Dark Matter through the 125 GeV Higgs window

Dark Matter @ LHC, Heidelberg, April 3-6, 2018

Christian Ohm (KTH Stockholm),
obo ATLAS and CMS

Introduction

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  $\Rightarrow$ No hints of BSM in property measurements :(

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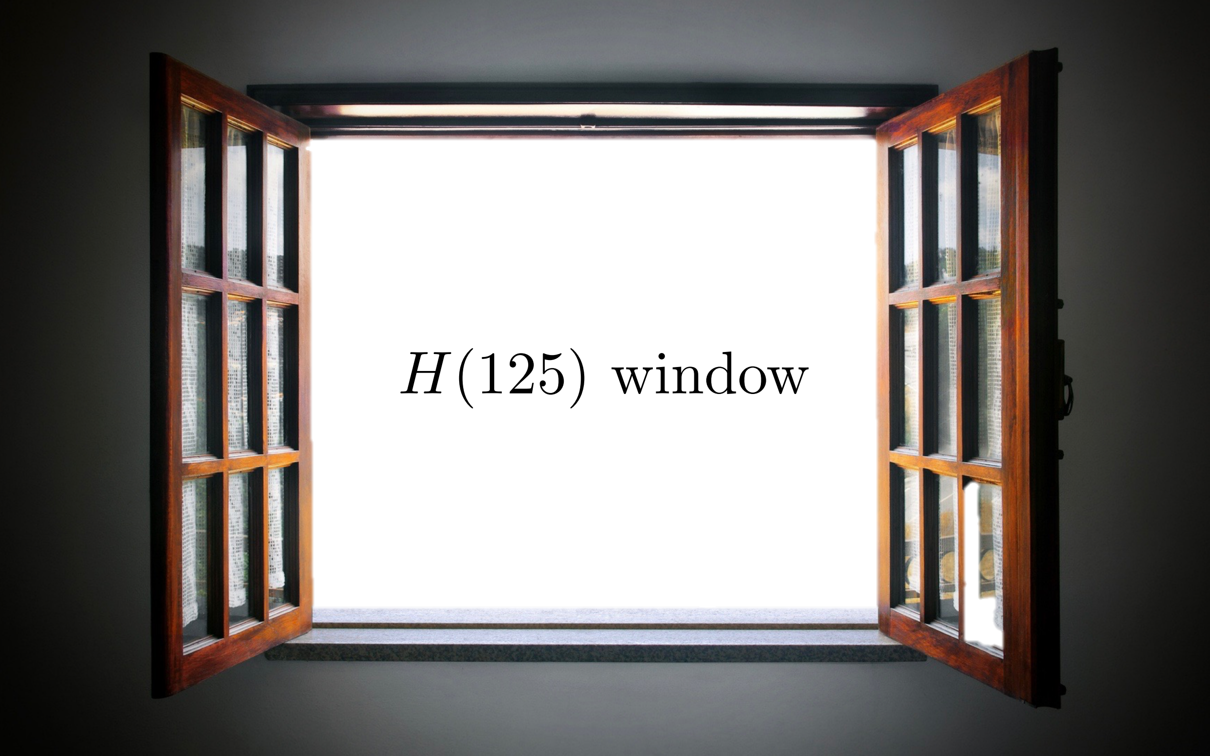
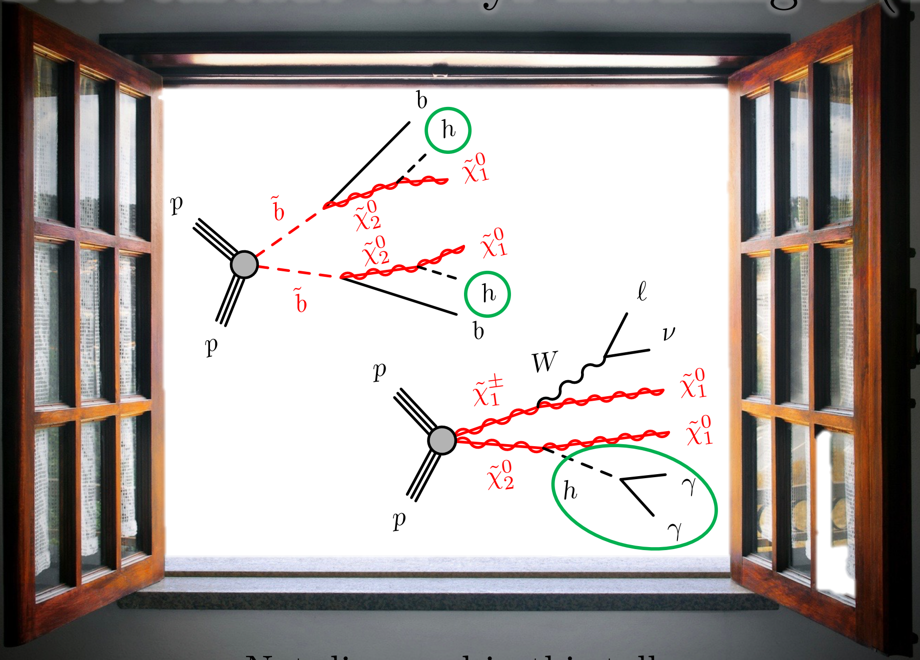
  $\Rightarrow$ No hints of BSM in property measurements :(
- It is the biggest discovery at the LHC. So far.
- Opportunity: SM Higgs can be powerful *tool* for finding BSM physics in general, and Dark Matter (DM) in particular


$H(125)$ window

Clearer view of BSM landscape

Not discussed in this talk

Look for cascade decays including $H(125)$



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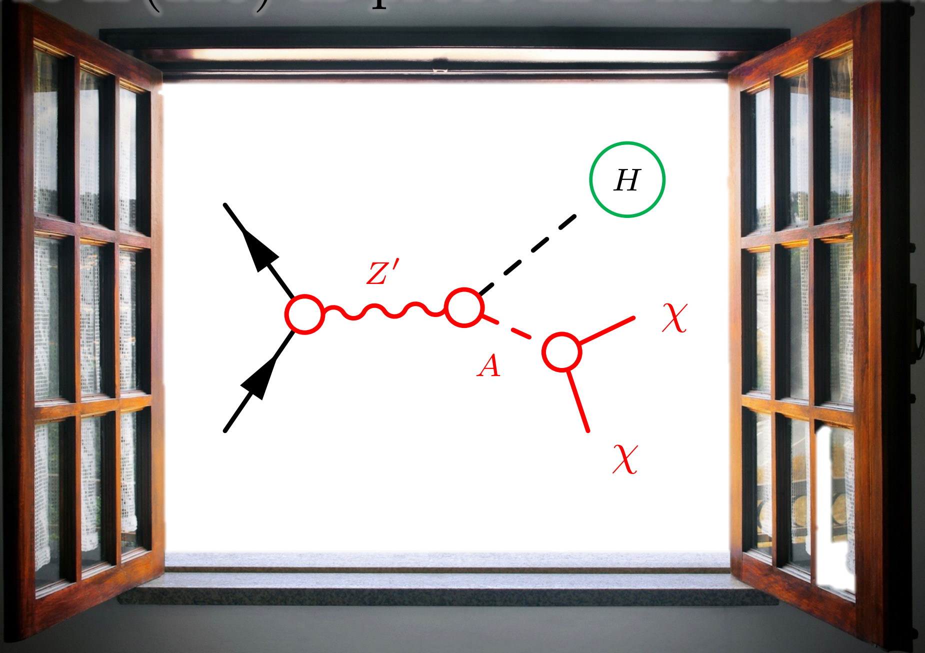
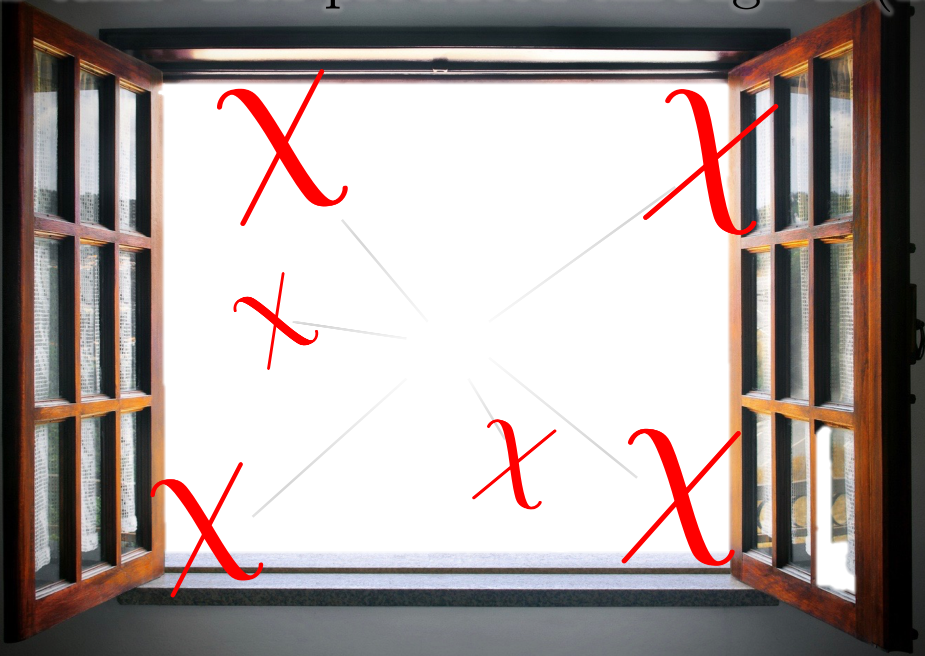
Use $H(125)$ as probe in DM searches



See talk by Shih–Chieh Hsu

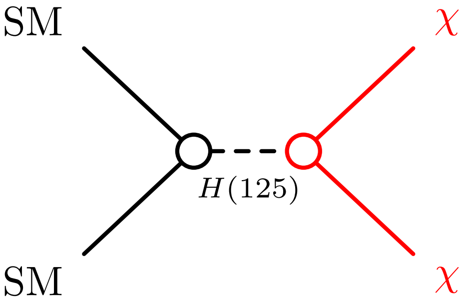
This talk: DM produced through $H(125)$



Scope: DM produced in decays of the 125 GeV Higgs boson

In the SM, $H \to \mathrm{invisible}$ only from
$H \to ZZ \to \nu\nu\nu\nu \Rightarrow$
$\mathcal{B}(H \to \mathrm{inv}) = 0.026 \times 0.20^2 = 0.1\%$

Any deviation would indicate BSM physics!



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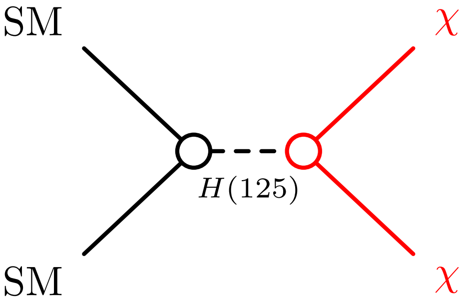
Shrock & Suzuki (1982) first noted possibility, since then a wealth of motivations:

$H \to$

- $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ in SUSY
- Graviscalars in extra-dimensions models
- BSM neutrinos (right-handed, 4th gen)
- ...



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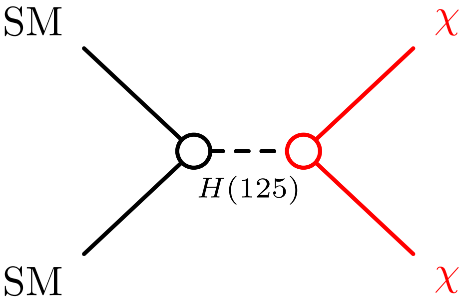
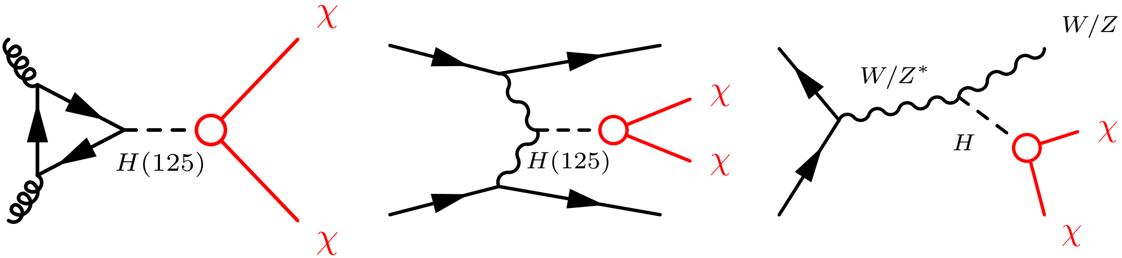


Powerful channel for DM searches if $m_{\mathrm{DM}} \leq m_H/2$

Overview of search channels for $H \to$ invisible

Gluon fusion: 49 pb | VBF: 3.8 pb | VH: 2.3 pb



Gluon fusion: 49 pb

- Need ISR ($\Rightarrow$ jet$+E_{\mathrm{T}}^{\mathrm{miss}}$) to trigger and tag
- Same final state as mono-jet search

VBF: 3.8 pb

- Tag using forward jets with large $\Delta\eta(jj)$
- Low background, $S/B \sim 0.5$ ($\mathcal{B}_{\mathrm{inv}} = 1$)

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- Tag using $Z \to \ell\ell$ or jets from $V(\mathrm{had})$
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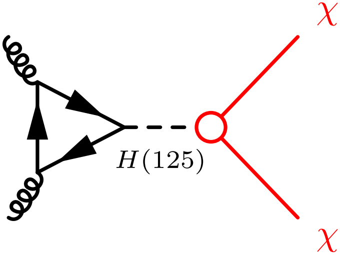

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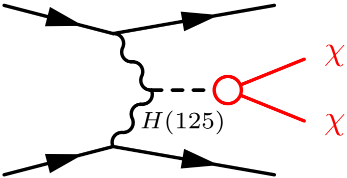

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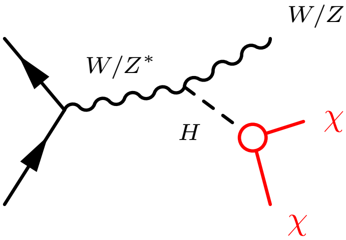

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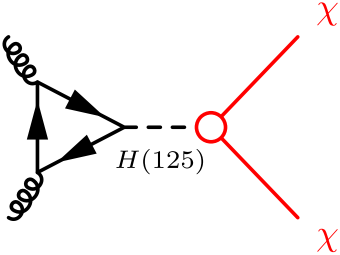

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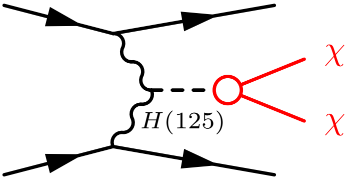

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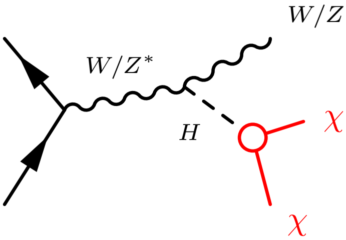

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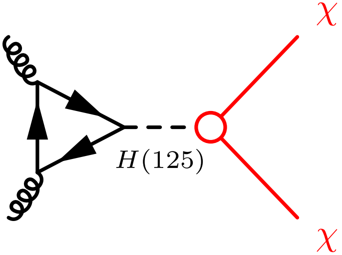	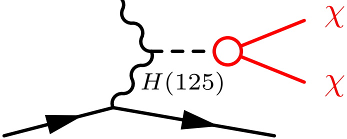	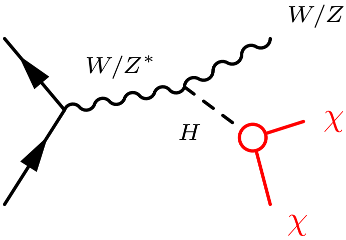

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- Intermediate sensitivity

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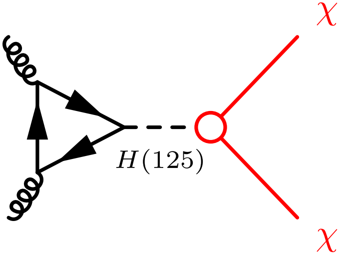

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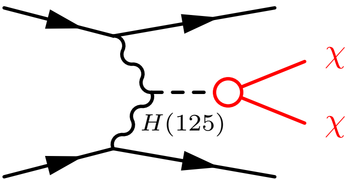

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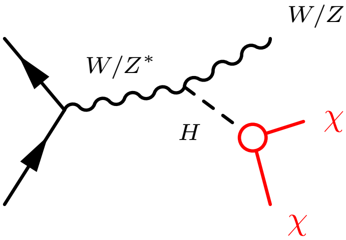
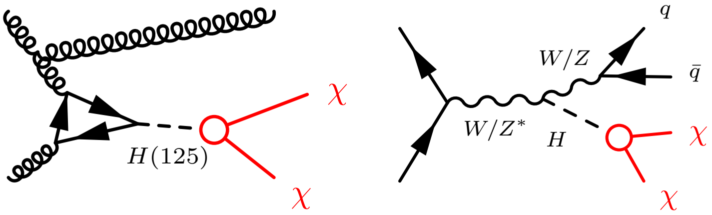


- Tag using $Z \to \ell\ell$ or jets from $V(\mathrm{had})$
- Same final state as $V + E_{\mathrm{T}}^{\mathrm{miss}}$ search
- Intermediate sensitivity

Many results from Run I and several from Run II, will focus on recent ones here!

1. Gluon fusion $H \to$ invisible (with ISR) and $V(\mathrm{had})H \to jj + MET$



Two new results from CMS during 2017! 1703.01651 and 1712.02345
$\Rightarrow$ *will focus on the last with full 2015+2016 dataset of 35.9 fb^{-1}!*

$H \to$ invisible with mono-jet and $V + E_{\mathrm{T}}^{\mathrm{miss}}$ searches CMS: 1712.02345

Details about these signatures and searches in talks by Z. Demiraglu and S-C. Hsu!

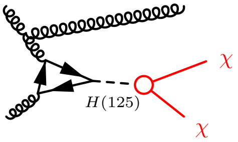
Common signal region (SR) selections:

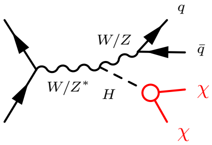
- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
- Leading jet: $p_{\mathrm{T}} > 100$ GeV
- $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}) > 0.5$
- Veto on ℓ (incl. τ!), γ, b-jet

$V + E_{\mathrm{T}}^{\mathrm{miss}}$ also requires $R = 0.8$ jet:

- $p_{\mathrm{T}} > 250$ GeV, $|\eta| < 2.4$
- 65 GeV $< m_{\mathrm{jet}} <$ 105 GeV
- Cut on substructure variables

Mono-jet and $V + E_{\mathrm{T}}^{\mathrm{miss}}$





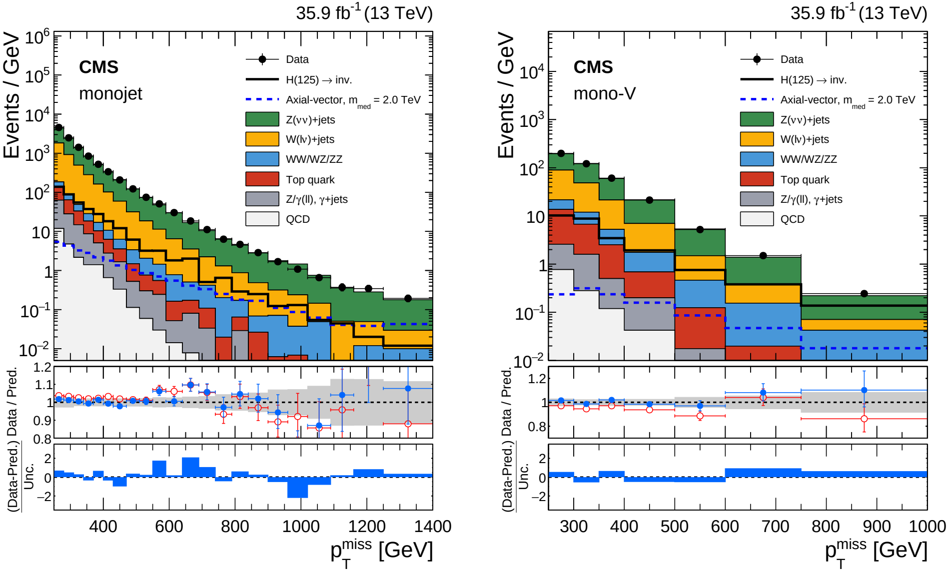
Main backgrounds $Z(\nu\nu)$+jets and $W(\ell\nu)$+jets (lost ℓ)

Measured in control regions (CRs):

- $\ell\ell$ for Z
- ℓ for W
- γ+jets to constrain Z

via transfer factors determined with MC

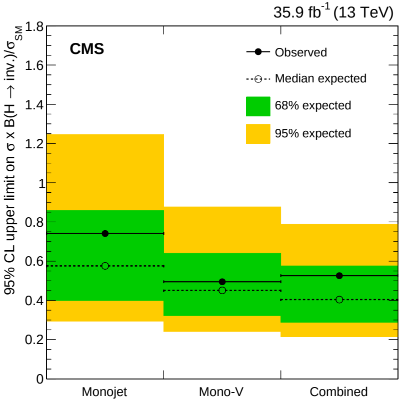
$H \to$ invisible with mono-jet and $V + E_T^{miss}$ searches CMS: 1712.02345



E_T^{miss} spectra in monojet (left) and $V + E_T^{miss}$ SRs (bgs from CR-only fit)

Combining results from mono-jet and $V(jj)H(\text{inv})$

CMS: 1712.02345



Expected composition in SR ⇒ both analyses sensitive to more than one channel

Mono-jet:

- 73% ggH
- 22% VBF

$V + E_{\mathrm{T}}^{\mathrm{miss}}$:

- 39% ggH
- 48% VH

Observed exclusion: $\mathcal{B}(H \to \text{inv}) > 0.53$

(0.40 expected)

Category	Observed (expected)	68% expected	Expected signal composition
Monojet	0.74 (0.57)	0.40–0.86	72.8% ggH, 21.5% VBF, 3.3% WH, 1.9% ZH, 0.6% ggZH
mono-V	0.49 (0.45)	0.32–0.64	38.7% ggH, 7.0% VBF, 32.9% WH, 14.6% ZH, 6.7% ggZH
Combined	0.53 (0.40)	0.29–0.58	—

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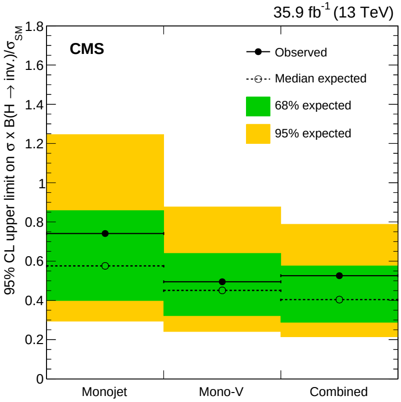
CMS: 1712.02345



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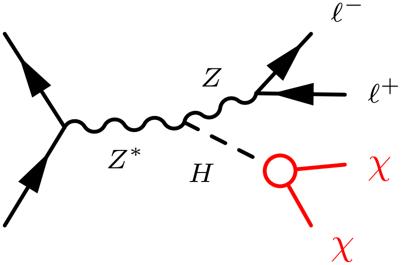
(For ATLAS $V(\text{had}) + E_{\mathrm{T}}^{\mathrm{miss}}$, see talk by S. Suchek on Thursday)

2. $ZH \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$



New results with 36 fb^{-1} from both ATLAS (1708.09624) and CMS (1711.00431)
$\Rightarrow$ *will use ATLAS result as example*

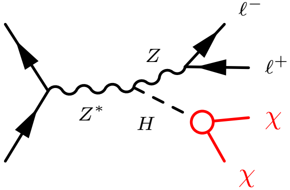
$ZH \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$: overview

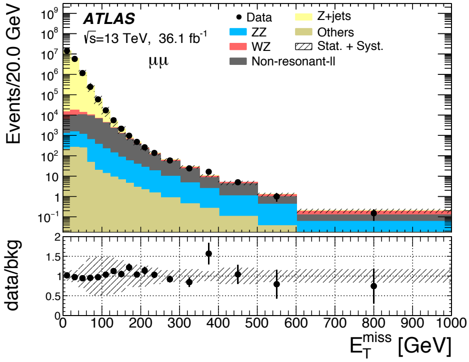
ATLAS: 1708.09624

Backgrounds:

- Irreducible background from diboson production:
  - $Z(\ell\ell)Z(\nu\nu)$ 60% $\Rightarrow$ rely on MC, 4ℓ data stats-limited
  - WZ where ℓ from W is lost 25% $\Rightarrow$ normalize in 3ℓ CR
- Non-resonant $\ell\ell$: WW, $t\bar{t}$, etc $\Rightarrow$ normalize in $e\mu$ CR

$Z \to \ell\ell$ powerful handle





Background composition after $m_{\ell\ell}$ cut

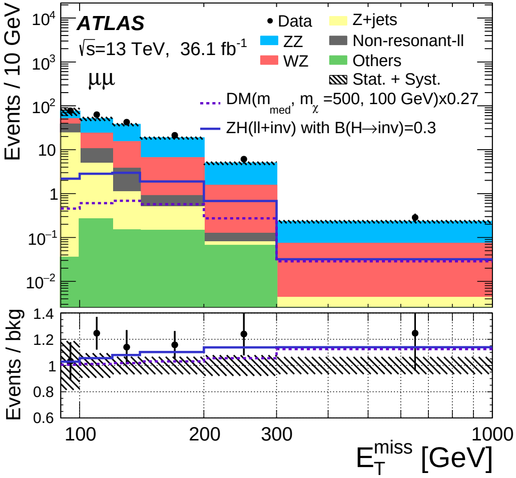
Event selection:

- OSSF ℓ pair: $p_{\mathrm{T}}^{1(2)} > 30(20)$ GeV, $|m_{\ell\ell} - m_Z| < 15$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\ell,j} > 0.6$
- $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.7$ (Z, H back-to-back)
- $\Delta R(\ell_1, \ell_2) < 1.8$ (boosted decay)

NB! Use of dilepton trigger gives access to lower-$E_{\mathrm{T}}^{\mathrm{miss}}$ region

$ZH \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$: results

ATLAS: 1708.09624



2.2σ excess in $\mu\mu$

$ZH \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$: results

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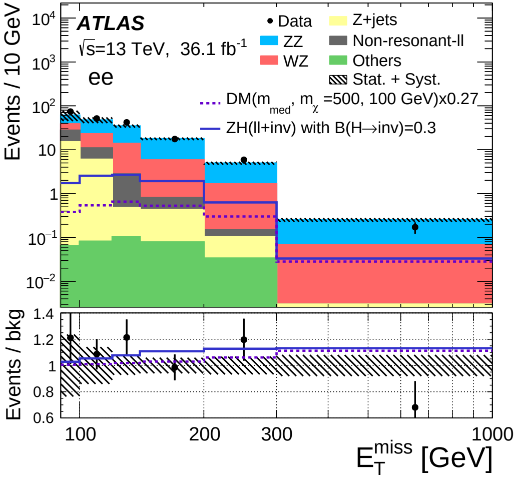
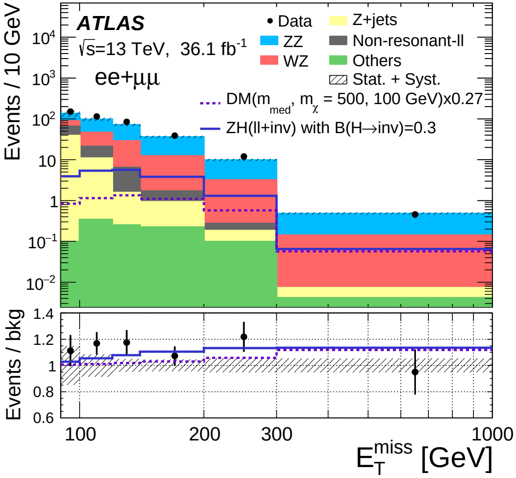
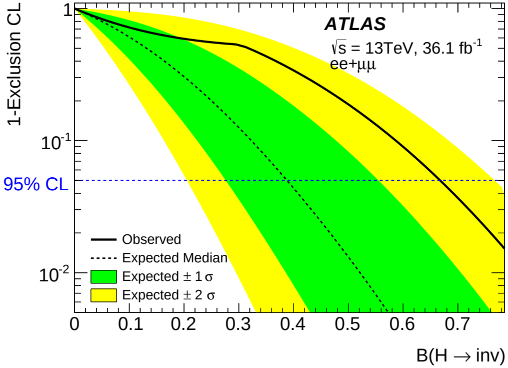


$< 1\sigma$ deviation in ee

$ZH \to \ell\ell + E_T^{\rm miss}$: results

ATLAS: 1708.09624





	Obs. $B_{H\to\mathrm{inv}}$ Limit	Exp. $B_{H\to\mathrm{inv}}$ Limit $\pm 1\sigma \pm 2\sigma$
ee	59%	$(51\ ^{+21}_{-15}\ ^{+49}_{-24})$ %
$\mu\mu$	97%	$(48\ ^{+20}_{-14}\ ^{+46}_{-22})$ %
$ee+\mu\mu$	67%	$(39\ ^{+17}_{-11}\ ^{+38}_{-18})$ %

1.5σ excess for $ee+\mu\mu$

See dedicated talk by C. Anelli on Thursday!

$ZH \to \ell\ell + E_T^{miss}$: results

ATLAS: 1708.09624

Events / 10 GeV

Events / bkg

inv)

$\pm 2\sigma$

$ZH \to \ell\ell + E_T^{miss}$: results from CMS - two strategies

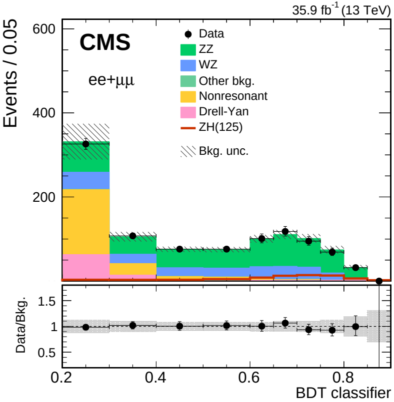
CMS: 1711.00431

E_T^{miss} shape: signal, bgs and data SR yields

Process	ee + $\mu\mu$
qqZH(inv.) $m_H = 125\,\text{GeV}$, $\mathcal{B}(H \to \text{inv.}) = 1$	158.6 ± 5.4
ggZH(inv.) $m_H = 125\,\text{GeV}$, $\mathcal{B}(H \to \text{inv.}) = 1$	42.7 ± 4.9
DM, vector mediator $m_{med} = 500\,\text{GeV}$, $m_{DM} = 150\,\text{GeV}$	98.8 ± 3.9
DM, axial-vector mediator $m_{med} = 500\,\text{GeV}$, $m_{DM} = 150\,\text{GeV}$	65.5 ± 2.6
ZZ	379.8 ± 9.4
WZ	162.5 ± 6.8
Nonresonant bkg.	75 ± 15
Drell–Yan	72 ± 29
Other bkg.	2.6 ± 0.2
Total bkg.	692 ± 35
Data	698

$\Rightarrow \mathcal{B}(H \to \text{inv}) < 0.45\ (0.44)$

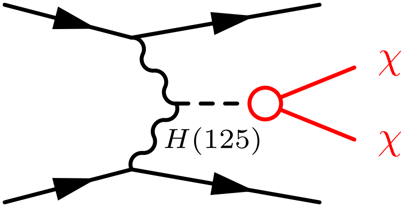
Multivariate discriminant



$\Rightarrow \mathcal{B}(H \to \text{inv}) < 0.40\ (0.42)$

See dedicated talk by C. Anelli on Thursday!

3. VBF $H \to$ invisible



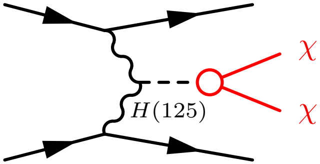
New result from CMS for Moriond! *HIG-17-023*

VBF $H \to$ invisible: overview

CMS: HIG-17-023

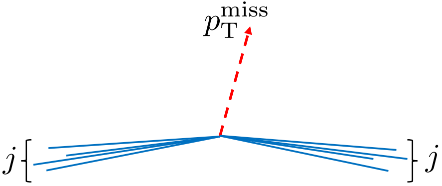
Two simultaneous approaches:

- Cut-and-count analysis: robust, model-independent strategy, selection tightened wrt Run I
- New! Shape-fit analysis in m_{jj} distribution: exploit discrimination potential due to difference in shape for signal and backgrounds



Selection:

- Jets: (sub)leading $p_{\mathrm{T}} > 80\ (40)$ GeV, $|\eta| < 4.7$
- $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
- $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}) > 0.5$, $\Delta\phi(j,j) < 1.5$
- Veto ℓ, γ, b-jets



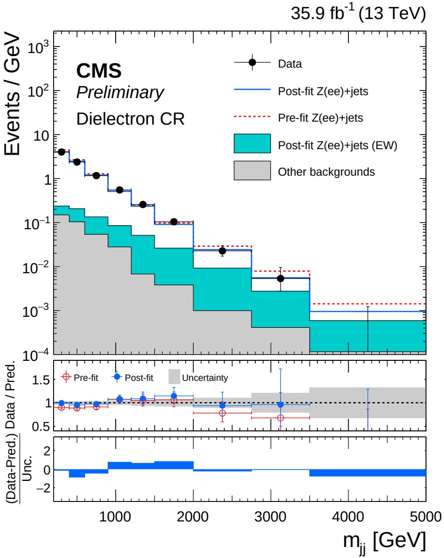
Cut and count	Shape fit
$m_{jj} > 1300$ GeV	$m_{jj} > 200$ GeV
$\Delta\eta(j,j) > 4.0$	$\Delta\eta(j,j) > 1.0$

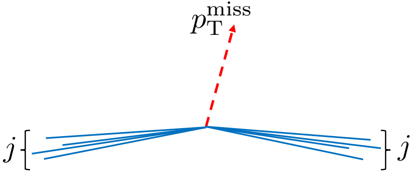
VBF $H \to$ invisible: backgrounds

CMS: HIG-17-023

Main backgrounds (95%): $Z(\nu\nu)$+jets and $W(\ell\nu)$+jets where ℓ is lost

(Mainly QCD processes , EW 2% at $m_{jj} = 200$ GeV $\to$ 20–50% at high m_{jj})





Strategy:

- Constrain using $Z(\ell\ell)$ and $W(\ell\nu)$ samples in CR, transfer to SR via known $\mathcal{B}$ and $\mathcal{A} \times \epsilon$ (e triggers used for e CRs)
- W/Z ratio from MC used with higher-stats W CRs to constrain Z+jets SR yields
- Cut-based: $n_{\mathrm{evt}}^{\mathrm{CR}} \times f_{\mathrm{transfer}} = n_{\mathrm{exp.}}^{\mathrm{SR}}$

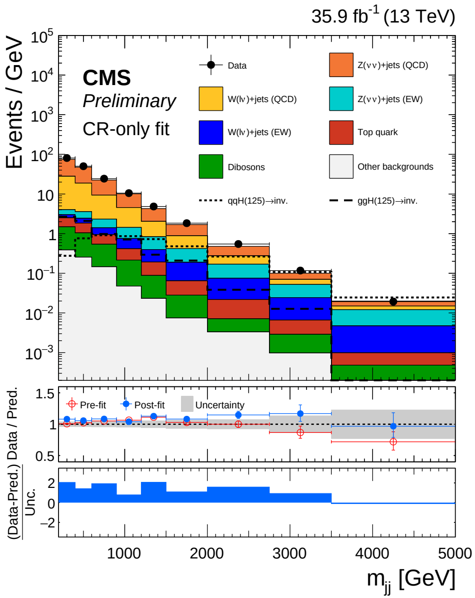
  Shape-fit: normalization from comb. fit in all CRs

(QCD $\sim 1\%$ with $\Delta\phi(E_T^{\mathrm{miss}}, \mathrm{jet})$ cut, CR by inverting)

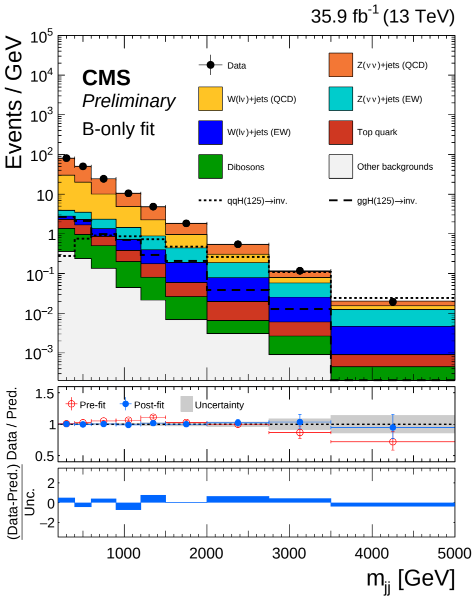
VBF $H \to$ invisible: results shape-fit analysis

CMS: HIG-17-023

Backgrounds fit in CRs only

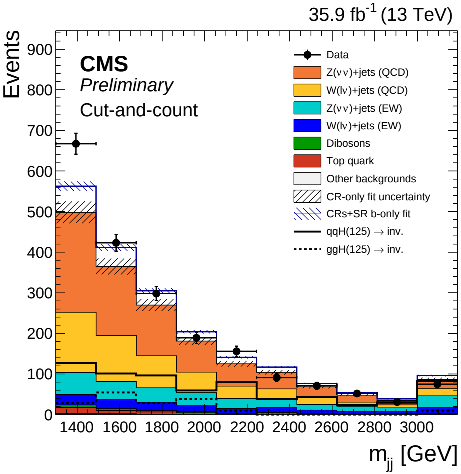


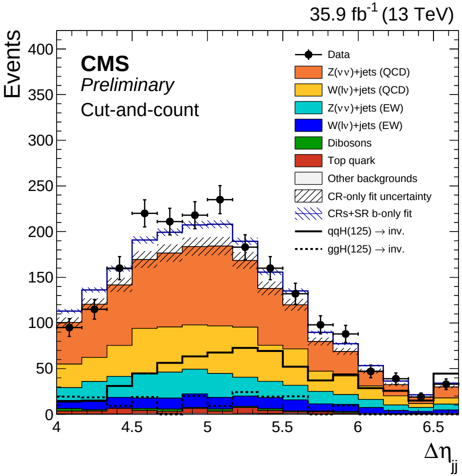
Background-only fit, in CRs+SR



VBF $H \to$ invisible: results cut-and-count analysis

CMS: HIG-17-023





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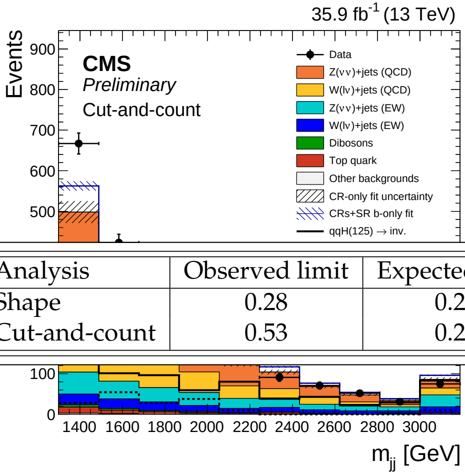
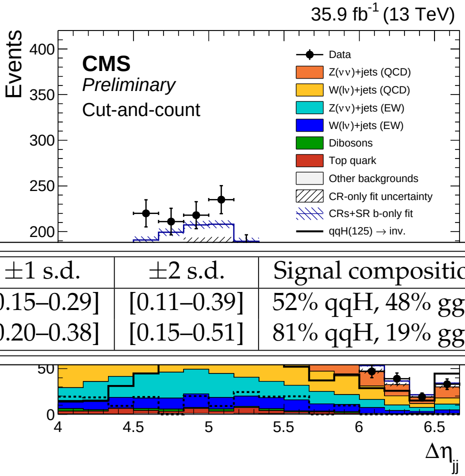
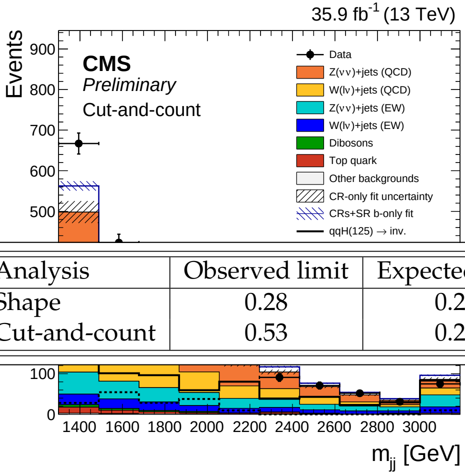


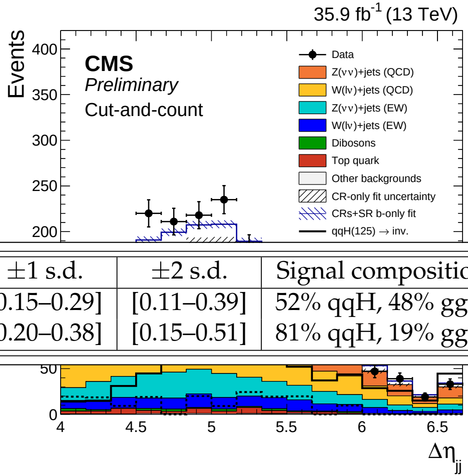


Analysis	Observed limit	Expected limit	±1 s.d.	±2 s.d.	Signal composition
Shape	0.28	0.21	[0.15–0.29]	[0.11–0.39]	52% qqH, 48% ggH
Cut-and-count	0.53	0.27	[0.20–0.38]	[0.15–0.51]	81% qqH, 19% ggH

VBF $H \to$ invisible: results cut-and-count analysis

CMS: HIG-17-023





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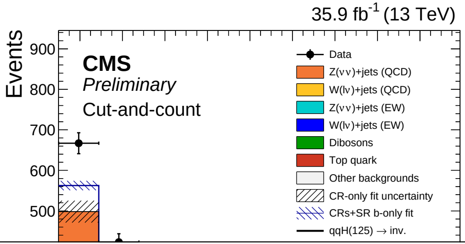
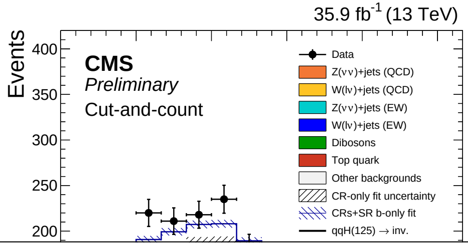
Uncertainties: theory V+jets (EW 48%, QCD 23%), exp. E_T^{miss} trigger (18%), τ veto (13%), μ id (8%)

VBF $H \to$ invisible: results cut-and-count analysis

CMS: HIG-17-023





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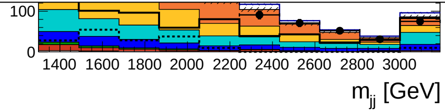
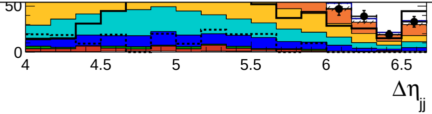
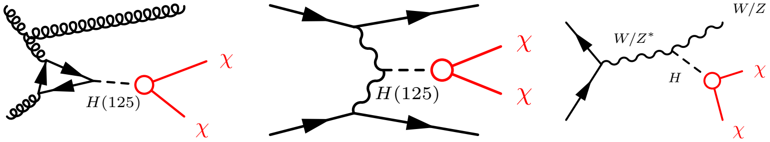




Uncertainties: theory V+jets (EW 48%, QCD 23%), exp. E_T^{miss} trigger (18%), τ veto (13%), μ id (8%)

NB! ATLAS 8 TeV VBF result still competitive:
$\mathcal{B}(H \to \text{inv}) = 0.28\ (0.31)$, see 1508.07869 (Update *soon!*).

4. Combining the results

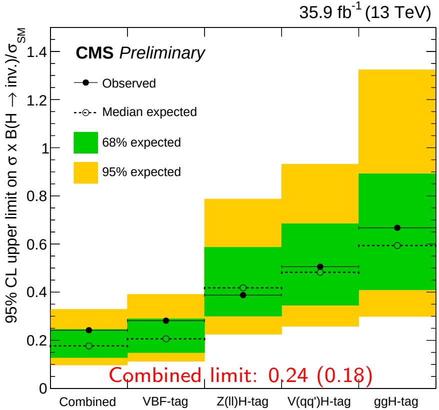


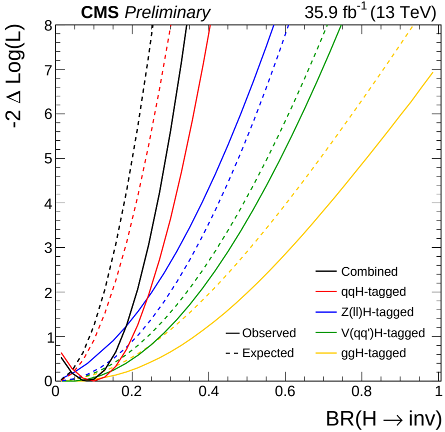
Combining several $H \to$ invisible channels

CMS: HIG-17-023

New VBF result from CMS include a combination with their other recent results:

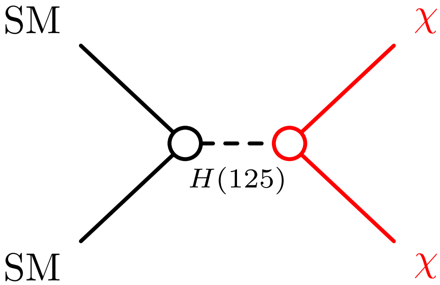
Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{miss}$	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{miss}$	39% ggH, 6% qqH, 33% WH, 22% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss}	80% ggH, 12% qqH, 5% WH, 3% ZH	0.66	0.59





Run I combinations: ATLAS 1509.00672, CMS: 1610.09218, ATLAS+CMS: 1606.02266 (indirect)

So far: Higgs decaying (only) to only invisible particles



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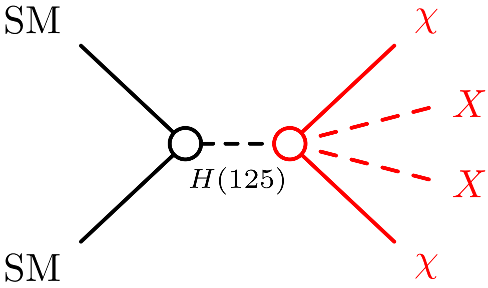
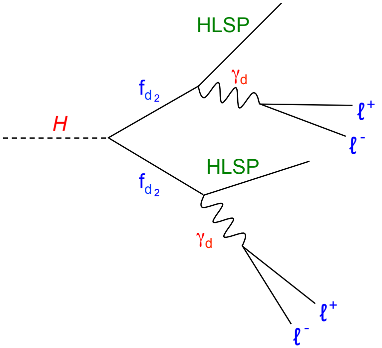


What if there's more?

Don't forget: $H(125) \to$ long-lived particles and $E_{\mathrm{T}}^{\mathrm{miss}}$

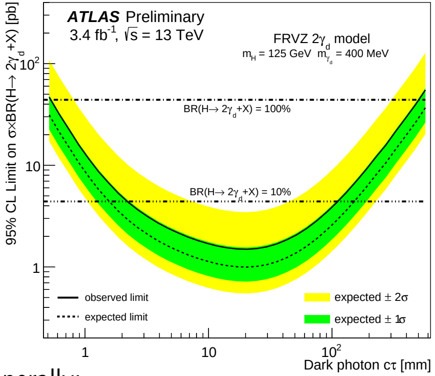
Example: ATLAS-CONF-2016-042:

$H(125) \to$ "lepton jets" (and $E_{\mathrm{T}}^{\mathrm{miss}}$)



Signature: collimated and displaced jets of leptons appearing in calorimeters or muon spectrometer, via long-lived particles (LLPs)

(More LLPs in talks by K. Hahn and A. Davoli)



Generally:

- $H(125)$ can be portal to a dark/hidden sector, which could also explain DM
- Weak couplings to this sector $\Rightarrow$ LLPs
- Displaced signatures *not trivial* $\Rightarrow$ interesting experimental work!

Summary

95% CL upper limits on $\mathcal{BR}(H \to \mathrm{inv})$ from Run I and Run II data.

Channel	ATLAS		CMS	
$Z(\ell\ell)H$	0.67	36.1 fb^{-1}	0.40	35.9 fb^{-1}
$V(\mathrm{had}) + E_{\mathrm{T}}^{\mathrm{miss}}$	0.78	20.3 fb^{-1}	0.49	35.9 fb^{-1}
Mono-jet	1.59	20.3 fb^{-1}	0.74	35.9 fb^{-1}
VBF	0.28	20.3 fb^{-1}	0.28	35.9 fb^{-1}
Combined	**0.25**	4.7+20.3 fb^{-1}	**0.24**	35.9 fb^{-1}

Stay tuned!

Backup slides

Indicative numbers for $H \to$ invisible at future colliders

- HL-LHC: extrapolation of CMS VBF result reaches $\mathcal{B}(H \to \mathrm{inv}) < 10\%$ for 300 fb^{-1} and $<$ 3–6% for 3 ab^{-1} (see CMS-FTR-16-002)

- ILC: 4.8% with 250 fb^{-1} at $\sqrt{s} = 250$ GeV using $Z(\mu\mu)$ only. Adding $Z(qq)$ they expect to reach 0.9%, and with ~ 1 ab^{-1} the limit is sqeezed to 0.4% (see ILC Higgs White Paper)

- FCC-ee: TLEP studies indicate upper limit of 0.5% achievable at $\sqrt{s} = 240$ GeV (see 1308.6176)

VBF $H \to$ invisible: results for cut-and-count analysis CMS: HIG-17-023

Process	Signal Region	Dimuon CR	Dielectron CR	Single-Muon CR	Single-Electron CR
$Z(\nu\nu)$ (QCD)	799 ± 72	-	-	-	-
$Z(\nu\nu)$ (EW)	275 ± 34	-	-	-	-
$Z(\ell\ell)$ (QCD)	-	90.1 ± 7.9	64.7 ± 5.8	26.8 ± 1.2	4.9 ± 0.2
$Z(\ell\ell)$ (EW)	-	32.7 ± 4.3	25.0 ± 3.4	5.9 ± 0.3	2.4 ± 0.2
$W(\ell\nu)$ (QCD)	497 ± 33	0.2 ± 0.2	0.8 ± 0.6	891 ± 31	533 ± 21
$W(\ell\nu)$ (EW)	145 ± 11	0.1 ± 0.1	-	416 ± 16	260 ± 11
Top-quark	43.7 ± 9.8	5.3 ± 1.6	3.7 ± 1.1	126 ± 22	83.1 ± 15.4
Dibosons	19.9 ± 6.1	2.6 ± 1.3	0.9 ± 0.5	23.5 ± 4.9	16.1 ± 4.1
Others	3.3 ± 2.6	-	-	25.6 ± 20.7	2.9 ± 2.9
Total Bkg.	1784 ± 97	131 ± 8	95.2 ± 5.9	1515 ± 34	902 ± 24
Data	2053	114	104	1512	914
Signal $m_{\mathrm{H}} = 125\,\mathrm{GeV}$	851 ± 148	-	-	-	-

VBF $H \to$ invisible: uncertainties

CMS: HIG-17-023

Source of uncertainty	Ratios	Uncertainty vs m_{jj}	Impact on $\mathcal{B}(H \to \text{inv})$
		Theoretical uncertainties	
Ren. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	9–12%	48%
Ren. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	9–12%	23%
Fac. scale V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	2–7%	4%
Fac. scale V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	2–7%	2%
PDF V+jets (QCD)	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	0.5–1%	$< 1\%$
PDF V+jets (EW)	$Z(\nu\nu)/W(\ell\nu)$ (EW)	0.5–1%	$< 1\%$
NLO EW corr.	$Z(\nu\nu)/W(\ell\nu)$ (QCD)	1–2%	$< 1\%$
		Experimental uncertainties	
Muon reco. eff.	$W(\mu\nu)/W(\ell\nu)$, $Z(\mu\mu)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	8%
Ele. reco. eff.	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	3%
Muon id. eff.	$W(\mu\nu)/W(\ell\nu)$, $Z(\mu\mu)/Z(\nu\nu)$	$\approx 1\%$ (per leg)	8%
Ele. id. eff.	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	$\approx 1.5\%$ (per leg)	4%
Muon veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 2.5 (2)% for EW (QCD)	7%
Ele. veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 1.5 (1)% for EW (QCD)	5%
τ veto	$W(CRs)/W(\ell\nu)$, $Z(\nu\nu)/W(\ell\nu)$	≈ 3.5 (3)% for EW (QCD)	13%
Jet energy scale	$Z(CRs)/Z(\nu\nu)$, $W(CRs)/W(\ell\nu)$	≈ 1 (2)% for Z/Z (W/W)	2%
Ele. trigger	$W(e\nu)/W(\ell\nu)$, $Z(ee)/Z(\nu\nu)$	$\approx 1\%$	$< 1\%$
p_T^{miss} trigger	All ratios	$\approx 2\%$	18%

$ZH \to \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$: yields

ATLAS: 1708.09624

Final State	ee	$\mu\mu$
Observed Data	437	497
Signal		
$ZH \to \ell\ell$ + inv ($B_{H\to\mathrm{inv}}$ = 30%)	32 ± 1 ± 3	34 ± 1 ± 3
DM (m_{med} = 500 GeV, m_χ = 100 GeV) × 0.27	10.8 ± 0.3 ± 0.8	11.1 ± 0.3 ± 0.8
Backgrounds		
$qqZZ$	212 ± 3 ± 15	221 ± 3 ± 17
$ggZZ$	18.9 ± 0.3 ± 11.2	19.3 ± 0.3 ± 11.4
WZ	106 ± 2 ± 6	113 ± 3 ± 5
Z + jets	30 ± 1 ± 28	37 ± 1 ± 19
Non-resonant-$\ell\ell$	30 ± 4 ± 2	33 ± 4 ± 2
Others	1.4 ± 0.1 ± 0.2	2.5 ± 2.0 ± 0.8
Total Background	399 ± 6 ± 34	426 ± 6 ± 28