Study of $WW \to qql\nu$ at the ILC

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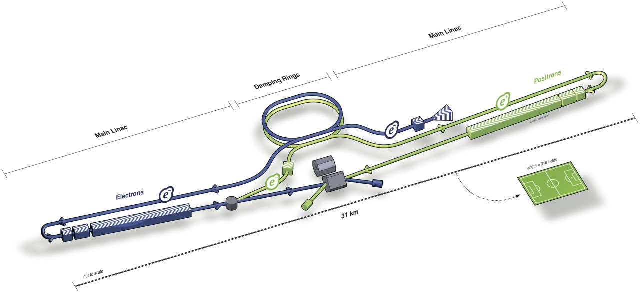
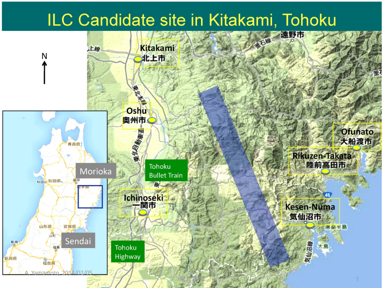
November 20, 2019

What is the ILC?

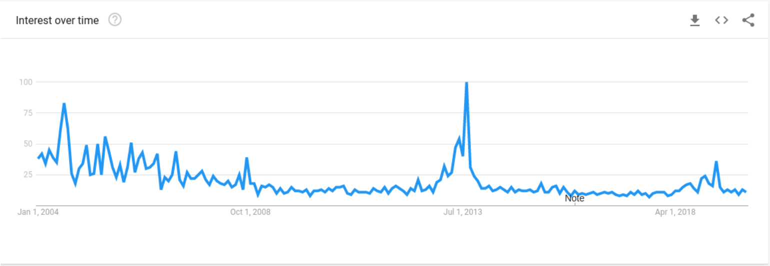


- A new e^+e^- linear collider
- Proposed cite in Japan
- Center of mass energy 250 GeV? 500 GeV? 0 GeV? – up to 1 TeV?
- Has tunable longitudinally polarized beams
- Single IP serviced by 2 detectors
- Currently in political limbo, will it get built???

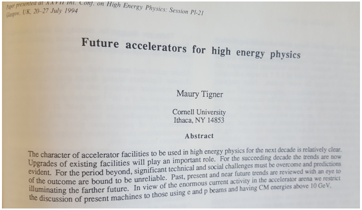


History of ILC

Google Trends "International Linear Collider" 2004-Present



- Origins predate Google history starting in 2004
- Linear collider discussed as next step for HEP as early as 1978
- Many early competing proposals: TESLA, NLC, CLIC, GLC, SLC (1994)
- ILC born from consolidating many proposals $\sim$ 2001



Paper presented at XXVII Int. Conf. on High Energy Physics: Session Pl-21
Glasgow, UK, 20–27 July 1994

Future accelerators for high energy physics

Maury Tigner

Cornell University
Ithaca, NY 14853

Abstract

The character of accelerator facilities to be used in high energy physics for the next decade is relatively clear. Upgrades of existing facilities will play an important role. For the succeeding decade the trends are now evident. For the period beyond, significant technical and social challenges must be overcome and predictions of the outcome are bound to be unreliable. Past, present and near future trends are reviewed with an eye to illuminating the farther future. In view of the enormous current activity in the accelerator arena we restrict the discussion of present machines to those using e and p beams and having CM energies above 10 GeV.

History of ILC

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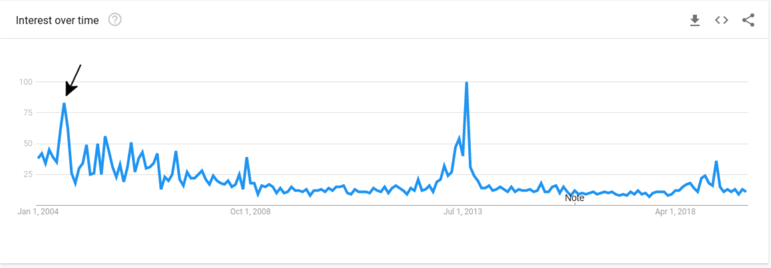
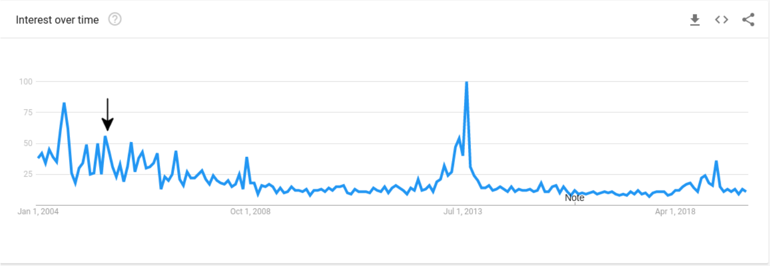


August 2004

- the International Technology Recommendation Panel (ITRP) recommended a superconducting radio frequency technology for the accelerator.
- This decision causes the Next Linear Collider (NLC), the Global Linear Collider (GLC) and Teraelectronvolt Energy Superconducting Linear Accelerator (TESLA) – to join their efforts (ILC)

History of ILC

Google Trends "International Linear Collider" 2004-Present



August 2005

- 2nd ILC Workshop, Snowmass Colorado – earliest web-documented planning for the development of the ILC
- LCnewsline founded, dedicated resource for news, milestones, and developments related to ILC
- No official host cite yet..

LC NEWSLINE
THE NEWSLETTER OF THE LINEAR COLLIDER COMMUNITY

History of ILC

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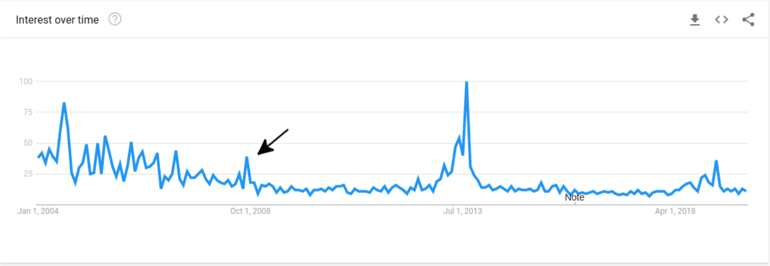

September 2008

- High Energy Physics in Philadelphia ICHEP 08
- Open house at KEK, Japan expresses interest in hosting ILC

History of ILC

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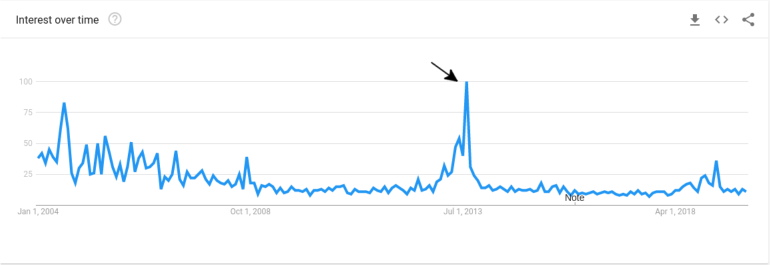
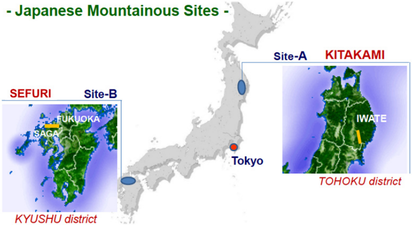


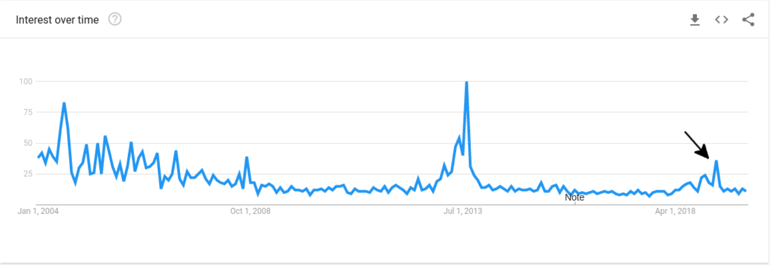
August 2013

- Japan announces candidate site for the ILC (Tohoku)
- Still expresses "interest in hosting" not guaranteeing hosting



History of ILC

Google Trends "International Linear Collider" 2004-Present

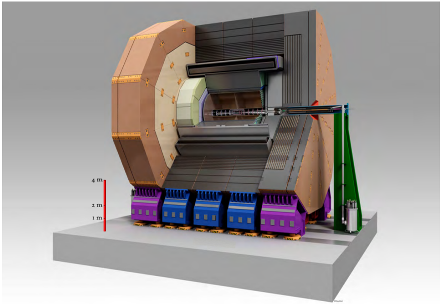


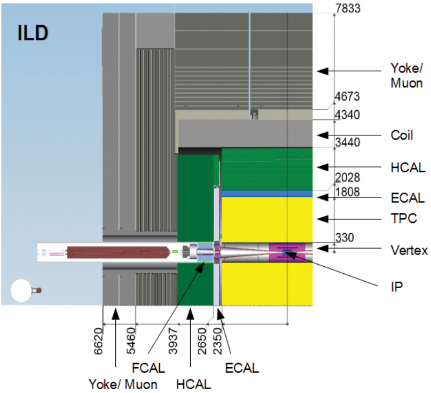
March 2019

- "The government has decided to not yet make a proposal to host the project, but has expressed interest in the ILC project and signalled to continue discussing it with other governments."
- Progress continues crawling forward
- Officially hosting requires negotiating costs with other governments

ILC Detector the ILD

The International Large Detector (ILD)





- Maximizes detector particle resolving power by being large
- 3.5T Magnetic Field
- Gaseous Tracker → bubble chamber-like tracks

Polarization primer

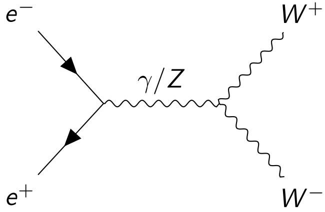
A key feature of ILC is beam polarization
Use beams to control physics – suppress or enhance certain processes which are sensitive to e/p helicity intital states

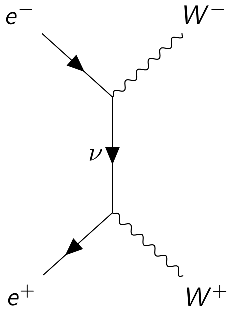
Example beam scenario : $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$
$P_{e^\pm}$ is related to the fraction of Left or Right handed electron/positrons in a beam

$P_{e^-} = -0.8$ means e^- beam is 90% L and 10% R
$P_{e^+} = +0.3$ means e^+ beam is 65$^{\%}$ R and 35% L

So.. in $(-0.8, +0.3)$
Most collisions will be between e^-_L and e^+_R (LR)
but sometimes the opposite occurs e^-_R and e^+_L (RL)
LL, RR is possible too (less important in WW)

Introduction / Motivation





- WW is a standard process with a large cross-section
- Semileptonic mode offers significant advantages over fully hadronic/leptonic modes
- Offers utility in both new physics potential and benchmarking detector performance
- 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 uses full simulation 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

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 most favorable polarization scenario

Step 4- Obtain physics measurements

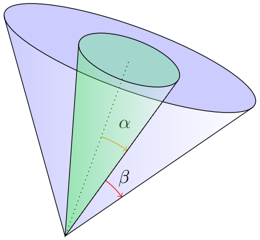
(1) TauFinder

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

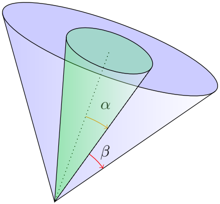
Operating Criteria/Acceptance Conditions

- **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]
- **Isolation Energy** - The total energy allowed within the isolation cone region [GeV]
- Invariant Mass - The upper limit on lepton candidate mass [GeV]
- $0 < \text{Max N Tracks} \leq 3$



(1) TauFinder Optimization

Optimization of 3 parameters
$\alpha \, , \beta \, , E_{iso}$
Fixed Mass ≤ 2 GeV



Maximize **Efficiency for true leptons**
using $WW \to qq\ell\nu$

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

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

Minimize **Probability of fake leptons**
using $WW \to qqqq$

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

$\varepsilon_b = N_b / N_{Btotal}$

- 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	n Lep ≥ 1	$1 - P_F$	ϵ_T	SearchCone [rad]	Iso.Cone [rad]	Iso.E [GeV]
Prompt μ	0.955 ± 0.003	0.974 ± 0.001	0.949 ± 0.003	0.03	0.15	3.0
Prompt e	0.920 ± 0.003	0.961 ± 0.001	0.904 ± 0.003	0.04	0.15	4.0
Inclusive τ	0.800 ± 0.005	0.943 ± 0.001	0.770 ± 0.006	0.07	0.15	4.5
$\tau \rightarrow \nu\nu\mu$	0.815 ± 0.012	0.974 ± 0.001	0.801 ± 0.013	0.03	0.15	3.0
$\tau \rightarrow \nu\nu e$	0.800 ± 0.012	0.963 ± 0.001	0.781 ± 0.013	0.05	0.15	3.5
τ Had-1p	0.744 ± 0.009	0.930 ± 0.002	0.707 ± 0.009	0.07	0.15	4.5
τ Had-3p	0.756 ± 0.015	0.930 ± 0.002	0.710 ± 0.016	0.07	0.15	5.5

- 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

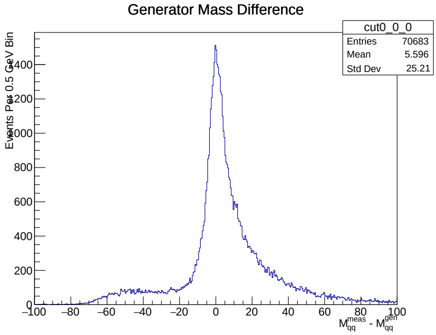
(2) Hadronic System

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”

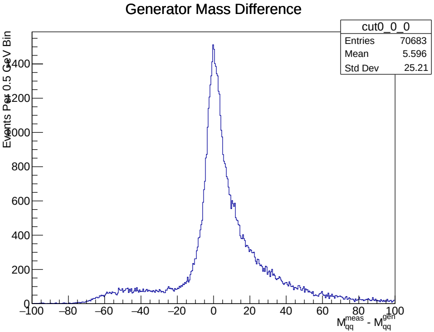
- tune y-cut($\propto M_{jet}^2$) values on the durham algorthim (eekt)
- apply simple cuts to the resulting “mini-jets”

(2) Optimized W Mass

Find best y-cut combined with kinematic cuts to optimize hadronic W mass

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

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

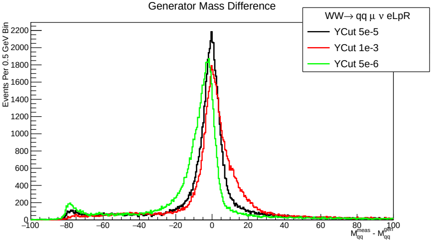


The Mode Entries is the number of entries in the Maximum bin + the number of Entries of the nearest left/right neighbor bins
The Mode is the weighted mean of the center of the 3 Mode bins

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

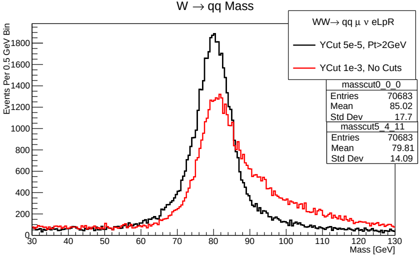
The edges of the Width for FWHM are the weighted average between the 2 bins around the half maximum (1 bin above 1 bin below)

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

Selection is optimized to maximize $\epsilon \cdot p$ for the subset of events where both fermion pairs are near the nominal W-mass

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 $M^2_{vis} = (P^{\mu}_{qq} + P^{\mu}_{\ell})^2$

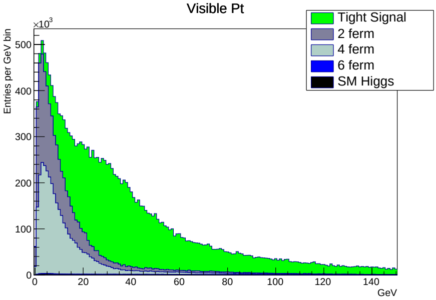
(3) Event Selection (Tight)

Example of the most powerful cuts:

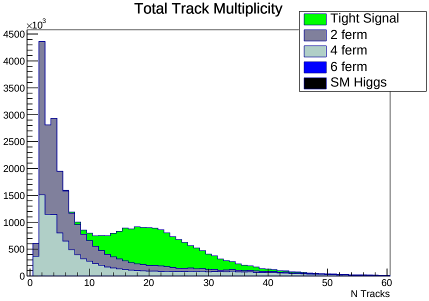
Tight Signal ⇒ muon cone for μ, e, τ signal events

All plots include an N Lepton $>$ 0 cut

Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1} (Includes off-shell types of events)



N Leptons $>$ 0

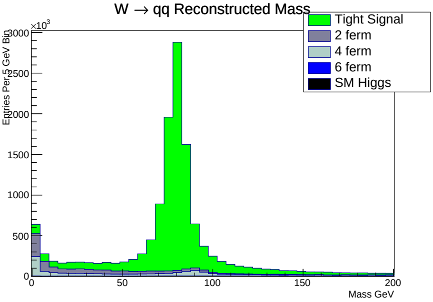


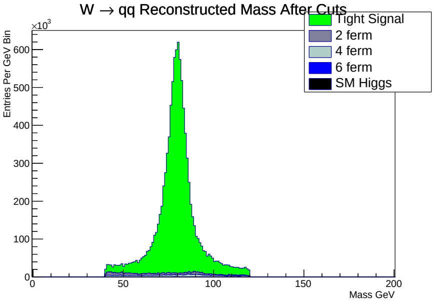
N Tracks $>$ 10

(3) Event Selection (Tight)

Hadronic Mass Before and After all cuts

Tight Signal $\Rightarrow$ muon cone for μ, e, τ signal events
Left plot includes an N Lepton > 0 cut
Polarization: (-0.8,+0.3) Luminosity: 1600 fb^{-1} (Includes off-shell types of events)





$40 < M_{qq} < 120$

(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

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

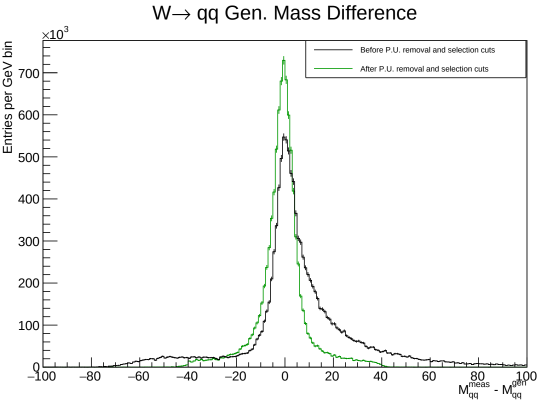
- Signal is only on-shell WW-like events
- Signal + O.S.(Off-Shell) includes both selections including the not WW-like signal events
- in LR we find ratio of S/B to be 1 order of magnitude
- Good efficiency and high purity for the signal case
- When adding O.S. events we only strengthen the purity, but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

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

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

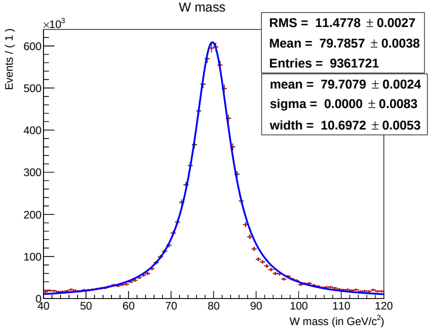
(4) W-Mass Measurement

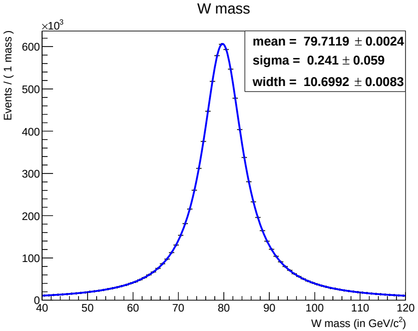
Comparison of Generator mass differences
Before & After pileup removal and selection cuts
Polarization: (-0.8,+0.3)   Luminosity: 1600 fb^{-1}



(4) W-Mass Measurement

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





- Applied Voigtian fit to get a model for W-mass shape
- Poor fit, and statistical errors correspond to unweighted number of events
- Fit params. $M_W = 79.7074$ GeV, width $\Gamma_W = 10.6972$ GeV and $\sigma_W = 4.847e-7$ GeV

- Fit a toy model based on previous shape fit
- Uses statistics of 1600 fb^{-1} (9M Events)
- $\Delta M_W(\text{stat.}) = 2.4\,\text{MeV}$ $\chi^2/ndof = 67.8/77$
- Estimate with good systematics $\rightarrow$ $\Delta M_W = 4.6$ MeV
- Current PDG value: $\Delta M_W = 12$ MeV

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 main polarization with 1600 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
- Do analysis at $\sqrt{s} = 250$ GeV

Future Plans:

- ILC progress doesn't grant much incentive to continue work
- Future focus: CMS exclusive
- compressed SUSY search w/ leptons, hopefully with new ML type approaches to analysis