A Study of the Higgs Recoil Mass at $\sqrt{s} = 350$ GeV Based on Fast Simulation of the ILD

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16 Feb 2010

(PRELIMINARY version)

1 Introduction

The intent of this work is to predict the result of the Higgs recoil mass measurement assuming a Higgs mass of 120 GeV at $\sqrt{s}$ =350 GeV with beam parameters SB2009 w/o travel focus (SB2009 350 w/o TF) [11] using the ILD detector concept [2]. We would like to compare this result with our previous result [2, 3, 4] at $\sqrt{s}$ =250 GeV with RDR [1] beam parameters (RDR 250) for the accelerator optimization reason.

The study uses the $ZH \to \mu^+\mu^- X$ channel, assuming a beam polarization of (e^- : -80%, e^+ : $+30\%$). It takes into account the beam effects by beam simulation using GUINEA-PIG [8] with beam parameters SB2009 350 w/o TF. I use PYTHIA [9] for the event generation with the beams simulated by GUINEA-PIG as inputs through the interface CALYPSO [10]. Thereafter, I developed a fast simulation algorithm [5] to include the detector effects of the ILD. After the fast simulation, I perform the analysis based on the same algorithm as of my previous study [3, 4]. In the end, I give the result and the comparison.

2 Beam Simulation

The beam effects are simulated using GUINEA-PIG, with the beam parameters SB2009 350 w/o TF given by reference [11]. Figure 1 and 2 show beam energies and center of mass energy distributions simulated with beam parameters SB2009 350 w/o TF. A validation of my simulation codes is detailed in Appendix A.

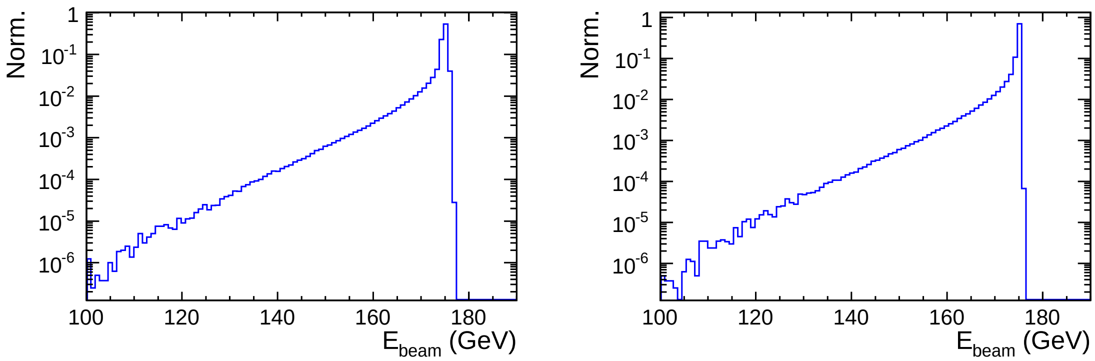

Figure 1: Simulated e^- (left) and e^+ (right) beam energy spectrum with beam parameters SB2009 350 w/o TF.

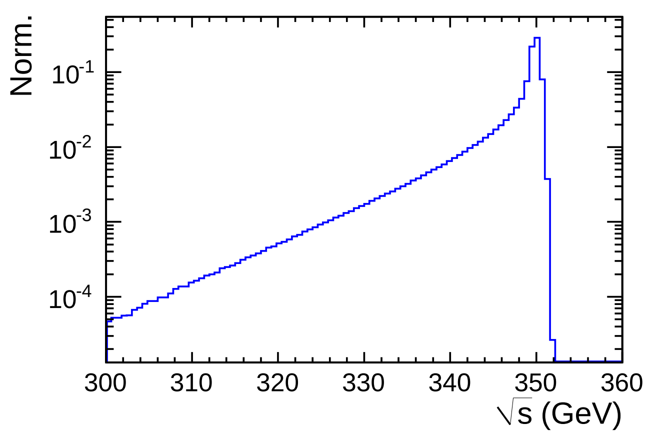

Figure 2: Simulated center of mass energy spectrum with beam parameters SB2009 350 w/o TF.

3 Event Generation

I use PYTHIA for the event generation. The event generation takes the beams simulated by GUINEA-PIG as inputs through the interface CALYPSO. A validation of the codes of the event generation is given in Appendix B.

I take the $ZH \to \mu^+\mu^- X$ channel under study, with two major background reactions the WW ($W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu_\mu}$) and the ZZ ($ZZ \to \mu^+\mu^- f\bar{f}$). Their cross-sections at $\sqrt{s}$ =350 GeV with beam polarization (e^- : -80%, e^+ : $+30\%$) are listed in Table 1. Appendix C gives a discussion of these numbers.

Reaction	Cross-Section
$\boldsymbol{ZH \to \mu\mu X}$	**7.1 fb**
WW	346 fb
ZZ	165 fb

Table 1: Reactions and cross sections at $\sqrt{s}$ =350 GeV with beam polarization (e^- : -80%, e^+ : $+30\%$). The signal is indicated by bold face letters.

If I take the RDR 500 peak luminosity ($\mathcal{L}_{\text{peak,RDR500}} = 2.0 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$) and integrated luminosity ($\mathcal{L}_{\text{int,RDR500}}$ =500 fb^{-1}) as reference, the estimated integrated luminosity of a given set of beam parameters should be [12]:

$$\mathcal{L}_{\text{int}} = \frac{\mathcal{L}_{\text{peak}}}{\mathcal{L}_{\text{peak,RDR500}}} \cdot \mathcal{L}_{\text{int,RDR500}} \tag{1}$$

Following this rule, these integrated luminosities for various beam parameters are listed in Table 2.

	RDR			SB2009 w/o TF				SB2009 w/ TF			
$\sqrt{s}$ (GeV)	250	350	500	250.a	250.b	350	500	250.a	250.b	350	500
Peak L ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	0.75	1.2	2.0	0.2	0.22	0.7	1.5	0.25	0.27	1.0	2.0
Integrated L (fb^{-1})	188	300	500	50	55	175	375	63	68	250	500

Table 2: Estimated Integrated luminosities for various beam parameters [11].

4 Fast Simulation

I developed a dedicated fast simulation algorithm for the ILD detector concept. The fast simulation firstly parameterizes the momentum resolution obtained from the full simulation of the ILD detector [6] as a function of momentum and $\cos\theta$. It thus smears the MC true momentum of a given lepton candidate according to the parameterized momentum resolution. This algorithm is detailed in reference [5], including a validation of it by comparing the fast simulation results with those of the full detector simulation.

The higgs recoil mass distribution of the signal after the fast simulation is shown in Figure 3, comparing with the one before fast simulation.

Figure 4 compares the recoil mass distributions of the fast simulated signal with beam parameters SB2009 w/o TF 250b and 350, with their integrated luminosity taken into

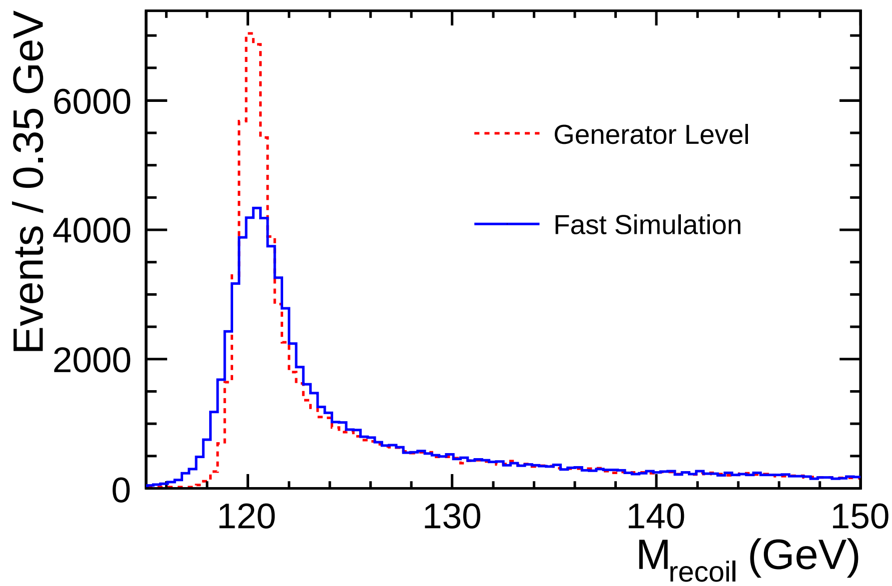

Figure 3: Comparison of the recoil mass distribution of the signal before and after fast simulation with beam parameters SB2009 350 w/o TF.

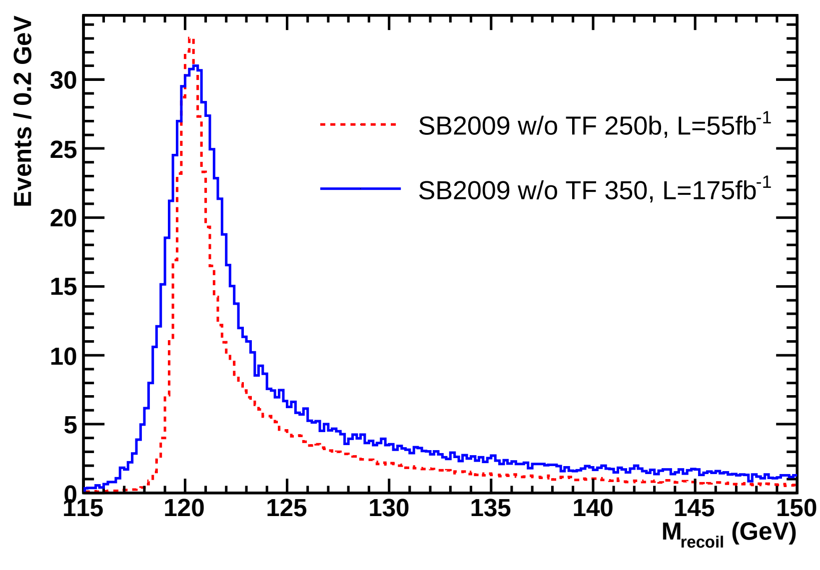

Figure 4: Comparison of the recoil mass distributions of the signal after fast simulation with beam parameters SB2009 w/o TF 250b and 350, with integrated luminosity taken into account. The beam polarization is (e^- : -80%, e^+ : $+30\%$).

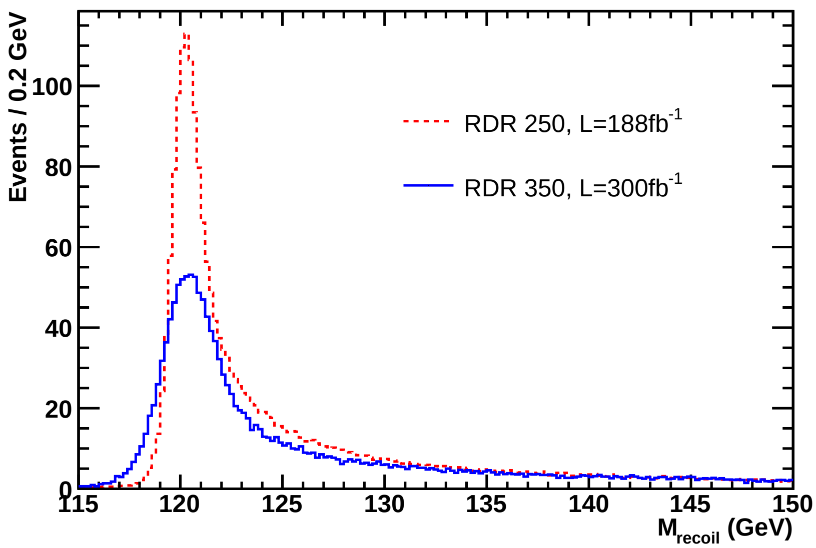

Figure 5: Comparison of the recoil mass distributions of the signal after fast simuation with beam parameters RDR 250 and RDR 350, with integrated luminosity taken into account. The beam polarization is (e^- : -80%, e^+ : $+30\%$).

account. Also compared are those of the RDR 250 and 350 beam parameters, as shown in Figure 5.

At $\sqrt{s}$ =250 GeV, the major contribution to the width of the mass peak is the beam energy spread [3]. While at 350 GeV, beam energy spread is no more the major contribution, instead, the detector momentum resolution, which increases proportional to the square of the lepton momentum, becomes dominant.

5 Analysis and Result

The analysis procedure [3] after the fast simulation is similar to that of my study based on the full simulation samples:

- A cut based background suppression. The cuts are defined in Table 3. These cuts are independent of the Higgs decay mode.
- A Likelihood further rejection of background [3]. The variables (P_{Tdl}, $\cos\theta_{dl}$, M_{dl} and *acolinearity*) employed in this Likelihood suppression are also independent of the Higgs decay mode.
- The resulting recoil mass (M_{recoil}) spectrum of signal and background is fitted to derive the results of the M_H and the ZH cross-section measurement [3]. I choose the physics motivated function [3] to describe the signal.

Cut-Chain
(1) $\lvert\cos\theta_\mu\rvert < 0.99$
(2) $P_{Tdl} > 20$ GeV
(3) $M_{dl} \in (80,\ 100)$ GeV
(4) $acop \in (0.2,\ 3.0)$
(8) $M_{recoil} \in (115,\ 150)$ GeV
(9) Likelihood Further Rejection (using variables P_{Tdl}, $\cos\theta_{dl}$, M_{dl} and $acol$)

Table 3: The cut-chain for background suppression.

After the background suppression, the remaining numbers of events of signal and background reactions are given in Table 4.

Reactions	$ZH \to \mu\mu X$	ZZ	WW
$N_{initial}$	1248	29k	61k
$N_{selected}$	633	658	30

Table 4: Numbers of events before and after background suppression, for signal and backgrounds.

Beam Par	$\mathcal{L}_{\text{int}}$ (fb^{-1})	ϵ	S/B	M_H (GeV)	σ (fb) ($\delta\sigma/\sigma$)
RDR 250	188	55%	62%	120.001 ± 0.043	11.63 ± 0.45 (3.9%)
RDR 350	300	51%	92%	120.010 ± 0.084	7.13 ± 0.28 (4.0%)
SB2009 w/o TF 250b	55	55%	62%	120.001 ± 0.079	11.63 ± 0.83 (7.2%)
SB2009 w/o TF 350	175	51%	92%	120.010 ± 0.110	7.13 ± 0.37 (5.2%)

Table 5: Results of different beam parameters, assuming a beam polarization of (e^- : -80%, e^+ : $+30\%$). The results of RDR 250 and SB2009 w/o TF 250b are scaled from my previous analysis based on full simulation according to the integrated luminosity. That of RDR 350 is estimated by scaling the result of SB2009 w/o TF 350 obtained here according to the integrated luminosity.

Figure 6 shows the fit to the recoil mass spectrum of remaining signal and background. An equivalent plot with beam parameters RDR 250 can be found in reference [3, 4].

From Figure 6, the derived results of the Higgs mass measurement is $M_H = 120.010 \pm 0.110$ GeV, and of the cross-section is $\sigma = 7.13 \pm 0.37$ fb ($\delta\sigma/\sigma = 5.2\%$). A comparison of the results with other beam parameters are shown in Table 5, together with the efficiency (ϵ) and signal over background (S/B). In this table, the results of RDR 250 SB2009 w/o TF 250b are scaled from my previous analysis [3, 4] based on full simulation according to the integrated luminosity. And the results of RDR 350 is estimated by scaling the result of SB2009 w/o TF 350 according to the integrated luminosity.

The higher S/B at $\sqrt{s}$ =350 GeV is due to better background suppression. For example the variable $\cos\theta_{dl}$, its distribution of ZH signal is much center for $\sqrt{s}$ =350 GeV than 250 GeV [3], while that of the ZZ background is much forward.

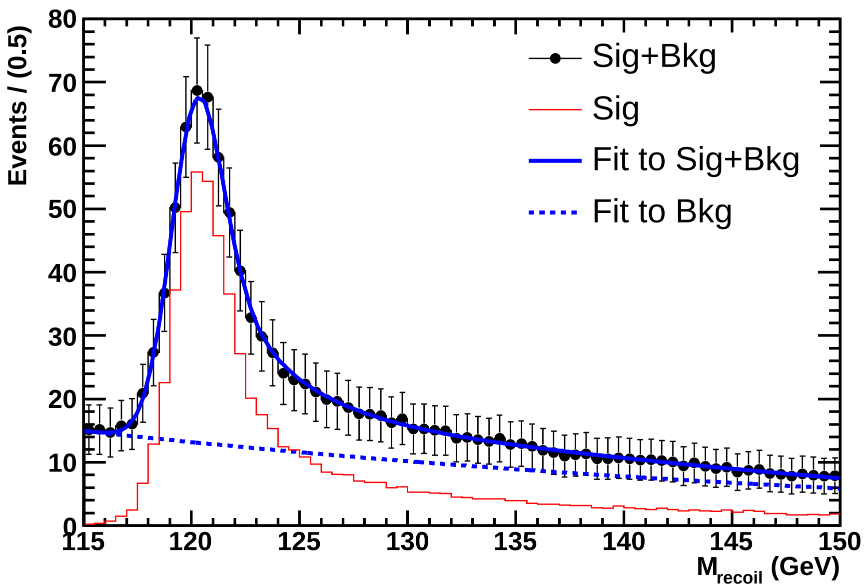

Figure 6: Fit to recoil mass spectrum of signal plus background based on the fast simulation, at $\sqrt{s}$ =350 GeV, with beam polarization (e^- : -80%, e^+ : $+30\%$) beam parameters SB2009 w/o TF, and assuming an integrated luminosity of 175 fb^{-1}.

When comparing RDR 250 and 350, the errors on the cross-section are similar, while the error on the M_H at 350 GeV is worse by a factor of 2 than that at 250 GeV.

When comparing SB2009 w/o TF 250 and 350, the higher luminosity at 350 GeV gives better result on cross-section, but not on the M_H, which is worse by 1.4 times due to the wider mass peak.

For a given $\sqrt{s}$, the results of SB2009 w/o TF are worse due to the decrease of luminosity.

Also, the comparison above shows the results on Higgs mass is about 3 times worse if we change to use beam parameters SB2009 350 w/o TF, and on the cross-section more than 1.5 times worse.

A Validation of the Beam Simulation

In order to validate my simulation codes, I firstly simulated the beam with beam parameters RDR 250 [1, 11] at $\sqrt{s}$ =250 GeV, and compared my simulation with that simulated centrally by SLAC for the Letter of Intent production [7].

Figure 7 and 8 show the comparisons of my simulated luminosity spectra and those of SLAC central production with beam parameters RDR 250. They confirm with each other.

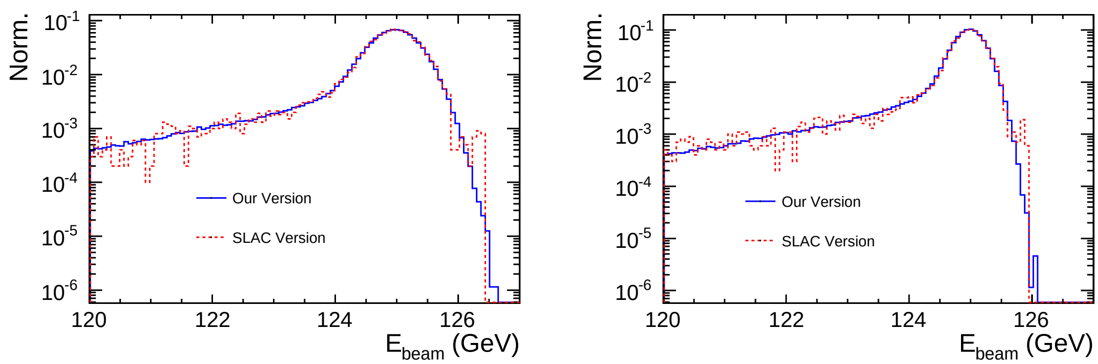

Figure 7: Comparison of e^- (left) and e^+ (right) beam energy spectra of our simulation and SLAC samples at $\sqrt{s}$ =250 GeV, with RDR 250 beam parameters. Good agreement can be observed.

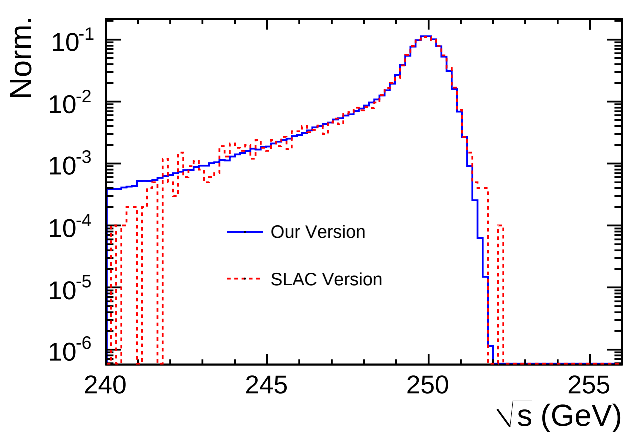

Figure 8: Comparison of center of mass energy spectra of our simulation and SLAC samples at $\sqrt{s}$ =250 GeV with RDR 250 beam parameters. Good agreement can be observed.

B Validation of the Event Generation

To valid the event generation, I compare some essential distributions with those of the SLAC samples [7]. This is done with the RDR 250 beam parameters.

Figure 9 and 10 show M_{dl}, M_H, P_{Tdl} and $\cos\theta_{dl}$ distributions of the $ZH \to \mu^+\mu^- X$ process, and compare with those of the SLAC samples, for $\sqrt{s}$=250 GeV. The two set of distributions confirm with each other. This validated my event generation algorithm can be used for the generation with beam parameters SB2009 350 w/o TF.

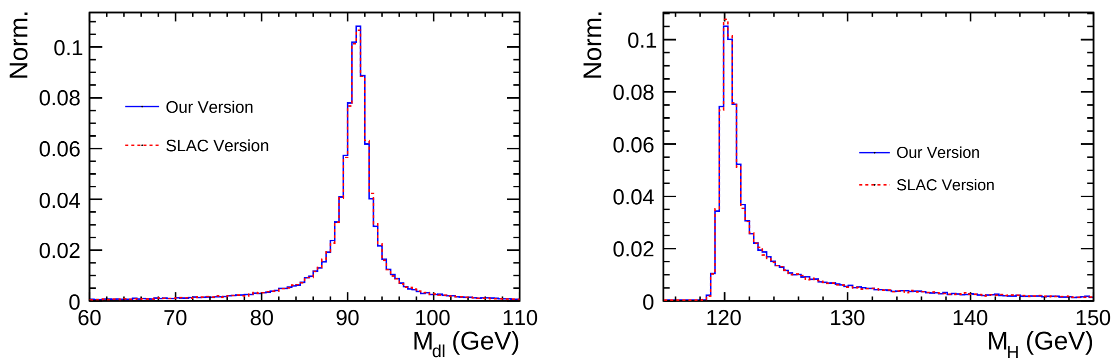

Figure 9: Comparison of the invariant mass M_{dl} of the lepton pair (left) and the recoil mass M_H (right) distributions from our event generation and from the SLAC samples at $\sqrt{s}$ =250 GeV. Good agreement can be observed.

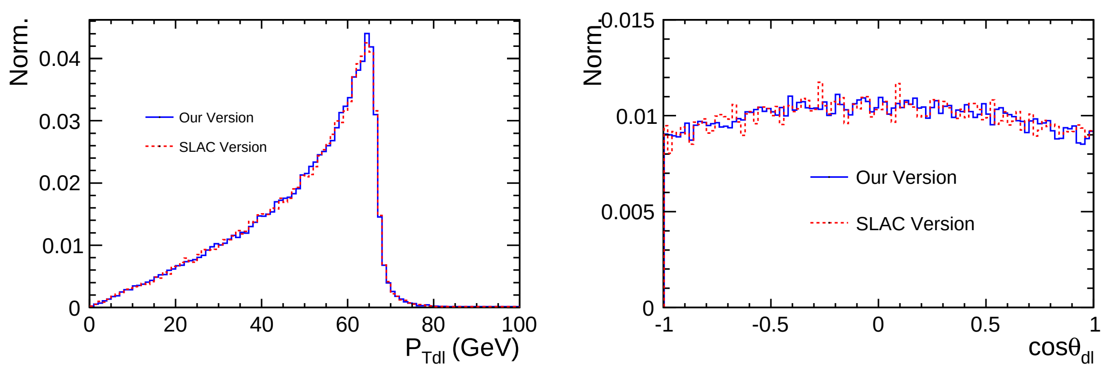

Figure 10: Comparison of the transverse momentum P_{Tdl} of the lepton pair (left) and the $\cos\theta_{dl}$ of the lepton pair (right) distributions from our event generation and from the SLAC samples at $\sqrt{s}$ =250 GeV. Good agreement can be observed.

C Estimate of the Cross-Sections at $\sqrt{s}$=350 GeV with Beam Polarization

Since the PYTHIA generator does not support beam polarization, we need to make some efforts to estimate the cross-sections of signal and background reactions at $\sqrt{s}$ =350 GeV with beam polarization ($e^-: -80\%,\ e^+: +30\%$).

After some studies [12], we believe:

- The distributions of the observable M_{recoil} and variables for our background suppression do not vary according to the beam polarization.
- Only the cross-sections do, but the ratios of the cross-sections between $\sqrt{s}$ =250 GeV and 350 GeV do not vary according to the beam polarization for the signal and ZZ background.
- For the WW background, the t-channel contribution to its cross-section is dominate. Thus, with the beam polarization ($e^-: -80\%,\ e^+: +30\%$), the contribution from right-handed electrons and left-handed positrons is negligible.

Based on the assumptions listed above and given the fact that the SLAC samples provide the cross-sections for the four 100% beam polarizations at $\sqrt{s}$ =250 GeV, I can now estimate the corresponding cross-sections at $\sqrt{s}$ =350 GeV with beam polarization ($e^-: -80\%,\ e^+: +30\%$).

As a first step, I generate the cross-sections using PYTHIA w/o beam polarization at $\sqrt{s}$ =250 GeV. These cross-sections are identical to the corresponding SLAC ones.

In the second step, I generate the cross-sections using PYTHIA w/o beam polarization at $\sqrt{s}$ =350 GeV. Then I can get the ratio between the cross-sections at $\sqrt{s}$ =350 GeV and 250 GeV. By simply times this ratio to the cross-section at $\sqrt{s}$ =250 GeV with beam polarization ($e^-: -80\%,\ e^+: +30\%$) given by SLAC, I can get the corresponding cross-section at $\sqrt{s}$ =350 GeV. This is how I estimate the cross-sections for the signal and ZZ background.

For the WW background, with the last assumption mentioned above, the cross-section with beam polarization ($e^-: -80\%,\ e^+: +30\%$) is approximately $\sim 2.34\sigma_{w/o}$, where $\sigma_{w/o}$ is that w/o beam polarization, which can be generated by PYTHIA at $\sqrt{s}$ =350 GeV.

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