# Search for the Higgs boson decay to a pair of muons

*with 79.8 fb$^{-1}$ at the ATLAS detector at the LHC*

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on behalf of the ATLAS Collaboration

APP and HEPP Annual Conference,
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Imperial College London

# UK leadership of the analysis

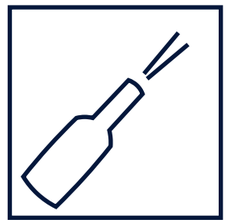
UNIVERSITY OF LIVERPOOL

UNIVERSITY OF BIRMINGHAM

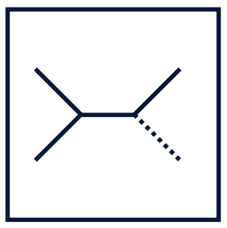
Queen Mary University of London

UNIVERSITY OF OXFORD

# Motivation



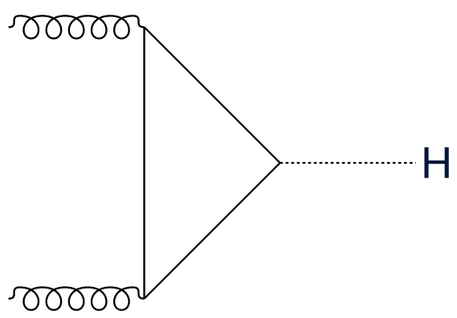
Higgs discovery in 2012 a major triumph of the Standard Model



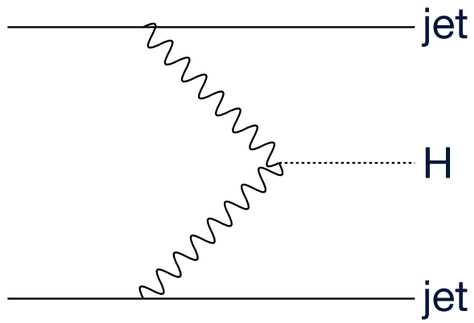
Observed in main production modes and many decay channels

H->μμ is a yet-unobserved tree-level decay the LHC can find

# Higgs Production Modes

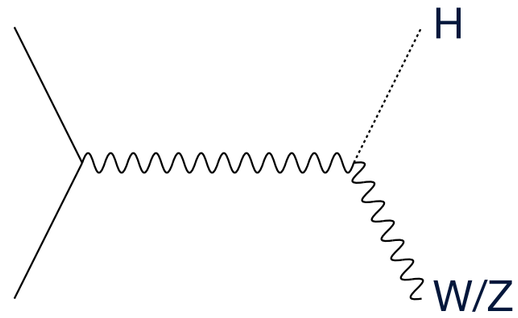



ggF

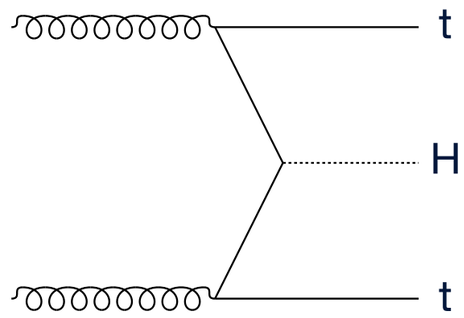



VBF

sensitive*

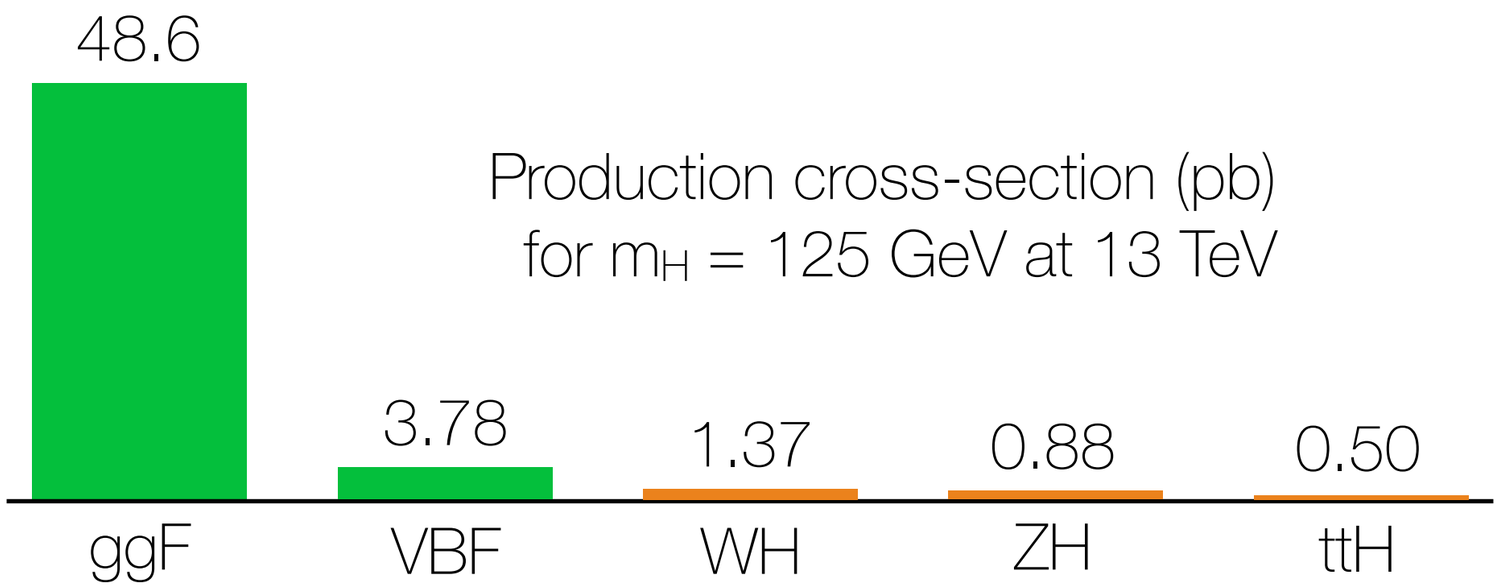



VH




ttH

less sensitive*




Production cross-section (pb)
for $m_H$ = 125 GeV at 13 TeV

*for the Hmumu analysis



X-secs from CERN Yellow Report 4

# H->μμ Branching Ratio

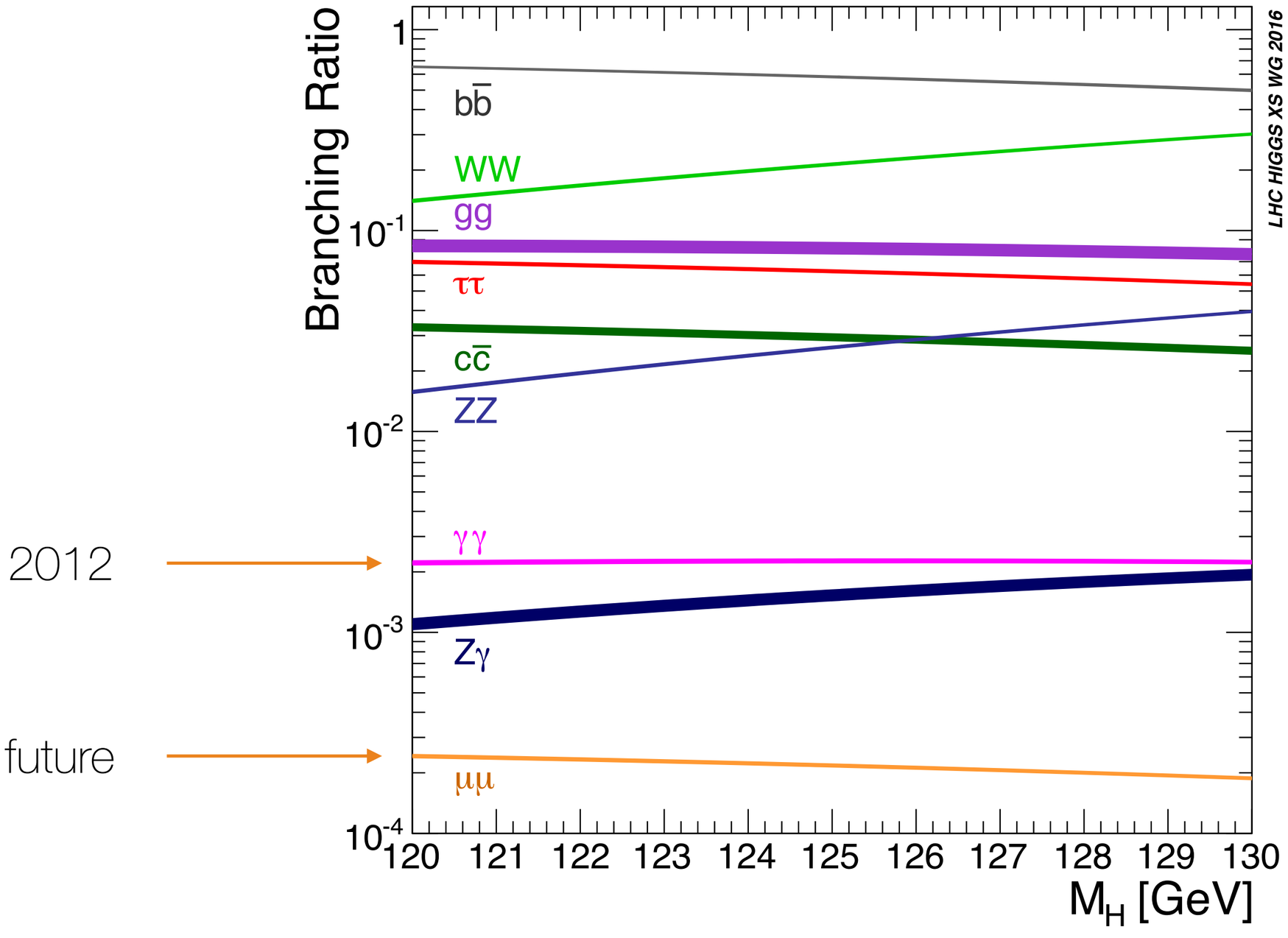
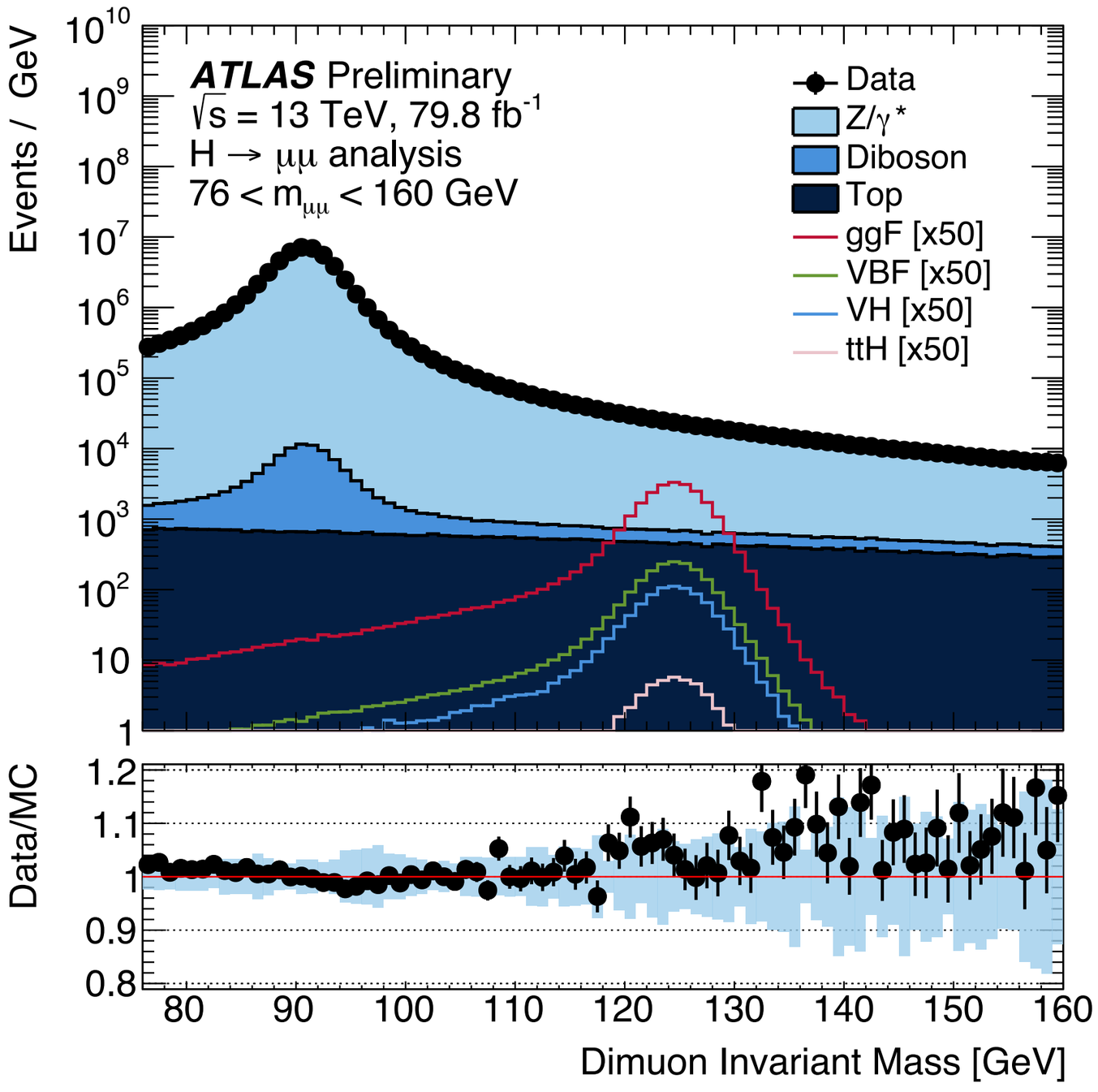





Figure from: CERN Yellow Report 4

# Challenging Drell-Yan Irreducible Background




Event yields in 80 fb$^{-1}$ for $M_{\mu\mu} \in [120, 130]$ GeV:

H->μμ: ~450

Z->μμ: ~ 220,000

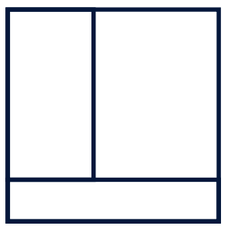
Large irreducible background (×500)



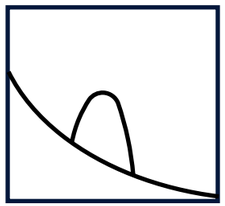
Figure from: ATLAS-CONF-2018-026

# Strategy

Loose muon and event selection

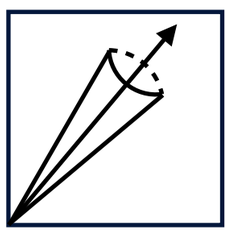


Categorisation of events to maximise sensitivity

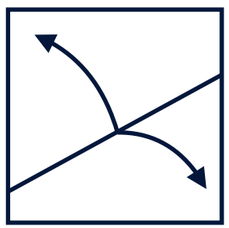


Analytical function fit to dimuon invariant mass in data

# Muon and Event Selection



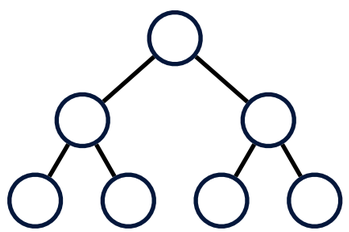
Loosest quality requirement
Loosest isolation requirement



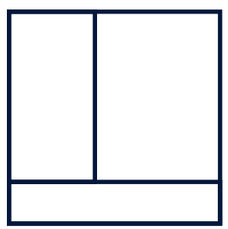
Loosest unprescaled single-μ triggers
2 opposite charge muons
Veto MET > 80 GeV
Veto events with b-tagged jet(s)

} suppress ttbar and di-boson

# Categorisation

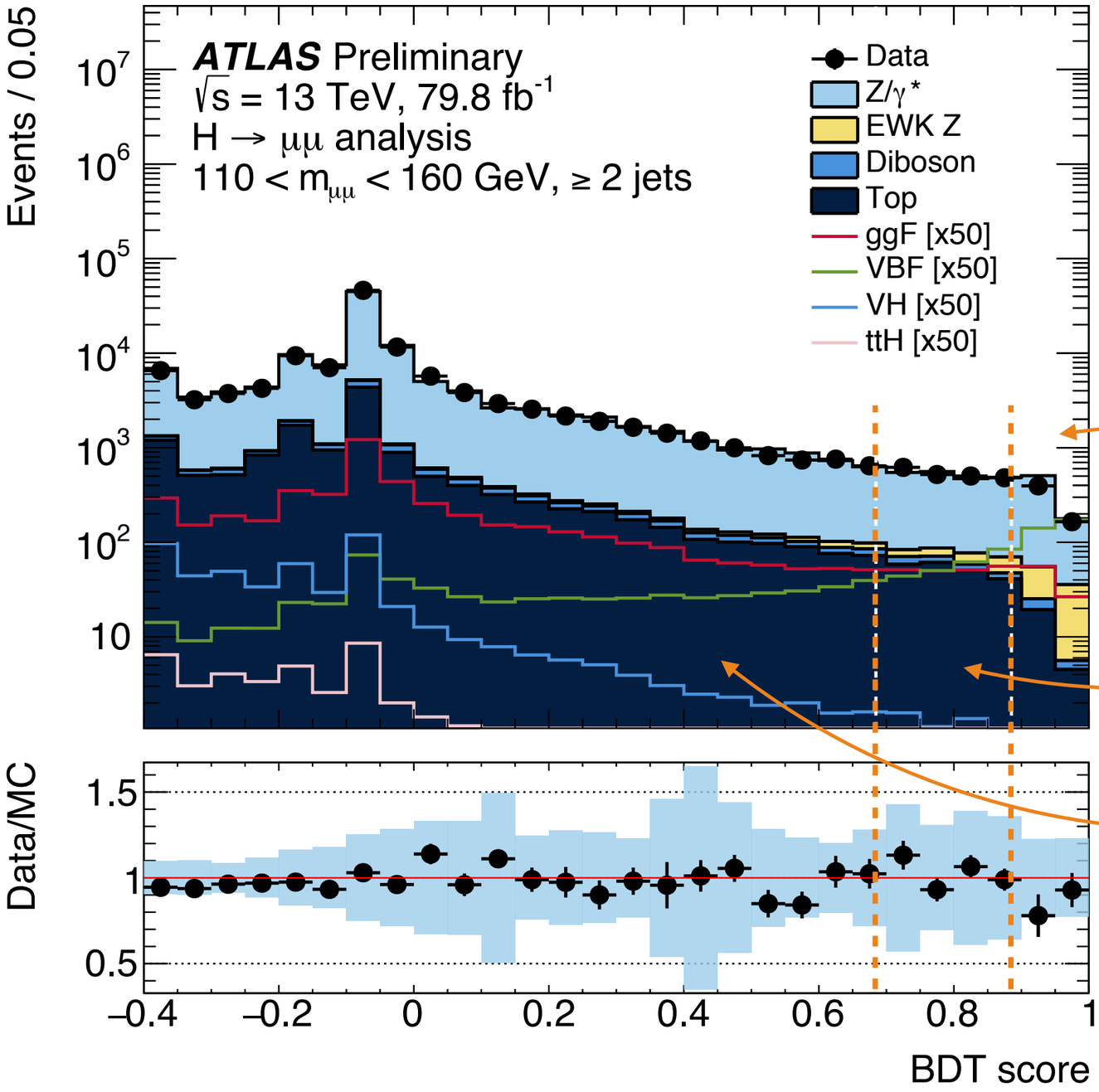


Boosted Decision Tree (BDT) selects VBF-like events



Cut-based categorisation of remaining events

# Boosted Decision Tree for VBF categories




BDT uses 14 variables sensitive to the VBF topology ($M_{jj}$, $\Delta\eta_{jj}$, $p_T^{\mu\mu}$, …)

It selects events for "VBF Tight" and "VBF Loose" categories.

Remaining events categorised using a cut-based approach



Figure from: ATLAS-CONF-2018-026

# ggF categorisation

## Idea 1: **signal purity**, use $p_T^{\mu\mu}$

More initial state radiation for the signal

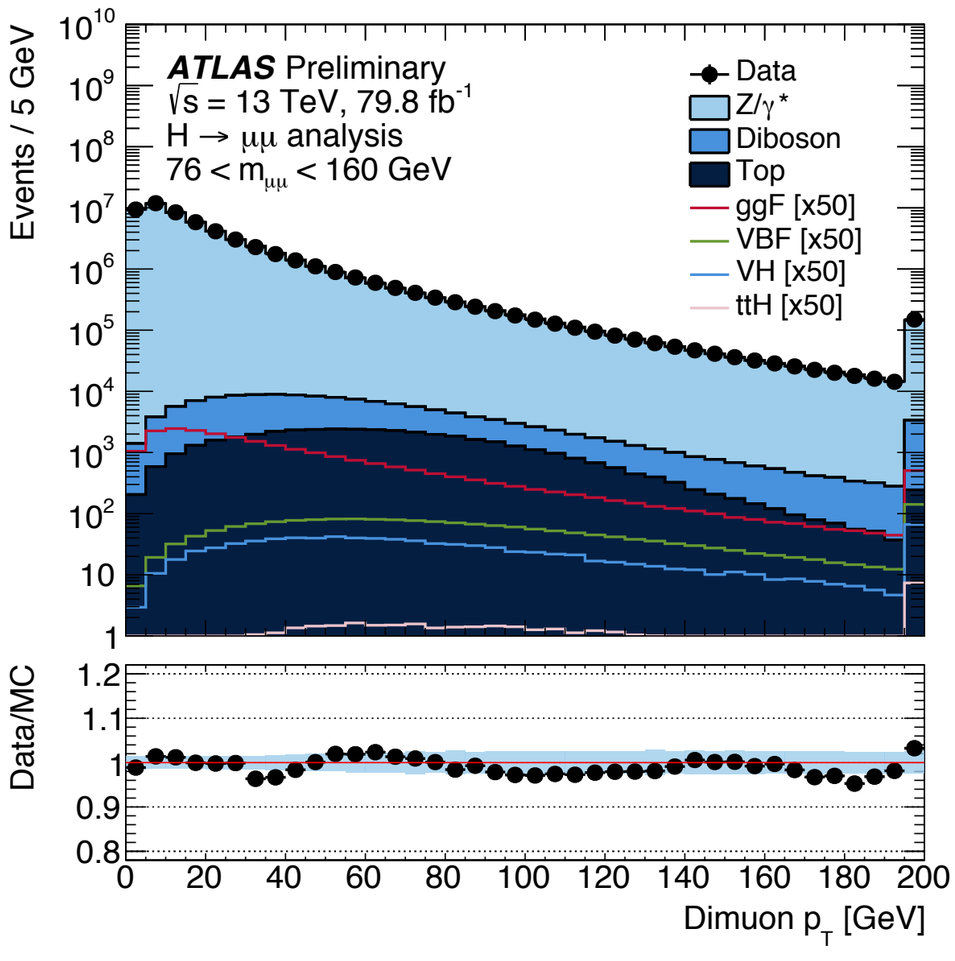



Figure from: ATLAS-CONF-2018-026

## Idea 2: **resolution**, use $\eta_{\mu 1}$, $\eta_{\mu 2}$

Better resolution in the central region

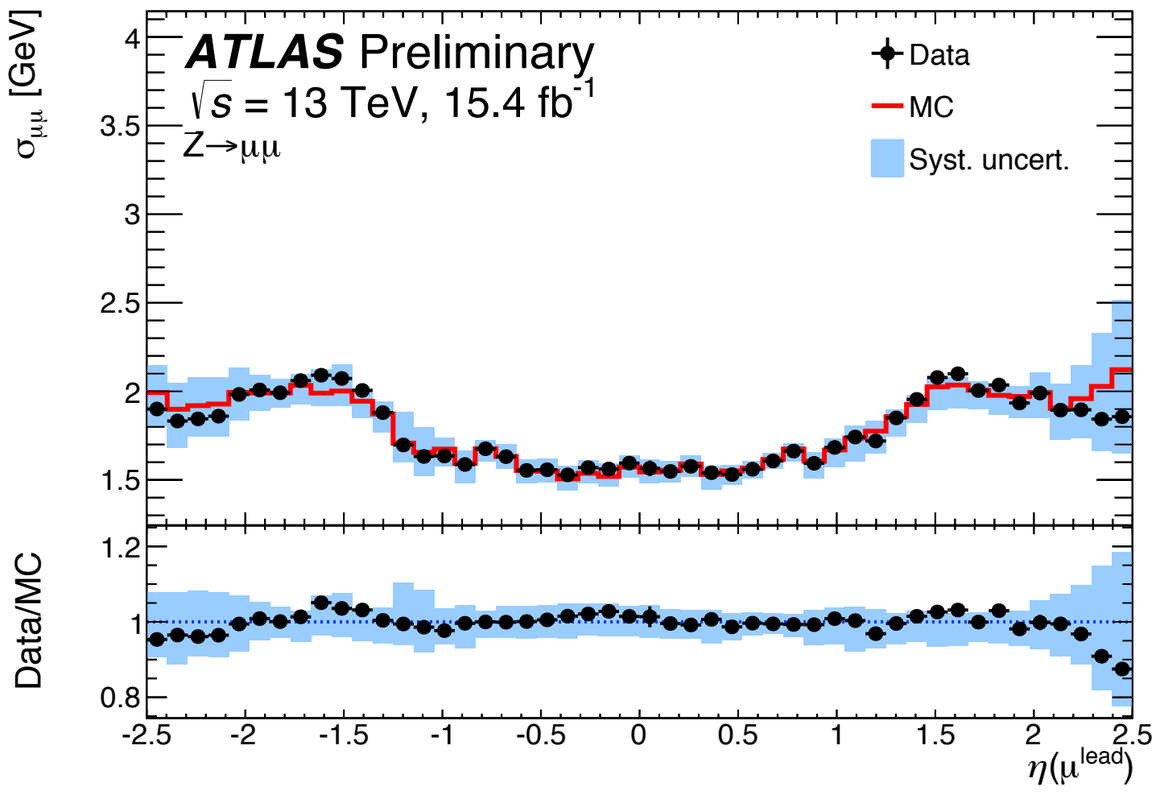
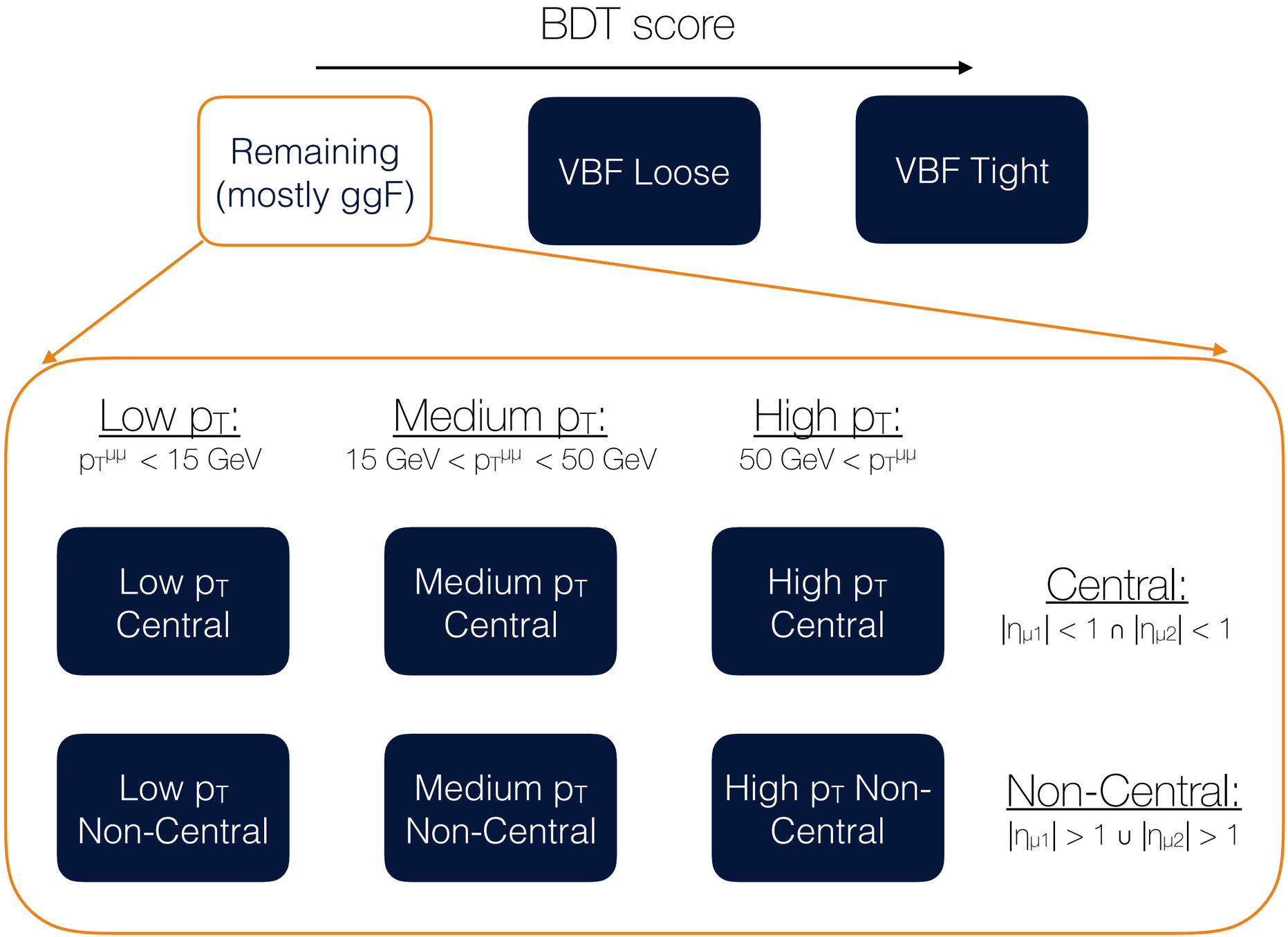
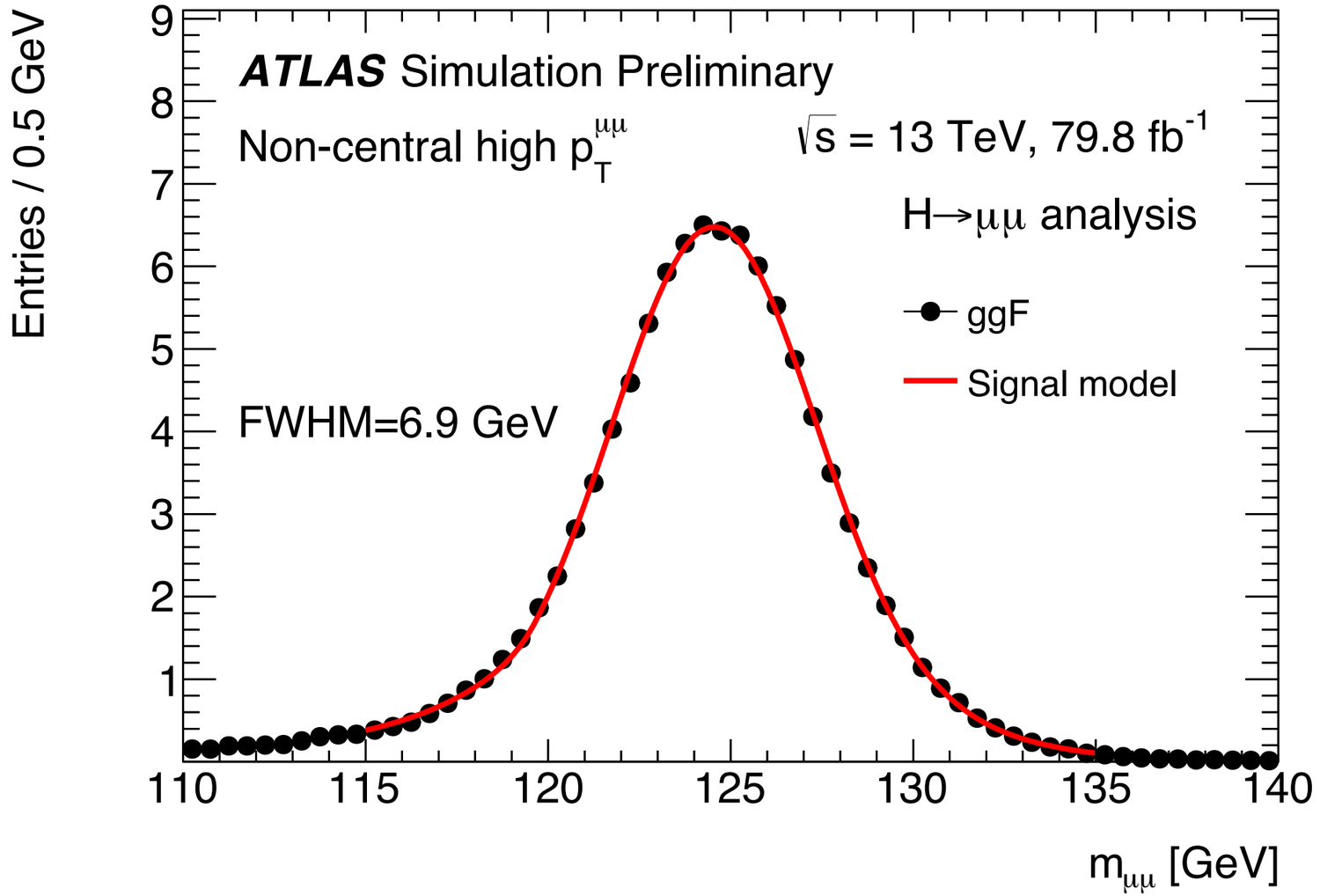



Figure from: MUON-2017-002

# Full categorisation



# Signal Fit



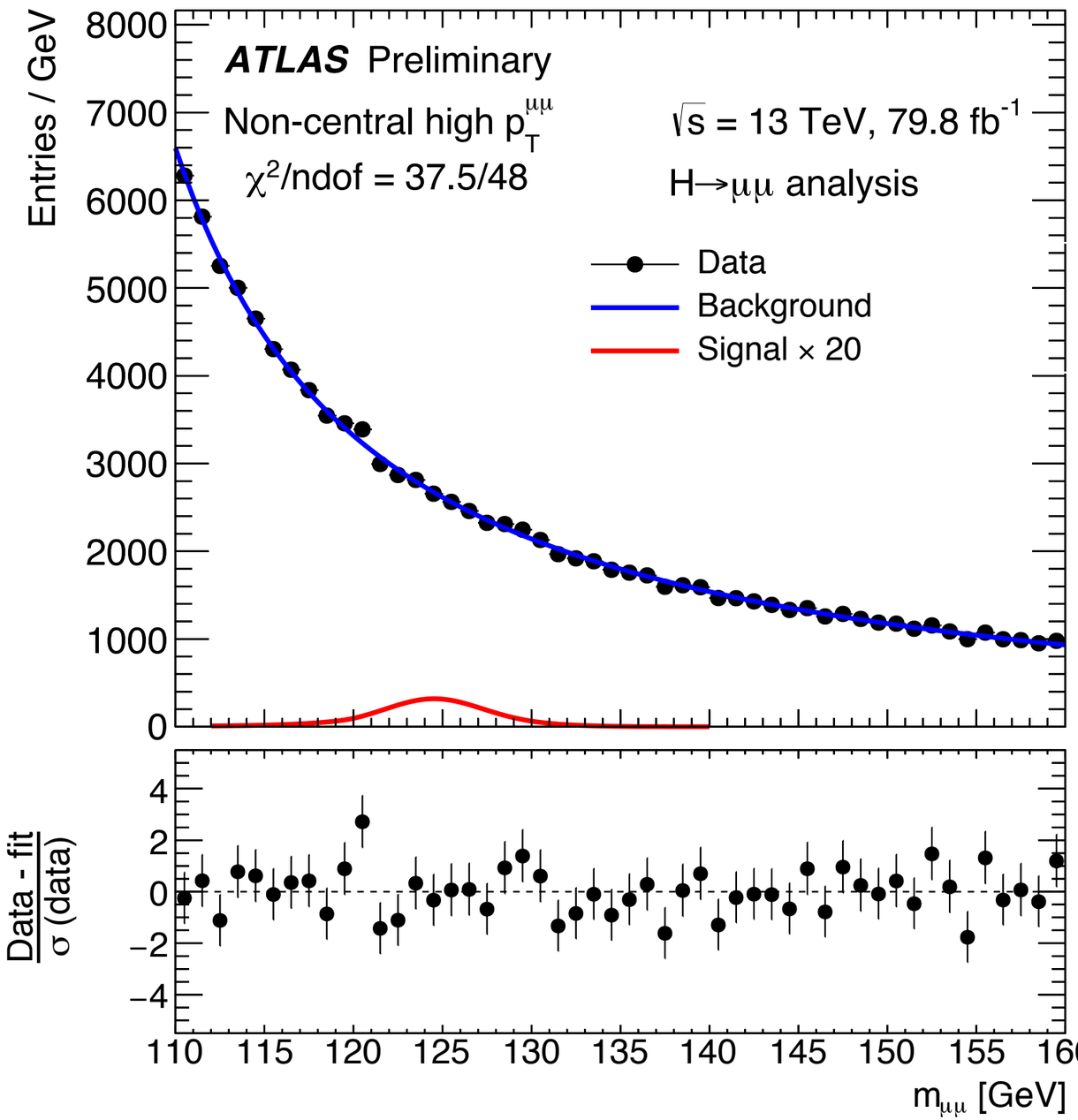

Gaussian + Crystal Ball

Parameters in each category determined from a fit to MC.



Figure from: ATLAS-CONF-2018-026

# Background Fit




$$f \times \text{Breit-Wigner} \otimes \text{Gaussian}$$
$$+$$
$$(1 - f) \times \text{Exponential}(A \times M_{\mu\mu}) \,/\, (M_{\mu\mu})^3$$

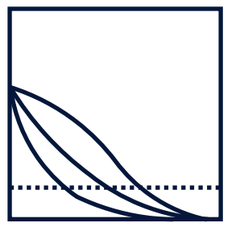
Two floating parameters of the background shape in each category.

Floating signal strength with fixed shape.

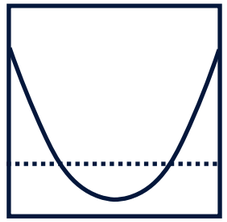


Figure from: ATLAS-CONF-2018-026

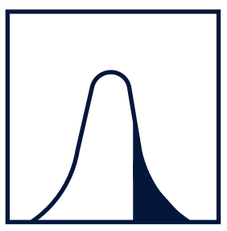
# Results



Limit (95% CL)  2.1 observed (2.0 expected*) × SM value



Measurement  $\mu = 0.1^{+1.0}_{-1.1}$

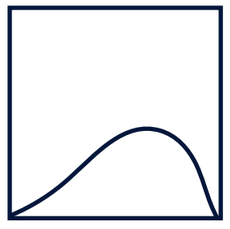


Significance  0.0σ observed (0.9σ expected)

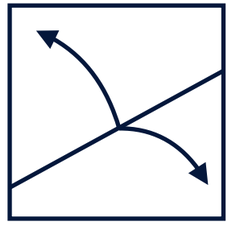


*profile-likelihood fit to the dimuon mass with background-only hypothesis

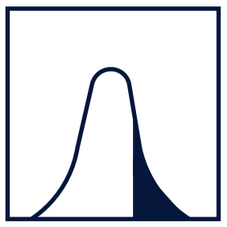
# Prospects



Extrapolation to HL-LHC with 3000 $fb^{-1}$

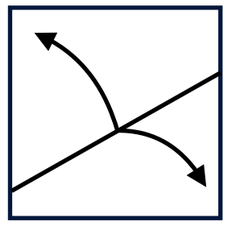


ITk resolution emulated, no spurious signal uncertainty

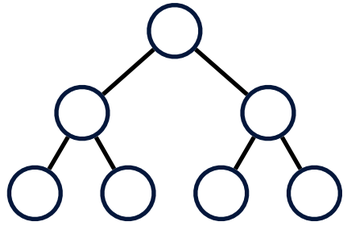


Signal strength measurements uncertainty at 15%

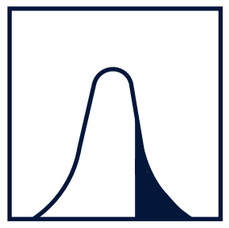
# Summary



Search for SM Higgs boson decay to muon pairs



Loose muon and event selection
BDT + cut based categorisation



Analysis sensitivity at the SM level

Thank you

# BONUS

# Event yields

| | $ggF$ | VBF | all signal | $Z$+jets | Top | Di-boson | Total bkg. | Data |
|---|---|---|---|---|---|---|---|---|
| Central low $p_{\mathrm{T}}^{\mu\mu}$ | 27.3 | 0.2 | 27.6 | $21800 \pm 280$ | $42 \pm 3$ | $50 \pm 2$ | $21900 \pm 280$ | 23318 |
| Non-central low $p_{\mathrm{T}}^{\mu\mu}$ | 71.3 | 0.7 | 72.4 | $81320 \pm 550$ | $133 \pm 5$ | $209 \pm 5$ | $81660 \pm 550$ | 86793 |
| Central medium $p_{\mathrm{T}}^{\mu\mu}$ | 51.3 | 1.9 | 54.1 | $18200 \pm 260$ | $335 \pm 9$ | $194 \pm 5$ | $18800 \pm 260$ | 19116 |
| Non-central medium $p_{\mathrm{T}}^{\mu\mu}$ | 131.2 | 5.1 | 139.3 | $64300 \pm 500$ | $1090 \pm 16$ | $944 \pm 11$ | $66340 \pm 500$ | 68856 |
| Central high $p_{\mathrm{T}}^{\mu\mu}$ | 38.4 | 4.3 | 45.7 | $7470 \pm 170$ | $697 \pm 13$ | $152 \pm 4$ | $8320 \pm 170$ | 8324 |
| Non-central high $p_{\mathrm{T}}^{\mu\mu}$ | 86.4 | 10.3 | 104.4 | $23800 \pm 320$ | $2150 \pm 22$ | $703 \pm 10$ | $26600 \pm 320$ | 26624 |
| VBF Loose | 3.5 | 3.8 | 7.3 | $426 \pm 12$ | $45 \pm 3$ | $9 \pm 1$ | $480 \pm 12$ | 475 |
| VBF Tight | 1.7 | 5.8 | 7.5 | $181 \pm 8$ | $8 \pm 1$ | $2 \pm 1$ | $191 \pm 8$ | 170 |
| Inclusive | 411.0 | 32.0 | 458.4 | $217500 \pm 910$ | $4497 \pm 32$ | $2263 \pm 17$ | $224200 \pm 910$ | 233676 |

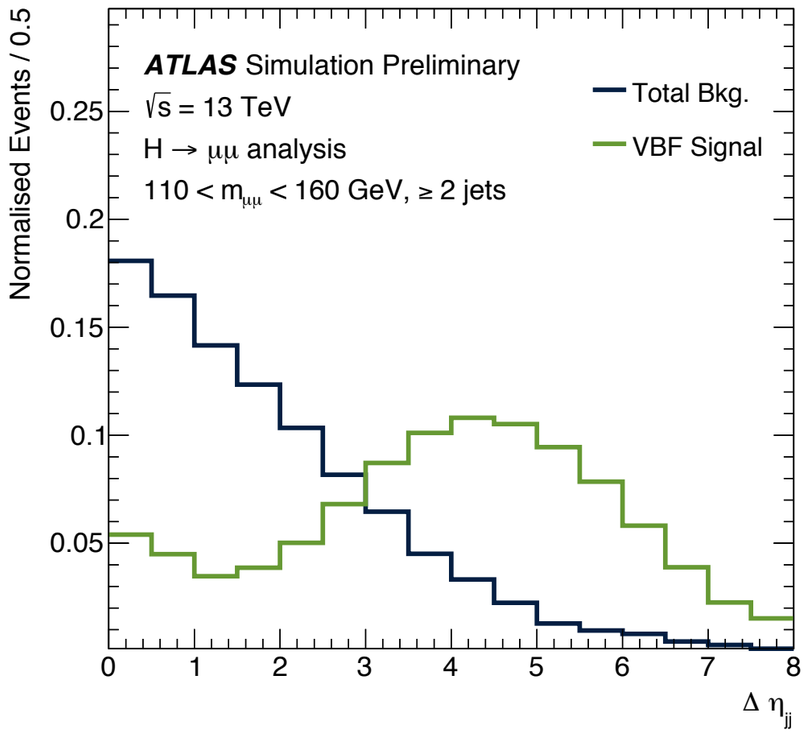
Table 1: Expected event yields normalized to 79.8 $\mathrm{fb}^{-1}$ for the different signal and background processes in eight categories, in the window $120 < m_{\mu\mu} < 130\,\mathrm{GeV}$. "All signal" includes $H \to \mu\mu$ contributions from $ggF$, VBF, $VH$, and $t\bar{t}H$ production channels. The contribution of the electroweak $Zjj$ process is included in the $Z$+jets category. All uncertainties are statistical only.

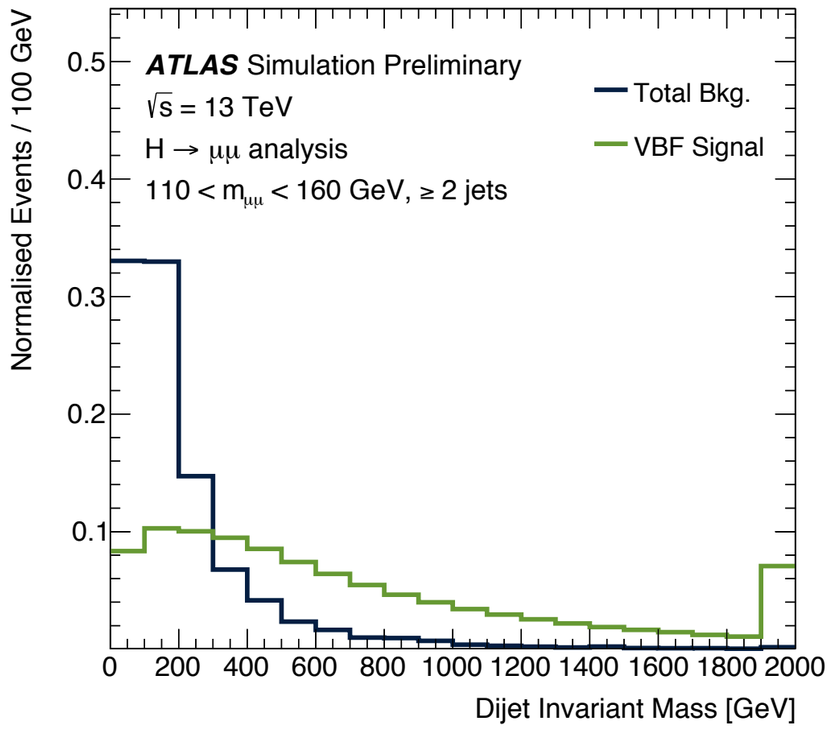
# Category significances

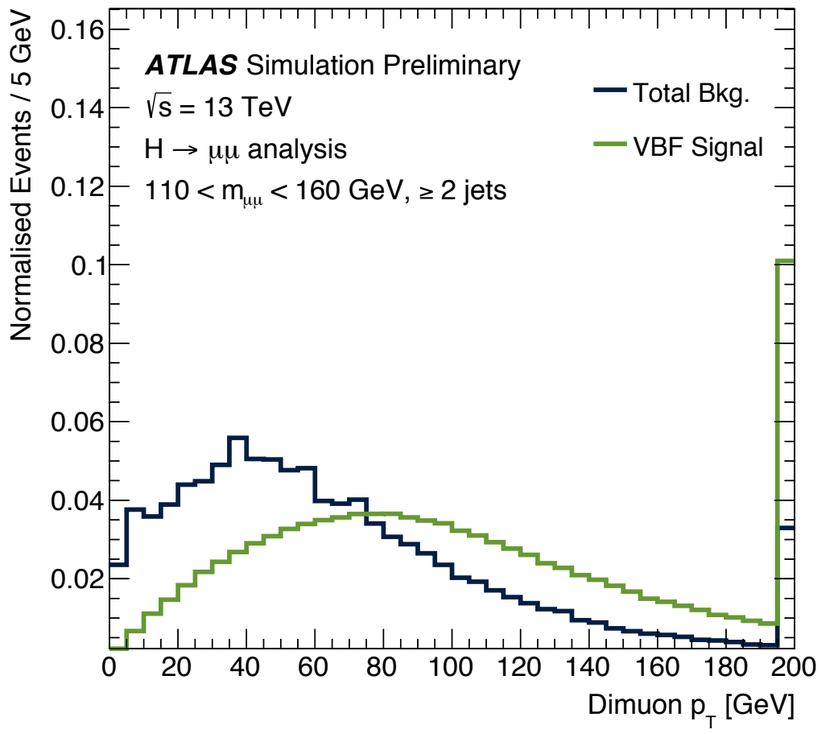
| | Expected significance | Observed significance |
|---|---|---|
| Central low $p_{\mathrm{T}}^{\mu\mu}$ | 0.10 | −0.49 |
| Non-central low $p_{\mathrm{T}}^{\mu\mu}$ | 0.03 | 0.44 |
| Central medium $p_{\mathrm{T}}^{\mu\mu}$ | 0.31 | 1.55 |
| Non-central medium $p_{\mathrm{T}}^{\mu\mu}$ | 0.30 | −1.16 |
| Central high $p_{\mathrm{T}}^{\mu\mu}$ | 0.38 | 0.48 |
| Non-central high $p_{\mathrm{T}}^{\mu\mu}$ | 0.43 | 0.15 |
| VBF Loose | 0.24 | −0.88 |
| VBF Tight | 0.42 | −0.26 |
| Combined | 0.88 | 0.04 |

Table 2: Expected and observed significances for each of the eight analysis categories as well as the combination of all categories. If the best-fit $\mu$ value is negative, then a negative significance is shown.

# BDT variables



# Systematics

The analysis is limited by statistics

~ 4% effect on the limit of spurious signal systematics

Other systematics are much smaller

# Full Object Selection

1) <u>Muons</u>
   - Loose muon Working Point
   - LooseTrackOnly isolation requirement
   - pT > 15 GeV
   - |eta| < 2.5
   - impact parameters: $|d_0$ significance$|$ < 3.0, $|z_0 \sin(\theta)|$ < 0.5 mm
2) <u>Jets</u>
   - Antikt4TopoEM algorithm
   - |eta| < 4.5
   - pT > 25 GeV for |eta| < 2.4
   - pT > 30 GeV for 2.4 < |eta| < 4.5
   - JetVertexTagging > 0.59 for (pT < 60 GeV && |eta| < 2.4)
   - pass MV2c10 60% WP for (|eta| < 2.5 && pT > 20 GeV). Only used for the b-veto purpose.
3) <u>Electrons (only used for overlap removal)</u>
   - *Medium* likelihood, pT > 7 GeV, |eta| < 2.47 excluding the crack region
   - *Loose* isolation
   - impact parameters: $|d_0$ significance$|$ < 3.0, $|z_0 \sin(\theta)|$ < 0.5 mm

# Full Event Selection

- Pass GRL and event cleaning for data
- Pass lowest unprescaled single muon trigger:
  - 2015: HLT_mu20_iloose_L1MU15 OR HLT_mu50
  - 2016&2017: HLT_mu26_ivarmedium OR HLT_mu50
- Trigger matching
- Two opposite sign muons
- Lead muon pT > 27 GeV
- Subleading muon pT > 15 GeV
- MET < 80 GeV
- Veto events with a b-jet