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# Search for Invisible Higgs Decays at the ILC

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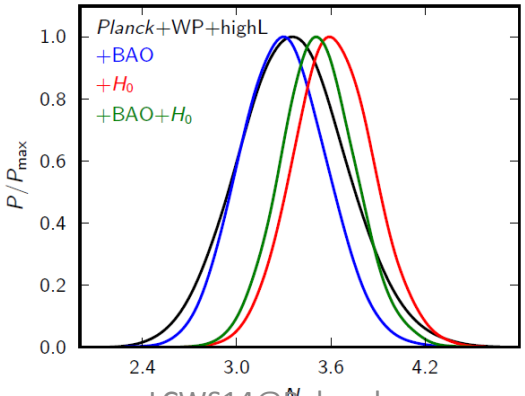
# Invisible Higgs Decays

- 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, especially, of Dark Sectors
  - Higgs Portal Dark Matter?
    - Cold matter in the universe
  - Dark Radiation?
    - Slight excess (less than 3σ) in effective # of ν from astro physical observations
    - Relativistic matter in the universe

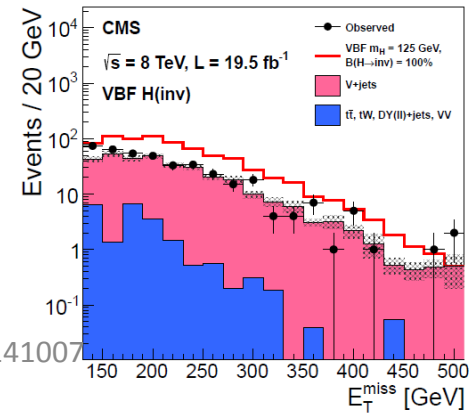


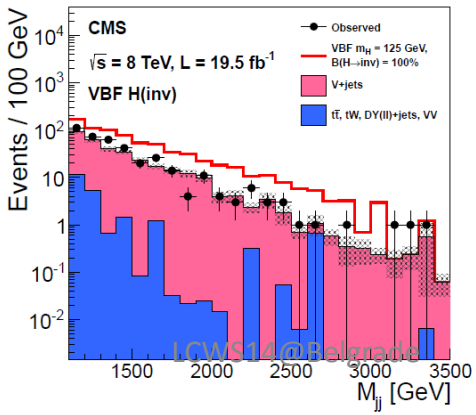

1303.5076

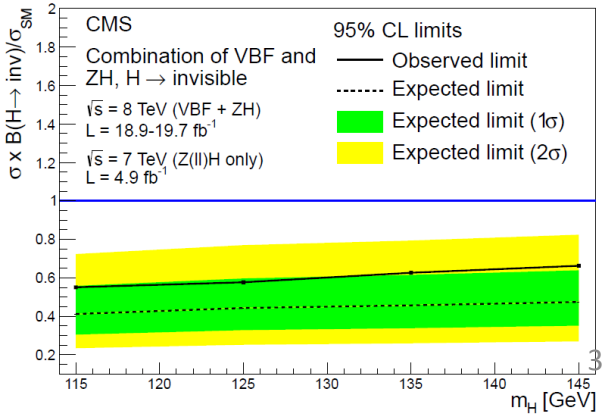
CMS Collaboration Eur. Phys. J. C 74 (2014) 2980

# Invisible Higgs Decays at the LHC

- Invisible Higgs Decays were searched with qq→ ZH and qq→ qqH (VBF) processes using missing $E_t$ (and $M_{qq}$).
  - They cannot reconstruct missing Higgs mass since they don't know momenta of initial quark pairs
- This method is model dependent since the cross sections in pp collision are assumed as those in the SM.
  - Current upper limit on BF is 58%@95%CL (expected 44%).
  - Very hard to achieve much better than 10% at the LHC

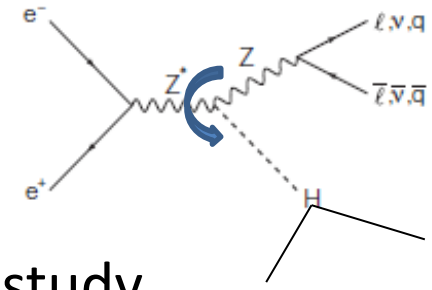


# Invisible Higgs Decays at the ILC

- Invisible Higgs can be searched using a recoil mass technique with model independent way!
  - e+e- → ZH
- 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!



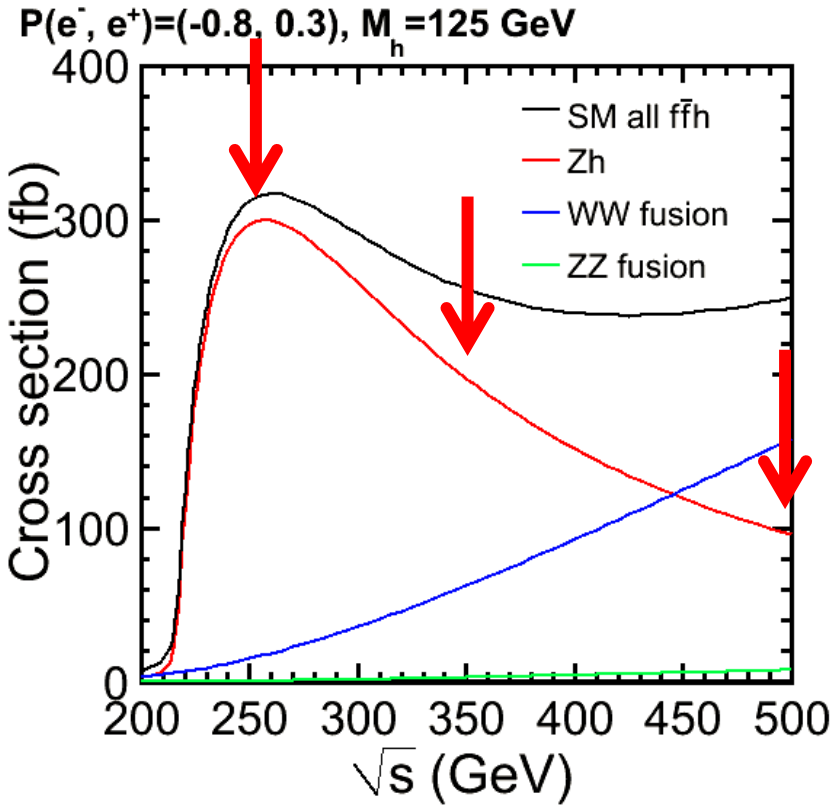

$$P_H = P_{e+e-} - P_Z$$

known measured

- In this study
  - Z→qq decay is used (BF(Z→qq) = 69.9%)
  - Ecm = 250GeV, 350GeV and 500GeV New!
    - 250GeV results were shown at Snowmass Seattle 2013

# Cross Section of $e^+e^-$ → ZH → qqH

- Three important energy points
  - 250GeV, 350GeV, 500GeV
- Two polarization configurations ($P_{e-}$, $P_{e+}$)
  - (-80%, +30%) = "Left"
  - (+80%, -30%) = "Right"
- The cross section is maximum around 250GeV and decreasing for higher energy

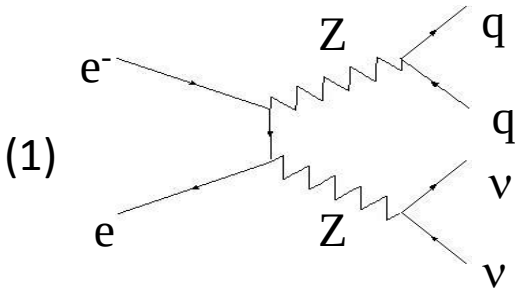


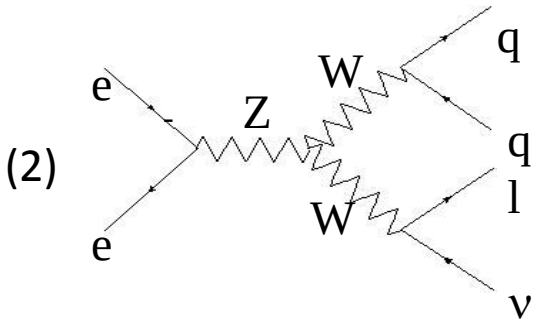

| $\sigma_{ZH\to qqH}$[fb] | "Left" | "Right" | Ratio to 250GeV |
|---|---|---|---|
| 250GeV | 210.2 | 142.0 | 1 |
| 350GeV | 138.9 | 93.7 | ~2/3 |
| 500GeV | 69.7 | 47.0 | ~1/3 |

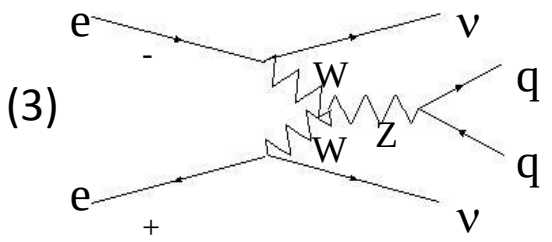
# Backgrounds

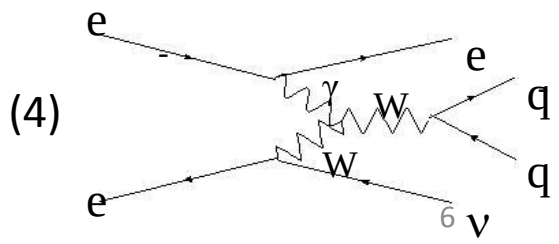
- Backgrounds
  - found qqll, qql$\nu$ and qq$\nu\nu$ final states are the dominant backgrounds.
    - other backgrounds also studied
    - Pure leptonic and hadronic final states are easily eliminated.

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



# MC setup, Samples and Cross Sections

- Generator : WHIZARD
  - Higgs mass 125GeV
  - Pseudo signal : $e^+e^- \rightarrow ZH$, $Z \rightarrow qq$, $H \rightarrow ZZ^* \rightarrow 4\nu$
- Samples
  - Official DBD samples + Private Productions (thanks Akiya and Jan) based on DBD setting
    - Full simulation with the ILD detector
  - Half of the samples are used for cut determination. The other used for efficiency calculation and backgrounds estimation.

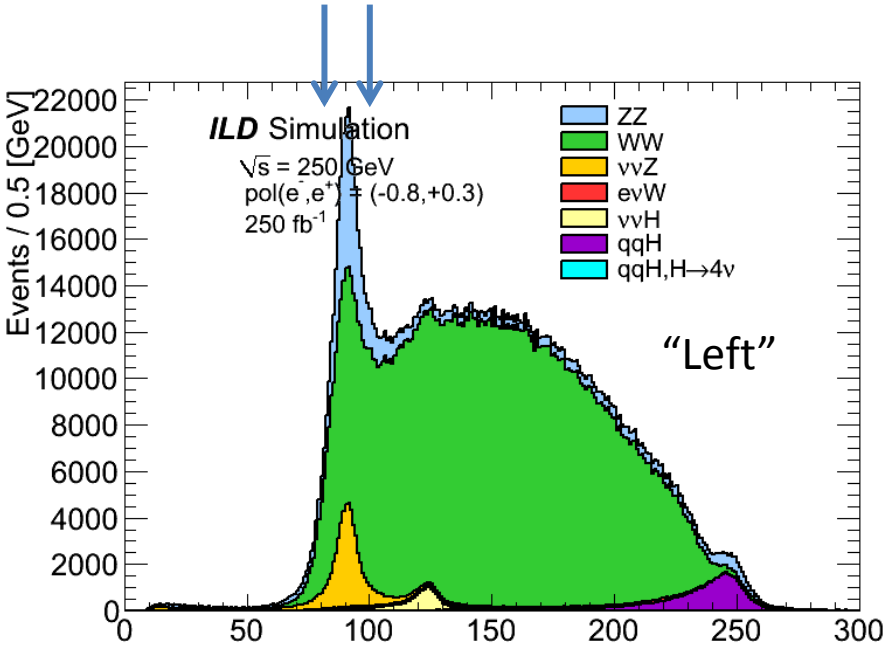
| $E_{CM}/\sigma$[fb] | Pol | ZZ sl | WW sl | $\nu_e\nu_e Z$ sl | $e\nu_e W$ sl | $\nu\nu H$ | qqH | qqH $H \rightarrow 4\nu$ |
|---|---|---|---|---|---|---|---|---|
| 250GeV | "Left" | 857 | 10993 | 272 | 161 | 78 | 210 | 0.224 |
| | "Right" | 467 | 759 | 93 | 102 | 43 | 142 | 0.151 |
| 350GeV | "Left" | 564 | 8156 | 355 | 4981 | 99 | 139 | 0.148 |
| | "Right" | 300 | 542 | 73 | 421 | 31 | 94 | 0.100 |
| 500GeV | "Left" | 366 | 5572 | 559 | 4853 | 167 | 70 | 0.074 |
| | "Right" | 190 | 360 | 68 | 572 | 23 | 47 | 0.050 |

# Overview of the Selections for 250GeV (350GeV, 500GeV)

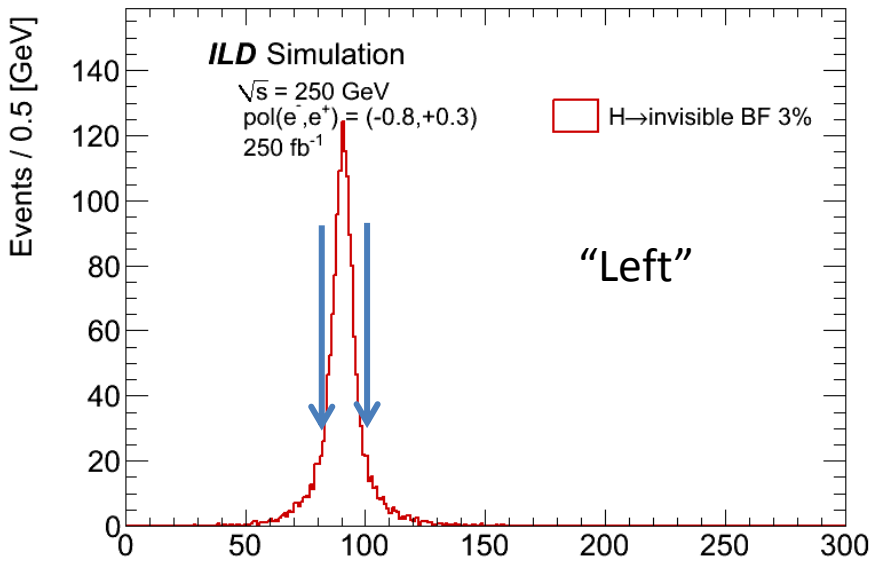
0. kt jet algorithm to eliminate pile-up events only for 500GeV
1. Forced two-jet reconstruction with Durham jet algorithm
2. Isolated lepton veto
3. Numbers of Particle Flow Objects (PFO) and charged tracks
   - $N_{PFO} > 16$ & $N_{trk} > 6$
   - Eliminate low multiplicity events like $\tau\tau$
4. Z mass reconstructed from di-jet : $M_Z$
   - $80GeV < M_Z < 100GeV$ ($80 < Mz < 104$, $80 < Mz < 120$)
   - Also used for Likelihood ratio cut
5. Polar angle of Z direction : $\cos(\theta_Z)$
   - Just apply < 0.99 (0.99, 0.98) to eliminate peaky eeZ background before making likelihood ratio
6. Loose Recoil mass selection : $M_{recoil}$
   - $100GeV < M_{recoil} < 160GeV$ ($100 < M_{recoil} < 240GeV$, $80 < M_{recoil} < 330GeV$ )
7. Likelihood ratio of $M_Z$, $\cos(\theta_Z)$, $\cos(\theta_{hel})$ to give the best upper limit : LR
   - $\cos(\theta_{hel})$ : Helicity angle of Z
   - LR > 0.3 (0.6, 0.6) for “Left” and LR > 0.4 (0.5, 0.6) for “Right”
8. Toy MC to set upper limit

# Z mass for 250GeV

- 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 5.5GeV



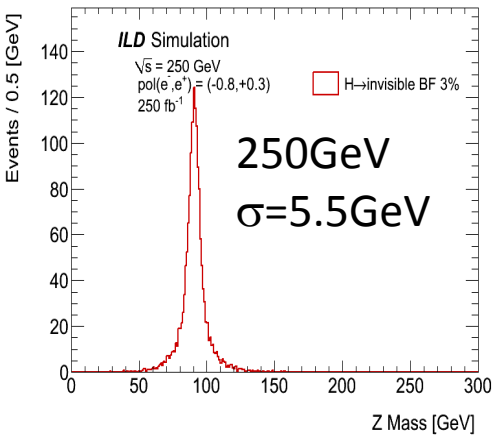

backgrounds

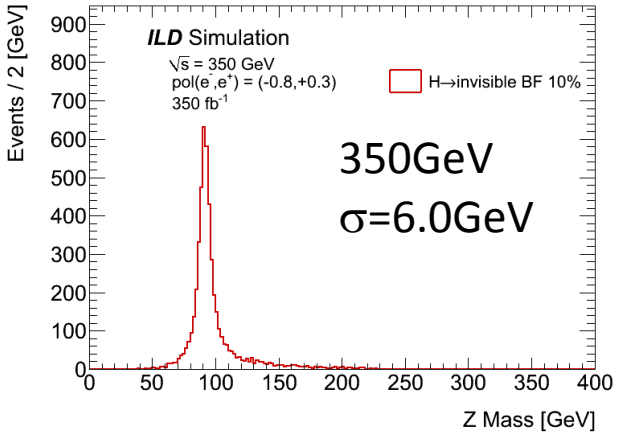


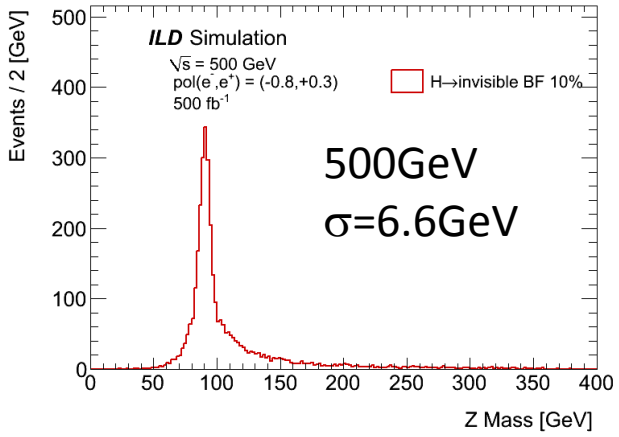

signal

# Comparison of Z mass resolution

- As you see, only 20% difference at peak regions thanks to good jet energy resolution.
  - Please do not take the σ's seriously since they can be changed by fitting region due to tails.
- There is a tail for higher side for 350GeV case which is due to pile-up events.
  - could be improved by pile-up reduction with kt jet algorithm
  - For 500GeV, the tail was much improved by kt algorithm but still there.

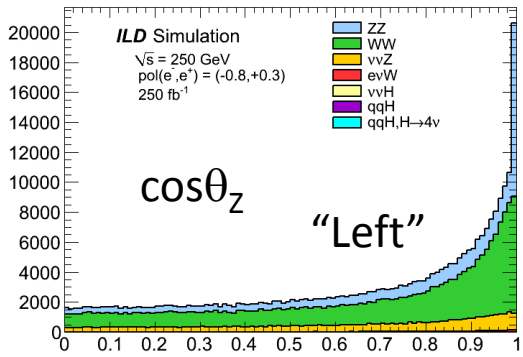


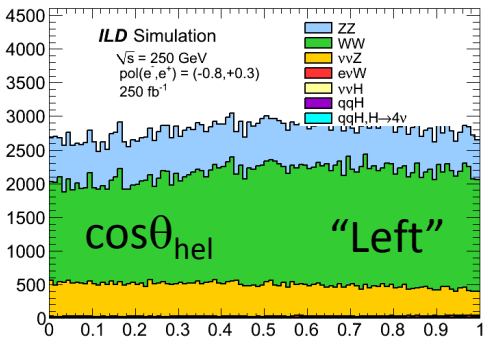



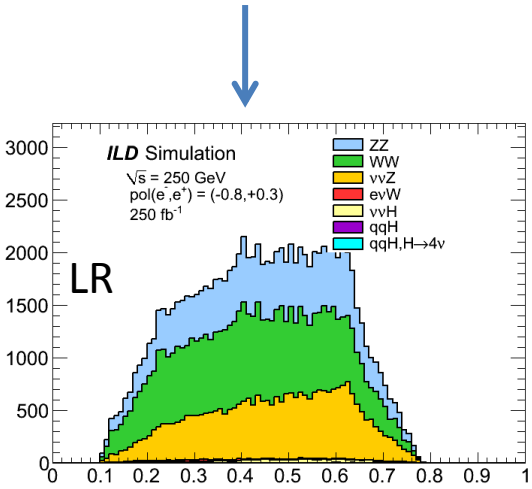



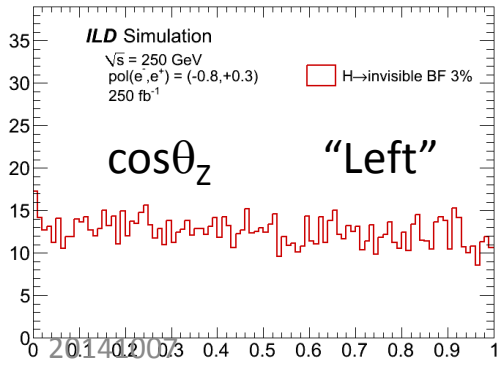
# Background Suppression for 250GeV

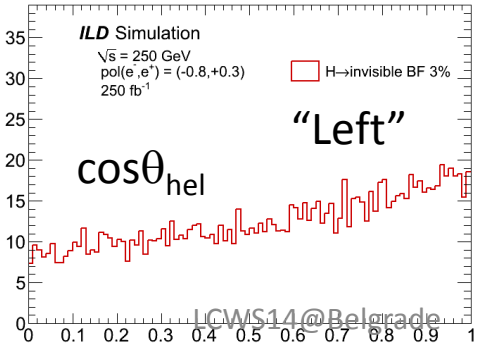
- Likelihood Ratio (LR) method is used to combine three variables
  - Z mass (see previous page)
  - Polar angle of Z direction : $\cos\theta_Z < 0.99$
  - Helicity angle of Z : $\cos\theta_{hel}$

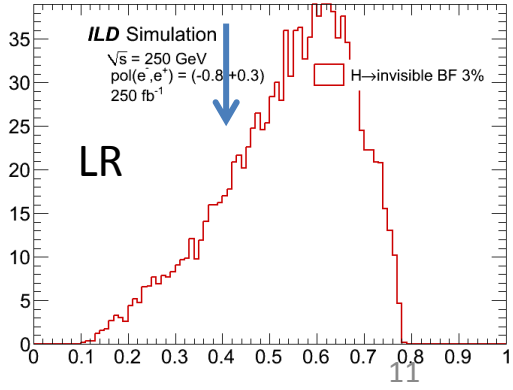


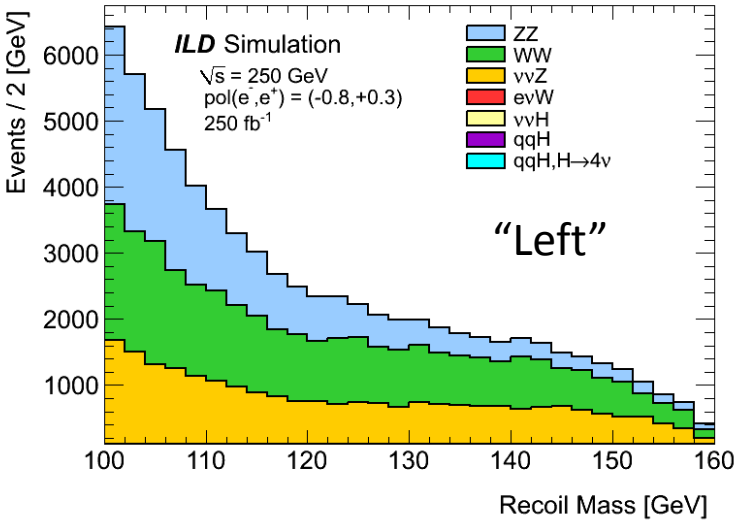



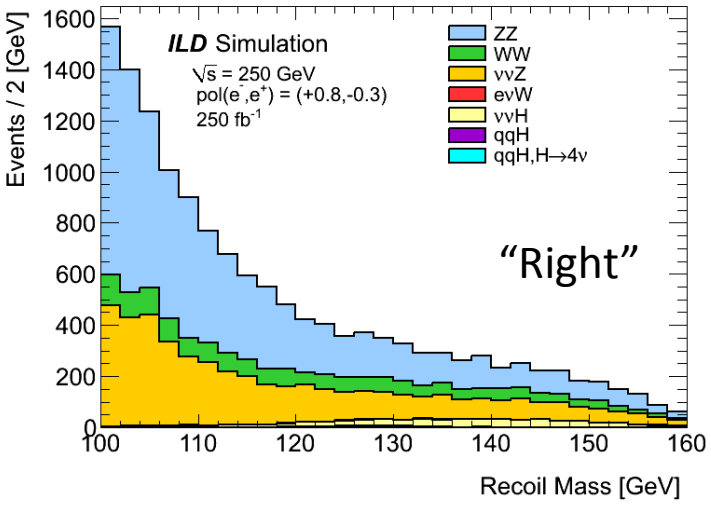



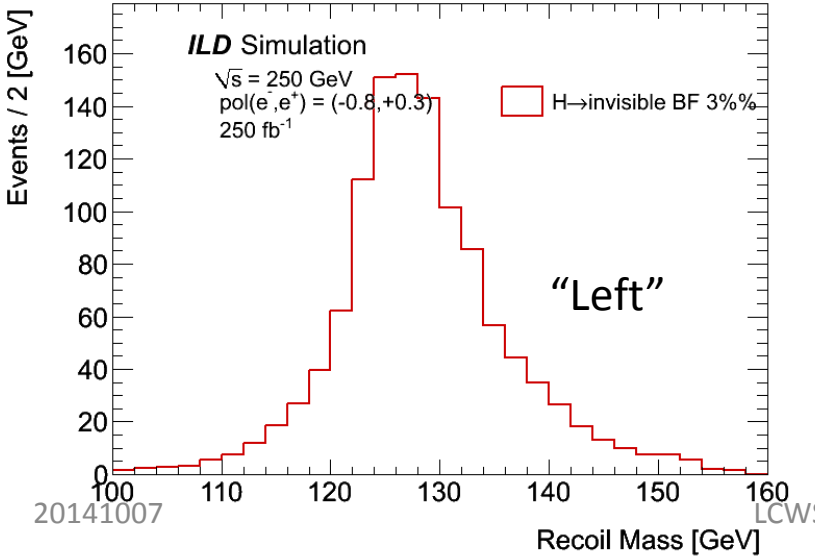



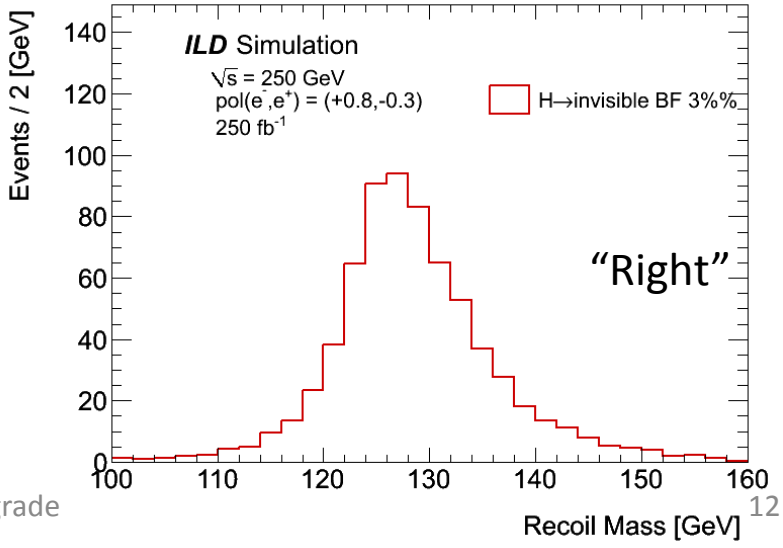
# Final Recoil Mass for 250GeV

- Dominant backgrounds are ZZ, WW, νν̄Z



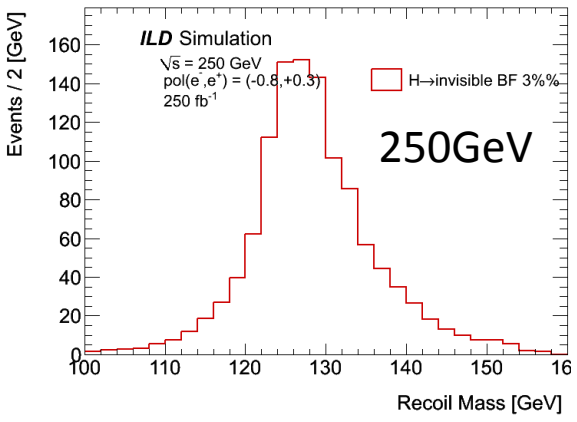



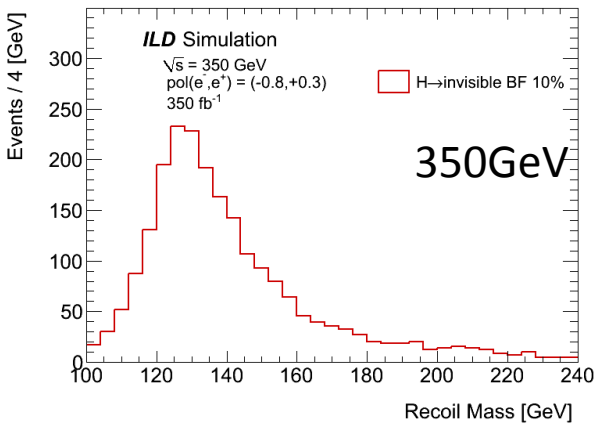



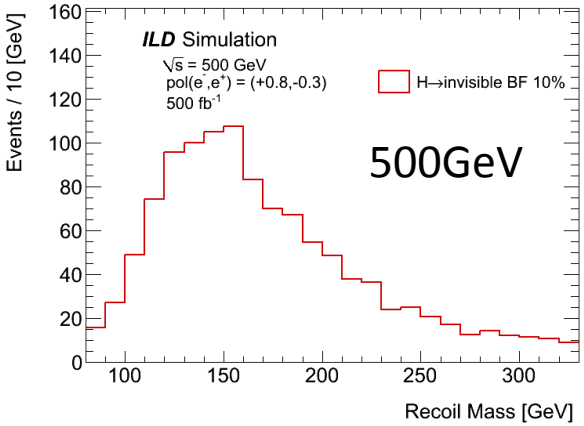
# Comparison of signal $M_{recoil}$ distributions

- Higher energy gives worse recoil mass resolution due to luminosity spectrum.
  - Beamstrahlung is larger for higher energy
- Recoil mass peak is also shifted to higher side.

Note. Scale and binning are different



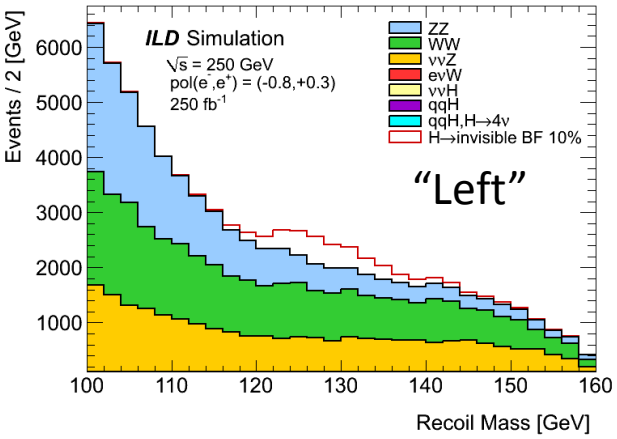



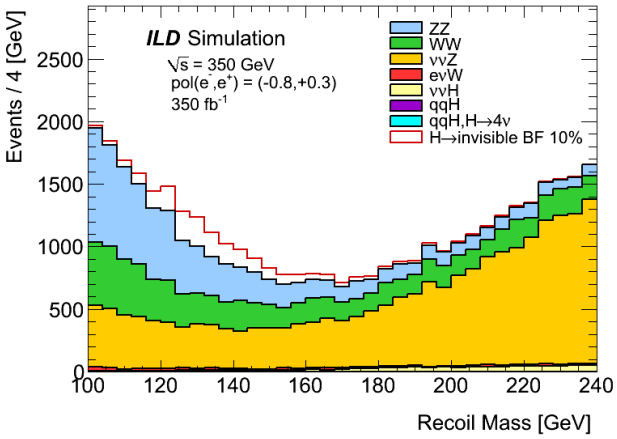
# Signal overlaid $M_{recoil}$ distributions

- BF(H→invisible) = 10% assumed.
- Dominant backgrounds are ZZ, WW, νν̄Z
- "Right" gives smaller backgrounds

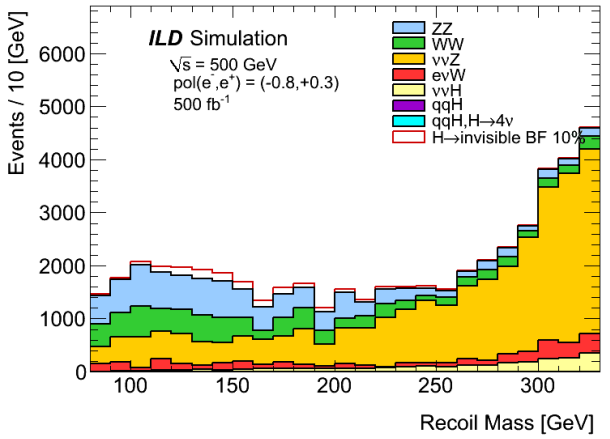
250GeV

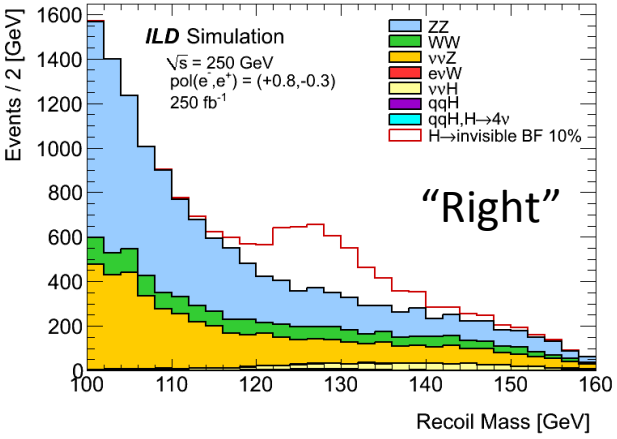


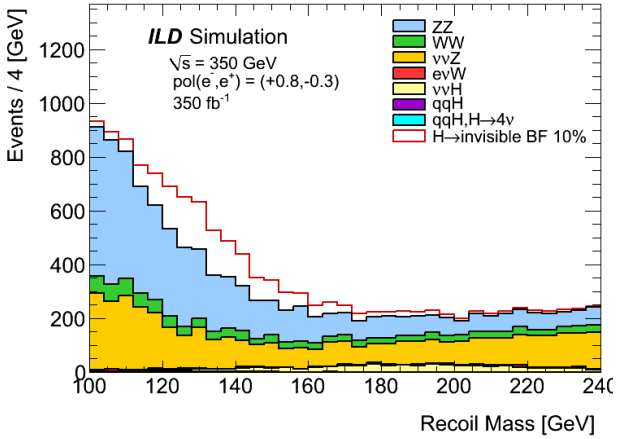

350GeV

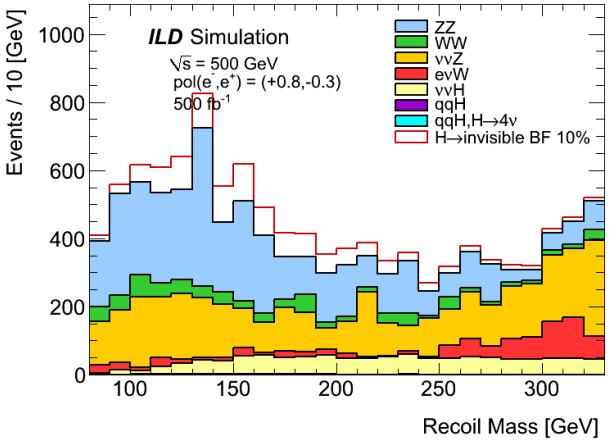



500GeV



# Upper Limits set by Toy MC

- We performed Toy MC to set the upper limit on BF(H→invisible).
  - This invisible does not include H→ZZ*→4ν
- Integrated luminosity assumed
  - $\int Ldt$ = 250, 350, 500fb$^{-1}$ for $E_{CM}$=250, 350, 500 GeV
  - Corresponding to running about 3 snowmass years (3x10$^7$ sec) with nominal ILC

- "Left" is about 1.5 times worse than "Right".
  - $1.5^2$=2.3 times longer running time needed to achieve the same sensitivity
- 350GeV (500GeV) is about 1.5 (3.2) times worse than 250GeV
  - $1.5^2$=2.3 ($3.2^2$=10) times longer running time needed to achieve the same sensitivity

| UL on BF [%] | "Left" | "Right" |
|---|---|---|
| 250GeV | 0.95 | 0.69 |
| 350GeV | 1.49 | 1.37 |
| 500GeV | 3.16 | 2.30 |

# Summary and Plan

- Full simulation studies of search for invisible Higgs decays at the ILD with the ILC using recoil mass technique are performed
  - e+e- →ZH, Z→qq processes
  - $E_{CM}$=250, 350, 500 GeV with ∫Ldt = 250, 350, 500fb$^{-1}$
  - Pol($e^-$,$e^+$) = (-0.8, +0.3) and (+0.8, -0.3)

| UL on BF [%] | "Left" | "Right" |
|---|---|---|
| 250GeV | 0.95 | 0.69 |
| 350GeV | 1.49 | 1.37 |
| 500GeV | 3.16 | 2.30 |

- These results should be also used as a input to running scenario
- Plan
  - Null polarization for positrons
  - LL and RR polarizations

# backup

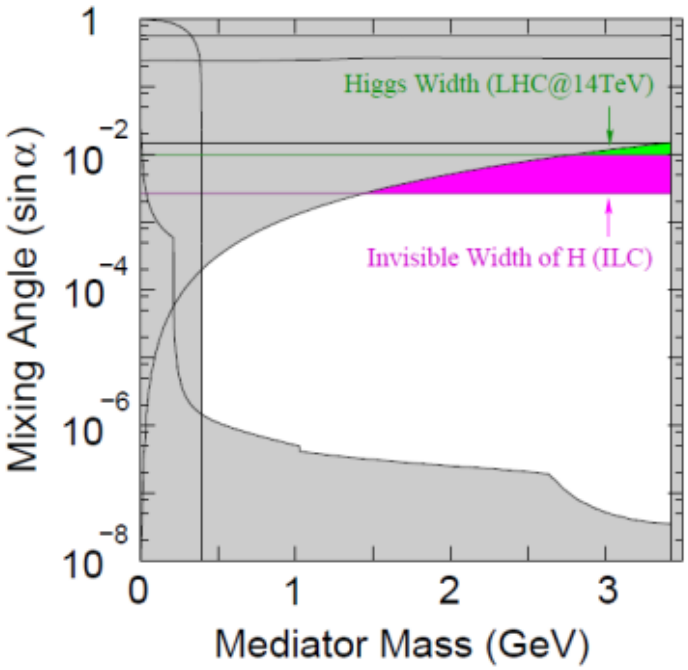
# Constraint?

## Asymmetric DM

Mixing angle of Dark scalar and SM Higgs, and mediator mass

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

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

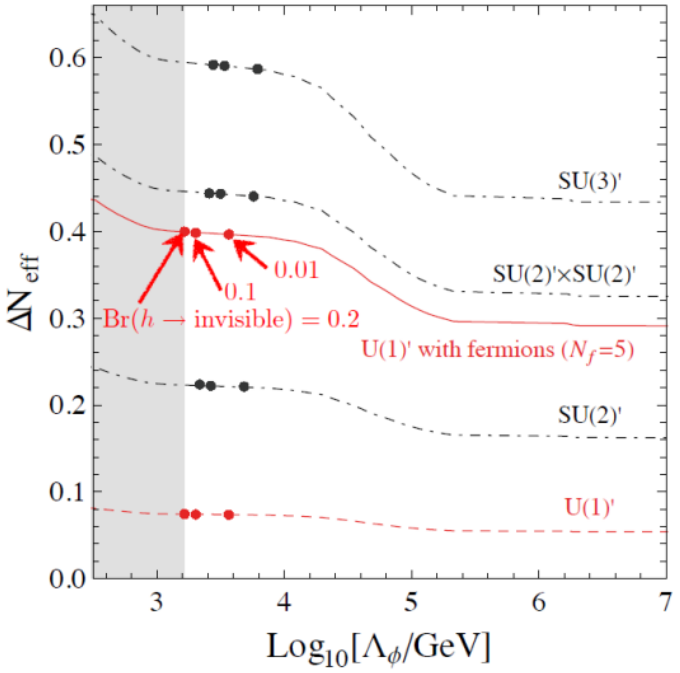



Fermionic Asymmetric DM
S. Matsumoto@ECFA 2013

## Dark radiation

together with number of effective neutrinos, gauge structure of hidden sector and scale of dark scalar determined

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




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