Exploring the semileptonic final state of W pair production in the ILD

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Abstract

It is important to know some angles of stuff for the analysis of the ILD. In this report we discuss how the computation methods required to extrct such angles and stuff. Using kinematic conservation laws to model particles invisible to a particles we are able to extract stuff blah blah blah
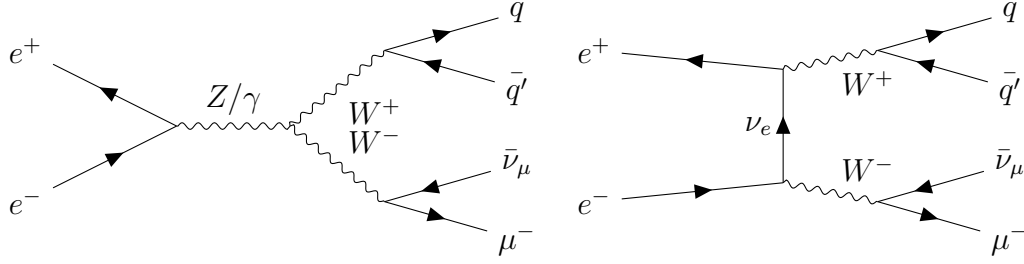
Contents

Figure 1: Lowest order Feynman diagram of semileptonic W pair decay in the $\mu\bar{\nu}q\bar{q}'$ final state at e^+e^- colliders. Alternately the W^+ could decay leptonically, which would result in a $\mu^+\nu q\bar{q}'$ final state (not drawn).

1 Introduction

*** THIS IS BS***

It is somewhat important for the ILD that I am here to help probes some sort of sensitivity somewhere I think I am not sure

I will be using some fake simulated data that is produced using some potentially relelvant moethods

I will be writing a Marlin processor to do some stuff

I will be extracting some angles for Jakob to use in his thing I think

*** THIS IS BS***

2 Example main text section

2.1 Neutrino Reconstruction

I AM ALWAYS APPLYING CUTS SUCH THAT 1 ISOLEP FOUND AND MC MUONS

Pair production of W bosons at e^+e^- colliders is well understood in the Standard Model. These W bosons then proceed to decay and the deacy prodcts leave signals in the detector which are used to analyse the bosons themselves. In my analysis I will be focusing on the semileptonic final state of the W pair decay specifically where the lepton is a muon (Figure. 1).

In the MC simulation, there is one hard collision simulated, as well as a bunch of overlay particles, which are important to model the spectator interstions of the other, non colliding, particles in the bunch. We need to make sure that these extra particles are not included in the reconstruction of the hard intertion. I used 'Fastjet' ***CITE*** processors to remove the overlay from the collection and to find the 2 jets corresponding to the 2 quarks in the final state. I also used the 'MyIsolatedLeptonTagger' ***CITE*** processor to extract the lepton from the recontructed particles. These three extracted particles make up the 'visible' portion of the system. The hadronically decaying W boson can be simply reconstructed by summing the 4-momenta of the 2 extracted quarks it decays into.

The leptonically decaying W boson can similarly be reconstructed by summing the 4-momenta of the extracted lepton and the neutrino, however, the neutrino does not leave a signal in the detector. There is also some initial state radiation of photons (ISR) which are aligned enough to the beam pipe that they are lost. This results in an 'invisible' system that is not at all detected by the detector, we must therefore come up with a way to attain the 4-momenta of

these invisible particles if we wish to have complete information about the W bosons.

The chosen method for reconstruction of the invisible system arises from purely conservation laws[1]. We consider the reconstructed visible system as being the hadronically decaying W boson plus the isolated lepton ($p^\mu = (E, p_x, p_y, p_z)$), and the invisible system as the accompanying neutrino and an ISR photon travelling parallel to the beam. We also assume the total center of mass energy is 500 GeV and that we are in the zero momentum frame (ZMF). Conservation of momentum and energy then gives us the 4-momenta of the ISR photon and the neutrino. In the MC simulation there are actually two ISR photons emitted, this menas that when combining the two photons into one 'photon', this 'photon' may have a non zero invarient mass. The ISR photon could be going in either direction with respect to the beam axis, resulting in two soltuions.

$$E_\gamma = \frac{\lambda(500 - E) \pm p_z \sqrt{\lambda^2 - [(500 - E)^2 - p_z^2]m_\gamma^2}}{(500 - E)^2 - p_z^2} \tag{1}$$

where $\lambda = \frac{1}{2}[(500 - E)^2 - p^2 + m_\gamma^2 - m_\nu^2]$ has been defined for convenience and no absolute values have been assumed.

My code will then select the solution that gives a better estimate for the invarient mass of the W boson. As described in ***CITE*** this might introduce a bias and so the appropriate cut was made to mitagate this.

It is worth noting at this point that it is numerically possible for the particle reconstruciton to result in a visible 4-momenta with a negative λ. It can be seen in the $m_\gamma = m_\nu = 0$ solution that this corresponds to the invisible part of the system having an imaginary invariant mass.

$$\lambda_{m_\gamma, m_\nu = 0} \propto (500 - E)^2 - p^2 = E_{inv}^2 - p_{inv}^2 = m_{inv}^2 \tag{2}$$

This is obviously not physical and will affect the solutions attained above. For example as $p_\gamma = \pm E_\gamma$, a negative energy will reverse the direction of the photon. This needs to be handled carefully in the code to avoid inconsistent solutions.

A simplified form of this equaiton with $m_\gamma = \pm m_\nu = 0$ is used in the thesis by I.M ***CITE*** that I am basing this analysis on.

$$E_\gamma = \frac{(500 - E)^2 - p^2}{1000 - 2E \mp 2p_z} \tag{3}$$

In the derivation I show how the full equation above leads to this when simplified, there is however one subtlty when this is done computationally. The $\sqrt{\lambda^2}$ will computationally evaluate as $|\lambda|$, so if λ is negative it will in effect reverse the effect of the $\pm$ in Equation. 1 and lead to the opposite solution found using the simplified form. So it is clear that these negative λ's may cause some issues.

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[1] a full mathematical derivation is included in the appendix for completeness (6)

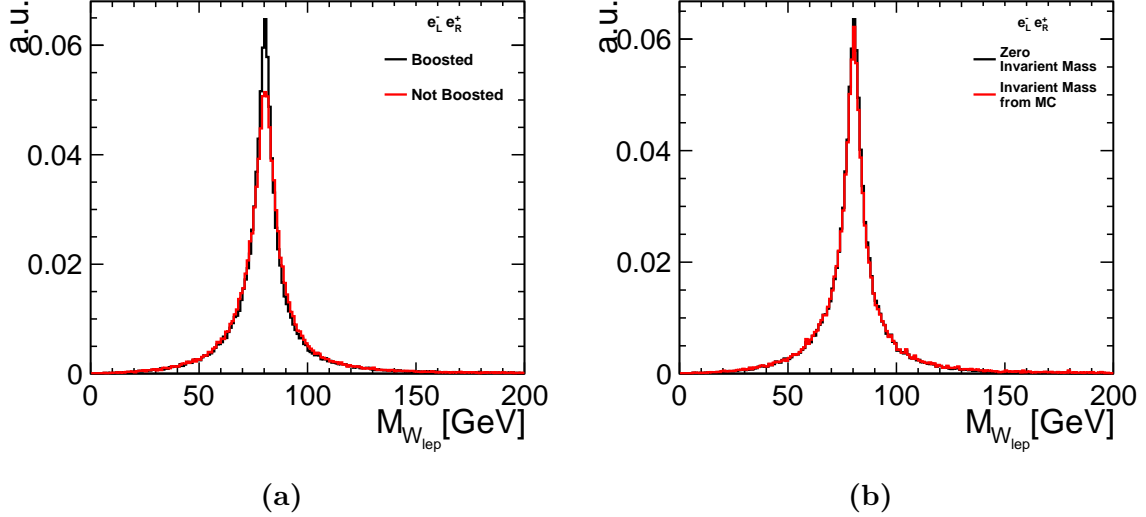**(a)**   **(b)**

Figure 2: Plots displaying the effect on the reconstructed invarient mass of the leptonically
decaying W with different reconstruction methods. The simulated e^+e^- collision is not head
on, but with a finite momentum in the x direction, (a) shows the effect of boosting into the
ZMF before applying the reconstruction method. (b) shows the effect of inputting a non-zero
invarient ISR photon mass into the reconstruction (extracted from the MC collection).

Using this method I was able to extract the 4-momentum of the leptonically decaying W
boson. As a test of the performance of this code I chose to look at the reconstructed invarient
mass, to see how accuratly it was reproduced. A peak at around 80 GeV was produced which
is close to the currently accepted measurement of 80.3 ***CITE*** which is good, so I explored
a few different variables . I found that boosting into the ZMF improved the reconstruction of
the mass as is expected (Figure. 2a). I found that including the true invarient mass of the ISR
photon (collected from the simulated MC particle collection performed worse than just setting
it to zero (Figure. 2b).

I also found that cheating the overlay removal process with the 'TJJetOverlayRemoval'
CITE processor peformed worse than properly using the 'Fastjet' overlay removal (Fig-
ure. 3). However, when we loot at the reconstruction of the hadronically decaying W boson it
performs significantly better.

Both of these results are slightly concerning as when provided with extra information, that
would not be available at a real detector, the reconstruction performs worse than if this extra
informaiton is withheld.

In my code I also gave the option for there to be no ISR photon, because there may be some
computational issues ***CITE??*** with the formula at low photon energies, and calculated
the kinematics as though the only invisible particle was the neutrino. I then observed the effect
this had on the boson mass distributions (Figure. 4). It appears that including this options
significantly improves the estimations, however I had to check that this isn't just a statistical
bais of adding a third possible option to get closer to the true mass. So in Figure. 5 I plotted
the reconstructed photon energy that would have been chosen were there no $E_{ISR} = 0$ option
agains the true MC photon energy, for the events where the full simulation chose the $E_{ISR} = 0$
option. We see no real correlation forming which is good becuase it means the $E_{ISR} = 0$ option
isnt performing worse, and we see that most of the times when this performed better was at
particulatrly low E_{MC} values where the formual struggled to get an accurate reconstruction of
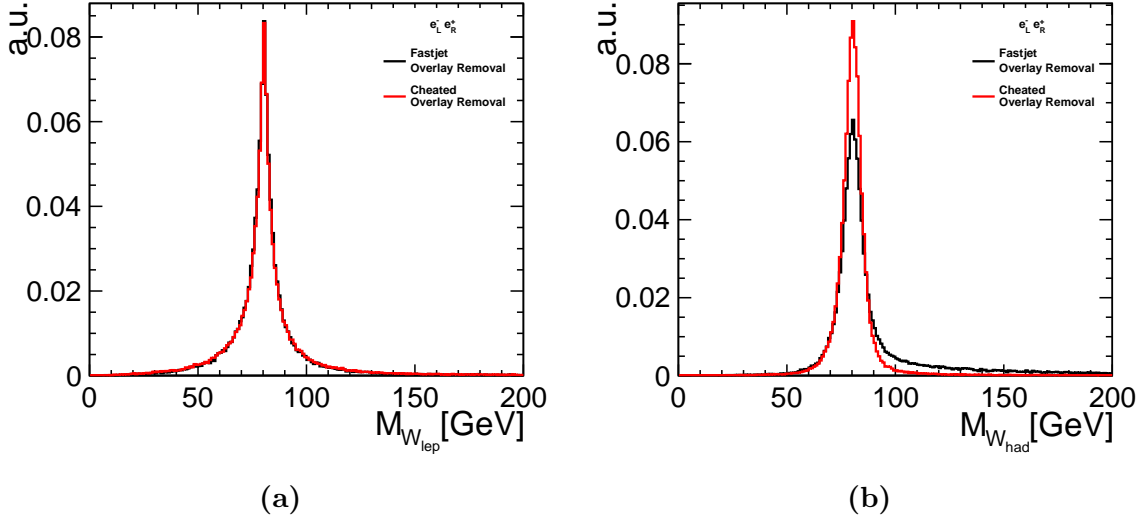
(a)

(b)

Figure 3: (a) shows how cheating the overlay removal effects the reconstruction of the leptonically decaying W mass. (b) shows how cheating the overlay removal effects the reconstruction of the hadronically decaying W mass.

the photon energy.

My only current explation for this is that the formula is rather un-sensitive to this change, and so the slight decrease in performance of the m_W^{lep} estimation is just a statistical fluctuation from the formula.

I then apply all of the cuts outlined in I.M. ***CITE*** thesis and see how this effects the selection efficiency. From here on I will be using the method above choosing the best of all 3 possible E_γ solutions with $m_\gamma = m_\nu = 0$. Applying the cuts outlined in Table. 1, I arrive at an efficiency flow diagram (Figure. 6).

2.2 Angle extractions

The next part of my project involved extracting a few angles from the hard reaction from the MC Collection. I picked out the semileptonic final state particles from the collection, and reconstructed the leptonic and hadronic jets by basic addition of the 4-momenta. It was then a simple matter of extracting the appropriate angles from the 4 momenta as described in Robert Karls thesis ***CITE*** (Figure. 3) from the MC collection.

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[2]track mulitplicity was taken as the number of reconstructed charged particles.

[3]τ_{discr} defined by $\tau_{discr} = \left(\frac{2E_{lep}}{\sqrt{s}}\right)^2 + \left(\frac{m_W^{lep}}{m_W^{true}}\right)^2$

[4]$\Delta\Omega_{iso}$ defined as,

$$(\phi_{lep} - \phi_{had}) < \pi \rightarrow \Delta\Omega_{iso} = \sqrt{(\theta_{lep} - \theta_{had})^2 + (\phi_{lep} - \phi_{had})^2} \qquad (4)$$

$$(\phi_{lep} - \phi_{had}) \geq \pi \rightarrow \Delta\Omega_{iso} = \sqrt{(\theta_{lep} - \theta_{had})^2 + (2\pi - |\phi_{lep} - \phi_{had}|)^2}. \qquad (5)$$
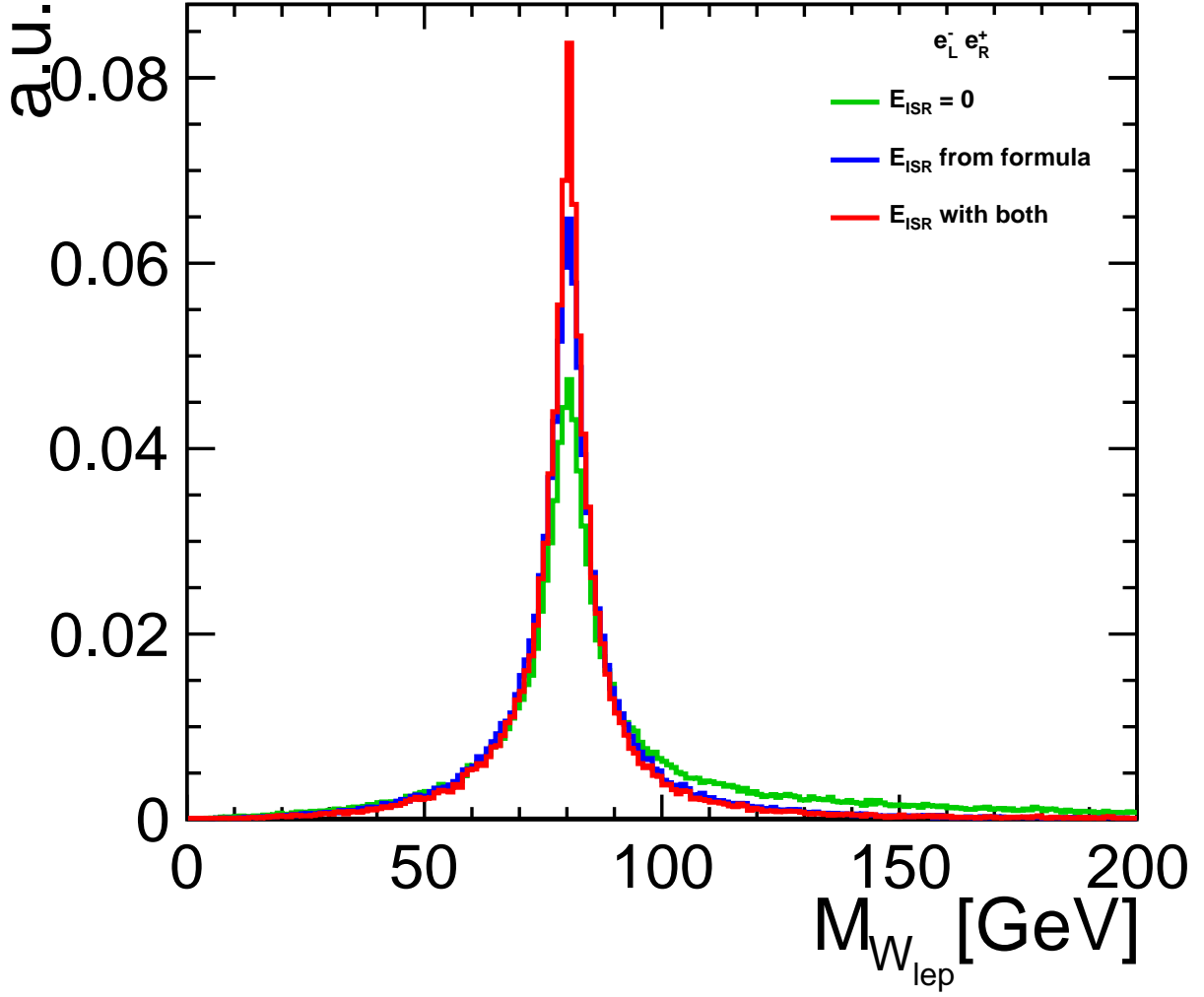
Figure 4: Histogram showing how well the 3 different E_γ claculation methods reconstruct the leptonically decaying W mass.

Table 1: Selection efficiency of sequantially applied cuts. Where the post ISR correction m_W^{lep} was calculated using all 3 possible E_γ solutions. (*) Means my and Ivan's cuts differ slightly

| Order	Cut description	Efficiency [%]		
		My Results		Ivan's Results
		n = 2129	n = 99419	n = 107233
0	muon signal	100.00	100.00	100.00
1	track multiplicity[2] $n_{tracks} \geq 10$	97.13	97.01	99.996
2	center of mass energy $\sqrt{s} > 100$ GeV	92.29	91.69	97.96
3	total transverse momentum $P_T > 5$ GeV	91.16	90.47	96.69
4	total energy $E_{SUM} < 500$ GeV	89.66	89.28	95.36
5	$\ln(y_+) \in [-12, -3]$ (*)	88.69	88.08	95.01
6	1 lepton found (*)	80.65	80.77	78.75
7	pre ISR correction $m_W^{lep} \in [20, 250]$ GeV	78.23	77.94	76.61
8	tau discrimination[3]	76.05	75.60	74.07
9	charged lepton (*)	76.05	75.60	73.51
10	isolation variable[4] $\Delta\Omega_{iso} > 0.5$	76.01	75.58	73.42
11	post ISR correction $m_W^{lep} \in [40, 120]$ GeV	72.90	72.77	70.13
12	post ISR correction $m_W^{had} \in [40, 120]$ GeV	63.21	62.92	66.93
13	$\cos\theta_W > -0.95$	63.02	62.65	66.78
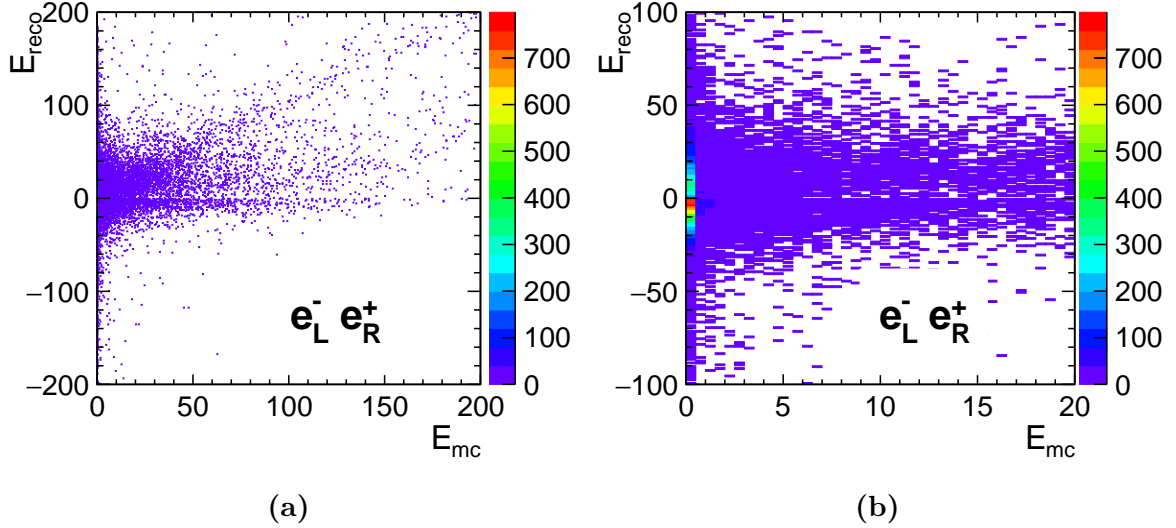
Figure 5: This figure shows the distribution of photon energies from the formula that would have been chosen were there no $E_{ISR} = 0$ option agains the true MC photon energy, for the events where the full simulation chose the $E_{ISR} = 0$ option. (b) is the same plot as (a) with a restricted axis range for clarity.

The first angle θ_{W^-} if defined as the angle between the negiativly charged W boson (W^-) and the beam pipe in the electron direction of travel (the z axis in the MC simuation). I extracted this in the center of mass frame of the e^+e^-, which required a boost of $\left(500\sin\left(\frac{0.014}{2}\right), 0, 0\right)$ GeV due to their non zero incidence angle. The rest of the coordinates were simply the polar coordinates of the muon, agian with z aligned to the beam pipe, in the center of mass frame of the leptonically decaying W boson (θ_l^* and ϕ_l^*) .

3   Conclusion

We know some stuff and that is cool. But we want to know more stuff.

So I had this idea to figure something new out. I did it in a cool way. And got some crazy results.

Now we know more about the thing. And that can potentially be relevant at some point in human history.
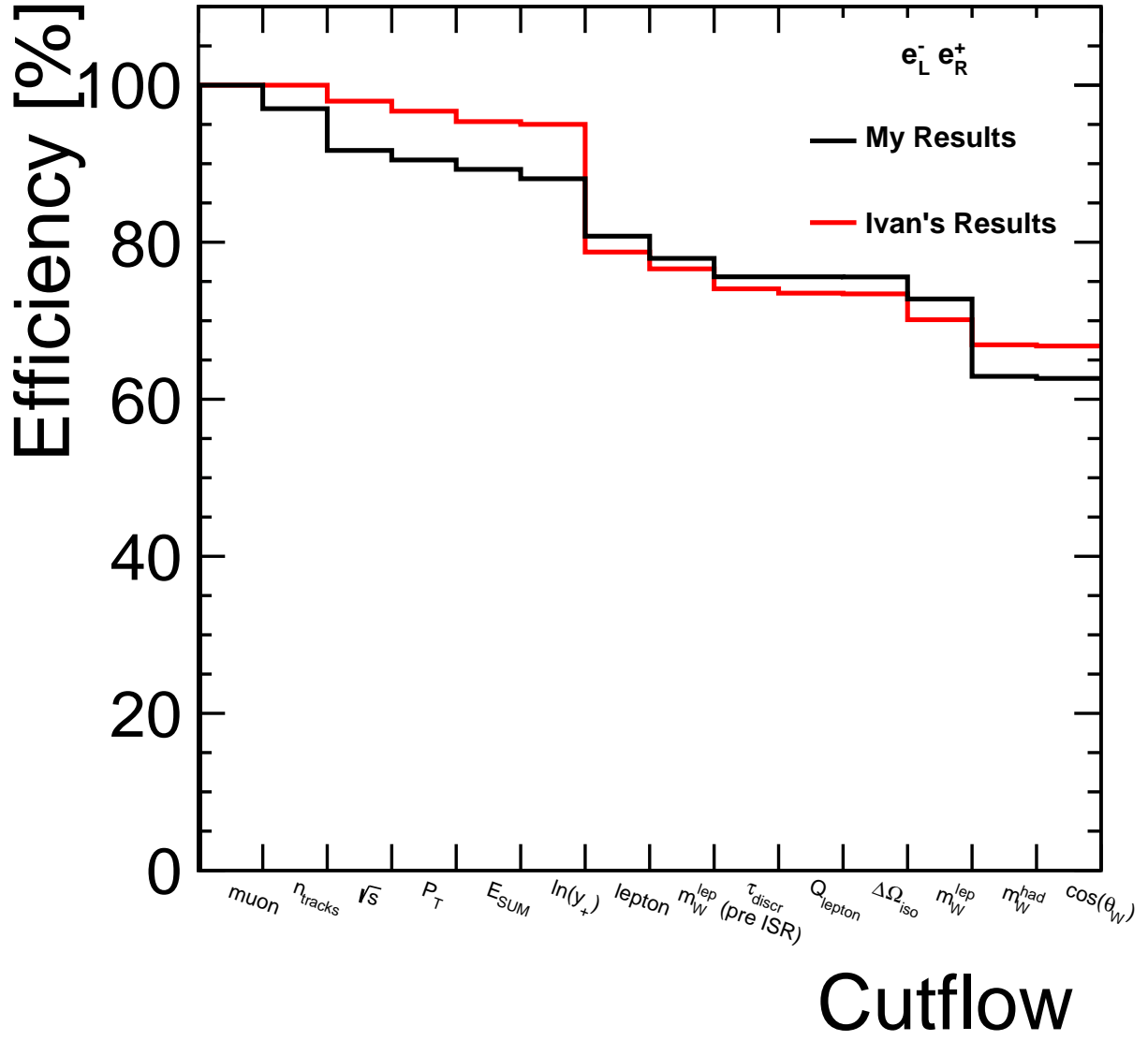
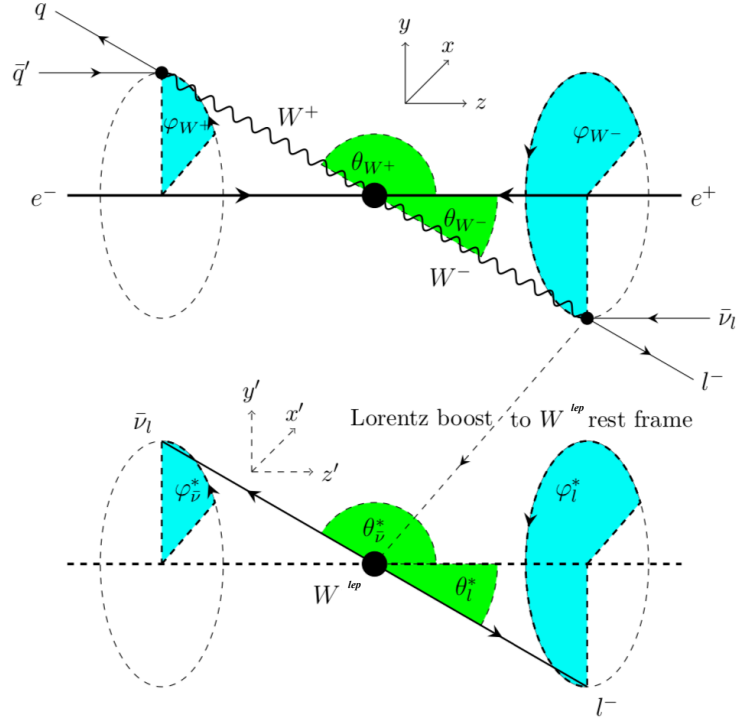**Figure 6:** Histogram showing the cut efficiency, with the cut labels defined in Table. 1

Figure 7: Angle definition for the 4-fermion final state from W^- pair production in the semileptonic channel in which the W decays leptonically. In the top part, the production angles θ_{W^-} and θ_{W^+} are defined by the axis of the initial colliding particles and the direction for the respective boson. The azimuthal angles ϕ_{W^-} and ϕ_{W^+} describe the rotation around the axis of the initial colliding particles.

The bottom picture shows the angular definition of the decay products of the W^{lep} boson in its rest frame. It shows the polar angles θ_l^* and θ_ν^* and the azimuth angles ϕ_l^* and ϕ_ν^* of the corresponding leptons. The denotes quantities in the rest frame of the W^{lep} boson. (Edited from Robert Karl ***CITE***)
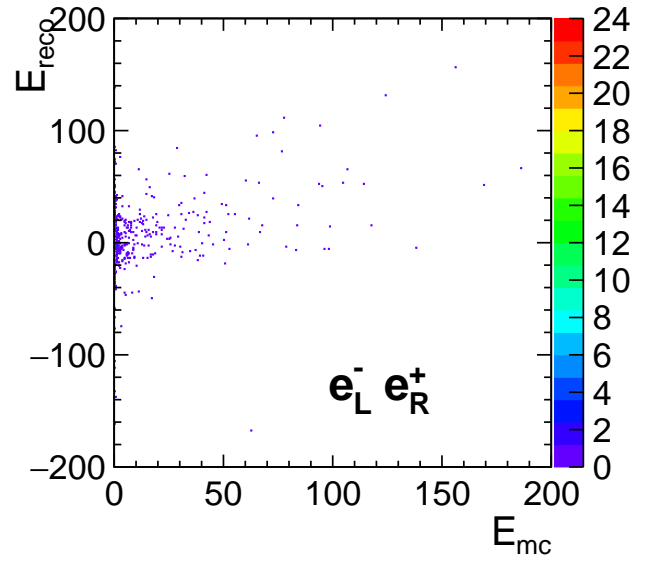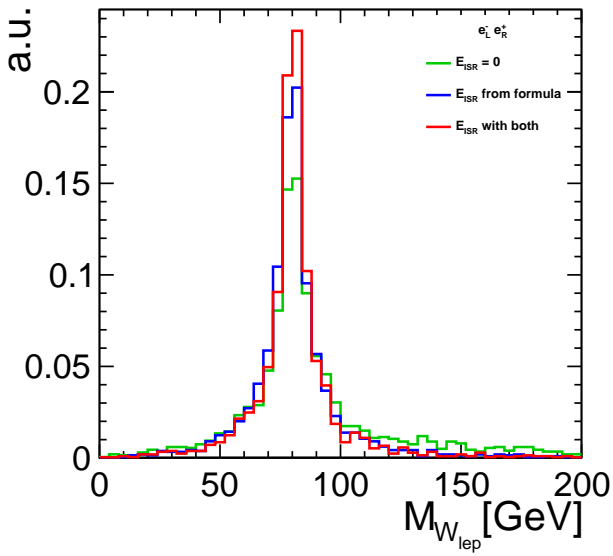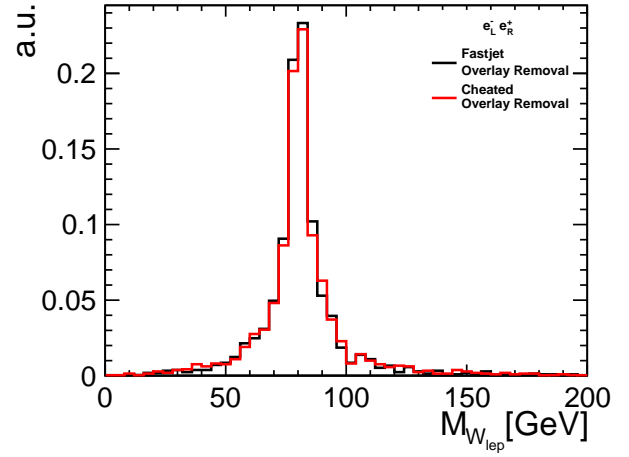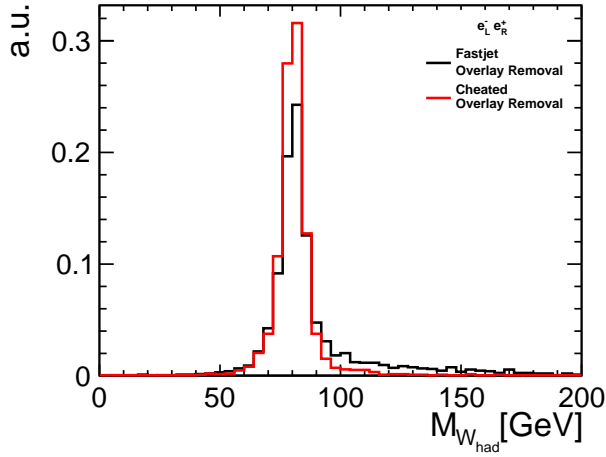
4 References
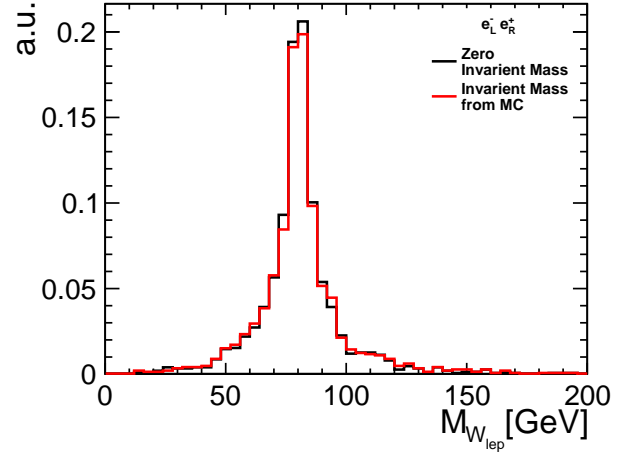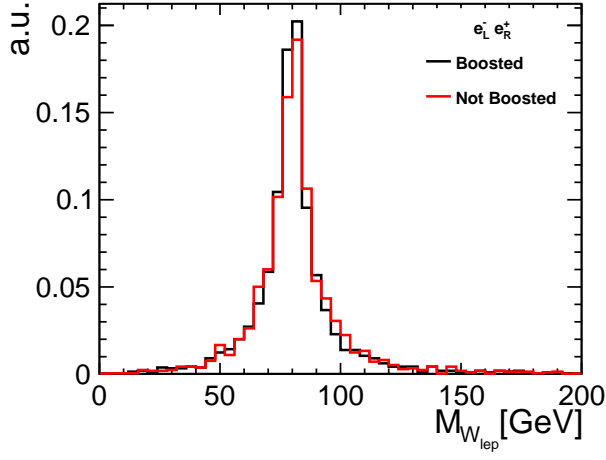
[1] Christian Fleper et al. "Scattering of W and Z Bosons at High-Energy Lepton Colliders". In: *Eur. Phys. J.* C77.2 (2017), p. 120. DOI: 10.1140/epjc/s10052-017-4656-5. arXiv: 1607.03030 [hep-ph].
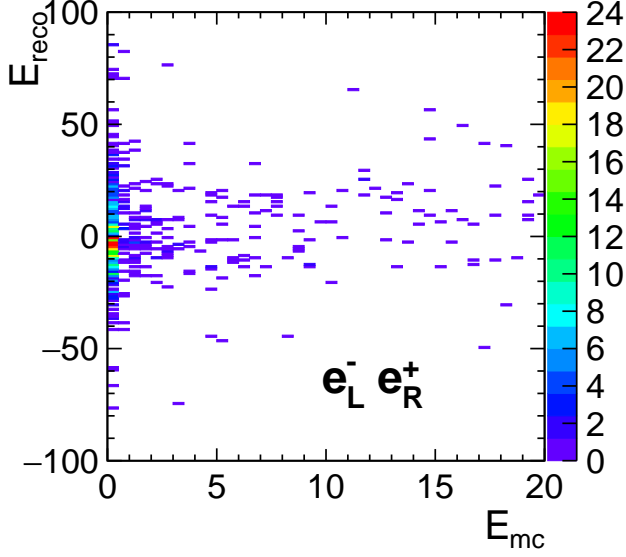
5 Acknowledgments

Special shout-out to coffee!

6 Appendix

6.1 Low Statistics Figures

$e_L^- \ e_R^+$

6.2 Derivation of the ISR energy E_γ with non-trivial m_γ and m_ν

Our initial assumptions are that the system is in the center of mass frame with an invariant mass of 500 GeV. The system contains a visible 4-momentum $p^\mu = (E, p_x, p_y, p_z)$ and an invisible 4-momentum (a neutrino $p_\nu^\mu = (E_\nu, p_{\nu,x}, p_{\nu,y}, p_{\nu,z})$ and an ISR photon $p_\gamma^\mu = (E_\gamma, 0, 0, p_\gamma)$). Both the neurino and the photon have a non trivial invariant mass leading to the following equations.

Conservation of 3-momentum

$$p_x + p_{\nu,x} = 0 \tag{6}$$
$$p_y + p_{\nu,y} = 0 \tag{7}$$
$$p_z + p_{\nu,z} + p_\gamma = 0 \tag{8}$$
$$\tag{9}$$

Conservation of Energy

$$E + E_\nu + E_\gamma = 500 \tag{10}$$

Energy-Momentum equations

$$E_\nu^2 = p_\nu^2 + m_\nu^2 \tag{11}$$
$$E_\gamma^2 = p_\gamma^2 + m_\gamma^2 \tag{12}$$
$$\tag{13}$$

For a unique solution of E_γ we require 2 more constraints on m_γ and m_ν which have yet to be imposed, but assuming these constraints are independent of E_γ we can arrive at a solution as follows.

From conservation of 3-momentum

$$p_\nu^2 = p_{\nu,x}^2 + p_{\nu,y}^2 + p_{\nu,z}^2 \tag{14}$$
$$= p_x^2 + p_y^2 + (p_\gamma + p_z)^2 \tag{15}$$
$$= p^2 + p_\gamma^2 + 2p_\gamma p_z \tag{16}$$
$$= p^2 + E_\gamma^2 - m_\gamma^2 + 2p_\gamma p_z \,. \tag{17}$$

Conservation of energy then gives us,

$$(500 - E)^2 - p^2 = (E_\nu + E_\gamma)^2 - p^2 \tag{18}$$

$$= E_\nu^2 + E_\gamma^2 - p^2 + 2E_\gamma E_\nu \tag{19}$$

$$= p_\nu^2 + m_\nu^2 + E_\gamma^2 - p^2 + 2E_\gamma E_\nu . \tag{20}$$

Substituting in the expression for p_ν,

$$(500 - E)^2 - p^2 = \cancel{p^2} + E_\gamma^2 - m_\gamma^2 + 2p_\gamma p_z + m_\nu^2 + E_\gamma^2 - \cancel{p^2} + 2E_\gamma E_\nu \tag{21}$$

$$(500 - E)^2 - p^2 + m_\gamma^2 - m_\nu^2 = 2(E_\gamma^2 + p_\gamma p_z + E_\gamma E_\nu) \tag{22}$$

$$= 2(\cancel{E_\gamma^2} + p_\gamma p_z + E_\gamma[500 - \cancel{E_\gamma} - E]) \tag{23}$$

$$= 2(p_\gamma p_z + 500E_\gamma - EE_\gamma) . \tag{24}$$

131 Where we have one again used conservation of energy.

132

133 For convenience lets define

$$\lambda = \frac{1}{2}[(500 - E)^2 - p^2 + m_\gamma^2 - m_\nu^2] \tag{25}$$

and use $E_\gamma^2 = p_\gamma^2 + m_\gamma^2$ to arrive at a solvable equation in E_γ .

$$\lambda = p_\gamma p_z + 500E_\gamma - EE_\gamma \tag{26}$$

$$[\lambda - (500 - E)E_\gamma] = p_\gamma p_z \tag{27}$$

$$[\lambda - (500 - E)E_\gamma]^2 = (E_\gamma^2 - m_\gamma^2)p_z^2 \tag{28}$$

$$\lambda^2 - 2\lambda(500 - E)E_\gamma + (500 - E)^2 E_\gamma^2 = p_z^2 E_\gamma^2 - p_z^2 m_\gamma^2 \tag{29}$$

$$[(500 - E)^2 - p_z^2]E_\gamma^2 - 2\lambda(500 - E)E_\gamma + (\lambda^2 + p_z^2 m_\gamma^2) = 0 \tag{30}$$

This can be solved with the quadratic formula to give,

$$E_\gamma = \frac{\lambda(500 - E) \pm \sqrt{\lambda^2(500 - E)^2 - [(500 - E)^2 - p_z^2][\lambda^2 + p_z^2 m_\gamma^2]}}{(500 - E)^2 - p_z^2} \tag{31}$$

$$= \frac{\lambda(500 - E) \pm p_z\sqrt{\lambda^2 - [(500 - E)^2 - p_z^2]m_\gamma^2}}{(500 - E)^2 - p_z^2} . \tag{32}$$

As expected, the solution with $m_\gamma = m_\nu = 0$ reduces to the previously calculated solution

$$\lambda = \frac{1}{2}[(500 - E)^2 - p^2 + \cancelto{0}{m_\gamma^2} - \cancelto{0}{m_\nu^2}] \tag{33}$$

$$E_\gamma = \frac{\lambda(500 - E) \pm p_z\sqrt{\lambda^2 - [(500 - E)^2 - p_z^2]\cancelto{0}{m_\gamma^2}}}{(500 - E)^2 - p_z^2} \tag{34}$$

$$= \frac{\lambda[(500 - E) \pm p_z]}{(500 - E)^2 - p_z^2} \tag{35}$$

$$= \frac{\frac{1}{2}[(500 - E)^2 - p^2]}{(500 - E) \mp p_z} \tag{36}$$

$$= \frac{(500 - E)^2 - p^2}{1000 - 2E \mp 2p_z} . \tag{37}$$

134 c.f. I. Marchesini

135 It can also easily be shown for this case that the two solutions correspond to ISR photons
136 travelling parallel or anti-parallel to the z axis. The $\mp$ in the denominator hence corresponds
137 to the sign of the photons z momentum,

$$E_\gamma = \frac{(500 - E)^2 - p^2}{1000 - 2E + 2sgn(p_\gamma)p_z} \tag{38}$$

138

$$E_\gamma = \frac{\lambda(500 - E) + sgn(p_\gamma)p_z\sqrt{\lambda^2 - [(500 - E)^2 - p_z^2]m_\gamma^2}}{(500 - E)^2 - p_z^2} \; . \tag{39}$$