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

## Research Practice Presentation

Jakob Beyer [1,2],
Michael Kobel [2], Jenny List [1]

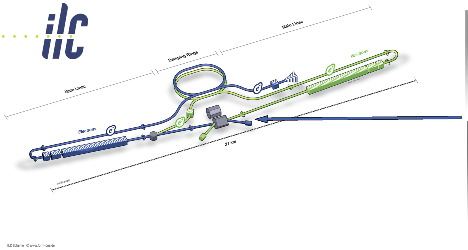
[1] DESY Hamburg

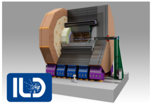
[2] Technische Universität Dresden

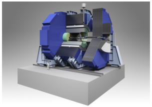
April 23, 2018

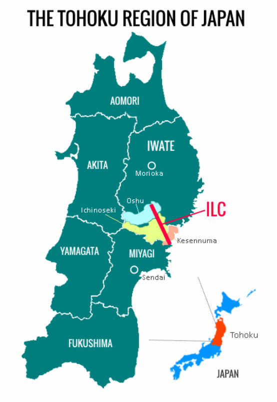
# Outline

# The International Linear Collider (ILC)



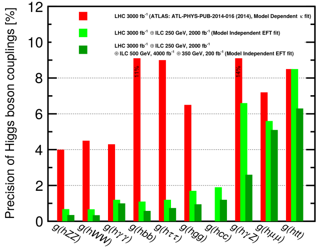


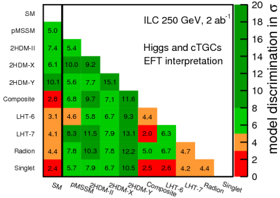

- Future linear $e^+e^-$ Collider:
  $\sqrt{s} = 250\,\text{GeV}$ (First stage, extendable up to $1\,\text{TeV}$)
- Construction under political consideration
  in the Kitakami mountains, Tōhoku region, Japan
- Both beams ($e^+$, $e^-$) are polarized: $P_{e^-} = \pm 80\%, \quad P_{e^+} = \pm 30\%$

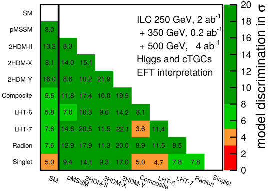
# ILC physics case

**Current running scenario:** $2\,\mathrm{ab}^{-1}$ @ $250\,\mathrm{GeV}$

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



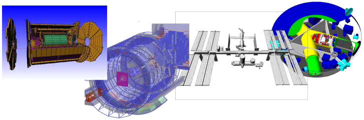

**Extendable up to $1$ TeV:**

- Top physics
- Electroweak measurements ⇒ **Quartic Gauge Couplings**
- New particles
- ...

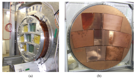
# Testing & Optimizing the physics case

Currently severe lack of ILC data...
$\Rightarrow$ Physics studies based on **detector simulations**

- Highly detailed simulation using **Geant4**
  $\rightarrow$ ATLAS, ALICE, ISS, LISA, ...
  (geant4.web.cern.ch)



- Simulation validated against R&D testbeam data

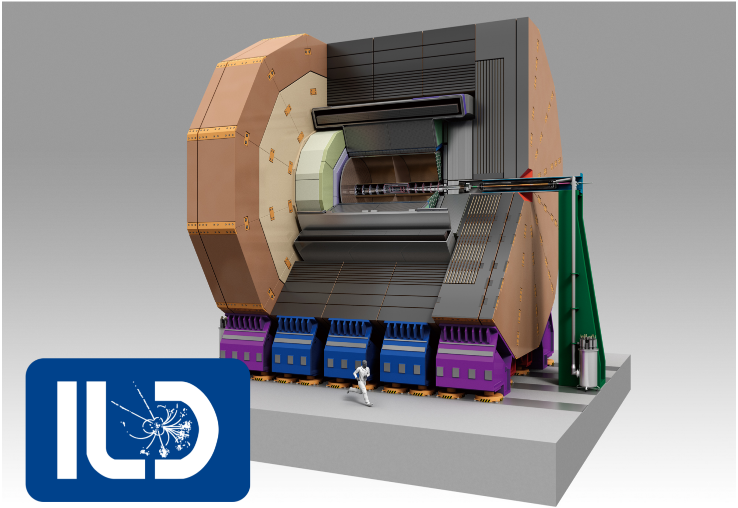


Recent developements:

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

# Outline

# The International Large Detector (ILD)



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

# The International Large Detector (ILD)

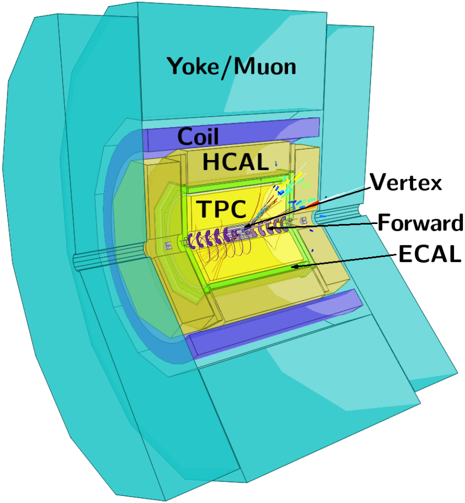



Figure : $\nu\nu + 4$ jets event in current ILD model.

- 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

# Electroweak precision at the ILD

- TPC + high-granularity calorimeters
  $\Rightarrow$ Cluster/Particle separation
- Particle Flow:
  - Find clusters & tracks $\xrightarrow{\text{Combine}}$ Particles
  - Charged particle info from tracker + PID (not CALs!)

  $\Rightarrow$ **Jet Energy Resolution (JER) $\sim$ few %**
- Can separate hadronic $W/Z$ decays! (BR$\sim$70%)
  $\rightarrow$ Precision EW physics in hadronic final states

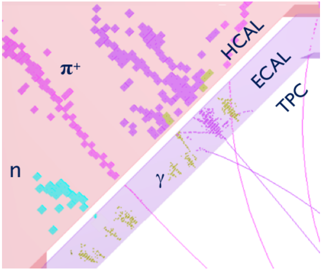
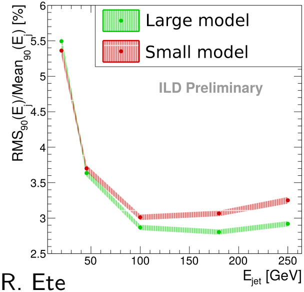



Figure : 250 GeV jet in the ILD [arXiv:1308.4537]




R. Ete

- Separate $W$ and $Z$ by invariant dijet mass

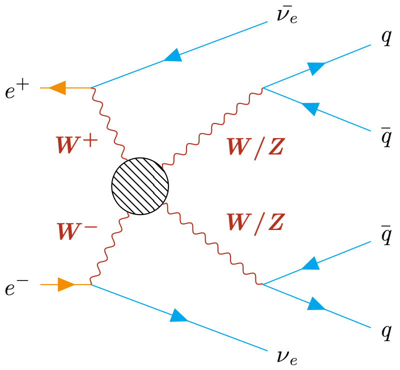
  $\rightarrow$ Benchmark: JER: $\sigma_E/E \sim 3-4\%$
- Tested in full detector MC simulation

  $\Rightarrow$ Achievable with current technology

# Outline

# $e^+e^- \longrightarrow \nu\nu q\bar{q}q\bar{q}$: 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: **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

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

# VBS searches: What can be achieved?

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

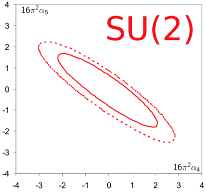
**Theory:**

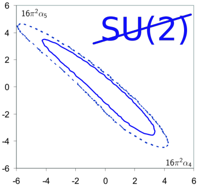
$$\mathcal{L}_0 = \mathcal{L}_{\text{SM}} + \sum_i \alpha_i \mathcal{L}_i^{\text{anomalous}} \text{ , e.g. } \mathcal{L}_4 = (\text{tr}\{V_\mu V_\nu\})^2$$

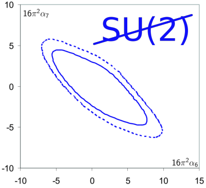
SU(2)

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

**Results:** $1\,\text{TeV},\ 1\,\text{ab}^{-1},\ 80\% e^-_L,\ 40\% e^+_R$




~~SU(2)~~

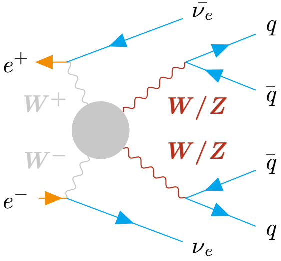
| coupling | $\sigma-$ | $\sigma+$ |
|---|---|---|
| $\alpha_4$ | -2.72 | 2.37 |
| $\alpha_5$ | -2.46 | 2.35 |
| $\alpha_6$ | -3.93 | 5.53 |
| $\alpha_7$ | -3.22 | 3.31 |
| $\alpha_{10}$ | -5.55 | 4.55 |

However: Study from 2006 → old software, detector model, theory...
⇒ Needs updates...

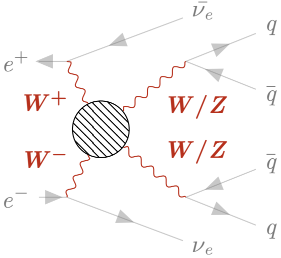
# Outline

# Steps toward VBS analysis

1. $\nu\nu q\bar{q}q\bar{q}$ final state reconstruction
   $\longrightarrow$ Investigate + optimize
   - $WW/ZZ$ separation
   - jet reconstruction




2. VBS analysis
   - Analysis with full SM and overlay background
   - Interpretation using Higgs EFT



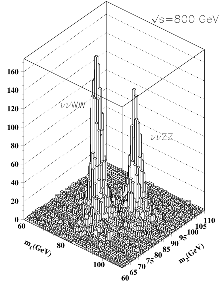
# Outline

# 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])

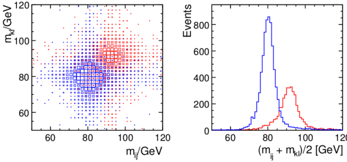
2001:




$\Longrightarrow$ 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 $e^+e^- \to \nu\nu WW/ZZ \to \nu\nu q\bar{q}q\bar{q}$ 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`)
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:

   $\rightarrow$ 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

   $\rightarrow$ Define $WW \rightarrow WW/ZZ$ events on generator level:

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

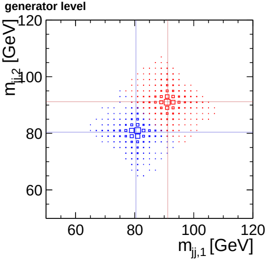



Figure : 2D di-quark mass distributions for events classified as $WW$ or $ZZ$ (normalized).

2. Detector simulation & event reconstruction using *iLCSoft* (`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 $e^+e^- \to \nu\nu WW/ZZ \to \nu\nu q\bar{q}q\bar{q}$

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`)
3. Apply preselection for SM background reduction
4. Find invariant masses of the $W/Z$ candidates

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

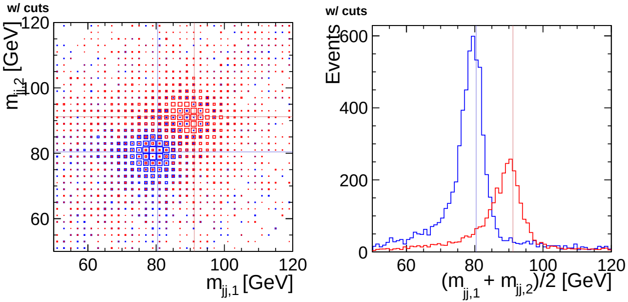
- Cluster particles into 4 jets
- Pair up jets into 2 boson-dijet candidates by minimizing $|m_{jj,1} - m_{jj,2}|$
- Plot boson masses $m_{jj}$ for ($WW$) and ($ZZ$) events

# $WW/ZZ$ separation plots

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

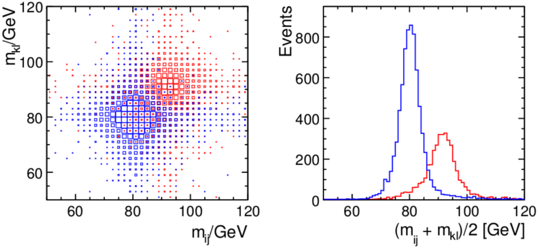
$\rightarrow$ Use reconstructed particle to calculate invariant masses of $W/Z$ candidates

- 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: $\mathcal{L} = 1\,\text{ab}^{-1}$, Polarisations: $P_{e^-} = -80\%$, $P_{e^+} = +30\%$



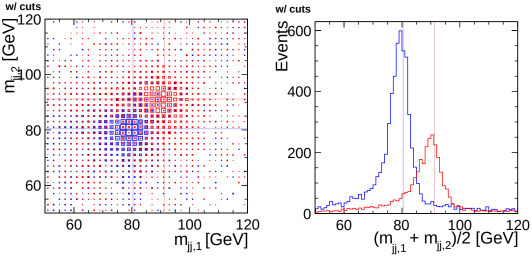

- **Good separation** of $WW$ and $ZZ$ peaks.
- **Shifted mass peaks** wrt. boson masses $\rightarrow$ **?**
- **Long tails** to high and low $m_{jj}$ $\rightarrow$ **?**

# Recreation of performance plots




Letter of Intent

- Well-separated and resolved $WW$ and $ZZ$ peaks




Own analysis

- Distribution tails (not observed in LoI)
- 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**!

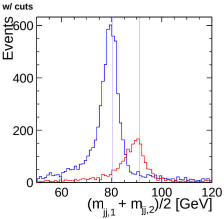



Figure : Using own pairing method.

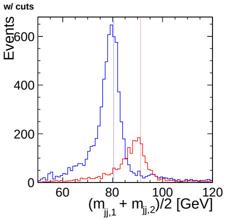
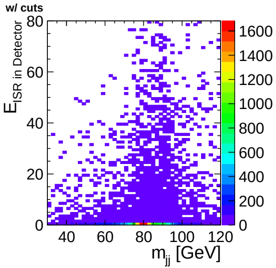
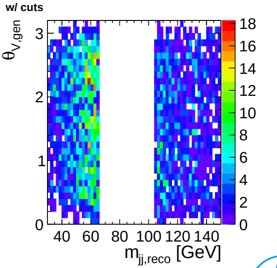



Figure : Using LoI pairing method.



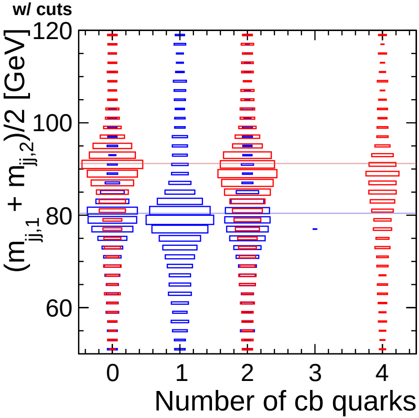



# Outline

# Influence of heavy quarks

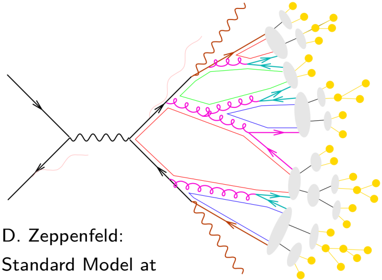
Conjecture: Mass peak shifted due to energy lost to neutrinos
$\Rightarrow$ Dominant in heavy quark jets

$\longrightarrow$ 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



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\to$ hadrons
- hadronic decays

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

quarks

↓ Parton shower

partons

↓ Hadronization, fragmentation

hadrons

↓ Detector acceptance

detected particles

↓ Det. resolution, Particle Flow

reconstructed particles

↓ Overlay, jet-clustering

clustered jets

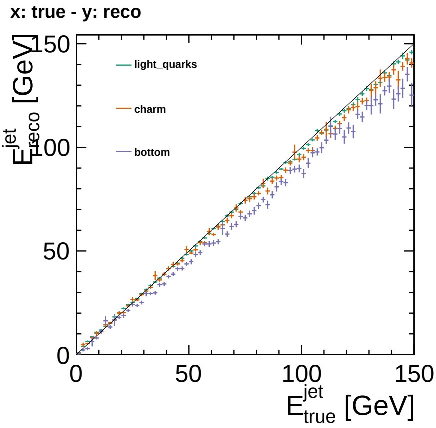
- **TrueJet**:
  - Processor within *iLCSoft*
  - Use MC/simulation information to check parton/jet information on intermediate stages of event measurement

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

# Comparing MC and Reconstructed

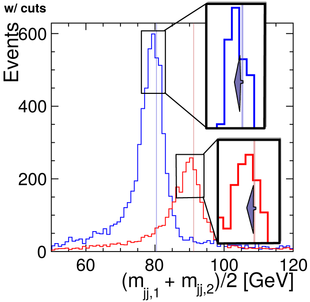
Deeper look into influence of **jet flavour**:

- 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

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

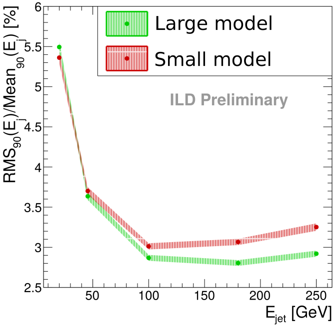


# Jet flavour influencing Jet Energy Resolution

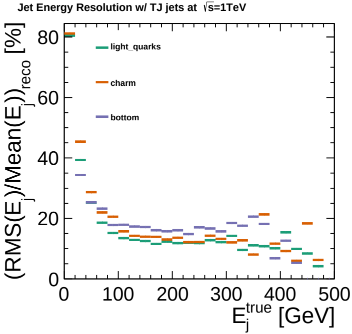
How is $\sigma_E/E$ influenced by jet flavour ($\rightarrow \nu$'s)?

$\Rightarrow$ 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

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

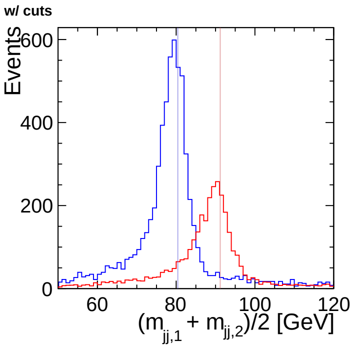



Figure : Own jet-clustering and jet pairing.

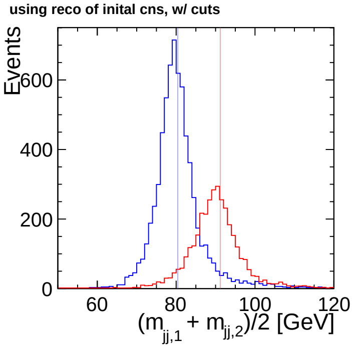



Figure : TJ-cheated jet-clustering and pairing.

$\Longrightarrow$ **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
  $\longrightarrow$ Difference to LoI: No $b$ quarks in samples!
- **Tails:** originating from jet-clustering
  $\longrightarrow$ Difference to LoI: Different clustering algorithm!
  - LoI: Undocumented $\rightarrow$ possibly cheated
  - Here: $e^+e^-$ $k_T$ algorithm

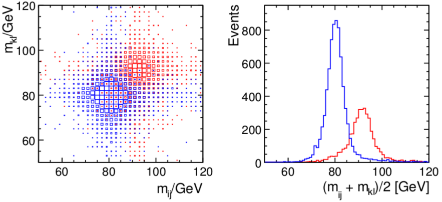



Figure : Letter of Intent results.

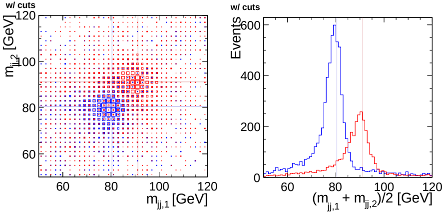



Figure : Own results.

# Results of jet investigation

So why the difference to Letter of Intent?

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

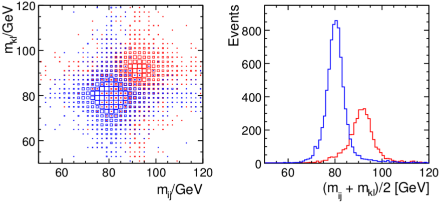



Figure : Letter of Intent results.

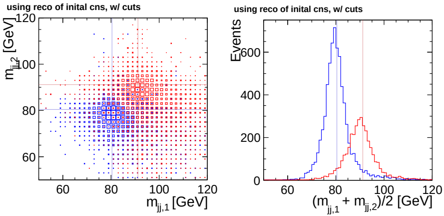



Figure : Own, jet clustering & pairing cheated

# Results of jet investigation

So why the difference to Letter of Intent?

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

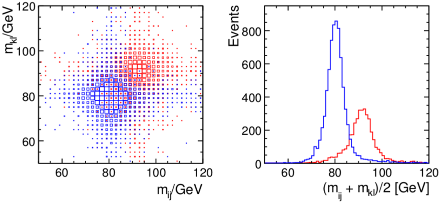



Figure : Letter of Intent results.

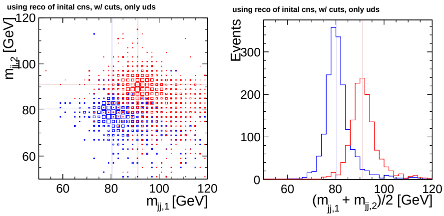



Figure : Own, jets cheated, uds only.

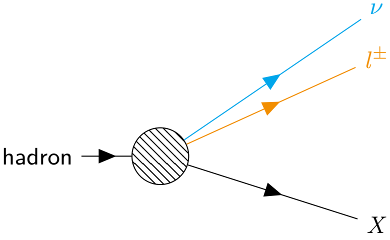
# Outline

# Neutrino corrections

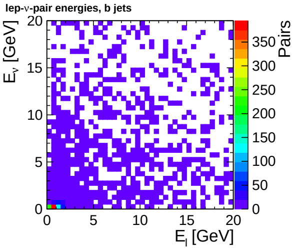
Hadron in jet gives off $l^{\pm}\nu$ pair

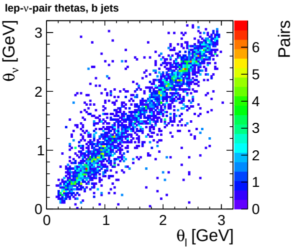
$\longrightarrow$ **Correctable** if:

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




$\Longrightarrow$ Investigate $l\nu$ pairs in TrueJet jets



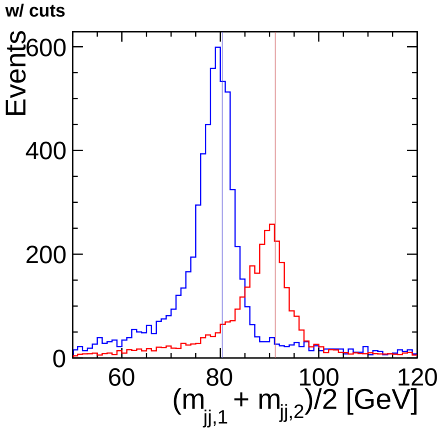

- No simple correction possible

$\rightarrow$ Find visible particles & secondary vertex
$+$ assume hadron mass

$\Rightarrow$ **Reconstruct $\nu$**

# Outline

# 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

$\Longrightarrow$ When run in full: **Test** for

detector model
$+$
simulation & reconstruction software!

Ongoing detector & software developments:

$\longrightarrow$ Use such plots for model / version validation

$\Longrightarrow$ *iLCSoft* contains **ILDPerformance** package (github.som/iLCSoft/ILDPerformance)
**Goal:** Standardized algorithms for performance plots!

# $WW/ZZ$ in ILDPerformance

Implemented script into ILDPerformance to run:

- Detector simulation → *DDSim* (github.com/iLCSoft/lcgeo)
- Event reconstruction → *PandoraPFA* (github.com/PandoraPFA) & *ILDConfig* (github.com/iLCSoft/ILDConfig)
- $WW/ZZ$ analysis → *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*
(A Tsaregorodtsev, 2010 J. Phys.: Conf. Ser. 219 062029)

⇒ Get plot starting from generator file within few hours!

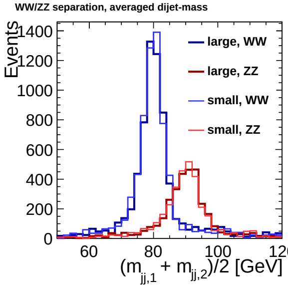



Figure : Plot with current software & detector model.

# Outline

# Conclusion & outlook

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

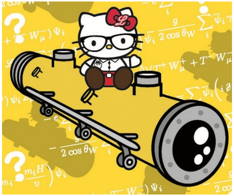
**So far:**

- 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

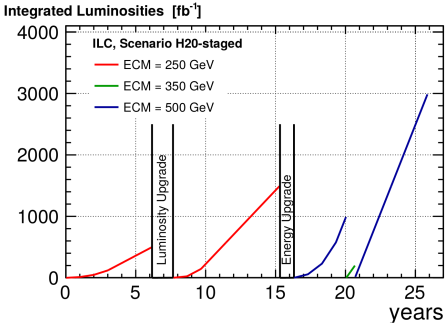
Thanks for your attention!

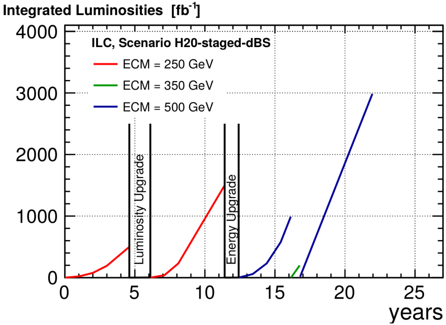


# BACKUP

Staging scenario changed from Technical Design Report (TDR, ILC-500)
$\Longrightarrow$ 2 possibilities (cost-neutral):

- Beam parameters as for ILC-500
- More aggressive beam parameters $\rightarrow$ Higher lumi, slightly more beamstrahlung



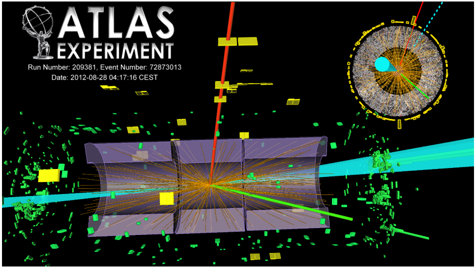
# Preselection

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

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`)
3. Apply preselection for SM background reduction:

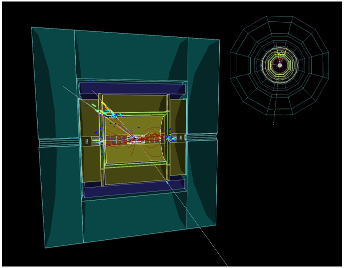
   $\to$ apply cuts as in previous work (ILD Letter of Intent arXiv:1006.3396):
   - Cuts on jet content to reject $t\bar{t}$ events
   - $Y_{34} > 0.0001 \to$ Event does not have less than 4 jets
   - Suppress 2- and 4-fermion and $ZWW/ZZZ(, Z \to \nu\nu)$ background using $m_{missing}$, $E_{T,visible}$ and $p_{T,visible}$
   - Missing momentum not from particles going to beam pipe
   - Suppress ISR-$\gamma$ $\to$hadrons events using highest energetic track
   - Reject $t\bar{t} \to b\bar{b}q\bar{q}l\nu$ using cone around most energetic track
4. Find invariant masses of the $W/Z$ candidates

## Pile-up (@ LHC) VS Overlay (@ ILC)




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-160/figaux_03.png

- Several interactions / bunch crossing (average ∼30-40)
- Background form 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*

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

$\Rightarrow$ Requires good **vertex position resolution**!