# Search for $H \to \mu\mu$ in pp collisions at 13 TeV with the ATLAS detector

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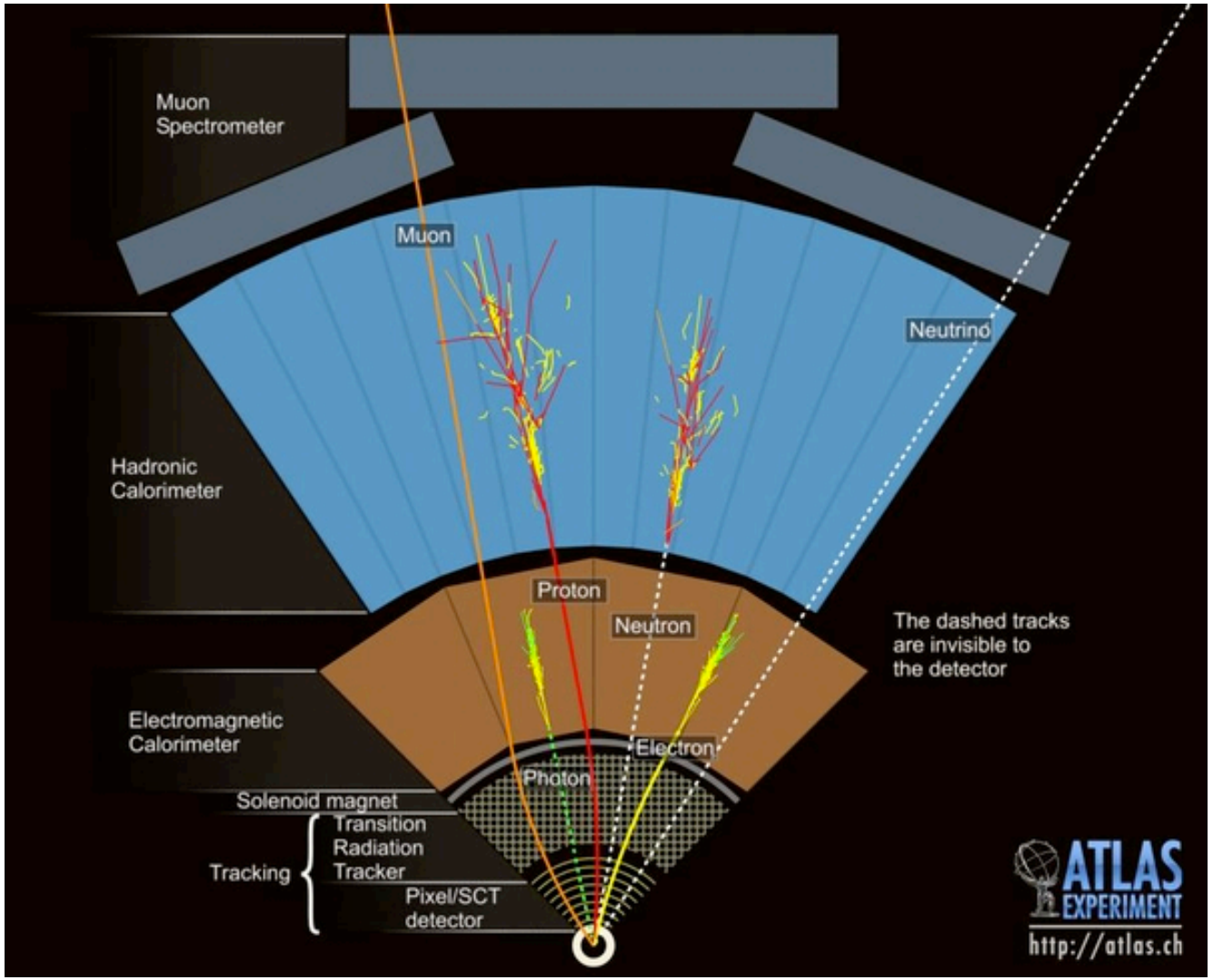
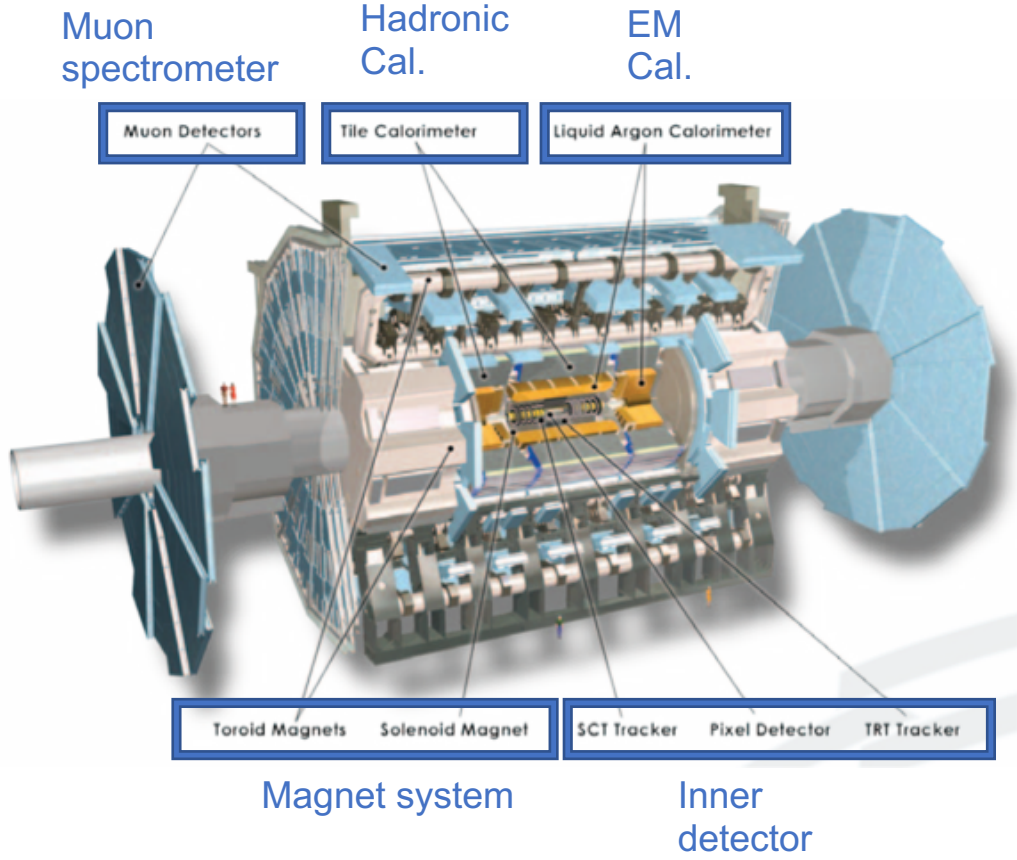
SM@LHC 2022

# The ATLAS Detector

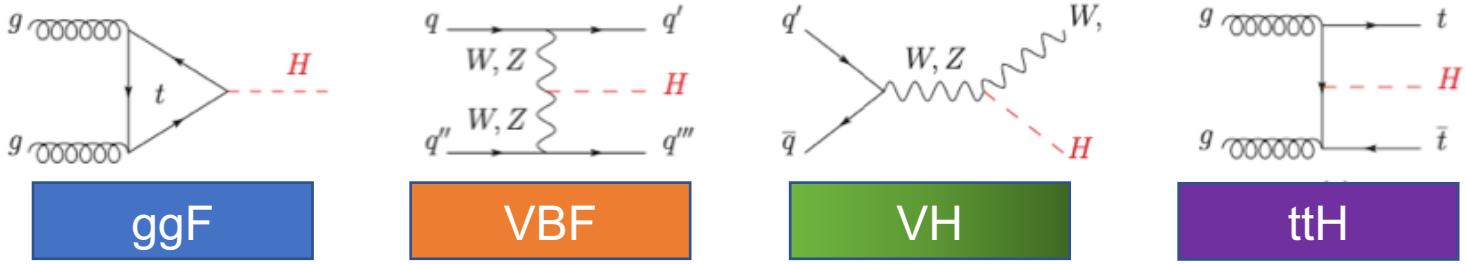


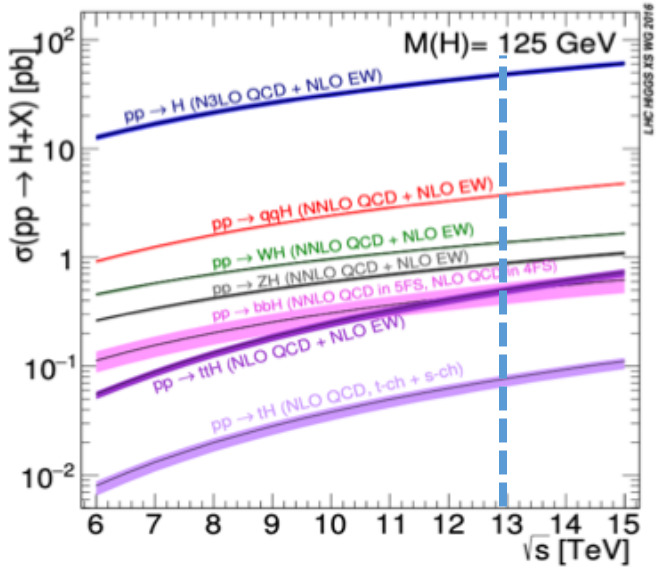

- Inner detector
- Hadronic calorimeter
- Electromagnetic calorimeter
- Muon spectrometer
- Magnet system

# Higgs physics

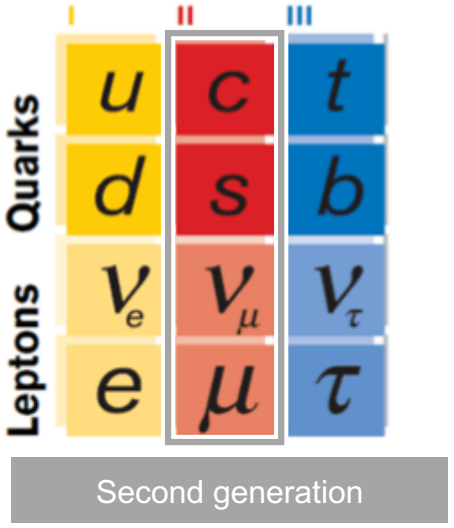
- Higgs production mode : ggF, VBF, VH, ttH



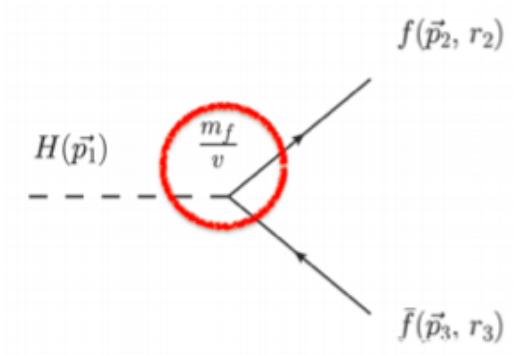

ggF | VBF | VH | ttH



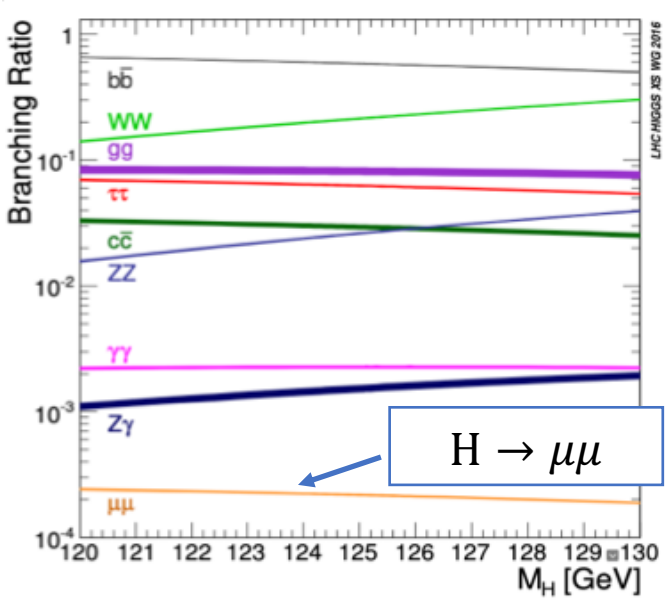

- Higgs coupling with 2nd generation fermions




Second generation




$H \to \mu\mu$
Good opportunity to measure the Higgs interactions with the 2nd generation fermions



# Analysis strategy for $H \to \mu\mu$

**Using the full Run 2 dataset with 139 fb$^{-1}$ , $\sqrt{s}$ = 13 TeV**

## 1. Basic events selection

- Leading and sub-leading muon for Higgs candidates
- Jet selection for different jet categories
- Mass window 110-160GeV : avoid Drell-Yan dominant area

## 2. Categorization:

- Optimized for different signal sensitivity
- Separate by BDT score

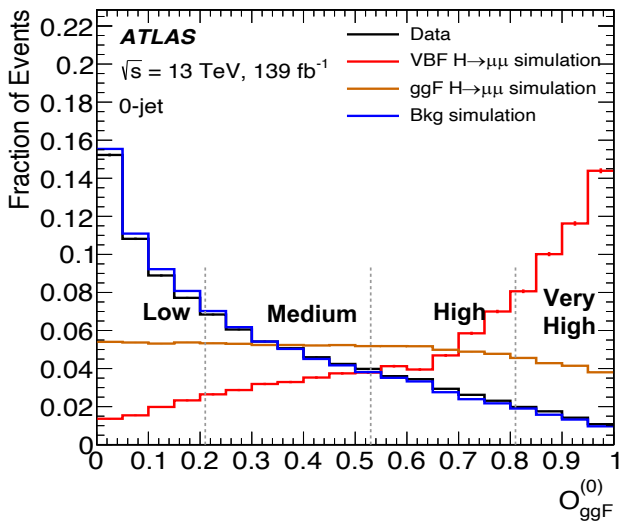
## 3. Analytical Function fit

- Fit $m_{\mu\mu}$ distribution for each separate category

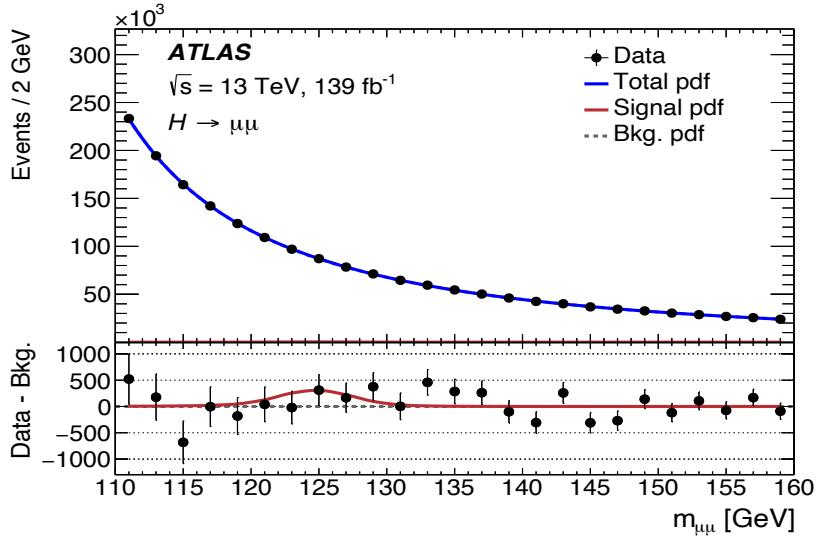
## ① Event Selection

| | Selection |
|---|---|
| Common preselection | Primary vertex<br>Two opposite-charge muons<br>Muons: $\lvert\eta\rvert < 2.7$, $p_{\mathrm{T}}^{\mathrm{lead}} > 27$ GeV, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ GeV (except $VH$ 3-lepton) |
| Fit Region | $110 < m_{\mu\mu} < 160$ GeV |
| Jets | $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.4$<br>or with $p_{\mathrm{T}} > 30$ GeV and $2.4 < \lvert\eta\rvert < 4.5$ |
| $t\bar{t}H$ Category | at least one additional $e$ or $\mu$ with $p_{\mathrm{T}} > 15$ GeV, at least one $b$-jet (85% WP) |
| $VH$ 3-lepton Categories | $p_{\mathrm{T}}^{\mathrm{sublead}} > 10$ GeV, one additional $e$ ($\mu$) with $p_{\mathrm{T}} > 15(10)$ GeV, no $b$-jets (85% WP) |
| $VH$ 4-lepton Category | at least two additional $e$ or $\mu$ with $p_{\mathrm{T}} > 8, 6$ GeV, no $b$-jets (85% WP) |
| $ggF$ +VBF Categories | no additional $\mu$, no $b$-jets (60% WP) |

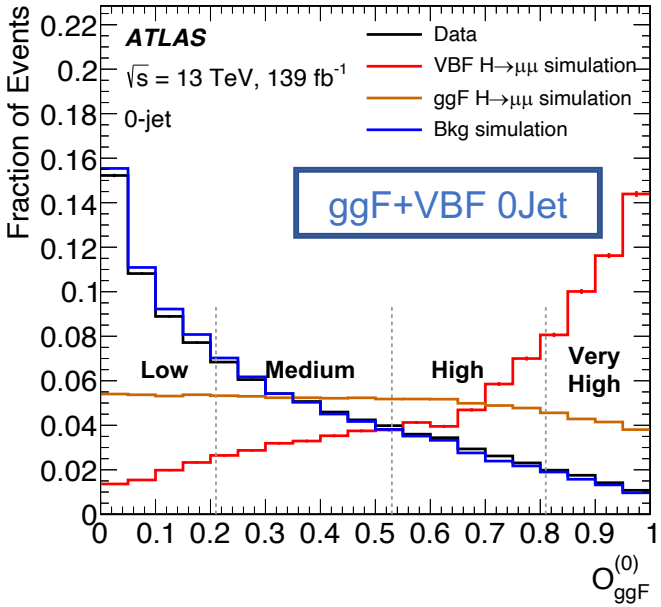
## ② Categorization by BDT Score

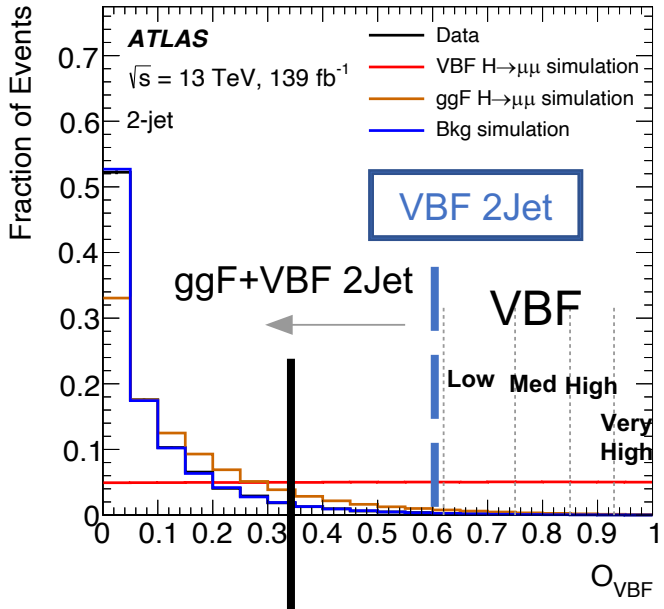


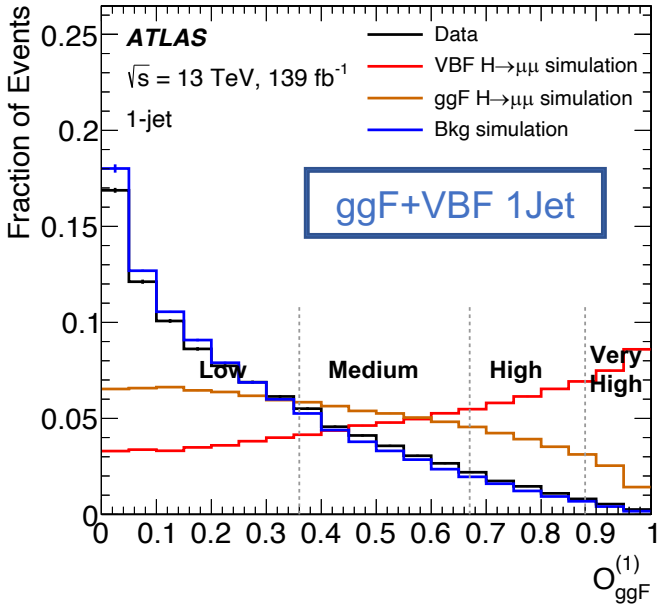

## ③ Analytical Function fit

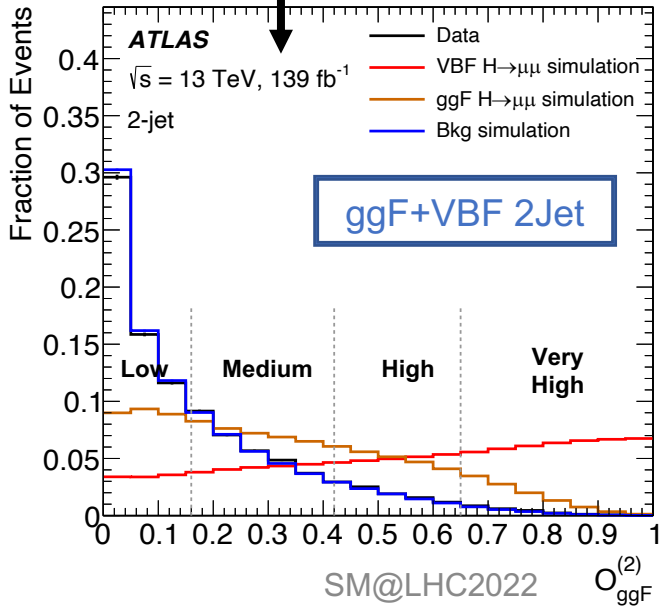


# ggF/VBF channel: 16 categories




- 16 categories for different signal sensitivity
  - Separate by BDT score & signal purity
  - 0-jet : 4 ggF+VBF category
  - 1-jet : 4 ggF+VBF category
  - 2-jet : 4 ggF+VBF category
  - 2-jet : 4 VBF category

- BDT Training variables:
  - **0-jet** : $p_T^{\mu\mu}$, $Y_{\mu\mu}$, $\cos\theta^*$
  - **1-jet** : **0-jet** + $p_T^{jet_1}$, $\eta^{jet_1}$, $\Delta\phi(jet_1, \mu\mu)$, $N_{track}^{jet_1}$
  - ≥ **2-jet** : **1-jet** + $p_T^{jet_2}$, $\eta^{jet_2}$, $\Delta\phi(jet_2, \mu\mu)$, $N_{track}^{jet_2}$, $p_T(jj)$, $\eta(jj)$, $\Delta\phi(jj, \mu\mu)$, $m_{jj}$, $MET$, $HT$

XGBoost Package

# VH & ttH channel: 4 categories

## VH: More than 2 muons → muon pairing for Higgs candidate

- WH channel : $\chi^{2,cand} = \frac{\left(M_{\mu\mu}^{cand} - 125\ GeV\right)^2}{(3.0\ GeV)^2} - \frac{\left(M_T^{cand} - 70\ GeV\right)^2}{(20\ GeV)^2}$
- ZH channel : $\chi^{2,cand} = \frac{\left(M_{\mu\mu}^{cand} - 125\ GeV\right)^2}{(3.0\ GeV)^2} - \frac{\left(M_{ll}^{cand} - 91.1\ GeV\right)^2}{(3\ GeV)^2}$

Pairing with Minimum $\chi^2$

| Categories | BDT score |
|---|---|
| VH3Lep-High | 3lep BDT $\geq 0.7$ |
| VH3Lep-Low | 3lep BDT $01. \sim 0.7$ |
| VH4Lep-High | 4lep BDT $\geq 0.12$ |

## VH BDT Training variables:

- 3-lep. region (WH) : $m_T^W, p_T^l,\ \Delta\eta(\mu\mu, l),\ \Delta\phi(\mu\mu, l),\ p_T^{j1},\ E_T^{miss},\ \Delta\phi\left(\mu\mu, E_T^{miss}\right), N_{jet}$
- 4-lep. region (ZH) : $m_{ll},\ p_T^{j_1}, p_T^{j_2}, \Delta\eta(\mu\mu, ll),\ \Delta\phi(\mu\mu, ll),\ \Delta\phi(l_1, l_2),\ \Delta\phi\left(\mu\mu, E_T^{miss}\right),\ N_{jet}$

## ttH BDT training variables

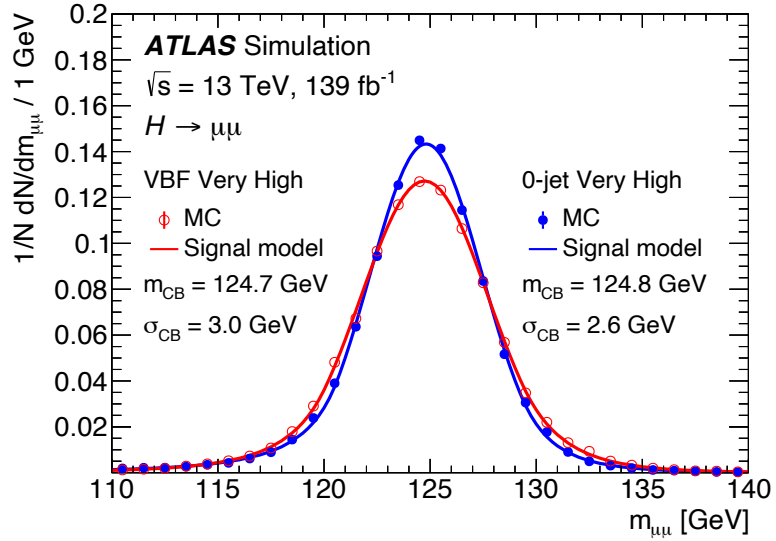
- Lepton related: $cos\theta^*, p_T^{\mu\mu},\ \Delta\eta(\mu\mu, l),\ \Delta\phi(\mu\mu, l),\ p_T^{l3}, p_T^{l4}, m_{l_3 l_4},\ m_{\mu\mu}^{subleading}$
- Invariant mass related : $m_{leptonic\ top}\left(m_T\ of\ l + E_T^{miss} + b - jet\right),\ m_{hadronic\ top}(2\ jets + b - jet),\ m_T^W$
- Jet related: $N_{j(central)},\ N_{b-jet}, H_T$

To get higher signal significance
Optimal cut on BDT result
BDT Score > 0.35

# Physics modeling strategy

## Signal modeling : Double-Sided Crystal Ball

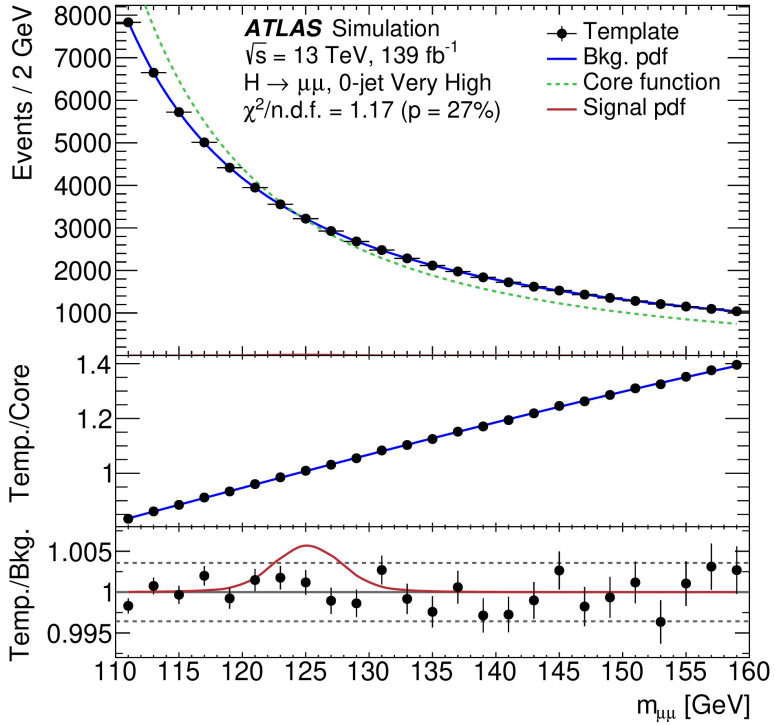
- $m_{\mu\mu}$ shape : $CB2(x, M_{CB}, \sigma_{CB}, \ \alpha_{low}, \alpha_{high}, n_{low}, n_{high})$
- Good description for signal distribution with well defined mean and width



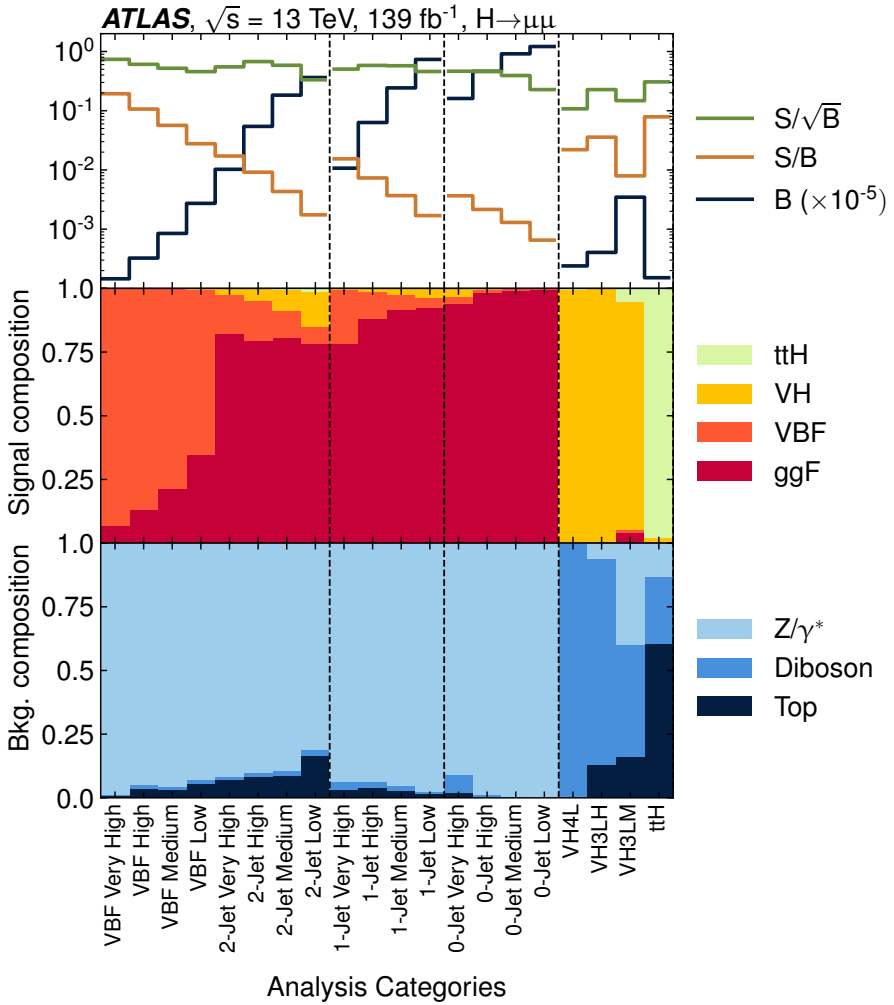

## Bkg. Modeling : core x empirical function

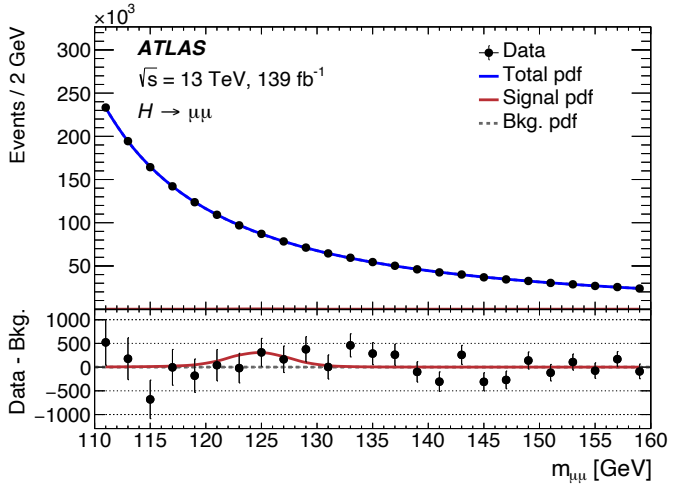
- **Core function** is physics-driven
  - **LO DY line − shape ⊗ detector resolution**
- **Empirical function** is flexible
  - Describe difference between core function and spectrum caused by kinematic selections
  - Choose the smallest bkg. mis-modeling function (spurious signal)

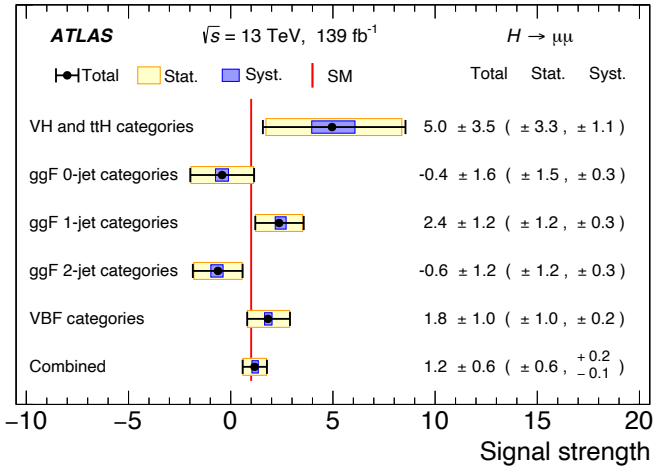
| Function | Expression |
|---|---|
| PowerN | $m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\ldots+a_N m_{\mu\mu}^N)}$ |
| EpolyN | $\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \ldots + a_N m_{\mu\mu}^N)$ |



# Statistical result




## Signal strength

- $\mu = 1.2^{+0.58}_{-0.57}(stat.) \pm 0.10(SS)^{+0.07}_{-0.03}(exper.)^{+0.13}_{-0.08}(theory)$

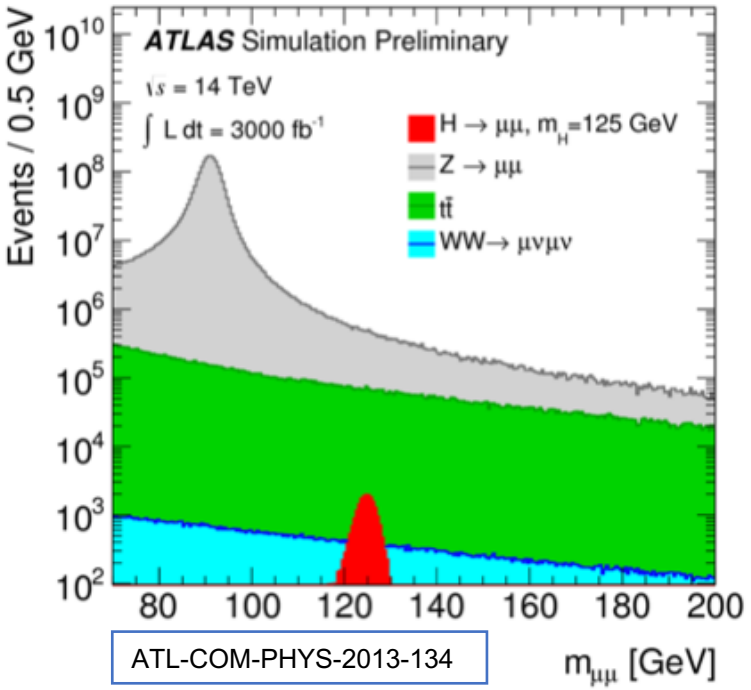
## Significance (bkg. only hypothesis)

- **Observed**: 2.0 $\sigma$ **Expected**: 1.7 $\sigma$

## Upper limit (95% CL, $\mu = 0$)

- **Observed**: 2.2 x SM, **Expected**: 1.1 x SM

# CMS result & Hi-Lumi LHC




ATL-COM-PHYS-2013-134

| $\mathcal{L}$ [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 |
| $\Delta^{sys}_{Bkg}$ (model) | 68 | 110 |
| $\Delta^{sys}_{Bkg}$ (fit) | 190 | 620 |
| $\Delta^{stat}_{S+B}$ | 750 | 2380 |
| Signal significance | $2.3\sigma$ | $7.0\sigma$ |
| $\Delta\mu/\mu$ | 46% | 21% |

ATL-COM-PHYS-2013-134

Run3
If using BDT can get further improvement

Hi-Lumi Discovery for H→ $\mu\mu$

| | Signal Strength $\mu$ | Significance | $BR(H \to \mu\mu)$ |
|---|---|---|---|
| ATLAS | $\mathbf{1.2^{+0.58}_{-0.57}}(stat.) \pm \mathbf{0.10}(SS)^{+0.07}_{-0.03}(exper.)^{+0.13}_{-0.08}(theory)$ | **Observed**: 2.0 $\sigma$<br>**Expected**: 1.7 $\sigma$ | $< 4.7\times 10^{-4}$ |
| CMS | $\mu = \mathbf{1.19^{+0.41}_{-0.40}}(stat).\ ^{+0.17}_{-0.13}(syst.)$ | **Observed**: 3.0 $\sigma$<br>**Expected**: 2.5 $\sigma$ | $< 4.5\times 10^{-4}$ |

# Summary

- The $H \rightarrow \mu\mu$ channel provides unique opportunity to measure the Higgs interactions with the 2nd generation fermions at the LHC.
- Using the full Run 2 dataset of 139 $fb^{-1}$ collected with the ATLAS detector in pp collisions at $\sqrt{s}$ = 13 TeV
- Comparable result with the CMS experiment for $H \rightarrow \mu\mu$ measurement
- Promising future for $H \rightarrow \mu\mu$ measurement in Hi-Lumi LHC

# Reference


- Search for the Dimuon Decay of the Higgs Boson in pp Collisions at √s=13 TeV with the ATLAS, PhysRevLett.119.051802 PRL 119, 051802 (2017)
- A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector, Phys. Lett. B 812 (2021) 135980
- Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters with the ATLAS detector at a HL-LHC, ATL-PHYS-PUB-2013-014
- Search for the standard model Higgs boson decaying into two muons in pp collisions at √s=13 TeV, CMS-PAS-HIG-17-019
- Evidence for Higgs boson decay to a pair of muons, JHEP 01 (2021) 148