

# Separation of hadronic $WW/ZZ$ decays at the ILC

## Research Practice Presentation

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**HELMHOLTZ**  
RESEARCH FOR GRAND CHALLENGES



# Outline

The International Linear Collider

The International Large Detector

Hadronic  $WW/ZZ$  decays

My plan

$WW/ZZ$  separation

Jet reconstruction

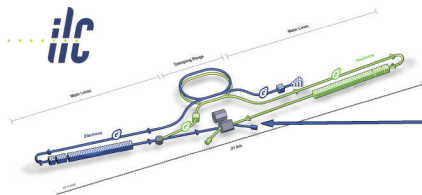
Jet corrections

$WW/ZZ$  separation as performance check

Summary



# The International Linear Collider (ILC)



ILCbeamline © SLAC National Accelerator Laboratory

- ▶ Future linear  $e^+e^-$  Collider:  
 $\sqrt{s} = 250 \text{ GeV}$  (First stage, extendable up to 1 TeV)
- ▶ Construction under political consideration  
 in the Kitakami mountains, Tōhoku region, Japan
- ▶ Both beams ( $e^+$ ,  $e^-$ ) are polarized:  $P_{e^-} = \pm 80\%$ ,  $P_{e^+} = \pm 30\%$



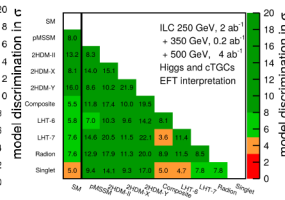
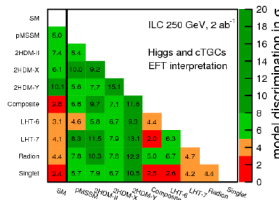
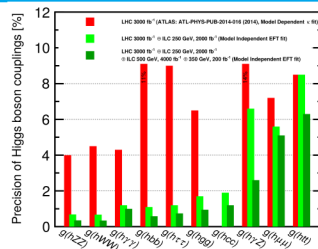
## THE TOHOKU REGION OF JAPAN



# ILC physics case

## Current running scenario: $2 \text{ ab}^{-1}$ @ 250 GeV

- ▶ Higgs factory
  - ▶ Model-independent measurements
  - ▶ Precision coupling measurements
- ▶ Precision electro-weak physics
  - ▶ Triple Gauge Couplings
  - ▶ BSM model discrimination
- ▶ New particles
  - ▶ Light scalar searches



## Extendable up to 1 TeV:

- ▶ Top physics
- ▶ Electroweak measurements  $\Rightarrow$  **Quartic Gauge Couplings**
- ▶ New particles
- ▶ ...

# Testing & Optimizing the physics case

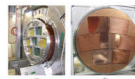
Currently severe lack of ILC data...

⇒ Physics studies based on **detector simulations**

- ▶ Highly detailed simulation using **Geant4**  
→ ATLAS, ALICE, ISS, LISA, ...  
([geant4.web.cern.ch](http://geant4.web.cern.ch))



- ▶ Simulation validated against R&D testbeam data



Recent developments:

- ▶ Geometry description switched to CERN-developed **DD4HEP**
- ▶ Detector & software optimizations
  - ▶ detector size
  - ▶ subdetector options (calorimeters types)
  - ▶ additional magnet structure

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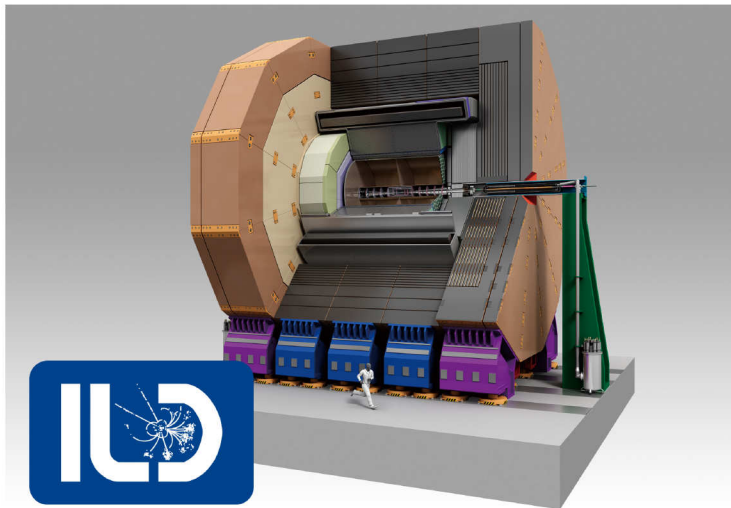
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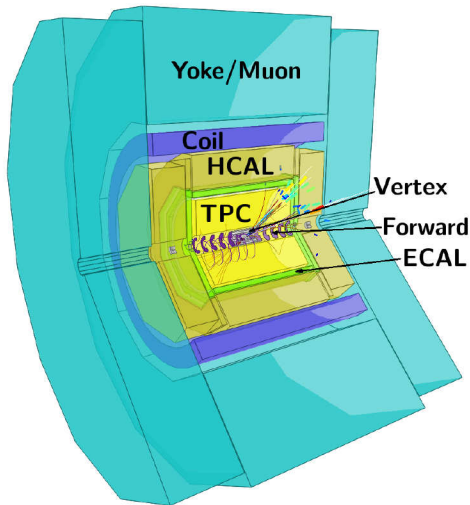


# The International Large Detector (ILD)



<http://www.linearcollider.org/images/>

# The International Large Detector (ILD)



- ▶ Optimized for:

**Particle Flow**  
and  
**precision physics**

- ▶ Particle Flow:  
Use only information from  
subdetector with best resolution
- ▶ Highly granular calorimeters
- ▶ Efficient tracking using Time  
Projection Chamber
- ▶ Full solid angle coverage

Figure :  $\nu\nu + 4\text{ jets}$  event in current ILD model.



## Electroweak precision at the ILD

- ▶ TPC + high-granularity calorimeters  
⇒ Cluster/Particle separation
- ▶ Particle Flow:
  - ▶ Find clusters & tracks  $\xrightarrow{\text{Combine}}$  Particles
  - ▶ Charged particle info from tracker + PID (not CALs!)
- ⇒ **Jet Energy Resolution (JER)  $\sim$  few %**
- ▶ Can separate hadronic  $W/Z$  decays! (BR $\sim$ 70%)  
→ Precision EW physics in hadronic final states

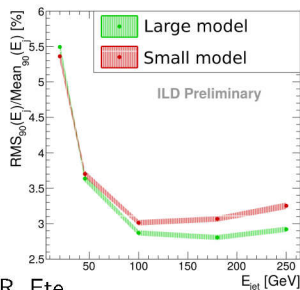


Figure : 250 GeV jet in the ILD  
[arXiv:1308.4537]

- ▶ Separate  $W$  and  $Z$  by invariant dijet mass  
→ Benchmark: **JER:  $\sigma_E/E \sim 3 - 4\%$**
- ▶ Tested in full detector MC simulation  
⇒ Achievable with current technology

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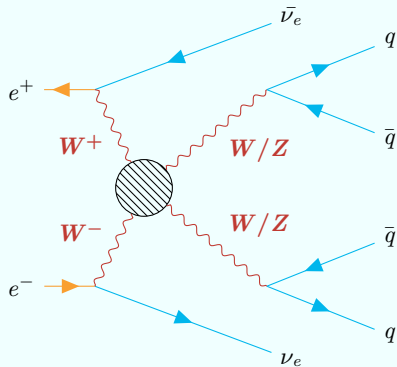
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$e^+e^- \rightarrow \nu\nu q\bar{q}q\bar{q}$ : physical motivation

Matrix Element (ME) for  $\nu\nu q\bar{q}q\bar{q}$  final state includes Vector Boson Scattering (VBS):



- ▶ In SM w/o Higgs:  $WW \rightarrow WW/ZZ$  scattering ME diverges at  $\sqrt{s} \geq 1.2$  TeV  $\Rightarrow$  Higgs restores unitarity
- ▶ If Higgs not SM-like: Scenarios of delayed unitarity restoration  $\rightarrow$  Test for BSM physics
- ▶ Semi-/Leptonic final states also possible, but:  $\text{BR}(W/Z \rightarrow q\bar{q}) \sim 70\%$
- ▶ Requires high  $\sqrt{s}$   $\Rightarrow$  Studies in this talk at  $\sqrt{s} = 1$  TeV  $\hookrightarrow$  Test of detector design

$\Rightarrow$  Study

$$e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q} \text{ at } \sqrt{s} = 1 \text{ TeV at the ILD}$$

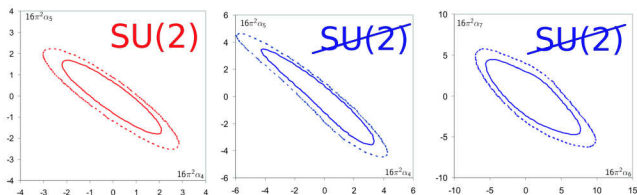
# VBS searches: What can be achieved?

Previous study (incl.  $WW \rightarrow WW/ZZ$  search) tested limit setting for EW extensions of SM w/ ILC [hep-ph/0604048]:

## Theory:

$$\mathcal{L}_0 = \mathcal{L}_{\text{SM}} + \sum_i \alpha_i \mathcal{L}_i^{\text{anomalous}}, \text{ e.g. } \mathcal{L}_4 = (\text{tr} \{ V_\mu V_\nu \})^2$$

**Results:** 1 TeV,  $1 \text{ ab}^{-1}$ , 80%  $e_L^-$ , 40%  $e_R^+$



## SU(2)

coupling	$\sigma^-$	$\sigma^+$
$\alpha_4$	-1.41	1.38
$\alpha_5$	-1.16	1.09

## SU(2)

coupling	$\sigma^-$	$\sigma^+$
$\alpha_4$	-2.72	2.37
$\alpha_5$	-2.46	2.35
$\alpha_6$	-3.93	5.53
$\alpha_7$	-3.22	3.31
$\alpha_{10}$	-5.55	4.55

**However:** Study from 2006  $\rightarrow$  old software, detector model, theory...  
 $\Rightarrow$  Needs updates...

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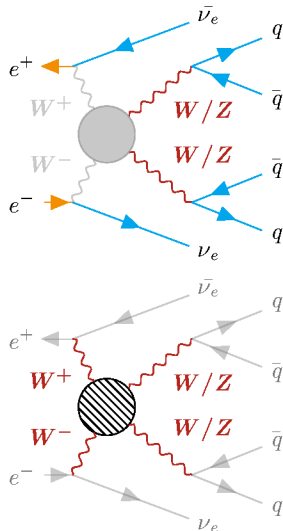
# Steps toward VBS analysis

## 1. $\nu\nu q\bar{q}q\bar{q}$ final state reconstruction → Investigate + optimize

- ▶  $WW/ZZ$  separation
- ▶ jet reconstruction

## 2. VBS analysis

- ▶ Analysis with full SM and overlay background
- ▶ Interpretation using Higgs EFT



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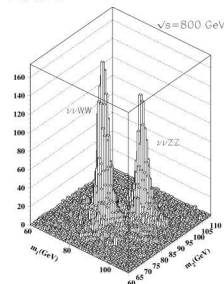


# Previous studies

Study has been performed before:

- ▶ 2001: Strong EWSB Singal in WW Scattering at TESLA (Chierici, Rosati, Kobel  [LC-PHSM-2001-038])
- ▶ 2009:  $\nu_e \bar{\nu}_e WW / \nu_e \bar{\nu}_e ZZ$  @ 1000 GeV for ILD Letter of Intent (Ward, Yan [arXiv:1006.3396])

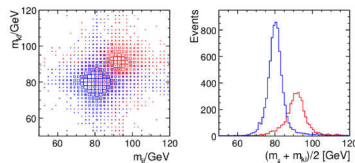
2001:



⇒ Follow the same **4 basics steps**:

1. Define  $WW/ZZ$  events in  $\nu\nu q\bar{q}q\bar{q}$  sample on generator level
2. Detector simulation & event reconstruction
3. Apply preselection for SM background reduction
4. Find invariant masses of the  $W/Z$  candidates

2009:





# Motivation for new study

**Goal:** Investigate separation of  $WW$  and  $ZZ$  in  $e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q}$  with new detector model, new software, new physics knowledge

1. Define  $WW/ZZ$  events in  $\nu\nu q\bar{q}q\bar{q}$  sample on generator level
2. Detector simulation & event reconstruction using *iLCSoft* ([github.com/iLCSoft](https://github.com/iLCSoft))
3. Apply preselection for SM background reduction
4. Find invariant masses of the  $W/Z$  candidates

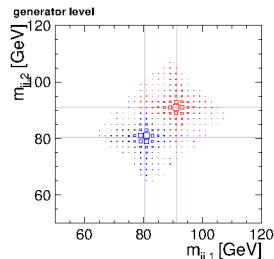
# WW/ZZ event definition

**Goal:** Investigate separation of  $WW$  and  $ZZ$  in  $e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q}$

## 1. Define $WW/ZZ$ events in $\nu\nu q\bar{q}q\bar{q}$ sample on generator level:

- Want events with  $q\bar{q}q\bar{q}$  from  $WW \rightarrow WW/ZZ$ , but samples use full  $\nu\nu q\bar{q}q\bar{q}$  ME
- Define  $WW \rightarrow WW/ZZ$  events on generator level:

- ▶ Incoming particles:  
 $e^-$  left-handed,  $e^+$  right-handed
- ▶ Quark flavours in agreement with  $WW/ZZ$
- ▶  $147.0 < m_{q\bar{q}}^1 + m_{q\bar{q}}^2 < 171.0$  ( $WW$ ),  
 $171.0 < m_{q\bar{q}}^1 + m_{q\bar{q}}^2 < 195.0$  ( $ZZ$ )
- ▶  $|m_{q\bar{q}}^1 - m_{q\bar{q}}^2| \leq 20.0 \text{ GeV}$
- ▶  $m_{\nu_e \bar{\nu}_e} \geq 100.0 \text{ GeV}$



**Figure :** 2D di-quark mass distributions for events classified as  $WW$  or  $ZZ$  (normalized).

2. Detector simulation & event reconstruction using *iLCS*oft ([github.com/iLCSOft](https://github.com/iLCSOft))
3. Apply preselection for SM background reduction
4. Find invariant masses of the  $W/Z$  candidates

# Find $W/Z$ invariant masses

**Goal:** Investigate separation of  $WW$  and  $ZZ$  in  $e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q}$

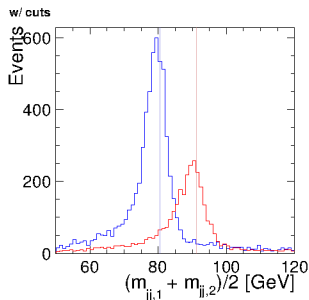
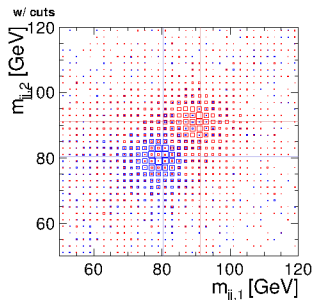
1. Define  $WW/ZZ$  events in  $\nu\nu q\bar{q}q\bar{q}$  sample on generator level
2. Detector simulation & event reconstruction using *iLCSoft* ([github.com/iLCSoft](https://github.com/iLCSoft))
3. Apply preselection for SM background reduction
4. Find invariant masses of the  $W/Z$  candidates
  - Use reconstructed particle to calculate invariant masses of  $W/Z$  candidates
    - ▶ Cluster particles into 4 jets
    - ▶ Pair up jets into 2 boson-dijet candidates by minimizing  $|m_{jj,1} - m_{jj,2}|$
    - ▶ Plot boson masses  $m_{jj}$  for ( $WW$ ) and ( $ZZ$ ) events

# WW/ZZ separation plots

## 4. Find invariant masses of the $W/Z$ candidates:

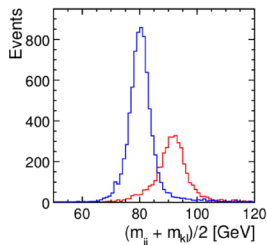
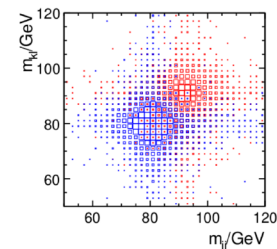
→ Use reconstructed particle to calculate invariant masses of  $W/Z$  candidates

- ▶ Cluster particles into 4 jets
- ▶ Pair up jets into 2 boson-dijet candidates by minimizing  $|m_{jj,1} - m_{jj,2}|$
- ▶ Plot boson masses  $m_{jj}$  for ( $WW$ ) and ( $ZZ$ ) events
- ▶ Lumi:  $\mathcal{L} = 1 \text{ ab}^{-1}$ , Polarisation:  $P_{e-} = -80\%$ ,  $P_{e+} = +30\%$



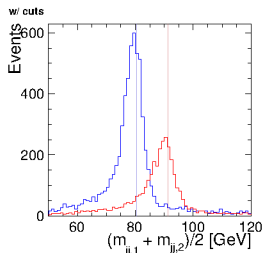
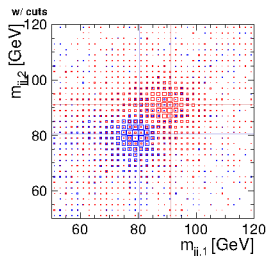
- ▶ **Good separation** of  $WW$  and  $ZZ$  peaks.
- ▶ **Shifted mass peaks** wrt. boson masses  
→ ?
- ▶ **Long tails** to high and low  $m_{jj}$   
→ ?

# Recreation of performance plots



## Letter of Intent

- ▶ Well-separated and resolved WW and ZZ peaks



## Own analysis

- ▶ Distribution tails (not observed in Lol)
- ▶ Mass peaks shifted wrt. boson masses

# Performance plots - Tail regions

First try: Cause for tail regions?

- ▶ Tested for **ISR effects**  
→ How much of detected energy linked to ISR?
- ▶ Tested for **detector region** using  $V$  ( $W/Z$ ) boson angle  
→ Is mass tail angle specific?
- ▶ Tested **jet pairing**  
→ Does my jet pairing method cause the tails?

⇒ **No cause found** → look into **jets!**

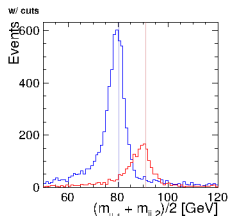


Figure : Using own pairing method.

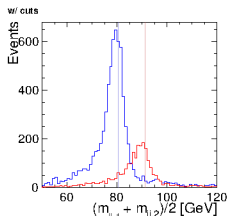
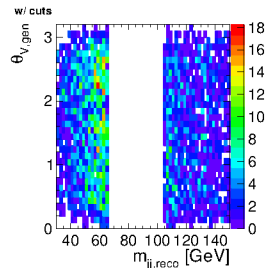
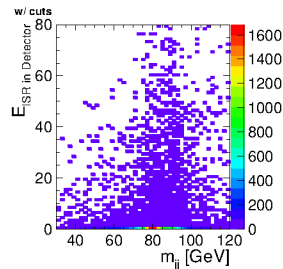


Figure : Using Lol pairing method.



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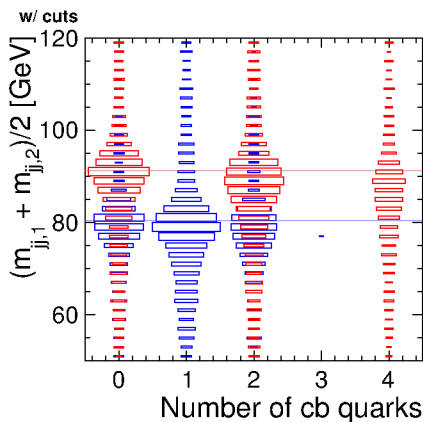
Summary



# Influence of heavy quarks

**Conjecture:** Mass peak shifted due to energy lost to neutrinos  
 $\Rightarrow$  Dominant in heavy quark jets

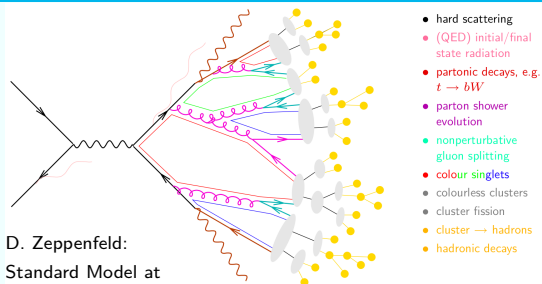
$\rightarrow$  Test influence of number of  $c$  and  $b$  quarks on reconstructed  $m_{jj}$  distributions



- ▶ Plot:
  - ▶  $WW$  &  $ZZ$  event definition on generator level
  - ▶ reconstructed  $m_{jj}$
- ▶ Heavy quarks shift mass peaks  
 $\Rightarrow$  Further investigation!
- ▶ Even without heavy quarks tail remains



# The TrueJet processor

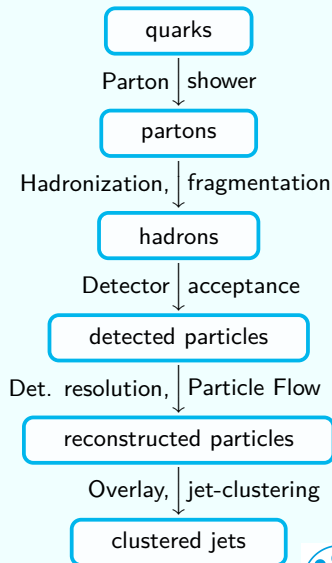


D. Zeppenfeld:  
Standard Model at  
Hadron Colliders  
(Lecture 2005)

## ► TrueJet:

- Processor within *iLCSOft*
- Use MC/simulation information to check parton/jet information on intermediate stages of event measurement

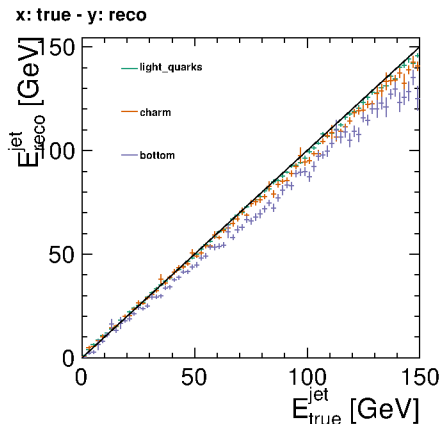
⇒ Distinguish clustering, detector resolution, detector acceptance, ...



# Comparing MC and Reconstructed

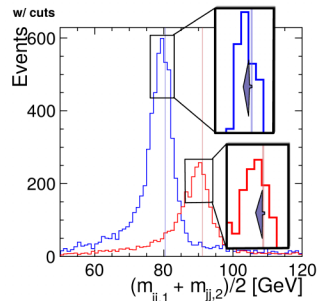
Deeper look into influence of **jet flavour**:

- ▶ Individual jet  $\rightarrow$  flavour of  $q$  origin (generator level)  
 $\rightarrow E_{jet}$ : generator level VS reconstructed



$\Rightarrow$  **b jets**: Reconstructed  $E_{jet}$  underestimated and stronger fluctuating

$\rightarrow$  Again: **Hint to  $\nu$ 's**



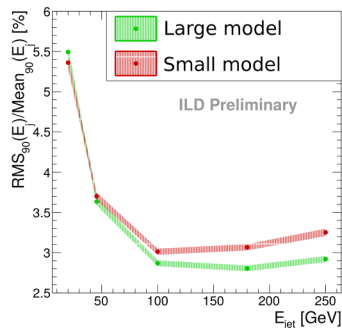
# Jet flavour influencing Jet Energy Resolution

How is  $\sigma_E/E$  influenced by jet flavour ( $\rightarrow \nu$ 's)?

$\Rightarrow$  Use TrueJet for **physical approach to JER**

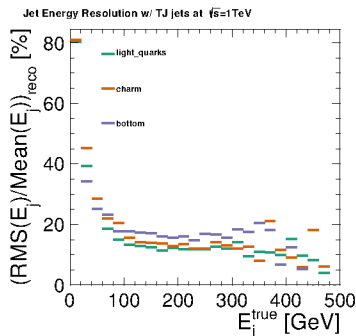
## ► JER plots so far:

- JER from **total energy** in  $uds$  dijet-event (not individual  $E_{jet}$ )
- *Truncated mean/sigma*: Used inner 90% of  $E$  distribution



## ► With TrueJet:

- Compare true and reconstructed  $E_{jet}$  for **individual jets**!
- Only clustering cheated unphysically ( $\rightarrow$  study separately)



# Cheating jet-clustering and pairing w/ TrueJet

**From generator level:**  $q$  colour information  $\Rightarrow$  Colour neutral  $\{q\bar{q}\} = W/Z$

- ▶ Take jets linked to initial colour neutrals

$\rightarrow$  Cheat jet clustering and jet pairing = realistic detector + ideal algorithm

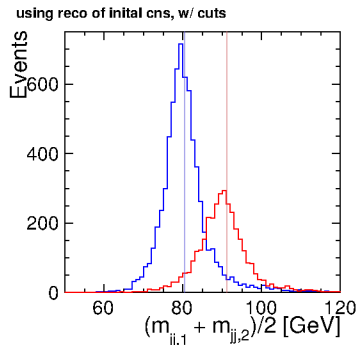
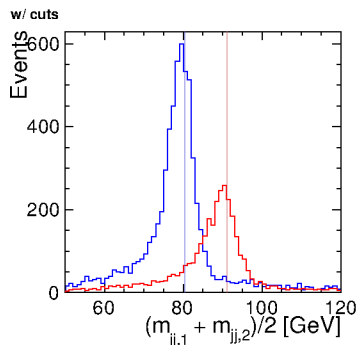


Figure : Own jet-clustering and jet pairing. Figure : TJ-cheated jet-clustering and pairing.

$\Rightarrow$  Tails seem to be problem with my jet-clustering/-pairing!

# Results of jet investigation

So why the difference to Letter of Intent?

- ▶ **Mass peaks:** originating from heavy quarks
  - **Difference to Lol:** No  $b$  quarks in samples!
- ▶ **Tails:** originating from jet-clustering
  - **Difference to Lol:** Different clustering algorithm!
    - ▶ Lol: Undocumented → possibly cheated
    - ▶ Here:  $e^+e^- k_T$  algorithm

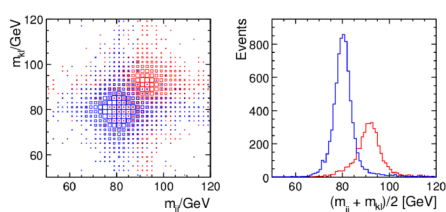


Figure : Letter of Intent results.

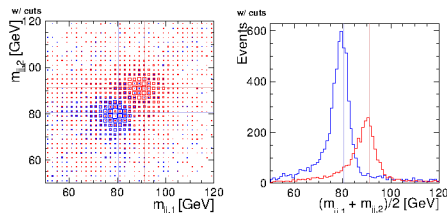


Figure : Own results.

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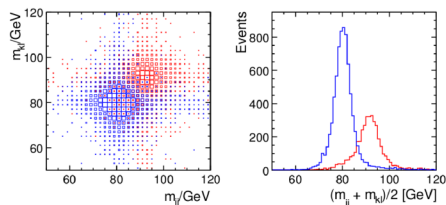


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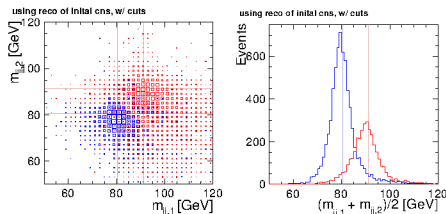


Figure : Own, jet clustering & pairing cheated

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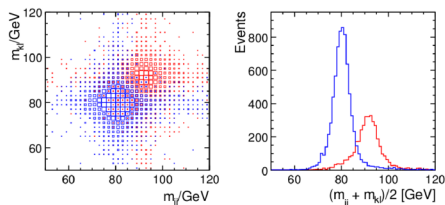


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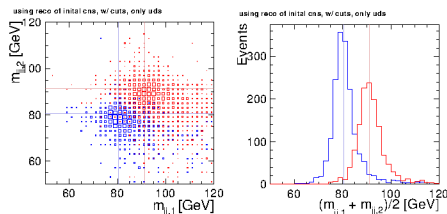


Figure : Own, jets cheated, uds only.

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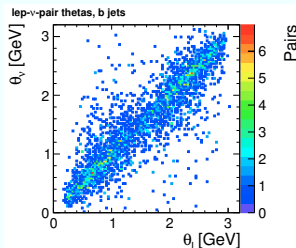
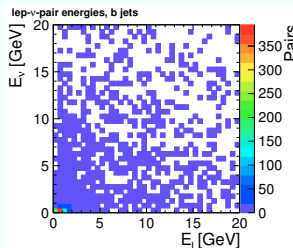
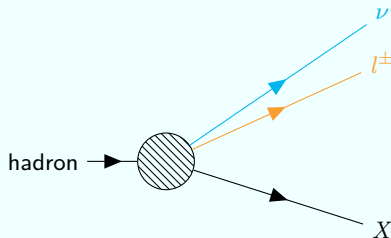
# Neutrino corrections

Hadron in jet gives off  $l^\pm \nu$  pair

→ **Correctable** if:

- ▶  $l^\pm$  found
- ▶ Secondary vertex found
- ▶  $X$  found
- ▶ Assumptions about initial hadron possible

⇒ Investigate  $l\nu$  pairs in TrueJet jets



▶ No simple correction possible

→ Find visible particles & secondary vertex  
+ assume hadron mass

⇒ **Reconstruct  $\nu$**

# Outline

The International Linear Collider

The International Large Detector

Hadronic  $WW/ZZ$  decays

My plan

$WW/ZZ$  separation

Jet reconstruction

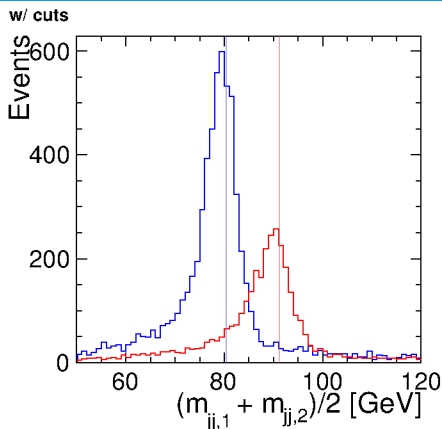
Jet corrections

$WW/ZZ$  separation as performance check

Summary



# Making a $WW/ZZ$ separation plot



## Recipe for this plot:

1.  $\nu\nu q\bar{q}q\bar{q}$  event generation
2. Detector simulation
3. Particle reconstruction
4. Event analysis

⇒ When run in full: **Test** for

detector model

+

simulation & reconstruction software!

Ongoing detector & software developments:

→ Use such plots for **model / version validation**

⇒ *iLCSoft* contains **ILDPerformance** package ([github.com/iLCSoft/ILDPerformance](https://github.com/iLCSoft/ILDPerformance))

**Goal:** **Standardized algorithms** for performance plots!

# WW/ZZ in ILDPerformance

Implemented script into ILDPerformance to run:

- ▶ Detector simulation → [DDSim](https://github.com/iLCSoft/lcgeo) (github.com/iLCSoft/lcgeo)
- ▶ Event reconstruction → [PandoraPFA](https://github.com/PandoraPFA) (github.com/PandoraPFA) & [ILDConfig](https://github.com/iLCSoft/ILDConfig) (github.com/iLCSoft/ILDConfig)
- ▶ WW/ZZ analysis → [Marlin](https://github.com/iLCSoft/Marlin) (github.com/iLCSoft/Marlin)

on existing generator files with simple command.

## Problem:

- ▶ simulation + reconstruction =  $\sim 5$  min/event
- ▶ need  $\sim 30$ k events

**Solution:** Run sim+reco distributed on grid with [ILCDirac](https://github.com/iLCSoft/ILCDirac)

(A Tsaregorodtsev, 2010 J. Phys.: Conf. Ser. 219 062029)

⇒ Get plot starting from generator file within few hours!

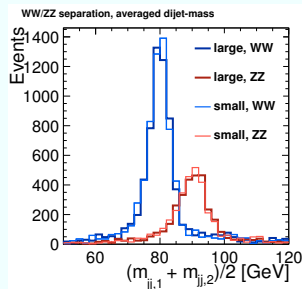


Figure : Plot with current software & detector model.

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Summary



$$e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q} \text{ at } \sqrt{s} = 1 \text{ TeV at the ILD}$$

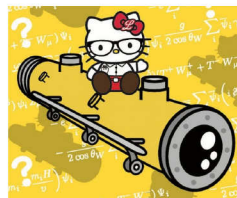
## So far:

- ▶ Investigated  $WW/ZZ$  separation
  - ▶ recreated previous studies
  - ▶ found deviations: shifted mass peaks + long tails
- ▶ Studied causes for deviations
  - ▶ Causes found in jet reconstruction
  - ▶ Shifted mass peak from  $\nu s$  in  $b$  jets
  - ▶ Tails from jet-clustering
- ▶ Started work on  $\nu$  correction
- ▶ Implemented  $WW/ZZ$  separation as performance check in *ILDPerformance*

## Plan:

- ▶ Build jet corrections ( $\nu$ , JES)
- ▶ VBS analysis using complete Standard Model background

Thanks for your attention!



# BACKUP





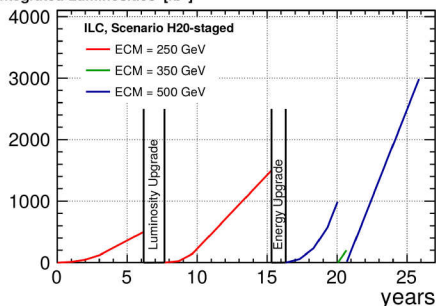
# ILC-250 staging

Staging scenario changed from Technical Design Report (TDR, ILC-500)

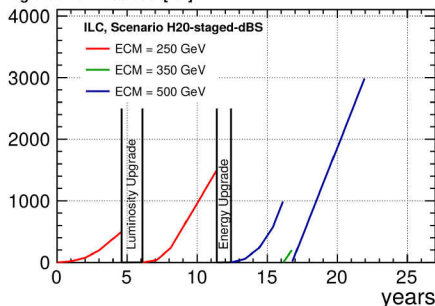
⇒ 2 possibilities (cost-neutral):

- ▶ Beam parameters as for ILC-500
- ▶ More aggressive beam parameters → Higher lumi, slightly more beamstrahlung

Integrated Luminosities [ $\text{fb}^{-1}$ ]

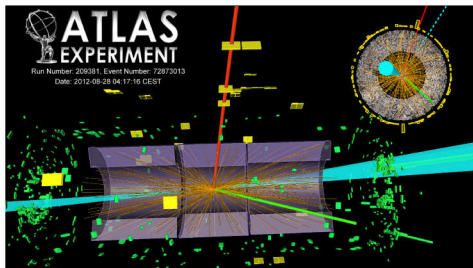


Integrated Luminosities [ $\text{fb}^{-1}$ ]



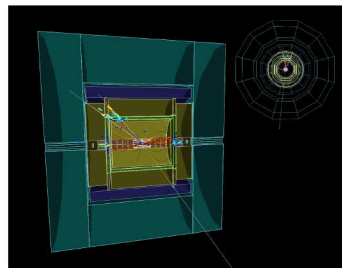
**Goal:** Investigate separation of  $WW$  and  $ZZ$  in  $e^+e^- \rightarrow \nu\nu WW/ZZ \rightarrow \nu\nu q\bar{q}q\bar{q}$

1. Define  $WW/ZZ$  events in  $\nu\nu q\bar{q}q\bar{q}$  sample on generator level
2. Detector simulation & event reconstruction using *iLCSoft* ([github.com/iLCSoft](https://github.com/iLCSoft))
3. Apply preselection for SM background reduction:
  - apply cuts as in previous work (ILD Letter of Intent arXiv:1006.3396):
    - ▶ Cuts on jet content to reject  $t\bar{t}$  events
    - ▶  $Y_{34} > 0.0001 \rightarrow$  Event does not have less than 4 jets
    - ▶ Suppress 2- and 4-fermion and  $ZWW/ZZZ$  ( $Z \rightarrow \nu\nu$ ) background using  $m_{\text{missing}}$ ,  $E_{T,\text{visible}}$  and  $p_{T,\text{visible}}$
    - ▶ Missing momentum not from particles going to beam pipe
    - ▶ Suppress ISR- $\gamma \rightarrow$  hadrons events using highest energetic track
    - ▶ Reject  $t\bar{t} \rightarrow b\bar{b}q\bar{q}l\nu$  using cone around most energetic track
4. Find invariant masses of the  $W/Z$  candidates



[https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-160/figaux\\_03.png](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-160/figaux_03.png)

- ▶ Several interactions / bunch crossing (average  $\sim 30-40$ )
- ▶ Background from other partons and other interactions



- ▶ average of 1 interaction per bunch crossing
- ▶ Background from beamstrahlung  $\Rightarrow$  pair production,  $\gamma\gamma \rightarrow$  hadrons
- ▶ background events are generated separately and overlayed onto samples

$\Rightarrow$  *overlay*

# Impact parameter resolution

Need to find **secondary vertex** to reconstruct  $\nu$ 's

⇒ Requires good **vertex position resolution!**

