$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment

Giacomo Artoni
on behalf of the ATLAS Collaboration

LHC Seminar – CERN, 8/9/2020
Introduction
In the Standard Model, all known elementary particles acquire mass through the BEH mechanism responsible for the Electroweak Symmetry Breaking.

- Fermions, in particular, acquire mass through Yukawa interactions with the Higgs boson.
  - EWSB does not provide any explanation of the flavour hierarchy!
- The “Yukawa sector”: unlike any other term probed so far.
  - not covered by electroweak precision tests
  - very intriguing sector, with a broad programme of measurements at the LHC.
Higgs couplings to fermions

• Thanks to LHC’s Run 2 data, ATLAS and CMS directly probed Higgs boson couplings to *third generation* fermions
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\[ H \rightarrow \tau \tau \]

Observation at 6.4 standard deviations

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\[ ttH \]
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Higgs couplings to fermions

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\[ H \rightarrow \tau \tau \]
Observation at 6.4 standard deviations

\[ ttH \]
Observation at 5.8 standard deviations

\[ VH, H \rightarrow bb \]
Observation at 6.7 standard deviations

...and established agreement with the Standard Model predictions at a level of 30%, see the most up-to-date results on our Higgs results public page

\[ H \rightarrow \mu^{+}\mu^{-} \] search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
Higgs couplings to fermions

Thanks to LHC’s Run 2 data, ATLAS and CMS directly probed Higgs boson couplings to third generation fermions.

Next milestone: establish couplings to second generation fermions.

$H \rightarrow \mu^+ \mu^-$ offers the best opportunity to accomplish this at the LHC!

$H \rightarrow \tau \tau$ observation at 6.4 standard deviations

$ttH$ observation at 5.8 standard deviations

$VH, H \rightarrow bb$ observation at 6.7 standard deviations

$H \rightarrow \mu^+ \mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
Main experimental challenges

- Rare process: branching ratio of $(2.17 \pm 0.04) \times 10^{-4}$
  - If compared to the third generation: 
    \[ \text{BR}_{H \rightarrow \mu\mu}/\text{BR}_{H \rightarrow \tau\tau} \sim (m_\mu/m_\tau)^2 = 0.35\% \]
- Large background from Drell-Yan $\mu^+\mu^-$ production
- Signal-to-background ratio of $\sim 0.2\%$ in signal region (120-130 GeV)
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- Signal-to-background ratio of \(\sim 0.2\%\) in signal region (120-130 GeV)

Key search ingredients

- Large dataset, thanks to the LHC!

- Excellent reconstruction performance, especially for muons
Dataset: Run 2 of the LHC (2015-2018)

- Large dataset delivered by the LHC
  - Peak instantaneous luminosity reaching twice the design luminosity in 2018
    impressive result, thanks LHC!

- Great operation of the ATLAS detector:
  - Delivered by the LHC: 156 fb\(^{-1}\)
  - Recorded by ATLAS: 147 fb\(^{-1}\)
    (Data taking efficiency 94.2%)
  - Good for Physics: 139 fb\(^{-1}\)
    (Efficiency 94.6%, high data quality)
Reconstruction performance: muons

• Muon reconstruction during Run 2: excellent performance and stability!

  • High efficiency for identification (top), isolation (bottom), and association to the primary vertex

  • Small impact from high rates and large pile-up interactions
    • also, well modelled by simulation

  • Extensive set of results available in ATLAS-CONF-2020-030

• Good dimuon mass resolution (1.7-2.3%)
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$H \rightarrow \mu^+\mu^-$ ATLAS search

Analysis strategy

- Maximise signal acceptance by employing the most efficient selection available
  - combination of single-muon triggers ($p_T > 26$ GeV and isolated, otherwise $p_T > 50$ GeV), with signal efficiency of 91% relative to event preselection
  - muons reconstructed from mostly combined tracks but also MS-only tracks ($|\eta|>2.5$, extending acceptance to $|\eta|=2.7$) as well as segment-/calo-tagged tracks ($|\eta|<0.1$)

- Categorise events to improve the inclusive signal-to-background ratio

- Extract signal from a binned, maximum likelihood S+B fit of the dimuon mass distribution in the 110-160 GeV range
  - Simultaneous fit to 20 categories, background estimated from sidebands in each category

Dimuon mass resolution improved by adding at most one final-state-radiation photon (ggF & VBF)

Use only photons close to muons, negligible contributions from $H\rightarrow Z(\rightarrow \mu\mu)\gamma$

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- $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
- Only events with FSR (5% of all)
  - Mean: 118.6 GeV
  - RMS: 4.7 GeV
  - Mean: 126.1 GeV
  - RMS: 4.3 GeV
Choice of analysis categories

- Sort events into mutually exclusive categories, targeting the various Higgs boson production modes
  - Category selections applied in a specific, exclusive order
- Employ process-specific boosted decision trees (using XGBoost)

Basic selection
targeting the various Higgs boson production modes
- trigger, primary vertex, two opposite-charge muons

ttH
- one extra electron or muon
- at least one b-tagged jet
- selection on dedicated BDT score

VH
- no b-tagged jets
- one (two) extra electron(s) or muon(s)
- selection on dedicated BDT score

VBF categories
- no b-tagged jets, no extra muons
- selection on dedicated BDT score

ggF categories
- no b-tagged jets, no extra muons

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ttH category

- Requiring at least one extra electron or muon and at least one b-tagged jet
  - target semi-/di-leptonic decays of the top pair
- Using the two highest-\(p_T\) muons with opposite charge as Higgs candidate
- BDT (12 features, see backup), trained to distinguish \(ttH(\rightarrow \mu \mu)\) signal from all known SM backgrounds, used to define the final ttH category
  - large reduction of tt background, other sources include ttZ, diboson and ttH events where the Higgs does not decay into a muon pair

Expected signal events: 1.2

\(ttH\) purity (wrt other Higgs modes): 98%

\(S/B = 8\%\)
VH categories

- Veto events with a b-tagged jet
  - 4-lepton selection, \( \geq 2 \) extra e/\( \mu \) (targeting \( Z(\rightarrow l\bar{l})H \))
  - 3-lepton selection, 1 extra e/\( \mu \) (targeting \( W(\rightarrow l\nu)H \))

- Relaxed \( p_T \) cut on muons if comparing to ggF/VBF case

- Pairing based on charges and minimisation of \( \chi^2 \) criterion (when \( n_\mu > 2 \))
  - taking into account reconstructed and expected masses for the two bosons
  - pairing efficiency: 93\% (4-lepton), 97\% (3-lepton)

- BDT discriminants trained separately for 3-lepton and 4-lepton events (8 and 7 features, see backup)

- Dominant source of background: diboson processes
VH categories

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VH categories

VH3LH (higher S/B)
Expected signal events: 1.4
VH purity (wrt other Higgs modes): >99%
S/B = 3.7%
VH categories

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Expected signal events: 1.4
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VH3MH (lower S/B)
Expected signal events: 2.8
VH purity (wrt other Higgs modes): 89%
S/B = 0.8%
VH categories

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VH4L
Expected signal events: 0.5
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S/B = 2.6%
VH categories

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VBF categories

- Veto events with a b-tagged jet or with an extra muon
- Select only events with at least 2 jets
- Trained dedicated BDT to separate VBF signal from background (17 features)
  - dimuon and dijet systems information
  - missing transverse energy and $H_T$ (against tt)
  - $N_{\text{tracks}}$ associated to each jet, providing discrimination between gluon- and quark-induced jets

- Using fully simulated samples in the 120-130 GeV window, BDT designed to be as insensitive to $m_{\mu\mu}$ as possible (same applies to ggF, see later)
VBF categories

- Four categories defined, remaining events will be tested for ggF categories (see next slide)

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\[ \sqrt{s} = 13 \text{ TeV, } 139 \text{ fb}^{-1} \]

![ATLAS plot](image-url)
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$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF categories

- Veto events with a b-tagged jet or with an extra muon
- Divide events into channels: N-jet = 0, 1 and ≥2
- Trained dedicated BDT to separate \( ggF + VBF \) signal from background
  - 3, 7, 17 features for 0-, 1-, and 2-jet, respectively (see backup)
  - 2-jet channel using the same features as in the VBF-dedicated BDT
- In each channel BDT used to create 4 categories
Categories - summary

- A total of 20 categories
  - $ttH$, $3xVH$, $4xVBF$, $4xN$-jet ($0$, $1$, $\geq 2$)
- $S/B$ ranging from $<0.1\%$ (0-jet Low) to $18\%$ (VBF Very High)
- Significance ranging from $0.1$ to $0.6 \sigma$
- Very good separation between the different production modes
- DY background dominant in the ggF/VBF categories
Signal modeling

- Signal shape dominated by detector resolution
- Using double-sided Crystal Ball (CB) as analytic parameterisation for the signal
  - Gaussian core + power-law tails on each side
- MC spectra created by summing over all production modes in each category
  - relative normalisation from SM assumed, negligible differences observed between modes
- Crystal Ball width ranges from 2.6 to 3.2 GeV

**Systematic uncertainties**
- BR, QCD scale, PDF uncertainties (all modes)
- Underlying event, parton showering (ggF/VBF)
- Pileup modelling, $N_{\text{tracks}}$(jet)
- Reconstruction efficiencies (e/µ/b-tag/jet)
- Muon momentum scale and resolution, Run1 Higgs mass uncertainty (240 MeV)
Background modelling

• Key element of the search, as S/B is generally quite low
  • Per-mille level precision necessary, to avoid biases in extracted signal yields
• Requires a large number of simulated events
• Dimuon mass spectrum parameterised with:
  \( F(m_{\mu\mu}, a_i)^{\text{cat}} = \text{Core}(m_{\mu\mu}) \times \text{Empirical}(m_{\mu\mu}, a_i)^{\text{cat}} \)
Background modelling

- **Core($m_{\mu\mu}$)** function:
  - Crucial to take into account the steepness of the DY background as well as resolution effects
  - Based on DY line-shape @LO, convolved with Gaussian to take into account $m_{\mu\mu}$-dependent resolution effects
  - Fully rigid (no extra degrees of freedom)
  - Same for all categories
Background modelling

- **Empirical** \((m_{\mu\mu}, a_i)^{\text{cat}}\) function:
  - Using two “families” of functions: *PowerN* (N+1 parameters) and *EpolyN* (N parameters)
  - One function per category, with varying number of free parameters
  - Corrects for distortions of the \(m_{\mu\mu}\) spectrum induced by:
    - category selections
    - HO theory corrections
    - sub-leading background contributions

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<td>EpolyN</td>
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Choice of empirical function

**Pre-selection: general fit quality**
Keep only functions that can fit *data sidebands, full-sim background* and *fast-sim DY* with $P(\chi^2) > 1\%$ (DY not required for ttH and VH)

**Spurious signal test**
Discard all functions with measured spurious signal larger than 20\% of the statistical error on the signal (in each category)

**Minimise statistical uncertainty**
Retain only functions with the smallest number of degrees of freedom

**Final stage**
Pick the function with the smallest estimated spurious signal (but typically at this point we are already left with just one)
Spurious signal

- Measured signal yield from a \( S+B \) fit performed on **background-only templates**
  - built from high-statistics background samples (fast DY simulation for ggF/VBF, full simulation for ttH/VH)
  - Taking maximum absolute value of spurious signal in the 120-130 GeV mass range

- Dominant experimental systematic
  - accounting for imperfect choice of analytic model for the background and potential local biases in the \( m_{\mu\mu} \) spectrum (induced by selections, for example)

- All spurious signal uncertainties considered uncorrelated
  - Expected significance only impacted by ~2% if switching to full correlation

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Drell Yan simulation

- Fully simulated background samples are used to train the classifiers described earlier and to test the background modelling
  - Integrated luminosity 5-20 times larger than data ⇒ limiting factor when aiming at per-mille precision in background modelling!
- Two fast-simulations developed, minimal requirement: 10 ab⁻¹ per category

**SHERPA 2.2.4 with LO matrix elements**
*(up to 3 extra partons)*

PYTHIA for QED and QCD parton showering and hadronisation

**POWHEG-BOX (0, 1 partons at NLO) + ALPGEN (2 partons at LO)**

Approximate QCD shower algorithm, PHOTOS for QED FSR

- Experimental effects included through parameterisations extracted from fully simulated samples or ATLAS data
  - Particular focus on detailed description of
    - muons: momentum resolution, trigger and reconstruction efficiency
    - pile-up and underlying event effects on missing transverse energy
    - hadronic jets from the primary interaction and pile-up
Results
Results

\[ \text{Weighted Events / 2 GeV} \]

\[ \text{ATLAS} \]
\[ \sqrt{s} = 13 \text{ TeV}, \text{ 139 fb}^{-1} \]
\[ H \rightarrow \mu \mu, \ln(1 + S/B) \text{ weighted} \]

\[ \text{Data - Bkg.} \]

\[ \pm 0.58 \]
\[ +0.13/-0.08 \]
\[ +0.07/-0.03 \]
\[ \pm 0.1 \]

Signal strength (best fit)

\[ 1.2 \pm 0.6 \]

Observed BR limit at 95% CL

\[ < 4.7 \times 10^{-4} \]

Significance (wrt no \( H \rightarrow \mu \mu \) signal hypothesis)

\[ \text{Observed: 2.0 \sigma} \]
\[ \text{Expected: 1.7 \sigma} \]

Results

\( H \rightarrow \mu^+\mu^- \) search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020

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Results

**Signal strength (best fit)**

1.2 ± 0.6
**Results**

*Signal strength (best fit)*

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(wrt no $H \rightarrow \mu\mu$ signal hypothesis)
- Observed: 2.0σ
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**Significance**
(wrt no $H\rightarrow\mu\mu$ signal hypothesis)
Observed: 2.0σ
Expected: 1.7σ

**Uncertainties (on signal strength)**
Statistics (data): ±0.58
Theory (signal): +0.13/-0.08
Experimental (signal): +0.07/-0.03
Background modelling: ±0.1

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Results

- Tested grouping categories (ttH+VH, VBF, 0-jet, 1-jet and 2-jet)
- Compatibility between signal strengths in the five groups: 20%
  - 2% when checking on ungrouped categorisation (20)
- Tested adding one extra degree of freedom to the background function for those categories with largest deviation from the average
  - Negligible impact on final result and compatibility check
Conclusions

- New $H \rightarrow \mu \mu$ results presented with the full Run 2 ATLAS dataset (139 fb$^{-1}$)
- Best-fit signal strength: $1.2 \pm 0.6$
- Observed significance: $2.0 \sigma$
- Large improvement over our previous publication, thanks to:
  - larger dataset (factor $\sim 2$)
  - more advanced techniques (+25%)
    - background modelling
    - definition of the categories

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  - more advanced techniques (+25%)
    - background modelling
    - definition of the categories

$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
Conclusions

- New $H\rightarrow\mu\mu$ results presented with the full Run 2 ATLAS dataset (139 fb$^{-1}$)
- Best-fit signal strength: $1.2 \pm 0.6$
- Observed significance: $2.0 \sigma$
- Large improvement over our previous publication, thanks to:
  - larger dataset (factor ~2)
  - more advanced techniques (+25%)
    - background modelling
    - definition of the categories
- Run 3 of vital importance to further increase sensitivity!

$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
Backup Slides
Object-level selections

**Muons**
- $|\eta|<2.7$, $p_T^{\text{lead}}>27$ GeV (matching event trigger), $p_T^{\text{sub}}>15$ GeV (10, for VH-3lep)
- Most efficient selections available
  - identification: mostly combined tracks but also including MS-only ($|\eta|>2.5$) and segment-/calo-tagged ($|\eta|<0.1$)
  - isolation: using ID tracks and calo deposits around the muon ($\Delta R<0.2$)

**Photons**
- only close to muons ($\Delta R(\gamma, \mu)<0.2$), with minimal $p_T$ requirement ranging from 3 GeV ($\Delta R=0$) to 8 GeV ($\Delta R=0.2$)

**Jets**
- Reconstructed using the particle flow algorithm
- $p_T>25$ GeV for $|\eta|<2.4$, $p_T>30$ GeV for $2.4<|\eta|<4.5$
- remove jets not coming from the primary vertex (only for jets with $|\eta|<2.4$ and $p_T<60$ GeV)

**Electrons**
- $|\eta|<2.47$ and $p_T>7$ GeV (excluding $1.37<|\eta|<1.52$)
- Isolated (ID tracks and calo clusters within $\Delta R<0.2$) and matching the primary vertex
Choice of analysis categories

- Sort event in mutually exclusive categories, targeting the various Higgs boson production modes
  - Category selections applied in a specific, exclusive order
- Employ process-specific boosted decision trees (using XGBoost)

### $H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
H→μ+μ− search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020

**ggF categories: 0-jet channel**

<table>
<thead>
<tr>
<th>Category</th>
<th>Expected signal</th>
<th>ggF+VBF purity</th>
<th>Expected S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet Very High</td>
<td>59</td>
<td>96%</td>
<td>0.4%</td>
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<td>0-jet High</td>
<td>99</td>
<td>99%</td>
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**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

![Graph showing the distribution of events for ggF and VBF categories](image)
ggF categories: 0-jet channel

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF categories: 0-jet channel

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$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
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$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF categories: 0-jet channel

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
**ggF categories: 1-jet channel**

<table>
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<tr>
<th>Category</th>
<th>Expected signal</th>
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<tbody>
<tr>
<td>1-jet Very High</td>
<td>16.5</td>
<td>99%</td>
<td>1.5%</td>
</tr>
<tr>
<td>1-jet High</td>
<td>46</td>
<td>98%</td>
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<td>1-jet Low</td>
<td>125</td>
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The graph shows the fraction of events as a function of $O^{(1)}_{ggF}$ for the ATLAS experiment with $\sqrt{s} = 13$ TeV and 139 fb$^{-1}$. The categories are color-coded and labeled with their respective values:

- **Data**
- **VBF $H \rightarrow \mu\mu$ simulation**
- **ggF $H \rightarrow \mu\mu$ simulation**
- **Bkg simulation**
**ggF categories: 1-jet channel**

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \rightarrow \mu^+ \mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
### ggF categories: 1-jet channel

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**ATLAS**
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

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**H→μ+μ− search with the ATLAS experiment** - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF categories: 1-jet channel

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**ATLAS**

Data
- VBF $H \rightarrow \mu \mu$ simulation
- ggF $H \rightarrow \mu \mu$ simulation
- Bkg simulation

$O_{ggF}^{(1)}$
ggF categories: 2-jet channel

<table>
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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF categories: 2-jet channel

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**Graph:**

- **Data**
- **VBF $H \rightarrow \mu\mu$ simulation**
- **ggF $H \rightarrow \mu\mu$ simulation**
- **Bkg simulation**

*ATLAS* \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

\( O_{ggF}^{(2)} \)
ggF categories: 2-jet channel

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

**ATLAS**

- Data
- VBF $H\rightarrow\mu\mu$ simulation
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$O_{ggF}^{(2)}$
### ggF categories: 2-jet channel

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ATLAS $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

![Graph showing fraction of events](image)
ggF categories: 2-jet channel

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$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
## Signal composition

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<thead>
<tr>
<th>Category</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>t(\bar{t})H</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF Very High</td>
<td>6.6%</td>
<td>93.3%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>VBF High</td>
<td>12.8%</td>
<td>87.1%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>VBF Medium</td>
<td>21.3%</td>
<td>78.5%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>VBF Low</td>
<td>34.8%</td>
<td>64.8%</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.0%</td>
</tr>
<tr>
<td>2-jet Very High</td>
<td>82.0%</td>
<td>15.7%</td>
<td>1.2%</td>
<td>1.0%</td>
<td>0.2%</td>
</tr>
<tr>
<td>2-jet High</td>
<td>79.3%</td>
<td>16.0%</td>
<td>2.7%</td>
<td>1.8%</td>
<td>0.3%</td>
</tr>
<tr>
<td>2-jet Medium</td>
<td>80.7%</td>
<td>10.4%</td>
<td>5.4%</td>
<td>3.0%</td>
<td>0.5%</td>
</tr>
<tr>
<td>2-jet Low</td>
<td>78.2%</td>
<td>6.6%</td>
<td>8.8%</td>
<td>4.9%</td>
<td>1.5%</td>
</tr>
<tr>
<td>1-jet Very High</td>
<td>78.2%</td>
<td>21.2%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>1-jet High</td>
<td>88.2%</td>
<td>10.4%</td>
<td>0.9%</td>
<td>0.6%</td>
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<td>6.1%</td>
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<td>0.9%</td>
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<tr>
<td>1-jet Low</td>
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<td>3.8%</td>
<td>2.6%</td>
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<td>0.0%</td>
</tr>
<tr>
<td>0-jet Very High</td>
<td>94.1%</td>
<td>2.5%</td>
<td>1.4%</td>
<td>2.0%</td>
<td>0.0%</td>
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<tr>
<td>0-jet High</td>
<td>98.3%</td>
<td>1.0%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.0%</td>
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<tr>
<td>0-jet Medium</td>
<td>99.1%</td>
<td>0.6%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>0-jet Low</td>
<td>99.5%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.0%</td>
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<tr>
<td>VH4L</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>99.5%</td>
<td>0.4%</td>
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<tr>
<td>VH3LH</td>
<td>0.3%</td>
<td>0.1%</td>
<td>96.9%</td>
<td>2.6%</td>
<td>0.1%</td>
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<tr>
<td>VH3LM</td>
<td>4.2%</td>
<td>1.0%</td>
<td>80.8%</td>
<td>8.6%</td>
<td>5.3%</td>
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<td>(t\bar{t}H)</td>
<td>0.1%</td>
<td>0.0%</td>
<td>1.5%</td>
<td>0.4%</td>
<td>98.0%</td>
</tr>
</tbody>
</table>

\[ H \rightarrow \mu^+\mu^- \] search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
# Background modelling uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Empirical Function</th>
<th>$\text{max}(SS/ \delta S)[%]$</th>
<th>$\text{max}(SS/S_{SM})[%]$</th>
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</thead>
<tbody>
<tr>
<td>VBF Very High</td>
<td>Epoly1</td>
<td>-20.3</td>
<td>-34.8</td>
</tr>
<tr>
<td>VBF High</td>
<td>Power0</td>
<td>11.7</td>
<td>20.0</td>
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<td>Power0</td>
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<td>16.4</td>
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<td>VBF Low</td>
<td>Power0</td>
<td>11.2</td>
<td>2.4</td>
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<td>2-jet Very High</td>
<td>Power1</td>
<td>-13.3</td>
<td>-34.5</td>
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<td>Epoly2</td>
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<td>-41.2</td>
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<td>Epoly3</td>
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<td>1-jet Very High</td>
<td>Epoly2</td>
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<td>VH3LM</td>
<td>Epoly3</td>
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<tr>
<td>$t\bar{t}H$</td>
<td>Power0</td>
<td>32.2</td>
<td>117</td>
</tr>
</tbody>
</table>
Background model choice

Function type

- Power1: 8
- Power0: 4
- Epoly1: 1
- Epoly2: 4
- Epoly3: 3

Number of free parameters

- $N = 2$: 12
- $N = 3$: 3
- $N = 1$: 5
## Compatibility with previous result

<table>
<thead>
<tr>
<th>$\mu$ ATLAS-CONF-2019-028</th>
<th>$\mu$ this work</th>
<th>Compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.5 \pm 0.7$</td>
<td>$1.2 \pm 0.6$</td>
<td>$1.4\sigma$</td>
</tr>
</tbody>
</table>

Values of the signal strengths ($\mu$) reported in the conference note ATLAS-CONF-2019-028 and this work.

Their compatibility in terms of data statistics only and expressed as number of standard deviations $\sigma$ is evaluated using a bootstrap technique (see Ref. Phys. Rev. D 39 (1989) 274) based on the data events passing the selection of either ATLAS-CONF-2019-028, or the one of the current analysis, or both.

All procedures of the respective analyses are preserved.

The correlation between the two signal strength measurements is evaluated to be 75%.
Broad excess at 135 GeV?

- Local fluctuations in different categories
- With scan of the background-only $p$-value as a function of $m_{\mu\mu}$, we find a local $p$-value of 2.5 $\sigma$ at 135 GeV
- Including the look elsewhere effect (see here for a reference):
  - the global significance goes down to 1.6 $\sigma$, when using the 130-150 GeV range for the test (trial factor ~9)
  - if considering the entire range of the sidebands (110-120, 130-160 GeV) then this would double the trial factor, bringing the global $p$-value below 1 $\sigma$
$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
Systematic uncertainties (breakdown)
Upper limits on Higgs to leptons BR

$\sqrt{s} = 13$ TeV, 36-139 fb$^{-1}$

$B(H \rightarrow l \bar{l})$ in %

$H\rightarrow\mu^+\mu^-$ search with the ATLAS experiment - Giacomo Artoni (University of Oxford) - Sept. 8, 2020
ggF/VBF categories - BDT features

• The inputs are the same between the VBF BDT and the ggF 2-jet one

• Features used:
  • All channels: $p_T^{\mu\mu}$, $y^{\mu\mu}$ and $\cos\theta^*$
  • 1-/2-jet channels: leading jet information ($p_T$, $\eta$, $N_{tracks}$, $\Delta\phi_{\mu\mu,i}$)
  • 2-jet channel:
    sub-leading jet information ($p_T$, $\eta$, $N_{tracks}$, $\Delta\phi_{\mu\mu,i}$) and
dijet system information ($p_T^{jj}$, $m^{jj}$, $y^{jj}$, $\Delta\phi_{\mu\mu,ij}$)
• Features used:

• multiplicity of jets, b-tagged jets and jets with $|\eta| < 2.5$

• total $H_T$ of jets (scalar sum of all their transverse momenta)

• missing transverse energy ($E_{\text{miss}}$)

• transverse momenta of the non-Higgs leptons in the event (that is those that are not part of the Higgs candidate pair)

• $p_T^{\mu\mu}$, $y^{\mu\mu}$ and $\cos\theta^*$

• leading and sub-leading jet information transverse momenta

• transverse masses of leptonic $W$ and top (3$^{\text{rd}}$ lepton + $E_{\text{miss}}$ + b-tagged jet)

• transverse masses of hadronic $W$ and top (using three jets, at least one b-tagged)

• sub-leading Higgs mass (extra muon + Higgs candidate muon with opposite charge)

• invariant mass of additional leptons (at least two muons or electrons)
VH (3-lepton) categories - BDT features

- Features used:
  - missing transverse energy ($E_{T\text{miss}}$)
  - $\Delta \phi$ between Higgs and $E_{T\text{miss}}$
  - transverse momentum of the $W$ candidate lepton
  - transverse mass of the $W$ candidate (lepton + $E_{T\text{miss}}$)
  - $\Delta \phi$ and $\Delta \eta$ between Higgs and extra lepton
  - number of jets
  - transverse momentum of the leading jet
Features used:

- number of jets
- transverse momentum of the leading and sub-leading jets
- $\Delta\phi$ between the leptons associated to a $Z$ boson
- $\Delta\phi$ and $\Delta\eta$ between Higgs and $Z$ candidate
- $Z$ candidate mass
Data/simulation comparisons (VBF)

- **ATLAS**
  - **VBF Very High**: Normalised Events / 2 GeV
  - **VBF High**: Normalised Events / 2 GeV
  - **VBF Medium**: Normalised Events / 2 GeV
  - **VBF Low**: Normalised Events / 2 GeV

- **ATLAS**: \( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

- **Data - non-DY**, **Fast-Sim Sherpa**, **Fast-Sim Powheg/Alpgen**, **Full-Sim**

- **ATLAS** = 13 TeV, 139 fb

- **Data / MC**
Data/simulation comparisons (2-jet)

**ATLAS**  
\(\sqrt{s} = 13\ \text{TeV}, 139 \text{ fb}^{-1}\)  
2-Jet Low

**ATLAS**  
\(\sqrt{s} = 13\ \text{TeV}, 139 \text{ fb}^{-1}\)  
2-Jet Medium

**ATLAS**  
\(\sqrt{s} = 13\ \text{TeV}, 139 \text{ fb}^{-1}\)  
2-Jet Very High

**ATLAS**  
\(\sqrt{s} = 13\ \text{TeV}, 139 \text{ fb}^{-1}\)  
2-Jet High
Data/simulation comparisons (1-jet)

**1-Jet Very High**

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**1-Jet High**

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**1-Jet Medium**

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**1-Jet Low**

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</table>
**Data/simulation comparisons (0-jet)**

**ATLAS**

- **0-Jet Very High**
- **0-Jet High**
- **0-Jet Medium**
- **0-Jet Low**

**Data - non-DY**

**Fast-Sim Sherpa**

**Fast-Sim Powheg/Alpgen**

**Full-Sim**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Fit breakdown on simulation (VBF)

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( H \rightarrow \mu\mu, \text{ VBF Very High} \)
\( \chi^2/\text{n.d.f.} = 1.21 \ (p = 22\%) \)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( H \rightarrow \mu\mu, \text{ VBF Very High} \)
\( \chi^2/\text{n.d.f.} = 1.21 \ (p = 22\%) \)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( H \rightarrow \mu\mu, \text{ VBF Very High} \)
\( \chi^2/\text{n.d.f.} = 1.21 \ (p = 22\%) \)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
\( H \rightarrow \mu\mu, \text{ VBF Very High} \)
\( \chi^2/\text{n.d.f.} = 1.21 \ (p = 22\%) \)

Events / 2 GeV
Fit breakdown on simulation (2-jet)

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
H \( \rightarrow \mu\mu, 2\)-jet Medium
\( \chi^2/\text{n.d.f.} = 0.99 \) (p = 48%)

Events / 2 GeV

110 115 120 125 130 135 140 145 150 155 160

Temp./Core

1.5

1.4

1.3

1.2

1.1

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

m_\mu [GeV]

3000 4000 5000 6000 7000 8000

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
H \( \rightarrow \mu\mu, 2\)-jet Very High
\( \chi^2/\text{n.d.f.} = 1.25 \) (p = 19%)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
H \( \rightarrow \mu\mu, 2\)-jet Low
\( \chi^2/\text{n.d.f.} = 0.97 \) (p = 50%)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
H \( \rightarrow \mu\mu, 2\)-jet Medium
\( \chi^2/\text{n.d.f.} = 0.99 \) (p = 48%)

Events / 2 GeV

ATLAS Simulation
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)
H \( \rightarrow \mu\mu, 2\)-jet High
\( \chi^2/\text{n.d.f.} = 1.36 \) (p = 12%)

Events / 2 GeV
Fit breakdown on simulation (1-jet)

**ATLAS Simulation**

\[ \sqrt{s} = 13 \text{ TeV}, \; 139 \text{ fb}^{-1} \]

- **H \rightarrow \mu \mu, 1-jet Very High**
- **H \rightarrow \mu \mu, 1-jet High**
- **H \rightarrow \mu \mu, 1-jet Medium**
- **H \rightarrow \mu \mu, 1-jet Low**

\[ \chi^2/\text{n.d.f.} = \begin{cases} 1.07 & (p = 38\%) \\ 1.07 & (p = 38\%) \\ 0.69 & (p = 85\%) \\ 0.72 & (p = 82\%) \end{cases} \]
Fit breakdown on simulation (0-jet)

**ATLAS Simulation**

\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

\( H \rightarrow \mu\mu, \text{ 0-jet Very High} \)

\( \chi^2 / \text{n.d.f.} = 1.17 \ (p = 27\%) \)

\( \chi^2 / \text{n.d.f.} = 1.65 \ (p = 3\%) \)

\( \chi^2 / \text{n.d.f.} = 0.80 \ (p = 73\%) \)

\( \chi^2 / \text{n.d.f.} = 1.65 \ (p = 3\%) \)

\( \chi^2 / \text{n.d.f.} = 0.80 \ (p = 73\%) \)
Fit breakdown on data (VBF)

**ATLAS**

- **Very High category**
  - $\bar{p}s = 13$ TeV, 139 fb$^{-1}$
  - $H \rightarrow \mu\mu$, VBF

- **High category**
  - $\bar{p}s = 13$ TeV, 139 fb$^{-1}$
  - $H \rightarrow \mu\mu$, VBF

- **Medium category**
  - $\bar{p}s = 13$ TeV, 139 fb$^{-1}$
  - $H \rightarrow \mu\mu$, VBF

- **Low category**
  - $\bar{p}s = 13$ TeV, 139 fb$^{-1}$
  - $H \rightarrow \mu\mu$, VBF
Fit breakdown on data (2-jet)

**ATLAS**
\(\sqrt{s} = 13\,\text{TeV},\ 139\,\text{fb}^{-1}\)
\(H \rightarrow \mu\mu,\ 2\text{-jet Very High category}\)

**ATLAS**
\(\sqrt{s} = 13\,\text{TeV},\ 139\,\text{fb}^{-1}\)
\(H \rightarrow \mu\mu,\ 2\text{-jet High category}\)

**ATLAS**
\(\sqrt{s} = 13\,\text{TeV},\ 139\,\text{fb}^{-1}\)
\(H \rightarrow \mu\mu,\ 2\text{-jet Medium category}\)

**ATLAS**
\(\sqrt{s} = 13\,\text{TeV},\ 139\,\text{fb}^{-1}\)
\(H \rightarrow \mu\mu,\ 2\text{-jet Low category}\)
Fit breakdown on data (1-jet)

**ATLAS**
\( \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \)

**1-jet Very High category**
- Data
- Core function
- Total pdf
- Signal pdf
- Bkg. pdf

**1-jet Medium category**
- Data
- Core function
- Total pdf
- Signal pdf
- Bkg. pdf

**1-jet Low category**
- Data
- Core function
- Total pdf
- Signal pdf
- Bkg. pdf
Fit breakdown on data (0-jet)

**0-jet High category**

- Data: Black line
- Core function: Green dashed line
- Total pdf: Blue line
- Signal pdf: Red line
- Bkg. pdf: Dark blue dashed line

**0-jet Very High category**

- Data: Black line
- Core function: Green dashed line
- Total pdf: Blue line
- Signal pdf: Red line
- Bkg. pdf: Dark blue dashed line

**0-jet Medium category**

- Data: Black line
- Core function: Green dashed line
- Total pdf: Blue line
- Signal pdf: Red line
- Bkg. pdf: Dark blue dashed line

**0-jet Low category**

- Data: Black line
- Core function: Green dashed line
- Total pdf: Blue line
- Signal pdf: Red line
- Bkg. pdf: Dark blue dashed line

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

$H \rightarrow \mu\mu$, 0-jet categories

**Events / 2 GeV**

**m_{\mu\mu} [GeV]**

**Data - Bkg.**

---

**m_{\mu\mu} [GeV]**

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**Data - Bkg.**

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**Data - Bkg.**

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Fit breakdown on data (ttH/VH)

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\( H \rightarrow \mu\mu \), VH4L category

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\( H \rightarrow \mu\mu \), VH3LM category

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\( H \rightarrow \mu\mu \), ttH category

**ATLAS**
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\( H \rightarrow \mu\mu \), VH3LH category