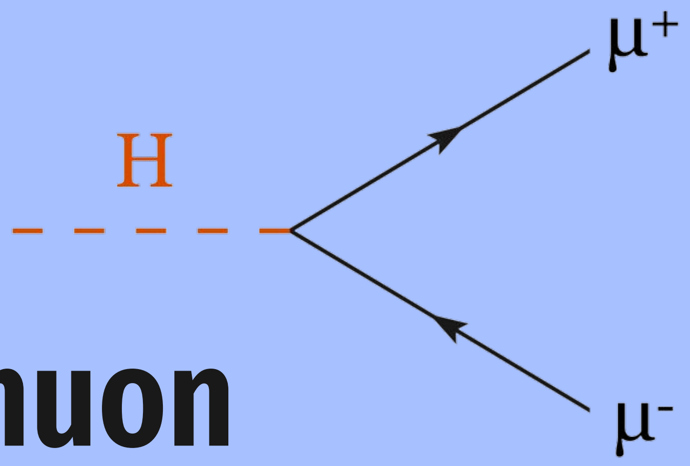
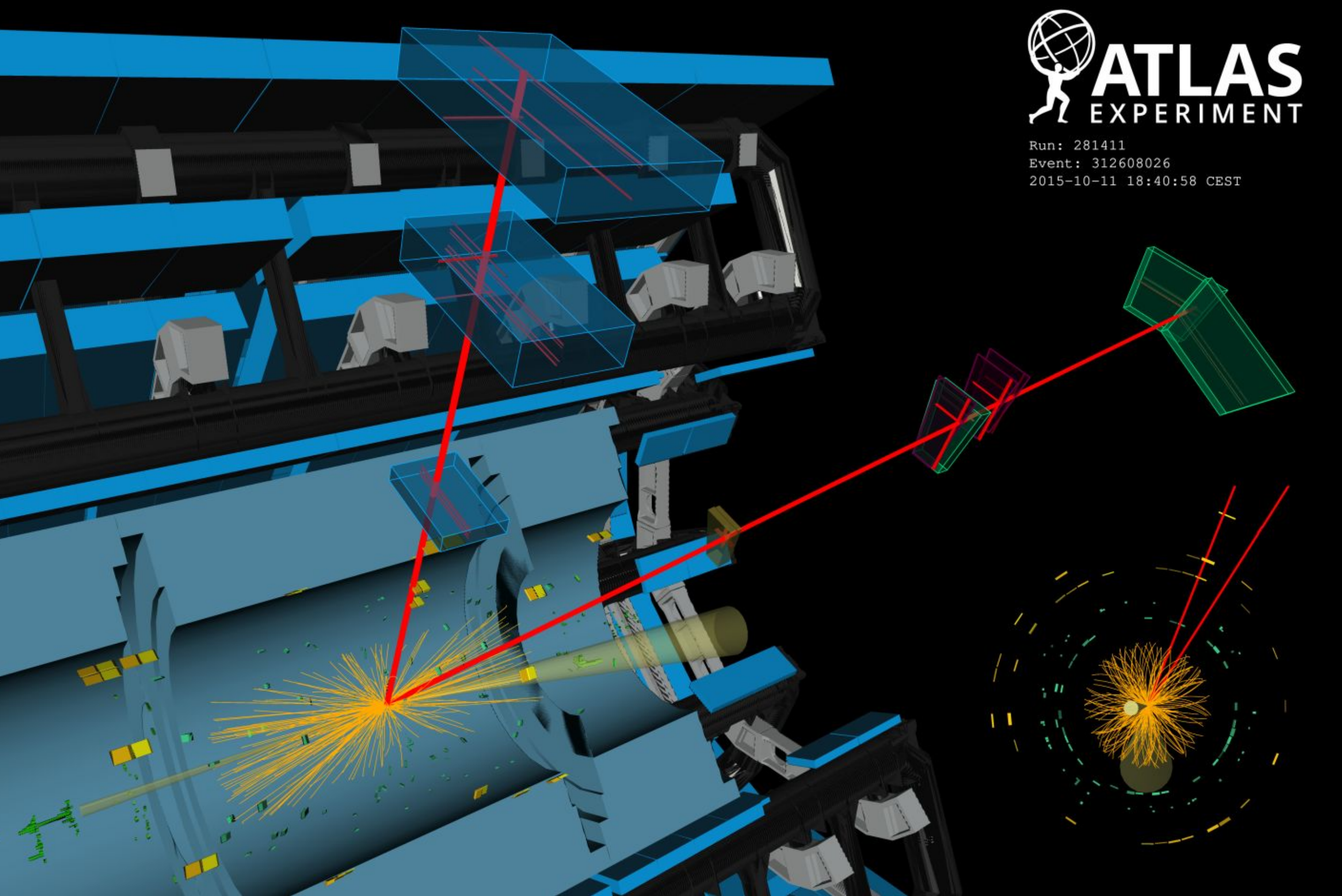


A search for the dimuon decay of the Higgs boson with the ATLAS detector

Group B

11th CERN LATIN-AMERICAN SCHOOL OF HIGH-ENERGY PHYSICS
San Esteban, Chile
15 - 28 March 2023



Overview

Motivation

ATLAS Detector

Event categorization

- $t\bar{t}H$
- VH
- ggF + VBF

Modelling

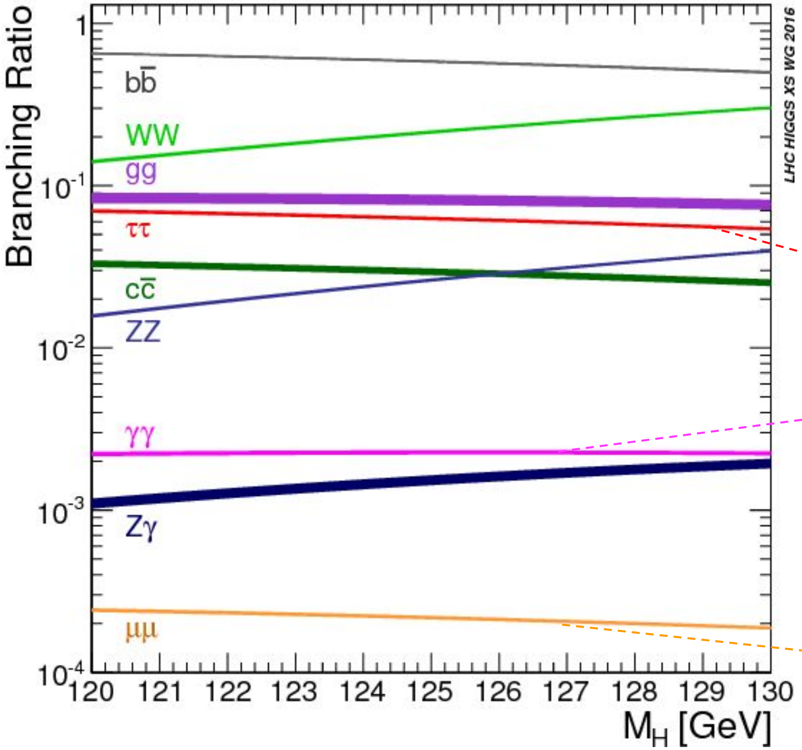
- Signal
- Background

Results

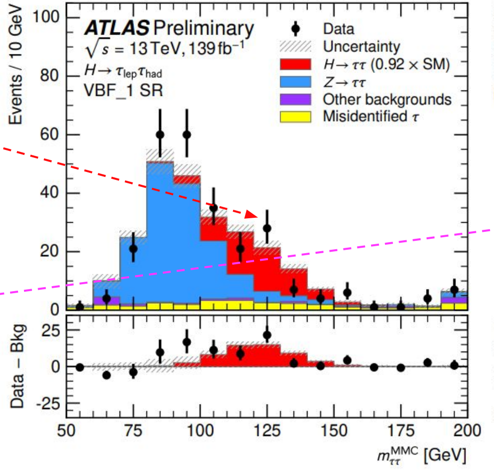
Future prospects

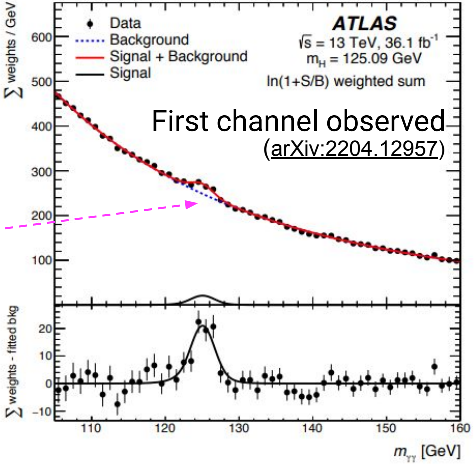
arXiv:2007.07830

Motivation



Observations of interaction between the Higgs boson and 3rd-generation (arXiv:2204.12957) leptons but not with 2nd-generation!



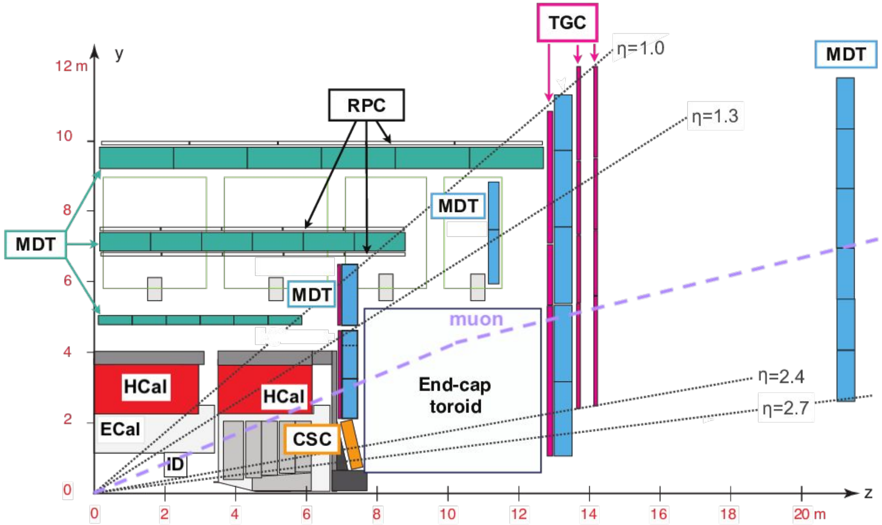


First channel observed (arXiv:2204.12957)

Very small Higgs to dimuon branching ratio (arXiv:1307.1347) of 0.02% but feasible candidate for detection due to clean final state.

ATLAS Detector & Muon Reconstruction

- **Inner Detector (ID)**: charged particle tracking $|\eta| < 2.5$.
- **Electromagnetic & Hadronic Calorimeter**:
  energy measurement: absorption of charged particles.
- **Muon Spectrometer**: with superconducting toroids
  - Trigger system $|\eta| < 2.4$:
    Resistive-plate Chamber & Thin-gap Chambers.
  - Precision tracking chambers $|\eta| < 2.7$:
    Monitored drift tubes & Cathode-strip Chambers.



- **Dataset**: full pp collision recorded with the ATLAS detector in the LHC Run 2 period (2015 -2018) at $\sqrt{s}$=13TeV, with an integrated luminosity of 139 fb^{-1}.
- **Events selection**:
  - two opposite-charge muon candidates.
  - leading muon p_T > 27 GeV & subleading muon p_T > 15 GeV.
  - one reconstructed pp collision vertex candidate, two associated ID tracks with p_T >0.5GeV.

$t\bar{t}$H Category

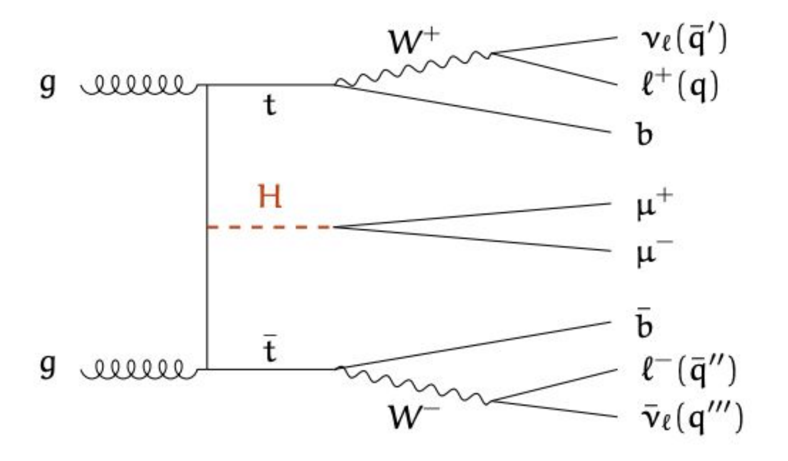
- Dileptonic and semi-leptonic decays of $t\bar{t}$ **system**.

- Selected events:
  - **H candidate: 2 highest-p_T opposite-charge muons.**
  - **≥ 1 lepton** (e or μ) with p_T > 15GeV.
  - **≥ 1 b-jet** selected with 85% efficiency working point.

- **Dominant backgrounds**: $t\bar{t}$Z, diboson (mainly ZZ), $t\bar{t}$ decays and $t\bar{t}H$, $H\rightarrow$X(not muons).

- Background suppression with **BDT**:
  - Signal $t\bar{t}H$, $H\rightarrow\mu\mu$ and background is all SM background processes.
  - Selection is applied to the BDT score to define a **$t\bar{t}H$-enriched category** - optimising the **signal sensitivity**.

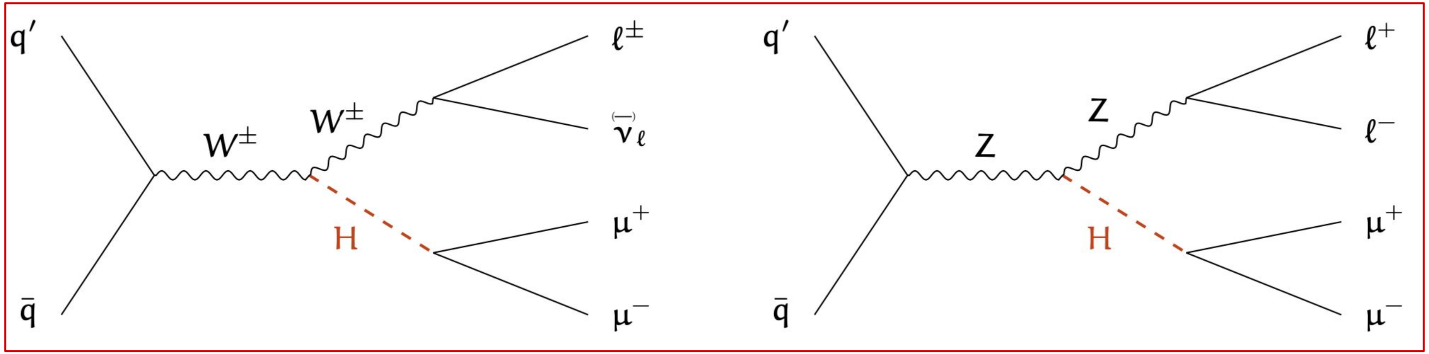
- **1.2 signal events** are expected in this category.



VH (Higgs-strahlung) Category

- H is radiated by W or Z, then decays to $\mu\bar{\mu}$
- Besides $\mu\bar{\mu}$, at least 1 additional lepton is required, Drell-Yan is greatly reduced
- No b-jet candidates
- Dominant background: $Z \rightarrow \mu\bar{\mu}$ (diboson), suppressed with 2 BDTs (3 and 4 leptons)

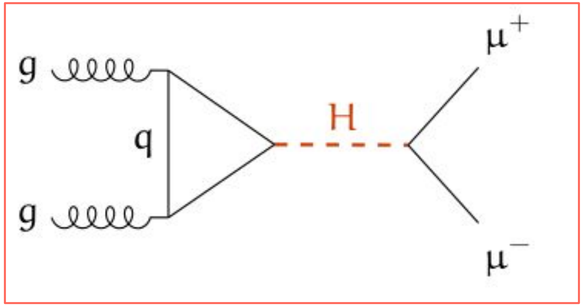
- Additional event selection:
  - 2 categories for 3 leptons case with different signal-to-background ratio: p_T > 15 GeV for $\mu\bar{\mu}$ and > 10 GeV for lepton
  - 1 category for 4 leptons case: p_T > 6 GeV for $\mu\bar{\mu}$ and > 8 GeV for e^+e^-
- Signal events expected for 3 leptons (medium and higher signal-to-background ratio), and 4 leptons: **2.8, 1.4 and 0.5** respectively

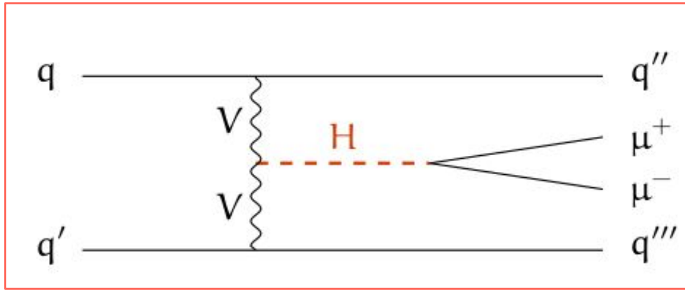


ggF and VBF Category

- 90% background: Drell-Yan.
- Event selection: reject b-tagged jets or when 3rd muon present.
- Background suppression with **BDT**. Variables used:

More than 2jets subcategory	**2jets, 1jet, 0jets** subcategory
For signal have larger transverse momentum and smaller rapidity	
Use $\cos\theta^*$	
p_T, η, $\Delta\Phi_{\mu\mu,j1}$, $\Delta\Phi_{\mu\mu,j2}$	For 1 jet use p_T, η, $\Delta\Phi_{\mu\mu,j1}$
discriminate gluon and quark jets in high p_T central region: multiplicity of ID tracks of two leading jets	





- Predicted SM signal events in VBF categories ranges between **2.8** and **7.5**.

Signal Modelling

Fit to the invariant mass of the dimuon system with a **Crystal Ball function**.

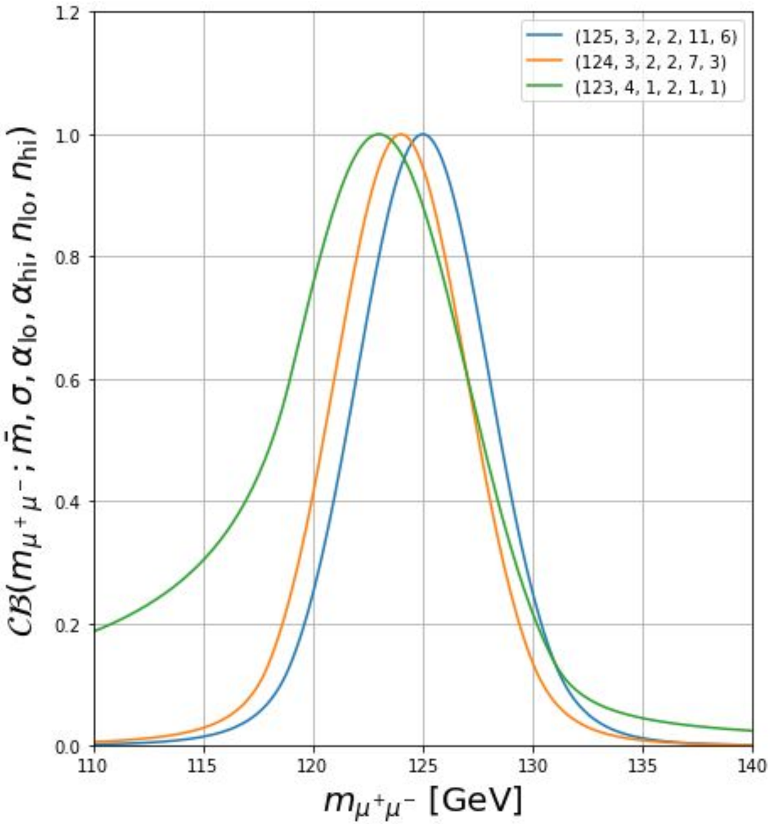
Systematic uncertainty sources:

1. **Theoretical**: Missing higher-order QCD corrections, hadronization, underlying event.

2. **Experimental**: Muon reconstruction and identification efficiencies, muon momentum scale and resolution, pile-up modelling.

3. Higgs mass: m_H = (125.09 ± 0.24) GeV (ArXiv: 1503.07589).

4. Branching ratio: BR($H \to \mu^+\mu^-$) = (2.17 ± 0.04) x 10^{-4} (ArXiv: 1610.07922).



Background Modelling

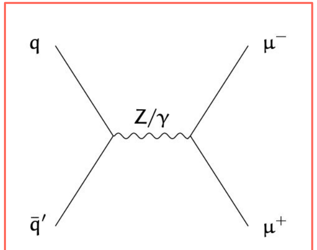
- Very low S/B ratio (0.2%) ➪ background mismodelling must be carefully checked.

- **Background model**: Core function (fixed) multiplied by an empirical function (with free parameters):
  - Core function: Analytical LO Drell-Yan lineshape convoluted with resolution effects.
  - Empirical function determined for each category.

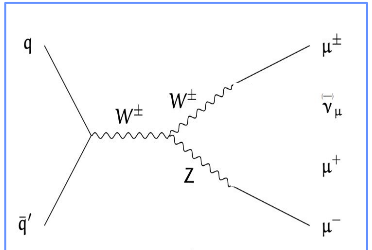
- Cross-checks are performed for systematic uncertainties:
  - Alternative MC samples.
  - Theoretical variations (e.g. alternative PDF sets).
  - Experimental variations (e.g. muon momentum resolution).

- No statistically significant mismodelling is found.

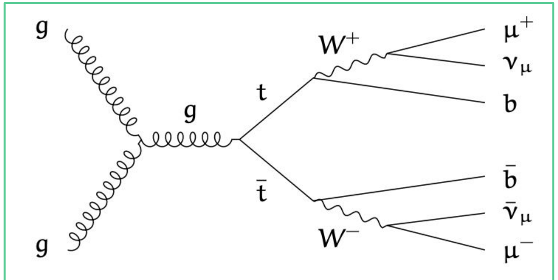
Dominant Backgrounds



Drell-Yan



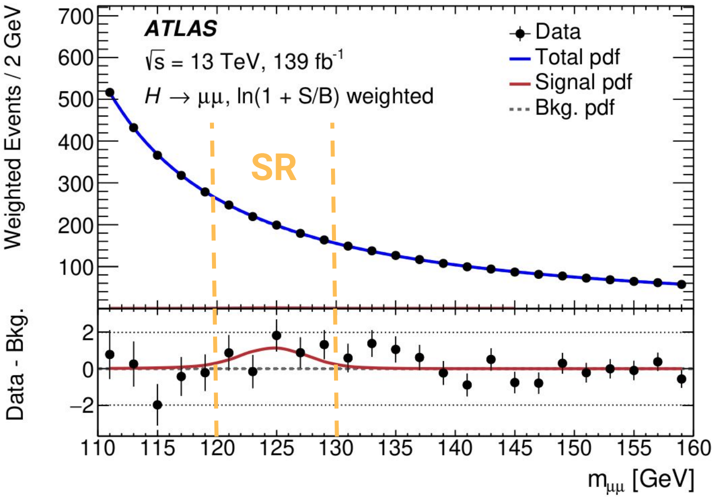
Diboson ($W^{\pm}Z$) decay



Top pair ($t\bar{t}$) decay

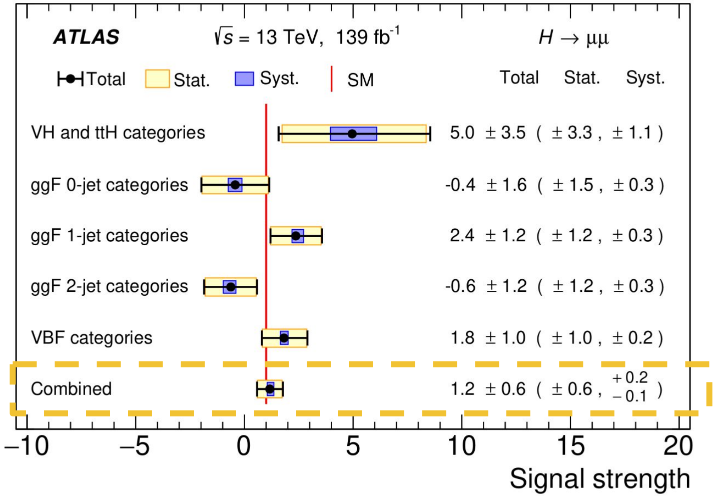
Results

Simultaneous binned maximum-likelihood fit (s+b) to $m_{\mu\mu}$ of the 20 categories.



Fit in 110-160 GeV area with bin size 0.1GeV.

Observed (expected) significance: 2.0σ (1.7σ).
Improvement of a factor of ~2.5 compared to previous ATLAS publication (mainly due to larger dataset).



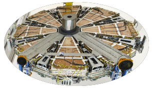
Signal strength (observed/SM expected signal)
μ=1.2±0.6

- Statistical uncertainties: 58% (dominant).
- Systematic uncertainties: +18/-13% (dominated by theory uncertainties).

Future Prospects

- Current ATLAS measurements ⟶ Observed (expected) significance: **2.0 σ** (1.7 σ)
- Current CMS measurements ⟶ Observed (expected) significance: **3.0 σ** (2.5 σ)
  arxiv:2009.04363

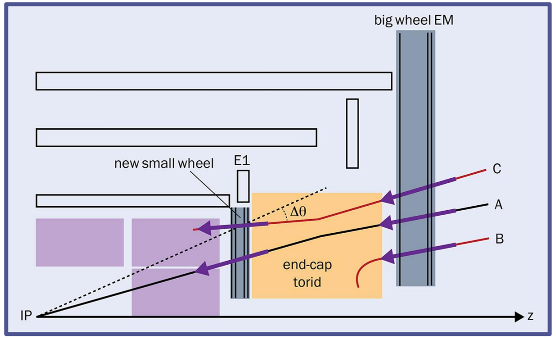
Run 2



4th November 2021, New Small Wheel successfully installed in the ATLAS detector (*See George Mikenberg's lecture*).

- The trigger rate will be improved by a factor of 100.
- Provide redundancy in the track reconstruction.

Run 3



- ~9σ significance is expected at the end of HL-LHC (3000 fb^{-1}).
- These results explore the mass hierarchy in the SM from different generation.
- Why does the higgs couple so differently to muons and taus while the W boson couples similarly to each generation?

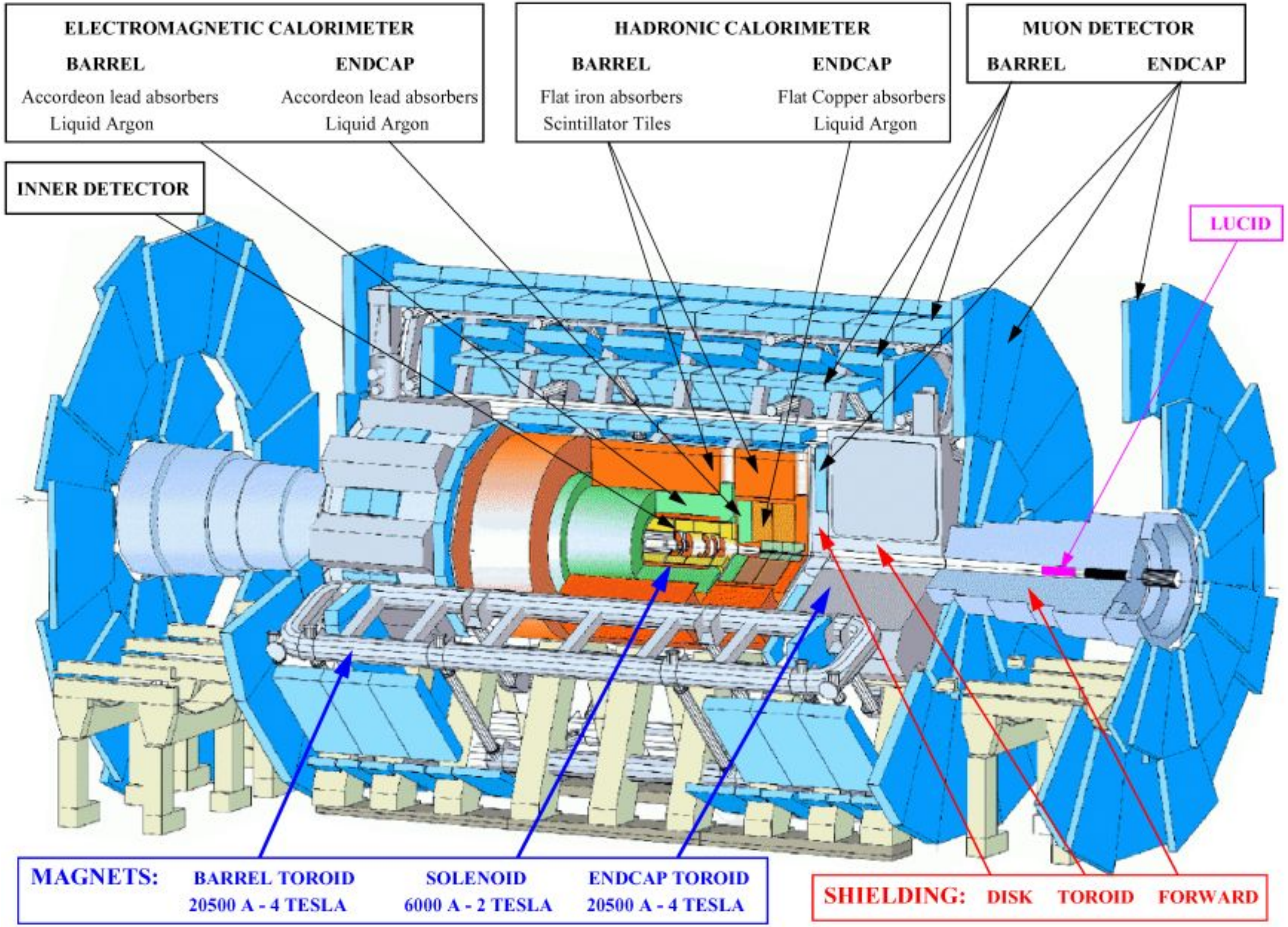
HL-LHC

“The more we learn about the Higgs, the more mysterious it seems!”

-John Ellis

Back-up slides

ATLAS Detector



*Crystal Ball function (backup slide)

$$
\mathcal{CB} = \begin{cases} e^{-\frac{1}{2}t^2} & \text{for } -\alpha_{lo} \leqslant t \leqslant \alpha_{hi} \\ e^{-\frac{1}{2}\alpha_{lo}^2}\left[\frac{\alpha_{lo}}{n_{lo}}\left(\frac{n_{lo}}{\alpha_{lo}} - \alpha_{lo} - t\right)\right]^{-n_{lo}} & \text{for } t < -\alpha_{lo} \\ e^{-\frac{1}{2}\alpha_{hi}^2}\left[\frac{\alpha_{hi}}{n_{hi}}\left(\frac{n_{hi}}{\alpha_{hi}} - \alpha_{hi} + t\right)\right]^{-n_{hi}} & \text{for } t > \alpha_{hi} \end{cases}
$$

- Continuous probability density function with continuous first derivative;

- Gaussian core; the power-law tails account for effects that disappear more slowly than the Gaussian. There are two examples in the text of why you would need a CB in the place of a pure Gaussian: final-state radiation could produces (small) fluctuations (the tail falls more slowly than the Gaussian, like a power law) in the lower tail, and the non-Gaussian response of the sensors creates (small) fluctuations in the higher tail.

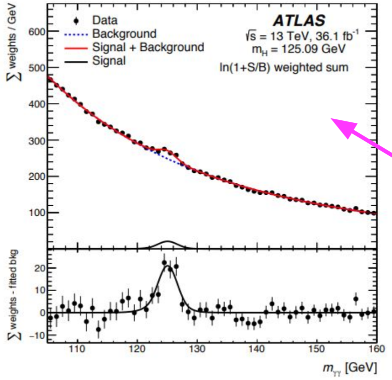
- For each of the 20 categories, the MC simulations yield the invariant mass of the dimuon system. Then, the CB curve is made for each category. The actual fit is done for the sum over all production modes, according to their relative presence as predicted by the SM.

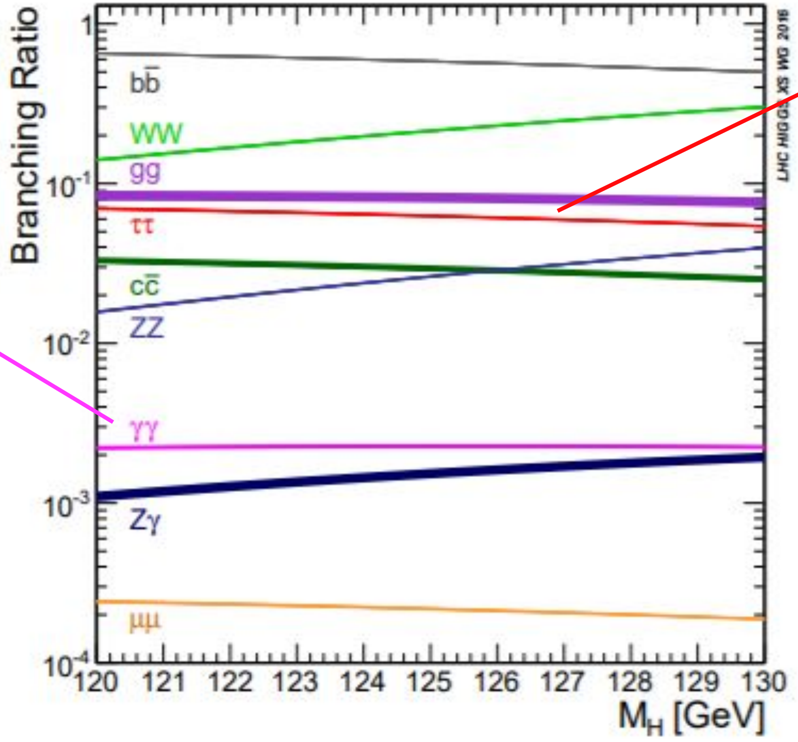
Background empirical functions

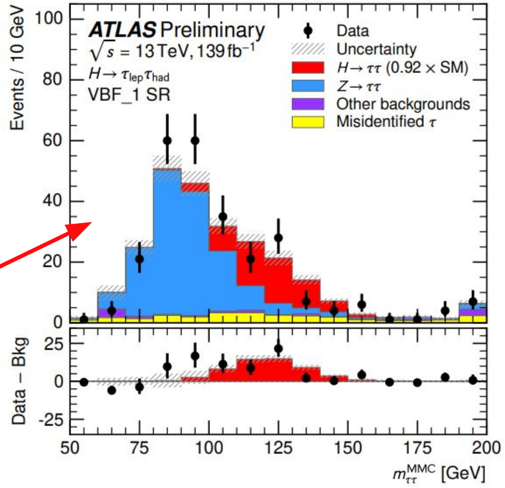
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\ldots+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp(a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \ldots + a_N m_{\mu\mu}^N)$

Motivation

H → γγ: First channel observed



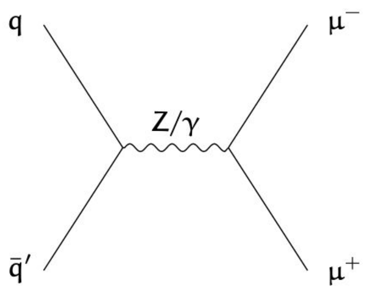




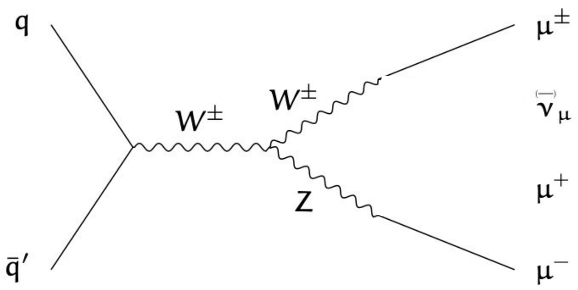
- Observations of interaction between the Higgs boson and 3rd-generation leptons but **not** with 2nd-generation!
- Very small Higgs to dimuon branching ratio of 0.02% but feasible candidate for detection due to clean final state

Event Categorization

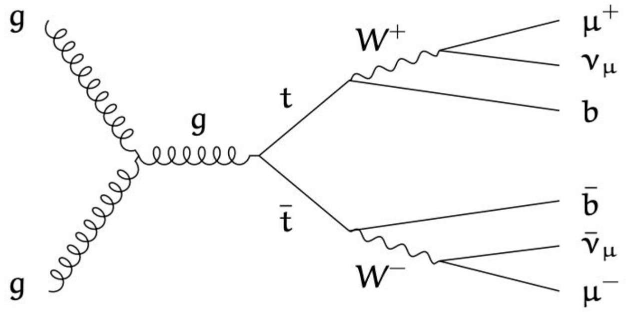
- Events are classified into **20 mutually exclusive categories**
- Exploits **topological and kinematic differences** between background processes and Higgs production modes: ggF, VBF, VH, ttH.
- The background is dominated by **Drell-Yan** with additional contributions from diboson production, tt and single-top production, ttV and Z→μμ.



Drell-Yan



Diboson ($W^\pm Z$) decay



Top pair ($t\bar{t}$) decay

Background Modelling

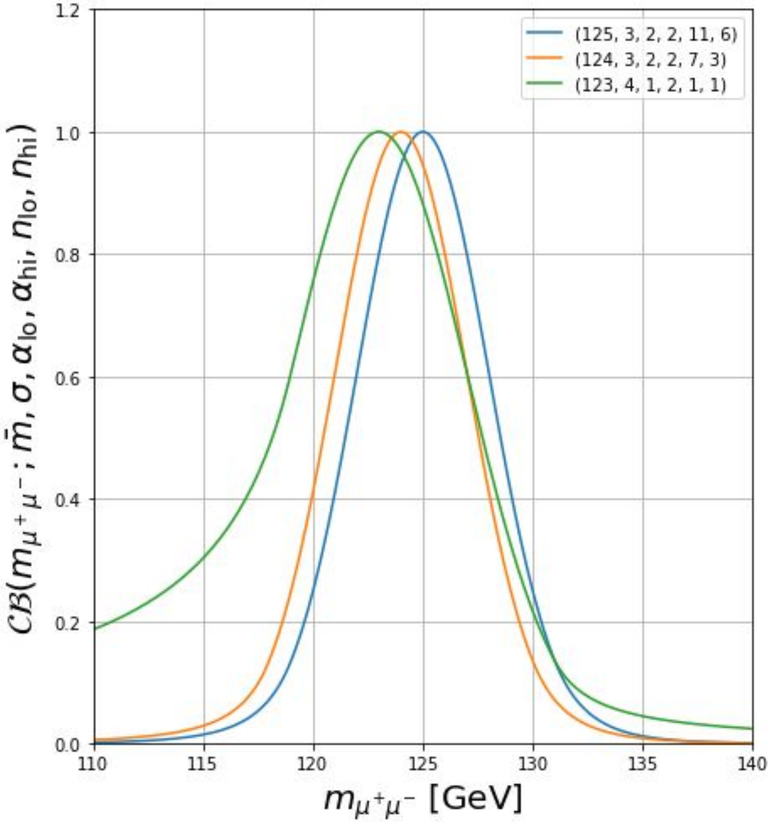
- Very low S/B ratio (0.2%) ⇨ background mismodelling must be carefully checked.
- Background model: Core function (fixed) multiplied by an empirical function (with free parameters).
    - Core function: Analytical LO Drell-Yan lineshape convoluted with resolution effects.
    - Empirical function determined for each category.
- Cross-checks are performed for systematic uncertainties:
    - Alternative MC samples
    - Theoretical variations (e.g. alternative PDF sets)
    - Experimental variations (e.g. muon momentum resolution)
- No statistically significant mismodelling is found.

Signal Extraction

Binned maximum-likelihood fit to the invariant mass of the dimuon system with a **Crystal Ball function**

Systematic uncertainty sources

1. **Theoretical**: Missing higher-order QCD corrections, hadronization, underlying event
2. **Experimental**: Muon reconstruction and identification efficiencies, muon momentum scale and resolution, pile-up modelling
3. Higgs mass: 125.09(24) GeV.



Fit model

Likelihood function

$$L(\mathbf{D} \mid \mu_c, \theta) = \prod_c \prod_i L(n_{c,i} \mid \mu_c, \theta) \prod_j C_j(\tilde{\theta}_j \mid \theta_j, \Delta\theta_j)$$

The parameter of interest follows a Poisson probability function

The systematic uncertainties are implemented in the fit as nuisance parameters

Analysis regions

Region	$m_{\mu\mu}$ range [GeV]
Z validation region	76-106
Signal region	120-130
Side-bands (control regions)	110-120 and 130-160
Fit region	**110-160**

Test statistics

$$t_{\mu_c} = -2\ln\lambda(\mu_c) = -2\ln\frac{L(\mathbf{D} \mid \mu_c, \hat{\hat{\theta}}(\mu_c))}{L(\mathbf{D} \mid \hat{\mu}_c, \hat{\theta})}$$

Signal strength

$$\mu_c = \frac{(\sigma_H BR_{\mu^+\mu^-})_{obs}}{(\sigma_H BR_{\mu^+\mu^-})_{SM}}$$

Results

Yields in SR

Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]	σ [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	$18\,320 \pm 90$	0.66	0.5	2.9
2-jet Low	36 409	63 ± 17	70 ± 40	$36\,340 \pm 140$	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	$24\,290 \pm 100$	0.67	0.4	2.7
1-jet Low	73 459	125 ± 17	150 ± 70	$73\,480 \pm 190$	0.53	0.2	2.8
0-jet Very High	15 986	59 ± 11	70 ± 40	$16\,090 \pm 90$	0.55	0.4	2.6
0-jet High	46 523	99 ± 13	120 ± 60	$46\,190 \pm 150$	0.54	0.3	2.6
0-jet Medium	91 392	119 ± 14	140 ± 70	$91\,310 \pm 210$	0.46	0.2	2.7
0-jet Low	121 354	79 ± 10	90 ± 50	$121\,310 \pm 280$	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
$t\bar{t}H$	17	1.19 ± 0.13	1.4 ± 0.7	15.1 ± 2.2	0.36	9.2	3.2

width of the Gaussian component of the double-sided Crystal Ball function

The uncertainties in S_{SM} correspond to the systematic uncertainty of the SM prediction, the uncertainty in S is given by that in μ, and the uncertainty in B is given by the sum in quadrature of the statistical uncertainty from the fit and the SS uncertainty.

ttH category BTD discriminants

$t\bar{t}H$ classification	
Variable	Description
N_{jets}	Multiplicity of jets in $\|\eta\| < 2.5$
$N_{b\text{-jets}}$	Multiplicity of b-jets
$p_T^{\mu^+\mu^-}$	Transverse momentum of the dimuon system
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$(p_T^{\ell_4})$	Transverse momentum of the fourth lepton
$\cos\theta^\star$	Cosine of the muon decay angle
H_T	Scalar sum of the transverse momenta of all the jets
$(m_{\ell_3\ell_4})$	Invariant mass of the third and fourth lepton
$(m_{t_{lep}})$	Invariant mass of the leptonically decaying top quark
$(m_{t_{had}})$	Invariant mass of the hadronically decaying top quark
$(m_{W_{lep}})$	Invariant mass of the leptonically decaying $W^\pm$ boson
$(m_{\mu_3^\pm\mu_{1,2}^\mp})$	Invariant mass of third muon and opposite charge muon from H

Additional information for VH event selection (1)

Selection criteria for each category

VH − 3ℓ selection	
Additional leptons	1e (μ) with $p_T > 15$ (10) GeV
Additional jets	no b-jet (85%WP)
Additional Z	no $Z \to \mu^+\mu^-$
VH − 4ℓ selection	
p_T^S	> 15 GeV
Additional leptons	$\geqslant 2e$ (μ) with $p_T > 8$ (6) GeV
Additional jets	no b-jet (85%WP)
Additional Z	$< 2\ Z \to \mu^+\mu^-$

Number of leptons, signal and background ratio per category

Category	Number of leptons	Signal (expected events)	Signal to background ratio (%)
VH3LM	3	2.8	0.8
VH3LH	3	1.4	3.7
VH4L	4	0.5	2.6

Additional information for VH event selection (2)

Observables used in VH BDT classification

VH − 3ℓ classification	
Variable	Description
N_{jets}	Multiplicity of jets
$\not{p}_T$	Missing transverse momentum
$p_T^{\ell_3}$	Transverse momentum of the third lepton
$(p_T^{jet_1})$	Transverse momentum of the leading jet
$m_{W^\pm}$	Invariant mass of the $W^\pm$ candidate
$\Delta\varphi_{\not{p}_T,H}$	Azimuthal separation between $\not{p}_T$ and the H candidate
$\Delta\varphi_{\ell_3,H}$	Azimuthal separation between the third lepton and H candidate
$\Delta\eta_{\ell_3,H}$	Pseudorapidity separation between the third lepton and H candidate

VH − 4ℓ classification	
Variable	Description
N_{jets}	Multiplicity of jets
$(p_T^{jet_1})$	Transverse momentum of the leading jet
$(p_T^{jet_2})$	Transverse momentum of the subleading jet
m_Z	Invariant mass of the Z candidate
$\Delta\varphi_{\ell_3,\ell_4}$	Azimuthal separation between the third and fourth lepton
$\Delta\varphi_{Z,H}$	Azimuthal separation between the Z and H candidates
$\Delta\eta_{Z,H}$	Pseudorapidity separation between the Z and H candidates

Simulated Event Samples

Google