Search for Invisible Higgs Decays at the ILC

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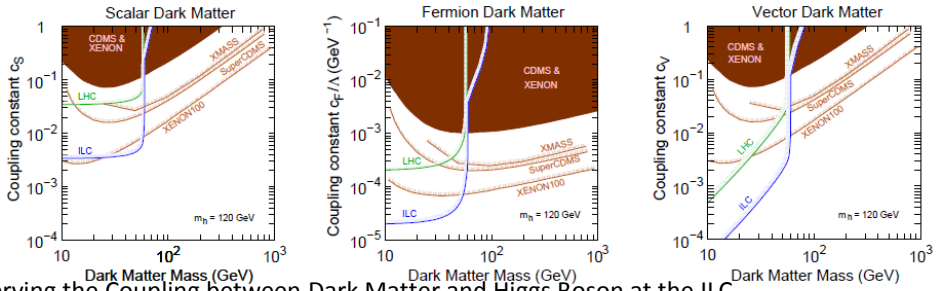
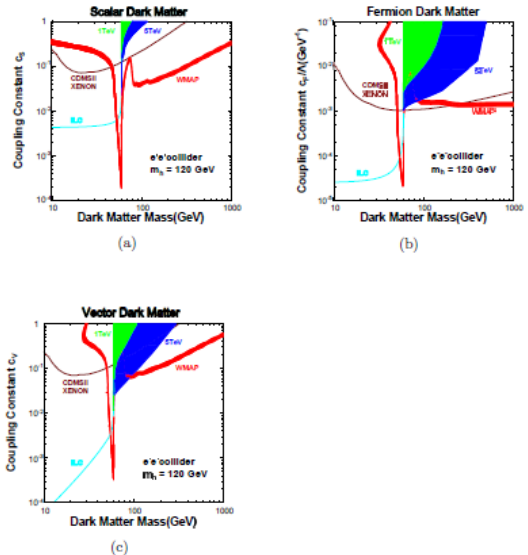
Invisible Higgs Decays

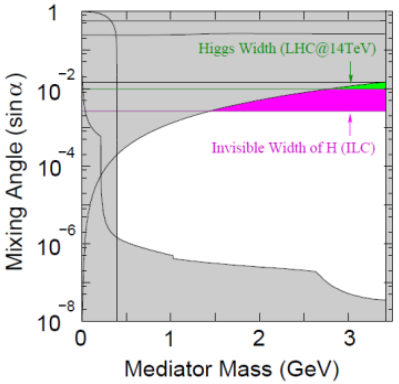
- In the SM, an invisible Higgs decay is H → ZZ* →4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - Higgs portal?
  - Dark radiation?



Observing the Coupling between Dark Matter and Higgs Boson at the ILC
Shigeki Matsumoto, Keisuke Fujii, Takahiro Honda, Shinya Kanemura,
Takehiro Nabeshima, Nobuchika Okada, Yosuke Takubo and Hitoshi Yamamoto

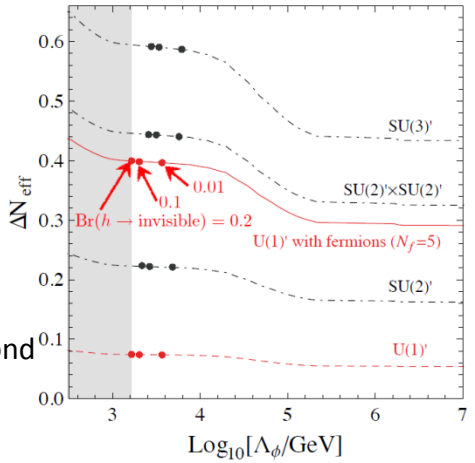
Testing Higgs portal dark matter via Z fusion at a linear collider
Shinya Kanemura, Shigeki Matsumoto,
Takehiro Nabeshima and Hiroyuki Taniguchi





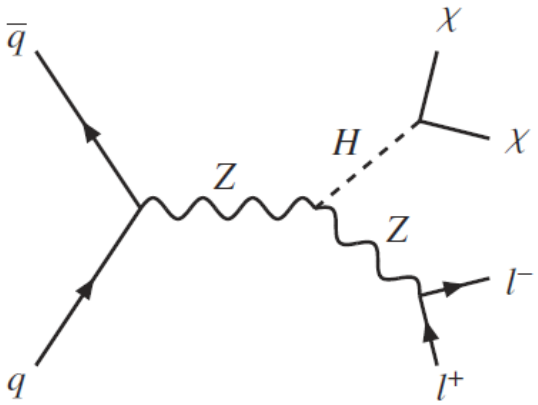
Fermionic Asymmetric DM
S. Matsumoto@ECFA 2013

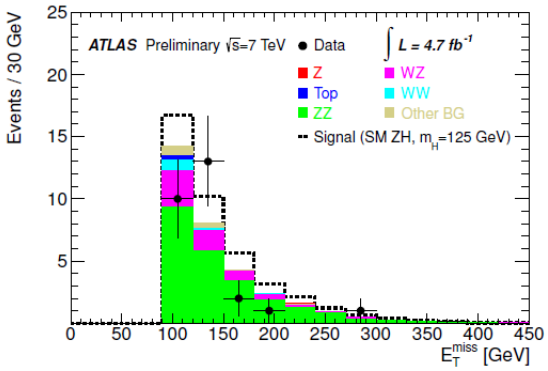
Precision Cosmology meets particle physics.
(Dark Radiation)
F. Takahashi@Higgs and Beyond

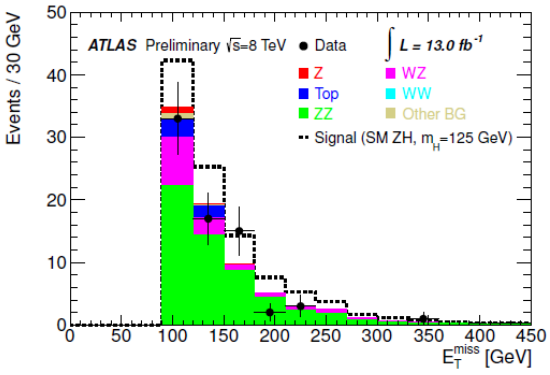


Invisible Higgs Decays at the LHC

- Invisible Higgs Decays are searched with a qq→ ZH process using missing E_t against leptonic Z decays.
  - They cannot reconstruct missing Higgs mass since they don't know momenta of initial quark pairs.
- This method is model dependent since the cross section of ZH in pp collision is assumed as that in the SM.
  - Current upper limit for the BF is 65%@95%CL (expected 84%).
  - It is really hard to achieve the upper limit of 10%.



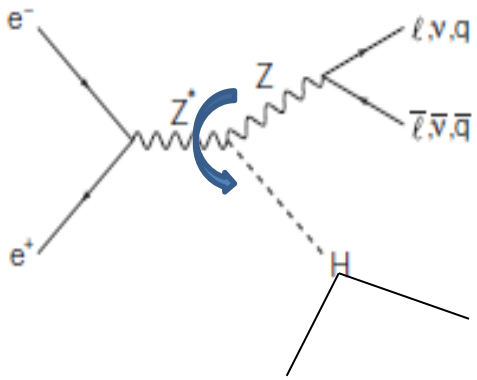




http://cds.cern.ch/record/1523696

Invisible Higgs Decays at the ILC

- We can search for the invisible Higgs using a recoil mass technique with model independent way!
  - e+e- → ZH
  - We can also measure the cross section of e+e- → ZH from a recoil mass.
- At the ILC, initial e+ e- momenta are known, and the four momentum of Z is measured from di-jet or di-lepton decays, we can reconstruct Higgs mass which is a powerful tool!



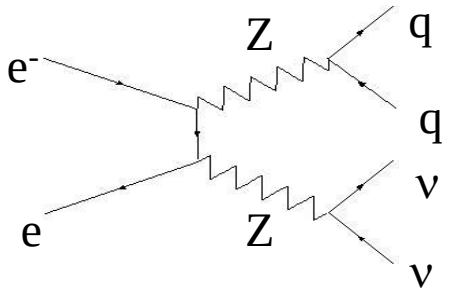
$$P_H = P_{e+e-} - P_Z$$

known measured

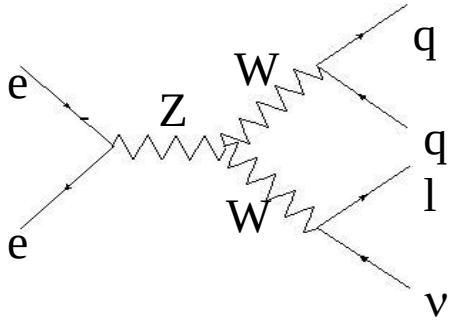
Signal and Backgrounds

- Signal
  - Pseudo signal : $e^+e^- \rightarrow ZH$, $Z \rightarrow qq$, $H \rightarrow ZZ^* \rightarrow 4\nu$
- Backgrounds
  - found qqll, qqlν and qq$\nu\nu$ final states are the dominant backgrounds.
    - other backgrounds also studied
    - Pure leptonic and hadronic final states are easily eliminated.

(1)



(2)



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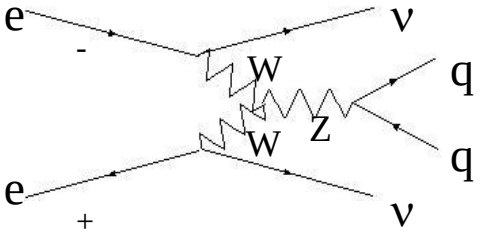

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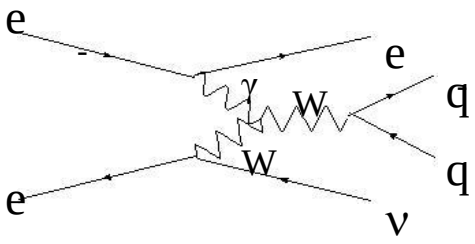
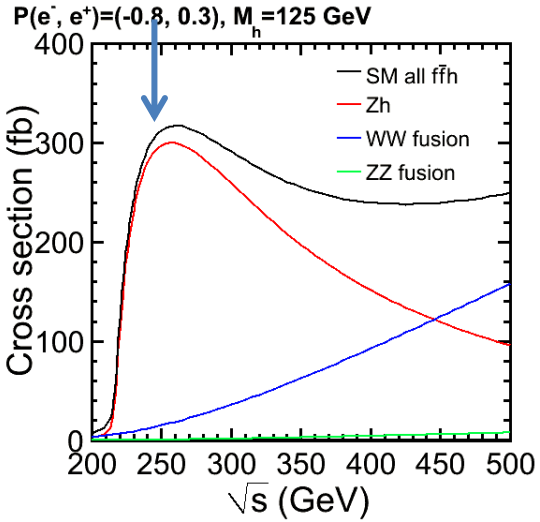


- (1) ZZ semileptonic : one $Z \rightarrow qq$, the other $Z \rightarrow ll$, $\nu_\mu\nu_\mu$, $\nu_\tau\nu_\tau$
- (2) WW semileptonic : one $W \rightarrow qq$, the other $W \rightarrow l\nu$
- (3) $Z\nu_e\nu_e$, $Z \rightarrow qq$
- (4) $We\nu_e$, $W \rightarrow qq$
- $\nu\nu H$, generic H decays
- qqH, generic H decays

MC setup and Samples



- Generator : Wizard
  - for both signal and backgrounds
  - E_{CM} = 250GeV
  - Higgs mass 125GeV
  - Polarizations of P(e+,e-)=(+30%,-80%), (-30%, +80%)
    - Throughout the slides, denoted as "Left" and "Right" polarizations
- Samples
  - Official DBD samples
    - Full simulation with the ILD detector
    - Interferences are considered, ex WW→e$\nu_e$qq and eν_eW →e$\nu_e$qq
  - Half of the samples are used for cut determination. The other used for efficiency calculation and backgrounds esitimation.

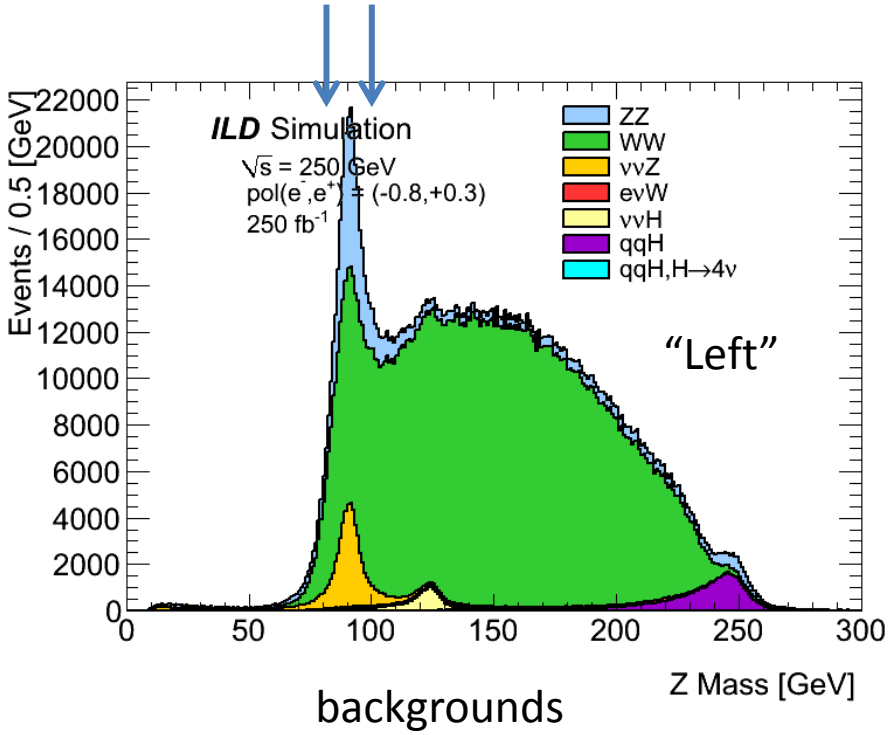
[fb]	ZZ sl	WW sl	ννZ sl	eνW sl	ννH	qqH	qqH H→4ν
"Left"	857	10993	272	161	78	210	0.224
"Right"	467	759	93	102	43	142	0.151

Overview of the Selections

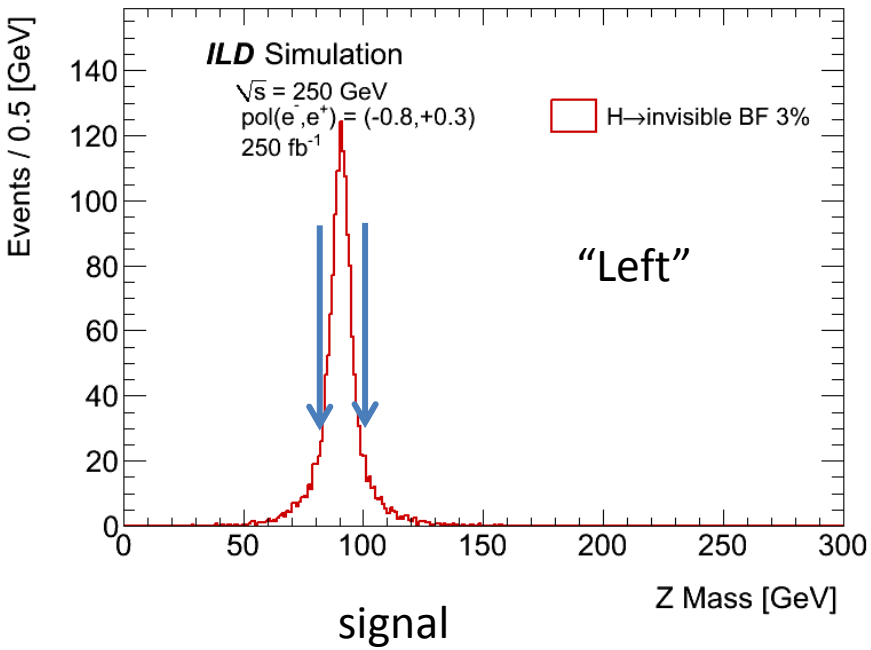
1. Forced two-jet reconstruction with Durham jet algorithm
2. Isolated lepton veto
3. Numbers of Particle Flow Objects (PFO) and charged tracks
   - $N_{PFO} > 16$ & $N_{trk} > 6$
   - Eliminate low multiplicity events like $\tau\tau$
4. Z mass reconstructed from di-jet : M_Z
   - $80GeV < M_Z < 100GeV$
   - Also used for Likelihood ratio cut
5. Polar angle of Z direction : $\cos(\theta_Z)$
   - Just apply < 0.99 to eliminate peaky eeZ background before making likelihood ratio
6. Loose Recoil mass selection : M_{recoil}
   - $100GeV < M_{recoil} < 160GeV$
7. Likelihood ratio of M_Z, $\cos(\theta_Z)$, $\cos(\theta_{hel})$ to give the best upper limits : LR
   - $\cos(\theta_{hel})$: Helicity angle of Z
   - LR > 0.3 for “Left” and LR > 0.4 for “Right”
8. Recoil mass
   - The final plot (Signal Box : $120GeV < M_{recoil} < 140$)
   - Perform toy MC by fitting to the recoil mass to set upper limit.

Z mass

- To suppress backgrounds not having Z in final states, Z mass reconstructed from di-jet are required
  - 80 GeV < mZ < 100GeV
  - RMS for Z mass for signal is 10.6GeV and fitted sigma with Gaussian is 6.0GeV



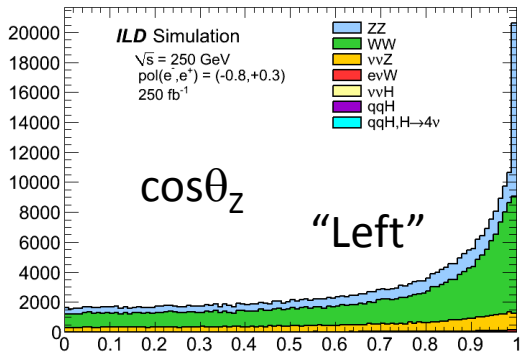
backgrounds

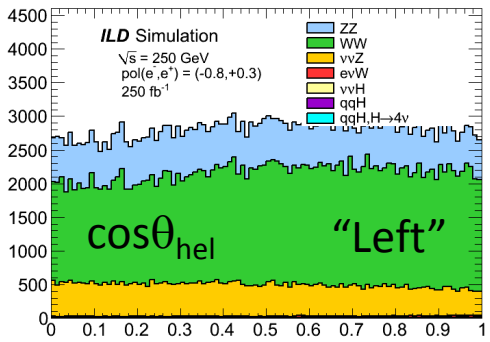


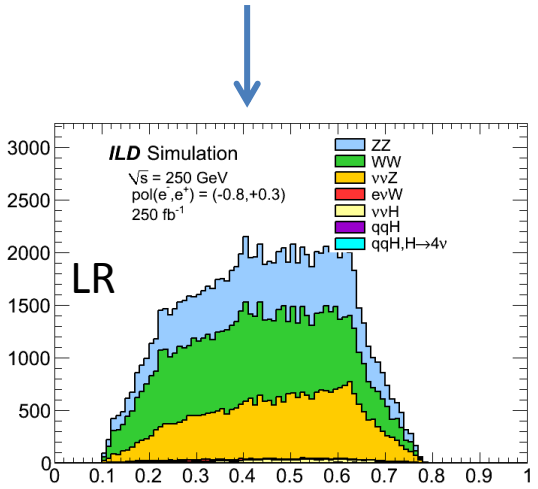
signal

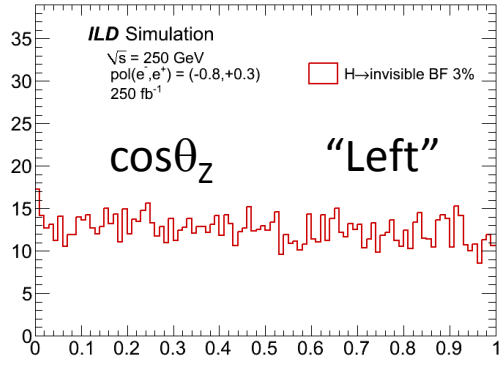
Background Suppression

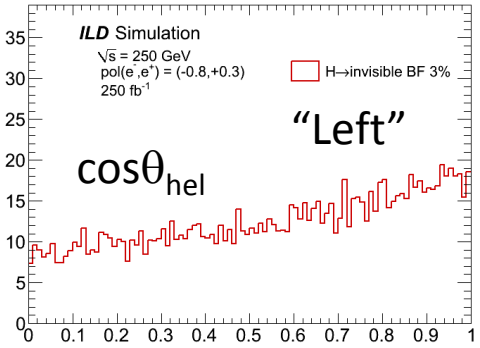
- Likelihood Ratio (LR) method is used to combine three variables
  - Z mass (see previous page)
  - Polar angle of Z direction : $\cos\theta_Z < 0.99$
  - Helicity angle of Z : $\cos\theta_{hel}$

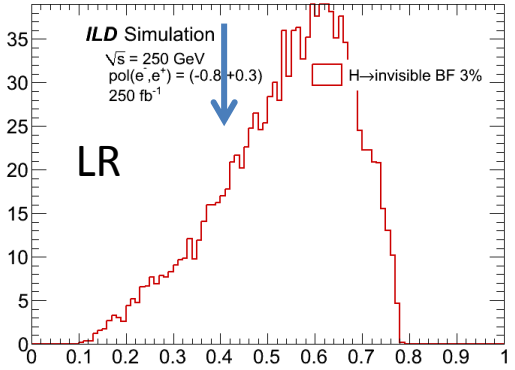












Cut Summary "Left"

- Number of events scaled to 250fb^{-1} and (Efficiency)

"Left"	ZZ	WW sl	nnZ	enW	nnH	qqH	qqH H→4n Pseudo signal
No cut	214232	2748230	67951	40296	19383	52546	56.07 (1.000)
No lepton	169058	1496080	67703	15482	17766	48244	55.80 (0.995)
Trk and PFO	166373	1490810	65783	15392	16544	48242	55.39 (0.988)
M_Z	75301	174634	47646	1759	1226	77	44.57 (0.795)
$\cos\theta_Z$	63729	166818	46533	1635	1211	77	44.19 (0.788)
Loose M_{Recoil}	27040	38917	27319	600	1146	75	44.10 (0.787)
LR	21577	29685	22587	351	1022	70	41.07 (0.786)
Signal Box	4471	10457	6608	319	448	51	33.49 (0.597)

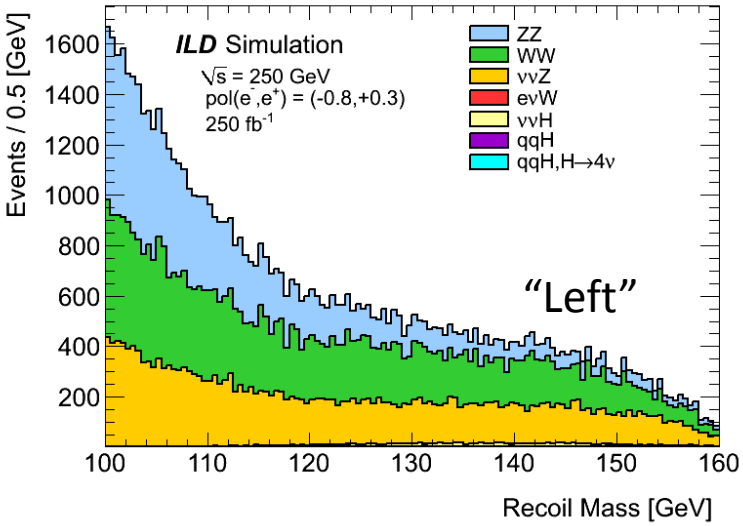
Cut Summary "Right"

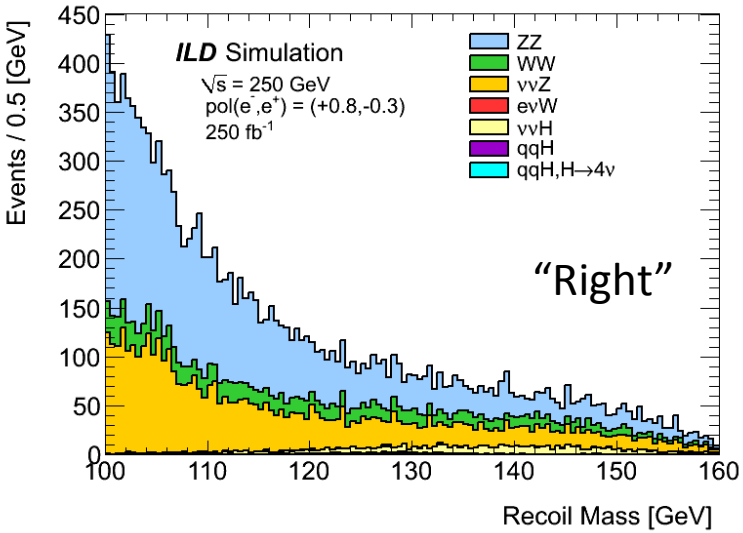
- Number of events scaled to 250fb^{-1} and (Efficiency)

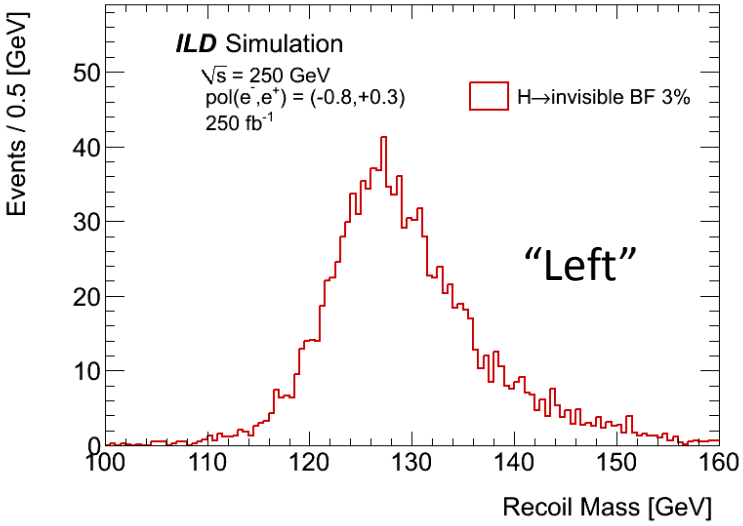
"Right"	ZZ	WW sl	nnZ	enW	nnH	qqH	qqH H→4n Pseudo signal
No cut	116797	189596	23124	25546	10646	35488	37.87 (1.000)
No lepton	91423	102778	23035	10694	9745	32552	37.68 (0.995)
Trk and PFO	89550	102416	22417	10623	9071	32548	37.38 (0.987)
M_Z	37239	12582	15997	1601	672	50	30.13 (0.796)
$\cos\theta_Z$	29694	12093	15553	1486	664	49	29.86 (0.788)
Loose M_{Recoil}	12513	2808	6984	546	634	48	29.78 (0.786)
LR	7603	1759	4434	232	512	41	24.41 (0.645)
Signal Box	1537	641	1037	211	235	31	20.14 (0.532)

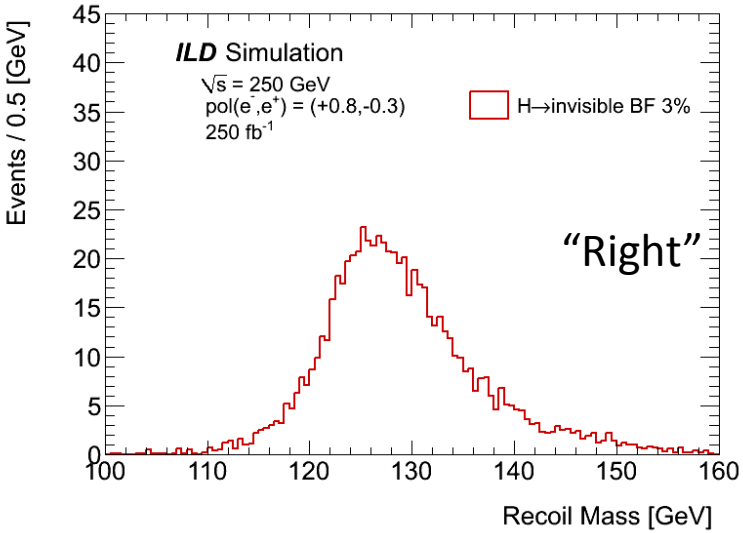
Final Recoil Mass

- Dominant backgrounds are ZZ, WW, ννZ



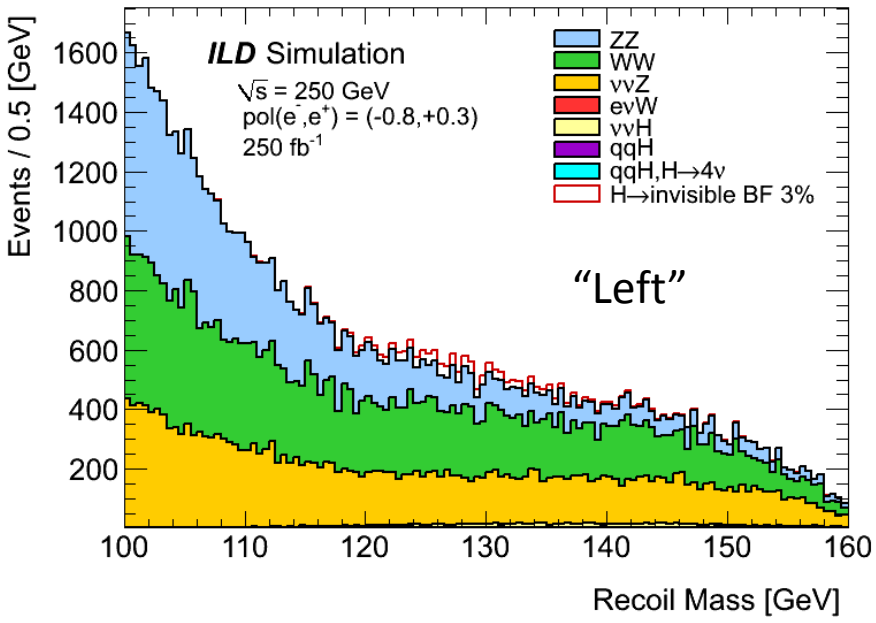


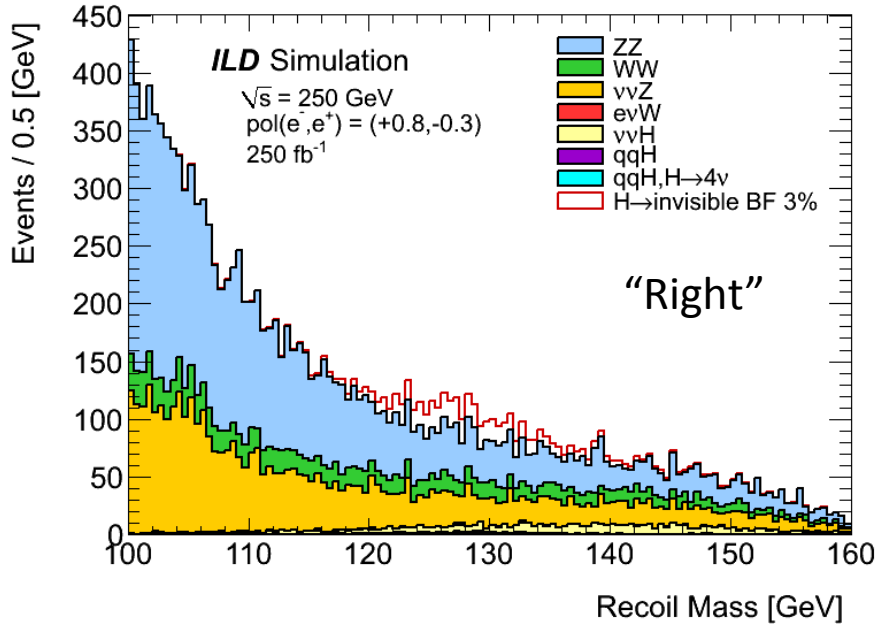




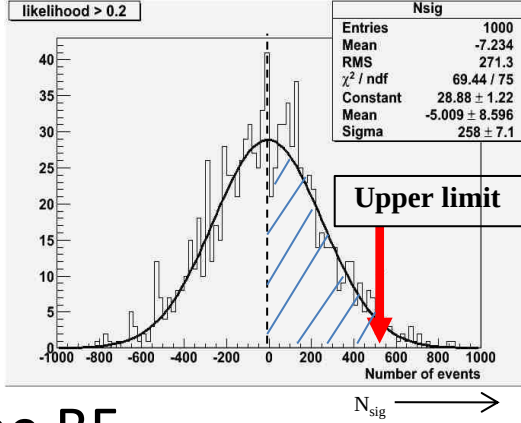
Signal Overlaid

- If BF(H→invisible) = 3%
  - Signal is clearly seen for “Right” polarization





Toy MC



- Toy MC are performed to set upper limits on the BF
  - In the fitting to M_{recoil}, Only yields for signal and backgrounds are floated.
    - The backgrounds include a peaking ZH, H→4ν component
  - 10000 pseudo experiments for each polarization
- The results with 250fb^{-1}
  - "Left" polarization : BF (H→invisible) < 0.95% @ 95% CL
  - "Right" polarization : BF (H→invisible) < 0.69% @ 95% CL
    - The invisible does not include a H→ZZ*→4ν final state.
  - If 1150fb^{-1} data is accumulated, 0.44% and 0.32% for "Left" and "Right"

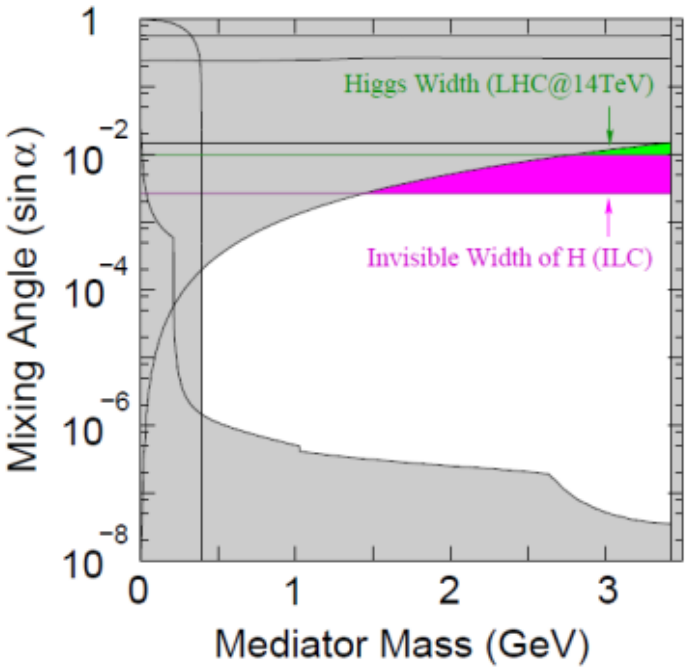
- From a crude toy MC scan, 5σ observation down to 2.8% and 2.0% for "Left" and "Right", respectively.
  - Need much more toy MC experiments.

Constraint?

$$\mathcal{L} = i\overline{\chi}\left(\partial\!\!\!/ - m_\chi\right)\chi + \frac{1}{2}\left[(\partial\phi')^2 - m_{\phi'}^2\phi'^2\right] - \kappa\,\overline{\chi}\chi\phi' - V(H',\phi')$$

$$h = (\cos\alpha)\,h' - (\sin\alpha)\,\phi' \quad \& \quad \phi = (\sin\alpha)\,h' + (\cos\alpha)\,\phi'$$

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + |D\phi|^2 + \frac{\lambda}{4}|\phi|^2|H|^2 + \mathcal{L}_{\rm SM}$$



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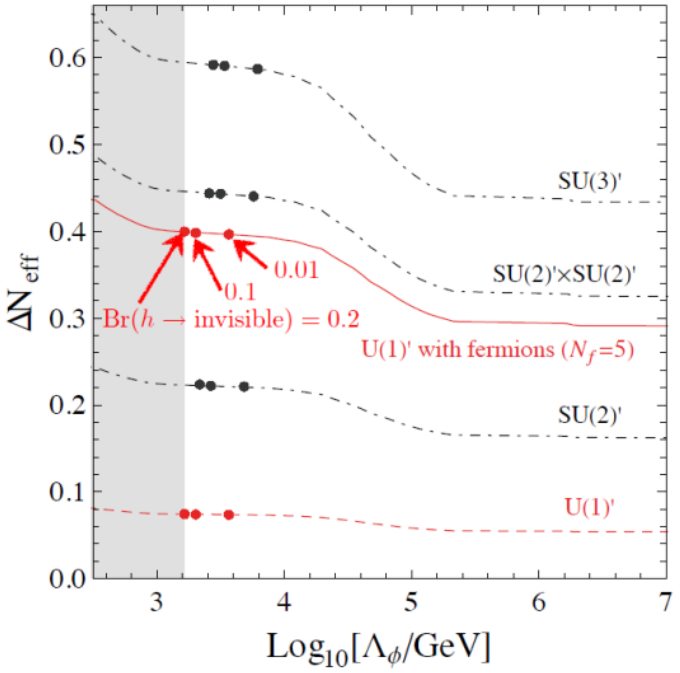

Precision Cosmology meets particle physics.
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Summary

- Full simulation studies of search for invisible Higgs decays at the ILD with ILC using Recoil mass technique are performed
  - e+e- →ZH, Z→qq processes
  - E_{CM}=250 GeV, ∫Ldt = 250fb^{-1} and Pol(e-,e+) = (-0.8, +0.3) and (+0.8, -0.3)

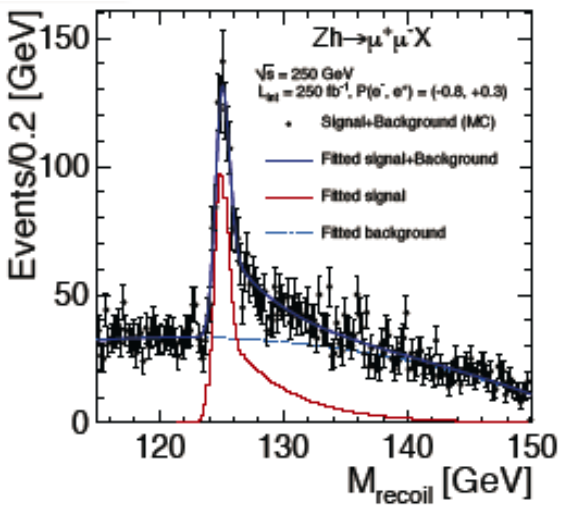
- The 95% CL upper limits on BF and lowest BFs for observation
  - 0.95% (0.44%)and 2.8% for "Left" polarization (for HL-ILC)
  - 0.65% (0.32%)and 2.0% for "Right" polarization (for HL-ILC)

Plan

- Inclusion of Beam Crossing of 14mrad
  - not considered in this analysis.
- Estimation of the lowest BF for 5σ observation by many toy MC experiments

- Combination with leptonic Z decays
  - The Recoil mass resolution for Gaussian peak for dimuon is 0.5 MeV!
  - But the BF is ~3.4%.
- Combination with the results at E_{CM} = 500GeV
  - Smaller σ but higher luminosity.

- Off shell Higgs?
- ee → eeH at 1TeV?



Recoil mass with Z→μμ by S.Watanuki