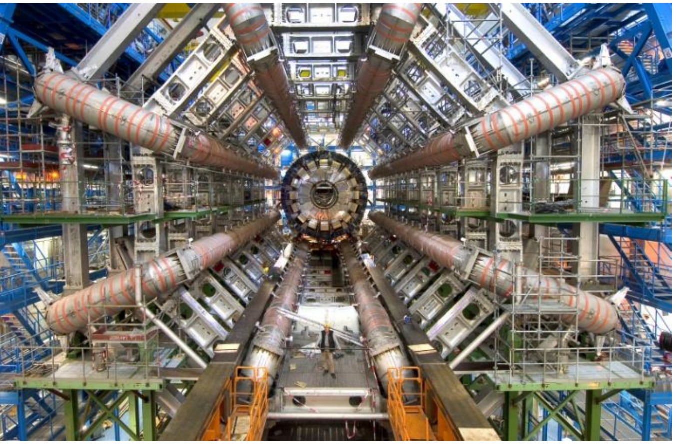
Searches for Invisible Higgs Boson Decays



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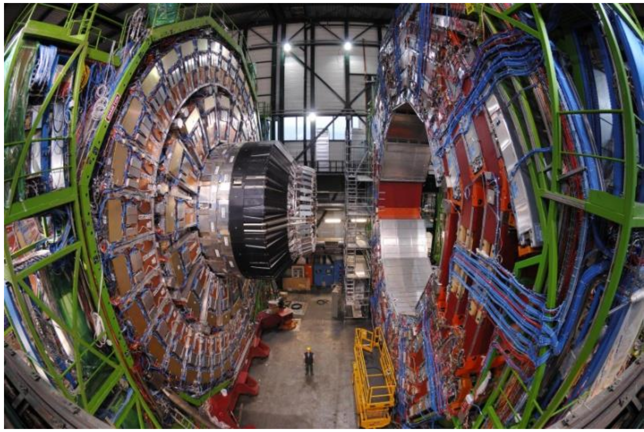


LPC – BSM Higgs Workshop, 2014

Outline

- Motivation and strategy
- Search via Vector Boston Fusion production
- Search with associated Z production
  - $Z \to \ell\ell$
  - $Z \to b\bar{b}$
- Limits
  - Production X branching fraction
  - SM ratio and invisible branching fraction
- Dark Matter interpretations
- Conclusions

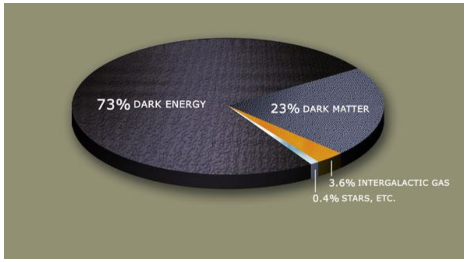
Invisible Decays of the Higgs Boson

- In MSM, invisible decays of the Higgs boson are extremely rare:

$$B(H \to Z^* Z \to \nu\bar{\nu}\nu\bar{\nu}) \approx 0.1\%$$

- Observation of substantial invisible decay rate would be definite sign of BSM physics. Long list of interesting invisible things that a Higgs might decay into:
  - LSPs of SUSY
    - Neutralinos, gravitinos
  - Graviscalars (large extra dimensions)
  - Dark matter
  - …

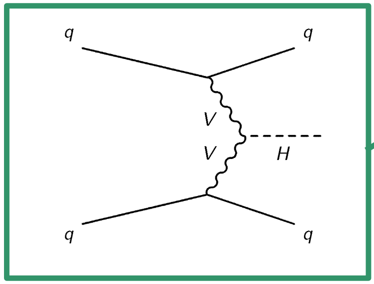
- Coupling to Dark matter
  - Higgs sector allows direct coupling to hidden sector that is renormalizable
    - Higgs portal

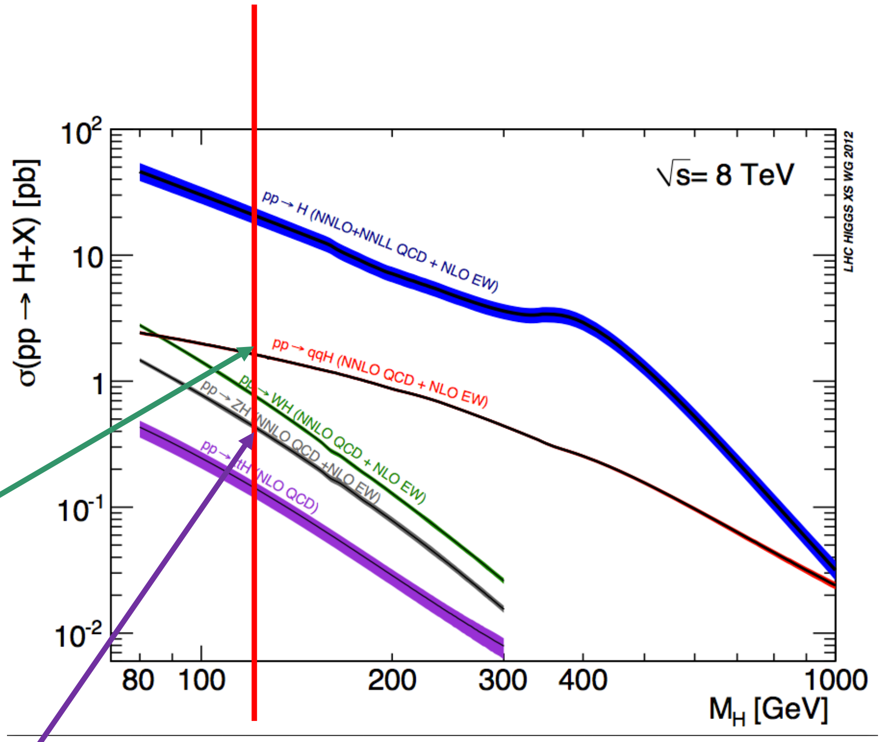


- Two approaches:
  - 125 GeV Higgs has been discovered – see how often it decays invisibly
  - Other Higgs states might have substantial invisible branching fractions, and thus escaped detection so far – scan Higgs mass hypothesis looking for invisible states

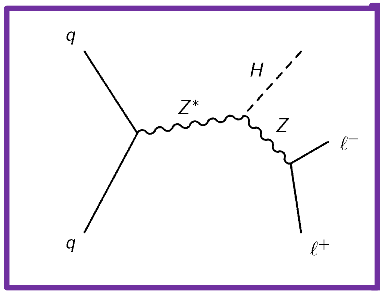
Invisible Higgs Detection method

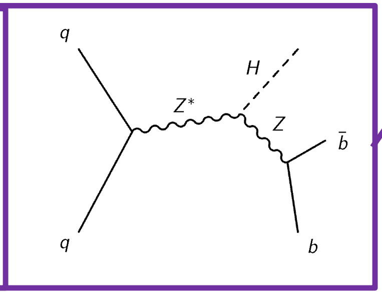
- Problem: how to detect a decay mode which is invisible
  - Need a recoiling system to tag the decay
  - Use associated production with forward/backward jets (Vector Boson Fusion)



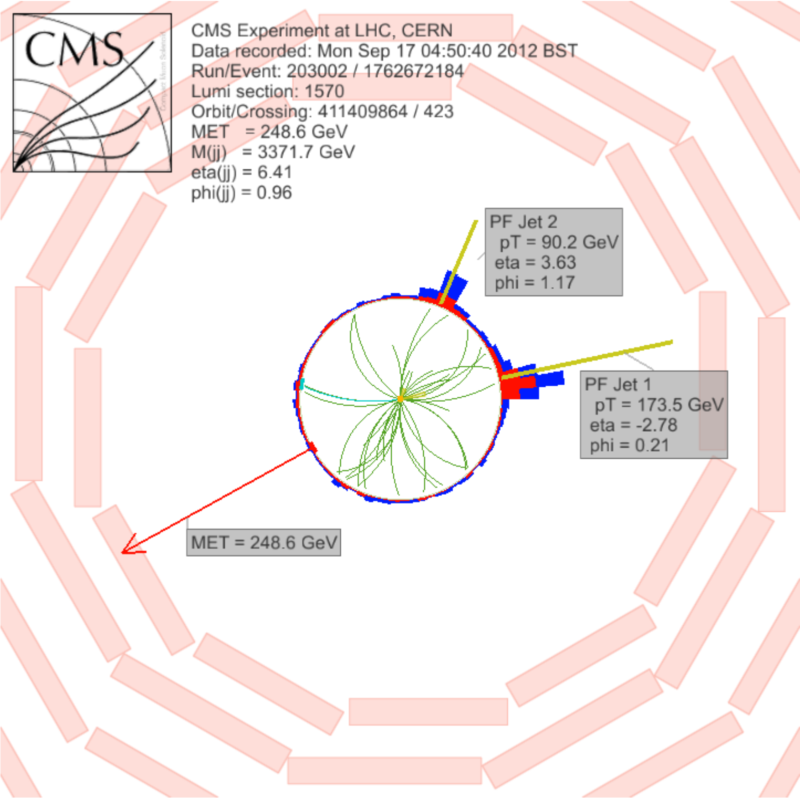


  - or with a Z boson

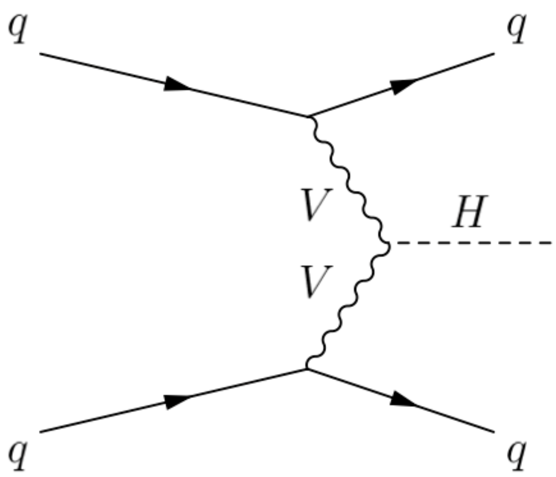




Vector Boson Fusion



- Signature:
  - Two jets at large positive and negative rapidities
  - Missing transverse energy



VBF selection

- 2 jets:
  - $p_T(j) > 50$ GeV
  - Opposite rapidity
  - $\Delta\eta(jj) > 4.2$
  - $M(jj) > 1100$ GeV
  - $\Delta\phi(jj) < 1.0$
- Missing $E_T > 130$ GeV
- Vetos:
  - Any leptons (reduce $W \rightarrow \ell\nu + jets$)
  - Central jets with $p_T >$ 30 GeV (reduce QCD multiljets)

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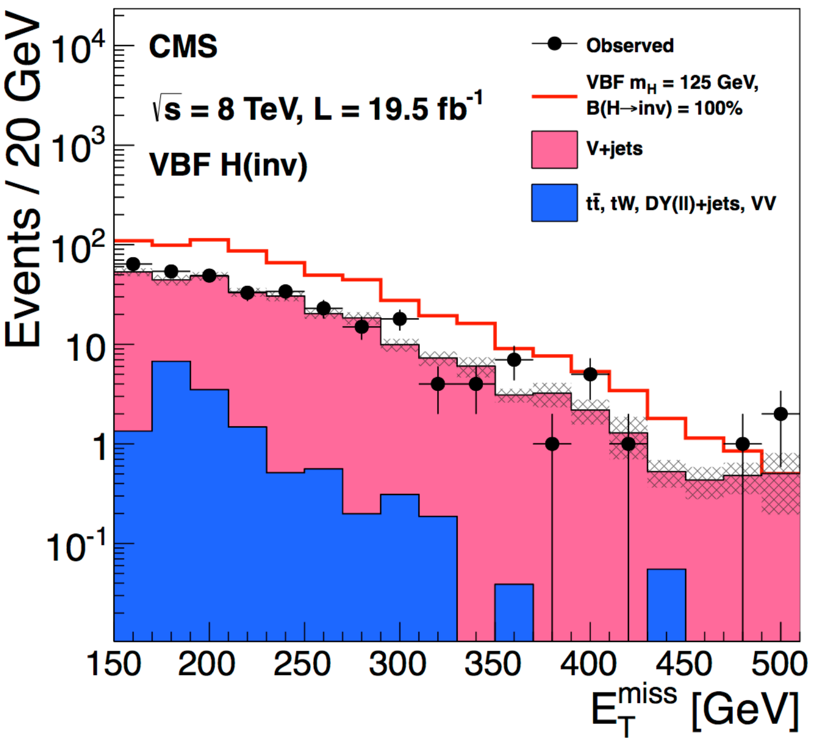
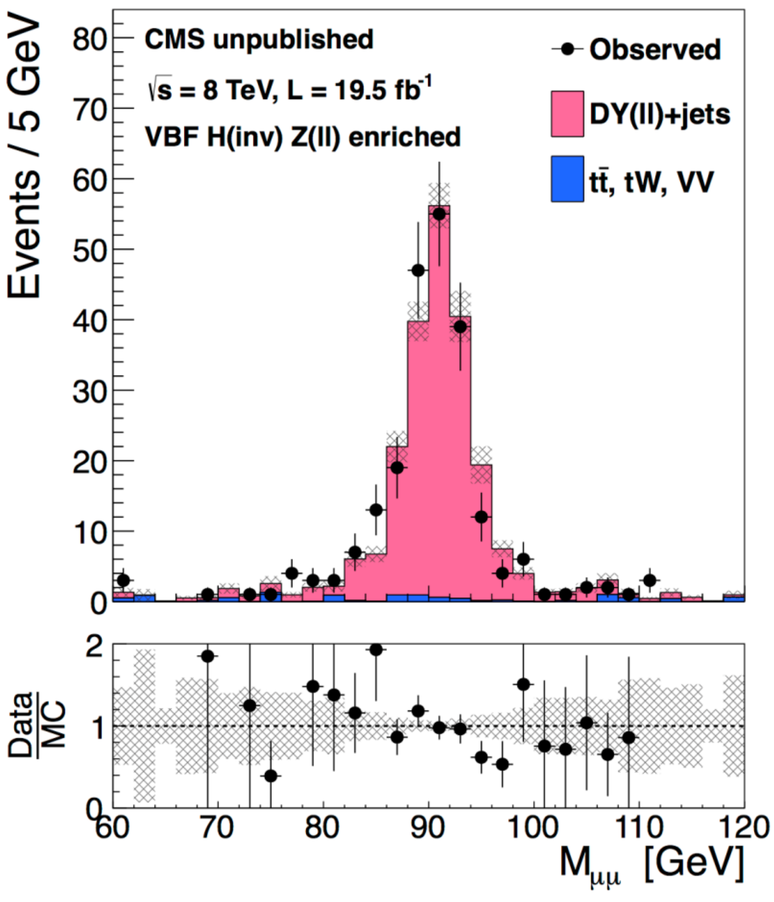


VBF background estimation



M(μμ) in control region with relaxed selection (no CJV, no Δη)

- Main background $(Z \to \nu\nu)$+jets estimated by measuring $Z \to \mu\mu$ and extrapolating with MC
  - Signal selection (without including muon in missing ET)
  - Two muons $60 < m(\mu\mu) < 120$ GeV
- $(W \to \ell\nu)$+jets estimated by requiring one e/μ/τ, and extrapolating from MC
- QCD multijet estimated by comparing regions in missing ET w/ and w/o central jet veto

VBF results

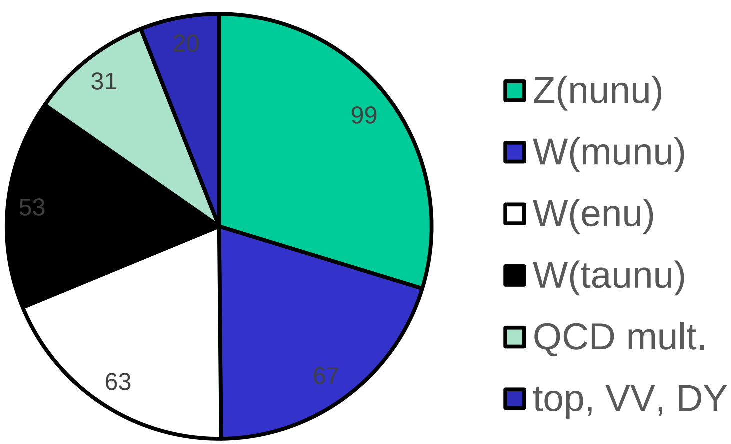
- Yields

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

- Uncertainties

Source	Total background	Signal
Control region statistics	11%	—
MC statistics	11%	4%
Jet/E_T^{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%

VBF background esitmates (events)



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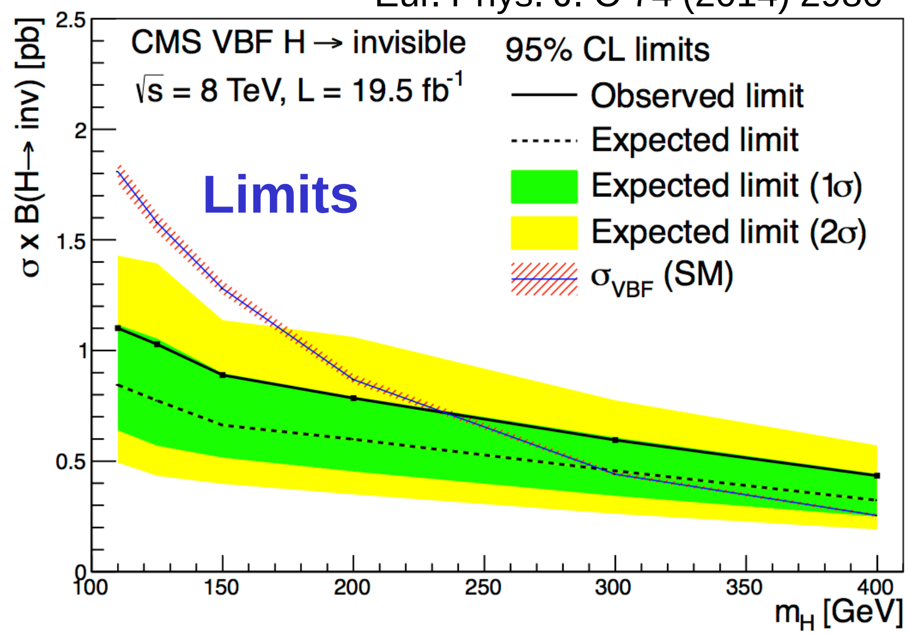
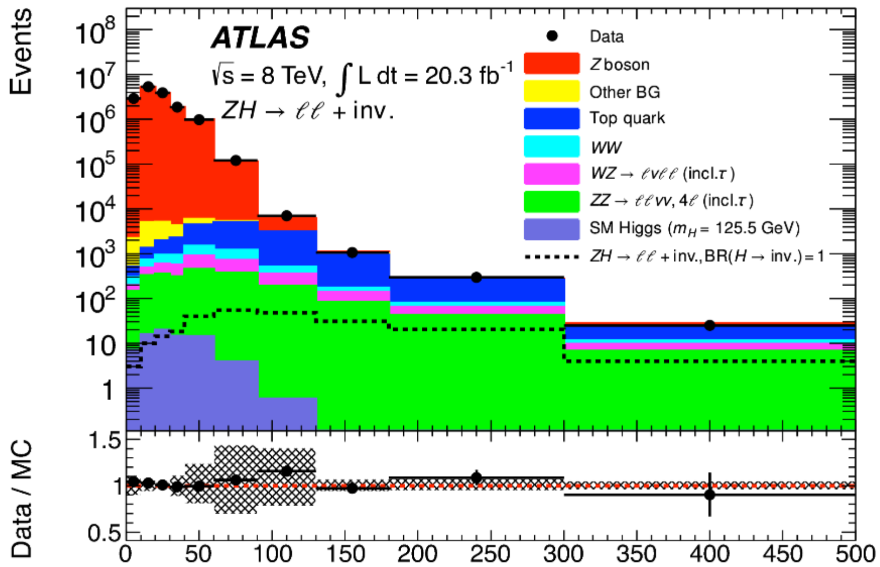


Z(ℓℓ)H(inv) - preselection

- Signature studied by both ATLAS and CMS
- Common preselections:
  - Pair of electrons or muons with opposite charge
  - Mass consistent with the Z boson mass



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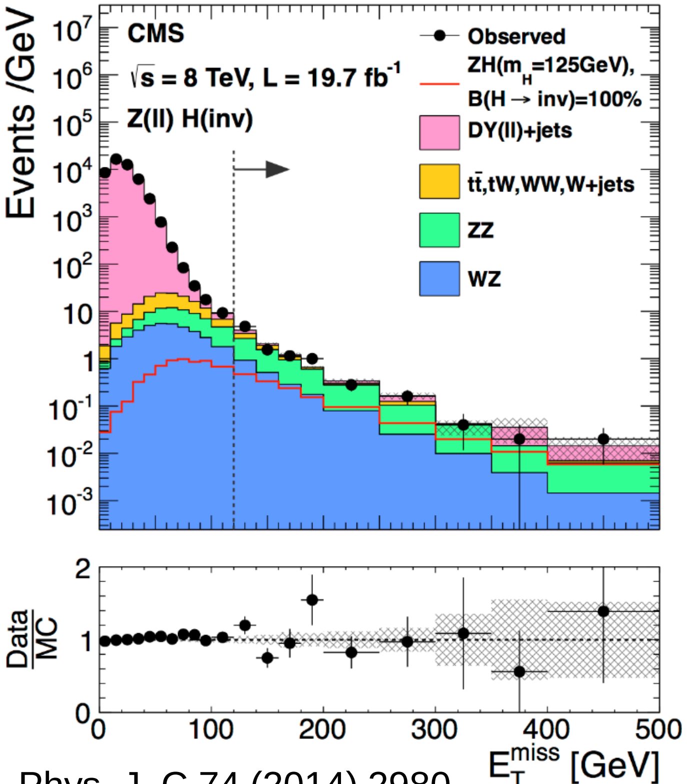
- Dominant background before Missing ET selection:
  - Drell-Yan Z→ℓℓ (+jets)



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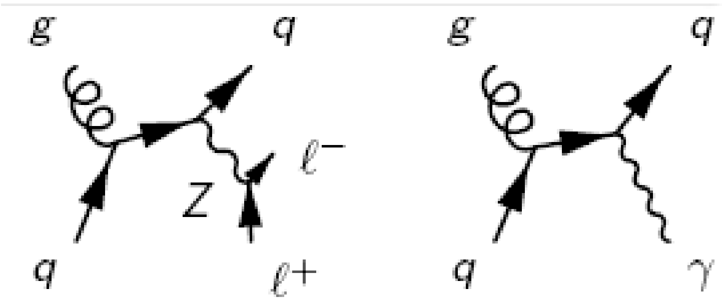
Background estimations $Z(\ell\ell)H(inv)$

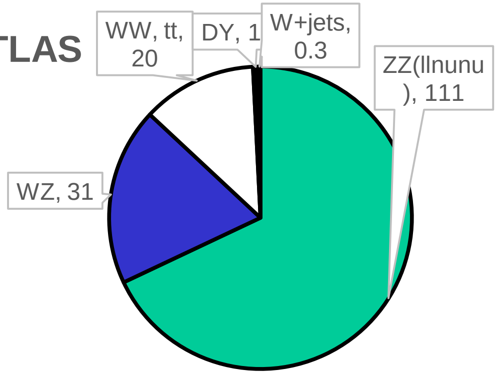
- DY (+jets) background: dominated by fake missing E_T – hard to estimate from MC
  - ATLAS – extrapolate from sideband regions in $\left|E_T^{miss} - p_T(\ell\ell)\right|/p_T(\ell\ell)$ and $\Delta\phi(E_T^{miss}, p_T^{miss})$
  - CMS – use $\gamma + jets$ data to model MET in $Z + jets$
    - Photon pT spectrum reweighted to match Z p_T
- Backgrounds without resonant $Z \rightarrow ee, \mu\mu$ are estimated from $e\mu$ events in data
  - $WW, t\bar{t}, Wt, Z \rightarrow \tau\tau$
- ZZ, WZ estimated from MC



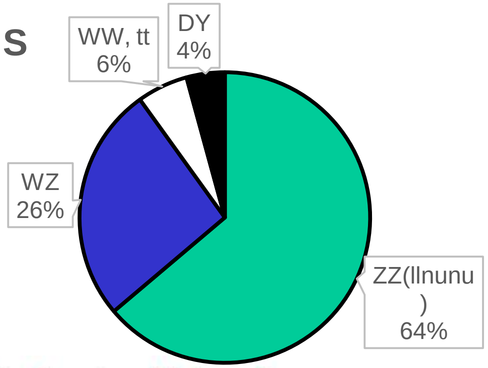
$Z(\ell\ell)H(inv.)$: final selections and yields

Selection	ATLAS	CMS
MET	>90 GeV	>120 GeV
$\Delta\phi(\ell\ell, MET)$	>2.6	>2.7
$\left\|E_T^{miss} - p_T(\ell\ell)\right\|/p_T(\ell\ell)$	<0.20	<0.25
Jet veto	<1 jets, p_T>25 GeV	<2 jets, p_T>30 GeV, veto b-jets > 20 GeV
	$\Delta\phi(E_T^{miss}, p_T^{miss})$>0.2, $\Delta\phi(\ell\ell) < 1.7$	
Yields (events)		
Backgrounds	163	138
Signal (100% B(inv))	53	35
Observed	180	134

ATLAS



CMS



Distributions used in final fits

- ATLAS
  - 1-D: Missing ET
- CMS
  - 8 TeV: 2-D: transverse mass vs. Δφ(ℓℓ)
  - 7 TeV: 1-D transverse mass

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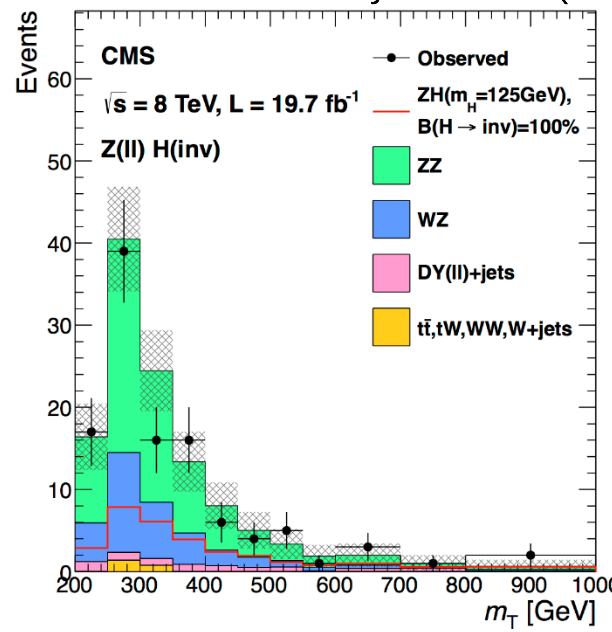

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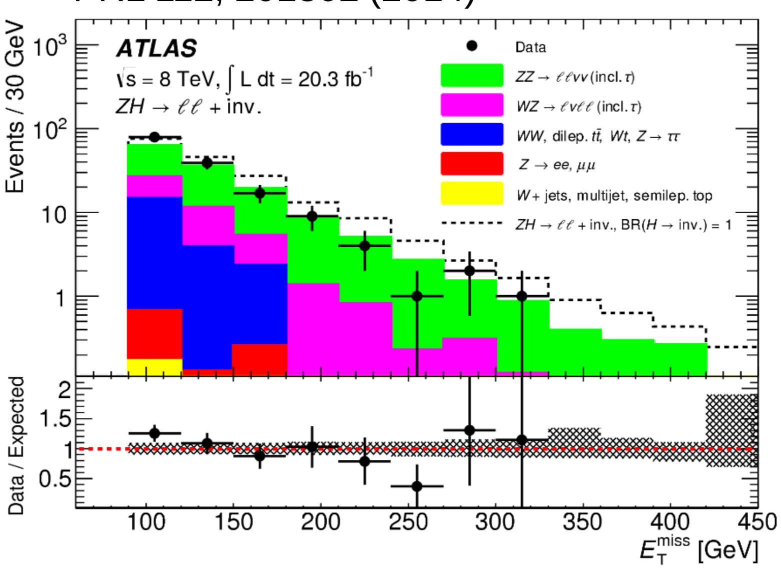
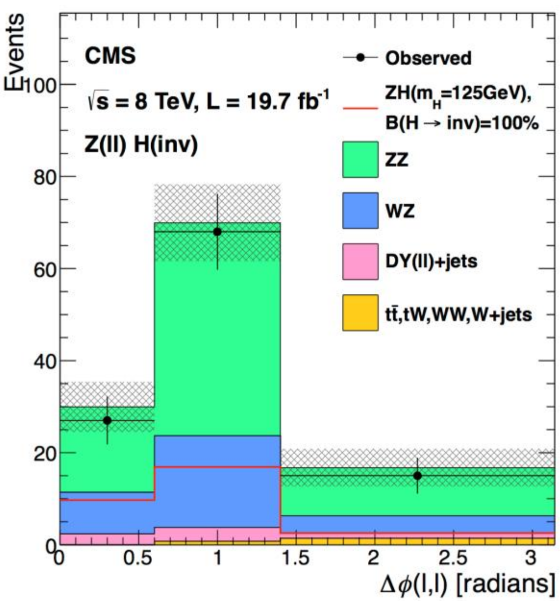




$Z(b\bar{b})H(inv.)$

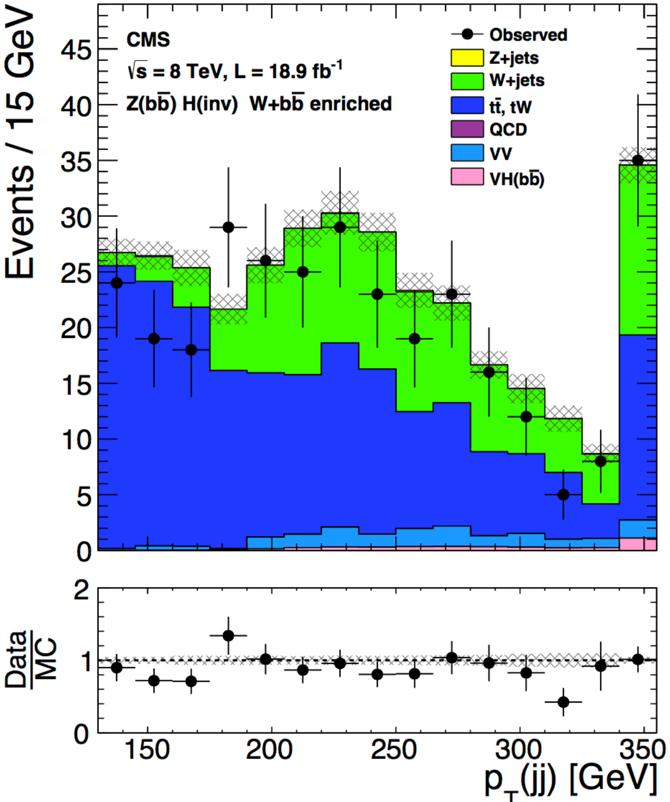
- Analysis closely based on CMS search for $Z(\nu\nu)H(b\bar{b})$
- Select a pair of jets consistent with a $Z(b\bar{b})$ hypothesis
  - p_T, invariant mass
  - b-tagging base on CSV
- Veto leptons to suppress ttbar and WZ
- Missing ET cuts to suppress QCD multijet background

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

$Z(b\bar{b})H(inv.)$

- Background normalized in seven background-enriched control regions:
  - Z+jets (0,1,2 b-jets)
  - W+jets (0,1,2 b-jets)
  - $t\bar{t}$
- Finally, Boosted Decision Tree (BDT) is used to distinguish signal from background

Example: $W + b\bar{b}$ control region:



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evnets	Low p_T	Intermediate p_T	High p_T
Background	40±4	65±4	181±10
Signal (B(inv.)=100%)	1.6±0.1	3.6±0.3	12.6±1.1
Observed	38	61	204

$Z(b\bar{b})H(inv.)$ - results

- No excess observed
  - Set limits
- Limit at 1.8 SM cross section (for 100% B(inv) at m=125 GeV)
  - Expected 2.0xSM

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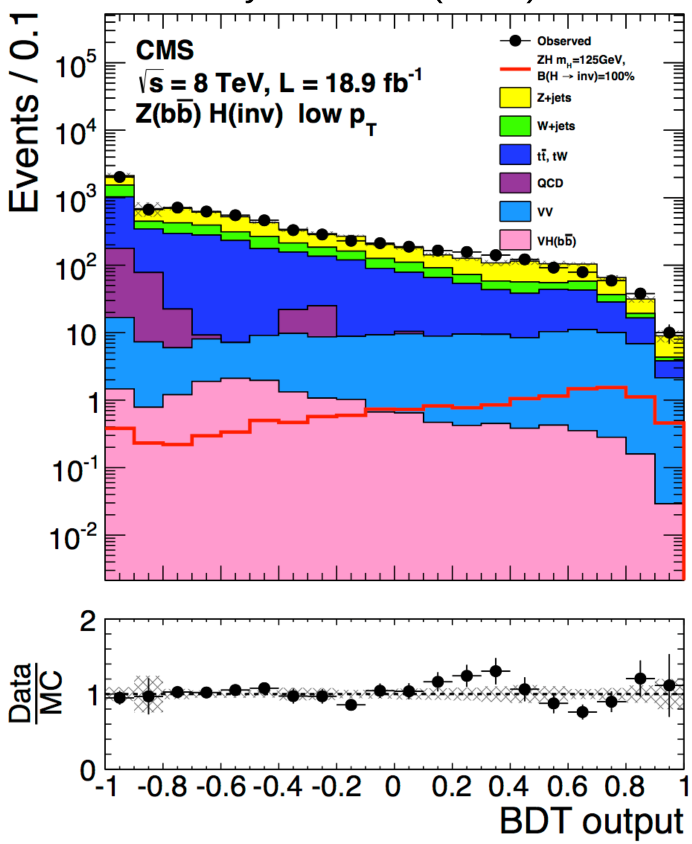

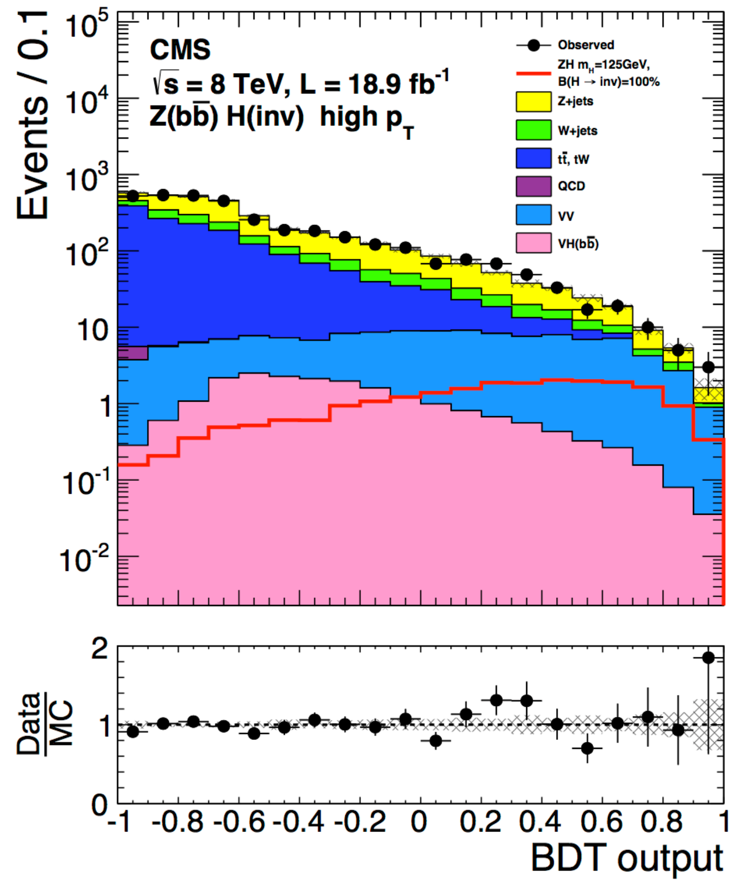

Limits from ZH modes

- Limits on ZH production times B(inv.)
  - Applicable to non-SM Higgs searches with some caveats

$ZH \to \ell\ell + inv$

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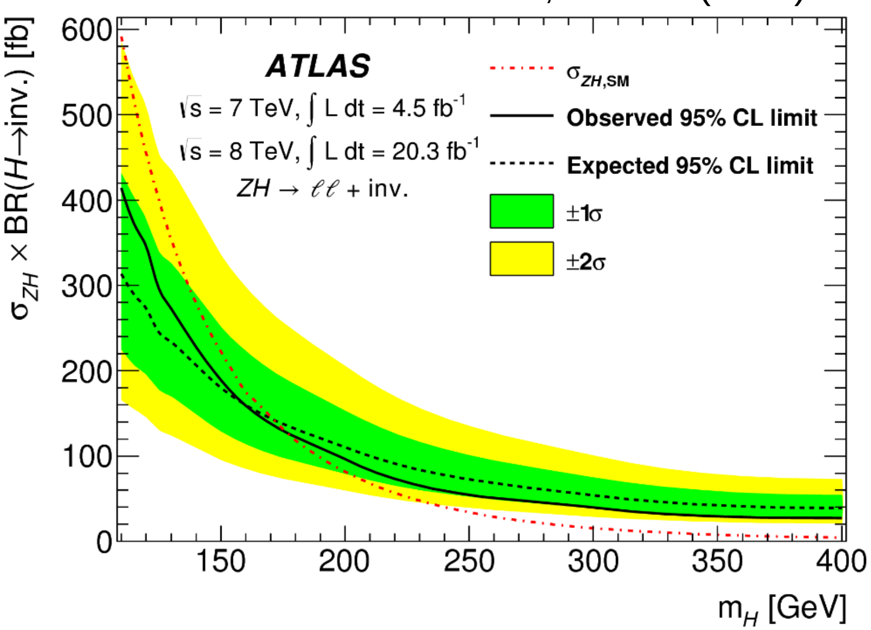

$ZH \to \ell\ell, b\bar{b} + inv$

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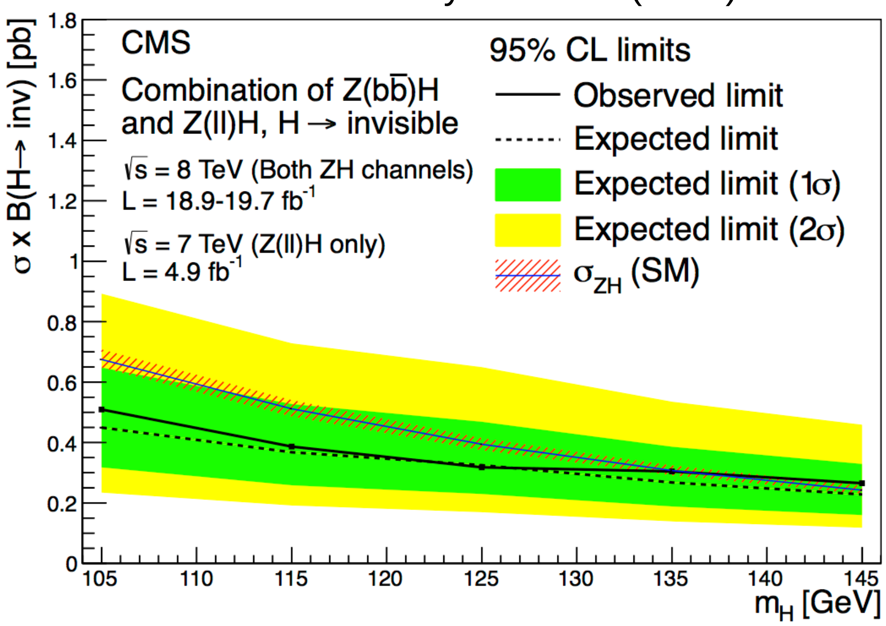
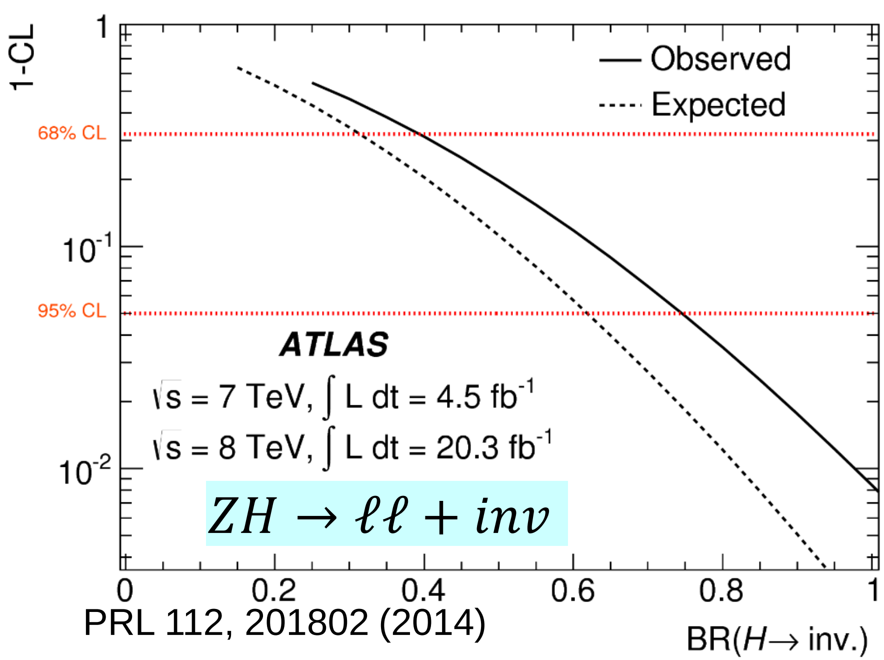


Normalized limits

- Normalized Limits can be interpreted as limits on B(inv) assuming production is same as in SM

- ATLAS (m_H=125.5 GeV)
  - B(inv)<75%
  - 62% expected

- CMS (m_H=125 GeV)
  - B(inv)<58%
  - 44% expected



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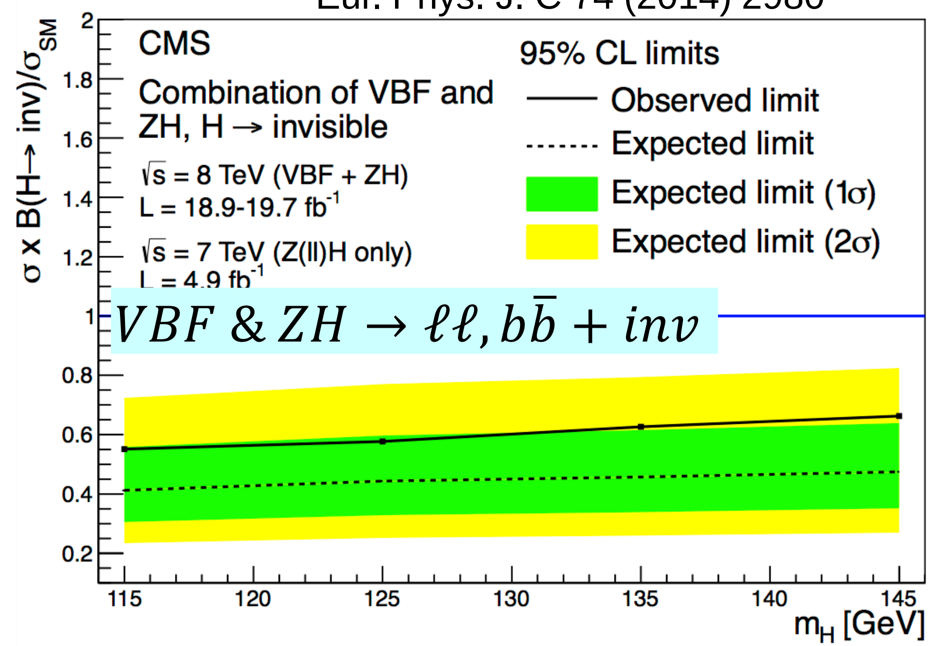


Indirect limits using constraints from visible decays

(see talks from N. Wardle and K. Schmieden on Monday)

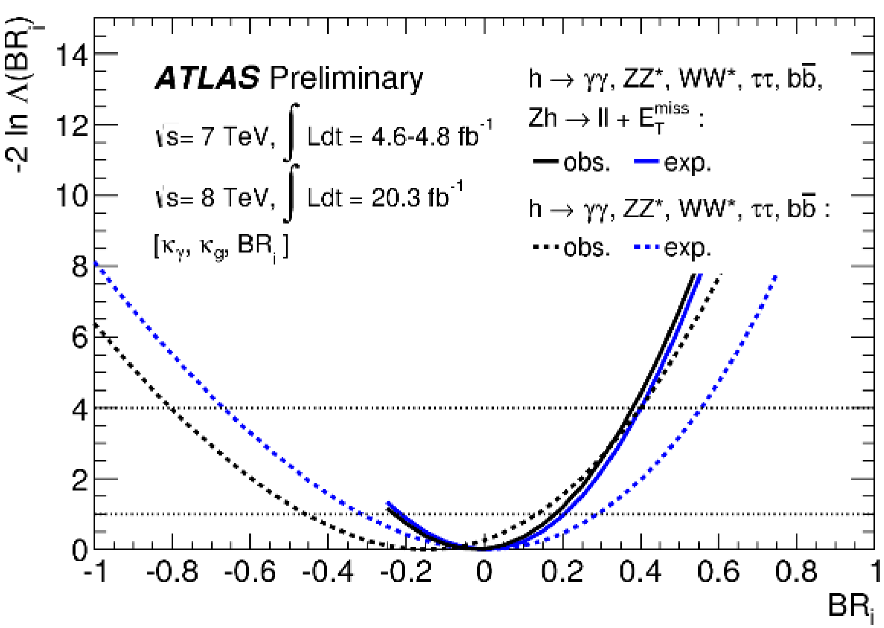
ATLAS direct+indirect

Observed (expected) 95% CL limit:
37% (39%)

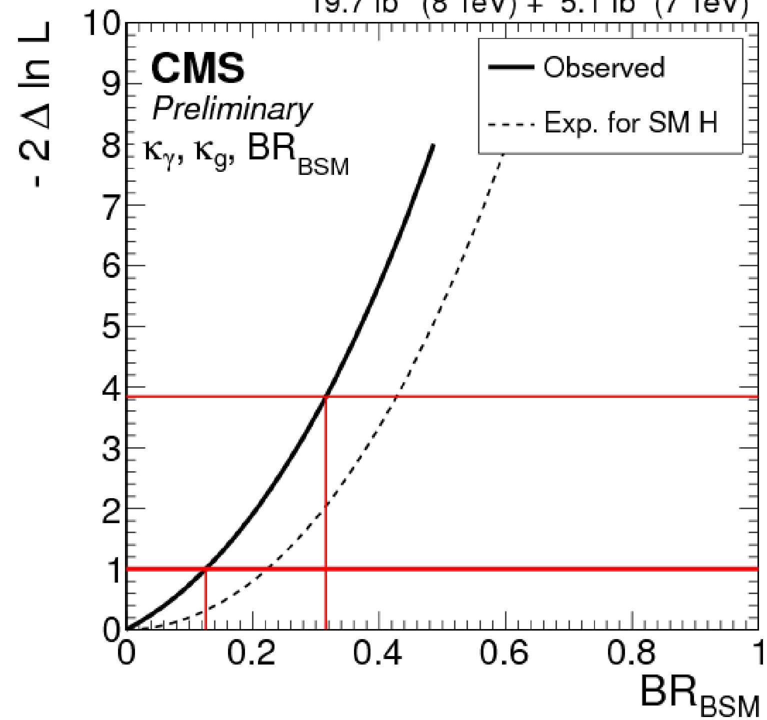
CMS indirect

Observed 95% CL limit:
32% (42%)

ATLAS-CONF-2014-010



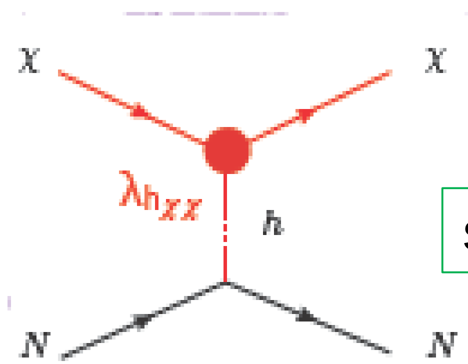
CMS-PAS-HIG-2014-009

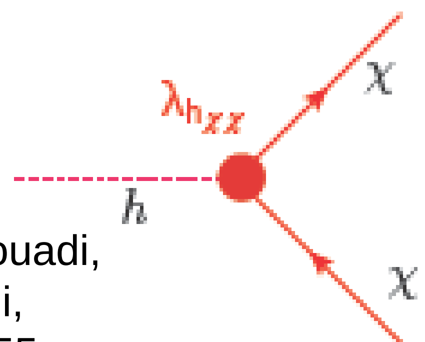


Dark Matter Interpretation

- If DM couples to the Higgs, then this provides a natural source of invisible decays
- In the context of the Higgs Portal DM models, constraints on B(inv) can give constraints on DM-nucleon cross sections

- Applicable when the mass of the DM particle, χ, is less than half of the Higgs mass



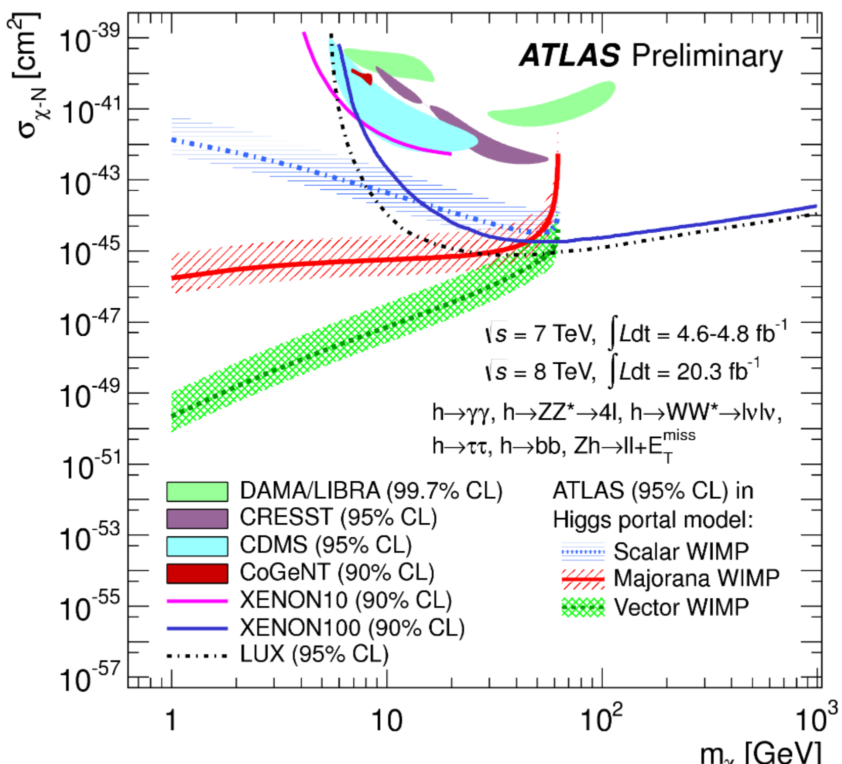


Higgs portal: Patt & Wilczek, arxiv:hep-ph.0605.188; Djouadi, Lebedev, Mambrini, Quevillon, PLB 790, 65; Djouadi, Falkoski, Mambrini, Quevillon, Eur. Phys. J. C73, 2455

Dark matter limits

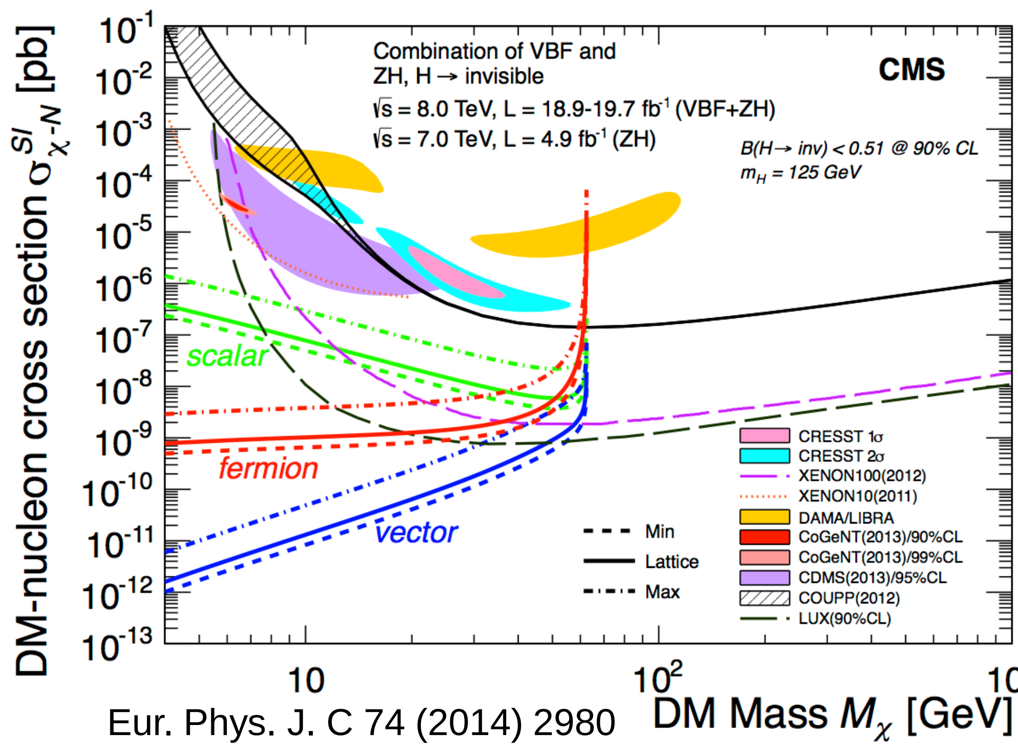
- Upper limits on spin-independent DM-nucleon cross sections
- More sensitivity than direct DM detection experiments in low-mass region in context of Higgs portal DM model

Input: ALTAS direct+indirect limit, B(inv)<0.37 @ 95% CL



ATLAS-CONF-2014-010

Input: CMS direct limit, B(inv)<0.51 @ 90% CL



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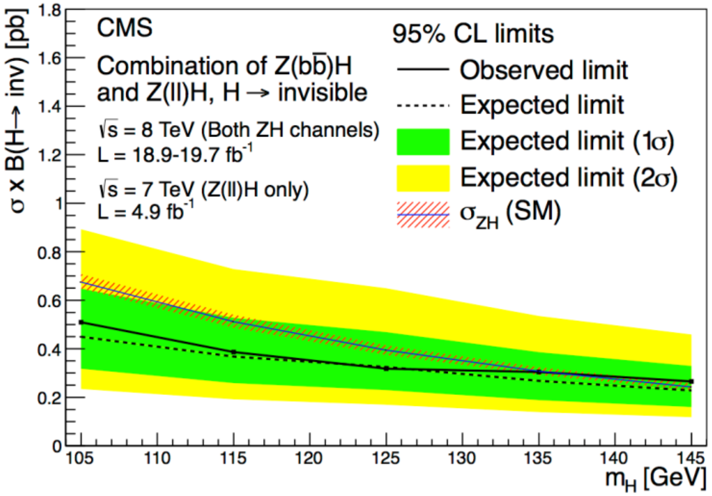
B to σ relations from Djouadi, Lebedev, Mambrini and Quevillon, PLB 709, 65

Summary

- LHC is sensitive to invisible decays of the Higgs through associated production modes with
  - Jets (VBF)
  - Z (ℓℓ), Z(bb)
- Strongest mode is VBF
- Limits on B(H→inv) at 95% CL
  - Direct: B<58% (CMS, VBF+ZH)
  - Indirect+direct: B<37% (ATLAS visible + ZH)
- In the Higgs portal model of Dark Matter, these results interpreted as limits on DM-nucleon scattering cross sections

BACKUPS

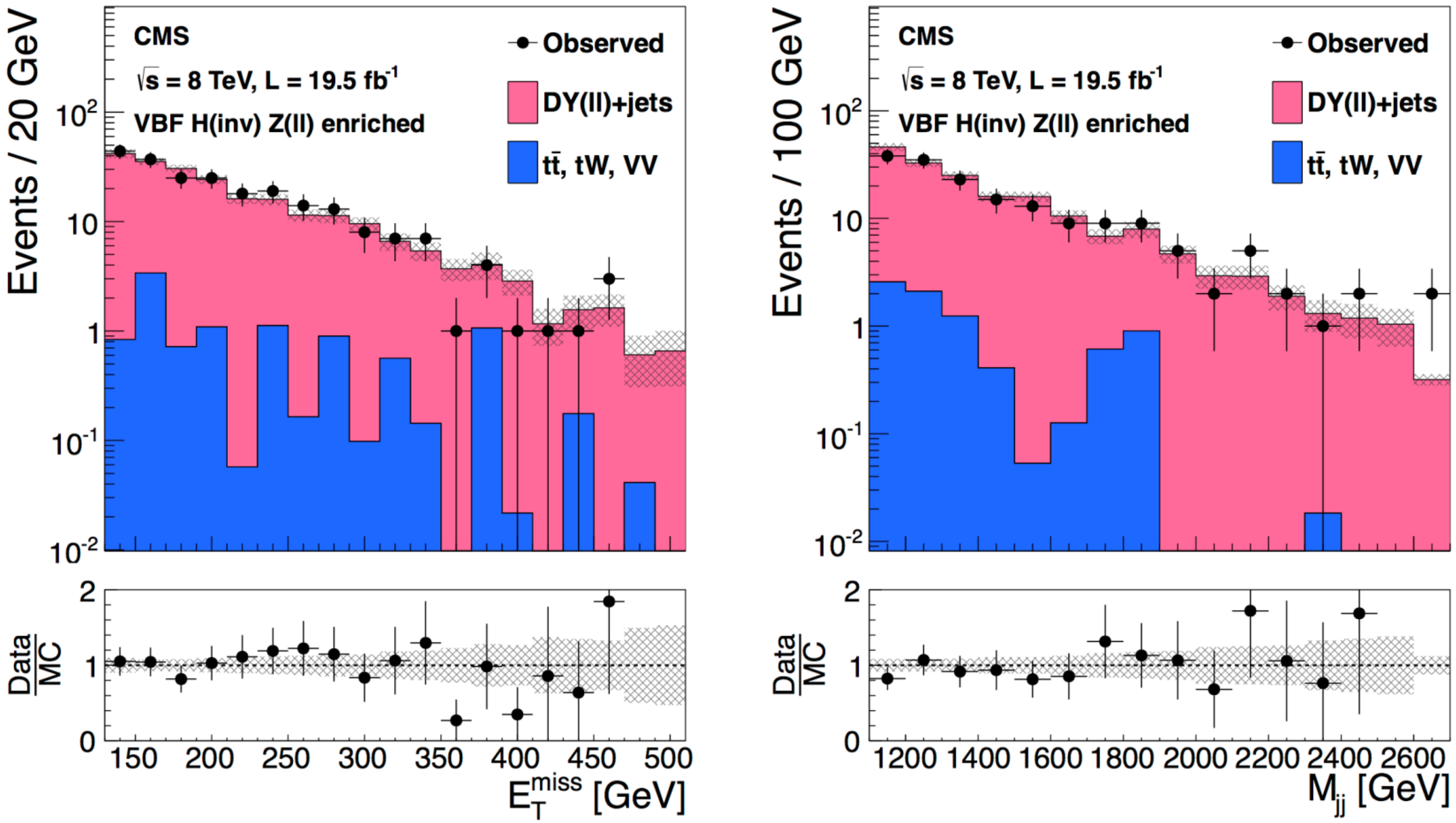
CMS ZH



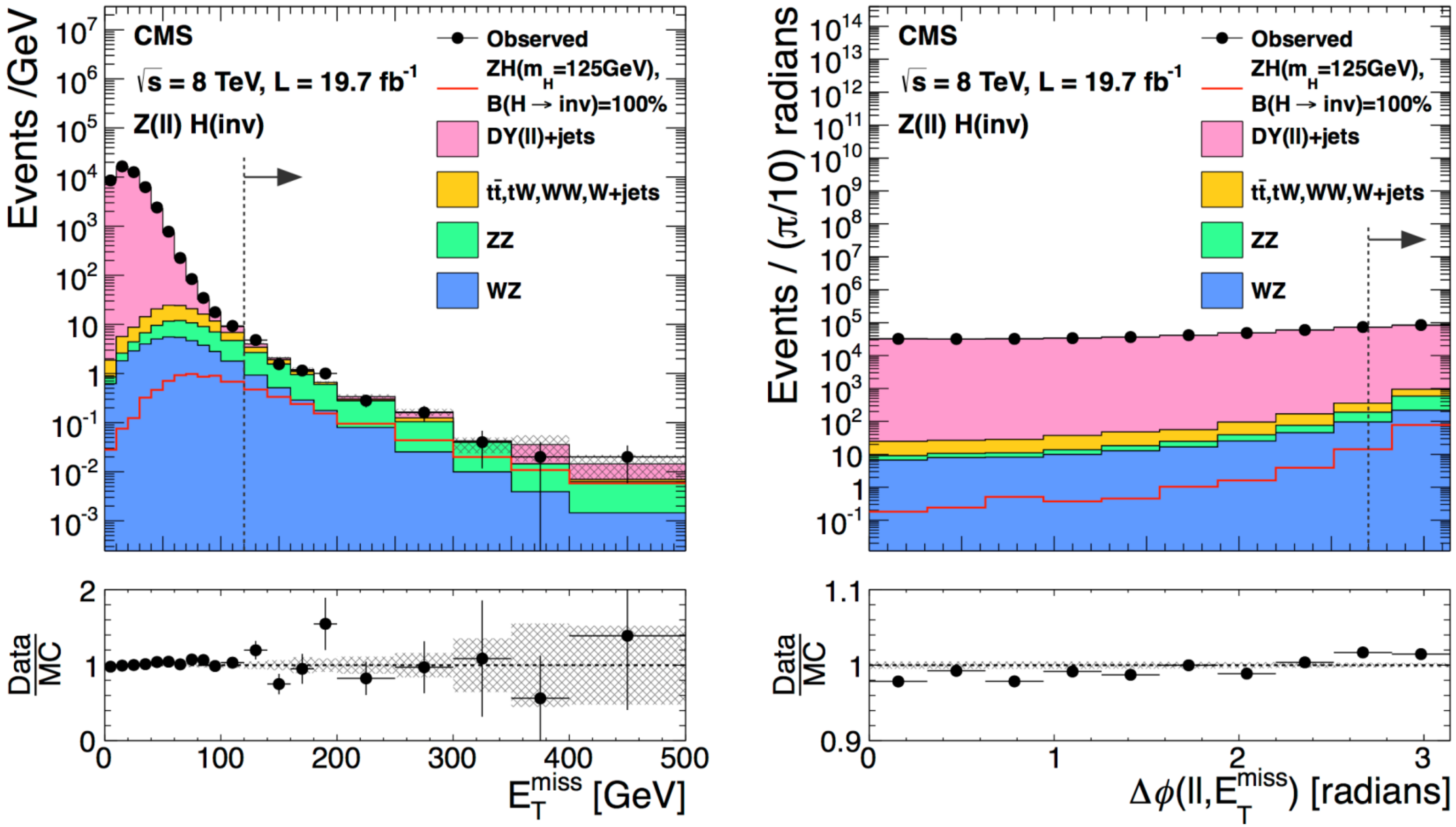
Type	Source	Background uncertainty(%)	Signal uncertainty(%)
	PDFs	5.0	5.7
	Factorization/renormalization scale	6.4	7.0
Norm.	Luminosity	2.3	2.2–2.6
	Lepton trigger, reconstruction, isolation	2.7	3.0
	Drell–Yan normalization	4.8	—
	$t\bar{t}$, Wt, WW & W+jets normalization	1.0	—
	MC statistics (ZH, ZZ, WZ)	1.8–3.8	3.0–4.0
	Control region statistics (DY($\ell\ell$)+jets)	0.6–1.2	—
Shape	Control region statistics ($t\bar{t}$, Wt, WW & W+jets)	2.0-3.8	—
	Pile up	0.2	0.3
	b-tagging efficiency	0.2	0.2
	Lepton momentum scale	0.9	1.0
	Jet energy scale/resolution	2.4–3.1	2.6–3.2
	E_T^{miss} scale	1.7–2.9	1.4–2.3

Type	Source	Background uncertainty(%)	Signal uncertainty(%)
	Luminosity	0.9	2.6
	Factorization/renormalization scale and PDFs	—	7
Norm.	Signal p_T boost EW/QCD corrections	—	6
	Background data/MC scale factors	8	—
	Single-top-quark cross section	1	—
	Diboson cross section	4	—
	Trigger	1	5
	Jet energy scale	4	3
Shape	Jet energy resolution	3	3
	E_T^{miss} scale	1	2
	b tagging	7	5
	MC statistics	3	3
	MC modelling (V+jets and $t\bar{t}$)	3	—

CMS VBF – Z control samples



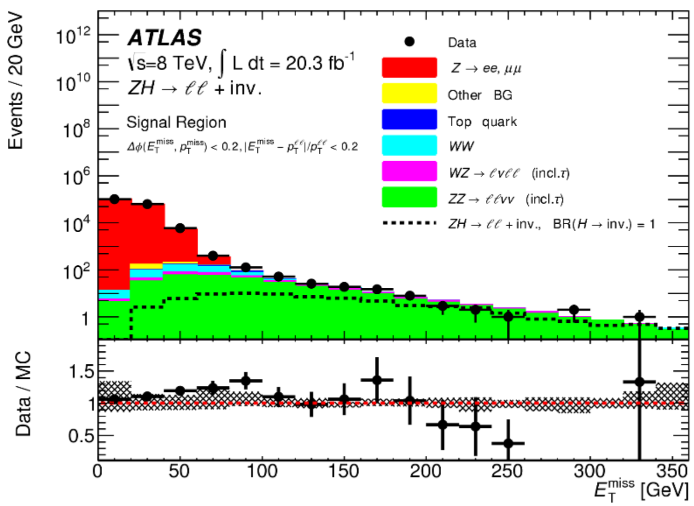
CMS $Z(\ell\ell)H(inv)$ preselection

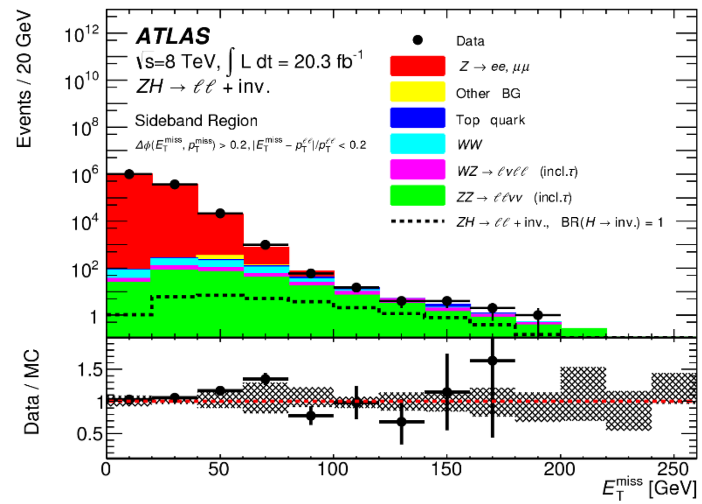


ATLAS $Z(\ell\ell)H(inv)$ – DY Background estimate

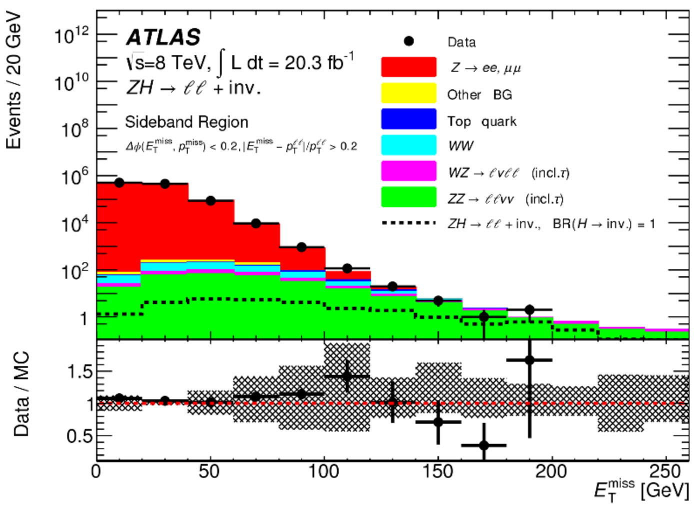
$\Delta\phi(E_T^{miss}, p_T^{miss}) < 0.2$ | $\Delta\phi(E_T^{miss}, p_T^{miss}) > 0.2$

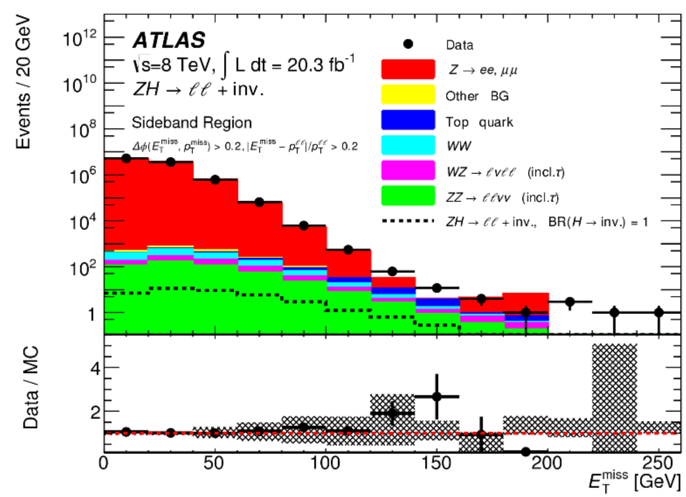
$|E_T^{miss} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.2$



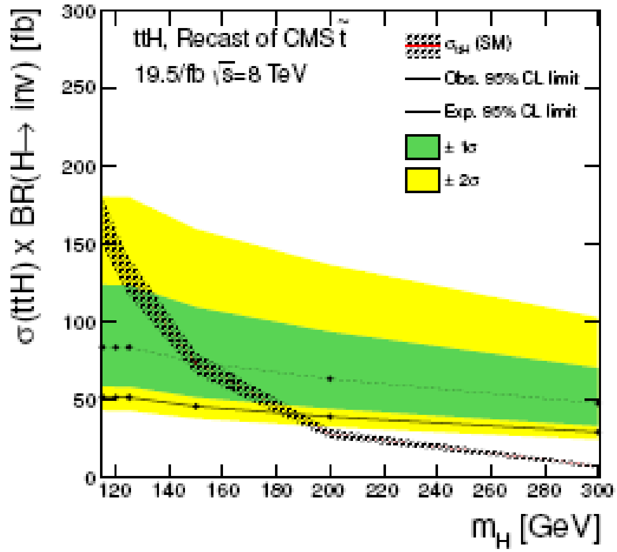


$|E_T^{miss} - p_T^{\ell\ell}|/p_T^{\ell\ell} > 0.2$





arXiv:1408.0011: $t\bar{t}H(inv)$ reinterpretation of CMS stop search



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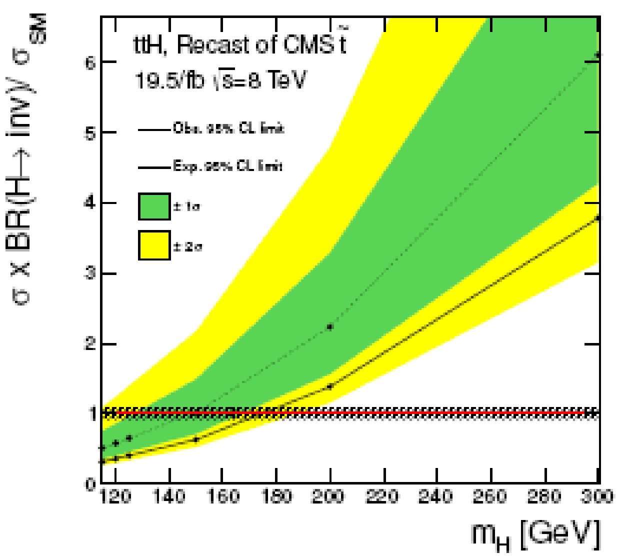

- Zhou, Khechadoorian, Whiteson and Tait
- Reinterpretation of CMS stop search
  - CMS, Eur.Phys.J. C73, 2677 (2013), 1308.1586.
- Signature: $t\bar{t} + E_T^{miss}$
- Observed (expected) 95% CL limits on B(inv):
  - 0.40 (0.65)

Conversion from Γ(inv) to σ(DM-N)

Scalar:

$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_{\mathrm{inv}}}{m_{\mathrm{H}}^3 v^2 \beta} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(M_\chi + m_{\mathrm{N}})^2},$$

Vector:

$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_{\mathrm{inv}} M_\chi^4}{m_{\mathrm{H}}^3 v^2 \beta (m_{\mathrm{H}}^4 - 4M_\chi^2 m_{\mathrm{H}}^2 + 12M_\chi^4)} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(M_\chi + m_N)^2},$$

Fermion:

$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_{\mathrm{inv}} M_\chi^2}{m_{\mathrm{H}}^5 v^2 \beta^3} \frac{m_{\mathrm{N}}^4 f_{\mathrm{N}}^2}{(M_\chi + m_{\mathrm{N}})^2}.$$