The Search for Invisible Higgs Boson Production With the CMS Detector at the LHC

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Outline

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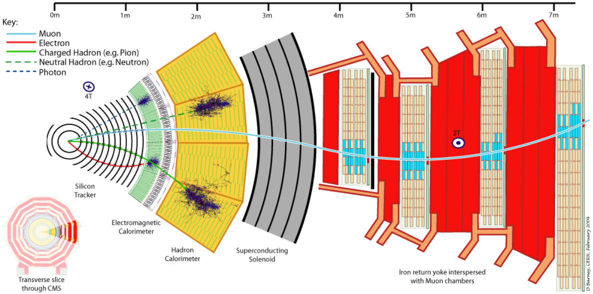
The Compact Muon Solenoid (CMS) Detector



- Inner silicon tracker
  - determines tracks and vertices of charged particles
  - electron, muon, jet
- $PbWO_4$ ECAL
  - measures energy and location of electrons
- Brass-scintillator HCAL
  - measures energy of jets
- Muon chambers
  - measures location and momentum of muons
- Combine information from subdetectors to measure missing transverse energy

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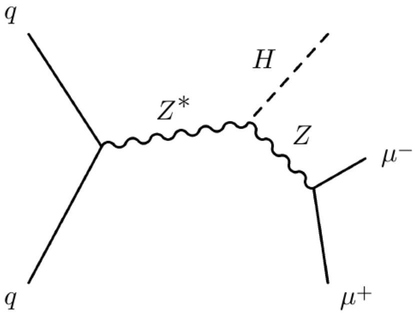
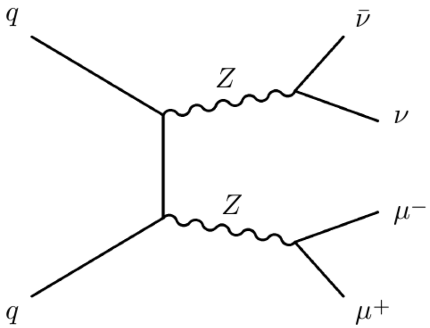
Signal: Invisible Decay Modes



- Z boson Higgs-strahlung
- Higgs decay products invisible to detector
  - Not a Standard Model phenomenon
  - Model-independent search
- Some theorized decay modes:
  - Decay into pair of Stable neutral Lightest SUSY Particles (LSP)
    - neutralinos (1)
  - Large extra dimensions
    - Higgs oscillates into a graviscalar and disappears from our brane (2)
  - Decay into pair of graviscalars (3)
  - Decay into light neutrino and heavy neutrino (4)
- Explore range of Higgs masses
  - 105-145 GeV

Main Background: ZZ Production



- Same final state as $ZH \to \ell^+\ell^- + H(inv)$
  - Two leptons from Z decay
  - Large $\not{E}_T$
- Irreducible Background
  - Comprises ~70% of total background at final selection
- Some kinematic differences between ZZ and ZH
  - Mass difference between Z and Higgs

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MC Samples For Signal And Background, and Datasets

Generators

- All ZH samples, $t\bar{t}$, tW generated with POWHEG (v2.0)
- $Z + jets$, and diboson with MADGRAPH (v5.1.3)
- Detector response modeled with GEANT4
- PDFs modeled through:
  - CTEQ6L parameterization at LO
  - CT10 parameterization at NLO

Calculations

- NLO $\sigma(ZZ)$, $\sigma(WZ)$ computed using MCFM
- $\sigma(ZH)$ computed at NNLO in QCD, and NLO in EW (5)

Datasets

- full 2011 and 2012 data samples at 7 TeV and 8 TeV
- Integrated luminosity at $\sqrt{s} = 7$ TeV: 5.1 fb^{-1}
- Integrated luminosity at $\sqrt{s} = 8$ TeV: 19.6 fb^{-1}

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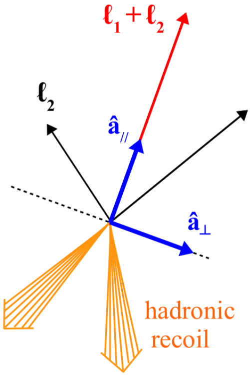
Hadronic Recoil



- $ZH \to \ell^+\ell^- + H(inv)$ and $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ characterized by large $\not{E}_T$ from neutrinos and/or non-standard particles
- Dominant background: $Z + jets$ with mis-measured large $\not{E}_T$
  - $\sigma(Z + jets) > 10^5 \cdot \sigma(ZZ \to \ell^+\ell^-\nu\bar{\nu})$
- The goal is to reduce $\not{E}_T$ of imbalanced events to effectively subtract the hadronic recoil and suppresses $Z + jets$ (6)
- $red\text{-}\not{E}_T$ variable:
  - $red\text{-}\not{E}^i_T = p_T^{\ell\ell\,i} + min(R_{cl}{}^i, R_{uncl}{}^i)$
    - $i = \perp, \parallel$ to dilepton p_T
  - $\overrightarrow{R_{cl}} = \sum_{jet}^{N_{jets}} \overrightarrow{p_T^{jet}}$
  - $\overrightarrow{R_{uncl}} = -\overrightarrow{\not{E}_T} - \overrightarrow{p_T^{\ell\ell}}$
  - $red\text{-}\not{E}_T = |\overrightarrow{red\text{-}\not{E}_T}|$

Discriminating Variables

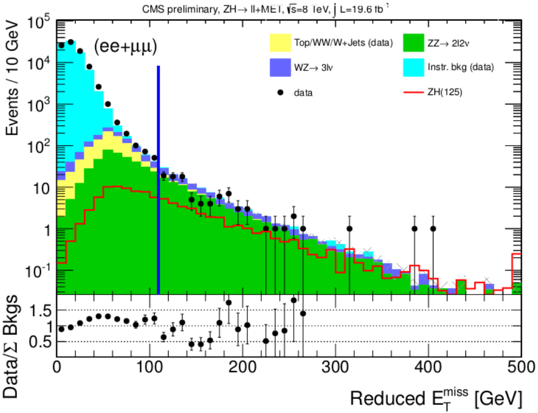
Main selection cuts

- Two leptons:
  - well-identified, isolated, same flavor leptons
  - $p_T^{\ell} > 20$ GeV
- Reject events with jets if:
  - $E_T > 30$ GeV
  - bjet:
    - soft-muon ($p_T > 3$ GeV)
    - b-tag and ($p_T > 20$ GeV and $|\eta| < 2.5$)
- Reject events with additional leptons if $p_T > 10$ GeV
- $|m_{\ell\ell} - m_Z| < 15$ GeV

+ Optimized cuts

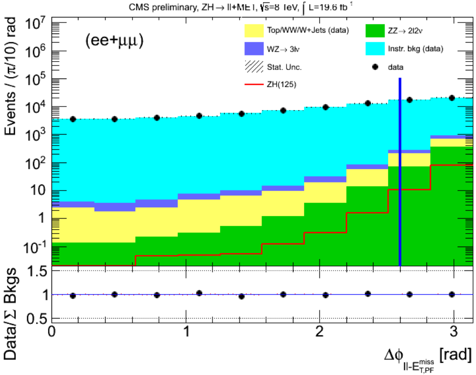
- $\Delta\phi_{\ell\ell-\not{E}_T} > 2.6$
- $0.8 < \frac{\not{E}_T}{p_T^{\ell\ell}} < 1.2$
- *red-*$\not{E}_T > 110$ GeV

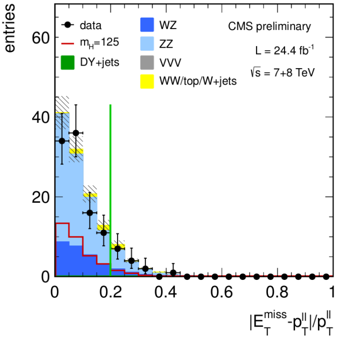
Reduced Missing Energy



- Preference of *red*-$\not{E}_T$ over $\not{E}_T$
  - Performs better in signal efficiency and Drell-Yan background suppression
  - Found to be more stable under pile-up condition and jet energy scale variations

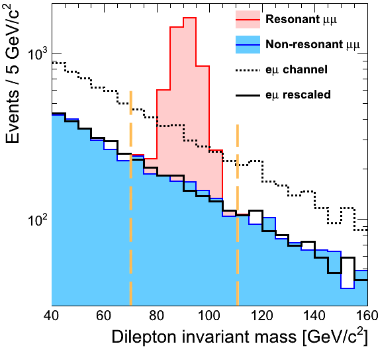
Other Optimization Variables





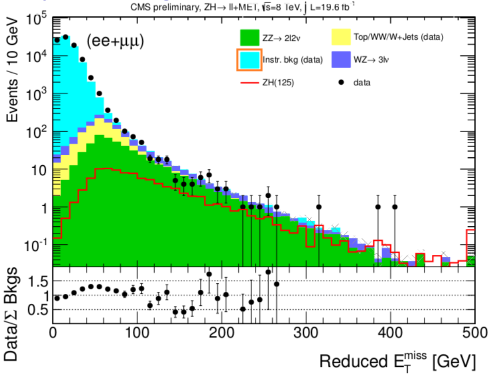
- Both used in ZH optimization along with *red-*$\not{E}_T$
  - Optimized to obtain best expected exclusion limits at 95% C.L.
- Suppress Drell-Yan and Top processes

Non-Resonant Background Estimation



- Non-resonant backgrounds are mainly leptonic W decays
  - WW, tW, $t\bar{t}$, single top, $Z \to \tau\tau$
- Calculate scale factors from data control region of $e^{\pm}\mu^{\mp}$ and $\ell^+\ell^-$ (e^+e^- or $\mu^+\mu^-$) events that pass selection cuts
  - Z-peak sidebands $40 < m_{\ell\ell} < 70$ GeV and $110 < m_{\ell\ell} < 200$ GeV
- Apply scale factors $\alpha_{\ell\ell} = \frac{N_{\ell\ell}^{SB}}{N_{e\mu}^{SB}}$
  - $N_{\ell\ell}^{peak} = \alpha_{\ell\ell} \cdot N_{e\mu}^{peak}$
- Checked with closure test

$Z + jets$ Background Estimation



- Normalize to $Z + jets$
- Reweighting factors as function of p_T^Z and number of reconstructed vertices
- Subtract EW processes w/ photons and neutrinos (MC)
- Modeling is improved for *red*-$\not{E}_T$ distribution for $Z + jet$

- Modeled from orthogonal $\gamma + jets$ control sample
  - larger statistics and topologically equivalent
  - MC may not fully model detector and pile-up effects in tail of *red*-$\not{E}_T$

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Systematic Uncertainties of ZH Analysis

Type	Source	Uncertainty(%)
Rate	PDF	4-5
	QCD scale variation (ZH)	7
	QCD scale variation (VV)	7-10
	Luminosity	2.2-4.4
	Lepton Trigger, Reco., Iso.	3
	$Z/\gamma* \to \ell\ell$ normalization	100
	Top, WW, W+jets normalization	25-100
Shape and Rate	MC statistics ZH,ZZ,WZ	1-5
	Control sample statistics $Z/\gamma* \to \ell\ell$	12-24
	Control sample statistics NRB	53-100
	Pile-up	0.1-0.3
	b-tagging Efficiency	0.2
	Lepton Momentum Scale	1
	Jet Energy Scale, Resolution	1-3
	Unclustered energy	1-4

- Combined relative signal efficiency uncertainty 12%
  - Theoretical uncertainty
  - PDF uncertainties
- Total relative uncertainty on background estimation 15%
  - Theoretical uncertainty (ZZ,WZ)

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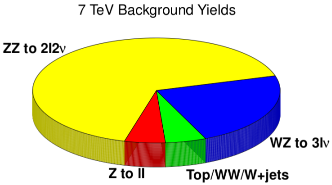
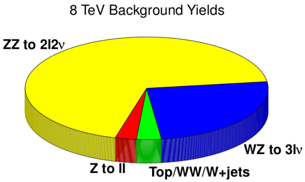
Final Yields of ZH Analysis

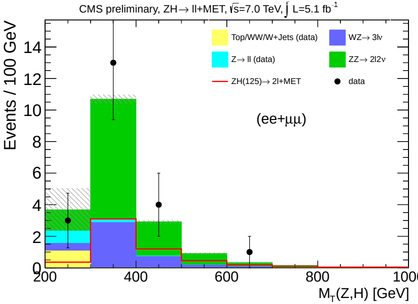
Process	$\sqrt{s} = 7$ TeV ee	$\sqrt{s} = 7$ TeV $\mu\mu$	$\sqrt{s} = 8$ TeV ee	$\sqrt{s} = 8$ TeV $\mu\mu$
$ZH(m_H = 125\text{ GeV})$	2.2 ± 0.3	3.3 ± 0.5	11.8 ± 1.9	16.7 ± 2.5
$Z/\gamma* \rightarrow \ell^+\ell^-$	0.3 ± 0.3	0.7 ± 0.7	1.0 ± 1.0	1.9 ± 1.9
$Top/WW/W + jets$	0.4 ± 0.4	0.6 ± 0.6	1.3 ± 0.8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

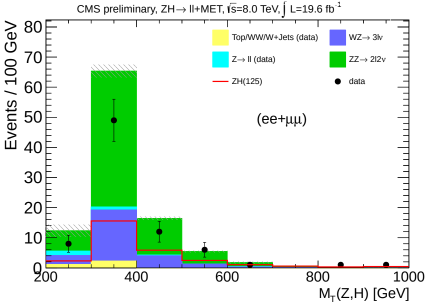




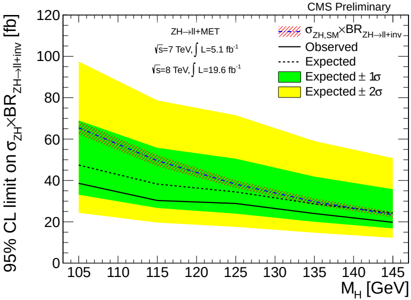
Shape Analysis for Invisible Higgs

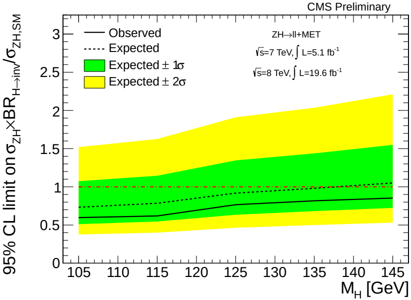
- $m_T^2 = \left(\sqrt{{p_T^{\ell\ell}}^2 + {m_{\ell\ell}}^2} + \sqrt{{\not{E}_T}^2 + {m_{\ell\ell}}^2}\right)^2 - \left(\overrightarrow{p_T^{\ell\ell}} + \overrightarrow{\not{E}_T}\right)^2$
- Exploit differences in kinematics
  - $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ and $ZH \rightarrow \ell^+\ell^- + H(inv)$ both have missing energy, but mass of missing particle is different
- Shape used for all Higgs masses
  - 105, 115, 125, 135, 145 GeV





Limits on Invisible Higgs Decay





- Upper limit on $BR(H \to \text{invisible})$
  - Assume SM production rate
- Use modified frequentist construction CL_s
- Use Shape of Transverse Mass of Z and H

- For Higgs with $m_H = 125$ GeV
  - Observed 95% C.L. upper limit 75%
  - Expected 95% C.L. upper limit 91%

m_H (GeV)	105	115	125	135	145
Obs Lim(%)	60	63	75	82	85
Exp Lim(%)	73	79	91	97	105

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Conclusions and looking forward.

- Set limits on invisible higgs branching fraction for SM-range masses
  - $m_H = 105$ GeV: Observed limit: $= 60\%$, Expected limit: $= 73\%$
  - $m_H = 115$ GeV: Observed limit: $= 63\%$, Expected limit: $= 79\%$
  - $m_H = 125$ GeV: Observed limit: $= 75\%$, Expected limit: $= 91\%$
  - $m_H = 135$ GeV: Observed limit: $= 82\%$, Expected limit: $= 97\%$
  - $m_H = 145$ GeV: Observed limit: $= 85\%$, Expected limit: $= 105\%$
- Comparable results to CMS and ATLAS indirect and direct searches (7) (8) (9)
- Continue analysis to explore Higgs masses beyond 150 GeV
- CMS-PAS-HIG-13-018 (10)

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