Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS

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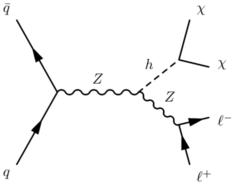
Outline

Motivation

- Search for invisible decay of Higgs in $ZH \rightarrow \ell^+\ell^- + invisible$



- SM Higgs ($m_H = 125\ GeV$) has $BR(H \rightarrow inv.) \sim 0.1\%$
- Many new physics models give a large $BR(H \rightarrow inv.)$: 4th generation neutrinos, SUSY, extra dimension
- Higgs would couple to massive invisible particles (dark matter particles)
- Place constraint on Higgs total width: $\Gamma_H = \Gamma_H^{SM}/(1 - BR(H \rightarrow inv.)), \Gamma_H^{SM} = 4.07\ MeV$

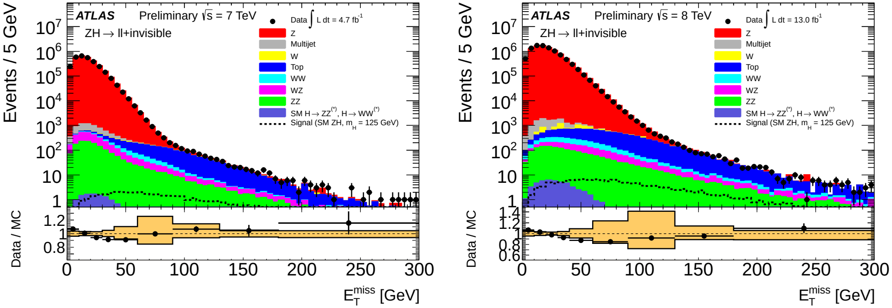
- Physics goals:
  - search for invisible decay of the 125 GeV Higgs
  - search for Higgs-like boson ($115\ GeV < m_H < 300\ GeV$) decaying predominantly to invisible particles
  - set limits on dark matter candidates in "Higgs portal" model

Analysis overview

- ATLAS preliminary results based on 4.7 fb^{-1} at 7 TeV and 13.0 fb^{-1} at 8 TeV
- Experimental signatures: Z (e^+e^-, $\mu^+\mu^-$) + E_T^{miss} final states
- Signal:
  - assume SM ZH production rate: $m_H = 125$ GeV, $\sigma_{ZH} = 316$ fb at $\sqrt{s} = 7$ TeV and $\sigma_{ZH} = 394$ fb at $\sqrt{s} = 8$ TeV
  - 100% branching ratio for Higgs decaying to invisible particles
- Background:
  - SM $ZZ \rightarrow \ell\ell\nu\bar{\nu}$: dominant and irreducible backgrounds, using Monte Carlo (MC) estimation
  - $WZ \rightarrow \ell\nu\ell\ell$: MC estimation
  - $WW/t\bar{t}/Wt/Z \rightarrow \tau\tau$: estimated with data-driven method, using the $e\mu$ events (MC estimation is used for 2011 data)
  - Z+jets: fake E_T^{miss}, estimated with an ABCD method
  - W+jets/multijet: fake lepton, estimated with the matrix method

Event selection and performance plots (1)

- Select exactly two opposite-charge leptons with high p_T ($p_T > 20\ GeV$)
- Z mass window cut: $76\ \mathrm{GeV} < m_{\ell\ell} < 106\ \mathrm{GeV}$
- $E_T^{miss} > 90 GeV$ (to suppress Z+jets)



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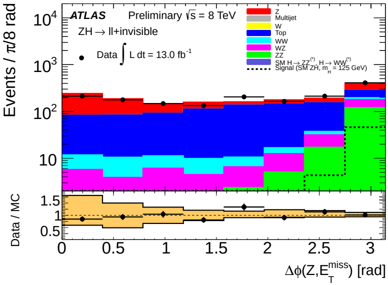
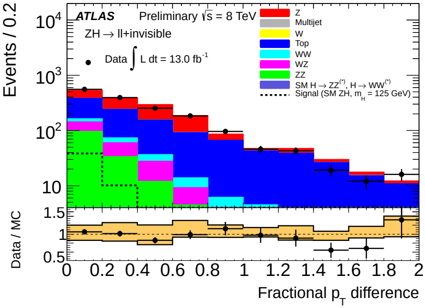
Event selection and performance plots (2)

- Azimuthal separation between the dilepton system and the E_T^{miss} : $\Delta\phi(Z, E_T^{miss}) > 2.6$
- Z p_T balance: fractional p_T difference $|E_T^{miss} - p_{\mathrm{T}}^{\ell\ell}|/p_{\mathrm{T}}^{\ell\ell} < 0.2$
- Azimuthal opening angle of the two leptons: $\Delta\phi_{\ell\ell} < 1.7$ (boosted Z)





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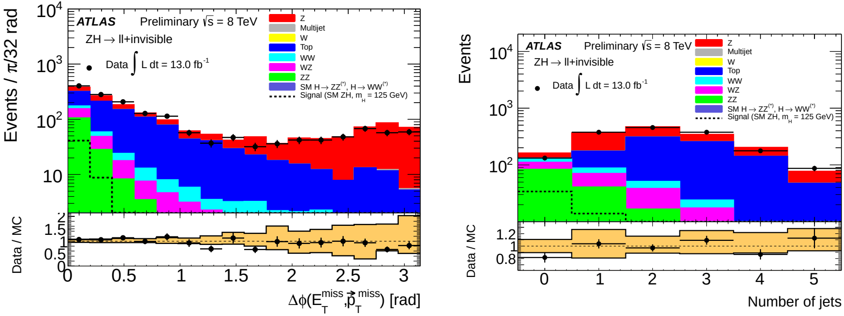
Event selection and performance plots (3)

- Azimuthal difference of the calorimeter based E_T^{miss} and the track based E_T^{miss} : $\Delta\phi(E_T^{miss}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 0.2$
  - calorimeter based E_T^{miss}:
    $E_{x(y)}^{miss} = -\sum p_{x(y)}^{e} - \sum p_{x(y)}^{\gamma} - \sum p_{x(y)}^{\tau} - \sum p_{x(y)}^{jets} - \sum p_{x(y)}^{SoftTerm} - \sum p_{x(y)}^{\mu}$
  - track based E_T^{miss}: $p_{x(y)}^{miss} = -\sum_{tracks} p_{x(y)}$
- Jet veto: no reconstructed jets with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$ (to reject *top*)



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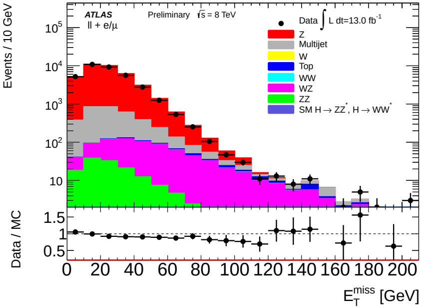
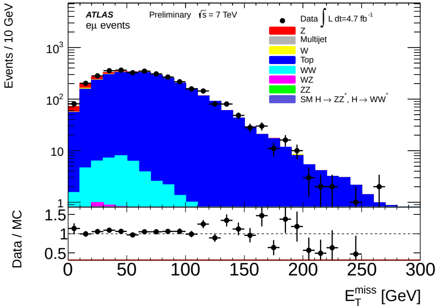
WZ and $e\mu$ control region

- Trilepton control region for 2012 data
  - select 3 lepton events with $76\ \mathrm{GeV} < m_{\ell\ell} < 106\ \mathrm{GeV}$
  - to validate MC simulation of *WZ* events
- $e\mu$ control region for 2011 data
  - select $e\mu$ events with a *b*-tagged jet
  - to validate the *top* modeling





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Data-driven background estimation (1)

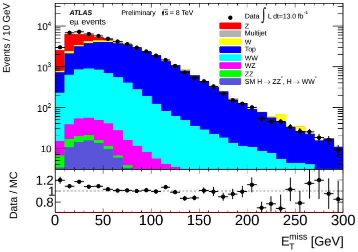
$WW/t\bar{t}/Wt/Z \to \tau\tau$

- estimated by exploiting the flavor symmetry in the final states of these processes: $ee : \mu\mu : e\mu = 1 : 1 : 2$
- $e\mu$ control region is used to extrapolate these backgrounds to the ee and $\mu\mu$ channels
- use a k-factor to correct for differences between the efficiencies of electrons and muons

$$N_{ee}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times k \qquad (1)$$

$$N_{\mu\mu}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times \frac{1}{k} \qquad (2)$$

$$k = \sqrt{\frac{N_{ee}^{\mathrm{data}}}{N_{\mu\mu}^{\mathrm{data}}}} \qquad (3)$$



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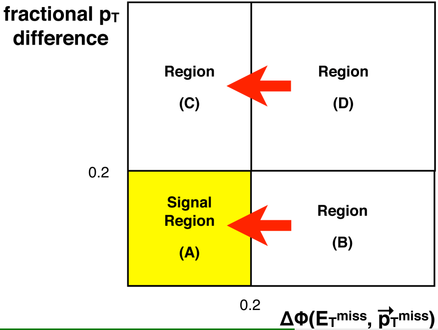
$N_{ee}^{\mathrm{bkg}}/N_{\mu\mu}^{\mathrm{bkg}}$: the number of background events to be estimated per E_T^{miss} bin

$N_{e\mu}^{\mathrm{data,sub}}$: the number of events in the $e\mu$ control region with non-$WW/t\bar{t}/Wt/Z \to \tau\tau$ backgrounds subtracted

Data-driven background estimation (2)

Z + jets

- *ABCD* method (the signal region A and three side-band regions B-D)
- extrapolate the background events from the side-band to the signal region
- using two uncorrelated variables: the $\Delta\phi(E_T^{miss}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ and fractional p_{T} difference



$$N_A^{\mathrm{est}} = N_B^{\mathrm{obs}} \times \frac{N_C^{\mathrm{obs}}}{N_D^{\mathrm{obs}}} \times \alpha \quad (4)$$

α: the correction factor for the correlation between the two variables

1.07 (1.04) for the 2011 (2012) data

Data-driven background estimation (3)

W + jets/multijet

- Matrix Method

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \times \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}. \quad (5)$$

  - observables: N_{XY} with $X, Y \in \{T, L\}$
    T: "tight" lepton (signal lepton selection); L: "loose" lepton (relaxed lepton selection)
  - "true" quantities: N_{XY} with $X, Y \in \{R, F\}$
    R: real lepton; F: fake lepton
  - matrix element:
    r_i: efficiency of a real lepton passing the tight selection, measured from Z events
    f_i: fake rate of a fake lepton passing the tight selection, measured from di-jet events
- estimation

$$N_{W+\text{jets}} = \sum_{i}^{N_{\text{events}}} N_{RF}^i \times r_1^i \times f_2^i + N_{FR}^i \times f_1^i \times r_2^i, \quad (6)$$

$$N_{\text{multijet}} = \sum_{i}^{N_{\text{events}}} N_{FF}^i \times f_1^i \times f_2^i. \quad (7)$$

Systematics

Process	Estimation method	Uncertainty (%) 2011	Uncertainty (%) 2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	-
Top quark	MC	90	-
Top quark, WW and $Z \to \tau\tau$	$e\mu$ CR	-	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

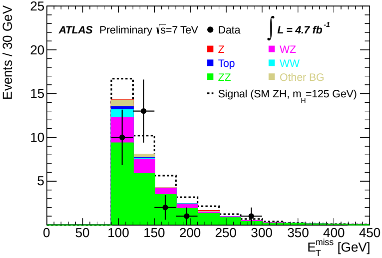
- ZH: experimental uncertainty (3-5%), cross section (4.9-5.1%), Higgs p_T (6%)
- ZZ: PDFs (5%), MC generator(10%)
- Luminosity uncertainty: 3.9% for 2011 data and 3.6% for 2012 data

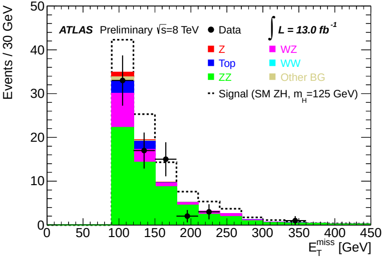
Results

- Summary of observed and predicted events:

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 $Z \rightarrow \tau\tau$ ($e\mu$ 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

- E_T^{miss} distribution in the signal region for 2011 and 2012 data:





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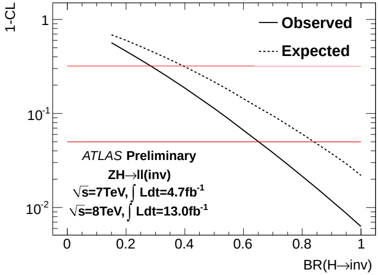
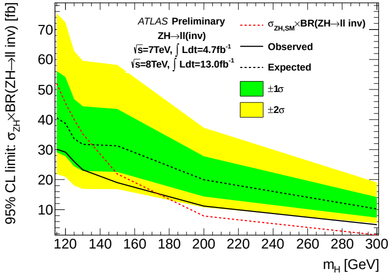
Limits

The limits are computed from a maximum likelihood fit to the E_T^{miss} distribution

- 95% confidence level (CL) limits on $BR(H \to inv.)$
  - observed: 65%, expected: 84%
- 95% CL limits on $\sigma_{ZH} \times BR(ZH \to \ell\ell + inv.)$ of such a Higgs boson in the mass range 115 GeV $< m_H <$ 300 GeV





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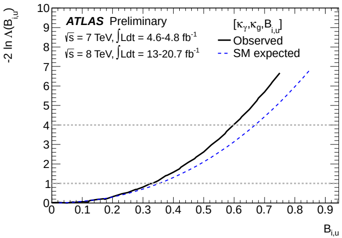
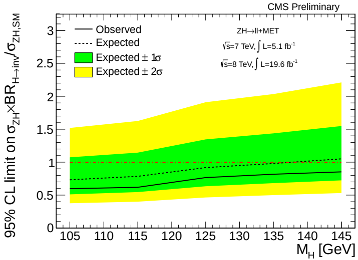
Note: the inclusive branching ratio of $Z \to \ell\ell$ is used (10.1%)

Recent limits on $BR(H \to inv.)$ at LHC

- Current limits at LHC ($m_H = 125\ GeV$, 95% CL)
  - ATLAS direct search (this work)
    - observed: 65%, expected: 84%
  - ATLAS indirect search: fit the couplings of (κ_g, κ_γ, $\mathrm{BR}_{inv.,undet.}$)
    - observed: $\sim$ 60%, expected: $\sim$ 66% (*ATLAS-CONF-2013-034*)
  - CMS direct search: $ZH \to \ell\ell + inv.$
    - observed: 75%, expected: 91% (*CMS-PAS-HIG-13-018*)





- Expected sensitivity on $BR(H \to inv.)$ with HL-LHC (from CMS *arXiv:1307.7135v1*)

L (fb^{-1})	$BR(H \to inv.)$
300	[17, 28]
3000	[6, 17]

Summary

- A direct search for evidence of invisible decays of a Higgs boson at the LHC has been performed
- No significant excess over the expected background is observed
- Limits are set on the allowed invisible branching fraction of the recently observed 125 GeV Higgs boson
  - 95% CL limits: observed: 65%, expected: 84%
- Limits are also set on $\sigma_{ZH} \times BR(ZH \to \ell\ell + inv.)$ of a possible additional Higgs-like boson with 115 GeV $< m_H <$ 300 GeV
- Results with full 2011 and 2012 data will be updated soon (along with the interpretation on new physics)

References

ATLAS-CONF-2013-011
https://cds.cern.ch/record/1516923

Belotsky, K. *et al.*, *"Invisible Higgs boson decay into massive neutrinos of fourth generation", Phys. Rev. D 68, 054027 (2003)*

Boudjema, F. et al., "Invisible Decays of the Supersymmetric Higgs and Dark Matter", arXiv:hep-ph/0206311

Cheng, H. et al., "Kaluza-Klein Dark Matter", Phys. Rev. Lett. 89, 211301 (2002)

Backup

ATLAS indirect search for invisible Higgs

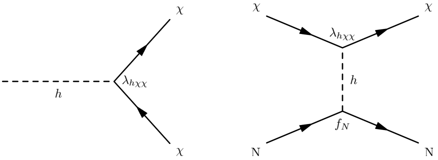
- All coupling scale factors of know SM particles are assumed to be in SM, $\kappa_i = 1$
- Except for $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$, effective scale factors κ_g and κ_γ are introduced to account for extra contribution from new particles in the loops

  $\sigma(gg \rightarrow H) * \mathrm{BR}(H \rightarrow \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91}$
- Further assume Higgs can decay to invisible or undetectable final states, $BR_{inv.,undet.}$

  $\sigma(gg \rightarrow H) * \mathrm{BR}(H \rightarrow \gamma\gamma) \sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{(0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91)/(1 - \mathrm{BR}_{inv.,undet.})}$
- Fit the free parameters: κ_g, κ_γ and $BR_{inv.,undet.}$

Higgs-portal Dark Matter model

- Higgs is the mediator of the couplings of dark matter particles with SM pariticles



- Map the limits on $BR(H \rightarrow inv.)$to dark matter - nucleon scattering cross section

$$BR_{\chi}^{inv.} = \frac{\Gamma(H\rightarrow\chi\chi)}{\Gamma_H^{SM}+\Gamma(H\rightarrow\chi\chi)} = \frac{\sigma_{\chi P}^{SI}}{\Gamma_H^{SM}/r_\chi+\sigma_{\chi P}^{SI}}$$

$\sigma_{\chi P}^{SI}$: spin-independent dark matter-nucleon scattering cross section

$r_\chi = \Gamma_H/\sigma_{\chi P}^{SI}$, only dependent on dark matter mass M_χ, nucleon mass m_P and coupling $\lambda_{H\chi\chi}$

arXiv:1205.3169v3