This study is conducted at 250 GeV

BSM search using Higgs to invisible decay at the ILC

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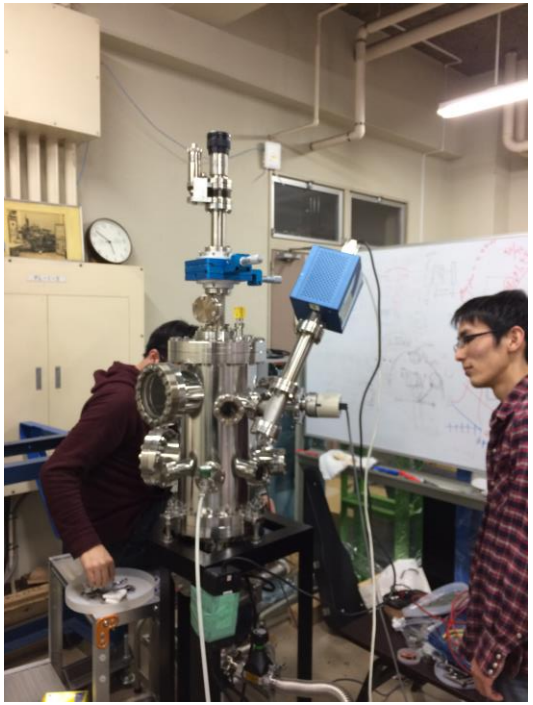
Annual ILC Detector Meeting @KEK Mar. 31, 2017

Status

- Evaluated UL based on Yamashita san's advice
- Made presentation in LCWS2016
- Pause this analysis for TPC experiment
- Come back around June

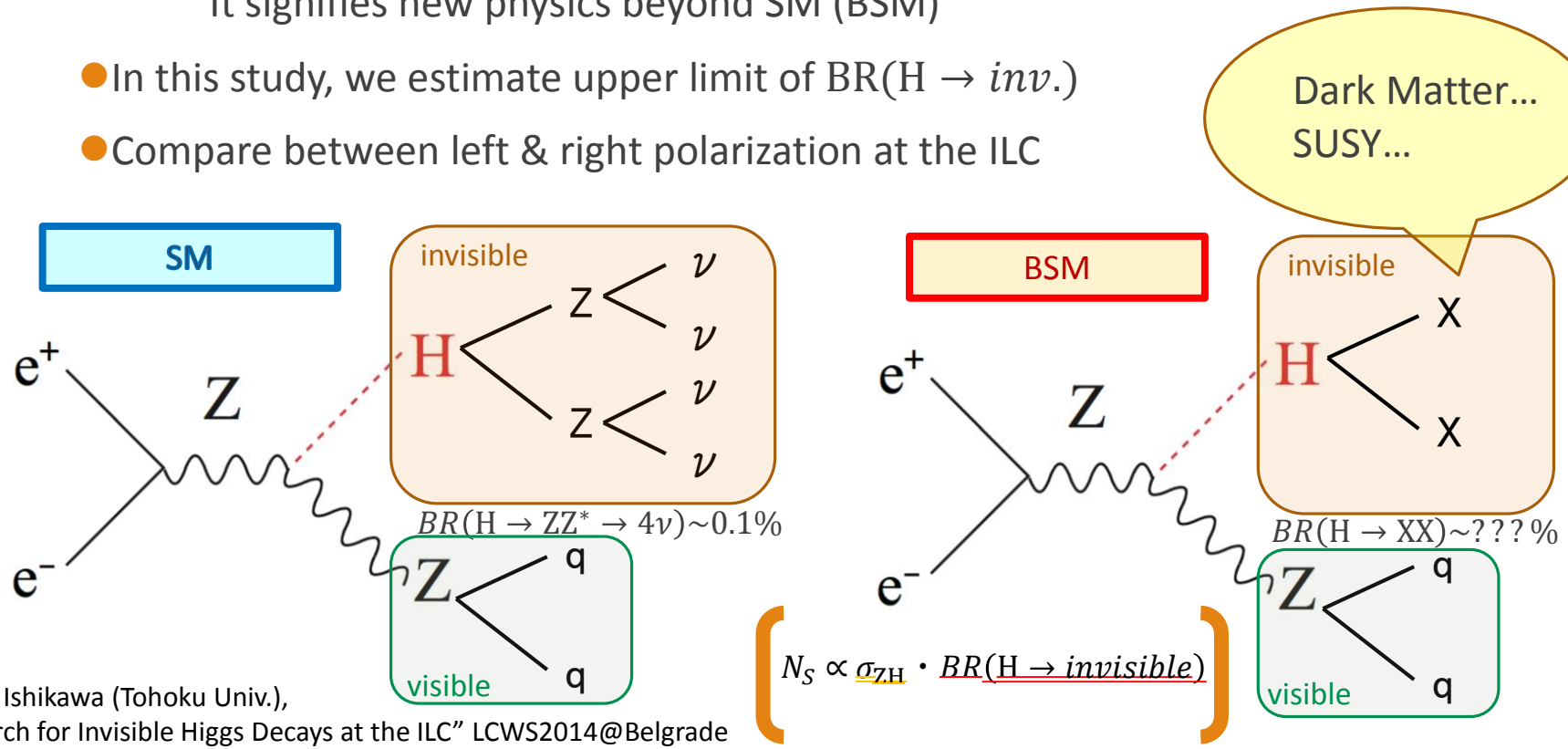


Outline

- Motivation
- Details of analysis
- Summary
- Plans

Motivation

- In SM, Higgs decays invisibly through
  $\mathrm{H} \rightarrow \mathrm{ZZ}^{*} \rightarrow 4\nu$ ($\mathrm{BR}(\mathrm{H} \rightarrow inv.) \sim 0.1\%$)
- If $\mathrm{BR}(\mathrm{H} \rightarrow inv.)$ exceeds SM prediction ,
  It signifies new physics beyond SM (BSM)
- In this study, we estimate upper limit of $\mathrm{BR}(\mathrm{H} \rightarrow inv.)$
- Compare between left & right polarization at the ILC



- A. Ishikawa (Tohoku Univ.), "Search for Invisible Higgs Decays at the ILC" LCWS2014@Belgrade
- M. A. Thomson (Univ. of Cambridge), arXiv: 1509.02853 (2015)

Setting & Flow of Analysis

- Setting
  - Generator: WHIZARD 1.95
  - Samples: DBD sample + Dirac sample ($e^+e^- \to qqH, H \to ZZ^* \to 4\nu$)
  - Detector: ILD full simulation
  - E_{cm} = 250 GeV, $\int Ldt$ = 250 fb^{-1} , $(P_{e^-}, P_{e^+}) = (-0.8, +0.3), (+0.8, -0.3)$
- Flow of analysis
  - Isolated lepton tagging → veto
  - Jet clustering
    - forced 2-jet reconstruction using LCFIPlus
  - Event selection (next page)
    - assume BR(H→invisible)=10%
  - Fit & Toy Monte Carlo to set upper limit

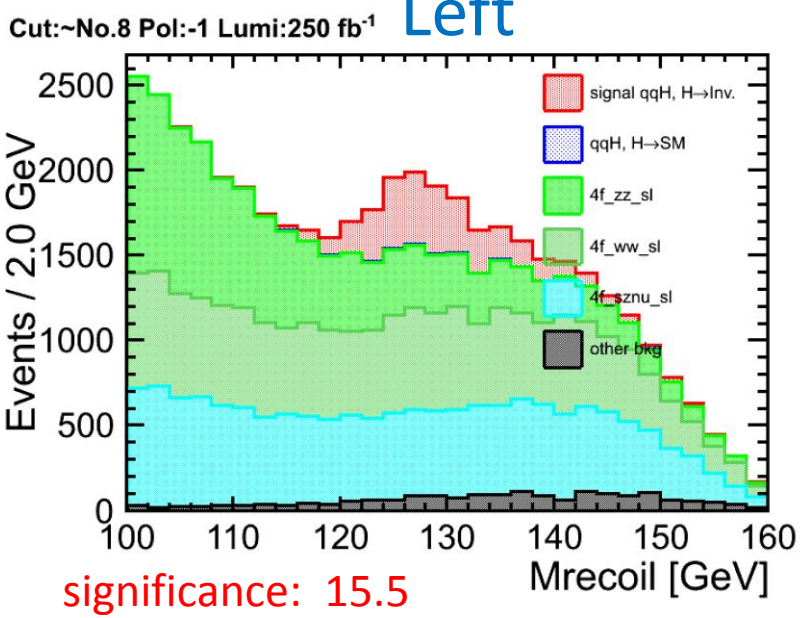
Event Selection

1. isolated lepton veto
2. loose restriction of transverse di-jet momentum, di-jet invariant mass, and recoil mass from di-jet
3. number of PFOs and charged tracks: N_{pfo}, N_{track}
4. di-jet (Z) pt: Pt_Z
5. di-jet mass: M_Z
6. di-jet polar angle: θ_Z
7. recoil mass: M_{recoil}
8. multi-variate analysis: Boosted Decision Tree(BDT) method

Preliminary

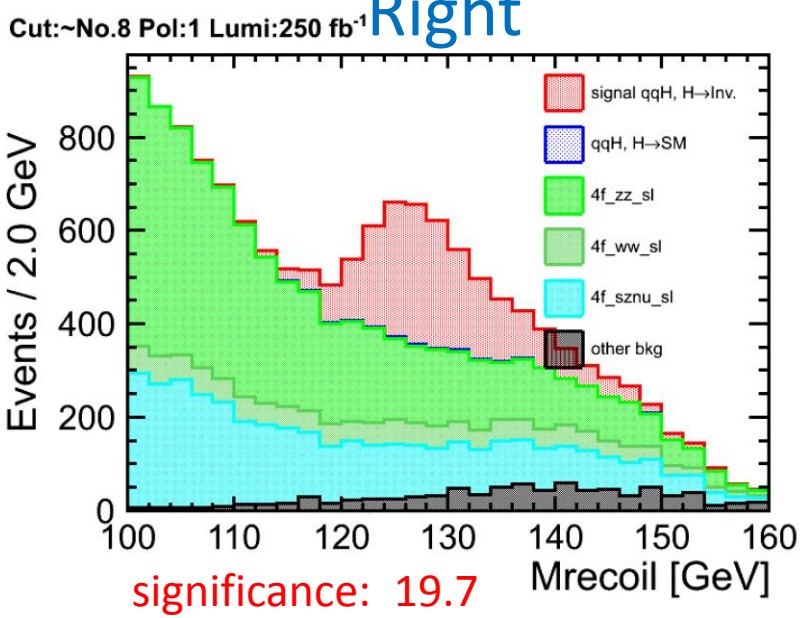
Recoil Mass Plots [Ecm = 250 GeV, 250 fb^{-1},BR(H->inv.)=10%]

Left



significance: 15.5
efficiency: 63.5%

Right



significance: 19.7
efficiency: 65.9%

MVA input variables	
mz	cosj1
cosz	cosj2

TMVA v-4.2.0

No.	Cut	No.	Cut
1	Isolated lepton veto	5	80 < Mz < 100
2	Loose Cut (Ptz,Mz,Mrecoil)	6	|cosθZ|<0.9
3	Npfo>15 & Ntrack>6 & Ntrackji>1	7	100 < Mrecoil < 160
4	20 < Ptz < 80	8	BDT cut

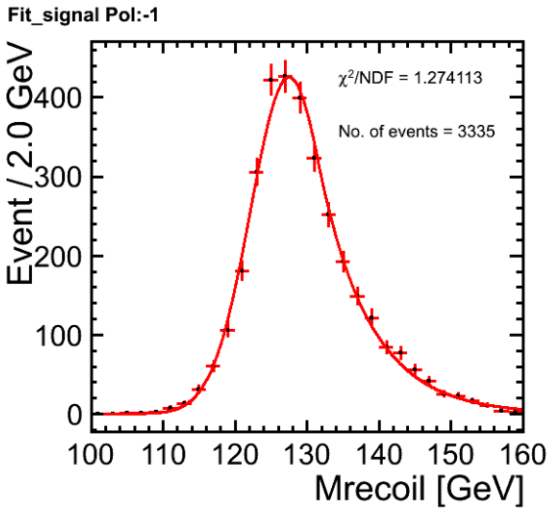
Preliminary

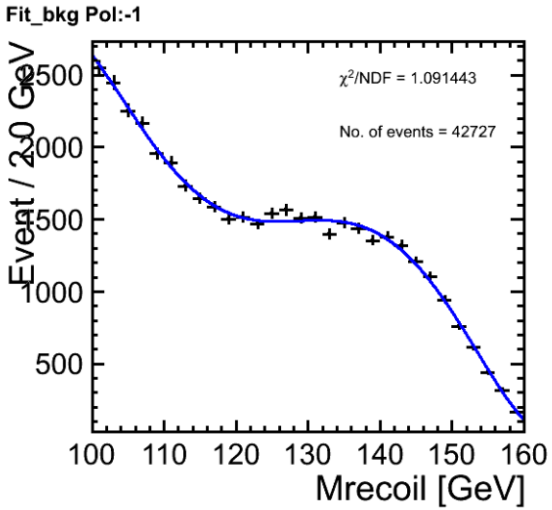
Fit Signal & Background

signal: GPET (Gaussian + Exponential)

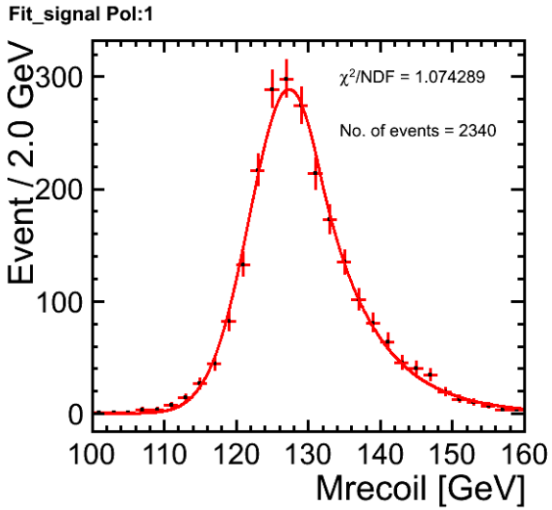
bkg : 5^{th} order polynomial

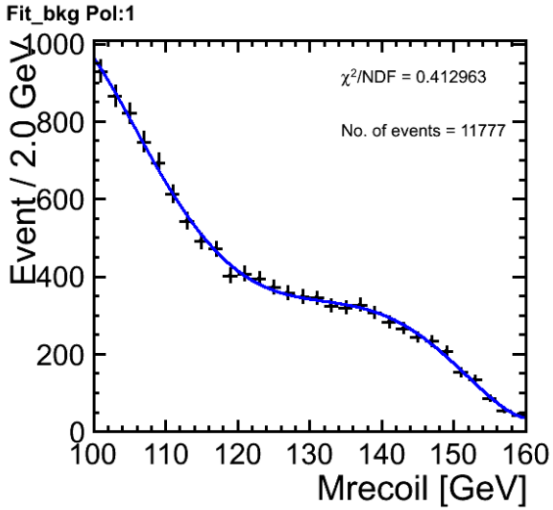
Left





Right

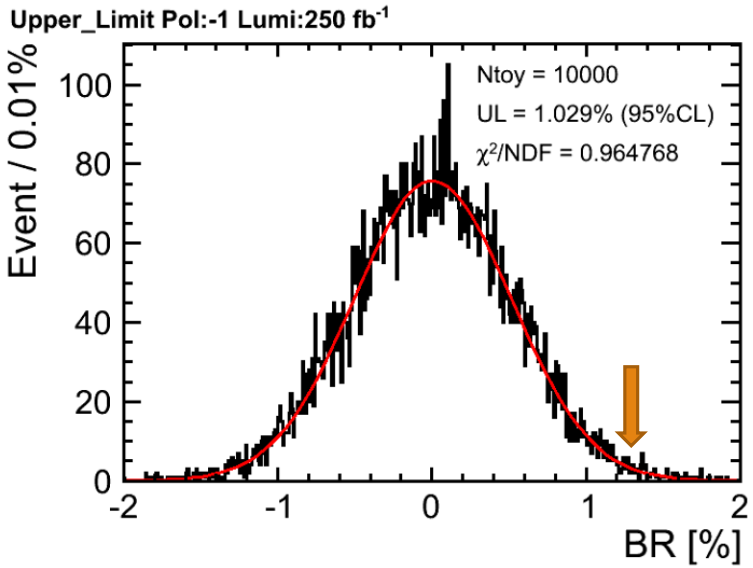




Preliminary

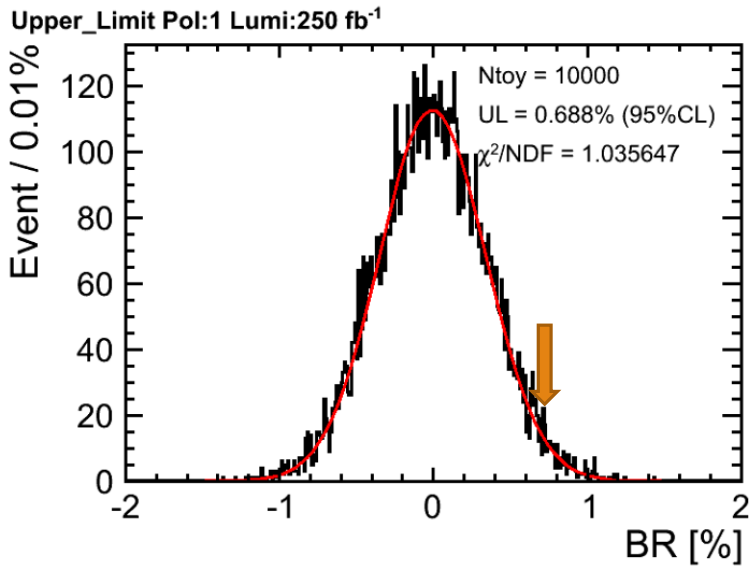
Toy Monte Carlo to Set Upper Limit

Left polarization



UL=1.03% (95%CL)

Right polarization



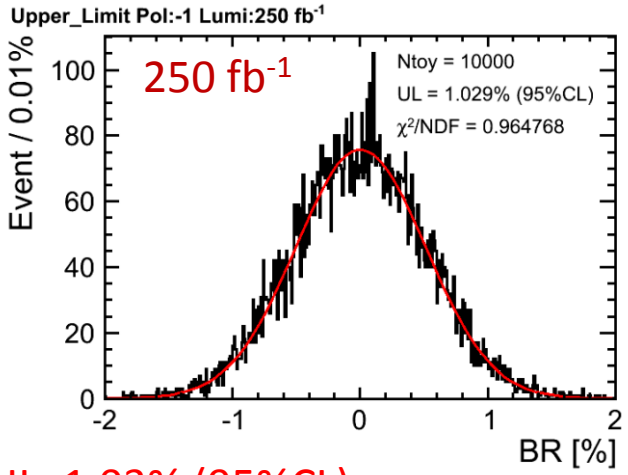
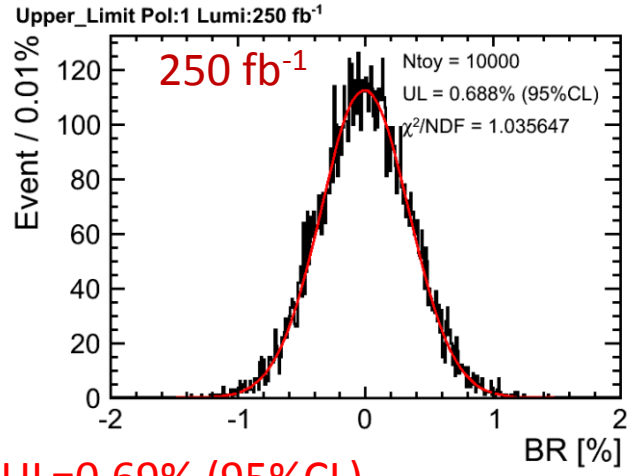
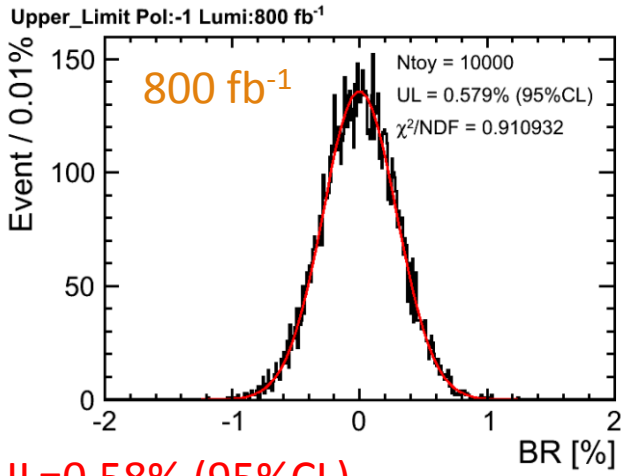
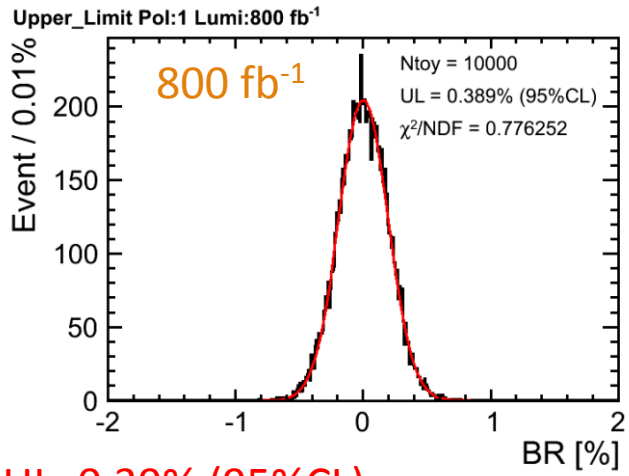
UL=0.69% (95%CL)

bkg : shape fixed, yields floated

- $\int Ldt$ = 250 fb^{-1}
- bkg yields floated → 10000 times pseudo experiment
- not include SM Higgs to invisible decay

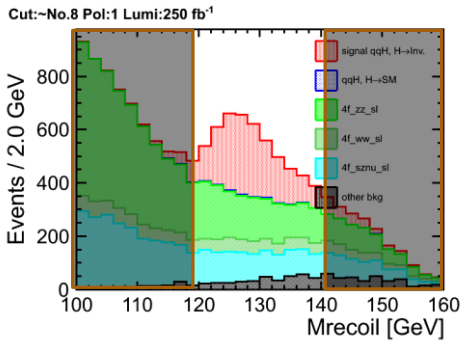
Preliminary

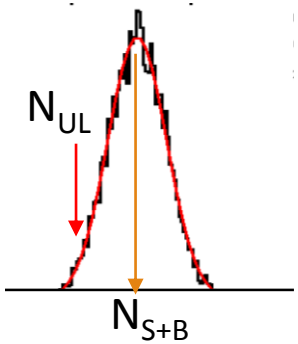
Toy Monte Carlo to Set Upper Limit

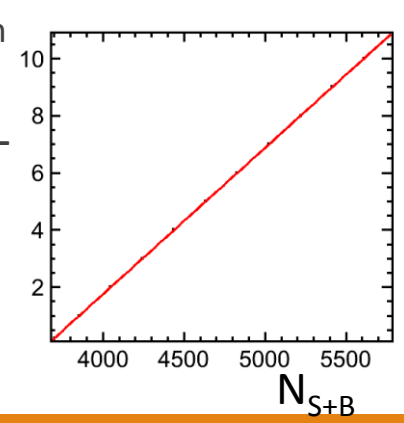
	Left polarization	Right polarization
250 fb^{-1}	 UL=1.03% (95%CL)	 UL=0.69% (95%CL)
H20 (800 fb^{-1})	 UL=0.58% (95%CL)	 UL=0.39% (95%CL)

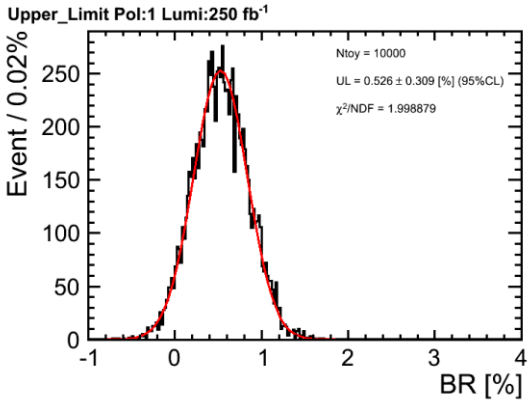
How to set UL [Statistical method]

- Template
  - Assume BR(H→invisible)=[1,2,…,10]% -> Event selection
  - Get # of events (N_{S+B}) in window range (Mrecoil∈[120,140] GeV)
  - Generate Poisson distribution of N_{S+B} -> Get 95% CL limit (N_{UL})
  - Repeat for each BR(H→invisible)=[1,2,…,10]% -> Get calibration line between N_{UL} and UL
- Toy MC
  - Fit template bkg -> Generate pseudo experiment by fluctuated bkg function
  - Get # of events (N_{S+B}) in window range (Mrecoil∈[120,140] GeV)
  - Translate N_{S+B} into UL of BR(H→invisible) using calibration line
  - Repeat 10000 times -> Obtain UL distribution



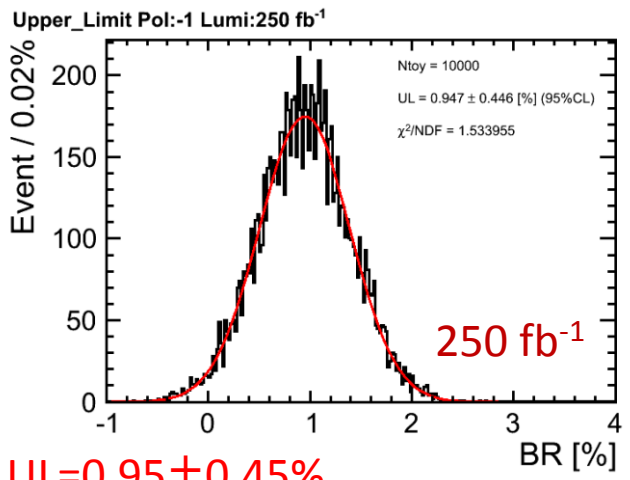
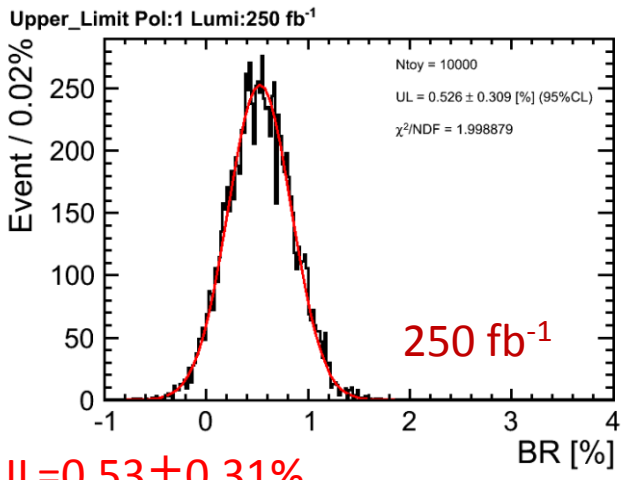
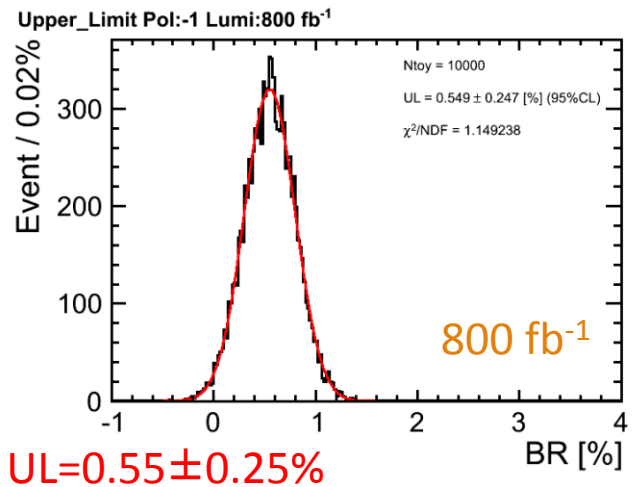
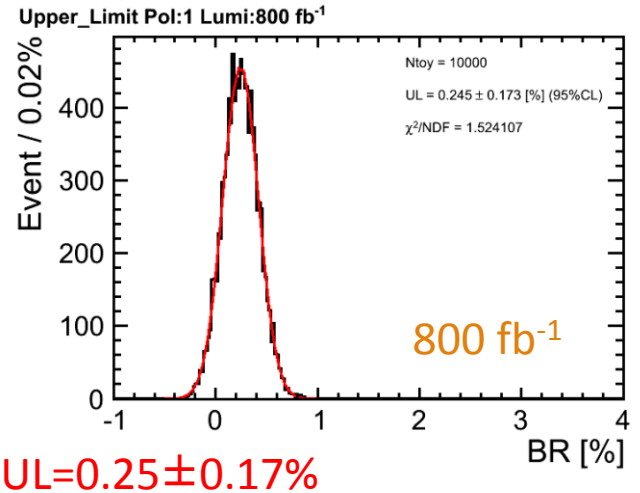






Preliminary

Statistical fluctuation of Upper Limit

	Left polarization	Right polarization
250 fb^{-1}	 UL=0.95±0.45%	 UL=0.53±0.31%
H20 (800 fb^{-1})	 UL=0.55±0.25%	 UL=0.25±0.17%

Summary

Use measurement of BR(H → $inv.$) as a means for indirect BSM search

- Motivation
  - set upper limit (UL) on BR(H → $inv.$)
  - develop analysis method to achieve high sensitivity
  - compare between alternative polarization
  - study is based on full ILD detector simulation, at E_{cm} = 250 GeV, assuming 250 fb^{-1}
- Status
  - optimized data selection methods

	Left polarization	Right polarization
significance [250 fb^{-1}]	15.5	19.7

  - set UL using toy MC for both left and right scenario

UL of BR [%] (95%CL)	Left polarization	Right polarization	Statistical Left	Statistical Right
250 fb^{-1}	1.03	0.69	0.95±0.45	0.53±0.31
H20 scenario (800 fb^{-1})	0.58	0.39	0.55±0.25	0.25±0.17
Previous study(250 fb^{-1})	0.95	0.69	-	-

Plans

- Come back around June
- Improve sensitivity through further optimization of analysis methods and jet energy resolution
- Analysis at $\mathrm{E_{cm}}$ = 350, 500 GeV, compare between different scenarios
  --> contribute to optimization of ILC run scenario

Back Up

Recoil Mass Method

- We can measure Higgs without directly looking at it
  → model independent

$$M_{rec}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

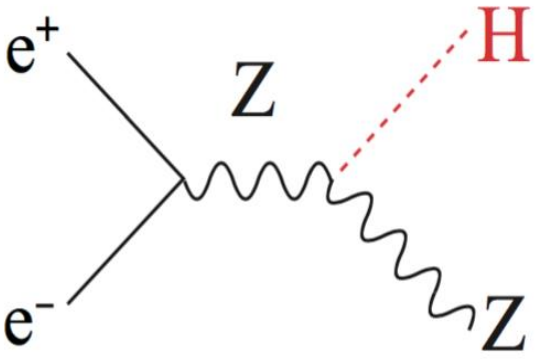
- Higgs-strahlung cross section can be obtained using leptonic decay of Z

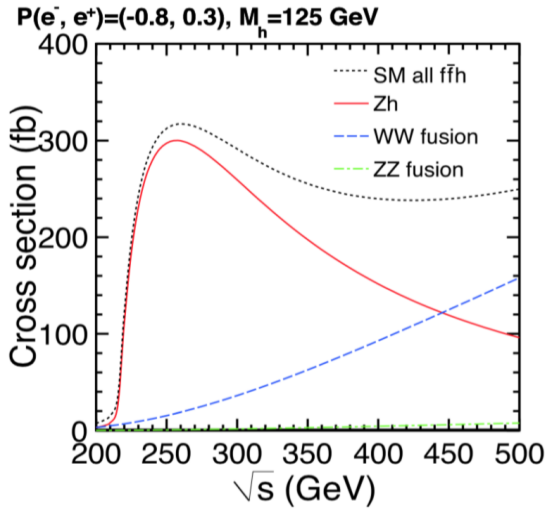
$$\sigma_{\mathrm{ZH}} = \frac{N_S}{BR(\mathrm{Z} \to l^+ l^-)\varepsilon_S L}$$

ε_S: signal efficiency, $\mathrm{N_S}$: # of signal, L : integrated luminosity

J.Yan(KEK) *et al.* Phys. Rev. D94 113002*(arXiv:1601.07524)* (2016)

- For BSM search, this study uses hadronic channel $Z \to qq$ and $E_{cm} = 250$ GeV





Hadronic Channel Analysis

Cut table [Ecm=250GeV,250fb^{-1},Left]

Polarization: (e-,e+) = (-0.8,+0.3)

Reduction Table

Process	:	4f_zz_sl	4f_ww_sl	4f_sznu_sl	llH	other bkg	all bkg	qqH	Signal	efficiency	Signf
Cross Section	:	856.843	10992.9	271.806	109.233	144955	157186	210.184	21.0184		
Generated	:	535103	1.96265e+06	147517	280686	1.71654e+07		568687	39601		
Expected	:	214211	2.74823e+06	67951.5	27308.2	3.62387e+07	3.92964e+07	52546	5254.6		0.837615
Cut0	:	214208	2.74823e+06	67950.8	27287.2	3.61422e+07	3.91999e+07	52546	5254.6	1	0.838644
Cut1	:	165397	1.27603e+06	67852.3	19514.9	2.58527e+07	2.73815e+07	47847.5	5249.24	0.99898	1.00218
Cut2	:	35026.2	69536.9	33851.7	6262.27	290488	435165	219.107	5025.8	0.956456	7.57315
Cut3	:	34331.3	67469	33236.2	5715.88	116081	256834	217.241	4946.97	0.941455	9.66475
Cut4	:	30206.2	56159.3	29165.9	5173.76	15422.6	136128	200.531	4688.05	0.892179	12.4841
Cut5	:	23532.4	29214.4	23675.4	983.939	2849.81	80256	64.0287	3918.8	0.745784	13.502
Cut6	:	20456.4	24819.4	21246.8	961.653	1705.09	69189.4	61.7585	3768.34	0.717151	13.9454
Cut7	:	20438.3	24750.6	21174.3	953.744	1676	68993	61.6123	3765.37	0.716586	13.9535
Cut8	:	12238.9	14411.4	14269.7	736.048	1021.8	42677.9	49.4017	3335.1	0.634701	15.5395
Cut9	:	3341.49	5437.22	5142.82	360.291	442.042	14723.9	37.5595	2771.04	0.527355	20.9277

Hadronic Channel Analysis

Cut table [Ecm=250GeV,250fb^{-1},Right]

Polarization: (e-,e+) = (+0.8,-0.3)

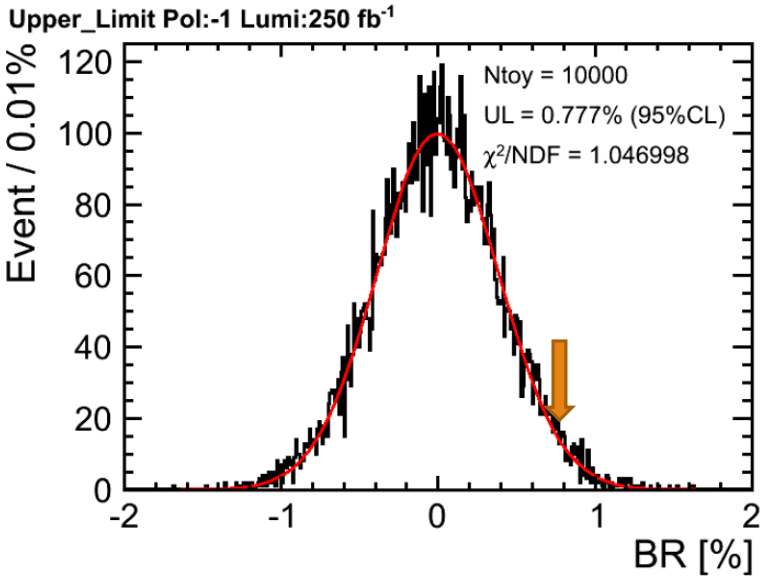
Reduction Table

Process	:	4f_zz_sl	4f_ww_sl	4f_sznu_sl	llH	other bkg	all bkg	qqH	Signal	efficiency	Signf
Cross Section	:	467.168	758.364	92.506	63.9953	84979.7	86361.8	141.951	14.1951		
Generated	:	535103	1.96265e+06	147517	280686	1.71654e+07		568687	39601		
Expected	:	116792	189591	23126.5	15998.8	2.12449e+07	2.15904e+07	35487.8	3548.78		0.763055
Cut0	:	116790	189591	23125.3	15986	2.11471e+07	2.14926e+07	35487.8	3548.78	1	0.764787
Cut1	:	89109.9	88064.9	23091.1	10974.2	1.36285e+07	1.38398e+07	32298.4	3544.72	0.998856	0.951603
Cut2	:	16372.6	4918.21	8969.3	3615.73	173001	206877	155.663	3390.6	0.955427	7.39145
Cut3	:	16028.4	4773.66	8786.34	3310.23	73899.5	106798	153.661	3330.78	0.938572	10.0298
Cut4	:	14018	4022.38	7793.66	3039.23	8467.26	37340.5	142.042	3143.98	0.885934	15.5982
Cut5	:	10827.8	2087.47	6120.51	540.655	1226.04	20802.5	45.7243	2632.46	0.741795	17.1794
Cut6	:	9387.11	1806.01	5372.76	528.538	565.119	17659.5	44.2793	2534.72	0.714252	17.8172
Cut7	:	9376.13	1800.16	5366.12	522.964	522.594	17588	44.2706	2532.1	0.713515	17.8316
Cut8	:	6082.28	1226.26	3615.04	477.344	336.129	11737.1	40.5283	2340.36	0.659485	19.6969
Cut9	:	1600.76	455.121	1054.3	238.312	121.227	3469.71	31.3941	1914.95	0.539607	26.0205

Preliminary

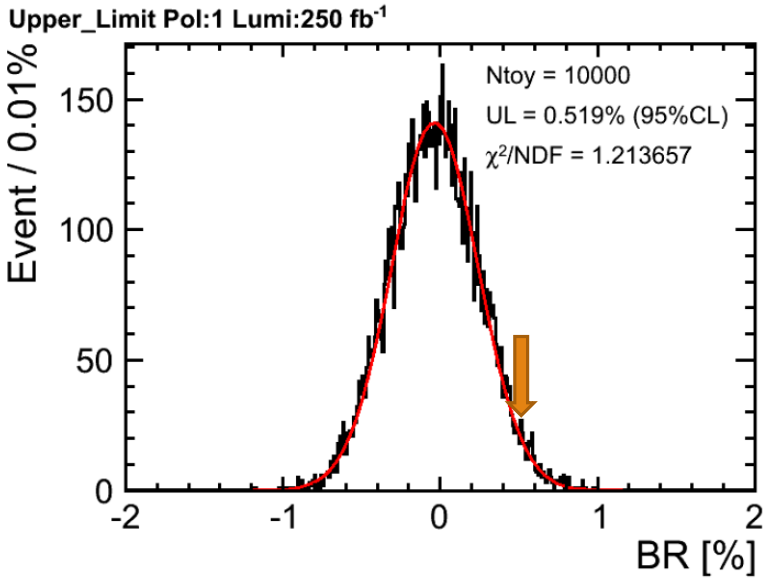
Toy Monte Carlo to set upper limit

Left



UL=0.78% (95%CL)

Right



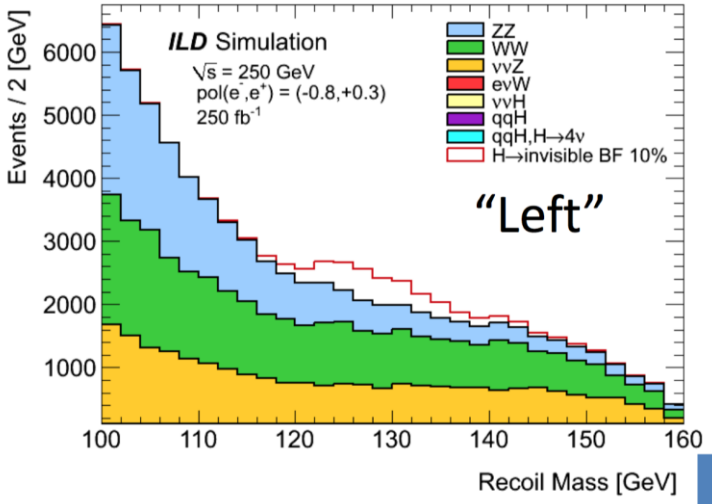
UL=0.52% (95%CL)

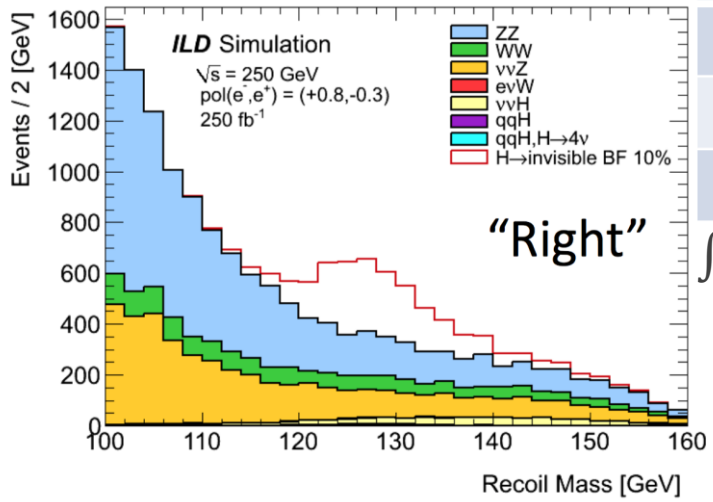
bkg : shape & yields fixed

- $\int Ldt$ = 250 fb^{-1}
- bkg fixed → 10000 times pseudo experiment
- not include SM Higgs to invisible decay

Previous Study

A. Ishikawa (Tohoku Unv.),
”Search for Invisible Higgs Decays at the ILC” LCWS2014@Belgrade



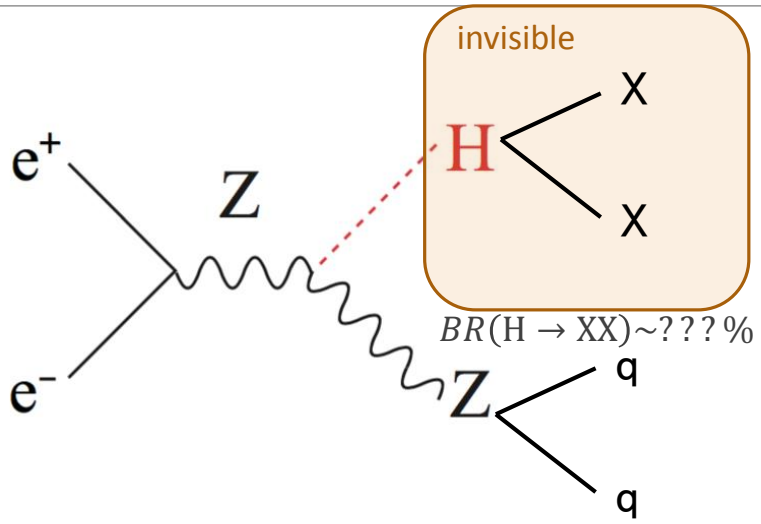


- Smaller upper limit of $\mathrm{BR}(\mathrm{H} \rightarrow inv.)$
  → higher sensitivity to BSM
- We aim to improve this result

UL on BF [%]	“Left”	“Right”
250GeV	0.95	0.69
350GeV	1.49	1.37
500GeV	3.16	2.30

$\int Ldt$ =250,350,500 fb^{-1} for $\mathrm{E_{cm}}$ =250,350,500 GeV

Signal feature [hadronic channel]



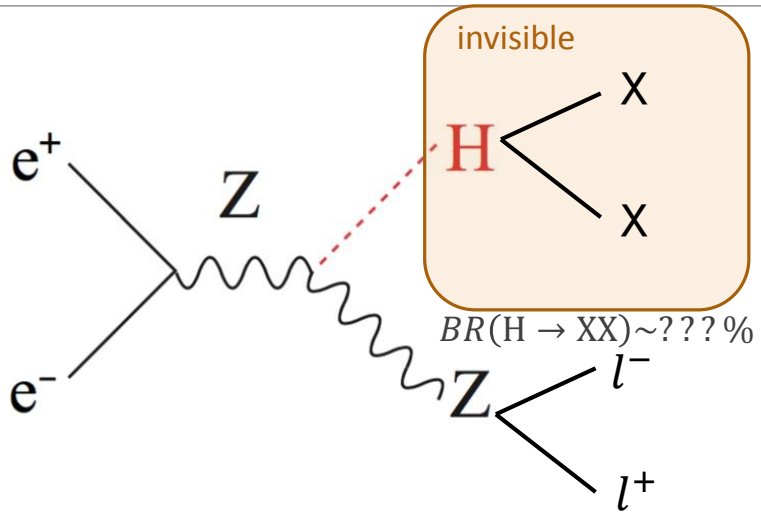
- Two-Jet
- Invisible particle exist
- $M_{qq} \approx M_Z$ $(BR(\mathrm{Z} \to qq) \sim 70\%)$
- $M_{recoil} \approx M_{Higgs}$

Major Backgrounds [hadronic channel]

The major backgrounds have the final states qqll,qqlv,qqvv.

1. ZZ semileptonic
2. WW semileptonic
3. $\mathrm{Z}\nu_e\nu_e, \mathrm{Z} \to \mathrm{qq}$
4. $\mathrm{W}\nu_e\nu_e, \mathrm{W} \to \mathrm{qq}$
5. $\nu\nu\mathrm{H}, \mathrm{H} \to \mathrm{ZZ}, \mathrm{Z} \to qq$
6. $\mathrm{qqH}, \mathrm{H} \to$ SM decay

Signal feature [leptonic channel]



- Two-leptons
- Invisible particles without neutrino
- $M_{ll} \approx M_Z$ $(BR(\mathrm{Z} \to ll)$~3.4%$)$
- $M_{recoil} \approx M_{Higgs}$

Major Backgrounds [leptonic channel]

The major backgrounds have the final states with di-lepton & missing energy .

1. ZZ leptonic
2. WW leptonic
3. single Z & $\nu_e\nu_e, \mathrm{Z} \to ll$
4. single W & e $\nu_e, \mathrm{W} \to \mathrm{e}\,\nu_\mathrm{e}$
5. $\nu\nu\mathrm{H}, \mathrm{H} \to \mathrm{ZZ}, \mathrm{Z} \to ll$
6. $ll\mathrm{H}, \mathrm{H} \to$ SM decay