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# SEARCH FOR INVISIBLE DECAY MODES OF THE HIGGS BOSON WITH THE ATLAS DETECTOR


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ATLAS EXPERIMENT

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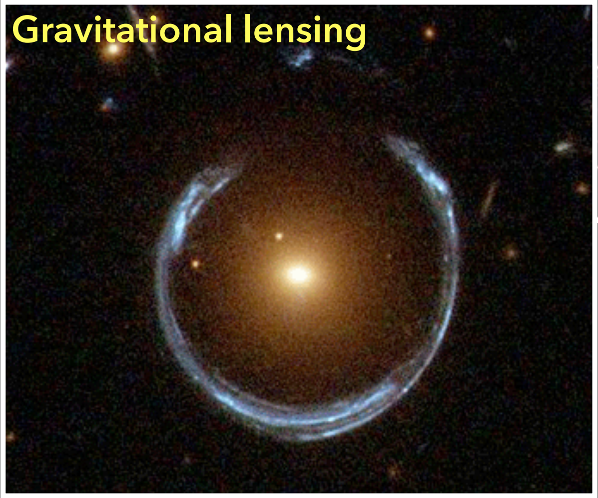
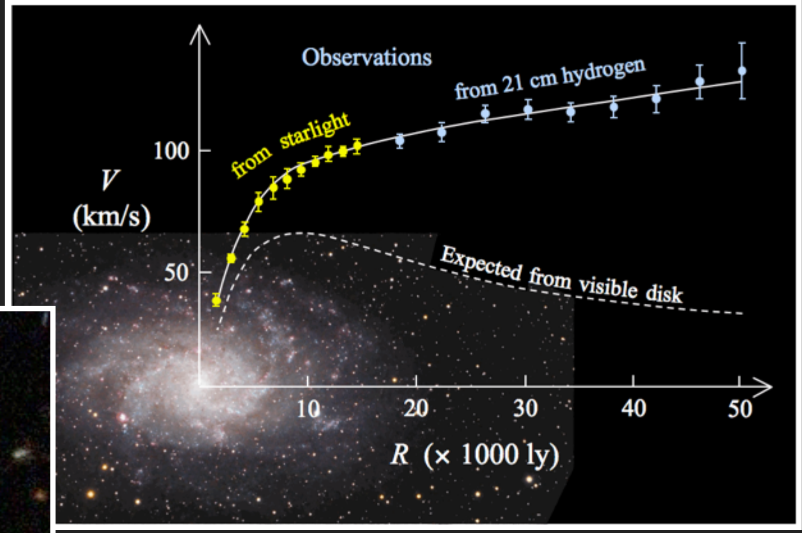
# HIGGS INVISIBLE DECAY SEARCHES: WHY?

- Standard Model (SM) theory remarkably successful in describing particles and interactions, but:
  1. Cannot accomodate general relativity as quantum field theory
  2. Hierarchy problem ($m_H << M_{Planck}$)
  3. **Dark Matter**
  4. …

  → Need to go beyond the SM


Gravitational lensing



Galaxies rotation curve

- The Higgs boson can play a role in probing BSM physics through searches for invisible decays:
  - SM BR(H → invisible) ~ 0.1% ( from **H** → ZZ* → 4ν )
  - BR enhanced if H → pairs of stable or long-lived massive particles (e.g WIMP) ⇒ any measurable rate would imply new physics
  - $\Gamma_H$ is not precisely constrained ⇒ still possible a sizeable BR in invisible particles
  - Higgs as a mediator between SM particles and Dark Matter particles (Higgs-portal Dark Matter Model)

# DIRECT HIGGS INVISIBLE DECAY SEARCHES: HOW? 

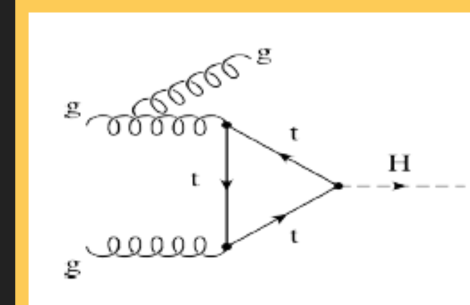
**Experimental signature:** H→invisible decay is INVISIBLE!

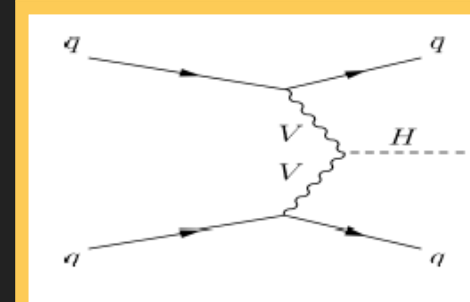
Will appear as large missing transverse momentum (MET) in the event

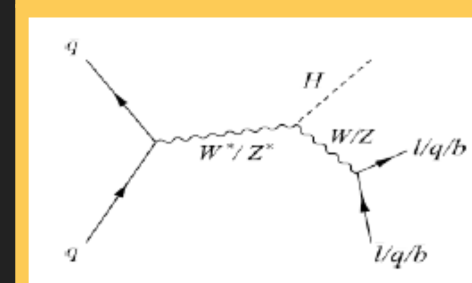
→ need a visible object to trigger the event

## Production modes:

- gluon-gluon fusion (ggF)
  - Tag the event with an ISR jet (Mono-jet search)
- Vector boson fusion (VBF)
  - Tag the event with the two well-separated jets
- Associated production with a boson VH
  - Tag the event through the leptons/hadrons from the vector boson (e.g. Z→ℓℓ or Z → jj)




## If not excess found over SM predictions:

- Limit on $\sigma_{prod}$ × BR
- BR (H→invisible) assuming production cross section & acceptance unchanged wrt SM
- Results interpreted in the context of WIMP-nucleon interaction models

Eur. Phys. J. C (2015) 75:299

# MONO-JET SEARCH



Experimental Signature: Energetic jet from ISR + high MET

🙂 High production rate at LHC

🙁 Primarily sensitive to ggF mode ⇒ large background

## Event Selection

- MET Trigger > 80 GeV
- Leading jet $p_T$ > 120 GeV, $|\eta|$ < 2.0
- MET > 150 GeV
- $\Delta\Phi$(jet, $p_T$miss) > 1.0 (suppress multi-jets background)

☞ different Signal Regions (SR) with increasing MET threshold

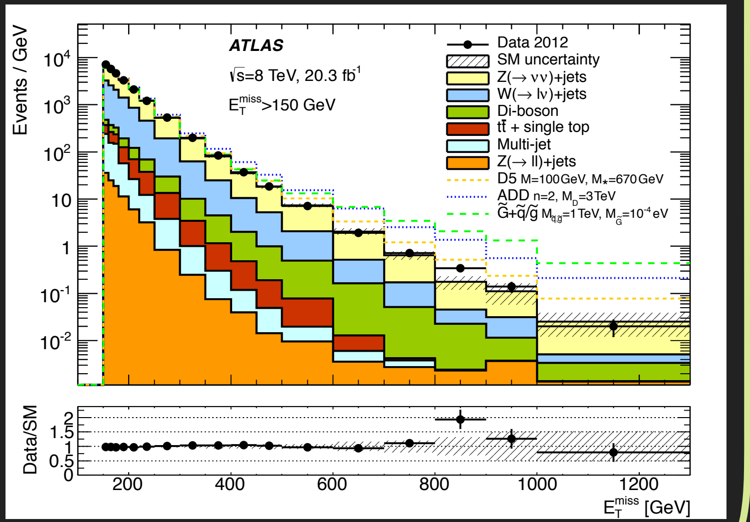
## Backgrounds estimation

**Dominant:**

- Z→νν + jets & W+jets (estimated from MC but normalised to data in Control Samples with e/μ)

**Sub-leading backgrounds:**

- Diboson (MC-only)
- Multijets (Data-driven)
- Z(→ℓℓ)+jets (MC-only)
- Non-collision (Data-driven)

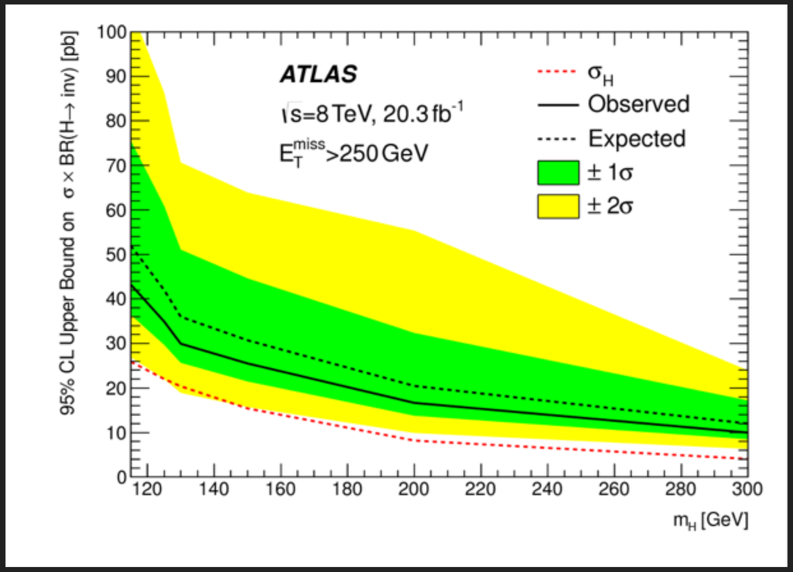



## Results

- Dominant uncertainties on jet & MET energy scale and resolution 8-10%
- No excess over the SM observed
- Results used to derive 95%CL upper limit on σ × BR(H→invisible) for $m_H$ = (115, 300) GeV, in ggF(dominant), VH & VBF production modes

@125 GeV, (σ × BR)obs < 1.59 $SM_{pred}$ with (σ × BR)exp < 1.91 $SM_{pred}$

- Better sensitivity at high $m_H$



# VBF CHANNEL

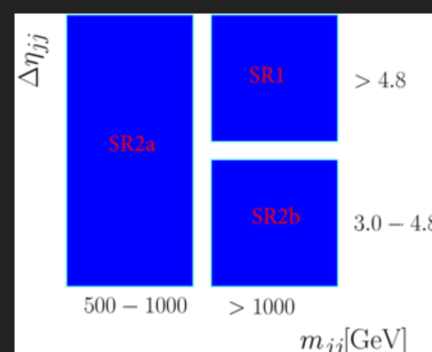


Experimental Signature: Two jets with large separation in pseudorapidity + high MET

- 🙂 Most sensitive channel for the Higgs invisible searches
- 🙂 High QCD-initiated backgrounds rejection ⇒ S/B ~ 0.5

## Event Selection

- MET Trigger > 80 GeV
- Exactly two high-$p_T$ jets
- MET > 150 GeV
- Large jets separation $|\Delta\eta_{jj}|$
- Large dijet mass $M_{jj}$




☞ different Signal Regions with different $M_{jj}$ and $\Delta\eta_{jj}$ cuts

## Backgrounds estimation

**Dominant:**

- Z→νν + jets & W+jets (from leptonic W/Z control samples in data)

**Sub-leading backgrounds:**

- Multijets (Data-driven data CR & jet smearing method for estimation
- Others (~1%, MC-only )

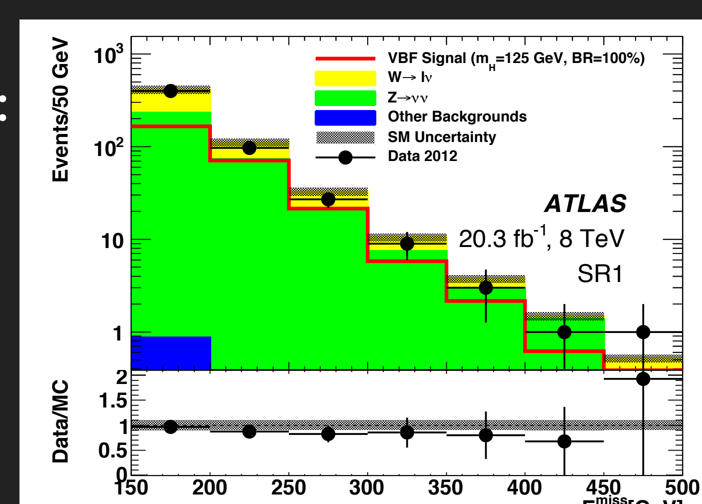
## Results

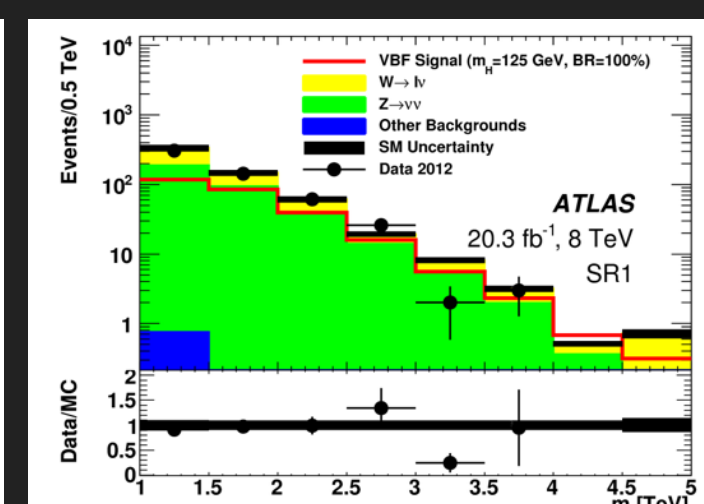
- Uncert. on MC predictions dominated by jet energy scale & resol. (flavour dependent)
- No excess over the SM found
- Derived 95%CL upper limit on BR(H→invisible):

@125 GeV, $BR_{obs} < 0.28$ with $BR_{exp} < 0.31$

- Model independent 95%CL upper limit on fiducial σ (small ggF+2jets treated as signal):

3.93 fb observed (4.78 fb expected)



Eur. Phys. J. C (2015) 75:337

# VH, V→JJ CHANNEL



Experimental Signature: Hadronically decaying vector boson (V=W/Z) in association with the invisible H
⇒ 2 jets + large MET

🙂 Intermediate sensitivity between Mono-jet and VBF analyses

## Event Selection

- MET Trigger > 80 GeV
- 2/3 jets
- MET > 120 GeV (correlated with $Vp_T$)
- $M_{jj} \sim M_{W/Z}$
- $\Delta R_{jj}$ (boosted V-boson)
  → no VBF contamination

☞ Four MET ranges and #b-jets (up to 2) for the event categorisation

## Backgrounds estimation

**Dominant:**

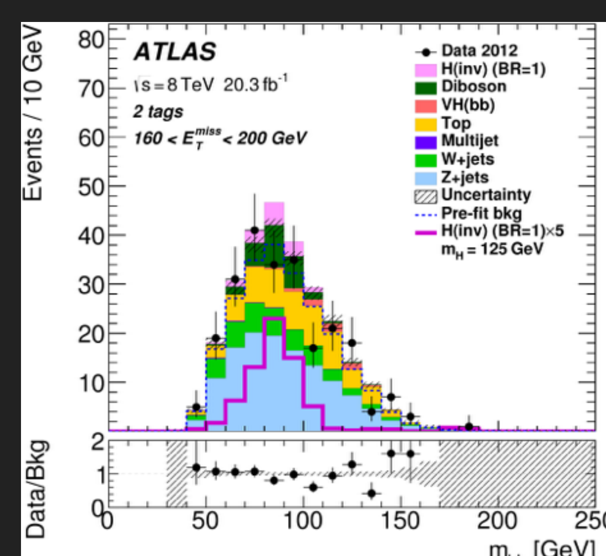
- Multi-jets background (from data with ABCD method)
- V+jets (data normalisation from CRs with ≥ 1 lepton with $p_T$ > 25 GeV + 2jets)

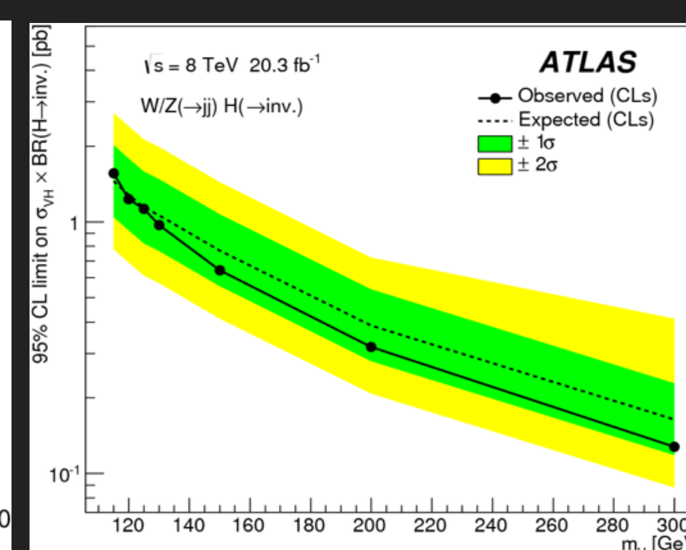
**Sub-leading backgrounds:**

- ttbar (Data-driven)

## Results

- Combined fit to the MET and $m_{jj}$ distributions in SRs and $p_T(V)$ in CRs
  → No excess over SM found: $\mu = -0.13 +0.43/-0.44$
- 95%CL upper limit on BR(H→invisible), SM VH & ggF contributions combined:
  @125 GeV, $BR_{obs}$ < 78% with $BR_{exp}$ < 86%
- 95%CL upper limit on $\sigma_{VH}$ x BR(H→invisible):
  1.1 pb observed (1.1 pb expected)



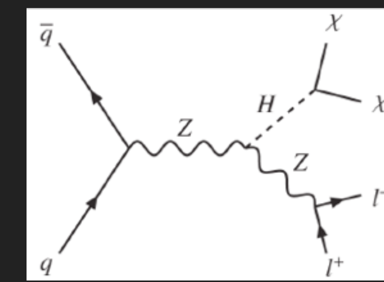
# ZH, $Z \to \ell\ell$ CHANNEL

FIRST 13TEV RESULT!!



Experimental Signature: Leptonically decaying Z-boson + high MET

- 🙂 Clean final state
- 🙁 Low sensitivity



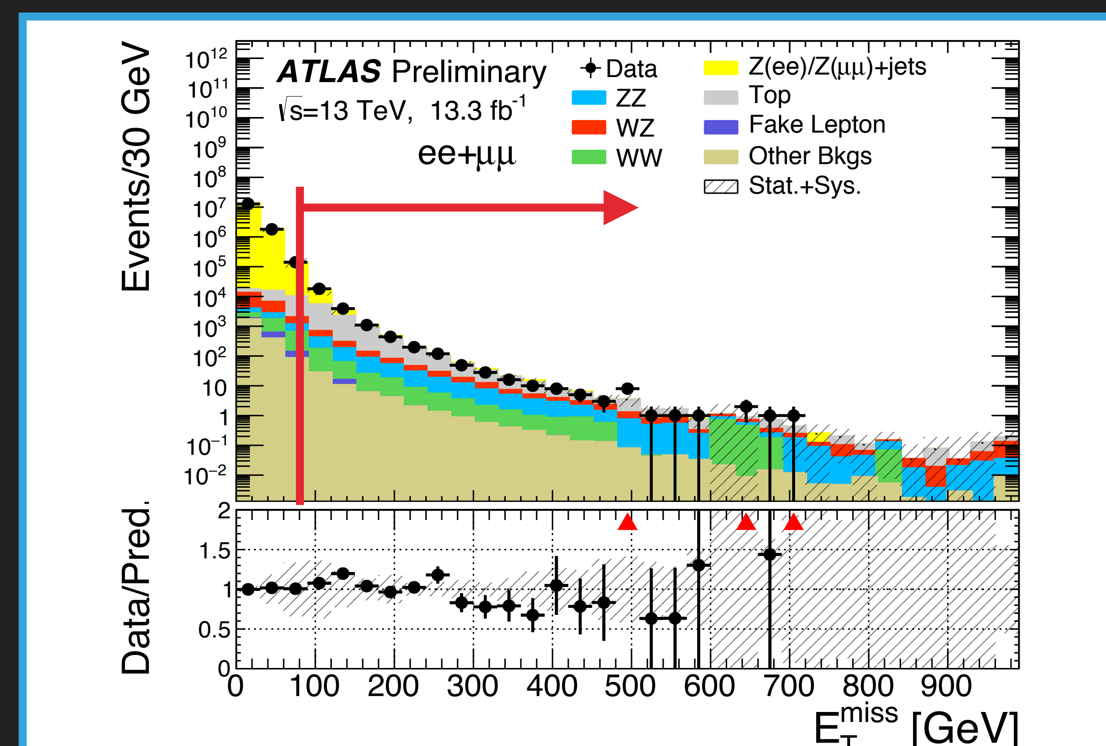

New energy regime to extend the sensitivity of this analysis and improve Run-I result
Result based on 2015+2016 integrated luminosity of 13.3 fb$^{-1}$

## Event Selection

Remarks: Quite different event selection & bkg composition wrt other channels, since **no jets** expected

- Single lepton trigger
- Exactly one $e^+e^-$ or $\mu^+\mu^-$ pair
- $|M_{\ell\ell} - M_Z| < 15$ GeV
- MET > 90 GeV
- $\Delta R_{\ell\ell}$ (boosted Z-boson)
- $\Delta\Phi$(Z, MET) > 2.7 (back-to-back)
- No b-tagged jets

MET distribution after $M_{\ell\ell}$ cut




Nice MET modelling

Specific selections to suppress Drell-Yan events

- $|p_T(\text{miss-jet}) - p_{T\ell\ell}| / p_{T\ell\ell} < 0.2$
- $\Delta\Phi$(MET, jet($p_T$>25GeV)) > 0.7
- $p_{T\ell\ell}/m_T < 0.9$

☞ Signal acceptance ~18% in both ee & μμ channels

# ZH, Z→$\ell\ell$ CHANNEL

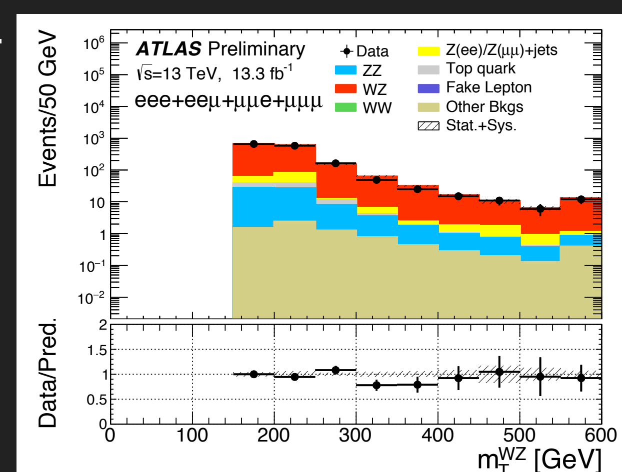


## Irreducible Background

- ZZ continuum background is the leading bkg (~50% qqZZ, ~3% ggZZ)
- Both contributions estimated from MC
- NNLO QCD & NLO EW corrections applied
- QCD scales and PDF variations have a ~3-4% impact on the normalisation
- ggZZ @LO, but 1.7±1.0 k-factor applied

## Reducible Backgrounds (data-driven)

- WZ, W→$\ell\nu$ Z→$\ell\ell$ is the 2nd leading background (~24%)
- Lepton from the W escaping detection or decaying hadronically
- Estimated from a 3-lepton CR. 20% correction of WZ normalisation in SR




- ttbar/WW/Wt/Z→ττ estimated in different flavour eμ events
- Low contaminated CR
- Extrapolate to SR by accounting for e/μ reco efficiency differences

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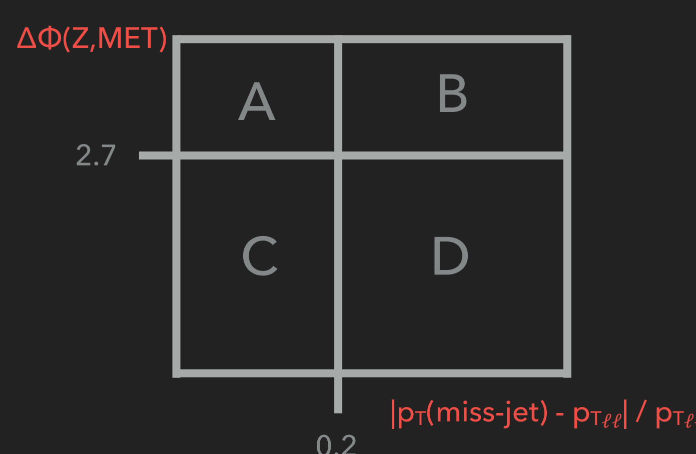
- Drell-Yan Z(→$\ell\ell$)+jets has no genuine MET, but may enter due to jets mis-measurements (Hard to model with MC!)
- Highly reduced by the event selection (~8-10% of total bkg in SR)
- Estimated with ABCD method
- Large uncertainties (~80%) on the final yield in SR due mainly to lack of statistics effects in the sideband regions → instabilities in the B/D ratio



# ZH, Z→ℓℓ CHANNEL

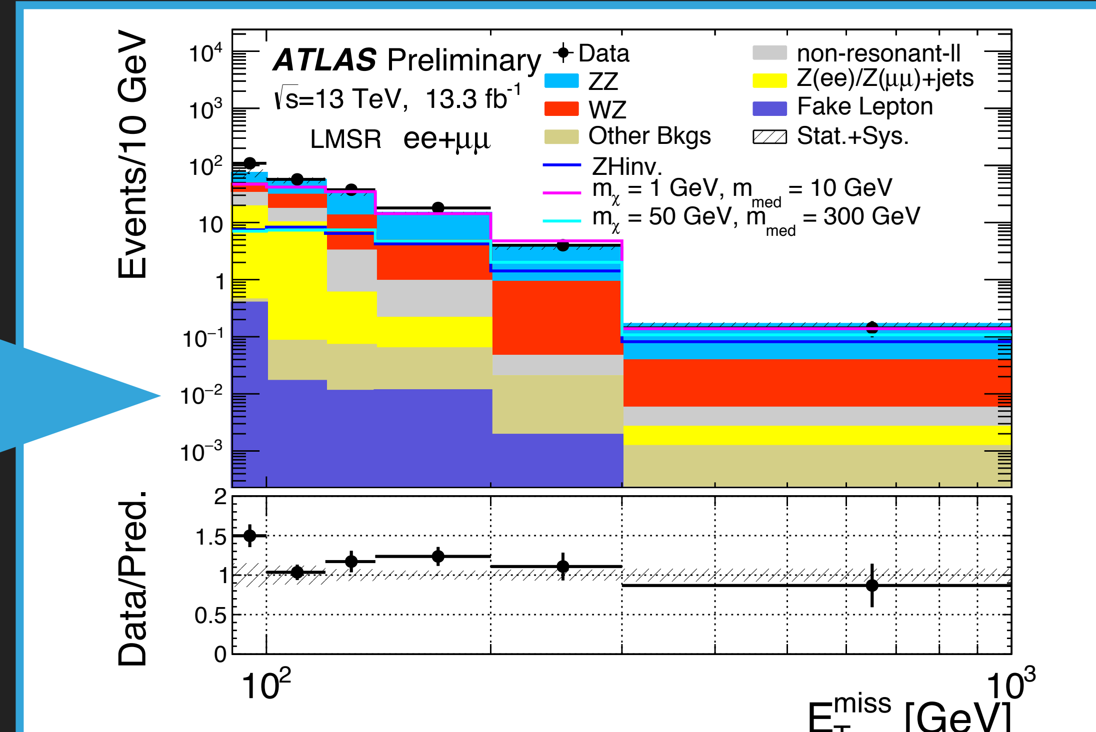


## Results

- The limit on the invisible branching ratio extracted with a maximum likelihood fit of the MET distribution
- Data-driven estimates used for the bkgs normalisation (but for ZZ), MET shape taken from MC
- ee and μμ results statistically combined

| Low Mass Signal Region | $ee$ | $\mu\mu$ |
|---|---|---|
| Data | 220 | 236 |
| Signals | | |
| $ZH$ ($m_H$ = 125 GeV) with BF($H \to$ invisible)=100% | 40.5 ± 1.2 ± 4.1 | 41.7 ± 1.2 ± 4.4 |
| Mono-$Z$ ($m_\chi$ = 1 GeV, $m_{\rm med}$ = 10 GeV) | 175 ± 24 ± 14 | 169 ± 21 ± 22 |
| Mono-$Z$ ($m_\chi$ = 50 GeV, $m_{\rm med}$ = 300 GeV) | 43.7 ± 2.3 ± 2.8 | 49.1 ± 2.6 ± 4.2 |
| Backgrounds | | |
| $qqZZ$ (MC-based) | 95.0 ± 1.5 ± 5.8 | 102.1 ± 1.6 ± 8.0 |
| $ggZZ$ (MC-based) | 5.6 ± 0.1 ± 3.3 | 5.7 ± 0.1 ± 3.4 |
| $WZ$ (Data-driven) | 44.0 ± 1.1 ± 3.3 | 50.5 ± 1.2 ± 3.3 |
| $Z(\to ee, \mu\mu)$+jets (Data-driven) | 23 ± 5 ± 11 | 16.9 ± 5.2 ± 6.7 |
| non-resonant-$\ell\ell$ (Data-driven) | 16.9 ± 2.8 ± 1.0 | 20.7 ± 3.4 ± 1.2 |
| fake-lepton (Data-driven) | 0.18 ± 0.04 ± 0.03 | 0.36 ± 0.46 ± 0.08 |
| $t\bar{t}V/VVV$ (MC-based) | 0.44 ± 0.02 ± 0.06 | 0.43 ± 0.02 ± 0.06 |
| Total background | 185 ± 6 ± 13 | 196 ± 7 ± 12 |

Moderate excess observed in both ee & μμ channels




No significant excess observed over SM predictions

| 95% CL limits results | Run-II result Obs. | Run-II result Exp. | Run-I result Obs. | Run-I result Exp. |
|---|---|---|---|---|
| Upper limit on BR(H→invisible) | 0.98 | 0.65 | 0.75 | 0.62 |
| Upper limit on σ(Z→ℓℓ) × BR(H→inv) [fb] | 88 | 58 | ~300 | ~240 |

# 8 TEV COMBINATION OF THE DIRECT SEARCHES



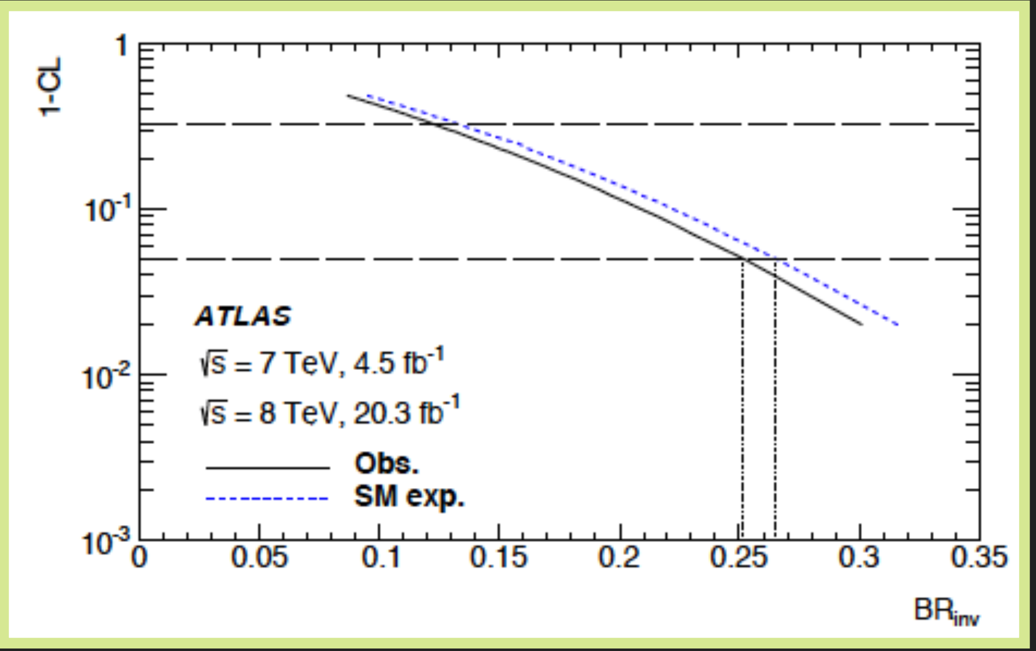
- A statistical combination of the Run-I searches was performed
- VH and VBF searches combined (Mono-jet left outside, since less sensitive to Higgs-mediated interactions), any possible overlap between SRs & CRs removed by jet veto and $m_{jj}$ cuts
- Simultaneous maximum likelihood fit to the event count in SRs & CRs
- Luminosity uncertainty, jet absolute energy scale and resolution uncertainties as well as theory uncertainties treated as fully correlated across the individual searches
- Uncertainty on the soft component of the MET affecting only ZH, Z→ℓℓ search

**Run-I only**

| | Upper limit on BR(H→inv) Obs. | Exp. |
|---|---|---|
| VBF | 0.28 | 0.31 |
| VH, V→JJ | 0.78 | 0.86 |
| VH, V→ℓℓ | 0.75 | 0.62 |
| Combined | 0.25 | 0.27 |

Sensitivity dominated by VBF search

Likelihood scan



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# INDIRECT CONSTRAINT ON H→INVISIBLE



- Use the measured visible rate in a more general couplings fit to constraint the H→invisible
- Visible rates indirectly sensitive to undetectable final states (e.g. $BR_{gg}$): $\Gamma_h = BR_{vis} + BR_{inv} + BR_{undetectable}$
- Extract a conservative limit on $BR_{inv}$ assuming $BR_{undetectable}$ ~0, as predicted in SM

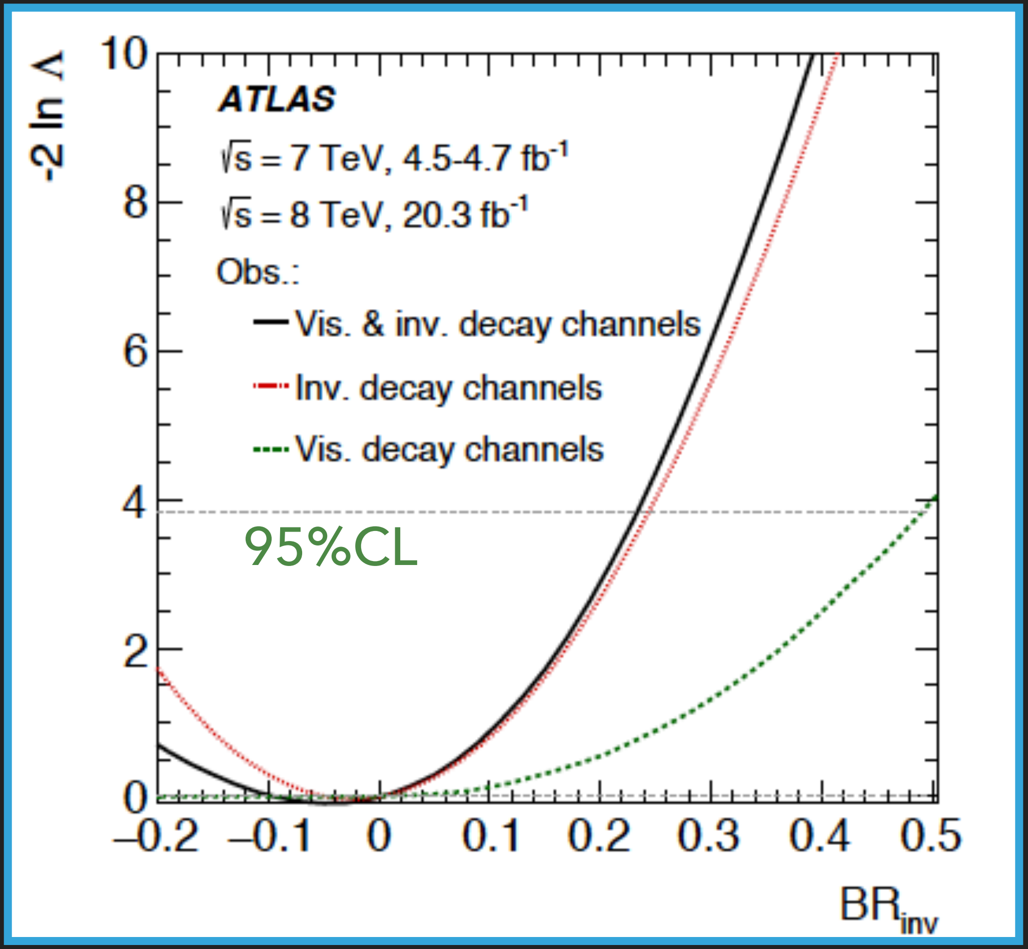
$$k_h^2 = \Gamma_h / \Gamma_{h,SM} = \sum_j k_j^2 BR_j / (1 - BR_{inv})$$

Scale factor for total width

New term added

- The coupling parametrisation includes separate scale factors for the coupling to bosons and fermions: $K_W$, $K_Z$, $K_t$, $K_b$, $K_\tau$, $K_\mu$
- Scale factors for effective loop-induced couplings to gluons/ photons and Zγ to include possible contributions from new particles in the loops
- Fit one POI and treat the others as nuisance parameter (NP)

| Coupling parametrisation | $k_i$ assumption | Upper limit on BRinv Obs. | Upper limit on BRinv Exp. |
|---|---|---|---|
| $k_W, k_Z, k_t, k_b, k_\tau, k_\mu, k_g, k_\gamma, k_{Z\gamma}$ | $k_{W,Z} \leq 1$ | 0.49 | 0.48 |

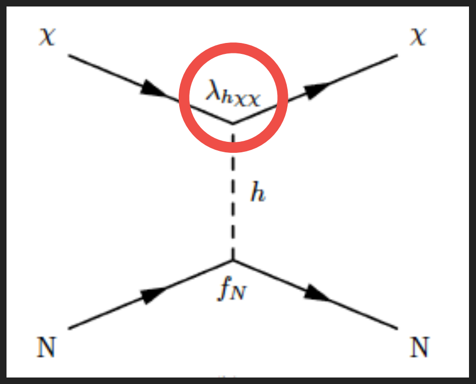


# INTERPRETATIONS



- Direct Dark Matter searches look for the atomic recoil from scatter of DM particles in the detector
- Results of the H→ invisible searches at LHC provide **complementary sensitivity** to these astroparticles searches, being sensitive to masses of the DM particle of $m_\chi < m_H/2$
- Run-I limits have been interpreted in terms of the Higgs-portal DM Model

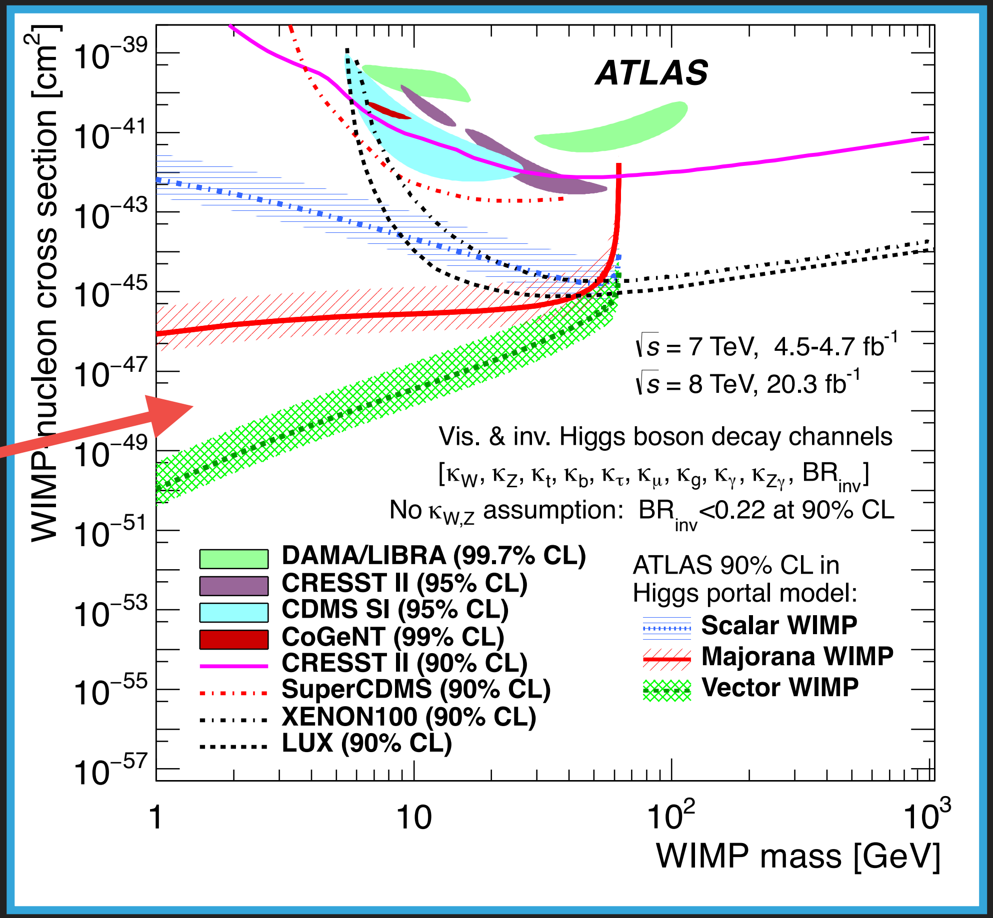
SM extended to introduce one new particle which couple exclusively to Higgs boson through $\lambda_{h\chi\chi}$




- Limits translated in upper bounds on the DM-Nucleon scattering cross section

$$\Gamma(H \to \chi\chi) \Leftrightarrow \lambda^2_{H\chi\chi} \Leftrightarrow \sigma_{N\chi}$$

- Scalar, vector and fermion hypothesis probed (model-dependent limits)
- Particular sensitive to low $m_\chi$ region



# SUMMARY OF H→INVISIBLE SEARCHES



✓ With data collected in the 8 TeV Run ATLAS has carried out a comprehensive programme of searches for the invisible decay of the Higgs boson

✓ Great number of analyses involved, different analysis techniques employed

✓ No evidence for the Higgs boson invisible decay has been observed

✓ Run-I concluded with a statistical combination of the H→invisible direct and indirect search, from the coupling parametrisation:

| Decay channels | Coupling parameterisation | $\kappa_i$ assumption | Upper limit on $BR_{inv}$ Obs. | Exp. |
|---|---|---|---|---|
| Invisible decays | $[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$ | $\kappa_{W,Z,g} = 1$ | 0.25 | 0.27 |
| Visible decays | $[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$ | $\kappa_{W,Z} \leq 1$ | 0.49 | 0.48 |
| **Inv. & vis. decays** | $[\boldsymbol{\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}}]$ | **None** | **0.23** | **0.24** |
| Inv. & vis. decays | $[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$ | $\kappa_{W,Z} \leq 1$ | 0.23 | 0.23 |

Table 7: Summary of upper limits on BR($h \to$ invisible) at the 95% CL from the combination of direct searches for invisible Higgs boson decays, the combination of measurements of visible Higgs boson decays, and the overall combination using both the invisible and visible Higgs boson decays. The results are derived using different assumptions about $\kappa_{W,Z}$. The results with the baseline configuration for the combination of invisible and visible decay channels are indicated in bold.

+11% improvement wrt visible alone

✓ The second run of the LHC offers the possibility to improve Run-I results

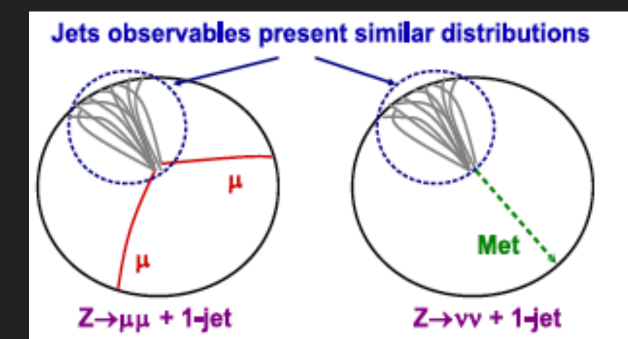
✓ First result from the ZH, Z→$\ell\ell$ H→invisible channel presented today, many more to come in the next months!

# BACKUP

# GENERAL METHODOLOGIES FOR BACKGROUNDS

**Z→νν & W→ℓν**

- Z→$\nu\nu$ + jets background constrained using a combination of estimates from W+jets & Z→$\ell\ell$+jets CRs:
  - Data control samples with identified e/μ & same requirements on jets/MET as in SR
  - data-driven techniques allow to reduce the theoretical & experimental systematic uncertainties associated with MC predictions




**W→μν & Z→μμ**

- MET online trigger w/o the μ information ⇒ events in the CR selected

  with the same trigger as in SR
- MET emulates the one in SR when it is not corrected for the presence of μ ⇒ treated as invisible

**W→eν & Z→ee**

- Use electrons online trigger
- MET corrected for removing the contribution of electrons energy cluster in the calorimeter

Example: Z→νν from W→μν

$$N^{Z(\to\nu\bar{\nu})}_{\mathrm{signal}} = \frac{\left(N^{\mathrm{data}}_{W(\to\mu\nu),\mathrm{control}} - N^{\mathrm{non}-W/Z}_{W(\to\mu\nu),\mathrm{control}}\right)}{N^{\mathrm{MC}}_{W(\to\mu\nu),\mathrm{control}}} \times N^{\mathrm{MC}(Z(\to\nu\bar{\nu}))}_{\mathrm{signal}} \times \xi_{\ell} \times \xi_{\mathrm{trg}}$$

MC-to-Data normalisation factor ~(0.9÷0.6) as MET increase (MC exceeds data for W/Z+jets processes)

Four corrections factors from the 4 CRs, results statistically combined

# GENERAL METHODOLOGIES FOR BACKGROUNDS 

**Non-collision background**

- Cosmic muons, beam-halo and detector noise give rise to large energy deposits in the calorimeter
- Below the percent level after the mono-jet event selection
- Collision jets are in time with the bunch crossing ⇒ events with one jet out-of-time are non-collision events
- Shape of the fake jets extracted from signal events identified as beam-induced backgrounds based on the spatial alignment of the signals in the calorimeter and the muon system

# HIGGS PORTAL DARK-MATTER MODEL



- Dark matter portal models introduce the existence of a WIMP as dark-matter candidate
- The WIMP is assumed to interact weakly with all the particles but for the Higgs boson
- The combined upper limit from visible & invisible searches is translated into constraint on the coupling of WIMP to the Higgs boson λ
- The partial width to the DM particles pairs depends on the spin of the DM particles

$$\text{scalar } S : \Gamma^{\text{inv}}(h \to SS) = \lambda^2_{hSS} \frac{v^2 \beta_S}{128\pi m_h}$$

$$\text{fermion } f : \Gamma^{\text{inv}}(h \to ff) = \frac{\lambda^2_{hff}}{\Lambda^2} \frac{v^2 \beta^3_f m_h}{64\pi}$$

$$\text{vector } V : \Gamma^{\text{inv}}(h \to VV) = \lambda^2_{hVV} \frac{v^2 \beta_V m^3_h}{512\pi m^4_V} \times \left(1 - 4\frac{m^2_V}{m^2_h} + 12\frac{m^4_V}{m^4_h}\right)$$

Used to deduce the couplings to the WIMP

$$\text{scalar } S : \quad \sigma_{S-N} = \lambda^2_{hSS} \frac{m^4_N f^2_N}{16\pi m^4_h (m_S + m_N)^2}$$

$$\text{fermion } f : \quad \sigma_{f-N} = \frac{\lambda^2_{hff}}{\Lambda^2} \frac{m^4_N f^2_N m^2_f}{4\pi m^4_h (m_f + m_N)^2}$$

$$\text{vector } V : \quad \sigma_{V-N} = \lambda^2_{hVV} \frac{m^4_N f^2_N}{16\pi m^4_h (m_V + m_N)^2}$$

Couplings re-parametrised in terms of the cross section for scattering between WIMP and nucleon, via the Higgs boson exchange