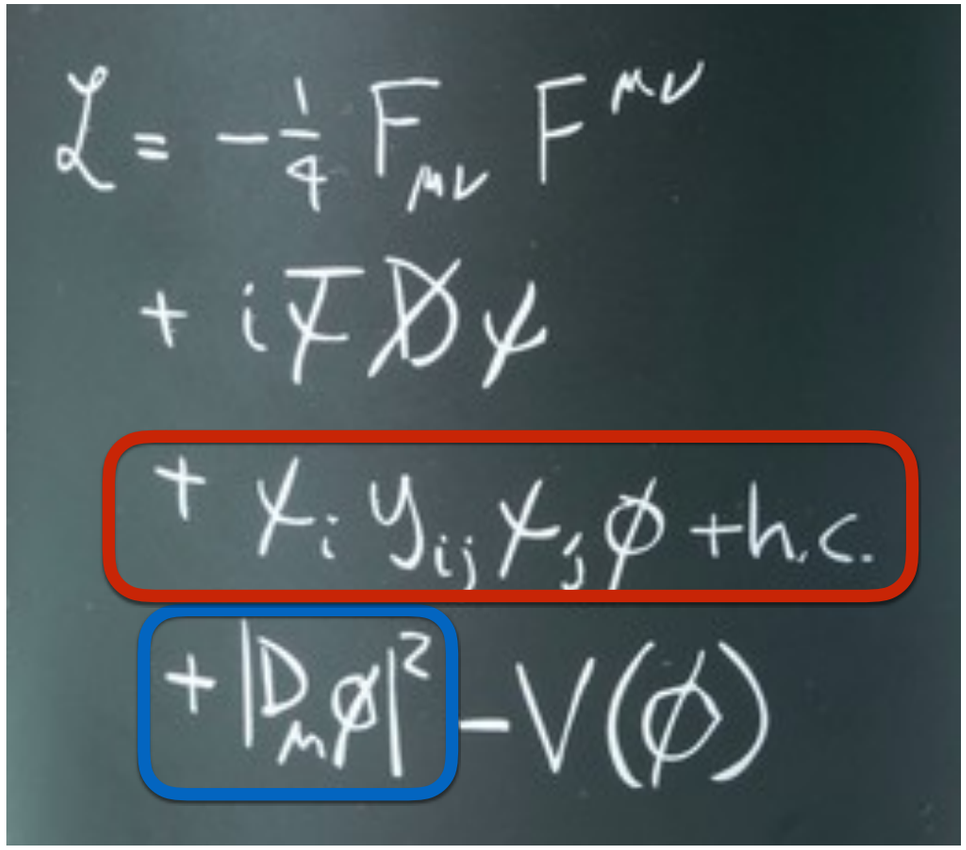
$H \rightarrow \mu^+\mu^-$ search with the ATLAS experiment

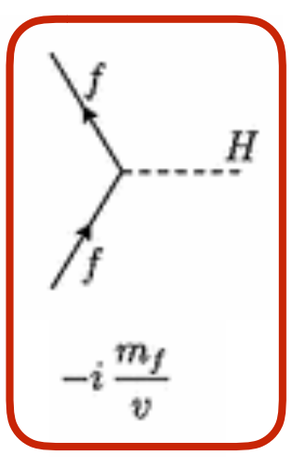
Giacomo Artoni
on behalf of the ATLAS Collaboration

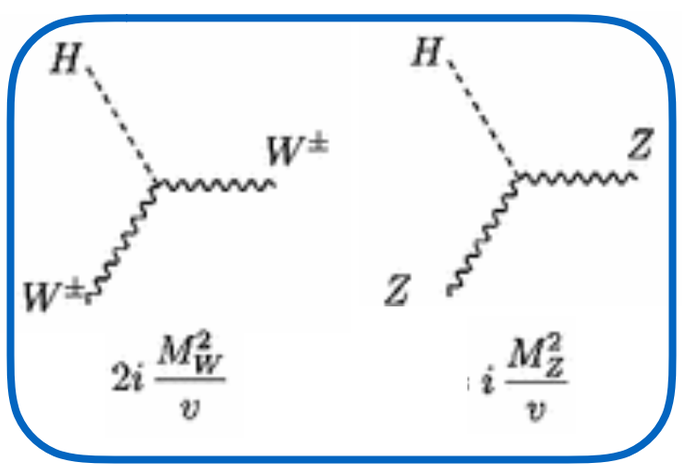
LHC Seminar – CERN, 8/9/2020

Introduction

The Higgs boson and the Standard Model







- 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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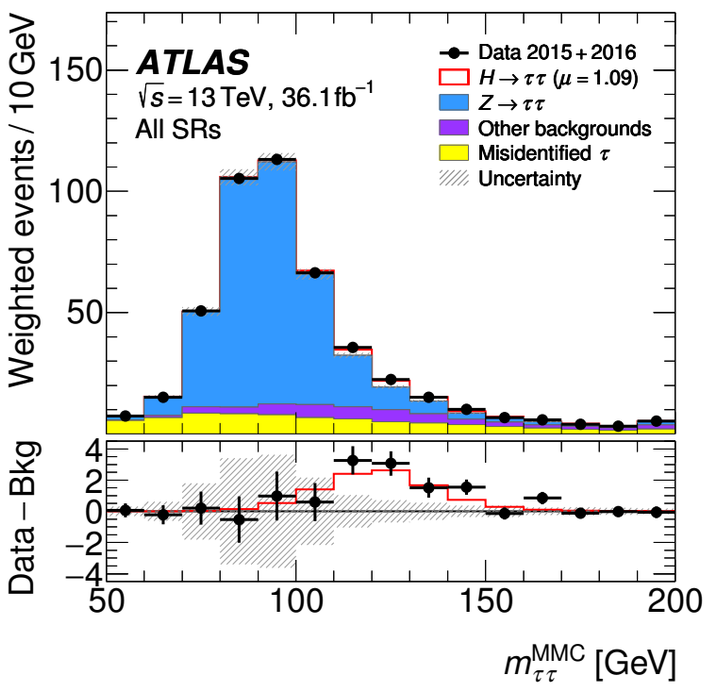
$H \rightarrow \tau\tau$

Observation at 6.4 standard deviations
[Phys. Rev. D 99 (2019) 072001)]



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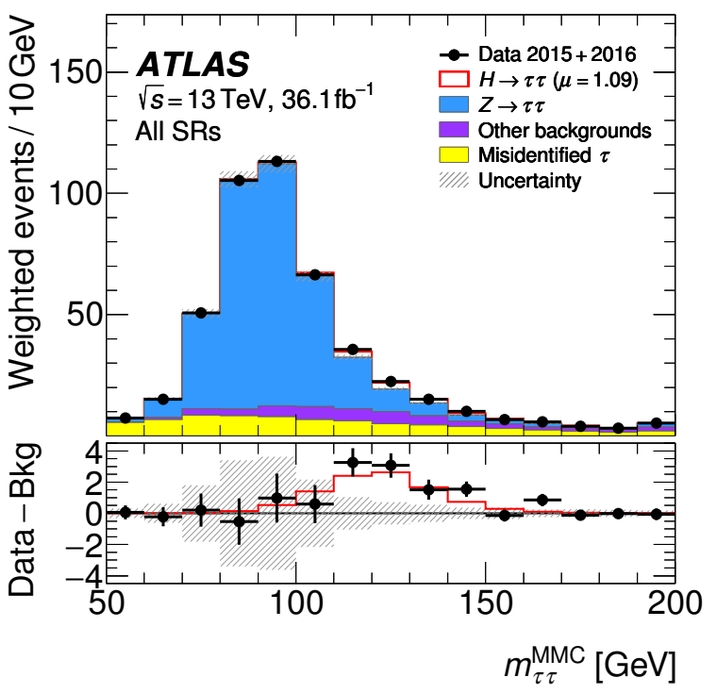
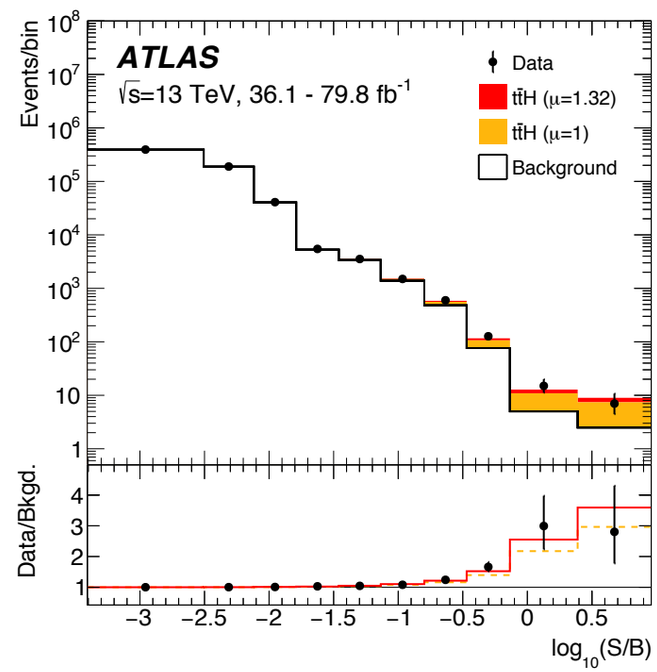


ttH

Observation at 5.8 standard deviations
[Phys. Lett. B 784 (2018) 173]



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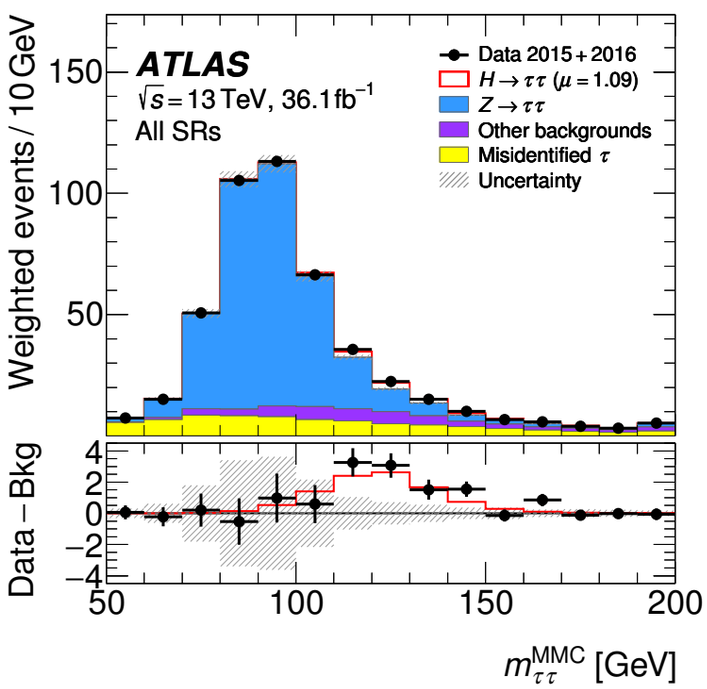

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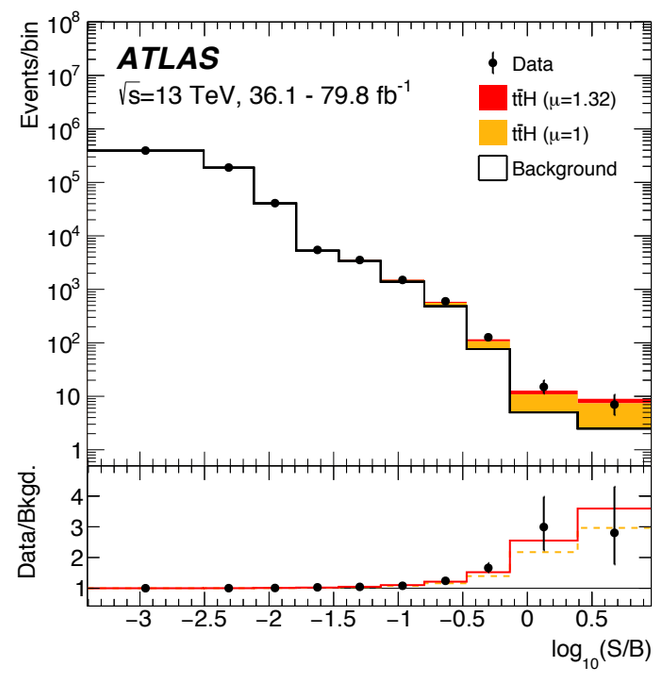
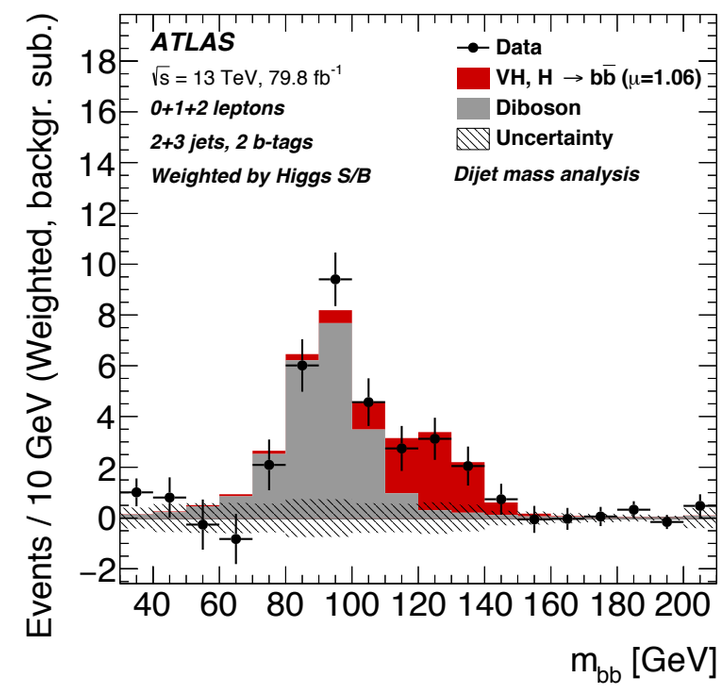


VH, H→bb

Observation at 6.7 standard deviations
[Phys. Lett. B 786 (2018) 59]



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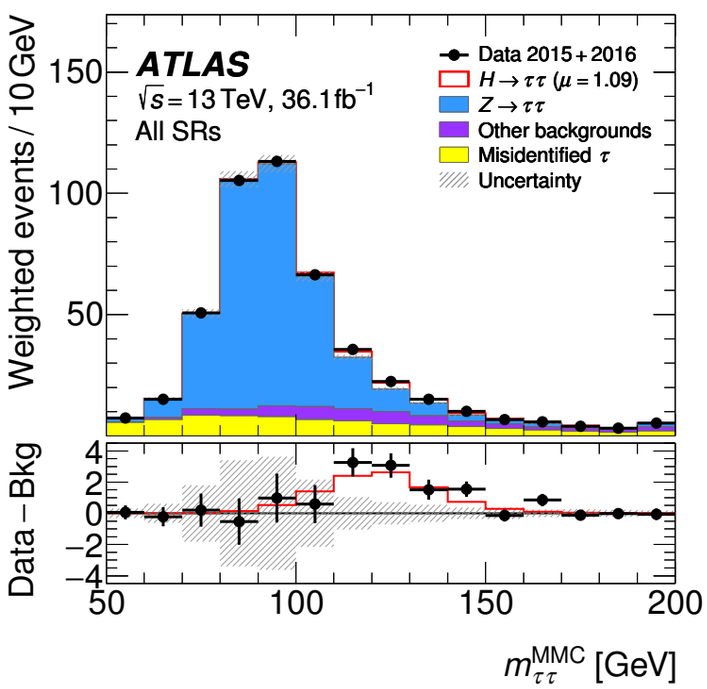

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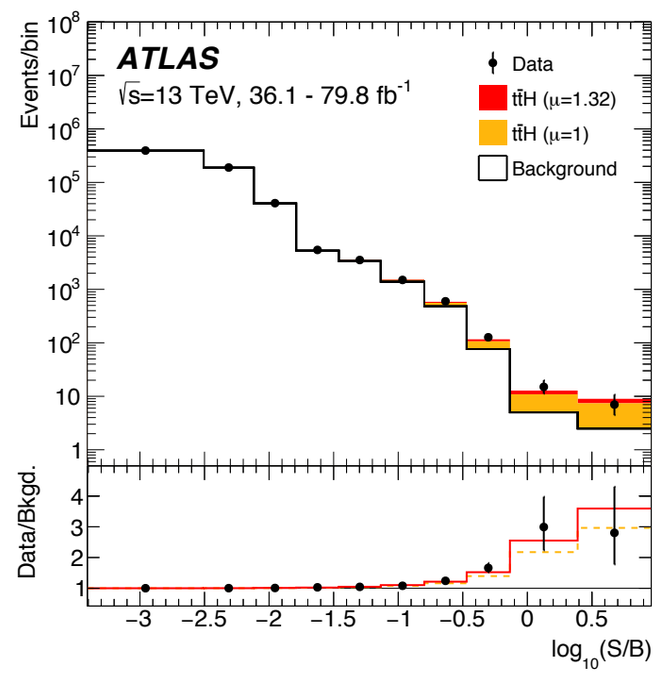

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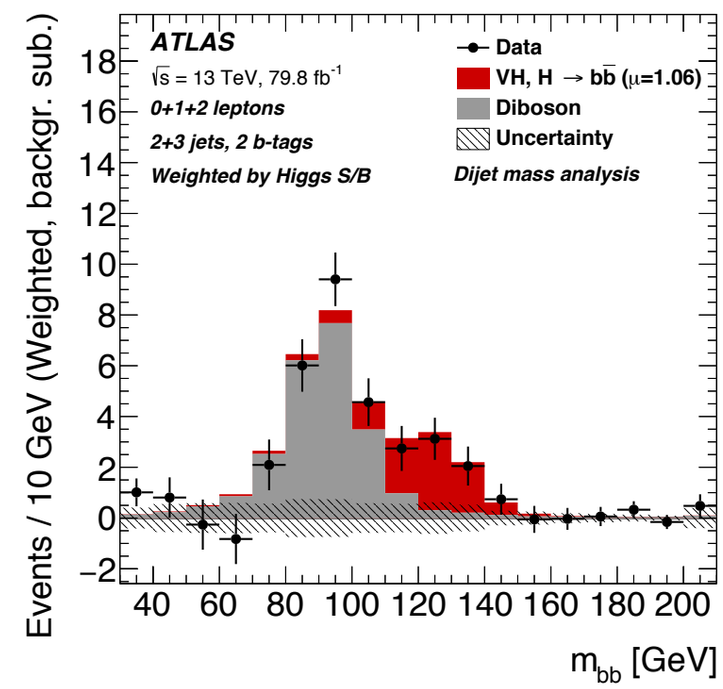

…and established agreement with the Standard Model predictions
at a level of 30%, see the most up-to-date results on our Higgs results public page

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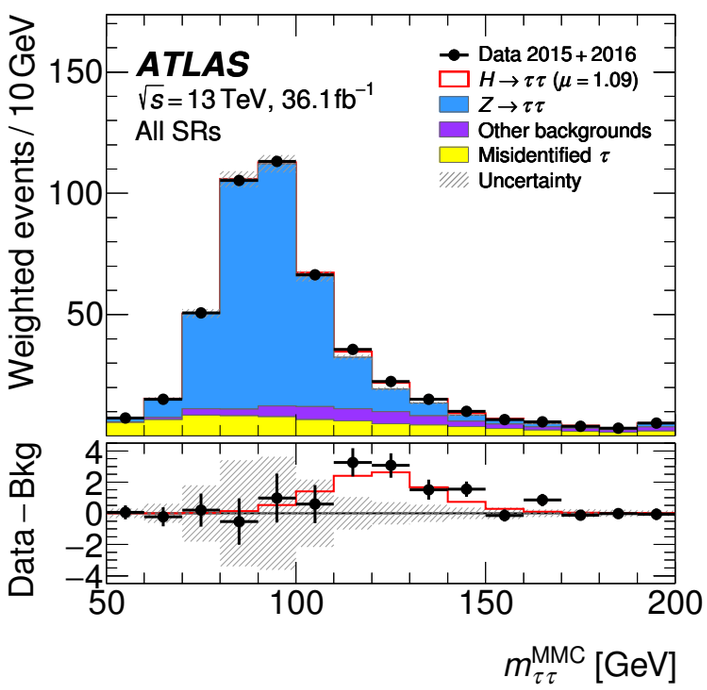

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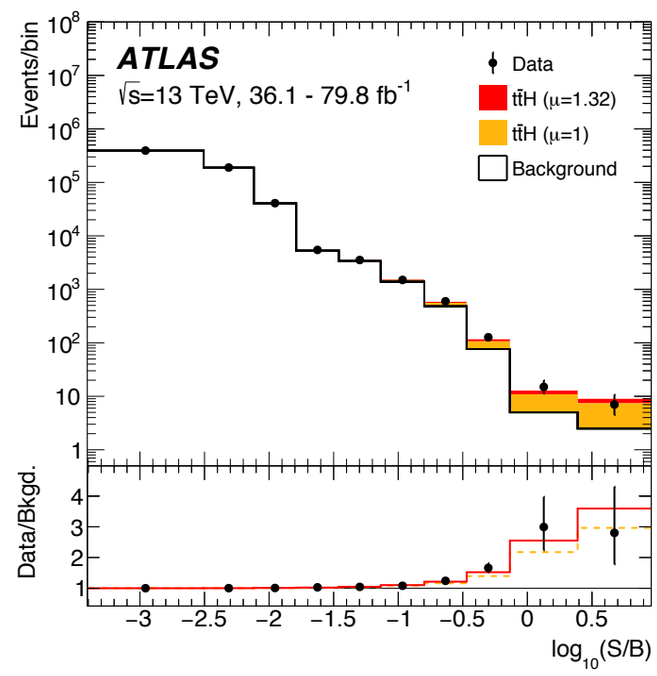

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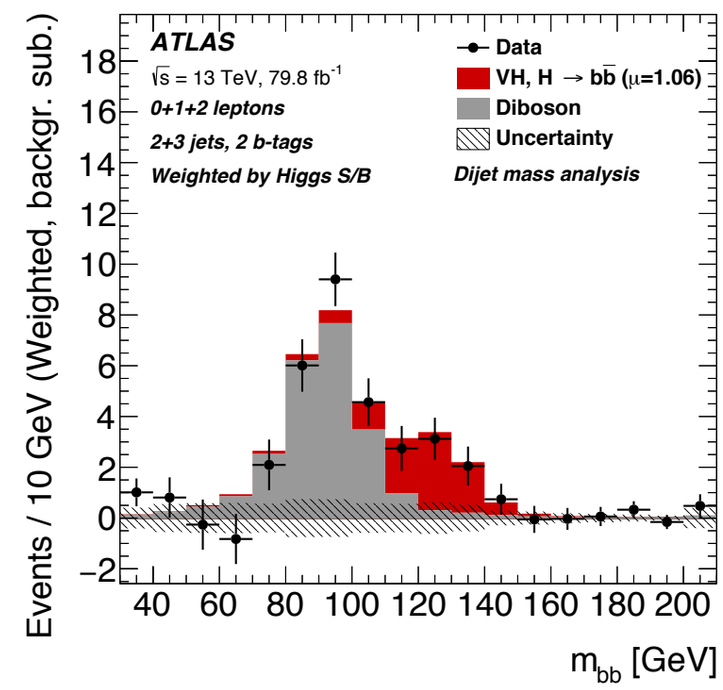
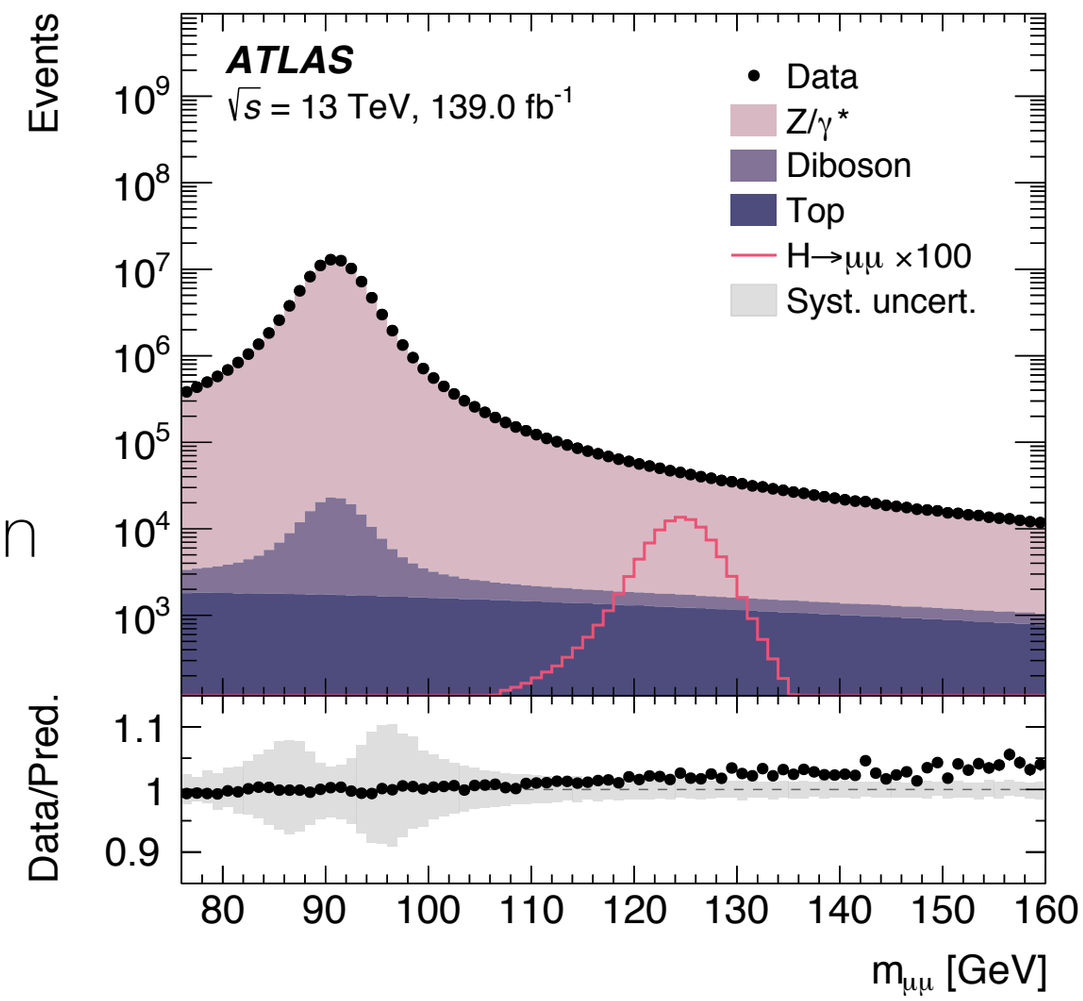


- Next milestone: establish couplings to second generation fermions
  - *H→μ⁺μ⁻* offers the best opportunity to accomplish this at the LHC!

$H \rightarrow \mu^+\mu^-$: a first look

Main experimental challenges

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



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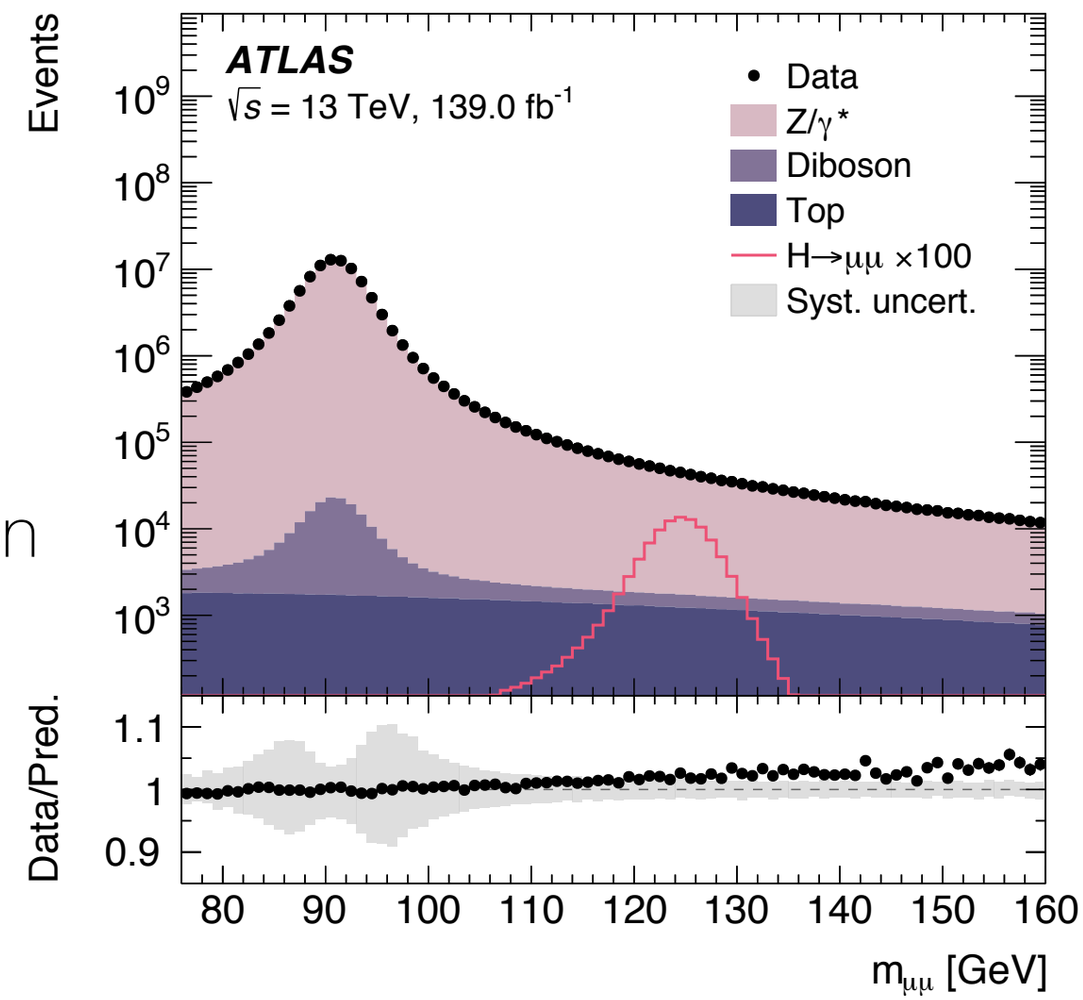


Key search ingredients

- 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!

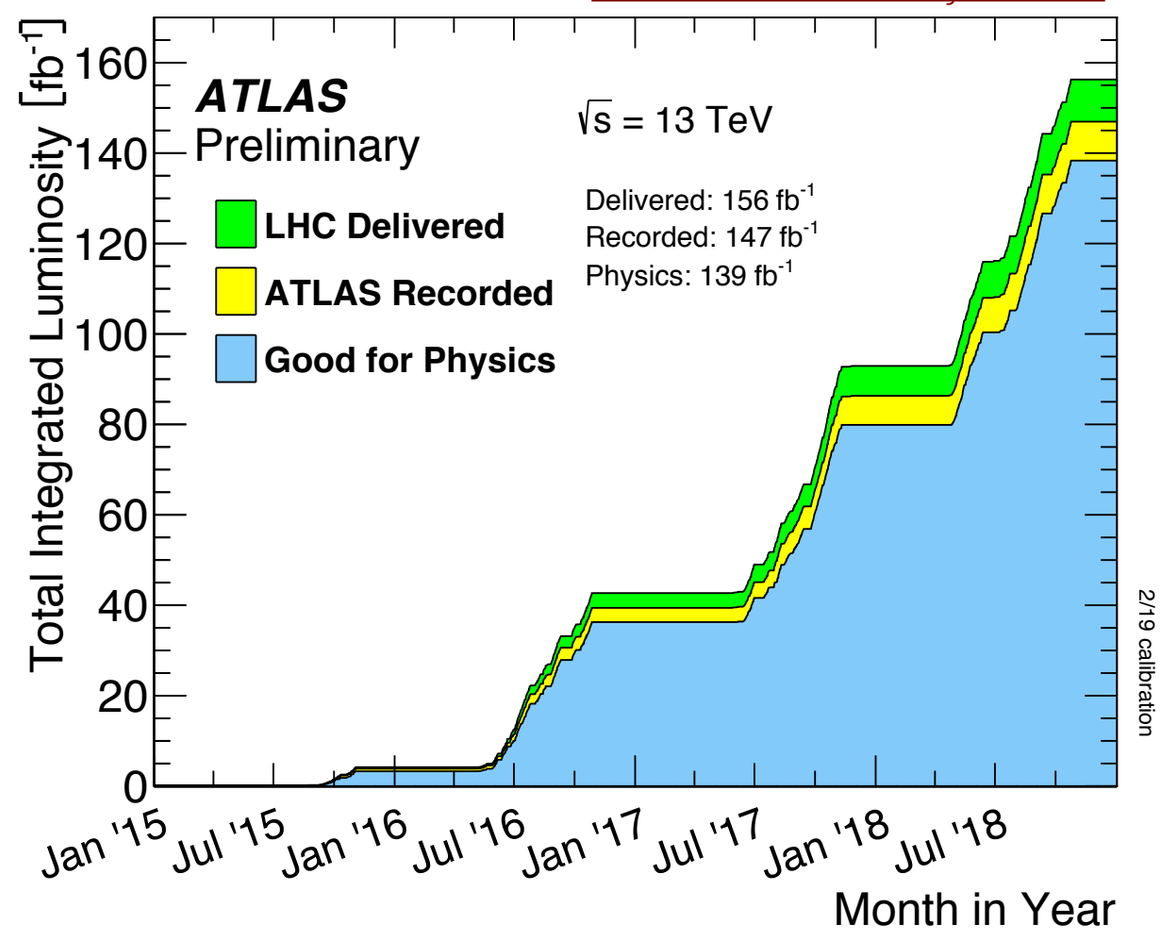
- Great operation of the ATLAS detector:

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)

from ATLAS Luminosity Run 2



Reconstruction performance: muons

- Muon reconstruction during Run 2: <u>excellent performance and stability!</u>
  - High efficiency for <u>identification (top)</u>, <u>isolation (bottom)</u> 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 <u>*ATLAS-CONF-2020-030*</u>
- Good dimuon mass resolution (1.7-2.3%)

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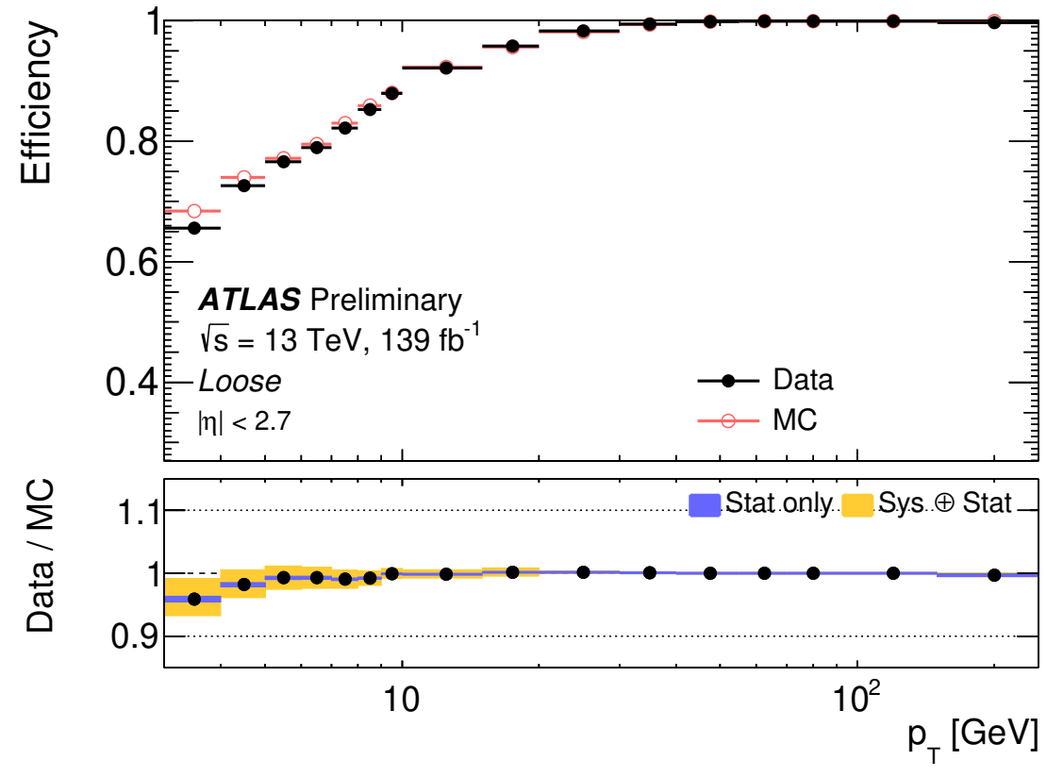

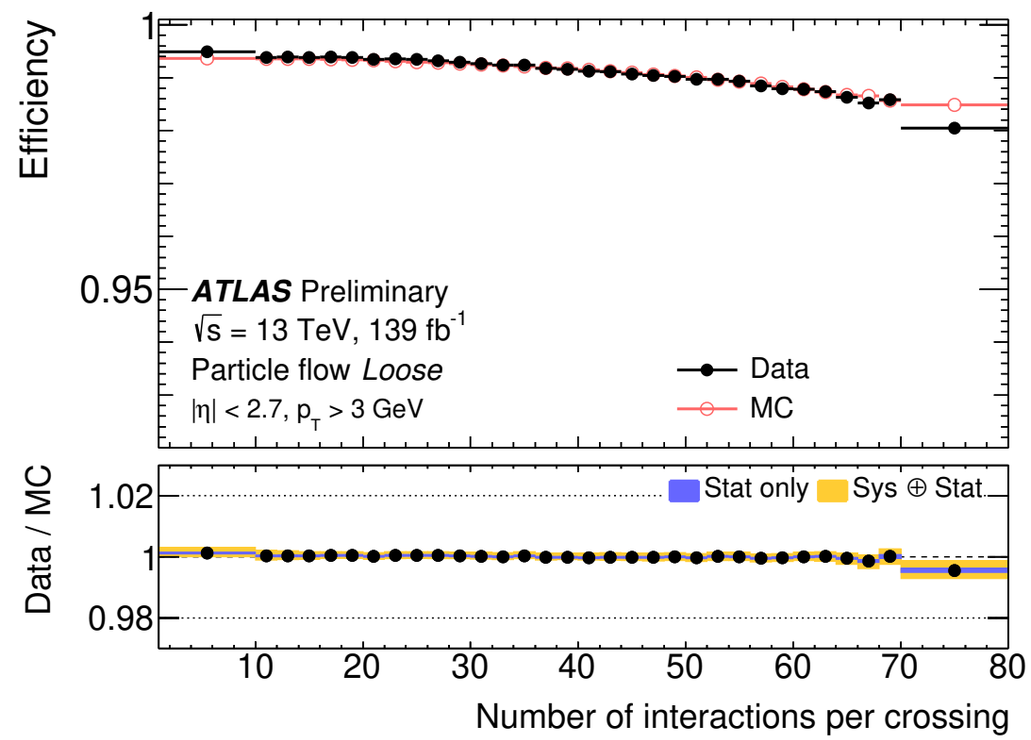

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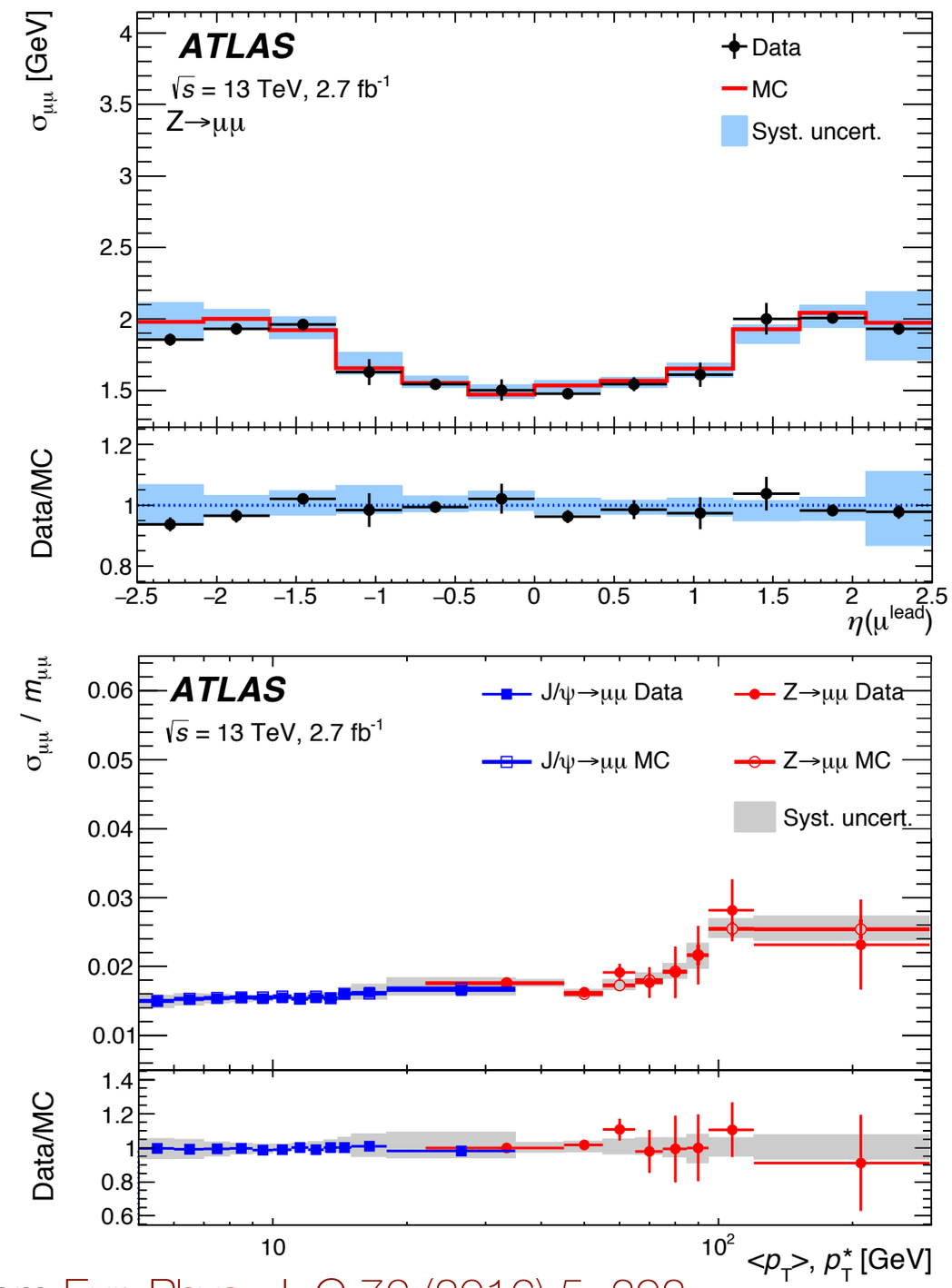


from <u>Eur. Phys. J. C 76 (2016) 5, 292</u>

$H \rightarrow \mu^+\mu^-$ ATLAS search

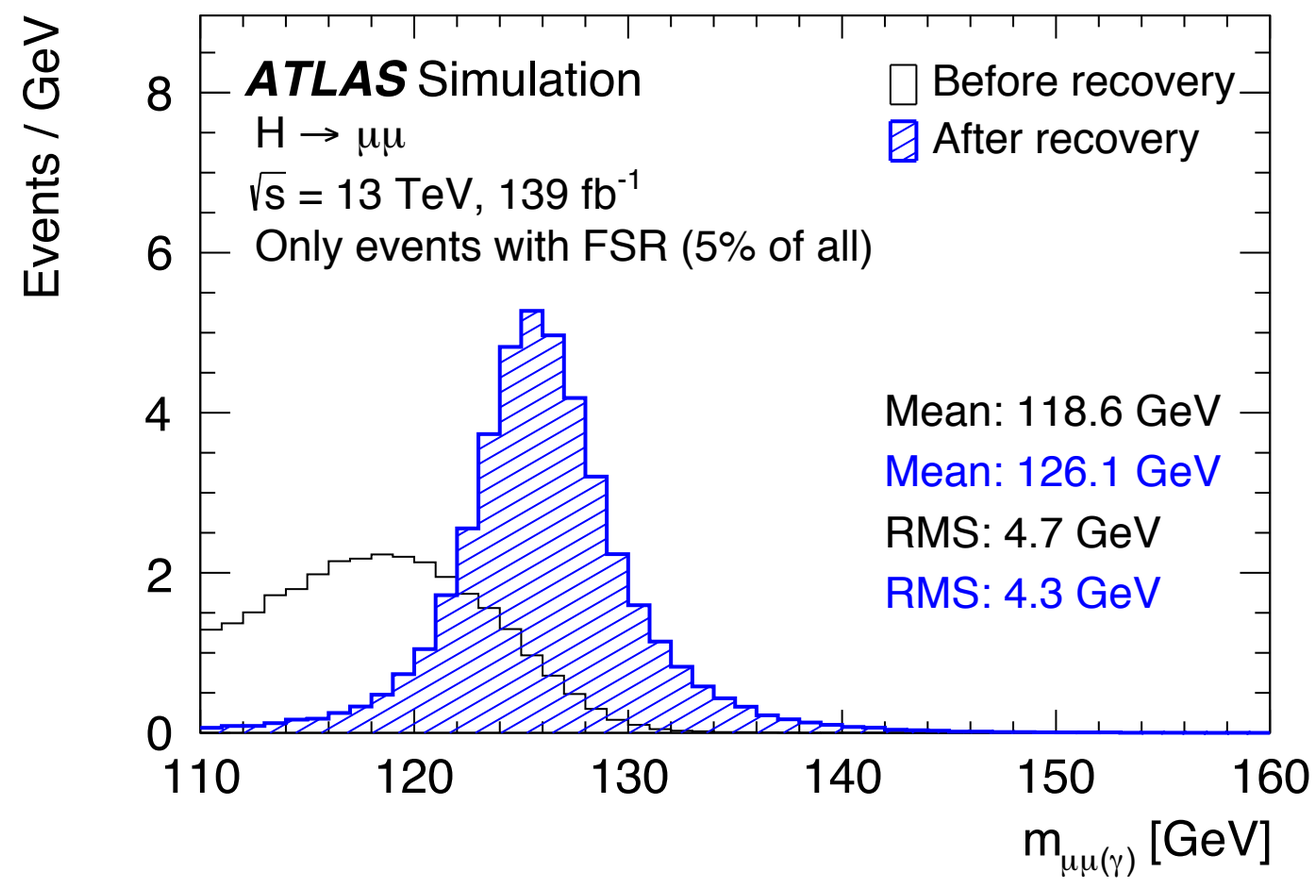
(arXiv:2007.07830 [hep-ex], submitted to Phys. Lett. B on July 16th, 2020)

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

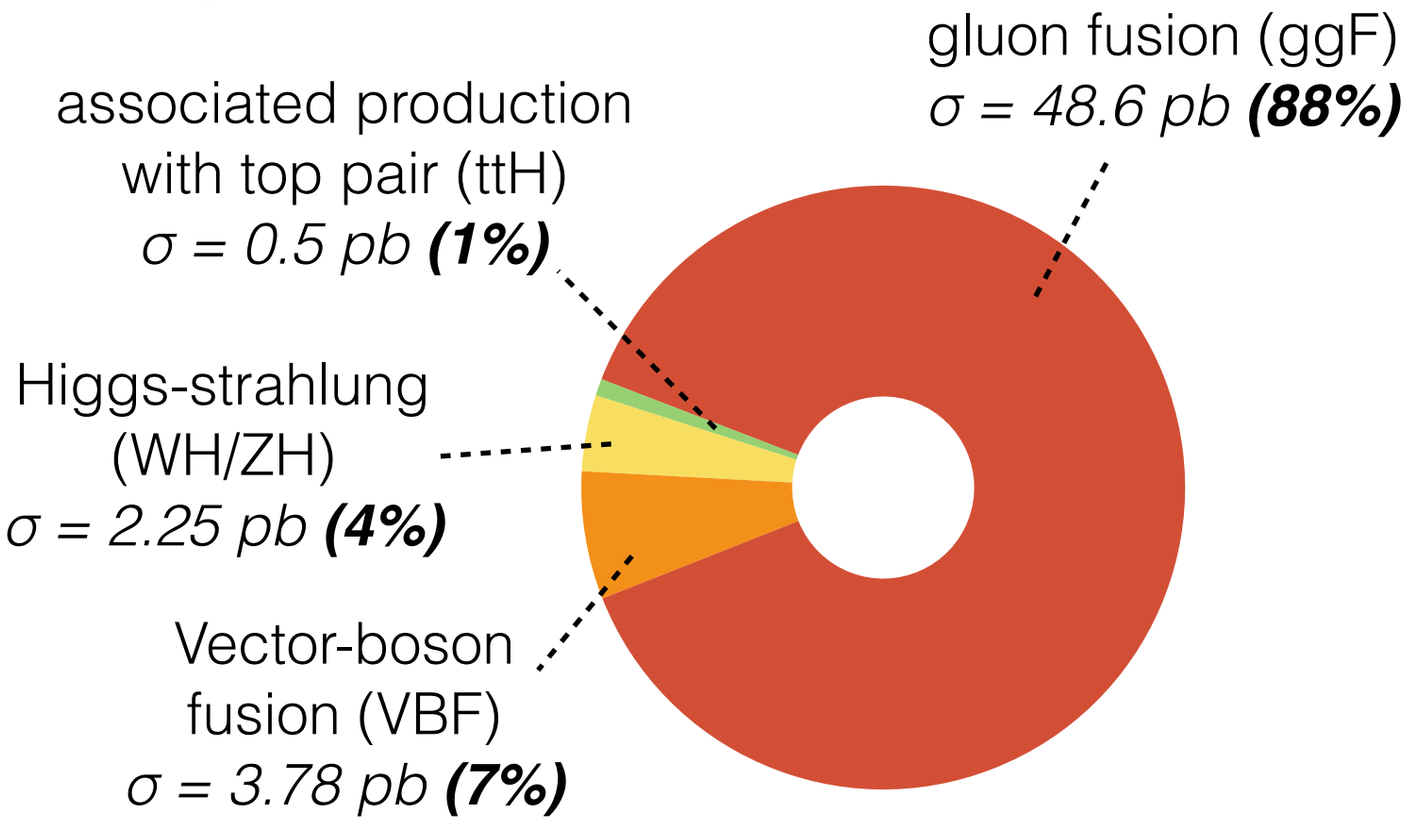
Dimuon mass resolution improved by adding at most one final-state-radiation photon (ggF & VBF)

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



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
trigger, primary vertex,
two opposite-charge muons

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

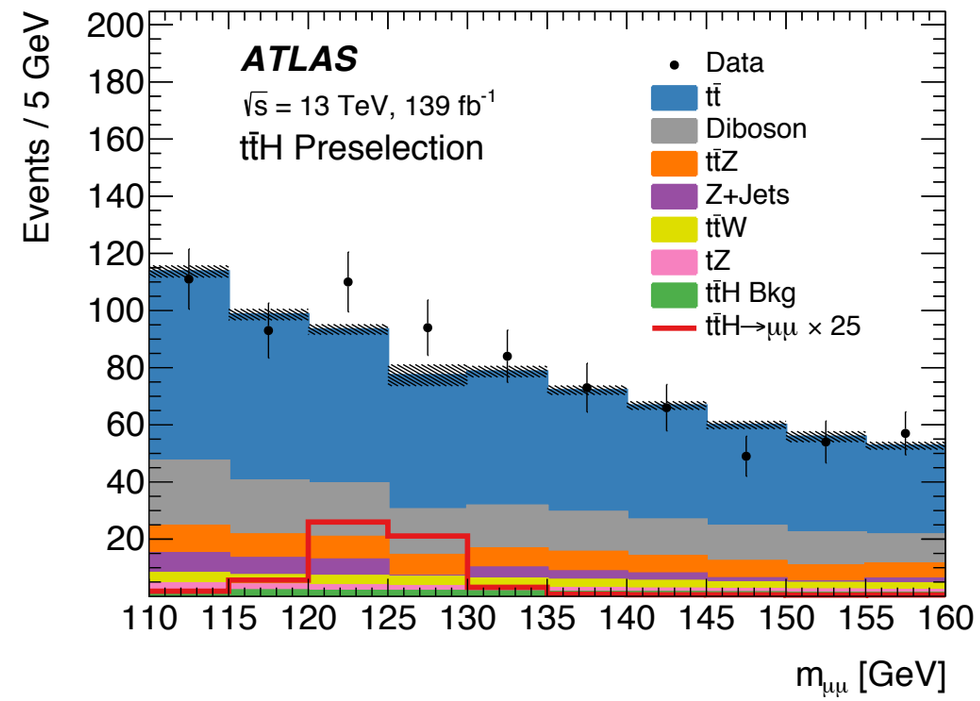
VH
no b-tagged jets
one (two) extra electron(s) or muon(s)
selection on dedicated BDT score

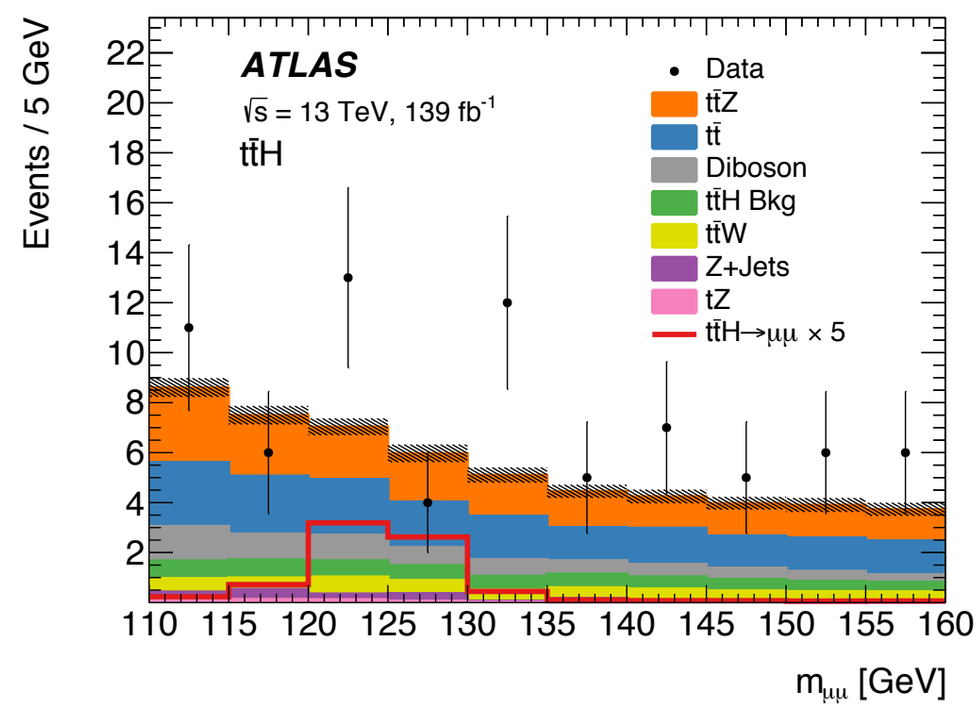
VBF categories
no b-tagged jets, no extra muons
selection on dedicated BDT score

ggF categories
no b-tagged jets, no extra muons

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*(→*μμ*) 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

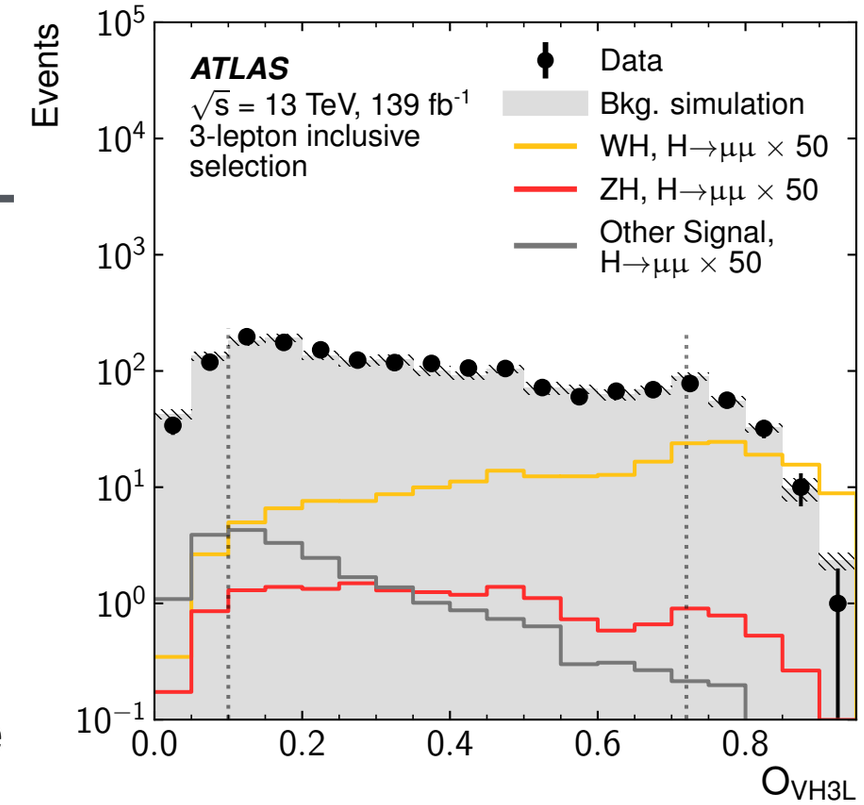


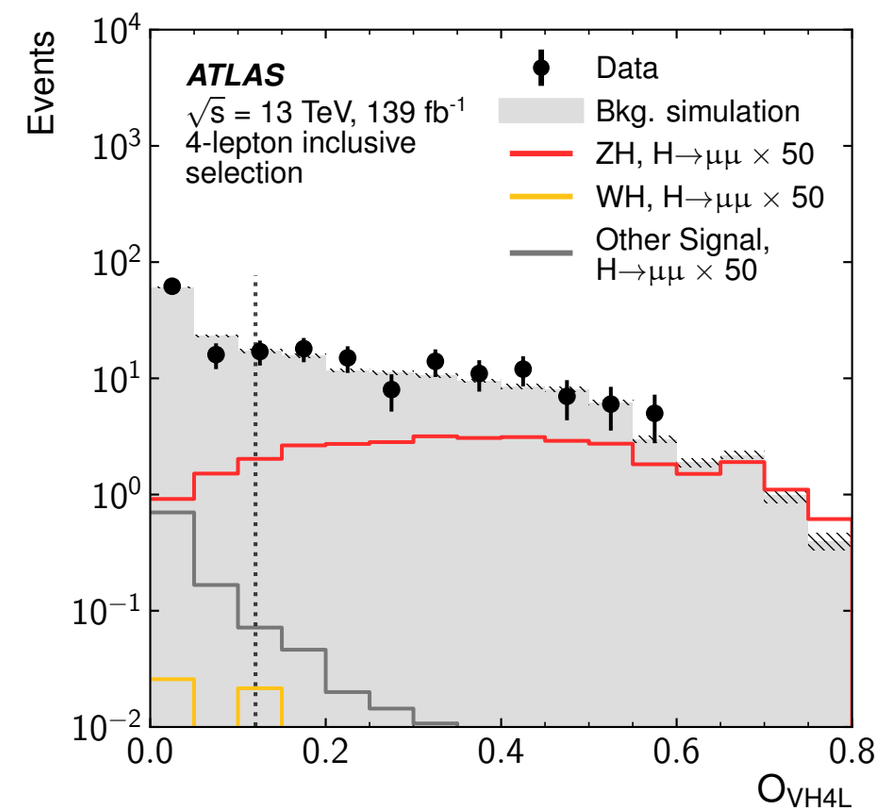


Expected signal events: *1.2*
ttH purity (wrt other Higgs modes): *98%*
S/B = *8%*

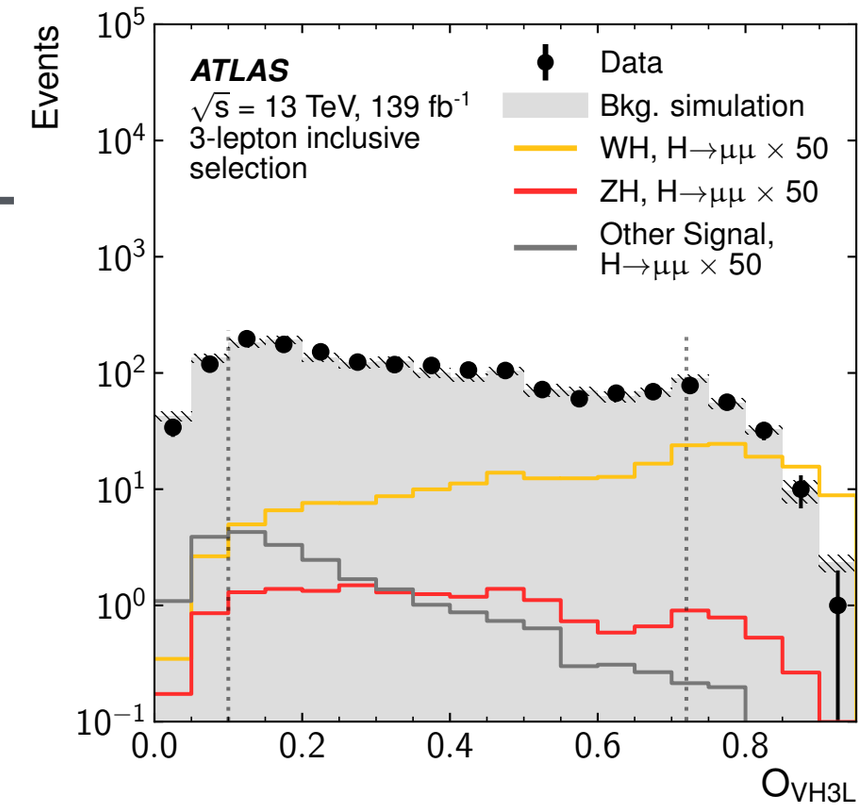
VH categories

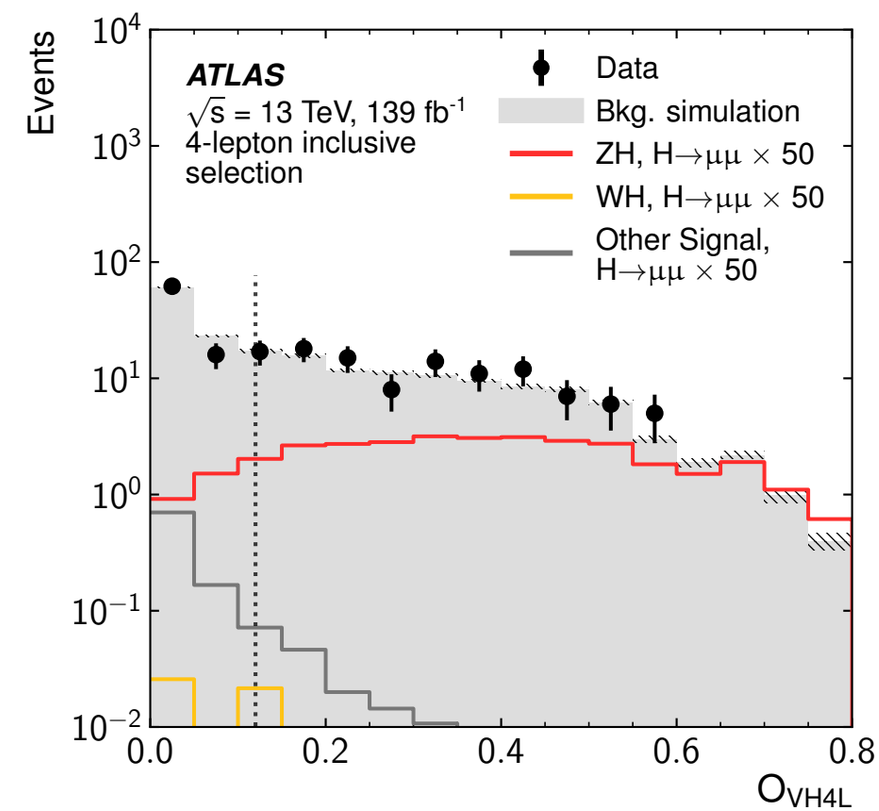
- Veto events with a b-tagged jet
- 4-lepton selection, ≥2 extra e/μ (targeting Z(→*ll*)H)
- 3-lepton selection, 1 extra e/μ (targeting W(→*lν*)H)
  - Relaxed p_T cut on muons if comparing to ggF/VBF case
  - Pairing based on charges and minimisation of χ^2 criterion (when n_μ>2)
    - taking into account 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





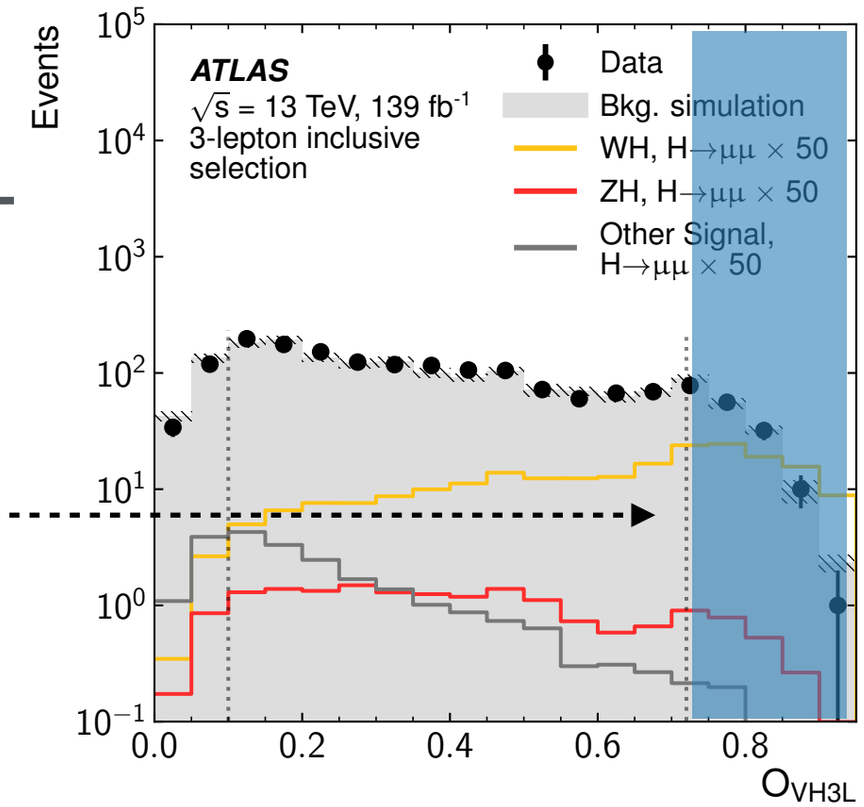
VH categories

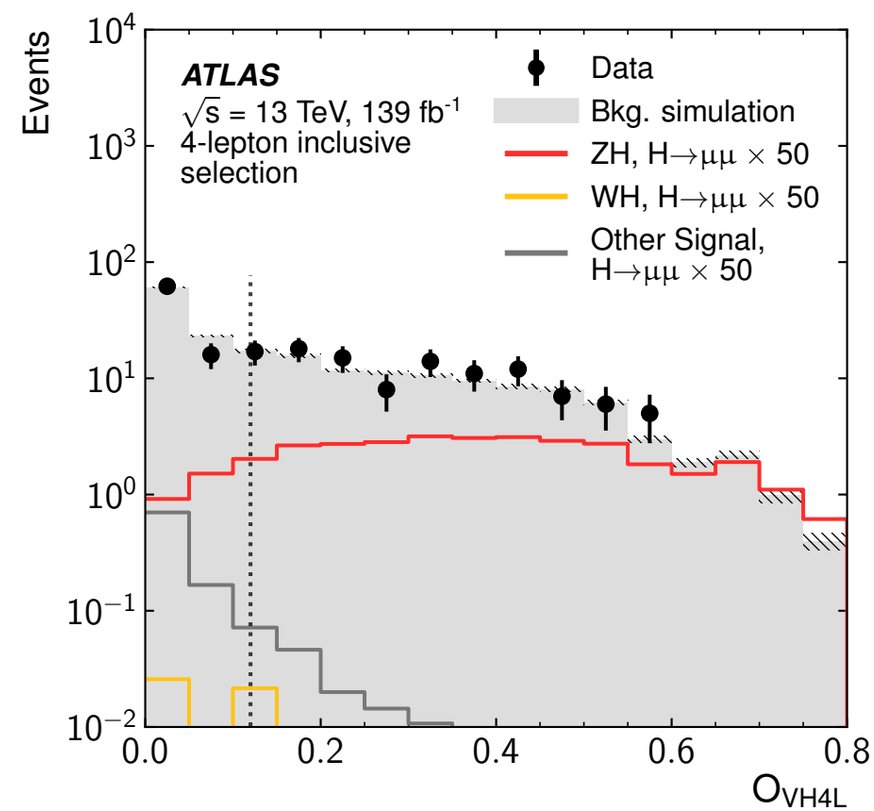




VH categories

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

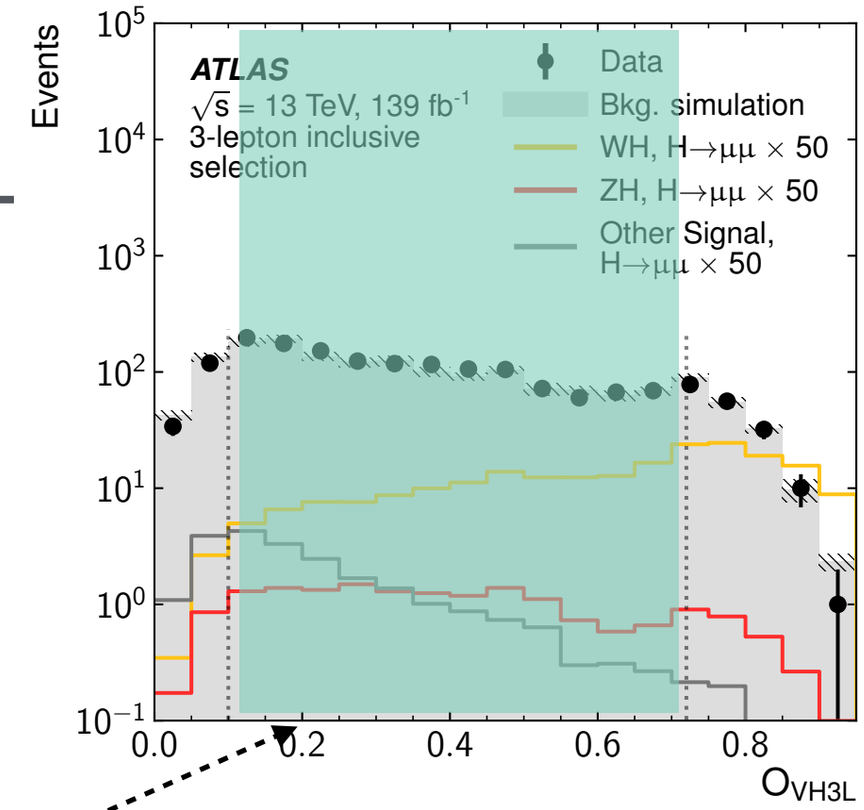


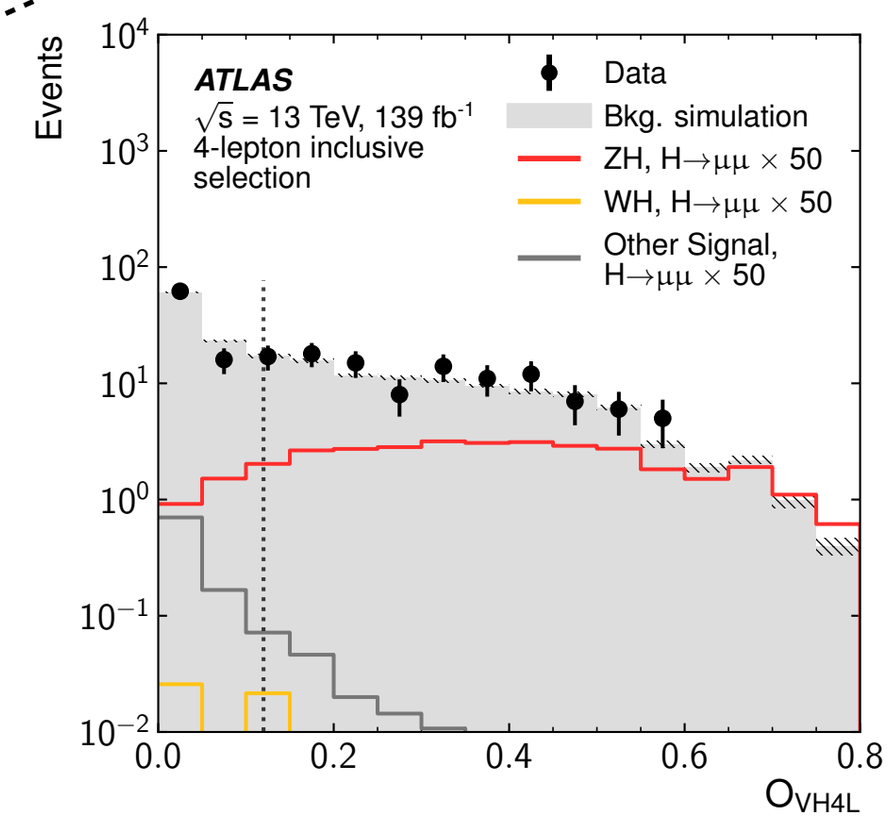


VH categories

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

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





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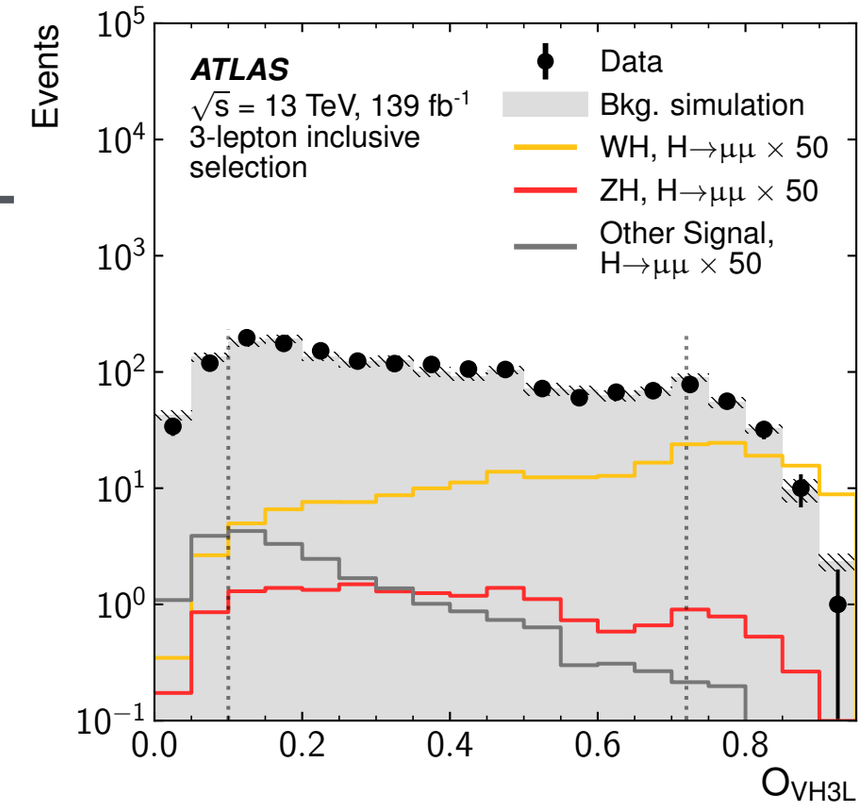
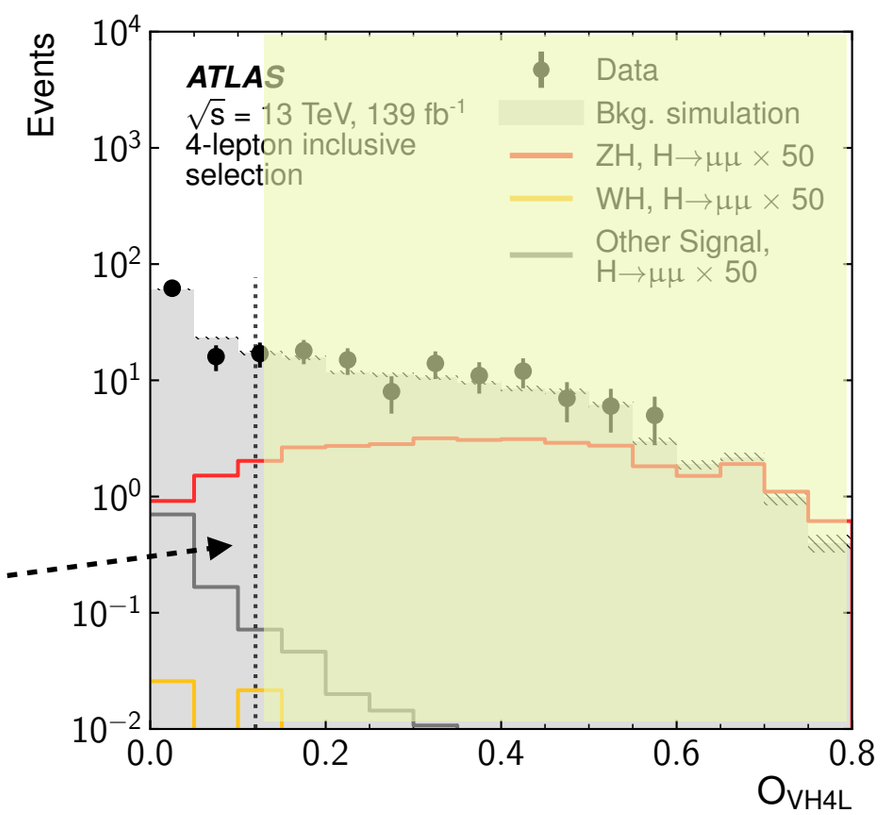
S/B = *0.8%*

VH4L
Expected signal events: *0.5*
VH purity (wrt other Higgs modes): *>99%*
S/B = *2.6%*





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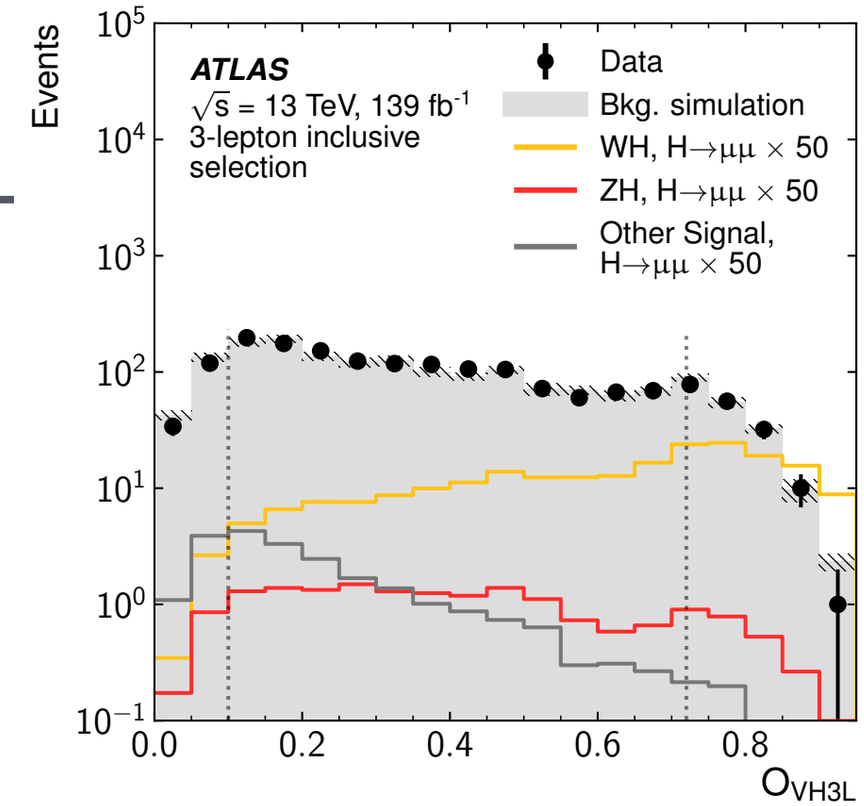
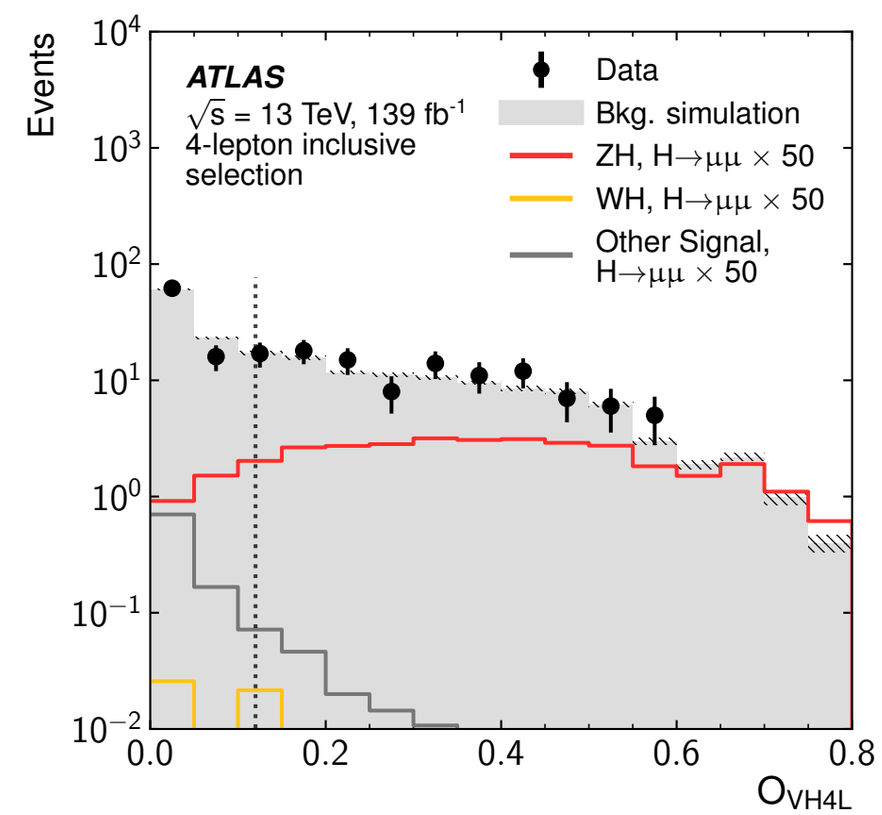
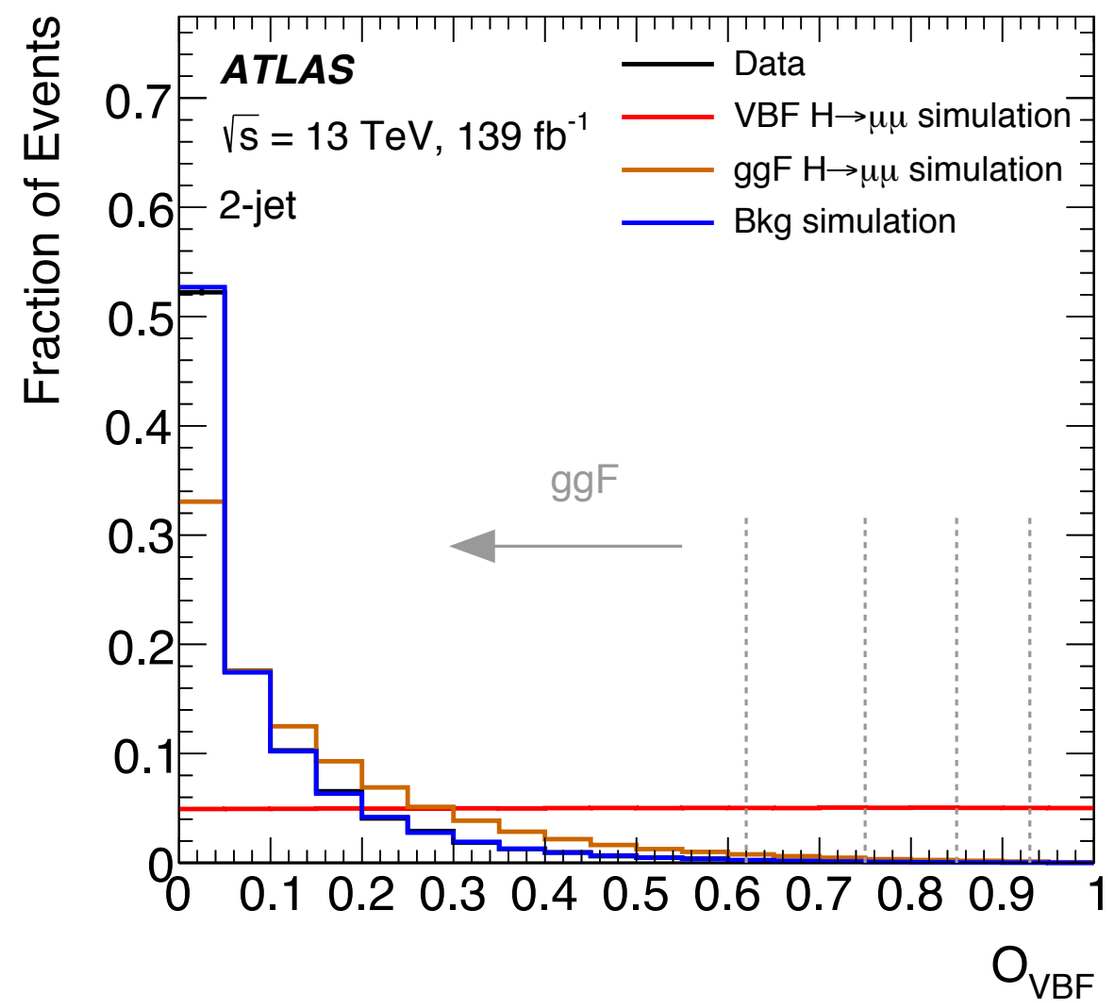




VBF categories

- 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_{tracks} associated to each jet, providing discrimination between gluon- and quark-induced jets

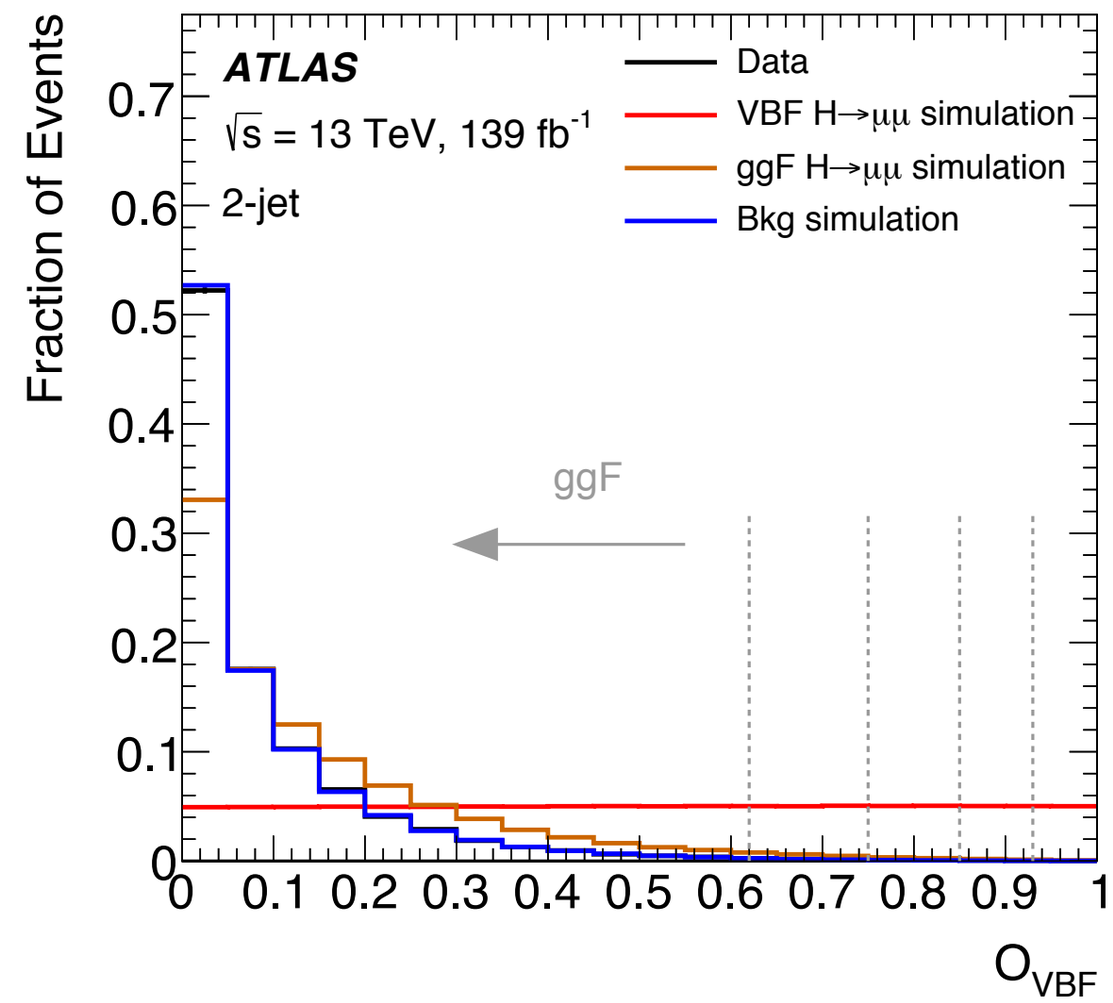


➡ Using fully simulated samples in the 120-130 GeV window, BDT designed to be as insensitive to $m_{\mu\mu}$ as possible (same applies to ggF, see later)

VBF categories

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

Category	Expected signal	VBF purity	Expected S/B
VBF Very High	2.8	93%	18%
VBF High	3.5	87%	10%
VBF Medium	4.8	78%	5%
VBF Low	7.5	65%	2.8%



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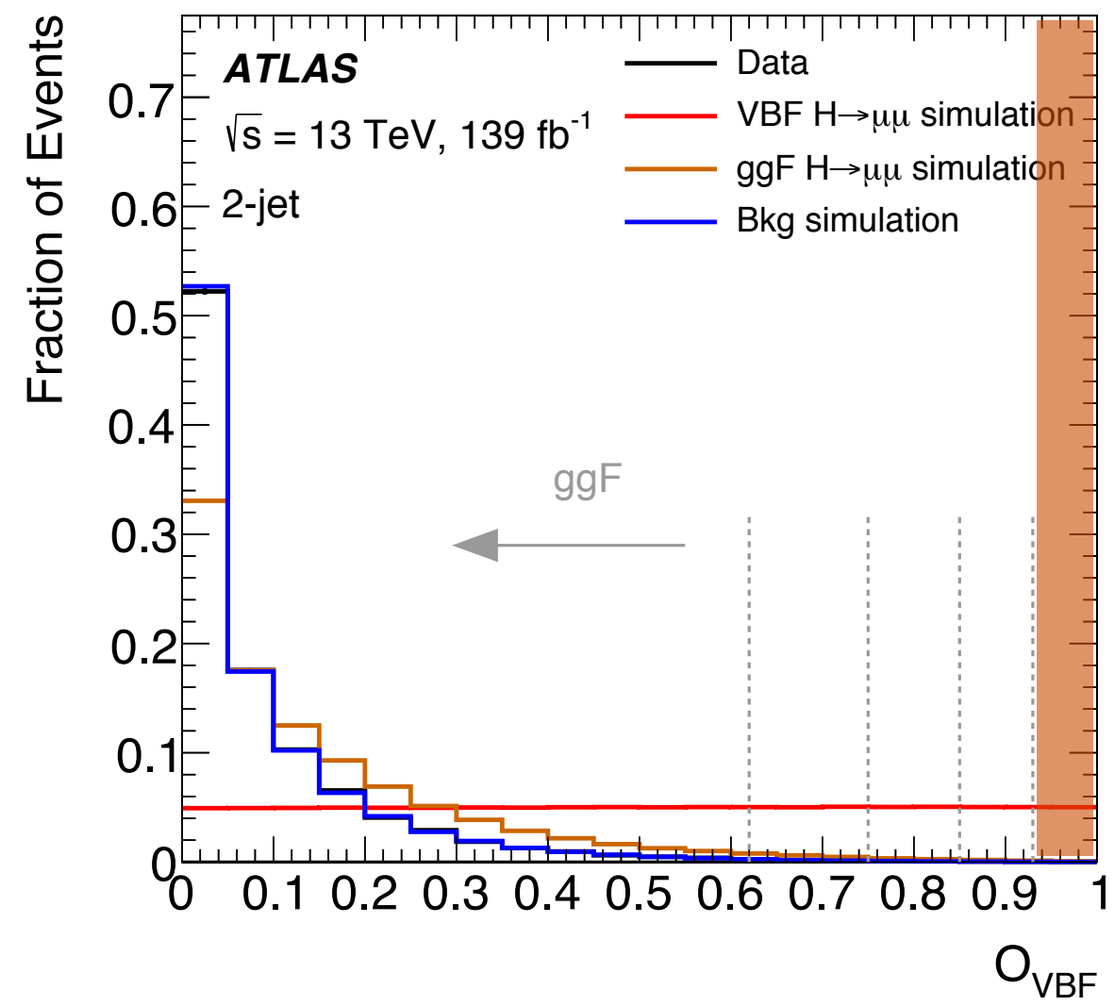
- Four categories defined, remaining events will be tested for ggF categories (see next slide)

Category	Expected signal	VBF purity	Expected S/B
VBF Very High	2.8	93%	18%
VBF High	3.5	87%	10%
VBF Medium	4.8	78%	5%
VBF Low	7.5	65%	2.8%



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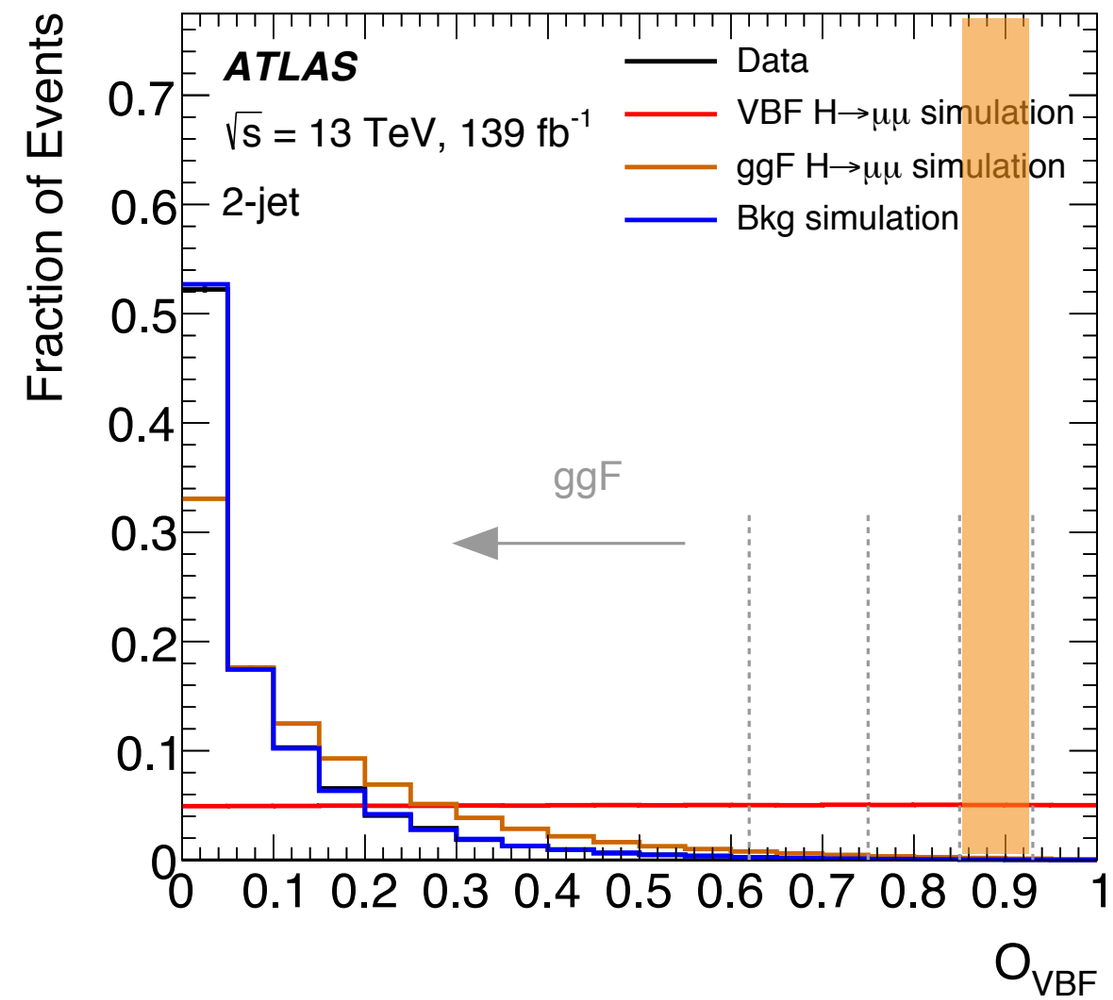

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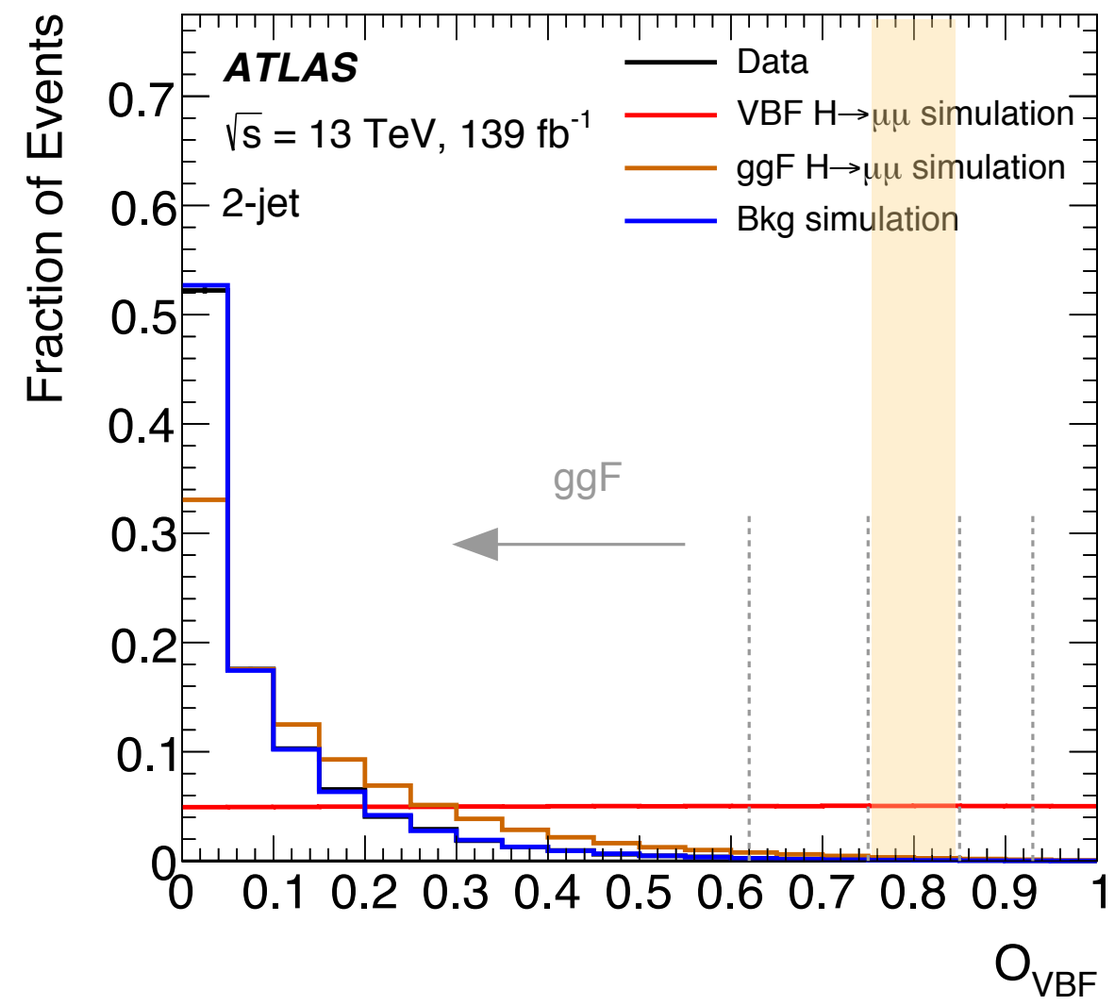

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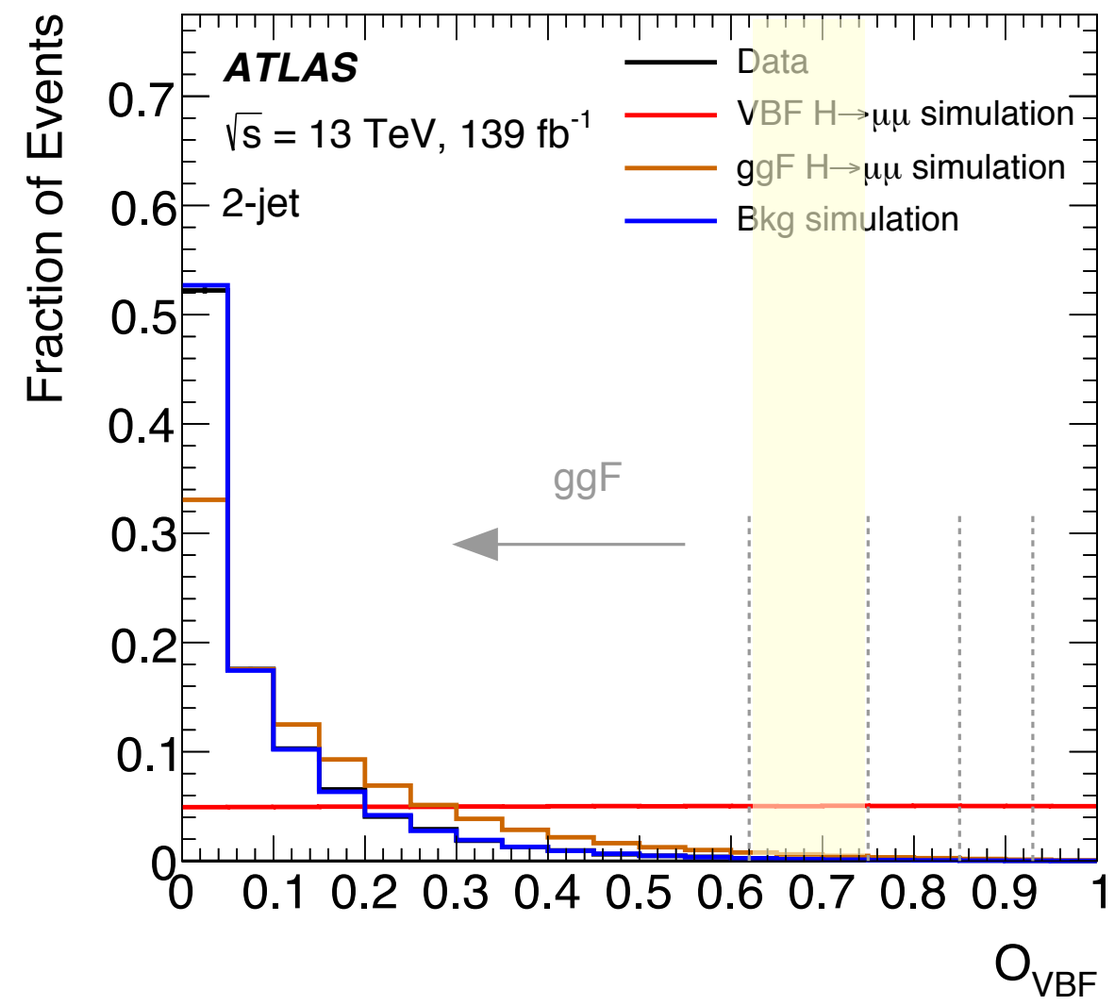

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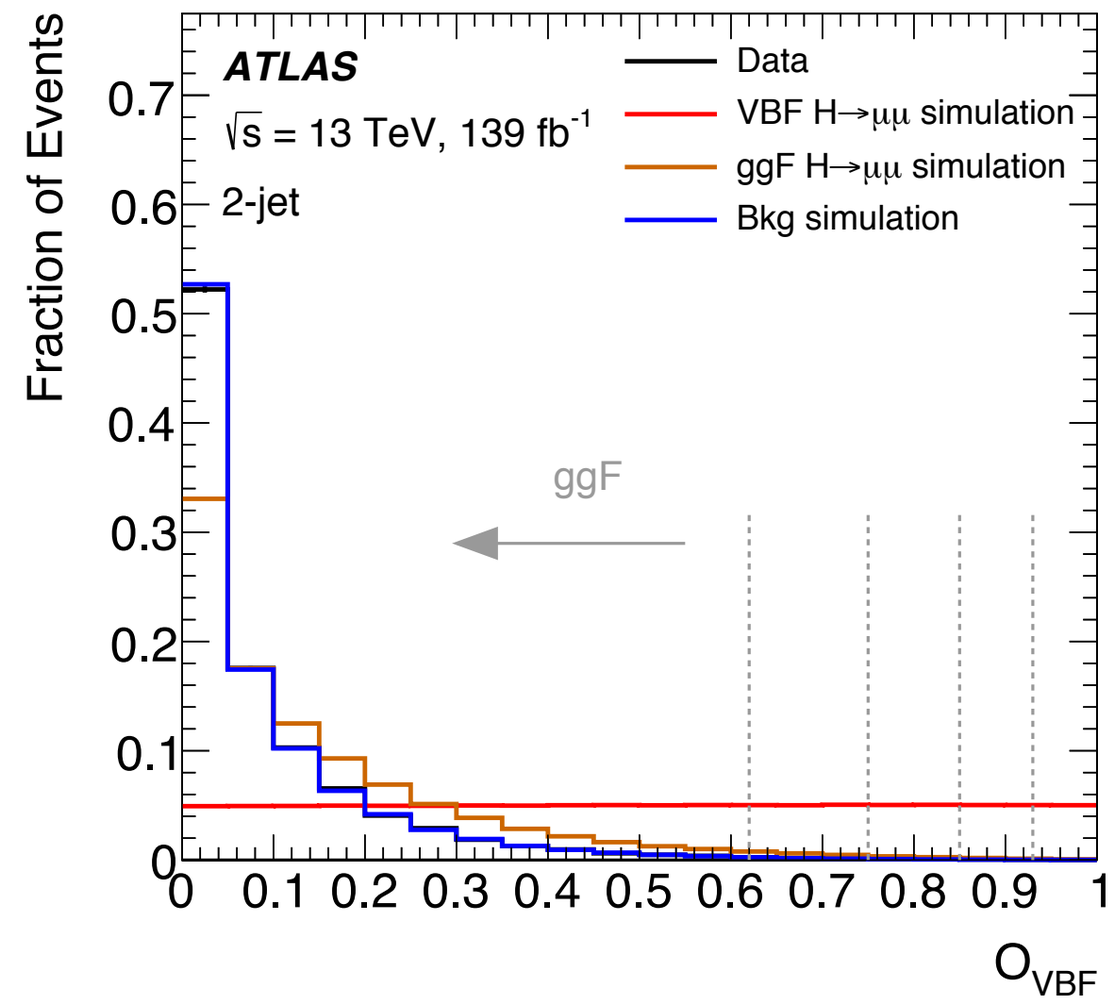
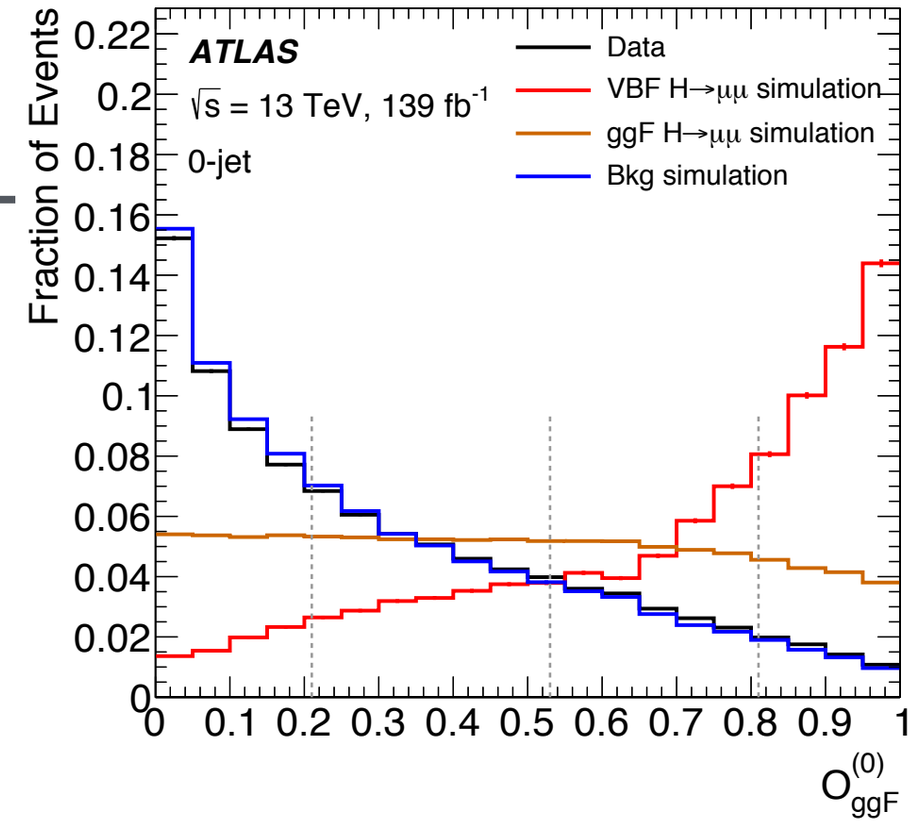
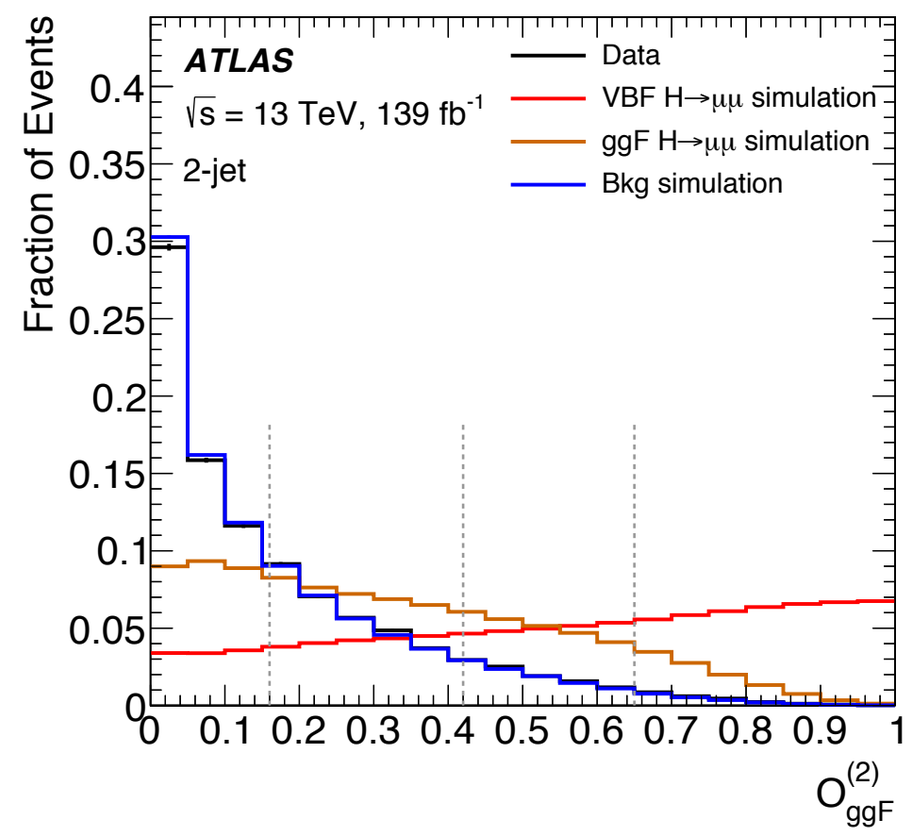


ggF categories

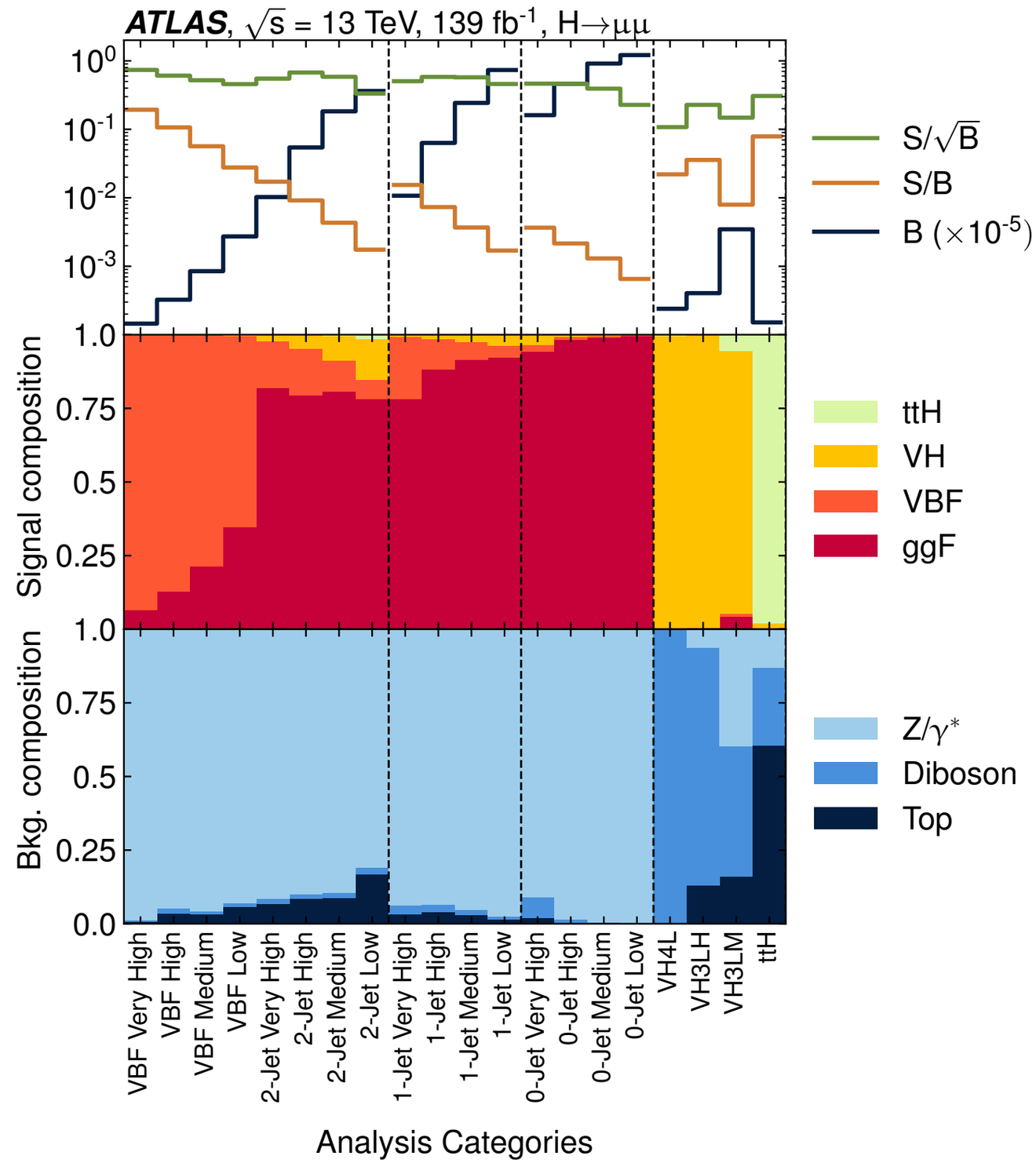
- Veto events with a b-tagged jet or with an extra muon
- Divide events into channels: N-jet = 0,1 and ≥2
- Trained dedicated BDT to separate **ggF+VBF** signal from *background*
  - 3, 7, 17 features for 0-,1- and 2-jet, respectively (see backup)
  - 2-jet channel using the same features as in the VBF-dedicated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





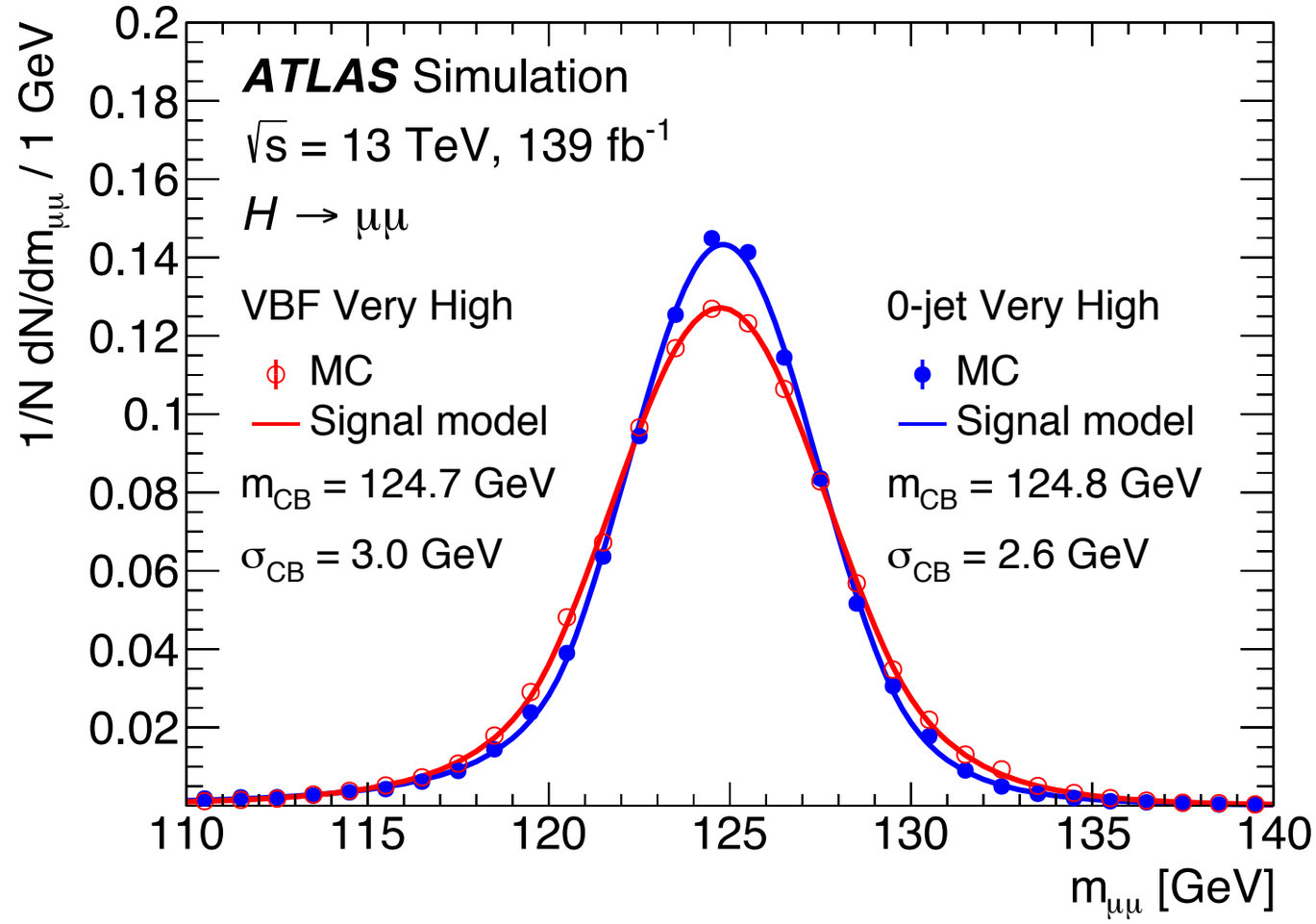
Categories - summary

- A total of 20 categories
  - ttH, 3xVH, 4xVBF, 4xN-jet (0, 1, ≥2)
- S/B ranging from <0.1% (0-jet Low) to 18% (VBF Very High)
- Significance ranging from 0.1 to 0.6 σ
- 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

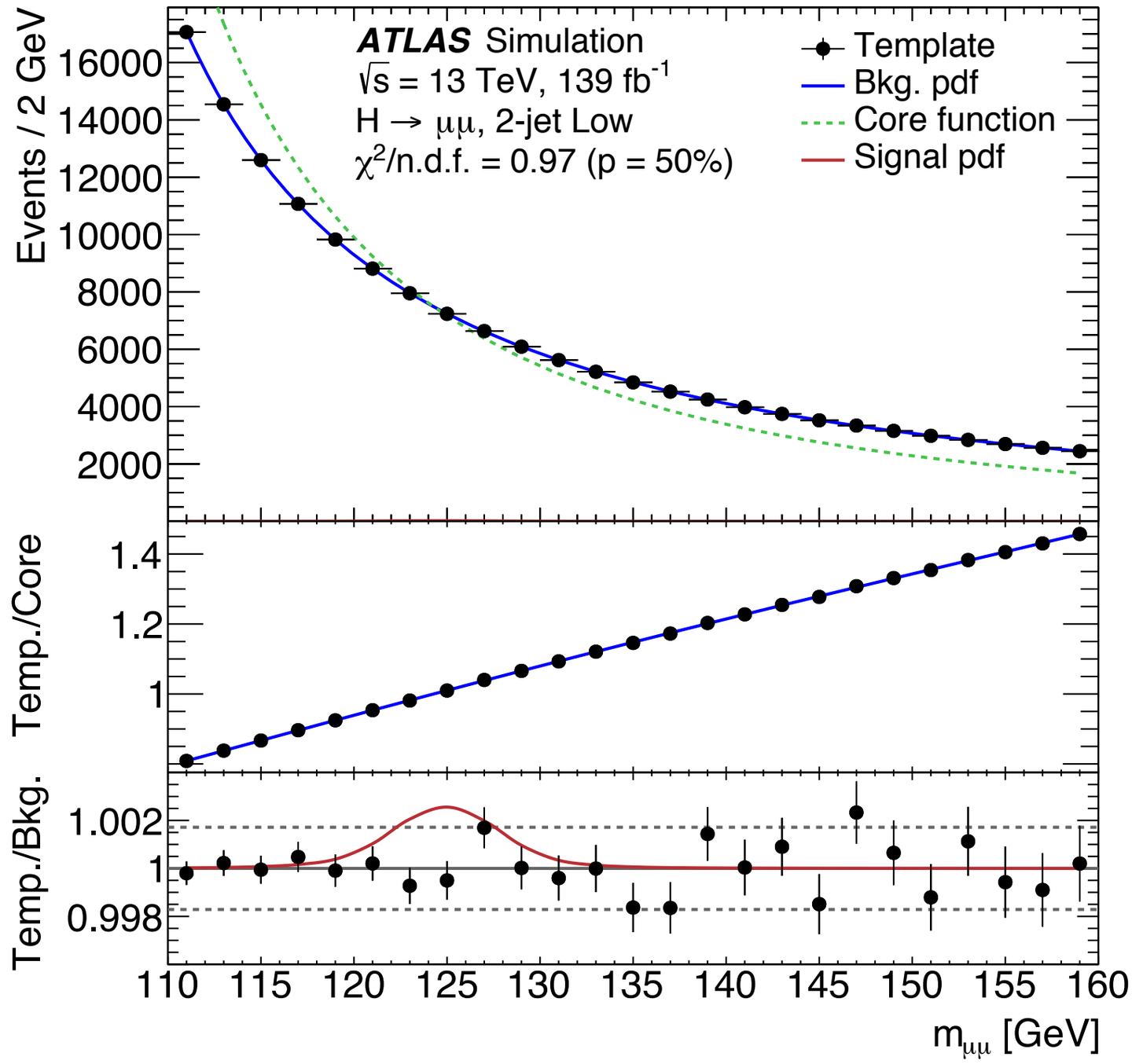
Theory
- BR, QCD scale, PDF uncertainties (all modes)
- Underlying event, parton showering (ggF/VBF)

Experimental
- Pileup modelling, N_{tracks}(jet)
- Reconstruction efficiencies (e/μ/b-tag/jet)
- Muon momentum scale and resolution, Run1 Higgs mass uncertainty (240 MeV)

Background modelling

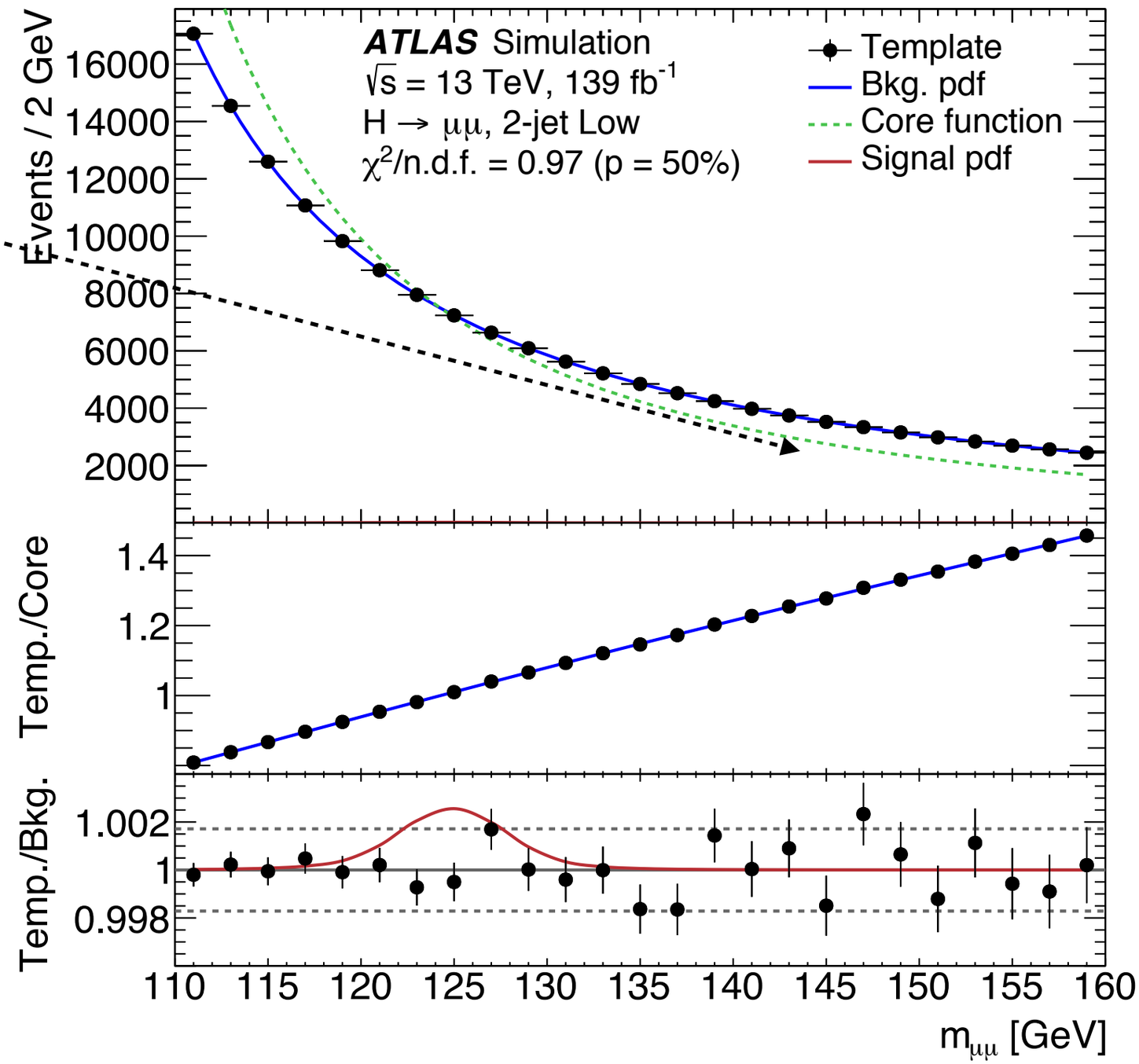
- Key element of the search, as S/B is generally quite low
  - Per-mille level precision necessary, to avoid biases in extracted signal yields
- Requires a large number of simulated events
- Dimuon mass spectrum parameterised with:

$$F(m_{\mu\mu}, a_i)^{cat} = Core(m_{\mu\mu}) \times Empirical(m_{\mu\mu}, a_i)^{cat}$$



Background modelling

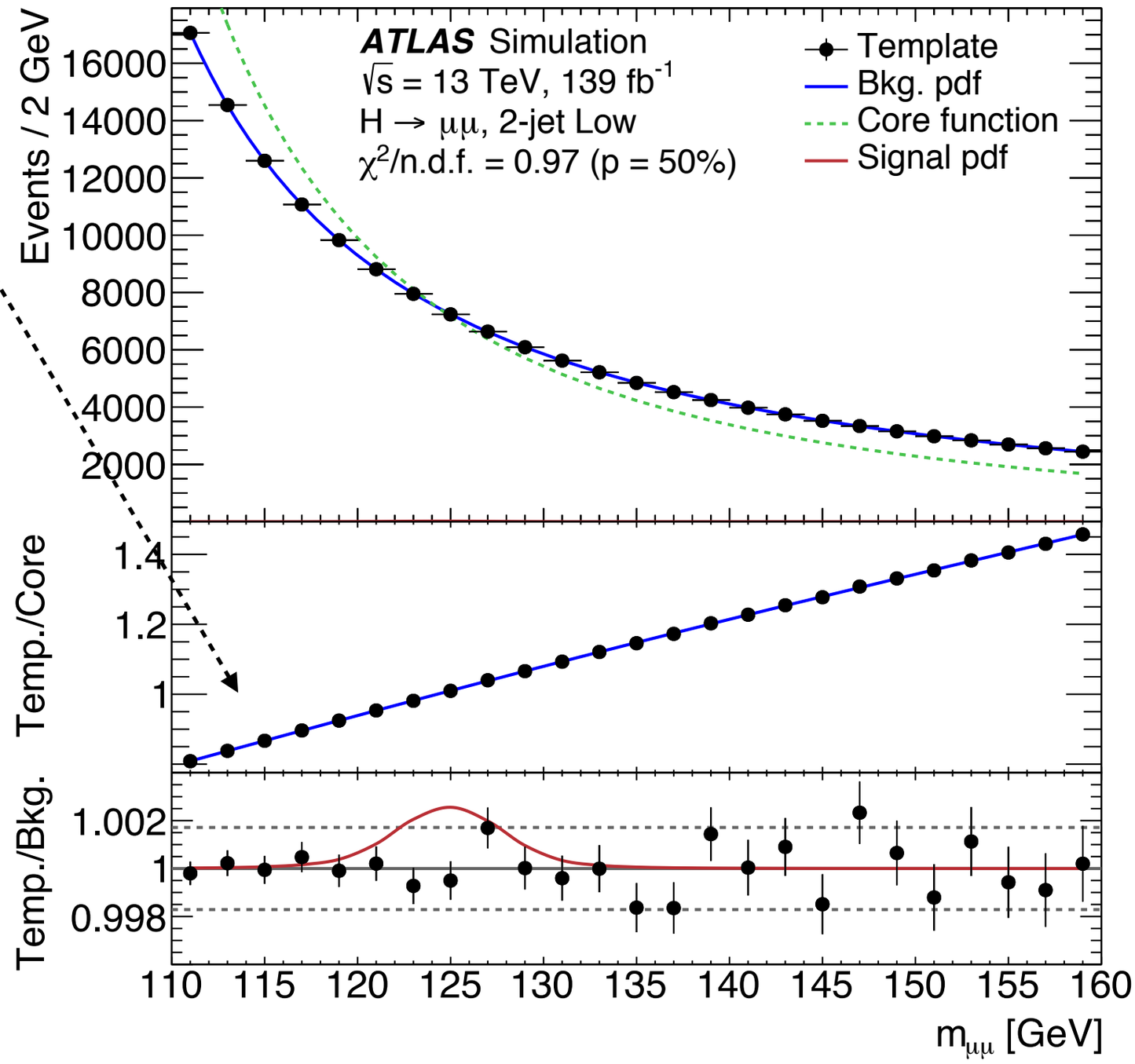
- **Core($m_{\mu\mu}$)** function:
  - Crucial to take into account the steepness of the DY background as well as resolution effects
  - Based on DY line-shape @LO, convolved with Gaussian to take into account $m_{\mu\mu}$-dependent resolution effects
  - Fully rigid (no extra degrees of freedom)
  -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



Background modelling

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

- **Empirical($m_{\mu\mu}$, a_i)^{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



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

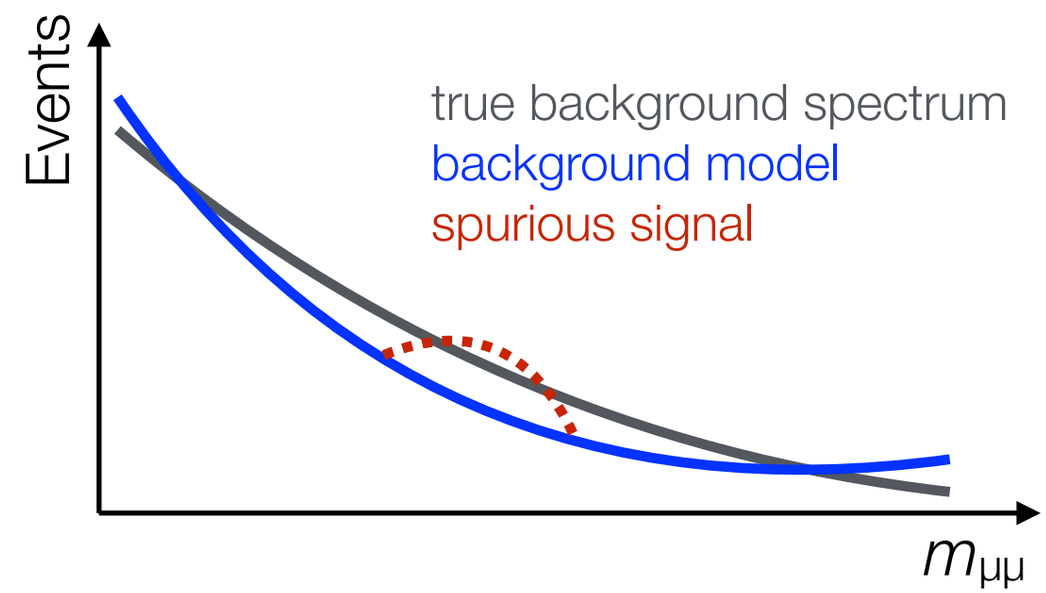
⇓

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 <u>background-only templates</u>
  - 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



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

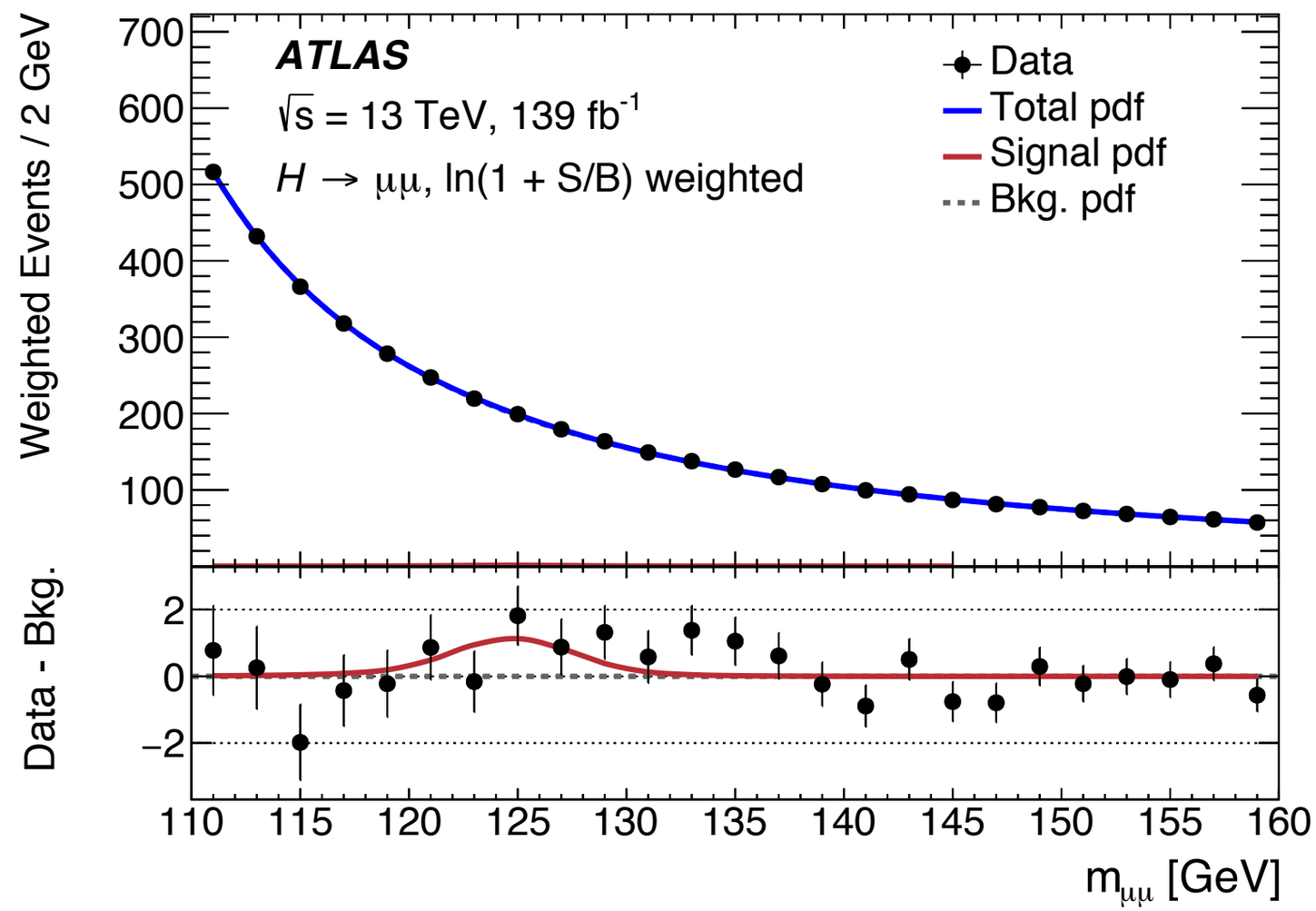
POWHEG-BOX (0, 1 partons at NLO) + ALPGEN (2 partons at LO)

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

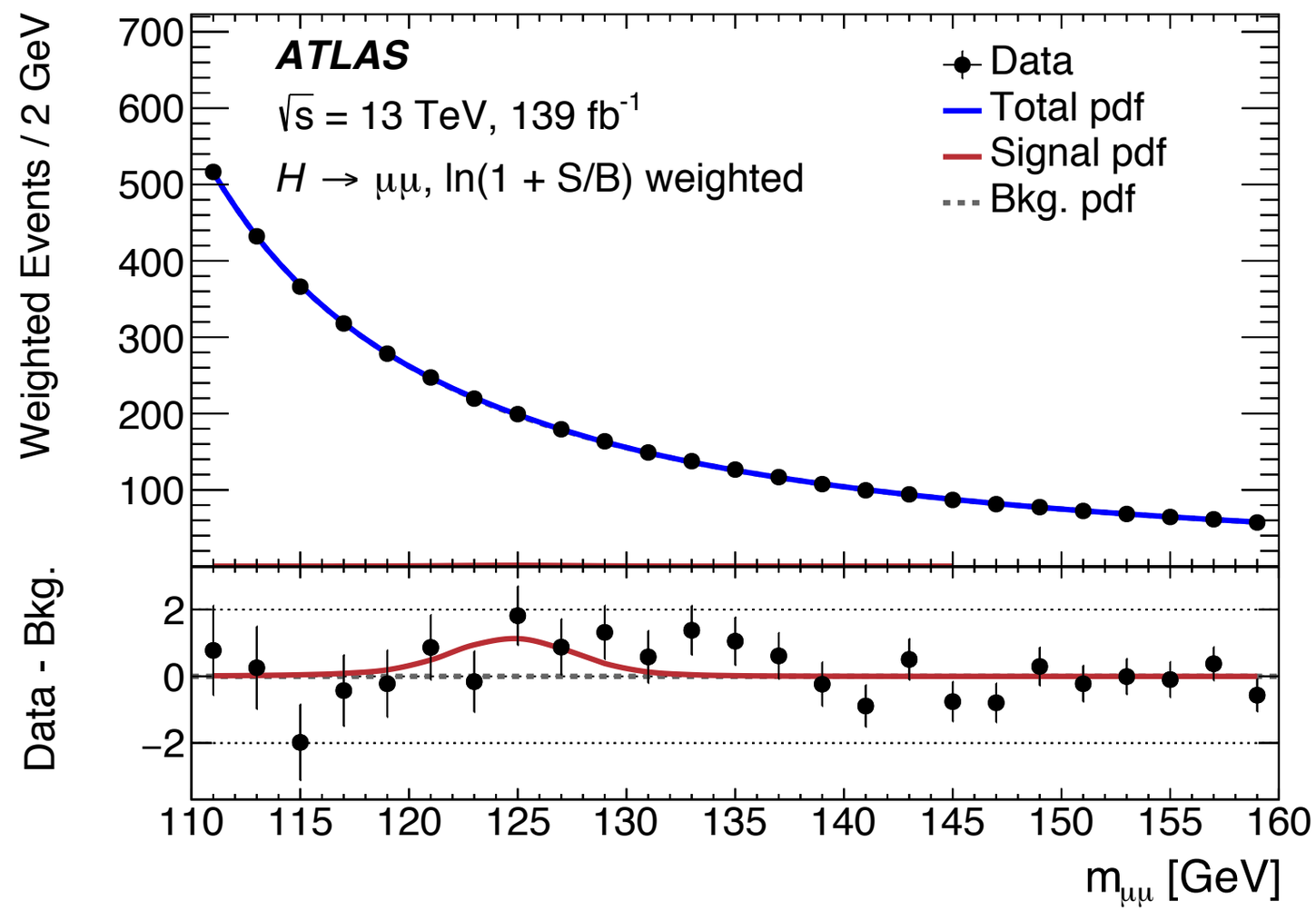
Results


ATLAS
√s = 13 TeV, 139 fb-1
H → μμ, ln(1 + S/B) weighted
Data
Total pdf
Signal pdf
Bkg. pdf
Weighted Events / 2 GeV
Data - Bkg.
mμμ [GeV]

Results

Signal strength (best fit)

1.2 ± 0.6



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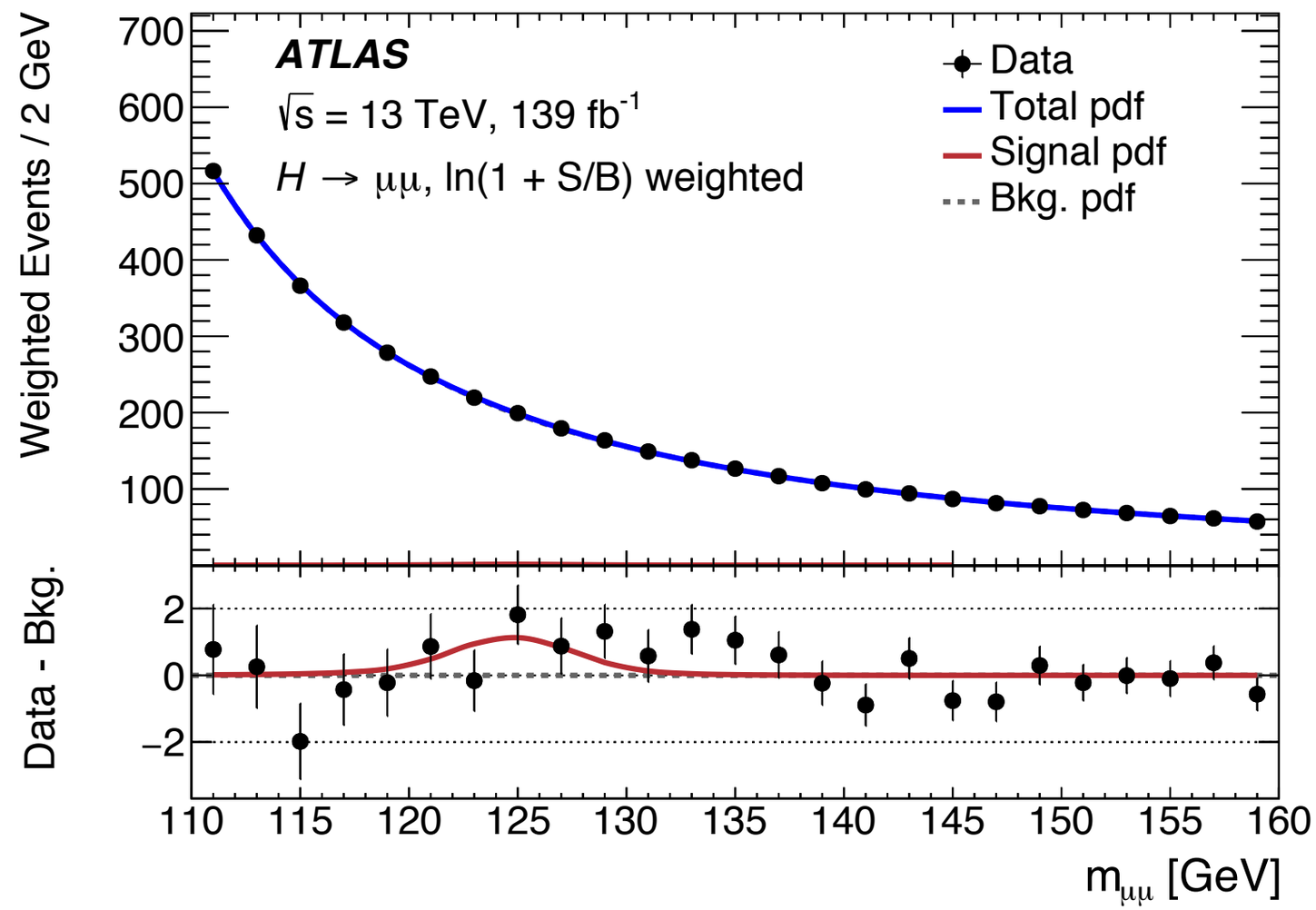
Observed BR limit at 95% CL

$<4.7 \times 10^{-4}$



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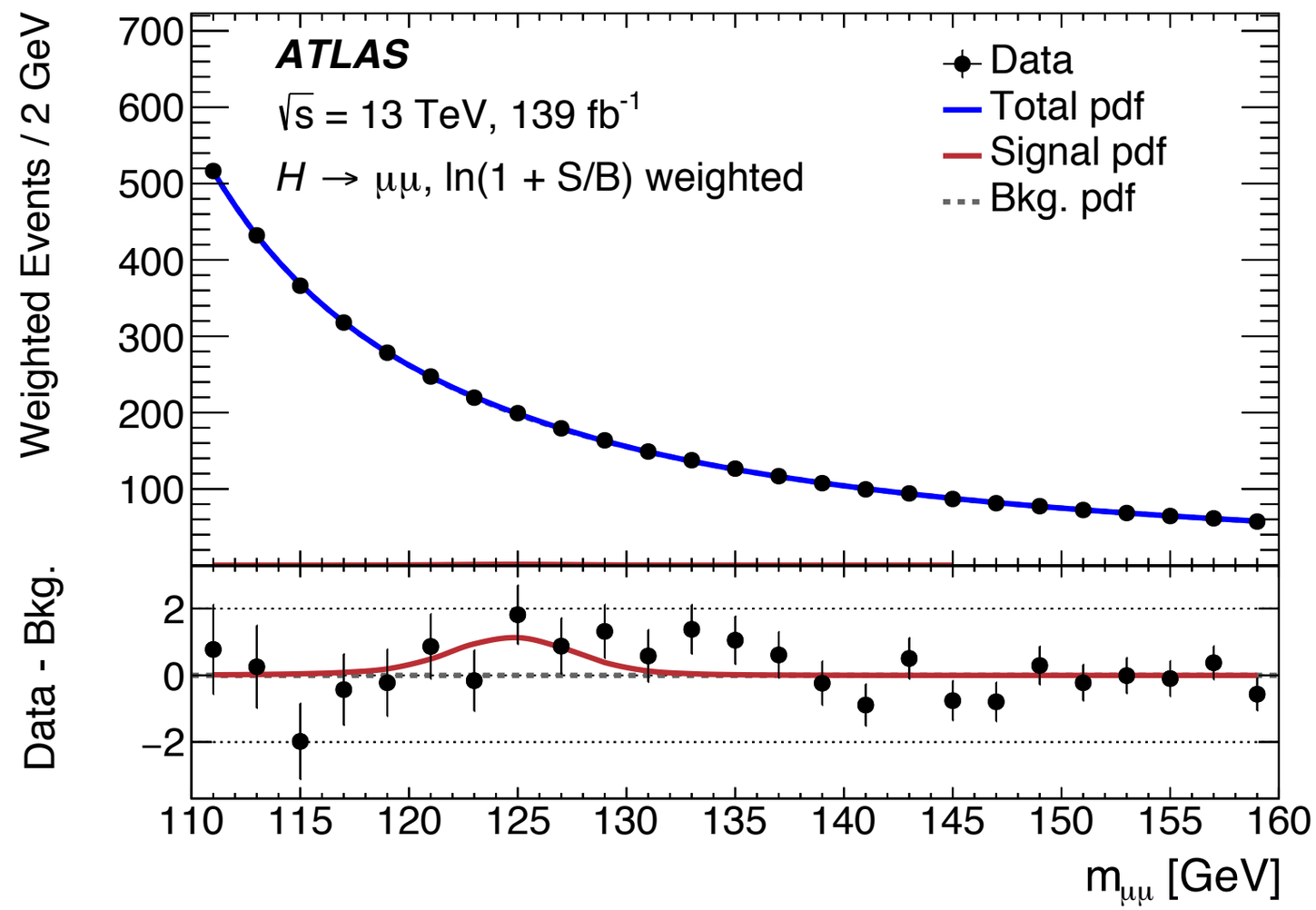
Significance

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

Observed: 2.0σ

Expected: 1.7σ



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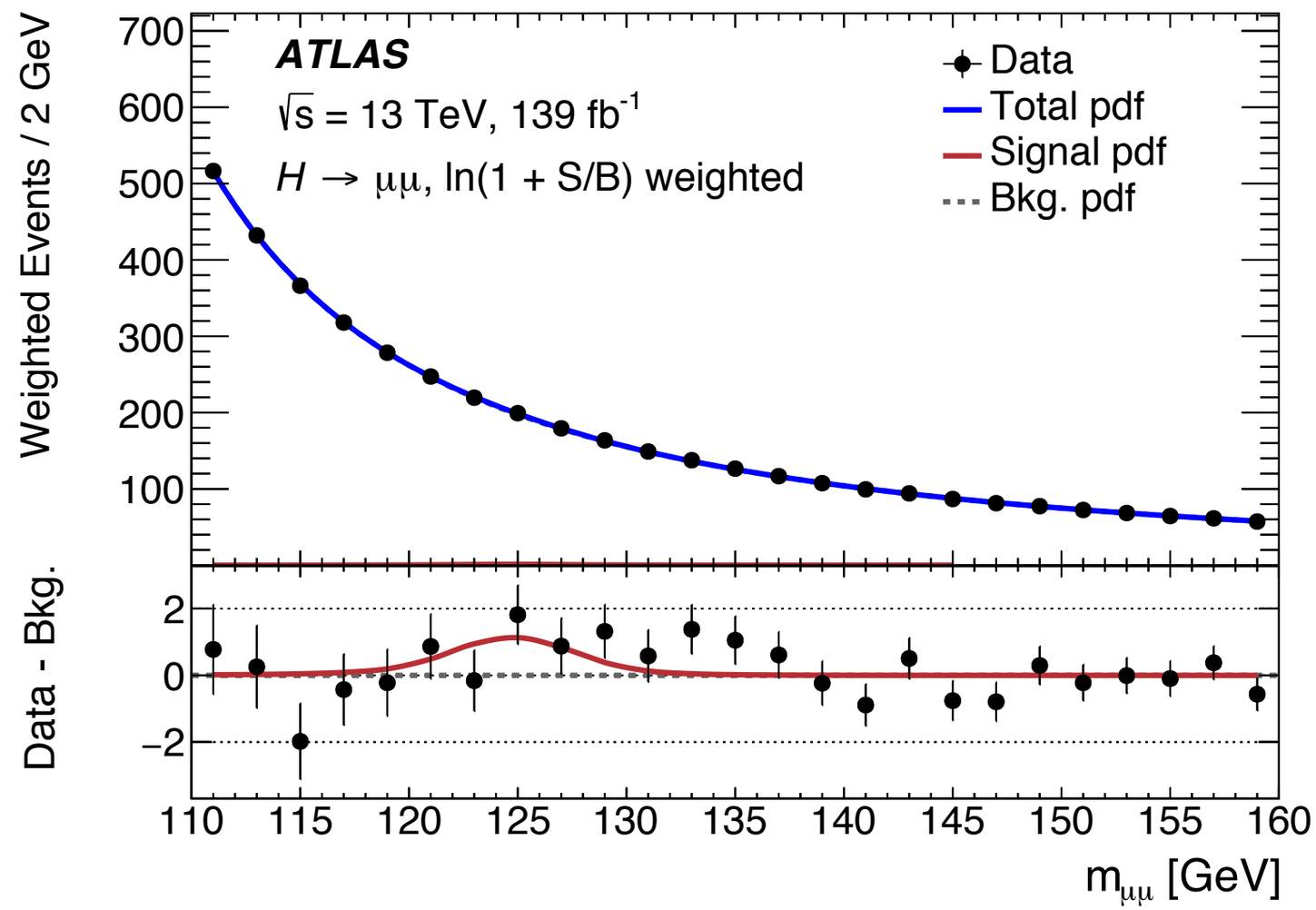


Uncertainties *(on signal strength)*

Statistics (data): ±0.58

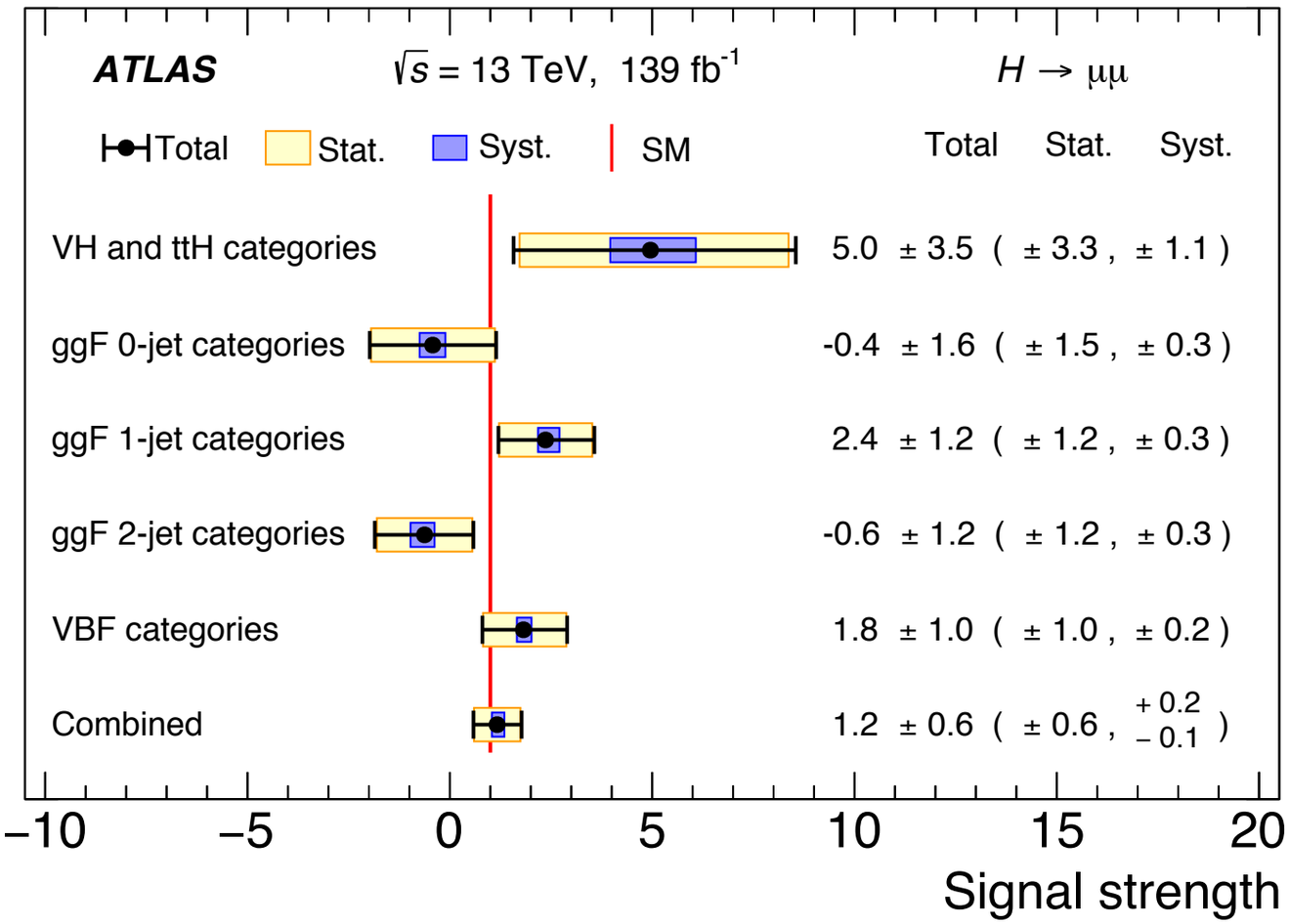
Theory (signal): +0.13/-0.08

Experimental (signal): +0.07/-0.03

Background modelling: ±0.1

Results

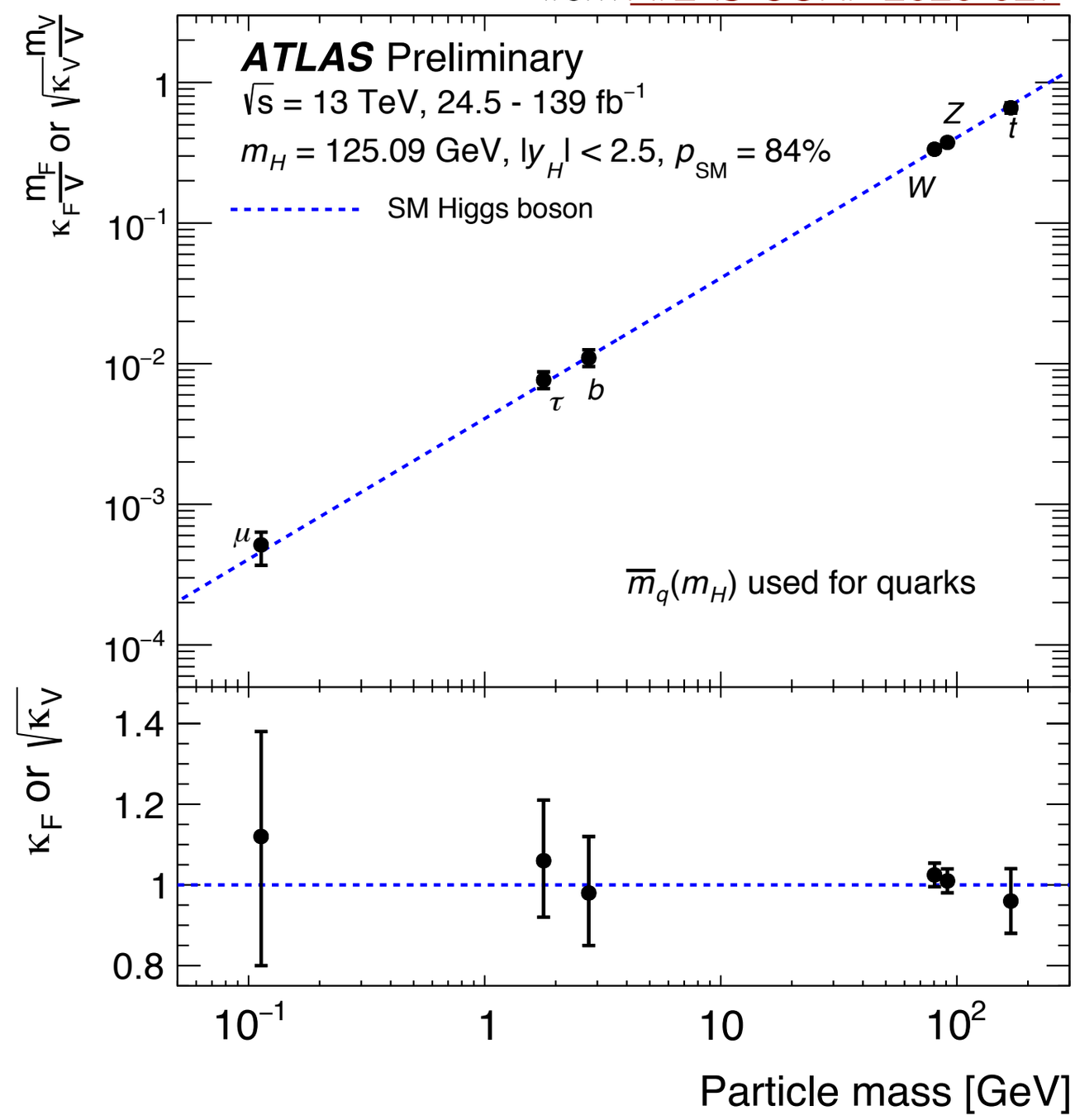
- Tested grouping categories (ttH+VH, VBF, 0-jet, 1-jet and 2-jet)
- Compatibility between signal strengths in the five groups: 20%
  - 2% when checking on ungrouped categorisation (20)
- Tested adding one extra degree of freedom to the background function for those categories with largest deviation 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 ± 0.6
- Observed significance: 2.0 σ
- Large improvement over our previous publication, thanks to:
  - larger dataset (factor ~2)
  - more advanced techniques (+25%)
    - *background modelling*
    - *definition of the categories*

from ATLAS-CONF-2020-027



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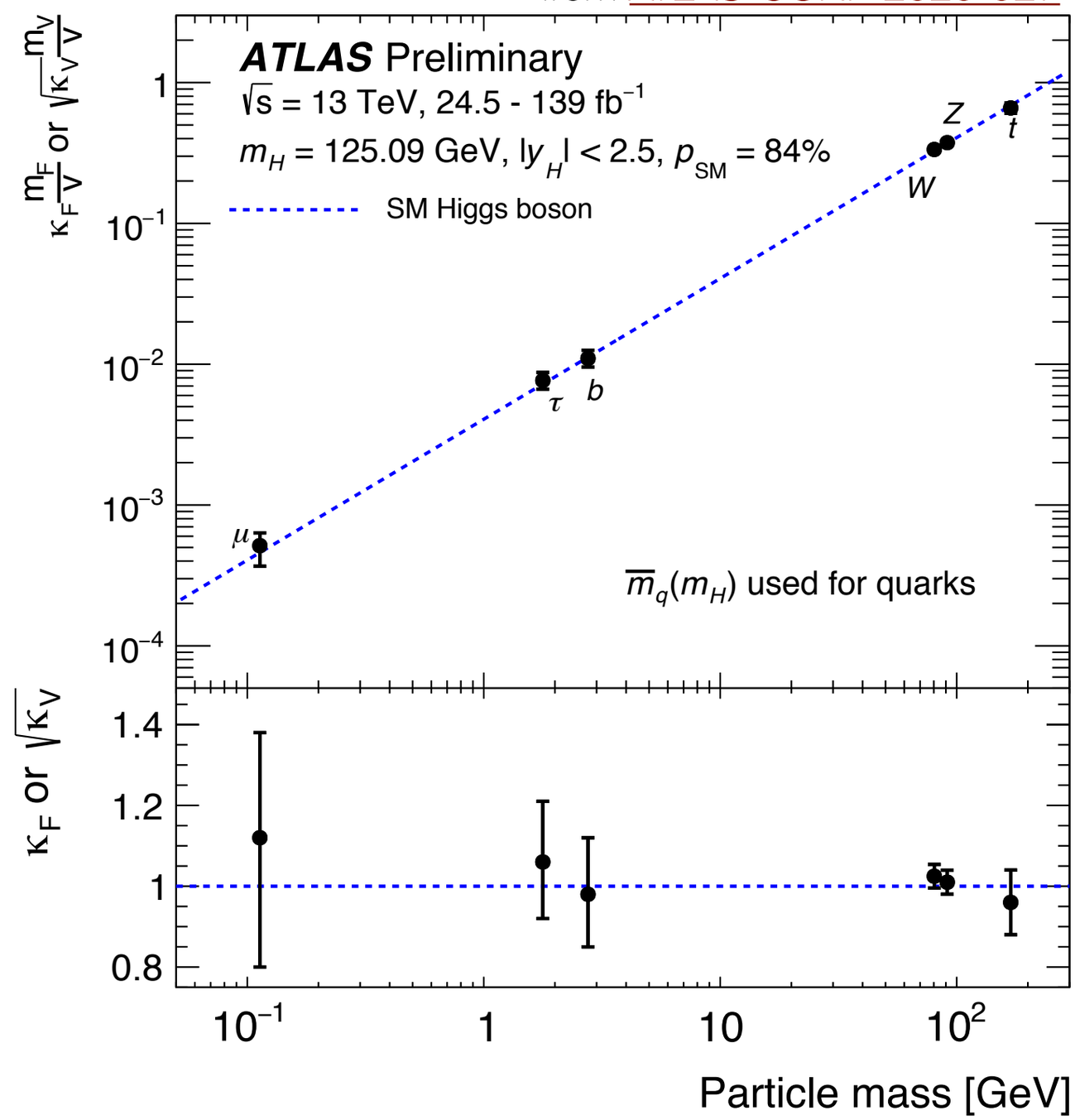

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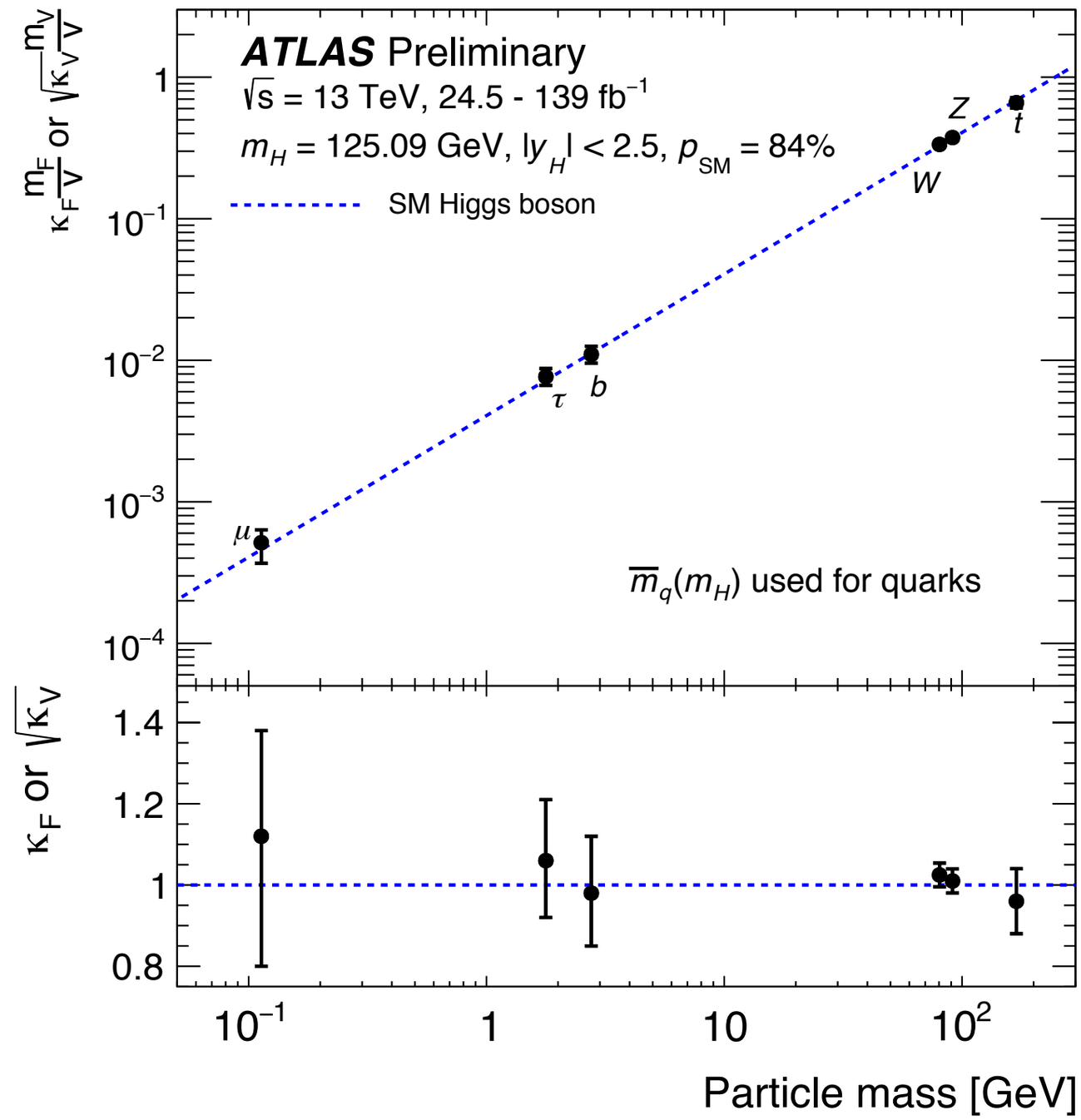

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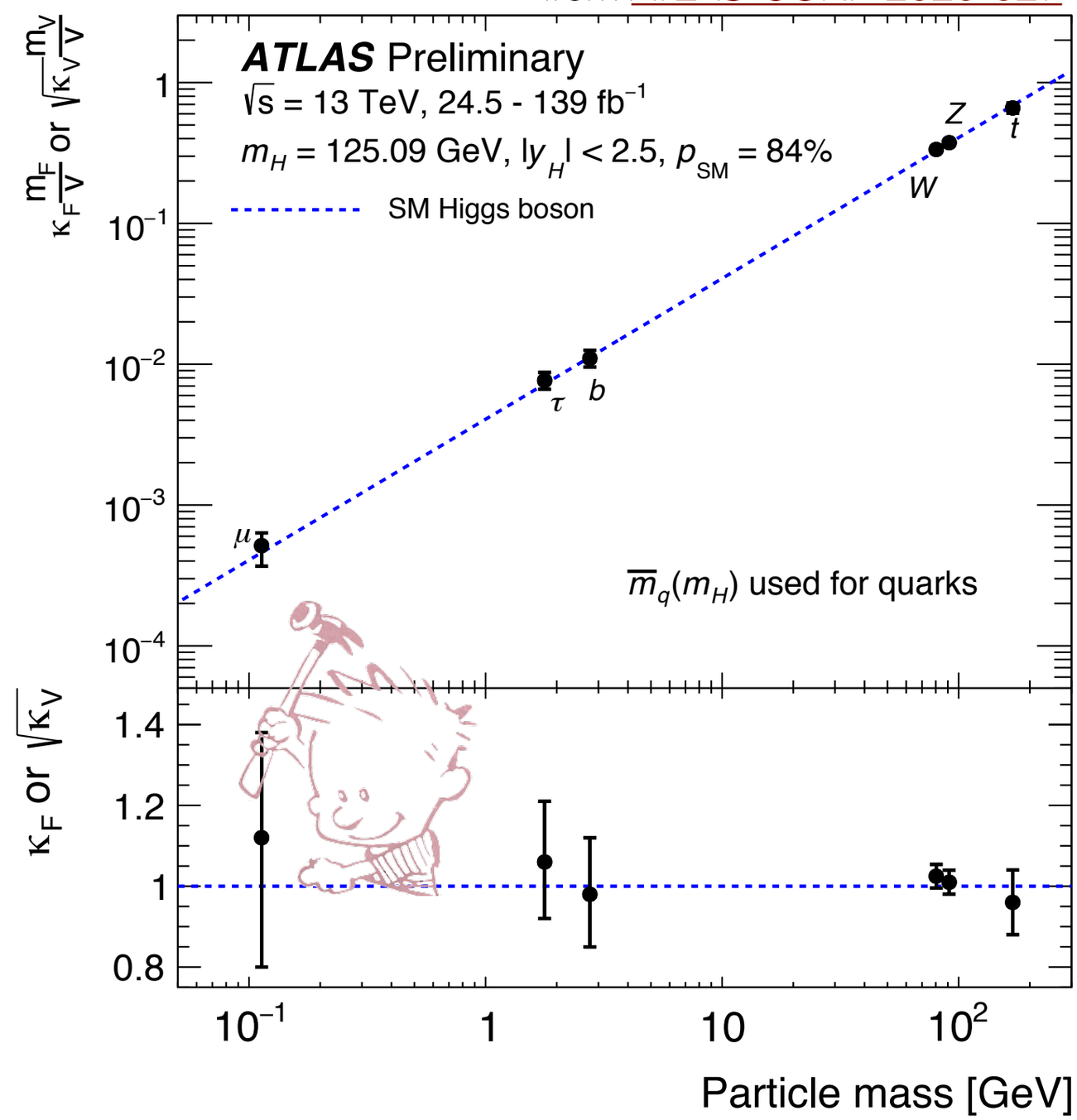
- *Run 3 of vital importance to further increase sensitivity!*

from ATLAS-CONF-2020-027



Backup Slides

Object-level selections

Muons

- $|\eta|<2.7$, $p_T^{lead}>27$ GeV (matching event trigger), $p_T^{sub}>15$ 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

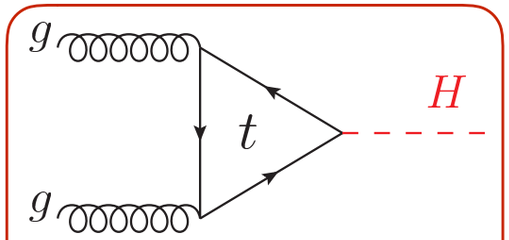
- Reconstructed using the particle flow algorithm
- $p_T>25$ GeV for $|\eta|<2.4$, $p_T>30$ GeV for $2.4<|\eta|<4.5$
- remove jets not coming from the primary vertex (only for jets with $|\eta|<2.4$ and $p_T<60$ GeV)

Electrons

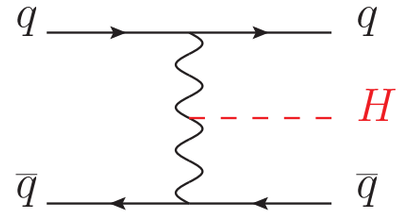
- $|\eta|<2.47$ and $p_T>7$ GeV (excluding $1.37<|\eta|<1.52$)
- Isolated (ID tracks and calo clusters within $\Delta R<0.2$) and matching the primary vertex

Choice of analysis categories

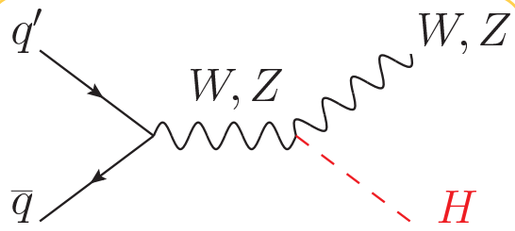
- Sort event in mutually exclusive categories, targeting the various Higgs boson production modes
  - Category selections applied in a specific, exclusive order
- Employ process-specific boosted decision trees (using XGBoost)



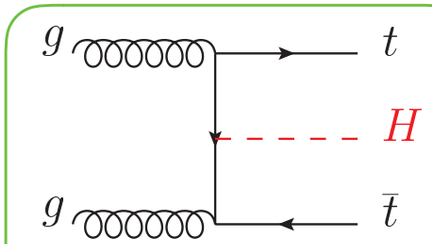
gluon fusion (ggF)
σ = 48.6 pb



Vector-boson fusion (VBF)
σ = 3.78 pb



Higgs-strahlung (*WH/ZH*)
σ = 2.25 pb



prod. with top pair (*ttH*)
σ = 0.5 pb

Basic selection
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

ggF categories: 0-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
0-jet Very High	59	96%	0.4%
0-jet High	99	99%	0.2%
0-jet Medium	119	99%	0.1%
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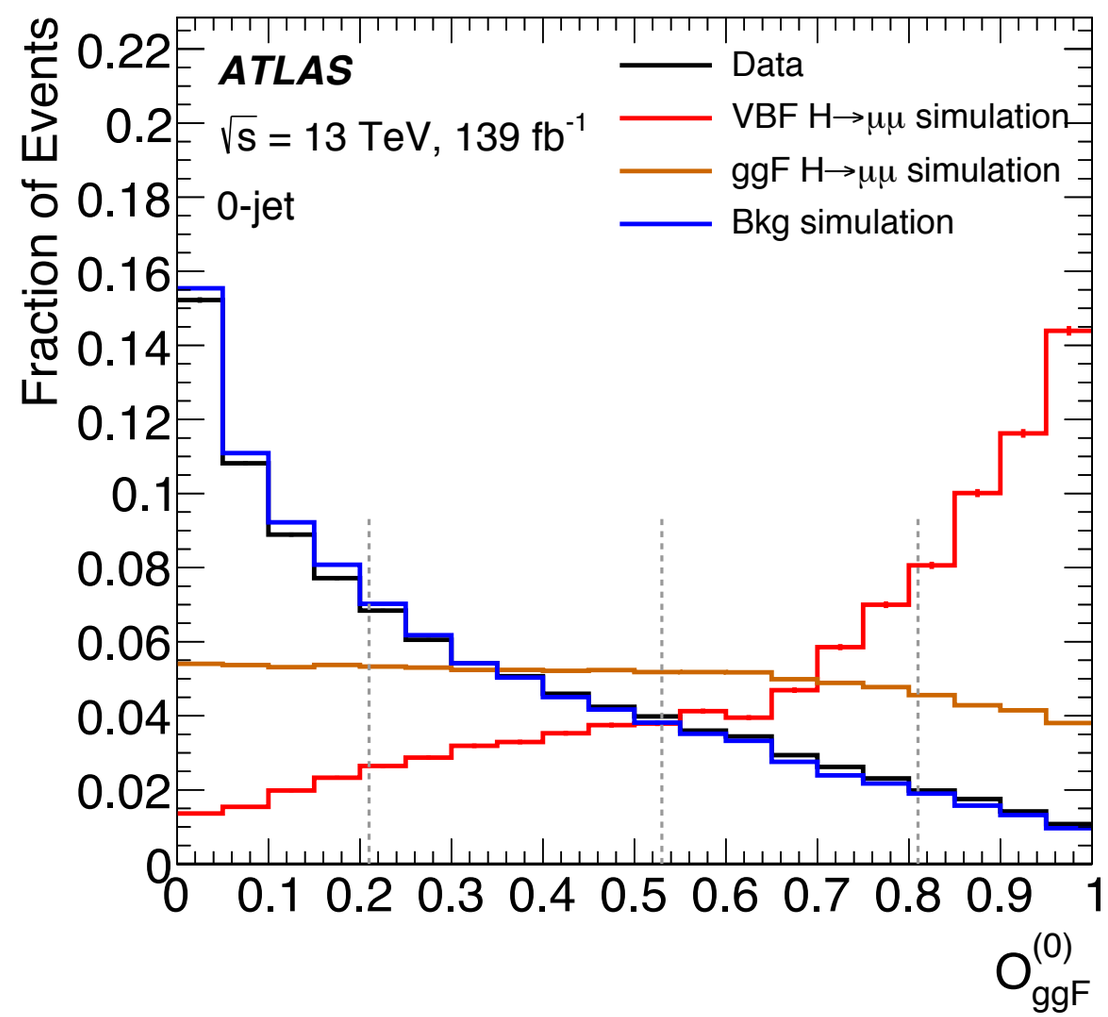

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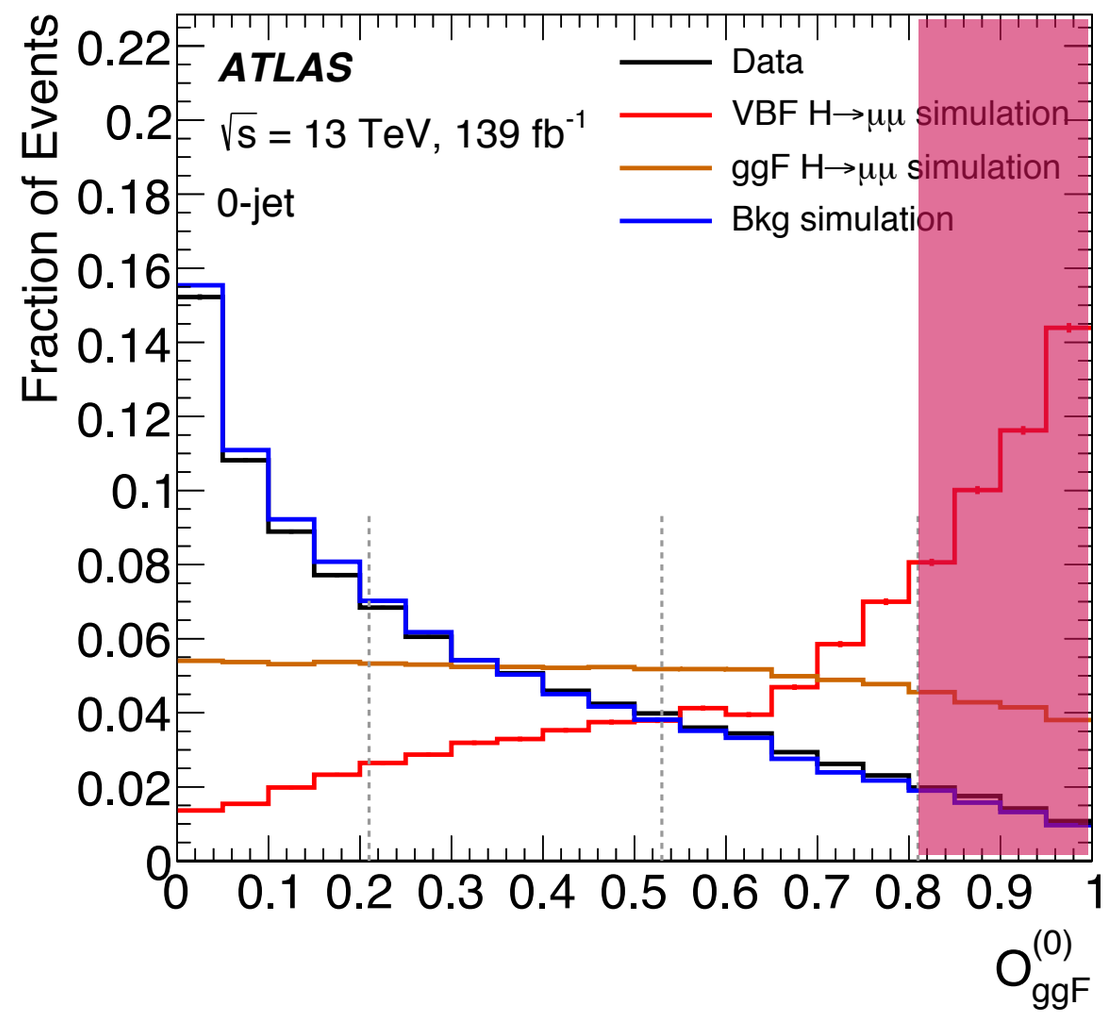

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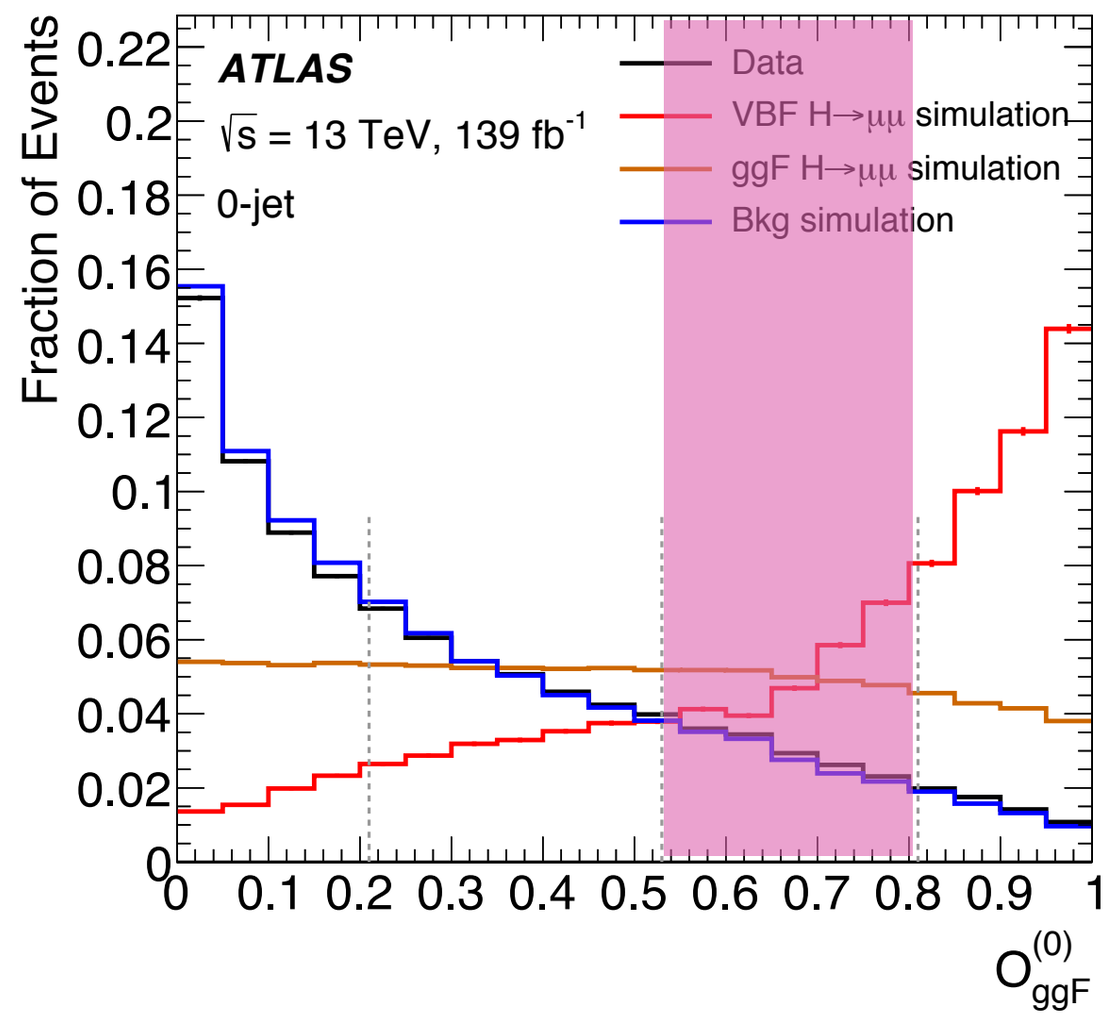

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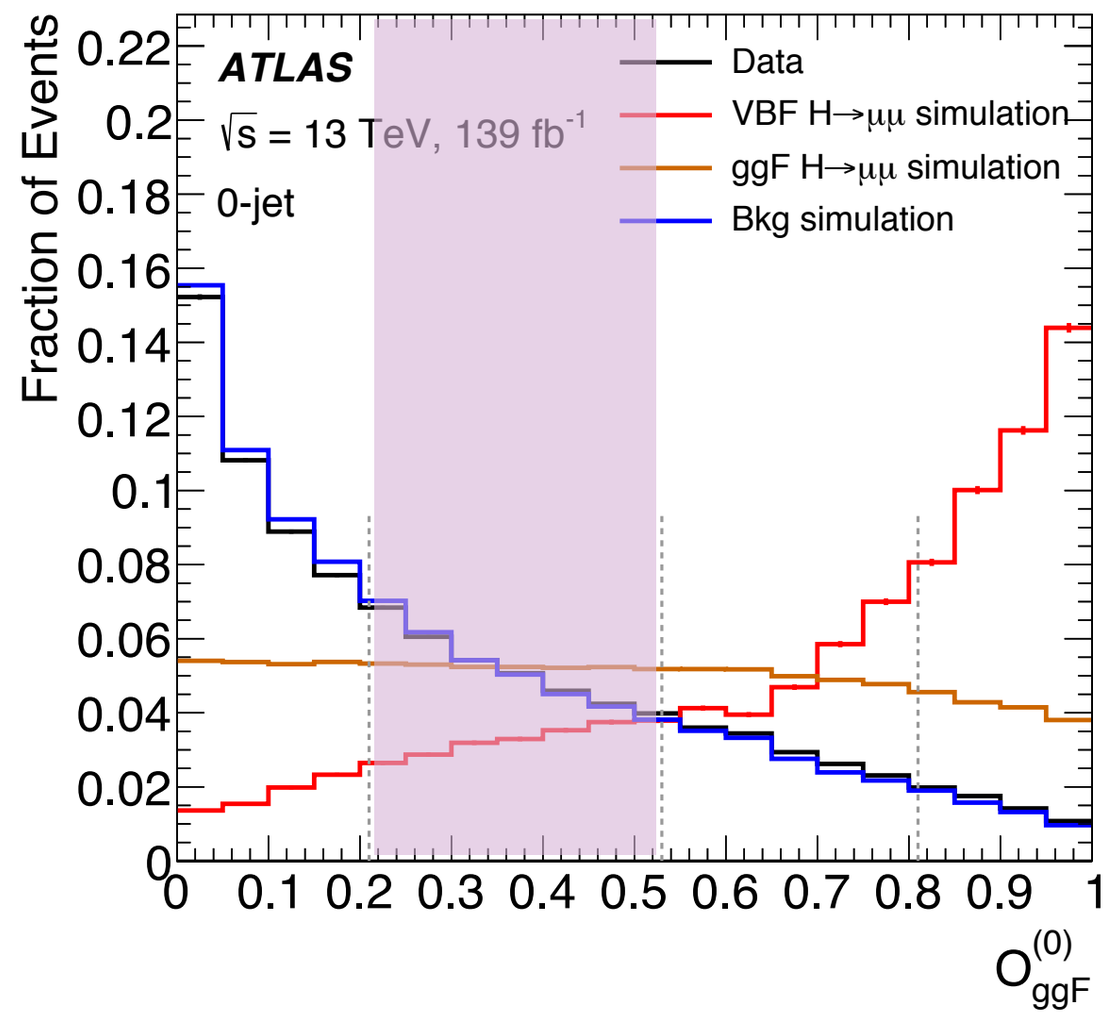

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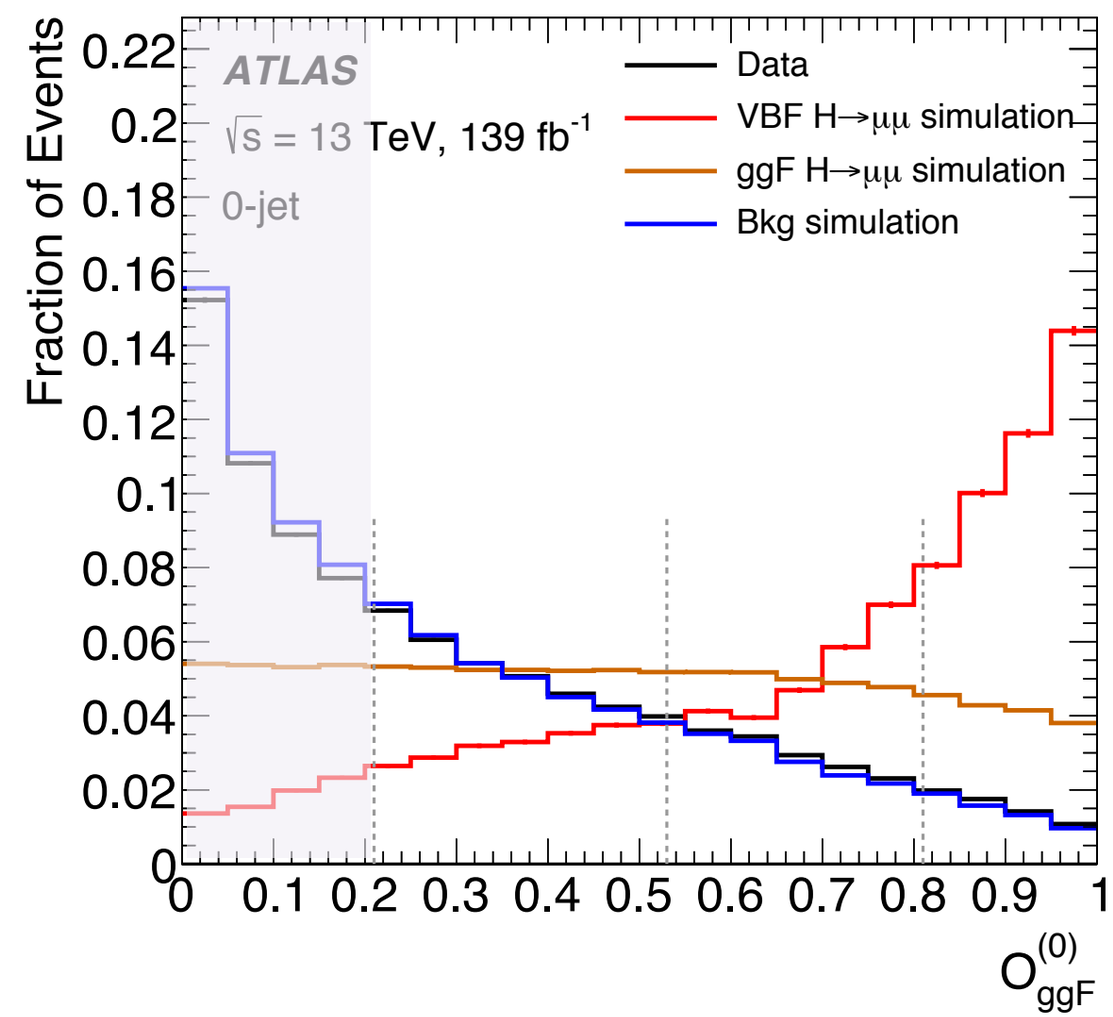
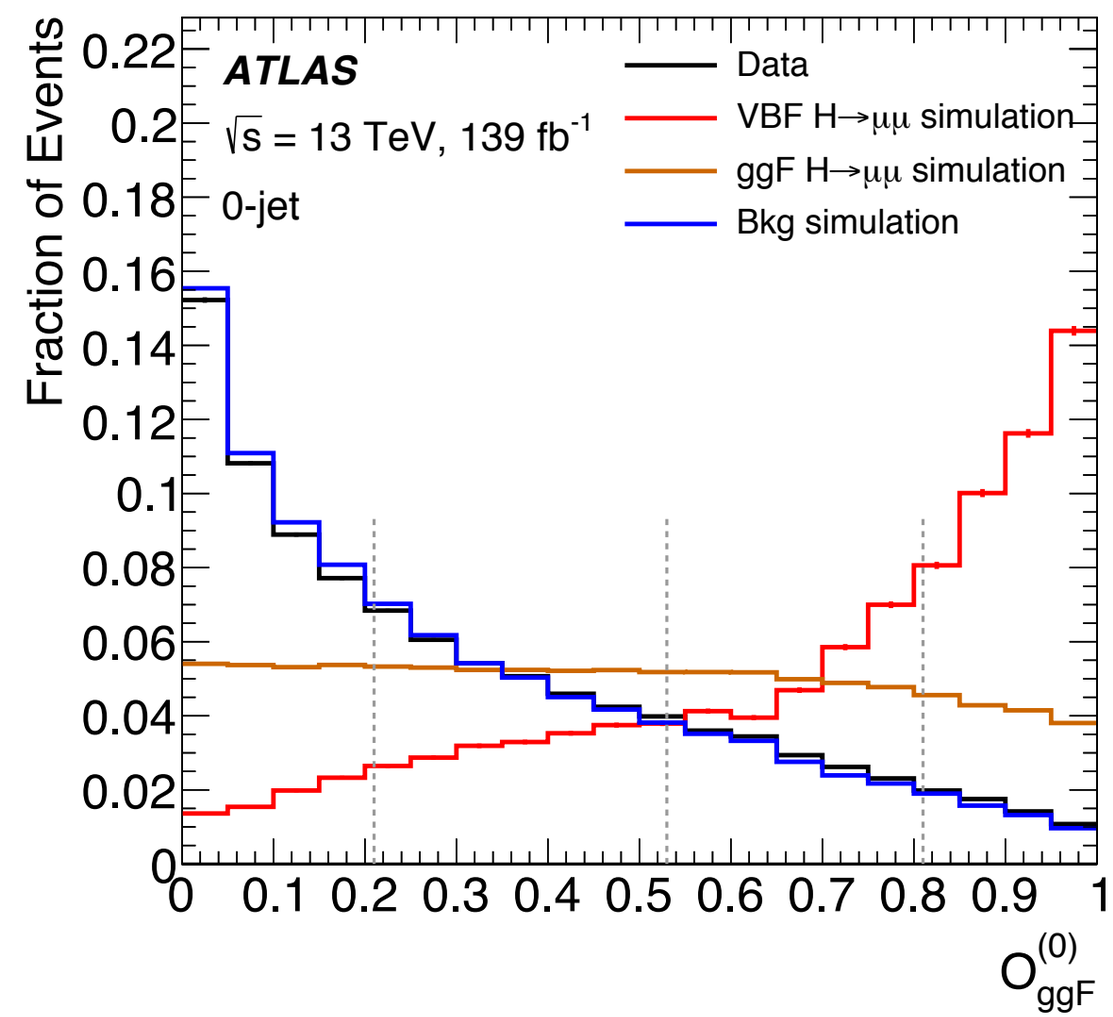


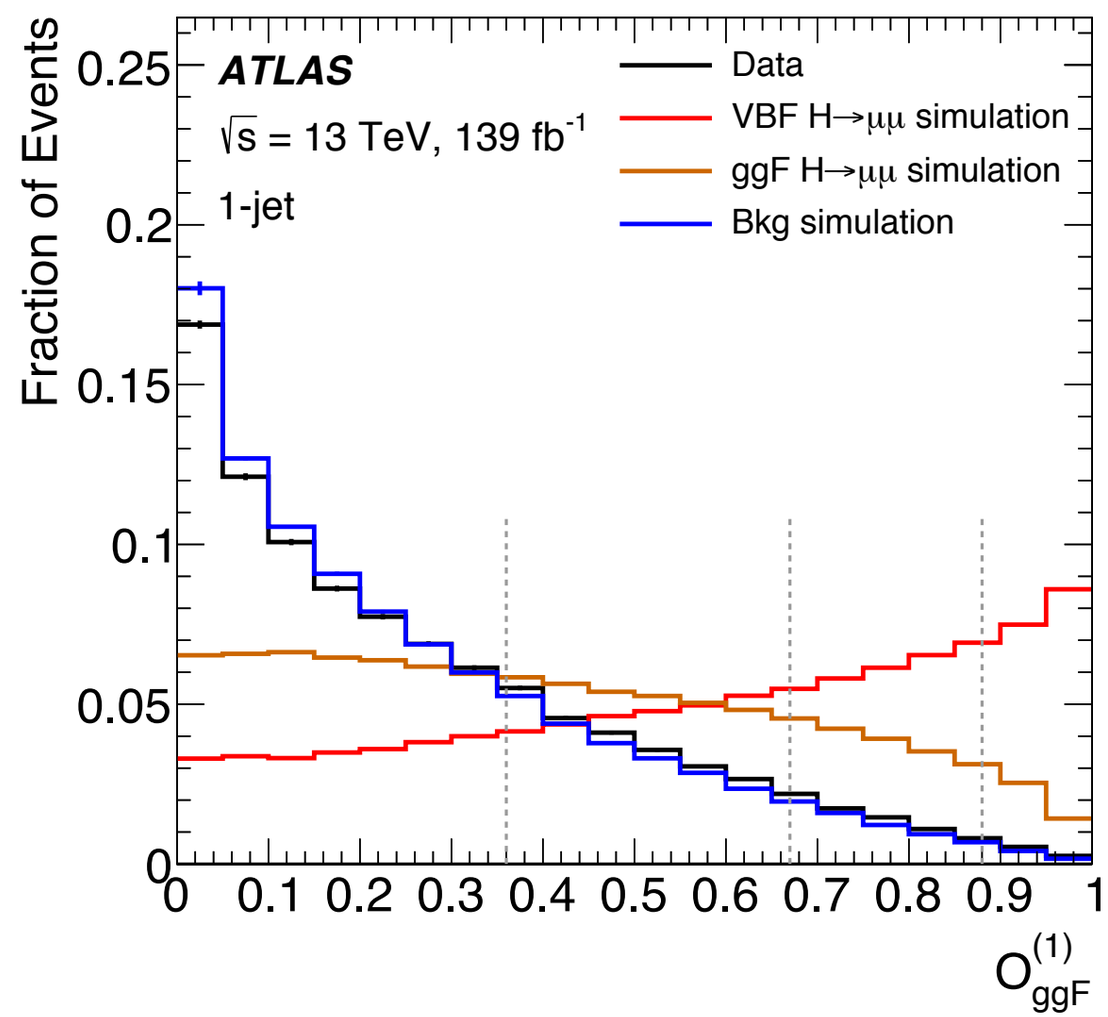
ggF categories: 0-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
0-jet Very High	59	96%	0.4%
0-jet High	99	99%	0.2%
0-jet Medium	119	99%	0.1%
0-jet Low	79	99%	0.1%



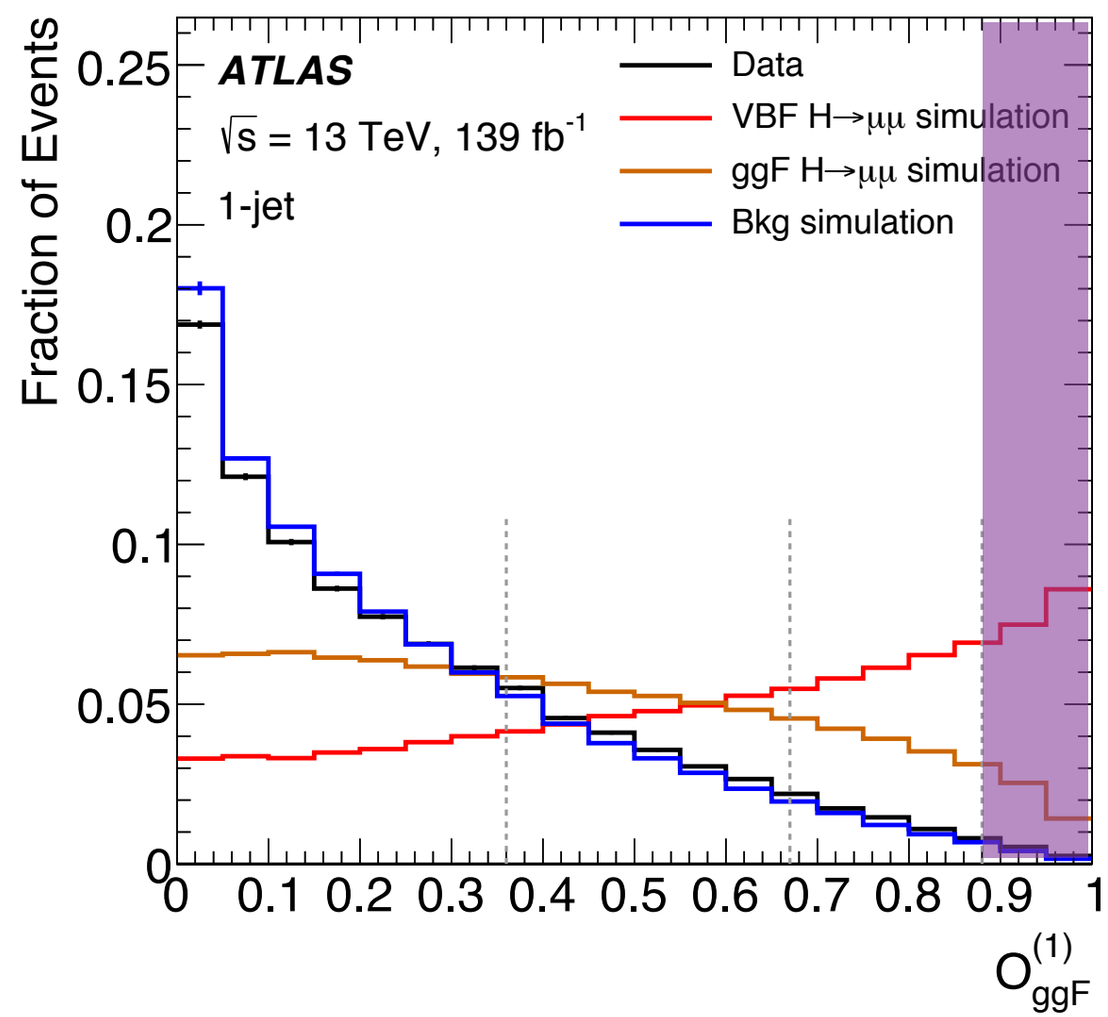
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



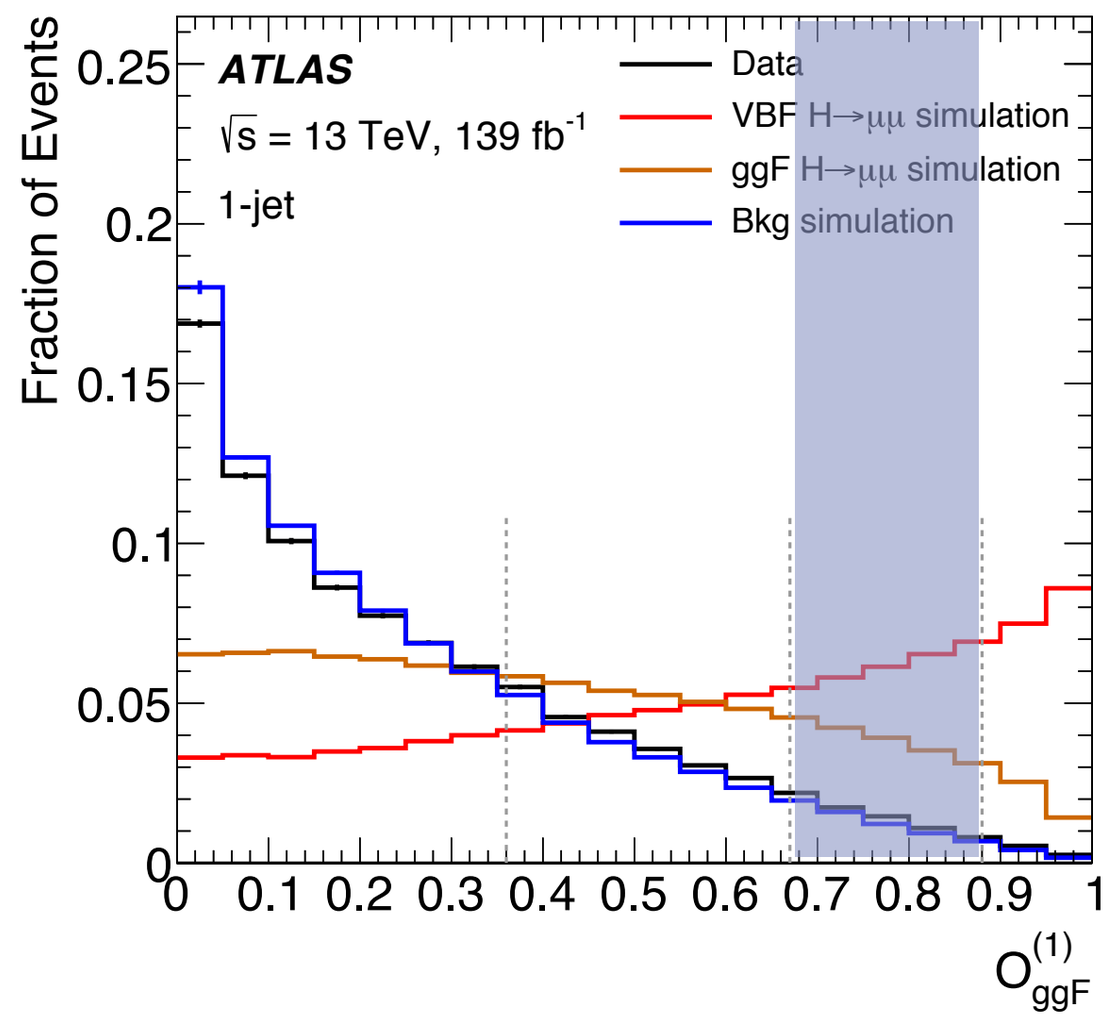
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



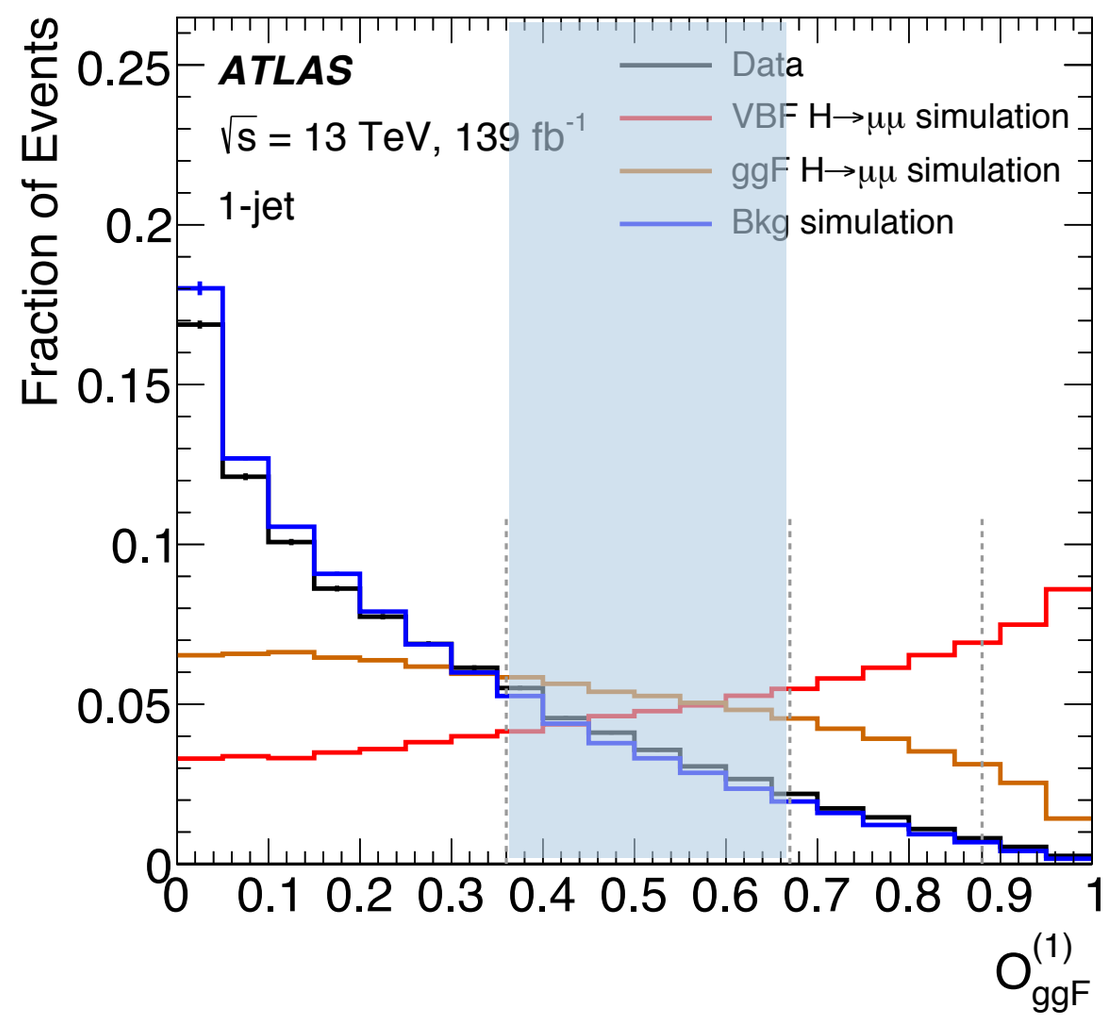
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



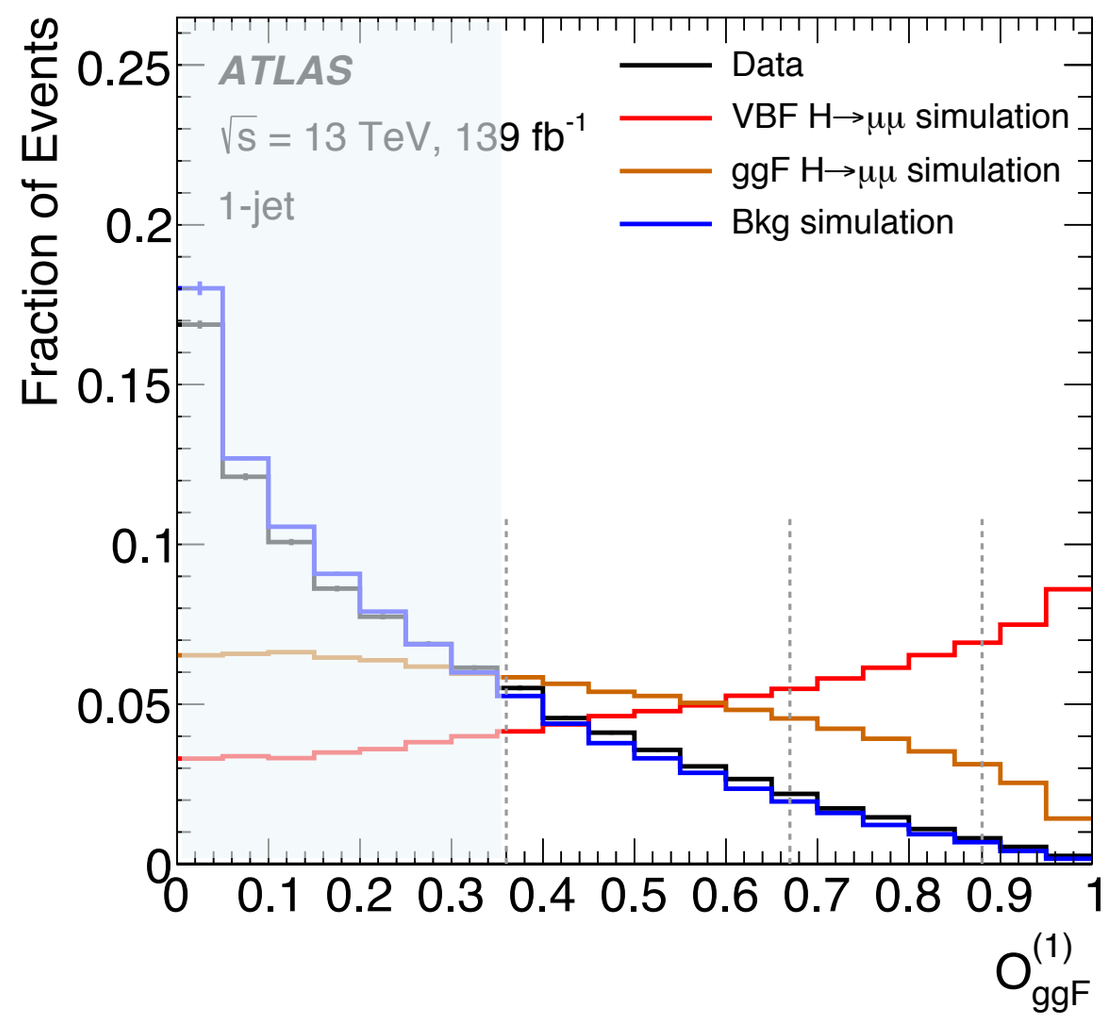
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



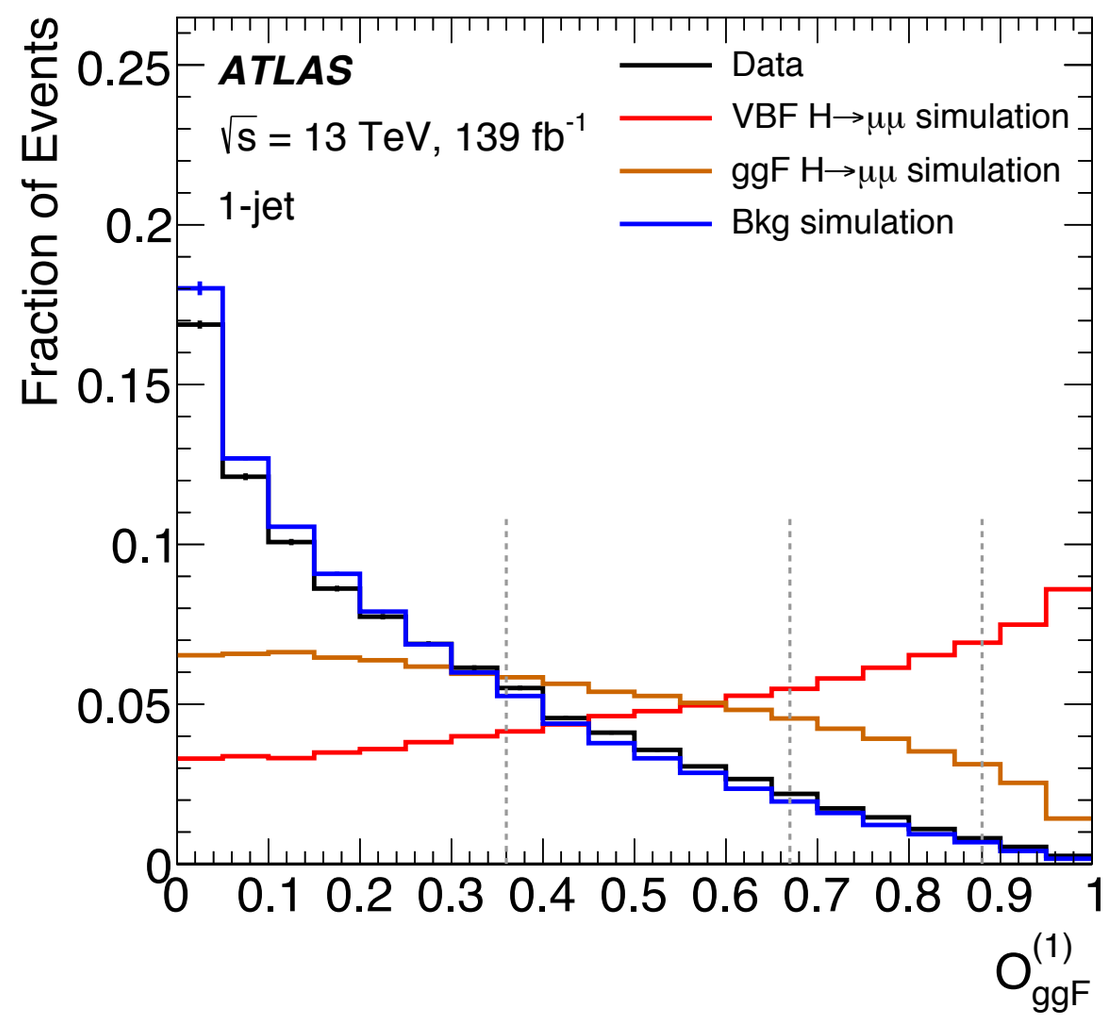
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



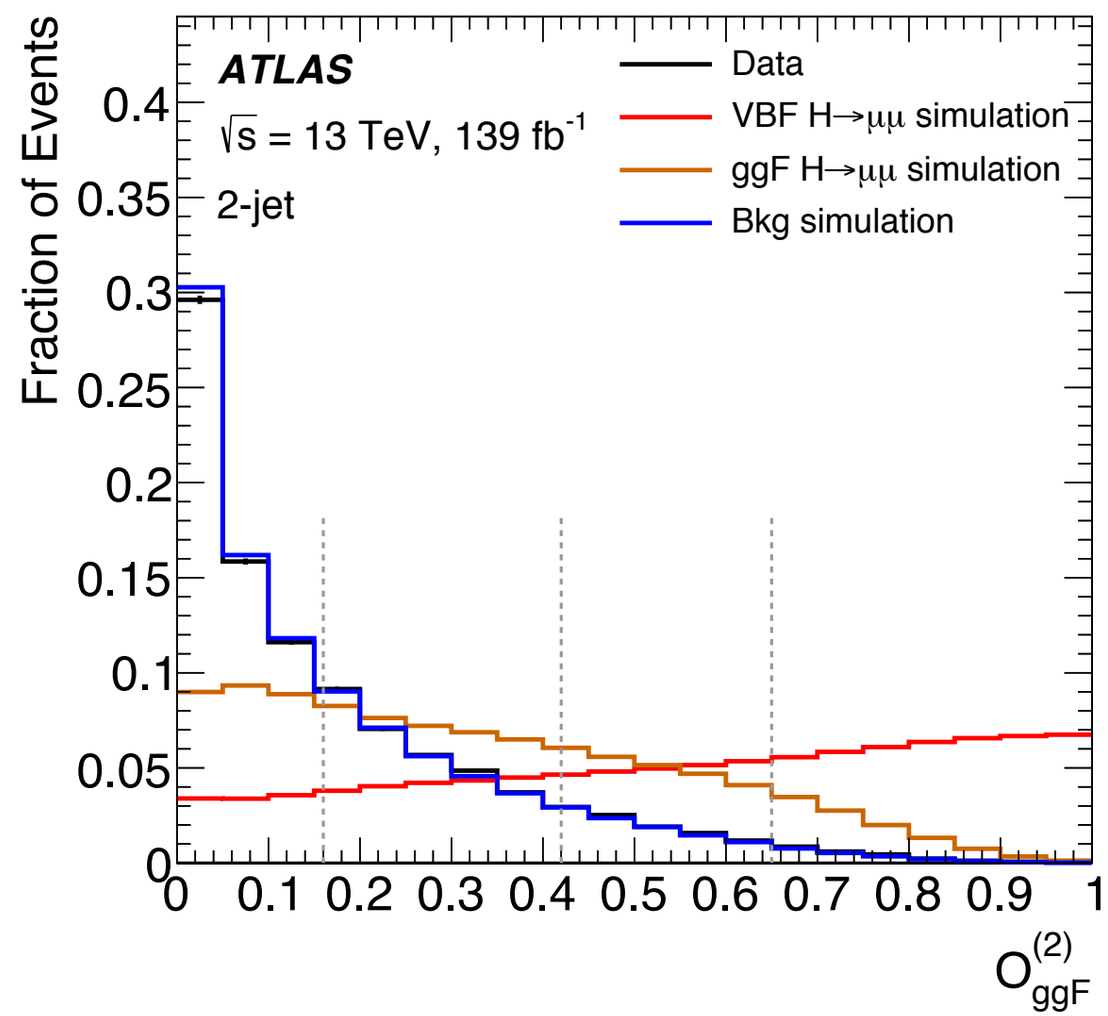
ggF categories: 1-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
1-jet Very High	16.5	99%	1.5%
1-jet High	46	98%	0.7%
1-jet Medium	90	97%	0.4%
1-jet Low	125	96%	0.2%



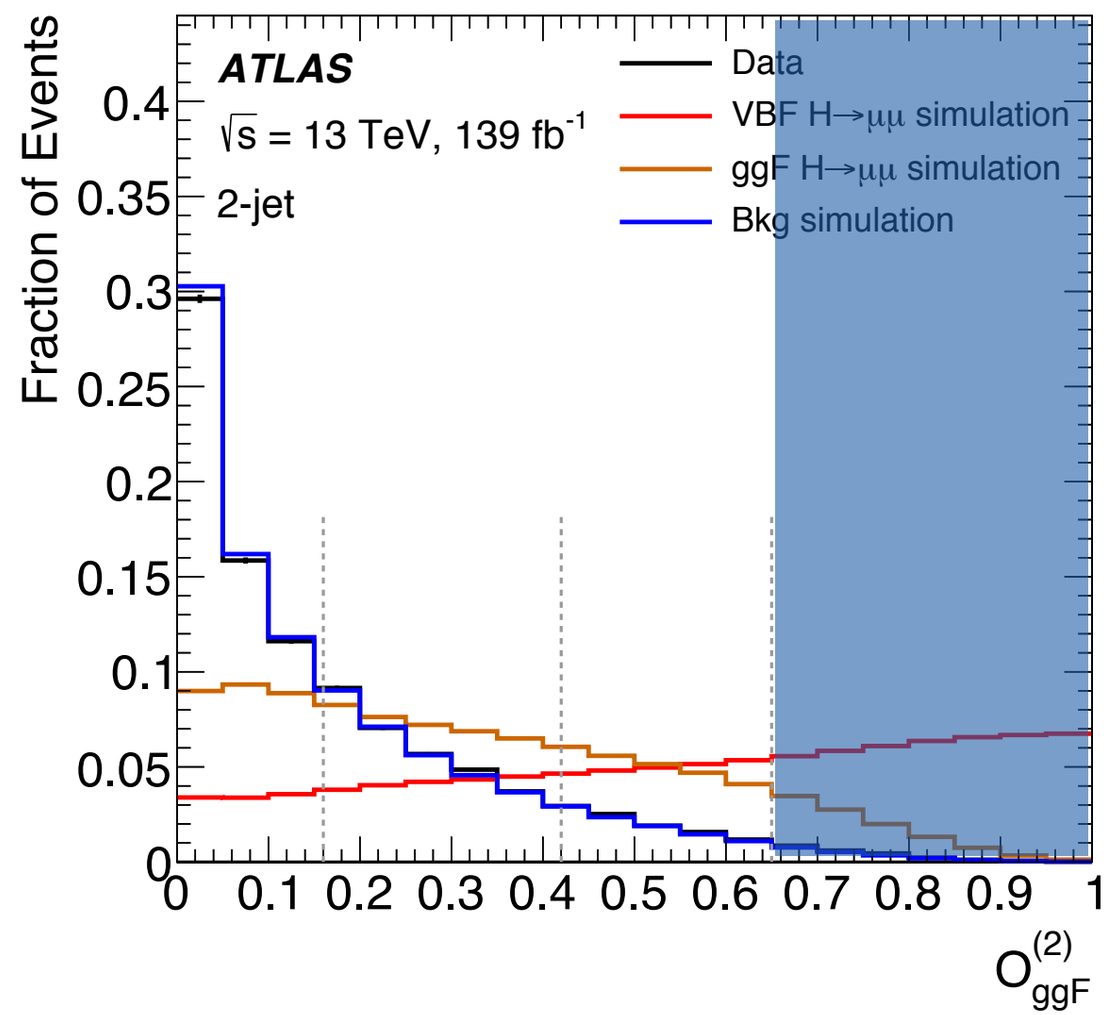
ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



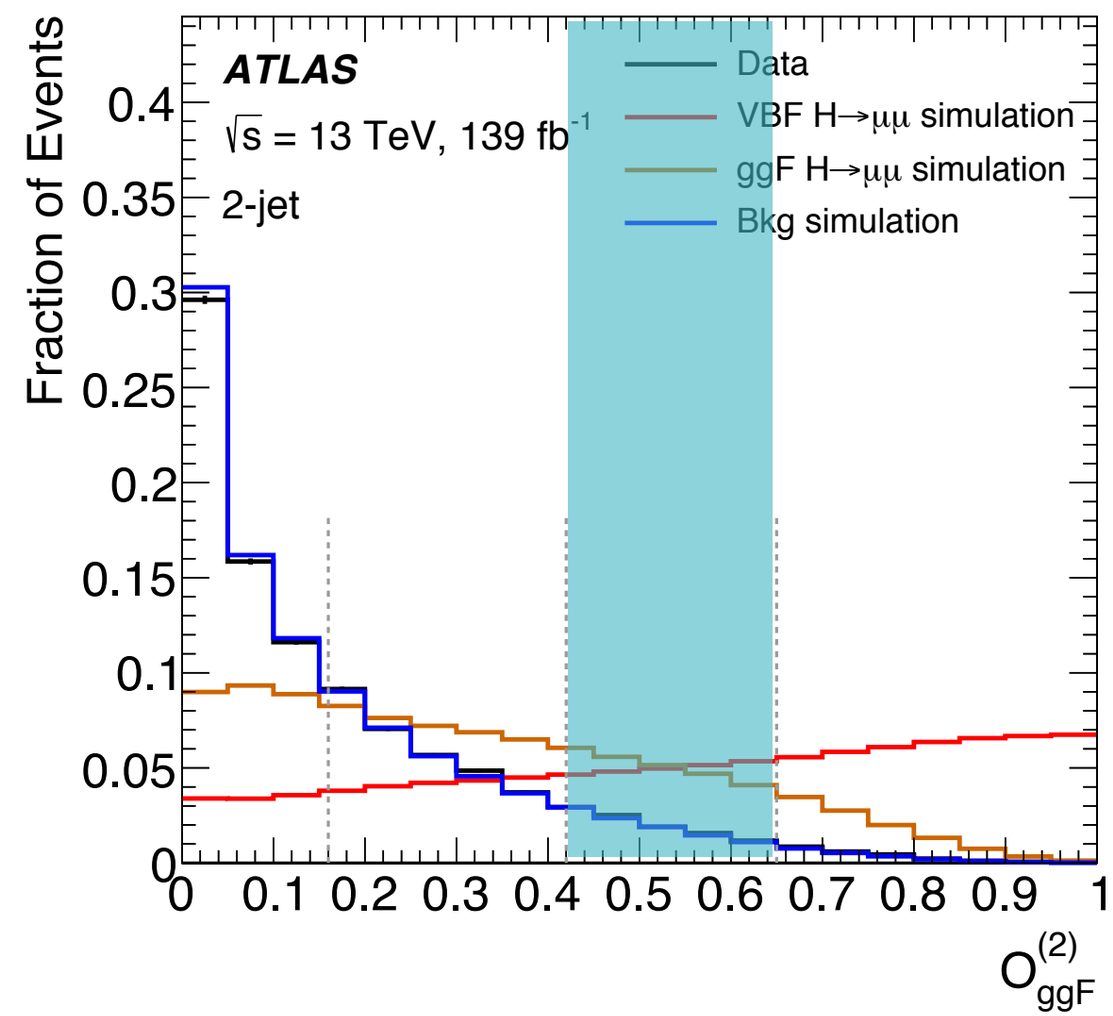
ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



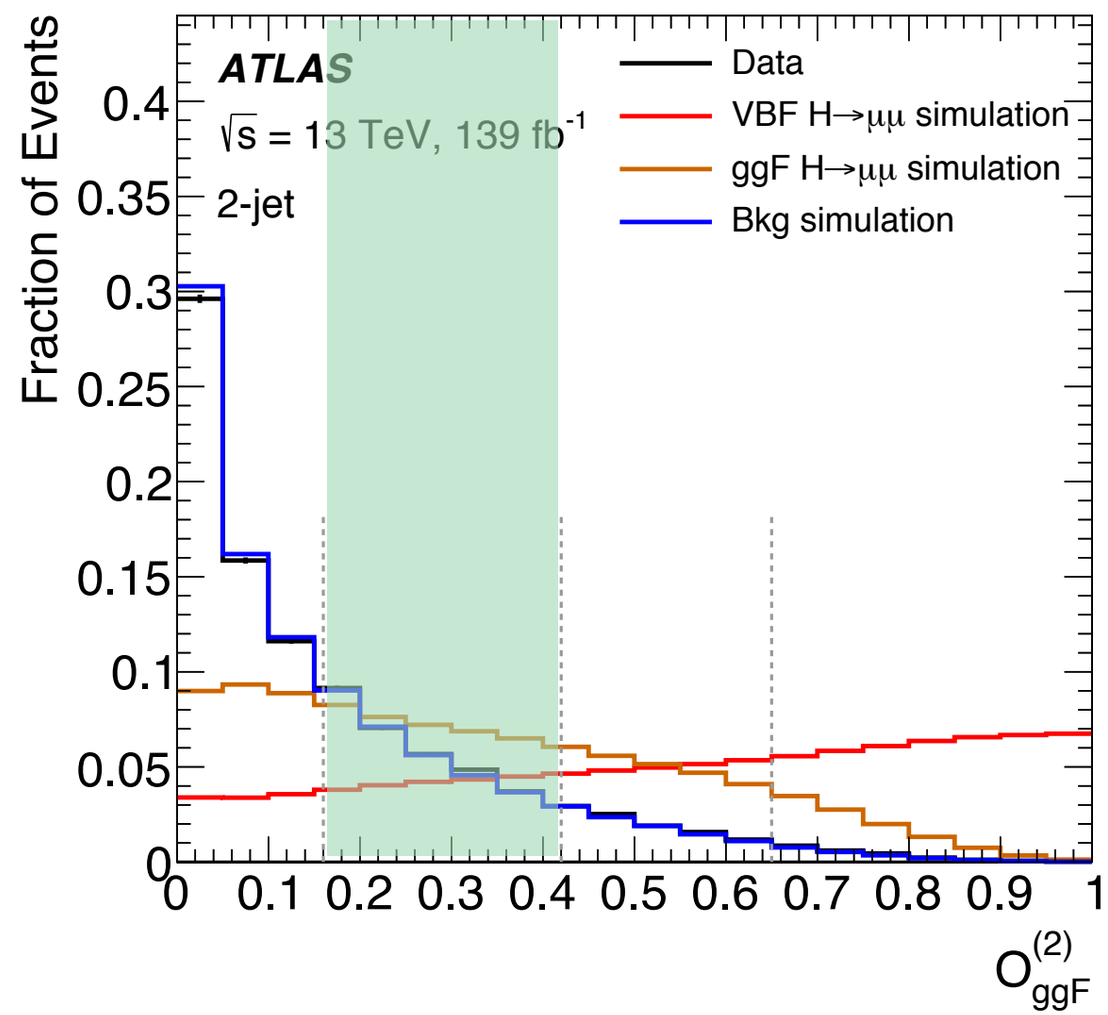
ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



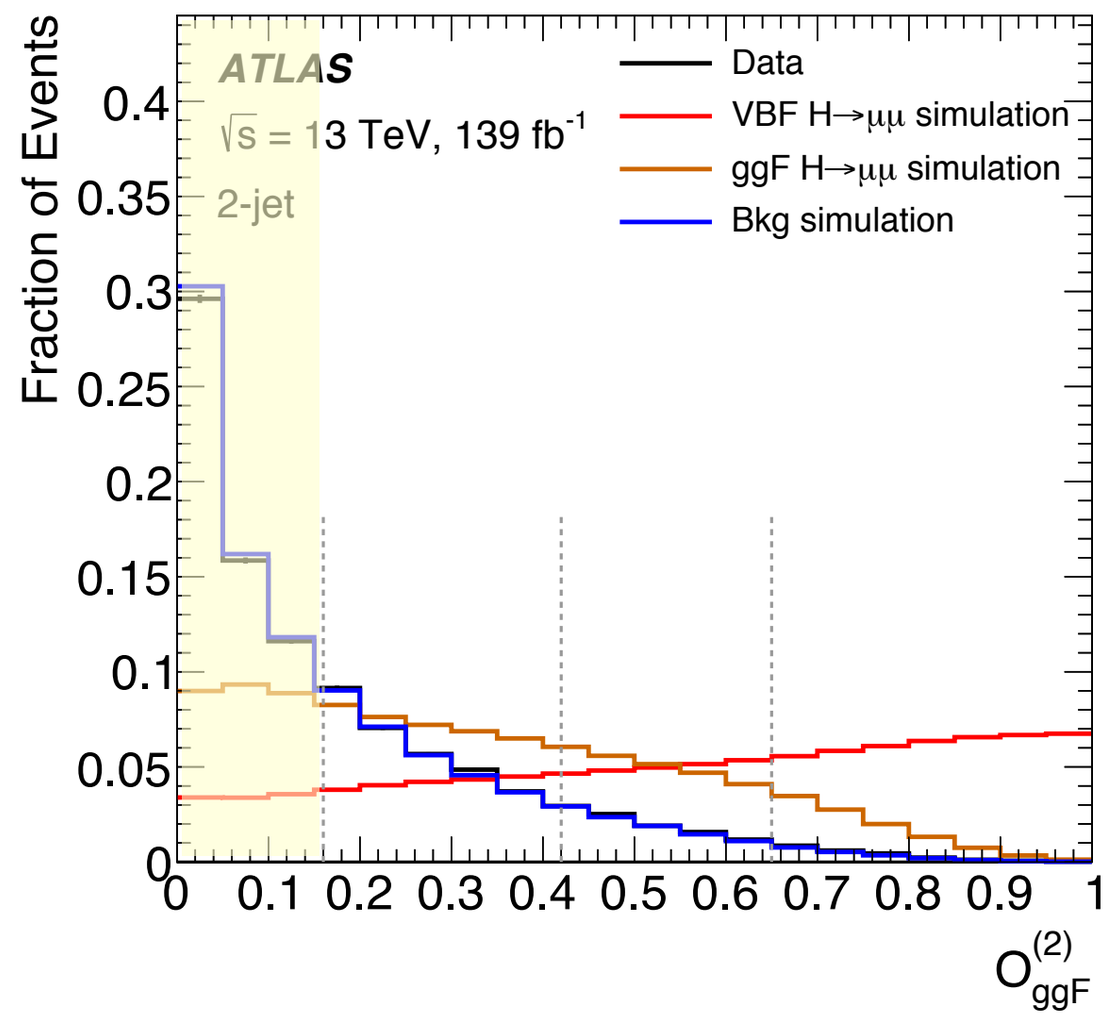
ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



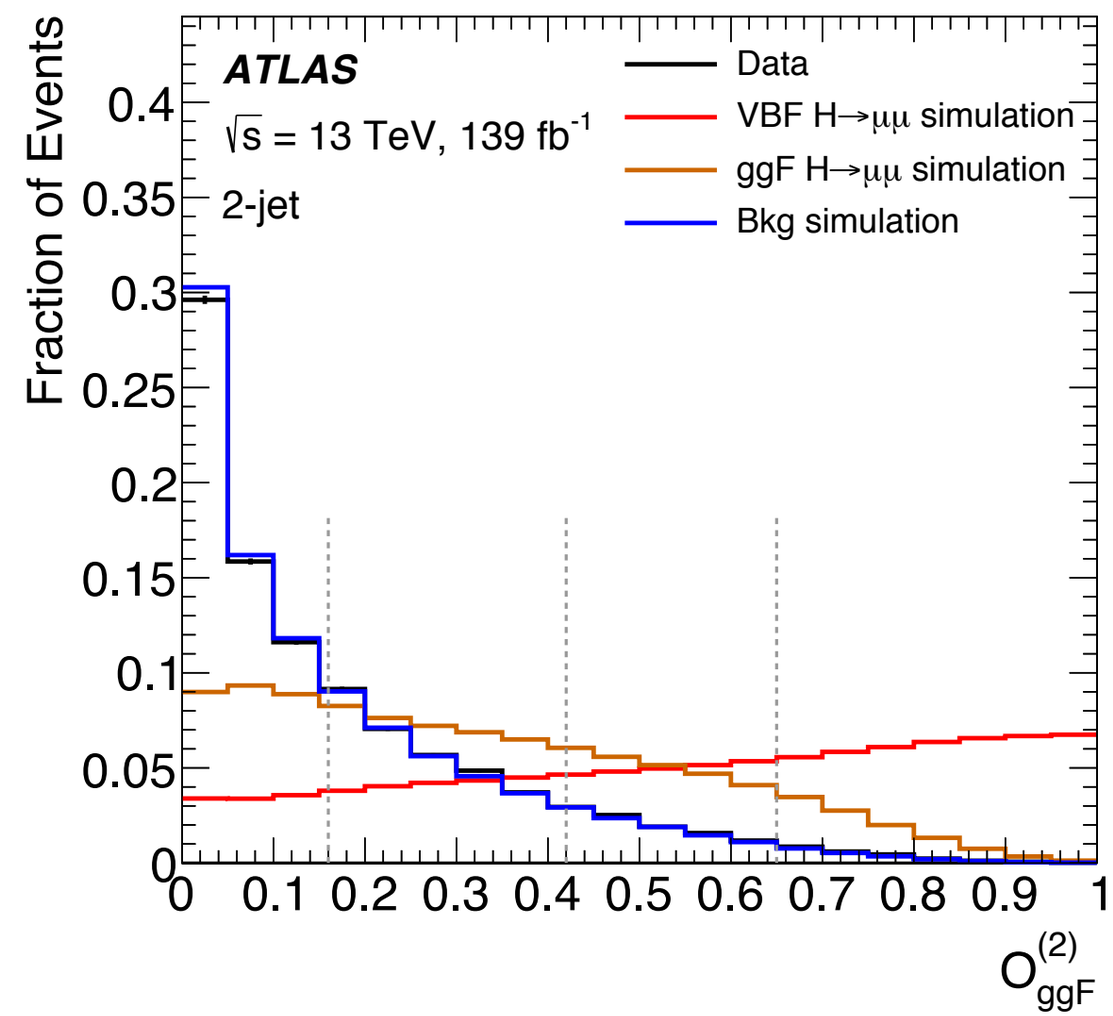
ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



ggF categories: 2-jet channel

Category	Expected signal	ggF+VBF purity	Expected S/B
2-jet Very High	17.6	98%	1.7%
2-jet High	50	95%	1%
2-jet Medium	79	91%	0.4%
2-jet Low	63	85%	0.2%



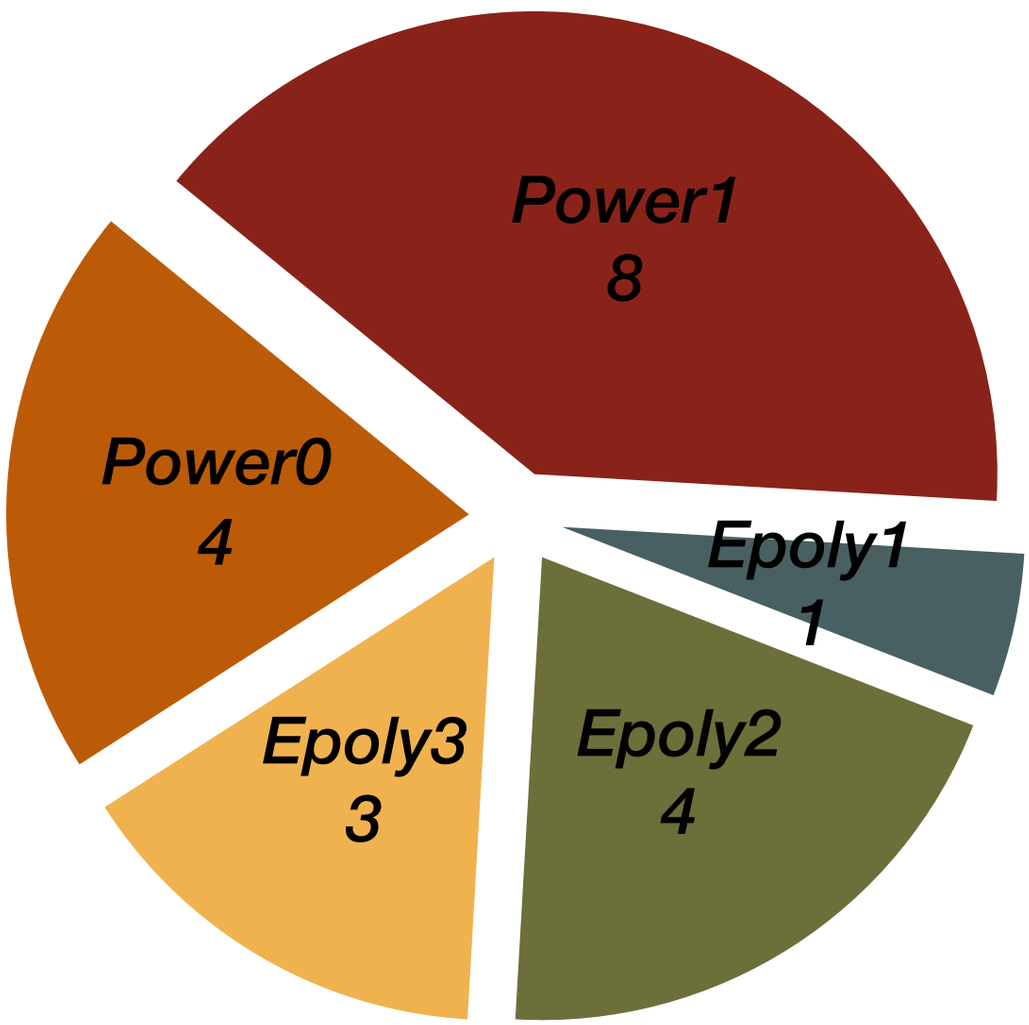
Signal composition

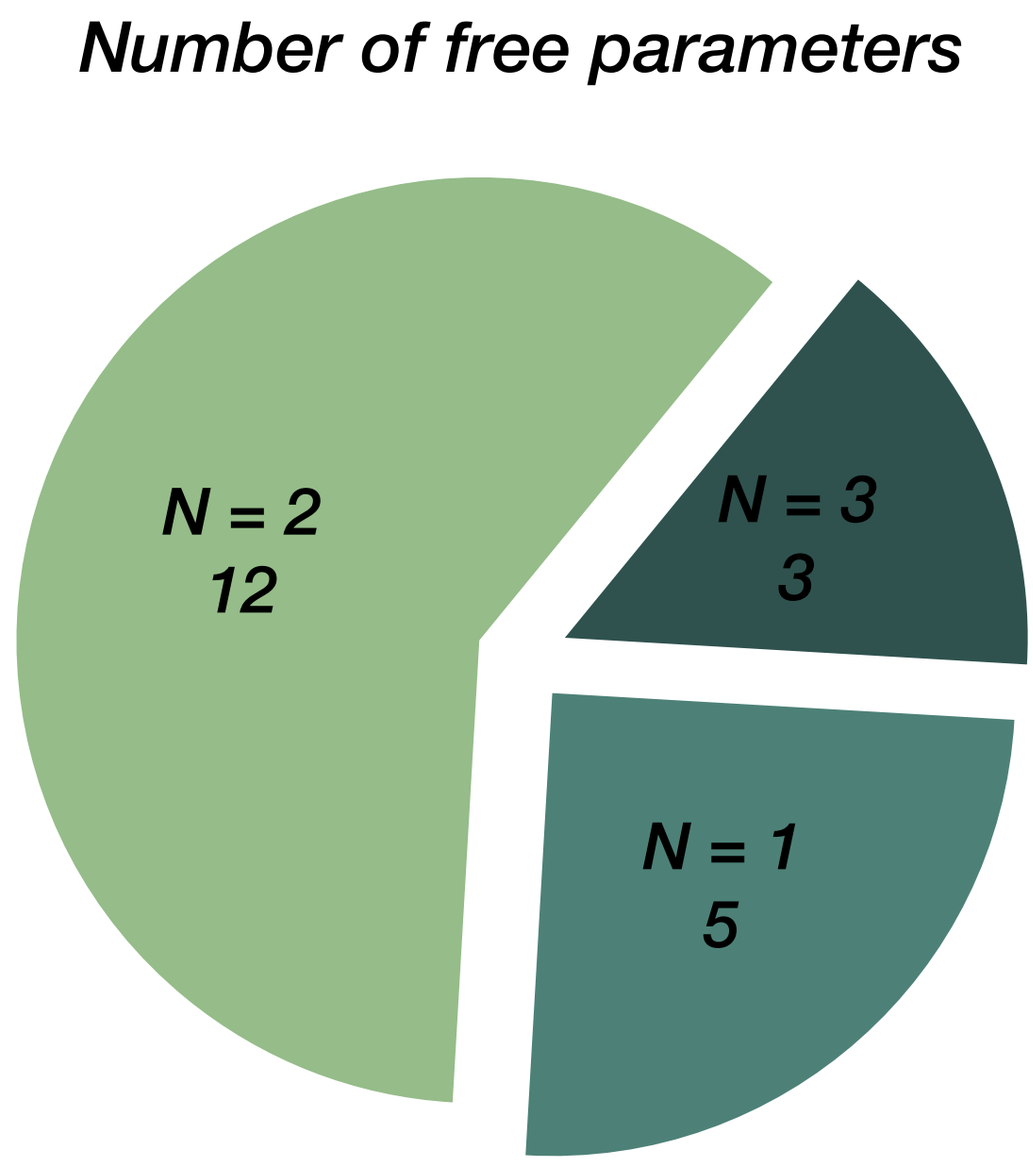
Category	ggF	VBF	WH	ZH	$t\bar{t}H$
VBF Very High	6.6%	93.3%	0.0%	0.0%	0.0%
VBF High	12.8%	87.1%	0.0%	0.0%	0.0%
VBF Medium	21.3%	78.5%	0.1%	0.1%	0.0%
VBF Low	34.8%	64.8%	0.2%	0.2%	0.0%
2-jet Very High	82.0%	15.7%	1.2%	1.0%	0.2%
2-jet High	79.3%	16.0%	2.7%	1.8%	0.3%
2-jet Medium	80.7%	10.4%	5.4%	3.0%	0.5%
2-jet Low	78.2%	6.6%	8.8%	4.9%	1.5%
1-jet Very High	78.2%	21.2%	0.3%	0.3%	0.0%
1-jet High	88.2%	10.4%	0.9%	0.6%	0.0%
1-jet Medium	91.4%	6.1%	1.6%	0.9%	0.0%
1-jet Low	92.4%	3.8%	2.6%	1.2%	0.0%
0-jet Very High	94.1%	2.5%	1.4%	2.0%	0.0%
0-jet High	98.3%	1.0%	0.4%	0.3%	0.0%
0-jet Medium	99.1%	0.6%	0.2%	0.1%	0.0%
0-jet Low	99.5%	0.3%	0.1%	0.1%	0.0%
VH4L	0.0%	0.0%	0.1%	99.5%	0.4%
VH3LH	0.3%	0.1%	96.9%	2.6%	0.1%
VH3LM	4.2%	1.0%	80.8%	8.6%	5.3%
$t\bar{t}H$	0.1%	0.0%	1.5%	0.4%	98.0%

Background modelling uncertainties

Category	Empirical Function	max(SS/ δS)[%]	max(SS/S_{SM})[%]
VBF Very High	Epoly1	-20.3	-34.8
VBF High	Power0	11.7	20.0
VBF Medium	Power0	8.5	16.4
VBF Low	Power0	11.2	2.4
2-jet Very High	Power1	-13.3	-34.5
2-jet High	Epoly2	-19.8	-41.2
2-jet Medium	Power1	19.8	40.9
2-jet Low	Epoly3	2.1	8.0
1-jet Very High	Epoly2	21.9	-53.4
1-jet High	Epoly2	-7.8	-18.5
1-jet Medium	Power1	4.2	7.9
1-jet Low	Power1	17.3	51.5
0-jet Very High	Power1	19.2	50.9
0-jet High	Power1	-19.4	43.5
0-jet Medium	Power1	25.8	69.4
0-jet Low	Epoly3	-20.8	-100.4
VH4L	Power1	20.7	230
VH3LH	Epoly2	36.9	210
VH3LM	Epoly3	33.6	276
$t\bar{t}H$	Power0	32.2	117

Background model choice





Compatibility with previous result

μ ATLAS-CONF-2019-028	μ this work	Compatibility
0.5 ± 0.7	1.2 ± 0.6	1.4σ

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

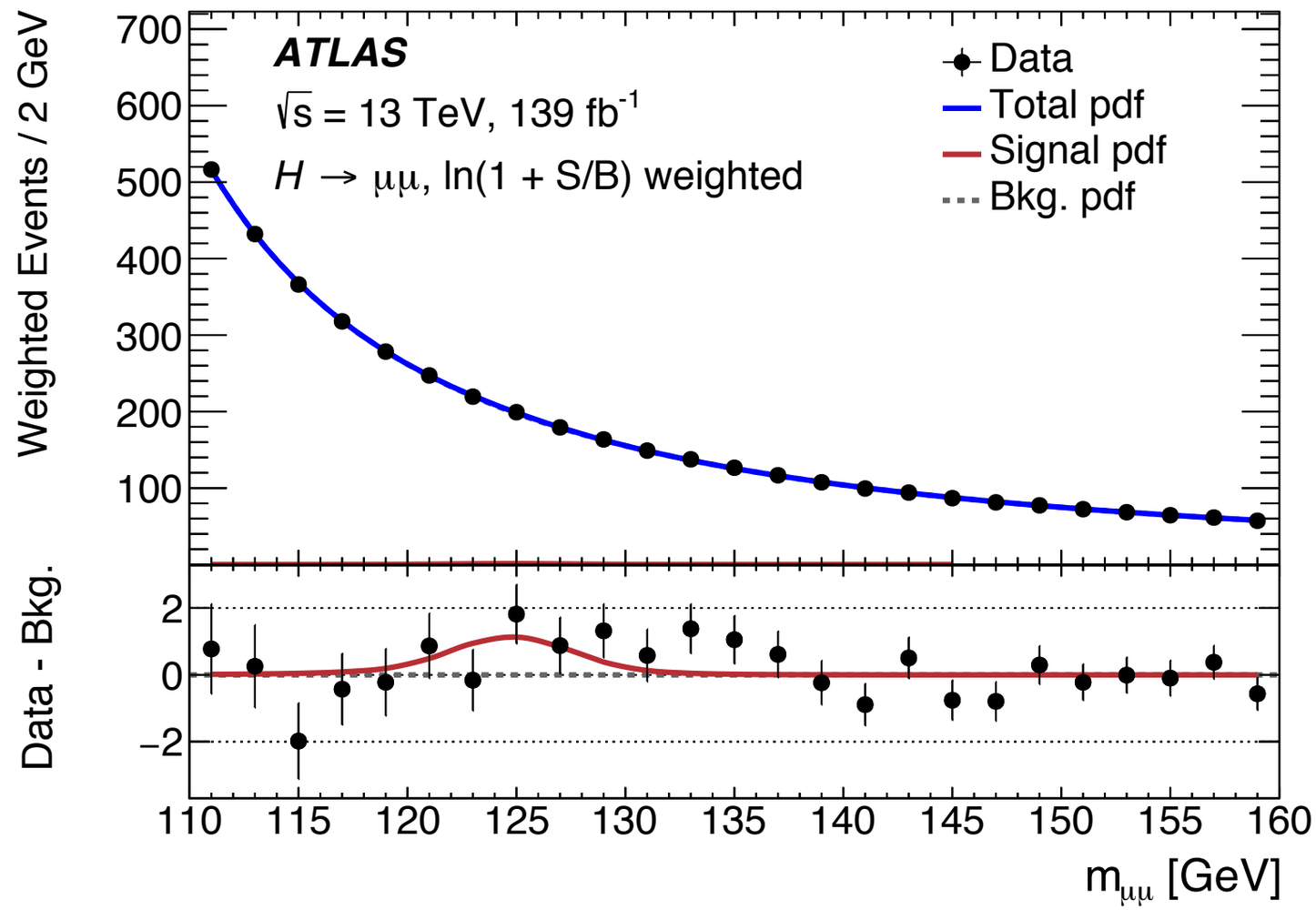
Their compatibility in terms of data statistics only and expressed as number of standard deviations σ is evaluated using a bootstrap technique (see Ref. Phys. Rev. D 39 (1 1989) 274]) based on the data events passing the selection of either ATLAS-CONF-2019-028, or the one of the current analysis, or both.

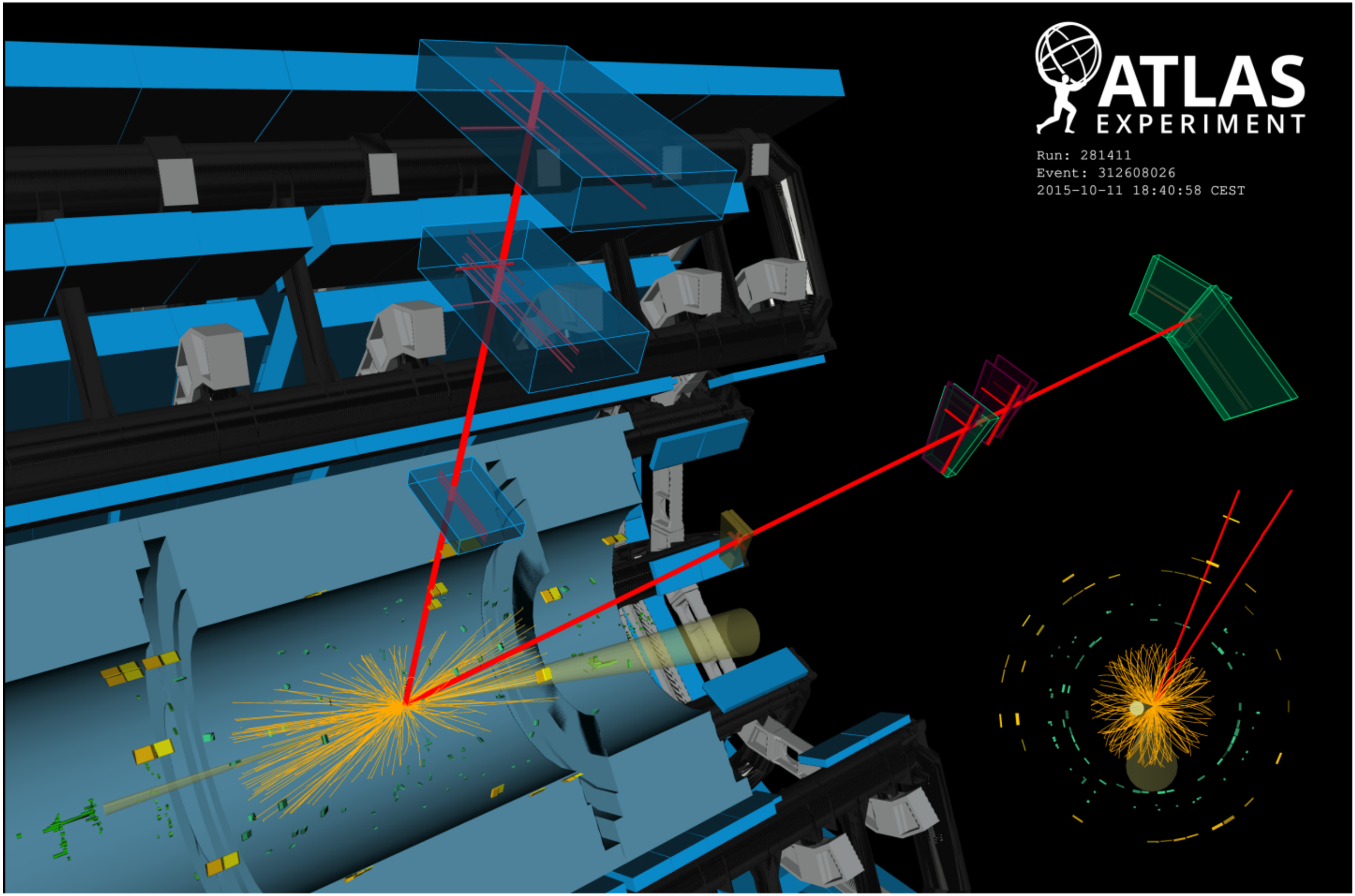
All procedures of the respective analyses are preserved.

The correlation between the two signal strength measurements is evaluated to be 75%.

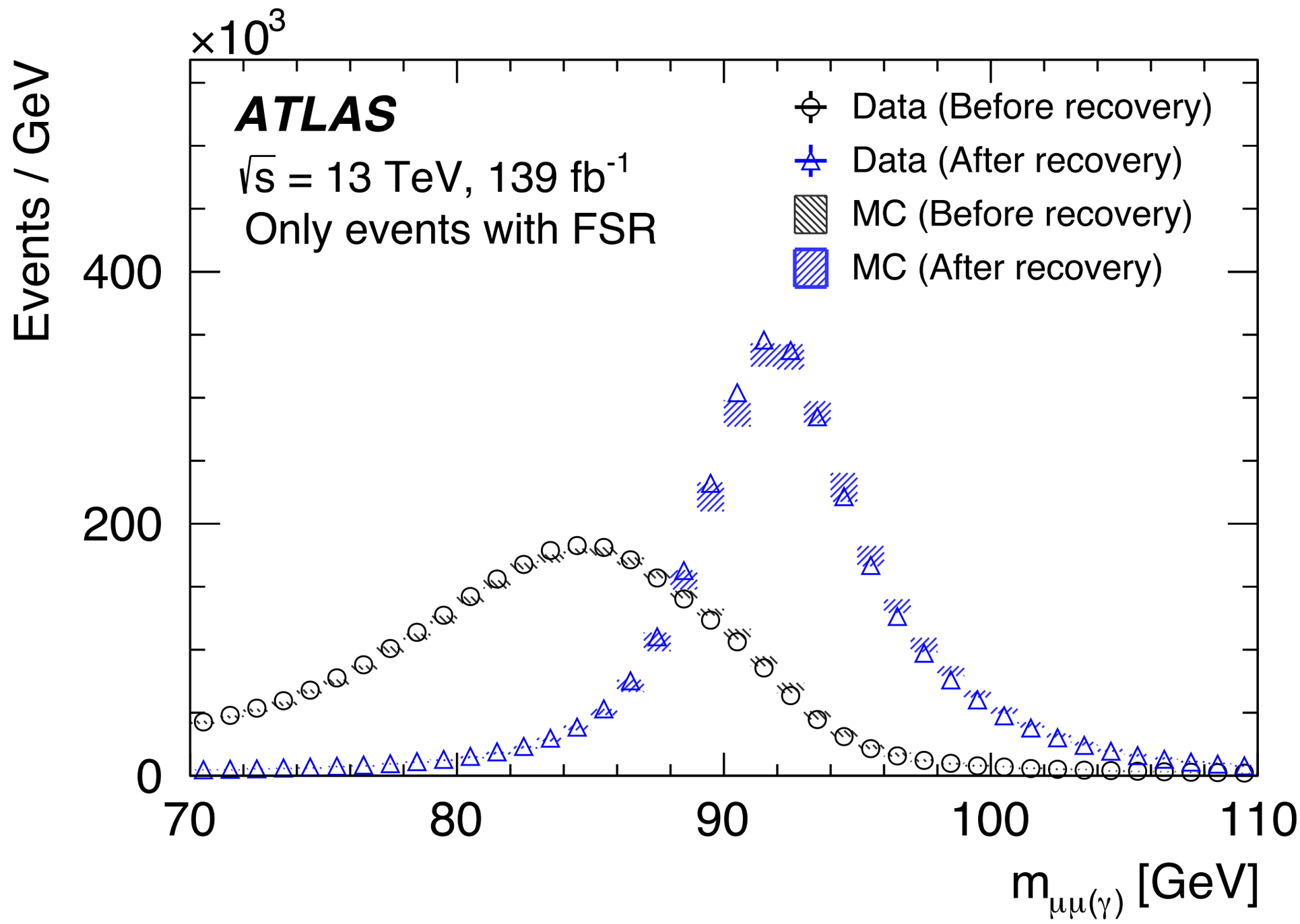
Broad excess at 135 GeV?

- 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 σ at 135 GeV
- Including the *look elsewhere effect* (see here for a reference):
  - the global significance goes down to 1.6 σ, when using the 130-150 GeV range for the test (trial factor ~9)
  - if considering the entire range range of the sidebands (110-120, 130-160 GeV) then this would double the trial factor, bringing the global *p*-value below 1 σ

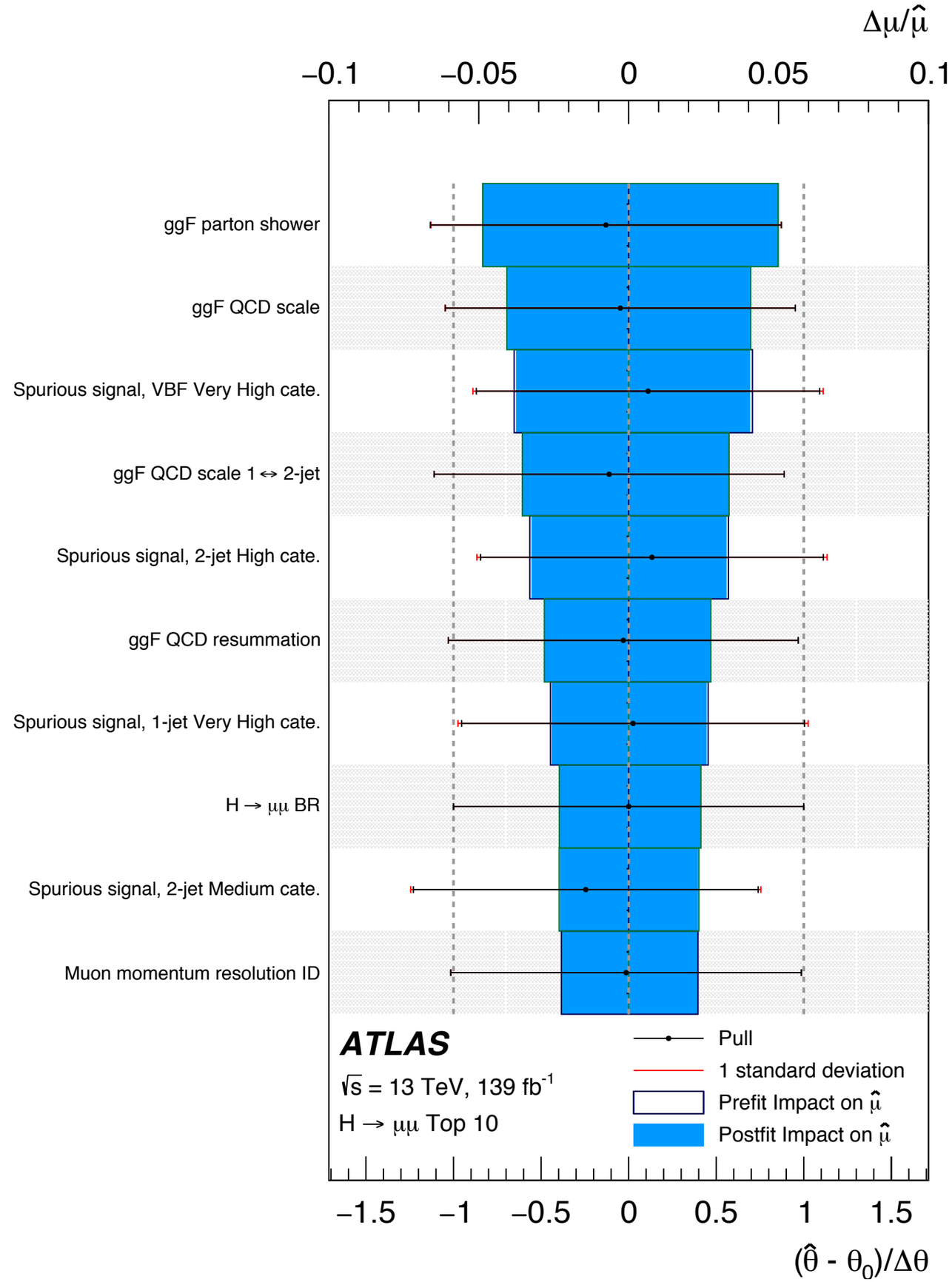



ATLAS
EXPERIMENT
Run: 281411
Event: 312608026
2015-10-11 18:40:58 CEST

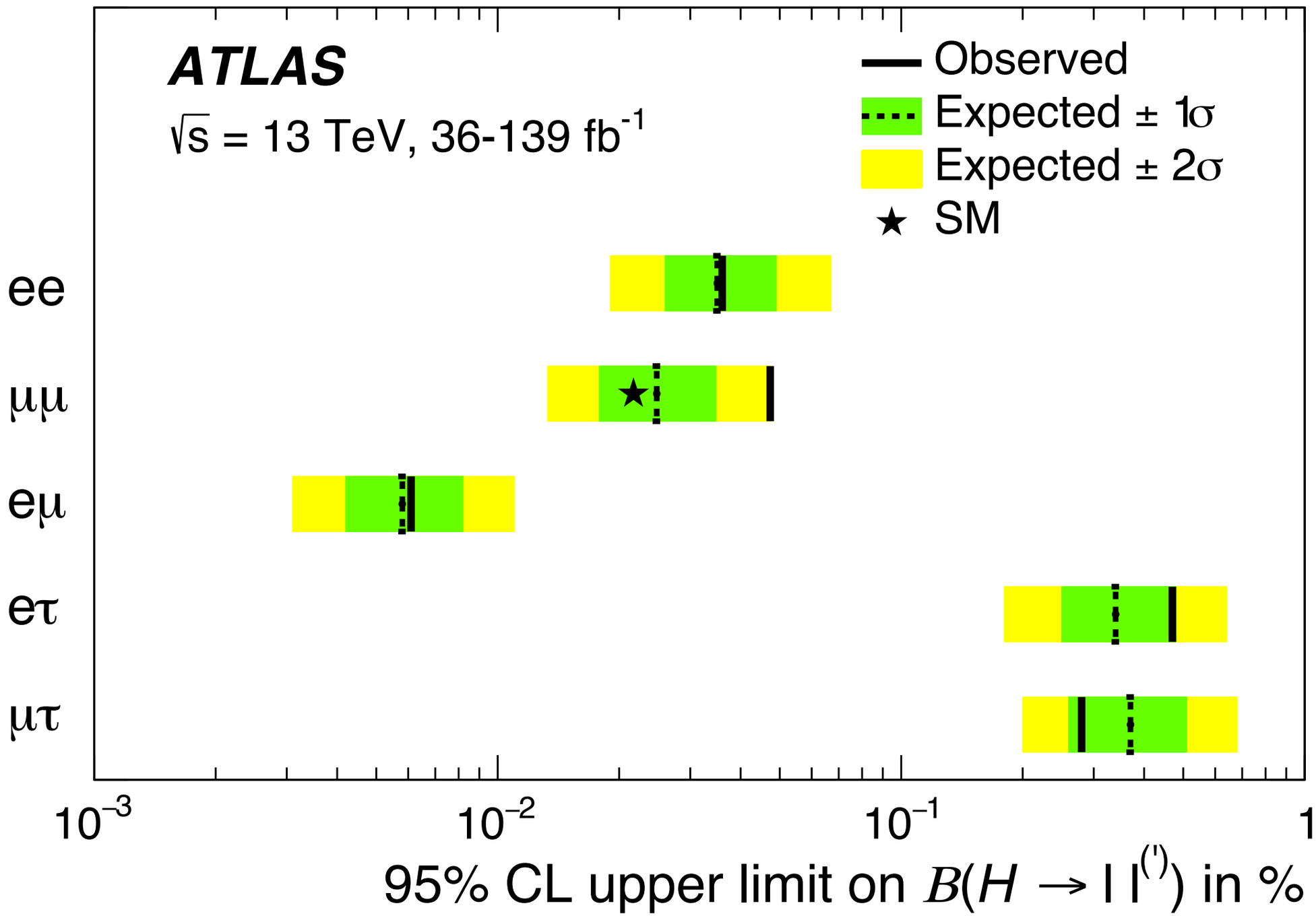
Data/simulation comparison (FSR recovery)



Systematic uncertainties (breakdown)



Upper limits on Higgs to leptons BR



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 $\cos\theta^*$ cosine the lepton decay angle in the Collins–Soper frame
  - 1-/2-jet channels: leading jet information(p_T, η, N_{tracks}, $\Delta\phi_{\mu\mu,j}$)
  - 2-jet channel:
    sub-leading jet information (p_T, η, N_{tracks}, $\Delta\phi_{\mu\mu,j}$) and
    dijet system information (p_T^{jj}, m^{jj}, y^{jj}, $\Delta\phi_{\mu\mu,jj}$)

ttH category - BDT features

- 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_T^{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 $\cos\theta^*$ cosine the lepton decay angle in the Collins–Soper frame
  - leading and sub-leading jet information transverse momenta
  - transverse masses of leptonic W and top (3rd lepton + E_T^{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)

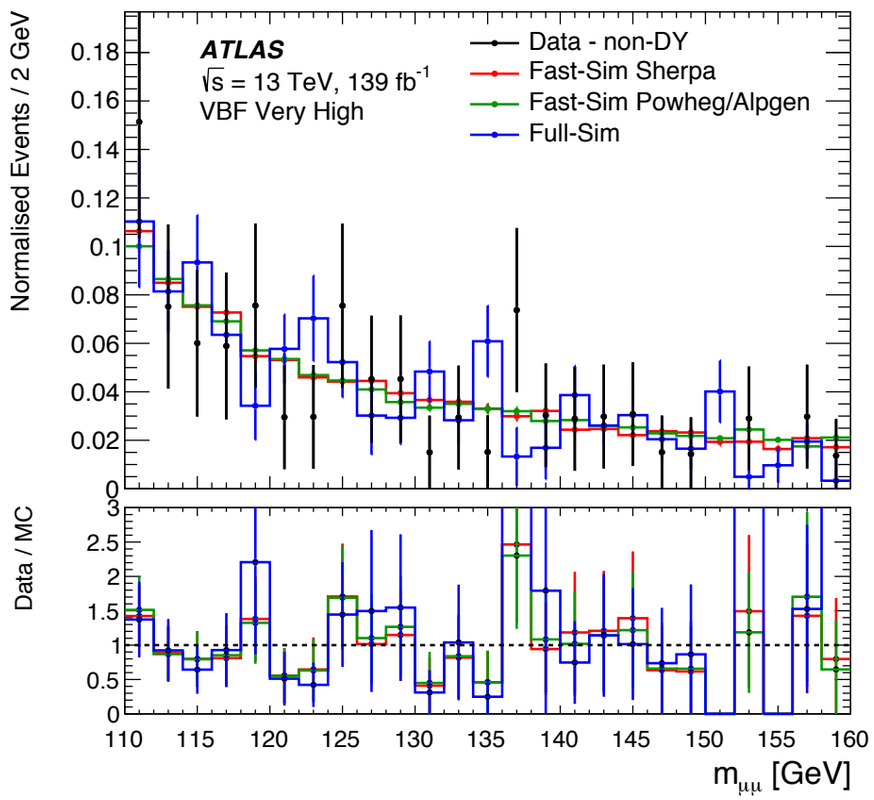
VH (3-lepton) categories - BDT features

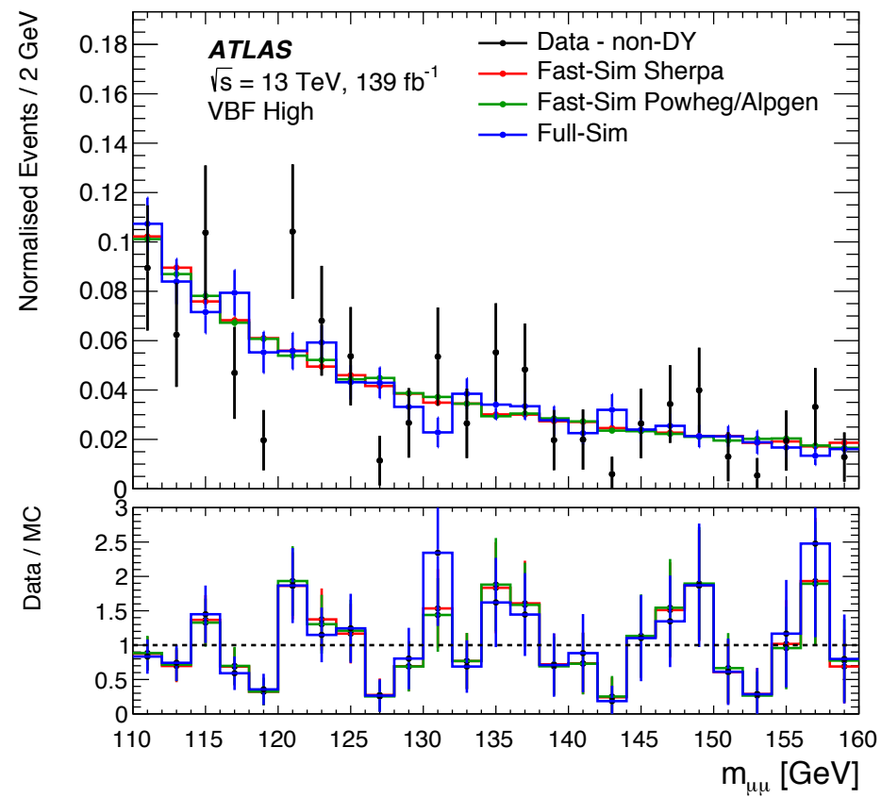
- Features used:
  - missing transverse energy (E_T^{miss})
  - $\Delta\phi$ between Higgs and E_T^{miss}
  - transverse momentum of the *W* candidate lepton
  - transverse mass of the *W* candidate (lepton + E_T^{miss})
  - $\Delta\phi$ *and* $\Delta\eta$ between Higgs and extra lepton
  - number of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

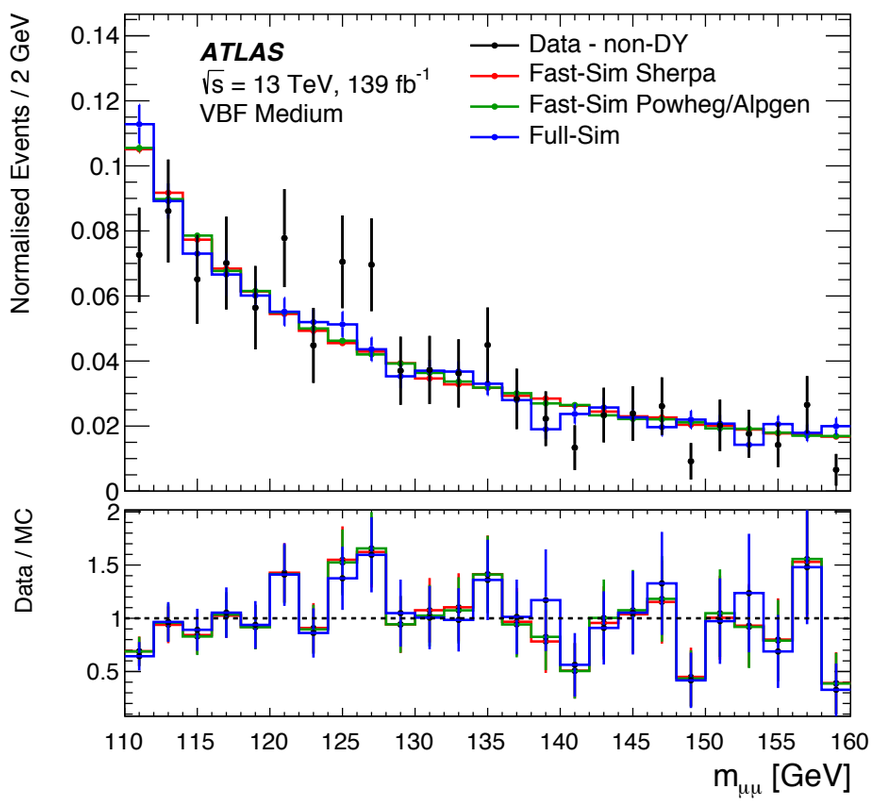
VH (4-lepton) categories - BDT features

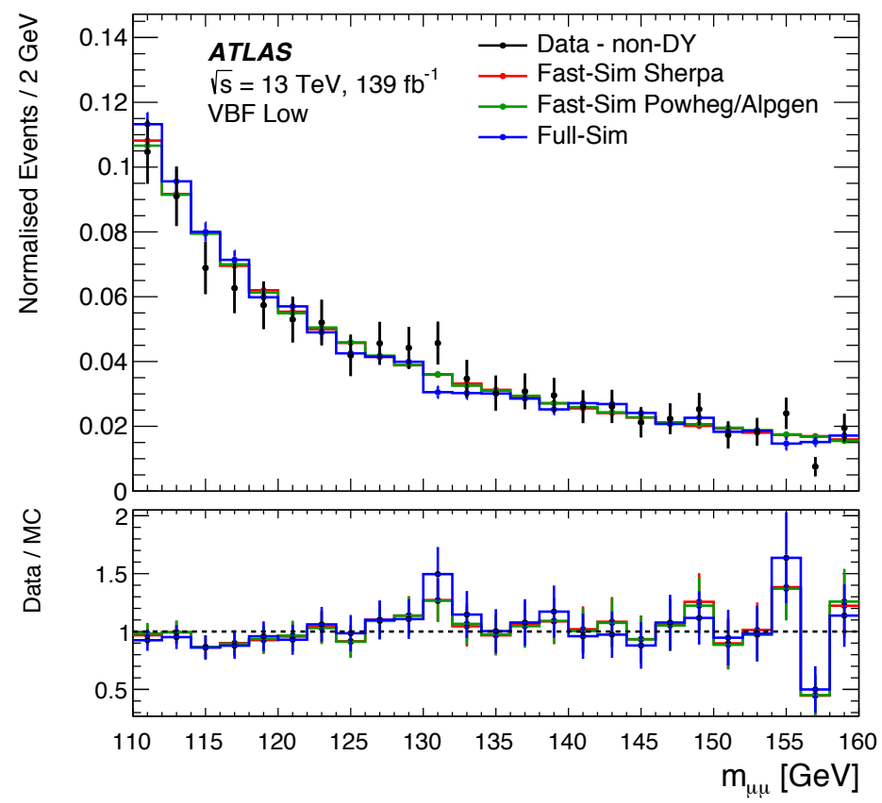
- Features used:
  - number of jets
  - transverse momentum of the leading and sub-leading jets
  - $\Delta\phi$ between the leptons associated to a Z boson
  - $\Delta\phi$ *and* $\Delta\eta$ between Higgs and Z candidate
  - Z candidate mass

Data/simulation comparisons (VBF)

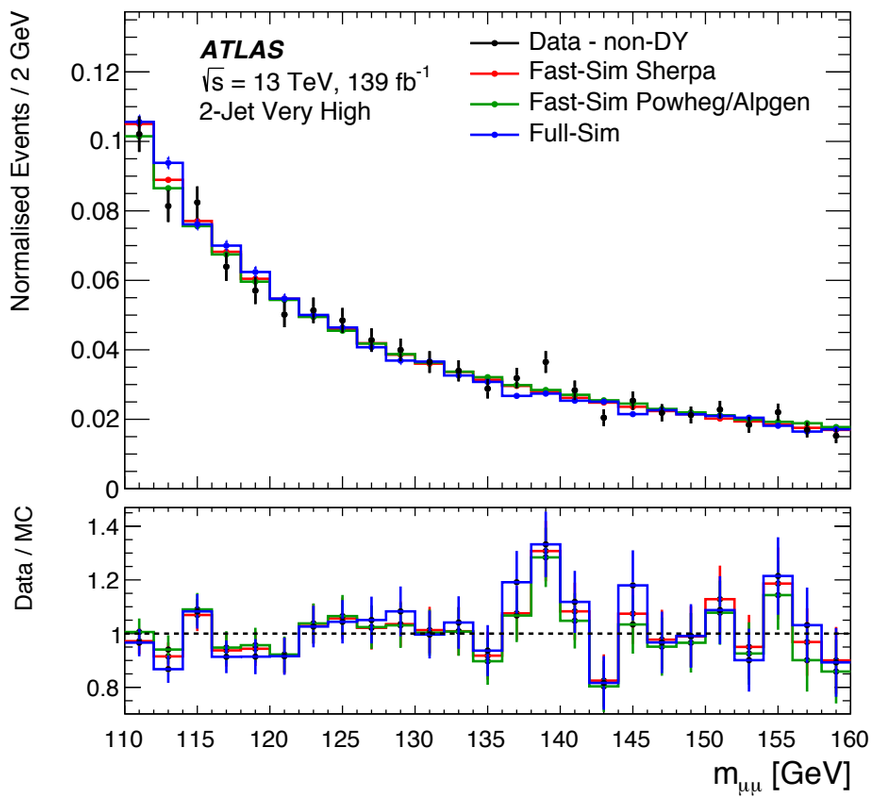


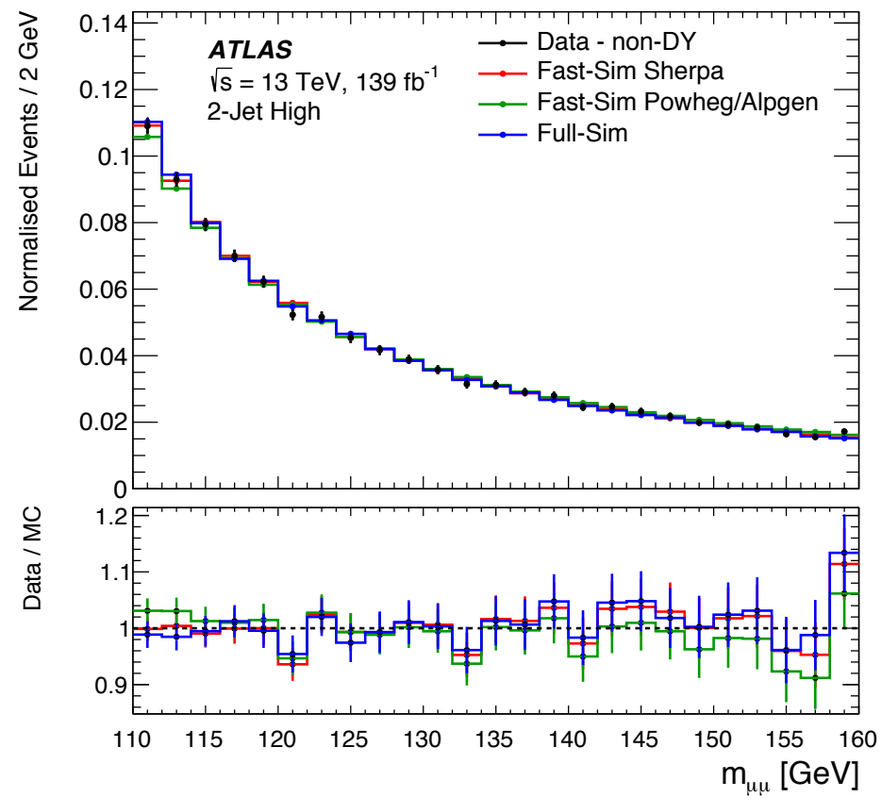


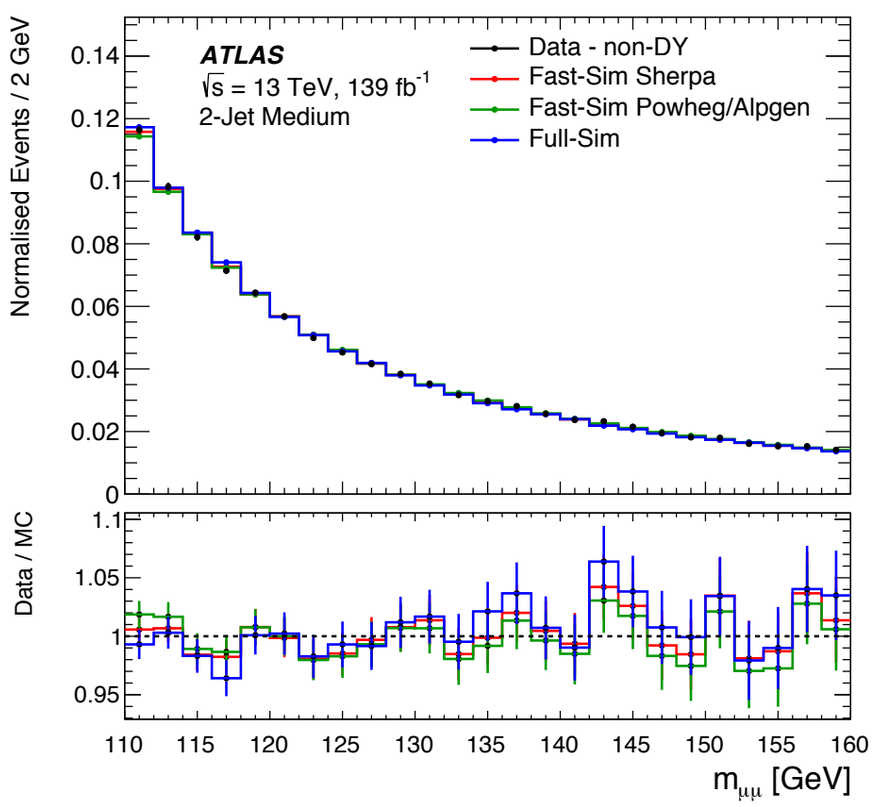


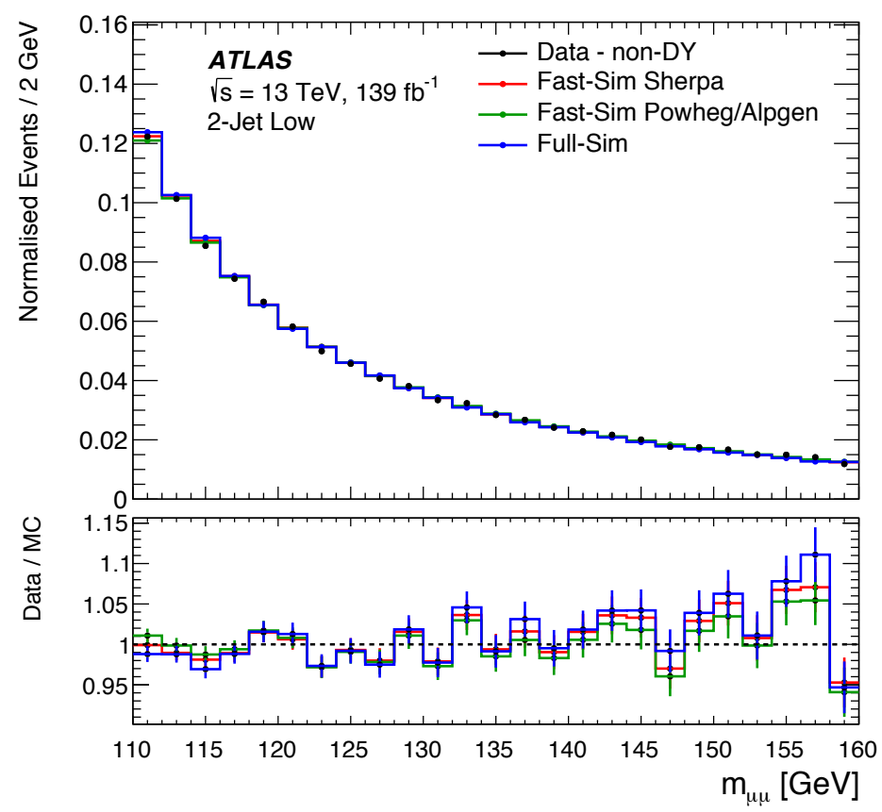


Data/simulation comparisons (2-jet)

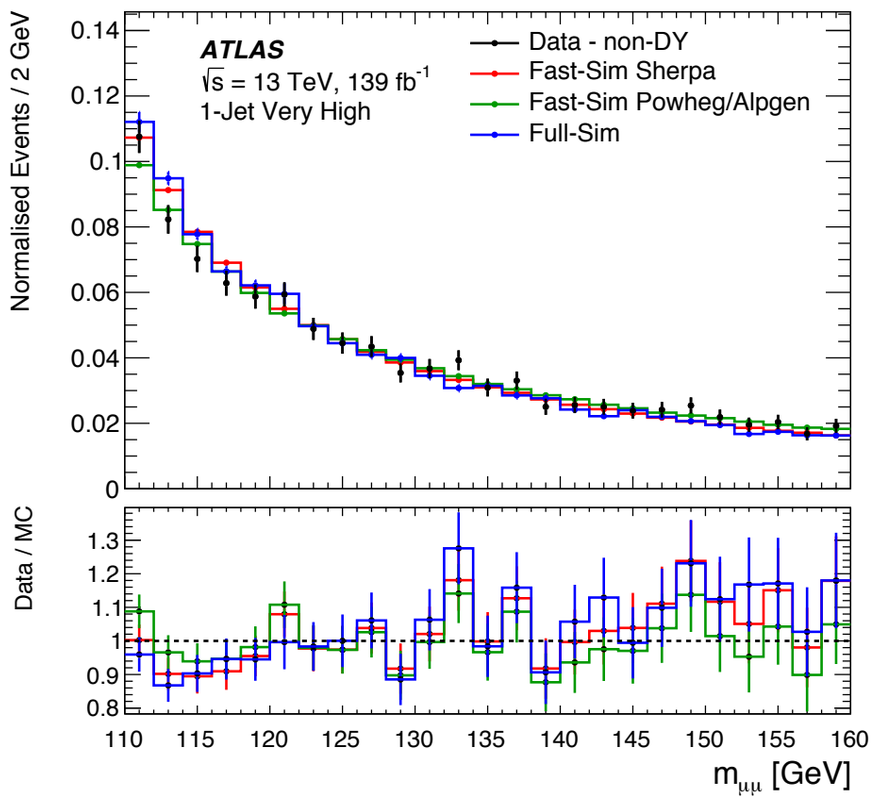


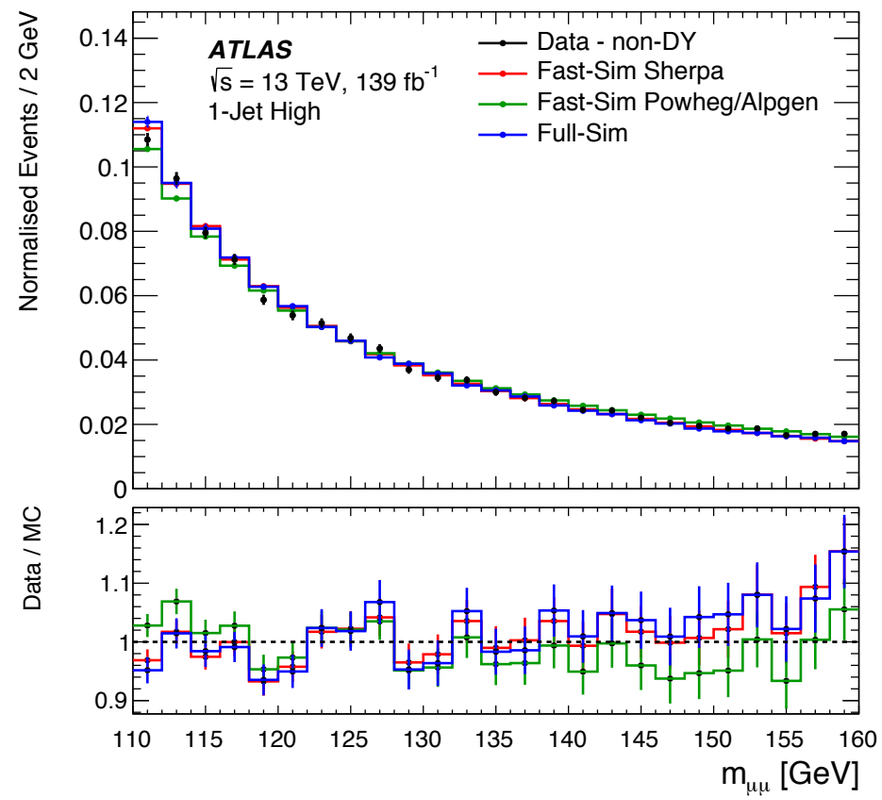


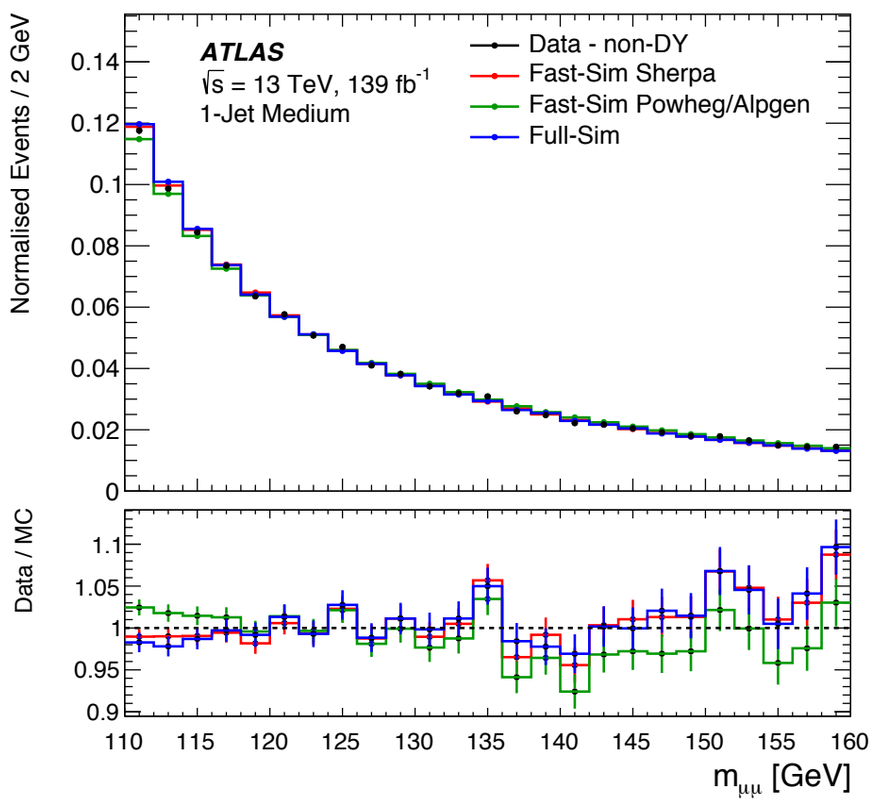


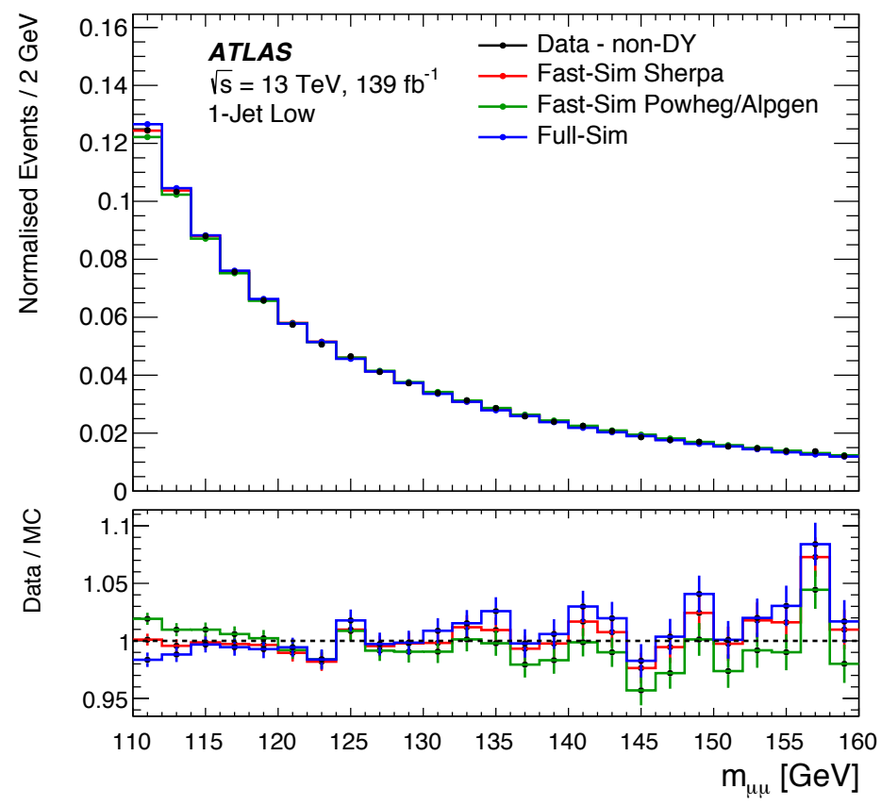


Data/simulation comparisons (1-jet)

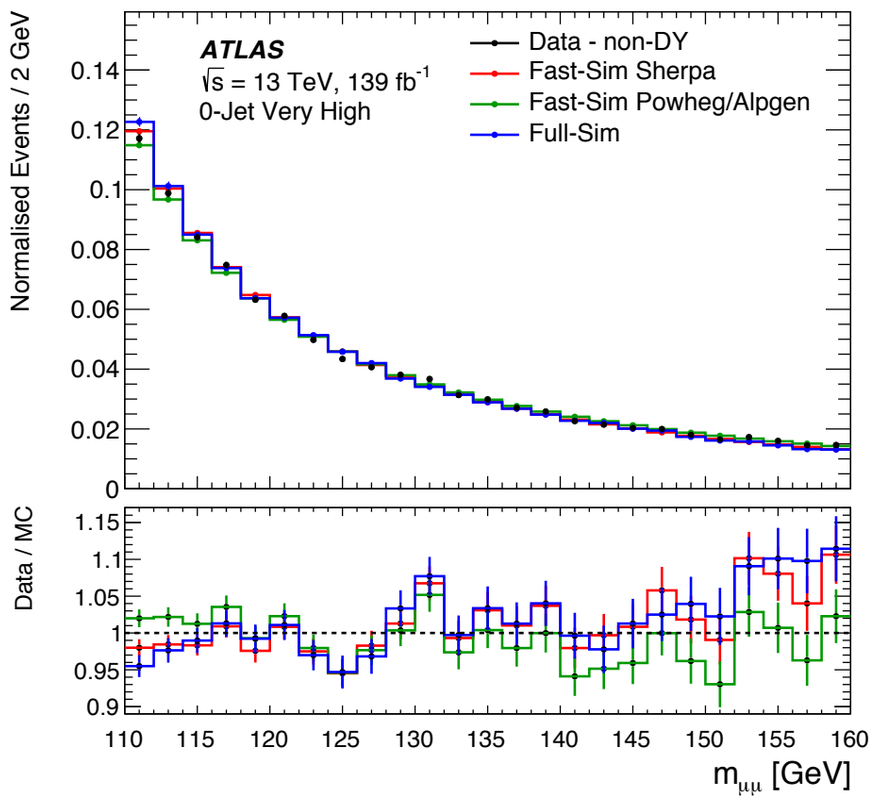


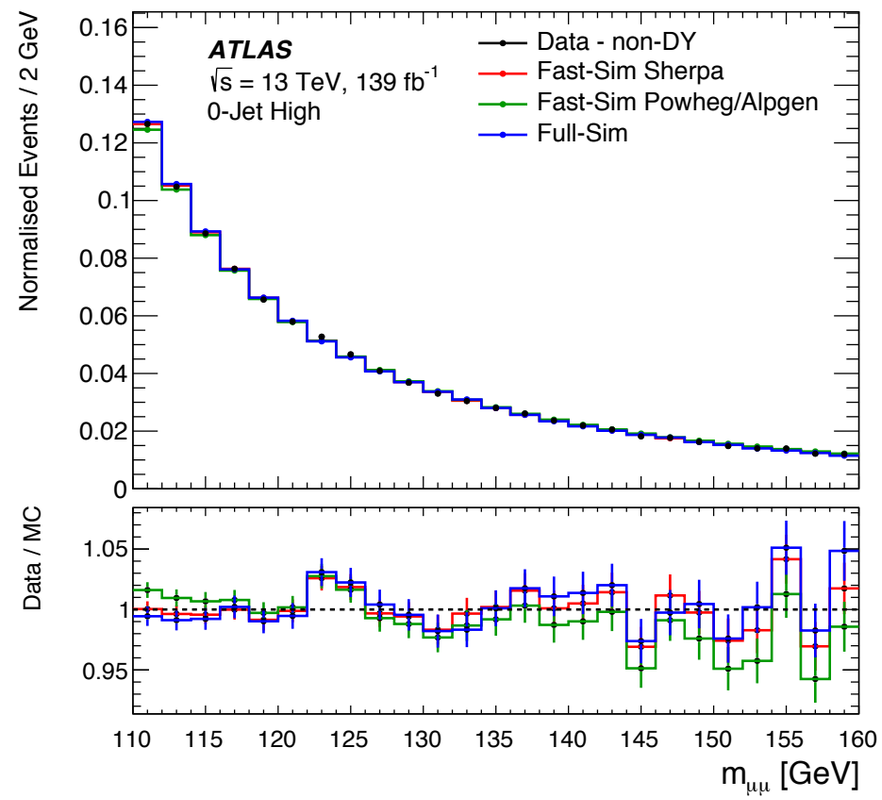


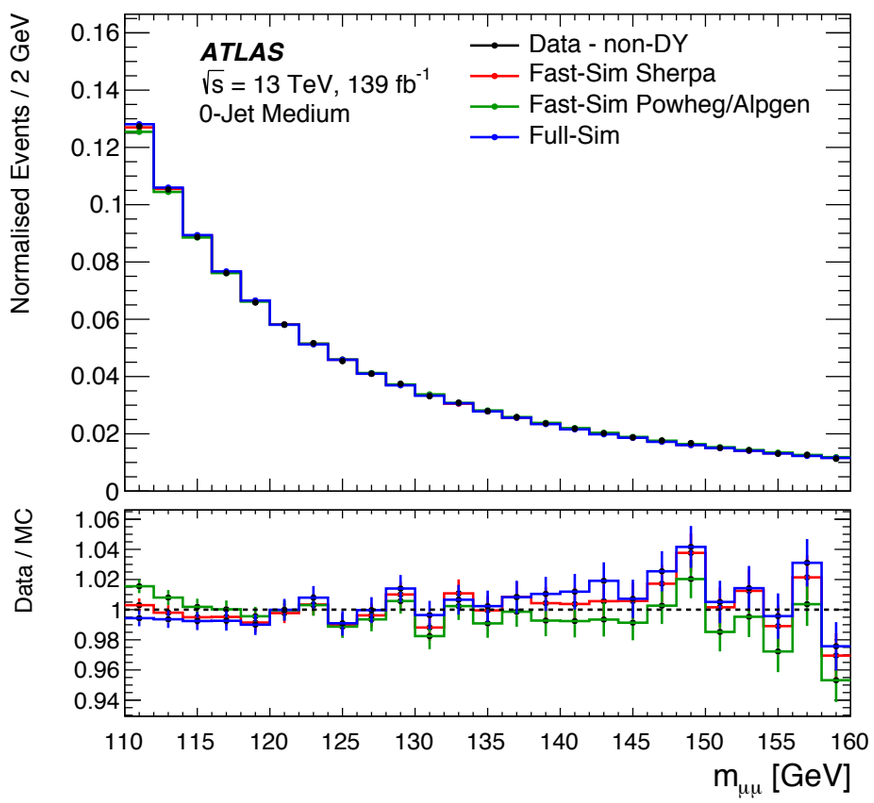


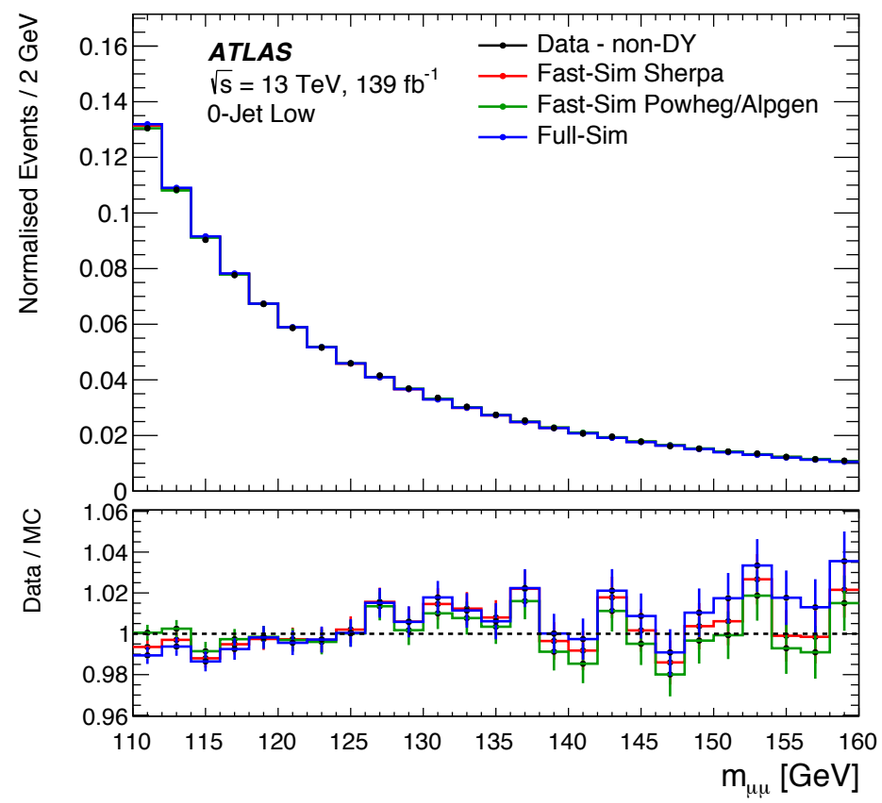


Data/simulation comparisons (0-jet)

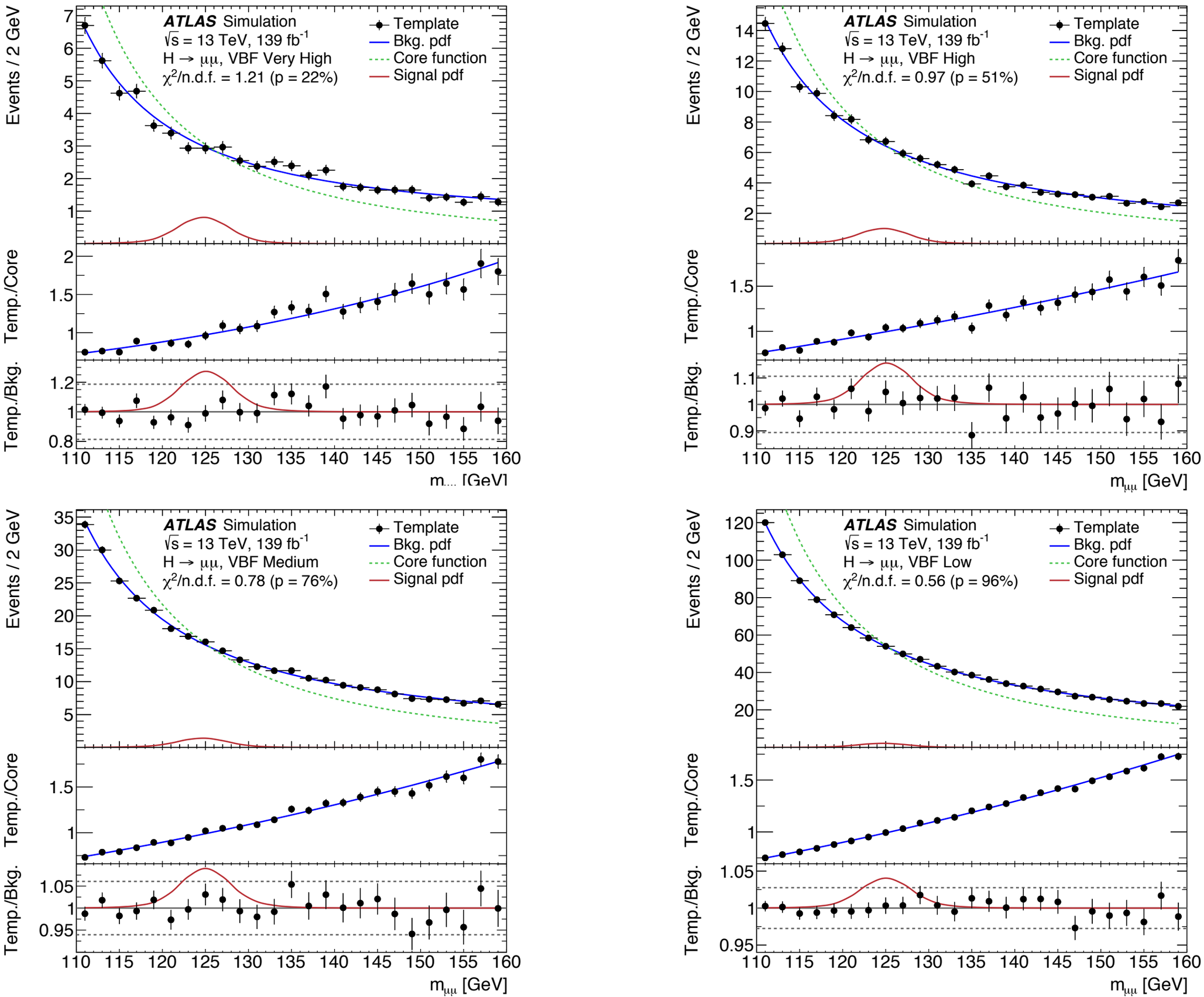




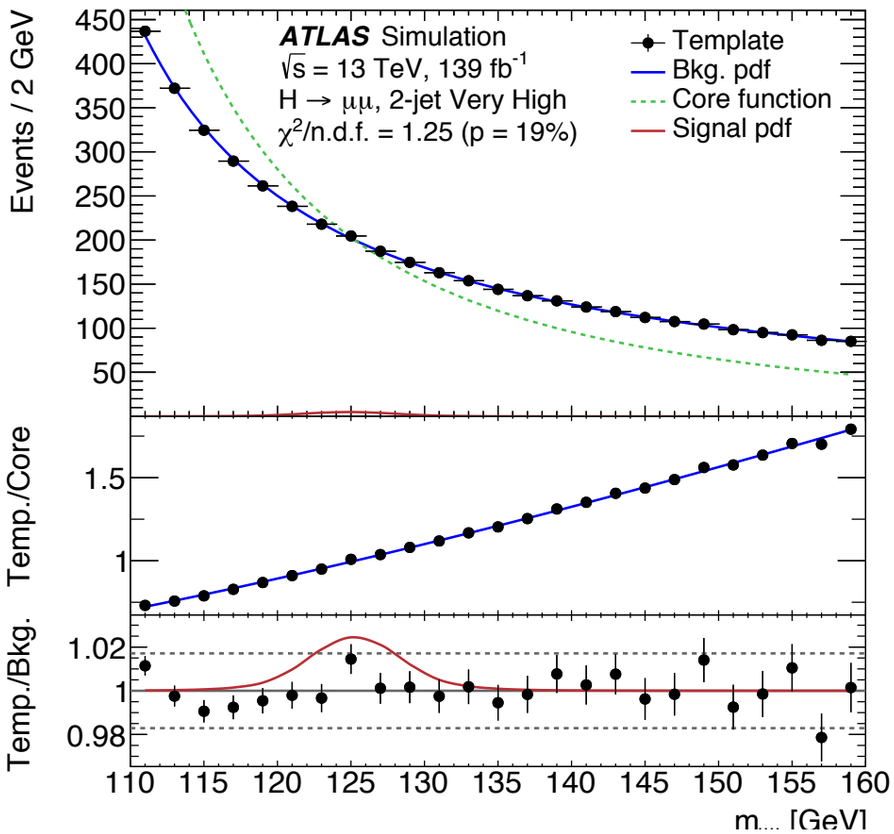


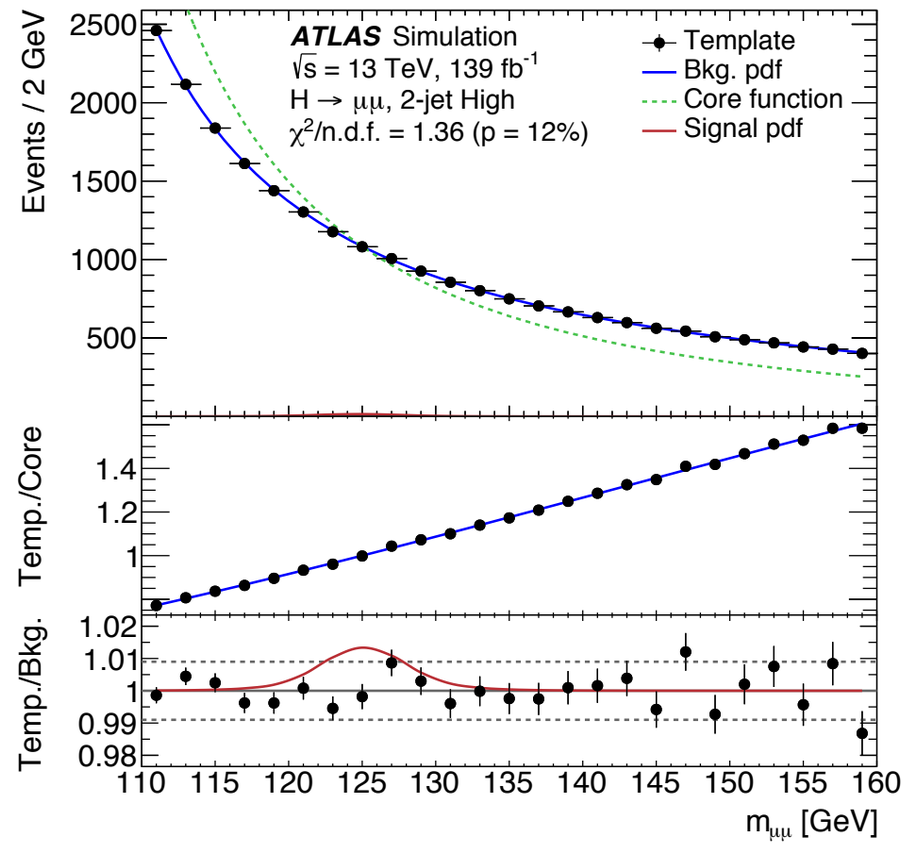


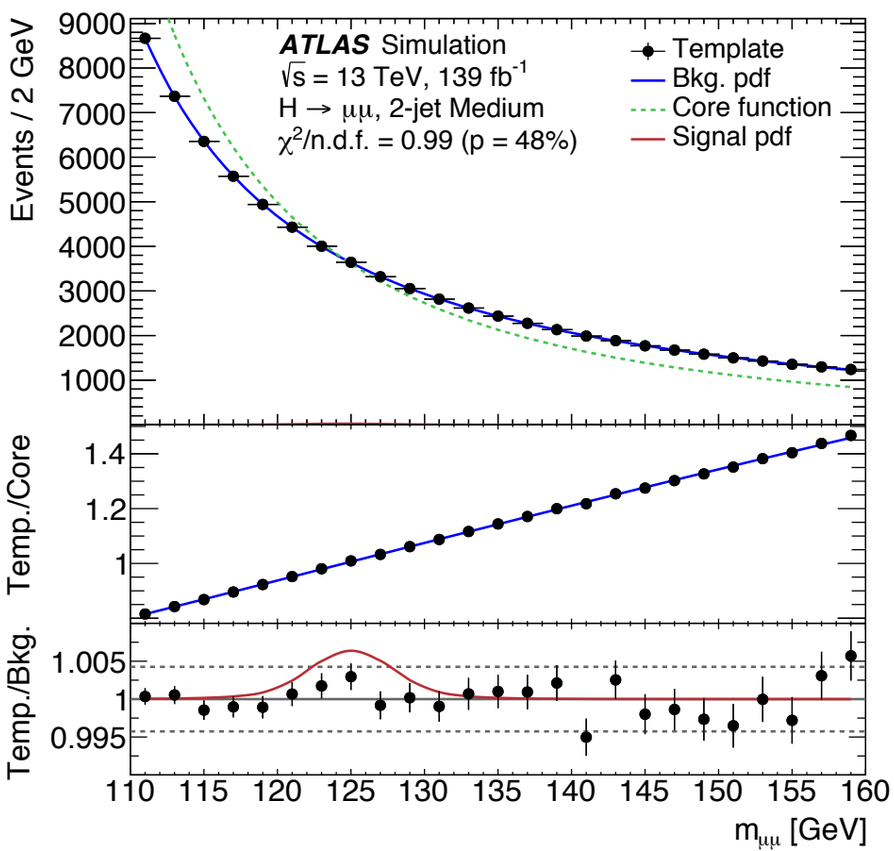
Fit breakdown on simulation (VBF)

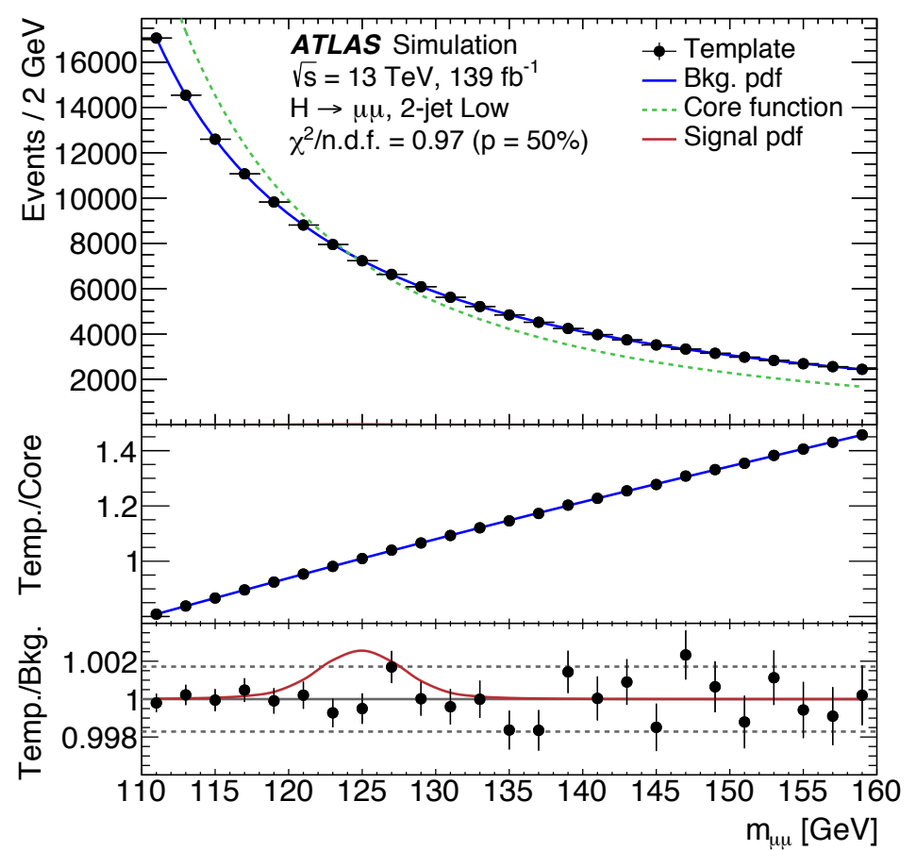


Fit breakdown on simulation (2-jet)

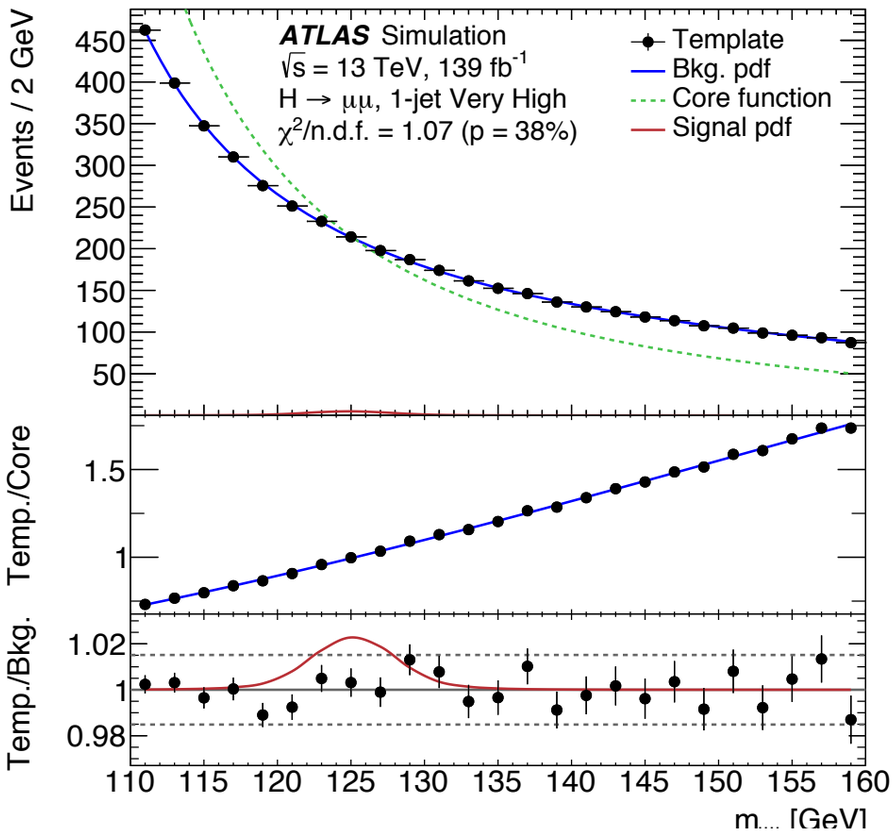


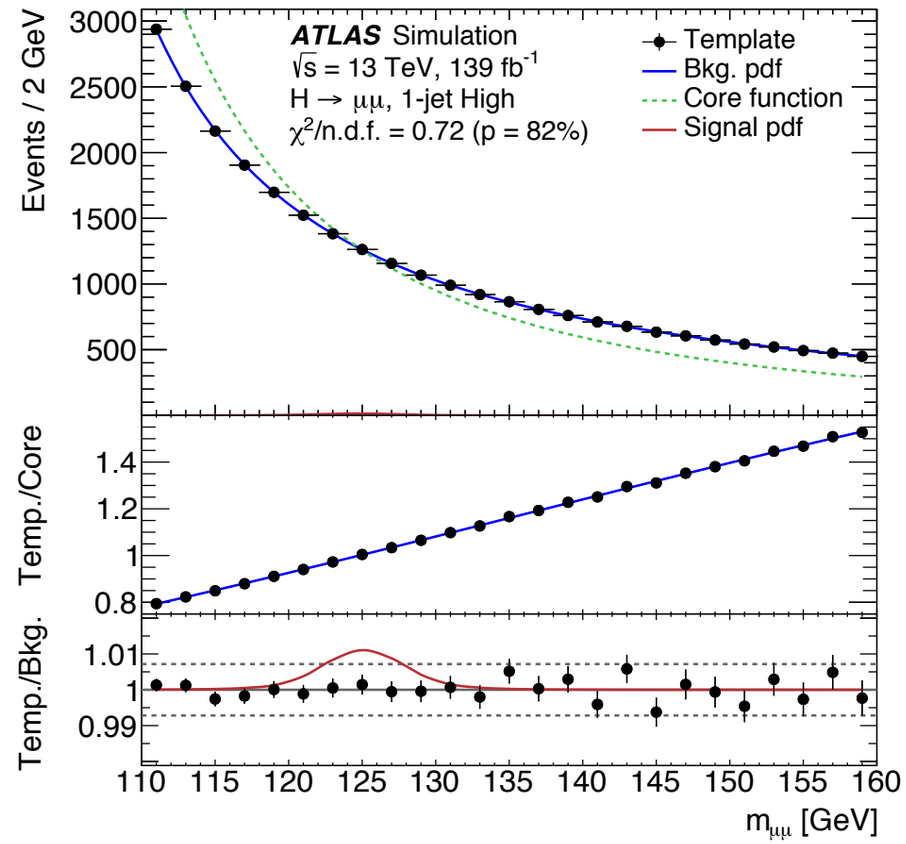


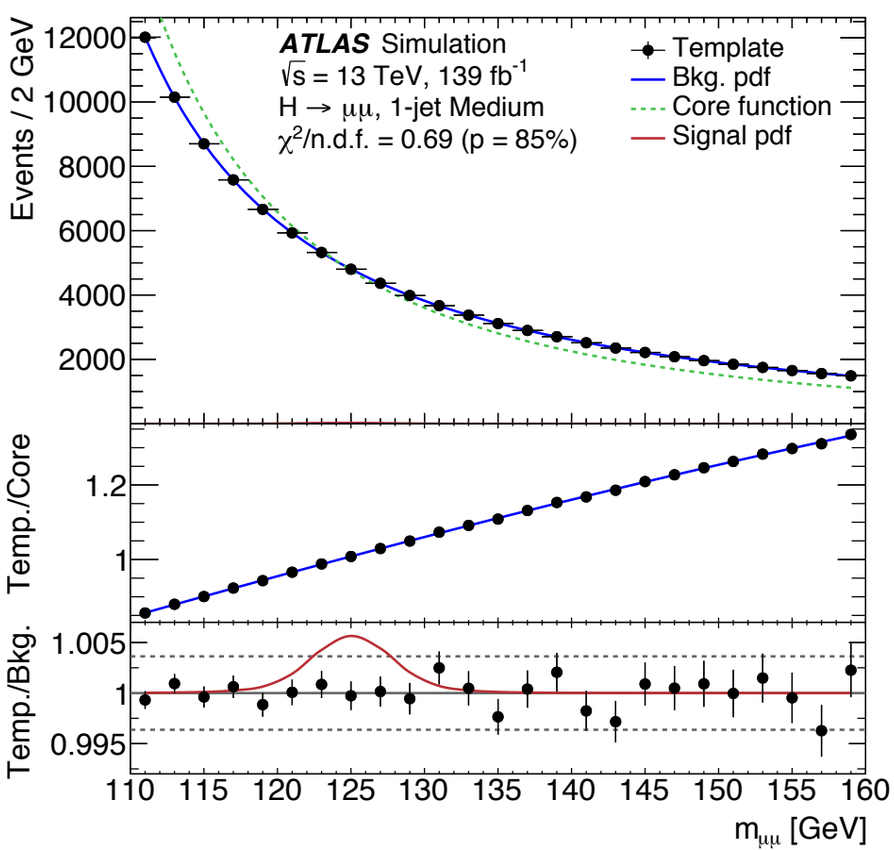


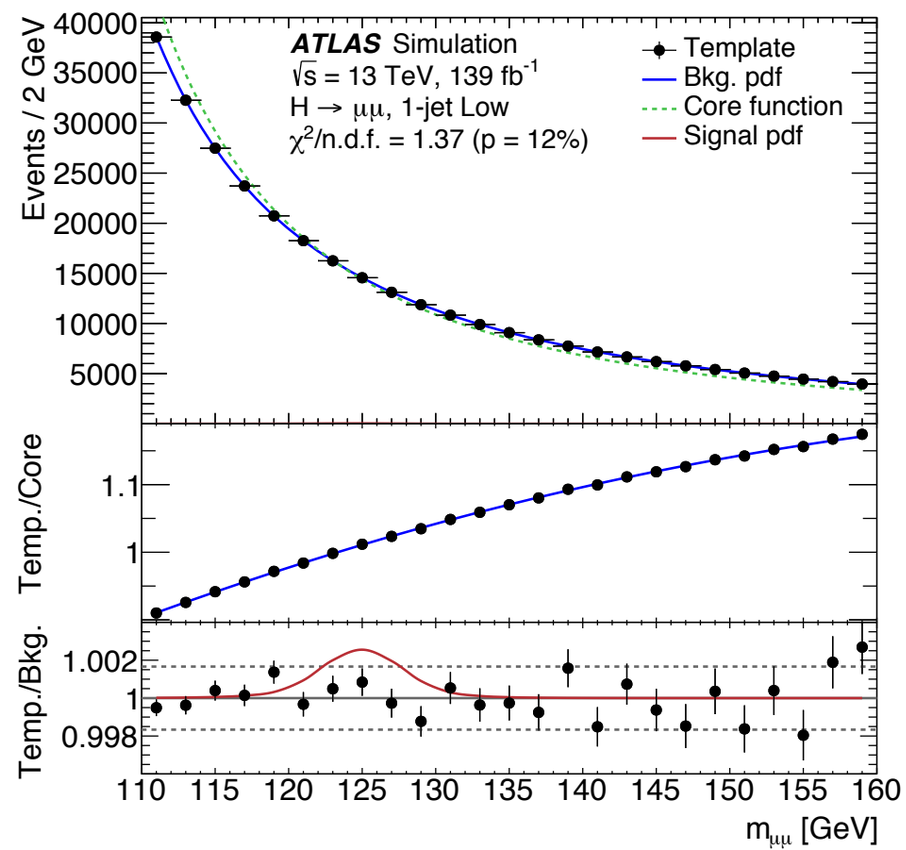


Fit breakdown on simulation (1-jet)

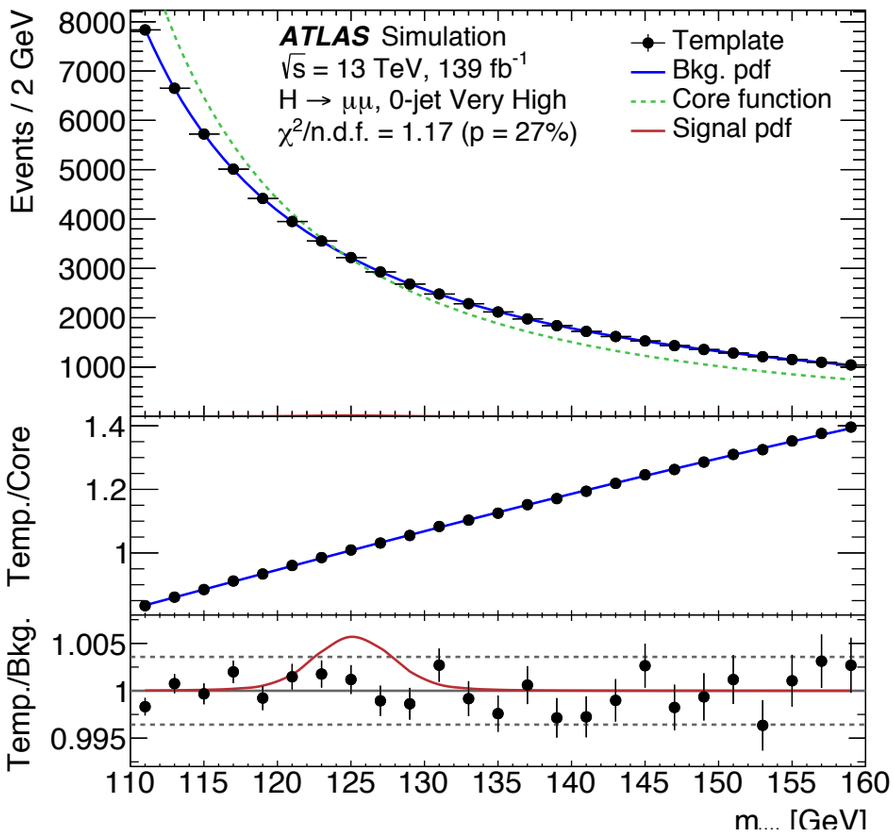


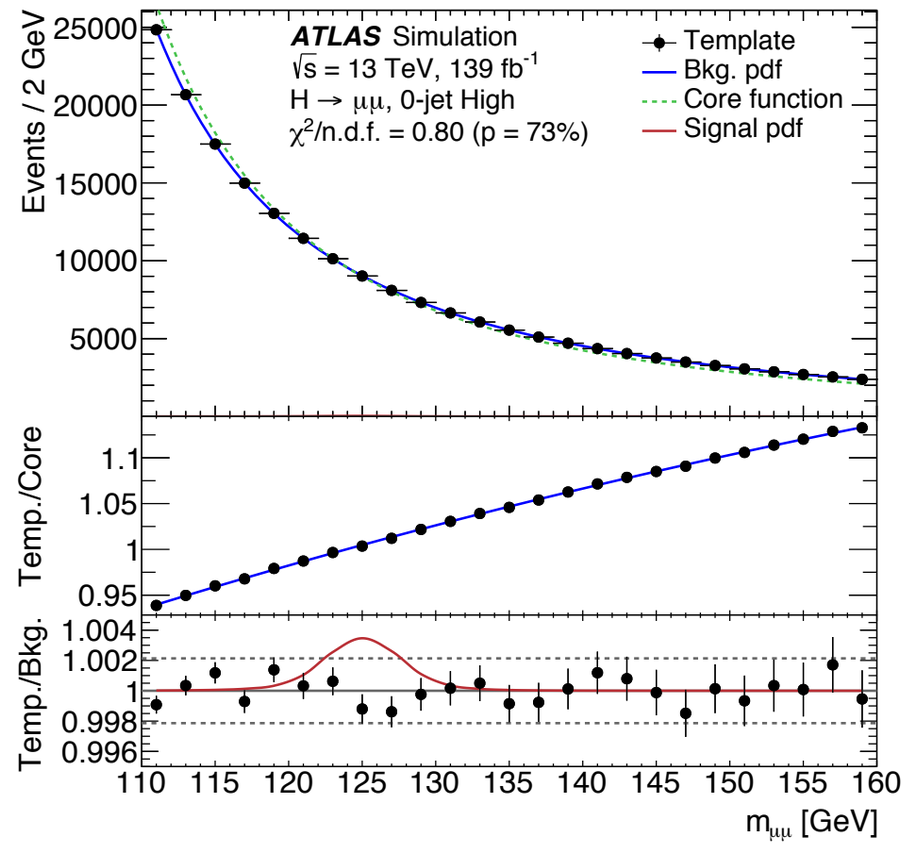


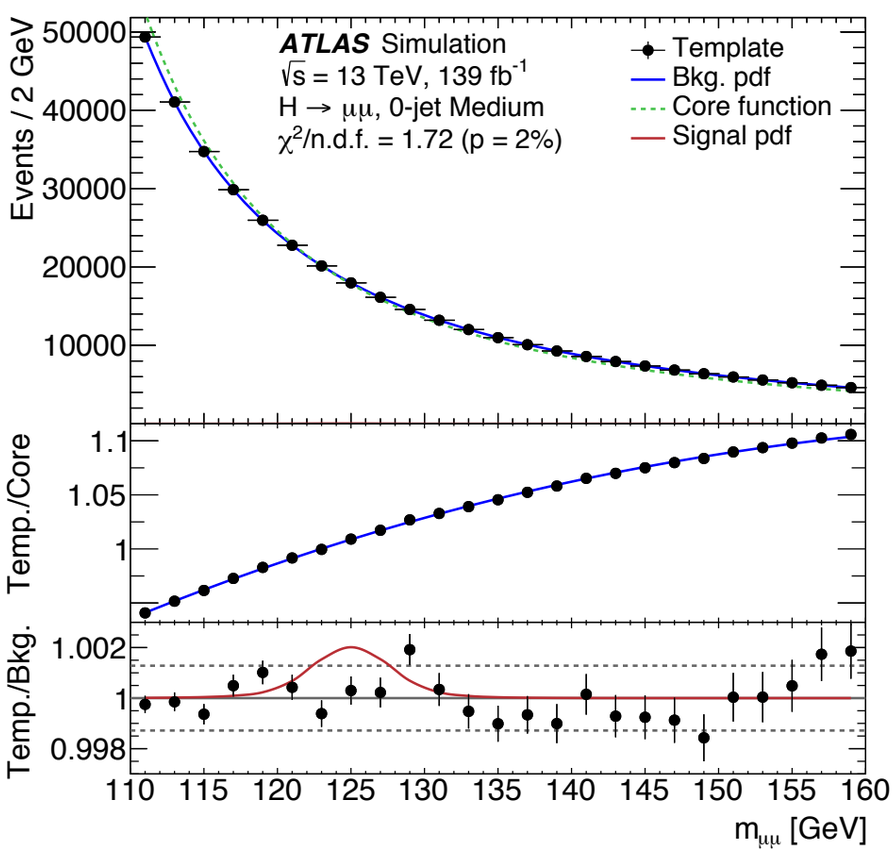


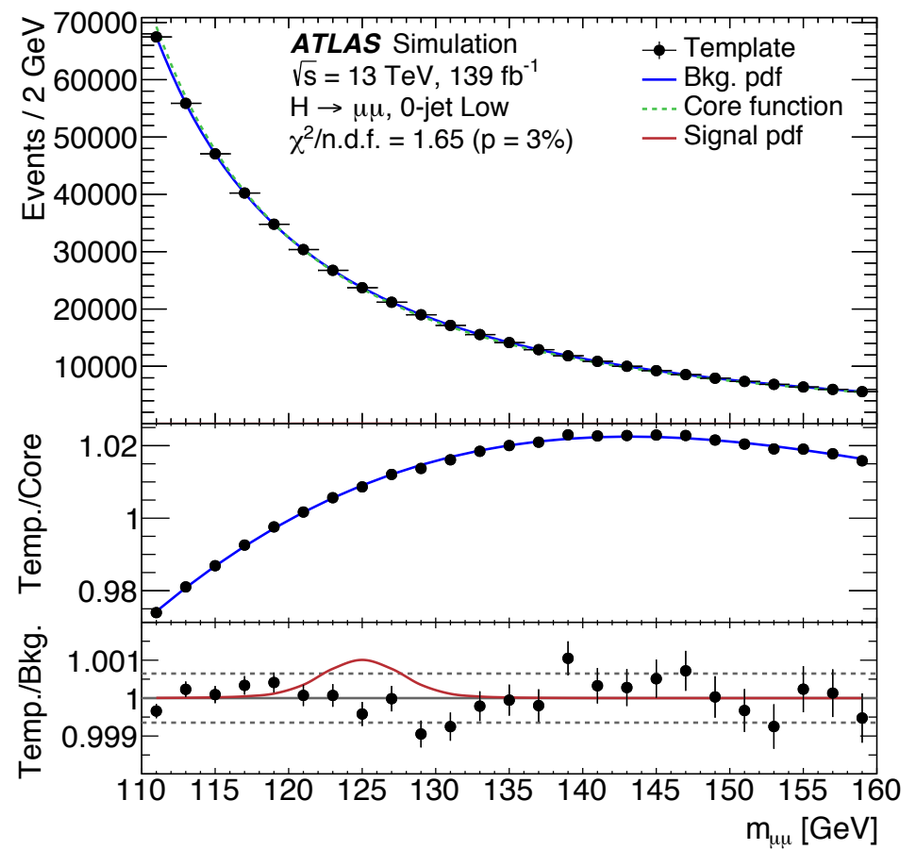


Fit breakdown on simulation (0-jet)

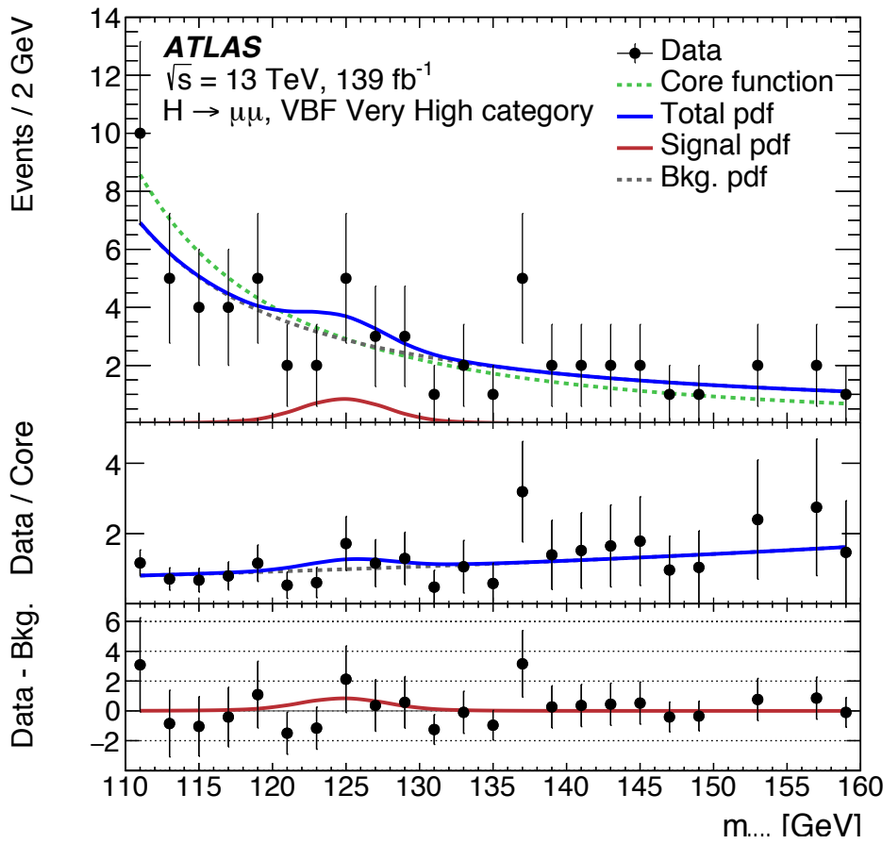


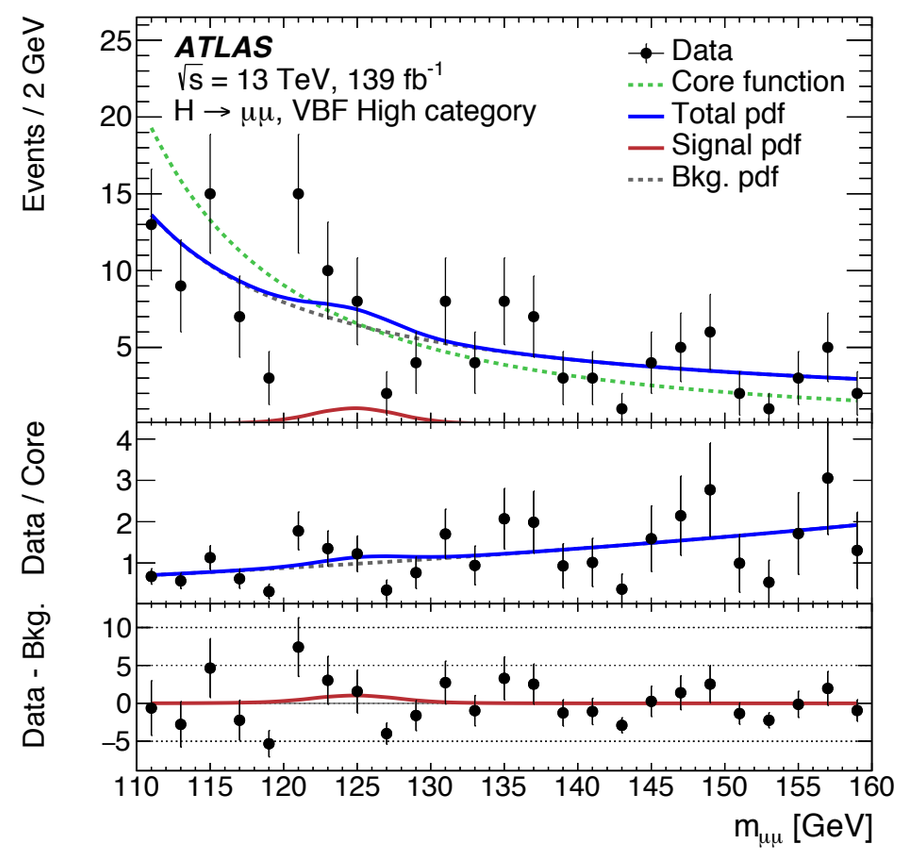


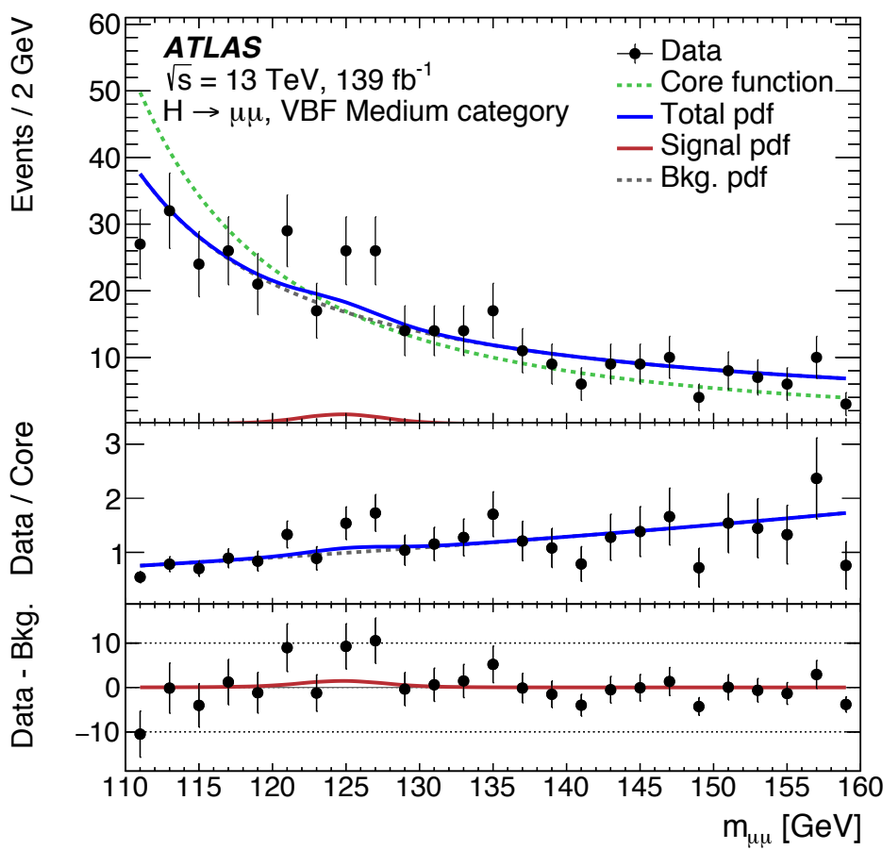


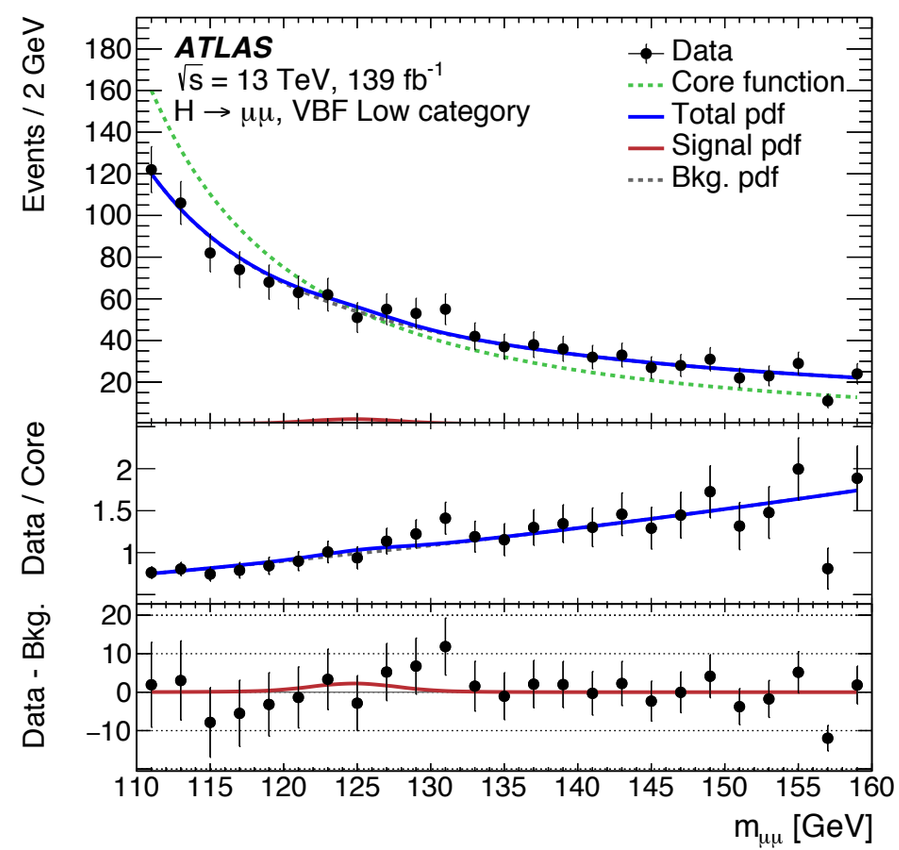


Fit breakdown on data (VBF)

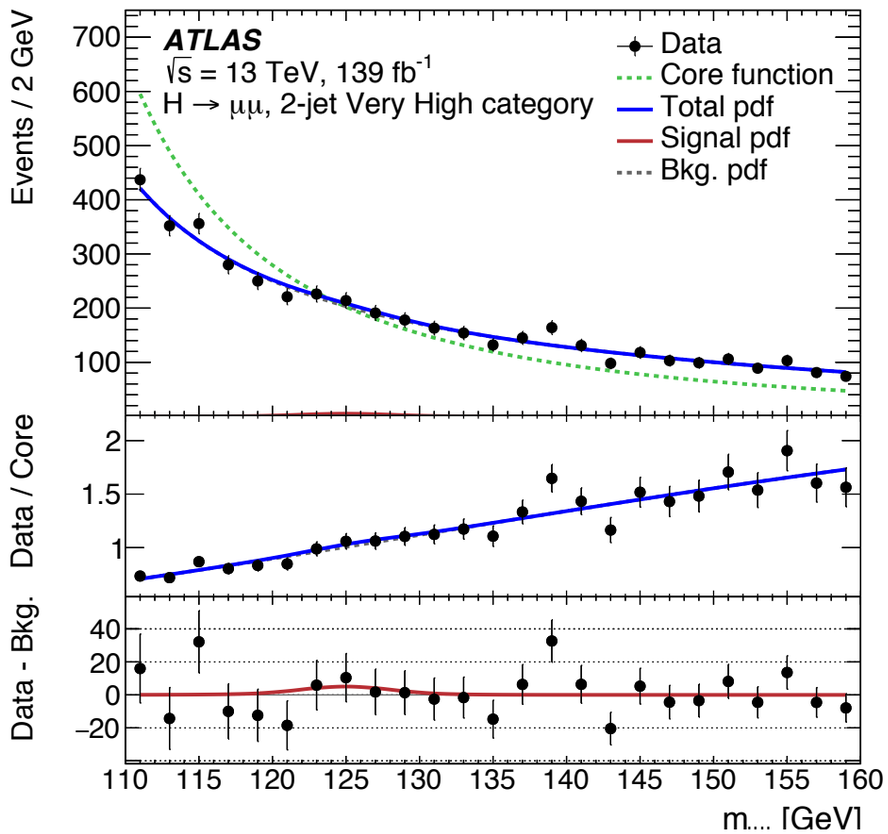


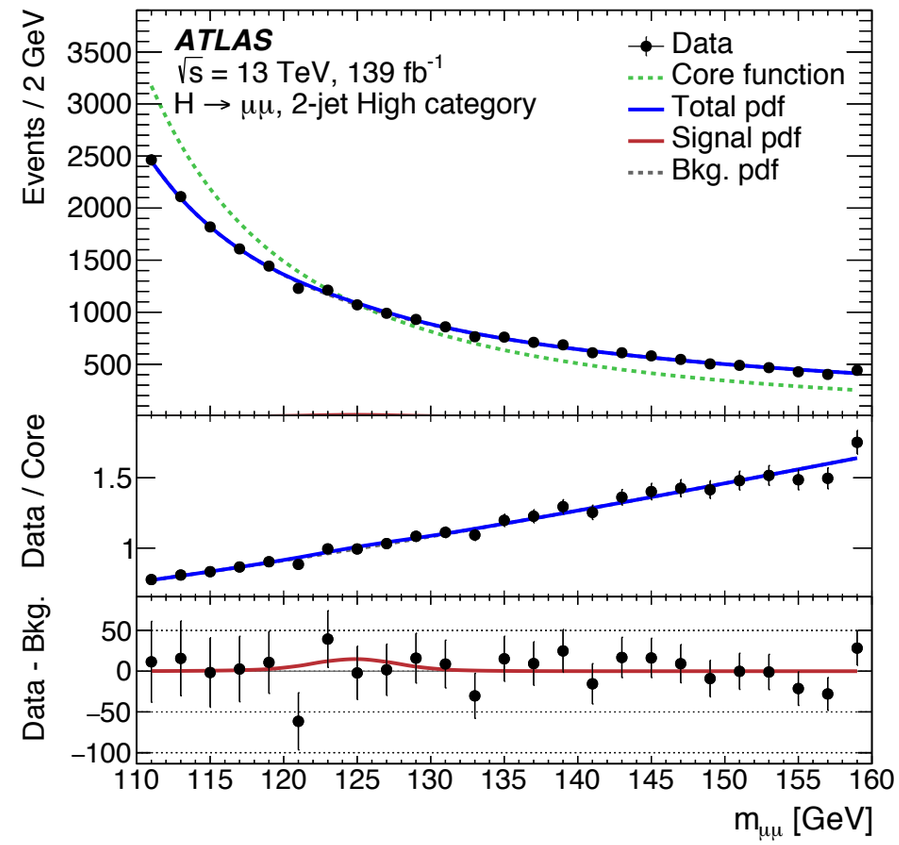


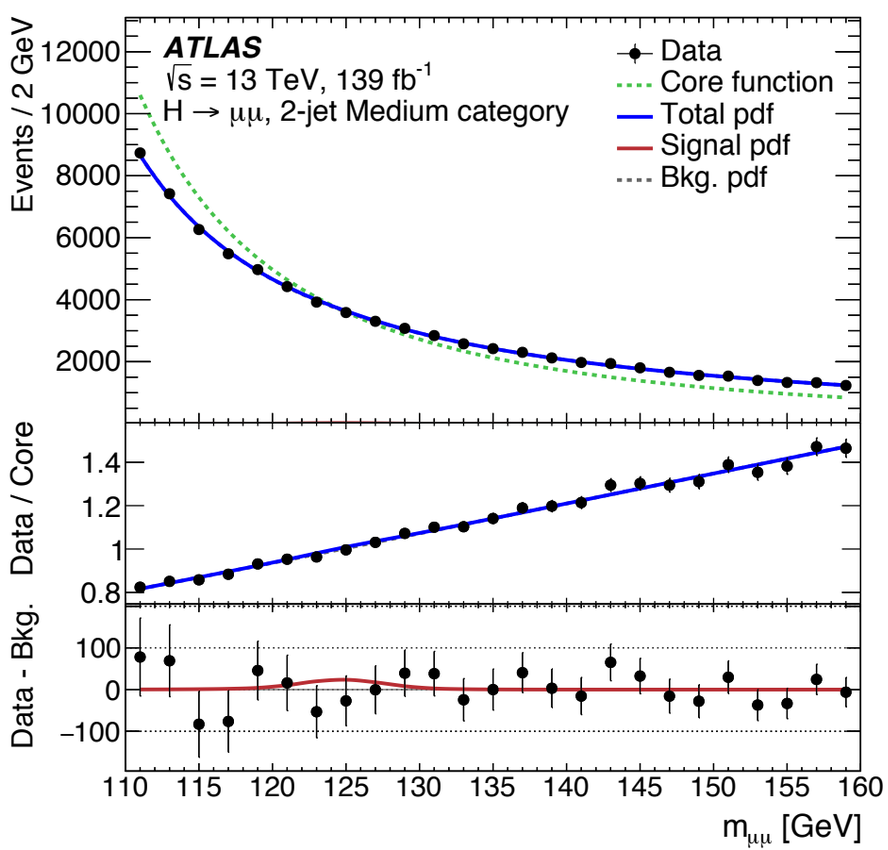


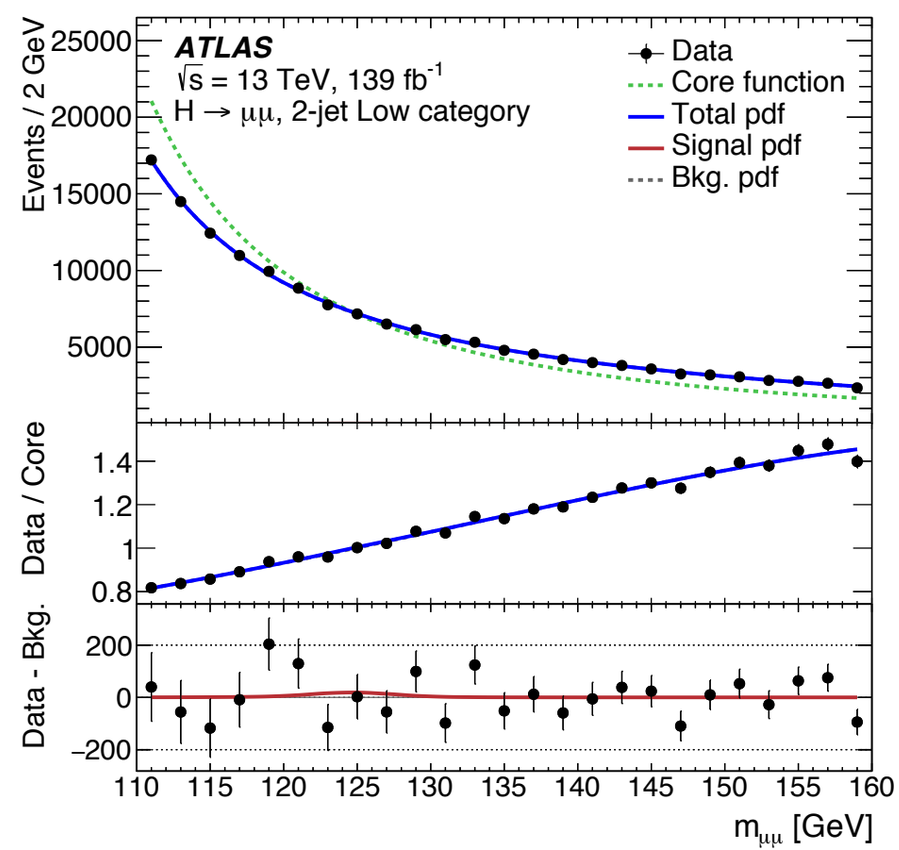


Fit breakdown on data (2-jet)

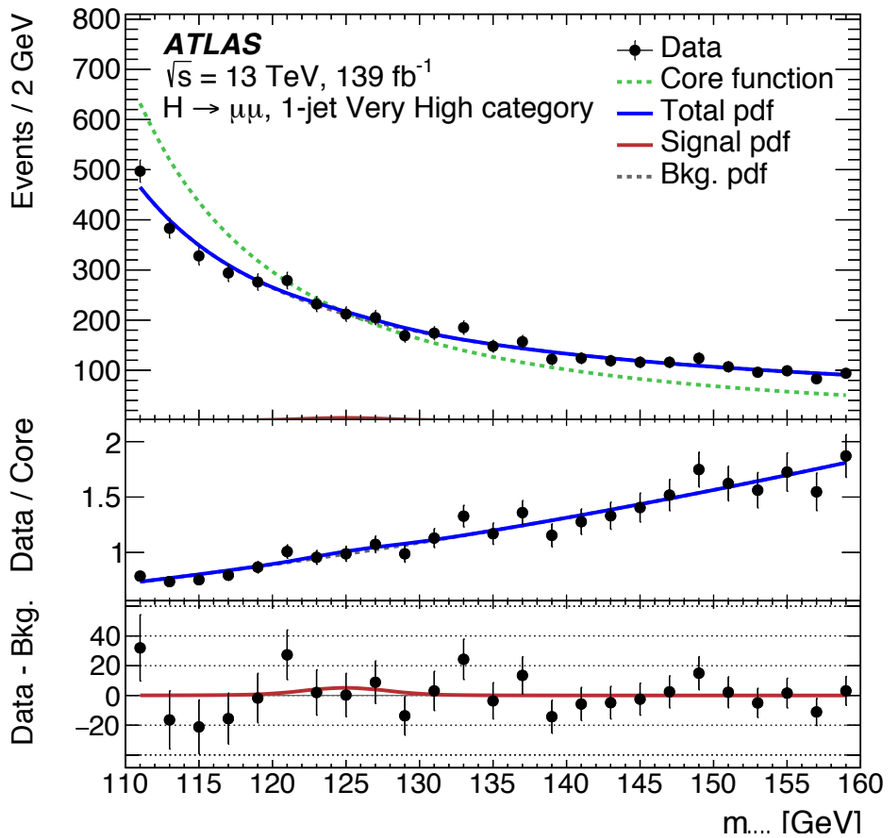


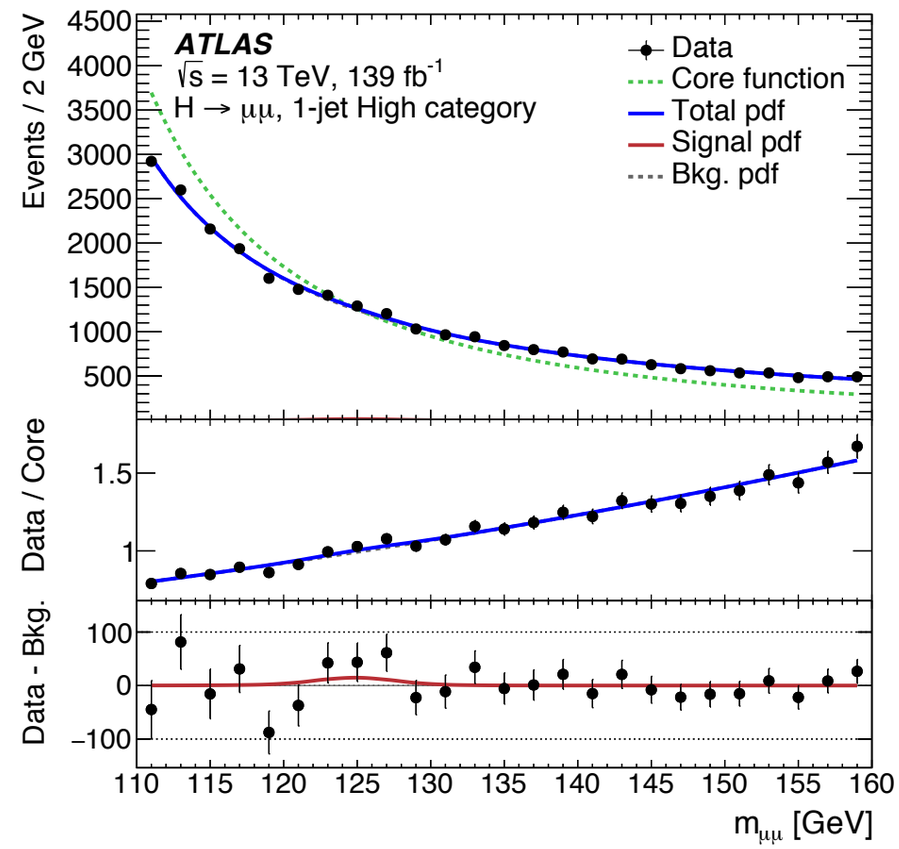


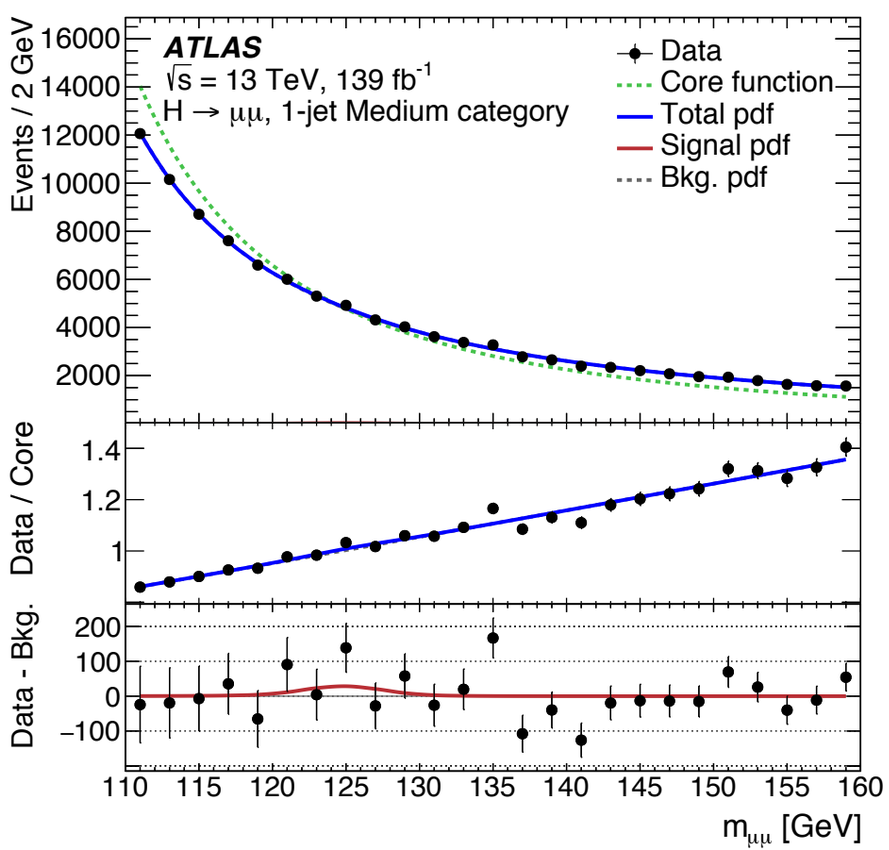


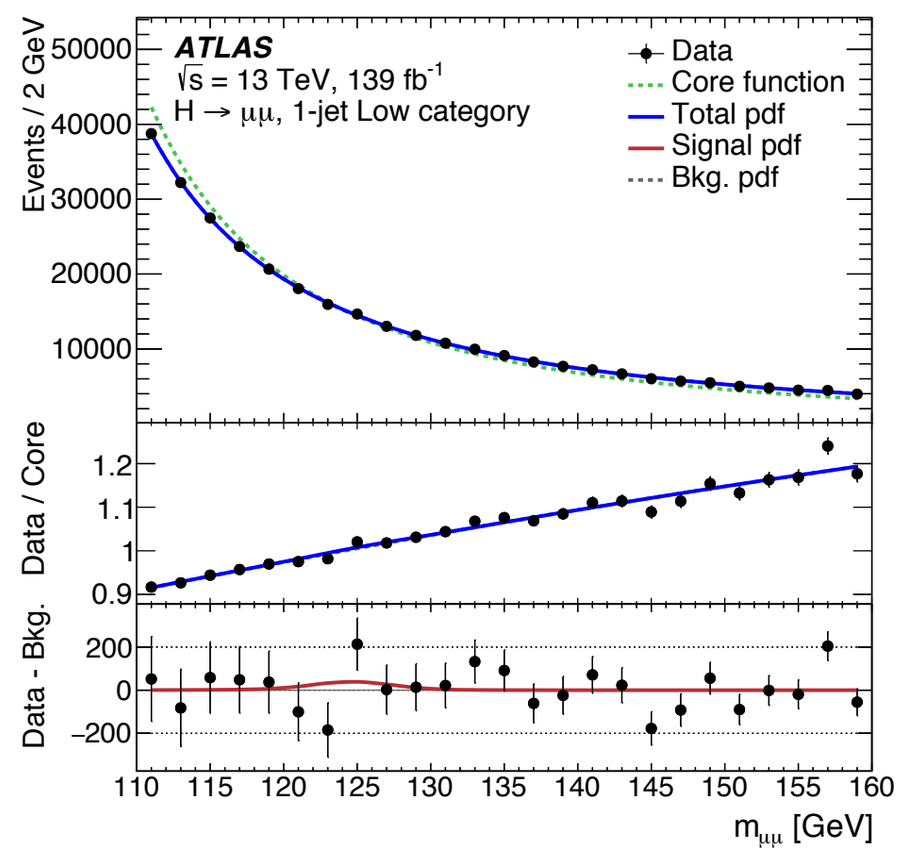


Fit breakdown on data (1-jet)

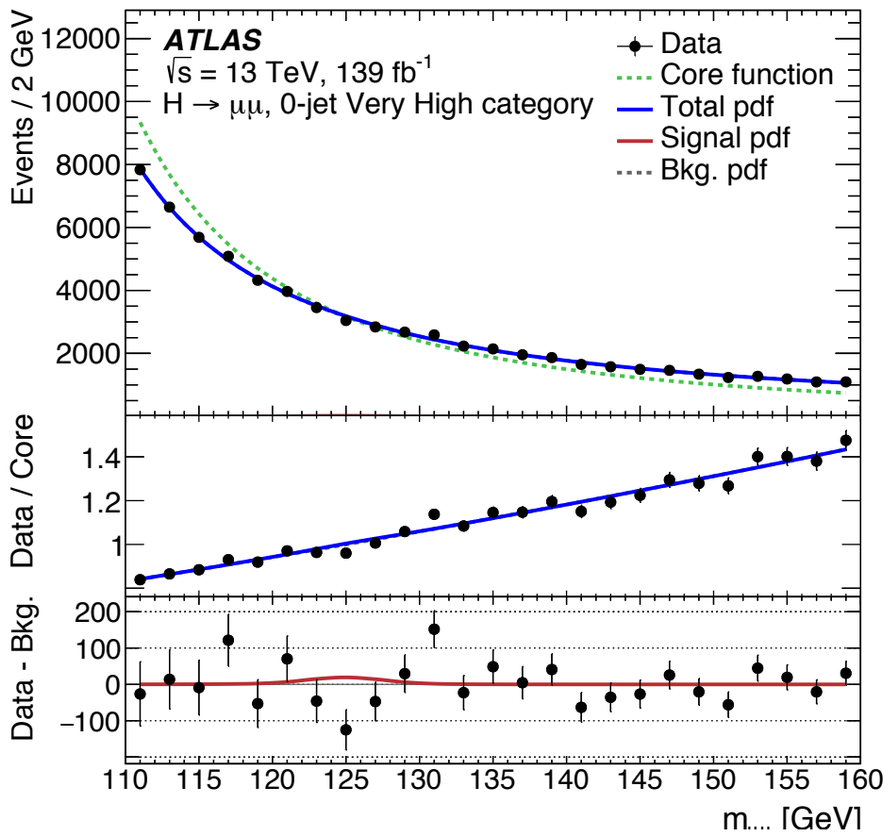


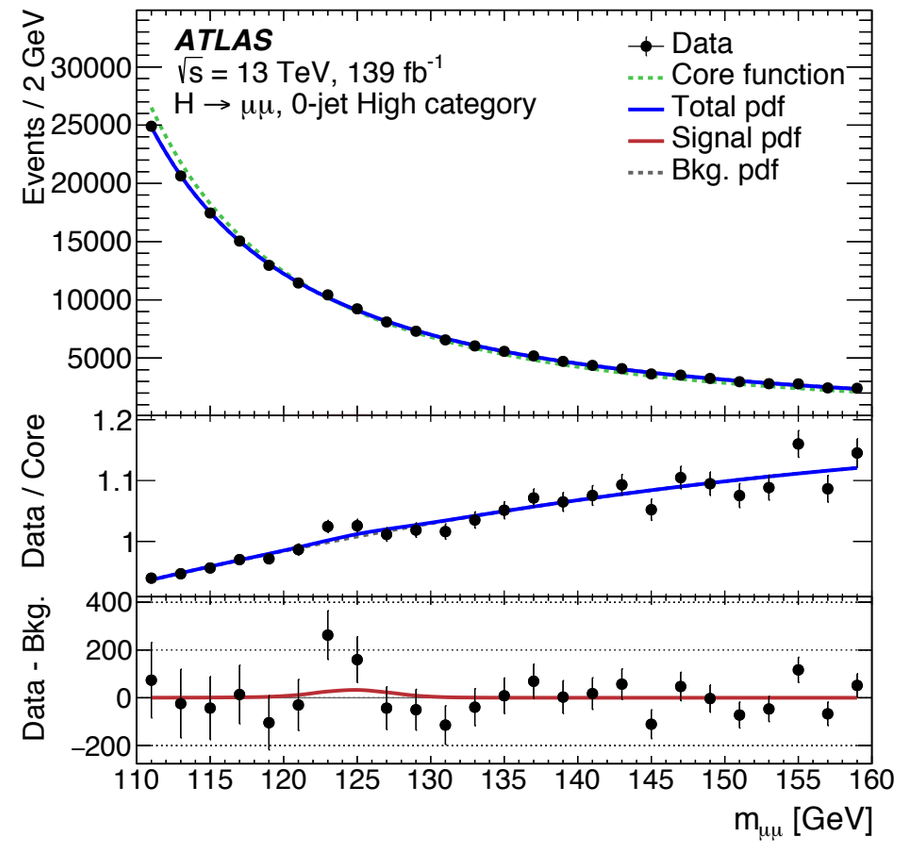


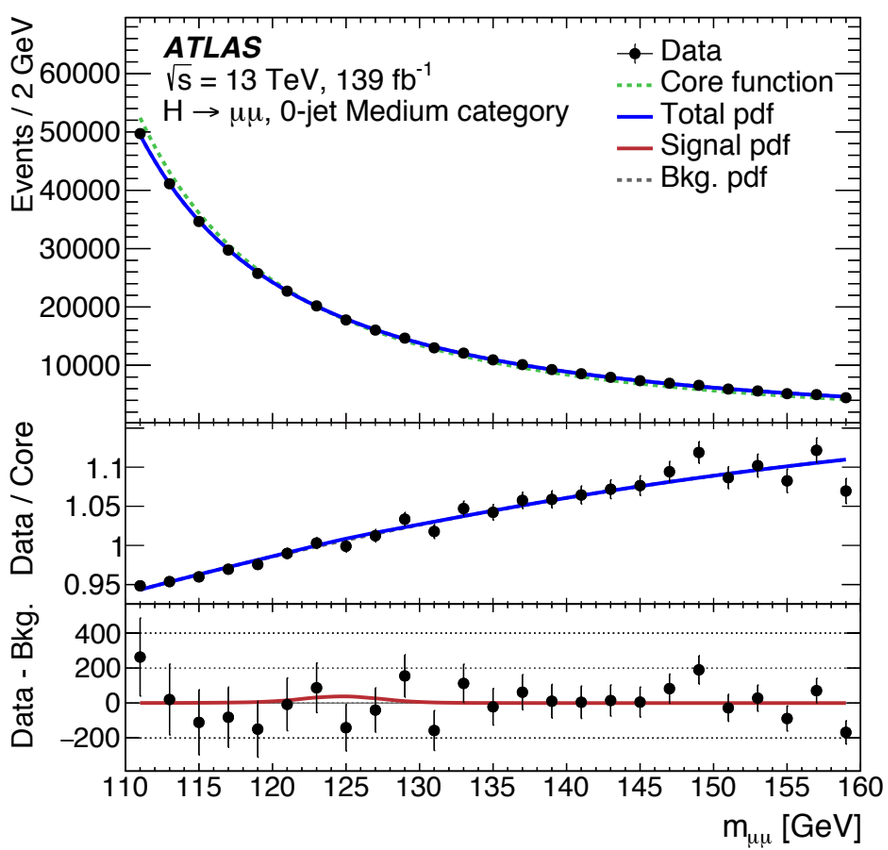


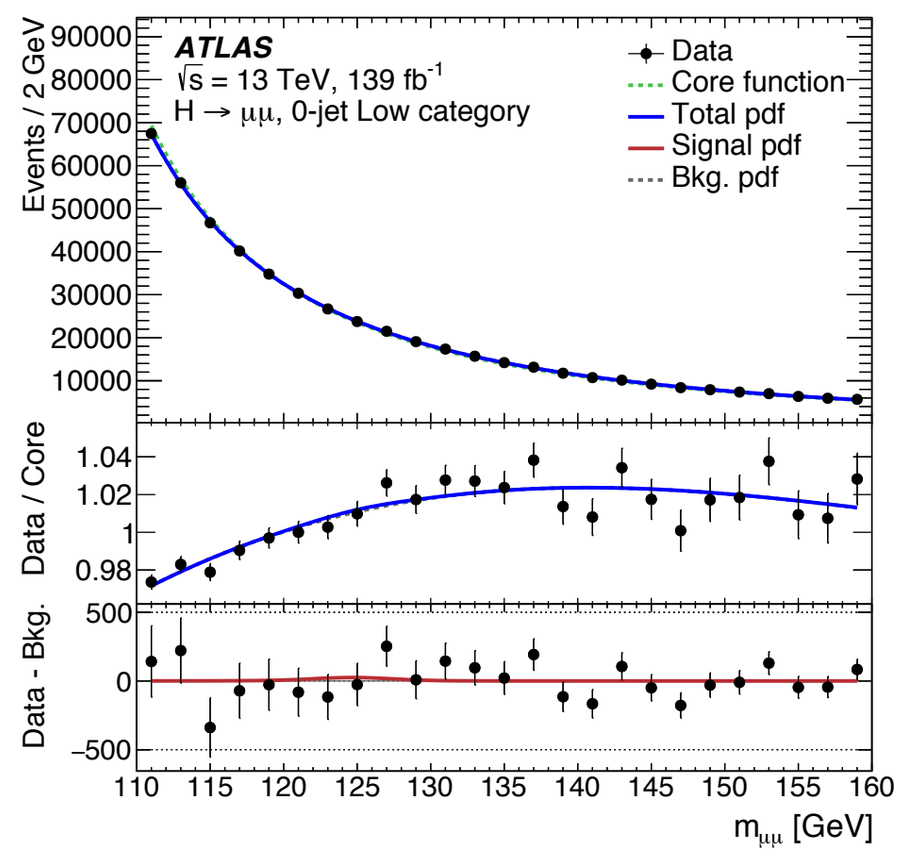


Fit breakdown on data (0-jet)









Fit breakdown on data (ttH/VH)