Study of $WW \to qql\nu$ at ILC500 with ILD

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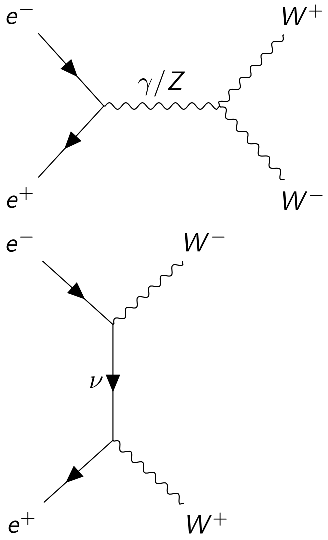
Introduction / Motivation



WW is a standard process with a large cross-section

- 15 pb in semileptonic channel at 500 GeV

Three central physics issues addressable by this channel are

- Dynamics of the charged triple gauge couplings
- Measurement of W boson mass, width, cross-section, and BR
- Beam polarization measurement

500 GeV Samples

Study here is at $\sqrt{s} = 500$ GeV

Total luminosity : 4000 fb^{-1}

Polarizations:

Pol.	(-0.8,+0.3)	(+0.8,-0.3)	(-0.8,-0.3)	(+0.8,+0.3)
Lum. [fb^{-1}]	1600	1600	400	400

Reco/Sim: `ILCSoftv02-00-02` `ILD_l5_o1_v02`

MC Background Samples (DBD)–

- 2-fermion
  - Z-bhabhag/hadronic/leptonic
- 4-fermion
  - singleW-leptonic
  - Zee/$\nu\nu$-leptonic/semileptonic
  - singleZsingleWMix-leptonic
  - WW-hadronic/leptonic
  - ZZ-hadronic/leptonic/semileptonic
  - ZZWWMix-hadronic/leptonic
- 6-fermion
  - eeWW, $\ell\ell$WW, $\nu\nu$WW, xxWW
  - ttbar
  - xxxxZ, yyyyZ
- SM Higgs
  - eeH, qqH, $\mu\mu$H, $\tau\tau$H, $\nu\nu$H

Note: signal events are split into WW-like and not WW-like events
events that contain an off shell W ($\pm 10 GeV$ to nominal mass) are considered to be not WW-like

Analysis Approach

Step 1-
Treat all lepton flavors universally
Identify signal lepton candidates with TauFinder

- Optimize TauFinder to efficiently find lepton jets based on decay signatures
- Simultaneously reject fake lepton jets from hadronic jets
- Examine 7 separate categories of lepton jets

Optimization Categories:

Prompt μ
Prompt e
Inclusive τ
$\tau \rightarrow \mu\nu_\mu\nu_\tau$
$\tau \rightarrow e\nu_e\nu_\tau$
$\tau \rightarrow$ hadronic (1-prong)
$\tau \rightarrow$ hadronic (3-prong)

Step 2-
With a selected lepton, treat the remaining system as hadronic components of $W \rightarrow qq$

Use y-cut and kinematic cuts on mini-jets to mitigate pileup ($\gamma\gamma$)

Step 3- Perform basic event selection for multiple polarization scenarios
Step 4- Obtain physics measurements

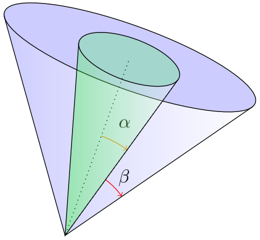
(1) TauFinder

TauFinder basic operation

- Seed lepton jet candidates with tracks ordered by $|P|$
- All particles within the search cone are added to the lepton jet
- Each candidate is subjected to acceptance conditions

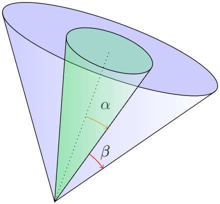
Operating Criteria/Acceptance Conditions

- **Search Cone Angle** α - The opening angle of the search cone for the lepton jet [rad]
- **Isolation Cone Angle** β - Outer isolation cone around the search cone of the lepton jet [rad]
- $\boxed{\textbf{Isolation Energy}}$ - The total energy allowed within the isolation cone region [GeV]
- Invariant Mass - The upper limit on lepton candidate mass [GeV]
- $0 <$ Max N Tracks ≤ 3



(1) TauFinder Optimization

Optimization of 3 parameters:
– SearchCone $\alpha \in [0, 0.15]$ rad with 0.01 rad steps
– IsolationCone $\beta \in [0, 0.15]$ rad with 0.01 rad steps
– IsolationEnergy $E_{iso} \in [0, 5.5]$ GeV with 0.5 GeV steps
For simplicity, fix invariant mass cut ≤ 2 GeV



Optimization metric definitions:

Efficiency for true leptons
using $WW \rightarrow qq\ell\nu$

$$\varepsilon_s = N_{matched}/N_{Stotal}$$

- $N_{matched} \geq 1$ candidate matched within 100 mrads of the Gen. lepton/visible components
- N_{Stotal} includes an acceptance cut with 3 visible Gen. fermions $|cos\theta| < 0.99$

Probability of fake leptons
using $WW \rightarrow qqqq$

$$P_{fake} = 1 - (1 - \varepsilon_b)^{\frac{1}{4}}$$

$$\varepsilon_b = N_b/N_{Btotal}$$

- P_{fake} = probability of 1 success(fake) given 1 trial(jet)
- $N_b \geq 1$ reconstructed lepton jet from all 4 jets
- N_{Btotal} includes an acceptance cut with 4 visible Gen. fermions $|cos\theta| < 0.99$

Optimal working point at:

$$\max[(1 - P_{fake})\varepsilon_s]$$

(1) TauFinder Optimization Results

Optimized against $qq\ell\nu$ and $qqqq$ samples with 100% $e_L^- e_R^+$ polarization

Channel	ε_s	$1 - P_{fake}$	% Matched	search-Cone [rad]	isoCone [rad]	isoE [GeV]
Prompt μ	0.905	0.974	0.992	0.03	0.15	3.0
Inclusive τ	0.736	0.943	0.958	0.07	0.15	4.5
$\tau \to \nu\nu\mu$	0.802	0.974	0.984	0.03	0.15	3.0
$\tau \to \nu\nu e$	0.781	0.963	0.981	0.05	0.15	3.5
τ Had-1p	0.707	0.943	0.951	0.07	0.15	4.5
τ Had-3p	0.709	0.930	0.937	0.07	0.15	5.5
Prompt e	0.839	0.961	0.970	0.04	0.15	4.0

- Trickier reconstruction suggests wider cones and more isolation energy
- Use two cones for analysis Prompt μ and Inclusive τ for a Tight and Loose selection
- Expect tight selection to best capture all high quality lepton candidates
- Loose selection should boost efficiency of hadronic τ

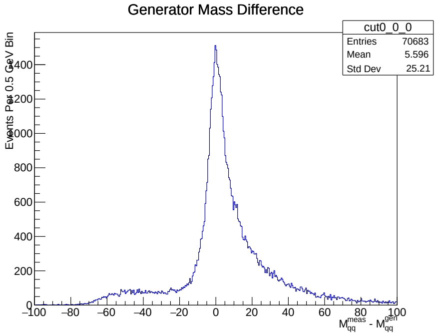
(2) Hadronic System

If a lepton has been found,

- select highest energy candidate as signal lepton
- shuffle remaining fakes back into the hadronic system.

At least one quark tends to be very forward, so pileup tends to mix into the jets

These beam particles cannot be cleanly removed by standard methods e.g. kT algorithm with tuned R values



100% $e_L^- e_R^+$ polarization
Measured mass is often larger than the true value

Mitigate Pileup with "Jet Fragmentation"

- tune y-cut($\propto M_{jet}^2$) values on the durham algorthim (eekt)
- apply simple cuts to the resulting "mini-jets"

(2) Optimized W Mass

Find best W jet parameters with signal prompt muons

Jet Clustering – yCut:$[1 \times 10^{-3}, 5 \times 10^{-6}]$

Kinematic cuts – $\begin{cases} pT : [0, 5] \text{ bins of } 0.5\text{GeV} \\ |cos\theta| : [0.9, 1] \ 0.01\text{bins} \end{cases}$

Use 2 optimization parameters from the $M_{qq}^{meas} - M_{qq}^{gen}$ dist.:

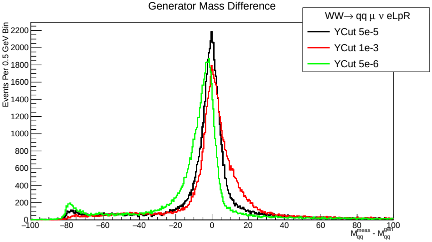
- Full Width Half Maximum (FWHM)
- Number of bin Entries in the Mode

The Mode Entries is the number of entries in the Maximum bin + the number of Entries of the nearest left/right neighbor bins
The Mode is the weighted mean of the center of the 3 Mode bins

The Maximum for the FWHM is the "Mode Average" or the average number of entries from the 3 mode bins

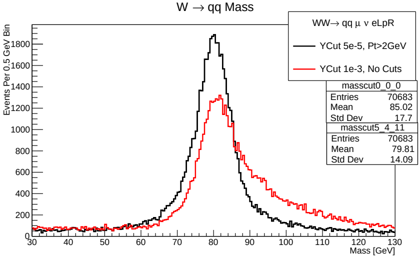
The edges of the Width for FWHM are the weighted average between the 2 bins around the half maximum (1 bin above 1 bin below)

(2) Hadronic System Results



Comparison of 3 YCuts with the same kinematic cuts Pt>2 GeV AND $|cos\theta| < 1$ (optimized for 5e-05)

Small peak around -80 GeV is where the W has been incorrectly thrown out



Significant Improvement !

Mass Difference Statistics:
ycut: 0.001 ptcut: 2 costcut: 1 FWHM: 11.769 RMS: 24.1855 Mode: -0.24211 mean: 0.782898 modeEnt: 5199
ycut: 5e-05 ptcut: 2 costcut: 1 FWHM: 9.7087 RMS: 25.2774 Mode: -0.25127 mean: -3.09776 modeEnt: 6326
ycut: 5e-06 ptcut: 2 costcut: 1 FWHM: 11.567 RMS: 25.7475 Mode: -1.75521 mean: -9.57673 modeEnt: 5475

Best Performance is reached with:

ycut= 5e-05 and removal of mini-jets with pT $<$ 2 GeV

(3) Event Selection Overview

Perform event selection with two mutually exclusive groups:
1st group will use μ cone (optimized for prompt muons)

- Tight selection will yield some efficiency ϵ_0 and purity p_0
- tight cuts will be targeted towards prompt signal leptons μ/e

2nd group will use the τ cone (optimized for inclusive τ decays)

- Loose selection will yield some efficiency ϵ_1 and purity p_1
- Loose cuts should address τs not reconstructed by muon cone
- orthogonalize selection require 0 tight leptons in loose selection

Overall efficiency $\epsilon = \epsilon_0 + \epsilon_1$

Overall purity $p = (N_0 + N_1)/(B_0 + B_1 + N_0 + N_1)$

Description of current cuts:(currently tight/loose are mostly the same)

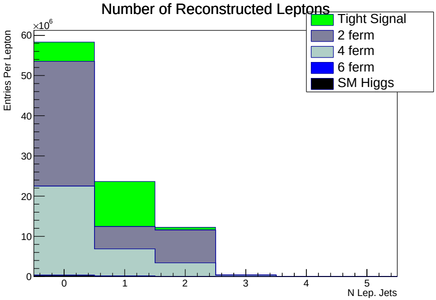
adapted from ref. I.MarchesiniDESY-THESIS2011

–Note reconstucted particles are boosted against crossing angle boost– (3.5 GeV in x)

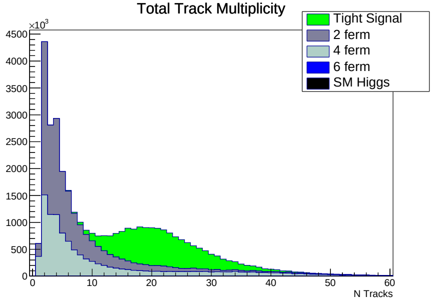
- **Lepton** - Require at least 1 reconstructed lepton
- **Track Multiplicity > 10** - more than 10 tracks in the event (Before pileup removal)
- **Pt > 5 GeV** - Reject events with no genuine missing Pt
- **$E_{vis} < 500$ GeV** Sum of the total visible energy in the event
- **$E_{com} > 100$ GeV** - Rest-frame energy with visible and inferred missing energy
  $E_{com} = E_{vis} + |P_{miss}|$ and $P^{\mu}_{miss} = (|P_{miss}|, -\sum \vec{p}_{vis})$
- **$40 < M_{qq} < 120$** - constrains hadronic system to be W-like
- **$-qcos\theta_W$** - limit the W^- backward scattering
- **$m^2_{\nu\, recoil} < 135,000$ GeV^2** - Require the visible system to recoil against a low mass object
  $m^2_{\nu\, recoil} = s + M^2_{vis} - 2\sqrt{s}E_{vis}$ and $M^2_{vis} = (P^{\mu}_{qq} + P^{\mu}_{\ell})^2$

(3) Event Selection (Tight)

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
All plots include an N Lepton $>$ 0 cut (except N Lepton plot)
Polarization: (-0.8,+0.3)   Luminosity: 1600 fb^{-1}



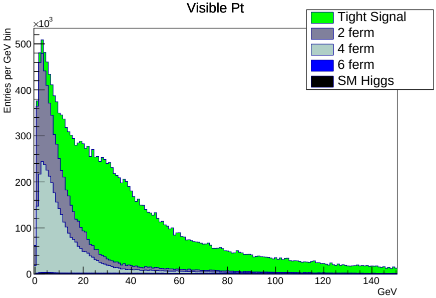
N Leptons $>$ 0

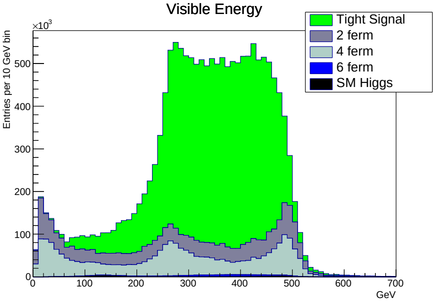


N Tracks $>$ 10

(3) Event Selection (Tight)

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
All plots include an N Lepton $>$ 0 cut
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}



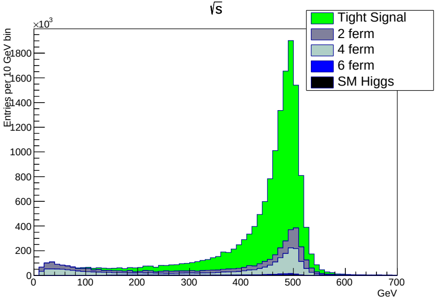


Visible Pt $>$ 5 GeV

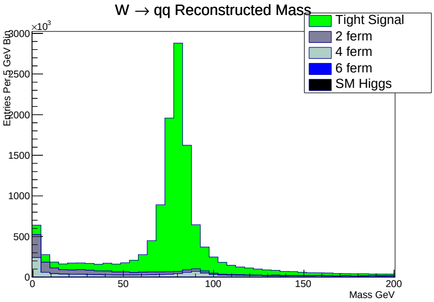
Visible Energy $<$ 500 GeV

(3) Event Selection (Tight)

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
All plots include an N Lepton $>$ 0 cut
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}



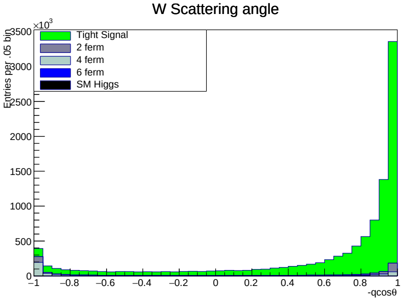
$E_{com} > 100$ GeV



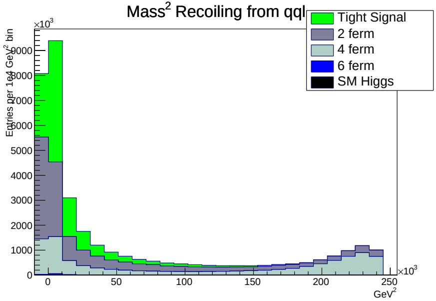
$40 < M_{qq} < 120$

(3) Event Selection (Tight)

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
All plots include an N Lepton > 0 cut
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}



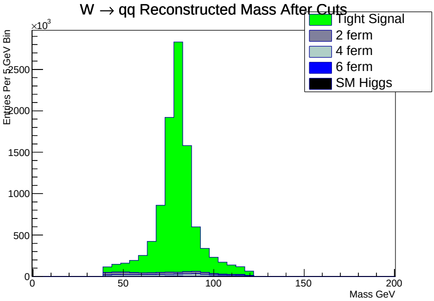
$-qcos\theta_W > -0.95$



$m^2_{\nu\, recoil} < 135,000$ GeV^2

(3) Event Selection – Example Distribution

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}
Example: Hadronic mass distribution after all event selection cuts



(3) Event Selection – “WW-like” Signal

Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}

Tight Selection with muon cone

	Prompt μ	Prompt e	τ	Tot. Sig.	2f	4f	6f	Higgs
Base Evts	3.87×10^6	3.89×10^6	3.90×10^6	1.17×10^7	4.22×10^7	3.22×10^7	2.14×10^5	4.12×10^5
Lepton	3.31×10^6	3.20×10^6	2.28×10^6	8.78×10^6	1.15×10^7	1.18×10^7	1.63×10^5	1.15×10^5
E_{vis}	3.28×10^6	3.11×10^6	2.27×10^6	8.67×10^6	1.06×10^7	1.15×10^7	1.62×10^5	1.11×10^5
N Tracks	3.19×10^6	3.03×10^6	2.21×10^6	8.43×10^6	2.54×10^6	2.59×10^6	1.49×10^5	8.89×10^4
$-qcos\theta$	3.18×10^6	3.01×10^6	2.18×10^6	8.37×10^6	2.19×10^6	2.26×10^6	1.44×10^5	8.52×10^4
$M_{qq} > 40$	2.94×10^6	2.80×10^6	2.03×10^6	7.77×10^6	1.13×10^6	1.33×10^6	1.42×10^5	7.56×10^4
$M_{qq} < 120$	2.72×10^6	2.57×10^6	1.83×10^6	7.13×10^6	5.68×10^5	2.68×10^5	2.02×10^4	2.97×10^4
E_{com}	2.72×10^6	2.57×10^6	1.83×10^6	7.13×10^6	5.58×10^5	2.65×10^5	2.02×10^4	2.96×10^4
Pt vis.	2.69×10^6	2.55×10^6	1.81×10^6	7.05×10^6	3.21×10^5	2.37×10^5	2.01×10^4	2.94×10^4
$m^2_{\nu recoil}$	2.69×10^6	2.54×10^6	1.80×10^6	7.03×10^6	2.93×10^5	2.02×10^5	1.94×10^4	2.23×10^4
ϵ	0.6944 ± 0.0024	0.6542 ± 0.0023	0.4616 ± 0.0027	0.6032 ± 0.0015	0.006941 ± 0.00012	$0.006255 \pm 7.6e-05$	0.09051 ± 0.00023	0.05407 ± 0.00045

Loose selection with tau cone

	Prompt μ	Prompt e	τ	Tot. Sig.	2f	4f	6f	Higgs
Base Evts	3.87×10^6	3.89×10^6	3.90×10^6	1.17×10^7	4.22×10^7	3.22×10^7	2.14×10^5	4.12×10^5
Lepton	3.36×10^6	3.30×10^6	2.82×10^6	9.48×10^6	1.30×10^7	1.36×10^7	1.77×10^5	1.38×10^5
Tight Lep. Veto	7.72×10^4	1.28×10^5	5.70×10^5	7.76×10^5	1.93×10^6	2.15×10^6	1.61×10^4	3.12×10^4
E_{vis}	7.64×10^4	1.26×10^5	5.70×10^5	7.72×10^5	1.82×10^6	1.94×10^6	1.54×10^4	3.02×10^4
N Tracks	7.37×10^4	1.21×10^5	5.54×10^5	7.49×10^5	1.50×10^6	1.64×10^6	1.51×10^4	2.71×10^4
$-qcos\theta$	6.30×10^4	1.12×10^5	5.32×10^5	7.07×10^5	1.11×10^6	1.41×10^6	1.45×10^4	2.56×10^4
$M_{qq} > 40$	4.92×10^4	9.72×10^4	4.86×10^5	6.33×10^5	5.98×10^5	1.30×10^6	1.44×10^4	2.33×10^4
$M_{qq} < 120$	4.04×10^4	7.81×10^4	4.16×10^5	5.35×10^5	2.58×10^5	1.11×10^5	1.11×10^3	1.24×10^4
E_{com}	4.04×10^4	7.81×10^4	4.16×10^5	5.34×10^5	2.50×10^5	1.10×10^5	1.11×10^3	1.24×10^4
Pt vis.	4.00×10^4	7.74×10^4	4.12×10^5	5.29×10^5	1.17×10^5	1.01×10^5	1.11×10^3	1.23×10^4
$m^2_{\nu recoil}$	3.94×10^4	7.70×10^4	4.07×10^5	5.24×10^5	1.02×10^5	7.59×10^4	1.02×10^3	9.73×10^3
ϵ	0.01017 ± 0.00053	0.01982 ± 0.00071	0.1046 ± 0.0018	0.04495 ± 0.00065	$0.002411 \pm 3.2e-05$	$0.002356 \pm 3.7e-05$	$0.004742 \pm 6.7e-05$	0.0236 ± 0.00024

(3) Event Selection – Not “WW-like” Signal

Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}
Signal events containing off-shell W
Signal events with at least 1 off off shell(O.S.) W are separated into a new category of not “WW-like” signal events

Tight Selection with muon cone

	Prompt μ O.S.	Prompt e O.S.	Tau O.S.
Base Evts	5.78×10^5	3.88×10^6	5.70×10^5
Lepton	5.11×10^5	2.27×10^6	3.42×10^5
E_{vis}	5.08×10^5	2.25×10^6	3.41×10^5
N Tracks	4.95×10^5	2.19×10^6	3.35×10^5
$-qcos\theta$	4.94×10^5	2.10×10^6	3.31×10^5
$M_{qq} > 40$	4.67×10^5	2.01×10^6	3.14×10^5
$M_{qq} < 120$	3.44×10^5	1.81×10^6	2.39×10^5
E_{com}	3.44×10^5	1.81×10^6	2.39×10^5
Pt vis.	3.40×10^5	1.80×10^6	2.36×10^5
$m^2_{\nu\, recoil}$	3.40×10^5	1.76×10^6	2.34×10^5
ϵ	0.5882 ± 0.006	0.4535 ± 0.0014	0.4108 ± 0.0063

Loose Selection with tau cone

	Prompt μ O.S.	Prompt e O.S.	Tau O.S.
Base Evts	5.78×10^5	3.88×10^6	5.70×10^5
Lepton	5.15×10^5	2.47×10^6	4.26×10^5
Tight Lep. Veto	8.18×10^3	2.61×10^5	8.83×10^4
E_{vis}	7.87×10^3	2.61×10^5	8.83×10^4
N Tracks	7.57×10^3	2.48×10^5	8.63×10^4
$-qcos\theta$	6.97×10^3	2.31×10^5	8.15×10^4
$M_{qq} > 40$	5.60×10^3	1.38×10^5	7.66×10^4
$M_{qq} < 120$	3.63×10^3	1.20×10^5	4.82×10^4
E_{com}	3.63×10^3	1.18×10^5	4.82×10^4
Pt vis.	3.63×10^3	1.18×10^5	4.77×10^4
$m^2_{\nu\, recoil}$	3.63×10^3	9.15×10^4	4.73×10^4
ϵ	0.006287 ± 0.0011	0.02358 ± 0.00046	0.08298 ± 0.0038

– selection is not that efficient for these types of events, and is not optimized to select these events

Event Selection Summary (LR)

(-0.8, +0.3) 1600 fb^{-}1

	Tight Selection			Tight + Loose Sel.		
	Sel. Total	Efficiency	Purity	Sel. Total	Efficiency	Purity
Bkg.	5.36e+05			7.25e+05		
Signal	4.49e+06	0.578 $\pm$ 0.002	0.893	4.93e+06	0.635 $\pm$ 0.002	0.872
Sig.+O.S.	6.93e+06	0.541 $\pm$ 0.001	0.928	7.47e+06	0.584 $\pm$ 0.001	0.912

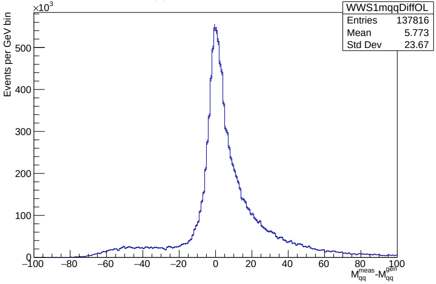
- Signal is only on-shell WW-like events
- Signal + O.S.(Off-Shell) includes both selections including the not WW-like signal events
- in LR we find ratio of S/B to be 1 order of magnitude
- Good efficiency and high purity for the signal case
- When adding O.S. events we only strengthen the purity, but efficiency drops because the events are not ideal for selection

With Sig.+O.S. and Tight + Loose Sel.

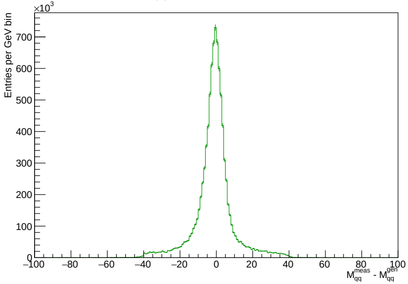
$\frac{\Delta\sigma}{\sigma}(stat.) = 0.04\%$

(4) W-Mass Measurement

Comparison of Generator mass differences
Polarization: (-0.8,+0.3)   Luminosity: 1600 fb^{-1}



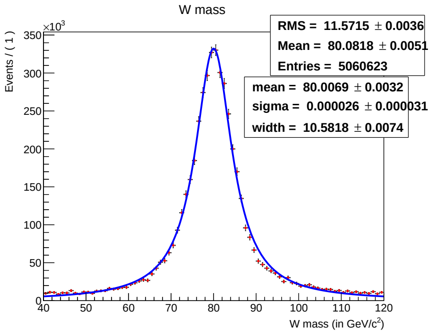
Before Event Selection and pileup removal

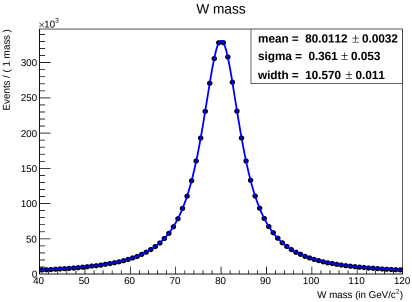


After Event selection and pileup removal

(4) W-Mass Measurement

Polarization: (-0.8,+0.3)   Luminosity: 1600 fb^{-1}
Tight Signal+O.S. μ, τ only





- Applied Voigtian fit to get a model for W-mass shape
- Poor fit, and statistical errors correspond to unweighted number of events

- Fit a toy model based on previous shape fit
- Uses statistics consistent with 1600 fb^{-1} (5.06M Events)
- $\Delta M_W(\text{stat.}) = 3.2\,\text{MeV}\ \ \chi^2/ndof = 52.2/77$

Summary

Completed Work:

- Performed a benchmarking analysis with $WW \rightarrow qq\ell\nu$
- Treated the leptons universally with TauFinder
- Rejected $\gamma\gamma$ pileup by fragmenting jets and making a Pt cut on the resulting mini-jets
- Performed a basic event selection for all polarizations for a total of 4000 fb^-1 of data
- Reported statistical errors ΔM_W and $\Delta\sigma$

TODO:

- Constrained fitting for W-mass and event selection improvements
- Study efficiency as a function of $cos\theta$ of the lepton
- Separate muonic taus and prompt muons using IP significance or constrained fits

Backup

(1) TauFinder Optimization

Optimization of 3 parameters:
– searchCone $\in [0, 0.15]$ rad with 0.01 rad steps
– isolationCone $\in [0, 0.15]$ rad with 0.01 rad steps
– isolationEnergy $\in [0, 5.5]$ GeV with 0.5 GeV steps
For simplicity, fix invariant mass cut at 3 GeV
Define optimization metrics:

Efficiency using $WW \rightarrow qqlnu$ for true leptons:
$\varepsilon_s = N_{matched}/N_{Stotal}$
– a tau candidate is considered matched within 100 mrads of the gen lepton
– if the gen lepton is a tau, the jet is matched to the gen visible components – excluding FSR
– N_{Stotal} is the Number of events with 3 visible gen fermions $|cos\theta| < 0.99$

fake leptons: Use $WW \rightarrow qqqq$
– $\varepsilon_b = N_b/N_{Btotal}$
N_b is any event with at least one reconstructed tau jet
4 quarks give 4 chances to create a tau jet ε_b
–Use a better tuning parameter P_{fake} which is the probability of reconstructing a tau jet from a single quark jet

$P_{fake} = 1 - (1 - \varepsilon_b)^{\frac{1}{4}}$
$\sigma_{P_{fake}} = \frac{1}{4}\sqrt{\frac{\varepsilon_b}{N_{Btotal}\sqrt{1-\varepsilon_b}}}$

The optimal working point is chosen from the two tuning parameters
$\max[(1 - P_{fake})\varepsilon_s]$

(3) Event Selection (Tight)

Performance of hadronic mass and W^- scattering angle
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1}
All cuts applied, tight selection only with μ, e, τ