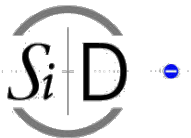


# H→invisible at the ILC with SiD

Amanda Steinhebel  
Jan Strube, Chris Potter, Jim Brau

University of Oregon

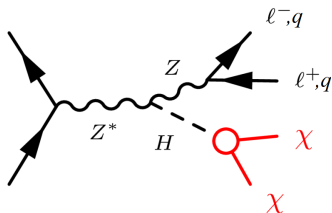
16 March 2021



# Physics Motivation for $H \rightarrow$ invisible



- SM  $H \rightarrow ZZ^* \rightarrow \nu\nu\nu\nu$ ,  $\mathcal{B}_{H \rightarrow \text{inv.}} \sim 0.1\%$
- Higgs portal DM - DM candidate couples directly to Higgs, would leave invisible detector signature
- Additional couplings of DM to Higgs ( $m_{DM} < m_H/2$ ) could increase BR by  $\mathcal{O}(10)\%$



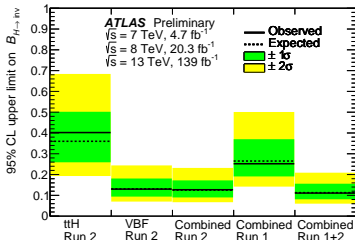
ILC is ideal for this precision  
EWK measurement:

- Hadronic interactions/pileup leave large uncertainties on MET from decay
- Detectors designed for particle flow reduce jet measurement uncertainties
- Systematics-limited analyses don't benefit much from increased stats

Current  $\mathcal{B}_{H\rightarrow\text{inv.}}$  Results

## LHC

- CMS - Run 1 and partial Run 2 [\[1809.05937\]](#)
  - $\mathcal{B}_{H\rightarrow\text{inv.}} < 19\%$ (15%) obs(exp)
- ATLAS - Run 1 and two Run 2 full analyses [\[ATLAS-CONF-2020-052\]](#)
  - $\mathcal{B}_{H\rightarrow\text{inv.}} < 11\%$ (11%) obs(exp)



## ILC

- ILD - [\[2002.12048\]](#)
  - Combined Z hadronic and leptonic channels
  - $\mathcal{B}_{H\rightarrow\text{inv.}} < 0.23\%$ (0.65%) for ILC250(500) at 95% C.L.
- SiD [LOI](#)
- SiD preliminary work [\[1\]](#), [\[2\]](#)

See LHC talk on rare SM processes

[Wed, Mar. 17 at 0930 GMT](#) by X. Zuo

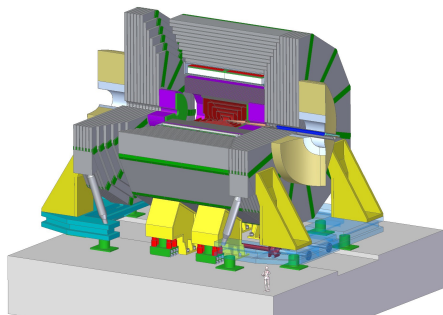
# SiD Detector Concept



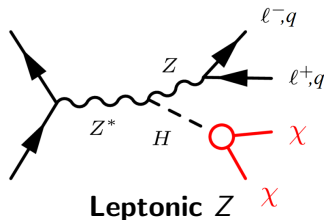
- Compact and cost-constrained
- Designed for particle-flow paradigm
- Highly granular pixelated Silicon-based tracker and EM Calorimeter, SiPM+Fe Hadron calorimeter
- Compact design with 5T magnetic field



[ILC TDR Vol. 4: Detectors](#)



# Background Processes



- $e^+e^- \rightarrow ZZ \rightarrow \nu\bar{\nu}l\bar{l}$   
(XS  $\sim 7.84 \text{ fb}^{-1}$ )
- $e^+e^- \rightarrow \mu\mu$   
(XS  $\sim 6190 \text{ fb}^{-1}$ )
- $e^+e^- \rightarrow WW \rightarrow l\nu l\nu$   
(XS  $\sim 442 \text{ fb}^{-1}$ )

\*XS values stated for  $\sqrt{s} + 250 \text{ GeV}$  with 80% LH electrons and 30% RH positrons

Contributions from 2-, 3-, and 4-fermion backgrounds

Consider recoil mass from Higgsstrahlung Z

## Hadronic Z

- $e^+e^- \rightarrow ZZ \rightarrow \nu\bar{\nu}q\bar{q}$   
(XS  $\sim 46.8 \text{ fb}^{-1}$ )
- $e^+e^- \rightarrow WW \rightarrow l\nu q\bar{q}$   
(XS  $\sim 2745 \text{ fb}^{-1}$ )
- $e^+e^- \rightarrow q\bar{q}$   
(XS  $\sim 47000 \text{ fb}^{-1}$ )

# Preliminary SiD Study, $Z(\text{lep})$



SiD fast simulation

ILC250 with  $\mathcal{B}_{H\rightarrow\text{inv.}} = 10\%$ ,

Polarization:

$$(P_{e^-}, P_{e^+}) = (\mp 0.8, \pm 0.3)$$

900 fb<sup>-1</sup> for both polarization  
configurations

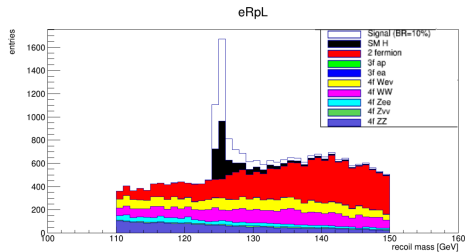
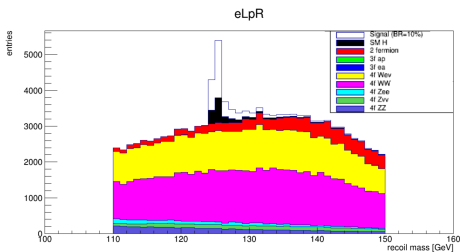
Backgrounds: 2-, 3-, 4-fermion bkg's,  
inclusive SM H (excluding signal)

$$\text{Significance} = S/\sqrt{S+B}$$

cut-and-count

Cut	S (LR)	B (LR)	Signif.	S (RL)	B (RL)	Signif.
All events	9.92e4	1.72e8	7.56	4.18e4	8.59e7	4.51
MET > 15 GeV	7.12e4	3.75e7	11.6	3.15e4	8.42e6	10.8
2 leptons	5.13e3	1.68e6	3.95	2.28e3	2.70e5	4.37
SFOS leptons > 10 GeV	4.87e3	1.41e6	4.09	2.16e3	1.90e5	4.94
75 < M <sub>vis</sub> < 105 GeV	4.62e3	3.02e5	8.32	2.05e3	6.49e4	7.93
20 < pt <sub>vis</sub> < 70 GeV	4.47e3	2.23e5	9.37	1.99e3	4.59e4	9.09
110 < m <sub>recoil</sub> < 150 GeV	4.41e3	1.17e5	<b>12.6</b>	1.96e3	2.17e4	<b>12.7</b>

## SiD Z(lep) Backgrounds - Recoil Mass



## Preliminary SiD Study, Z(had)



SiD full simulation

ILC250 with  $\mathcal{B}_{H\rightarrow\text{inv.}} = 10\%$ ,

Polarization:

$$(P_{e^-}, P_{e^+}) = (\mp 0.8, \pm 0.3)$$

Backgrounds: 2-, 3-, 4-fermion bkg

900 fb<sup>-1</sup> for both polarization  
configurations

cut-and-count

Full Simulation

Requirement (Full)	S(LR)	B(LR)	$\frac{S}{\sqrt{S+B}}$	S(RL)	B(RL)	$\frac{S}{\sqrt{S+B}}$
$20 \leq p_T^{vis} \leq 70$ GeV	1.25e+04	7.71e+06	4.48	8.84e+03	1.07e+06	8.53
$75 \leq m_{vis} \leq 105$ GeV	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$N_{jet} = 2$	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$-0.9 \leq \cos \theta_{jj} \leq -0.2$	1.08e+04	8.68e+05	11.5	7.65e+03	1.78e+05	17.7
$110 \leq m_{recoil} \leq 150$	1.03e+04	3.6e+05	17	7.33e+03	8.39e+04	24.2

# Combined SiD Studies



		S Yield	B Yield	$S/\sqrt{S+B}$
Z(had)	eLpR	1.03e4	3.6e5	17
	eRpL	7.33e3	8.39e4	24.2
Z(lep)	eLpR	4.41e3	1.17e5	12.6
	eRpL	1.96e3	2.17e4	12.7
Combined	eLpR	1.47e4	4.77e5	21.0
	eRpL	9.29e3	1.06e5	27.4
	Combined	2.40e4	1.54e5	56.9

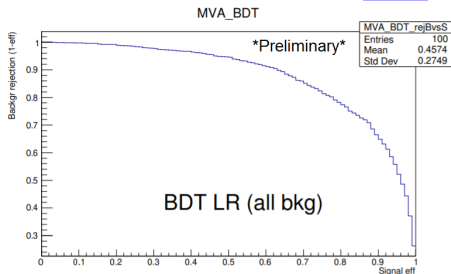
Combined SiD Limit:  $\mathcal{B}_{H \rightarrow \text{inv.}} \lesssim 0.3\%$

Recall LHC results:  $\mathcal{B}_{H \rightarrow \text{inv.}} < 11\% \text{ (11)\%}$

# SiD Optimizations



Further optimize signal selection,  
investigate MVA techniques ([study](#) )



Preliminary application with  
 $Z(\text{had})H_{\text{inv}}$

Potential improvement of  $\times 2$

Understand impact of geometry and strengths of SiD design

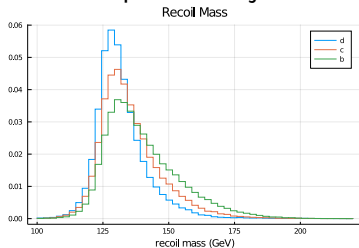
- Active work to understand impact of HCal tile size
- Consider inclusion of Monolithic Active Pixels (MAPS) for silicon readout

# Systematics Studies



- Work underway to understand which systematic errors may drive degradation of expected limit on  $\mathcal{B}_{H\rightarrow\text{inv.}}$
- Jet Energy Resolution plays large role
  - Work in progress to quantify

## Minor impact from jet flavor



see SiD Plenary talk for more background info and ways to get involved!

[Wed, Mar. 17 at 1440 GMT](#) by M. Stanitzki

# Summary and Future Outlook



- SM precision can be approached with peak ILC detector/accelerator performance - levels the LHC cannot reach
- Preliminary SiD studies estimate  $\mathcal{B}_{H\rightarrow\text{inv.}} < 0.3\%$  - 100x stricter than current LHC limits
- Joint SiD approach to further refine study and reduce error
  - investigate potential physics gains from MVA approach
  - understand limitations of study through systematics studies

# Backup Slides

# Abstract



While the Standard Model (SM) predicts a branching ratio of the Higgs boson decaying to invisible particles of  $O(0.001)$ , the current measurement of the Higgs boson coupling to other SM particles allows for up to 30% of the Higgs boson width to originate from decays beyond the SM (BSM). The small SM-allowed rate of Higgs boson decays to invisible particles can be enhanced if the Higgs boson decays into new particles such as dark matter. Upper limits have been placed on  $\mathcal{B}_{H\rightarrow\text{inv.}}$  by ATLAS and CMS at  $O(0.1)$ , but the hadron environment limits precision. The ILC 'Higgs factory' will provide unprecedented precision of this electroweak measurement. Studies of the search for H→invisible processes in simulation are presented with SiD, a detector concept designed for the ILC. Preliminary results for expected sensitivity are provided, as well as studies considering potential systematics limitations.

# Upper Limit Estimation

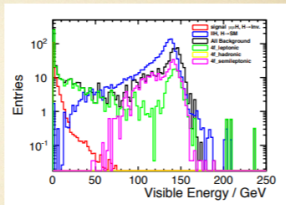


- Outlined in [ILD paper](#)
- Compute number of signal  $N_S$  and background  $N_B$  events surviving cuts
- Calculate significance  $sig = N_S / \sqrt{N_S + N_B}$ 
  - For ILD shape fit, do this for each bin of  $m_{recoil}$  and Root Mean Square combine
  - For rough values, consider all events
- 95% confidence U.L[%] =  $\frac{SM \mathcal{B}_{H \rightarrow inv.} [\%] \times 1.65}{sig}$

ILD Z(l $\nu$ )

## update: invisible decay using Z → ll @ ILC

- analysis is extremely simple: 2-isolated-lepton + missing
- event selections are almost identical to leptonic recoil mass analysis
- except one more cut on visible 4-momentum other than the di-lepton



$P(e, e^+) = (+0.8, -0.3)$ ; 250 fb $^{-1}$  @ 250 GeV

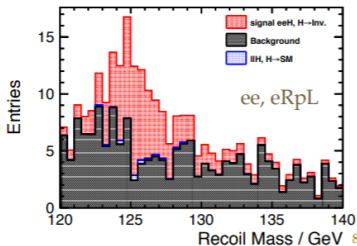
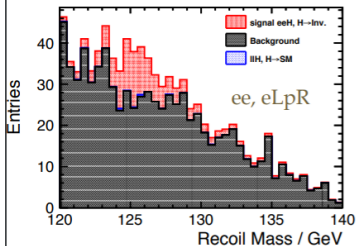
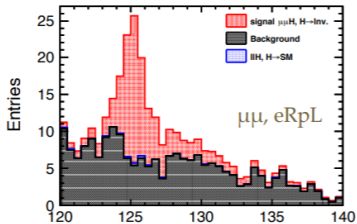
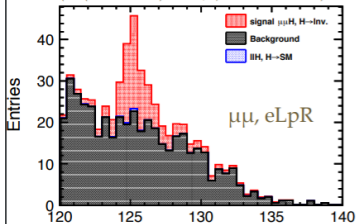
250 GeV BR(inv)=10%	$\mu\mu H$ H → inv	llH (SM)	4f_l	4f_sl	4f_h	BG	significance
#expected	176	3778	3.67E+05	5.16E+05	3.92E+05	2.16E+07	0.037
pre-selection	166	1636	1.89E+05	1.30E+05	0	5.20E+05	0.23
cut0	133	1236	542	314	0	1084	2.7
cut_vis	130	3.0	314	0	0	325	6.1
cut_mva	122	2.9	227	0	0	232	6.4

Note: cut0 includes all the usual cuts used in leptonic recoil mass analysis

study

ILD Z(l $\nu$ ) Cont'd

invisible decay using Z → ll @ 250 GeV

(Br(H → inv.) = 10%, 250 fb<sup>-1</sup> data)

study

## Z(had) Cutflow for ILC250



SiD

Full Simulation						
Requirement (Full)	$S(LR)$	$B(LR)$	$\frac{S}{\sqrt{S+B}}$	$S(RL)$	$B(RL)$	$\frac{S}{\sqrt{S+B}}$
$20 \leq p_T^{vis} \leq 70$ GeV	1.25e+04	7.71e+06	4.48	8.84e+03	1.07e+06	8.53
$75 \leq m_{vis} \leq 105$ GeV	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$N_{jet} = 2$	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$-0.9 \leq \cos \theta_{jj} \leq -0.2$	1.08e+04	8.68e+05	11.5	7.65e+03	1.78e+05	17.7
$110 \leq m_{recoil} \leq 150$	1.03e+04	3.6e+05	17	7.33e+03	8.39e+04	24.2

ILD

**Table 2:** Selection table for  $\sqrt{s} = 250$  GeV,  $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$ .

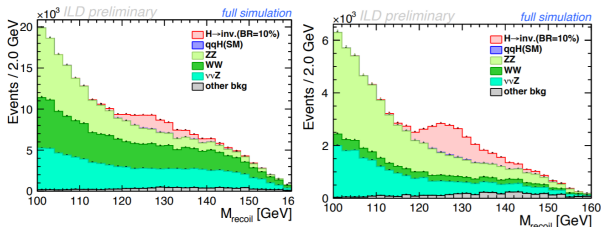
cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	18917 (1.000)	$1.417 \times 10^8$ (1.000)	1.59
$N_{lep} = 0$	18880 (0.998)	$9.732 \times 10^7$ (0.687)	1.91
Pre-Cut	18202 (0.962)	$3.358 \times 10^6$ (0.024)	9.91
$N_{pfo} > 15 \& N_{charged} > 6$	17918 (0.947)	$2.539 \times 10^6$ (0.018)	11.2
$p_{Tjj} \in (20, 80)$ GeV	16983 (0.898)	$1.368 \times 10^6$ (0.010)	14.4
$M_{jj} \in (80, 100)$ GeV	14158 (0.748)	713194 (0.005)	16.6
$ \cos \theta_{jj}  < 0.9$	13601 (0.719)	539921 (0.004)	18.3
$M_{recoil} \in (100, 160)$ GeV	13585 (0.718)	244051 (0.002)	26.8

**Table 3:** Selection table for  $\sqrt{s} = 250$  GeV,  $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$ .

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	12776 (1.000)	$7.785 \times 10^7$ (1.000)	1.45
$N_{lep} = 0$	12752 (0.998)	$4.893 \times 10^7$ (0.628)	1.82
Pre-Cut	12270 (0.960)	$1.329 \times 10^6$ (0.017)	10.6
$N_{pfo} > 15 \& N_{charged} > 6$	12067 (0.945)	852285 (0.011)	13.0
$p_{Tjj} \in (20, 80)$ GeV	11394 (0.892)	285847 (0.004)	20.9
$M_{jj} \in (80, 100)$ GeV	9481 (0.742)	165798 (0.002)	22.6
$ \cos \theta_{jj}  < 0.9$	9126 (0.714)	130070 (0.002)	24.5
$M_{recoil} \in (100, 160)$ GeV	9115 (0.713)	62979 (0.001)	33.9

SiD background rates greater because 3-fermion backgrounds are included  
(not used in ILD study)

## ILD Z(had) Study



**Figure 2:** Recoil mass distribution after event selection at  $\sqrt{s} = 250$  GeV. (left):  $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$ , (right):  $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$ .

**Table 6:** 95% C.L. UL on  $\text{BR}(H \rightarrow \text{invisible})$  for  $\sqrt{s} = 250$  GeV. **Table 7:** 95% C.L. UL on  $\text{BR}(H \rightarrow \text{invisible})$  for  $\sqrt{s} = 500$  GeV.

Mode	(-0.8,+0.3)	(+0.8,-0.3)	combined
$Z \rightarrow q\bar{q}$	0.44%	0.31%	0.25%
$Z \rightarrow l\bar{l}$	1.06%	0.67%	0.57%
combined	-	-	0.23%

Mode	(-0.8,+0.3)	(+0.8,-0.3)	combined
$Z \rightarrow q\bar{q}$	1.30%	0.98%	0.78%
$Z \rightarrow l\bar{l}$	2.03%	1.48%	1.19%
combined	-	-	0.65%

## ILD Z(had) Backgrounds



type	process name	final state
Higgs	qqh_zz_4n (signal) higgs_ffh	qq4ν ffh
2f	2f_Z_bhabhag 2f_Z_hadronic 2f_Z_leptonic	eeγ qq μμ, ττ
4f	4f_singleW_leptonic 4f_singleW_semileptonic 4f_singleZee_leptonic  4f_singleZee_semileptonic 4f_singleZnu_nu_leptonic 4f_singleZnu_nu_semileptonic 4f_singleZsingleWMix_leptonic 4f_WW_hadronic 4f_WW_leptonic 4f_WW_semileptonic 4f_ZZ_hadronic  4f_ZZ_leptonic  4f_ZZ_semileptonic 4f_ZZWWMix_hadronic 4f_ZZWWMix_leptonic	evμν, evτν evq <sub>u</sub> q <sub>d</sub> eeee, eeμμ, eeττ, eeν <sub>μ</sub> ν <sub>μ</sub> , eeν <sub>τ</sub> ν <sub>τ</sub> eeqq μμν <sub>e</sub> ν <sub>e</sub> , ττν <sub>e</sub> ν <sub>e</sub> ν <sub>e</sub> ν <sub>e</sub> q <sub>u</sub> q <sub>u</sub> , ν <sub>e</sub> ν <sub>e</sub> q <sub>d</sub> q <sub>d</sub> eeν <sub>e</sub> ν <sub>e</sub> ucq <sub>d</sub> q <sub>d</sub> , uuds, uddb, ccdd, ccbb μν <sub>μ</sub> τν <sub>τ</sub> qqν <sub>μ</sub> μ, qqν <sub>τ</sub> τ q <sub>u</sub> q <sub>u</sub> q <sub>u</sub> q <sub>u</sub> , q <sub>d</sub> q <sub>d</sub> q <sub>d</sub> q <sub>d</sub> , uuss, uusb, uubb, ccdd, ccdb, ccbb μμμμ, ττττ, μμττ, ττν <sub>μ</sub> ν <sub>μ</sub> , μμν <sub>τ</sub> ν <sub>τ</sub> μμqq, ν <sub>μ</sub> ν <sub>μ</sub> qq, ν <sub>τ</sub> ν <sub>τ</sub> qq, ττqq uudd, ccss μμν <sub>μ</sub> ν <sub>μ</sub> , ττν <sub>τ</sub> ν <sub>τ</sub>