Higgs boson	Observed
$\sigma \cdot BR / (\sigma \cdot BR)_{SM}$	4.4	5.2	6.6

$H \to Z\gamma$, $Z \to ee(\mu\mu)$ and $H \to \gamma^*\gamma$, $\gamma^* \to \mu\mu$

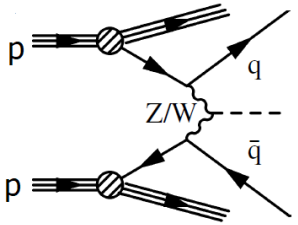
Events selection:
2 same flavor leptons and 1 photon
Separation $Z\gamma$ and $\gamma^*\gamma$ at m_{ee}, $m_{\mu\mu}$= 50 GeV



Categorization in order to increase S/B
Signal efficiency 22-29%, sensitivity enhancement by categorization 11-18%



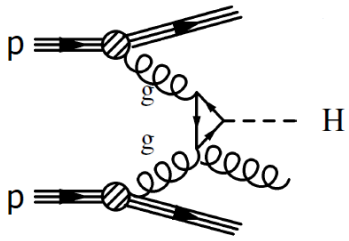
Lepton tag:
electron pT>7 GeV
muon pT> 5 GeV



Dijet tag:

$$N_{jets} \geq 2,\ \Delta\eta_{jj} > 3.5,\ m_{jj} > 500 GeV$$

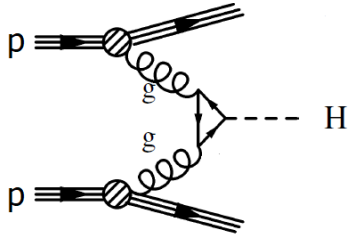
$$\eta_{ll\gamma} - (\eta_{j1} + \eta_{j2})/2 < 2.4$$



Boosted tag:

$$p_T^{\gamma ll} > 60\, GeV$$

Untagged categories



to enhance momentum resolution of reconstructed γ μ e

CMS PAS HIG-17-007

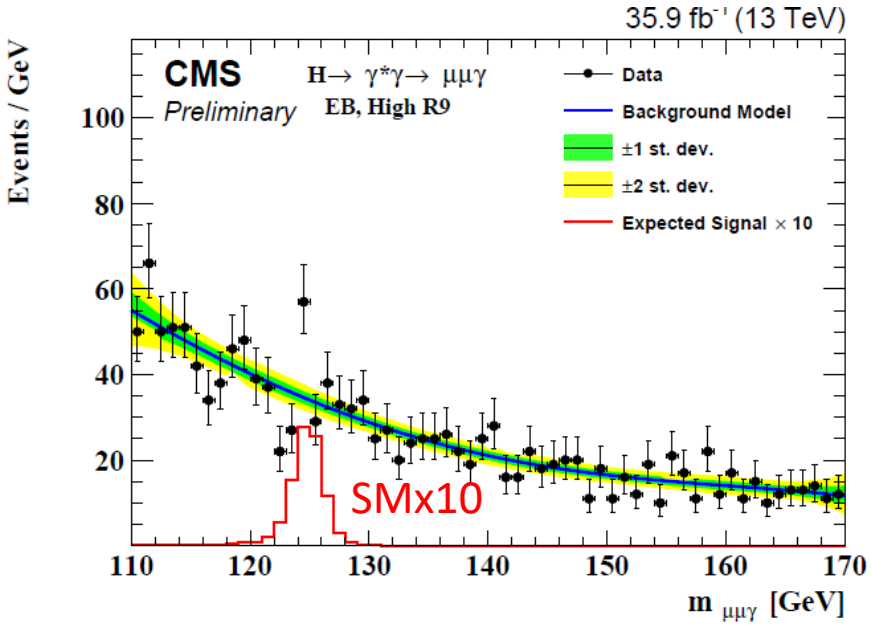
Signal and background modeling

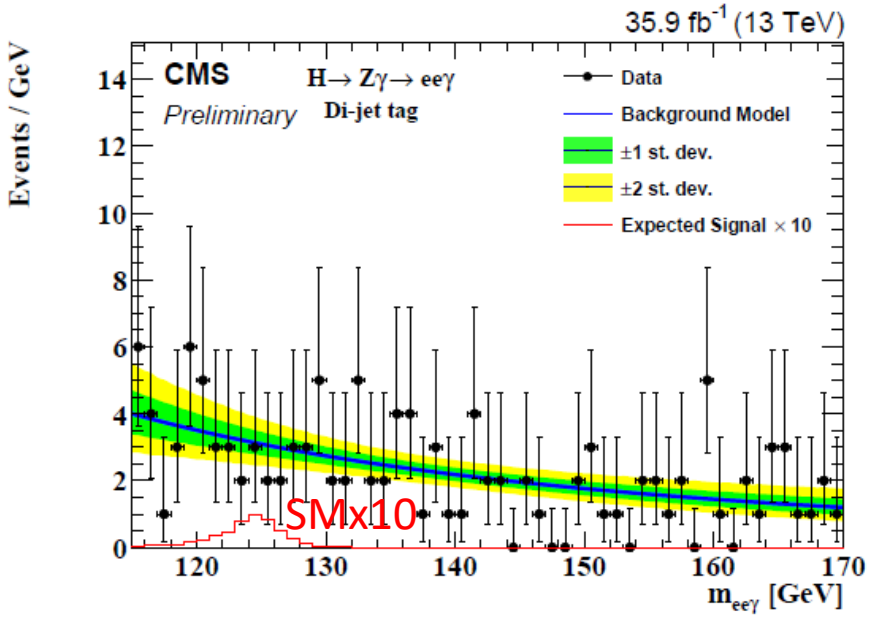
Search for signal by shape-based analysis

Background fit function minimizes the bias introduced by selected shape

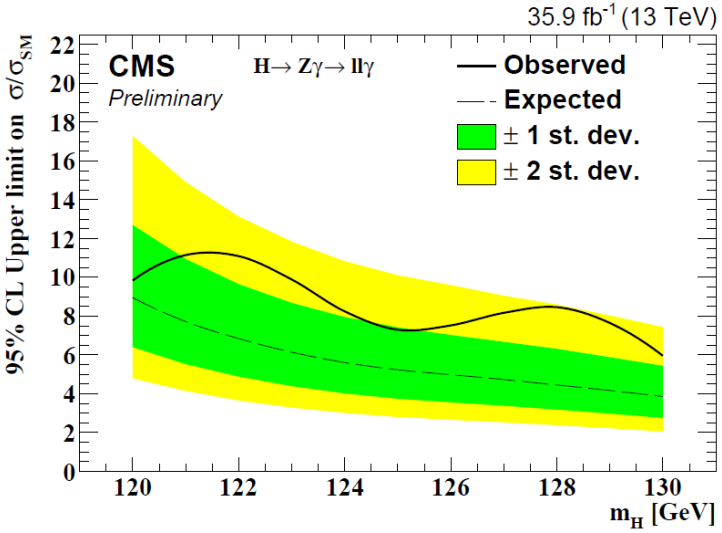
Background estimated from data and fitted by smooth falling functions

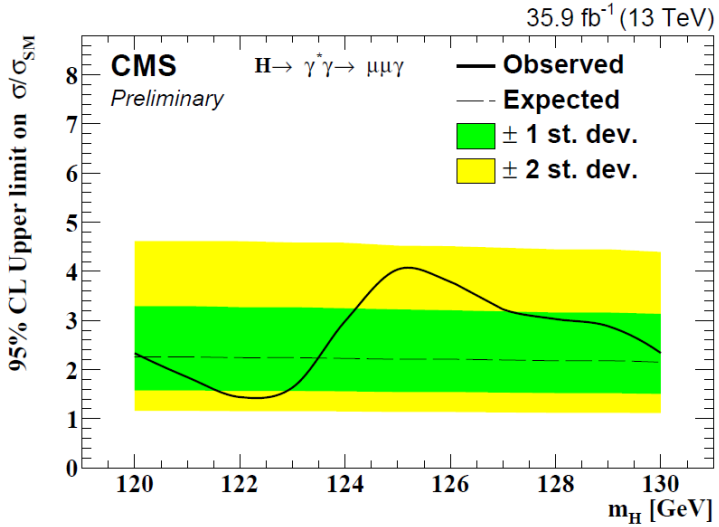
Signal is model:
- Double sided Crystal Ball for $\gamma^*\gamma$
- Convolution Crystal Ball and Gauss for $Z\gamma$

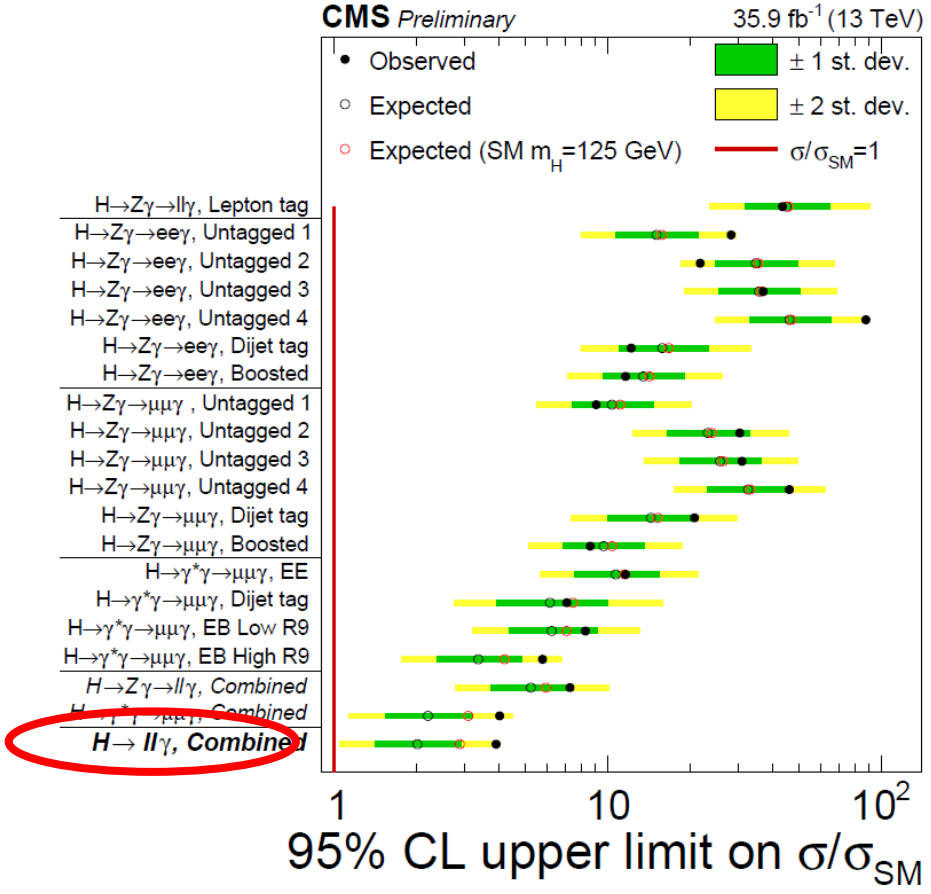




Observed (expected) upper limit for σ/σ_{SM} (H→*ll*γ) is 3.9(2.0)







Search for exclusive Higgs decays to $\varphi\gamma$ and $\rho\gamma$ with ATLAS

Rare exclusive decays $H \to \varphi\gamma$, $\varphi \to K^+K^-$ and $H \to \rho\gamma$, $\rho \to \pi^+\pi^-$ to probe

- Higgs couplings to light quarks (the ***s***-quark, and the up- and down-quarks)
- potential deviations from the SM prediction

Decays $\phi \to K^+K^-$ and $\rho \to \pi^+\pi^-$ reconstructed from pairs of oppositely charged inner detector tracks

Background from random tracks and γ combinations in multijet and γ+jet s events

No significant excess of events observed above the background

Upper limits at 95% CL the branching

$B(H\to\phi\gamma)$ 4.8×10^{-4}

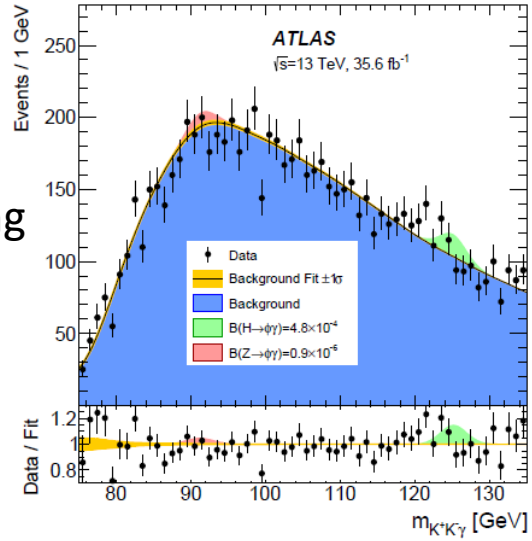
$B(H\to\rho\gamma)$ 8.8×10^{-4}

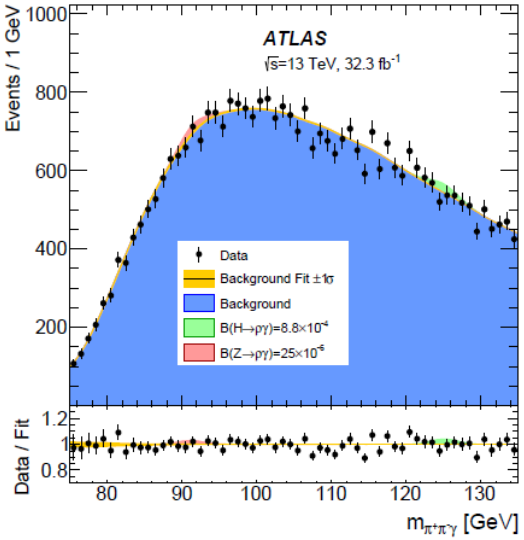
and respectively

$\sigma \otimes B(H\to\phi\gamma) \sim 25.3$ fb $\sim 208 \times$ SM

$\sigma \otimes B(H\to\rho\gamma) \sim 45.5$ fb $\sim 52 \times$ SM

CERN-EP-2017-273





Higgs decays to $c\bar{c}$ with ATLAS

Associated Higgs Boson production $ZH \to l^+l^- c\bar{c}, l = e, \mu$

CERN-EP-2017-334

2 charm-tagging MVAs used to identify the signature $H \to cc$

Events selection criteria:

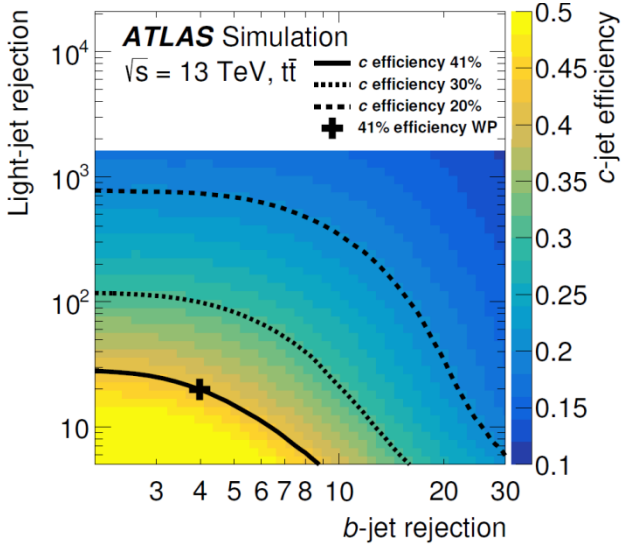
- two same flavor leptons, 81< m_{ll} <101 GeV (consistent with *Z*)

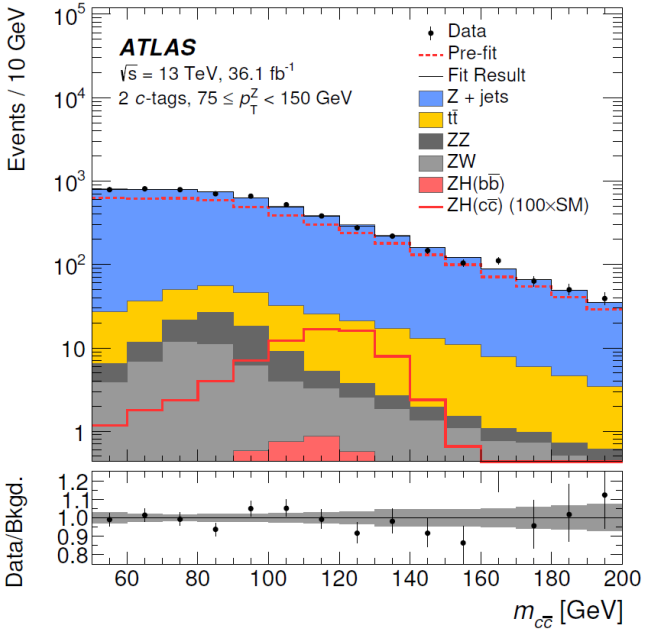
-2 jets, at least 1 jet identified as *c*-jet
jets pT>20 GeV, $|\eta|$<2.5

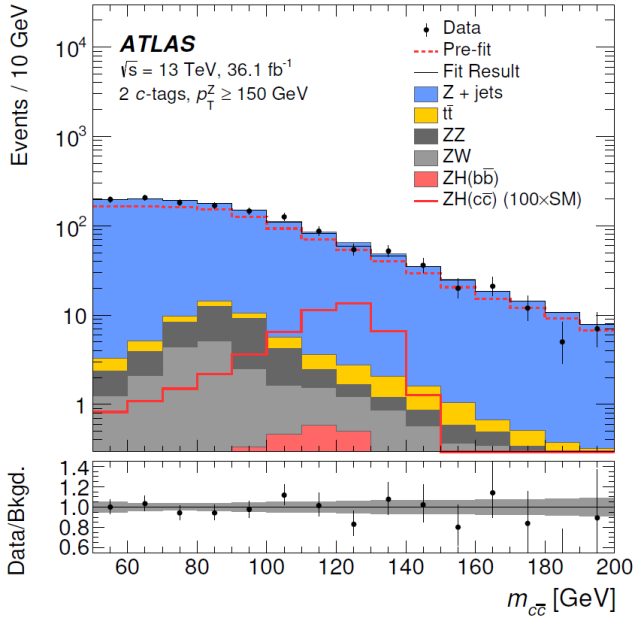
The observed (expected) upper limit at 95% CL on:

$$\sigma(pp \to ZH) \otimes \mathrm{B}(H \to c\bar{c}) = 2.7(3.9^{+2.1}_{-1.1})\, pb$$

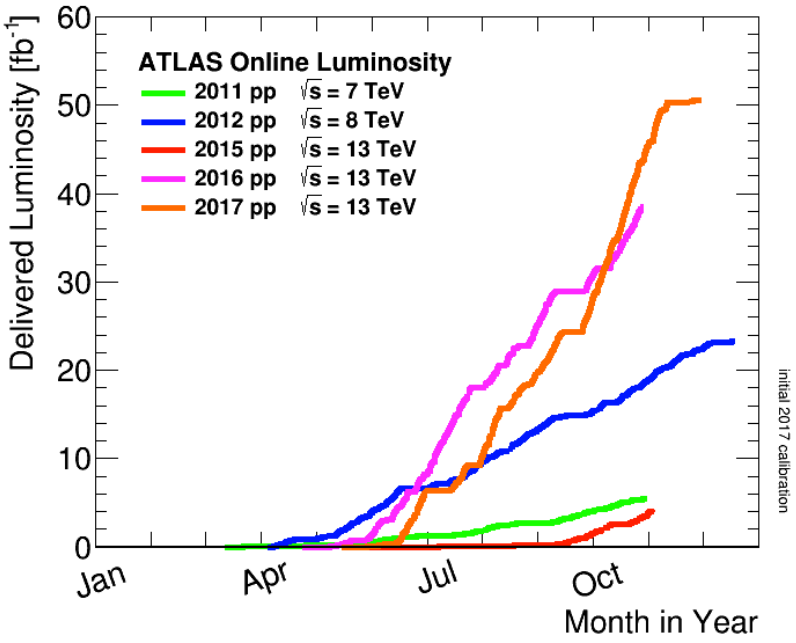
$$\mu = 110\ (150^{+80}_{-40})$$

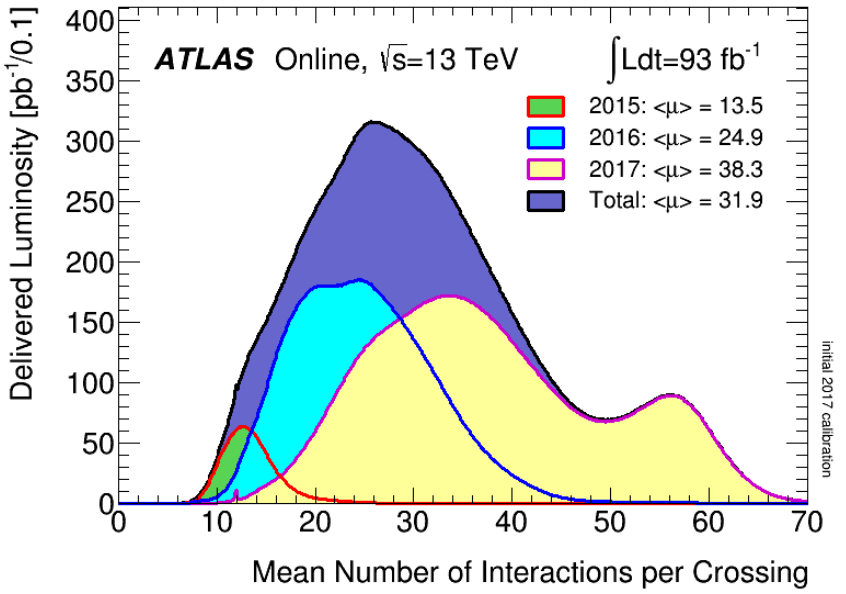






ATLAS delivered luminosity



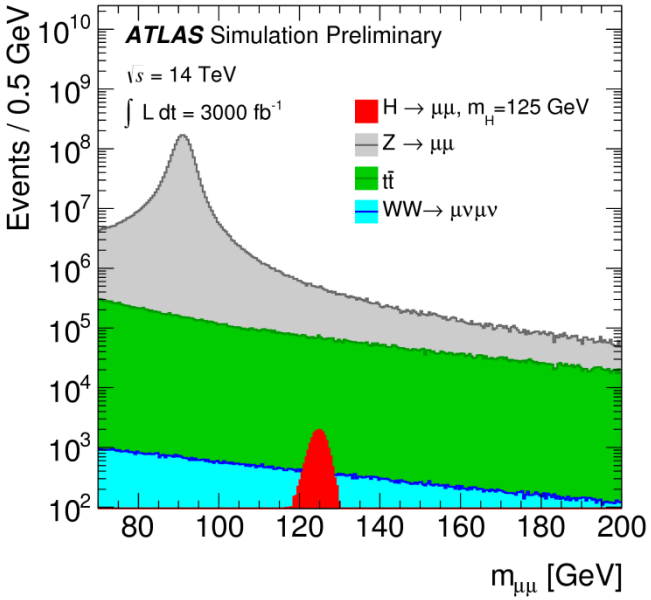


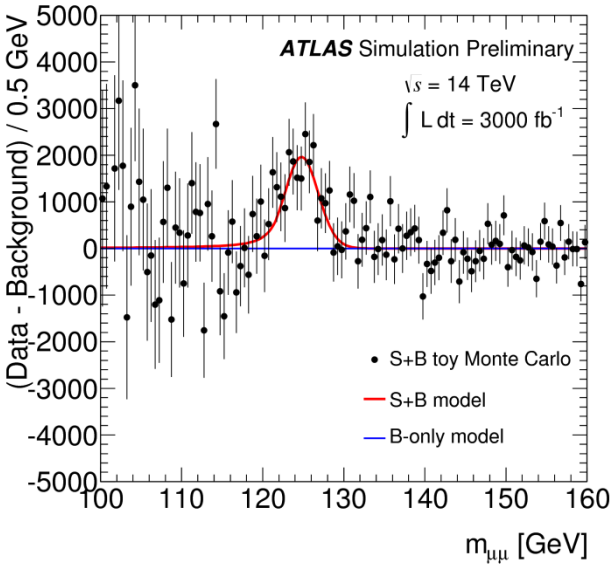
LHC exceeds expecting performance
– Run I: ~30 fb-1 of 7 and 8 TeV pp collision data recorded
– Run II: ~90 fb-1 of 13 TeV pp collision data recorded – Peak luminosity above design
Up to 70 inelastic pp interactions per bunch crossing

Only a small fraction of acquired data analyzed!

Projection for HL-LHC: Higgs coupling to $\mu^+\mu^-$

ATL-PHYS-PUB-2013-014





$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

Coupling to 2nd generation fermions: litmus test for HL-LHC

Small branching 2×10^{-4} ATLAS Run2 (36 fb-1) 13 TeV : $\mu=-0.1\pm1.5$

Main background from Z/γ^*, $t\bar{t}$ and WW

300 fb-1 2.3 σ $\Delta\mu/\mu$ $\pm45\%$

3000 fb-1 7.0 σ $\Delta\mu/\mu$ $\pm20\%$

Optimized cut based analysis in the ATLAS Muon TDR

Summary

Standard Model and Higgs measurements reaching unprecedented precision

New analyses trying to target tough Higgs decays

LHC performance beyond design: 2017 another record year - data on tape larger than what analyzed so far at 13 TeV

SM holding up very well to LHC tests
– Probing energy frontier
– Crucial understanding in the search for New Physics

The future of LHC could be in precision SM physics, depending on the scale for new physics

2018 will bring even more data for pp and heavy ion collisions

Hopefully the High Luminosity LHC will provide the precision needed to further test the Standard Model, Higgs Boson physics and better constraining or discovery BSM

Please follow public results by the ATLAS and CMS collaborations
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
http://cms-results.web.cern.ch/cms-results/public-results/publications/

References

Search for the Dimuon Decay of the Higgs Boson in pp Collisions at √s=13 TeV with the ATLAS
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.119.051802
PRL 119, 051802 (2017)

Search for the standard model Higgs boson decaying into two muons in pp collisions at √s=13 13TeV
https://cds.cern.ch/record/2292159
CMS-PAS-HIG-17-019

Searches for the Zγ decay mode of the Higgs boson and for new high-mass resonances in *pp* collisions at √s=13 TeV with the ATLAS detector
https://link.springer.com/content/pdf/10.1007%2FJHEP10%282017%29112.pdf

Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment
https://arxiv.org/pdf/1802.04329.pdf
CERN-EP-2017-334 , Submitted to PRL

Search for Higgs and Z Boson Decays to J/ψγ and Υ(nS)γ with the ATLAS Detector
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.121801

Search for exclusive Higgs and Z boson decays to φγ and ργ with the ATLAS Detector
https://cds.cern.ch/record/2273873
CONF-17-057 cds:2273873