

# $4\ell + \text{MET}$ analysis: unblinded results

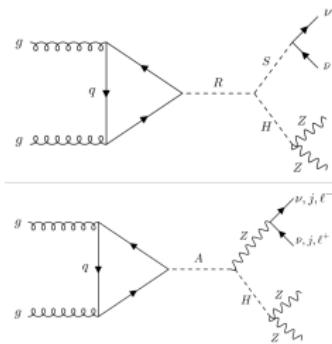
Abdualazem Fadol

February 27, 2023

# Introduction

2

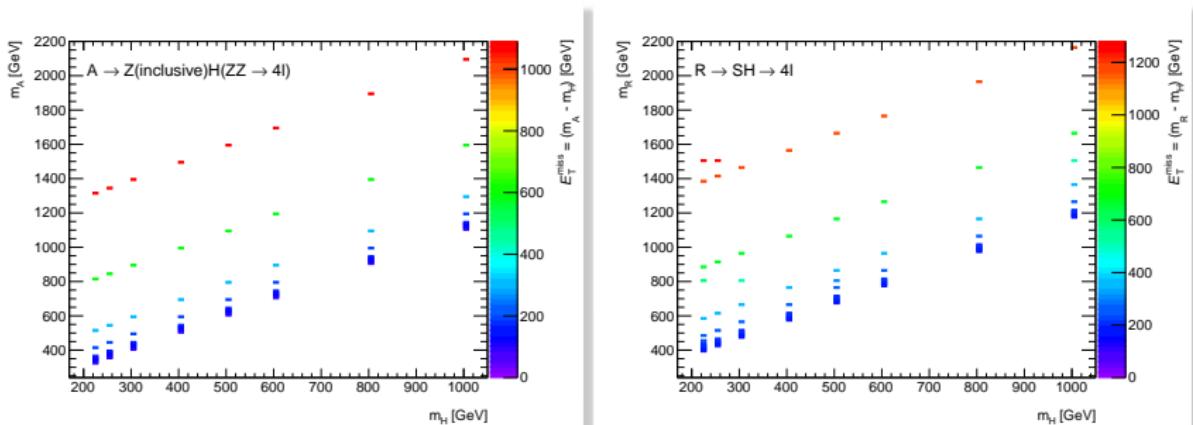
- In this analysis, we're searching for heavy resonances in final states
- with four leptons and missing transverse energy or jets.
- Interpret the data in terms of two models:
  - $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$ , [1]
  - $A \rightarrow ZH \rightarrow 4\ell + X$ , [2,3]
- We unblinded the Run-2 dataset with luminosity of  $139 \text{ fb}^{-1}$ .
- Expected and observed 2D limit on the  $m_{A/R}-m_H$  plane.



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- [1] JHEP 03 (2017) 094
  - [2] Phys.Rev.Lett.113
  - [3] Eur. Phys. J. C (2016)

# Benchmark

- Data: Run-2 dataset (unblinded now)
- Signal samples:
  - $A \rightarrow ZH \rightarrow 4\ell + X$ :  $A \rightarrow Z(\rightarrow 2\ell)H(\rightarrow 2\ell + X)$  and  $A \rightarrow Z(\rightarrow X)H(\rightarrow 4\ell)$
  - $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$ : The  $S$  decays to neutrinos, and its mass is **fixed** 160 GeV.



- SM backgrounds:**
  - The dominant backgrounds are  $q\bar{q} \rightarrow ZZ$  and  $gg \rightarrow ZZ$ — 85% & 11%.
  - Small contribution from  $VVV$ ,  $t\bar{t}V$ ,  $t\bar{t}$ ,  $Z + \text{jets}$ ,  $WZ$  and  $q\bar{q} \rightarrow ZZ(EW)$
  - The background shapes are taken from simulation for all SM backgrounds.
  - Fit range (bin, xmini, xmaxi)  $\equiv (2000, 200, 1200)$

# Event selection

## Triggers:

- single-lepton
- di-lepton
- tri-lepton

## Jets:

- using central jets
- b-jets: 77% efficiency

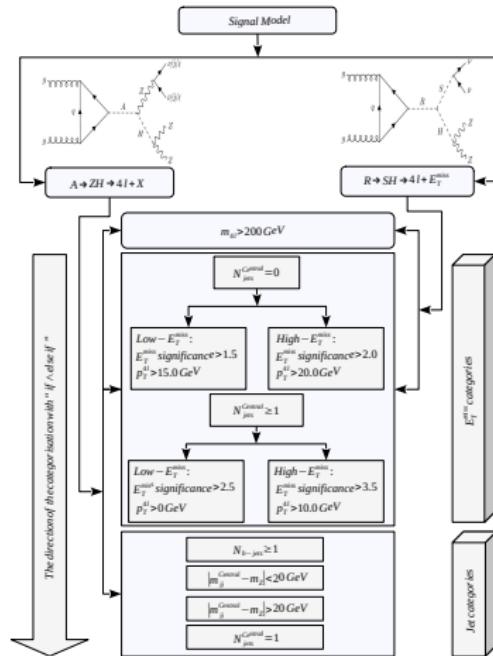


## 4 $\ell$ +MET specific selection to optimise:

- $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$
- $A \rightarrow ZH \rightarrow 4\ell + X$

Physics Objects	
ELECTRONS	Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $ \eta  < 2.47$ Interaction point constraint: $ z_0 \cdot \sin \theta  < 0.5$ mm (if ID track is available)
MUONS	Loose identification with $p_T > 5$ GeV and $ \eta  < 2.7$ Calo-tagged muons with $p_T > 15$ GeV and $ \eta  < 0.1$ , segment-tagged muons with $ \eta  < 0.1$ Stand-alone and silicon-associated forward restricted to the $2.5 <  \eta  < 2.7$ region Combined, stand-alone (with ID hits if available) and segment-tagged muons with $p_T > 5$ GeV Interaction point constraint: $ d_0  < 1$ mm and $ z_0 \cdot \sin \theta  < 0.5$ mm (if ID track is available)
JETS	anti- $k_T$ jets with <i>bad-lose</i> identification, $p_T > 30$ GeV and $ \eta  < 2.5$ (Central jets only)
OVERLAP REMOVAL	Jets within $\Delta R < 0.2$ of an electron or $\Delta R < 0.1$ of a muon are removed
VERTEX	At least one collision vertex with at least two associated track
PRIMARY VERTEX	Vertex with the largest $p_T^2$ sum
Event Selection	
QUADRUPLET SELECTION	<ul style="list-style-type: none"><li>- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements:<ul style="list-style-type: none"><li>- <math>p_T</math> thresholds for three leading leptons in the quadruplet: 20, 15 and 10 GeV</li><li>- Maximum one calo-tagged or stand-alone muon or silicon-associated forward per quadruplet</li><li>- Leading di-lepton mass requirement: <math>50 &lt; m_{Z_1} &lt; 106</math> GeV</li><li>- Sub-leading di-lepton mass requirement: <math>m_{\text{threshold}} &lt; m_{Z_2} &lt; 115</math> GeV</li><li>- <math>\Delta R(\ell, \ell') &gt; 0.10</math> for all leptons in the quadruplet</li><li>- Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives <math>m_{\ell\ell} &lt; 5</math> GeV</li><li>- Keep all quadruplets passing the above selection</li></ul></li></ul>
ISOLATION	<ul style="list-style-type: none"><li>- Contribution from the other leptons of the quadruplet is subtracted</li><li>- FixedCutPFlowLoose WP for all leptons</li></ul>
IMPACT PARAMETER SIGNIFICANCE	<ul style="list-style-type: none"><li>- Apply impact-parameter significance cut to all leptons of the quadruplet</li><li>- For electrons: <math>d_0/\sigma_{d_0} &lt; 5</math></li><li>- For muons: <math>d_0/\sigma_{d_0} &lt; 3</math></li></ul>
BEST QUADRUPLET	<ul style="list-style-type: none"><li>- If more than one quadruplet has been selected, choose the quadruplet with highest Higgs decay ME according to channel: <math>4\mu, 2e2\mu, 2\mu2e</math> and <math>4e</math></li></ul>
VERTEX SELECTION	<ul style="list-style-type: none"><li>- Require a common vertex for the leptons:</li><li>- <math>\chi^2/\text{ndof} &lt; 6</math> for <math>4\mu</math> and <math>\chi^2/\text{ndof} &lt; 9</math> for others decay channels</li></ul>

# Specific selection depending on the model



# The fit strategy

- We use the TRExFitter statistical tool to perform the fit.
- The fit is performed on the invariant mass of the four-lepton system;
- The fit range is between 200 and 1200 GeV with 0.5 GeV as a step for each bin.
- A binned maximum-likelihood fit is used to fit signal-plus-background Asimov data.
- For  $A \rightarrow ZH \rightarrow 4\ell + X$ : seven categories are fitted simultaneously.
- For  $A \rightarrow ZH \rightarrow 4\ell + X$ : three categories are fitted simultaneously.
- Float  $q\bar{q} \rightarrow ZZ$  and  $gg \rightarrow ZZ$  with a normalisation that depends on the category.
- The  $VVV$  and others backgrounds are fixed to the SM prediction.
- All nuisance parameters are floated during the fit.

# Fit results

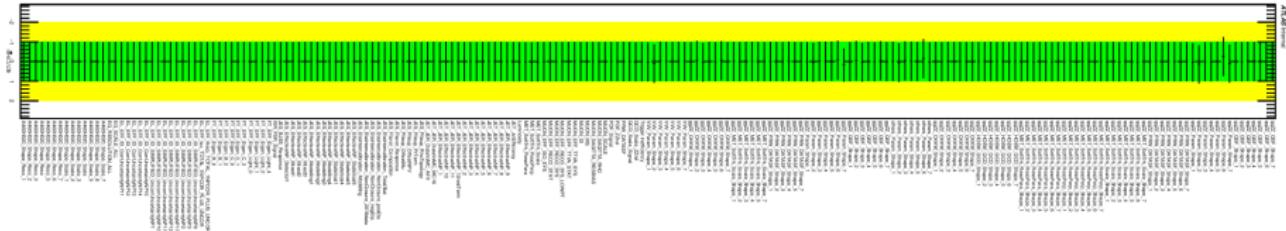
## Correlation Matrix

ATLAS Internal	
Luminosity	
ATLAS_Luminosity	1.00
PDF_Zfit	-0.60
ggZZ_CKWW_Shape_1	0.20
ggZZ_CKWW_Shape_2	0.10
ggZZ_CKWW_Shape_3	0.10
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00
ggZZ_CKWW_Shape_1	0.00
ggZZ_CKWW_Shape_2	0.00
ggZZ_CKWW_Shape_3	0.00
ggZZ_HDM_FCZD_Shape_1	0.00
ggZZ_HDM_FCZD_Shape_2	0.00
ggZZ_HDM_FCZD_Shape_3	0.00
BT_SuffN_Recov_Pix_Shape_1	0.00
BT_SuffN_Recov_Pix_Shape_2	0.00
BT_SuffN_Recov_Pix_Shape_3	0.00
BT_SuffN_Recov_Pix_Shape_1	0.00
BT_SuffN_Recov_Pix_Shape_2	0.00
BT_SuffN_Recov_Pix_Shape_3	0.00
BT_SuffN_Recov_Pix_Prep_Shape_1	0.00
BT_SuffN_Recov_Pix_Prep_Shape_2	0.00
BT_SuffN_Recov_Pix_Prep_Shape_3	0.00
Z_MET_SuffN_Scale_Shape_1	0.00
Z_MET_SuffN_Scale_Shape_2	0.00
Z_MET_SuffN_Scale_Shape_3	0.00
ggZZ_Parav_Shape_1	0.00
ggZZ_Parav_Shape_2	0.00
ggZZ_Parav_Shape_3	0.00
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00
Luminosity	1.00
ATLAS_Luminosity	0.99
PDF_Zfit	-0.60
ggZZ_CKWW_Shape_1	0.20
ggZZ_CKWW_Shape_2	0.10
ggZZ_CKWW_Shape_3	0.10
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00
ggZZ_CKWW_Shape_1	0.00
ggZZ_CKWW_Shape_2	0.00
ggZZ_CKWW_Shape_3	0.00
ggZZ_HDM_FCZD_Shape_1	0.00
ggZZ_HDM_FCZD_Shape_2	0.00
ggZZ_HDM_FCZD_Shape_3	0.00
BT_SuffN_Recov_Pix_Shape_1	0.00
BT_SuffN_Recov_Pix_Shape_2	0.00
BT_SuffN_Recov_Pix_Shape_3	0.00
BT_SuffN_Recov_Pix_Shape_1	0.00
BT_SuffN_Recov_Pix_Shape_2	0.00
BT_SuffN_Recov_Pix_Shape_3	0.00
BT_SuffN_Recov_Pix_Prep_Shape_1	0.00
BT_SuffN_Recov_Pix_Prep_Shape_2	0.00
BT_SuffN_Recov_Pix_Prep_Shape_3	0.00
Z_MET_SuffN_Scale_Shape_1	0.00
Z_MET_SuffN_Scale_Shape_2	0.00
Z_MET_SuffN_Scale_Shape_3	0.00
ggZZ_Parav_Shape_1	0.00
ggZZ_Parav_Shape_2	0.00
ggZZ_Parav_Shape_3	0.00
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00
ATLAS_Luminosity	0.99
PDF_Zfit	-0.60
ggZZ_CKWW_Shape_1	0.20
ggZZ_CKWW_Shape_2	0.10
ggZZ_CKWW_Shape_3	0.10
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00
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BT_SuffN_Recov_Pix_Shape_1	0.00
BT_SuffN_Recov_Pix_Shape_2	0.00
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BT_SuffN_Recov_Pix_Shape_1	0.00
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BT_SuffN_Recov_Pix_Prep_Shape_1	0.00
BT_SuffN_Recov_Pix_Prep_Shape_2	0.00
BT_SuffN_Recov_Pix_Prep_Shape_3	0.00
Z_MET_SuffN_Scale_Shape_1	0.00
Z_MET_SuffN_Scale_Shape_2	0.00
Z_MET_SuffN_Scale_Shape_3	0.00
ggZZ_Parav_Shape_1	0.00
ggZZ_Parav_Shape_2	0.00
ggZZ_Parav_Shape_3	0.00
ggZZ_GSF_Shape_1	0.00
ggZZ_GSF_Shape_2	0.00
ggZZ_GSF_Shape_3	0.00

□ Correlation between nuisance parameters for the  $(m_R, m_H) = (420, 250)$  GeV signal

# Fit results

## Pull plot

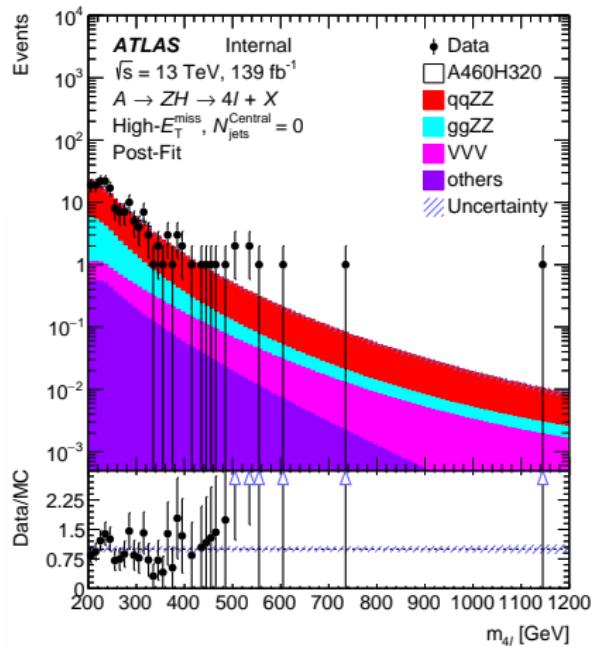
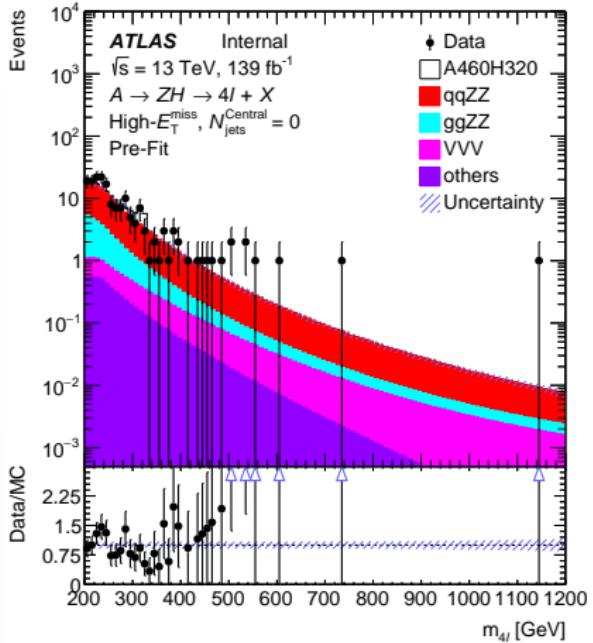


- Well constrained nuisance parameters within  $\pm 1\sigma$  for the  $(m_R, m_H) = (420, 250)$  GeV signal.

# Fit results

Background+Signal fit for  $A \rightarrow ZH \rightarrow 4\ell + X$

9

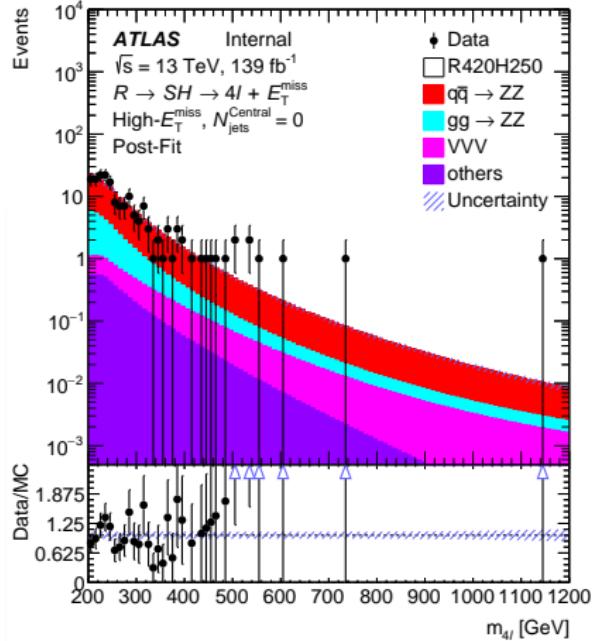
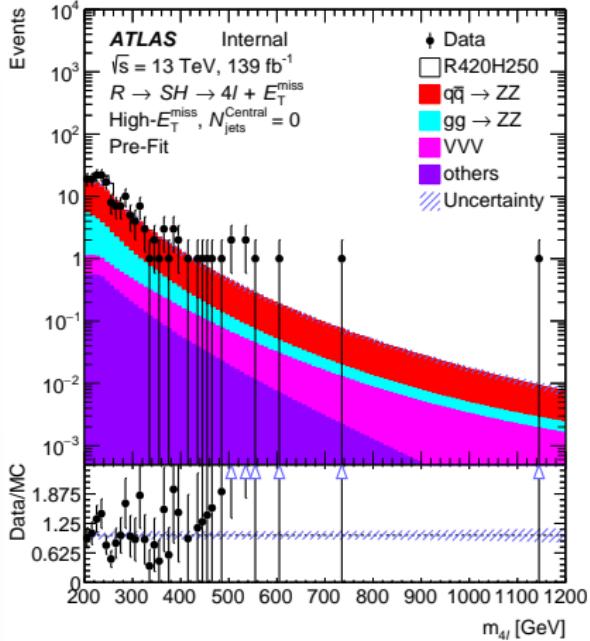


Pre-fit (left) and post-fit (right)

# Fit results

Background+Signal fit for  $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$

10

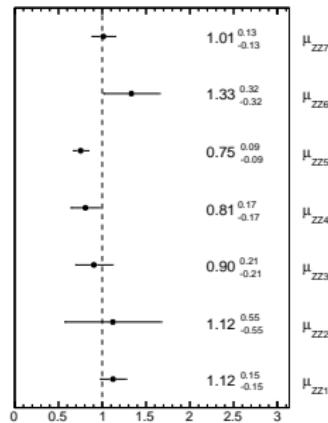


Pre-fit (left) and post-fit (right)

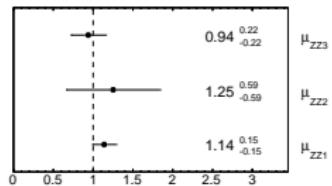
# Fit results

Background+Signal fit

ATLAS Internal



ATLAS Internal



$R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$ : R420H250

$A \rightarrow ZH \rightarrow 4\ell + X$ : A460H320

# Fit results

The impact of NPs parameter on the POI

Pre-fit impact on  $\sigma(gg \rightarrow F)$



Post-fit impact on  $\sigma(gg \rightarrow F)$



—●— Nuis. Param. Pull

A320H220\_Shape\_Scale

ggZZ\_Param\_Shape\_7

JES\_Flavor\_Composition

qqZZ\_Param\_Shape\_4

others\_Param\_Shape\_6

qqZZ\_Param\_Shape\_6

Luminosity

A320H220\_Shape\_Scale\_6

qqZZ\_Param\_Shape\_7

JET\_JER\_EffectiveNP\_1

JES\_Pileup\_RhoTopology

JET\_JER\_EffectiveNP\_2

qqZZ\_Param\_Shape\_5

MET\_SoftTrk\_Scale

JES\_Flavor\_Response

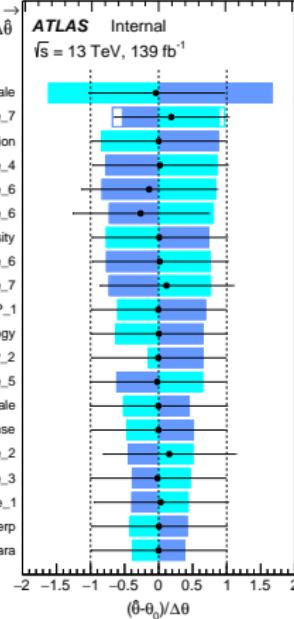
qqZZ\_Param\_Shape\_2

qqZZ\_Param\_Shape\_3

qqZZ\_Param\_Shape\_1

MET\_SoftTrk\_ResoPerp

MET\_SoftTrk\_ResoPara



A320H220

Pre-fit impact on  $\sigma(gg \rightarrow F)$



Post-fit impact on  $\sigma(gg \rightarrow F)$



—●— Nuis. Param. Pull

ggZZ\_CKKW\_Shape\_2

ggZZ\_QSF\_Shape\_2

others\_Param\_Shape\_2

qqZZ\_Param\_Shape\_2

VVV\_Param\_Shape\_2

PRW\_DATASF

PDF\_ZZrel

qqZZ\_Param\_Shape\_1

ggZZ\_CKKW\_Shape\_1

ggZZ\_QSF\_Shape\_1

ET\_SoftTrk\_ResoPerp\_Shape\_1

ET\_SoftTrk\_ResoPara\_Shape\_1

Z\_MET\_SoftTrk\_Scale\_Shape\_2

ET\_SoftTrk\_ResoPerp\_Shape\_2

R390H220\_Shape\_Scale\_1

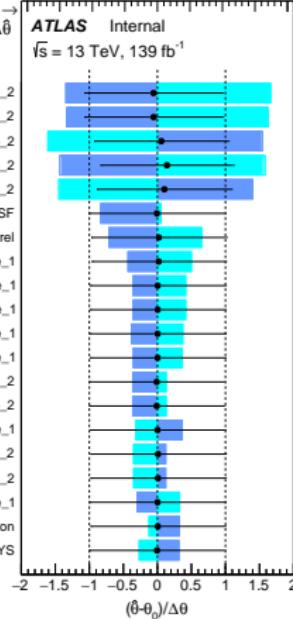
qqZZ\_QSF\_Shape\_2

qqZZ\_CKKW\_Shape\_2

Z\_MET\_SoftTrk\_Scale\_Shape\_1

JES\_Flavor\_Composition

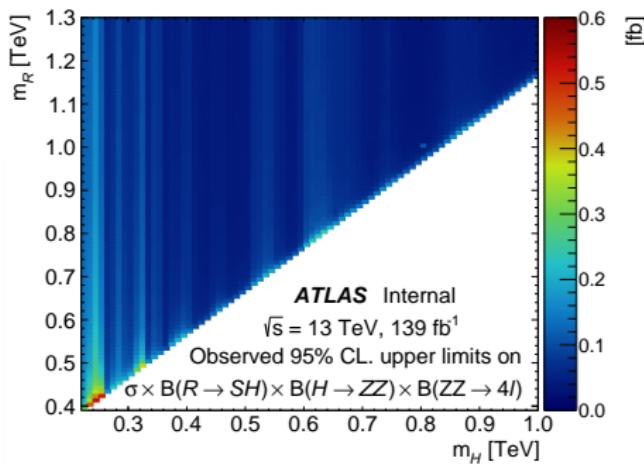
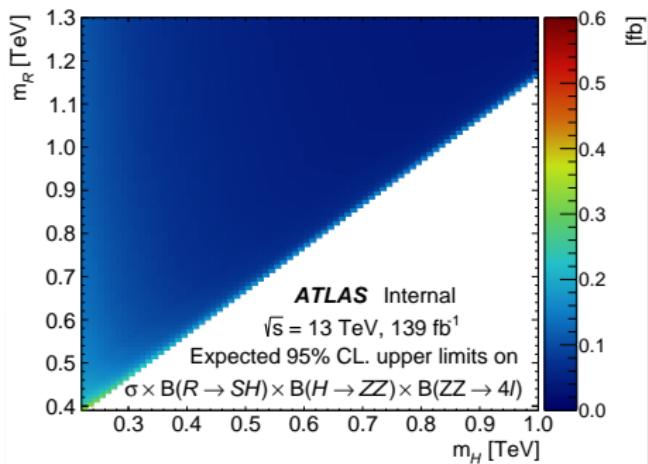
MUON\_EFF\_ISO\_SYS



R390H220

# Expected and observed upper limits

on the  $(m_H, m_R)$  plane for the  $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$  model

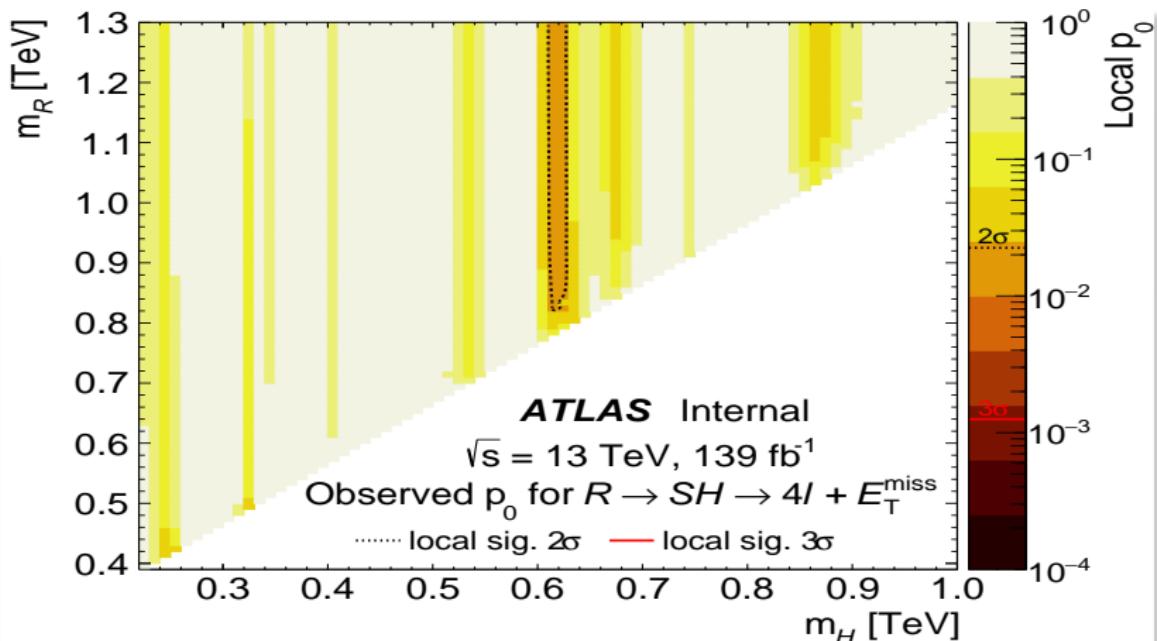


- Expected upper limits at 95% CL between [0.030 - 0.322] fb on (320, 1300) - (220, 1000) GeV.
- Expected upper limits at 95% CL between [0.027 - 0.532] fb on (320, 1300) - (220, 1000) GeV.

# Observed local p values

on the  $(m_H, m_R)$  plane for the  $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$  model

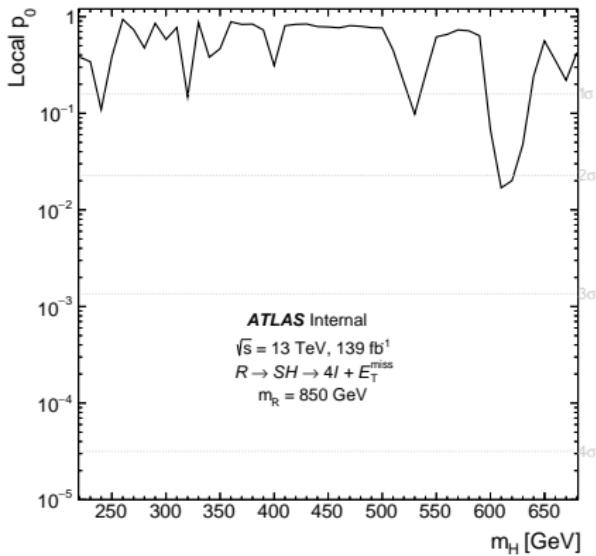
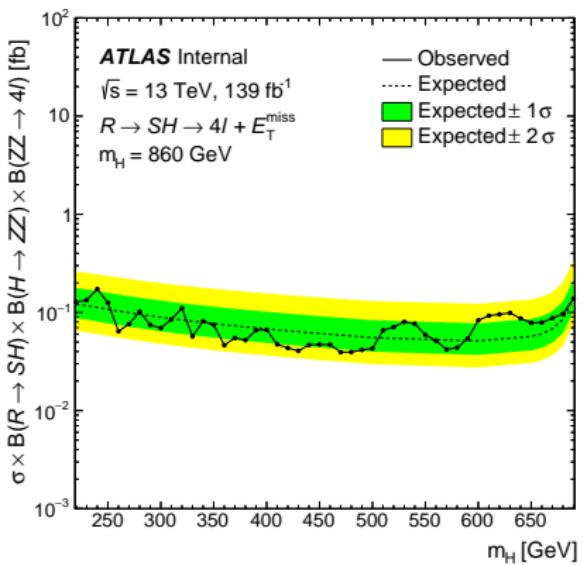
14



- The highest observed excess is around  $m_H = 620$  for  $m_R \in [820, 1300]$  within a local significance of  $2\sigma$ .

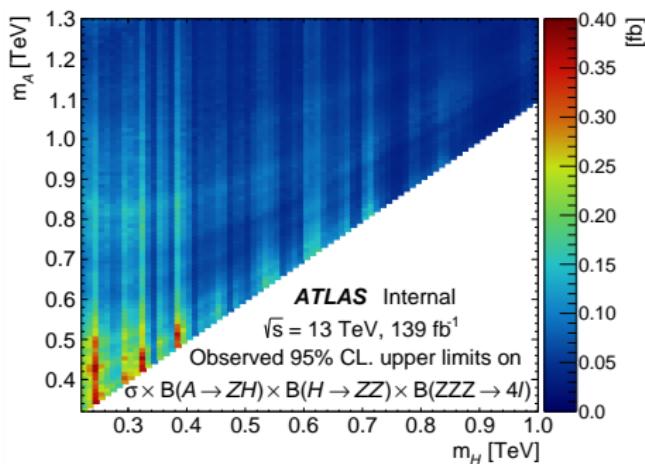
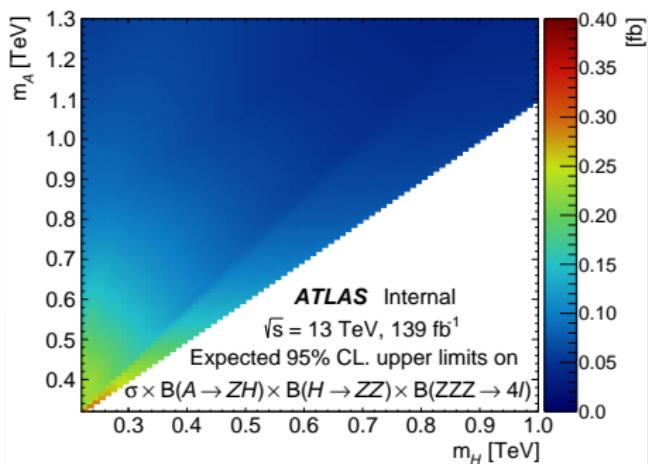
# Expected and observed 1D upper limit for the $R \rightarrow SH \rightarrow 4\ell + E_T^{\text{miss}}$ model

15



# Expected and observed upper limits

on the  $(m_H, m_A)$  plane for the  $A \rightarrow ZH \rightarrow 4\ell + X$  model

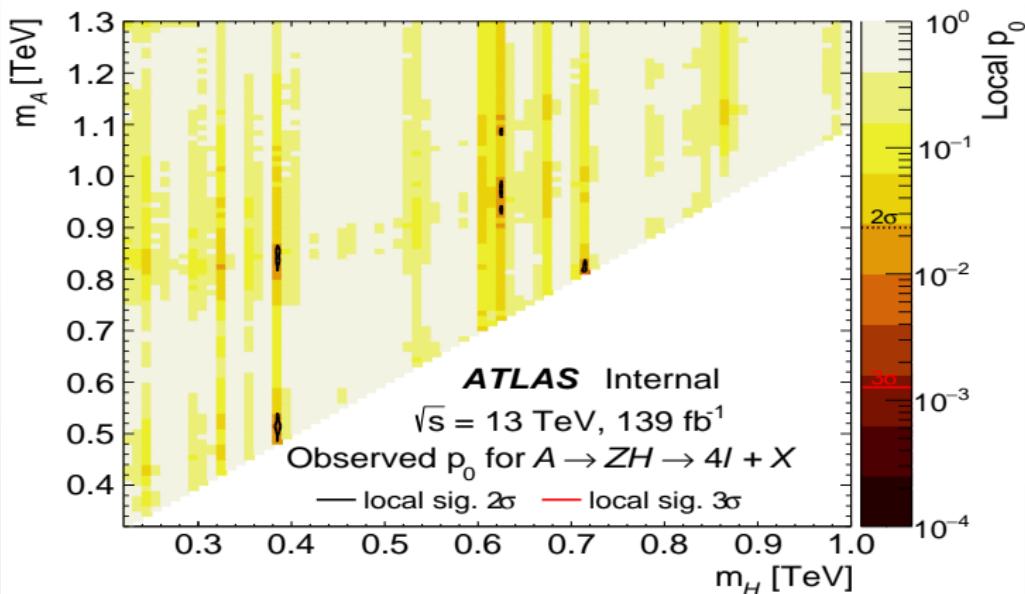


- Expected upper limits at 95% CL between [0.028 - 0.289] fb on (320, 1300) - (220, 1000) GeV.
- Observed upper limits at 95% CL between [0.023 - 0.378] fb on (320, 1300) - (220, 1000) GeV.

# Observed local p values

on the  $(m_H, m_A)$  plane for the  $A \rightarrow ZH \rightarrow 4\ell + X$  model

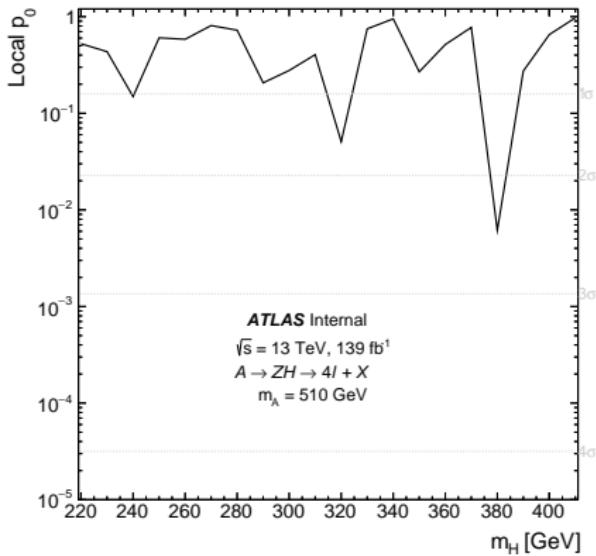
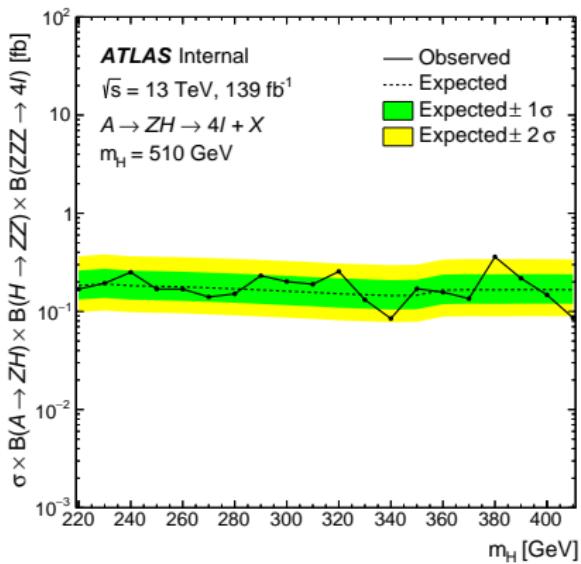
17



- There're excesses within  $2\sigma$ :
  - $m_H = 380$  &  $m_A \in [480, 530] \cap [820, 860]$
  - $m_H = 620$  &  $m_A \in [930, 960, 970, 980, 1000]$
  - $m_H = 710$  &  $m_A \in [810, 820, 830]$
- With the highest excess observed around  $(m_H, m_A) = (380, 510)$  GeV with local significance of  $2.5\sigma$

# Expected and observed 1D upper limit for the $A \rightarrow ZH \rightarrow 4\ell + X$ model

18



# Summary

- We showed the unblinded results for the  $4\ell + \text{MET}$  analysis.
- No significance deviation beyond the Standard Model background was observed.
- There are still a few jobs running for some mass points that will be added soon.

# Additional slides

## Cut-flow table

	$q\bar{q} \rightarrow ZZ$	$gg \rightarrow ZZ$	$q\bar{q} \rightarrow ZZ^*(EW)$	$t\bar{t}V$	$VVV$	$Z + \text{jets}$	$WZ$	$t\bar{t}$	Data	Expected
Preselection	2518.94±4.23	349.23±0.67	32.77±0.27	47.18±0.44	19.05±0.11	3.85±1.15	4.89±0.31	2.80±0.19	3296.00	2978.72±7.38
High- $E_T^{\text{miss}}$ & $N_{\text{jets}}^{\text{Central}} = 0$	115.24±1.15	27.74±0.19	0.48±0.03	2.07±0.08	7.48±0.06	0.58±0.07	1.73±0.19	0.64±0.08	177.00	155.96±1.86
Low- $E_T^{\text{miss}}$ & $N_{\text{jets}}^{\text{Central}} = 0$	177.34±1.04	34.58±0.18	0.49±0.03	0.19±0.03	0.79±0.02	0.33±0.03	0.45±0.08	0.06±0.02	258.00	214.23±1.42
High- $E_T^{\text{miss}}$ & $N_{\text{jets}}^{\text{Central}} \geq 1$	12.93±0.23	2.68±0.06	0.38±0.02	5.31±0.15	4.78±0.06	0.05±0.02	0.75±0.12	0.58±0.07	32.00	27.47±0.74
Low- $E_T^{\text{miss}}$ & $N_{\text{jets}}^{\text{Central}} \geq 1$	44.15±0.46	8.54±0.11	1.18±0.04	1.79±0.09	1.51±0.03	0.11±0.03	0.32±0.08	0.20±0.07	55.00	57.78±0.91
$N_{\text{b-jets}} \geq 1$	60.68±0.49	6.79±0.10	1.80±0.06	34.94±0.38	0.50±0.02	0.12±0.03	0.14±0.05	0.95±0.13	135.00	105.91±1.26
$ m_{jj}^{\text{Central}} - m_Z  < 20$	44.10±0.29	7.38±0.10	2.16±0.07	0.30±0.04	0.19±0.01	0.00±0.00	0.04±0.03	0.01±0.01	49.00	54.16±0.54
$ m_{jj}^{\text{Central}} - m_Z  > 20$	196.51±0.60	27.79±0.19	15.09±0.16	1.35±0.09	1.09±0.02	0.80±0.73	0.31±0.08	0.08±0.02	197.00	243.01±1.89
$N_{\text{jets}}^{\text{Central}} \geq 1$	537.70±1.94	82.98±0.33	9.20±0.15	1.06±0.06	1.60±0.03	0.24±0.05	0.69±0.12	0.17±0.04	665.00	633.64±2.71