SEARCH FOR AN INVISIBLY DECAYING HIGGS BOSON IN DILEPTON EVENTS AT CDF

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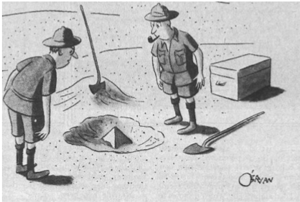
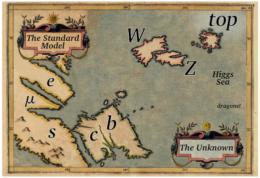
Theoretical Motivation

- After the discovery of a Higgs boson, the main task will be to establish its properties.
- Observing an invisible Higgs decay would be an indication of Physics Beyond the Standard Model.



"This could be the discovery of the century. Depending, of course, on how far down it goes."



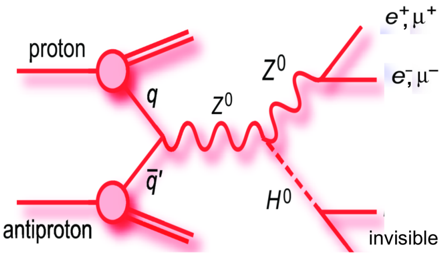
- Many BSM models allow for invisible Higgs decay whose branching ratio can be much larger than zero: *Fourth Generation Neutrino, SUSY, Extra-Dimension.*

Introduction: What are we searching for?

Aim: Search for a Higgs boson that decays to invisible particles.

If Higgs boson decays to weakly interacting and neutral particles,
$\Rightarrow$ Only missing transverse energy in the final state.

One of the cleanest signatures for this process is when H is produced in association with a $Z \to \ell^+\ell^-$:



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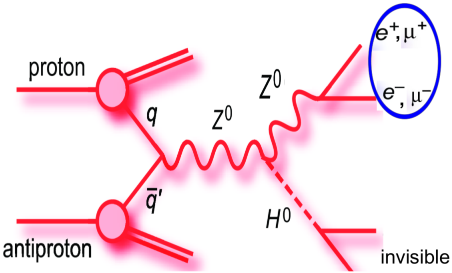

- **2 Leptons from Z**

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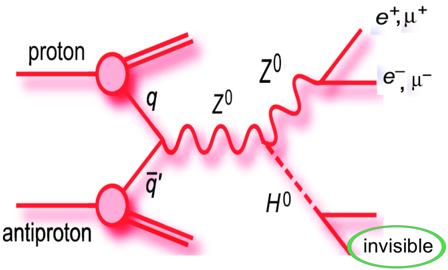

- **2 Leptons from Z**
- **Missing $\not{E}_T$ from H**

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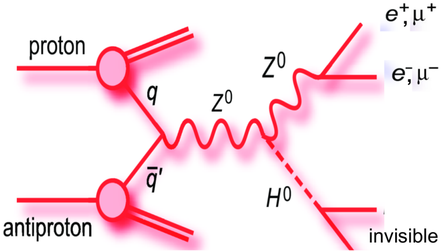


- **2 Leptons from Z**
- **Missing $\not{E}_T$ from H**
- **No jets**

Analysis Procedure

This analysis was performed using the full CDF data set corresponding to $\mathcal{L} = 9.7\,\text{fb}^{-1}$ of integrated luminosity.

Use of a sample of $Z-$resonant dileptons.

Hypotheses for the m_H

Higgs mass range from 115 to 150 GeV/c^2 for the ZH signal.

Assumptions for the ZH signal

$\sigma_{ZH,\text{SM}} \times \left[\mathcal{B}\left(H \rightarrow \text{ invisible}\right) = 100\%\right]$

The NNLO production cross section for ZH $m_H = 125\text{GeV}/c^2$

σ_{ZH} (fb)	scale (%)	PDF+$\alpha_s{}^{exp}$ (%)	$\alpha_s{}^{th}$
78.5	$^{+0.7}_{-1.0}$	$^{+6.6}_{-6.7}$	$^{+0.8}_{-0.6}$

Event Selection

ZH production mode allows to

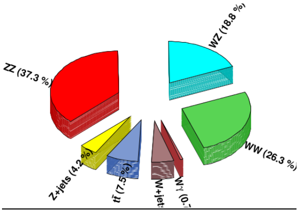
- High-p_T muon and high-E_T electron as triggers

Request:

- $\mathbf{Z} \rightarrow \ell^+\ell^-$
  - Exactly two opposite charge and same flavor leptons
  - Reconstructed invariant mass: $82 \leq m_{\ell\ell} \leq 100\,\mathrm{GeV}/c^2$
- $\mathbf{Z} \rightarrow \ell^+\ell^-$ **candidates**
  - $p_T(\ell\ell) \geq 45\,\mathrm{GeV}/c$ Signal sample
  - $30 \leq p_T(\ell\ell) \leq 45\,\mathrm{GeV}/c$ Control sample
- **Reduce background events**
  - No reconstructed jets with $\Delta\phi \geq 2.0$ rad from the Z
  - $\not{E}_T \geq 60\,\mathrm{GeV}$
  - $\Delta\phi(\not{E}_T, \ell) \geq 0.5$ rad

Background processes modeling

The signature considered is shared also by other processes, which are background contribution to our search.



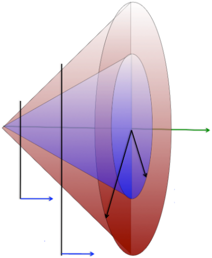
- **ZZ** $\rightarrow \ell\ell\nu\nu$: Irreducibile SM background, exactly same final state.
- **WZ** $\rightarrow \ell\nu\ell\ell$: Similar signature if one lepton is missing from leptonic decay mode
- **WW** $\rightarrow \ell\nu\ell\nu$: Same final state, non resonant dileptons
- **Z + jets**: Largest cross section, fake $\not{E}_T$ in the event.
- **W** γ: Background process when γ mimic a lepton.
- **W + jets**: Background process when jet mimic a lepton.
- $\mathbf{t\bar{t}}$: Dilepton final state with large jet multiplicity.

ΔR as Final Discriminant

Highest discriminating power between signal and background:

$$\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

Takes in account the recoil of a $Z \to \ell\ell$ with respect to the particle decaying invisibly.

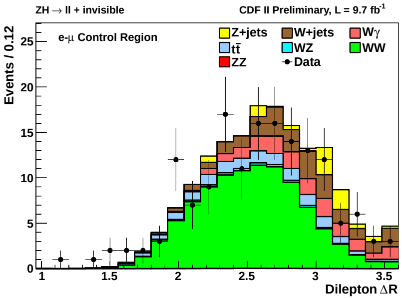


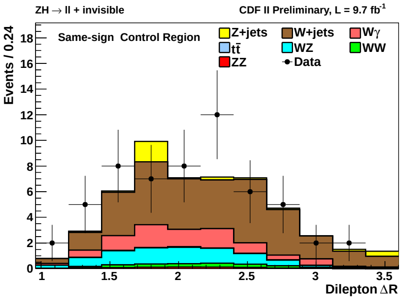
- Leptons recoiling against H
- Leptons recoiling against Z

Background Modelling

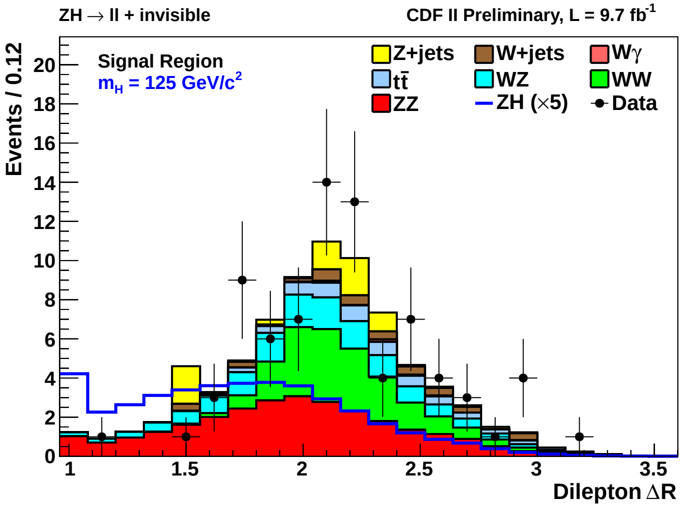
Background simulation validated in different Control Region

- WW/W+jets (DATA DRIVEN) validation: $e - \mu$ events.
- W γ/ W+jets (DATA DRIVEN) validation: Same Sign leptons.





Signal Region definition



Result

Data compatible with background expected events

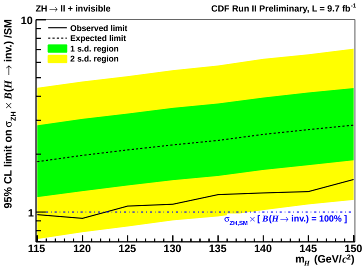
$ZH \to \ell^+\ell^-$ + **invisible** (signal region) CDF Run II Preliminary, $\mathcal{L} = 9.7\ \text{fb}^{-1}$	
Z +jets	7.1 ± 3.1
W+jets	3.8 ± 0.6
$W\gamma$	0.5 ± 0.1
$t\bar{t}$	5.5 ± 0.9
WZ	13.7 ± 1.5
WW	19.2 ± 1.8
ZZ	27.2 ± 2.9
Total prediction	$\mathbf{76.9 \pm 7.2}$
ZH ($m_H = 125$ GeV$/c^2$)	8.2 ± 1.3
Data	**78**

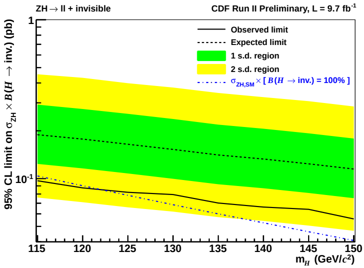
Evaluate the limit using a binned likelihood (*Bayesian approach*) to be fitted:

$$\mathcal{L} = (\prod_i \frac{{\mu_i}^{n_i} e^{-\mu_i}}{n_i!}) \cdot \prod_c e^{-\frac{{S_C}^2}{2}}$$

$(Z \to ll)(H \to \nu\nu)$ production Limit Calculation

We see no evidence of a Higgs boson decaying invisibly in the mass range considered





We exclude at 95% Credibility Level

- $\mathcal{B}\left(H \to \ invisible\right) = 100\%$ assumption at Higgs boson masses lower than $120 GeV/c^2$
- $\sigma_{ZH} \times \mathcal{B}(H \to \ \text{inv}) \geq 90$ fb at a Higgs boson mass of $125 GeV/c^2$

Summary

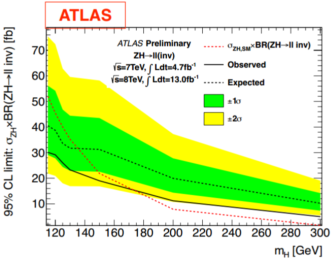
- We present the first search at the Tevatron for a Higgs boson decaying to an invisible final state.
- We search in the associated ZH production mode, 2 leptons and $\not{E}_T$ in the final state
- We are able to exclude
  - $\mathcal{B}\left(H \rightarrow \ invisible\right) = 100\%$ assumption at Higgs boson masses lower than $120 GeV/c^2$
  - $\sigma_{ZH} \times \mathcal{B}(H \rightarrow \ \mathrm{inv}) \geq 90$ fb at a Higgs boson mass of $125 GeV/c^2$

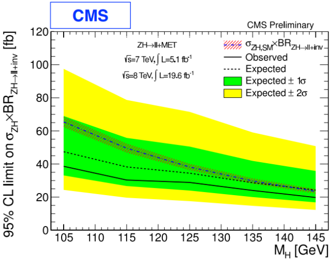
Backup slides

CMS[1]/ATLAS[2]?

Different searches have been carried out, by ATLAS and CMS, taking advantage of the VBF and VH production signatures [1] [2]

	ATLAS	CMS
$W, Z \to$ fatjet, $H \to$ inv.	1.6 (2.2)	–
$Z \to \ell^+\ell^-$, $H \to$ inv.	65% (84%)	75% (91%)
$Z \to b\bar{b}$, $H \to$ inv.	–	1.8 (2.0)
VBF $H \to$ inv.	–	69% (53%)





[1] ATLAS Collab., arXiv:1309.4017 [hep-ex] (2013). ATLAS Collab., ATLAS-CONF-2013-011 (2013)

Efficiency of the cuts for Signal

Description	$ZH\ m_H = 125\ \text{GeV}/c^2$
Events after skim	20.60
Cut 1 (diletonType $\neq$ -1)	1
Cut 2 (dileptonFlavor $\neq$ kflav_ em | kflav_ etau | | kflav_ mtau)	0.99
Cut 3 (dileptonType $\neq$ k_ PHX_ PHX | | k_ PHX_ PLBE | | k_ PLBE_ PLBE)	0.98
Cut 4 (N_{jeAw} <0.)	0.85
Cut 5 ($\Delta\phi(\not{E}_T, ll) >$ 0.5)	0.91
Cut 6 ($Z_{Pt} >$ 45. GeV/c)	0.75
Cut 7 ($82.$ <dimass $< 100.$ GeV/c^2)	0.85
Cut 8 ($\not{E}_T >$ 60. GeV)	0.85
Cut 9 (cutMask == true)	0.96
Cut 10 (SS regions reject PHX)	1
Cut 11 (SS regions reject PHX)	1
Overall efficiency	0.40
Expected events	8.17

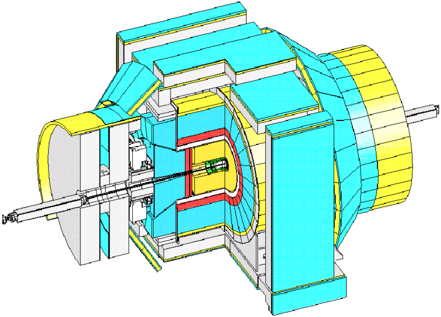
Efficiency of the cuts for Data

Description	Data
Events after skim	$1.42 \cdot 10^6$
Cut 1 label	0.97
Cut 2 label	0.99
Cut 3 label	0.95
Cut 4 label	0.80
Cut 5 label	0.64
Cut 6 label	0.003
Cut 7 label	0.34
Cut 8 label	0.16
Cut 9 label	0.78
Cut 10 label	1
Cut 11 label	1
Overall efficiency	$5.49 \cdot 10^{-5}$
Expected events	78

Process	Modeling	σ[pb]
ZZ	PYTHIA	1.511
$WZ(\to \ell\nu\ell\ell)$	PYTHIA	3.46
$WW(\to \ell\nu\ell\nu)$	MC@NLO	12.4
$Z + jets$	PYTHIA + data-driven	490
$W\gamma$	BAUR	18.6
$W + jets$	data-driven	
$t\bar{t}$	PYTHIA	0.81

$ZH \to \ell^+\ell^-$ + **invisible**	CDF Run II Preliminary, $\mathcal{L} = 9.7\ \mathrm{fb}^{-1}$					
m_H (GeV/c^2)	95% C.L. on $\sigma_{ZH} \times \mathcal{B}(H \to \mathrm{invisible})/\sigma_{ZH,\mathrm{SM}}$					
	-2 s.d.	-1 s.d.	**Exp.**	+1 s.d.	+2 s.d.	**Obs.**
115	0.73	1.19	**1.82**	2.81	4.37	**0.93**
120	0.79	1.29	**1.97**	3.04	4.78	**0.97**
125	0.84	1.37	**2.10**	3.26	5.08	**1.04**
130	0.90	1.46	**2.23**	3.47	5.47	**1.16**
135	0.95	1.53	**2.35**	3.64	5.77	**1.17**
140	1.03	1.65	**2.52**	3.91	6.18	**1.26**
145	1.09	1.75	**2.67**	4.16	6.64	**1.38**
150	1.15	1.85	**2.82**	4.38	6.97	**1.37**

The CDF Detector



- Multipurpose detector, BØ interaction point at Tevatron
- Tracking system in magnetic field at 1.4 T
- Calorimeters
  - Electromagnetic and hadronic
  - Sampling
  - Projective towers
- Muon chambers
  - 4 layers of drift chambers
- Trigger system
  - Three levels of online selection