



# Search for heavy resonances decaying to $4\ell$ and missing transverse energy

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September 26, 2022

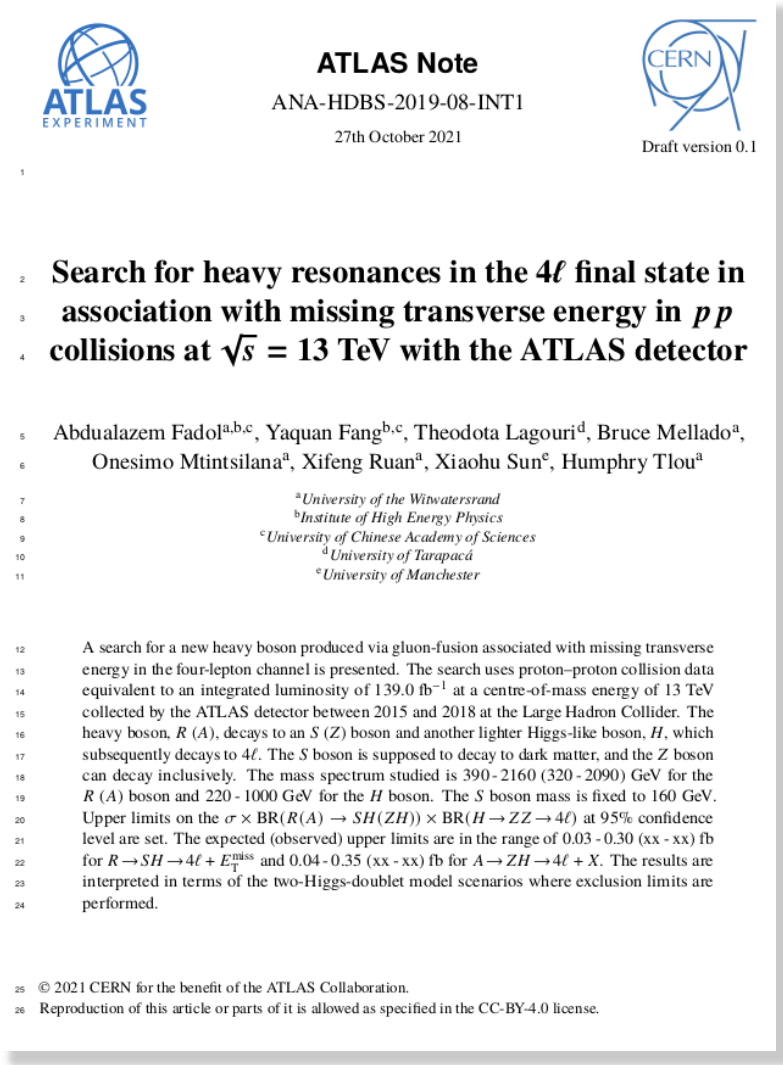
# Documentation



- ☐ 4ℓ+MET analysis:
  - Glance link
  - TWiki (still developing)
  - Supporting note in the CDS ⇒
  - Recent communication through the CDS

- ☐ **Common *H*4ℓ note:**
  The note can be found here, where the 4ℓ selection is discipled.

- ☐ **High mass note:**
  This note is very useful. We use the same minitrees production code, statistical tools, control region signal modelling and background shape uncertainty study.



ATLAS EXPERIMENT

**ATLAS Note**

ANA-HDBS-2019-08-INT1

27th October 2021

CERN

Draft version 0.1

**Search for heavy resonances in the 4ℓ final state in association with missing transverse energy in *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector**

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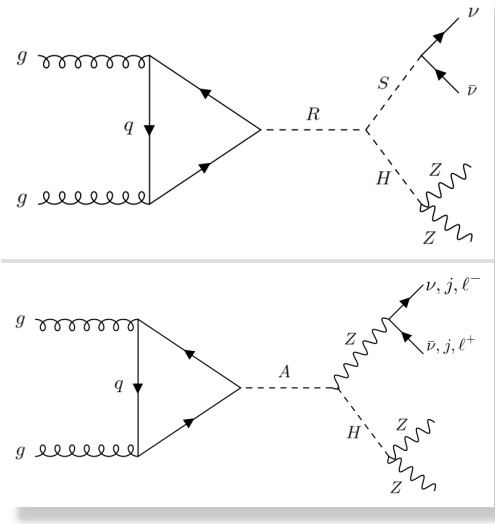
A search for a new heavy boson produced via gluon-fusion associated with missing transverse energy in the four-lepton channel is presented. The search uses proton–proton collision data equivalent to an integrated luminosity of 139.0 fb$^{-1}$ at a centre-of-mass energy of 13 TeV collected by the ATLAS detector between 2015 and 2018 at the Large Hadron Collider. The heavy boson, $R$ ($A$), decays to an $S$ ($Z$) boson and another lighter Higgs-like boson, $H$, which subsequently decays to 4ℓ. The $S$ boson is supposed to decay to dark matter, and the $Z$ boson can decay inclusively. The mass spectrum studied is 390 - 2160 (320 - 2090) GeV for the $R$ ($A$) boson and 220 - 1000 GeV for the $H$ boson. The $S$ boson mass is fixed to 160 GeV. Upper limits on the $\sigma \times \mathrm{BR}(R(A) \to SH(ZH)) \times \mathrm{BR}(H \to ZZ \to 4\ell)$ at 95% confidence level are set. The expected (observed) upper limits are in the range of 0.03 - 0.30 (xx - xx) fb for $R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ and 0.04 - 0.35 (xx - xx) fb for $A \to ZH \to 4\ell + X$. The results are interpreted in terms of the two-Higgs-doublet model scenarios where exclusion limits are performed.

# Introduction



- The $4\ell$+MET analysis searches for heavy resonances.
- Heavy bosons decay to $4\ell$ in association with missing transverse energy.
- Interpret the data in terms of two models:
  - $R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$, [1]
  - $A \to ZH \to 4\ell + X$, [2,3]
- Targets Run-II dataset with luminosity of 139 fb$^{-1}$.
- Expected and observed 2D limit on the $m_{A/R}$-$m_H$ plane.
- Set upper limits on the 2D mass contour of the $m_A$-$m_H$ plane.




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

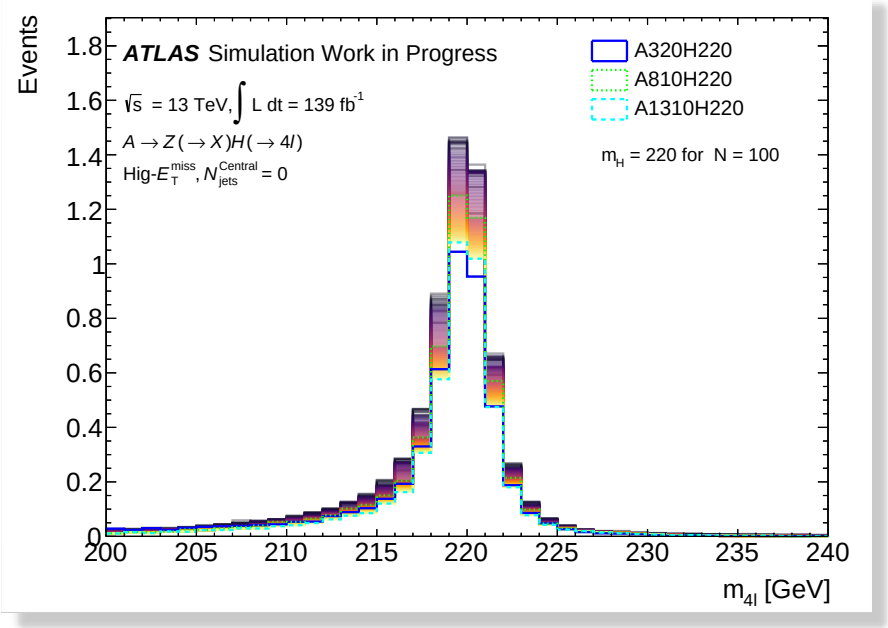
# New updates

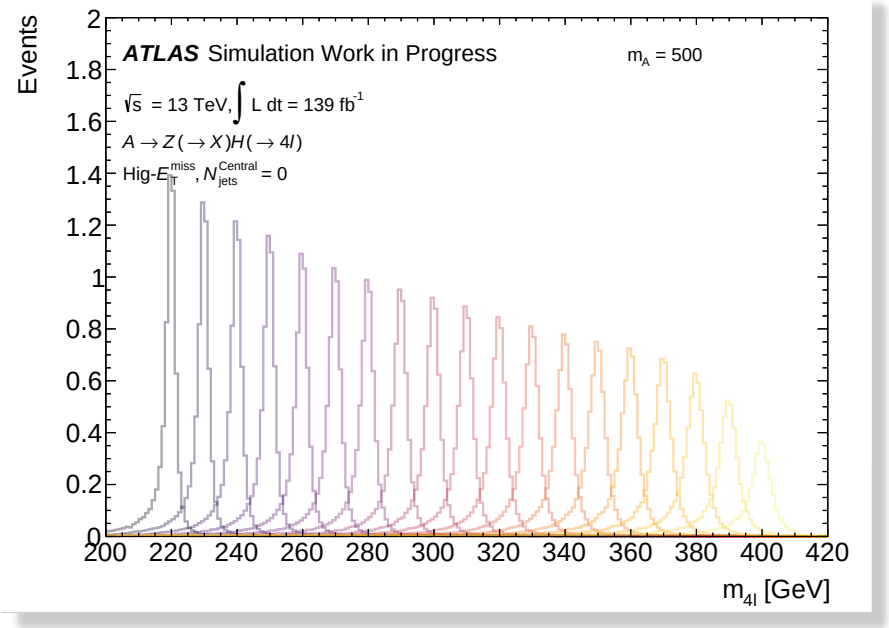


- A new $A \to Z(\to 2\ell)H(\to 2\ell + X)$ signal to the main $A \to Z(\to X)H(\to 4\ell)$ signal;
- Using histograms directly in the fit instead of DSCB+Gaussian function;
- The DSCB+Gaussian function is used to estimate the systematic on the signal shape;
- Statistical results are produced using TRExFitter instead of the HZZWorkspace:
  - comparison was done here
  - a bit faster than the previous one
  - automatic plotting
- limits on the $(m_{R/A}, m_H)$ plane using limits of 79k samples not interpolating limit for 72.
- The "islands" problem on the exclusion plots is solved and generate plots with new limits.

# Signal interpolation
## $A \to Z(\to X)H(\to 4\ell)$



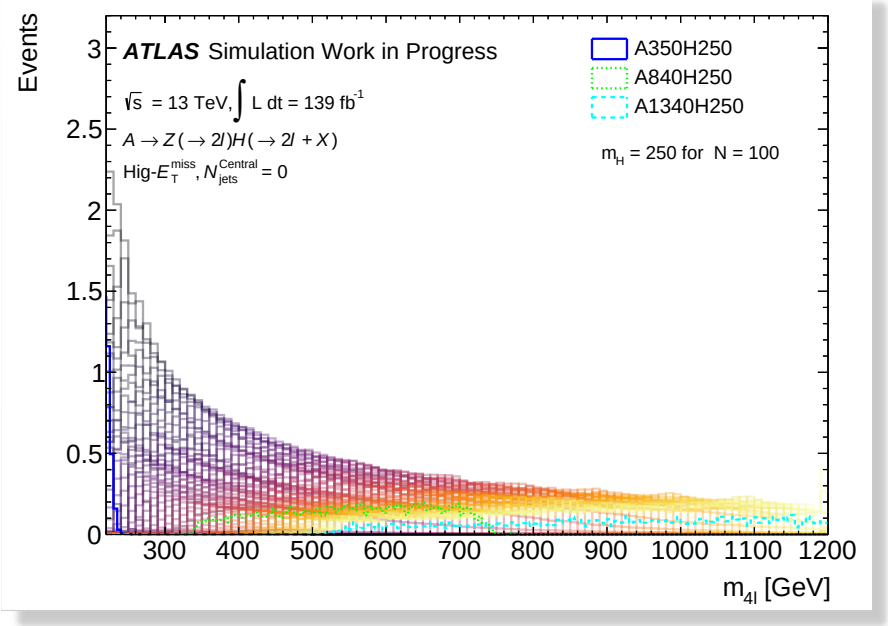


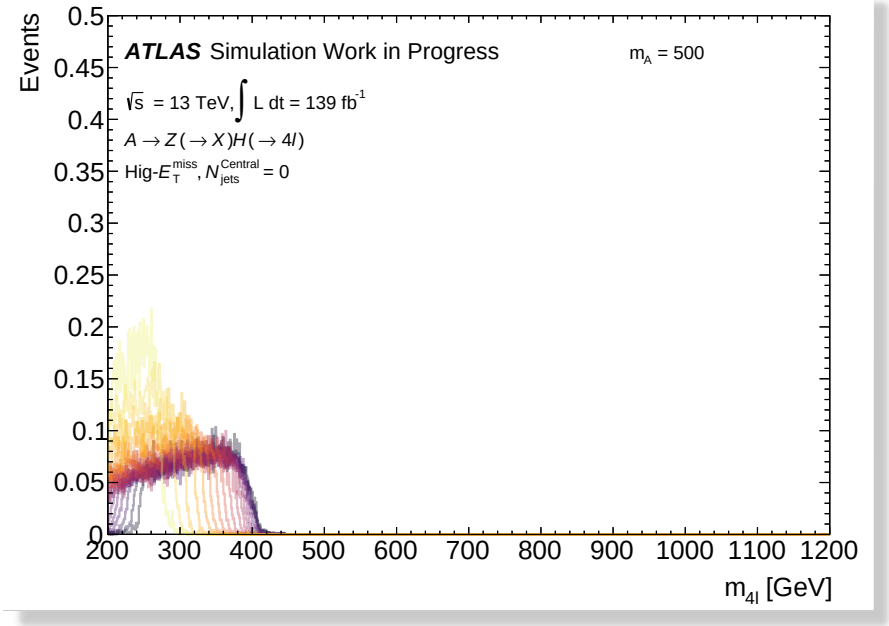




- Interpolation the signal is done in two steps:
  - fix $m_H$ and interpolate $m_A - m_H$ or $m_A$ (711 out of 72 mass points)
  - fix the $m_A - m_H$ and interpolate $m_H$ (7.9k out of 711 mass points)

# Signal interpolation
## $A \to Z(\to 2\ell)H(\to 2\ell + X)$



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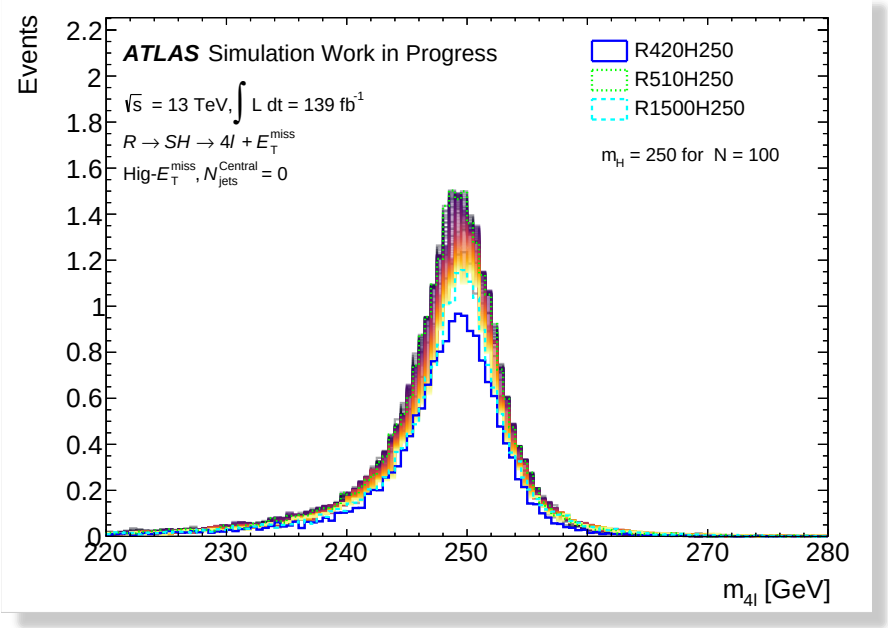
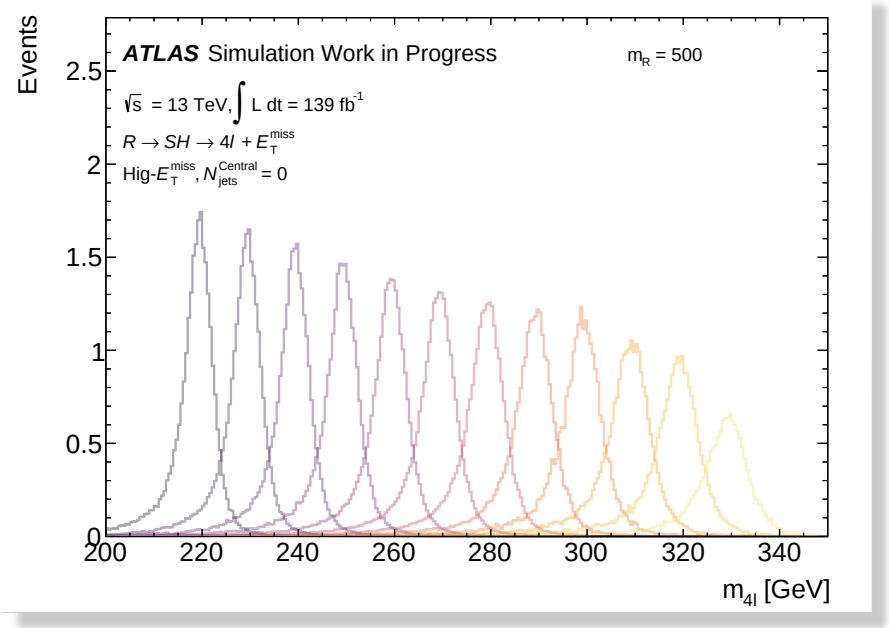
# Signal interpolation

$R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$



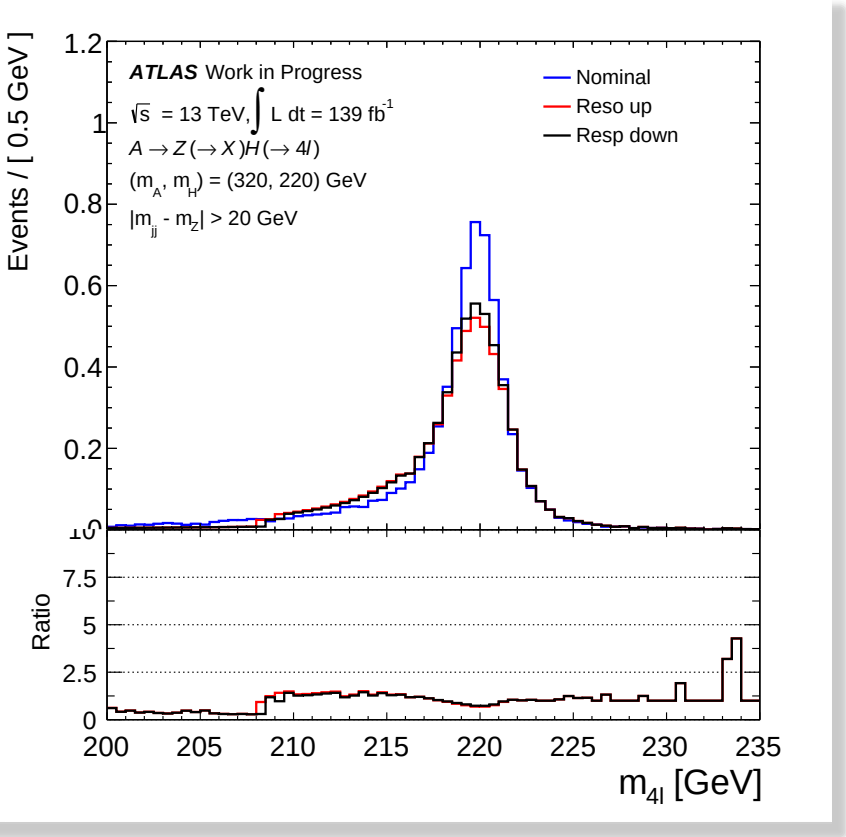


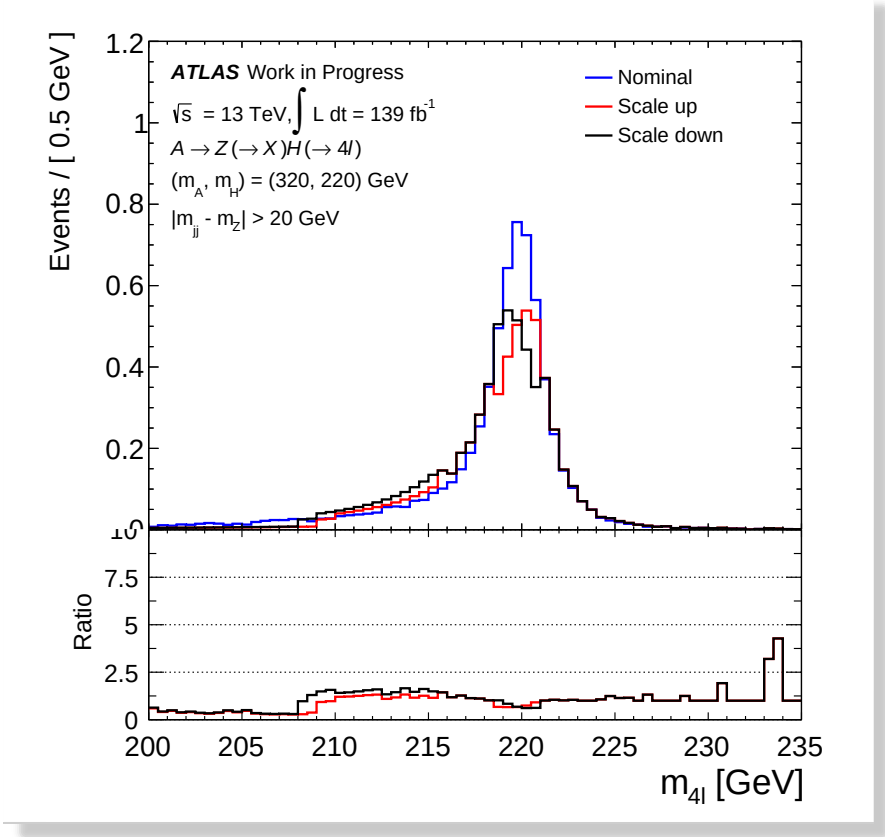




- Interpolation the signal is done in two steps:
  - fix $m_H$ and interpolate $m_R - m_H$ or $m_R$ (711 out of 72 mass points)
  - fix the $m_R - m_H$ and interpolate $m_H$ (7.9k out of 711 mass points)

# Systematic on the signal shape





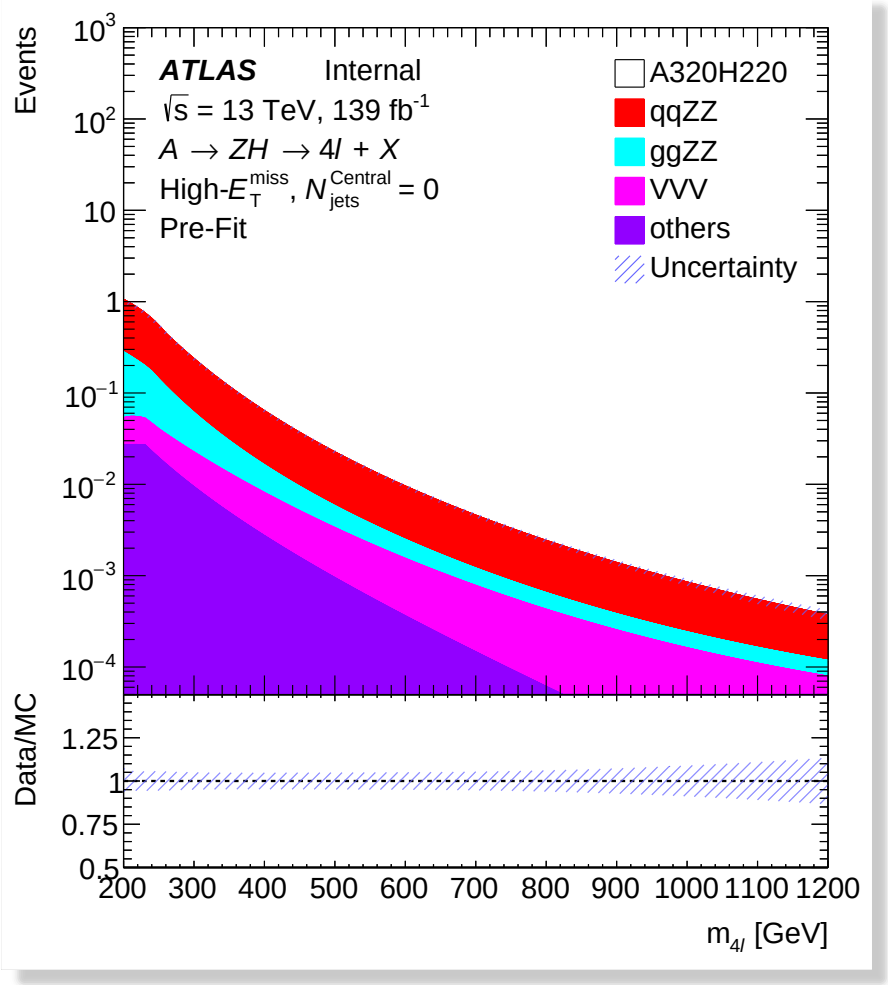



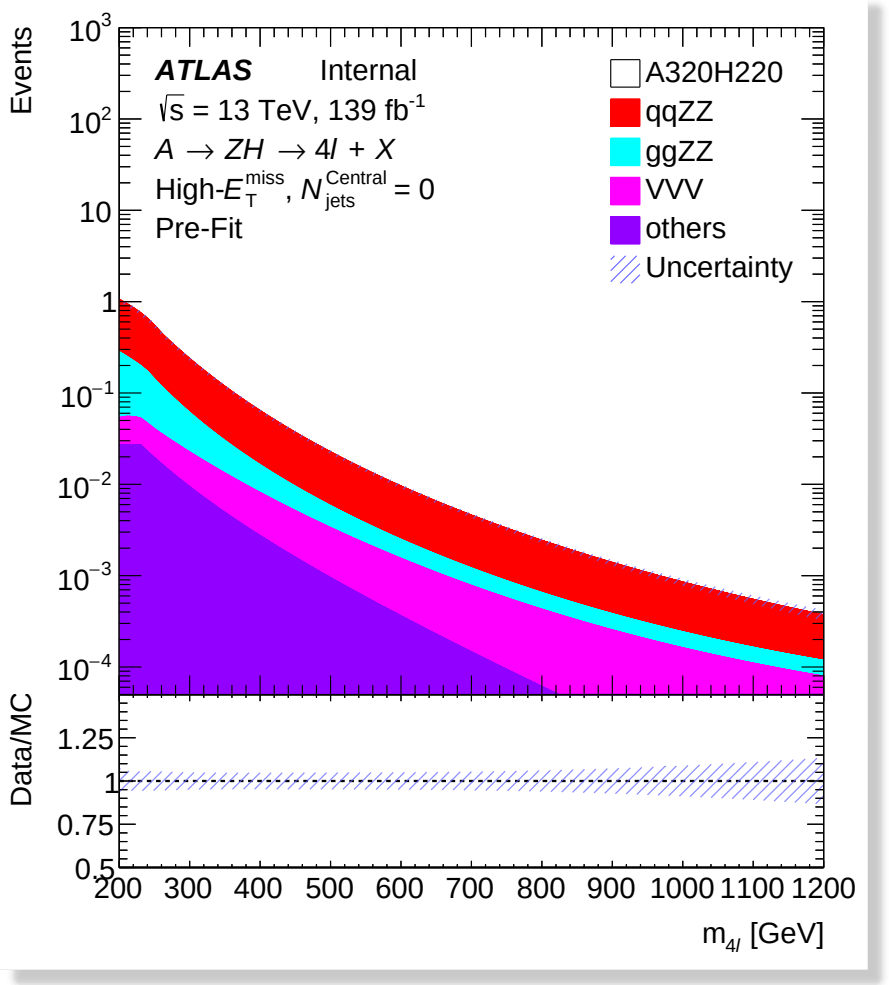

- First the nominal signal is fitted to DSCB+Gaussian and then get the $\sigma$ and $\mu$ values
- Resolution: the $\sigma$ is modified by 1.4% (up/down)
- Scale: the $\mu$ ism modified by 0.23% (up/down)

# Fit results

## Background only Asimov data





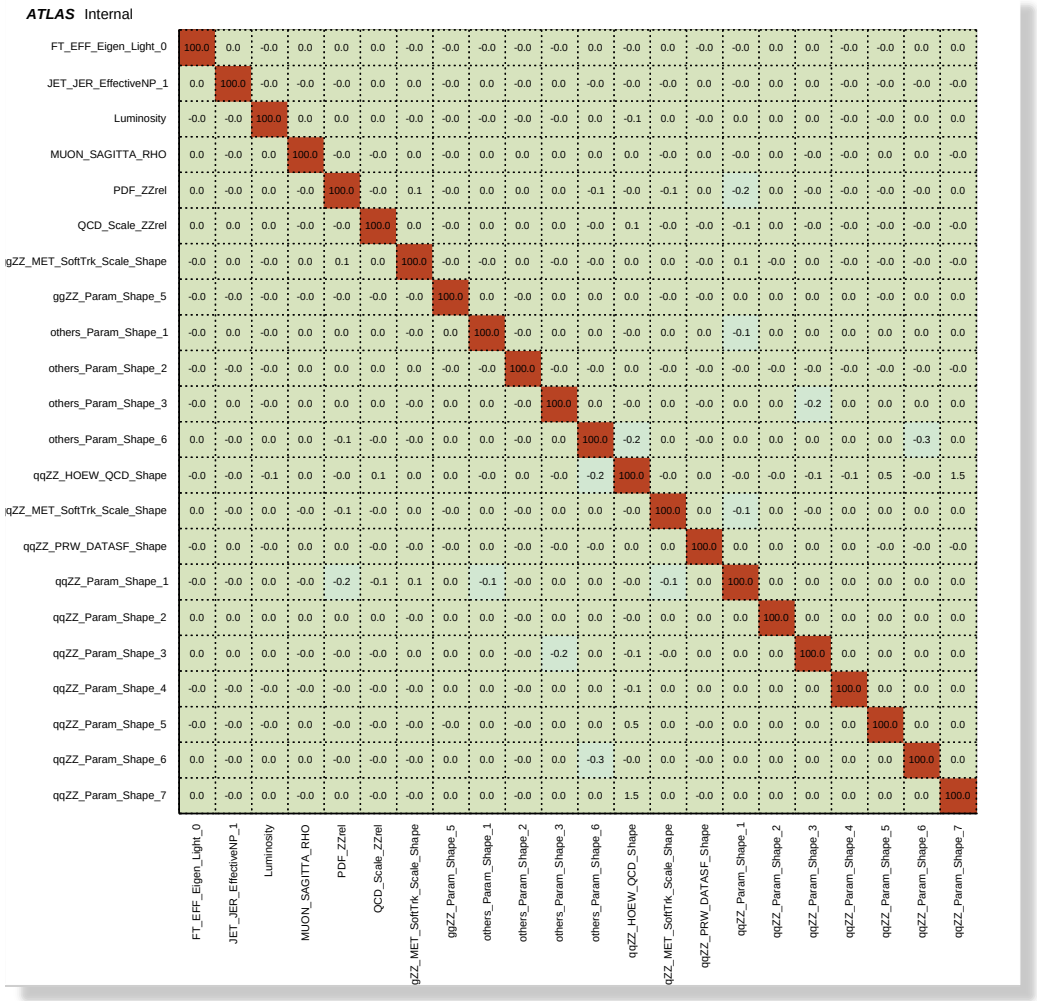




- The expected upper limit is found to be 0.284 fb its 7% better than the previous results.
- The main difference is using the full histogram range instead of DSCB+Gaussian.

# Fit results

## Background only Asimov data



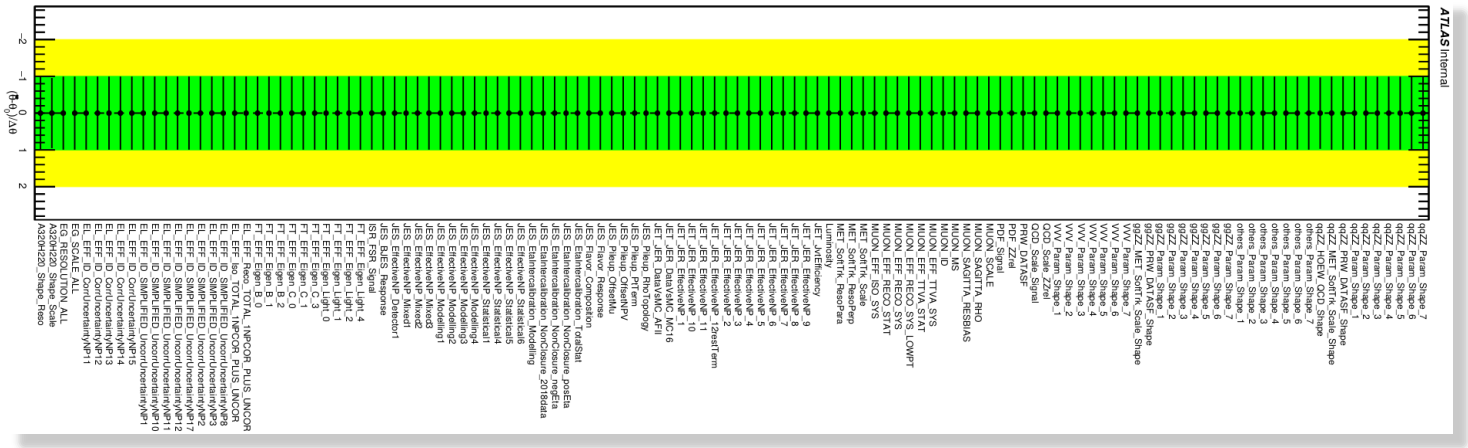



- Correlation between nuisance parameters for the $(m_A, m_H) = (320, 220)$ GeV signal

# Fit results

## Background only Asimov data



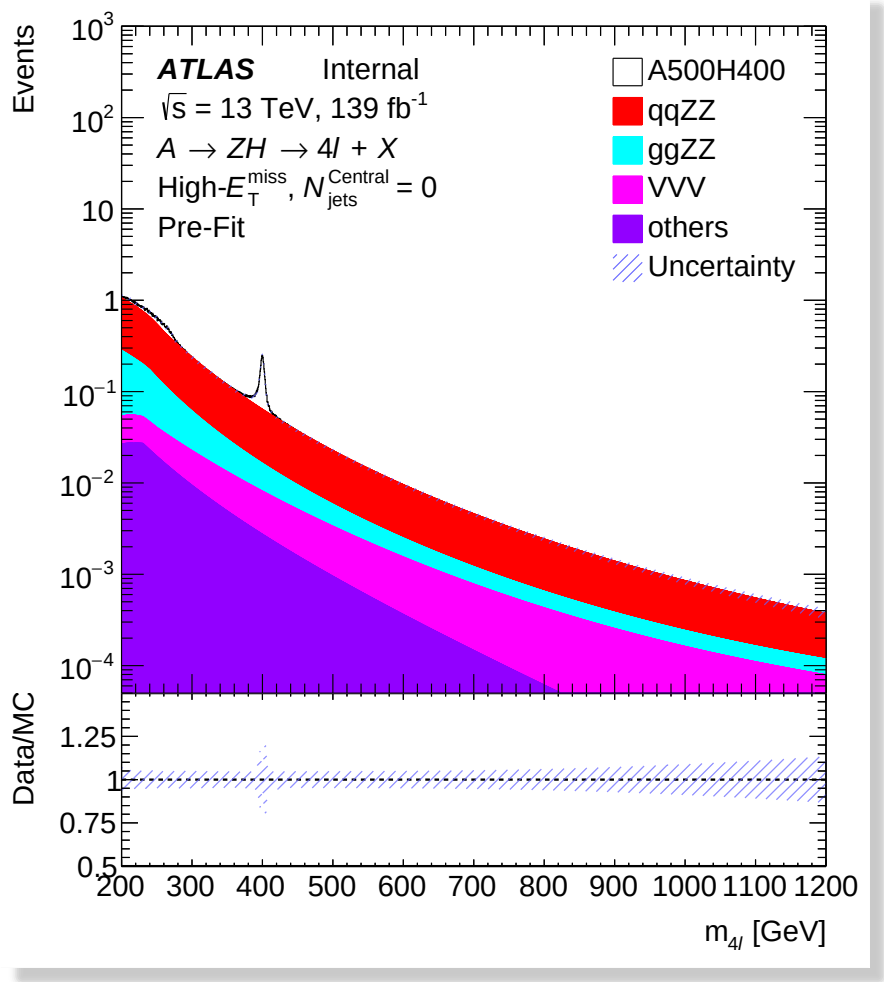


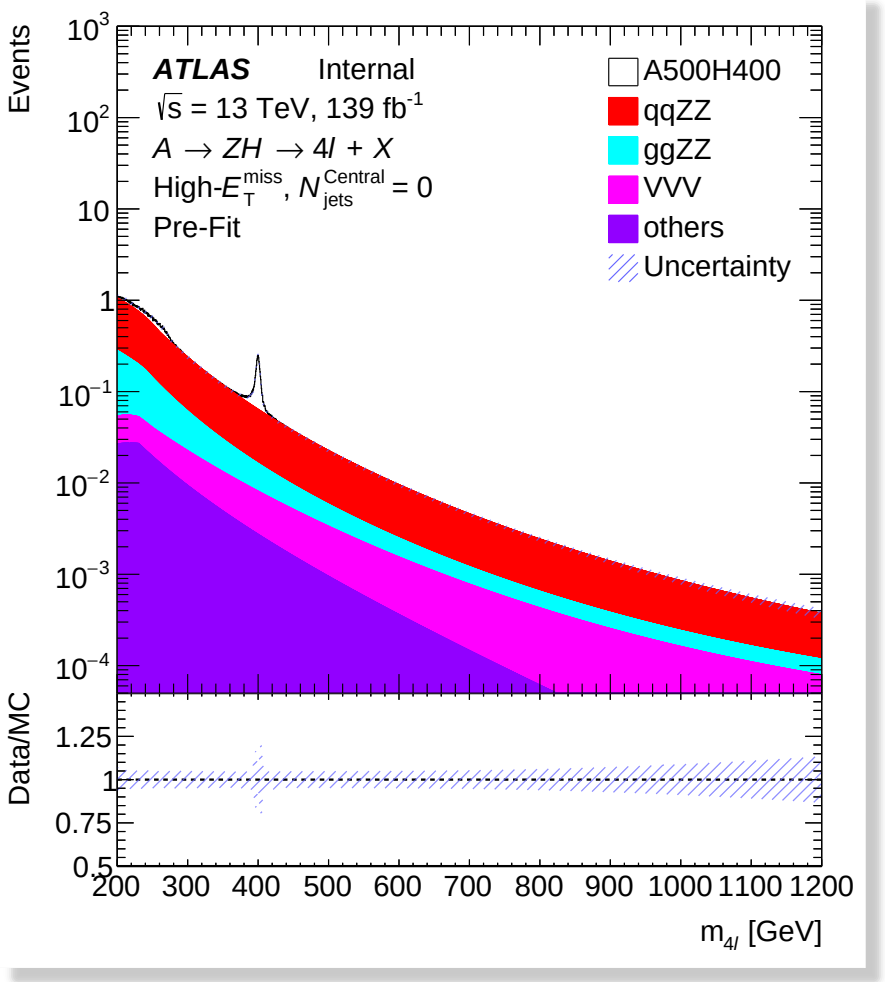

- Well constrained nuisance parameters within $\pm 1\sigma$ for the $(m_A, m_H) = (320, 220)$ GeV signal.

# Fit results

## Background+Signal Asimov data





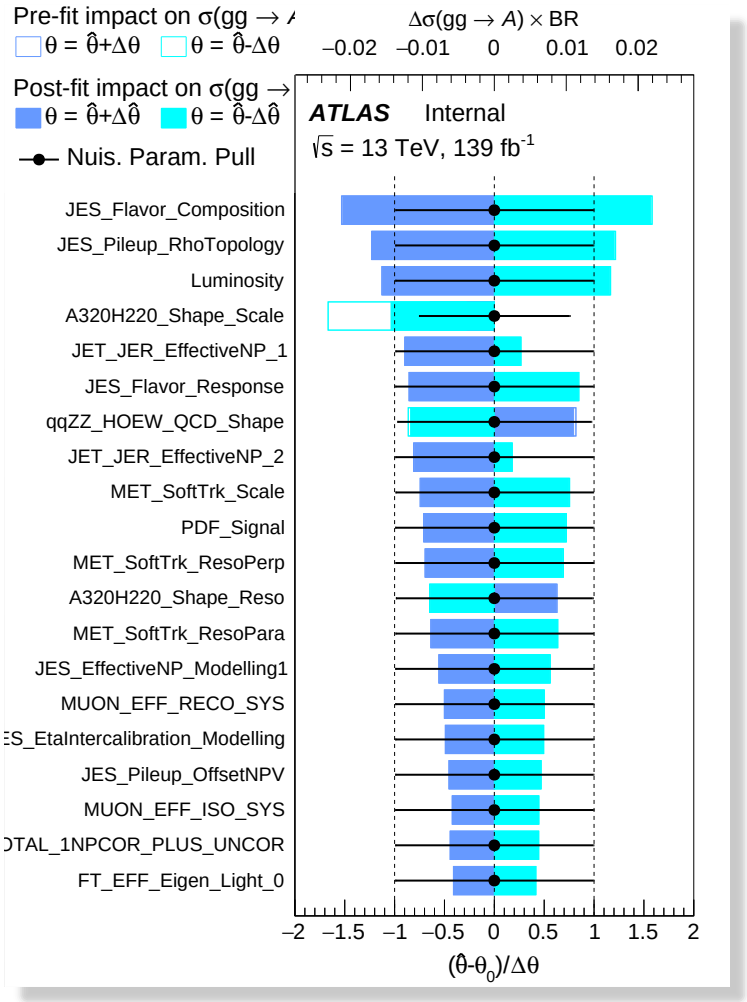




- Injecting a signal by setting the POI to one.

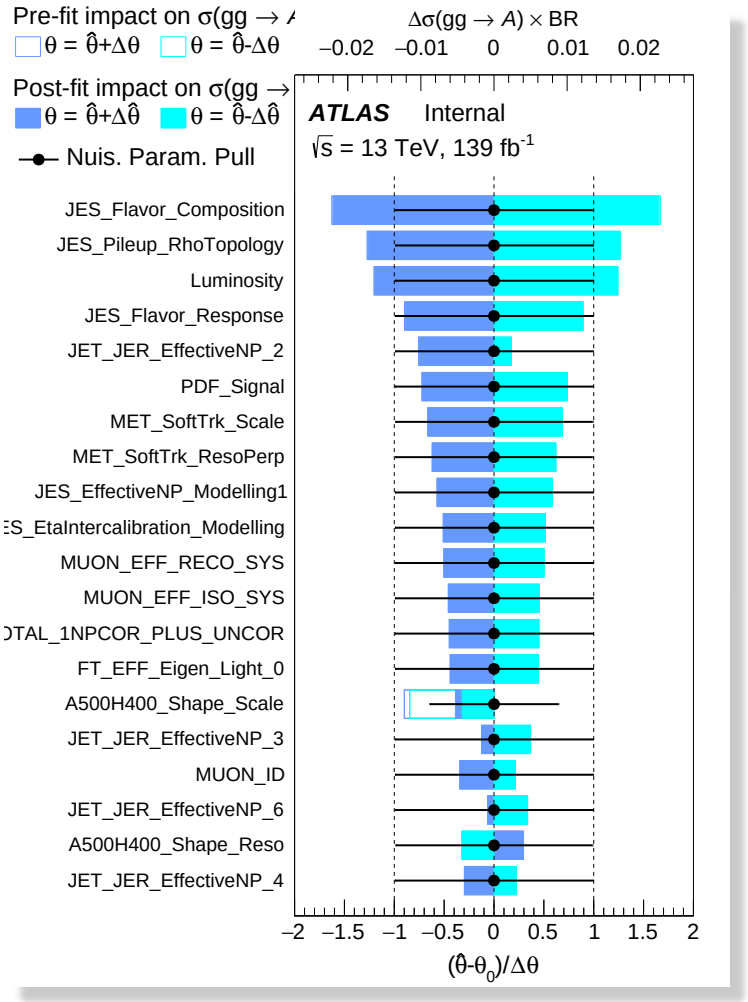
# Fit results

## Background+Signal Asimov data






A320H220

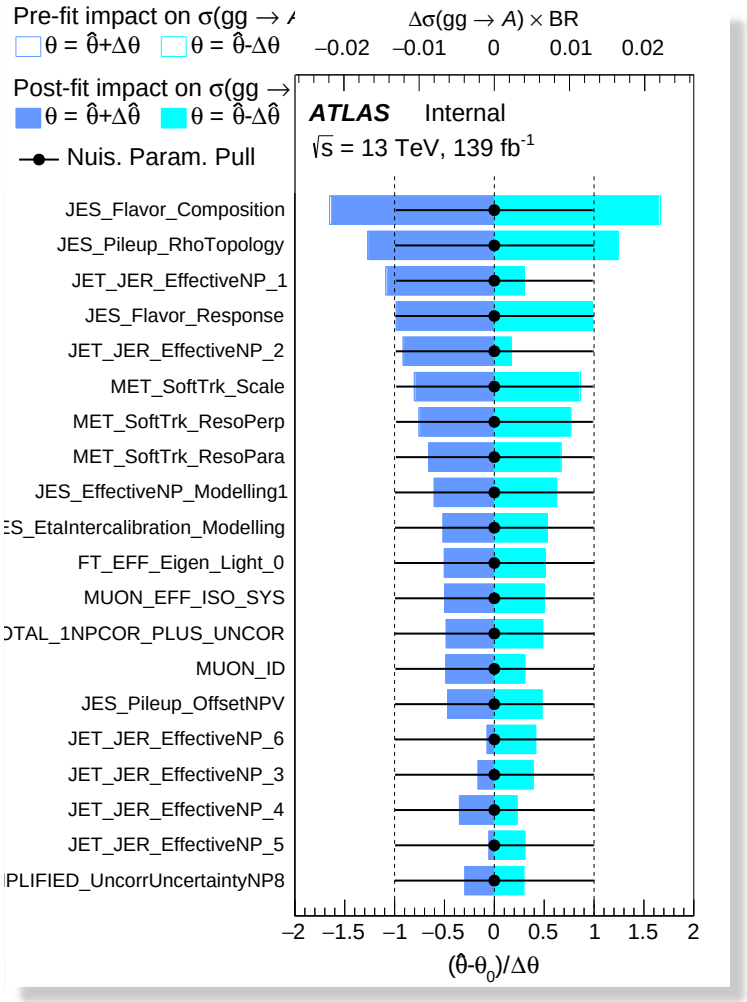



A500H400

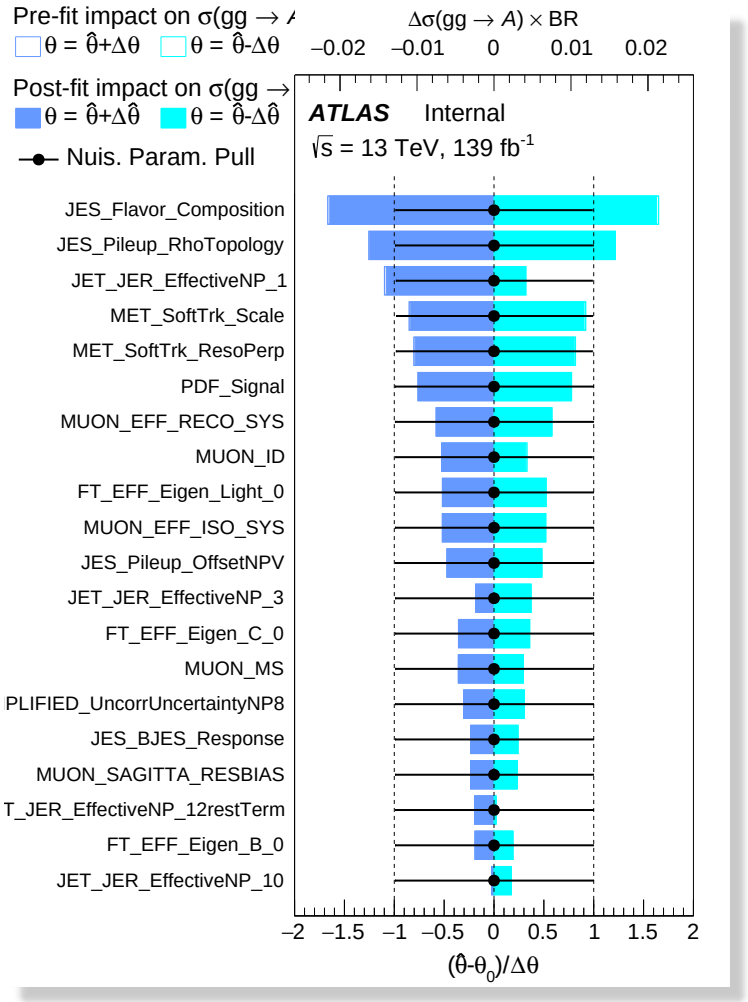
# Fit results

## Background+Signal Asimov data






A1340250

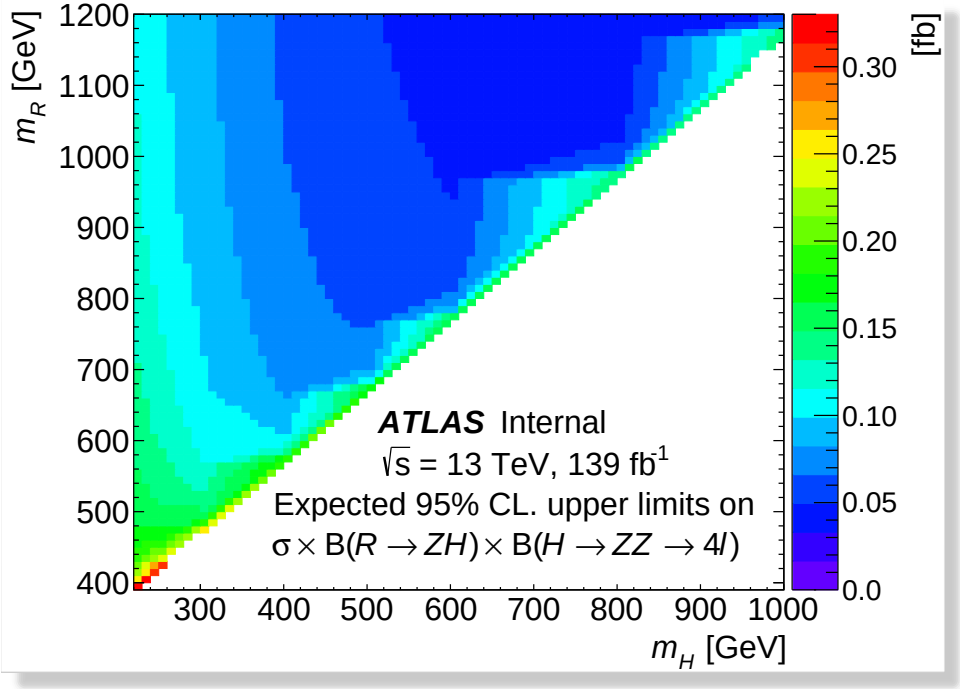


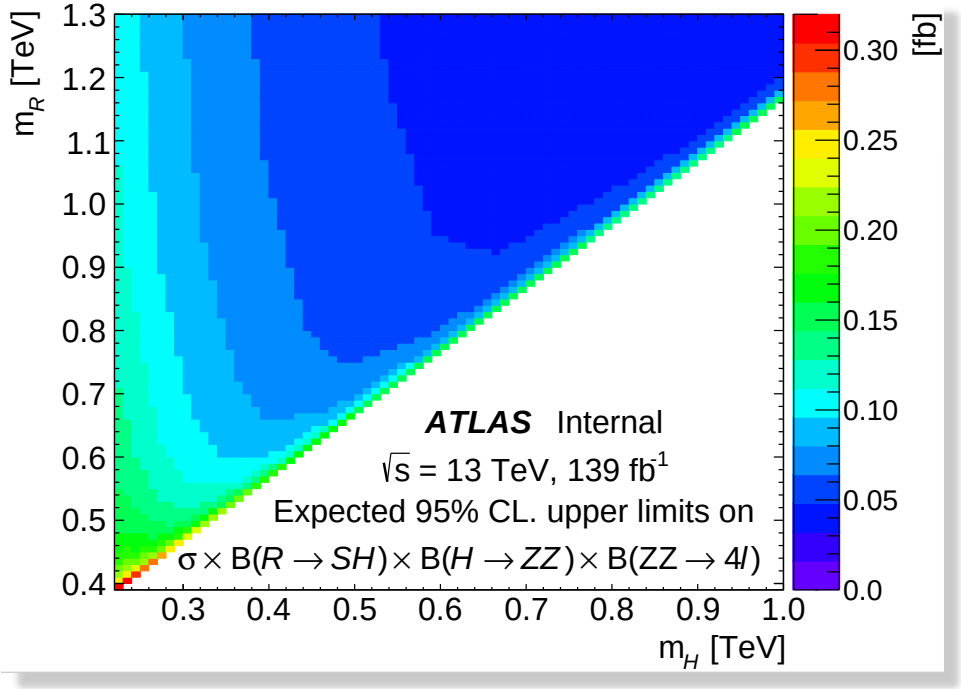

A2090H1000

# Expected upper limits

on the $(m_R, m_H)$ plane for the $R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ model



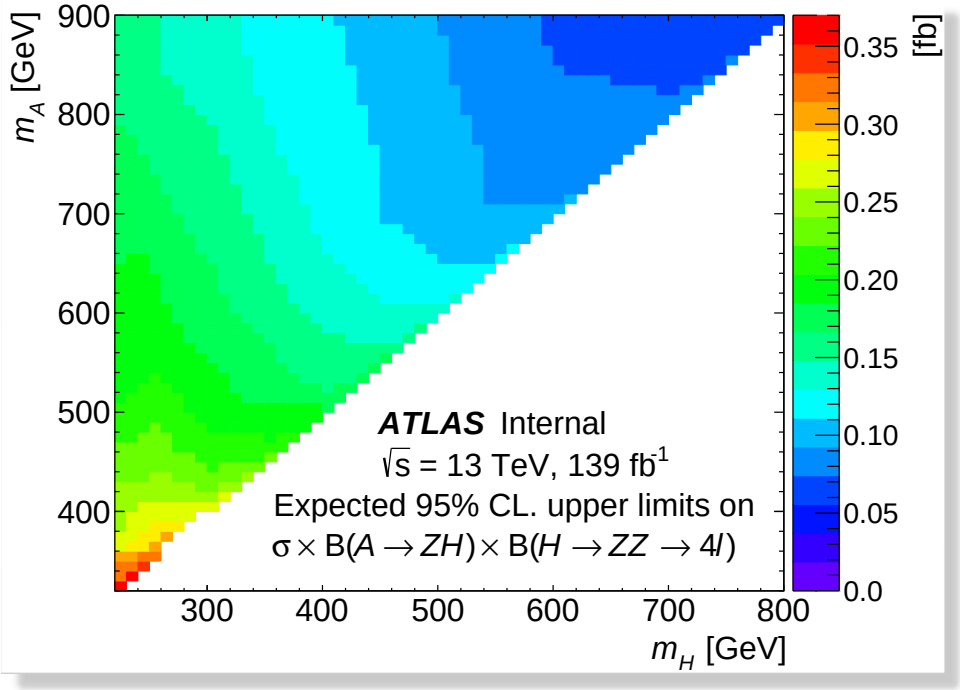


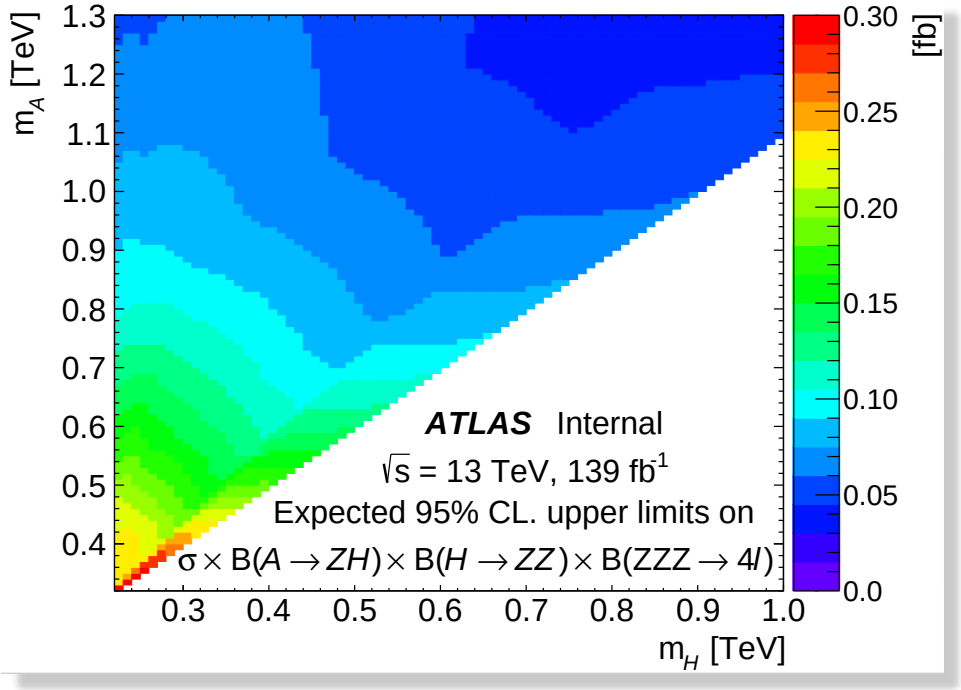




- Upper limits at 95% CL between [0.030 - 0.305] fb on (320, 1300) - (220, 1000) GeV.
- Interpolating the limit of 72 mass points (left), and using 7900 mass points (right).

# Expected upper limits
## on the $(m_A, m_H)$ plane for the $A \to ZH \to 4\ell + X$ model





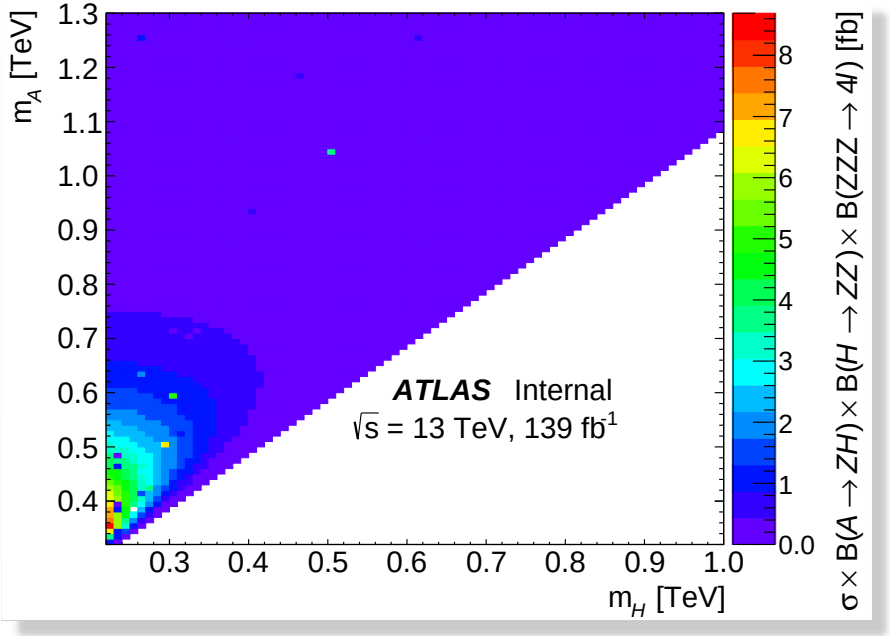




- Upper limits at 95% CL between [0.028 - 0.293] fb on (320, 1300) - (220, 1000) GeV.
- Interpolating the limit of 72 mass points (left), and using 7900 mass points (right). scale

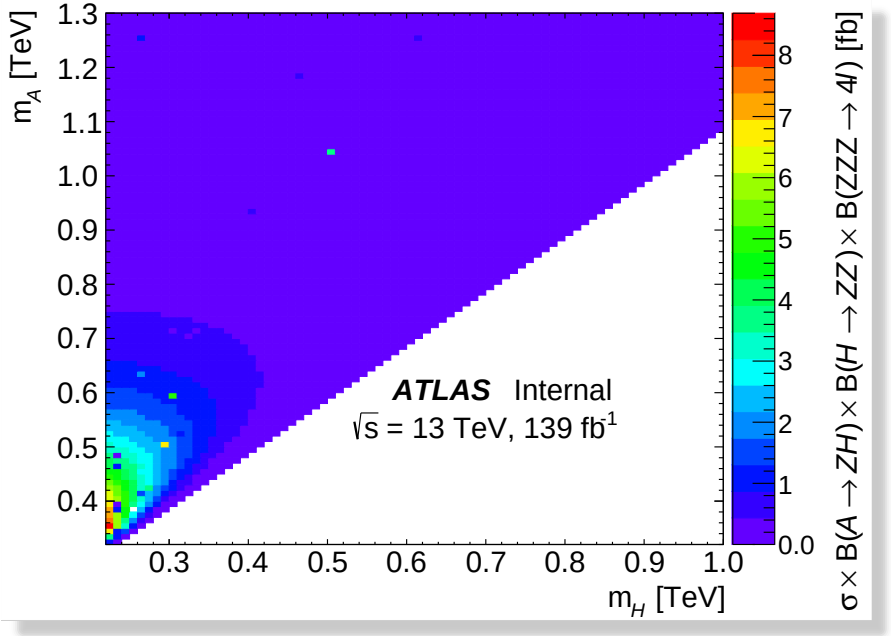
# 2HDM cross-section

## $A \to ZH \to 4\ell + X$ cross-section calculation






Type-I




Type-II

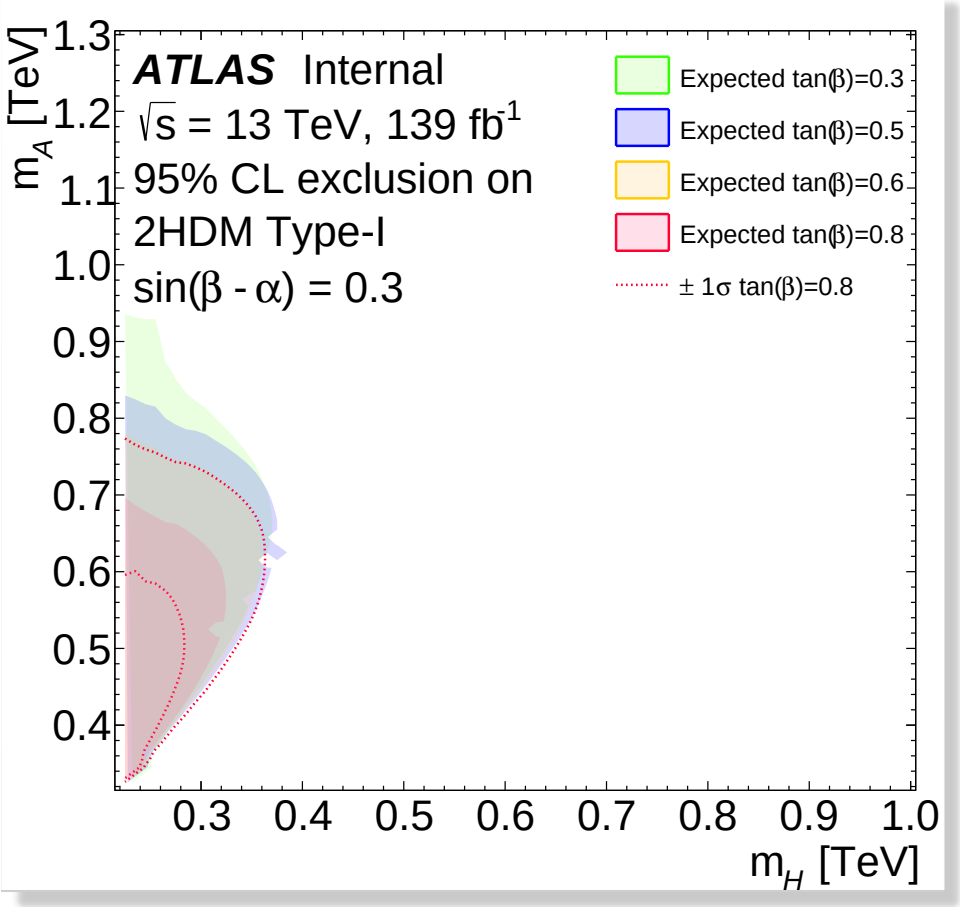
- Two CP-even ($m_H, m_h$), one CP-odd ($m_A$) and two charged scalars ($m_{H^\pm}$)
- Mixing angle for the neutral Higgses ($\alpha$), and vev ratio $\tan(\beta) = \mu_1/\mu_2$.
- The $Z_2$ breaking symmetry $m_{12} = m_H^2 \cdot \tan(\beta)/(1 + \tan^2(\beta))$
- Corresponds to $\sin(\beta - \alpha) = 0.8$ and $\tan(\beta) = 2.0$
- Cross-section calculated using 2HDM calculator [4]

♠[4] HBSM 2HDM Recommendations

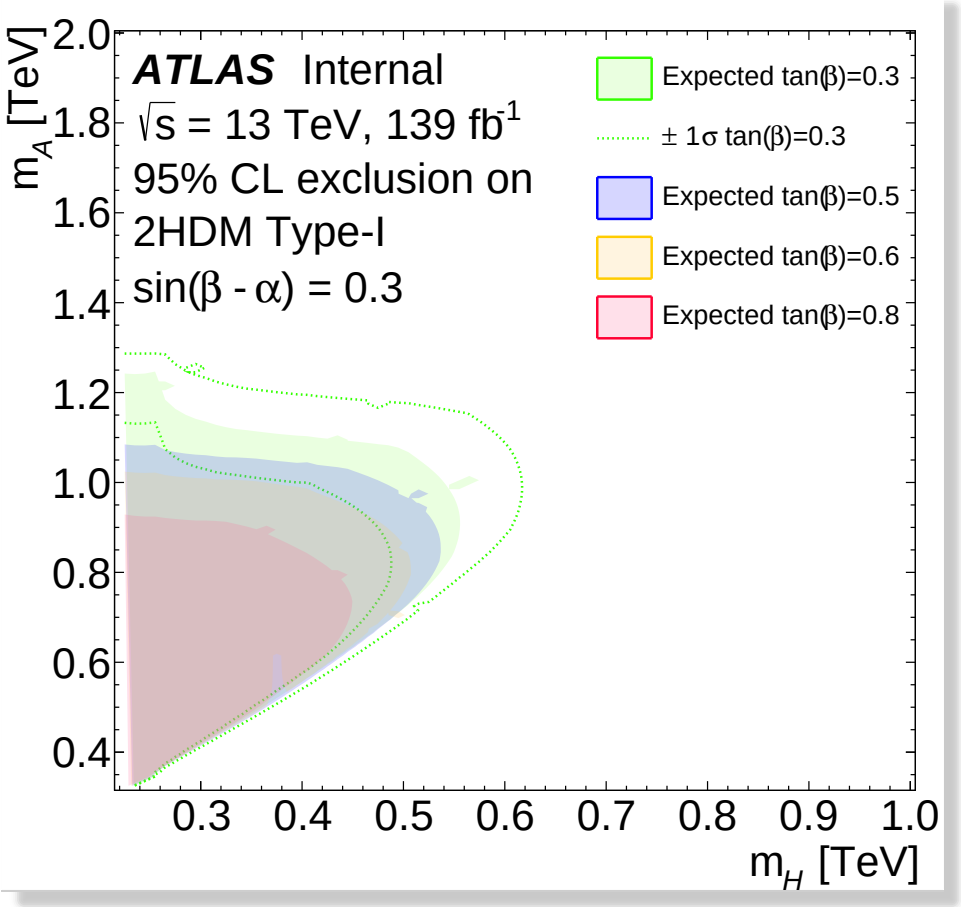
# Interpretation in the 2HDM

## The exclusion at 95% CL in the 2HDM Type-I






$B(ZZ \to 4l)$

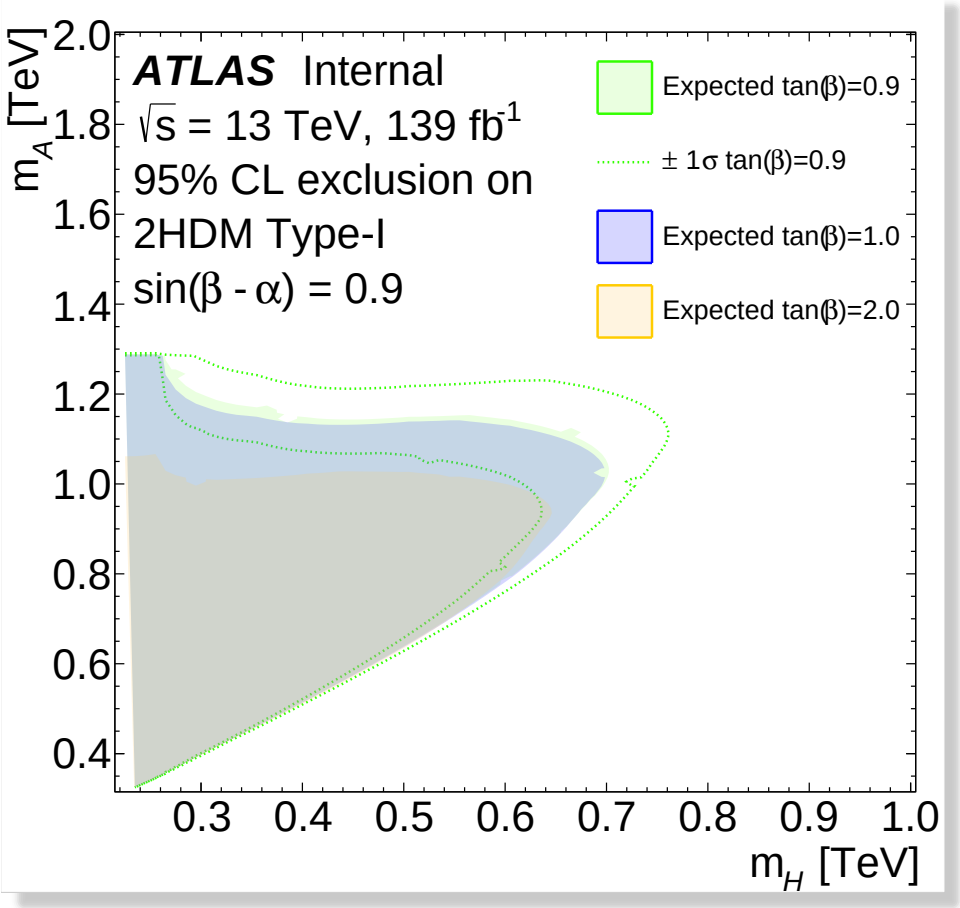



$B(ZZZ \to 4l)$

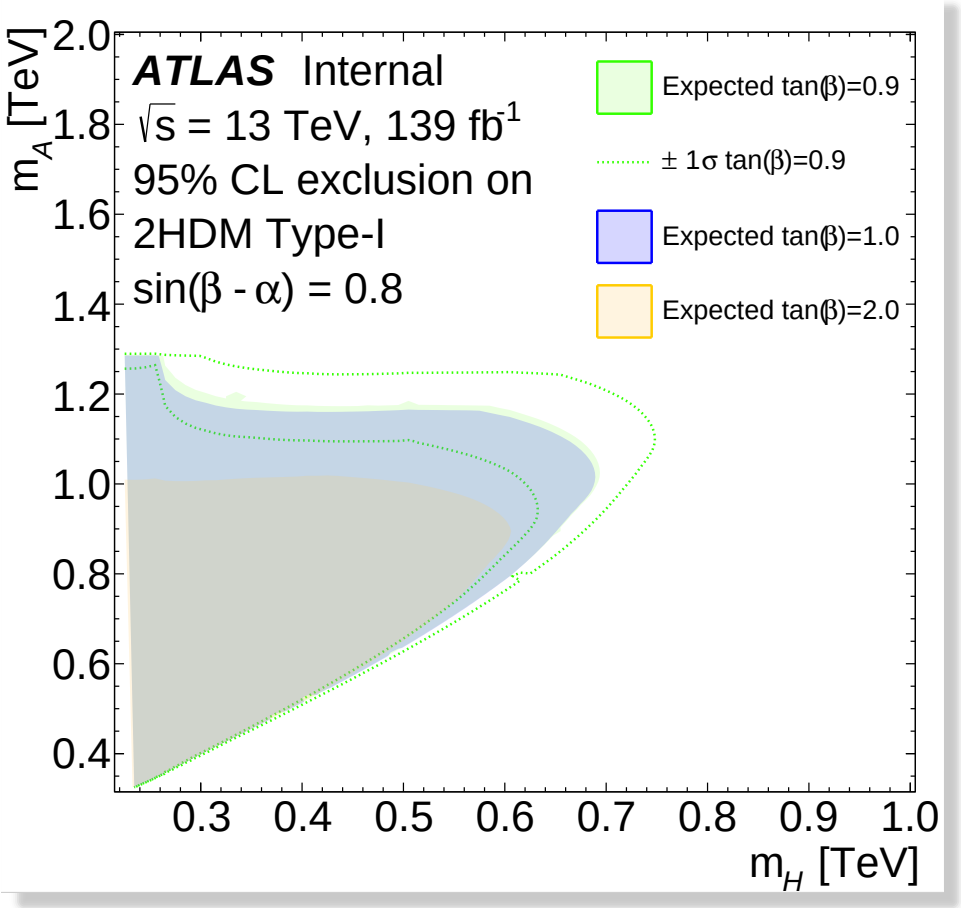
# Interpretation in the 2HDM

## The exclusion at 95% CL in the 2HDM Type-I and-II






Type-I




Type-II

# Summary



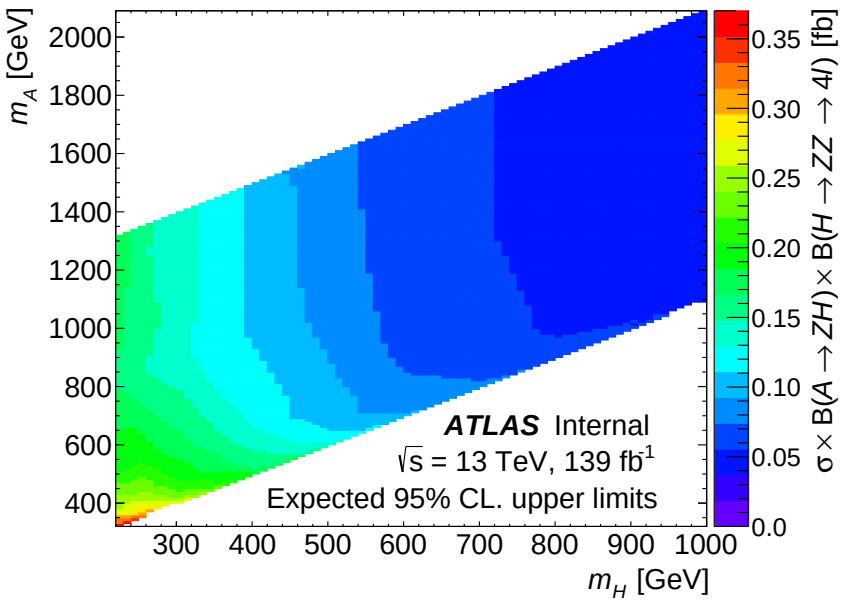
- ☐ All the technical problems were solved:
  - Using the actual histograms after interpolating them
  - Extract the systematic shape on the signal form the DSCB plus Gaussian
- ☐ A new $A \to Z(\to 2\ell)H(\to 2\ell + X)$ is added to the main signal.
- ☐ Expected upper limit on the $(m_{A/R}, m_H)$ plane for both models is show; and
- ☐ Exclusion in the 2HDM Type-I and Type-II is provided for the $A \to ZH \to 4\ell + X$ signal.
- ☐ We would like to know if everyone is happy to go for un-blinding approval procedures.

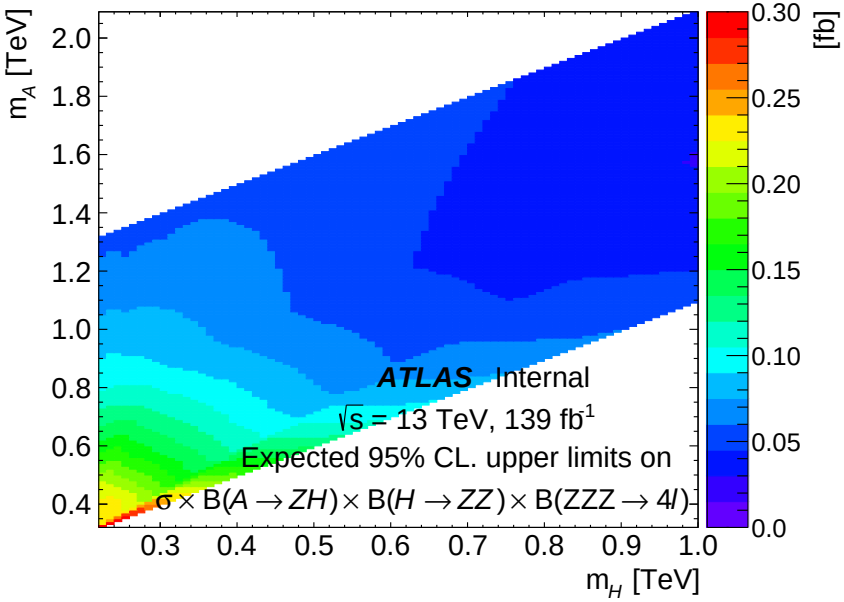
- ☐ **Target**: since most conference deadlines have passed, we aim to publish a paper directly.

# Additional slides

## $A \to ZH \to 4\ell + X$ limit on the full range





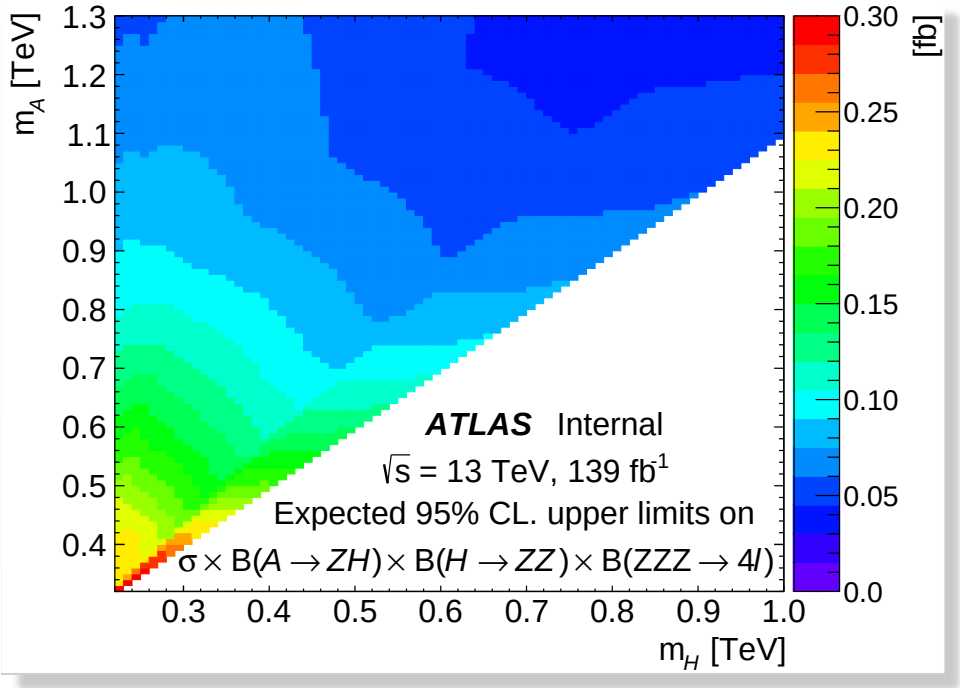




- old limit(left) and new limit (right)

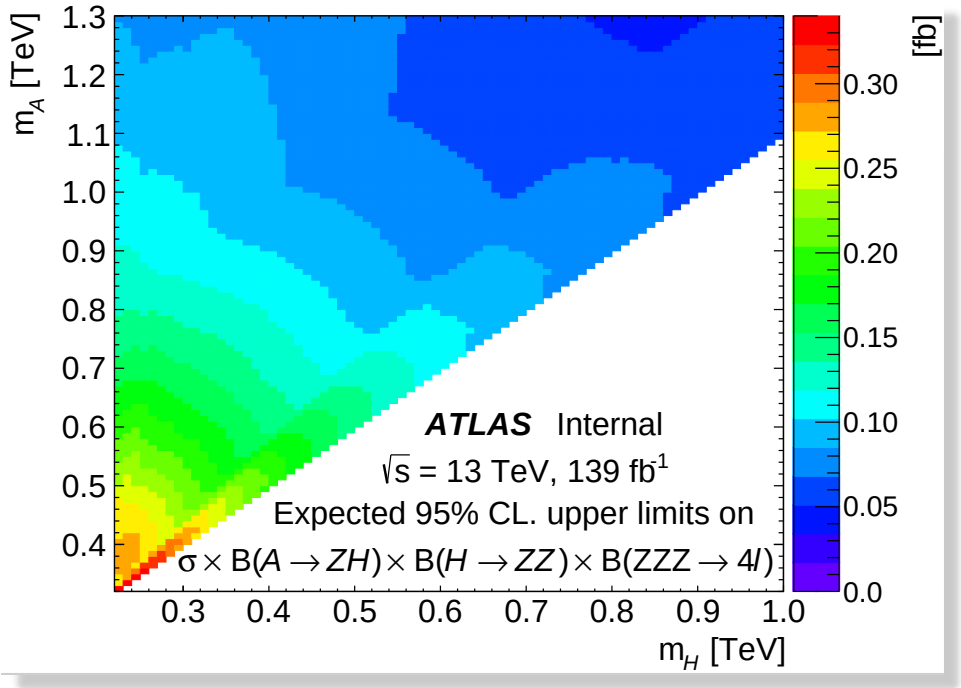
# Additional slides

## Upper limits for the $A \to ZH \to 4\ell + X$






all categories




non-MET categories only