Seeing an invisible Higgs at Tevatron and LHC

Heather Logan
University of Wisconsin, Madison

Fermilab
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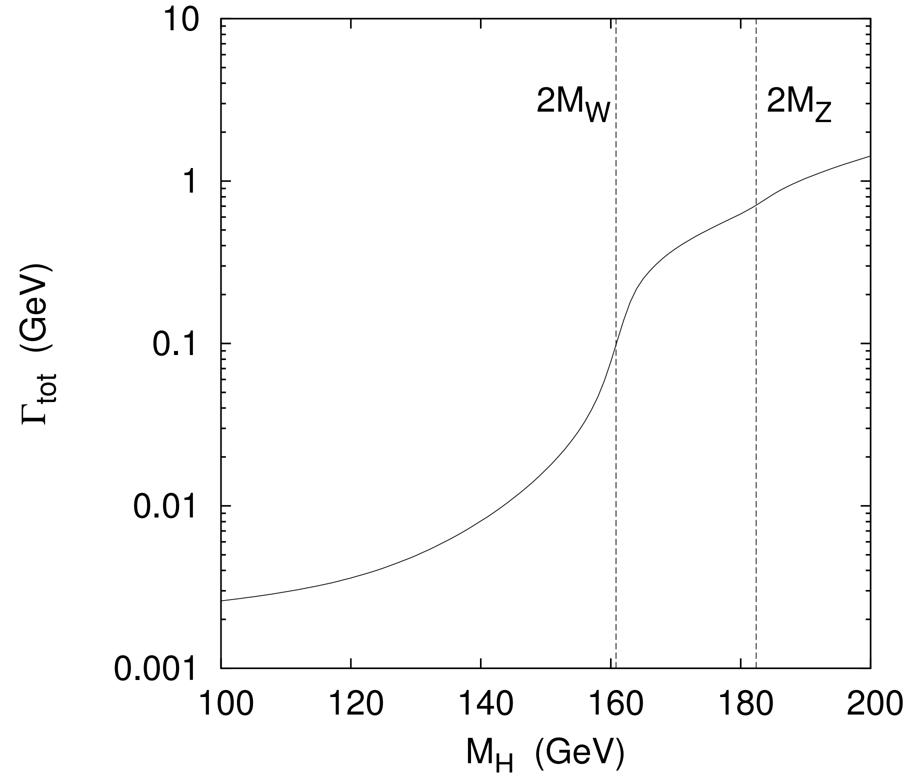
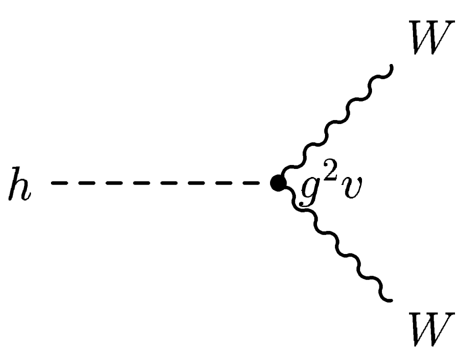
Based on Davoudiasl, Han, H.L., hep-ph/0412269

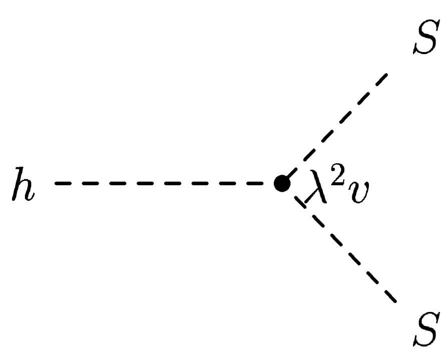
Why an invisible Higgs?

The SM Higgs is very narrow for $m_h \lesssim 160$ GeV.

If the Higgs couples with electroweak strength to a neutral (quasi)stable particle (e.g., dark matter) with mass $< m_h/2$, then $h \to$ invisible can be the dominant decay mode.







The Higgs *could* decay invisibly

- $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ in MSSM, NMSSM
- $h \to SS$ in simple models of scalar dark matter
- $h \to$ KK neutrinos in extra dimensions
- $h \to$ Majorons
- $\ldots$

$\longrightarrow$ Cover all our bases!
We shouldn't just assume the Higgs will be SM-like – even small additions (such as scalar singlet dark matter) can make BR($h \to$ invis.) large.

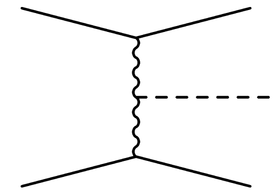
"Invisible" Higgs is not that hard to "see": $\not{p}_T$
$h \to jj$ is much harder.

Outline

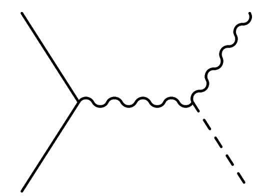
- Motivation
- LHC
- Tevatron
- Mass extraction
- Conclusions

An invisible Higgs at the LHC

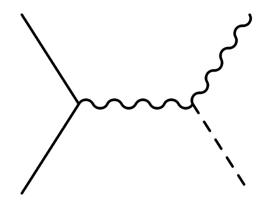
Search modes:



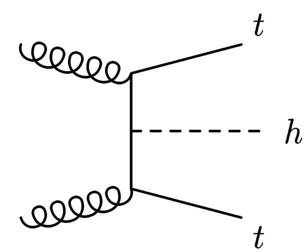
- WBF $\to h_{inv}$ Eboli & Zeppenfeld (2000)
Signal is $jj\not{p}_T$; jets are hard and forward



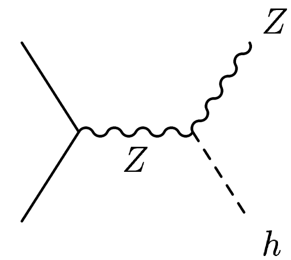
- $Z + h_{inv}$ Frederiksen, Johnson, Kane & Reid (1994); Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003); Davoudiasl, Han & H.L. (2004)
Signal is $\ell^+\ell^-\not{p}_T$, with $m(\ell^+\ell^-) = m_Z$ $(\ell = e, \mu)$



- $W + h_{inv}$ Choudhury & Roy (1994); Godbole, Guchait, Mazumdar, Moretti & Roy (2003)
Signal is $\ell\not{p}_T$; totally swamped by background.



- $t\bar{t}h_{inv}$ Gunion (1994); Kersevan, Malawski & Richter-Was (2002)
Signal is $bjj + b\ell + \not{p}_T$.



Associated $Z + h_{inv}$ production at LHC

Higgs decays invisibly; consider Z decays to leptons.
$\rightarrow$ Signal is $\ell^+\ell^-\not{p}_T$ ($\ell = e, \mu$)

Major backgrounds:

- $Z(\rightarrow \ell^+\ell^-)Z(\rightarrow \nu\bar{\nu})$
- $W(\rightarrow \ell^+\nu)W(\rightarrow \ell^-\bar{\nu})$
- $W(\rightarrow \ell\nu)Z(\rightarrow \ell^+\ell^-)$ with missed lepton
- $Z(\rightarrow \ell^+\ell^-) + j$ with fake $\not{p}_T$

We simulated the $Z+h_{inv}$ signal and the ZZ, WW, and WZ backgrounds using Madgraph.

The $Z+j$ background with fake $\not{p}_T$ comes from $Z+j$ events in which the jet(s) are missed: either they are too soft or they go down the beampipe. We took results for this background from Frederiksen, Johnson, Kane & Reid.

Cuts:

We start with some "minimal cuts":

$$p_T(\ell^\pm) > 10 \text{ GeV}, \qquad |\eta(\ell^\pm)| < 2.5, \qquad \Delta R(\ell^+\ell^-) > 0.4$$

The leptons in the signal reconstruct to the Z mass. The WW background can be largely eliminated by a Z mass cut:

$$|m_{\ell^+\ell^-} - m_Z| < 10 \text{ GeV}$$

This also removes Drell-Yan $Z \to \tau\tau$.

The leptons from the WW background also tend to be back-to-back; this background can be further reduced with an angular cut:

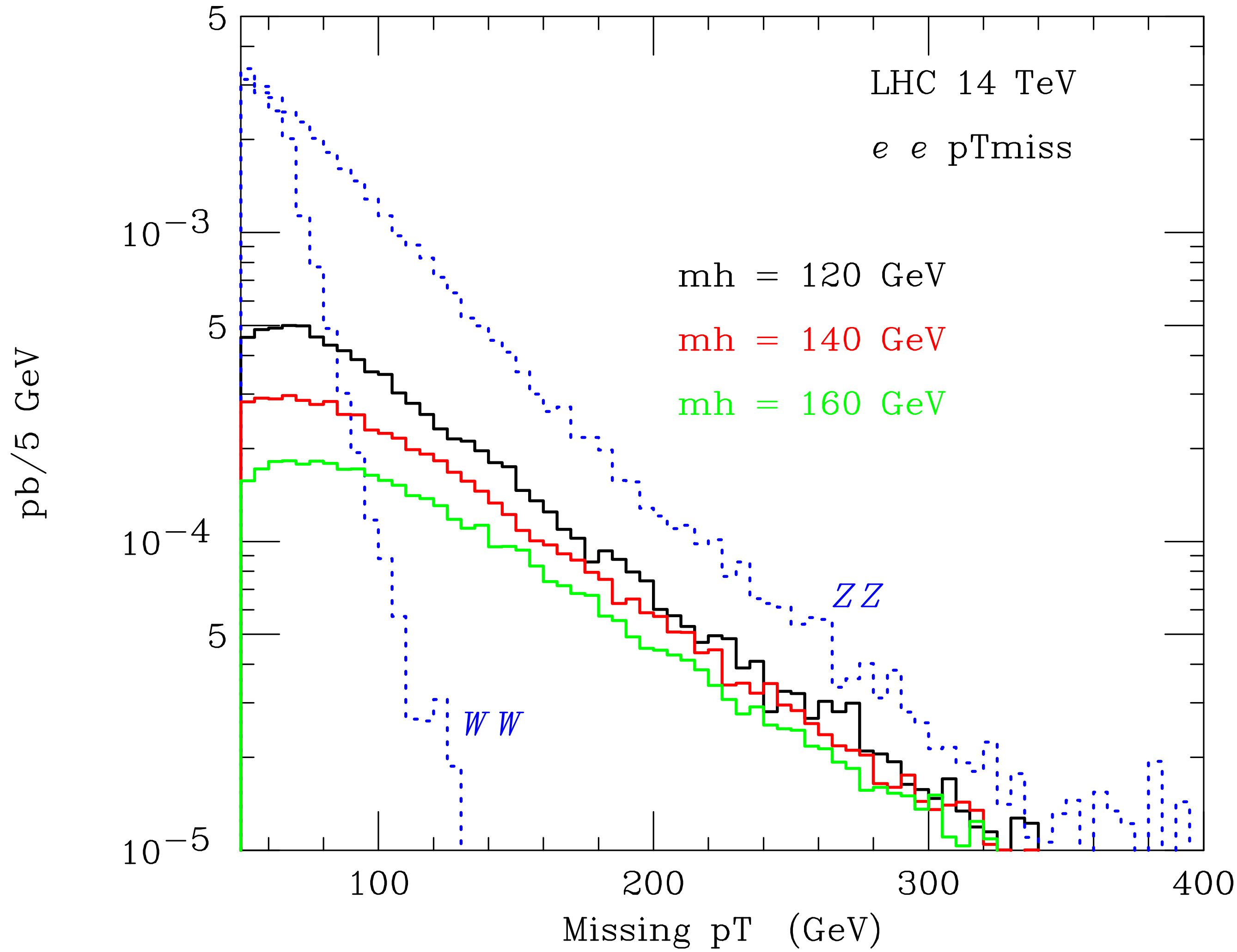
$$\Delta\phi_{\ell^+\ell^-} < 2.5$$

This cut also eliminates Drell-Yan with mismeasured $\ell^\pm$ energy.

To cut down the WZ background, we veto events with a third lepton with

$$p_T > 10 \text{ GeV}, \qquad |\eta| < 3.0 \qquad \text{(lepton veto)}$$

Final cut is on $\not{p}_T$:



• $\not{p}_T$ of WW background tends to be soft, since it comes from the neutrinos in two independent W decays.
• $\not{p}_T$ of ZZ background is softer than signal: ZZ is t-channel while $Z + h_{inv}$ is s-channel.
• $\not{p}_T$ of Signal increases with m_h.

$Z + j$ background with fake $\not{p}_T$:

Fake $\not{p}_T$ due to missed jets – too soft or too large rapidity
$\longrightarrow$ escape the jet veto
Proper treatment for modern ATLAS/CMS design requires detector simulation – beyond the scope of our study.

Was studied in Frederiksen, Johnson, Kane & Reid (1994) for various $\not{p}_T$ cuts and rapidity coverage of hadronic calorimeter
$\longrightarrow$ we adapt their results for our study.

• With $\Delta R(\ell^+\ell^-) > 0.4$, we have larger lepton acceptance by a factor of 1.6 than Frederiksen, Johnson, Kane & Reid (who used $\Delta R(\ell^+\ell^-) > 0.7$)
$\longrightarrow$ better statistics with same luminosity.

• We consider a range of $\not{p}_T$ cuts
Frederiksen, Johnson, Kane & Reid considered lower $\not{p}_T$, Godbole et al considered higher $\rightarrow$ optimize $\not{p}_T$ cut to improve signal significance

Comparison to Godbole et al (2003) study of $Z + h_{inv}$

They included hadronization using PYTHIA/HERWIG and detector simulation using CMSJET/GETJET (respectively).

No big surprises – our results are consistent with theirs.

- jet veto on ISR $\leftrightarrow$ NLO K-factor
- $t\bar{t}$
- WZ lepton veto

Results (LHC, $ee+\mu\mu$)

Signal and background cross sections (after cuts):

$\not{p}_T$ cut	B(ZZ)	B(WW)	B(ZW)	B($Z+j$)*	S($Z+h_{inv}$) $m_h=120$	140	160 GeV
65 GeV	48.0 fb	10.6 fb	10.2 fb	22 fb	14.8 fb		
75 GeV	38.5 fb	4.3 fb	7.4 fb	9 fb	12.8 fb	9.4 fb	7.0 fb
85 GeV	30.9 fb	1.8 fb	5.5 fb		11.1 fb	8.3 fb	6.3 fb
100 GeV	22.1 fb	0.6 fb	3.6 fb		8.7 fb	6.8 fb	5.3 fb

*B($Z+j$) extrapolated from Frederiksen, Johnson, Kane & Reid

Significance: (parentheses: includes $Z+j$)

$\not{p}_T$ cut	$m_h=120$ GeV S/B	$m_h=120$ GeV S/$\sqrt{B}$ (10 fb^{-1})	$m_h=120$ GeV S/$\sqrt{B}$ (30 fb^{-1})	$m_h=140$ GeV S/$\sqrt{B}$ (30 fb^{-1})	$m_h=160$ GeV S/$\sqrt{B}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)		
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

$m_h = 120$ GeV: $> 5\sigma$ signal with 10 fb^{-1}.

With 30 fb^{-1}, 5σ discovery extends out to $m_h = 160$ GeV.

• $Z + h_{inv}$: $S/\sqrt{B} \gtrsim 5$ for $m_h = 120$ GeV and 10 fb^{-1}.

Comparison to WBF$\rightarrow h_{inv}$ process

[Eboli & Zeppenfeld]

• WBF $\rightarrow h_{inv}$ gives much better significance:
$S/\sqrt{B} \simeq 24$ for $m_h = 120$ GeV and 10 fb^{-1}.

• $Z + h_{inv}$ provides an independent discovery channel:
very different search with different systematics
independent handle on h_{inv} production

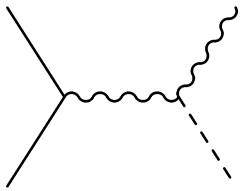
Comparison to $t\bar{t}h_{inv}$ process

[Gunion; Kersevan, Malawski & Richter-Was]

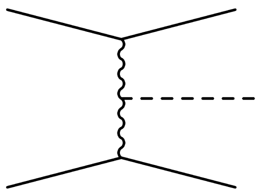
• $t\bar{t}h_{inv}$ is a complicated process – *many* particles in the final state and many backgrounds.
$S/\sqrt{B} \sim 4$ for $m_h = 120$ GeV and 10 fb^{-1}.

An invisible Higgs at the Tevatron

Search modes:

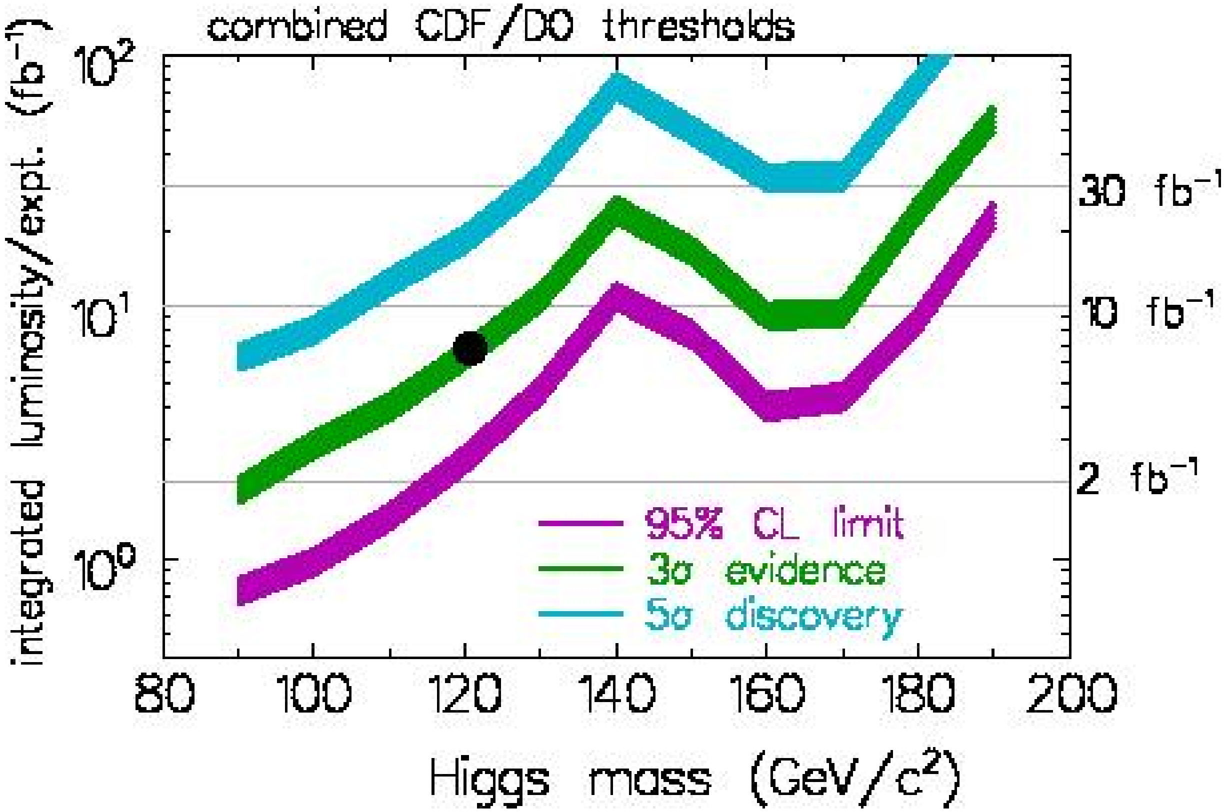


• $Z + h_{inv}$ Martin & Wells (1999)
Signal is $\ell^+\ell^-\not{p}_T$, similar to LHC search.
120 GeV Higgs, 10 fb^{-1}: $S/\sqrt{B} \simeq 1.9$



• WBF$\rightarrow h_{inv}$ Davoudiasl, Han & H.L. (2004)
Signal is $jj\not{p}_T$; jets are hard and forward.
120 GeV Higgs, 10 fb^{-1}: $S/\sqrt{B} \simeq 1.6$

Looks very depressing... but combining both channels and data from both detectors, can get 3σ with "only" 7 fb^{-1} of delivered luminosity. Tevatron has a shot at this before the LHC!



3σ requires ~ 7 fb^{-1} for $m_h = 120$ GeV.

Comparable to SM Higgs sensitivity.

Weak boson fusion $\to h_{inv}$ at the Tevatron

Higgs decays invisibly; signal is $jj\not{p}_T$

Major backgrounds:

- $Z(\to \nu\bar{\nu}) + 2j$, from QCD
- $Z(\to \nu\bar{\nu}) + 2j$, from EW (WBF) – kinematics similar to signal
- $W(\to \ell\nu) + 2j$, from QCD – with the lepton missed
- $jj\not{p}_T$ with fake $\not{p}_T$

We simulated the WBF signal and the $Z + 2j$ and $W + 2j$ backgrounds using Madgraph.

The $jj\not{p}_T$ background with fake $\not{p}_T$ comes from dijet events in which the jet(s) are mismeasured and from multijet events in which the extra jets are too soft or they go down the beampipe. We took a conservative upper limit for this background of 5 fb from a CDF study of $jj\not{p}_T$.

Cuts:

We again start with some "minimal cuts":

$$p_T(j) > 10 \text{ GeV}, \qquad |\eta(j)| < 3.0, \qquad \Delta R(jj) > 0.4, \qquad \not{p}_T > 90 \text{ GeV}$$

The $\not{p}_T > 90$ GeV requirement serves as a trigger.

The jets in WBF tend to be separated by a large rapidity gap and reconstruct to a large invariant mass. The $Z + 2j$ and $W + 2j$ backgrounds from QCD can be significantly reduced by "WBF cuts":

$$\Delta\eta_{jj} > 2.8, \qquad m_{jj} > 320,\ 340,\ 360,\ 400 \text{ GeV}$$

The $W + 2j$ background can be further reduced by vetoing leptons with

$$p_T(\ell) > 8 \text{ GeV}, \qquad |\eta(\ell)| < 3.0 \qquad \text{(lepton veto)}$$

To reduce the $jj\not{p}_T$ background with fake $\not{p}_T$ from jet energy mismeasurements, we require that the $\not{p}_T$ is not aligned with either of the jets:

$$\Delta\phi(j, \not{p}_T) > 30^\circ$$

Results (Tevatron Run II, $m_h = 120$ GeV)

Signal and background cross sections (after cuts):

m_{jj} cut	S($h_{inv} + 2j$)	B($Z + 2j$,QCD)	B($Z + 2j$,EW)	B($W + 2j$,QCD)
320 GeV	4.1 fb	55 fb	1.7 fb	7 fb
340 GeV	3.6 fb	43 fb	1.6 fb	5 fb
360 GeV	3.2 fb	34 fb	1.4 fb	5 fb
400 GeV	2.4 fb	21 fb	1.2 fb	2 fb

Number of signal events, S/B, and significance:

m_{jj} cut	S (10 fb^{-1})	S/B	S/$\sqrt{\text{B}}$ (10 fb^{-1})
320 GeV	41 evts	0.060	1.6
340 GeV	36 evts	0.066	1.5
360 GeV	32 evts	0.070	1.5
400 GeV	24 evts	0.082	1.4

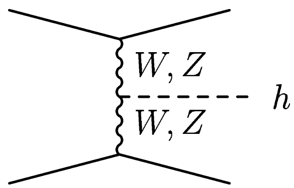
$m_h = 120$ GeV: 1.6σ signal with 10 fb^{-1}.

Background must be understood at $< 10\%$ level.

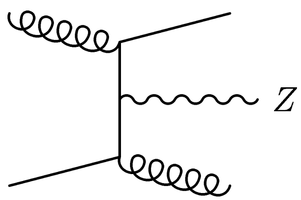
This could be improved...

Central jet veto

The LHC study of WBF$\rightarrow h_{inv}$ uses a central jet veto to reduce the background. Takes advantage of different color structures of signal and background.



WBF: no color flow between forward/backward jets: expect little jet activity in central region.



QCD $Z+2j$: final-state jets are color-connected: expect additional jet radiation in central region.

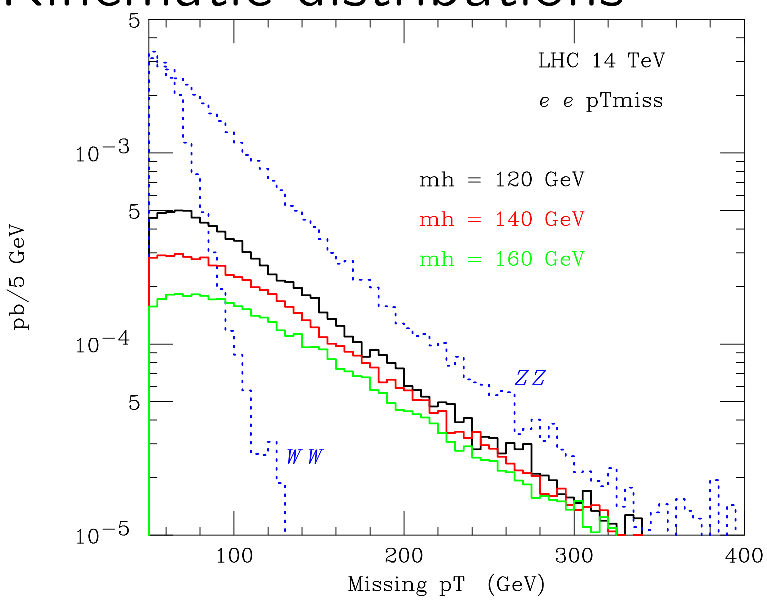
Eboli & Zeppenfeld applied a central jet veto (from Rainwater) – improves S/B by a factor of three without significantly reducing signal rate.

We have not imposed a central jet veto. If similar background reduction could be achieved at Tevatron, WBF$\rightarrow h_{inv}$ channel *alone* could give a 3σ observation with “only” 6 fb^{-1} per detector, with S/B $\simeq 1/5$.

Extracting the mass of an invisible Higgs

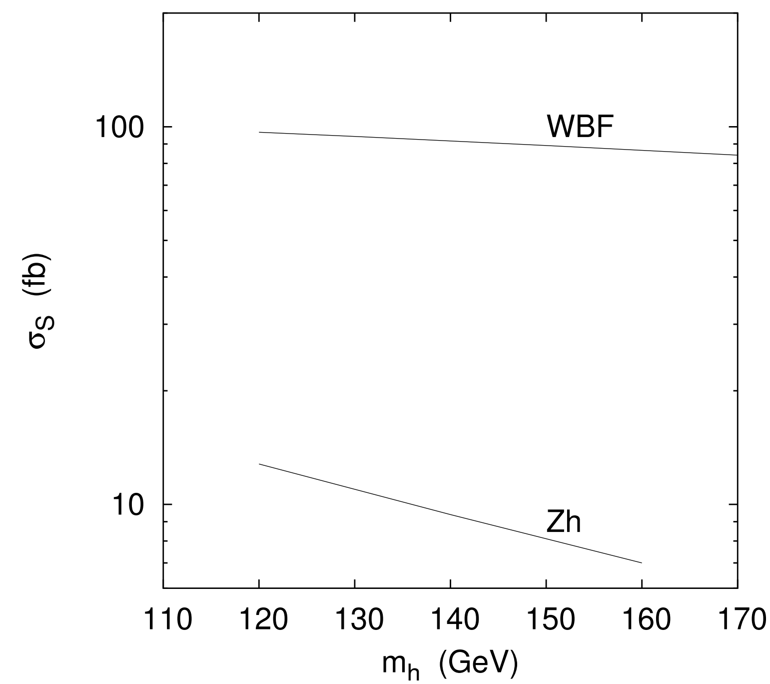
- Mass of h_{inv} accessible only through production process:

Kinematic distributions



(future direction)

Cross sections (LHC)



- Measure signal rate
- Assume SM production cross section, 100% invisible decay.*

$\longrightarrow$ Higgs mass.

*Will remove these assumptions later!

Uncertainties:

- Statistical uncertainty:

$\Delta\sigma_S/\sigma_S = \sqrt{S+B}/S$

- Background normalization:

Backgrounds for $Z + h_{inv}$ and WBF are dominated by $Z \to \nu\nu$. Can *measure* background rates/shapes in $Z \to \ell\ell$ channel!
Less statistics: $\text{BR}(Z \to \ell\ell)/\text{BR}(Z \to \nu\nu) \simeq 0.28$.

$\Delta\sigma_S/\sigma_S = \sqrt{B \times \text{BR}(\ell\ell)/\text{BR}(\nu\nu)}/S$

- Theory uncertainty: QCD + PDFs

4% for WBF, 7% for $Z + h_{inv}$

- Uncertainty on experimental efficiencies:

5% for WBF forward-jet tag / central-jet veto
4% dilepton tagging (2% per lepton)

- Luminosity normalization: 5%

Higgs mass determination from $Z + h_{inv}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$(d\sigma_S/dm_h)/\sigma_S$ (1/GeV)	−0.013	−0.015	−0.017
Statistical uncert.	21% (6.6%)	28% (8.8%)	37% (12%)
Background normalization uncert.	33% (10%)	45% (14%)	60% (19%)
Total uncert.	40% (16%)	53% (19%)	71% (24%)
Δm_h (GeV)	30 (12)	35 (12)	41 (14)

$Z + h_{inv}$: $\Delta m_h =$ 30–40 (12–14) GeV with 10 (100) fb^{-1}

Higgs mass determination from WBF$\to h_{inv}$, with 10 (100) fb^{-1}:

m_h (GeV)	120	130	150	200
$(d\sigma_S/dm_h)/\sigma_S$ (GeV^{-1})	−0.0026	−0.0026	−0.0028	−0.0029
Statistical uncert.	5.3% (1.7%)	5.4% (1.7%)	5.7% (1.8%)	6.4% (2.0%)
Background norm.	5.2% (2.1%)	5.3% (2.1%)	5.6% (2.2%)	6.5% (2.6%)
Total uncert.	11% (8.6%)	11% (8.6%)	11% (8.6%)	12% (8.8%)
Δm_h (GeV)	42 (32)	42 (33)	41 (31)	42 (30)

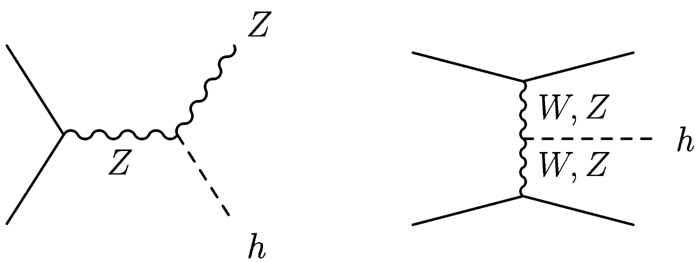
WBF: $\Delta m_h \simeq$ 40 (30) GeV with 10 (100) fb^{-1}

$Z + h_{inv}$ cross section falls faster with m_h than WBF – more m_h dependence but less statistics.

Extracting m_h from a single cross section relies on SM assumption for production couplings.

Ratio of $Z + h_{inv}$ and WBF rates $\rightarrow$ more model-independent m_h extraction!

$Z + h_{inv} \sim hZZ$ coupling; WBF $\sim hWW, hZZ$ couplings $-$ related by SU(2) in models with only Higgs doublets/singlets.



Example: MSSM (or 2HDM)

ZZh coup $= (g m_Z / \cos\theta_W) \sin(\beta - \alpha)$

WWh coup $= g m_W \sin(\beta - \alpha)$

Higgs mass determination from ratio method with 10 (100) fb^{-1}:

m_h (GeV)	120	140	160
$r = \sigma_S(Zh)/\sigma_S(\text{WBF})$	0.132	0.102	0.0807
$(dr/dm_h)/r$ (1/GeV)	-0.011	-0.013	-0.013
Total uncert., $\Delta r/r$	41% (16%)	54% (20%)	72% (25%)
Δm_h (GeV)	36 (14)	43 (16)	53 (18)

Can now learn more about the Higgs!

Test 100% invisible decay:

- Look for visible decays in all detectable channels $\rightarrow$ upper bounds on BRs
- $\sum \text{BR}_i = 1 \longrightarrow \text{BR}_{inv} = 1 - \sum \text{BR}_{other}$
- Cannot exclude certain decays, e.g. $h \rightarrow$ light quarks, $h \rightarrow gg$: background is overwhelming

Assume SU(2) doublets and/or singlets only
(same assumption as we made for ratio method m_h extraction):
hWW and hZZ couplings $\leq$ SM values.
$Z + h$ and WBF *production* cross sections bounded from above by SM values.
$\longrightarrow$ Relatively model-independent *lower bound* on BR_{inv} to produce observed rates in $Z + h_{inv}$ and WBF$\rightarrow h_{inv}$.

Test the assumption of SM production cross section:

- Measure m_h using ratio method
- Compute SM prediction for $\sigma_S(Z+h)$ and σ_S(WBF)
- Compare to measured $\sigma_S(Z+h_{inv})$ and σ_S(WBF)

$\rightarrow$ Probe hZZ, hWW couplings! (modulo BR$_{inv}$)

If we assume no significant branching fraction for $h \rightarrow gg, jj$ (so that BR$_{inv}$ + BR$_{SM\ decays} \simeq 1$), then:

- Compute $\Gamma(h \rightarrow WW)$ from hWW coupling and m_h
- Add upper bound on BR($h \rightarrow WW$) from non-observation in WBF$\rightarrow$ $h \rightarrow WW$

$\longrightarrow$ *lower* bound on total Higgs width Γ_{tot}

$\longrightarrow$ lower bound on $\Gamma(h \rightarrow invis)$.

$\rightarrow$ Test models of invisibly-decaying Higgs.

Test the top quark Yukawa coupling:

- Compute SM prediction for $\sigma_S(t\bar{t}h)$
- Compare to measured $\sigma_S(t\bar{t}h_{inv})$

$\rightarrow$ Probe htt coupling! (again modulo BR$_{inv}$)

Conclusions

• SM Higgs width very small below WW threshold: unexpected decay modes could have large BRs.

The Higgs could decay invisibly!

• LHC:

- WBF well studied, good significance
- $Z + h_{inv}$ is a promising second channel
- $t\bar{t}h_{inv}$ offers access to top Yukawa

• Tevatron:

- $Z + h_{inv}$, WBF both depressingly small
- Combining two channels and two detectors gives Tevatron a chance with 7 fb^{-1}
- Central jet veto could improve WBF significantly at the Tevatron

• Relatively model-independent m_h measurement by combining WBF and $Z + h_{inv}$ at LHC:

$\Delta m_h \simeq$ 15–20 GeV with 100 fb^{-1}.

Compare with measured cross sections to test Higgs couplings.