Using Single Photons for WIMP Searches at the ILC

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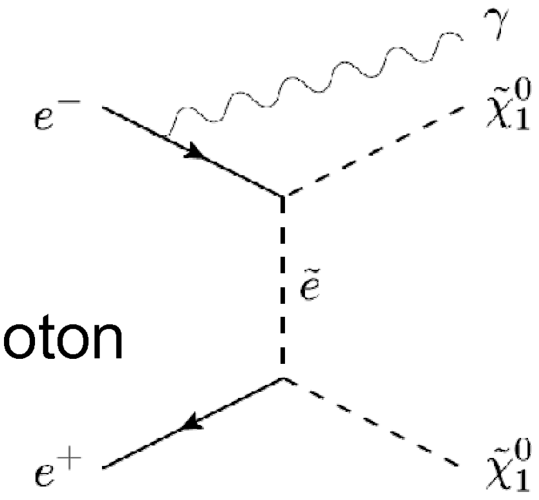
Introduction

- New physics models which contain WIMPs are important study targets at the ILC. Here, we consider the case where only the WIMP is kinematically accessible.
- Example: Neutralino as the LSP in mSUGRA (Bino-like)
  - $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$
  - Assume
    CM Energy $\sqrt{s}$=500GeV
    Luminosity $\int L dt$ = 500 fb^{-1}



- The only detectable particle is the ISR photon
- Past Studies:
  - Measurements and Searches at LEP
  - C. Bartels, J. List, *WIMP Searches at the ILC using a model-independent Approach* [arXiv:0901.4890]
    - Cut-and-count analysis
    - Cross section fixed by astronomical observations

Analysis Procedure

1. Event Generation using Whizard
2. ILD *full detector simulation* using Mokka
3. Reconstruction using Marlin (Pandora PFA)
4. Photon cluster merging
5. Event selection: Energy, angle, particle ID
6. Likelihood analysis using the 2d distribution of energy and angle for the signal and background events

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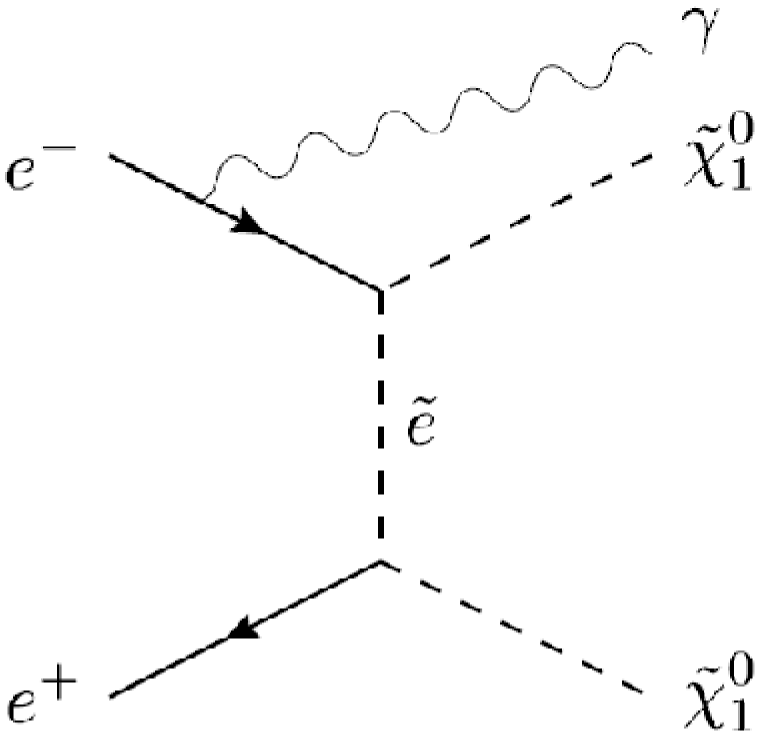
Event Generation

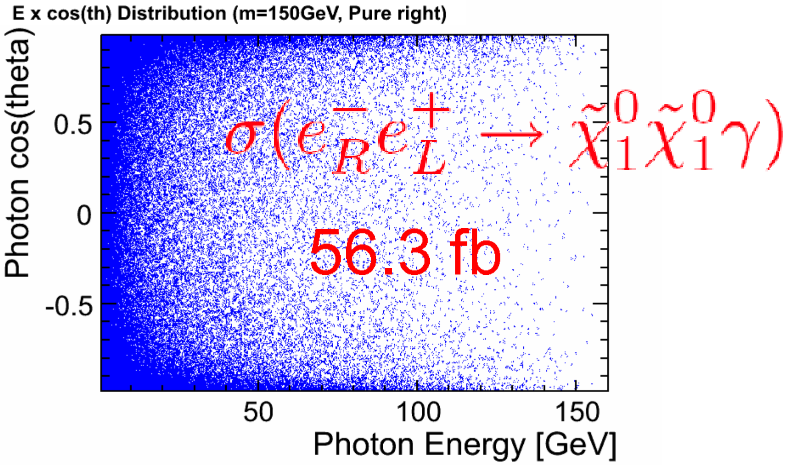
- We considered the t-channel process. We generated two samples with different neutralino mass. (Assume mSUGRA)
  - $m_{\tilde{\chi}_1^0} = 151\text{GeV} \quad (m_{\tilde{e}_L} = 395\text{GeV}, m_{\tilde{e}_R} = 333\text{GeV})$
  - $m_{\tilde{\chi}_1^0} = 200\text{GeV} \quad (m_{\tilde{e}_L} = 453\text{GeV}, m_{\tilde{e}_R} = 354\text{GeV})$
- Set generator-level cut.
  E ≥ 0.1 GeV and |cosθ| ≤ 0.9955



Generated (E, cosθ) Distribution

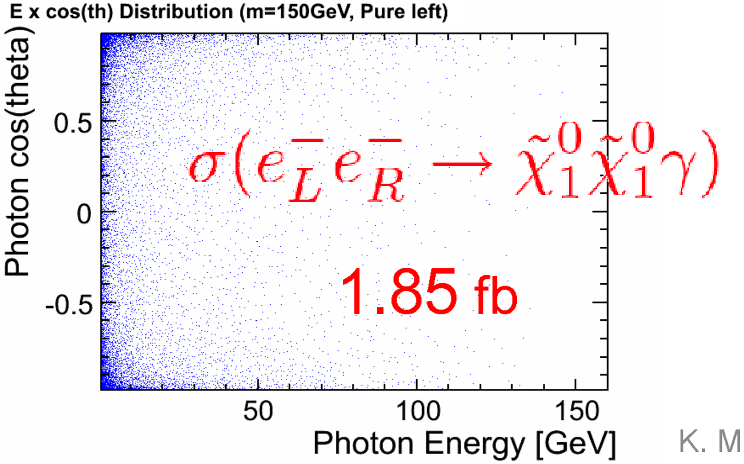
- The signal distributions for different beam polarizations are shown. We chose the polarization (P_{e-}, P_{e+}) = (+0.8, -0.3) in our analysis because it has the larger cross section.

Signal (m=150GeV)


E x cos(th) Distribution (m=150GeV, Pure right)

$\sigma(e_R^- e_L^+ \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma)$

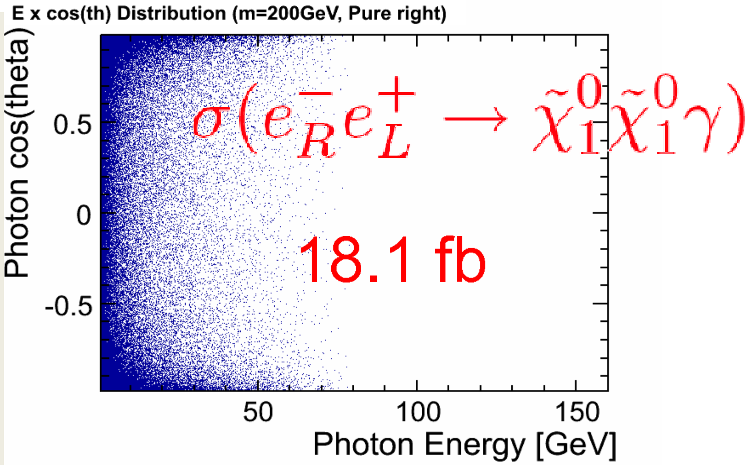
56.3 fb


E x cos(th) Distribution (m=150GeV, Pure left)

$\sigma(e_L^- e_R^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma)$

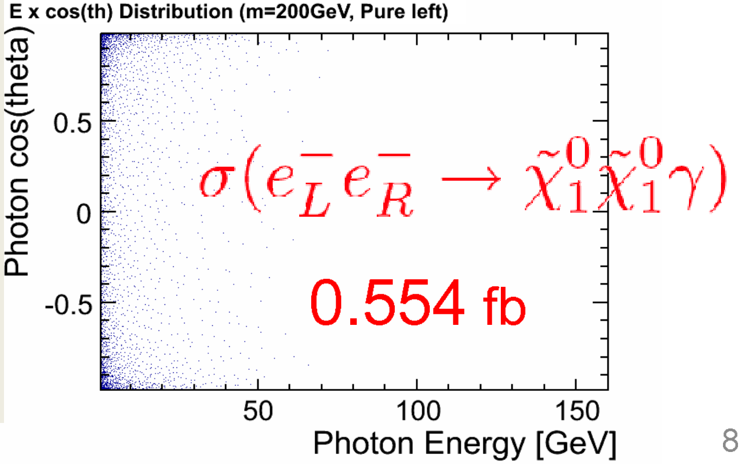
1.85 fb

Signal (m=200GeV)


E x cos(th) Distribution (m=200GeV, Pure right)

$\sigma(e_R^- e_L^+ \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma)$

18.1 fb

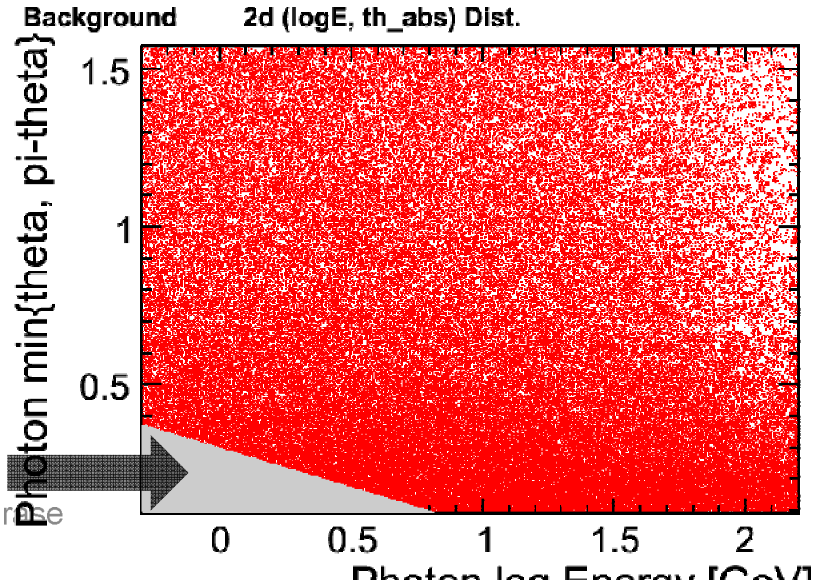

E x cos(th) Distribution (m=200GeV, Pure left)

$\sigma(e_L^- e_R^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma)$

0.554 fb

Backgrounds

- We ran our analysis over all the SM background samples produced for ILD LoI. Of those the following processes are found to be the dominant.
  - Two photon processes
    $\gamma\gamma \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ 1112fb (after event selection)
  - $e^+e^- \to \nu\nu\gamma$ 783fb (after event selection)
- Since the observable values are only the energy and angle, we performed a likelihood analysis using the 2d distribution.
- Because some background samples have been generated with the cuts as shown in the plot, we were forced to apply the same cuts in our analysis as we will see later.



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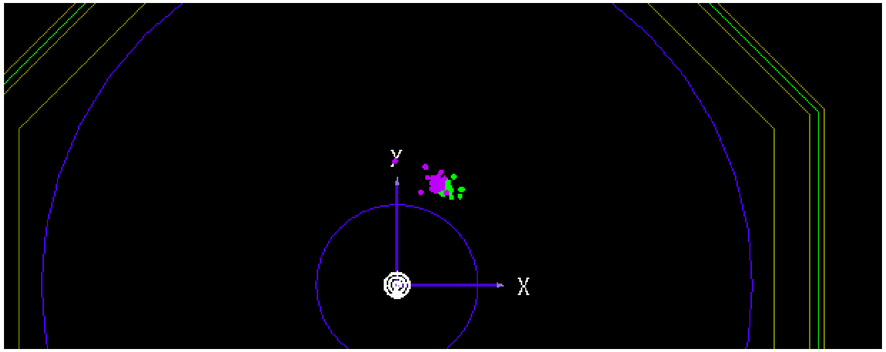
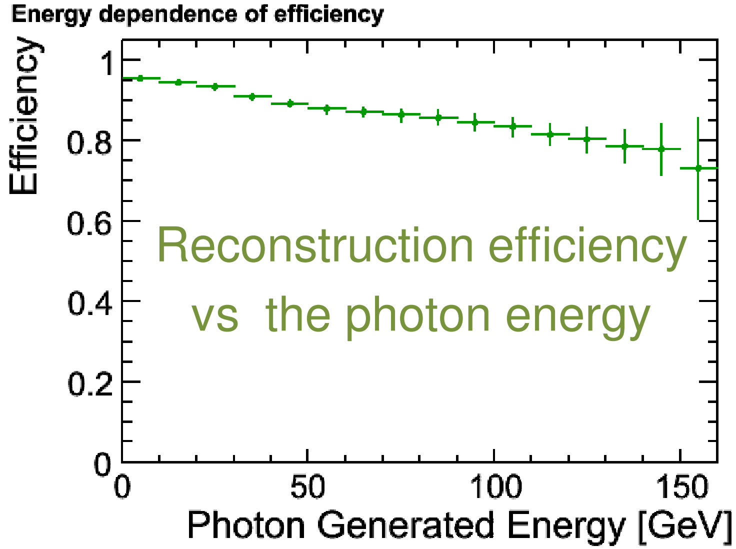
Event reconstruction

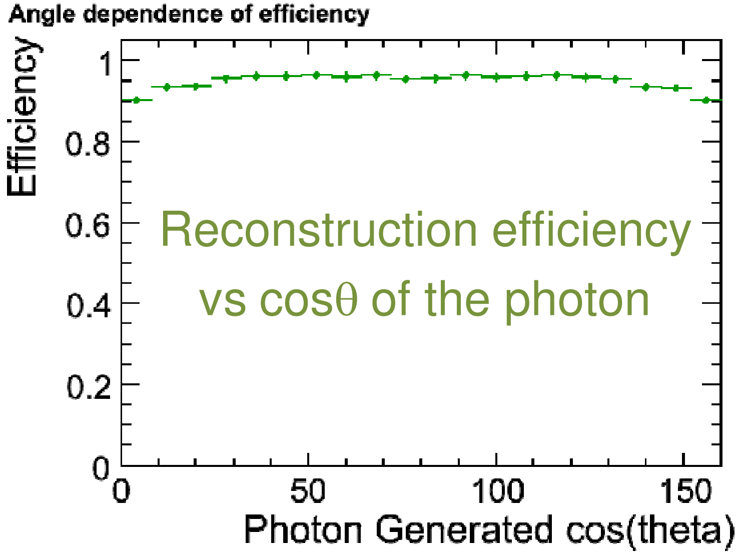
1. Cluster Merging
   - 

   - We merged clusters which lie within 1.5 degree around the most energetic cluster.
2. Event Selection

Cut flow	Typical Signal Efficiency
Generated events	100%
A. No charged particles	95%
B. Only one neutral particle	94%
C. Particle ID: $E_{ECAL}/(E_{ECAL}+E_{HCAL}) > 0.9$	94%



Reconstruction efficiency vs the photon energy



Reconstruction efficiency vs cosθ of the photon

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Binning and Likelihood

- We split up the 2d (energy, angle) distribution into *N* bins
- We constructed the log likelihood as follows.

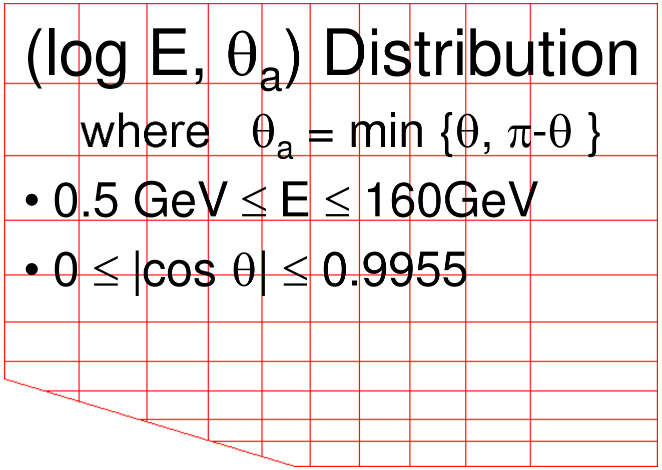
$$\ln \mathcal{L}(n_1, \ldots, n_N) = \sum_{i \in \mathrm{bins}} \ln \frac{P(n_i; b_i + s_i)}{P(n_i; b_i)}$$

$$P(n; \lambda) = \frac{\lambda^n}{e^\lambda n!}$$

  - b_i is the expected number of background in the *i*-th bin.
  - s_i is the expected number of **150GeV (a reference mass) signal** in the *i*-th bin.
  - n_i is the observed number of events in the *i*-th bin.
- In order to check the sensitivity of this likelihood function, we performed MC experiments by fluctuating the observed number of events in each bin .
- We compared the likelihood distributions for:
  - Background + Signal
  - Background only

Binning

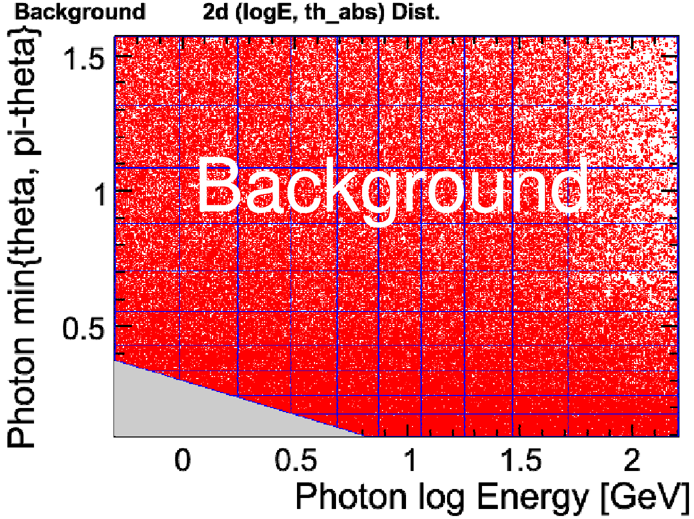
- We used the binning as shown here. The lower-left corner is cut off because of the cut in the background samples.

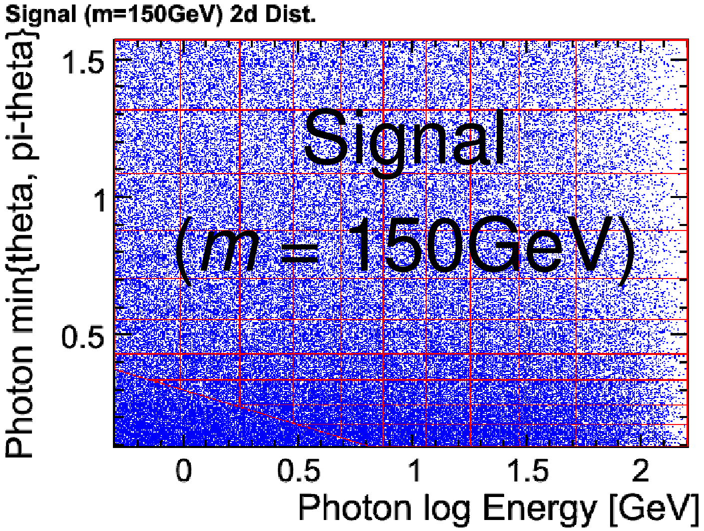


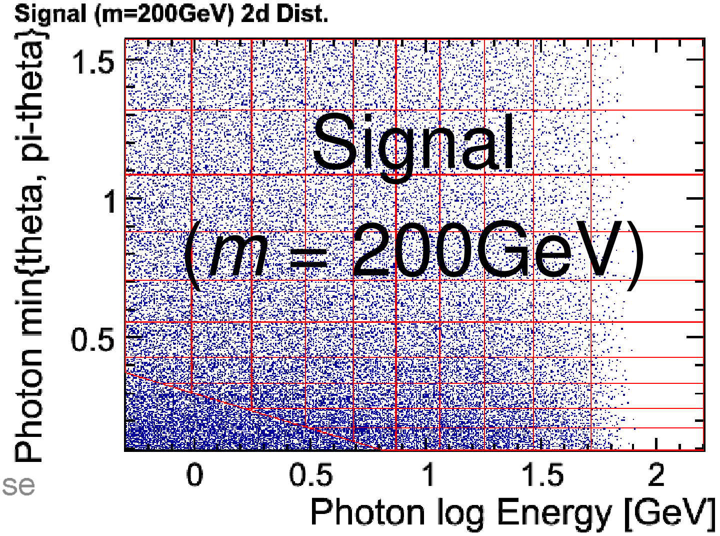
(log E, θ_a) Distribution

where $\theta_a = \min\{\theta, \pi-\theta\}$

- 0.5 GeV ≤ E ≤ 160GeV
- 0 ≤ |cos θ| ≤ 0.9955

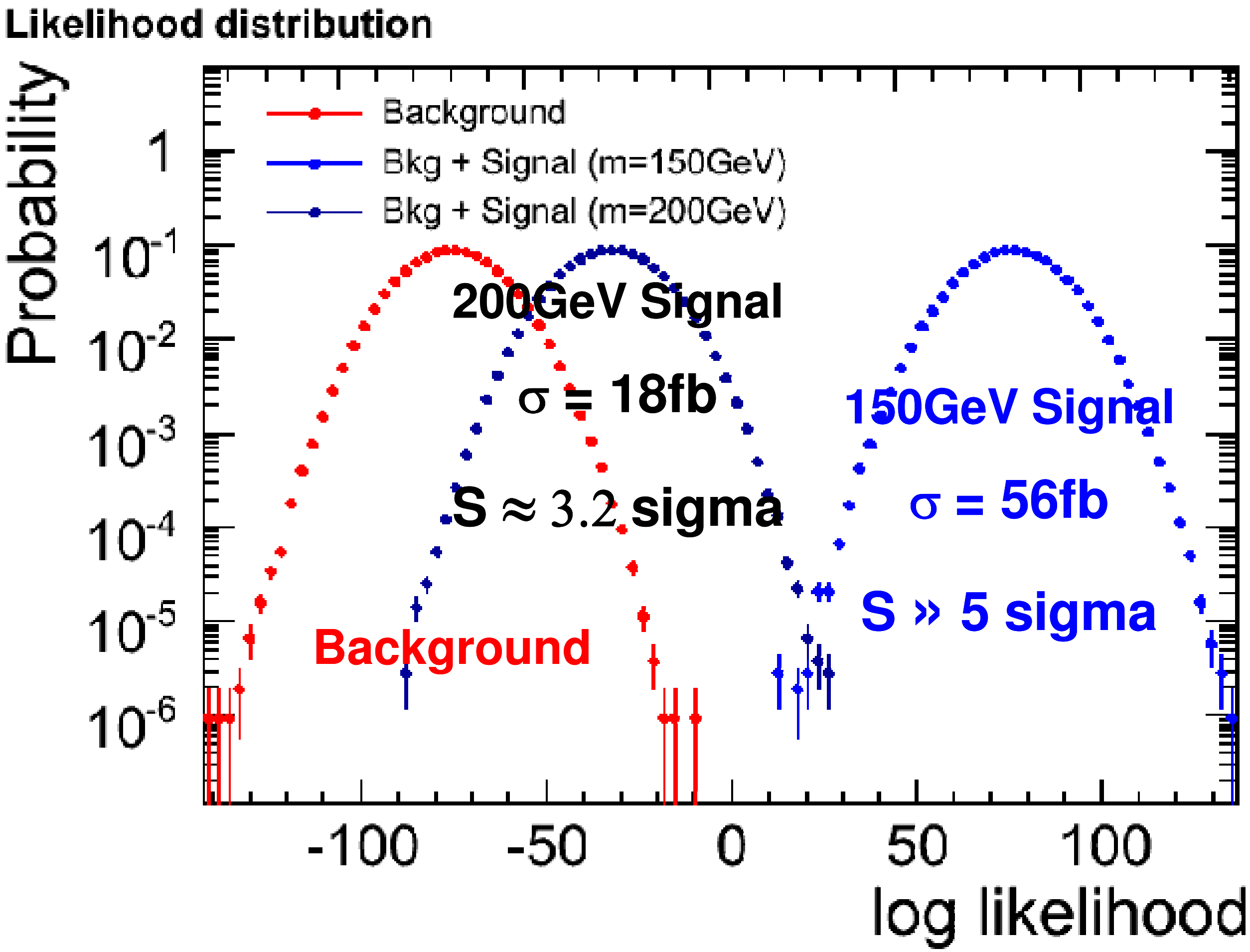






Likelihood Distribution

- The likelihood distributions for background + signal (for m = 151 GeV and m = 205 GeV), and background only are shown.



200GeV Signal

σ = 18fb

S ≈ 3.2 sigma

Background

150GeV Signal

σ = 56fb

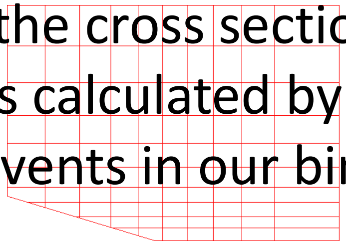
S » 5 sigma

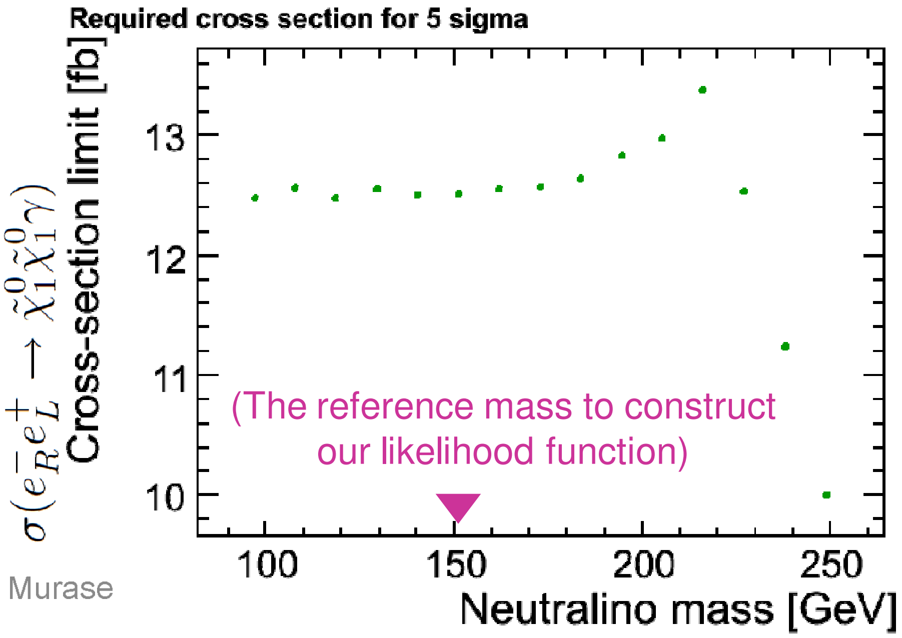
- The difference between two signals are mainly due to their cross sections which are dependent upon SUSY parameters.

Mass and Cross Section Limit

So far, the full simulation was used for all parts of our analysis. We found that the agreement between the true photon energy and the reconstructed energy is good. So in the following, we rely on generated distributions.

- We can determine the cross section needed to achieve 5σ observation with a 50% probability at a given mass, assuming that the shape of the 2d distribution remains the same.
- We performed a scan over the neutralino mass in the range from 100 to 240 GeV to determine the cross-section limit for 5σ.
- Note that the cross section in the right plot is calculated by counting events in our binning range.





(The reference mass to construct our likelihood function)

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Summary and Plan

- We have looked at the neutralino analysis as an example of a WIMP search with single photons. In principle, this method can be applied to a broader class of WIMP searches.
- Using the 2d (energy, angle) distribution, we constructed a binned likelihood. Then, we compared the likelihood distribution and obtained the cross-section limits as a functions of the neutralino mass.
- We plan to apply this method to the s-channel process next. We also plan to develop a way to determine the mass from the 2d distribution.

(Backup)

Signal

- m = 150GeV

$$\begin{aligned} m_0 &= 300\text{GeV} \\ M_{\frac{1}{2}} &= 375\text{GeV} \\ A_0 &= 0 \\ \tan\beta &= 5 \\ \text{sgn}\mu &= +1 \end{aligned}$$

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = \begin{pmatrix} -0.993160248 & 0.0345983356 & -0.101092212 & 0.0470759608 \\ -0.0629963353 & -0.961890221 & 0.219995722 & -0.149668127 \\ 0.0360936709 & -0.0528083816 & -0.702663720 & -0.708641052 \\ 0.0914414227 & -0.266047925 & -0.669063389 & 0.687903523 \end{pmatrix} \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}_3^0 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

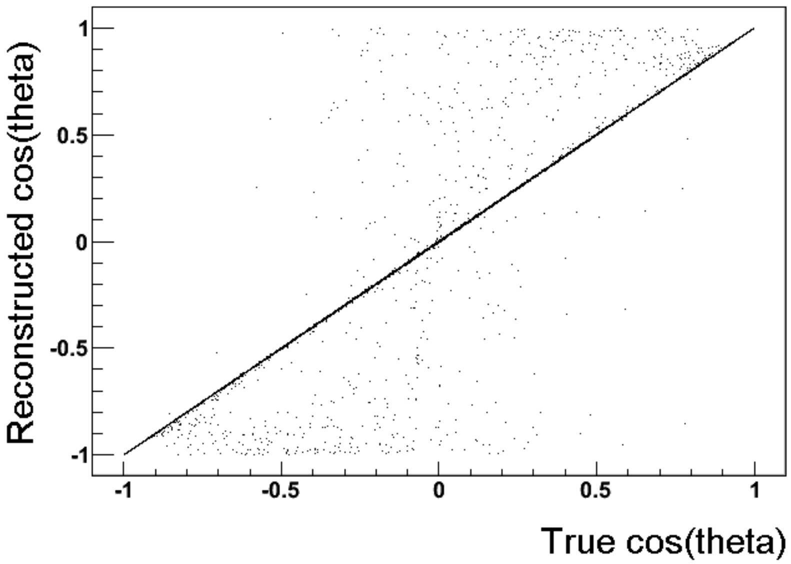
- m = 200GeV

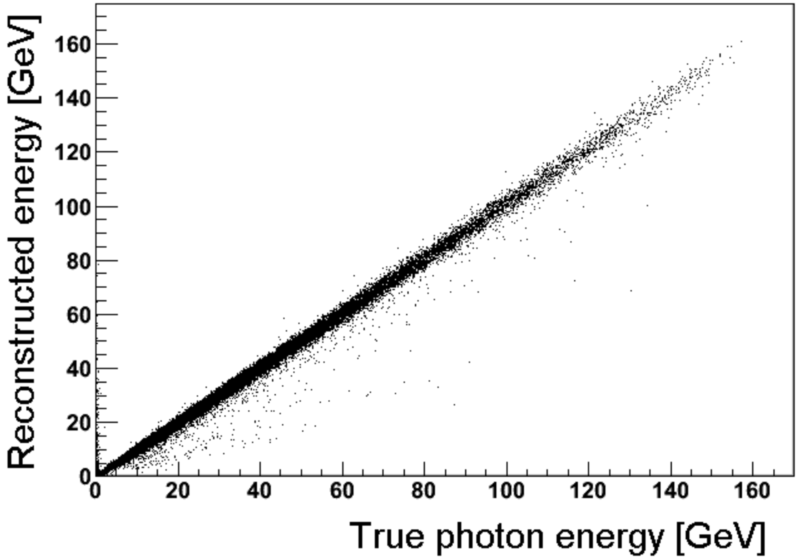
$$\begin{aligned} m_0 &= 300\text{GeV} \\ M_{\frac{1}{2}} &= 500\text{GeV} \\ A_0 &= 0 \\ \tan\beta &= 5 \\ \text{sgn}\mu &= +1 \end{aligned}$$

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = \begin{pmatrix} 0.996082485 & -0.0201418605 & 0.0776847601 & -0.0371378660 \\ -0.0390776210 & -0.972951114 & 0.186058611 & -0.131229252 \\ 0.0277294274 & -0.0403365903 & -0.704486728 & -0.708027244 \\ -0.0743225887 & 0.226568446 & 0.680474699 & -0.692890406 \end{pmatrix} \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}_3^0 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

Reconstructed (E, cosθ)

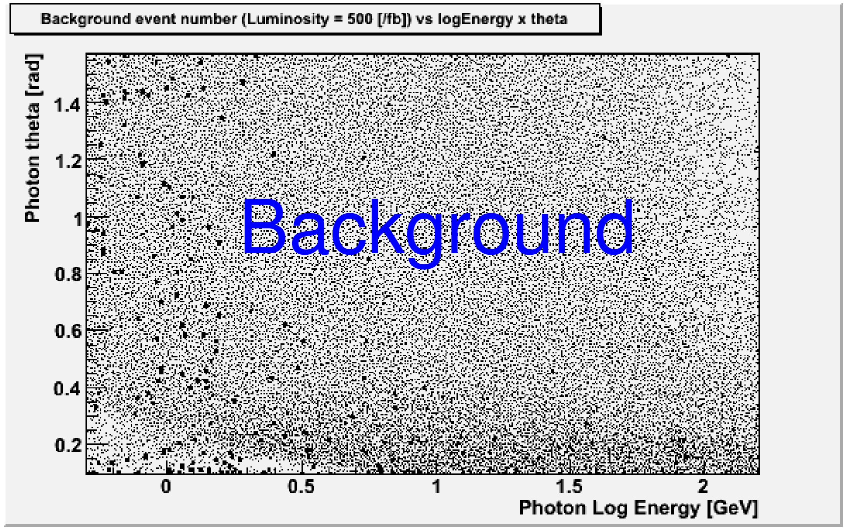
- Before reconstruction and After

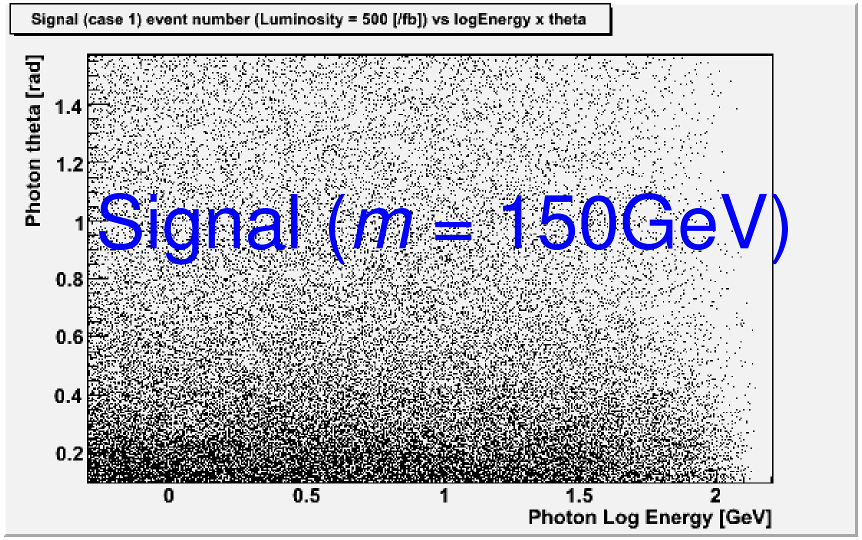


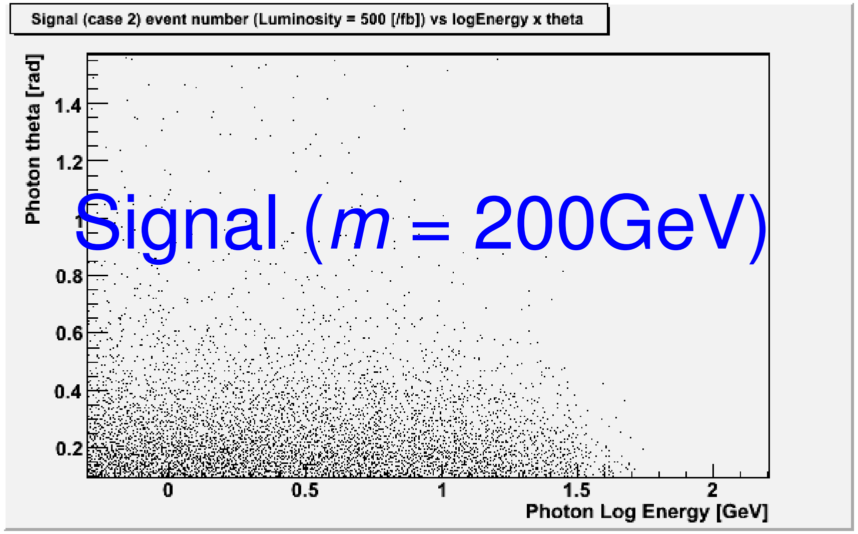


($\log E$, θ_a) Distribution

2d distribution of ($\log E$,θ_a)

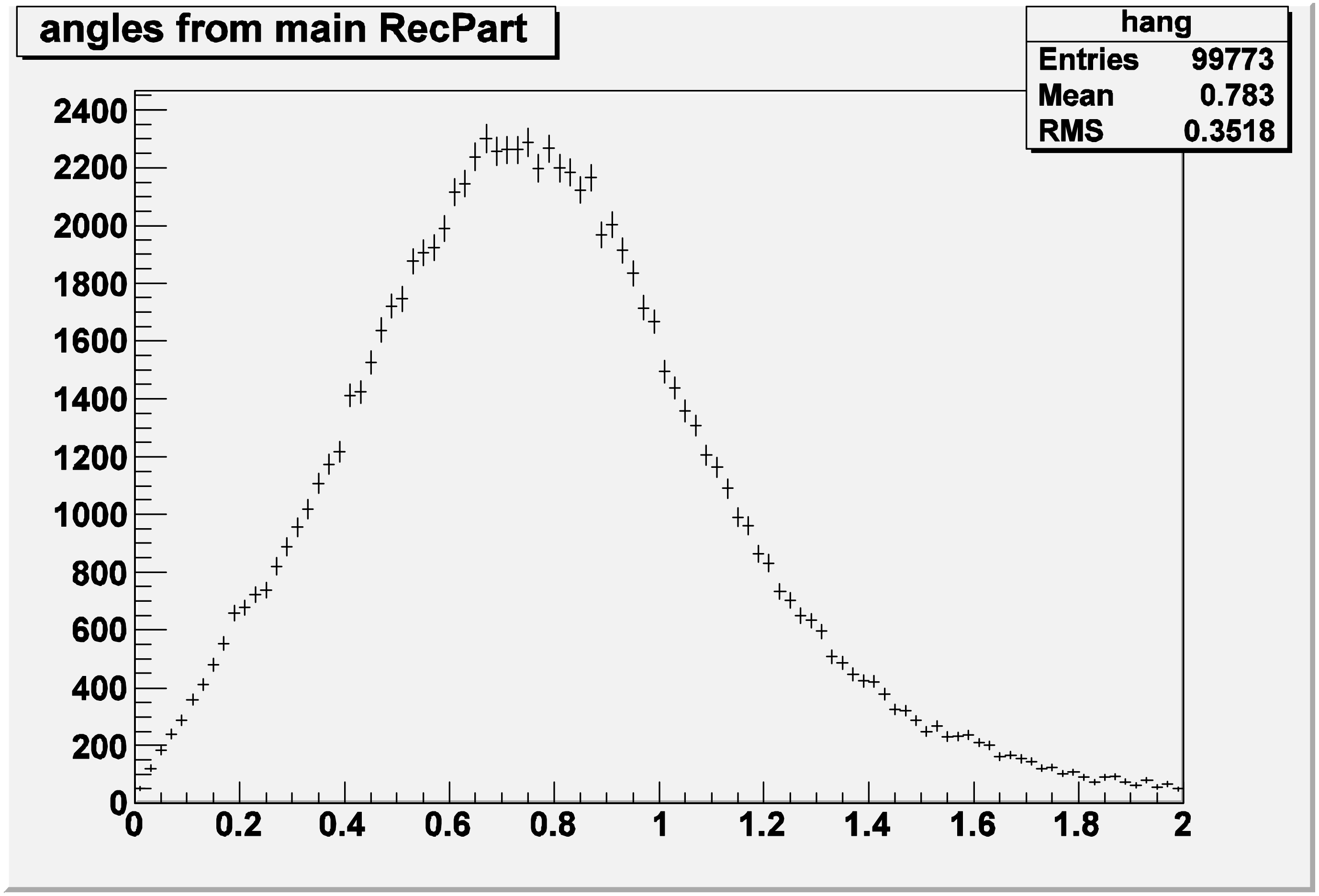






Event Selection

1. Photon merging
   The distribution of the angle from the most energetic cluster



Event Selection

3. The distribution of $E_{ECAL}/(E_{ECAL}+E_{HCAL})$