Higgs Boson Rare Decays from ATLAS

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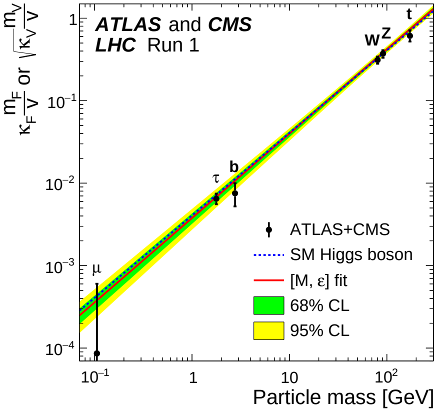
中国物理学会高能物理分会第十届全国会员代表大会，
上海，2018年6月20-24日

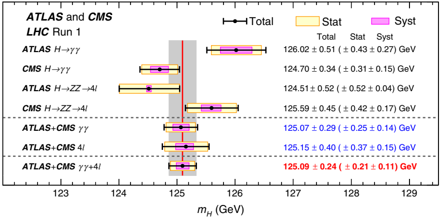
Introduction

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

JHEP 08 (2016) 045

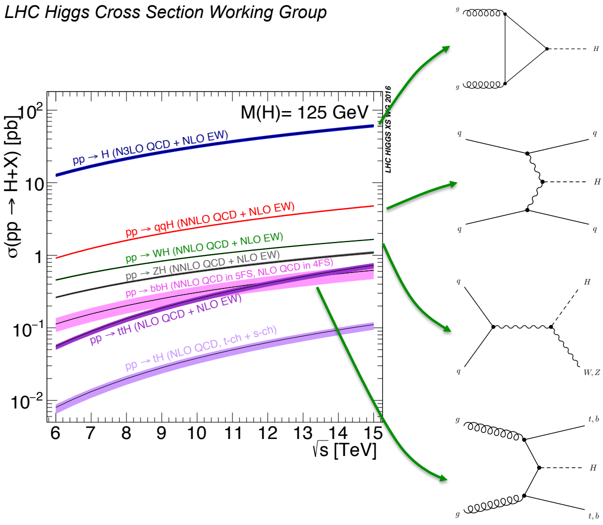


PRL 114, 191803 (2015)



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

Higgs Boson Production at the LHC



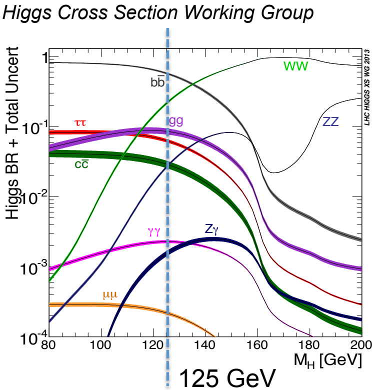
ggF: dominant, larger initial state radiation from gluons

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

VH: vector boson (lν, ll', qq')

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

Higgs Boson Decays



Decay mode	Branching fraction [%]
$H \to bb$	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
$H \to \mu\mu$	0.022 ± 0.001

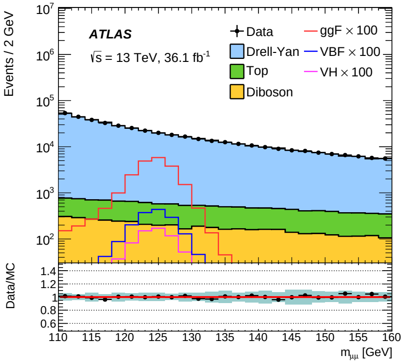
$BR(H \to \mu\mu) = 2.18 \times 10^{-4}$, $BR(H \to cc) = 2.90 \times 10^{-2}$

c: charm quark

$$H \to \mu\mu$$

$H \rightarrow \mu\mu$ Analysis Strategy

- ggF, VBF and VH signal processes are considered
- Dedicated categories for ggF and VBF
- Dominant background is Drell-Yan process



- Use analytic functions to model signal and background

Event Selections

Data

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

Muon object selection

- Muons are reconstructed using the information of inner tracking and muon spectrometer
- Muon $p_T > 15$ GeV, $|\eta| < 2.5$

Event selection

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

Categorization

- Use a BDT trained by 14 variables to select VBF events: `VBF loose` and `VBF tight`
- The rest of events are considered as ggF-like events which are separated by muon η and $p_T^{\mu\mu}$: 2 η $\times$ 3 $p_T^{\mu\mu}$ categories
- There are 8 categories in total

0.7<BDT<0.9

VBF Loose

BDT>0.9

VBF Tight

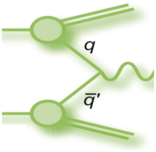
	Both muons |η|<1	Rest
$p_T^{\mu\mu}$<15 GeV	Central Low Ptll	Non-cent. Low Ptll
15<$p_T^{\mu\mu}$<50 GeV	Central Med. Ptll	Non-cent. Med. Ptll
$p_T^{\mu\mu}$>50 GeV	Central High Ptll	Non-cent. High Ptll

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

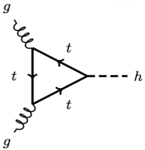
Categorization – ggF

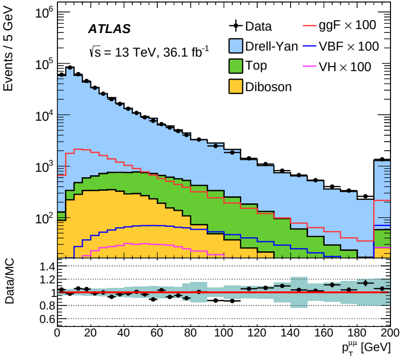
- Signal has more ISR than background. Signal tends to have large p_T^{ll} than background

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

- 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 $>$ 0.9) and `VBF Loose` (0.7$<$ BDT $<$ 0.9)
- Events with BDT $<$ 0.7 are classified as ggF-like events

Event Yields

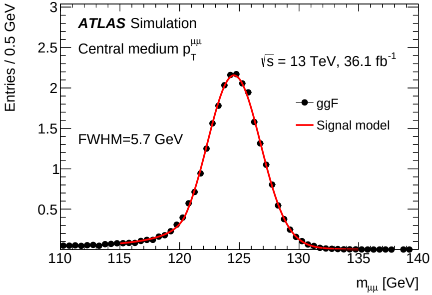
	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3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

Signal event yields are not small

Cate. with higher sensitivities

Signal Modelling

- Signal $m_{\mu\mu}$ distributions are modelled using a Crystal Ball $+$ Gaussian function
- The parameters are fixed when extracting signal strength
- Easy to do interpolation between different Higgs mass points

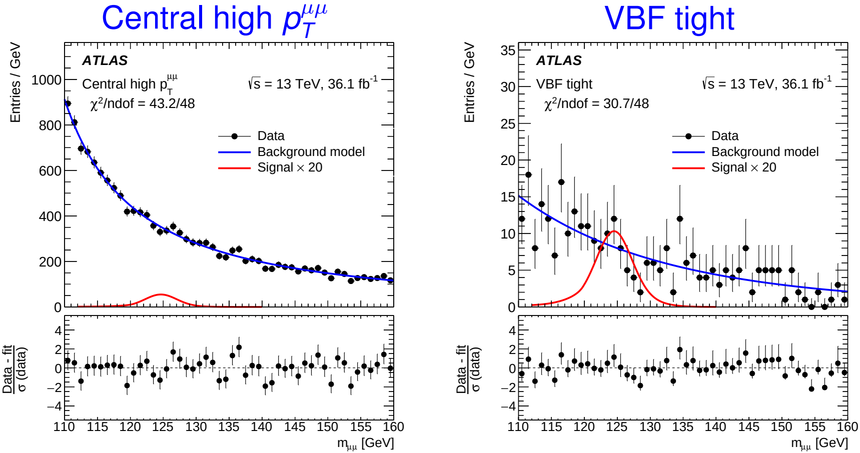


FWHM: Central regions: 5.7 GeV; Non-central: 7.1 GeV

Background Modelling

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

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



Results of $H \to \mu\mu$

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

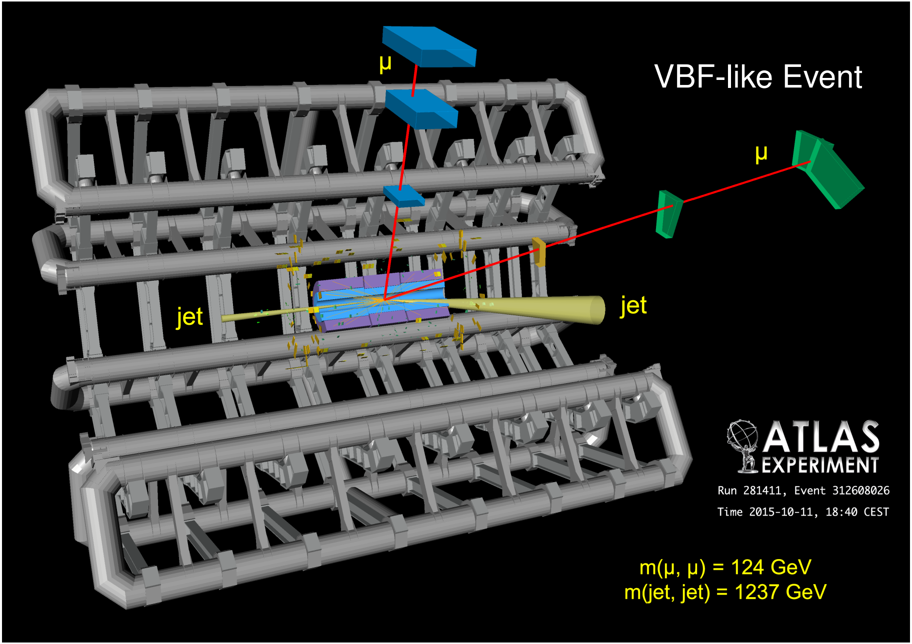
PRL Editors' Suggestion

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


VBF-like Event
μ
μ
jet
jet
ATLAS EXPERIMENT
Run 281411, Event 312608026
Time 2015-10-11, 18:40 CEST
m(μ, μ) = 124 GeV
m(jet, jet) = 1237 GeV

$$H \rightarrow cc$$

$H \to cc$ Analysis Strategy

Dataset: LHC pp collisions 36.1 fb^{-1}

- Use $pp \to Z(ll)H(cc)^{a}$ production to probe $H \to cc$.
- The two leptons from Z will be used to trigger the detector
- Use charm-jet (c-jet) tagging to select signal-like events.

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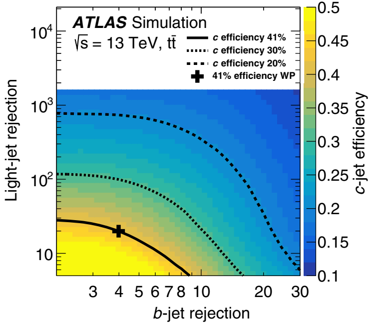
[a] l: electron or muon

c-jet tagging

- Exploit the different lifetimes of *b*, *c* and light-flavor hadrons.
- BDT are trained to obtained two discriminants: to separate *c* jets from *l* jets and *c* jets from *b* jets



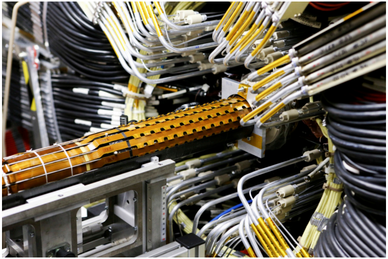
PRL 120, 211802 (2018)

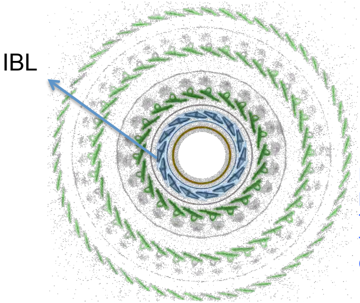
- Use similar method with *b*-tagging [1] [2]
- The efficiencies are calibrated to data using *b* quarks from $t \to Wb$ and *c* quarks from $W \to cs, cd$

[1] J. Instrum. **11**, P04008 (2016)
[2] ATL-PHYS-PUB-2016-012

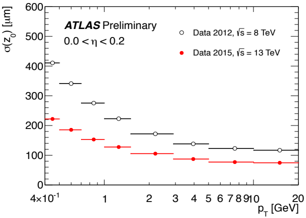
ATLAS Phase-0 Upgrade

- Innermost silicon pixel detector layer (IBL)
- 33 mm from beam
- Improve tracking and bjet tagging (~4 times better for light flavor jet rejection)





B hadron with p_T=50 GeV will travel 3 mm in the transverse direction



Event Selections

Try to select Z and H events

$Z \rightarrow ll$ Selections

- Two same flavor leptons, opposite charge
- $81 < m_{ll} < 101$ GeV
- $p_T^Z > 75$ GeV

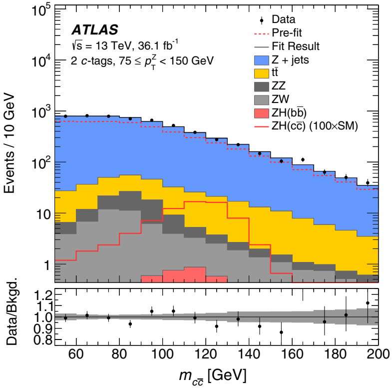
$H \rightarrow cc$ Selections

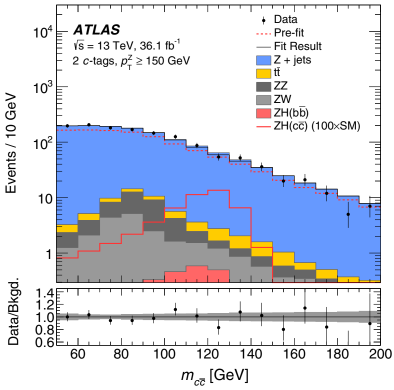
- At least two jets in the event
- Leading jet $p_T > 45$ GeV
- Two leading jets chosen to form $H \rightarrow cc$ candidate
- Either 1 or 2 c-tagged jets
- $\Delta R_{jj} < 2.2, 1.5, 1.3$ for p_T^Z $\{75 - 150\}, \{150 - 200\}, \{200-\}$ GeV regions

Categorization

- Categorize events into four signal regions $75 < p_T^Z 150$ based on c-jet multiplicity (1 or 2 c-jet) and p_T^Z ($75 < p_T^Z 150$ GeV and $p_T^Z > 150$ GeV)

PRL 120, 211802 (2018)





Event Yields and Systematics

Sample	Yield, 50 GeV $< m_{c\bar{c}} <$ 200 GeV			
	1 c tag		2 c tags	
	$75 \leq p_T^Z < 150$ GeV	$p_T^Z \geq 150$ GeV	$75 \leq p_T^Z < 150$ GeV	$p_T^Z \geq 150$ GeV
$Z +$ jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	$-143 \pm 170\,(2.4)$	$-84 \pm 100\,(1.4)$	$-30 \pm 40\,(0.7)$	$-20 \pm 29\,(0.5)$
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating $Z +$ jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%

$H \to cc$ Results

- No significant excess is observed
- Upper limit on $\sigma(pp \to ZH) \times \mathcal{B}(H \to cc)$ is 2.7 pb at 95% C.L.. Upper limit on signal strength is 110.

Conclusions

- Searches for $H \to \mu\mu$ and $H \to cc$ are performed using 36.1 fb^{-1} of data collected with the ATLAS detector in pp collisions at $\sqrt{s}$ =13 TeV.
- No significant excess is observed in data.
- $H \to \mu\mu$ is approaching SM sensitivity wiht LHC Run-2/Run-3 data
- Need e^+e^- collider to probe SM $H \to cc$ signal

Backup

- Most $H \rightarrow \mu\mu$ signal have muon pT between 50 GeV and 100 GeV.
- Sensitivity to signal is proportional to the $1/\sqrt{\sigma}$

$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma}}$$

Improving the dimuon mass resolution is the key to find $H \rightarrow \mu\mu$ signal at LHC