Search for rare and lepton-flavour-violating decays of the Higgs boson with the ATLAS detector

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on behalf of the ATLAS Collaboration

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Introduction

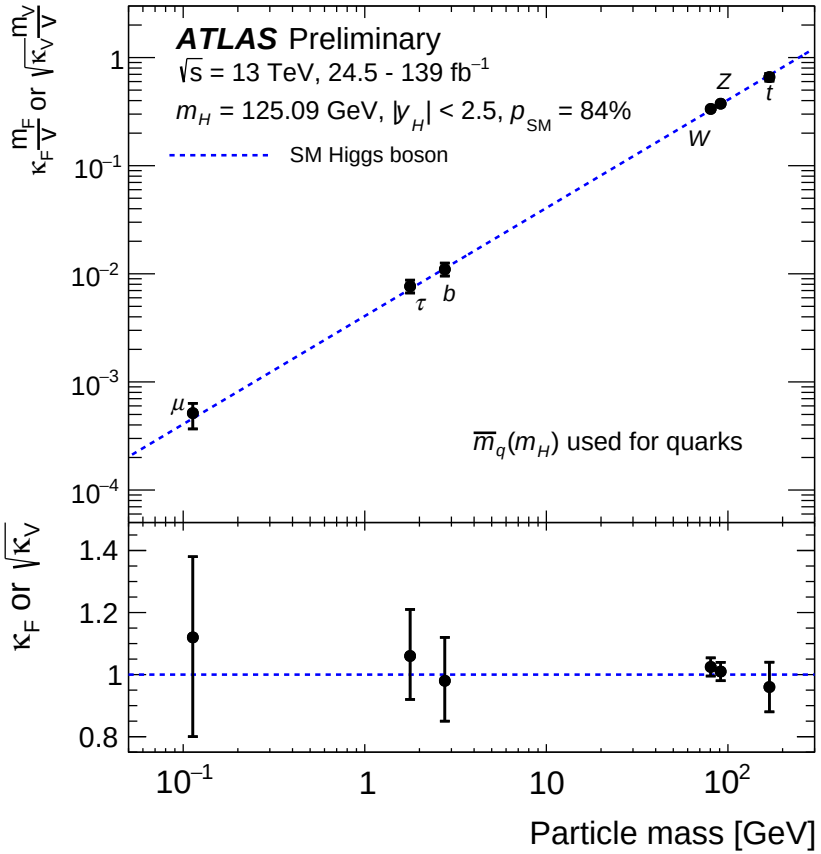
Motivation

- Test of the yet unobserved Higgs boson couplings to 1st and 2nd generation fermions
- Probe of Yukawa interactions in SM
- Test of BSM models by searching for lepton-flavour-violating (LFV) Higgs boson decays

Searches covered here

- $H \to \mu\mu$, 139 fb^{-1} **NEW!**
  arXiv:2007.07830
- $H \to ee$ & $H \to e\mu$, 139 fb^{-1}
  Phys. Lett. B 801 (2020) 135148
- $H \to e\tau$ & $H \to \mu\tau$, 36 fb^{-1}
  Phys. Lett. B 800 (2020) 135069

from ATLAS-CONF-2020-027



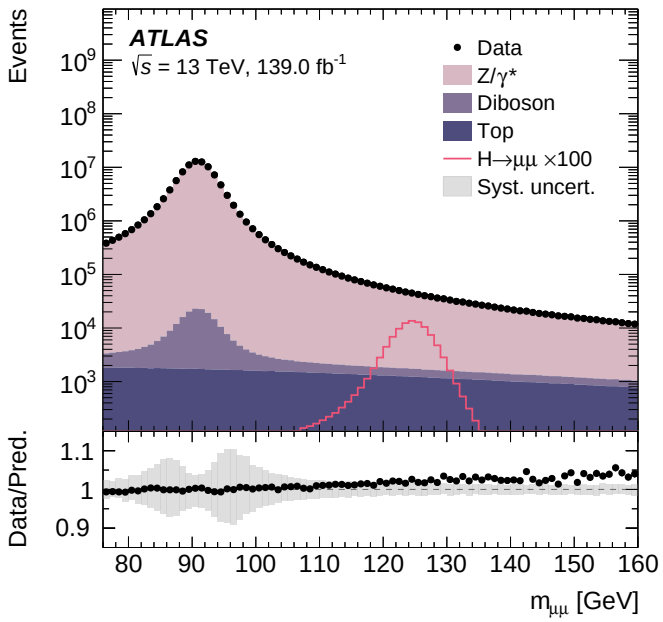
$H \to \mu\mu$ analysis overview

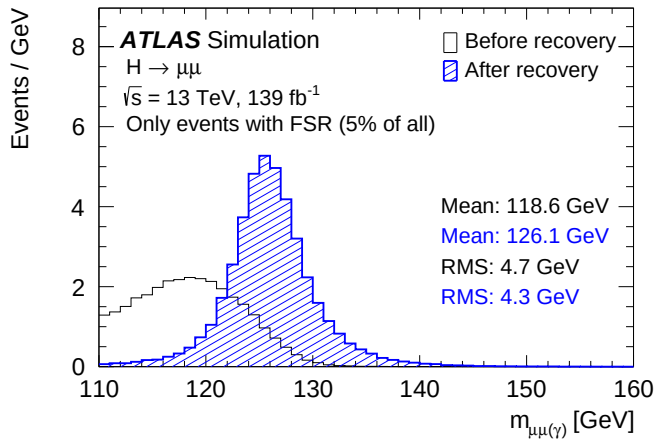
Introduction

- Very small branching ratio of $2.2 \cdot 10^{-4}$
- Large irreducible background dominated by Drell-Yan (DY)
  - $S/B = 0.2\%$ for $m_{\mu\mu} \in (120, 130)$ GeV

Analysis strategy

- Loose selection to maximise signal acceptance
- Adding up to one final-state-radiation photon to improve dimuon mass resolution (only in ggF and VBF categories)
- Production-driven categorisation using BDTs
  - targeting production channels in the following order: $t\bar{t}H$, VH, VBF and ggF
- Signal extraction from an S+B fit to dimuon mass distribution in mass range 110–160 GeV





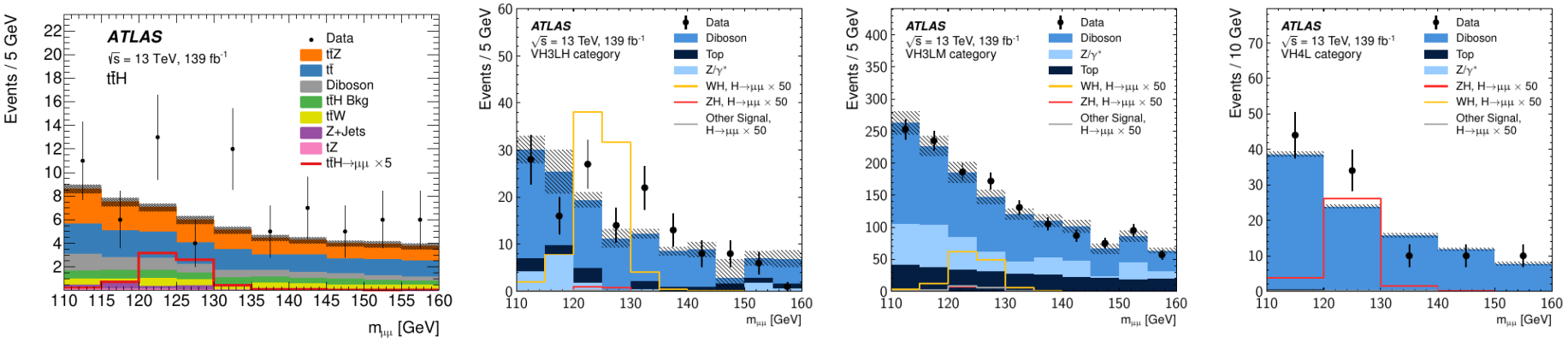
$H \to \mu\mu$ $t\bar{t}H$ and VH categories

$t\bar{t}H$

- Targeting dileptonic or semileptonic decays of $t\bar{t}$
  - requiring at least one additional lepton (μ or e) and at least one b-jet
- BDT discriminant used to further reduce background
- Background dominated by $t\bar{t}Z$
- Expected signal yield: 1.2 events
- Expected $S/B = 8\%$

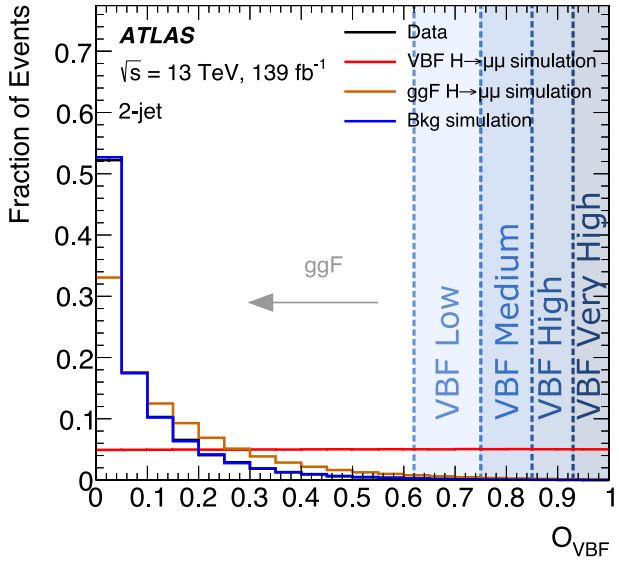
VH

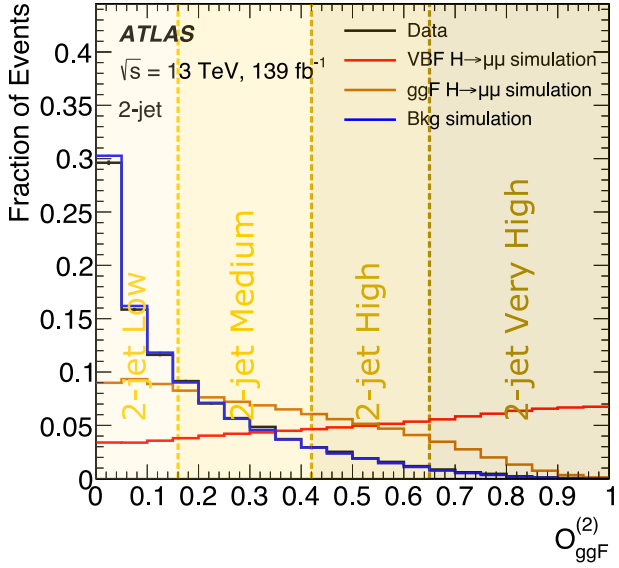
- Targeting leptonic decays of vector boson, either $W \to \ell\nu$ (VH3L) or $Z \to \ell\ell$ (VH4L), $\ell = \mu, e$
  - requiring at least one additional lepton, no b-jets
- Separate training of BDTs in VH3L and VH4L
- Two categories defined in VH3L, single category in VH4L
- Background dominated by diboson
- Expected signal yields (S/B): 1.4 (3.7%) in VH3LH, 2.8 (0.8%) in VH3LM, 0.5 (2.6%) in VH4L



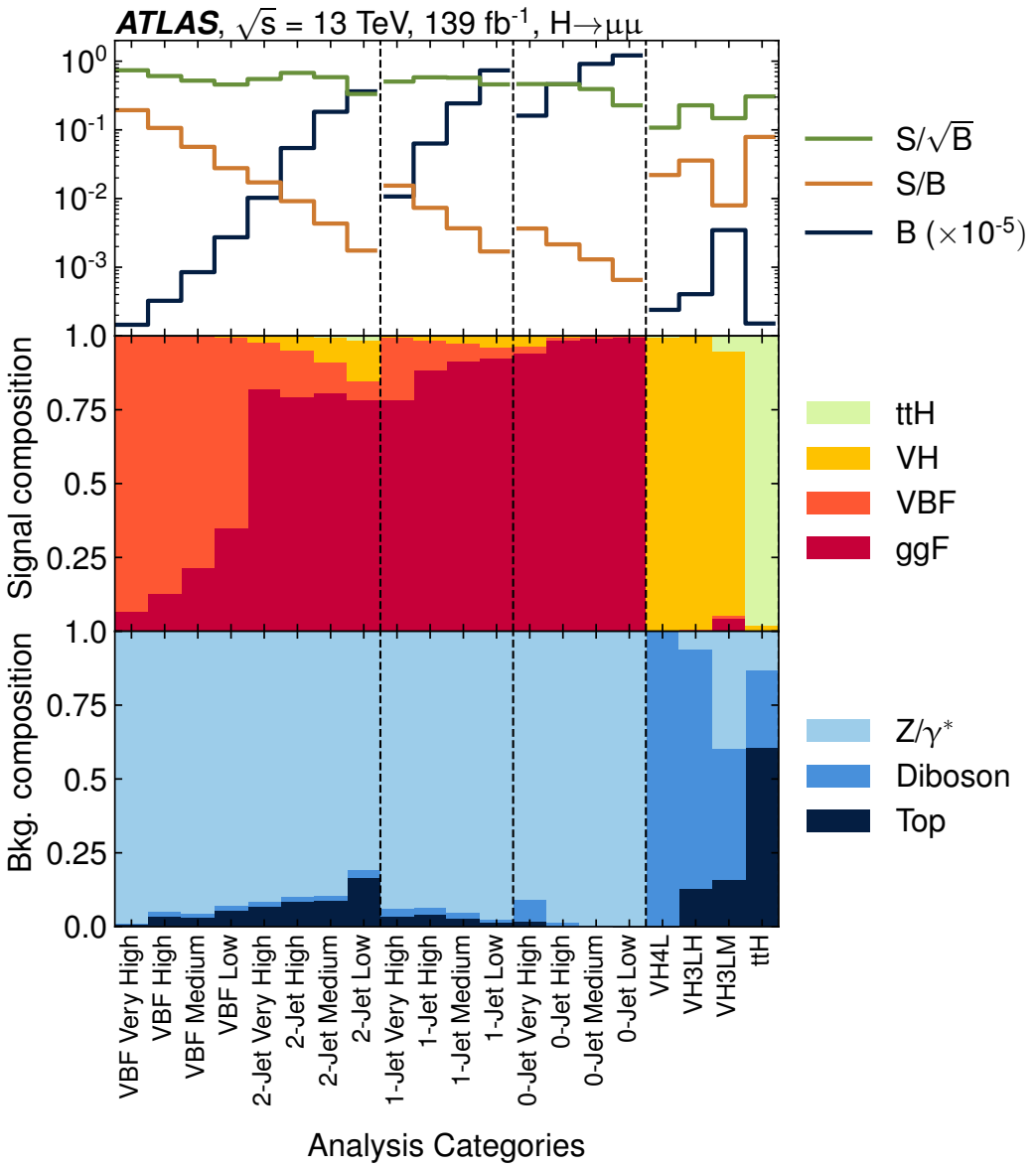
$H \to \mu\mu$ *VBF* and *ggF* categories

- Requiring events with exactly two opposite-sign muons, no b-jets
- Events divided into N-jet channels: 0-, 1- and 2-jet (including ≥ 2 jets)
- Separate training of classifiers in different channels to fully exploit differences between S and B
- Events categorised based on dedicated BDT output in each N-jet channel
  - 4 categories in 2-jet channel with the highest priority targeting ***VBF*** production mode based on BDT output O_{VBF}
  - 4 categories in each N-jet channel targeting ***ggF*** production process based on BDT output $O_{ggF}^{(N)}$
  - in the order of decreasing purity categories are: Very High, High, Medium and Low





$H \to \mu\mu$ signal and background composition



- Very good separation of production modes
- Wide range of S/B from 0.1% to 20%
- Every category contributes in between 0.1 and 0.6σ

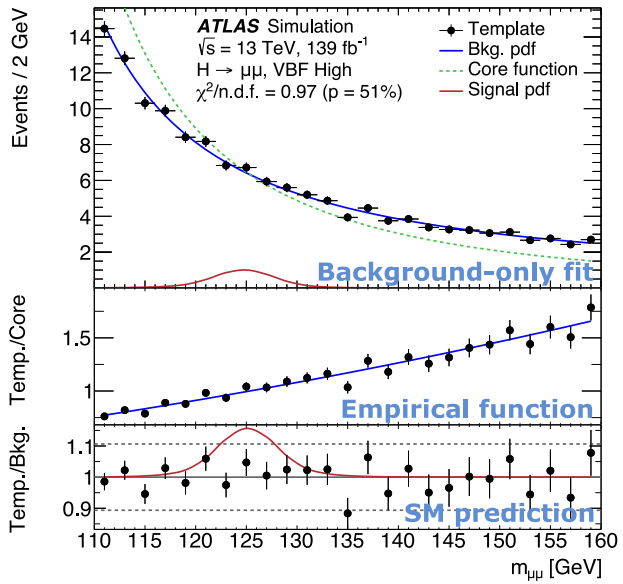
$H \to \mu\mu$ signal and background modelling

- Signal modelled with a double-sided Crystal Ball function
- Background model tested on high-statistics fast DY MC simulation and created from two components:

$$PDF_{bkg}(m_{\mu\mu}) = \text{(Core function)} \times \text{(Empirical function)}$$

- Core function is a LO DY line-shape convolved with a Gaussian to account for resolution effects
  - no free parameters, same in all categories
- Empirical function corrects for distortions of the mass shape induced by the selection of each category
  - selected based on a few criteria from two families of functions
  - number of free parameters depending on category

Function	Expression
PowerN	$m_{\mu\mu}^{(a_0+a_1 m_{\mu\mu}+a_2 m_{\mu\mu}^2+\cdots+a_N m_{\mu\mu}^N)}$
EpolyN	$\exp\left(a_0 + a_1 m_{\mu\mu} + a_2 m_{\mu\mu}^2 + \cdots + a_N m_{\mu\mu}^N\right)$



$H \to \mu\mu$ results

Observed signal strength:

$\mathbf{1.2 \pm 0.6}$

Major uncertainties:

- data statistics: ± 0.58
- signal theory systematic: $^{+0.13}_{-0.08}$
- signal experimental systematic: $^{+0.07}_{-0.03}$
- background modelling: ± 0.10

Observed (expected) significance:

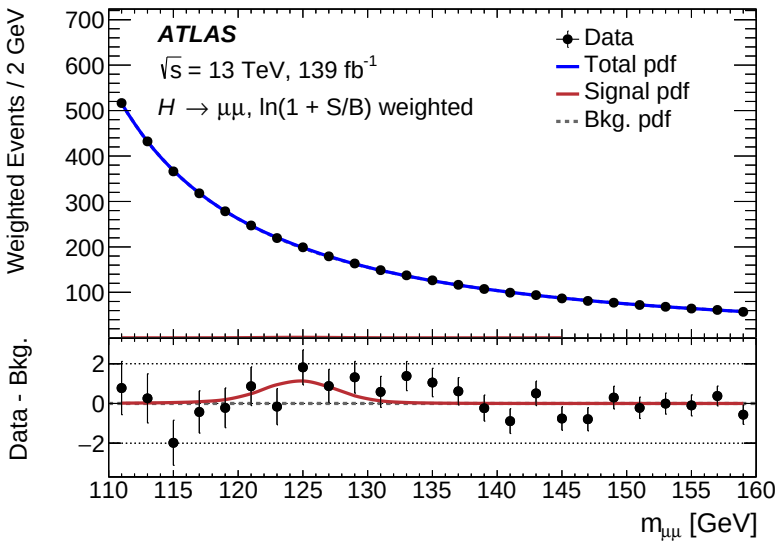
$\mathbf{2.0\sigma\ (1.7\sigma)}$

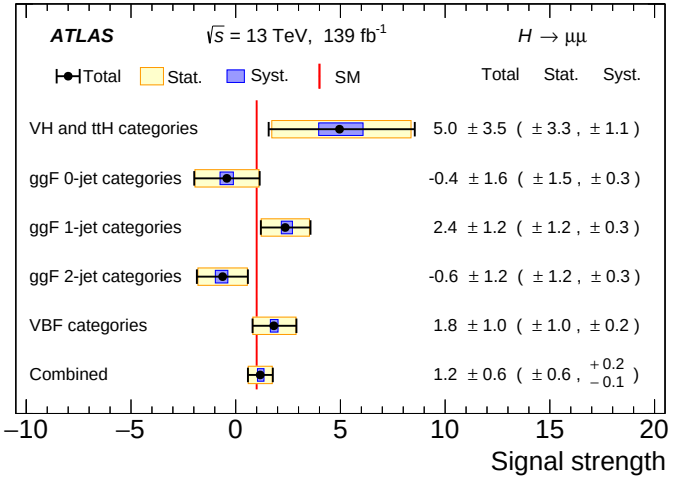
Observed (expected) limit on signal strength at 95% CL:

2.2 (**1.1** for the case of no $H \to \mu\mu$ signal)

Observed limit on branching fraction at 95% CL:

$\mathcal{B}(H \to \mu\mu) < 4.7 \cdot 10^{-4}$

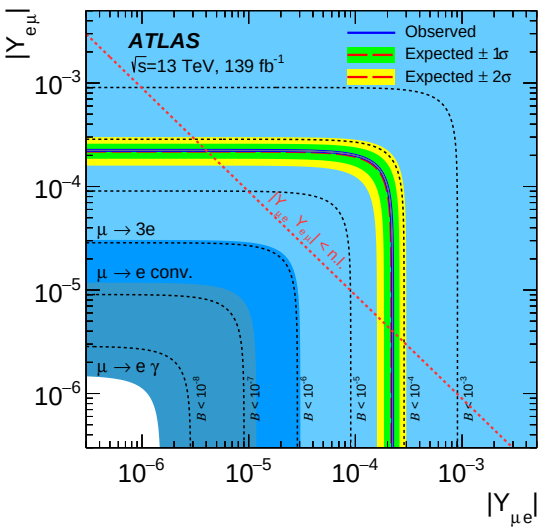




$H \to ee$ and $H \to e\mu$ searches overview

Introduction

- $H \to ee$ branching ratio $\sim 5 \cdot 10^{-9}$ far below sensitivity of any experiment
- Large irreducible backgrounds
- Test of BSM models

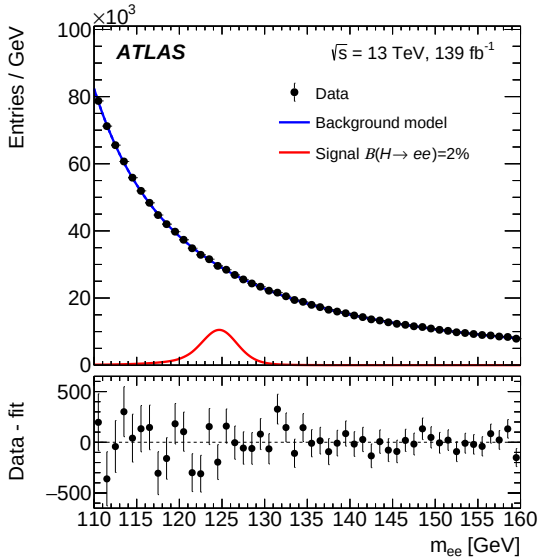


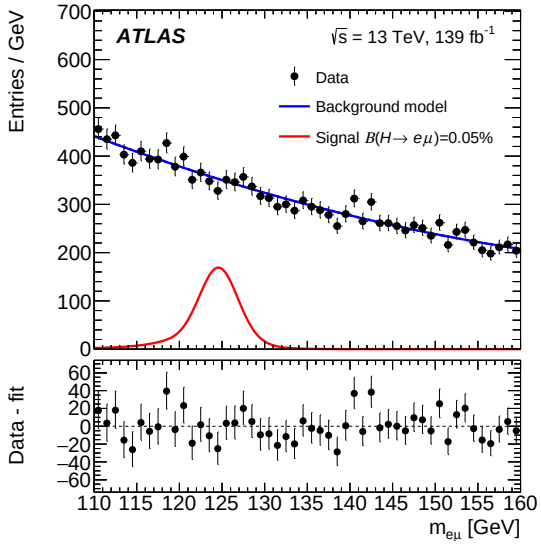
Analysis strategy

- Similar strategy to the $H \to \mu\mu$ 36 fb^{-1} search (Phys. Rev. Lett. 119 (2017) 051802)
- Selection based on:
  - exactly two opposite-sign leptons with $p_{\mathrm{T}}^{\ell 1}(p_{\mathrm{T}}^{\ell 2}) > 27(15)$ GeV
  - vetoing events with b-jets or high $E_{\mathrm{T}}^{\mathrm{miss}}$ significance
- Categorisation targeting ggF and VBF production modes
  - cut-based VBF category requiring 2 forward jets with large rapidity gap between them
  - remaining events divided into six ggF categories split by $p_{\mathrm{T}}^{\ell\ell}$ and $|\eta_{\ell 1,\, \ell 2}|$
  - additional low-p_{T} category in $e\mu$ with either lepton p_{T} below 27 GeV (larger fake contrib.)
- $S+B$ fit to dilepton mass distribution to extract signal from a falling background

$H \to ee$ and $H \to e\mu$ fits and results

- Signal in both channels modelled with a sum of Crystal Ball and Gaussian functions
- Background model in $H \to ee$ the same as the one used in the $H \to \mu\mu$ 36 fb^{-1} analysis (the same dominating background – DY)
- $H \to e\mu$ background composition more complex ($Z/\gamma^* \to \tau\tau$, top, diboson, W+jets, misidentified jets) → background modelled with Bernstein polynomial of degree two





	$H \to ee$	$H \to e\mu$
$\mathcal{B}(H \to \ell\ell)$	$(0.0 \pm 1.7(\text{stat.}) \pm 0.6(\text{syst.})) \cdot 10^{-4}$ largest syst.: background modelling	$(0.4 \pm 2.9(\text{stat.}) \pm 0.3(\text{syst.})) \cdot 10^{-5}$ largest syst.: Higgs prod. xsection
Observed limit at 95% CL	$3.6 \cdot 10^{-4}$	$6.2 \cdot 10^{-5}$
Expected limit at 95% CL	$3.5 \cdot 10^{-4}$	$5.9 \cdot 10^{-5}$

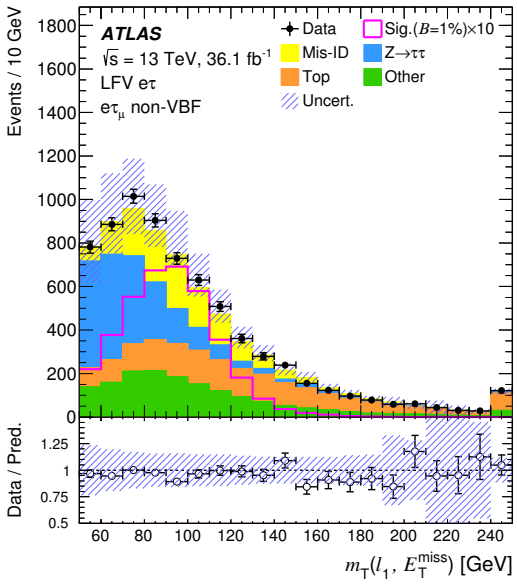
$H \to e\tau$ and $H \to \mu\tau$ searches overview

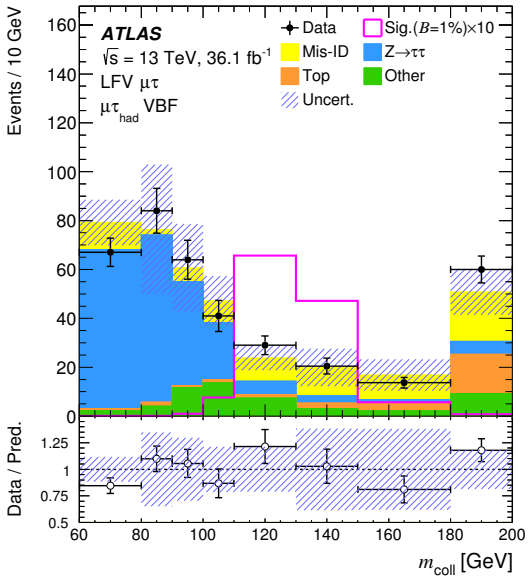
Introduction

- Test of BSM models
- Many methods reused from $H \to \tau\tau$ analysis (Phys. Rev. D 99 (2019) 072001)

Analysis strategy

- Considering: $e\tau_\mu$, $e\tau_{\text{had}}$, $\mu\tau_e$ and $\mu\tau_{\text{had}}$ channels
- Each channel divided into VBF and non-VBF SRs
- Additional top and $Z \to \tau\tau$ CRs in $\ell\tau_{\ell'}$ channel
- Using BDTs to enhance separation between S and B in SRs
- Combined binned likelihood fit to all BDT bins in SRs and CR yields independently in $e\tau$ and $\mu\tau$
  - constrain background and extract $\mathcal{B}(H \to \ell\tau)$





$H \to e\tau$ and $H \to \mu\tau$ modelling and results

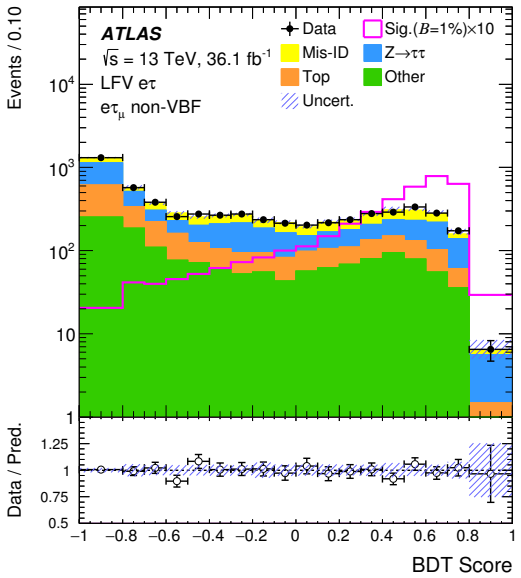
Main backgrounds

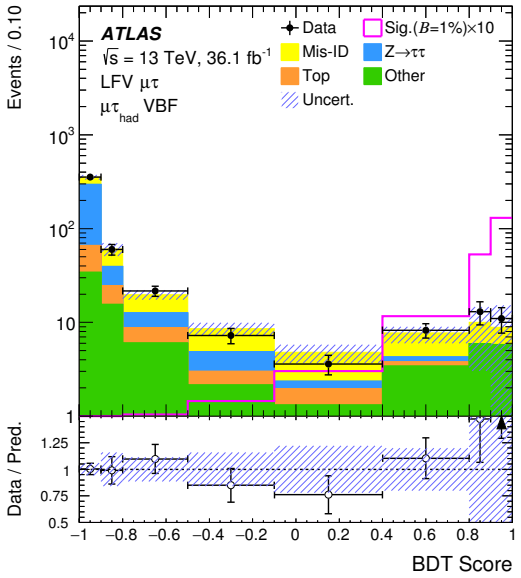
- Events with misidentified objects - estimated using data-driven techniques
- $Z \to \tau\tau$ and top - shape from MC, normalisation from fit
- Other ($Z \to \mu\mu$, diboson, $H \to \tau\tau$, $H \to WW$) - constrained to SM prediction

Main sources of systematic uncertainties

- Estimation of backgrounds from misidentified objects
- Jet energy scale

	$H \to e\tau$	$H \to \mu\tau$
$\mathcal{B}(H \to \ell\tau)$	$(0.15^{+0.18}_{-0.17})\%$	$(-0.22 \pm 0.19)\%$
Observed limit at 95% CL	0.47%	0.28%
Expected limit at 95% CL	$(0.34^{+0.13}_{-0.10})\%$	$(0.37^{+0.14}_{-0.10})\%$





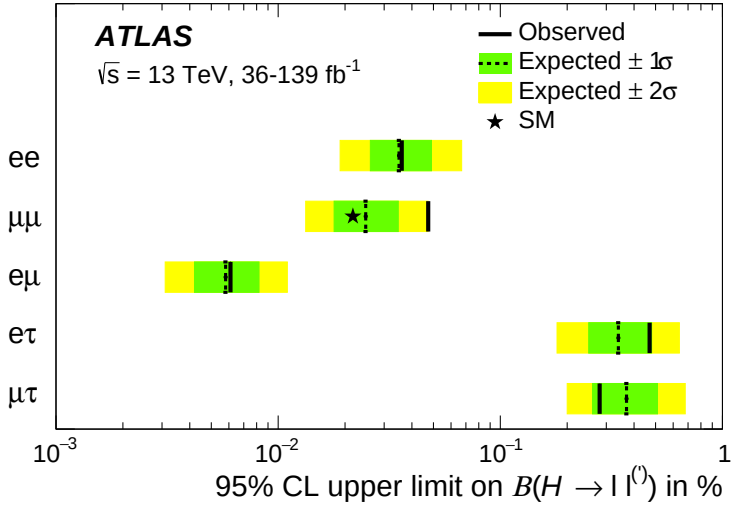
Conclusions

Presented new $H \to \mu\mu$ result using full Run-2 data (139 fb^{-1})

- Signal strength: 1.2 ± 0.6, significance: 2.0σ
- Factor 2.5 improvement in expected sensitivity w.r.t. the previous published result (36 fb^{-1})
- Larger dataset and improvements in the analysis including:
  - more categories defined only based on BDT classifiers
  - additional categories targeting VH and $t\bar{t}H$ production
  - improved background modelling
  - FSR recovery

Presented also searches for $H \to ee$ and LFV decays

- No evidence → limits set on the branching ratios



Additional material

$H \to \mu\mu$ selection

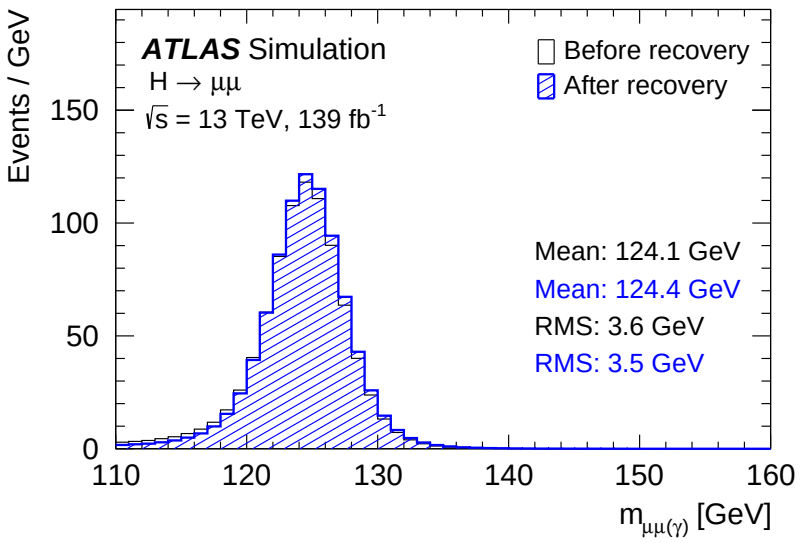
	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\lvert\eta\rvert < 2.7$, $p_{\mathrm{T}}^{\mathrm{lead}} > 27\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\,\mathrm{GeV}$ (except VH 3-lepton)
Fit Region	$110 < m_{\mu\mu} < 160\,\mathrm{GeV}$
Jets	$p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$ or with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $2.4 < \lvert\eta\rvert < 4.5$
$t\bar{t}H$ Category	at least one additional e or μ with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$, at least one b-jet (85% WP)
VH 3-lepton Categories	$p_{\mathrm{T}}^{\mathrm{sublead}} > 10\,\mathrm{GeV}$, one additional e (μ) with $p_{\mathrm{T}} > 15(10)\,\mathrm{GeV}$, no b-jets (85% WP)
VH 4-lepton Category	at least two additional e or μ with $p_{\mathrm{T}} > 8, 6\,\mathrm{GeV}$, no b-jets (85% WP)
ggF +VBF Categories	no additional μ, no b-jets (60% WP)

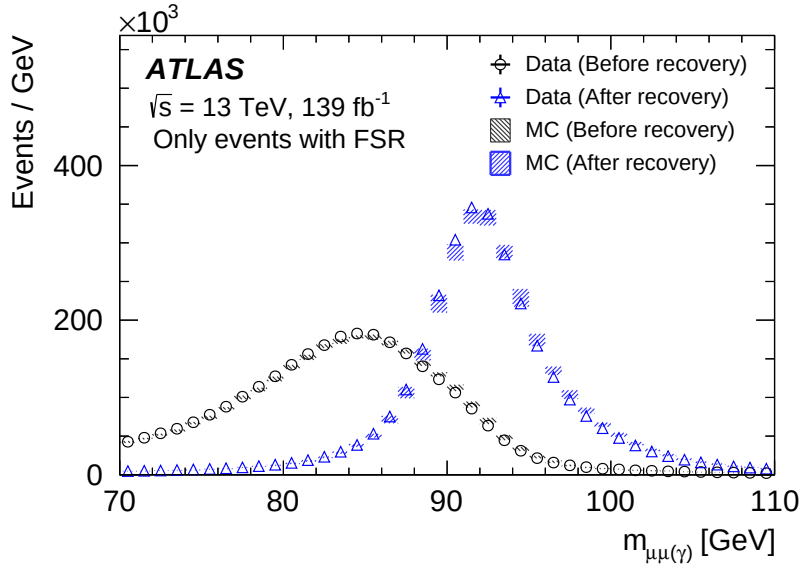
$H \to \mu\mu$ FSR recovery

- Selecting photons only with $\Delta R(\mu, \gamma) < 0.2$
- Variable p_{T}threshold for the photon to reduce pile-up induced background:

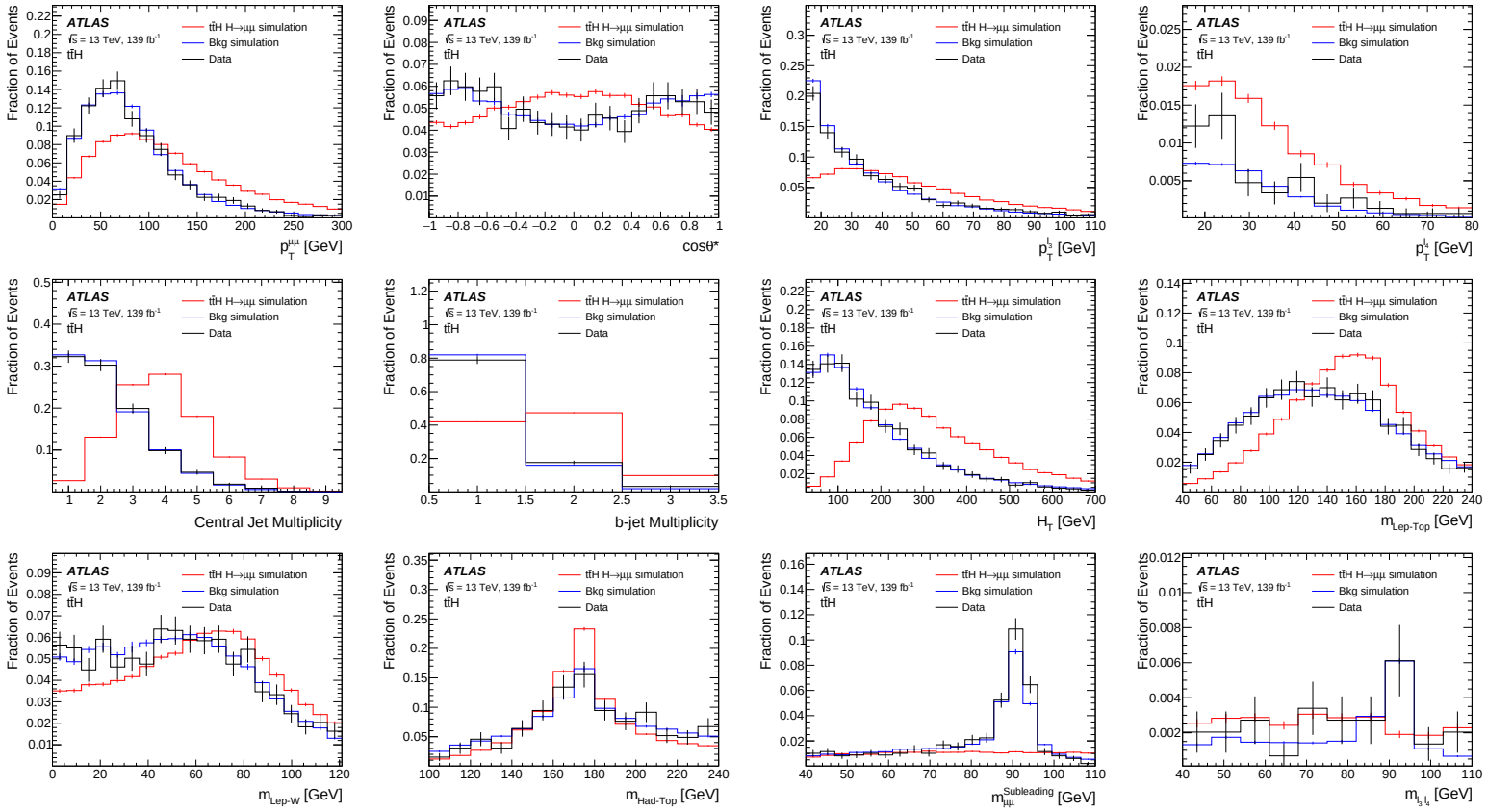
$$p_{\mathrm{T}}^{\gamma}\,[\mathrm{GeV}] \geq 3 + 25 \cdot \Delta R(\mu, \gamma)$$

- If more than one photon passes the selection the one with highest p_{T} is chosen
- Width of the signal mass peak reduced by 3% after FSR recovery
- Negligible contribution from loop-induced $H \to Z\gamma,\ Z \to \mu\mu$ process

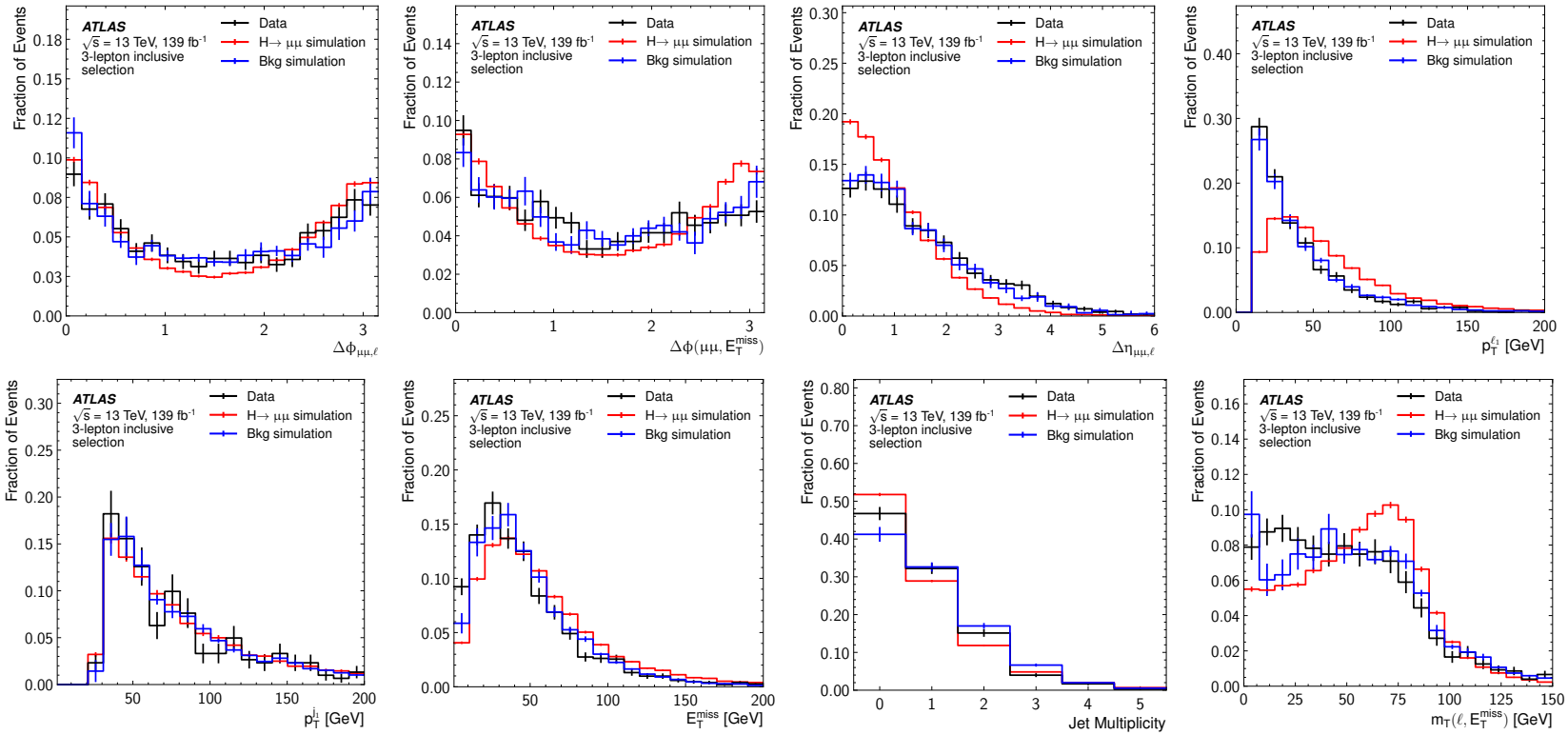




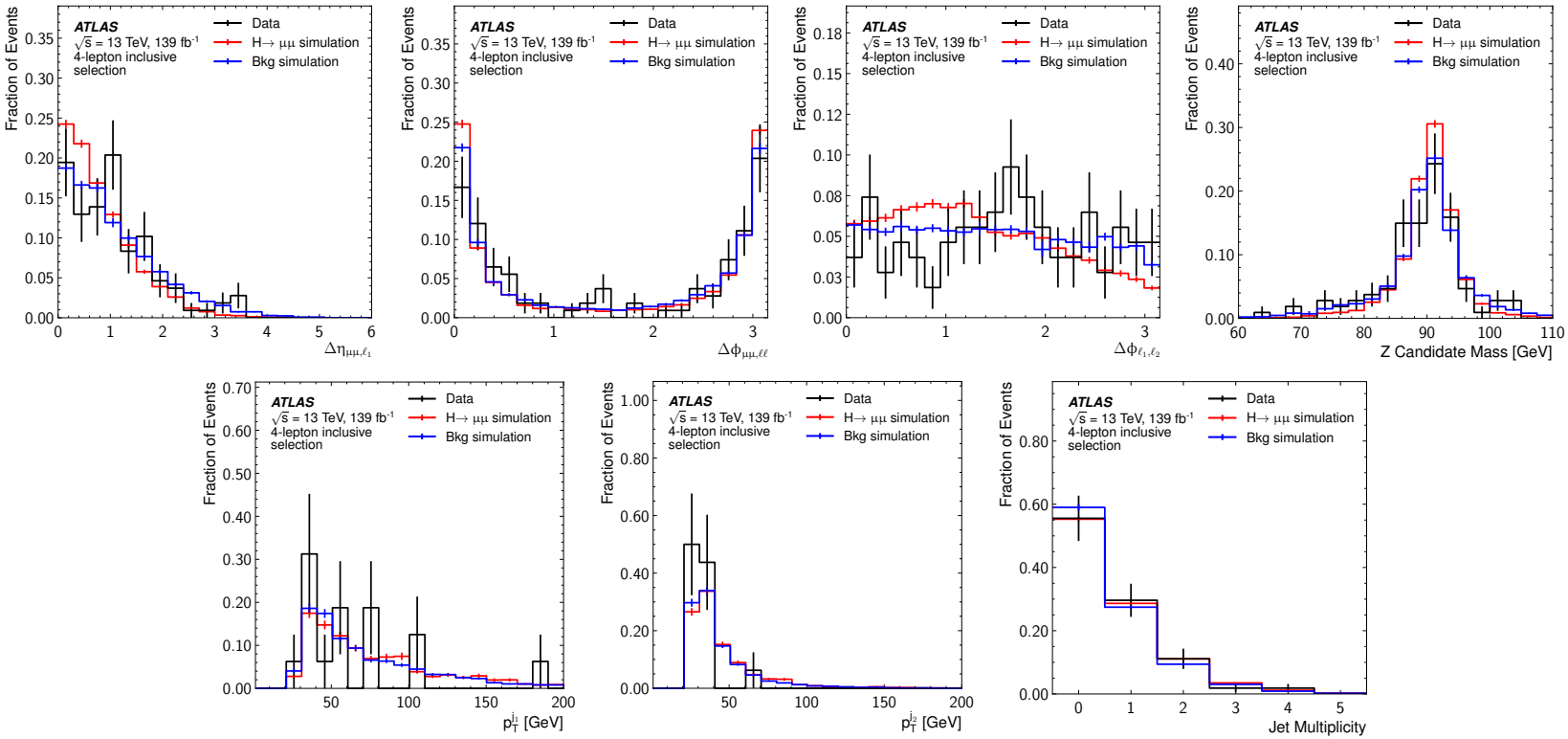
$H \to \mu\mu$ $t\bar{t}H$ training variables



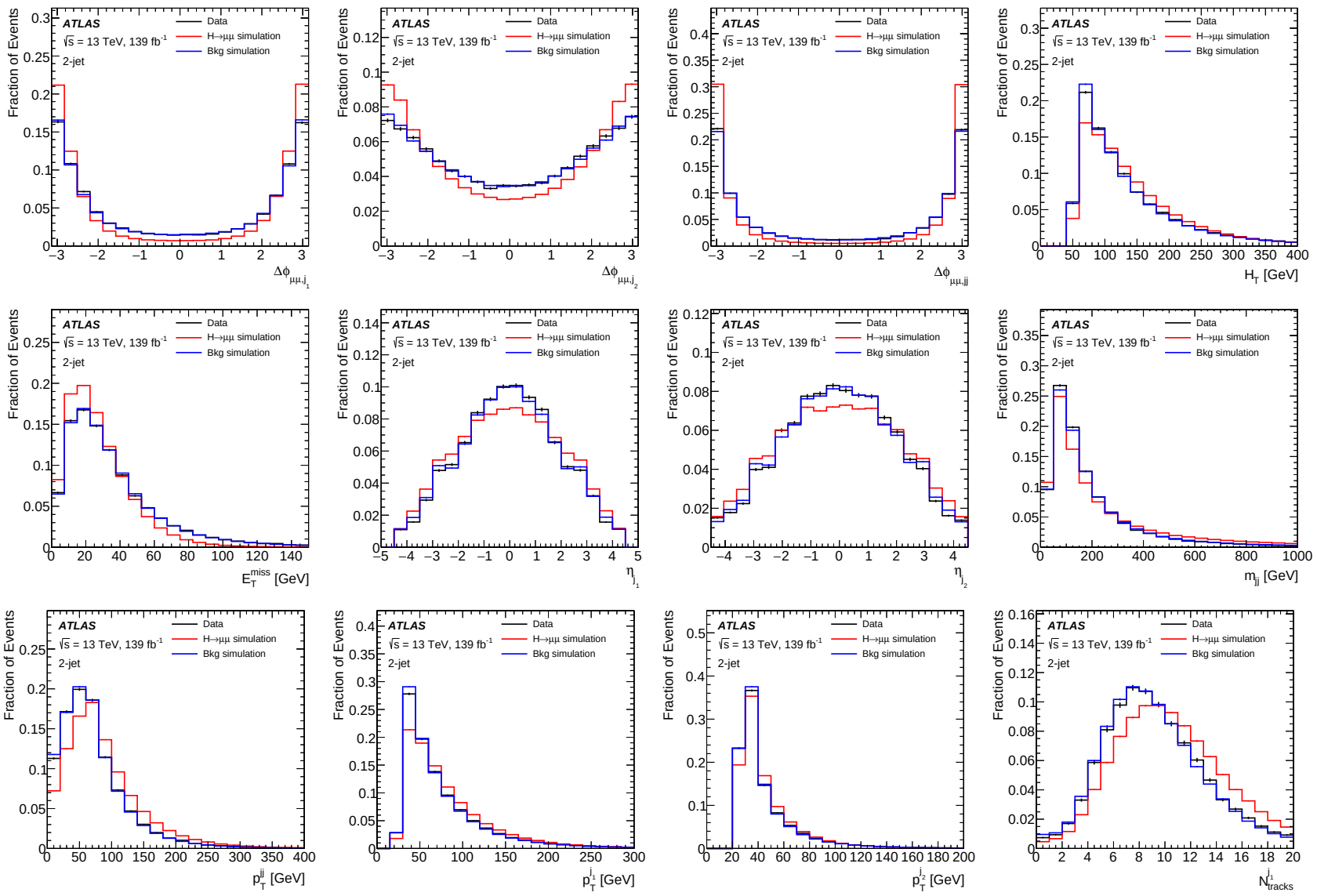
$H \to \mu\mu$ VH 3-lepton training variables



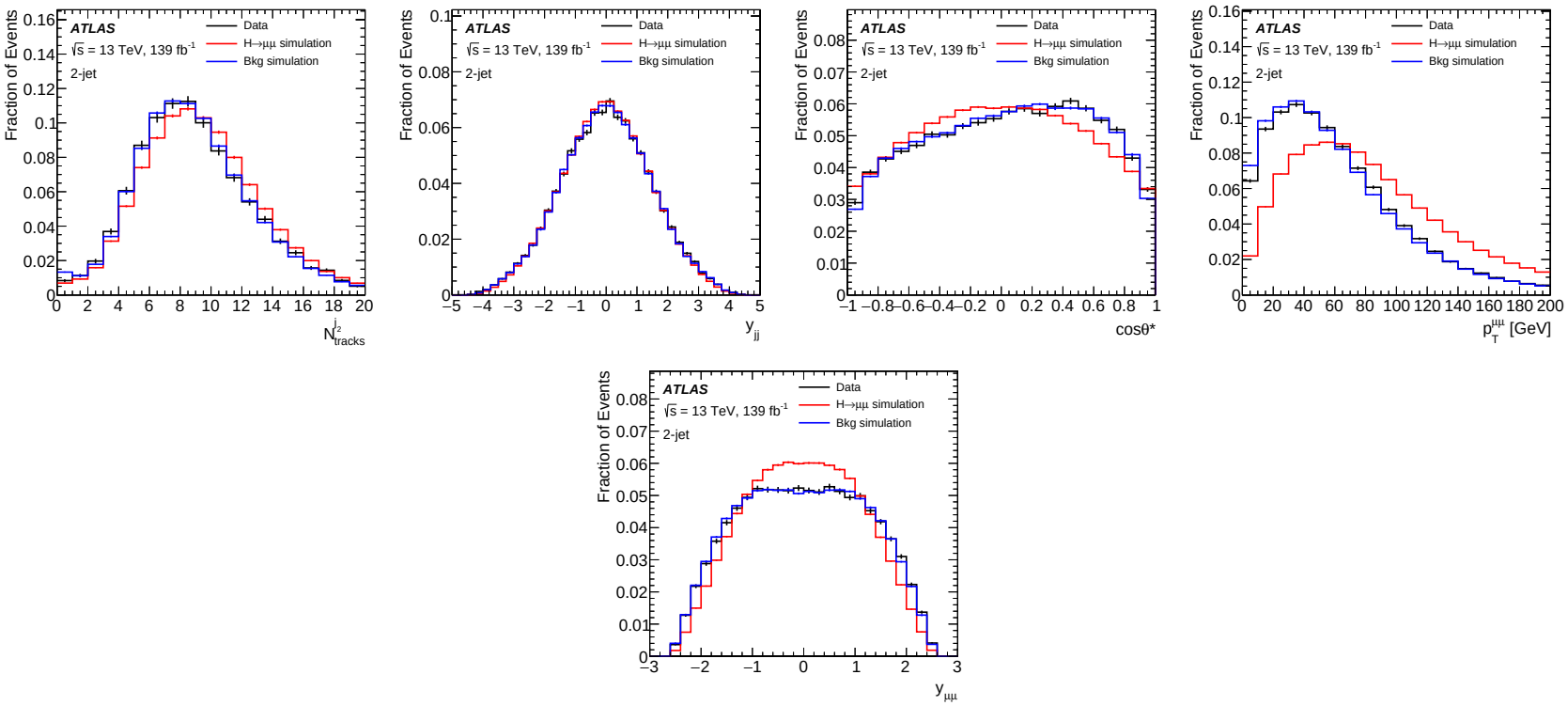
$H \to \mu\mu$ VH 4-lepton training variables



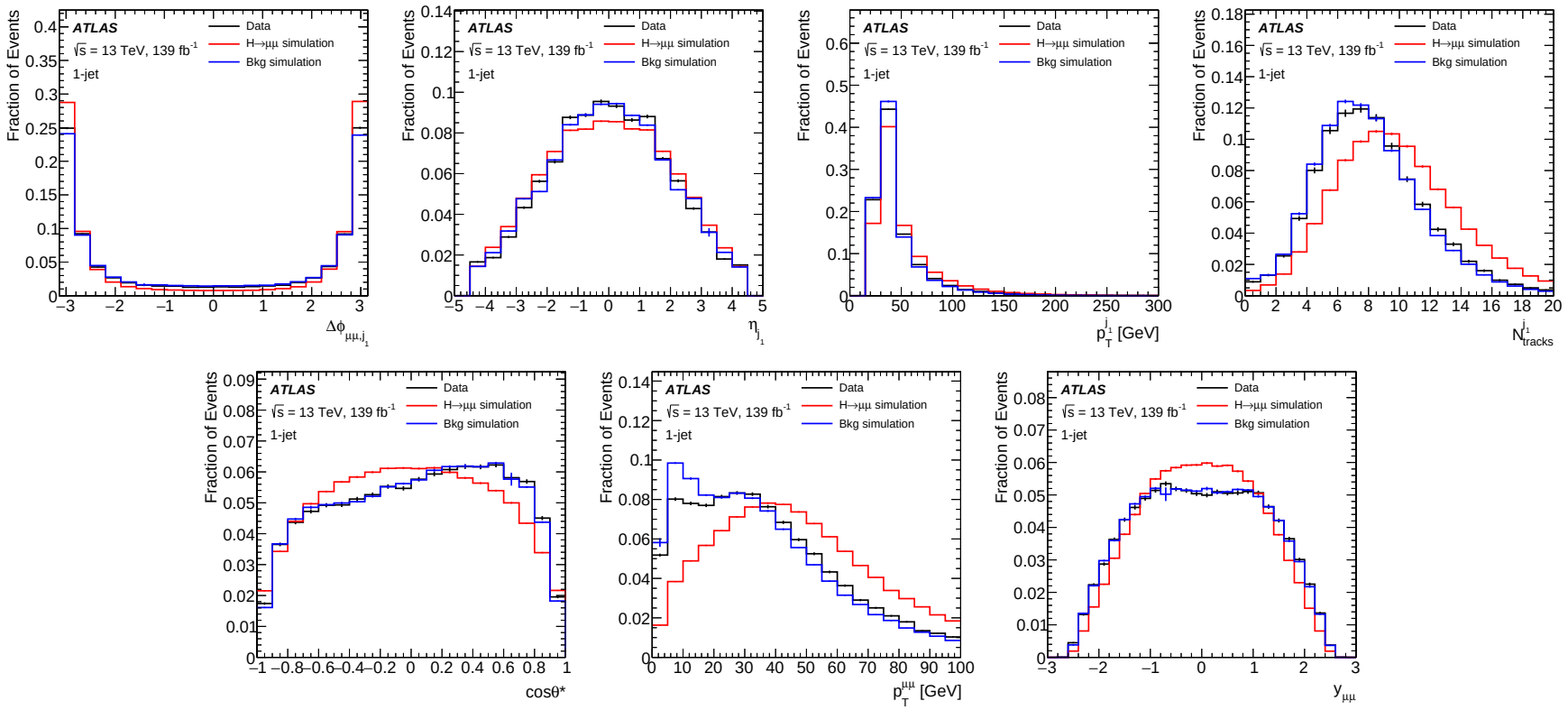
$H \to \mu\mu$ 2-jet channel training variables



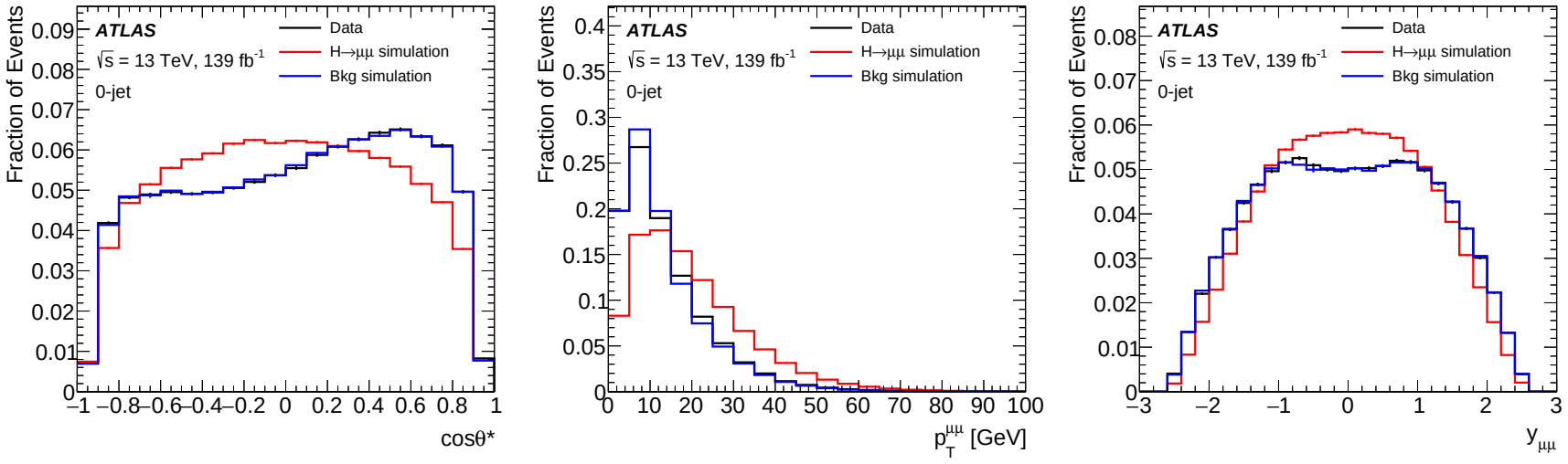
$H \to \mu\mu$ 2-jet channel training variables



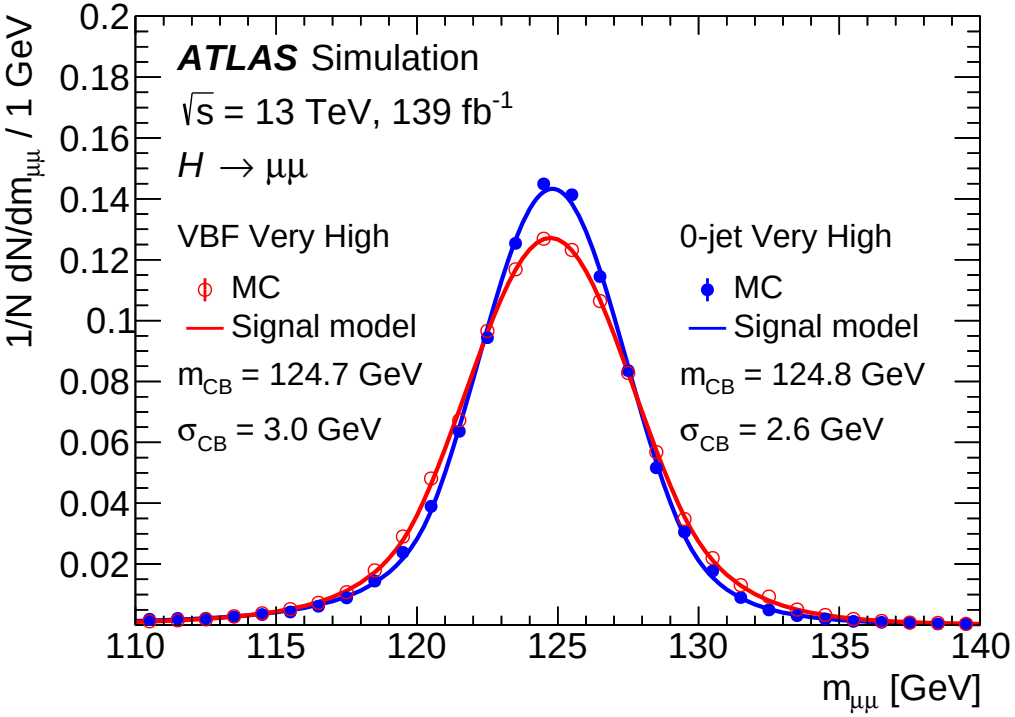
$H \to \mu\mu$ 1-jet channel training variables



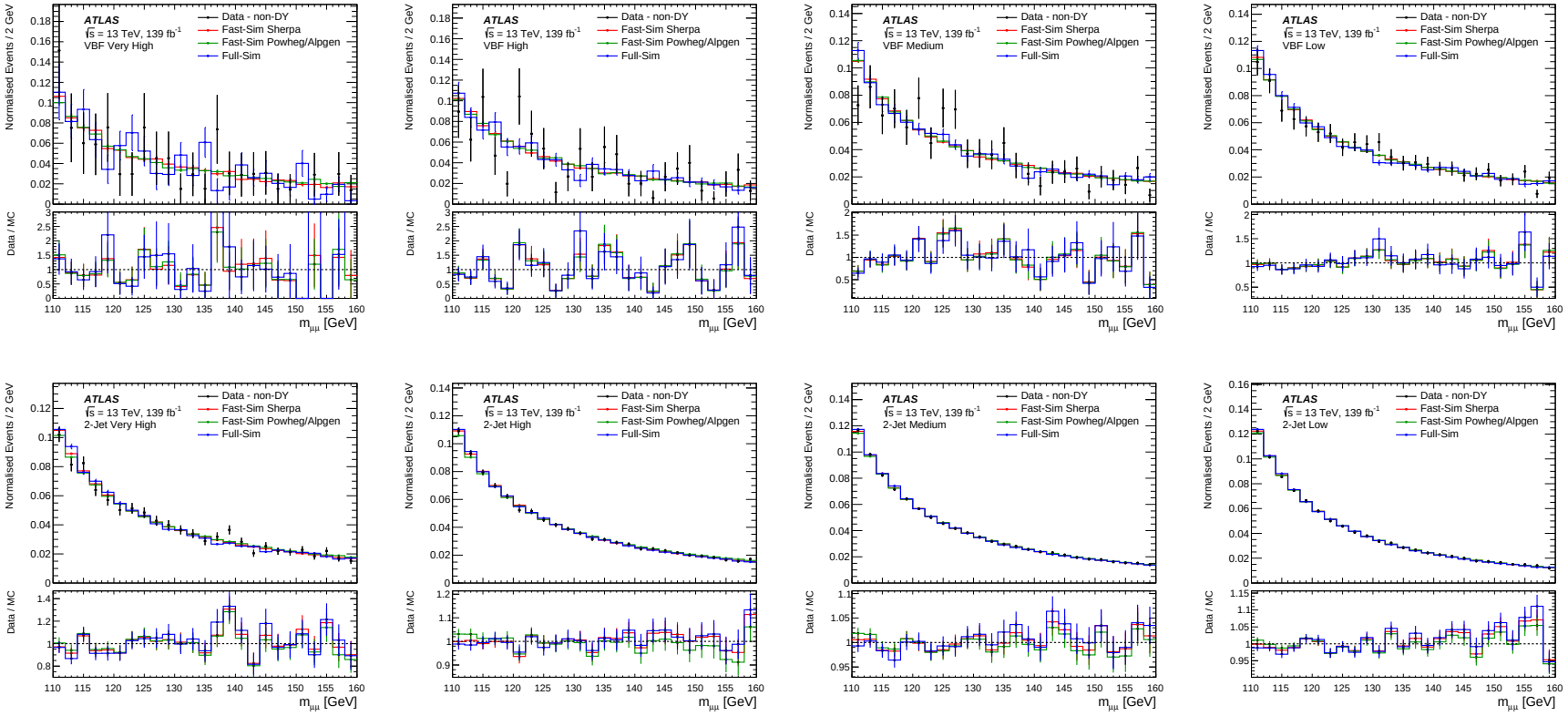
$H \to \mu\mu$ 0-jet channel training variables



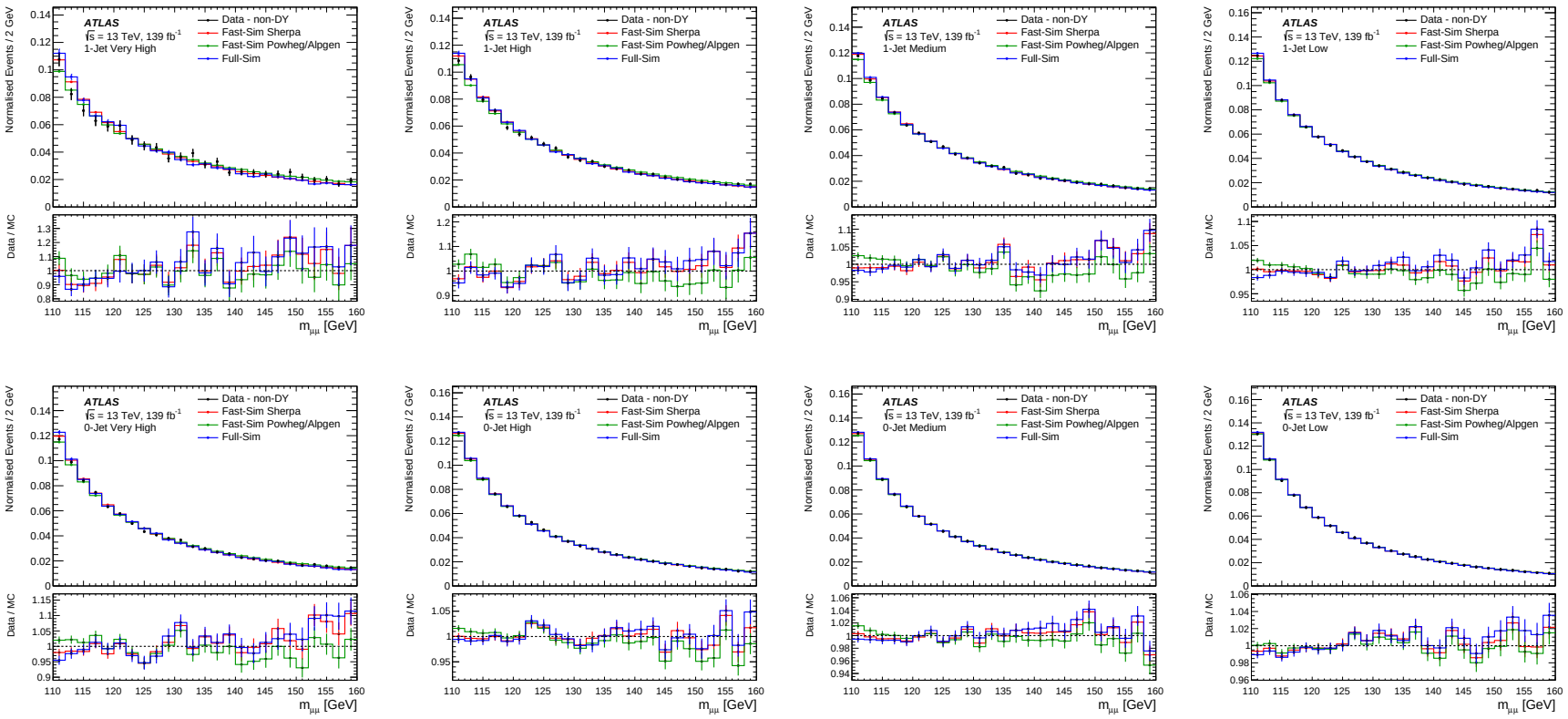
$H \to \mu\mu$ signal model



$H \rightarrow \mu\mu$ mass distributions in fast simulation



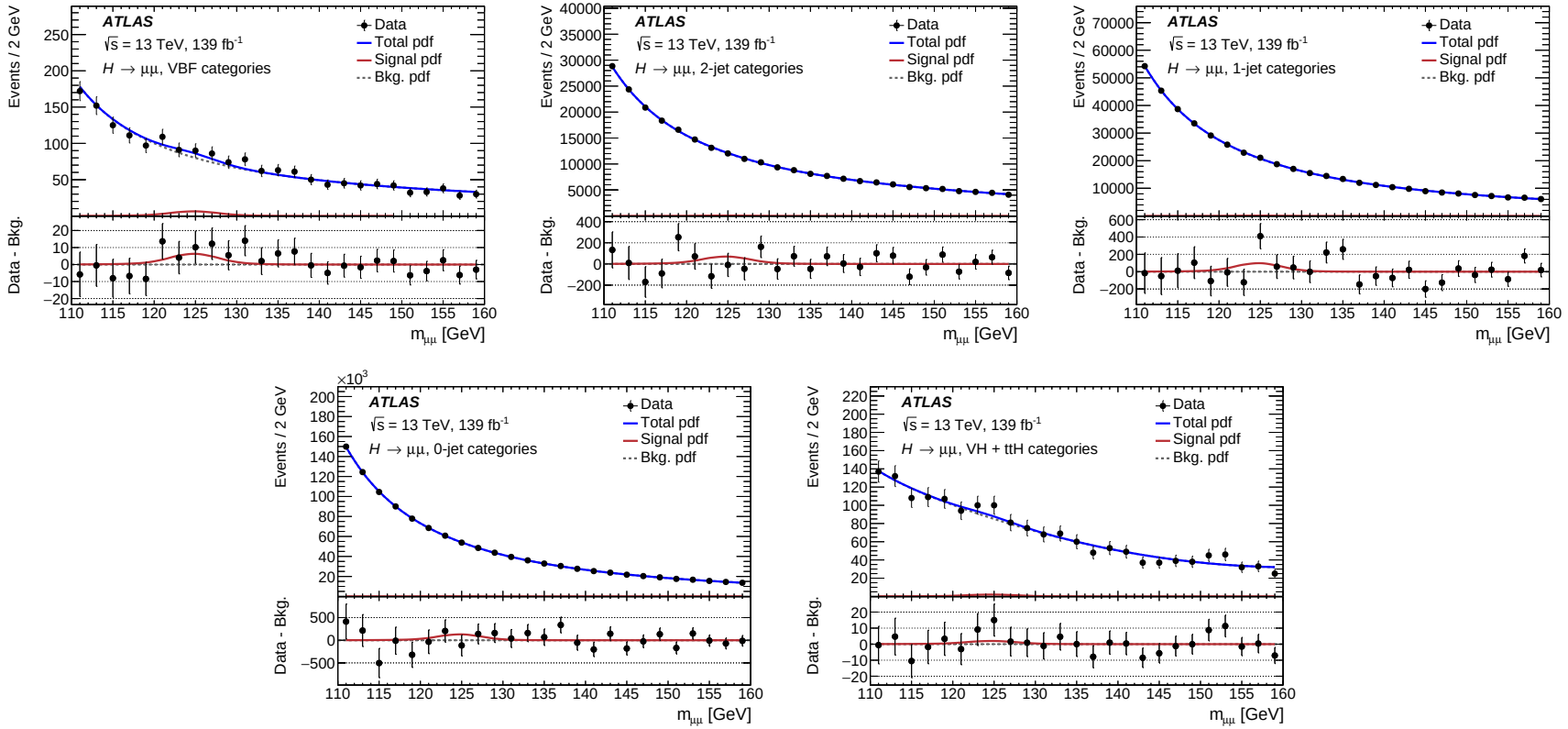
$H \to \mu\mu$ mass distributions in fast simulation



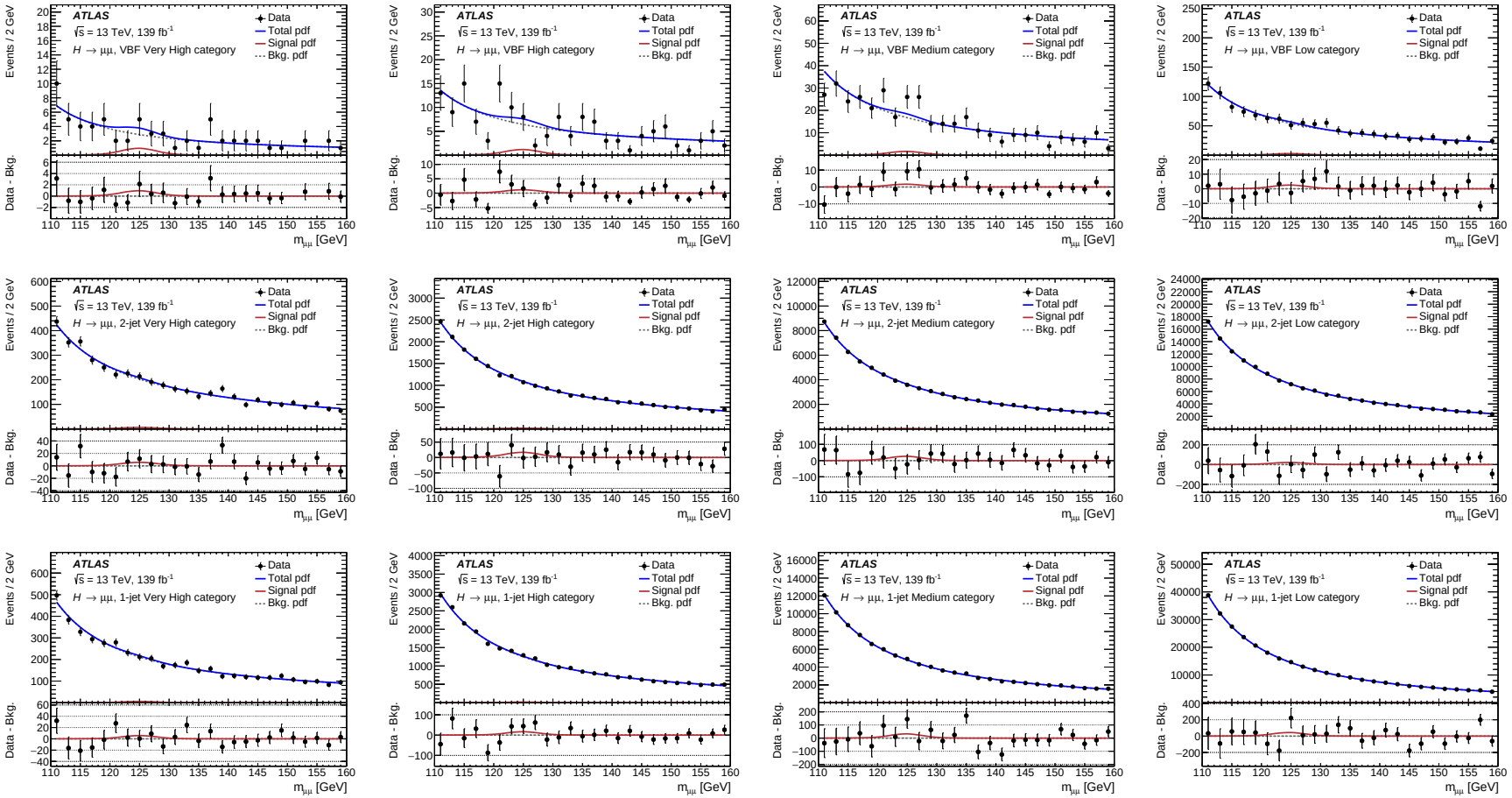
$H \to \mu\mu$ selection criteria for empirical function

1. Tested background model must fit with the χ^2 probability above 1% the dimuon mass distribution in:
   - data sidebands ($m_{\mu\mu} \in (110, 120) \cup (130, 160)$)
   - full MC simulation
   - fast simulation of the DY background (only in ggF and VBF categories)
2. The associated spurious signal uncertainty must be lower than 20% of the statistical uncertainty
3. If more than one function passes criteria 1. and 2. the one with lowest number of degrees of freedom and then lowest spurious signal is selected

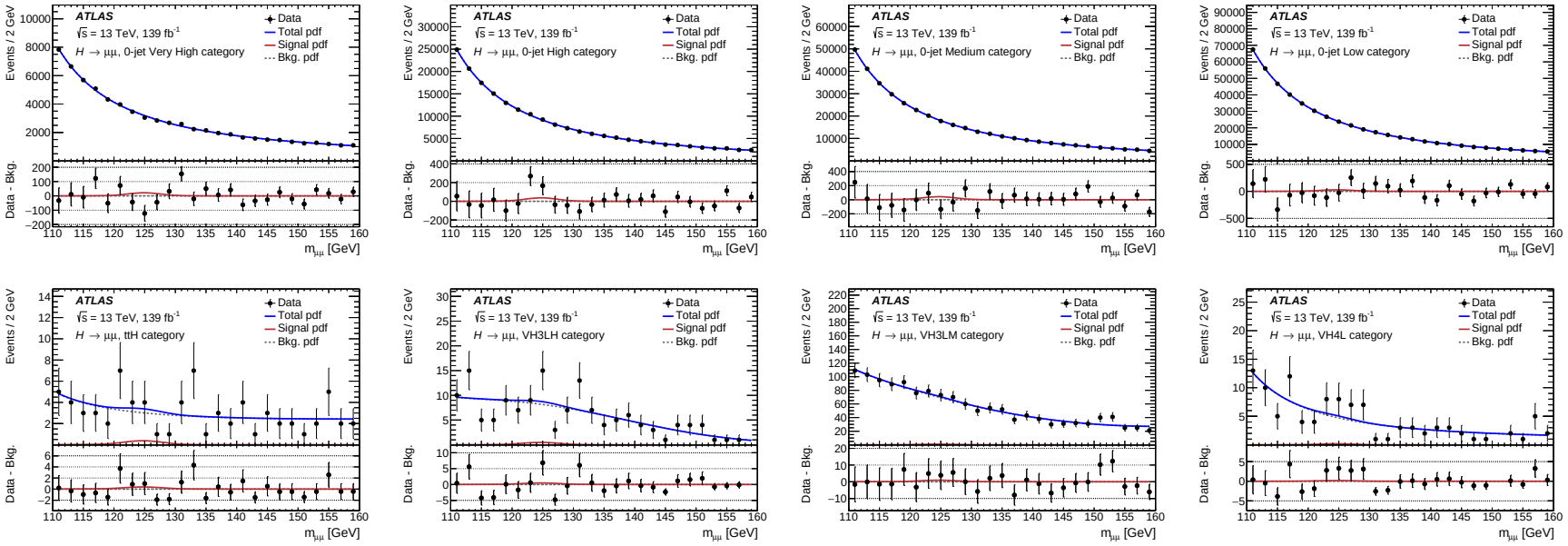
$H \to \mu\mu$ $S+B$ fits in major groups of categories



$H \to \mu\mu$ $S+B$ fits in categories



$H \to \mu\mu$ $S+B$ fits in categories



$H \to \mu\mu$ signal and background yields

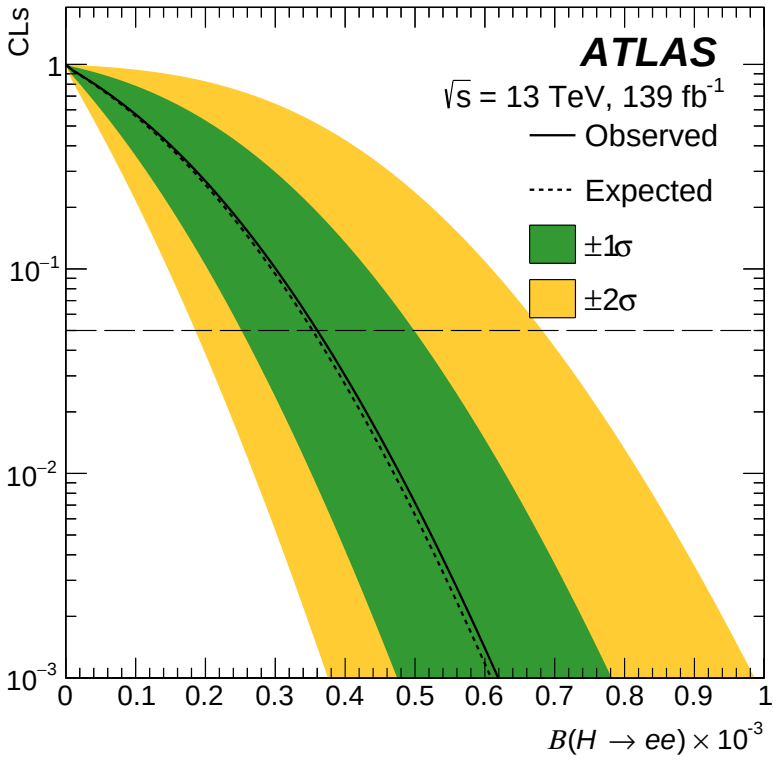
Category	Data	S_{SM}	S	B	$S/\sqrt{B}$	S/B [%]
VBF Very High	15	2.81 ± 0.27	3.3 ± 1.7	14.5 ± 2.1	0.86	22.6
VBF High	39	3.46 ± 0.36	4.0 ± 2.1	32.5 ± 2.9	0.71	12.4
VBF Medium	112	4.8 ± 0.5	5.6 ± 2.8	85 ± 4	0.61	6.6
VBF Low	284	7.5 ± 0.9	9 ± 4	273 ± 8	0.53	3.2
2-jet Very High	1030	17.6 ± 3.3	21 ± 10	1024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

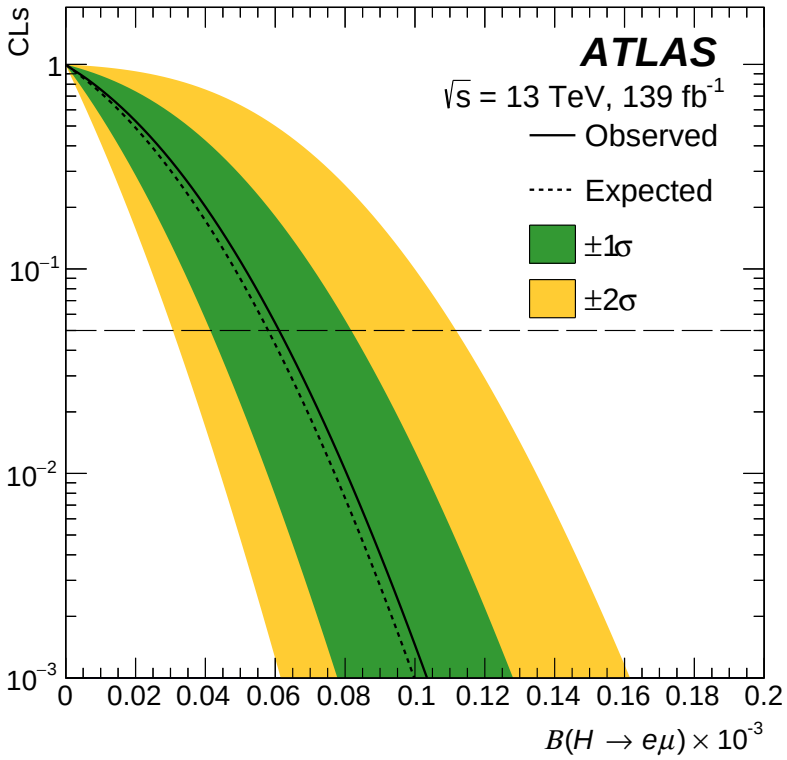
Comparison between new and preliminary $H \to \mu\mu$ result

- Checked the compatibility with preliminary $H \to \mu\mu$ result presented in ATLAS-CONF-2019-028 using bootstrap technique
- The correlation between the two signal strength measurements is evaluated to be 75%

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

CL_s scans in the $H \to ee$ and $H \to e\mu$

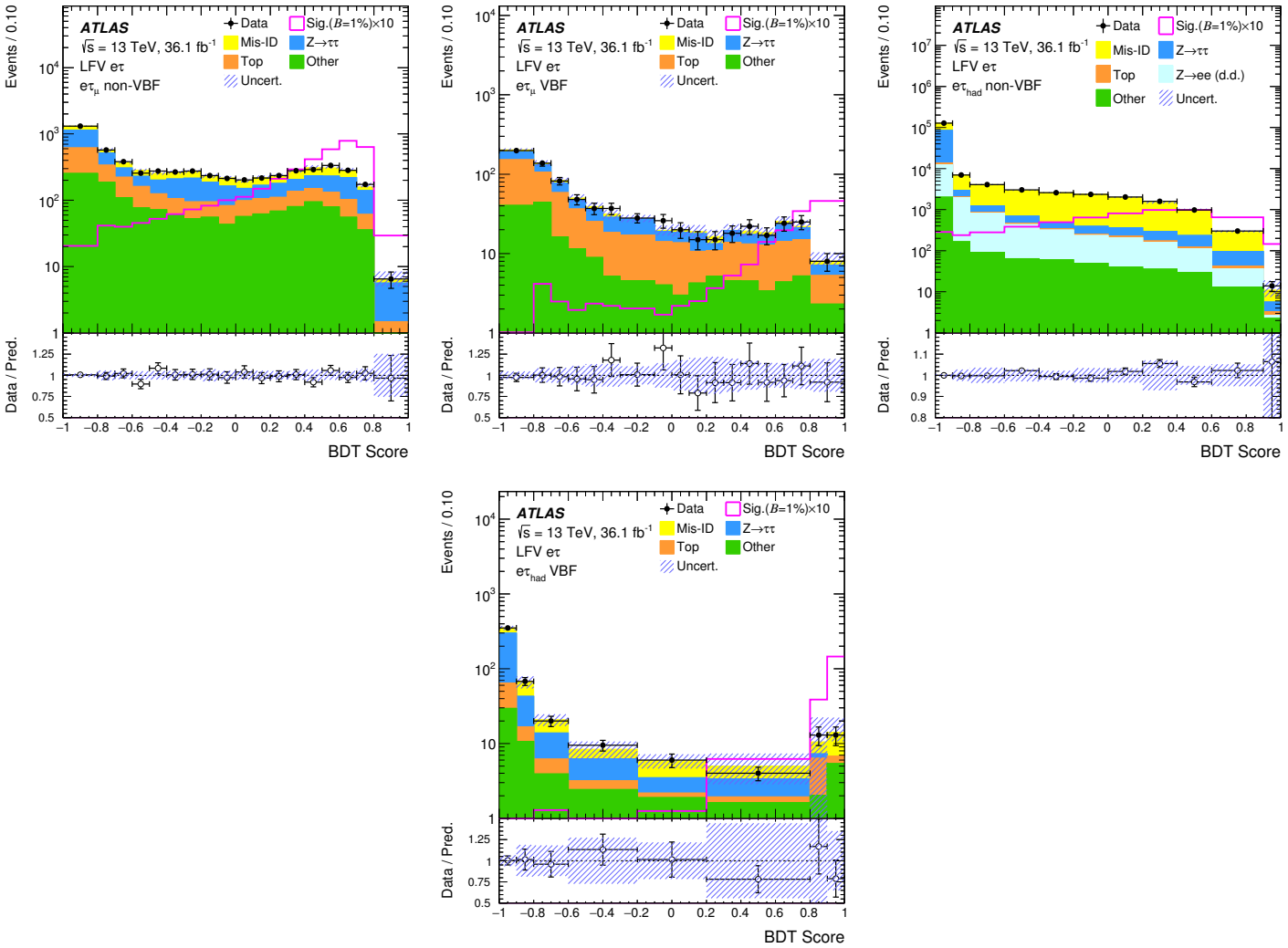




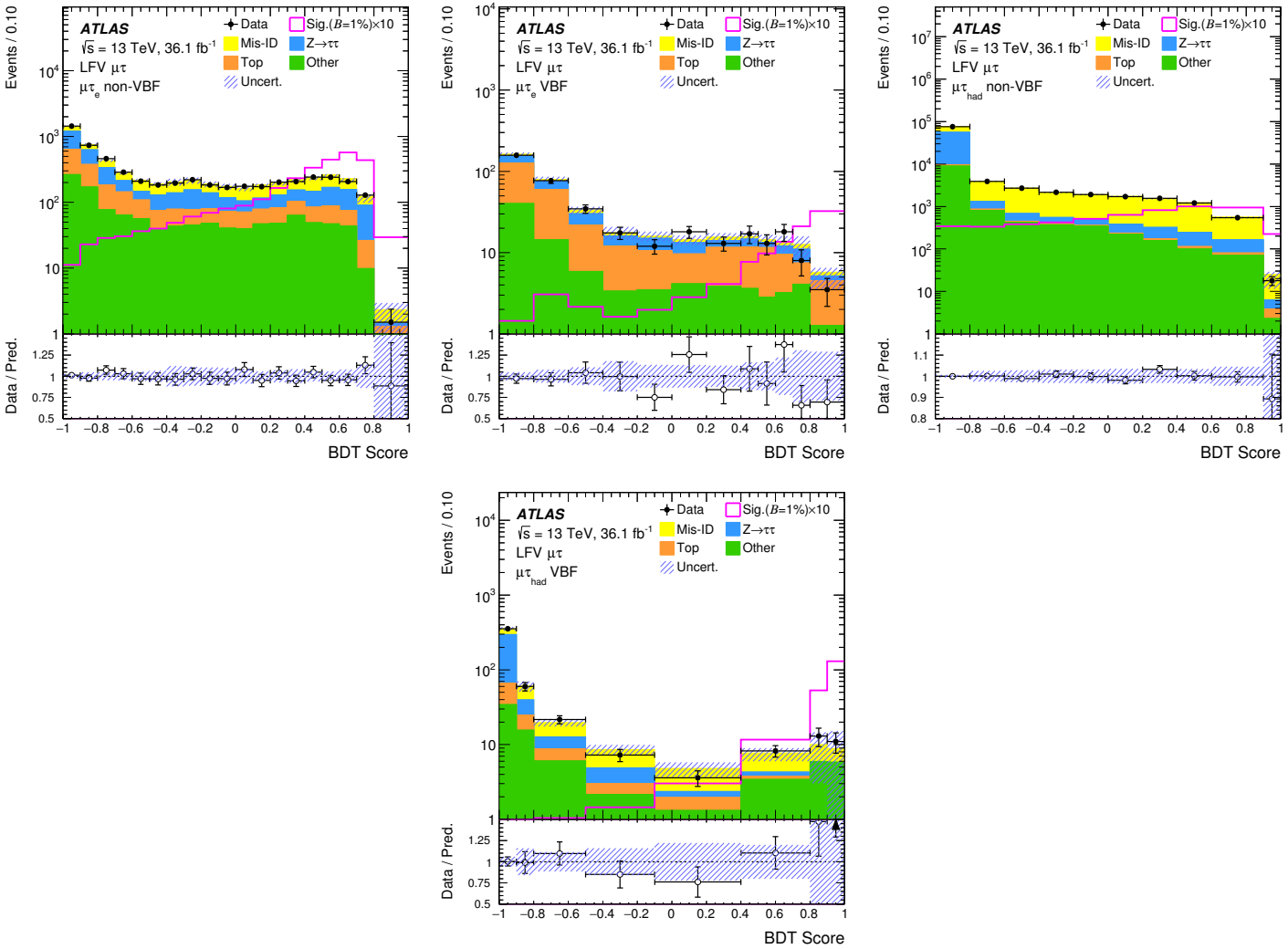
BDT inputs in $H \to e\tau$ and $H \to \mu\tau$ searches

$\ell\tau_{\ell'}$			$\ell\tau_{\text{had}}$		
Variable	VBF	non-VBF	Variable	VBF	non-VBF
m_{MMC}	HR	HR	m_{coll}	HR	HR
$p_{\text{T}}^{\ell_1}$	•	•	p_{T}^{ℓ}	•	HR
$p_{\text{T}}^{\ell_2}$	HR	HR	$p_{\text{T}}^{\tau_{\text{had-vis}}}$	•	HR
$\Delta R(\ell_1, \ell_2)$	HR	•	$\Delta R(\ell, \tau_{\text{had-vis}})$	•	•
$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}})$	•	HR	$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}})$	HR	•	$m_{\text{T}}(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	HR	HR
$\Delta\phi(\ell_1, E_{\text{T}}^{\text{miss}})$	•	•	$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})$		HR	$\Delta\phi(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	•	
$m(\text{j}_1, \text{j}_2)$	•		$m(\text{j}_1, \text{j}_2)$	•	
$\Delta\eta(\text{j}_1, \text{j}_2)$	HR		$\Delta\eta(\text{j}_1, \text{j}_2)$	•	
$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1}$		HR	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}})$	•	•
			$E_{\text{T}}^{\text{miss}}$	HR	•
			m_{vis}		HR
			$\Delta\eta(\ell, \tau_{\text{had-vis}})$		•
			η^{ℓ}		•
			$\eta^{\tau_{\text{had-vis}}}$		•
			ϕ^{ℓ}		•
			$\phi^{\tau_{\text{had-vis}}}$		•
			$\phi(E_{\text{T}}^{\text{miss}})$		•

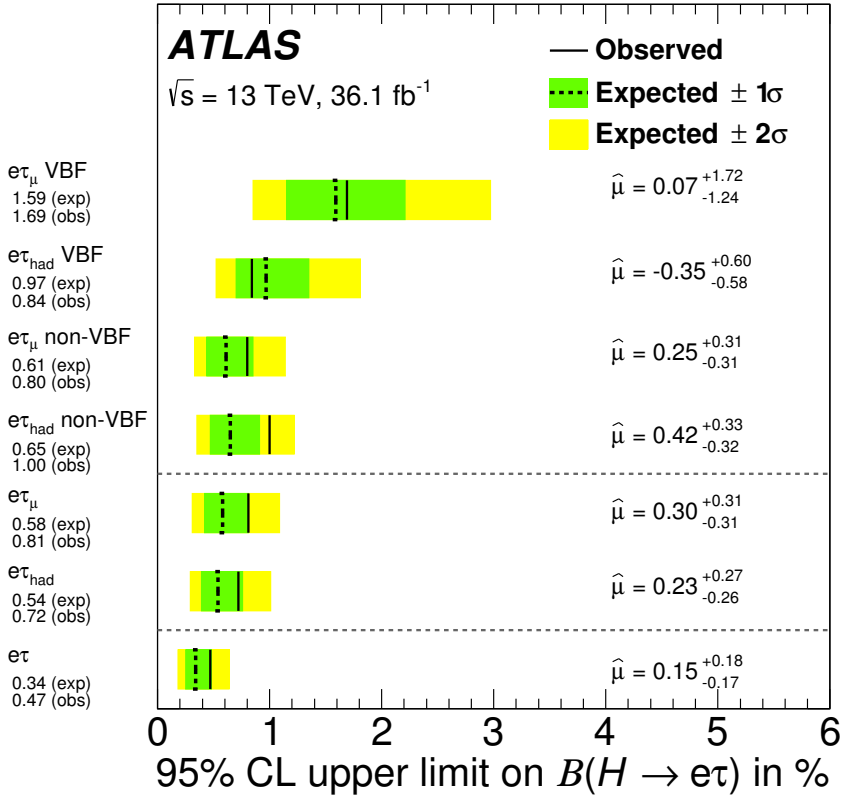
$H \to e\tau$ post-fit BDT score distributions in SRs

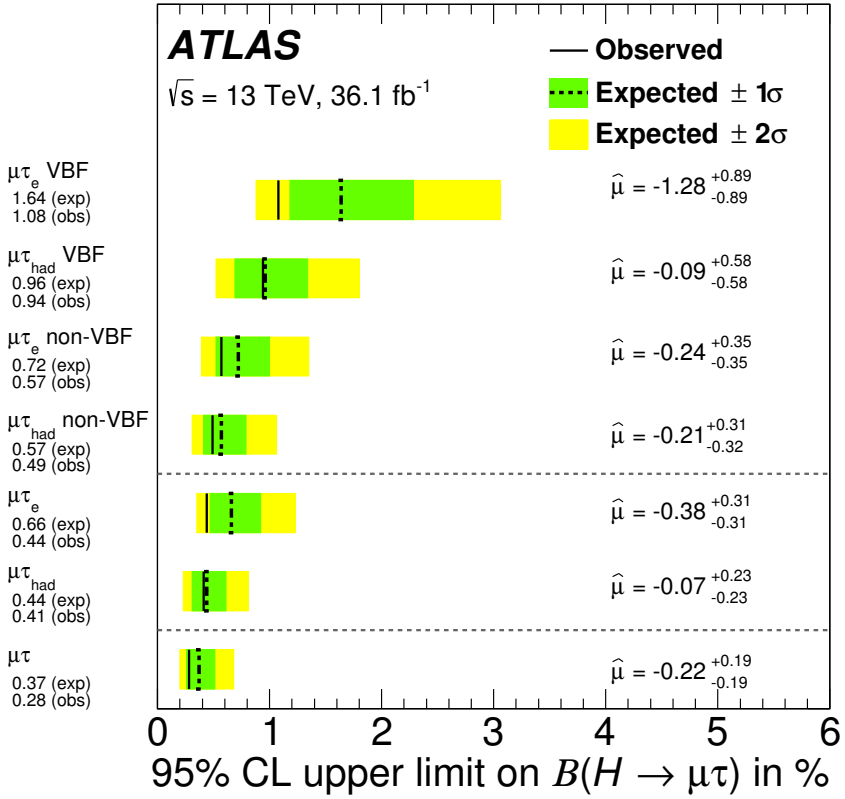


$H \to \mu\tau$ post-fit BDT score distributions in SRs



Upper limits on $\mathcal{B}(H \to \ell\tau)$ in SRs





Upper limits on the absolute values of $Y_{\ell\tau}$ couplings

$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H}\frac{\mathcal{B}(H\to\ell\tau)}{1-\mathcal{B}(H\to\ell\tau)}\Gamma_H$$