



# Search for $H \rightarrow \mu\mu$ with ATLAS

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# Outline

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- Introduction
- Analysis Details
  - Event selection
  - BDT categorization
  - Signal & background modelling
  - Systematics
- Summary



# Introduction

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# Motivation

- Standard Model

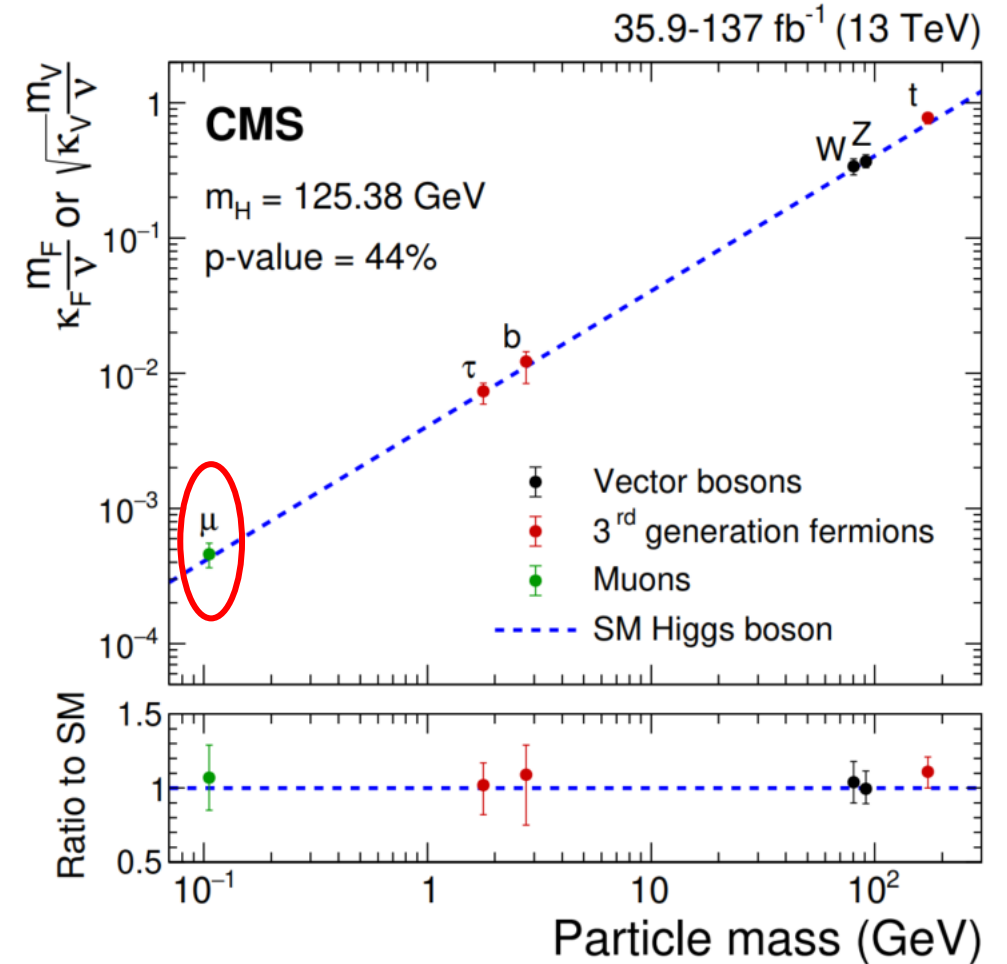
- Higgs coupling strength to vector bosons & fermions  $\propto$  particle mass
- Reduced coupling strength modifiers (in Fig)

$$y_V = \sqrt{\kappa_V} m_V/\nu$$

$$y_F = \kappa_F m_F/\nu$$

- $H \rightarrow \mu\mu$  channel

- The most sensitive channel where Higgs couplings to the **2nd generation fermions** can be measured at the LHC
- Status Run2:  $2\sigma$  @ ATLAS;  $3\sigma$  @ CMS
- Run3: data taking undergoing



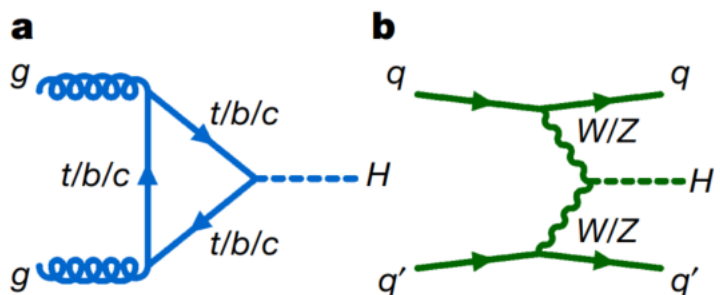
# Analysis Overview

- Signature

- Two opposite-charged muons

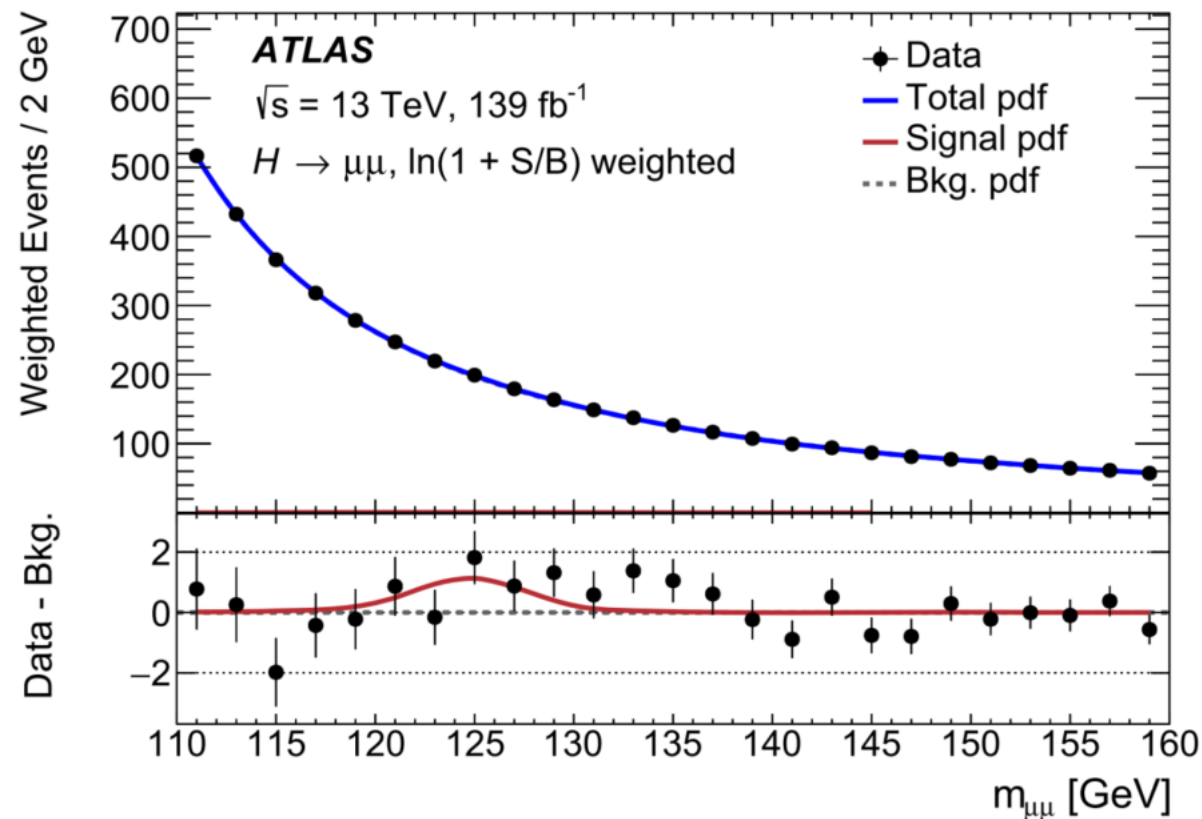
- Signal

- Main production modes: ggF, VBF



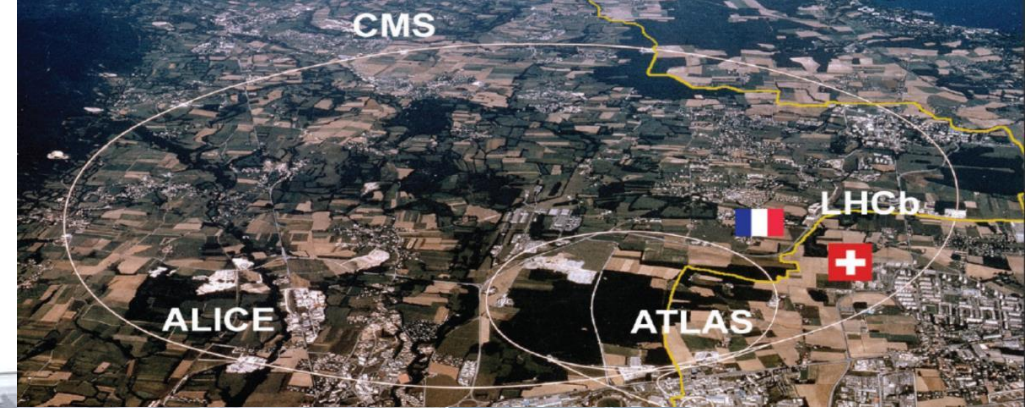
- Irreducible background

- Drell-Yan (DY) process:  $Z \rightarrow \mu\mu$  (Dominant)
- Diboson and top processes
- Signal-background ratio  $\sim 0.2\%$ , Run2 expected signal events: 868



Run2 result

# ATLAS Detector



## Muon Spectrometer (MS)

Trigger & meas. of  $\mu$

- RPC + MDT (barrel region)
- CSC + TGC+MDT (endcap region)

## EM/Hadron Calorimeters

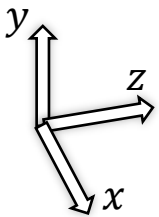
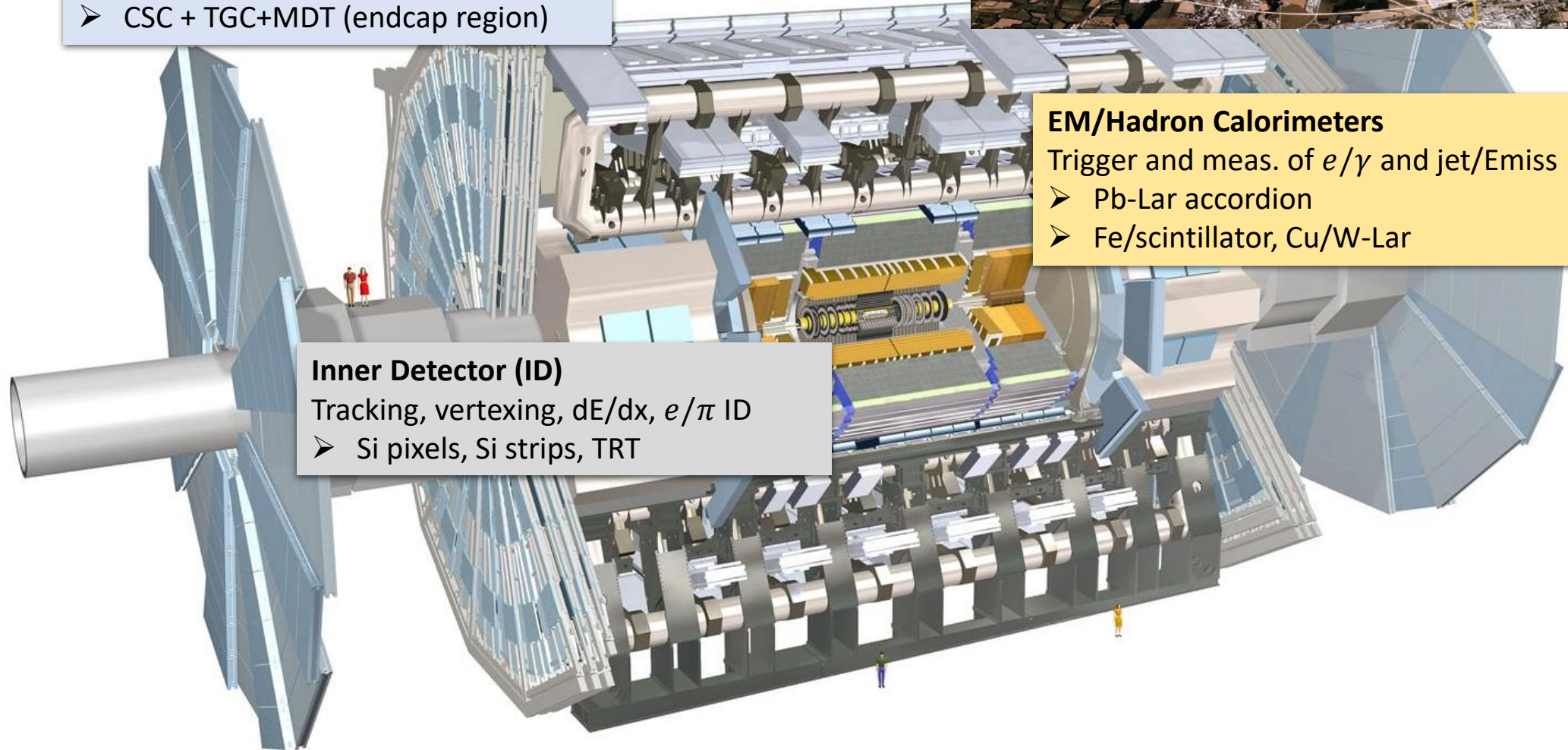
Trigger and meas. of  $e/\gamma$  and jet/Emiss

- Pb-Lar accordion
- Fe/scintillator, Cu/W-Lar

## Inner Detector (ID)

Tracking, vertexing,  $dE/dx$ ,  $e/\pi$  ID

- Si pixels, Si strips, TRT





# Analysis Details

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# Event Selection

- Muon reconstruction

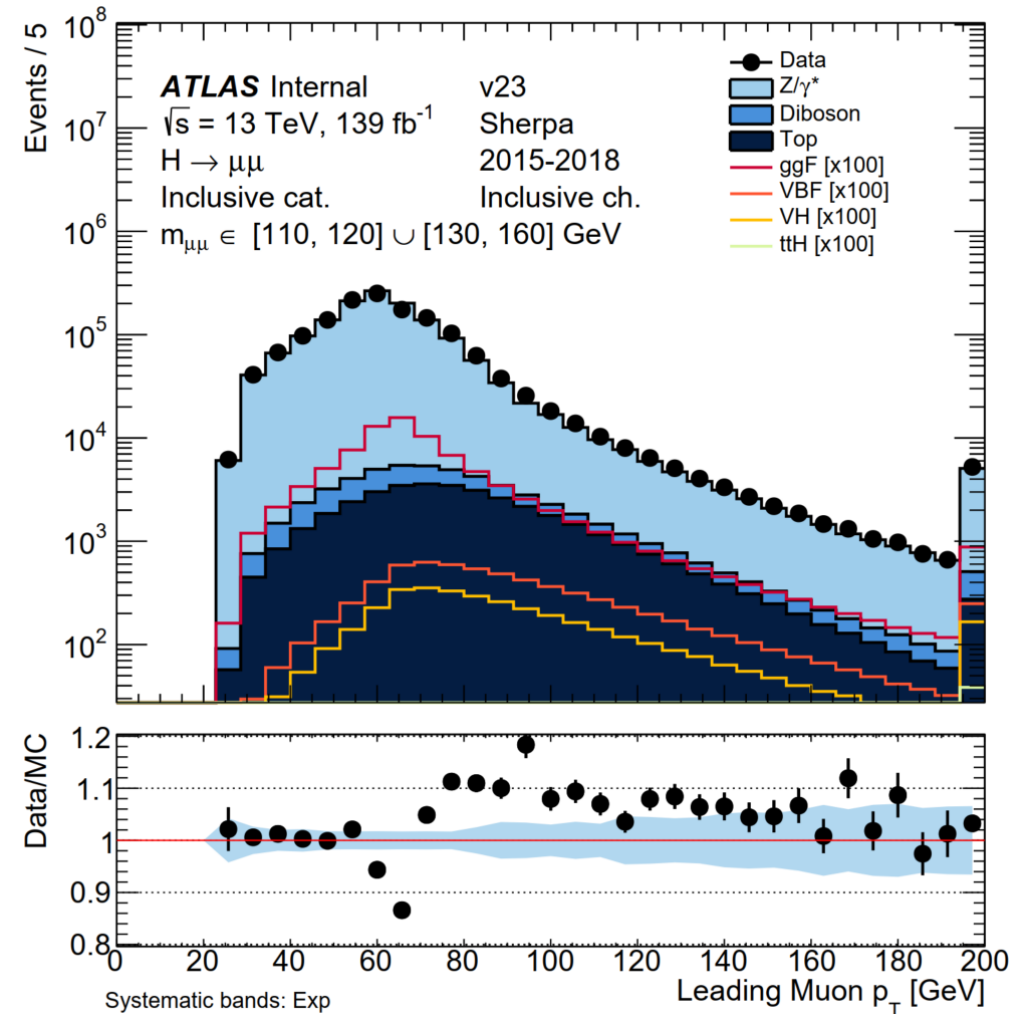
1. Combined (ID + MS)
2. Segment-Tagged (ID → MS)
3. Calorimeter-Tagged (ID → Cal)
4. Standalone (MS)

- Pre-selection

- b-jet veto at 60% Working Point
- To suppress top background

- Selection criteria

- $|\eta| < 2.7$
- Leading muon  $p_T > 27$  GeV
- Sub-Leading muon  $p_T > 15$  GeV
- To ensure high muon trigger efficiency
- *Dimuon mass range* [110,160] GeV



Validation plot: muons reconstructed properly

# BDT Categorization

- Motivation

- Exploit Multi-Variable kinematics features for signal & background
- Improve total sensitivity

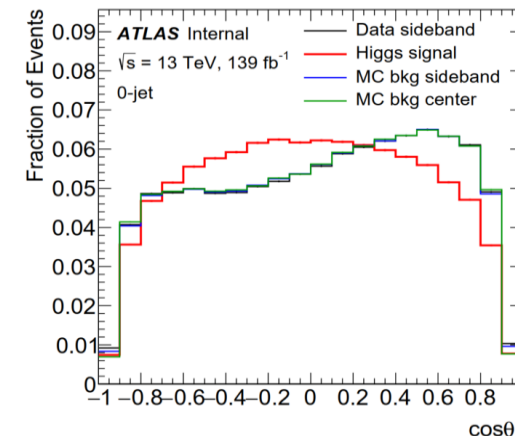
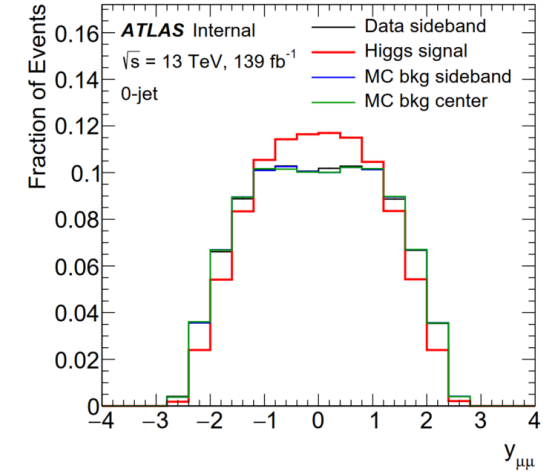
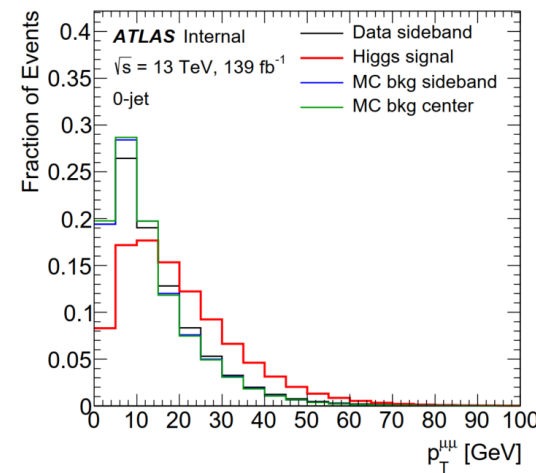
- MVA Tool: XGBoost package

- Workflow for ggF + VBF BDT

1. Divide events into 3 jet bins (0,1,≥2)
2. In each bin, train BDT model with MC signal against background in SR:[120,130] GeV
3. In ≥2 jet bin, further train VBF signal against other processes: **VBF is cleanest**
4. Optimize BDT score boundaries

- Other minor processes:  $VH, t\bar{t}H$

Jet channel	$n_j = 0$	$n_j = 1$	$n_j \geq 2$
Common	$p_{T\mu\mu}, Y_{\mu\mu}, \cos\theta^*$		
$n_j \geq 1$	-	$p_{Tj_1}, \eta_{j_1}, \Delta\phi_{j_1,\mu\mu}, N_{\text{track}}^{j_1}$	
$n_j \geq 2$	-	-	$p_{Tj_2}, \eta_{j_2}, \Delta\phi_{j_2,\mu\mu}, N_{\text{track}}^{j_2},$ $p_{Tjj}, Y_{jj}, \Delta\phi_{jj,\mu\mu},$ $m_{jj}, p_T^{\text{miss}}, H_T$



$N_j = 0$

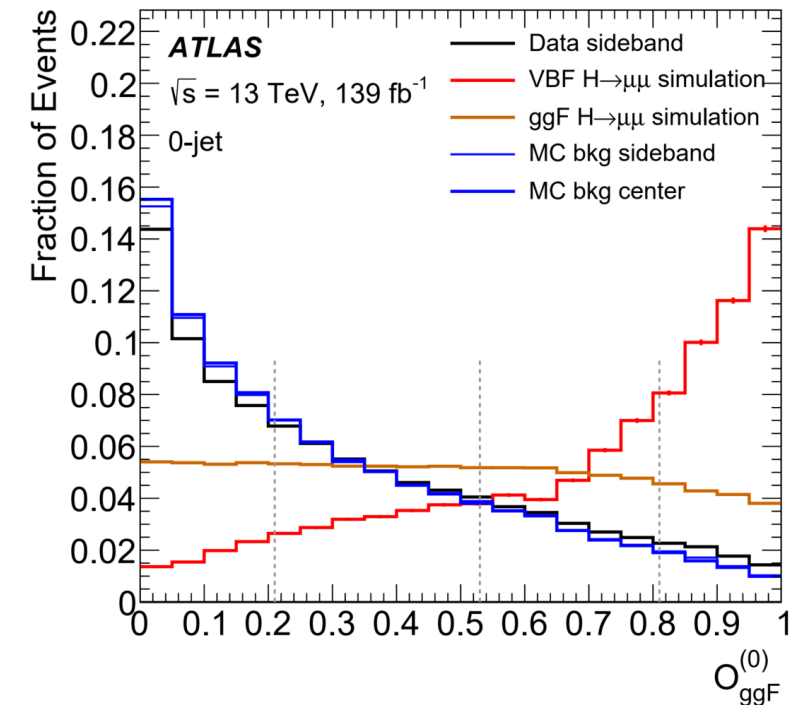
# BDT Categorization

- Avoid overfitting: 4-fold training
  - Each 1/4 from event index%4
  - Test set not used in training
  - Trained model applied to test set
  - Combine 4 test sets for final evaluation
- BDT score boundaries (ggF+VBF)
  - In each jet bin, divide events into 4 bins with score Very-High, High, Medium, Low
  - With descending s/b ratio
  - Optimize boundaries to maximize overall number-counting significance

$$Z_i = \sqrt{2 \left( (s_i + b_i) \log \left( \frac{s_i + b_i}{b_i} \right) - s_i \right)}$$

- Background is estimated by data sideband to avoid MC mis-modelling

	25%	25%	25%	25%
1 <sup>st</sup> fold	Training set	Training set	Validation set	Test set
2 <sup>nd</sup> fold	Test set	Training set	Training set	Validation set
3 <sup>rd</sup> fold	Validation set	Test set	Training set	Training set
4 <sup>th</sup> fold	Training set	Validation set	Test set	Training set



# Signal & Background Modelling

- In each BDT category
- Signal: Double-Sided Crystal Ball (CB2) parameterization
  - Gaussian core + exponential tail
- Background: core function and empirical function
  - DY analytical line-shape

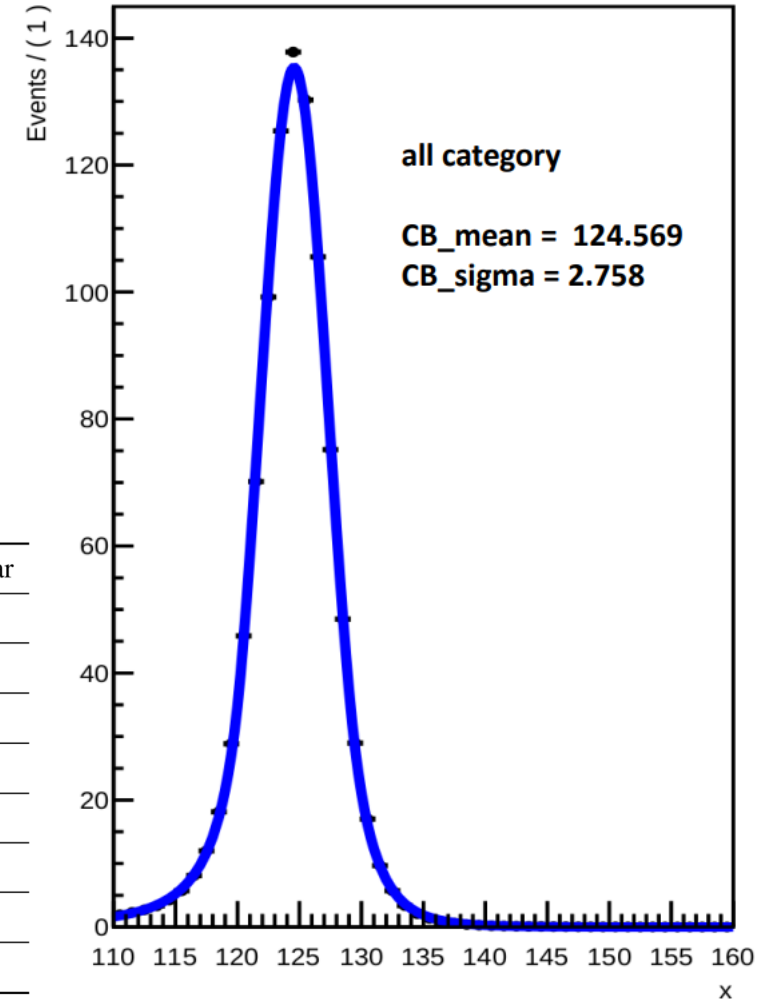
$$DY_{LS}(m_{\mu\mu}) = \sum_q L_{qq} \cdot \sigma_{qq} \cdot m_{\mu\mu}, q = u, s, d$$

- Power & Epoly functions fit and determined by data, to model remaining difference between the spectrum and core function

$$S = \begin{cases} \exp\left(-\frac{(m - m_0)^2}{2\sigma^2}\right), & \text{for } \alpha_L < \frac{m - m_0}{\sigma} < \alpha_H \\ A_L\left(B_L - \frac{m - m_0}{\sigma}\right)^{-n_L}, & \text{for } \frac{m - m_0}{\sigma} \leq \alpha_L \\ A_H\left(B_H - \frac{m - m_0}{\sigma}\right)^{-n_H}, & \text{for } \frac{m - m_0}{\sigma} \geq \alpha_H \end{cases}$$

Function	Expression	nPar
Epoly1	$\exp(a_1 m_{\mu\mu})$	1
Epoly2	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2)$	2
Epoly3	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3)$	3
Epoly4	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3 + a_4 m_{\mu\mu}^4)$	4
Power0	$\text{pow}(m_{\mu\mu}, a_0)$	1
Power1	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu})$	2
Power2	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2)$	3
Power3	$\text{pow}(m_{\mu\mu}, a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + a_3 m_{\mu\mu}^3)$	4

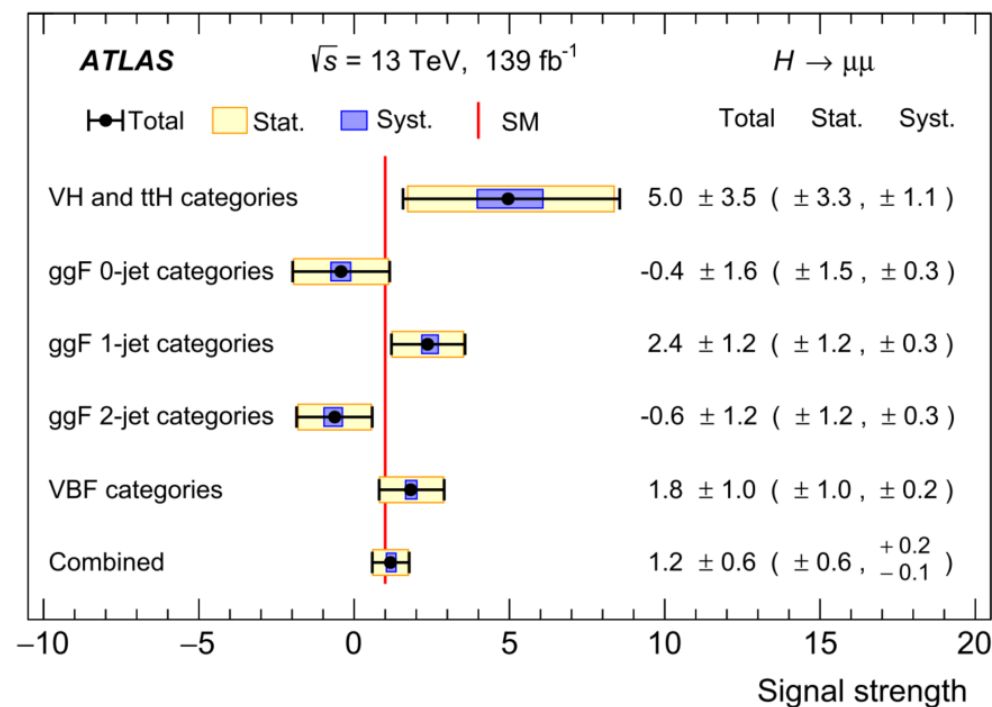
Fit to Rel. 22 signal  $m_{\mu\mu}$



# Results

- Statistical method:
  - Simultaneous binned maximum-likelihood fit to the  $m_{\mu\mu}$  distributions of the 20 categories in the range 110-160 GeV.
- Signal strength:
  - Observed signal yield / SM expected
  - $\mu = 1.2 \pm 0.6$
  - Correspond to  $2.0\sigma$  (observed),  $1.7\sigma$  (expected)
- Discussion
  - Uncertainty: statistical error dominant
  - $\mu = 1.2 \pm 0.58$  (stat)  $^{+0.18}_{-0.13}$  (syst)
  - Compatibility check: float  $\mu$  in each category

Category	Data	$S_{SM}$	$\mu \times S_{SM}$	$B$	$S/\sqrt{B}$	$S/B$ [%]	CB2 Gaussian width
			$S$				$\sigma$ [GeV]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6	3.0
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4	3.0
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6	2.9
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2	3.0
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024 ± 22	0.63	2.0	3.1
2-jet High	5433	50 ± 8	58 ± 30	5440 ± 50	0.77	1.0	2.9
2-jet Medium	18 311	79 ± 15	90 ± 50	18 320 ± 90	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	36 340 ± 140	0.37	0.2	2.9
1-jet Very High	1097	16.5 ± 2.4	19 ± 10	1071 ± 22	0.59	1.8	2.9
1-jet High	6413	46 ± 7	54 ± 28	6320 ± 50	0.69	0.9	2.8
1-jet Medium	24 576	90 ± 11	100 ± 50	24 290 ± 100	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	73 480 ± 190	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	16 090 ± 90	0.55	0.4	2.6
0-jet High	46 523	99 ± 13	120 ± 60	46 190 ± 150	0.54	0.3	2.6
0-jet Medium	91 392	119 ± 14	140 ± 70	91 310 ± 210	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	121 310 ± 280	0.26	0.1	2.7
VH4L	34	0.53 ± 0.05	0.6 ± 0.3	24 ± 4	0.13	2.6	2.9
VH3LH	41	1.45 ± 0.14	1.7 ± 0.9	41 ± 5	0.27	4.2	3.1
VH3LM	358	2.76 ± 0.24	3.2 ± 1.6	347 ± 15	0.17	0.9	3.0
t̄tH	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2	3.2



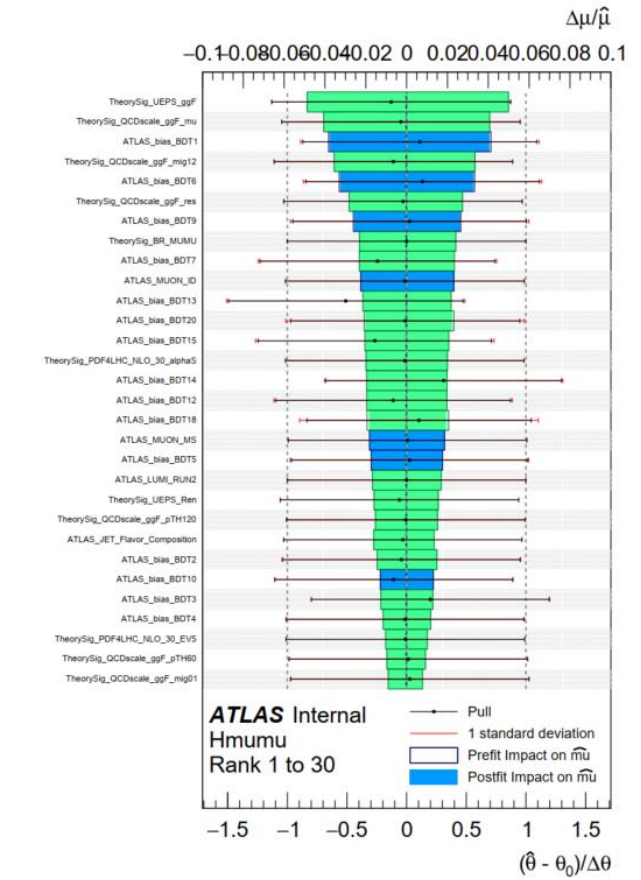
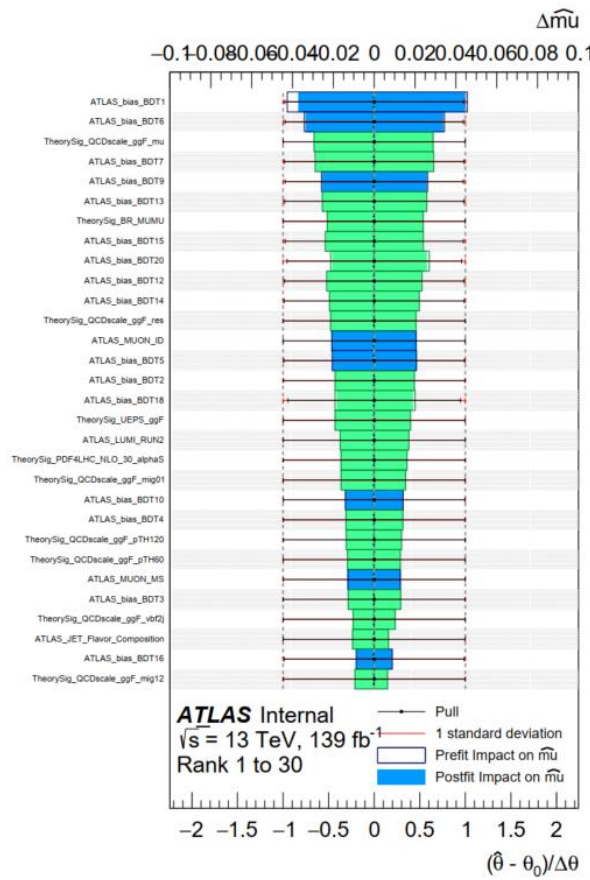
# Systematics

- Theoretical

- Missing higher-order QCD corrections
- PDF and hadronization
- QCD scale
- .....

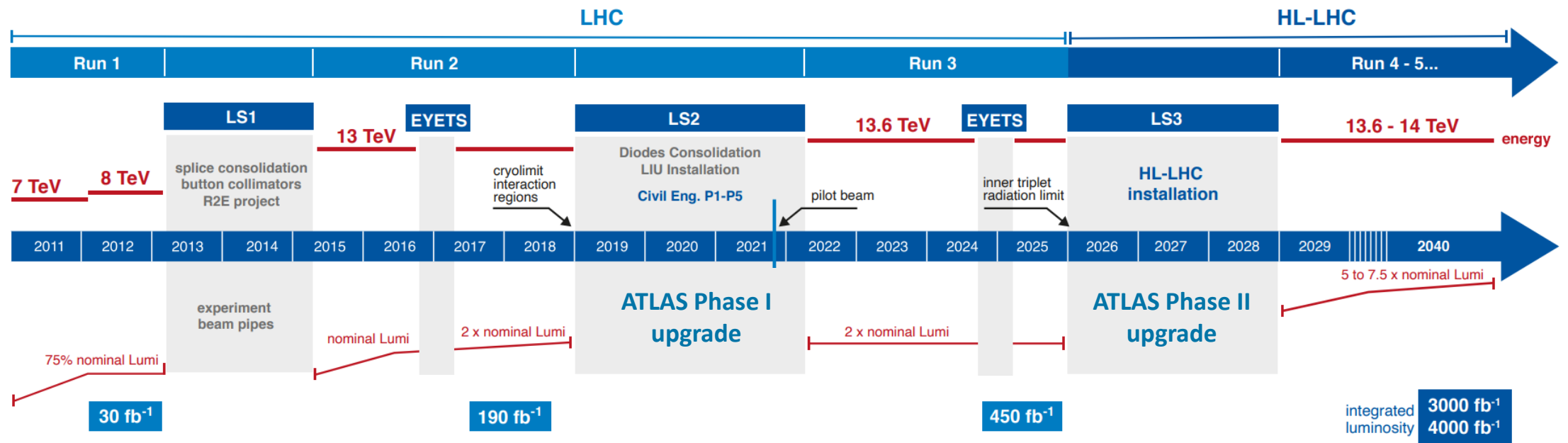
- Experimental

- Spurious signals
- Luminosity uncertainty: 1.7%



# Summary

- Detailed search for  $H \rightarrow \mu\mu$  on ATLAS is presented
- Events selected, classified into 20 BDT bins, then fitted
- Current result is statistical dominated,  $2.0\sigma$  significance
- Prospect: HL-LHC!



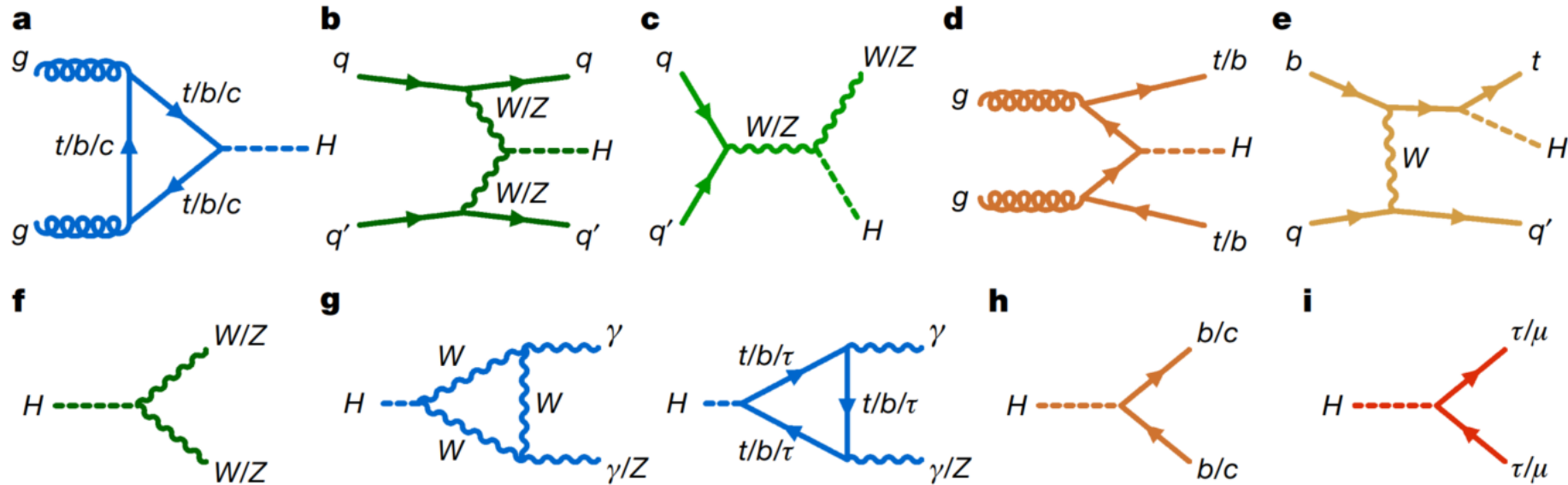


# Backup

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# Backup

- All processes

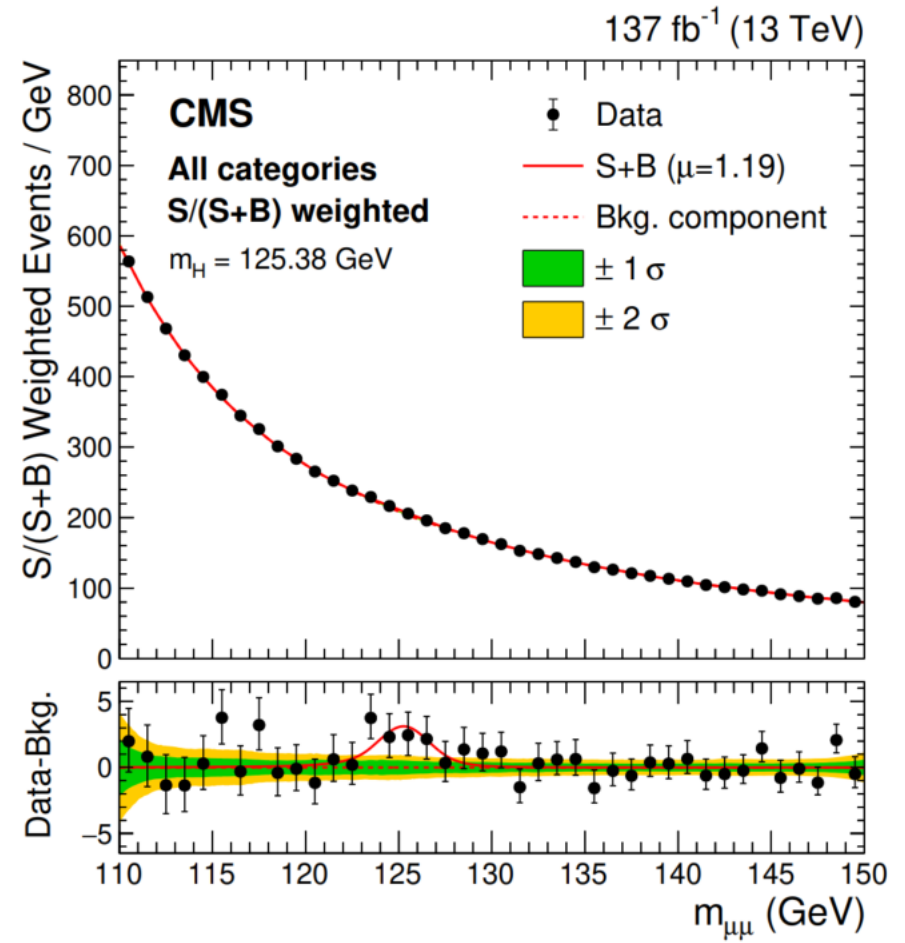
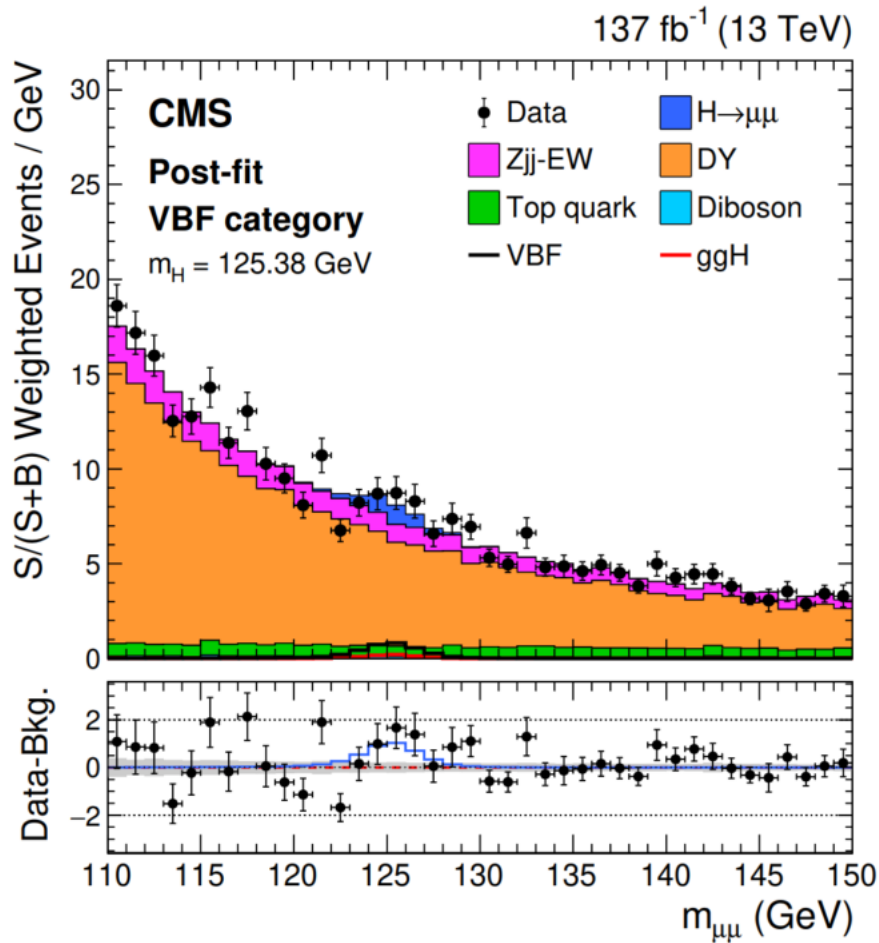


**Fig. 1 | Examples of Feynman diagrams for Higgs boson production and decay.** **a–e**, The Higgs boson is produced via gluon–gluon fusion (**a**), vector boson fusion (VBF; **b**) and associated production with vector bosons (**c**), top or  $b$  quark pairs (**d**), or a single top quark (**e**). **f–i**, The Higgs boson decays into a pair of vector bosons (**f**), a pair of photons or a  $Z$  boson and a photon (**g**), a pair

of quarks (**h**), and a pair of charged leptons (**i**). Loop-induced Higgs boson interactions with gluons or photons are shown in blue, and processes involving couplings to  $W$  or  $Z$  bosons in green, to quarks in orange, and to leptons in red. Two different shades of green (orange) are used to separate the VBF and  $VH$  ( $t\bar{t}H$  and  $tH$ ) production processes.

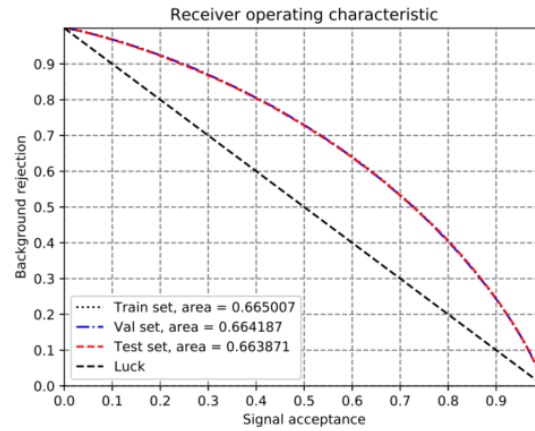
# Backup

- CMS result

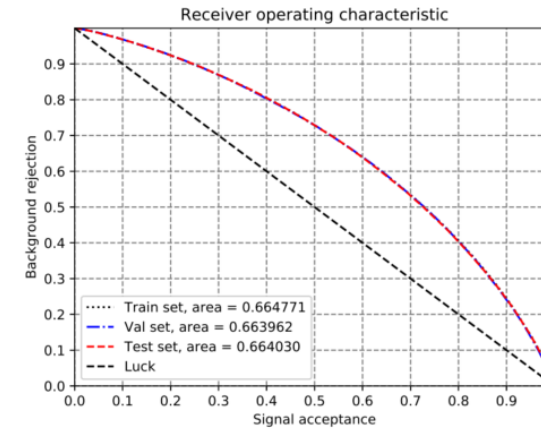


# Backup

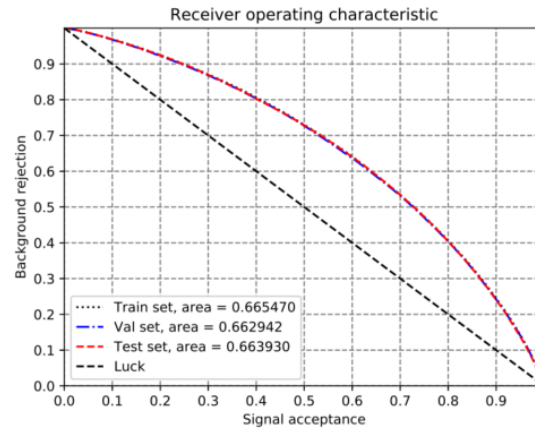
- ROC curves: zero jet



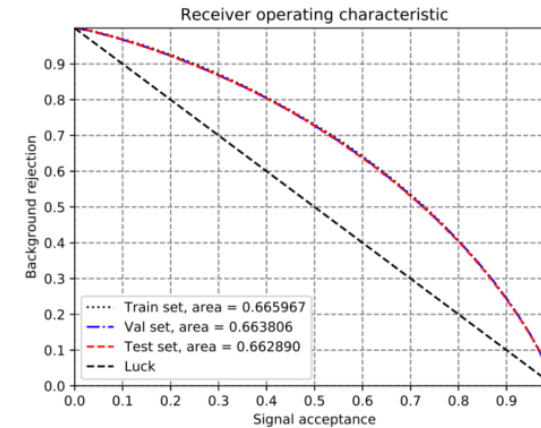
(a) Fold 0



(b) Fold 1



(c) Fold 2

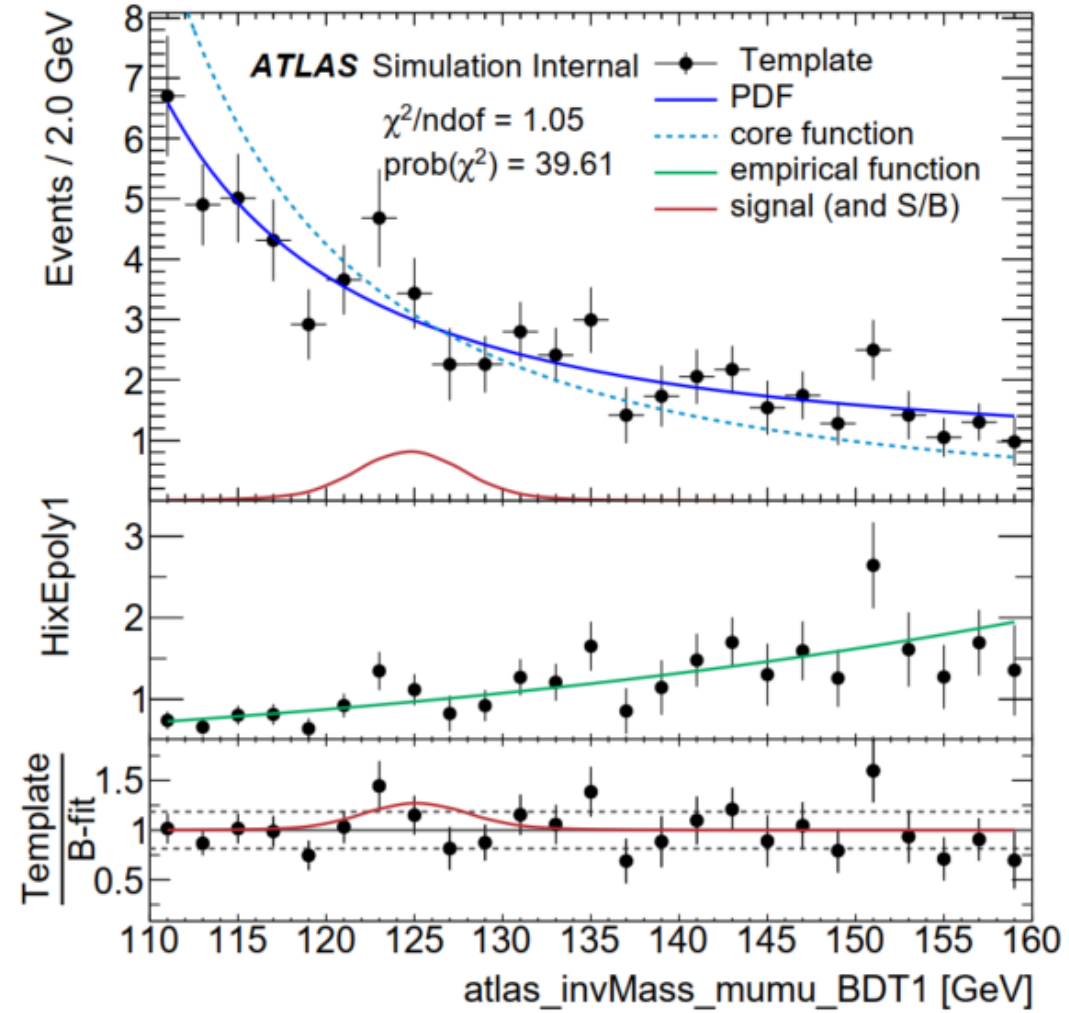


(d) Fold 3

Jet multiplicity	Significance			
	training set A	training set B	validation set	test set
$n_j = 0$	$0.826\sigma$	$0.826\sigma$	$0.824\sigma$	$0.824\sigma$
$n_j = 1$	$1.036\sigma$	$1.036\sigma$	$1.006\sigma$	$1.006\sigma$
$n_j \geq 2$	$2.420\sigma$	$2.398\sigma$	$1.361\sigma$	$1.352\sigma$

# Backup

- Core + empirical



# Backup

- cutflow

Cut	ggF		VBF		$Z \rightarrow \mu\mu$		Data	
	Events	Eff.	Events	Eff.	Events	Eff.	Events	Eff.
Preslim	1981467.46	-	448392.55	-	176471012.14	-	42998169	-
DAOD	1788657.76	90.27%	421388.92	93.98%	122771079.98	69.57%	9373471	21.80%
Trigger	1602988.33	89.62%	375893.91	89.20%	95811913.78	78.04%	3757696	40.09%
GRL	1602988.33	100.00%	375893.91	100.00%	95811913.78	100.00%	3741710	99.57%
Event cleaning	1602988.33	100.00%	375893.91	100.00%	95811913.78	100.00%	3741710	100.00%
Jet cleaning	1596042.61	99.57%	374085.03	99.52%	95441274.32	99.61%	3709769	99.15%
$N_{\text{muons}} \geq 2$	1323313.74	82.91%	310700.04	83.06%	73105593.90	76.60%	368096	9.92%
Trigger matching	1313884.33	99.29%	308642.38	99.34%	70935778.16	97.03%	351231	95.42%
$p_T^{\text{lead (sub)}} > 27$ (15) GeV	1292216.98	98.35%	300209.56	97.27%	69249800.58	97.62%	330264	94.03%
Opposite charge $\mu$	1292183.29	100.00%	300198.88	100.00%	69249800.58	100.00%	330169	99.97%
$N_{\text{muons}} == 2$	1291791.54	99.97%	300007.16	99.94%	69235155.08	99.98%	329929	99.93%
b-jet veto	1274621.07	98.67%	294372.22	98.12%	68690230.51	99.21%	324940	98.49%
$m_{\mu\mu} \in [110, 160]$ GeV	1226871.38	96.25%	283399.48	96.27%	1192750.87	1.74%	5549	1.71%