ATLAS invisible Higgs searches

Sapienza Università di Roma

INFN

ATLAS Experiment

Introduction

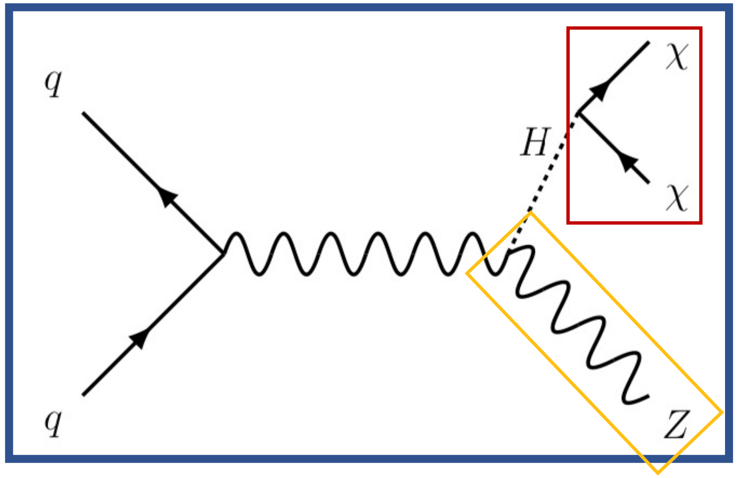
Overview of the two most recent ATLAS results and the conf on Run1+2 combination

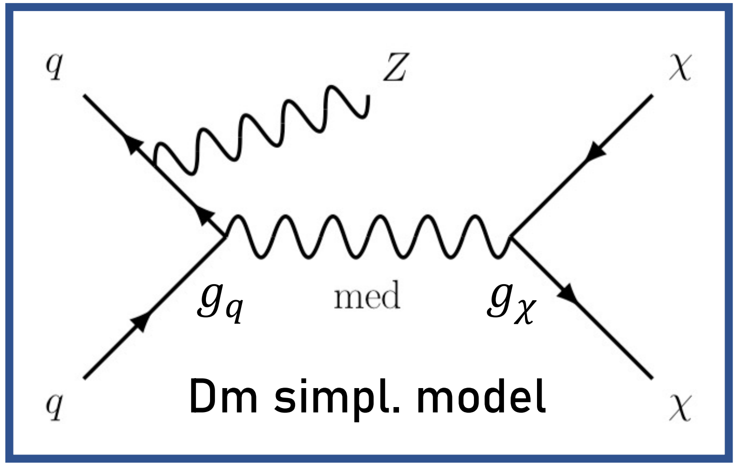
- Mono-Z(H $\rightarrow$invisible)
- VBF H $\rightarrow$invisible + γ

- Preliminary Run1 + 2 combination

Mono-Z(H →invisible)

arXiv:2111.08372



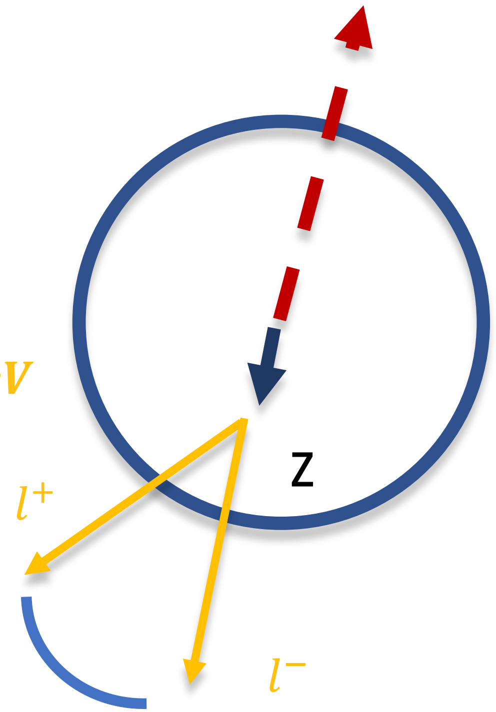


5 parameters: $\{m_{med}, m_\chi, g_q, g_\chi, g_l\}$

Key SR selections:

- $E_T^{miss} > 90\ GeV$
- $S_{E_T^{miss}} > 9$
- $S_{E_T^{miss}} = \frac{E_T^{miss}}{\sigma_L \sqrt{1-\rho_{LT}^2}}$

- 2 leptons $p_T > 30\ (20)\ GeV$
- $76 < m_{ll} < 106\ GeV$
- $\Delta R < 1.8$



Backgrounds

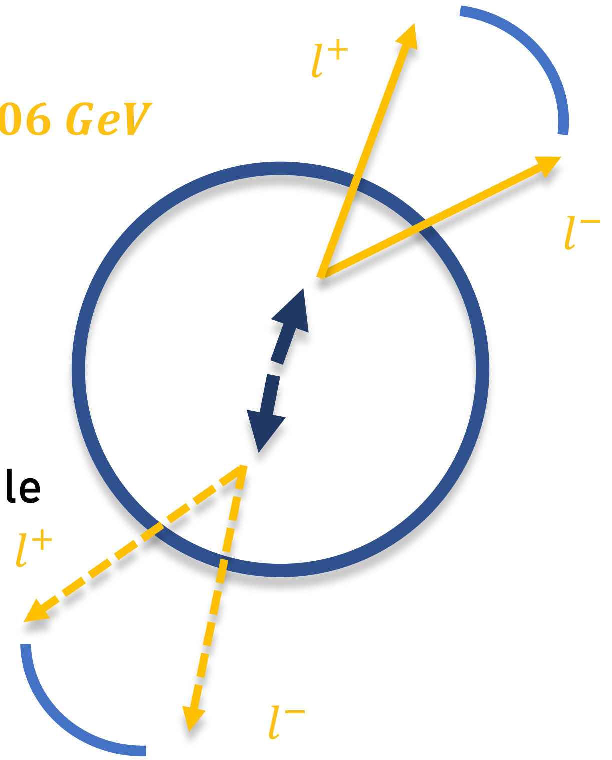
Dedicated 4l CR

1. ZZ($\rightarrow ll$ + invisible)
2. WZ($\rightarrow ll$ + invisible)
3. Z + Jets
4. Non-resonant Backgrounds (WW, $t\bar{t}$, single top, Z $\rightarrow \tau\tau$)
5. Others (tribosons prod., $t\bar{t} + V$, ZZ$\rightarrow 4l$)

Same signal topology
One Z decaying to neutrinos

- **4 leptons**
- $76 < m_{ll,1}, m_{ll,2} < 106\ GeV$

1 pair treated as invisible

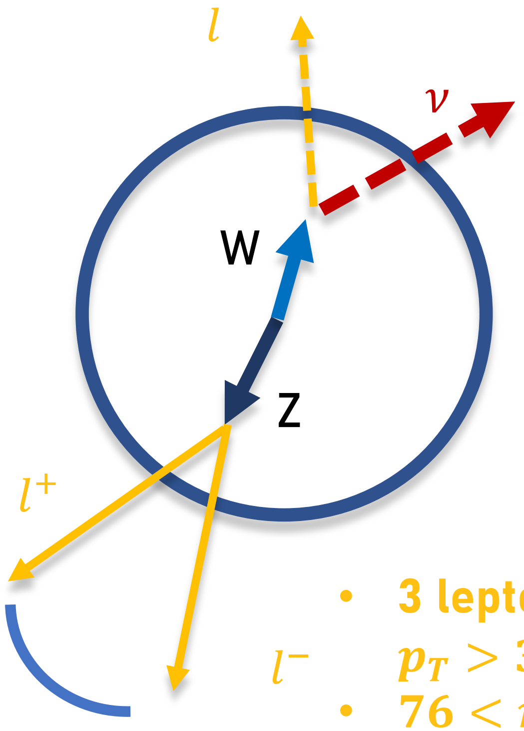


Backgrounds

1. ZZ($\rightarrow ll$ + invisible)
2. WZ($\rightarrow ll$ + invisible)
3. Z + Jets
4. Non-resonant Backgrounds (WW, $t\bar{t}$, single top, Z $\rightarrow \tau\tau$)
5. Others (tribosons prod., $t\bar{t} + V$, ZZ$\rightarrow 4l$)

Dedicated 3l CR

One lepton missed in reconstruction

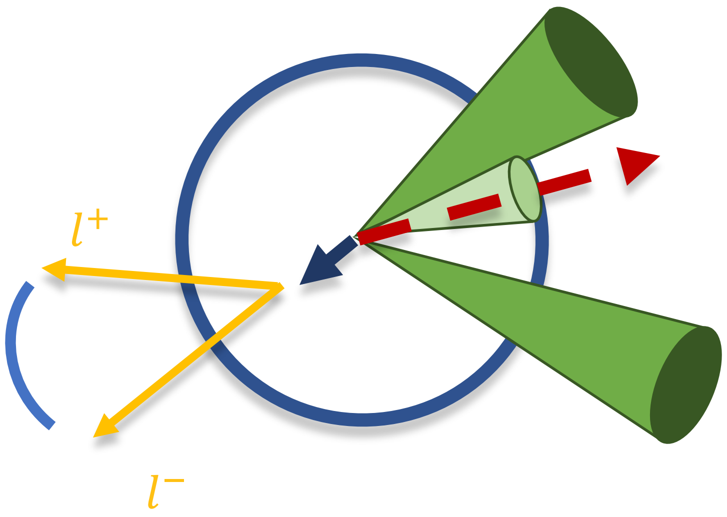


- $E_T^{miss} > 30\ GeV$
- $S_{E_T^{miss}} > 3$
- $m_T^W > 60\ GeV$

- 3 leptons $p_T > 30\ (20, 20)\ GeV$
- $76 < m_{ll} < 106\ GeV$

Backgrounds

1. ZZ($\rightarrow ll$ + invisible)
2. WZ($\rightarrow ll$ + invisible)
3. Z + Jets
4. Non-resonant Backgrounds (WW, $t\bar{t}$, single top, Z $\rightarrow \tau\tau$)
5. Others (tribosons prod., $t\bar{t} + V$, ZZ$\rightarrow 4l$)



- E_T^{miss} Arises mostly from Jets mismeasurements

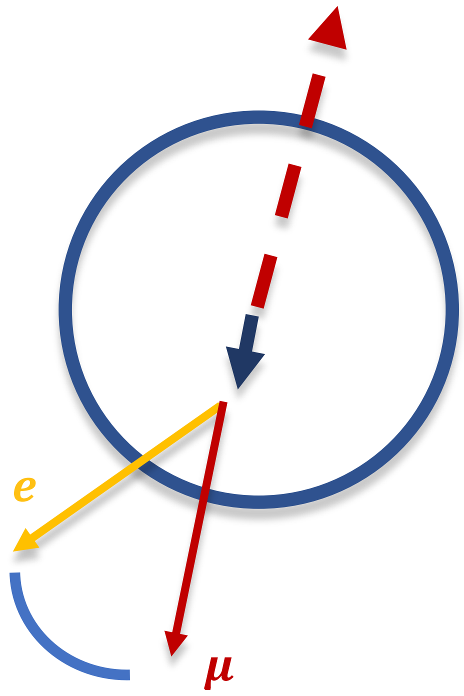
Constrained through MC
Predictions verified in a $S_{E_T^{miss}} < 9$ region and through a γ+Jets sample (similar production diagram)

Backgrounds

1. ZZ($\rightarrow ll$ + invisible)
2. WZ($\rightarrow ll$ + invisible)
3. Z + Jets
4. Non-resonant Backgrounds (WW, $t\bar{t}$, single top, Z $\rightarrow \tau\tau$)
5. Others (tribosons prod., $t\bar{t} + V$, ZZ$\rightarrow 4l$)

Dedicated $e\mu$ CR

Same as SR, but two different lepton flavor



Backgrounds

1. ZZ($\rightarrow ll$ + invisible)
2. WZ($\rightarrow ll$ + invisible)
3. Z + Jets
4. Non-resonant Backgrounds (WW, $t\bar{t}$, single top, Z $\rightarrow \tau\tau$)
5. Others (tribosons prod., $t\bar{t} + V$, ZZ$\rightarrow 4l$)

Uncertainties

Uncertainty source	$\Delta\mathcal{B}$ [%]
Statistical uncertainty	5.1
Systematic uncertainties	7.4
Theory uncertainties	4.9
Signal modelling	0.4
ZZ modelling	4.4
Non-ZZ background modelling	2.1
Experimental uncertainties (excl. MC stat.)	4.6
Luminosity, pile-up	1.5
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.0
Flavour tagging	0.4
Electrons, muons	1.2
MC statistical uncertainty	1.6
Total uncertainty	9.0

- Uncertainties impact evaluated fixing the corresponding NP to their best-fit values, and subtracting the square of the resulting uncertainty from the square of the total uncertainty to evaluate

← Among Theoretical Unc. ZZ modelling dominates

← Among Experimental Unc. JES and JER dominates

Results

A BDT is used to separate Signal and Bkg

8 variables:

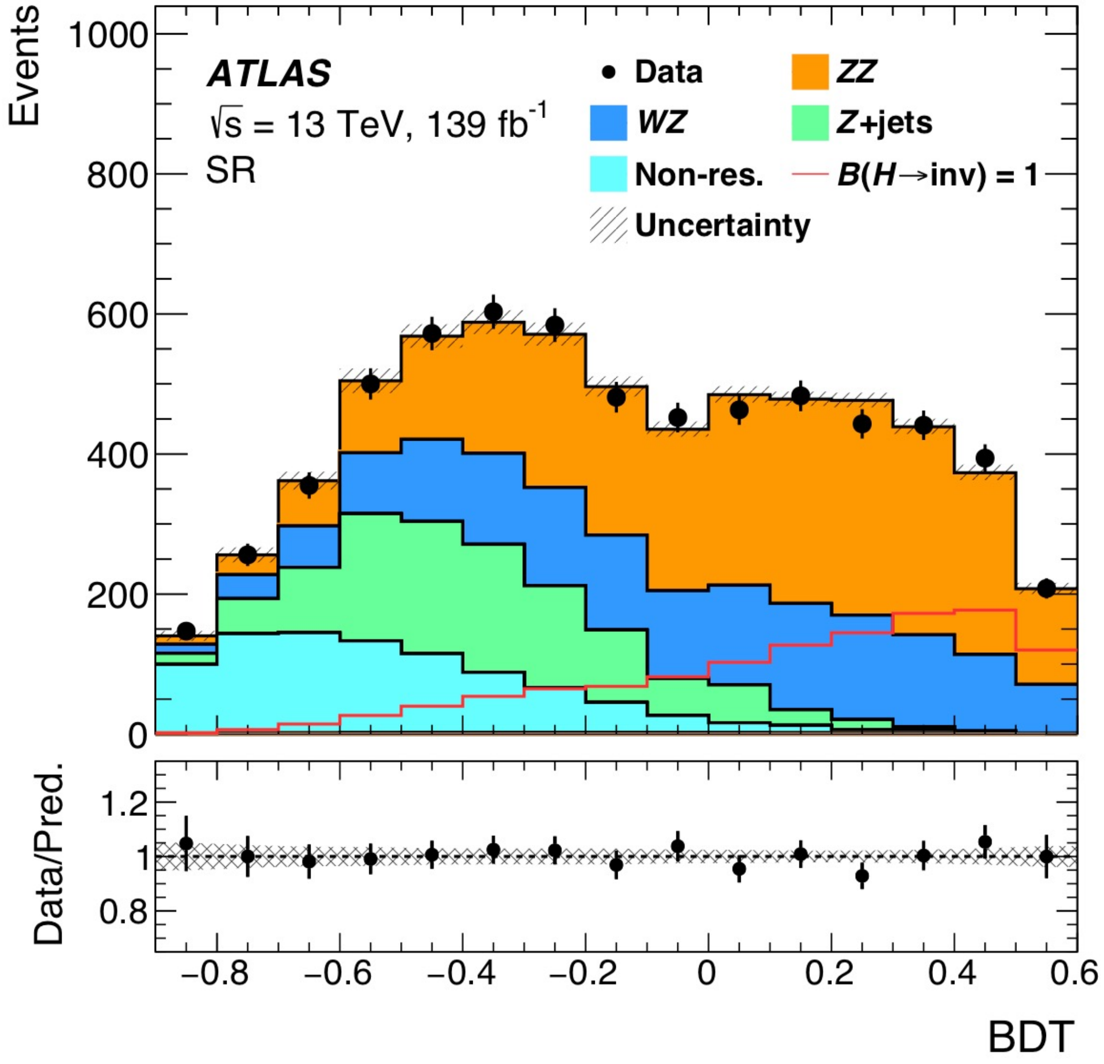
$E_T^{miss}/H_T,\ S_{E_T^{miss}},\ H_T,\ f_{soft},\ m_{ll},\ \Delta R_{ll},\ y_{ll},\ \Delta\varphi(ll, \overrightarrow{E_T^{miss}})$

Simultaneous fit of SR and all CR

Profile likelihood:

SR, $e\mu$ CR → BDT score

3l CR, 4l CR → E_T^{miss}



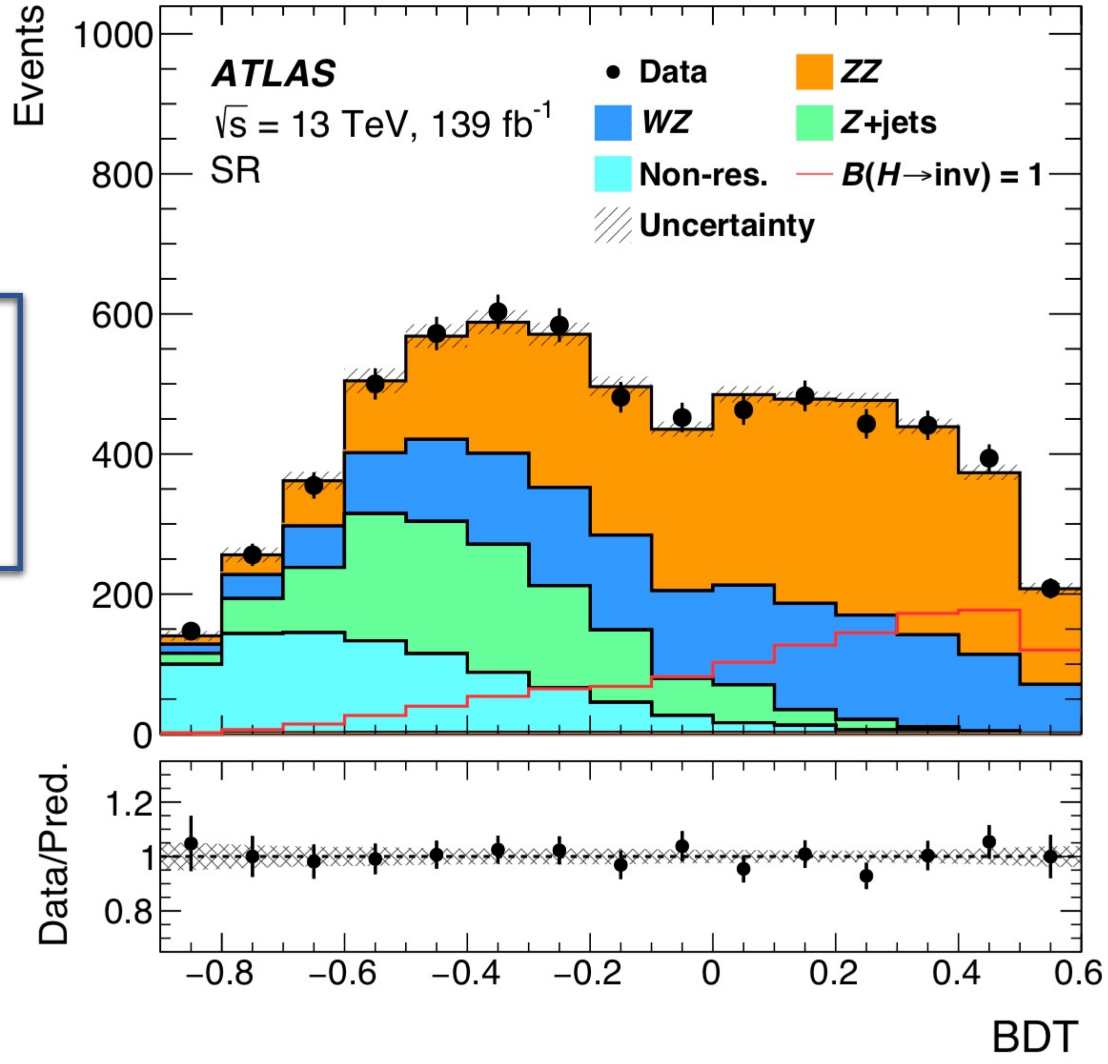
Results

No significant excess is observed.

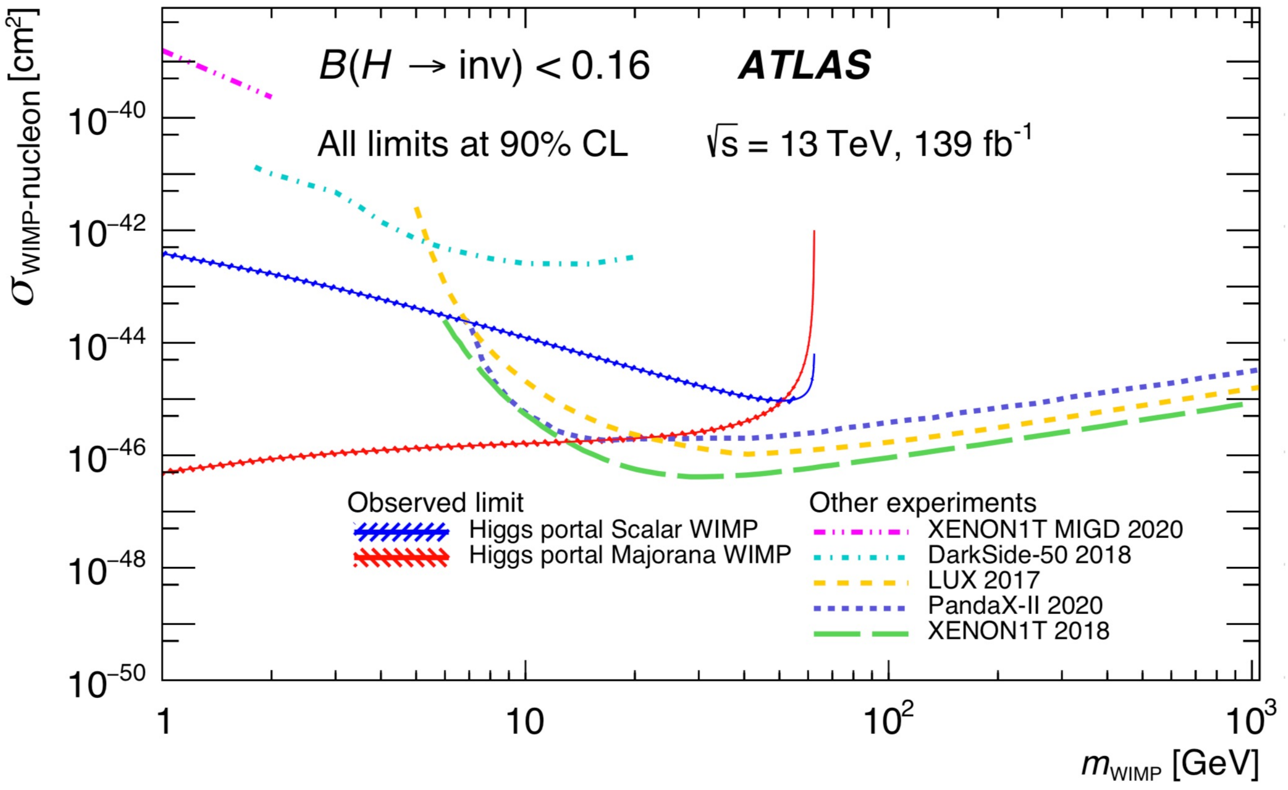
Observed (expected) 95% CL limit:

$BR_{H\to inv.}$ → 0.19 (0.19)

45% improvement!
(compared to the previous result scaled for stat.)



Results

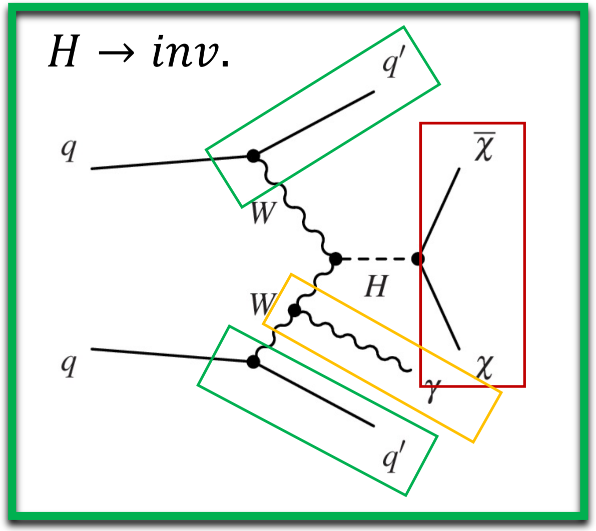


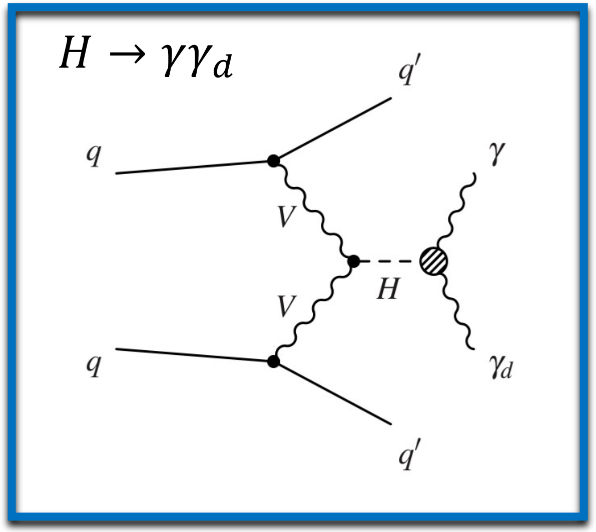
Scalar σ_{WIMP-N}: down to $10^{-45} cm^2$

Fermion Majorana σ_{WIMP-N}: down to $10^{-46} cm^2$

VBF H →invisible + γ

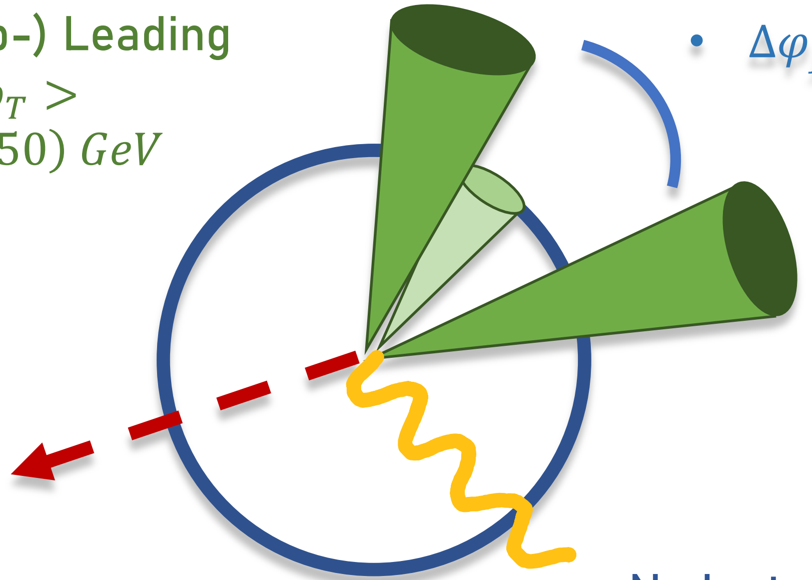
arXiv:2109.00925

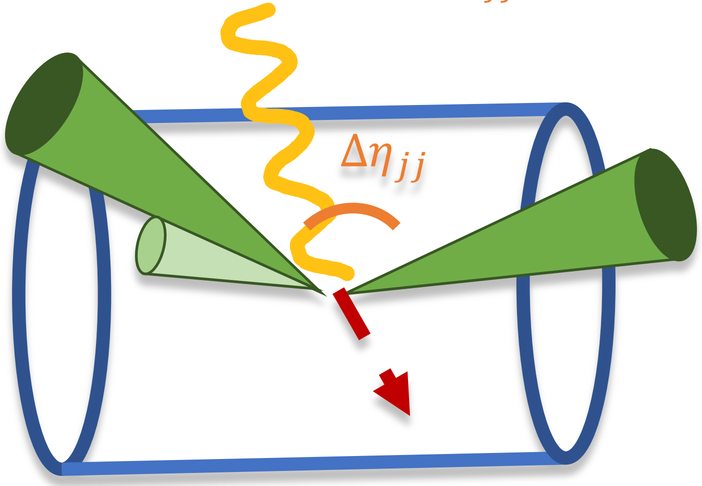




Key Events selections:

- (Sub-) Leading jet $p_T >$ 60 (50) GeV
- $\Delta\varphi_{jj} < 2.5$
- $|\Delta\eta_{jj}| > 3$





- $E_T^{miss} > 150\ GeV$
- No leptons
- 1 photon

Dominant Backgrounds

- $pp \to Z(\to \nu\nu) + \gamma + jets$
- $pp \to W(\to l\nu) + \gamma + jets$

- Dominant irreducible background:

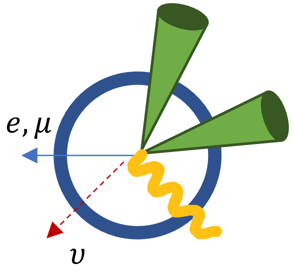
$$Z(\to \upsilon\bar{\upsilon}) + jets + \gamma$$

- SM MC predictions constrained using orthogonal CRs

W CR

$W(\to l_{lost}\upsilon) + jets + \gamma$ ~

$W(\to l\upsilon) + jets$

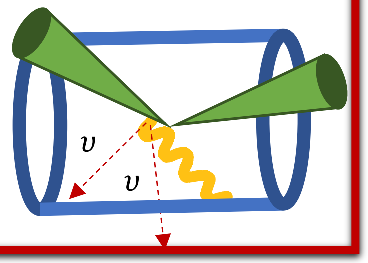


Z CR

$Z(\to \upsilon\bar{\upsilon}) + jets + \gamma$ ~

$Z(\to \upsilon\bar{\upsilon}) + jets$

reversed centrality



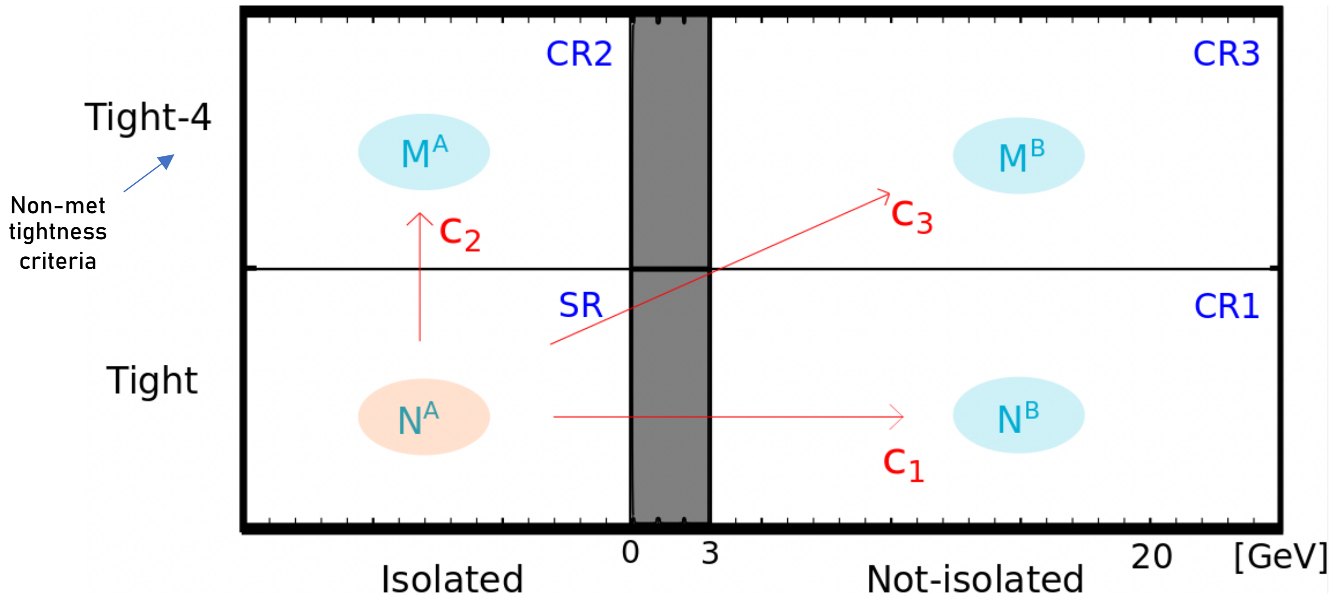
Backgrounds

- $pp \to Z(\to \nu\nu) + \gamma + jets$
- $pp \to W(\to l\nu) + \gamma + jets$
- $pp \to Z(\to \nu\nu) + jets$
- $pp \to W(\to e\nu) + jets$
- $pp \to \gamma + jets$

Jet faking photon
One of the jets is reconstructed as a photon.

Estimated through data using an **ABCD** method: three background regions and one signal regions are defined in the photon isolation-tightness plane.

~1.56 % of the total Hinv SR Bkg with an 80-90% syst. unc.



Backgrounds

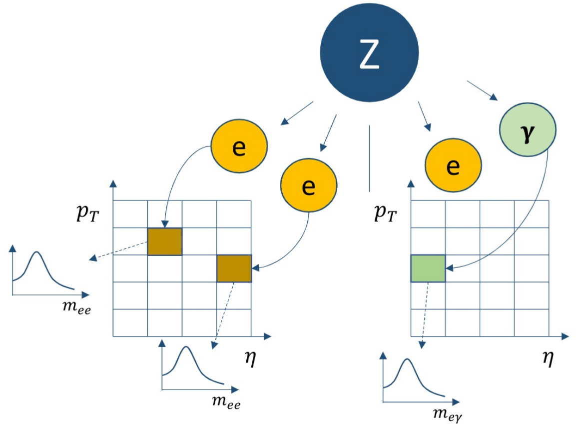
- $pp \to Z(\to \nu\nu) + \gamma + jets$
- $pp \to W(\to l\nu) + \gamma + jets$
- $pp \to Z(\to \nu\nu) + jets$
- $pp \to W(\to e\nu) + jets$
- $pp \to \gamma + jets$

Electron faking photon

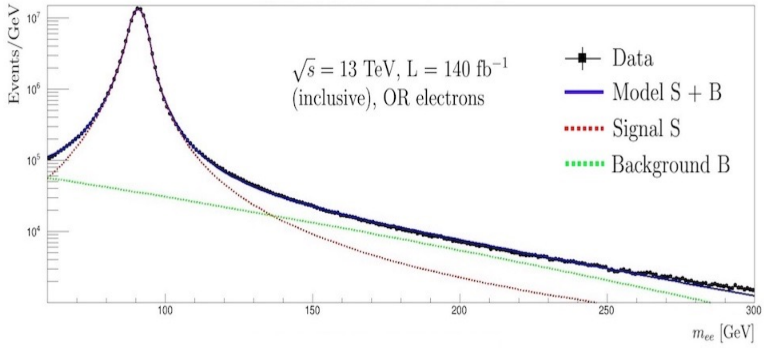
When the electron is reconstructed as a photon.

Data driven estimation. Determined from a comparison of the rate of Z boson reconstruction in the $e^{\pm}\gamma$ and $e^{+}e^{-}$ final states. The full Run 2 dataset is used to select $Z \to ee$ events in which the electron pairs in the final state are reconstructed either as an $e^{+}e^{-}$ pair or mis-reconstructed as an $e^{\pm}\gamma$ pair.
(mis-reconstruction rate between 1.5% and 9%)

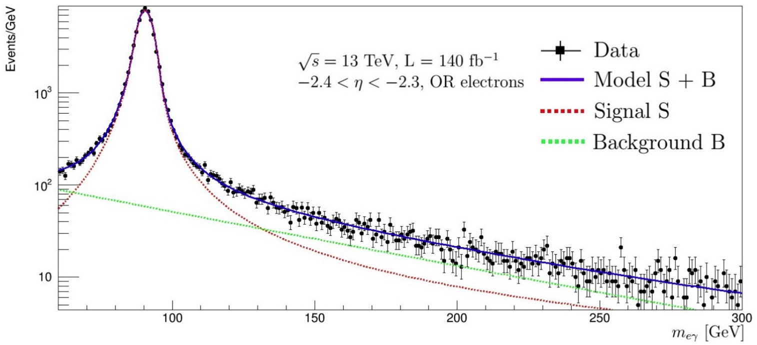
~6.5 % (30%) of the total Hinv ($H \to \gamma\gamma_d$) SR Bkg with a 15-30% syst. unc.



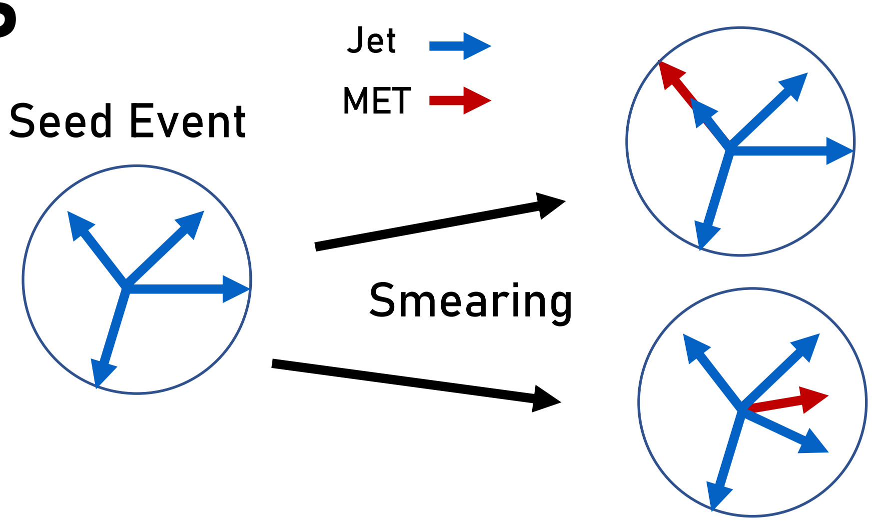
m_{ee}

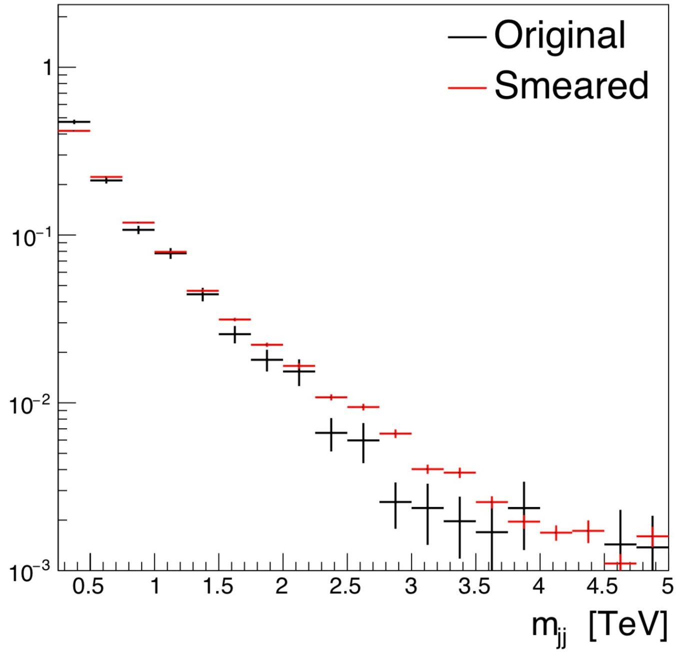


$m_{e\gamma}$



Backgrounds





- $pp \to Z(\to \nu\nu) + \gamma + jets$
- $pp \to W(\to l\nu) + \gamma + jets$
- $pp \to Z(\to \nu\nu) + jets$
- $pp \to W(\to e\nu) + jets$
- $pp \to \gamma + jets$

MultiJet

Minor background since these events do not have intrinsic E_T^{miss}.

MC sample stat enhanced by a factor of 20 through jet smearing (smeared quantities: $E_{jet}, \eta_{jet}, \varphi_{jet}$)

~0.5 % of the total Hinv SR Bkg with a 94% syst. unc.

Uncertainties

Source	1σ Uncertainty on $\mathcal{B}_{\text{inv}}$
Jet scale and resolution	0.045
$V\gamma+$jets theory	0.044
pile-up	0.021
Photon	0.031
$e\rightarrow\gamma$, jet$\rightarrow e,\gamma$ Bkg.	0.034
Lepton	0.003
$E_{\text{T}}^{\text{miss}}$	0.018
Signal theory shape	–
Signal theory acceptance	–
Data stats.	0.11
$W\gamma+$jets/$Z\gamma+$jets Norm.	0.013
MC stats.	0.046
Total	0.15

- Uncertainties impact evaluated as in the monoZ analysis

← Second highest contribution (Jet scale and resolution)

← Dominated by Data stats.

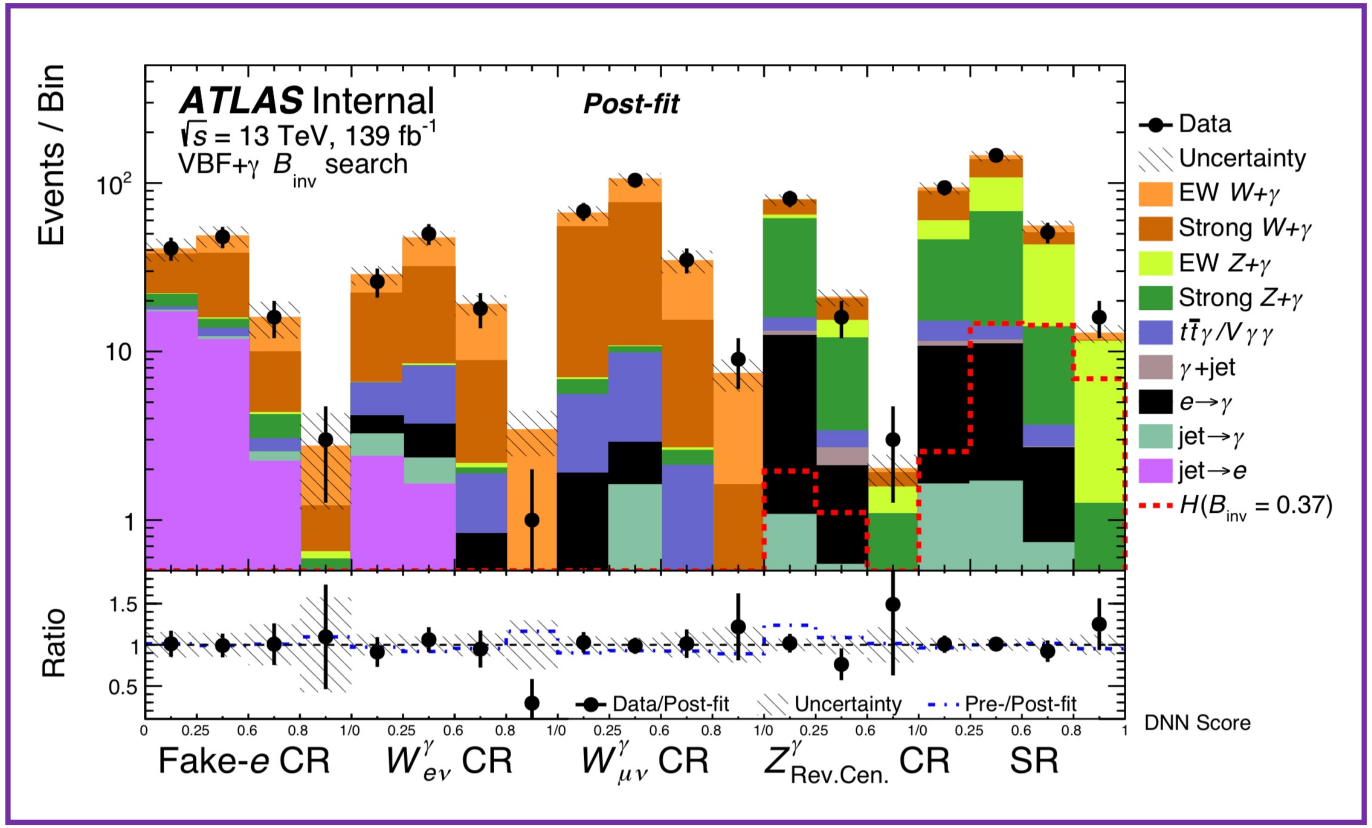
Results

- Simultaneous likelihood fit to ***DNN score*** distribution in CR + SR to improve background estimation

No significant excess is observed.

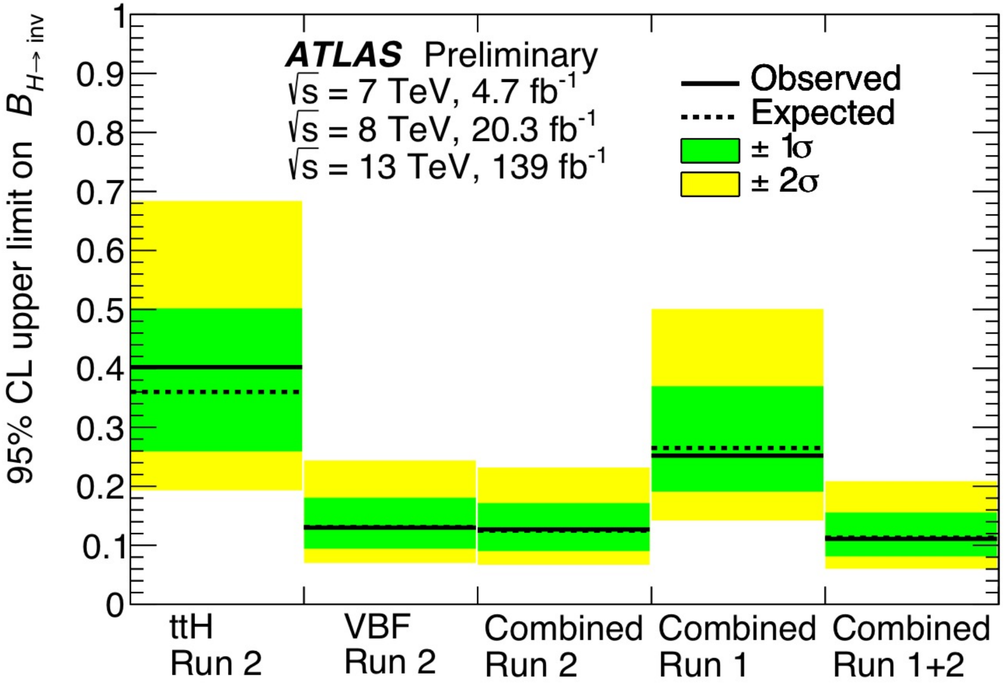
Observed (expected) 95% CL limit:

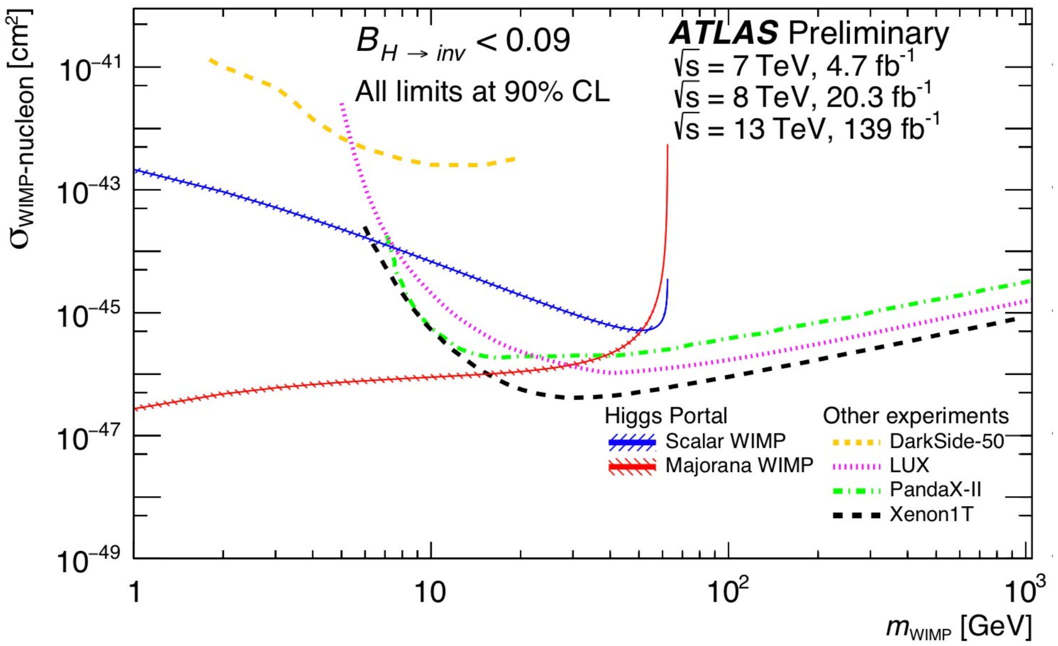
$BR_{H\to inv.}$ → $0.37(0.34^{+0.15}_{-0.10})$



ATLAS-CONF-2020-052

$H \rightarrow$ inv. combination





Run2 analysis:

- ttH
- VBF $H \rightarrow invisible$

Many others not included yet (e.g. Mono-Jet, Mono-Z(ll))

Scalar σ_{WIMP-N}: down to less than $10^{-45} cm^2$

Fermion Majorana σ_{WIMP-N}: down to $10^{-47} cm^2$

Combination of Run1+2 set a limit on the $BR_{H \rightarrow inv.}$ = **0.11**

Conclusion

- Mono-Z presented! arXiv:2111.08372
- VBF+ MET + γ! arXiv:2109.00925
- Run1+2 combination! ATLAS-CONF-2020-052

..and more to come

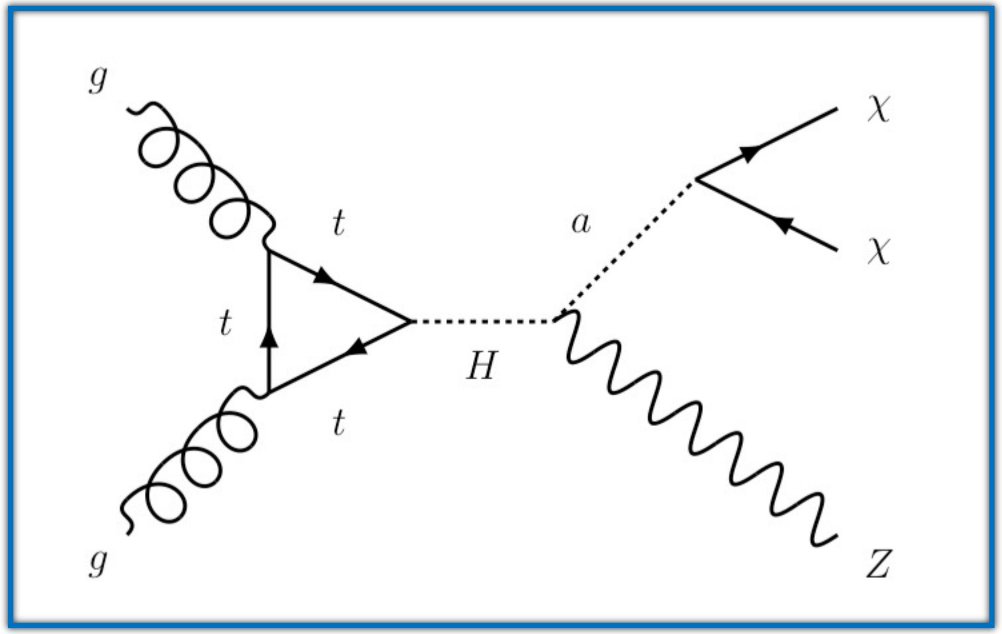
- VBF + MET
- Mono-V(had)
- Complete combination

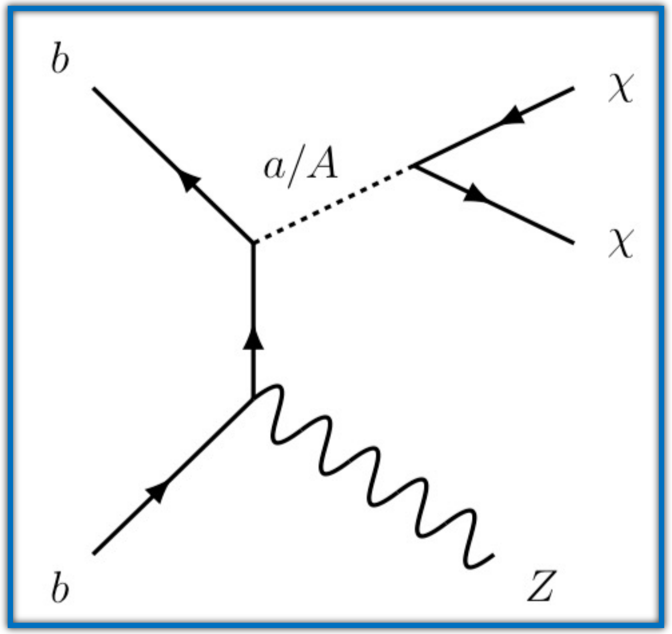
Backup

monoZ SR selection efficiencies

Signal	$A\times\epsilon$	Events
$ZH \to ll + inv.$	8%	120
DM model $(m_\chi = 1\ Gev, m_{med} = 900\ GeV)$	20%	145
2HDM+a $(tan\beta = 1.0, \quad sin\theta = 0.7$ $m_A = 600\ GeV, m_a = 400\ GeV, m_\chi = 10\ Gev)$	32%	182

2HDM + a

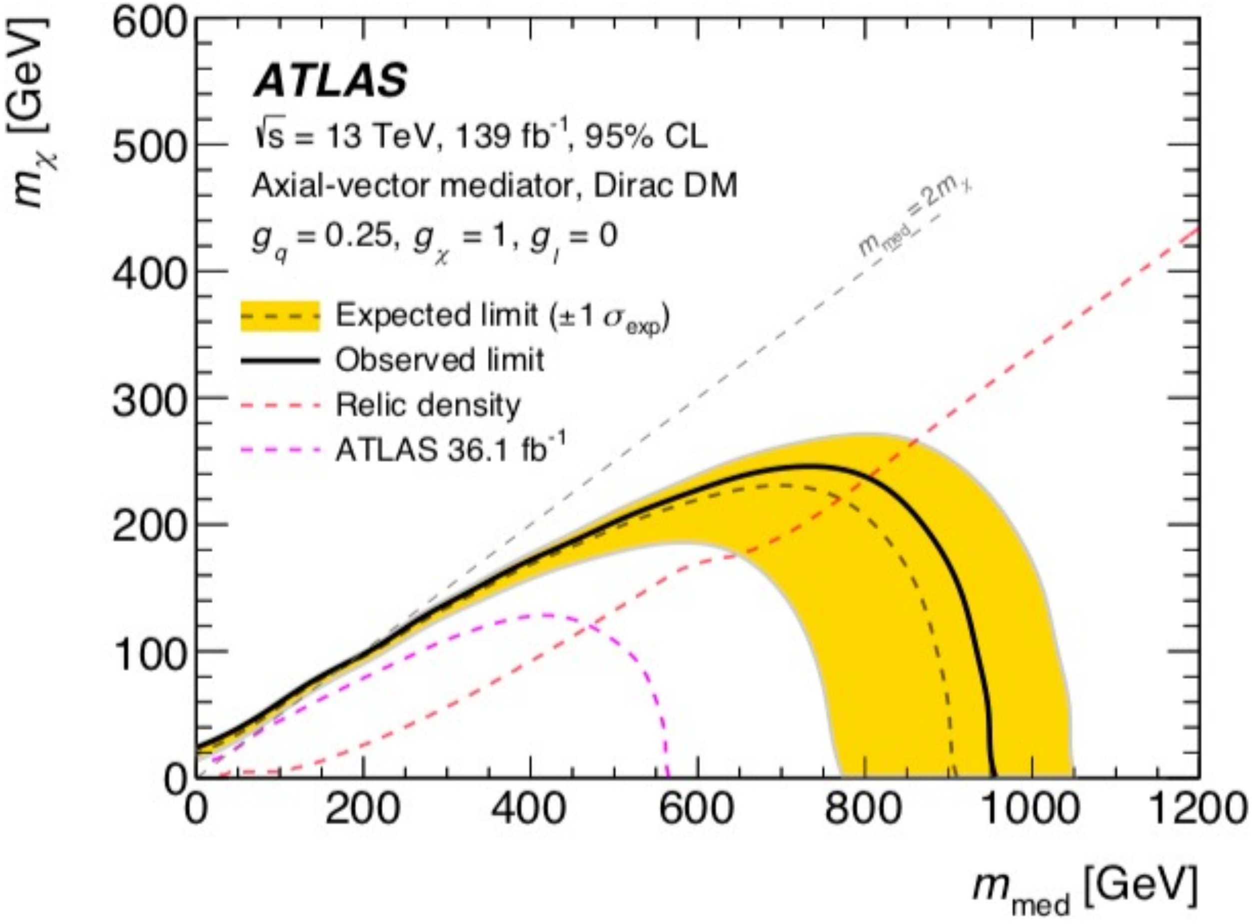




- More complex model
- Implements
  2 Higgs doublets
  (5 Higgs bosons)
- More parameters

$$\{m_A, m_a, m_\chi, \tan\beta\,, \sin\theta\}$$

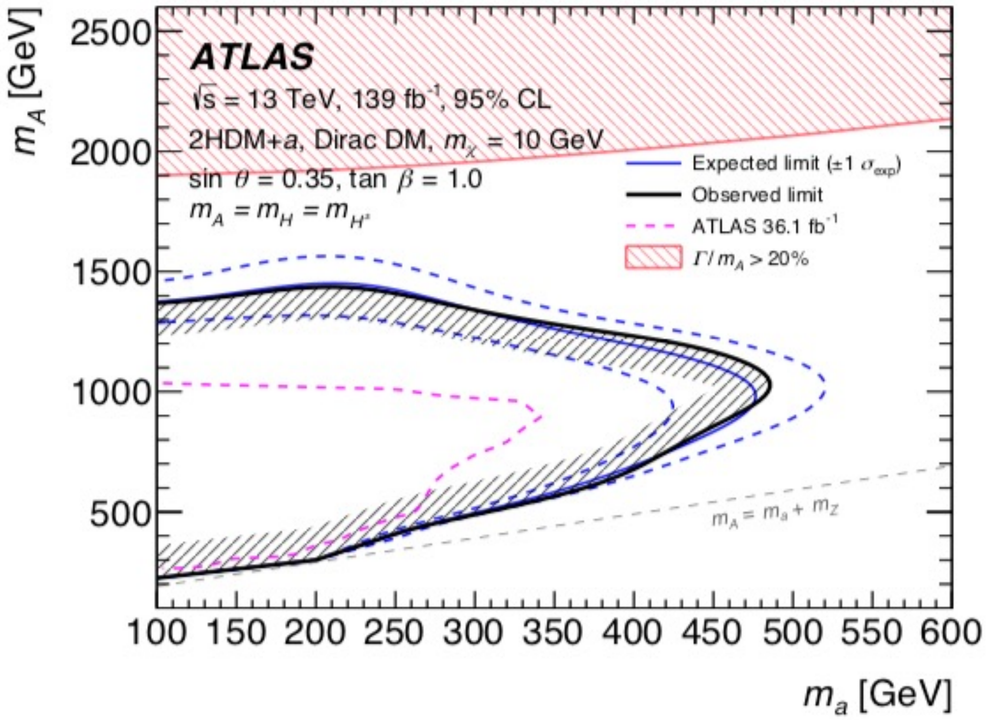
Results

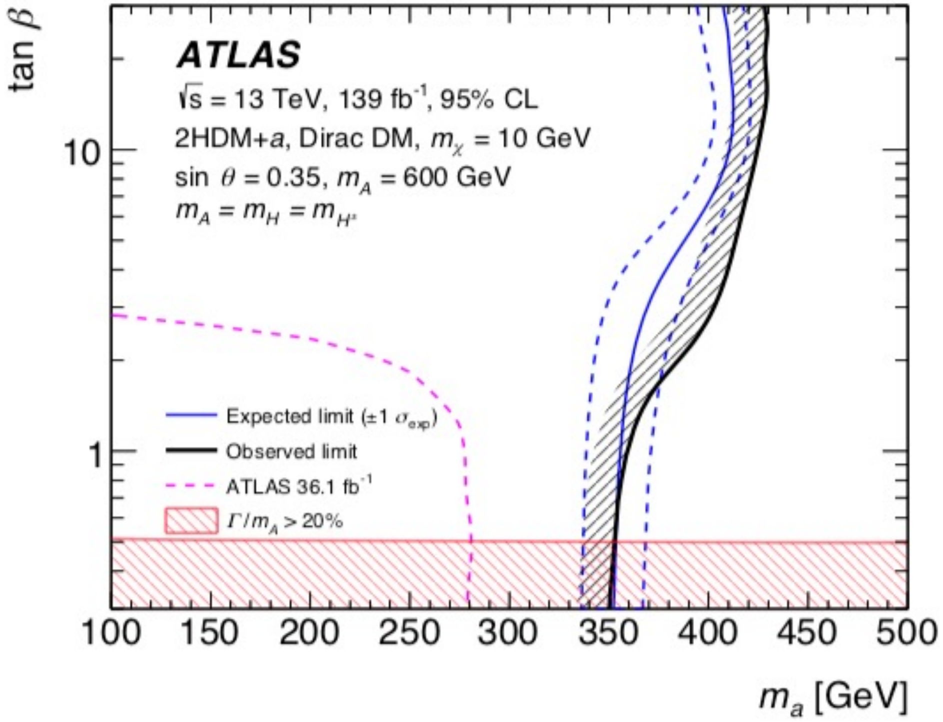


ATLAS
√s = 13 TeV, 139 fb-1, 95% CL
Axial-vector mediator, Dirac DM
g_q = 0.25, g_χ = 1, g_l = 0
Expected limit (±1 σ_exp)
Observed limit
Relic density
ATLAS 36.1 fb-1
m_med = 2m_χ
m_χ [GeV]
m_med [GeV]
0
100
200
300
400
500
600
0
200
400
600
800
1000
1200

Results

For the 2HDM+a interpretation, the profile likelihood uses the m_T of the dominant ZZ background for all SR and CR

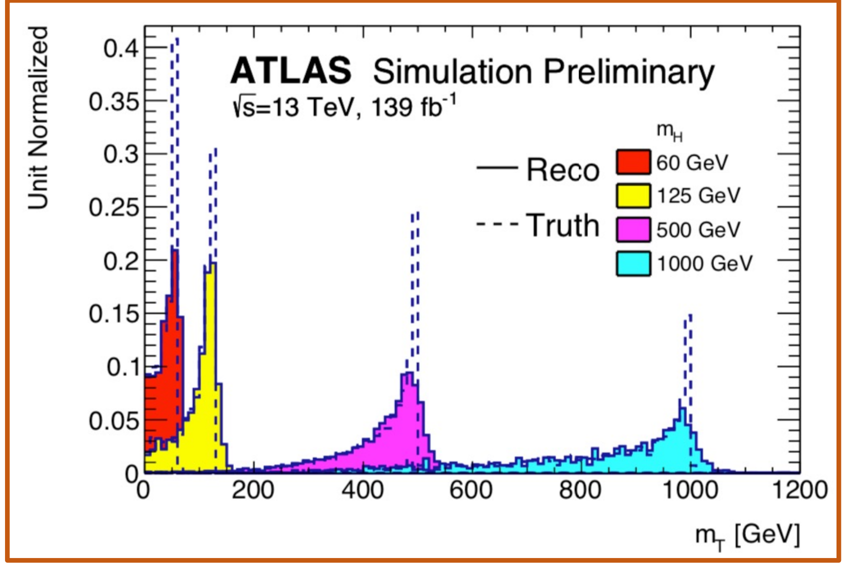




The hashed red area indicates that the width of one of the Higgs bosons is larger than 20% of its mass

VBF $H \rightarrow invisible + \gamma$

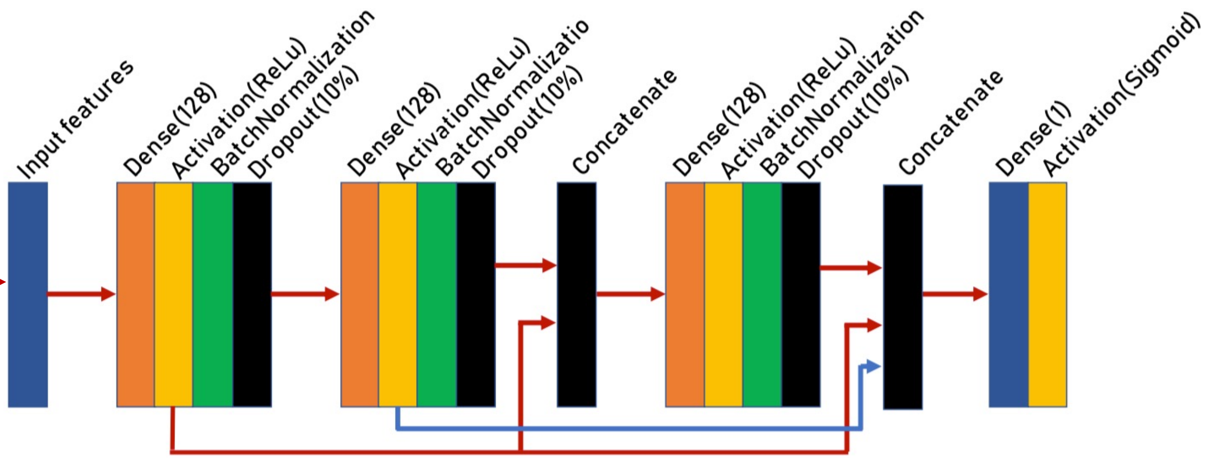
Discriminating variables for the final fit



The analysis aims to find an excess in the *DNN score spectum* for the invisible decay, in the m_T *spectrum* for the $\gamma\gamma_d$ decay

Input features

1. $\Delta\eta_{jj}$
2. $\Delta\varphi_{jj}$
3. m_{jj}
4. $E_T^{miss,no-lep}$
5. $\eta(\gamma)$
6. $p_T(j_1)$
7. $p_T(j_2)$
8. $\eta(j_2)$



Output:
1 ~ signal like
0 ~ bkg like

$$\mathcal{E}^{-1} = \sqrt{\sum_{i \in \text{bins}} \mathcal{E}_i^{-2}}, \qquad \mathcal{E}_i = 2\frac{\sqrt{b_i + \left(b_i^{V\gamma} \cdot \frac{\sqrt{d_i(\text{CR}) + \sum_{j \in \text{ev}} w_{i,j}(\text{CR})}}{b_i^{V\gamma}(\text{CR})}\right)^2 + \sum_{j \in \text{ev}} w_{i,j}^2}}{s_i},$$

Binning = [0, 0.25, 0.6, 0.8, 1]

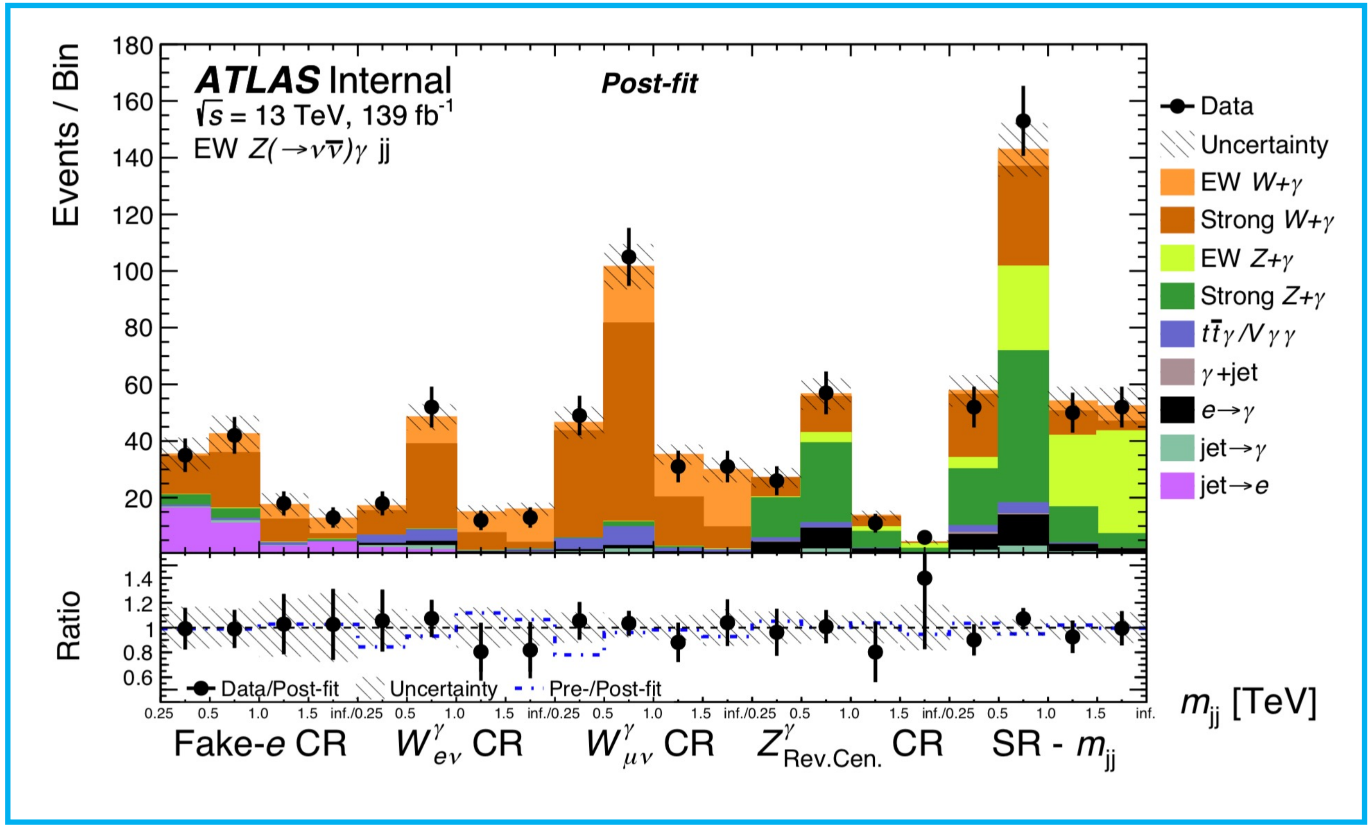
Results

- Simultaneous likelihood fit to m_{jj} distribution in CR + SR to improve background estimation

Observation of SM EW $Z\gamma + jets$ reported with an observed (expected) 5.2 σ (5.1 σ)

Highest sensitivity ✓ to date

$\sigma^{fid.}_{Z(\rightarrow\nu\bar{\nu})\gamma EW}$ → $1.31 \pm 0.29\ fb$



Results

- Simultaneous likelihood fit to m_T distribution in CR + SR to improve background estimation

No significant excess is observed.

Observed (expected) 95% CL limit:

$BR_{H^{125GeV} \to \gamma\gamma_d}$ → $0.018\ (0.017^{+0.007}_{-0.005})$

most stringent to date ✓

CMS result: 0.029