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

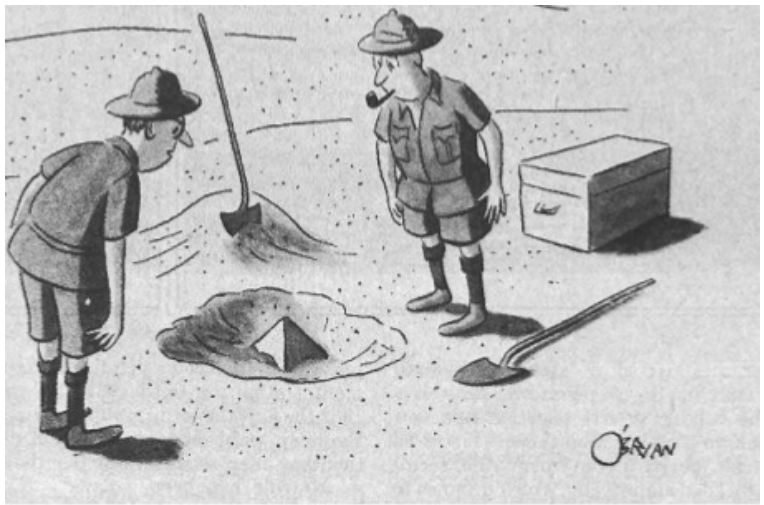
C. Principato on behalf of the CDF collaboration

University of Virginia

New Perspectives 2015

Theoretical Motivation

- After the discovery of a Higgs boson, the main task will be to establish its properties.



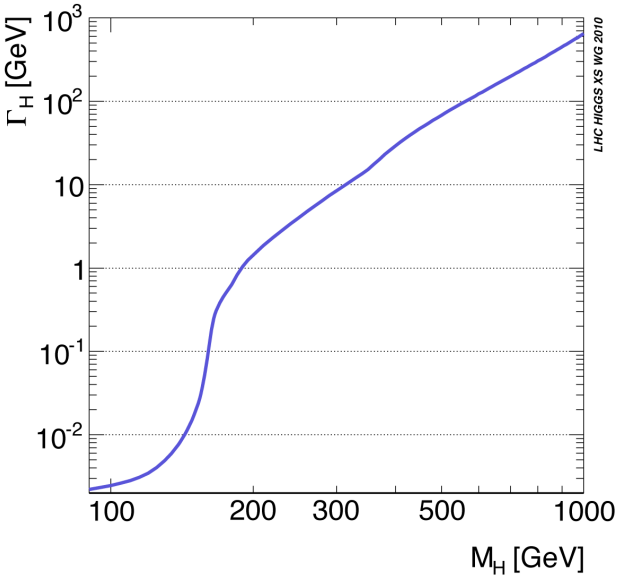
"This could be the discovery of the century. Depending, of course, on how far down it goes."

- Ideal places to investigate new physics Beyond Standard Model

What's the Standard Model width of a 125 GeV Higgs?

The total decay width of the SM Higgs boson:

$$\mathbf{\Gamma_H}^{\mathbf{Tot}} = \mathbf{4.07\,MeV} \pm 4\% \text{ for } m_H = 125\,\mathrm{GeV}/c^2. \quad (1)$$



Direct limits are inherently weak:
$\mathbf{\Gamma_H} < 6.9$ GeV,
$\mathbf{\Gamma_H} \lesssim \mathbf{1600\Gamma_H}^{\mathbf{SM}}$

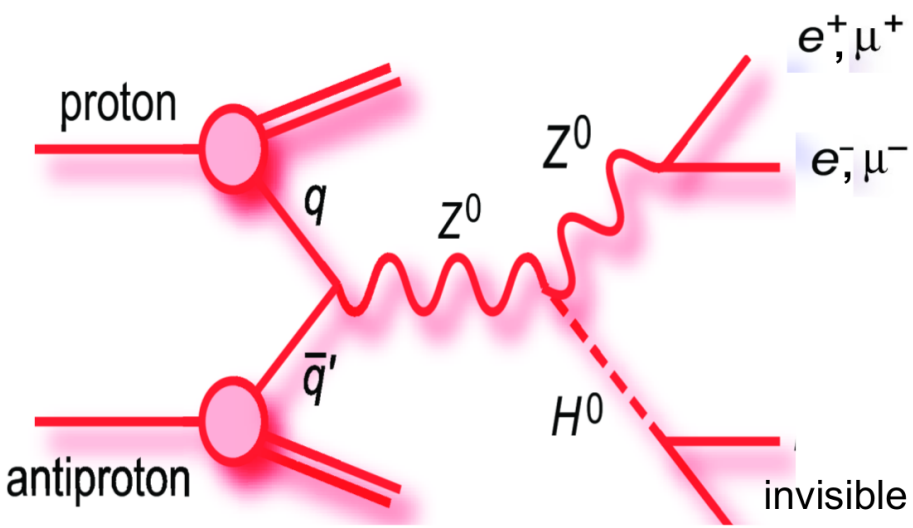
$\Rightarrow$ Many BSM models allow for invisible Higgs decay whose branching ratio can be much larger than zero:
Fourth Generation Neutrino, SUSY, Extra-Dimension.

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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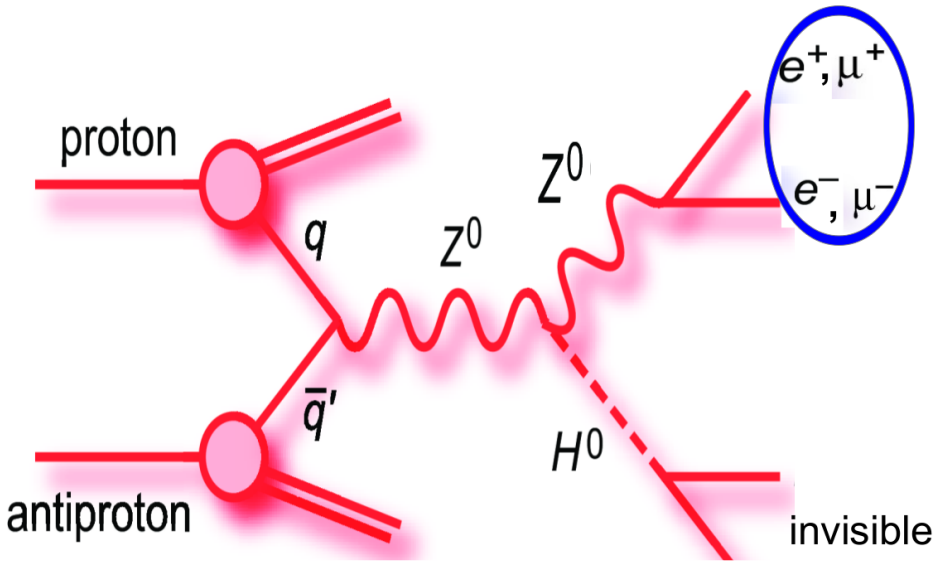

- **2 Leptons from Z**

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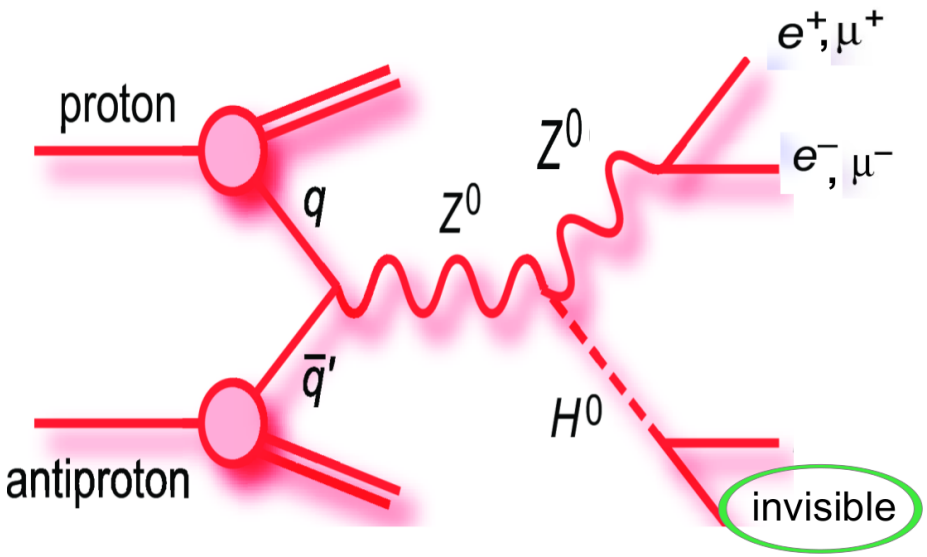

- **2 Leptons from Z**
- **Missing E_T from H**

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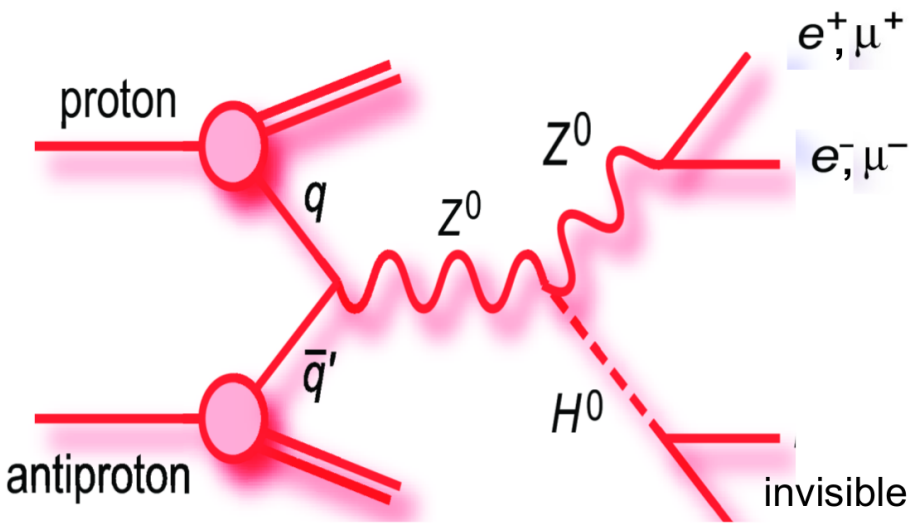


- **2 Leptons from Z**
- **Missing E_T from H**
- **No jets**

Analysis Procedure

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

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

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

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

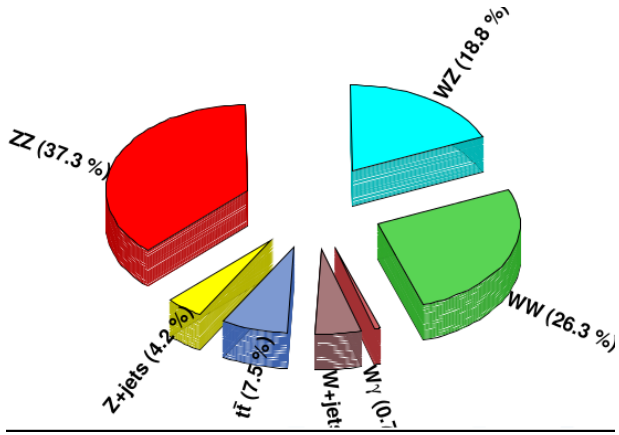
- High-p_T muon and high-E_T electron as triggers

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
- **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.



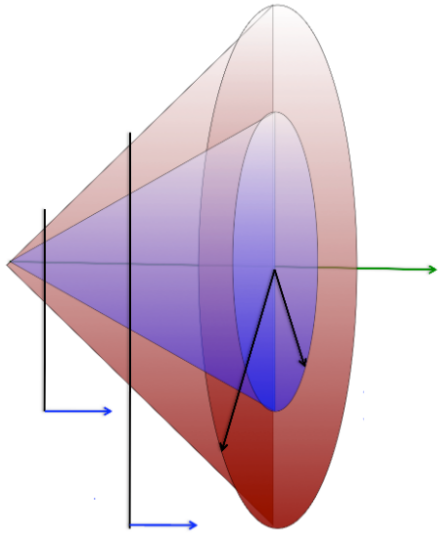
- $\mathbf{ZZ} \to \ell\ell\nu\nu$: Irreducibile SM background, exactly same final state.
- $\mathbf{WW} \to \ell\nu\ell\nu$: Same final state, non resonant dileptons
- $\mathbf{WZ} \to \ell\nu\ell\ell$: Similar signature if one lepton is missing from leptonic decay mode
- $\mathbf{Z}$ + **jets**: Largest cross section, fake $\not\!\!E_T$ in the event.
- $\mathbf{W}\,\gamma$: Background process when γ mimic a lepton.
- $\mathbf{W}$ + **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.

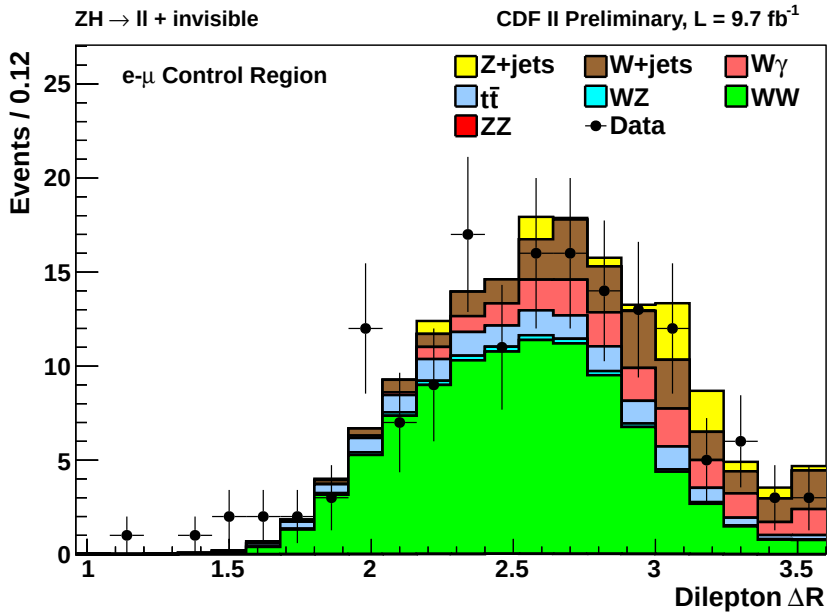


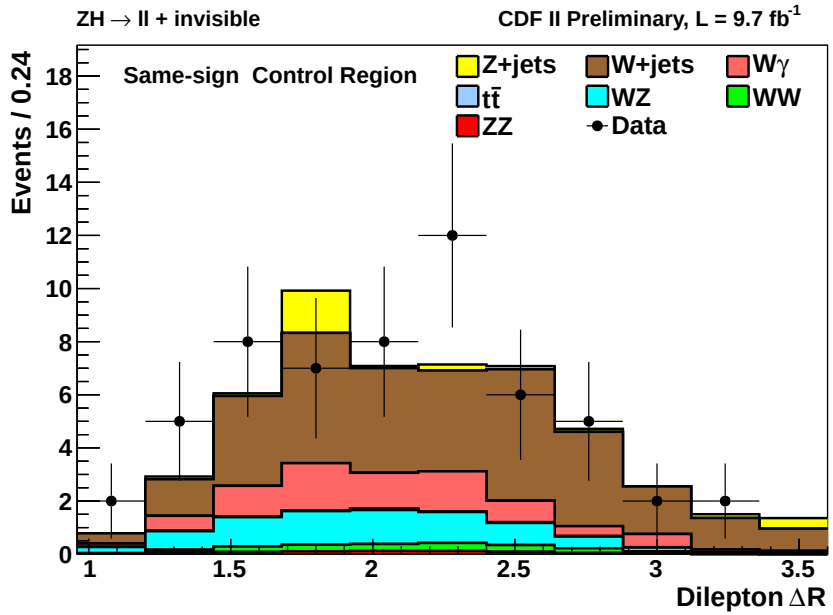
- Leptons recoiling against H
- Leptons recoiling against Z

Background Modelling

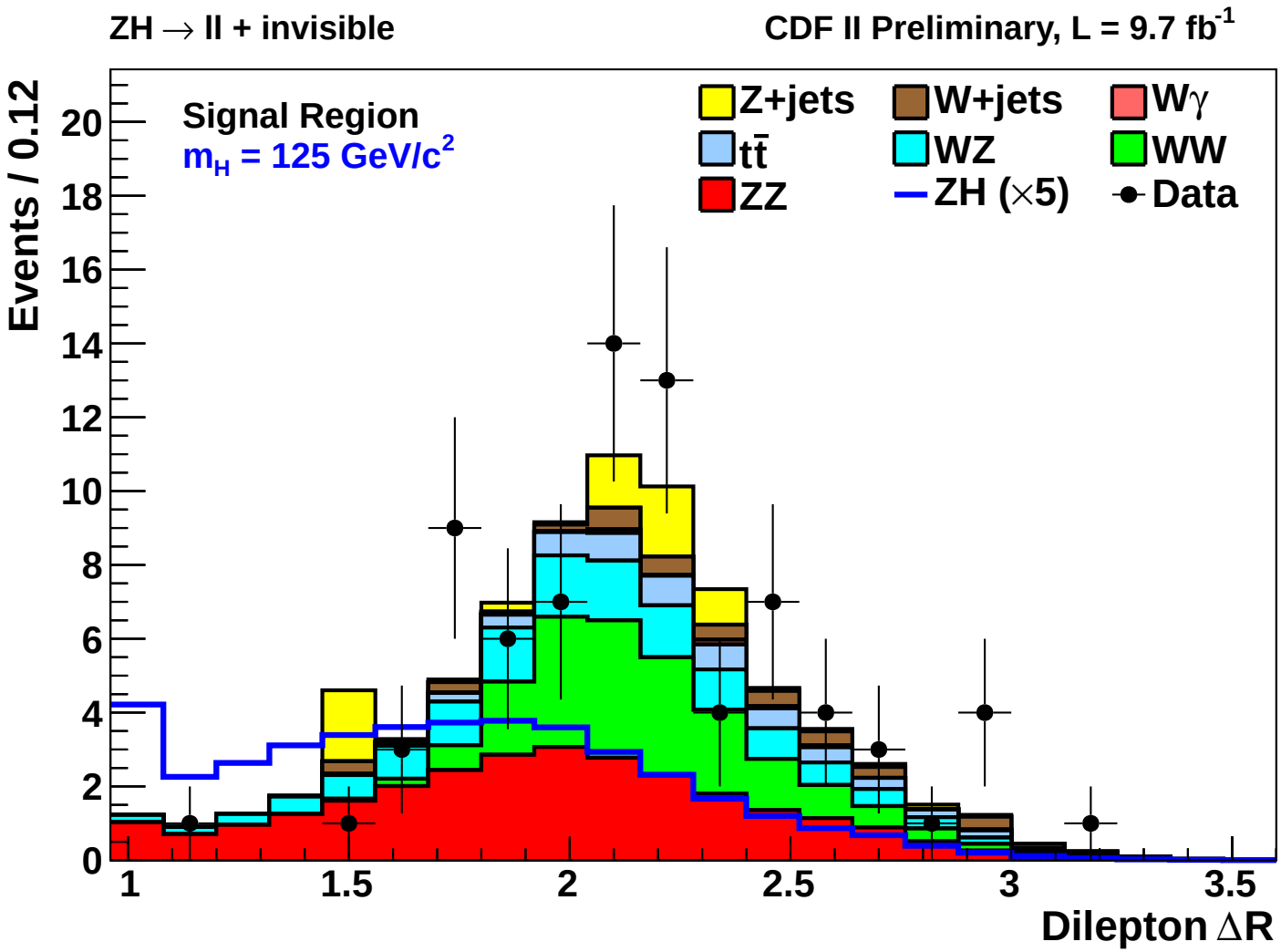
Background simulation validated in different Control Region

- 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

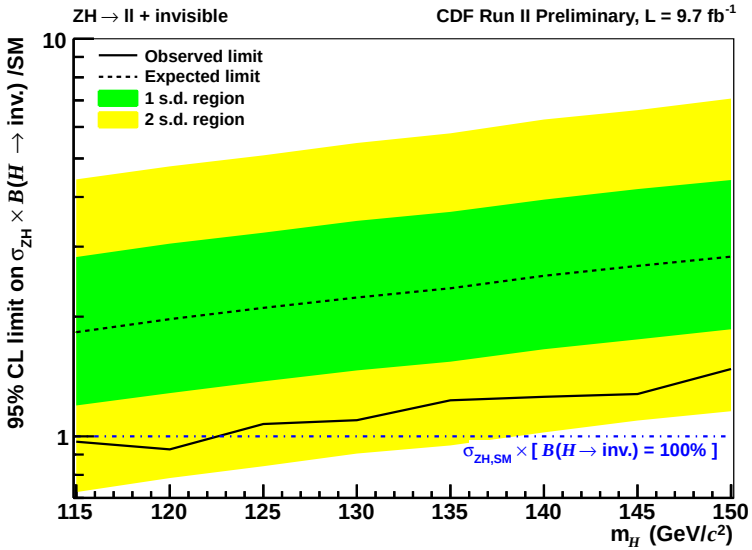
$ZH \to \ell^+\ell^-$ + **invisible** (signal region) CDF Run II Preliminary, $\mathcal{L} = 9.7$ fb^{-1}	
Z +jets	7.1 ± 3.1
W+jets	3.8 ± 0.6
$W\gamma$	0.5 ± 0.1
$t\bar{t}$	5.5 ± 0.9
WZ	13.7 ± 1.5
WW	19.2 ± 1.8
ZZ	27.2 ± 2.9
Total prediction	$\mathbf{76.9 \pm 7.2}$
ZH ($m_H = 125$ GeV/c^2)	8.2 ± 1.3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

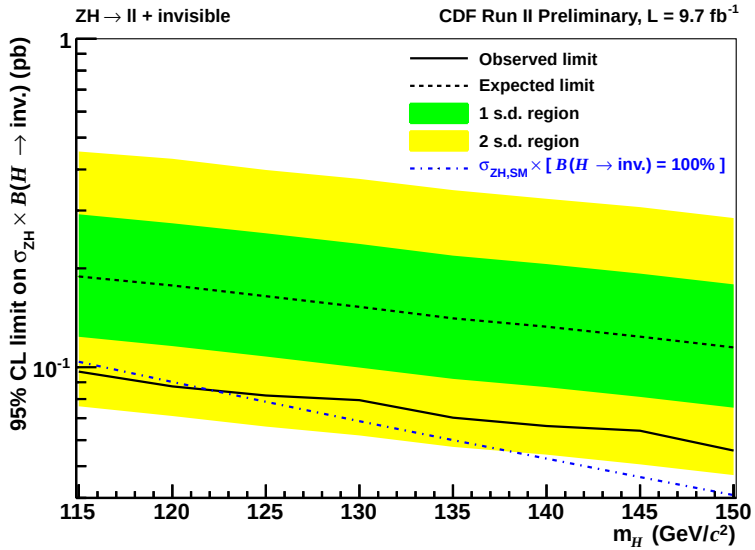
Evaluate the limit using a binned likelihood (*Bayesian approach*) to be fitted:

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

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

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





We exclude at 95% Credibility Level

- $\mathcal{B}\,(H \to\ invisible) = 100\%$ assumption at Higgs boson masses lower than $123 GeV/c^2$
- $\sigma_{ZH} \times \mathcal{B}(H \to\ \text{inv}) \geq 90$ fb at a Higgs boson mass of $125 GeV/c^2$

Summary

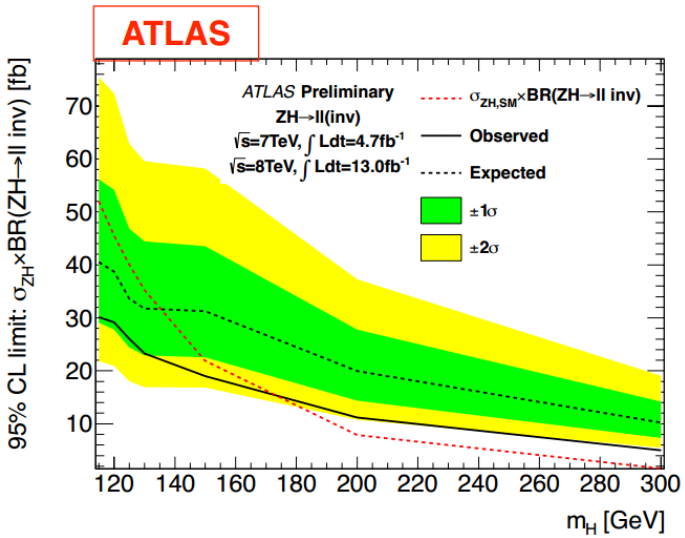
- We present the first search at the Tevatron for a Higgs boson decaying to an invisible final state.
- We search in the associated ZH production mode, 2 leptons and $\not\!\!E_T$ in the final state
- We are able to exclude
  - $\mathcal{B}\left(H \rightarrow\ invisible\right) = 100\%$ assumption at Higgs boson masses lower than $123 GeV/c^2$
  - $\sigma_{ZH} \times \mathcal{B}(H \rightarrow\ \text{inv}) \geq 90$ fb at a Higgs boson mass of $125 GeV/c^2$

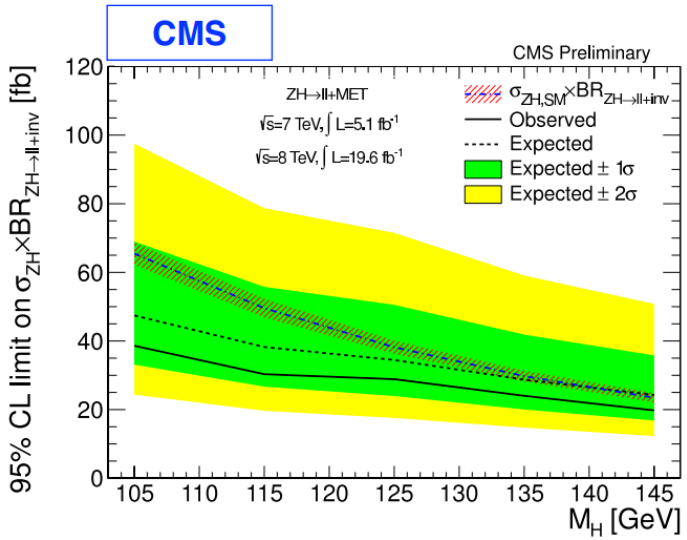
Backup slides

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)

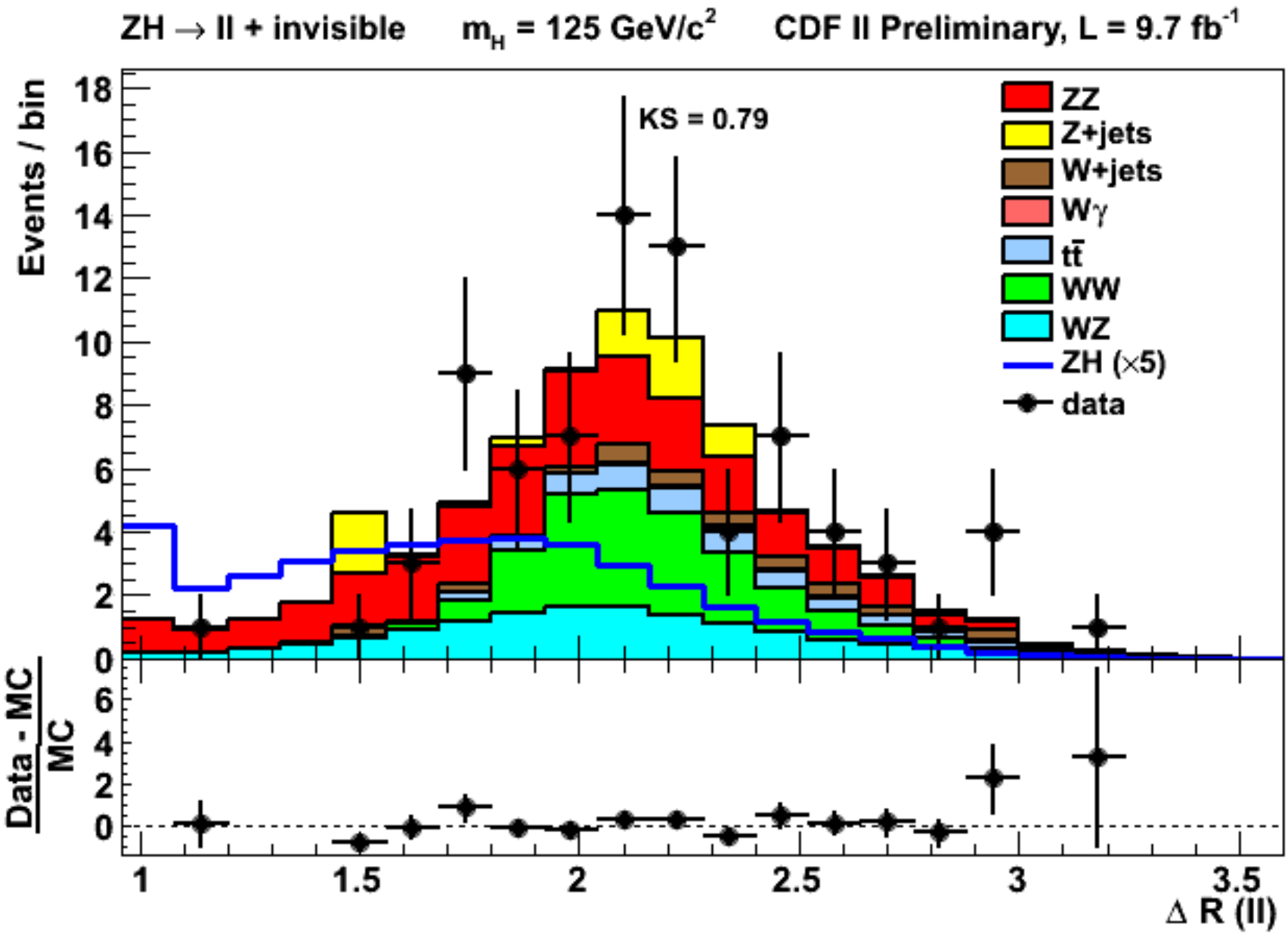
Efficiency of the cuts for Signal

Description	$ZH\ m_H = 125\ \mathrm{GeV}/c^2$
Events after skim	20.60
Cut 1 (dileptonType $\neq$ -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

$ZH \to \ell^+\ell^-$ + invisible	CDF Run II Preliminary, $\mathcal{L} = 9.7$ fb^{-1}					
m_H (GeV/c^2)	95% C.L. on $\sigma_{ZH} \times \mathcal{B}(H \to \text{invisible})/\sigma_{ZH,\text{SM}}$					
	-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**


ZH → ll + invisible
m_H = 125 GeV/c^2
CDF II Preliminary, L = 9.7 fb^-1
KS = 0.79
ZZ
Z+jets
W+jets
Wγ
tt̄
WW
WZ
ZH (×5)
data
Events / bin
Data - MC / MC
Δ R (ll)