Search for the Dimuon Decay of the Higgs Boson with the ATLAS Detector

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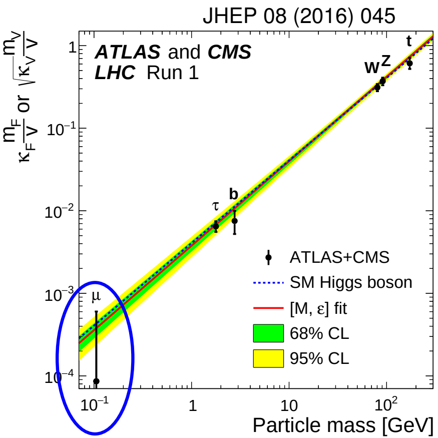
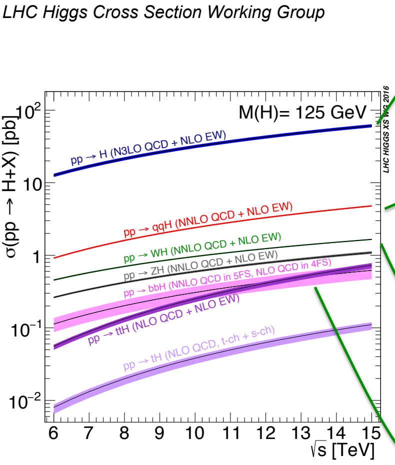
Introduction

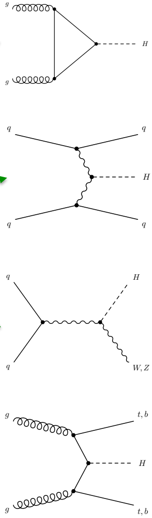
- The discovery of the Higgs boson is a triumph of the SM.



- $H \to \mu\mu$ is a sensitive channel to probe the Higgs coupling to second-generation fermions

Higgs Boson Production at the LHC





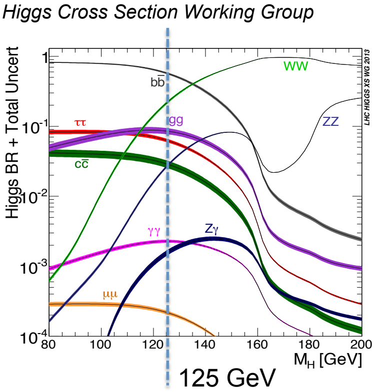
ggF: dominant, larger initial state radiation from gluons

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

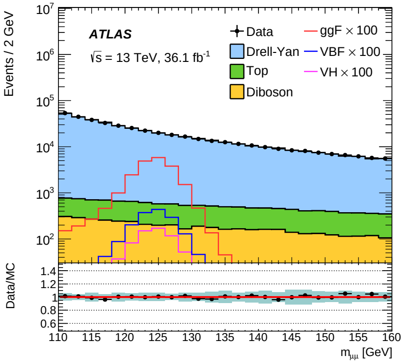


Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Note: $BR(H \to \mu\mu) = 2.18 \times 10^{-4}$

$H \to \mu\mu$ 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

Data and 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

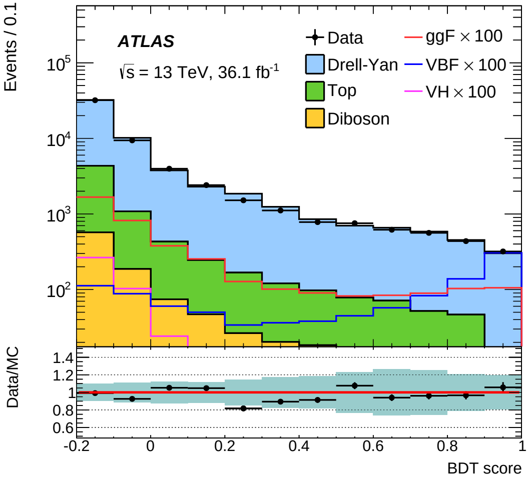
	Both muons $\|\eta\|<1$	Rest
$p_T^{\mu\mu}<15$ GeV	Central Low Ptll	Non-cent. Low Ptll
$15<p_T^{\mu\mu}<50$ GeV	Central Med. Ptll	Non-cent. Med. Ptll
$p_T^{\mu\mu}>50$ GeV	Central High Ptll	Non-cent. High Ptll

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

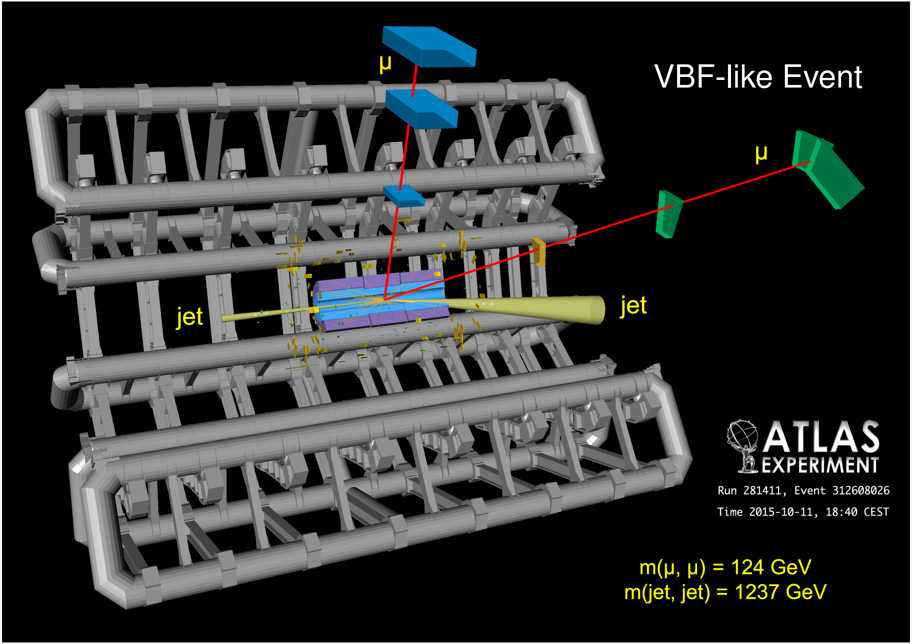
Categorization – VBF

- 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

BDT Score in Signal Region



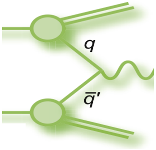
- Clear separation of signal from backgrounds
- Good description by MC


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

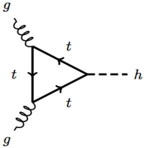
Categorization – ggF

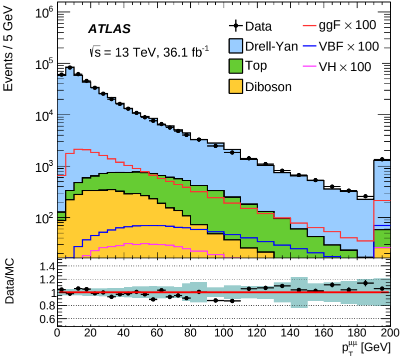
- Signal has more ISR than background. Signal tends to have large p_T^{ll} than background

Background



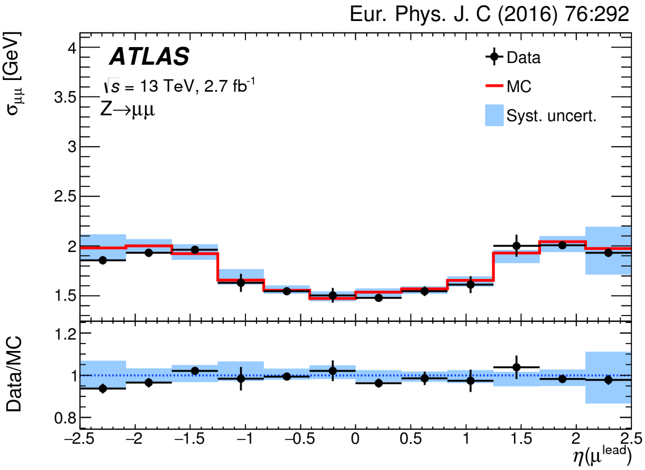
Signal





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

Dimuon Mass Resolution from Z Events



(1) Central: both muons $|\eta| < 1$ (2) Non-central: rest

Event Yields

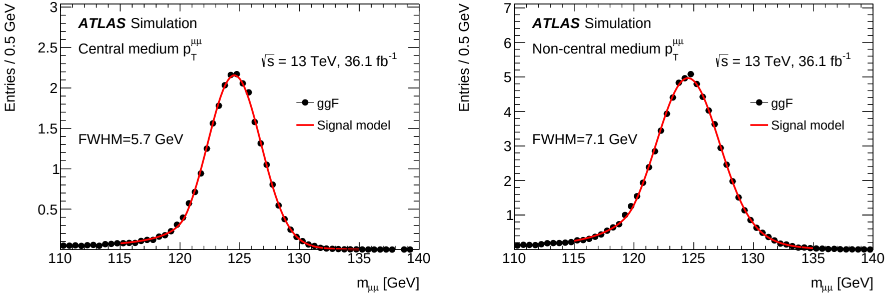
	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 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



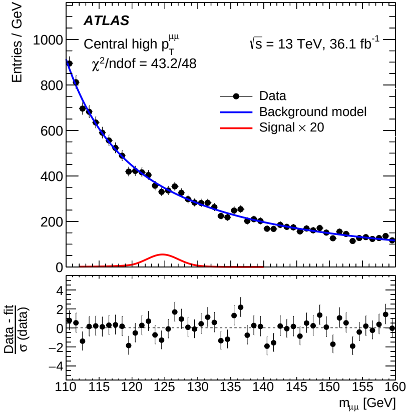
FWHM: Central regions: 5.7 GeV; Non-central: 7.1 GeV

Background Modelling

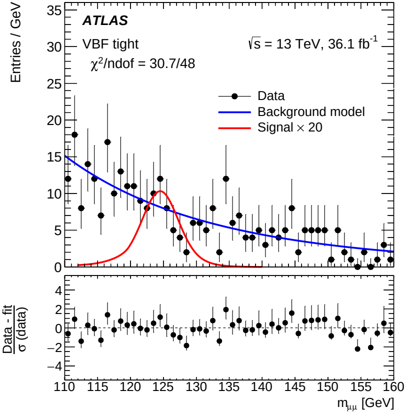
Background $m_{\mu\mu}$ distributions are modelled by

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

Central high $p_T^{\mu\mu}$



VBF tight



Background Modelling Uncertainties

- Any systematic bias in the background model when describing the underlying $m_{\mu\mu}$ spectrum might result in spurious signal events in the measurement. In each category, the number of spurious signal events (N_{spur}) is estimated by fitting the parameterized S+B model to the simulated background $m_{\mu\mu}$ distribution in the range 110–160 GeV.
- The impact of the background mismodeling on the expected upper limit on the signal strength is about 2%.

Results of $H \to \mu\mu$

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

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

Conclusions

- A search for the dimuon decay of the Higgs boson is 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, and an upper limit is set on the signal strength.
- When combined with LHC Run 1 data, the observed (expected) upper limit is 2.8 (2.9) times the Standard Model prediction.

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

Backup

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

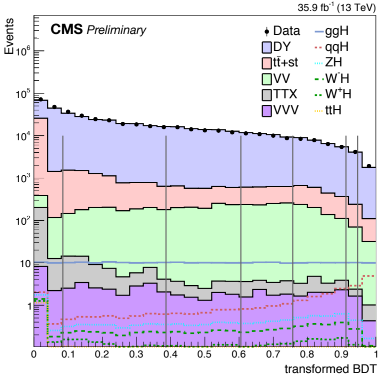
$$\frac{S}{\sqrt{B}} \sim \frac{1}{\sqrt{\sigma}}$$

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

Higgs p_T

Signal samples were generated by `Powheg NLO`. Higgs p_T is reweighted to `HRes`. Consider the migration between Higgs pT bins with "Stewart-Tackmann" method. Uncertainties in three $p_T^{\mu\mu}$ categories for ggF signal samples.

CMS: BDT



Three η categories:

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

- Categories are separated by gray lines
- The left most category and last two categories have only one η category
- The rest regions have three η categories

CMS Results

- CMS PAS HIG-17-019
- 13 TeV data used: 35.9 fb^{-1}
- Upper limit on signal strength with 13 TeV data: 2.64 (2.08) for observed (expected)
- Upper limit on signal strength with 7/8/13 TeV data: 2.64 (1.89) for observed (expected)

CMS Limits and p-value

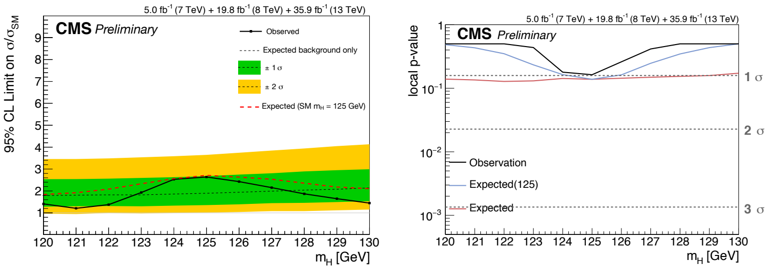


Figure 5: The 95% CL upper limit on the signal strength modifier, μ, for the combination of the 7, 8, and 13 TeV datasets (left) together with the expected limit obtained background hypothesis and in the signal-plus-background hypothesis (red-line) for a SM Higgs boson with $m_{\rm H} = 125\,\text{GeV}$. The combined local p-value and significance as a function of the SM Higgs boson mass hypothesis (right). The observation (black) is compared to the expectation (red) for the Higgs boson, and (blue) for the Higgs boson mass of 125 GeV.