ICEPP
The University of Tokyo

BSM search using Higgs to invisible decay at the ILC

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The 50th general meeting @KEK Feb. 4, 2017

Status

- Reproduced all root file without using kt algorithm, and reanalyzed
- Evaluated UL based on Yamashita san's advice
- Made presentation in LCWS2016
- Pause analysis for TPC experiment

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

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, $\int L dt$ = 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

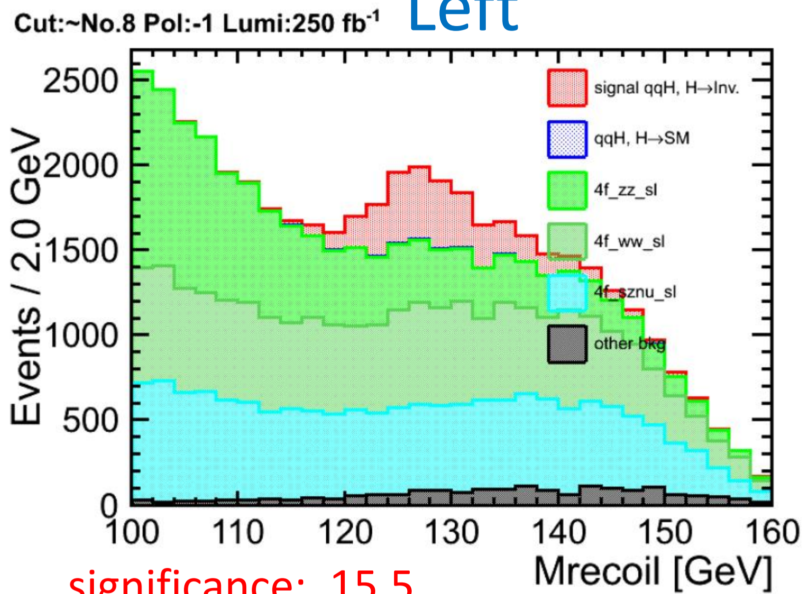
Event Selection

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

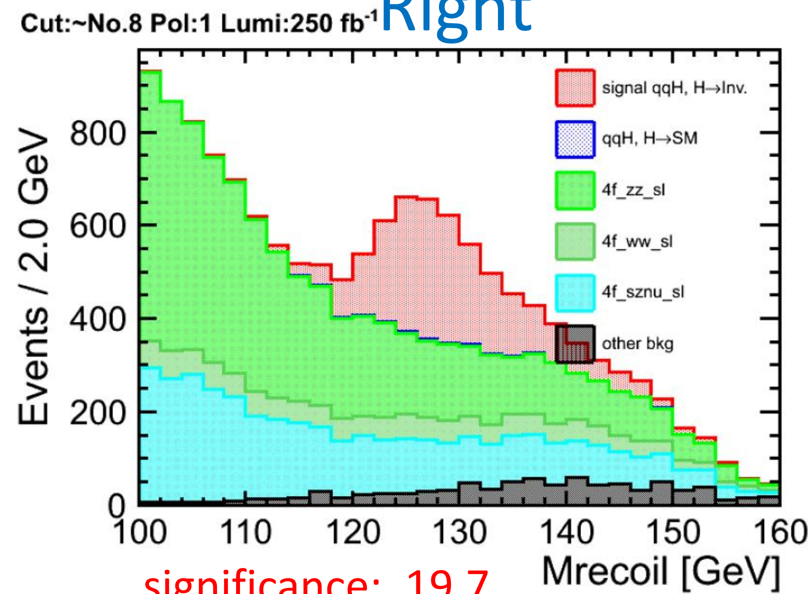
Recoil Mass Plots [Ecm = 250 GeV, 250 fb^{-1},BR(H->inv.)=10%]

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

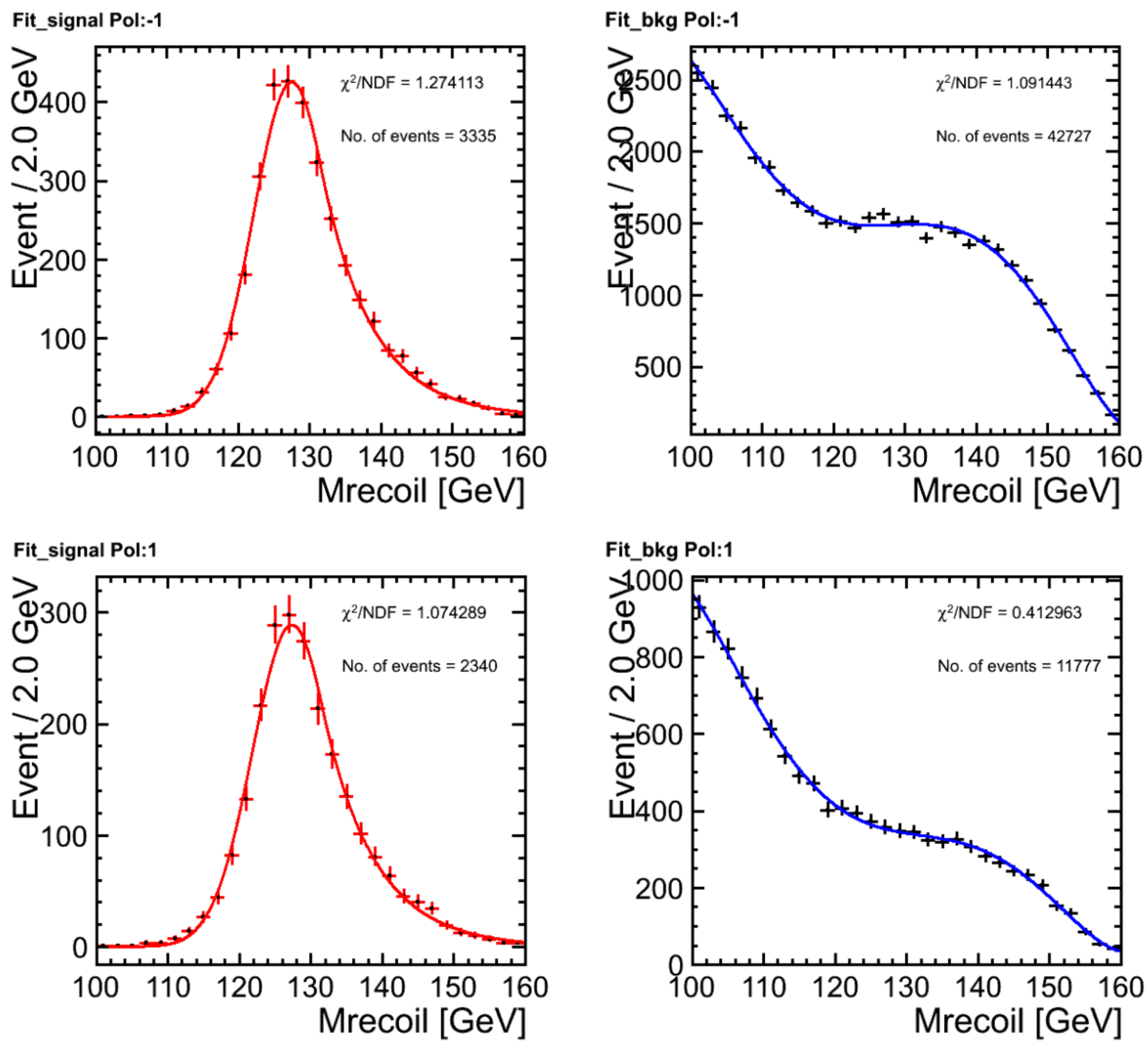
Fit Signal & Background

signal: GPET (Gaussian + Exponential)

bkg : 5^{th} order polynomial

Left

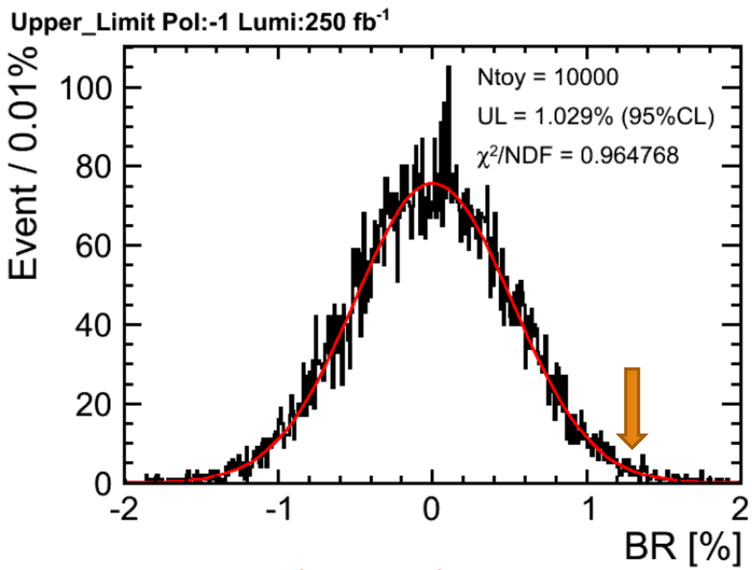
Right



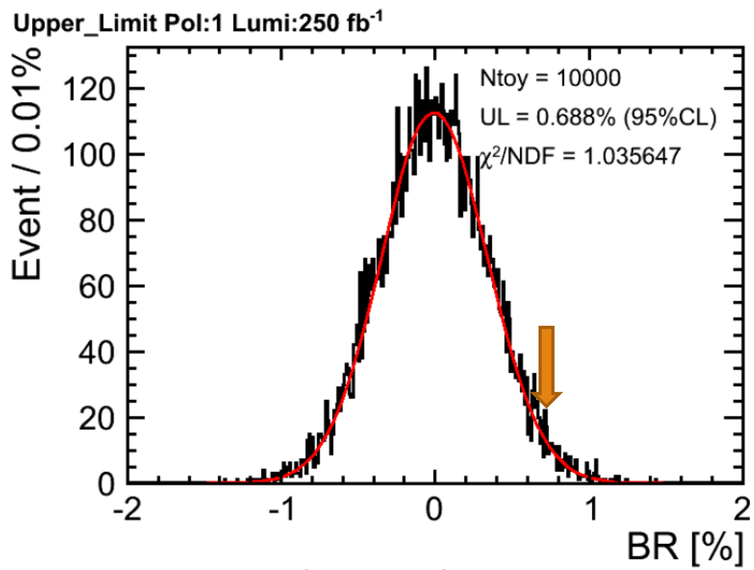
Preliminary

Toy Monte Carlo to Set Upper Limit

Left polarization	Right polarization



UL=1.03% (95%CL)



UL=0.69% (95%CL)

bkg : shape fixed, yields floated

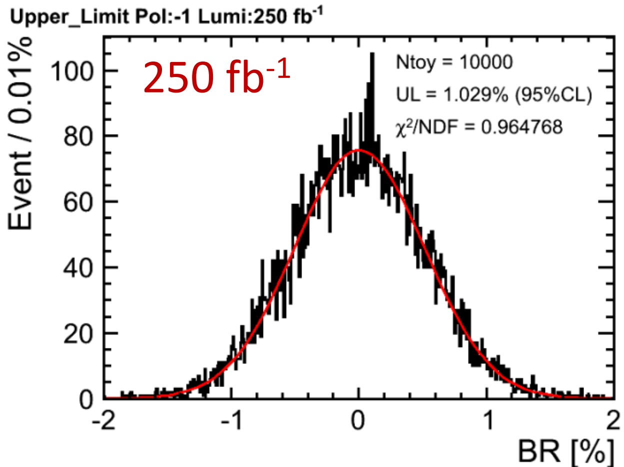
- $\int L dt$ = 250 fb^{-1}
- bkg yields floated → 10000 times pseudo experiment
- not include SM Higgs to invisible decay

Preliminary

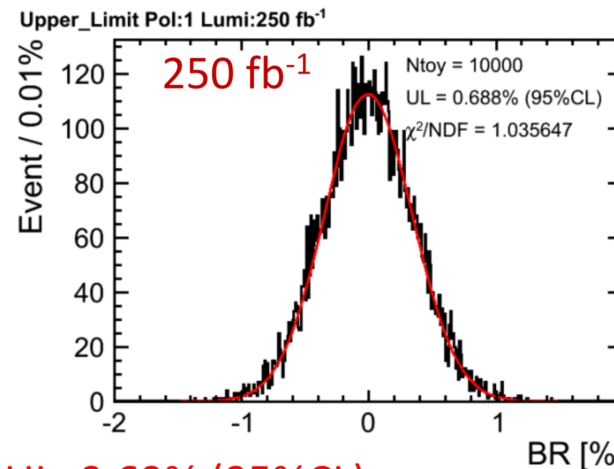
Toy Monte Carlo to Set Upper Limit

Left polarization | Right polarization

250 fb^{-1}

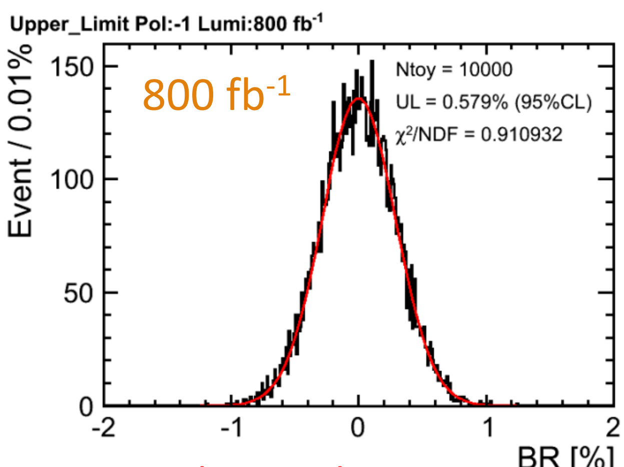


UL=1.03% (95%CL)

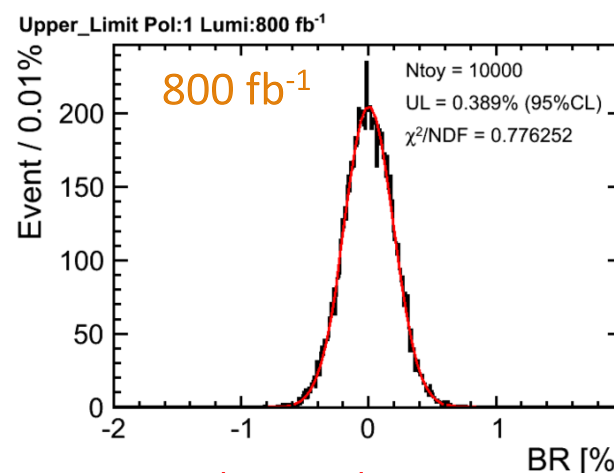


UL=0.69% (95%CL)

H20 (800 fb^{-1})



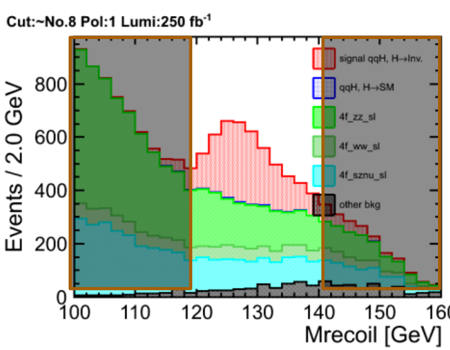
UL=0.58% (95%CL)

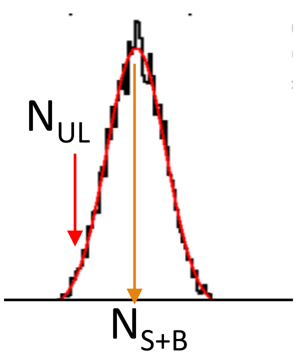


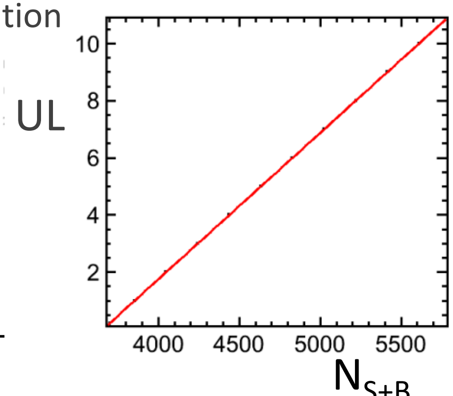
UL=0.39% (95%CL)

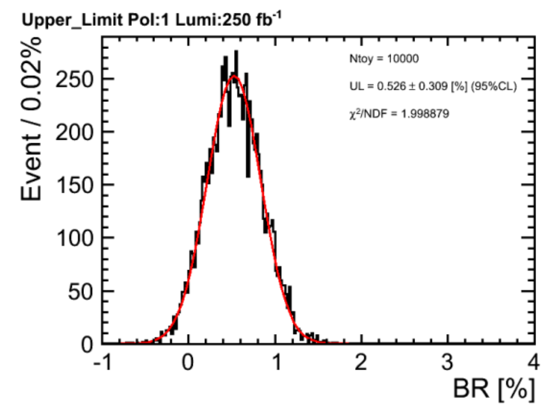
How to set UL [Statistical method]

- 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



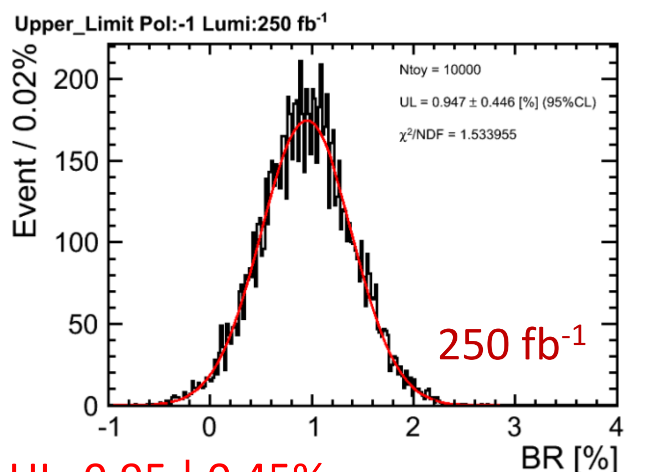
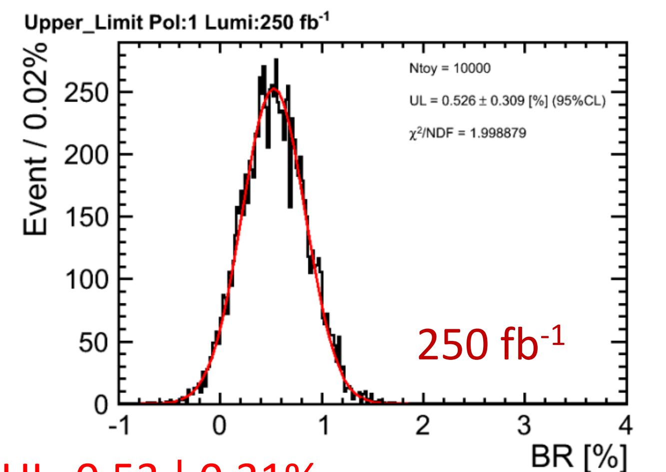
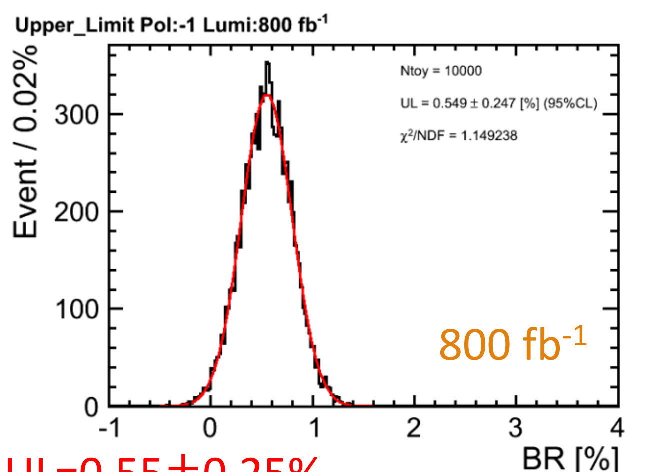
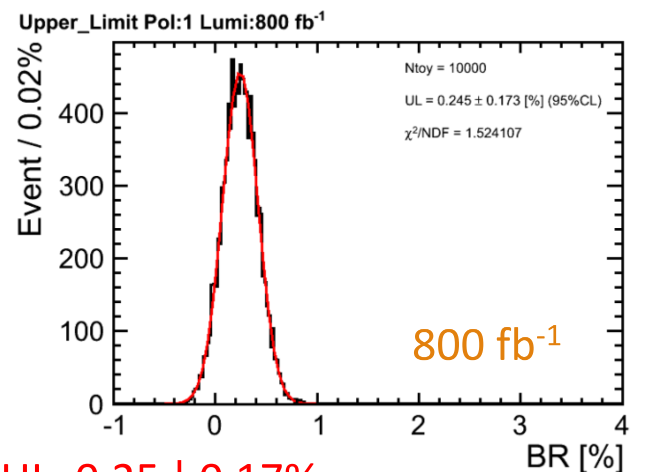






Preliminary

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 $\mathrm{BR}(\mathrm{H} \to inv.)$ as a means for indirect BSM search

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

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

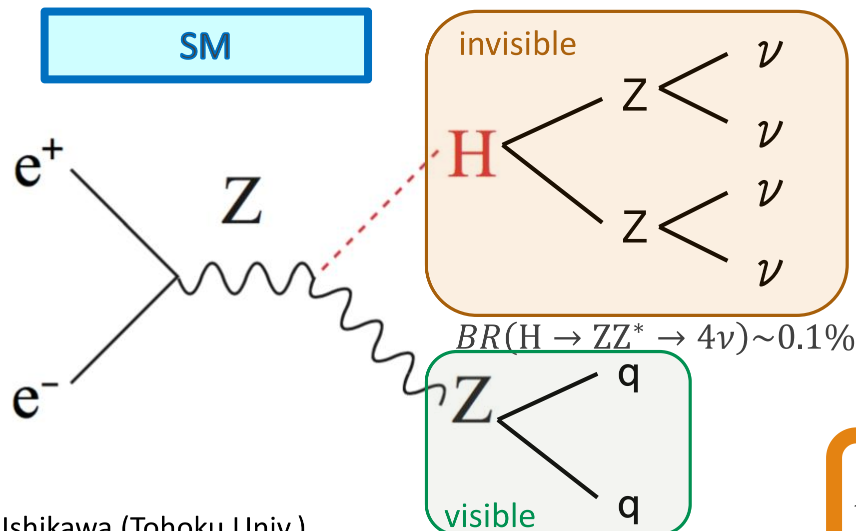
  - set UL using toy MC for both left and right scenario

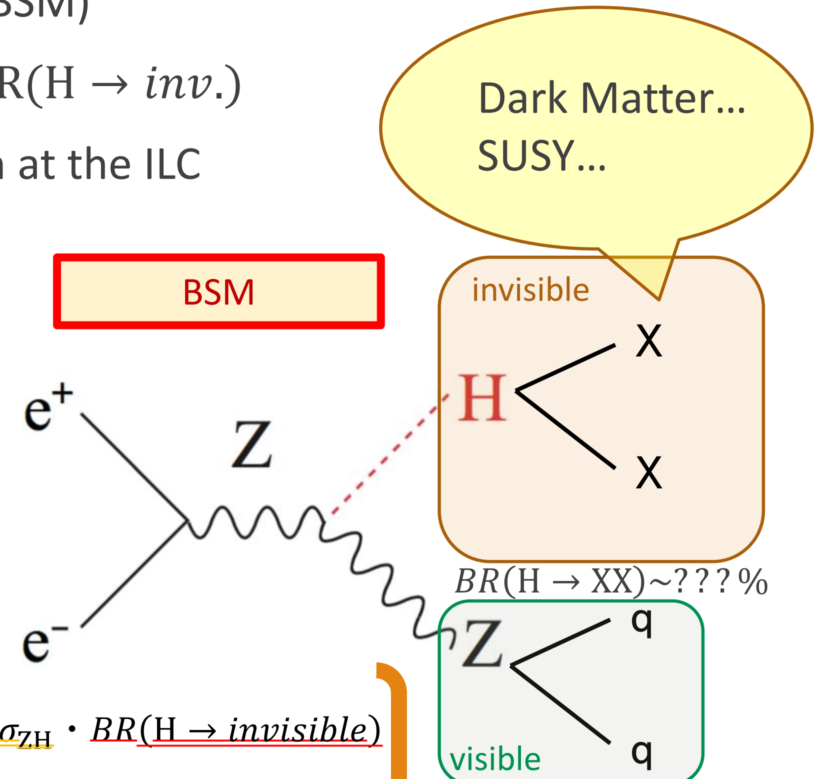
UL of BR [%] (95%CL)	Left polarization	Right polarization	Statistical Left	Statistical Right
250 fb^{-1}	1.03	0.69	0.95±0.45	0.53±0.31
H20 scenario (800 fb^{-1})	0.58	0.39	0.55±0.25	0.25±0.17
Previous study(250 fb^{-1})	0.95	0.69	-	-

Back Up

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





$$N_S \propto \sigma_{\mathrm{ZH}} \cdot BR(\mathrm{H} \rightarrow invisible)$$

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

Recoil Mass Method

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

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

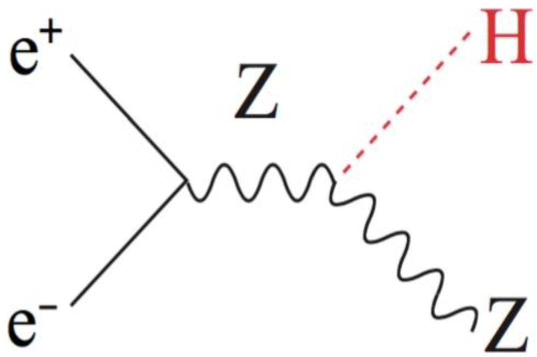
- Higgs-strahlung cross section can be obtained using leptonic decay of Z

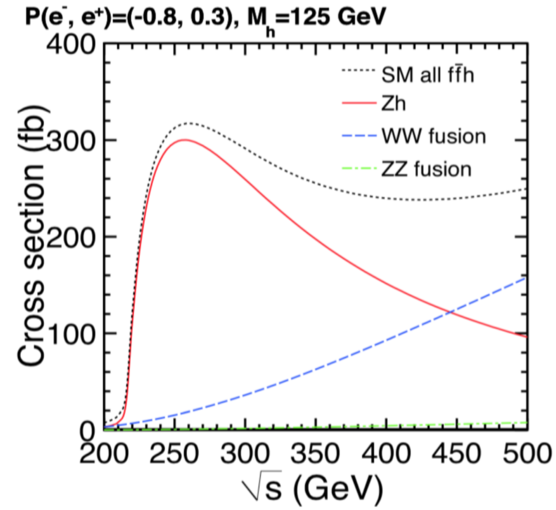
$$\sigma_{\mathrm{ZH}} = \frac{N_S}{BR(\mathrm{Z} \to l^+ l^-)\varepsilon_S L}$$

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]

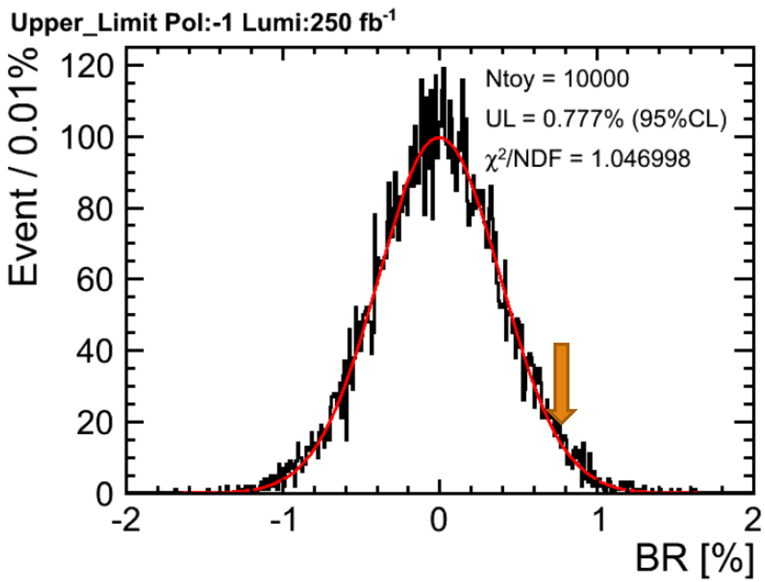
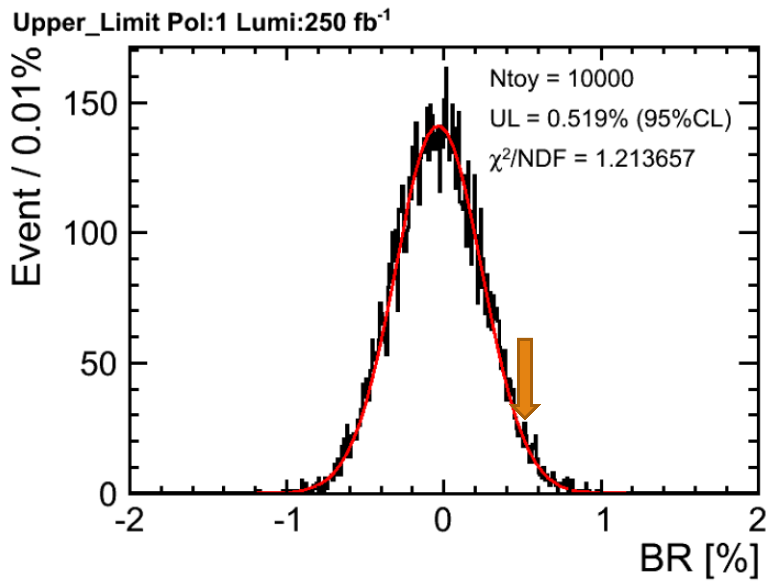
Polarization: (e-,e+) = (+0.8,-0.3)

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

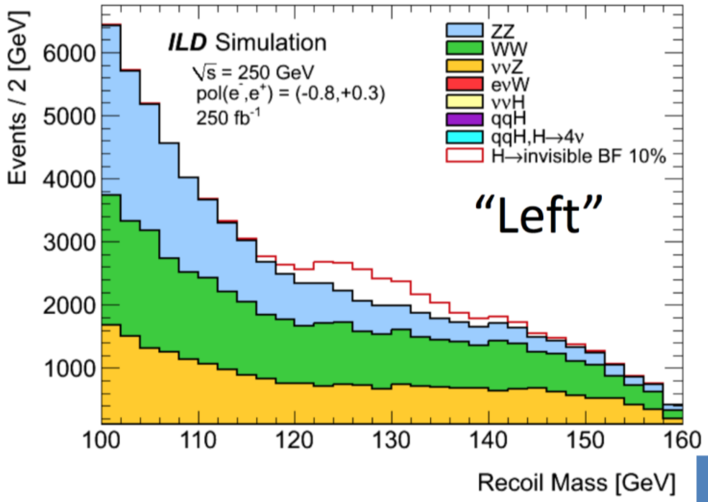
Left	Right
	
UL=0.78% (95%CL)	UL=0.52% (95%CL)

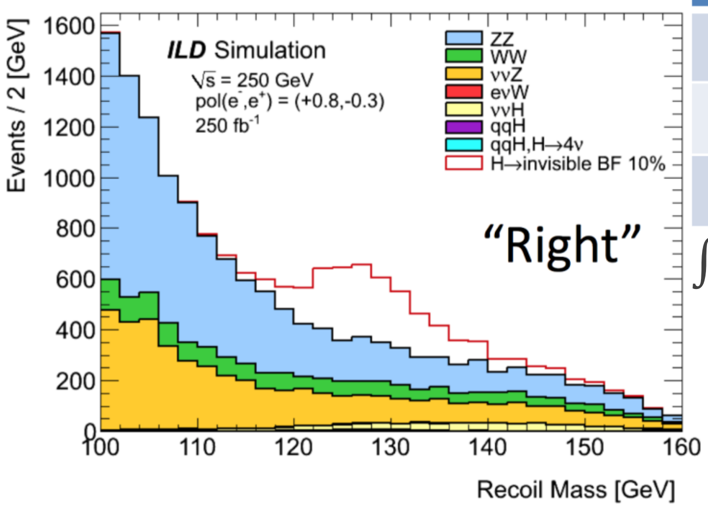
bkg : shape & yields fixed

- $\int L dt$ = 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



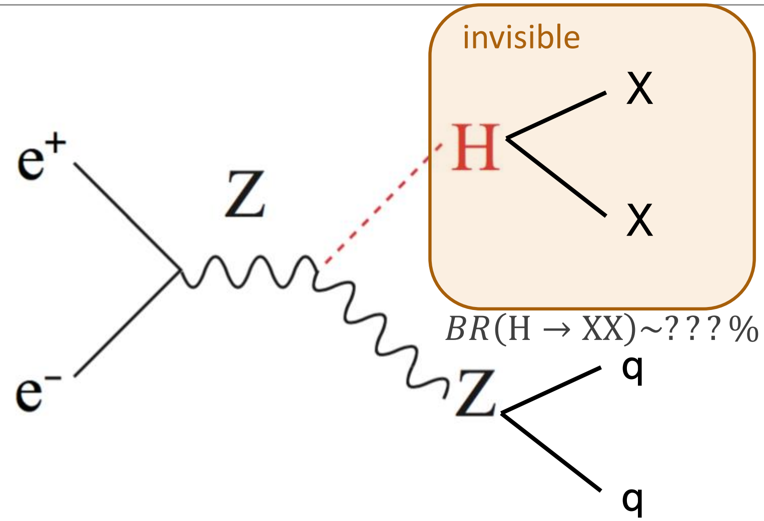


- Smaller upper limit of $\mathrm{BR}(\mathrm{H} \to inv.)$
  → higher sensitivity to BSM
- We aim to improve this result

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]



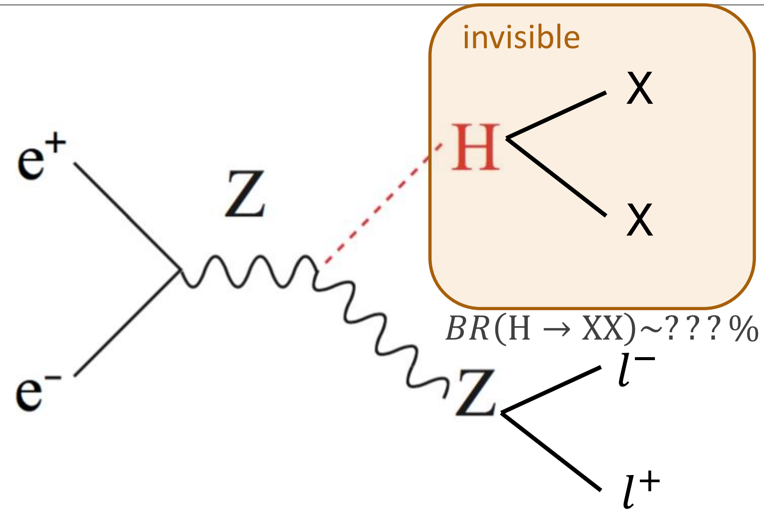
- Two-Jet
- Invisible particle exist
- $M_{qq} \approx M_Z$ ($BR(\mathrm{Z} \rightarrow qq)$~70%)
- $M_{recoil} \approx M_{Higgs}$

Major Backgrounds [hadronic channel]

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

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

Signal feature [leptonic channel]



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

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 & $\nu_e\nu_e, \mathrm{Z} \rightarrow ll$
4. single W & $\mathrm{e}\ \nu_e, \mathrm{W} \rightarrow \mathrm{e}\ \nu_\mathrm{e}$
5. $\nu\nu\mathrm{H}, \mathrm{H} \rightarrow \mathrm{ZZ}, \mathrm{Z} \rightarrow ll$
6. $ll\mathrm{H}, \mathrm{H} \rightarrow$ SM decay