Search for Higgs to Invisible States at ATLAS

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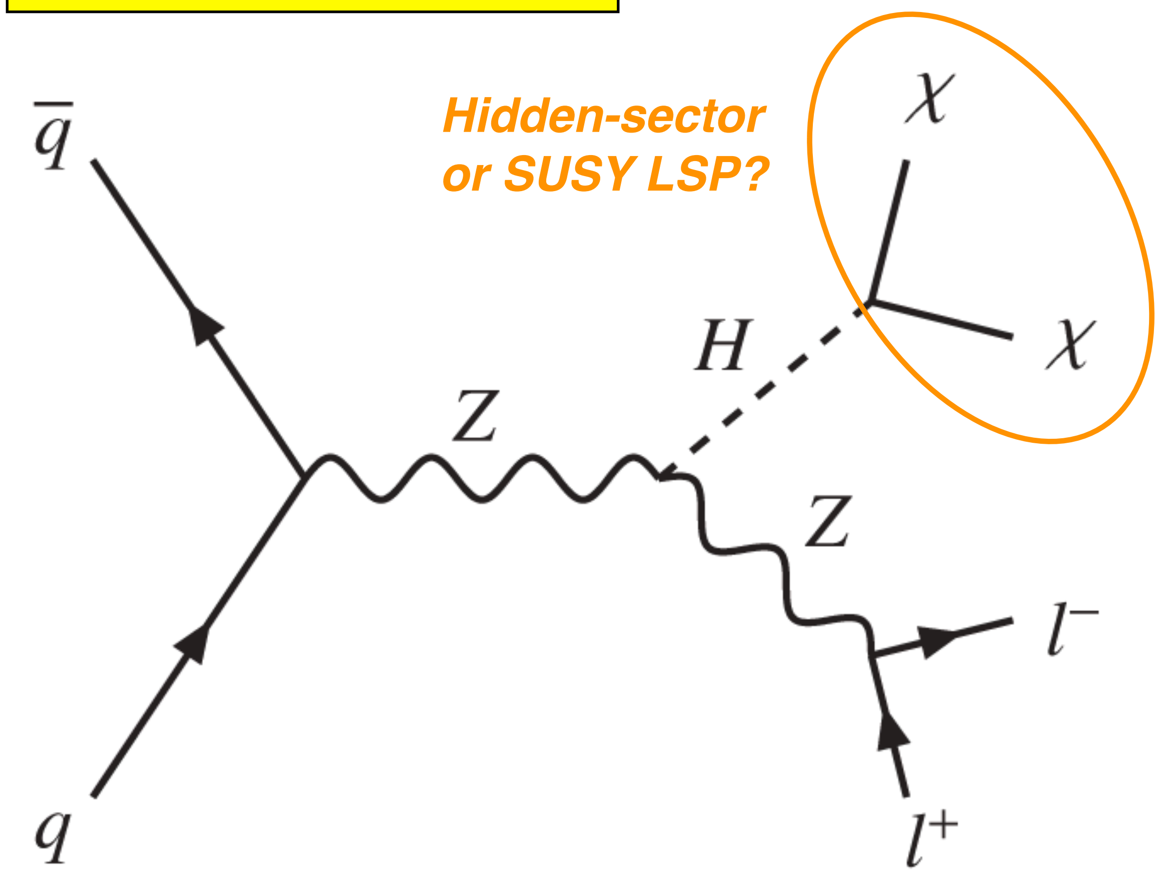
Why Invisible Higgs Decays?

ATLAS-CONF-2013-011, ATL-PHYS-PUB-2013-014

ZH→ll + invisible

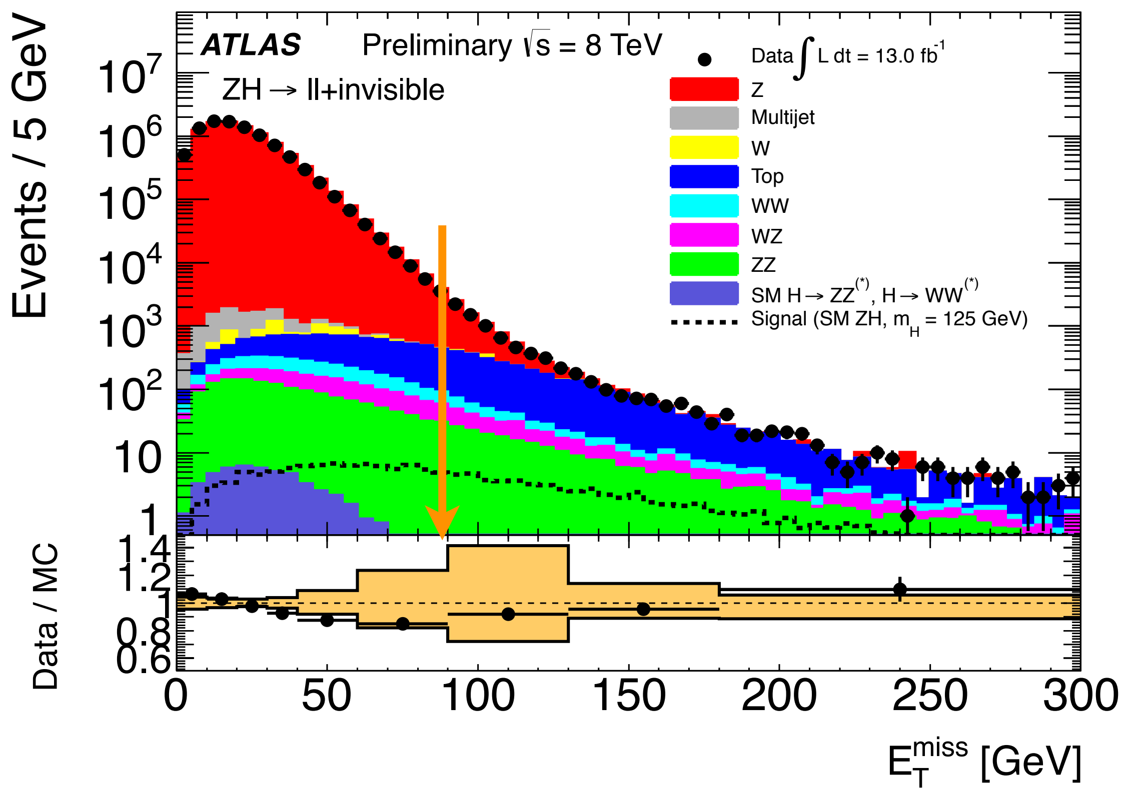


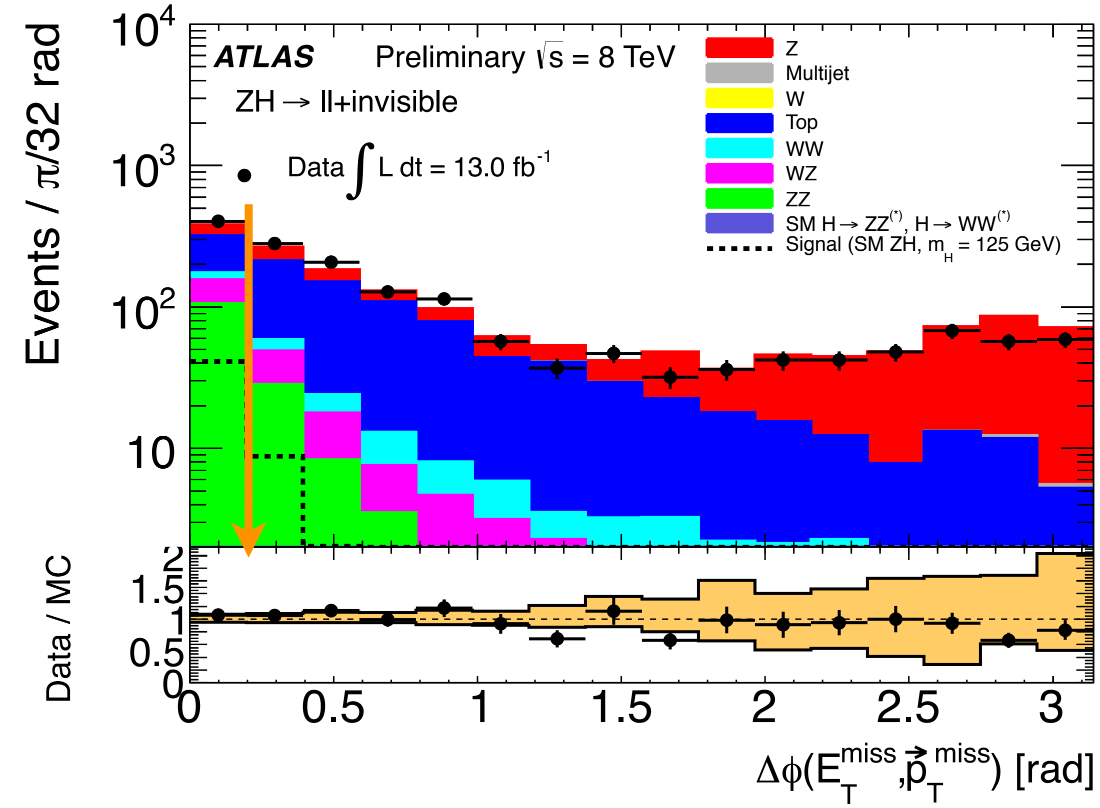
- **BSM processes. Highly interesting from the dark matter perspective.**
- **Search for coupling of the Higgs to:**
  - **The hidden sector (i.e. dark matter particle)**
  - **Other BSM particles (e.g. SUSY)**
- **ZH→ll+E_T^{miss} has one of the highest sensitivities among direct H(→inv) search channels.** (cf. VBF, monojet, W+E_T^{miss})

- **Complementary and more model-independent approach than the Higgs coupling studies** (*ATLAS-CONF-2013-034*)

Event Selection

ATLAS-CONF-2013-011





- 2 opposite-sign lepton w/ $76 < M_{ll} < 106$ GeV; 3rd lepton veto (p_T>7 GeV)
- **$E_T^{miss} > 90$ GeV**
- **Fractional p_T difference ($|E_T^{miss} - p_T^{ll}| / p_T^{ll}$) < 0.2**
- **$d\phi(E_T^{miss}, E_T^{miss,trk}) < 0.2$**
- $d\phi(l,l) < 1.7$
- **$d\phi(p_T^{ll}, E_T^{miss}) > 2.6$**
- Jet veto ($p_T > 20$ GeV, $|\eta| < 2.5$)

E_T^{miss}-related; key variables to suppress the Z BG

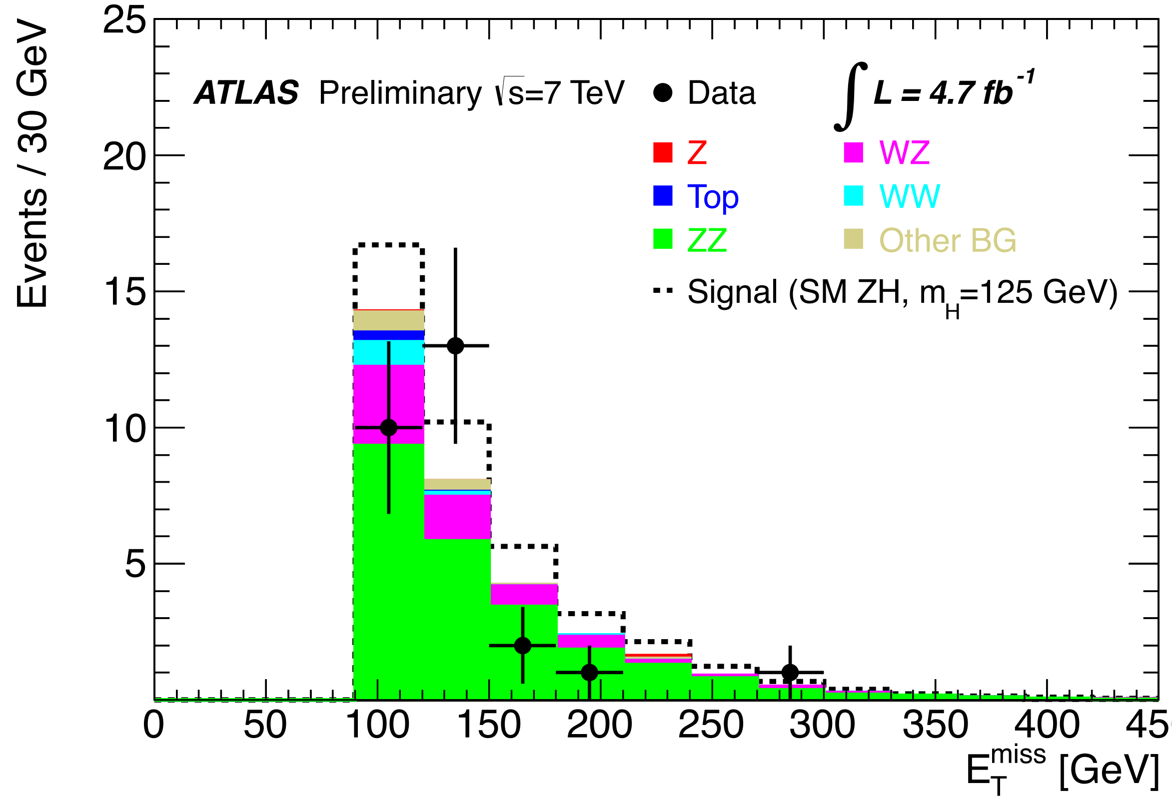
Background

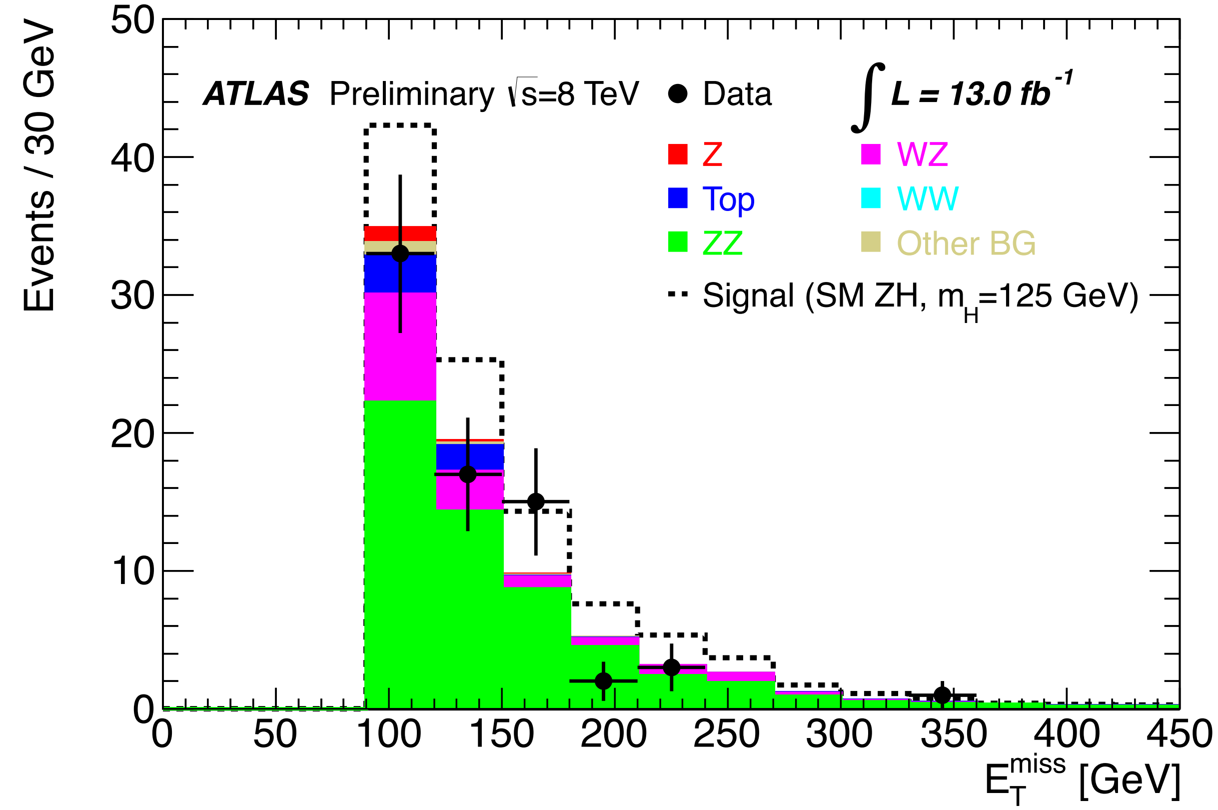
BG Size

- **ZZ:** The dominant and irreducible background. Estimated with Monte Carlo (MC).
- **WZ:** MC-based, and validated using a trilepton control region.
- **WW/ttbar&Wt/Z($\to\tau\tau$):** Estimated with data-driven ways using the e-μ CR. MC used for 2011 due to limited data statistics.
- **Z+jets:** Estimated with data-driven methods. ABCD method as the nominal estimate. Gamma+jets method was investigated as well.
- **W+jets/multijet:** Estimated with the Matrix Method, cross-checked with like-sign control region & MC scaling.

Estimated by MC **Estimated by data-driven methods**

Results

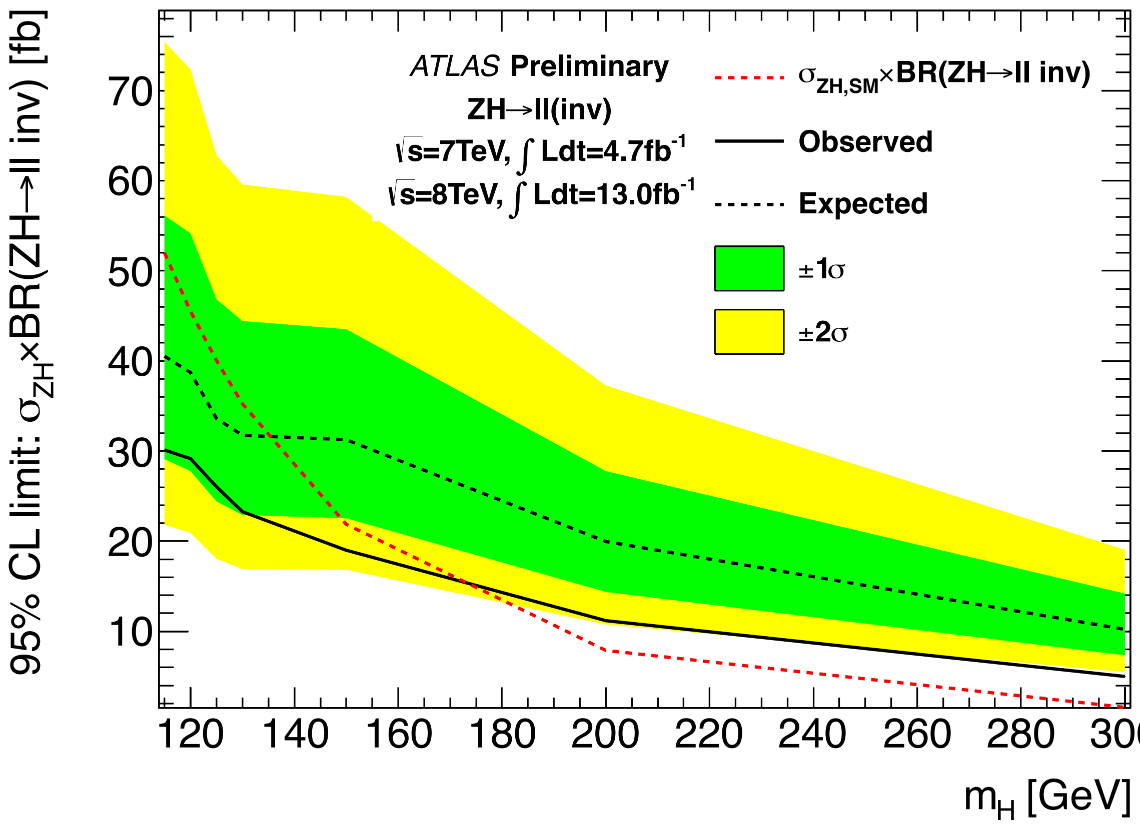


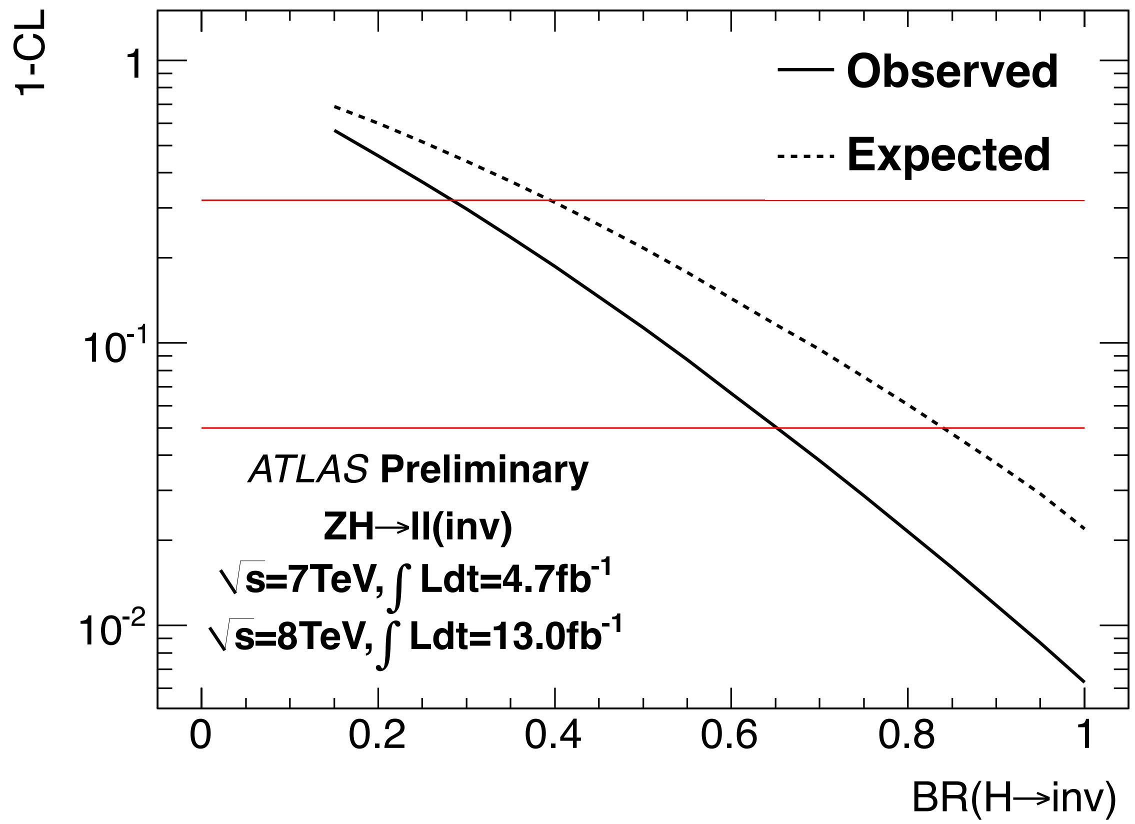


Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	$23.5 \pm 0.8 \pm 2.5$	$56.5 \pm 1.2 \pm 5.7$
WZ	$6.2 \pm 0.4 \pm 0.7$	$13.9 \pm 1.2 \pm 2.1$
WW	$1.1 \pm 0.2 \pm 0.2$	used $e\mu$ data-driven
Top quark	$0.4 \pm 0.1 \pm 0.4$	used $e\mu$ data-driven
Top quark, WW and $Z \to \tau\tau$ ($e\mu$ data-driven)	used MC	$4.9 \pm 0.9 \pm 0.2$
Z	$0.16 \pm 0.13 \pm 0.09$	$1.4 \pm 0.4 \pm 0.7$
W + jets, multijet	$1.3 \pm 0.3 \pm 0.2$	$1.4 \pm 0.4 \pm 0.3$
Total BG	$32.7 \pm 1.0 \pm 2.6$	$78.0 \pm 2.0 \pm 6.5$
Observed	27	71

No significant excess observed throughout the E_T^{miss} distribution

Limits

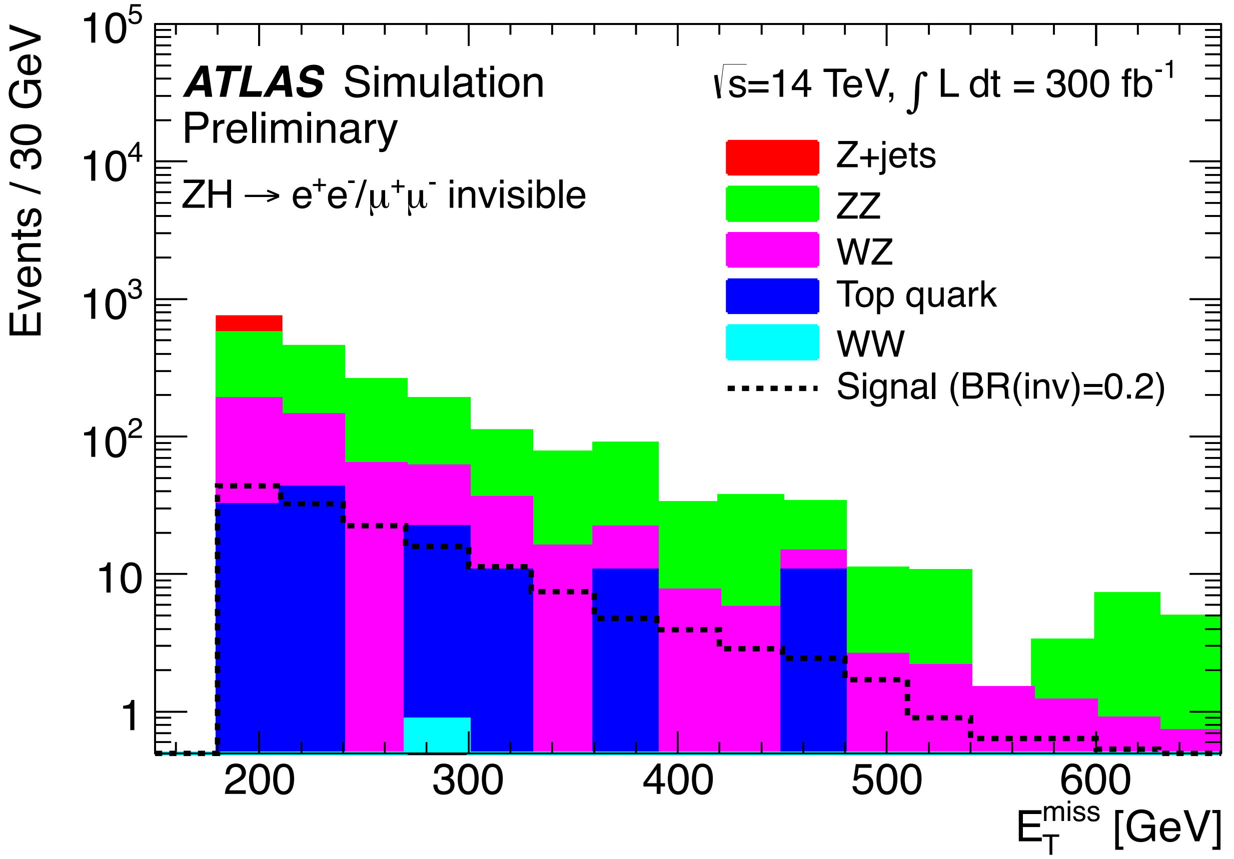




- Model-independent limits on σ × BR(ZH→ll+inv) are set for "another" Higgs.
- We also set a **limit on BR(H→inv)** assuming m_H = 125 GeV & $\sigma_{ZH} = \sigma_{ZH}^{SM}$. **BR(H→inv)<0.65 (observed) & 0.84 (expected)** @ 95% CL.
- Higgs coupling studies (***ATLAS-CONF-2013-34***) give an observed limit of BR(H→inv+undetected)<0.6 @ 95% CL.

Sensitivity w/ Future LHC

ATL-PHYS-PUB-2013-014



- Target is to reach BR(inv)~10%, where SUSY could become visible.
- Estimated the expected sensitivity to the invisible Higgs decay with the future Phase-1 and Phase-2 LHC.
- Pileup conditions of <μ>=60 & 140 are considered for Phase-1 & 2.

- Two scenarios of systematics
  - Conservative: same systematics size as the 7+8 TeV analysis
  - Realistic: reduced systematics for ZZ & WZ BG due to more expected data

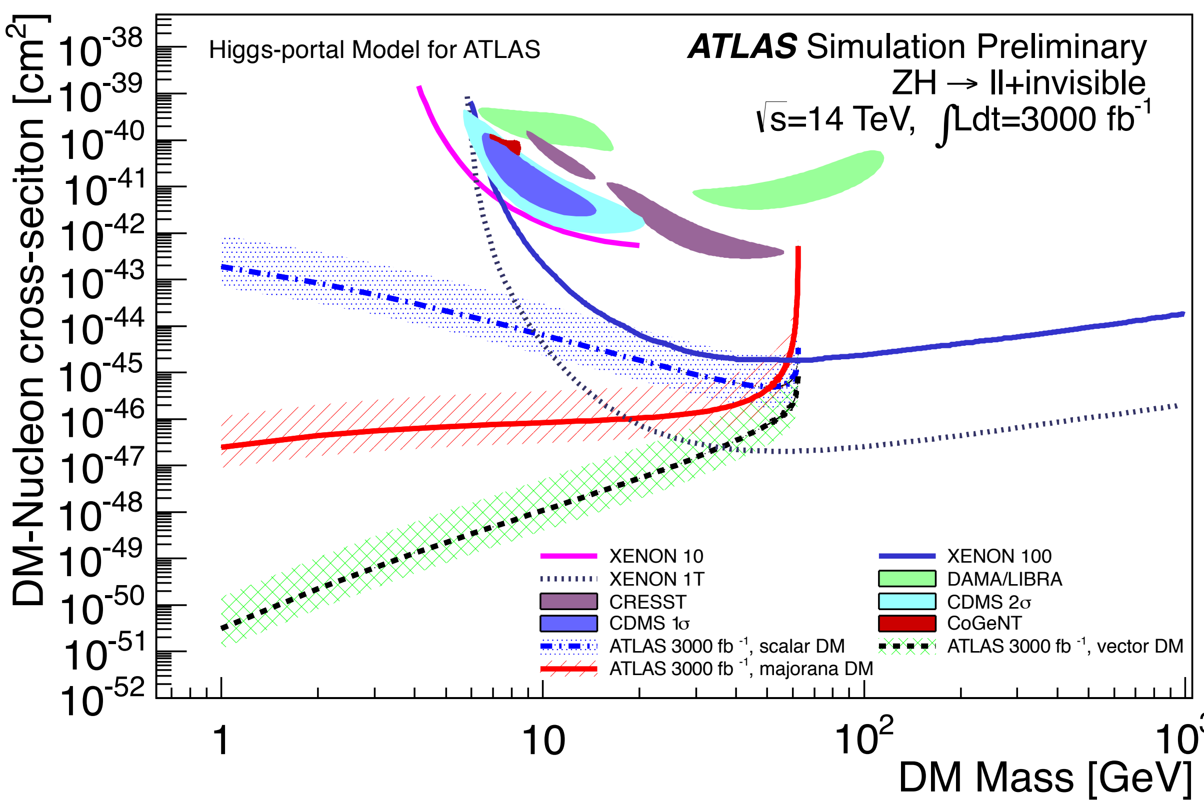
	Phase-1 300 fb^{-1}	Phase-2 3000 fb^{-1}
BR(H→inv) 95% CL limits	23-32%	8-16%

Higgs-Portal Interpretation

BR(H→inv) limit could be mapped to bounds on the coupling of Higgs-dark matter (DM) & DM-nucleon cross section for Higgs-portal DM models

Higgs invisible decay		*Higgs-DM coupling*		*DM-nucleon xsec*
$\Gamma(h \to \chi\chi)$	$\Leftrightarrow$	$\lambda^2_{h\chi\chi}$	$\Leftrightarrow$	$\sigma_{N\chi}$

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$



- Very good sensitivity in $m_\chi < m_H/2$ region.
- Significantly exceeds the limits from the direct detection experiments for the low mass region.
- LHC could provide complementary results to the DM experiments.

Summary

- Searched for invisible decays of the Higgs boson in the ZH process using 7 & 8 TeV dataset (4.7+13.0 fb^{-1}). No significant excess is observed.
- Model-independent limits are set on σ x BR for m_H=115-300 GeV.
- Limit is also set on BR(H→inv) for 125 GeV Higgs assuming the SM ZH production cross section. BR(H→inv) < 65% (obs) @ 95% CL.
- Sensitivity from the future LHC has also been studied. Expected to reach BR(H→inv) < 23-32% (8-16%) w/ 300 fb^{-1} (3000 fb^{-1}), where SUSY could start to show up.
- BR(H→inv.) limit is interpreted with the Higgs-portal dark matter scenario. We have very good sensitivity in $m_{DM}<m_H/2$ region & exceeds the limits from the direct DM detection experiments.

backups

WW/Top/Z(→ττ): Data-Driven

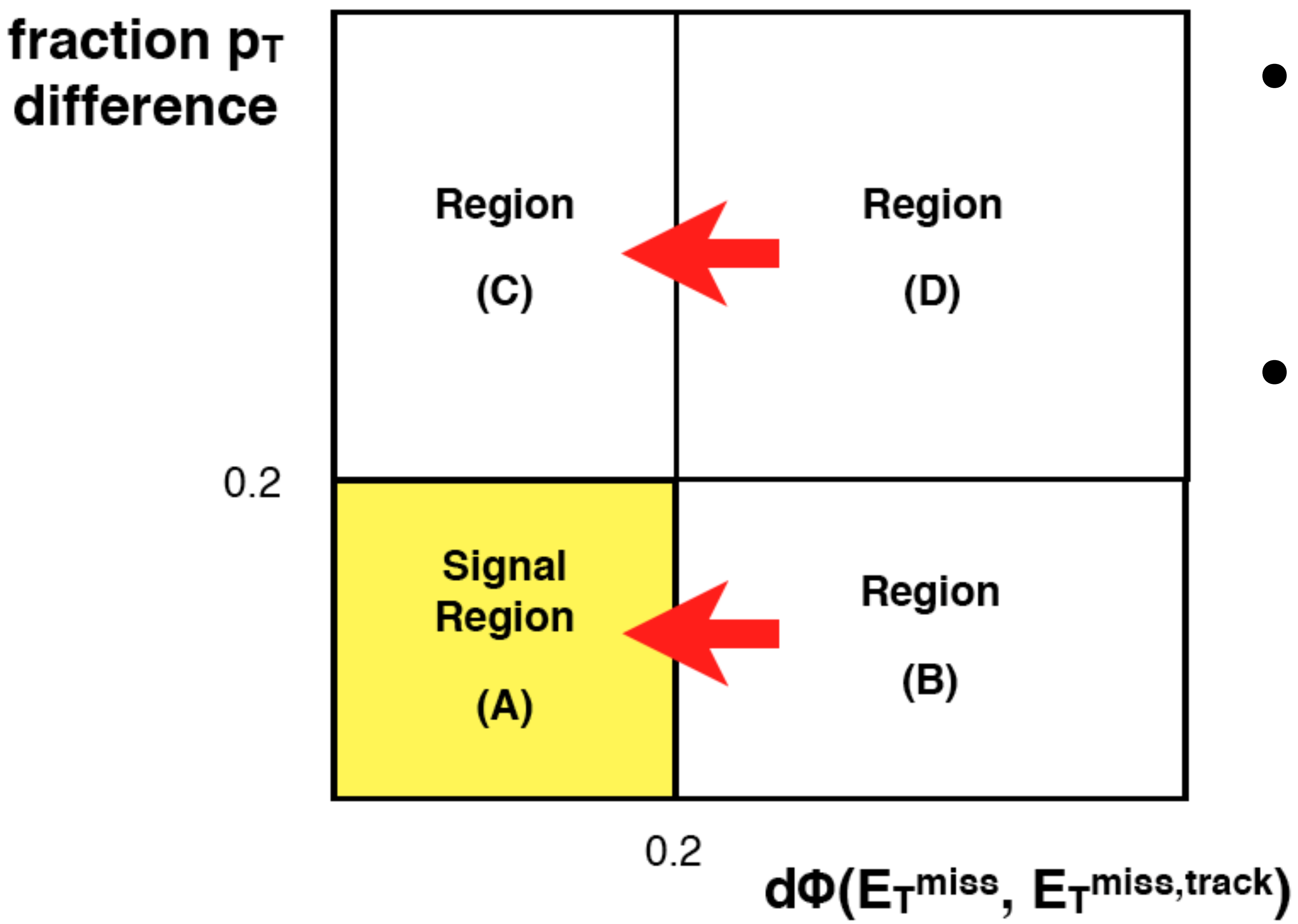
- **Using the flavor symmetry** in **WW/dilep. ttbar & Wt/Z(→ττ) processes.**
- A data-driven method which **inclusively estimates those BGs** from the e-μ control region.

$$N_{ee}^{BG,est.} = \frac{1}{2} \times N_{e\mu}^{data,sub} \times k \qquad k = \sqrt{\frac{N_{ee}^{data}}{N_{\mu\mu}^{data}}}$$

$$N_{\mu\mu}^{BG,est.} = \frac{1}{2} \times N_{e\mu}^{data,sub} \times \frac{1}{k}$$

- $N_{e\mu}^{data,sub}$ corresponds to data events in the CR, but contributions from non-WW/Top/Z (→ττ) BG are subtracted with MC
- k-efficiency factor & MC subtraction are the main source of systematics
- This method is now used for both 2011 & 2012 data

ABCD Method for Z BG



- Purely data-driven except for the MC subtraction of the non-Z background
- Assume that

$$N_A = N_B \times \frac{N_C}{N_D}$$

Corrects for difference between N_A/N_B & N_C/N_D

$$N_A = N_B \times \frac{N_C}{N_D} \times \alpha$$

W+jets/QCD: Matrix Method

Data-driven method to estimate the fake background (W+jets/QCD)

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \times \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

Data
(N_{ij}: # of events with lepton i,j)

To be extracted from data using control regions
r: 1-lep real eff. = "loose" real lepton passing "tight" selection,
f: 1-lep fake rate = "loose" fake lepton passing "tight" selection

To be estimated
(R: real lepton, F: fake lepton)

- **Tight lepton:** nominal lepton criteria in this analysis
- **Loose lepton:** same as nominal but,
  - e: loose++ & no track isolation
  - μ: no track isolation

BG Estimates

$$N_{W+jets} = \sum_i^{N_{events}} N^i_{RF} \times r^i_1 \times f^i_2 + N^i_{FR} \times f^i_1 \times r^i_2$$

$$N_{di-jet} = \sum_i^{N_{events}} N^i_{FF} \times f^i_1 \times f^i_2$$

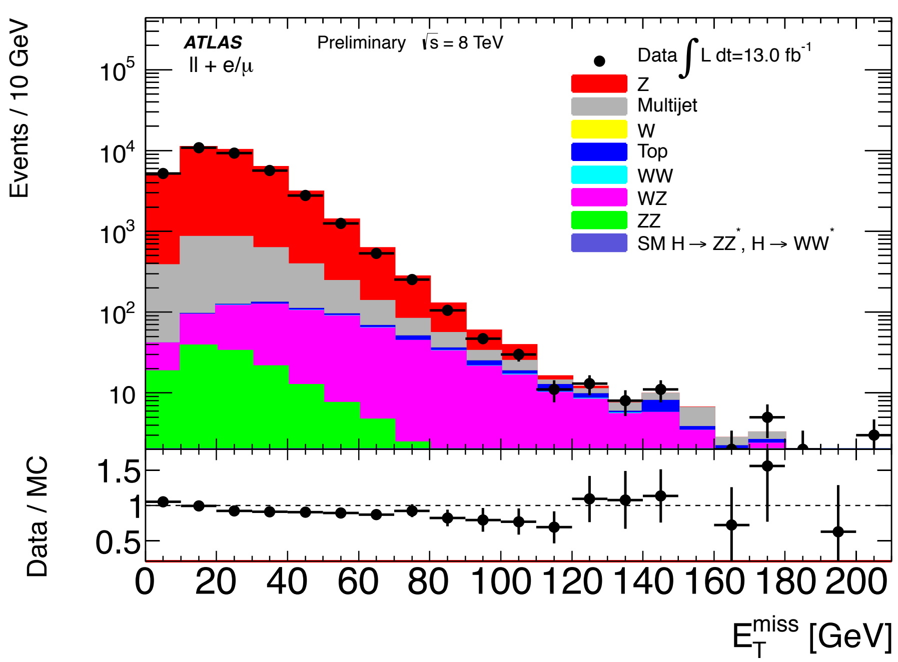
ZZ & WZ

- Irreducible and the most dominant BG for our search
- Estimated with MC.
- The latest ATLAS measurement@8TeV in the ZZ→4l channel gives consistent cross section with the NLO prediction.

$$\sigma^{\text{measured}}(ZZ) = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst}) \pm 0.2(\text{lumi.})\text{pb}$$

$$\sigma^{\text{NLO}}(ZZ) = 7.2^{+0.3}_{-0.2}\text{pb}$$

ATLAS-CONF-2013-020

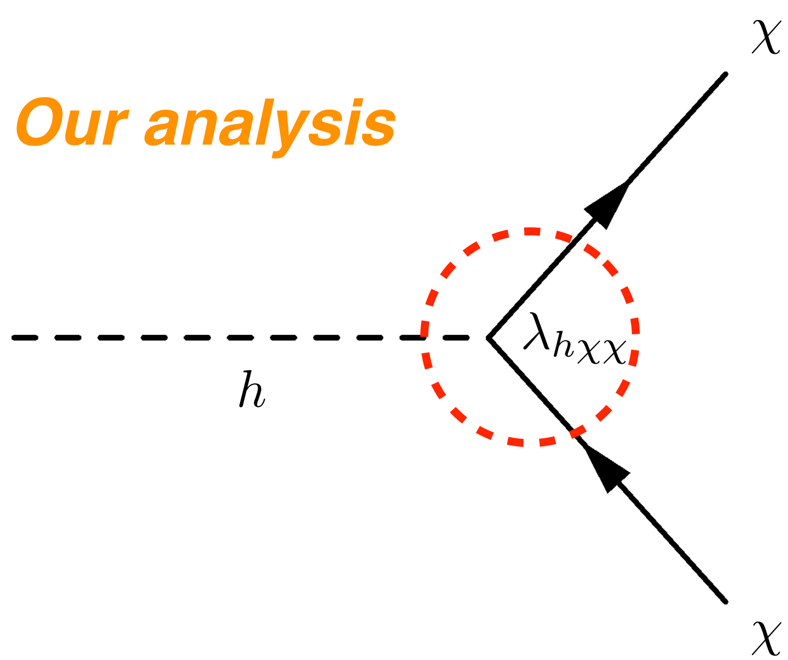


- WZ estimation is validated in the trilepton control region. The CR is well described by MC for E_T^{miss} & other kinematic variables.

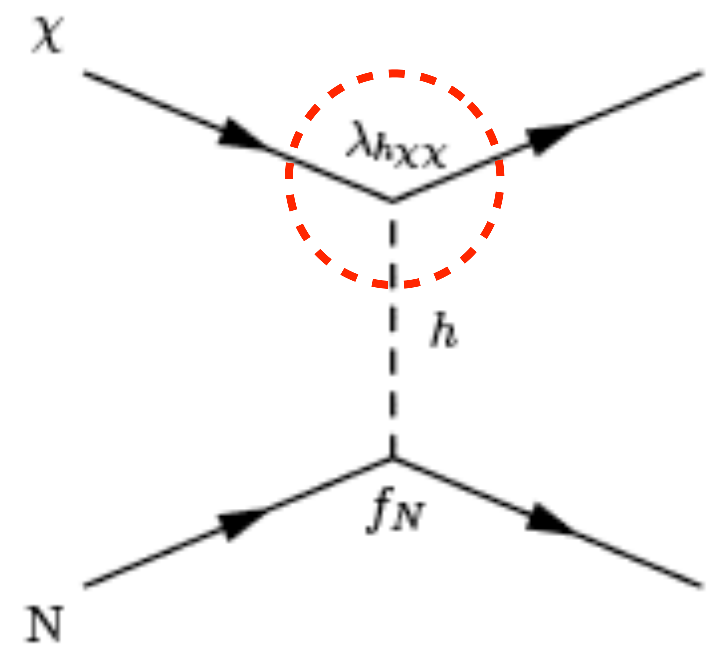
Higgs-Portal Interpretation

Higgs decaying to DM

Our analysis



DM-nucleon scattering in Higgs-portal DM Model



Direct DM detection experiments (XENON, DAMA, etc.)

- The limits on BR(H→inv) could be mapped to bounds on the coupling of Higgs-dark matter (DM) & DM-nucleon cross section for Higgs-portal DM models
- The Higgs-portal is a particular type of DM models, where DM interacts through the couplings to Higgs.

Mapping & DM-types

Higgs invisible decay | **Higgs-DM coupling** | **DM-nucleon xsec**

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

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$

We consider three DM types: scalar, vector, majorana fermion

$$\Gamma^{\text{Scalar}}(h \to \chi\chi) = \frac{\lambda^{2\,\text{Scalar}}_{h\chi\chi} v^2}{64\pi m_h}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2} \qquad \sigma^{\text{Scalar}}_{\chi N} = \frac{\lambda^{2\,\text{Scalar}}_{h\chi\chi}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\Gamma^{\text{Vector}}(h \to \chi\chi) = \frac{\lambda^{2\,\text{Vector}}_{h\chi\chi} v^2}{256\pi m_\chi^4 m_h}\left[m_h^4 - 4m_\chi^2 m_h^2 + 12 m_\chi^4\right]\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2} \qquad \sigma^{\text{Vector}}_{\chi N} = \frac{\lambda^{2\,\text{Vector}}_{h\chi\chi}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\Gamma^{\text{Majorana}}(h \to \chi\chi) = \frac{\lambda^{2\,\text{Majorana}}_{h\chi\chi} v^2 m_h}{32\pi\Lambda^2}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2} \qquad \sigma^{\text{Majorana}}_{\chi N} = \frac{\lambda^{2\,\text{Majorana}}_{h\chi\chi}}{4\pi\Lambda^2 m_h^4}\frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$