Search for Rare Decays of the Higgs Boson with ATLAS

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On behalf of the ATLAS Collaboration

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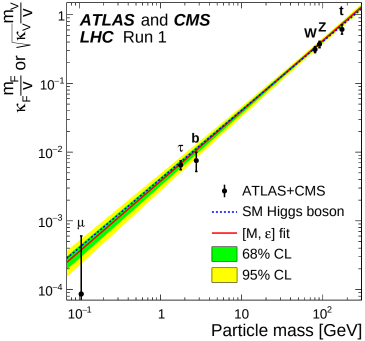
Outline

1. Introduction
2. Search for SM Higgs to dimuon (new results with 2017 data)
3. Search for SM Higgs to $Z\gamma$
4. Summary

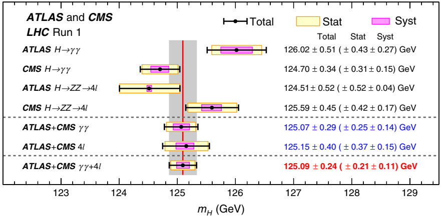
Introduction

- The discovery of the Higgs boson is a triumph of the SM.

JHEP 08 (2016) 045

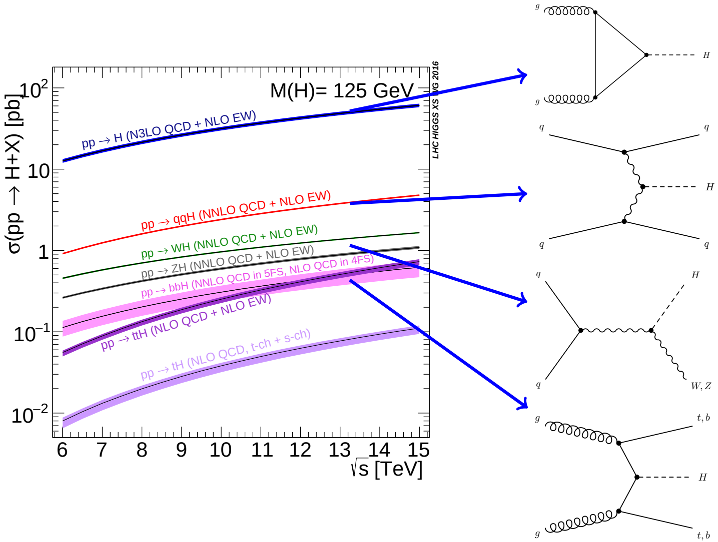


PRL 114, 191803 (2015)



- Important to look at all the possible decay channels of Higgs boson at the LHC

Higgs Boson Production at the LHC



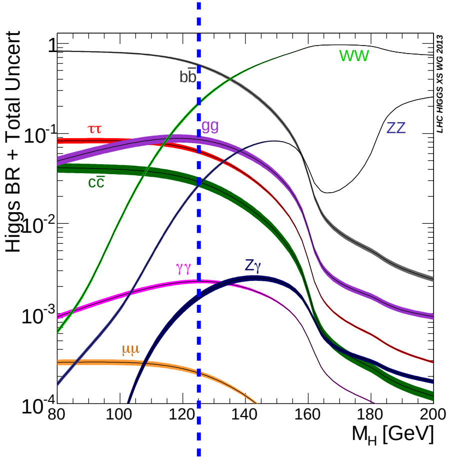
ggF: dominant, larger initial state radiation from gluons

VBF: two forward jets with high mass and large rapitidy gap

VH: vector boson (lv, ll', qq')

ttH: many b-jets, leptons, E_T^{miss}

Higgs Boson Decays



$m_H = 125$ GeV

m_H=125 GeV

Higgs decays	BR [%]
$H \to bb$	57.8
$H \to WW$	21.4
$H \to gg$	8.19
$H \to \tau\tau$	6.27
$H \to ZZ$	2.62
$H \to cc$	2.89
$H \to \gamma\gamma$	0.227
$H \to Z\gamma$	0.153
$H \to \mu\mu$	0.022

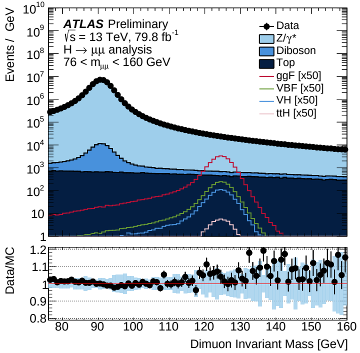
Yellow Report 4

$$H \to \mu\mu$$

New

$H \to \mu\mu$ Analysis Strategy and Event Selections

- Data: LHC 2015-2017 *pp* collisions data, 79.8 fb^{-1}
- Dominant background is Drell-Yan process
- Dedicated categories for ggF and VBF
- Use analytic functions to model signal and background



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Event selections

- At least one primary vertex associated with at least two tracks
- Exactly have two muons. Leading muon $p_T > 27$ GeV
- $E_T^{miss} < 80$ GeV. Veto events with any *b*-jet
- Signal region: $110 < m_{\mu\mu} < 160$ GeV

Categorization – ggF

Categories make use of better $S/\sqrt{B}$ for different regions

- Signal has more ISR than background. Signal tends to have large $p_T^{\mu\mu}$ than background

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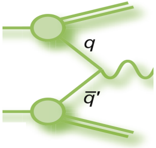
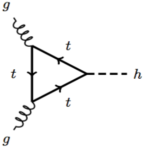
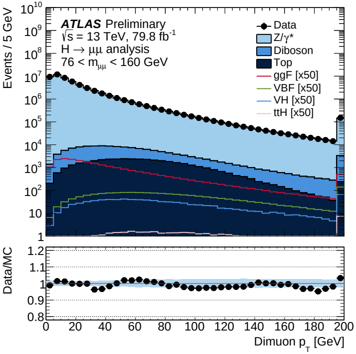
Background



Signal





(1) $p_T^{\mu\mu} < 15$ GeV; (2) $15 < p_T^{\mu\mu} < 50$ GeV; (3) $p_T^{\mu\mu} > 50$ GeV;

Categorization – VBF

Categories make use of better $S/\sqrt{B}$ for different regions

- Multivariate analysis method is used for VBF category to get better sensitivity
- 14 variables are used to train a BDT (most sensitive ones: m_{jj}, $\Delta\eta_{jj}$, $p_T^{\mu\mu}$, ΔR_{jj})
- Cut on BDT score to have `VBF Tight` (BDT $>$ 0.885) and `VBF Loose` (0.685$<$ BDT $<$ 0.885) [1]
- Events with BDT $<$ 0.685 are classified as ggF-like events

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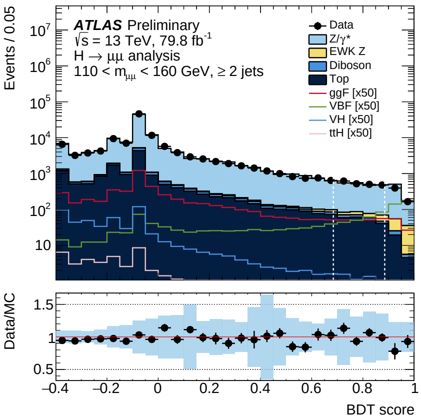


[1] Chosen to retain signal efficiency used in the last publication PRL 119, 051802 (2017)

Categorization

BDT< 0.685

	Both muons $\|\eta\| < 1$	Rest	
	Central low $p_T^{\mu\mu}$	Non-cent. low $p_T^{\mu\mu}$	$p_T^{\mu\mu} < 15$ GeV
	Central med. $p_T^{\mu\mu}$	Non-cent. med. $p_T^{\mu\mu}$	$15 < p_T^{\mu\mu} < 50$ GeV
	Central high $p_T^{\mu\mu}$	Non-cent. high $p_T^{\mu\mu}$	$p_T^{\mu\mu} > 50$ GeV

VBF Loose
0.685<BDT< 0.885

VBF Tight
BDT> 0.885

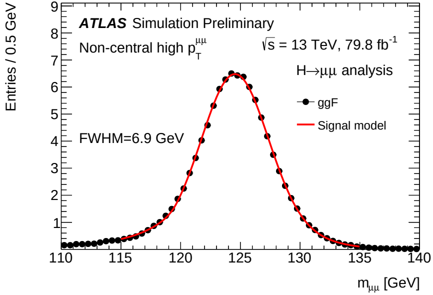
Event Yields

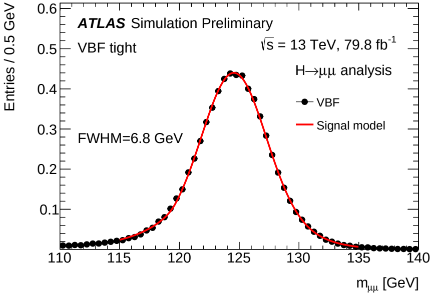
	ggF	VBF	all signal	Z+jets	Top	Di-boson	Total bkg.	Data
Central low $p_T^{\mu\mu}$	27.3	0.2	27.6	21800 ± 280	42 ± 3	50 ± 2	21900 ± 280	23318
Non-central low $p_T^{\mu\mu}$	71.3	0.7	72.4	81320 ± 550	133 ± 5	209 ± 5	81660 ± 550	86793
Central medium $p_T^{\mu\mu}$	51.3	1.9	54.1	18200 ± 260	335 ± 9	194 ± 5	18800 ± 260	19116
Non-central medium $p_T^{\mu\mu}$	131.2	5.1	139.3	64300 ± 500	1090 ± 16	944 ± 11	66340 ± 500	68856
Central high $p_T^{\mu\mu}$	38.4	4.3	45.7	7470 ± 170	697 ± 13	152 ± 4	8320 ± 170	8324
Non-central high $p_T^{\mu\mu}$	86.4	10.3	104.4	23800 ± 320	2150 ± 22	703 ± 10	26600 ± 320	26624
VBF Loose	3.5	3.8	7.3	426 ± 12	45 ± 3	9 ± 1	480 ± 12	475
VBF Tight	1.7	5.8	7.5	181 ± 8	8 ± 1	2 ± 1	191 ± 8	170
Inclusive	411.0	32.0	458.4	217500 ± 910	4497 ± 32	2263 ± 17	224200 ± 910	233676

Signal event yields are not small

Signal Modelling

- Signal $m_{\mu\mu}$ distributions are modelled using a Crystal Ball + Gaussian function
- The parameters are fixed when extracting signal strength





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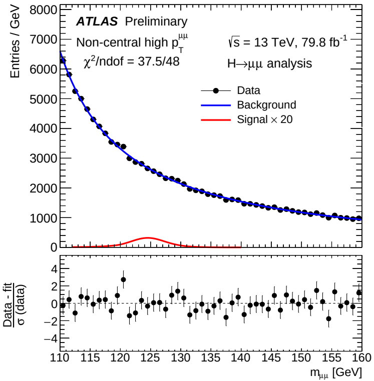
Background Modelling

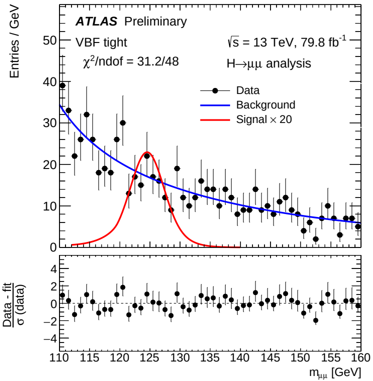
Background $m_{\mu\mu}$ distributions are modelled by

$$f \times [\mathrm{BW}(m_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) \otimes \mathrm{GS}(\sigma^{\mathrm{B}}_{\mathrm{GS}})](m_{\mu\mu}) + (1 - f) \times \mathrm{e}^{A \cdot m_{\mu\mu}} / m^3_{\mu\mu},$$

Non-central high $p_T^{\mu\mu}$



VBF tight



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$H \to \mu\mu$ Results with 79.8 fb^{-1} Data ATLAS-CONF-2018-026

No obvious excess is observed around $m_H = 125$ GeV

Upper limit on signal strength

	Observed	Expected
Run-2	2.1	2.0

Measurement of signal strength

	$\hat{\mu}$
Run-2	$0.1^{+1.0}_{-1.1}$

Significance

	Observed	Expected
Run-2	0.0 σ	0.9 σ

Link to the CONF note:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-026/

$$H \to Z\gamma$$

Event Selections

Use 13 TeV pp collision data with 36.1 fb^{-1}

Z selections

- Select two same flavor opposite charge leptons (electrons or muons)
- For $Z \to \mu\mu$ candidates, correct muon momentum using FSR (include any EM cluster with $p_T > 1.5$ GeV and $\Delta R < 0.15$)

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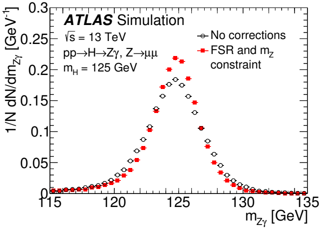


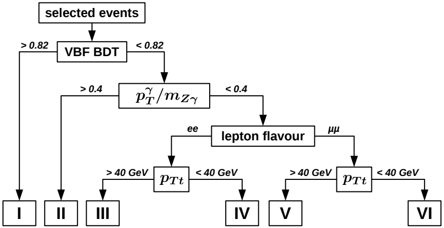
- For all Z candidates, apply kinematic fit with Z mass constraint.

Photons

- Isolated photon; Photon $p_T > 15$ GeV

Categorization

A BDT is used to select VBF-like events. The variables used by the BDT are m_{jj}, $\Delta\eta_{jj}$, p_{Tt} *etc.*
($p_{Tt} = 2|p_x^Z p_y^\gamma - p_x^\gamma p_y^Z|/p_T^{Z\gamma}$)



Six regions:

- BDT > 0.82: VBF: VBF-enriched
- BDT < 0.82 and $p_T^\gamma/m_{Z\gamma} > 0.4$: High relative p_T
- BDT < 0.82 and $p_T^\gamma/m_{Z\gamma} < 0.4$ and $p_{Tt} < 40$ GeV, *ee*: *ee* low p_{Tt}
- BDT < 0.82 and $p_T^\gamma/m_{Z\gamma} < 0.4$ and $p_{Tt} < 40$ GeV, $\mu\mu$: $\mu\mu$ low p_{Tt}
- BDT < 0.82 and $p_T^\gamma/m_{Z\gamma} < 0.4$ and $p_{Tt} > 40$ GeV, *ee*: *ee* high p_{Tt}
- BDT < 0.82 and $p_T^\gamma/m_{Z\gamma} < 0.4$ and $p_{Tt} > 40$ GeV, $\mu\mu$: $\mu\mu$ high p_{Tt}

Signal Efficiency

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	ggF		VBF		WH		ZH	
Category	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]	ϵ[%]	f[%]
VBF-enriched	0.25	30.5	6.5	67.5	0.34	1.3	0.24	0.6
High relative p_{T}	1.1	71.5	2.6	14.3	4.0	8.3	4.1	5.3
ee high $p_{\mathrm{T}t}$	1.7	80.8	2.8	11.0	3.2	4.7	3.6	3.3
ee low $p_{\mathrm{T}t}$	7.1	93.2	3.6	4.1	3.7	1.5	4.2	1.1
$\mu\mu$ high $p_{\mathrm{T}t}$	2.2	80.4	3.6	11.3	4.1	4.8	4.2	3.1
$\mu\mu$ low $p_{\mathrm{T}t}$	9.2	93.4	4.7	4.1	4.6	1.5	4.8	1.0
Total efficiency (%)	21.5		23.8		20.2		21.0	
Expected events	35		3.3		1.0		0.7	

- Signal selection efficiency varies from 20% to 24% for different processes

Signal and Background Modelling

Signal modelling: double-sided Crystal Ball function

Background modelling:

- VBF-enriched and High relative p_T: use second-order Bernstein polynomial
- Other categories: fourth-order Bernstein polynomial

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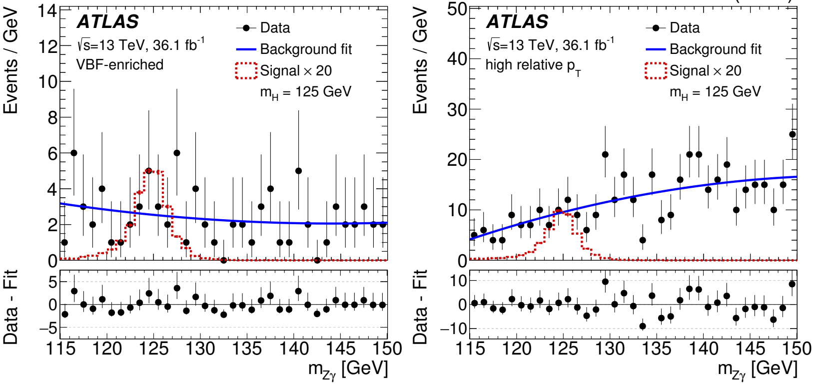


$H \to Z\gamma$ Results JHEP10 (2017) 112

- No obvious excess is found near $m_H = 125.09$ GeV region
- Upper limits for $\sigma(pp \to H) \cdot \mathcal{B}(H \to Z\gamma)$ is 6.6 times SM prediction (the expected limit on signal strength is 4.4)

Summary

- ATLAS has performed searches for $H \to \mu\mu$ and $H \to Z\gamma$ with LHC Run 2 data
- $H \to \mu\mu$ is using 79.8 fb^{-1} data. $H \to Z\gamma$ is using 36.1 fb^{-1} data.
- No significant excess is observed in data.
- For $H \to \mu\mu$, upper limit on signal strength is 2.1 at 95% C.L.. For $H \to Z\gamma$, upper limit on signal strength is 6.6 at 95% C.L..

Outlook

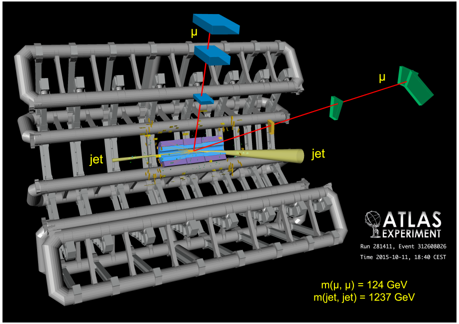
- $H \to \mu\mu$ is approaching SM sensitivity with LHC Run-2/Run-3 data
- Need HL-LHC to reach the SM sensitivity for $H \to Z\gamma$

Backup

$H \to \mu\mu$ Results from Last Publication

Data: 2015+2016 LHC *pp* collisions data. Integrated luminosity: 36.1 fb^{-1}

Phys. Rev. Lett. 119, 051802 (2017)
PRL Editors' Suggestion



Upper limit on signal strength

	Observed	Expected
Run-2	3.0	3.1
Run-1&Run-2	2.8	2.9

Measurement of signal strength

	$\hat{\mu}$
Run-2	-0.1 ± 1.5
Run-1&Run-2	-0.1 ± 1.4

$H \to Z\gamma$ Systematics

Sources	$H \to Z\gamma$	$X \to Z\gamma$
Luminosity [%]		
Luminosity	3.2	3.2
Signal efficiency [%]		
Modelling of pile-up interactions	0.02–0.03	$<$ 0.01–0.2
Photon identification efficiency	0.7–1.7	2.0–2.6
Photon isolation efficiency	0.07–0.4	0.6–0.6
Electron identification efficiency	0.0–1.6	0.0–2.6
Electron isolation efficiency	0.0–0.2	0.0–3.5
Electron reconstruction efficiency	0.0–0.4	0.0–1.0
Electron trigger efficiency	0.0–0.1	0.0–0.2
Muon selection efficiency	0.0–1.6	0.0–0.7
Muon trigger efficiency	0.0–3.5	0.0–4.2
MC statistical uncertainty	–	1.2–2.0
Jet energy scale, resolution, and pile-up	0.2–10	–
Total (signal efficiency)	2.1–10	4.0–6.3
Signal modelling on $\sigma_{\rm CB}$ [%]		
Electron and photon energy scale	0.6–3.5	1.0–4.0
Electron and photon energy resolution	1.1–4.0	4.0–30
Muon momentum scale	0.0–0.5	0.0–3.0
Muon ID resolution	0.0–3.7	0.0–2.0
Muon MS resolution	0.0–1.7	0.0–4.0
Signal modelling on $\mu_{\rm CB}$ [%]		
Electron and photon energy scale	0.1–0.2	0.2–0.6
Muon momentum scale	0.0–0.03	0.0–0.03
Higgs mass	0.2	–
Background modelling [Events]		
Spurious signal	1.7–25	0.005–6.1

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Sources	
Total cross section and efficiency [%]	
Underlying event	5.3
ggF perturbative order	3.9
ggF PDF and $\alpha_{\rm s}$	3.2
VBF perturbative order	0.4
VBF PDF and $\alpha_{\rm s}$	2.1
WH (ZH) perturbative order	0.5 (3.8)
WH (ZH) PDF and $\alpha_{\rm s}$	1.9 (1.6)
Interference	5.0
$B(H \to Z\gamma)$	5.9
Total (total cross section and efficiency)	10
Category acceptance [%]	
ggF $H + 2$-jets in VBF-enriched category	0.5–45
ggF BDT variables	0.2–15
ggF Higgs $p_{\rm T}$	8.4–22
PDF and $\alpha_{\rm s}$	0.2–2.0
Underlying event	2.9–25
Total (category acceptance)	9.5–49