Invisible H searches at the LHC

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Outline

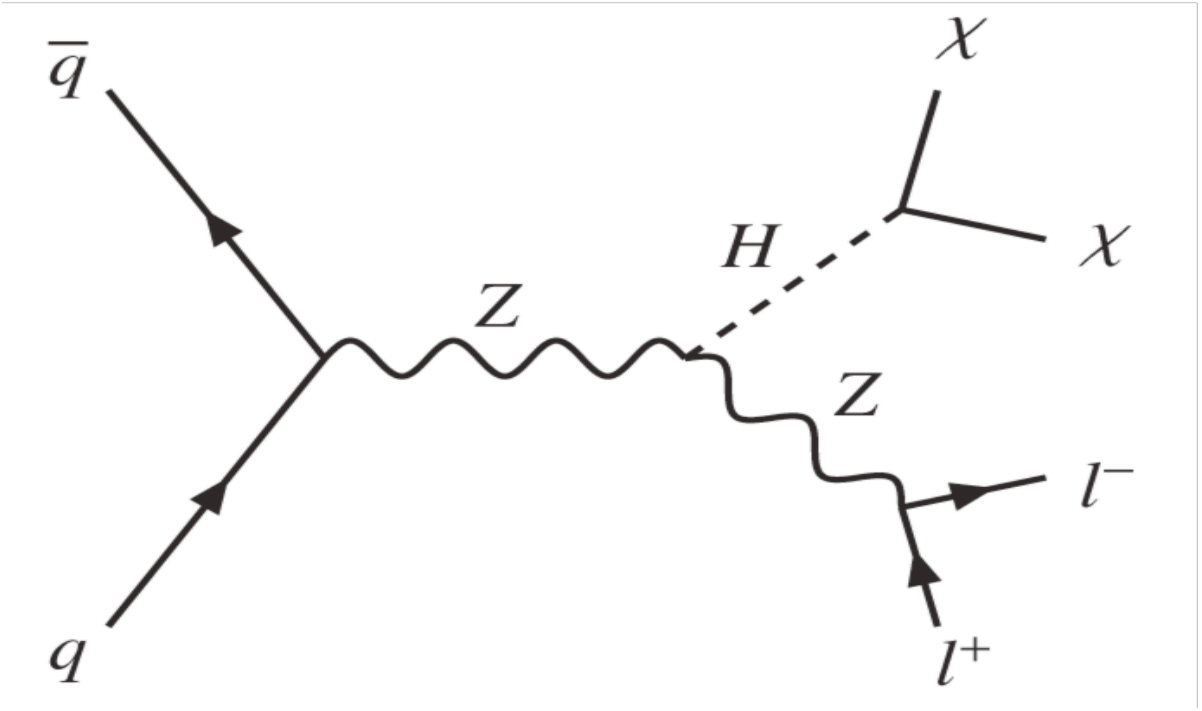
- H → invisible searches in ATLAS
- Theory interpretation of ATLAS and CMS monojet results
- H → invisible in CMS

Direct searches for H -> Invisible

1. **Z (→ ll) H, H → Invisible**
   - ZH production channel
   - 2l+MET events
   - Jet veto
2. **VBF H → Invisible**
   - VBF production channel
   - 2j+MET events
   - Lepton veto
3. **VH (V→qq. H → invisible)**
   - VH production channel
   - 2j+MET event
   - Lepton veto
4. **Monojet H → Invisible**
   - ggF production channel
   - 1j+MET events
   - Lepton veto

H → invisible

- Assuming the Higgs-like particle discovered around ~125 GeV is the SM Higgs
  - Does it have a substantial branching to invisible particle?
- Is there another Higgs boson at some different mass with substantial branching to invisible particle?
- Interpretation for different models

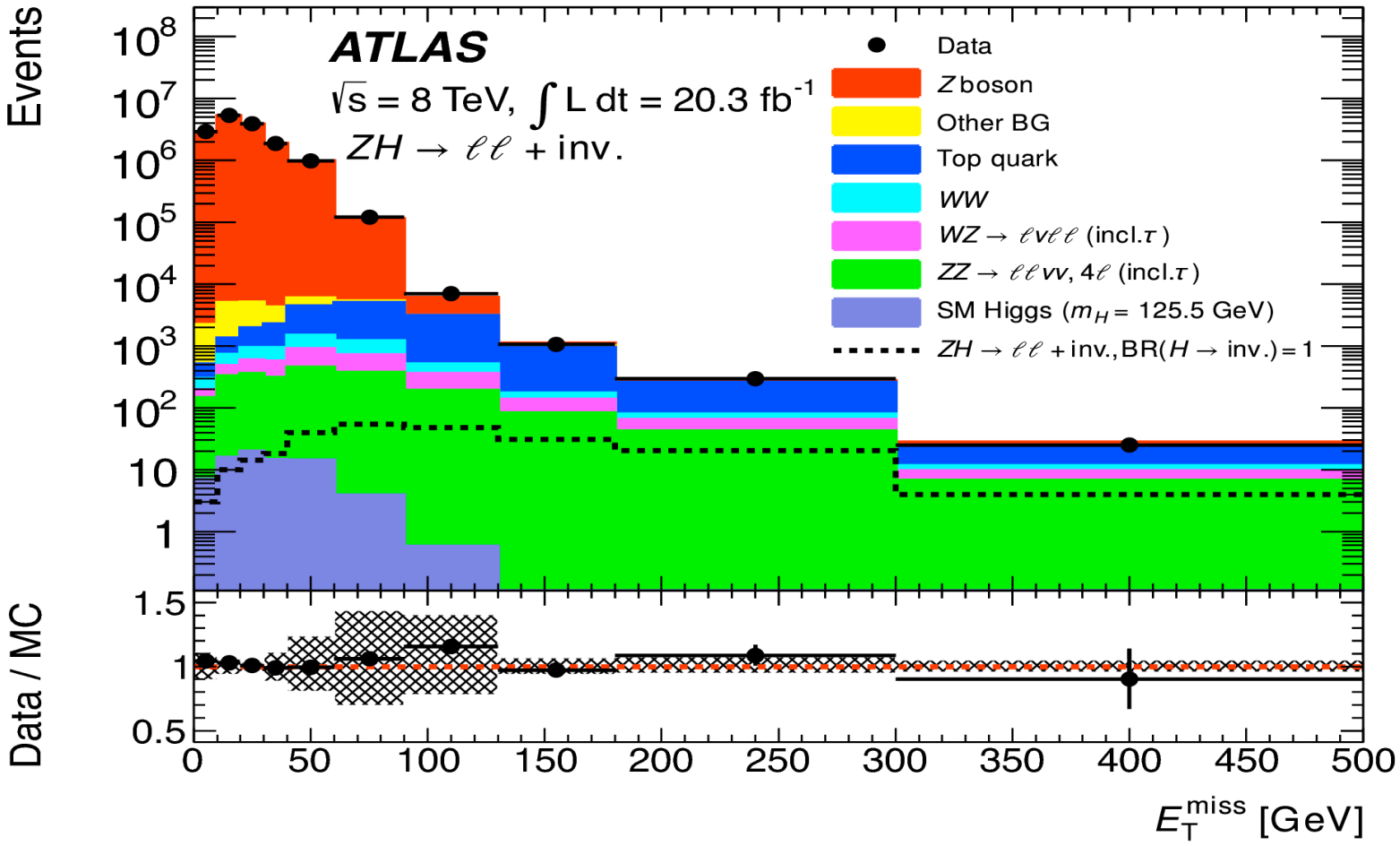


ATLAS ZH, Z → ll and H → Invisible

- The signal is the associated production, ZH (Z -> ll and H -> invisible)
- Signal mass points considered mH = 110, 115, 120, 125, 130, 150, 200 and 300, 400 GeV
- Requires 2 oppositely charged electrons or muons with pT > 20 GeV, consistent with the Z
- 3rd lepton veto: event is removed if an additional electron or muon is reconstructed with pT > 7 GeV
- Jet Veto. Events with jet pT > 20 GeV and |eta| < 2.5 are removed

ATLAS ZH, Z → ll and H → Invisible

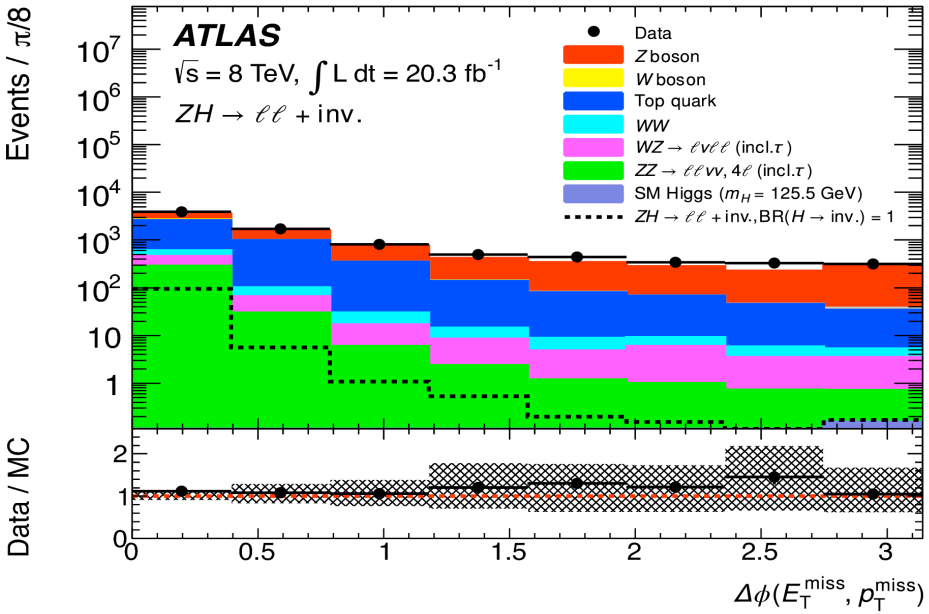
arXiv:1402.3244

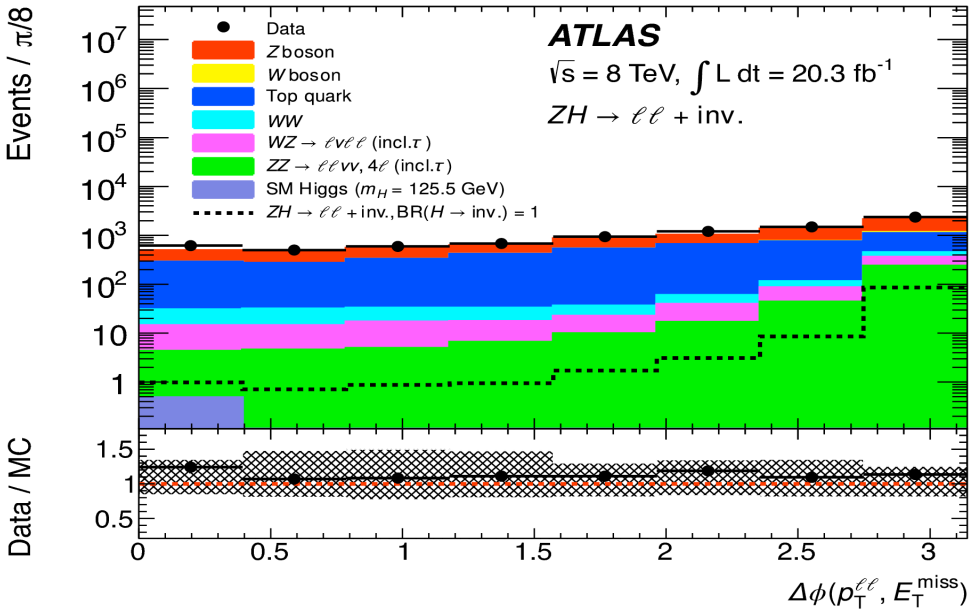


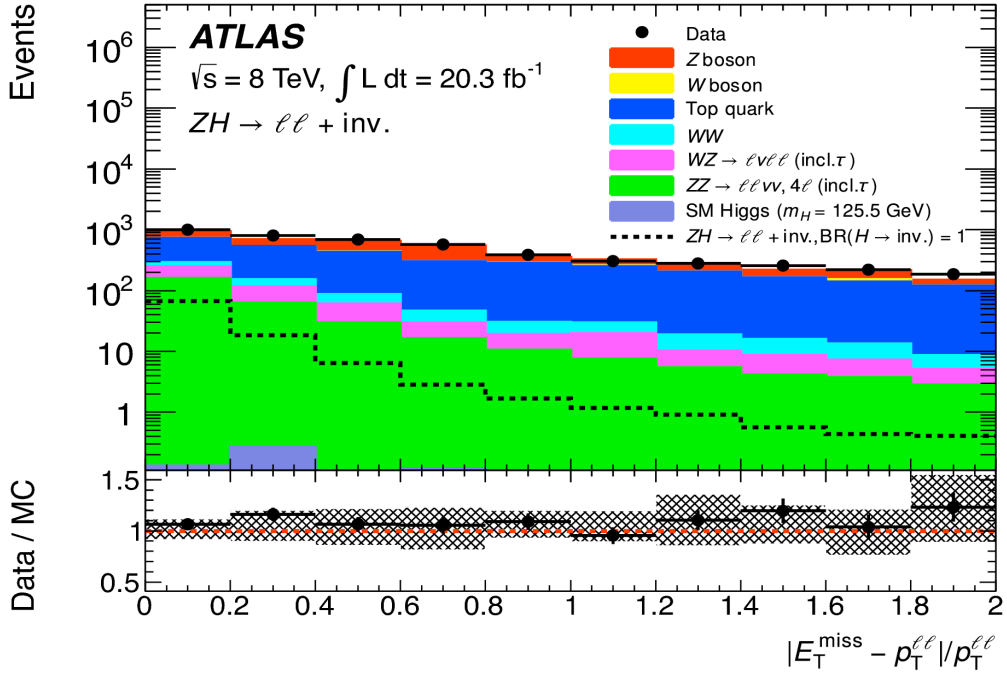
Missing energy

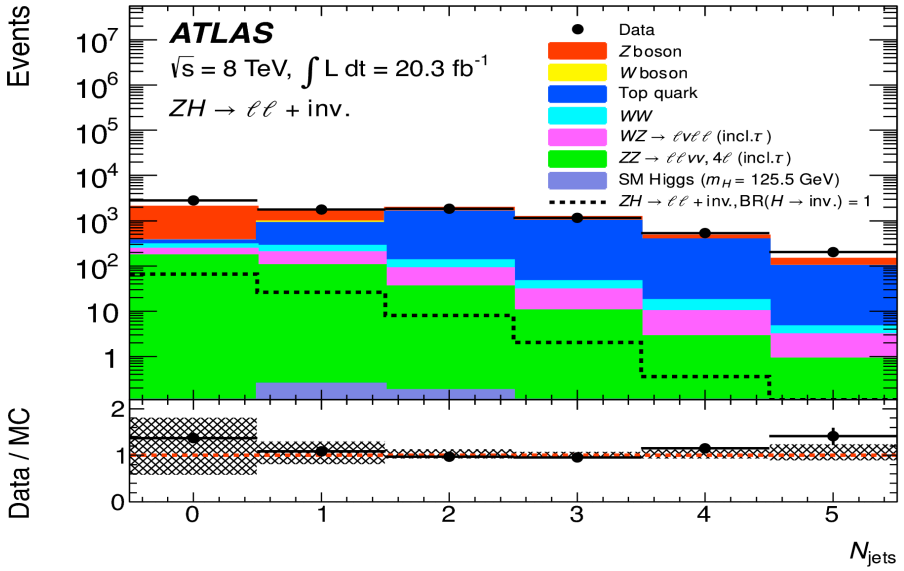
- after the di-lepton mass requirements 76 < mll < 106 GeV
- Backgrounds from MC

ATLAS ZH, Z → ll and H → Invisible



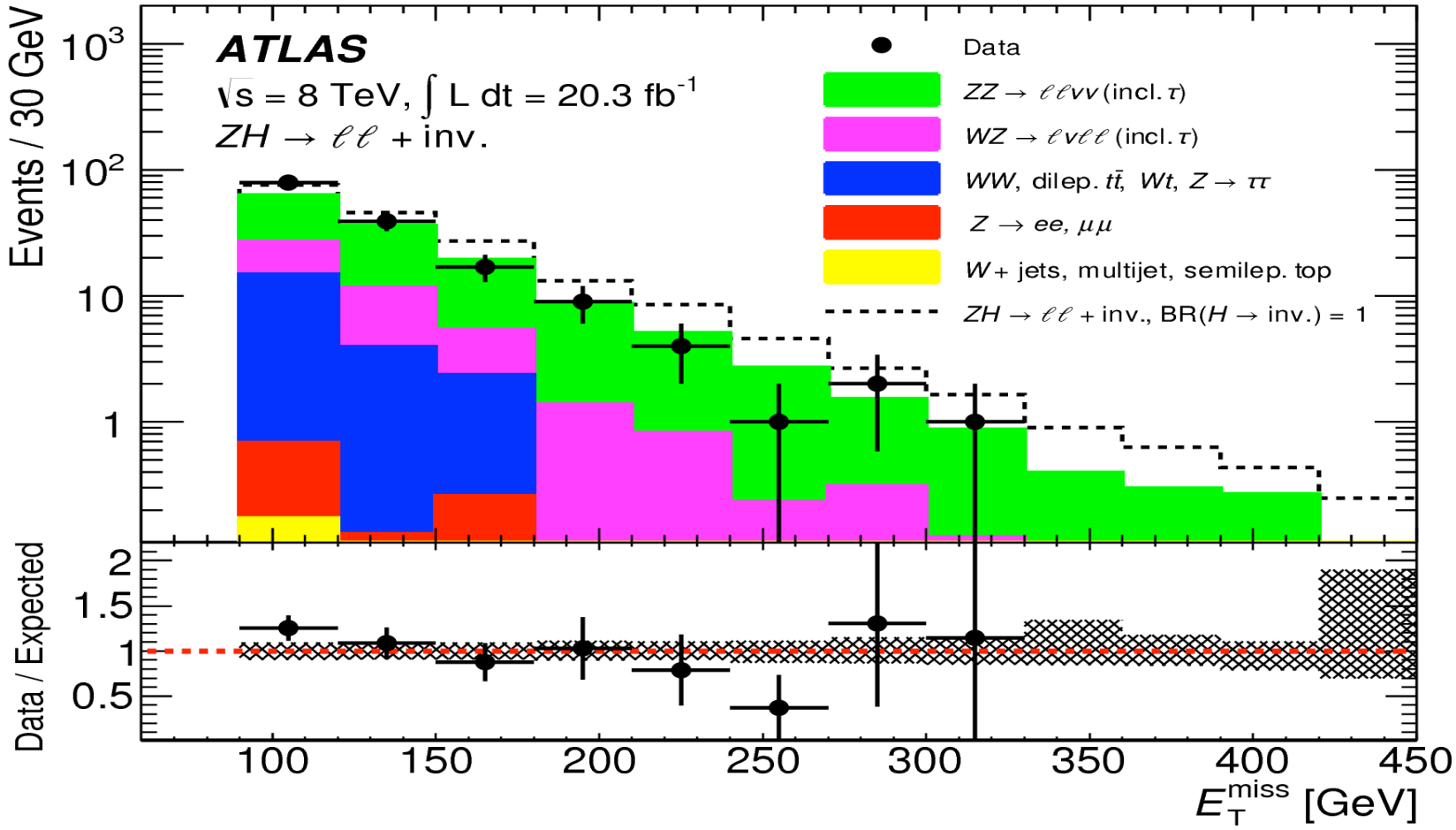






ATLAS ZH, Z → ll and H → Invisible

arXiv:1402.3244

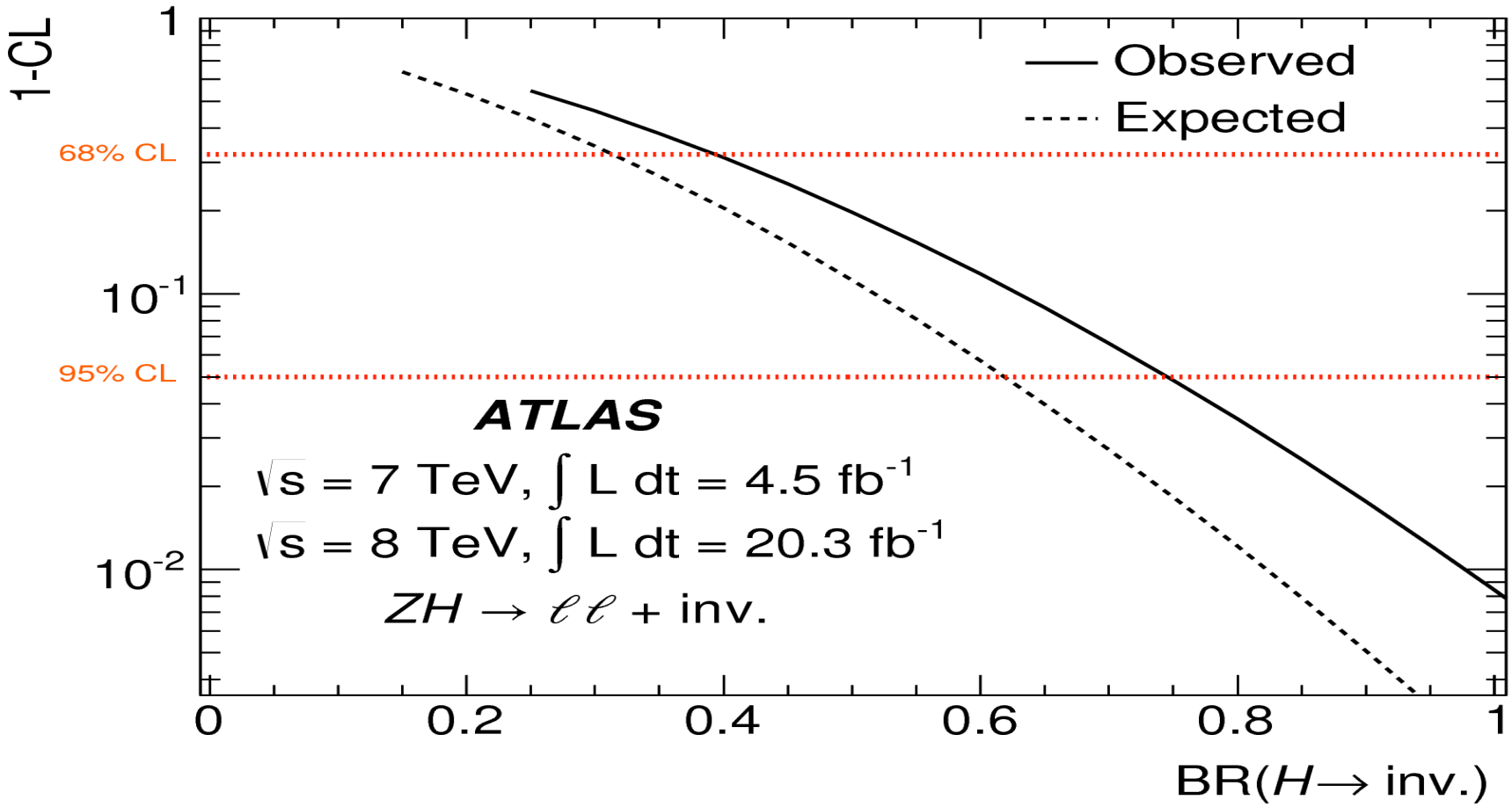


Missing energy

- after all selections
- Backgrounds from data-driven estimations

ATLAS ZH, Z → ll and H → Invisible

arXiv:1402.3244

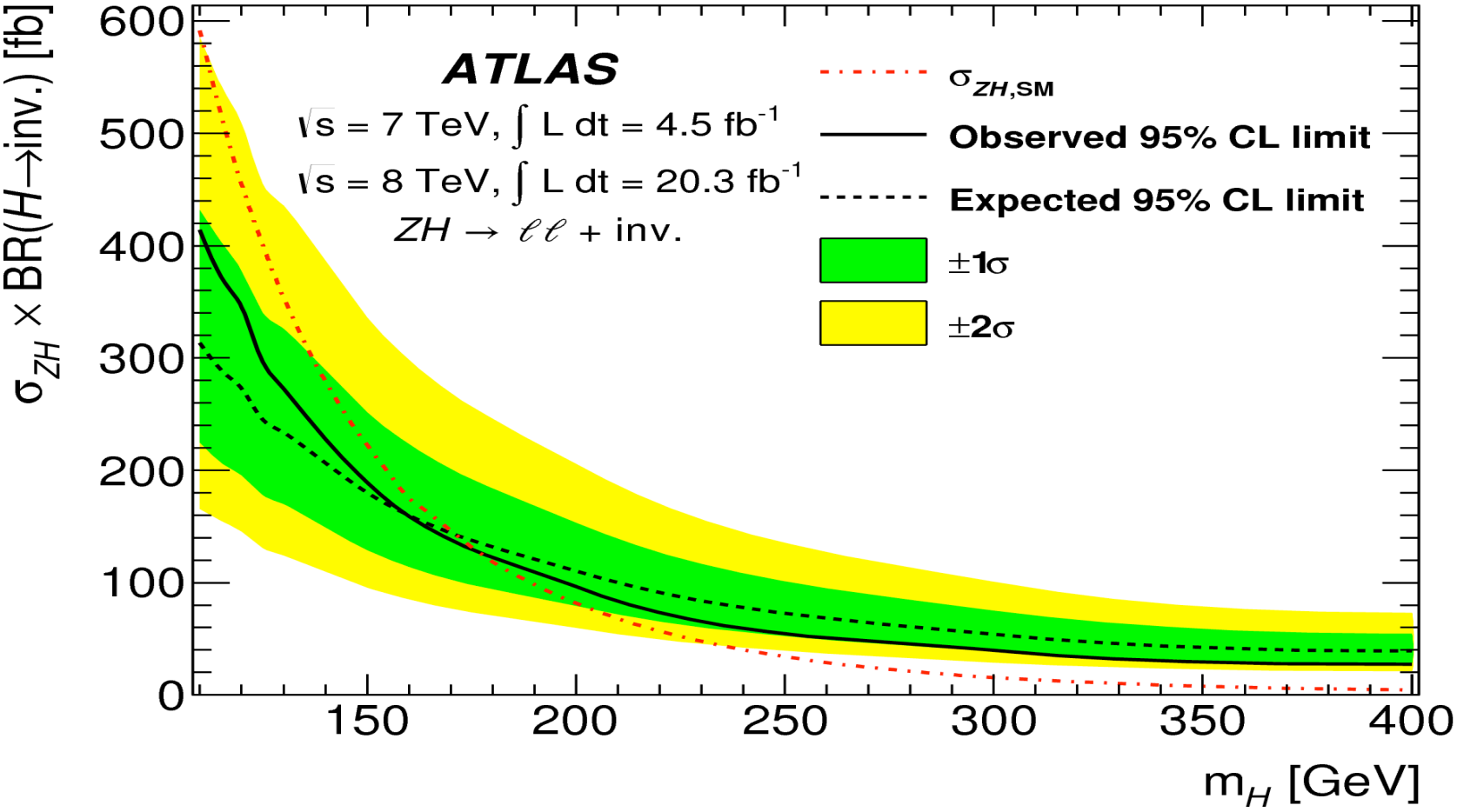


Confidence Level (CL) scan against BR Hinv for mH = 125.5 GeV

Upper bound: 0.75 @95% CL

ATLAS ZH, Z → ll and H → Invisible

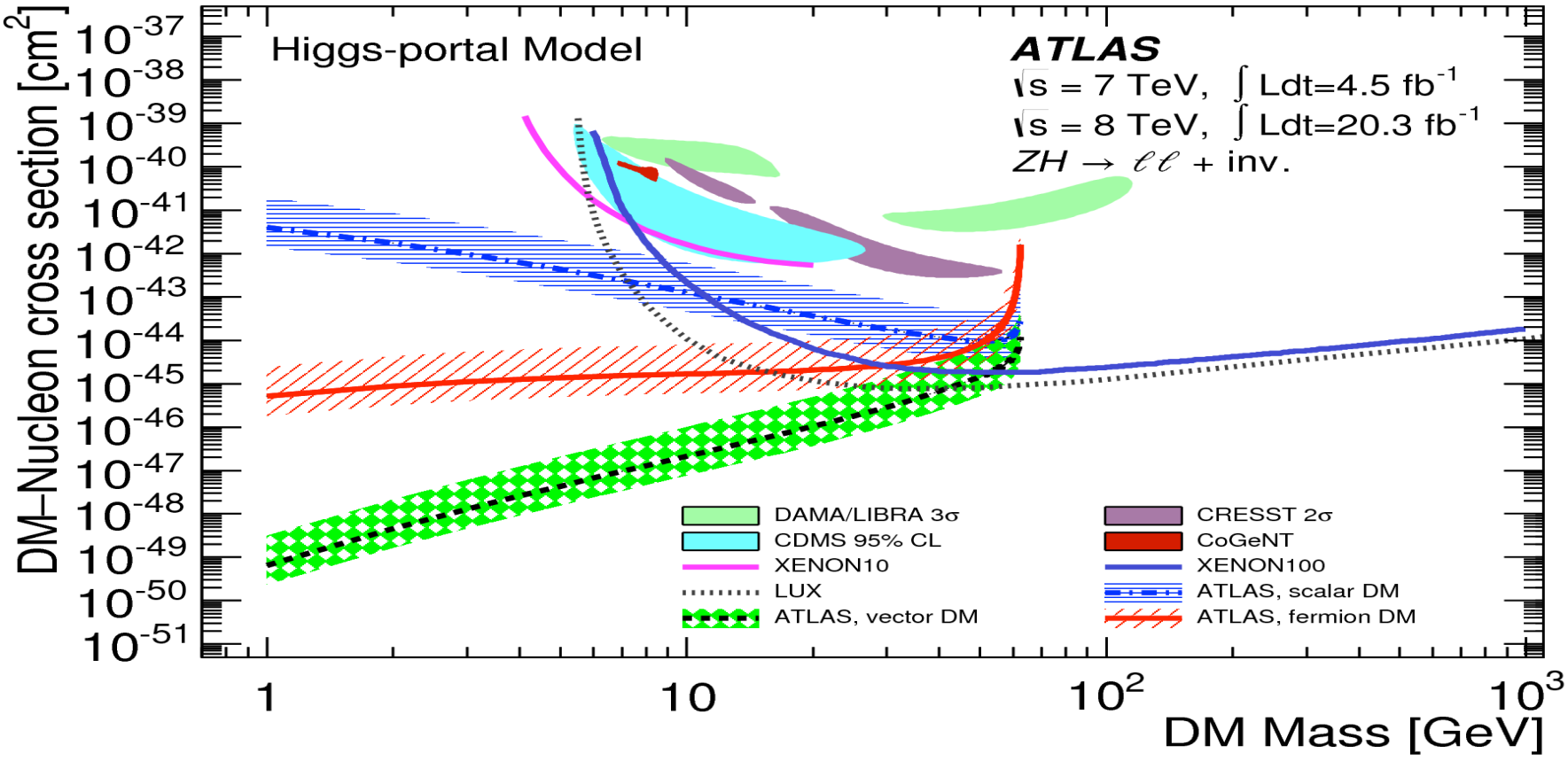
arXiv:1402.3244



Upper limit on σ x BR (Hinv) at 95% CL for 110 < mH < 400 GeV

ATLAS ZH. Z → ll and H → Invisible

arXiv:1402.3244

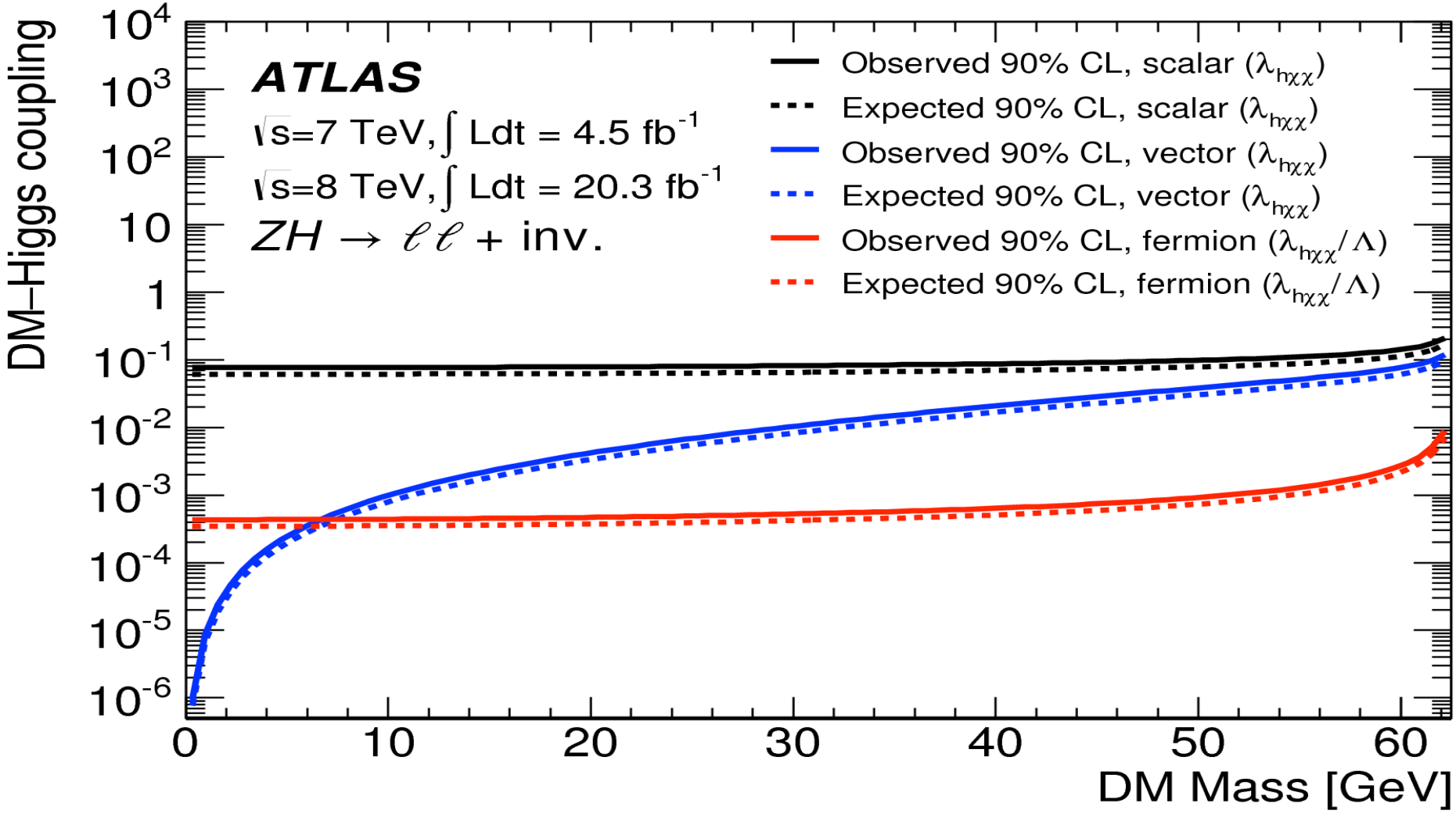


Limits on the DM-nucleon scattering cross section at 90% CL, extracted from the BR(H→inv.) limit in a Higgs-portal scenario, compared to results from direct-search experiments.

The results from the direct-search experiments do not depend on the assumptions of the Higgs-portal scenario.

ATLAS ZH, Z → ll and H → Invisible

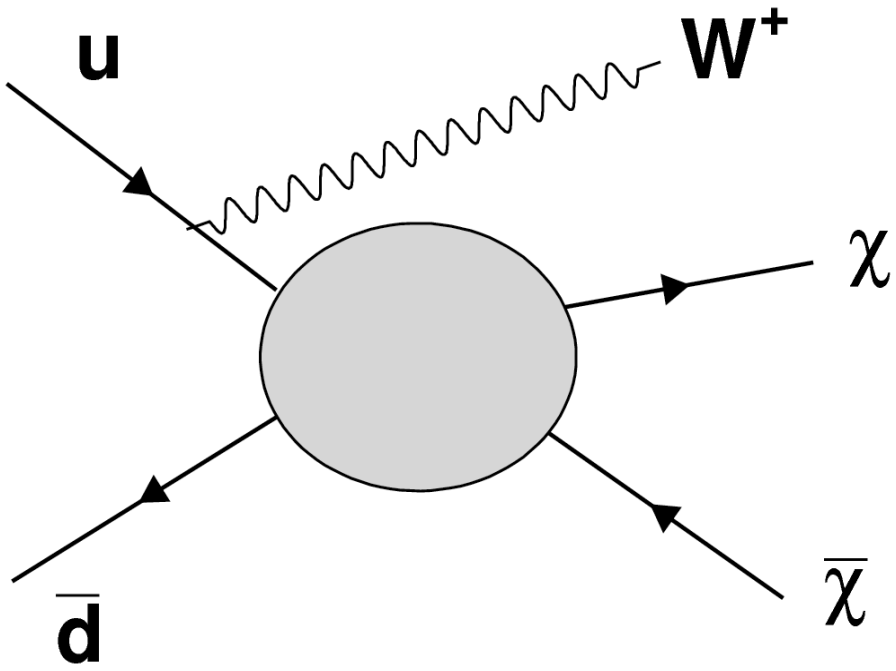
arXiv:1402.3244

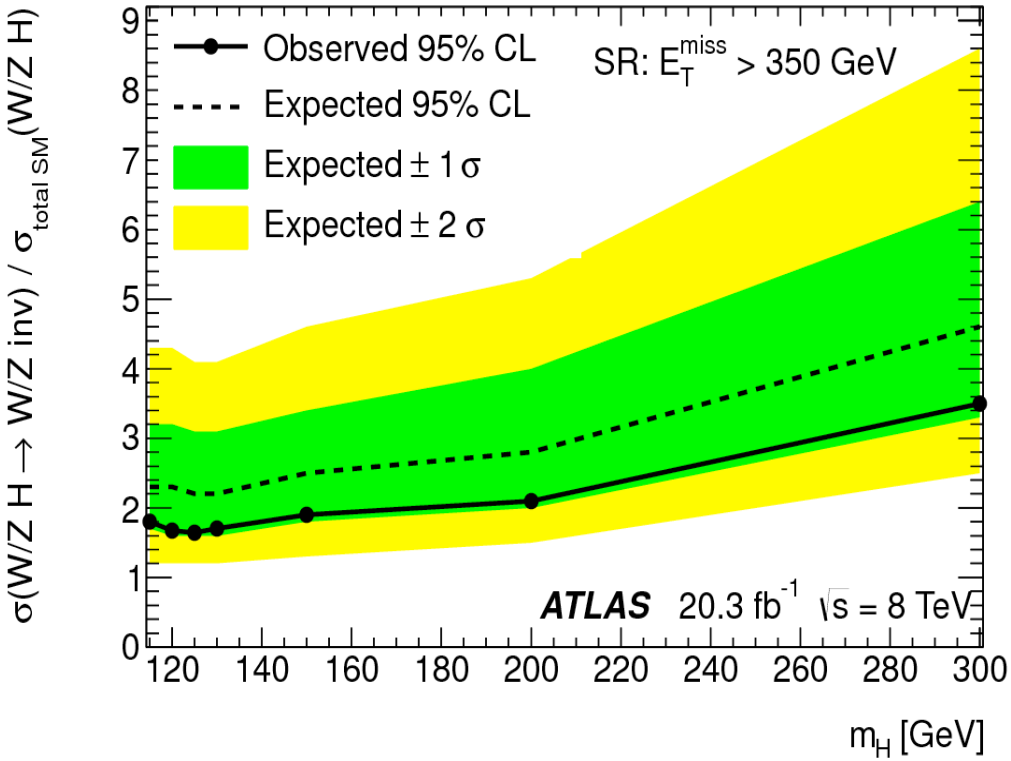


Limits on the dark matter (DM)-Higgs couplings at 90% CL in a Higgs-portal scenario, extracted from the ATLAS Higgs to invisible particles branching ratio limit. The results are shown for three model variants in which the DM candidate is a scalar, a vector or a Majorana fermion particle.

ATLAS MonoV interpretation for H → invisible

arXiv:1309.4017

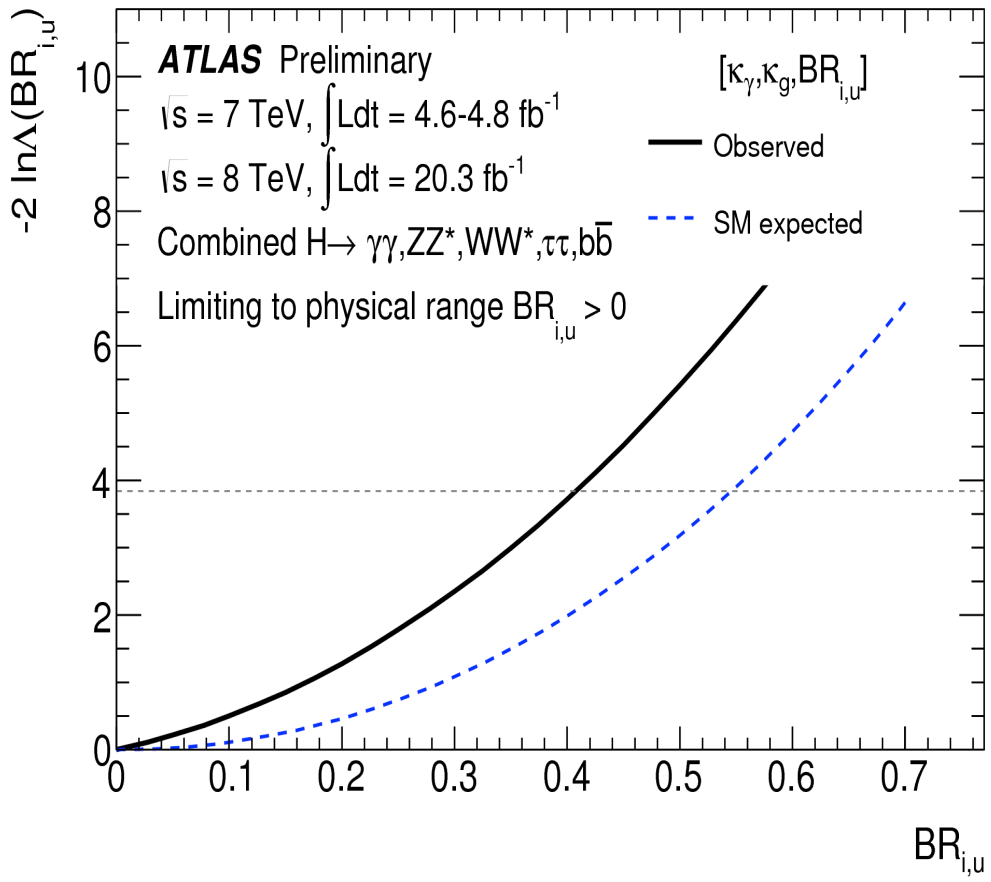


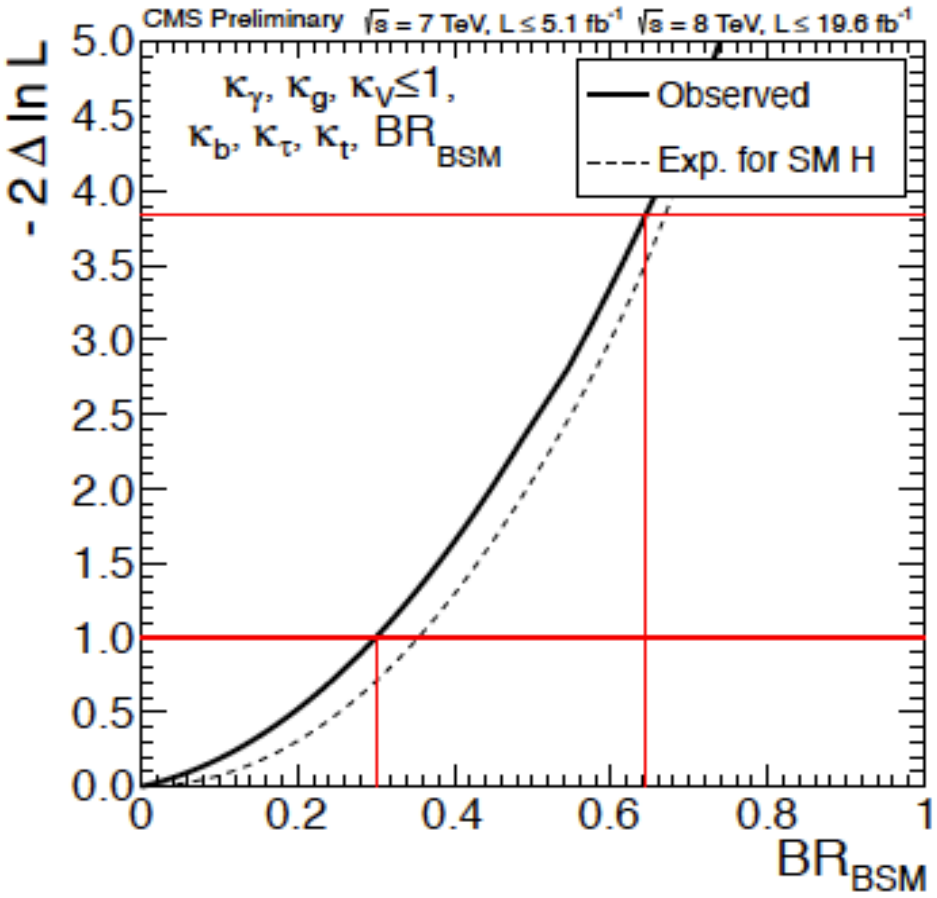


- 95% CL @125 GeV. R = 1.6
- On-going dedicated analysis of V (→jj)Hinv should improve this limit

From coupling fit

ATLAS-CONF-2014-010





BR (H → invisible)

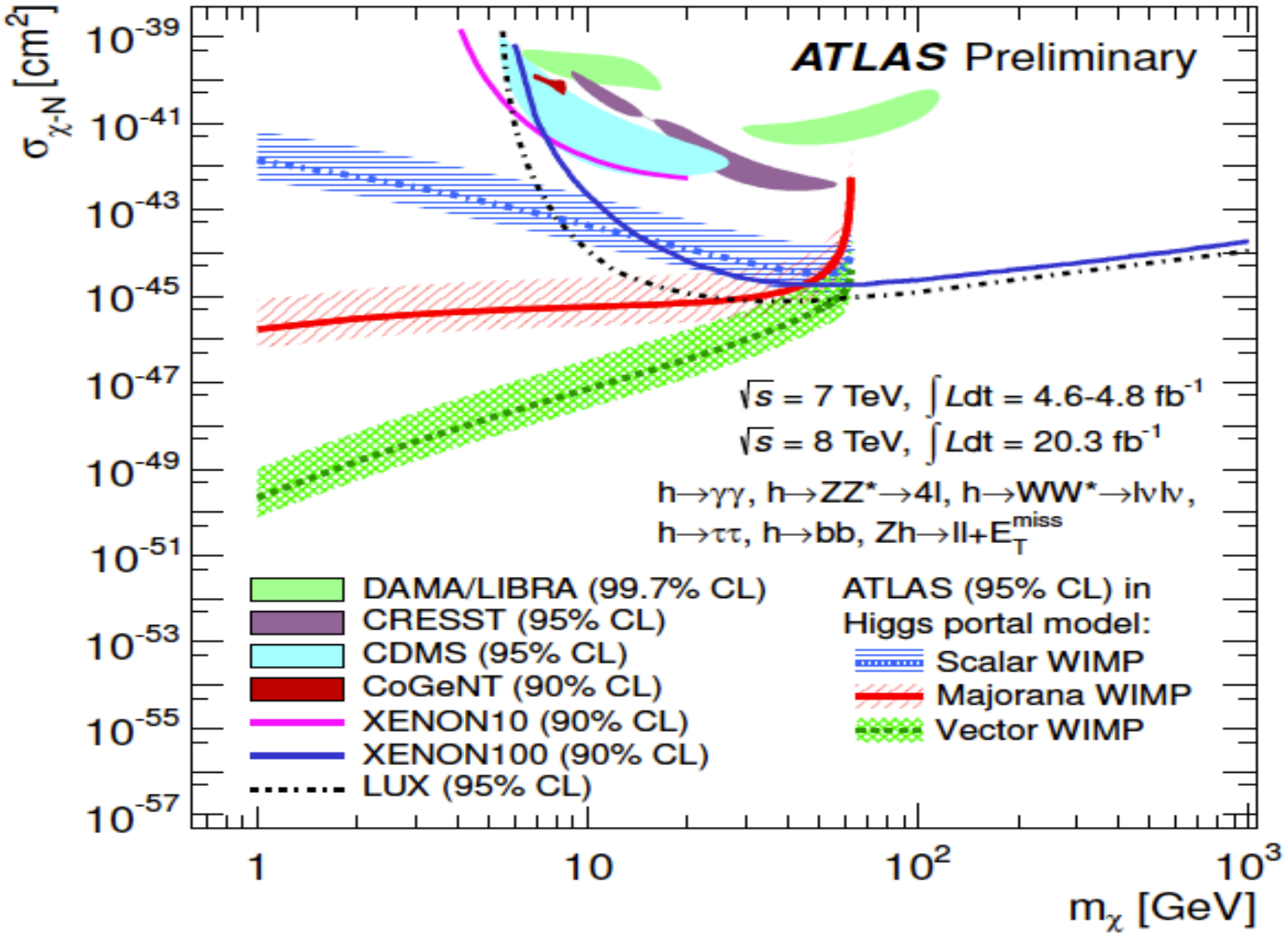
- **< 0.41 (95%)**
- **< 0.37 by including Z(ll) Hinv**

BR (H → invisible)

– < 0.64 (95%)

From the coupling fit

ATLAS-CONF-2014-010



Monojet H → invisible

Direct detection of Higgs–portal dark matter at the LHC

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We consider the process in which a Higgs particle is produced in association with jets and show that monojet searches at the LHC already provide interesting constraints on the invisible decays of a 125 GeV Higgs boson. Using the existing monojet searches performed by CMS and ATLAS, we show the 95% confidence level limit on the invisible Higgs decay rate is of the order of the total Higgs production rate in the Standard Model. This limit could be significantly improved when more data at higher center of mass energies are collected, provided systematic errors on the Standard Model contribution to the monojet background can be reduced. We also compare these direct constraints on the invisible rate with indirect ones based on measuring the Higgs rates in visible channels. In the context of Higgs portal models of dark matter, we then discuss how the LHC limits on the invisible Higgs branching fraction impose strong constraints on the dark matter scattering cross section on nucleons probed in direct detection experiments.

$$R_{\rm inv}^{\rm ggF} = \frac{\sigma(gg \to H) \times {\rm BR}(H \to {\rm inv.})}{\sigma(gg \to H)_{SM}},$$

$$R_{\rm inv}^{\rm VBF} = \frac{\sigma(qq \to Hqq) \times {\rm BR}(H \to {\rm inv.})}{\sigma(qq \to Hqq)_{SM}}.$$

$p_T^{\rm miss}$[GeV]	$N_{\rm inv}^{\rm gg}$	$N_{\rm inv}^{\rm V}$	$\Delta N_{95\%}^{\rm exp}$	$\Delta N_{95\%}^{\rm obs}$	exp. $R_{\rm inv}^{\rm pp}$	obs. $R_{\rm inv}^{\rm pp}$
250	250	110	779	600	2.1	1.6
300	110	50	325	368	2.1	2.3
350	46	25	200	158	2.8	2.2
400	22	13	118	95	3.4	2.7

$p_T^{\rm miss}$[GeV]	$N_{\rm inv}^{\rm gg}$	$N_{\rm inv}^{\rm V}$	$\Delta N_{\rm Bkg}$	exp. $R_{\rm inv}^{\rm pp}$	obs. $R_{\rm inv}^{\rm pp}$
120	5694	1543	12820	3.5	4.4
220	904	286	1030	1.7	1.6
350	110	45	171	2.2	3.3
500	15	9	73	6.0	1.4

$R_{\rm inv}^{\rm pp} \leq 1.10$ at 95% CL.

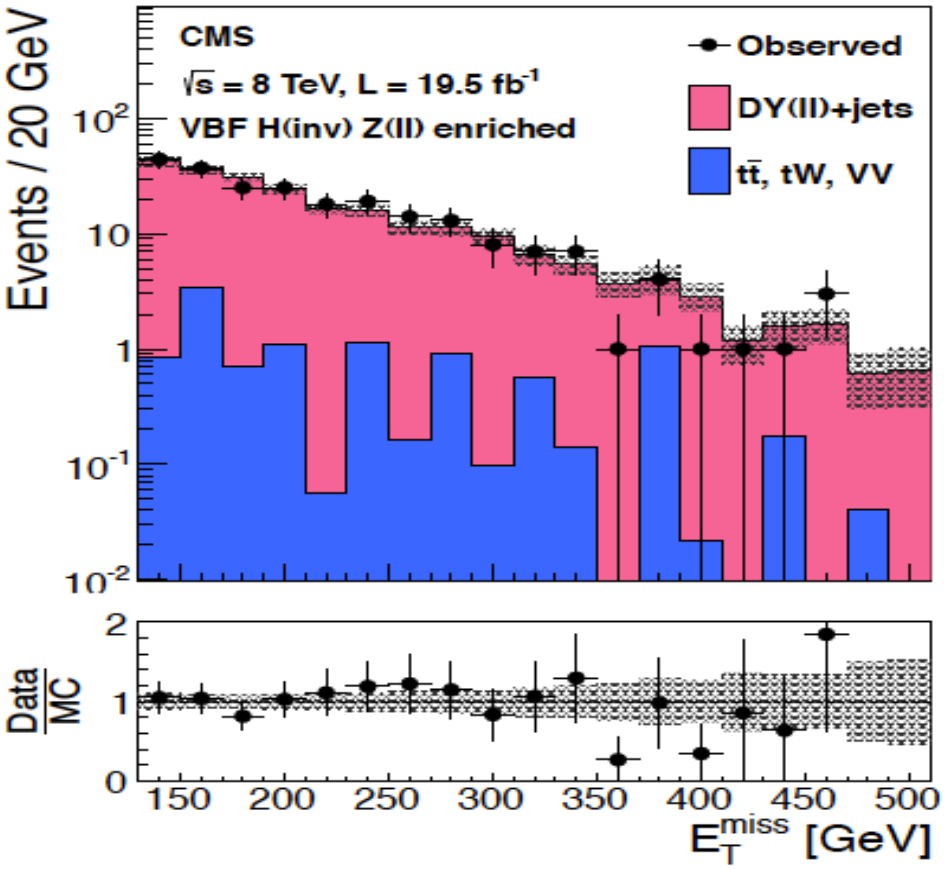
CMS VBF Hinv

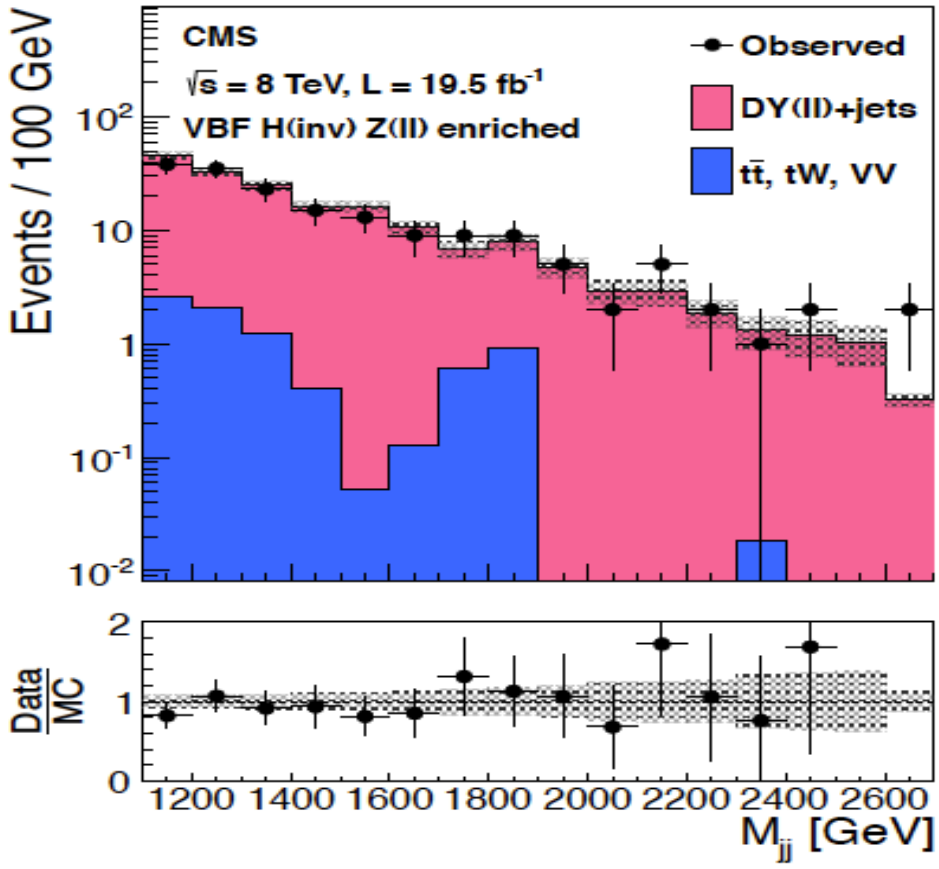
- **Special VBF + MET L1&HL triggers**
  - MET > 65 GeV in association with a pair of jets (pT>40 GeV) with VBF topology
  - At trigger level, MET calculation does not include muons. To allow for control samples of $W\mu\nu$ and $Z\mu\mu$ to be taken with same trigger
- **Offline selections**
  - Veto events with electrons or muons of pT > 10 GeV
  - Require VBF tag jet pair: pT > 50 GeV, $\eta_1\eta_2<0$, $|\eta|<4.7$ and $|\delta\eta|>4.2$, m_{jj} > 1100 GeV and MET > 130 GeV

CMS VBF H → invisible

arXiv:1404.1344

- Zνν estimated from Zμμ
- Wlν estimated from single lepton control region
- QCD multijet estimated using ACBD method MET and fail/pass CJV (subtracting EW backgrounds using MC)





Data consistent with the background. Dominated by V+jets

CMS VBF Hinv

- Uncertainties

Source	Total background	Signal
Control region statistics	11%	—
MC statistics	11%	4%
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale/resolution	7%	13%
QCD background estimation	4%	—
Lepton efficiency	2%	—
Tau ID efficiency	1%	—
Luminosity	0.2%	2.6%
Cross sections	0.5–1%	—
PDFs	—	5%
Factorization/renormalization scale	—	4%
Gluon fusion signal modelling	—	4%

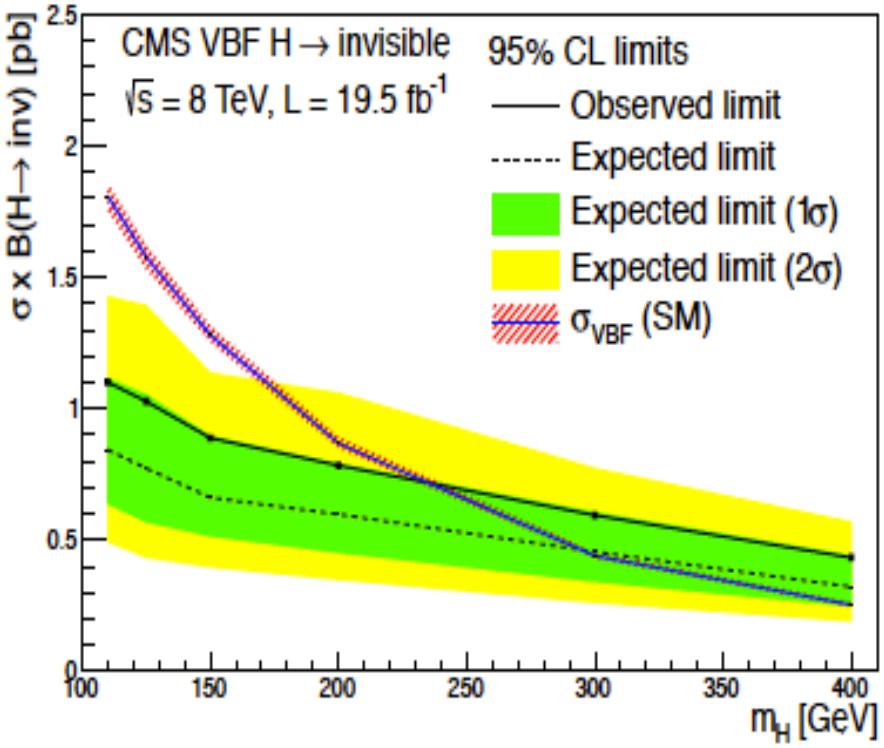
CMS VBF Hinv

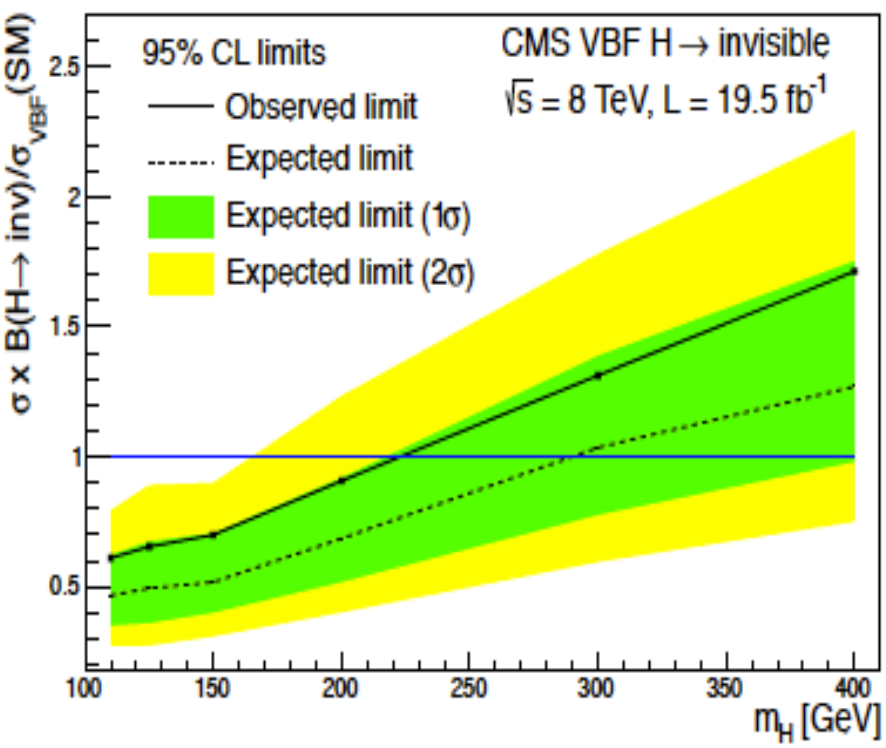
Process	Event yields
$Z(\nu\nu)$+jets	99 ± 29 (stat.) ± 25 (syst.)
$W(\mu\nu)$+jets	67 ± 5 (stat.) ± 16 (syst.)
$W(e\nu)$+jets	63 ± 9 (stat.) ± 18 (syst.)
$W(\tau_h\nu)$+jets	53 ± 18 (stat.) ± 18 (syst.)
QCD multijet	31 ± 2 (stat.) ± 23 (syst.)
Sum ($t\bar{t}$, single top quark, VV, DY)	20.0 ± 8.2 (syst.)
Total background	332 ± 36 (stat.) ± 46 (syst.)
VBF H(inv.)	210 ± 30 (syst.)
ggF H(inv.)	14 ± 11 (syst.)
Observed data	390
S/B (%)	70

- For mH = 125 GeV, assuming BR Hinv = 100%

CMS VBF H → invisible

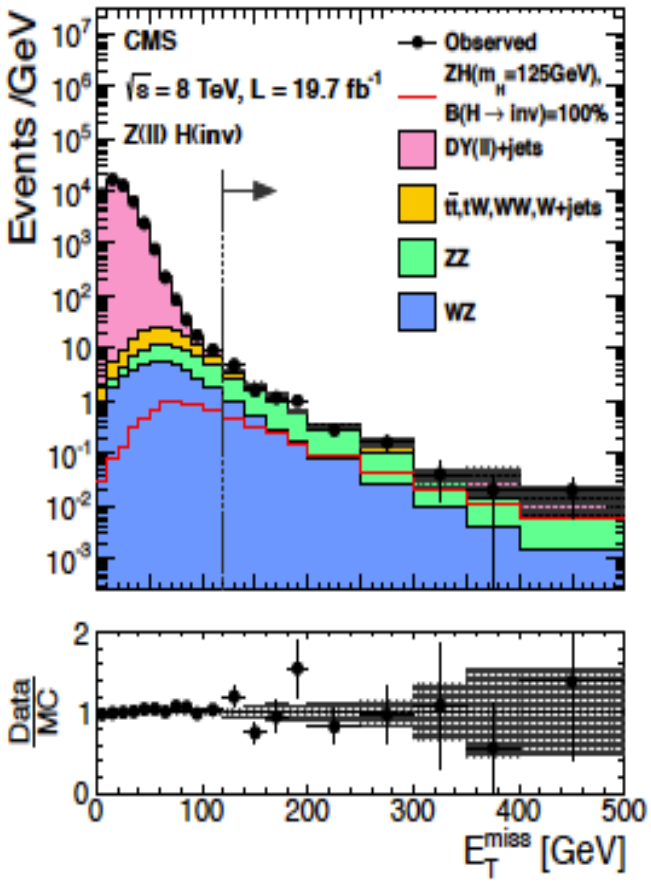
arXiv:1404.1344

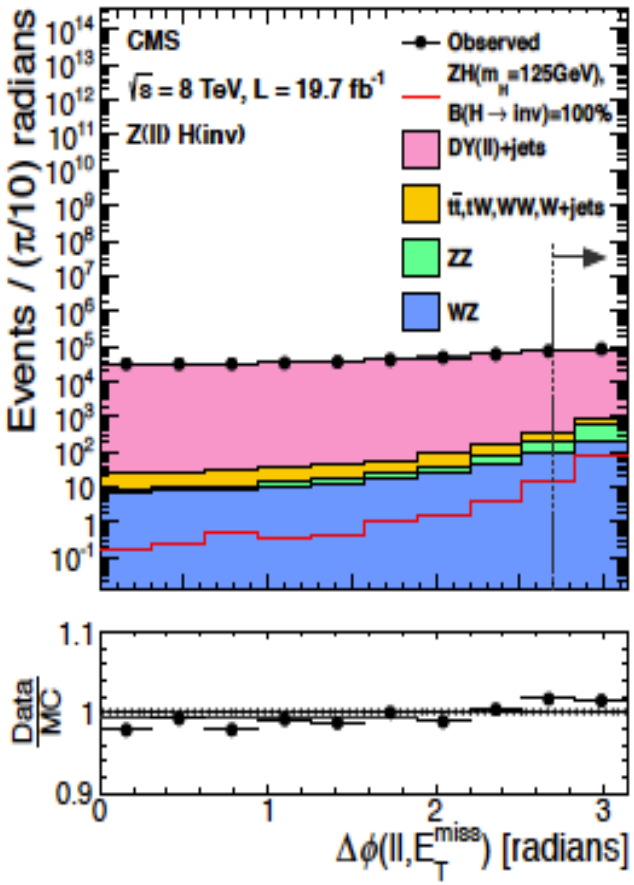


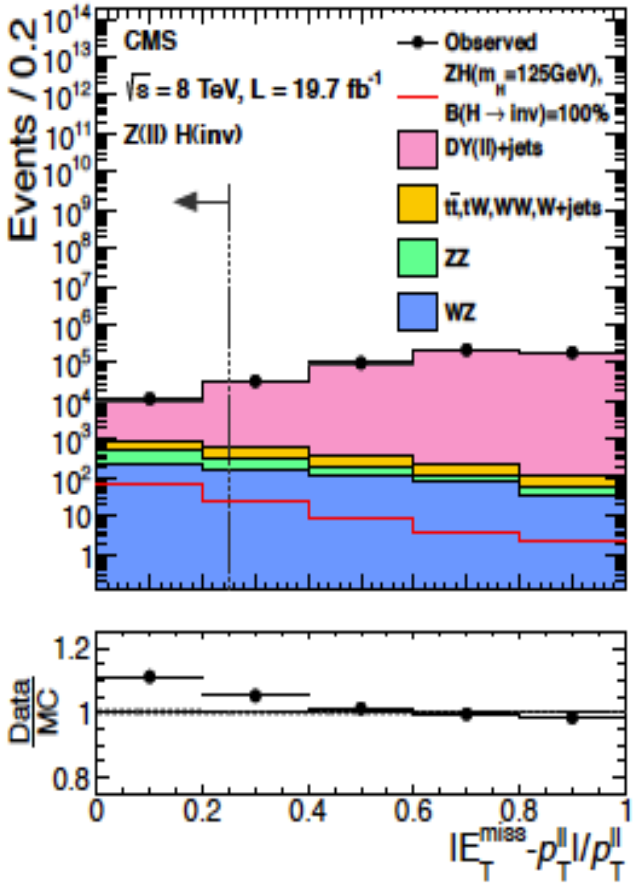


- 95% CL upper bound on BR (H->invisible) @ 125 GeV = 65% (49% expected)

CMS ZH (Z→ll, H → invisible)

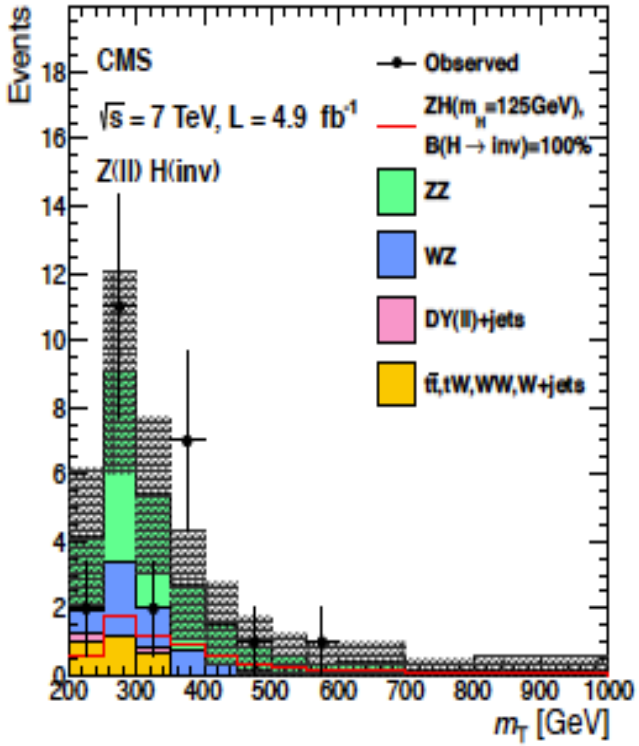


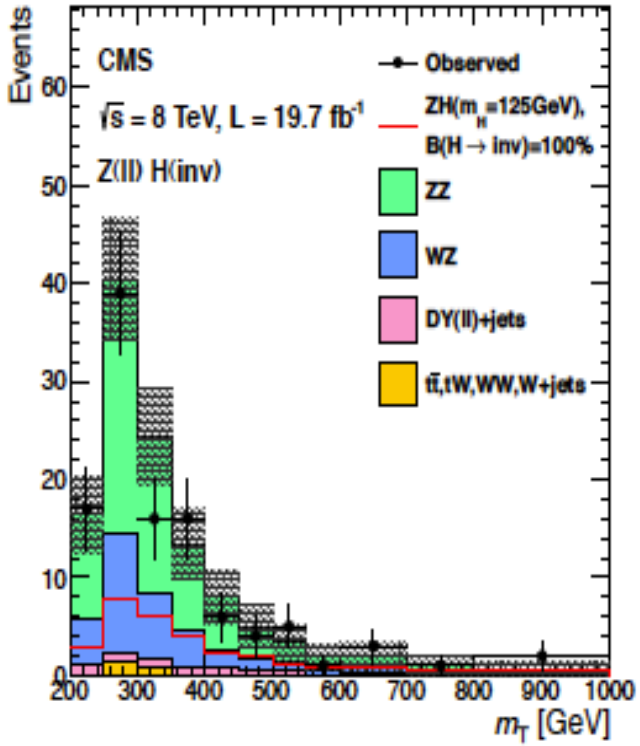


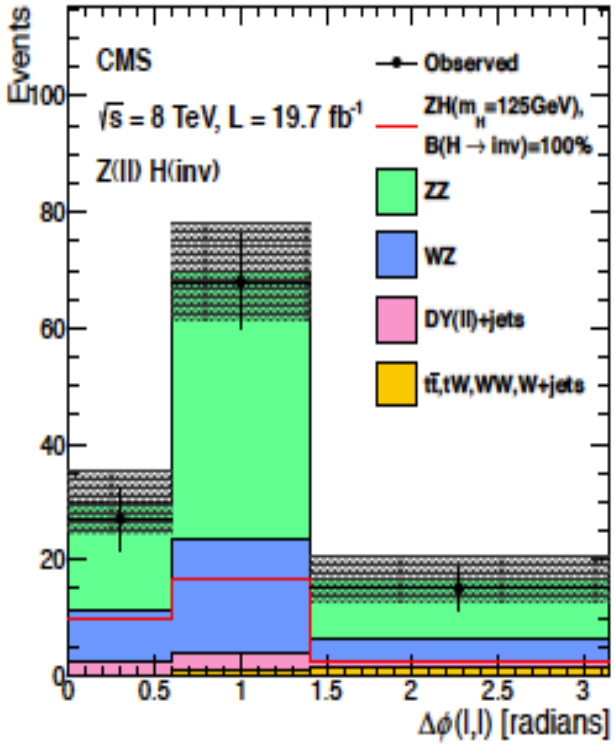


The arrows correspond to the cut applied for the final selections

CMS ZH (Z→ll, H → invisible)







- The distributions used for setting limits

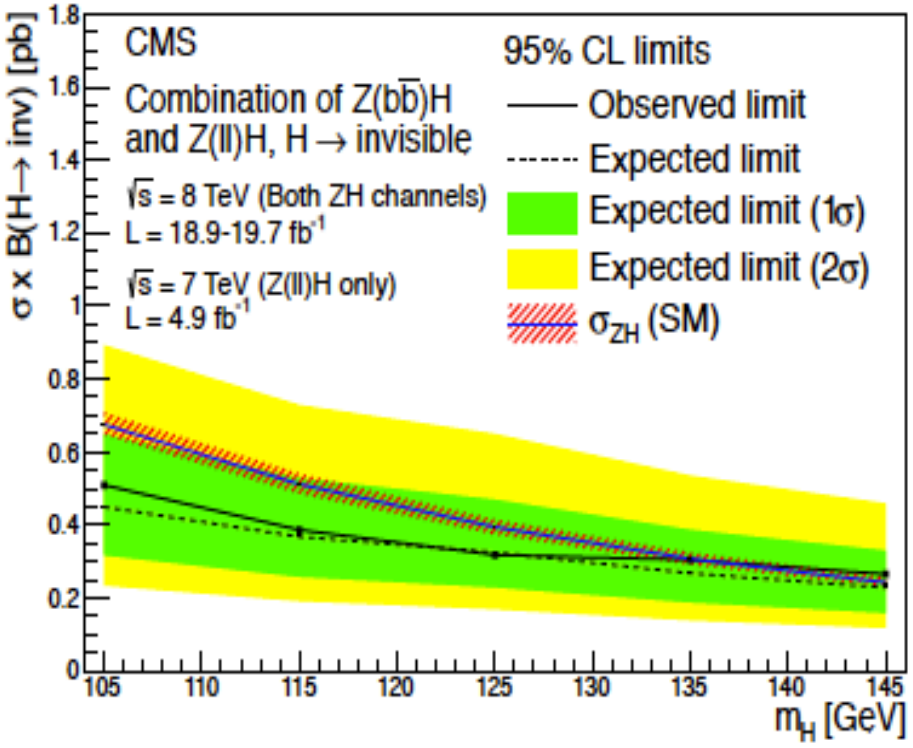
CMS ZH (Z→ll, H → invisible)

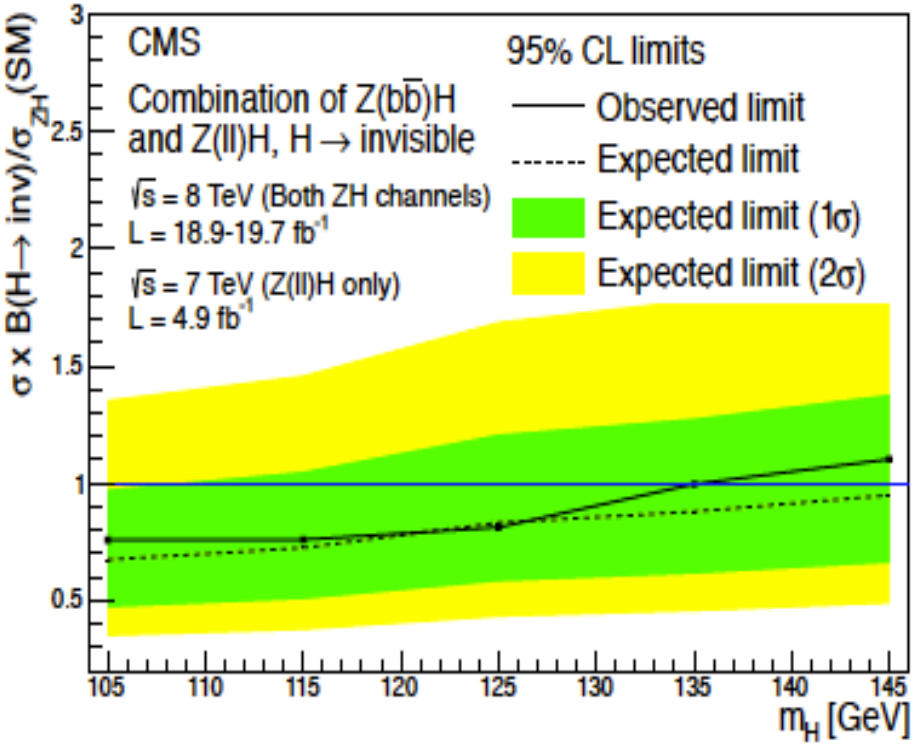
Process	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	ee	$\mu\mu$	ee	$\mu\mu$
$ZH(125)$	2.2 ± 0.3	3.3 ± 0.5	11.8 ± 1.9	16.7 ± 2.5
$Z/\gamma^* \to \ell^+\ell^-$	0.3 ± 0.3	0.7 ± 0.7	1.0 ± 1.0	1.9 ± 1.9
$WZ \to 3\ell\nu$	2.0 ± 0.3	2.3 ± 0.3	11.0 ± 1.6	14.8 ± 2.1
$ZZ \to 2\ell 2\nu$	5.1 ± 0.6	7.3 ± 0.8	29.8 ± 3.6	40.8 ± 4.5
$Top/WW/W + Jets$	0.4 ± 0.4	0.6 ± 0.6	1.3 ± 0.8	2.1 ± 1.3
total bkg.	7.8 ± 0.8	11.0 ± 1.3	43.1 ± 4.1	59.6 ± 5.5
Data	10	11	33	45

No excess observed

CMS ZH (Z→ll, H → invisible)

arXiv:1404.1344





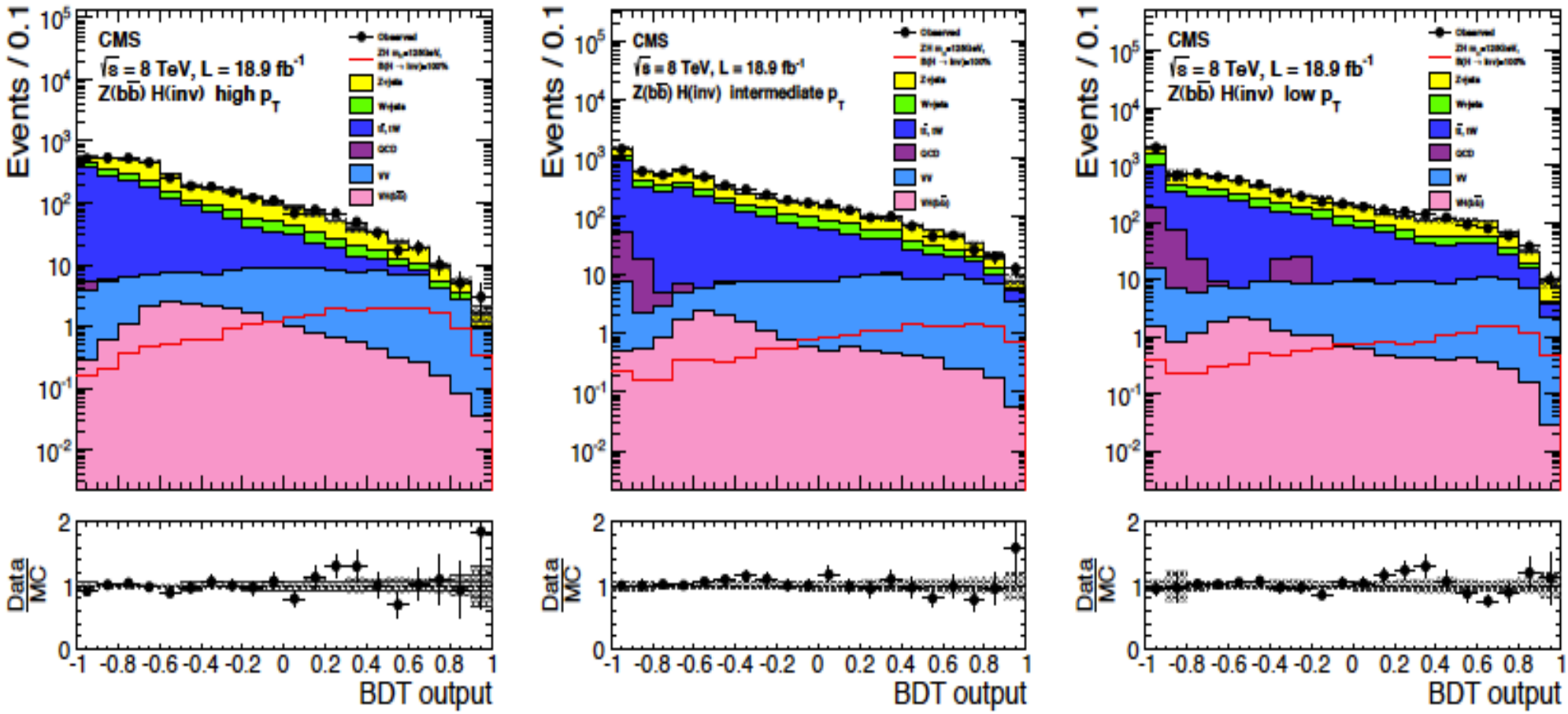
- Z(ll) Hinv: 95% CL @125 GeV BR (H → invisible) < 083% (0.86% Exp.)
- Z(bb)Hinv: 95% CL @125 GeV R(H→ invisible) < 1.82 (1.99)

CMS Z(bb)Hinv

Table 5: Selection criteria for the $Z(b\bar{b})H(inv)$ search, in the 3 $p_T(V)$ regions. The variables used are either described in the text or in Table 6.

Variable	Selection		
	Low p_T	Intermediate p_T	High p_T
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z, H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss}, j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss}, E_T^{miss}{}_{trk})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used

CMS Z(bb)Hinv

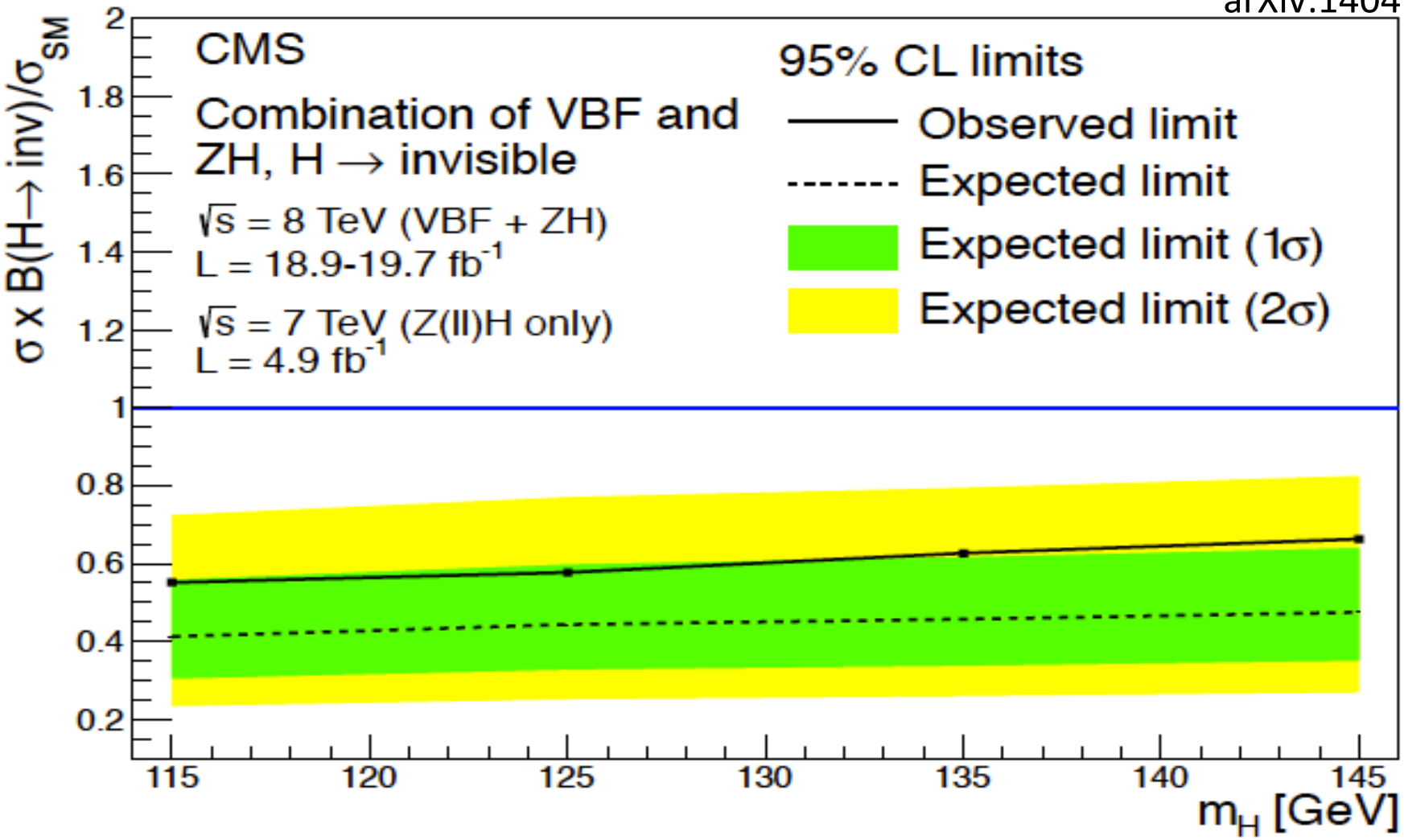


BDT output used for limit setting, for each of the pT bin categories

Z(bb)Hinv: 95% CL @125 GeV R(H→ invisible) < 1.82 (1.99 exp)

CMS VBF and ZH Combination

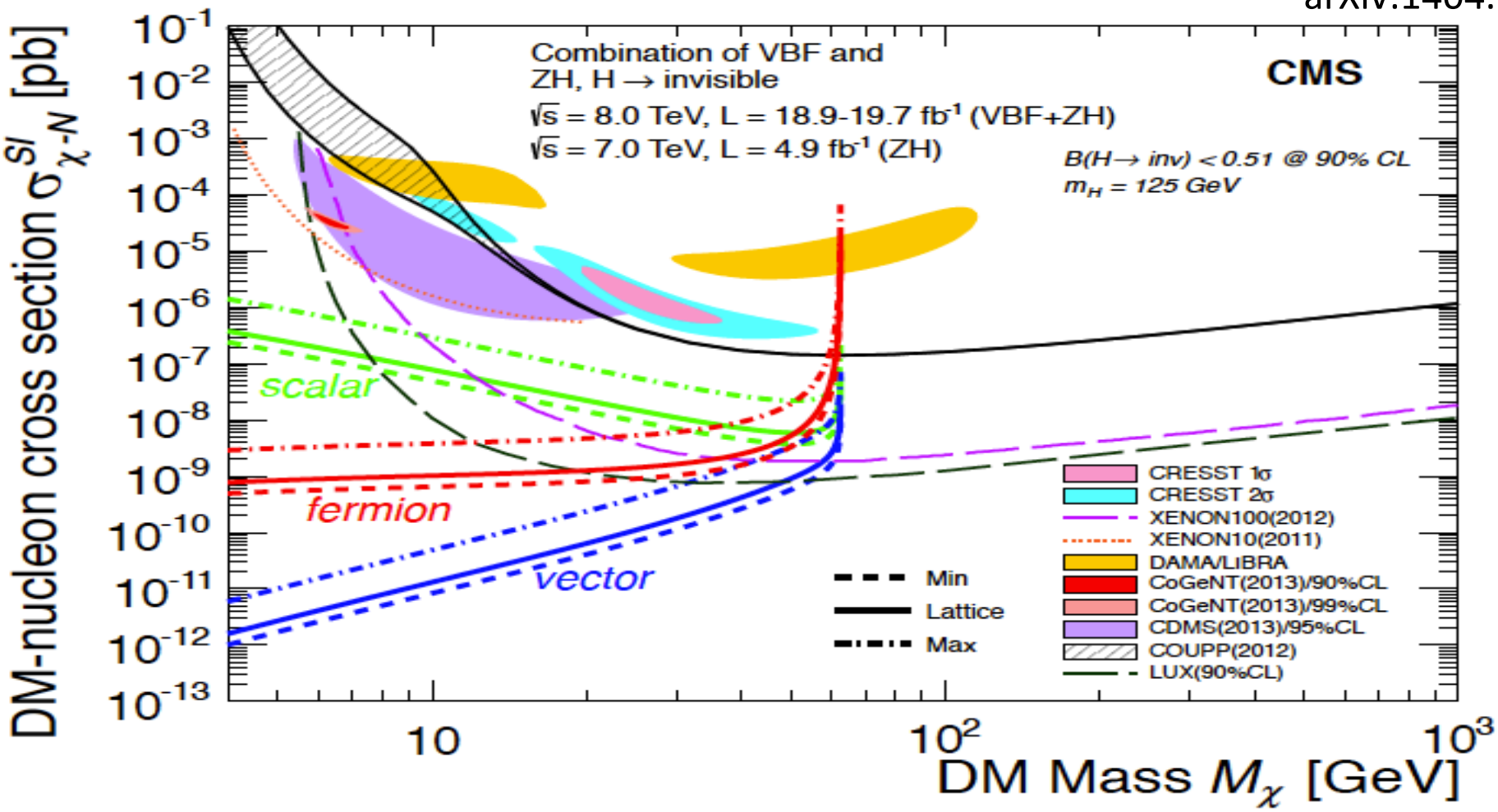
arXiv:1404.1344



- Z(ll+bb) + VBF Hinv: 95% CL @125 GeV BR (H → invisible) < 58% (0.44% Exp.)

CMS DM interpretation

arXiv:1404.1344



Limits on the DM-nucleon scattering cross section at 90% CL, extracted from the BR(H→inv.) limit in a Higgs-portal scenario, compared to results from direct-search experiments.

The results from the direct-search experiments do not depend on the assumptions of the Higgs-portal scenario.

Summary – current situation

H->invisible searches	ATLAS	CMS	Djouadi et al
ZH (Z→ll, H → invisible)	BR (Hinv) < 0.75	BR (Hinv) < 0.83	N/A
VBF H → invisible	In progress	BR (Hinv) < 0.65	N/A
Monojet H → invisible	In progress	?	R < 1.1 (CMS) R < 1.4 (ATLAS)
MonoV H → invisible	R < 1.6 (in progress)	?	N/A
Combination	In progress	0.58	N/A
From coupling fit	BR (Hinv) < 0.41	BR (Hinv) < 0.64?	

Projection for Run 2

ATL-PHYS-PUB-2013-014, CMS NOTE-13-002

From ZH→ll+invisible

	ATLAS	CMS
300 fb^{-1}	[23,32]%	[17,28]%
3000 fb^{-1}	[8,16]%	[6,17]%

From couling measurements

	ATLAS	CMS
300 fb^{-1}	[25,28]%	[14,18]%
3000 fb^{-1}	[12,15]%	[7,11]%

- With **300 fb^{-1}** of data, sensitivity reaches **BR(inv.) =23-32%** with ZH invisible channel alone. Similar reach from the coupling measurements.
- **Combination among channels & coupling measurement would provide even better sensivity.** → ATL-CONF-2014-010
- We may reach the sensitivity of BR(inv.)~10% before the HL-LHC.
- **Run 2 will be a very important milestone for the invisible Higgs search.**

Projection for Run 2

- ZH→ll+inv.: single lepton & dilepton triggers. Relatively high lepton p_T threshold would not be a problem, since Z is boosted. Anyway, dilepton triggers would stay in the future, so **this channel wil not suffer from the trigger menus.**

  CMS already has a VBF Hinv trigger

- VBF inv.: Currently xe80_tclcw or xe80_tclcw_loose. **Need to raise the MET threshold for Run 2 or use the VBF trigger?**

- Monojet: Currently xe80_tclcw. The offline E_T^{miss} cut is very high, so the trigger may not be a problem.

- VH→jj+inv.: **Will switch to the topological triggers?**