H→invisible at the ILC with SiD

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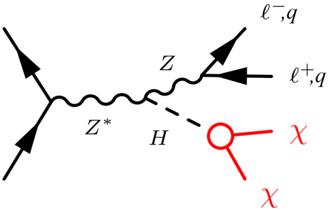
3 March 2021

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 $\mathcal{B}_{H\rightarrow\mathrm{inv.}}$ 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.

Physics Motivation

- SM $H \to ZZ^* \to \nu\nu\nu\nu$, $\mathcal{B}_{H\to\text{inv.}} \sim 0.1\%$
- Higgs potal 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 $\mathcal{O}(10)\%$
- Directly probes of H→inv. process



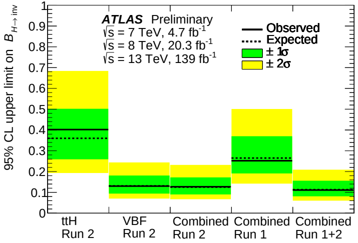
ILC is ideal for this precision EWK measurement:

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

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

LHC

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

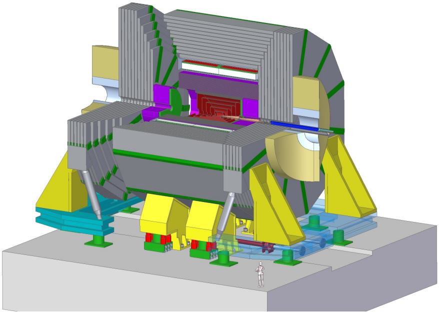


ILC

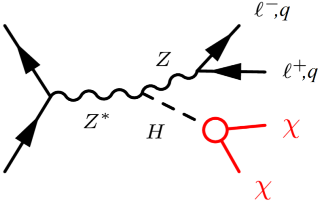
- ILD - [2002.12048]
  - Combined Z hadronic and leptonic channels
  - $\mathcal{B}_{H\to\text{inv.}} < 0.23\%(0.65\%)$ for ILC250(500) at 95% C.L.
- SiD LOI
- SiD preliminary work [1] ,[2]

SiD Detector Concept

- Compact and cost-constrained
- Designed for particle-flow paradigm
- Highly granular pixelated Silicon-based tracker and EM Calorimeter, steel RPC Hadron calorimeter
- Compact design with 5T magnetic field
- ILC TDR Vol. 4: Detectors



Background Processes



- $e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$ (XS $\sim$ 46.8 fb^{-1})
- $e^+e^- \to WW \to \ell\nu q\bar{q}$ (XS $\sim$ 2745 fb^{-1})
- $e^+e^- \to q\bar{q}, \mu\mu$ (XS $\sim$ 47000,6190 fb^{-1})

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

I want to put a recoil mass plot here, but let's look at these in more detail in a few slides....

*XS values stated for $\sqrt{s} = 250$ GeV with 80% LH electrons and

Preliminary SiD Study, Z(had)

- Kinematics cuts to define signal region
  - $N_{jet} == 2$
  - $20 < p_T^{vis} < 70$ GeV
  - $75 < m_{vis} < 105$ GeV
  - $-0.9 < \cos\theta_{jj} < -0.2$
  - $110 < m_{recoil} < 150$ GeV

SiD full simulation
ILC250 with $\mathcal{B}_{H\to\text{inv.}} = 10\%$, 900 fb^{-1} for both polarizations (80/30)

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

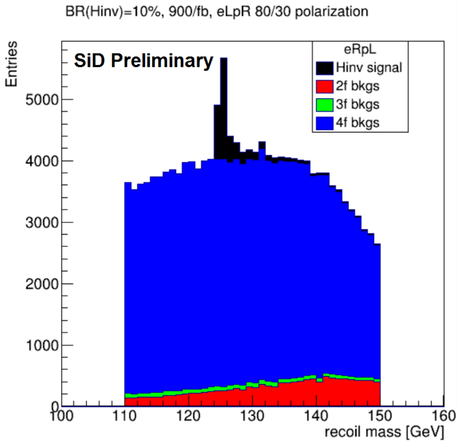
Preliminary SiD Study, Z(lep)

- Kinematics cuts to define signal region
  - Similar to Z(had) cuts
  - $N_\ell == 2$ (same flavor, opposite sign)
  - $20 < p_T^{vis} < 70$ GeV
  - $75 < m_{vis} < 105$ GeV
  - $110 < m_{recoil} < 150$ GeV

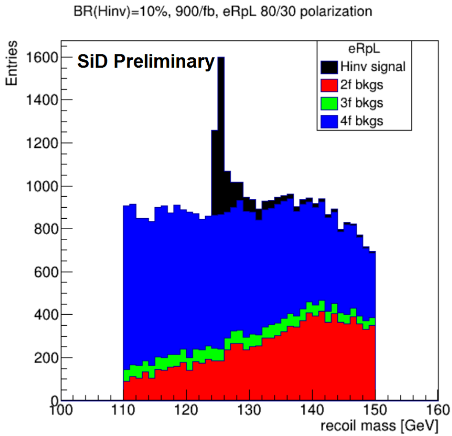
SiD full simulation
ILC250 with $\mathcal{B}_{H\to\text{inv.}} = 10\%$, 900 fb^{-1} for both polarizations for SiD
(80/30)

Cut	S (LR)	B (LR)	Signif.	S (RL)	B (RL)	Signif.
All events	99158.4	1.71504e+08	7.56949	41778	8.5734e+07	4.51092
2 leptons	5390.72	8.57074e+06	1.84078	2392.23	5.45306e+06	1.02421
SFOS leptons	5388.79	8.53414e+06	1.84406	2391.46	5.43225e+06	1.02583
$75 < m_{vis} < 105$ GeV	4941.09	3.26039e+06	2.73439	2196	2.09218e+06	1.51741
$20 < p_T^{vis} < 70$ GeV	4622.55	368678	7.56575	2058.05	111210	6.11506
$110 < m_{recoil} < 150$ GeV	4556.48	149428	11.6116	2027.9	34743.1	10.5753

Preliminary SiD Study, Z(lep) Cont'd



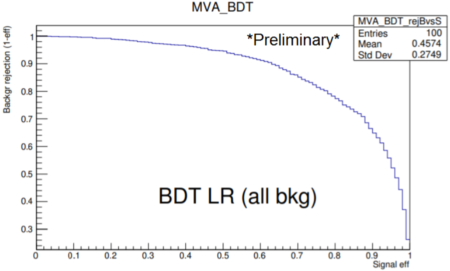
Integrals:
signal = 4556.48, 2f=12243.6, 3f=2723.9, 4f=134460.7



Integrals:
Signal= 2027.9, 2f=10291.5, 3f=2168.1, 4f=22283.6

SiD Optimizations

Further optimize signal selection, investigate MVA techniques (study)



Preliminary application with Z(had)Hinv

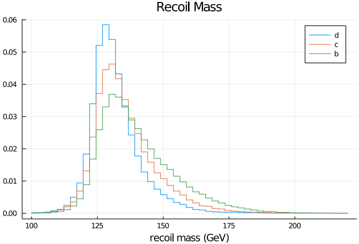
Understand impact of geometry and strengths of SiD design

- Active work to understand impact of HCal tile size on energy resolution

Systematics Studies

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

Minor impact from jet flavor



hopefully put quantified comment about impact on limit

Future Outlook

		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	4556.48	149428	11.6116
	eRpL	2027.9	34743.1	10.5753
Combined	eLpR	14856.48	509428	20.52
	eRpL	9357.9	118643.1	26.16
	Combined	24214.38	628071.1	29.9

chris, you have a lepton veto in Z(had) and these are orthogonal, right? modulo rounding

- Joint SiD approach - investigate potential physics gains from MVA approach; understand limitations of study through systematics studies
- Incomplete but evolving collaborative study
- Inform Snowmass2021

Backup Slides

Z(had) Cutflow for ILC250

SiD

Full Simulation

Requirement (Full)	S(LR)	B(LR)	$\frac{S}{\sqrt{S+B}}$	S(RL)	B(RL)	$\frac{S}{\sqrt{S+B}}$
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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)	1.417×10^8 (1.000)	1.59
$N_{lep} = 0$	18880 (0.998)	9.732×10^7 (0.687)	1.91
Pre-Cut	18202 (0.962)	3.358×10^6 (0.024)	9.91
$N_{pfo} > 15 \& N_{charged} > 6$	17918 (0.947)	2.539×10^6 (0.018)	11.2
$p_{T jj} \in (20, 80)$GeV	16983 (0.898)	1.368×10^6 (0.010)	14.4
$M_{jj} \in (80, 100)$GeV	14158 (0.748)	713194 (0.005)	16.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	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)	7.785×10^7 (1.000)	1.45
$N_{lep} = 0$	12752 (0.998)	4.893×10^7 (0.628)	1.82
Pre-Cut	12270 (0.960)	1.329×10^6 (0.017)	10.6
$N_{pfo} > 15 \& N_{charged} > 6$	12067 (0.945)	852285 (0.011)	13.0
$p_{T jj} \in (20, 80)$GeV	11394 (0.892)	285847 (0.004)	20.9
$M_{jj} \in (80, 100)$GeV	9481 (0.742)	165798 (0.002)	22.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	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)

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[%]$=\frac{\mathrm{SM}\ \mathcal{B}_{H\rightarrow\mathrm{inv.}}[\%]\times 1.65}{sig}$

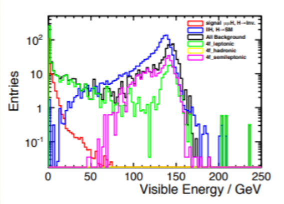
ILD Z(had) Backgrounds

type	process name	final state
Higgs	qqh_zz_4n (signal)	$qq4\nu$
	higgs_ffh	ffh
2f	2f_Z_bhabhag	$ee\gamma$
	2f_Z_hadronic	qq
	2f_Z_leptonic	$\mu\mu$, $\tau\tau$
4f	4f_singleW_leptonic	$e\nu\mu\nu$, $e\nu\tau\nu$
	4f_singleW_semileptonic	$e\nu q_u q_d$
	4f_singleZee_leptonic	eeee, $ee\mu\mu$, $ee\tau\tau$, $ee\nu_\mu\nu_\mu$, $ee\nu_\tau\nu_\tau$
	4f_singleZee_semileptonic	eeqq
	4f_singleZnunu_leptonic	$\mu\mu\nu_e\nu_e$, $\tau\tau\nu_e\nu_e$
	4f_singleZnunu_semileptonic	$\nu_e\nu_e q_u q_u$, $\nu_e\nu_e q_d q_d$
	4f_singleZsingleWMix_leptonic	$ee\nu_e\nu_e$
	4f_WW_hadronic	$ucq_d q_d$, uuds, uudb, ccds, ccsb
	4f_WW_leptonic	$\mu\nu_\mu\tau\nu_\tau$
	4f_WW_semileptonic	$qq\nu_\mu\mu$, $qq\nu_\tau\tau$
	4f_ZZ_hadronic	$q_u q_u q_u q_u$, $q_d q_d q_d q_d$, uuss, uusb, uubb, ccdd, ccdb, ccbb
	4f_ZZ_leptonic	$\mu\mu\mu\mu$, $\tau\tau\tau\tau$, $\mu\mu\tau\tau$, $\tau\tau\nu_\mu\nu_\mu$, $\mu\mu\nu_\tau\nu_\tau$
	4f_ZZ_semileptonic	$\mu\mu qq$, $\nu_\mu\nu_\mu qq$, $\nu_\tau\nu_\tau qq$, $\tau\tau qq$
	4f_ZZWWMix_hadronic	uudd, ccss
	4f_ZZWWMix_leptonic	$\mu\mu\nu_\mu\nu_\mu$, $\tau\tau\nu_\tau\nu_\tau$

ILD Z(lep)

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



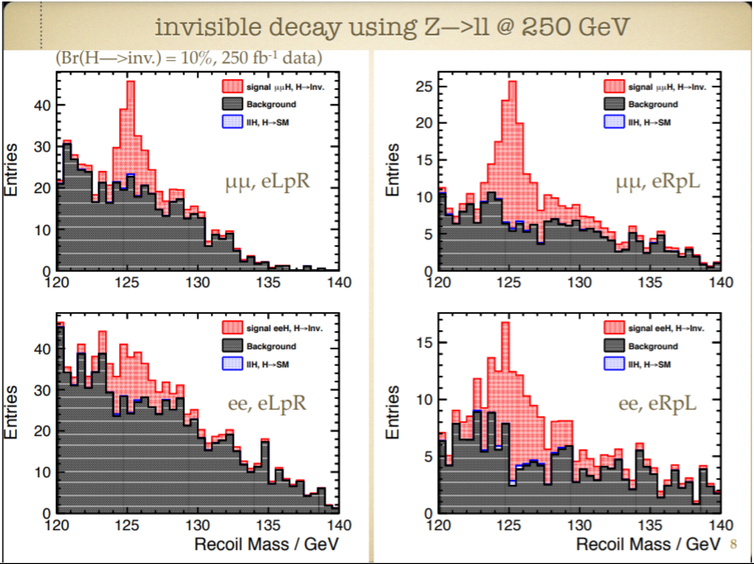
P(e-,e+) = (+0.8,-0.3); 250 fb^{-1} @ 250 GeV

250 GeV BR(inv)=10%	μμH 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(lep) Cont'd



study