WW/ZZ separation in their hadronic decays at the ILC

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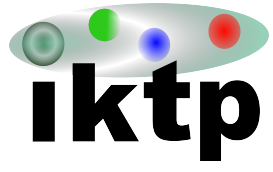
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



TECHNISCHE
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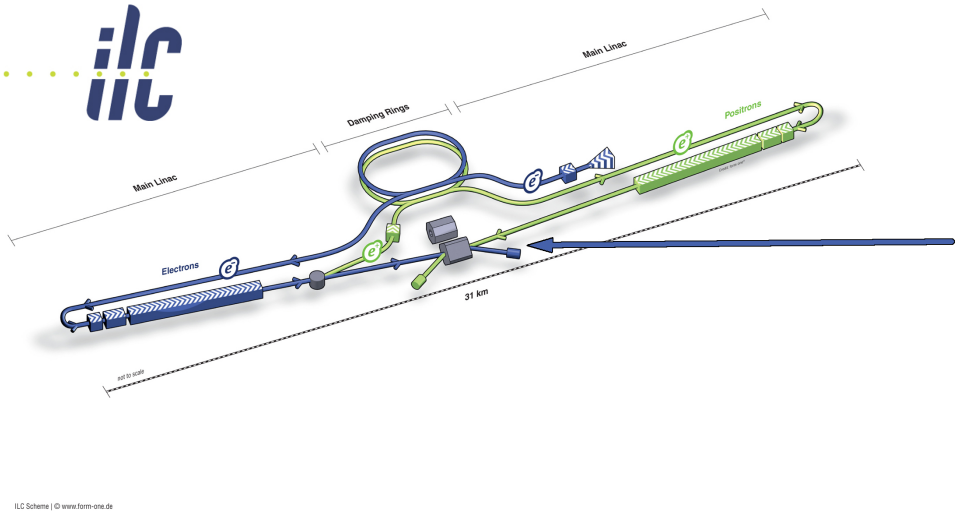
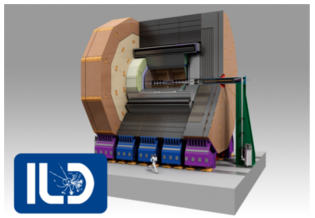
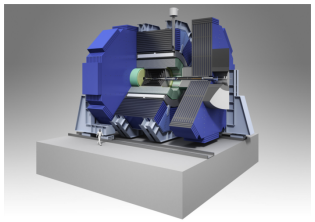
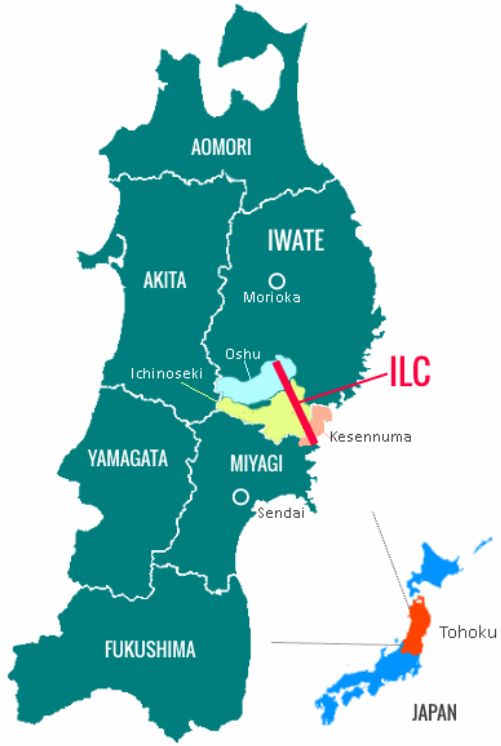
The International Linear Collider (ILC)









- 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 region, Prefecture Iwate, Japan
- Both beams (e^+, e^-) are polarized: $P_{e^-} = \pm 80\%, \quad P_{e^+} = \pm 30\%$
- Designed for precision studies for physics of the standard model and beyond

The International Large Detector (ILD)

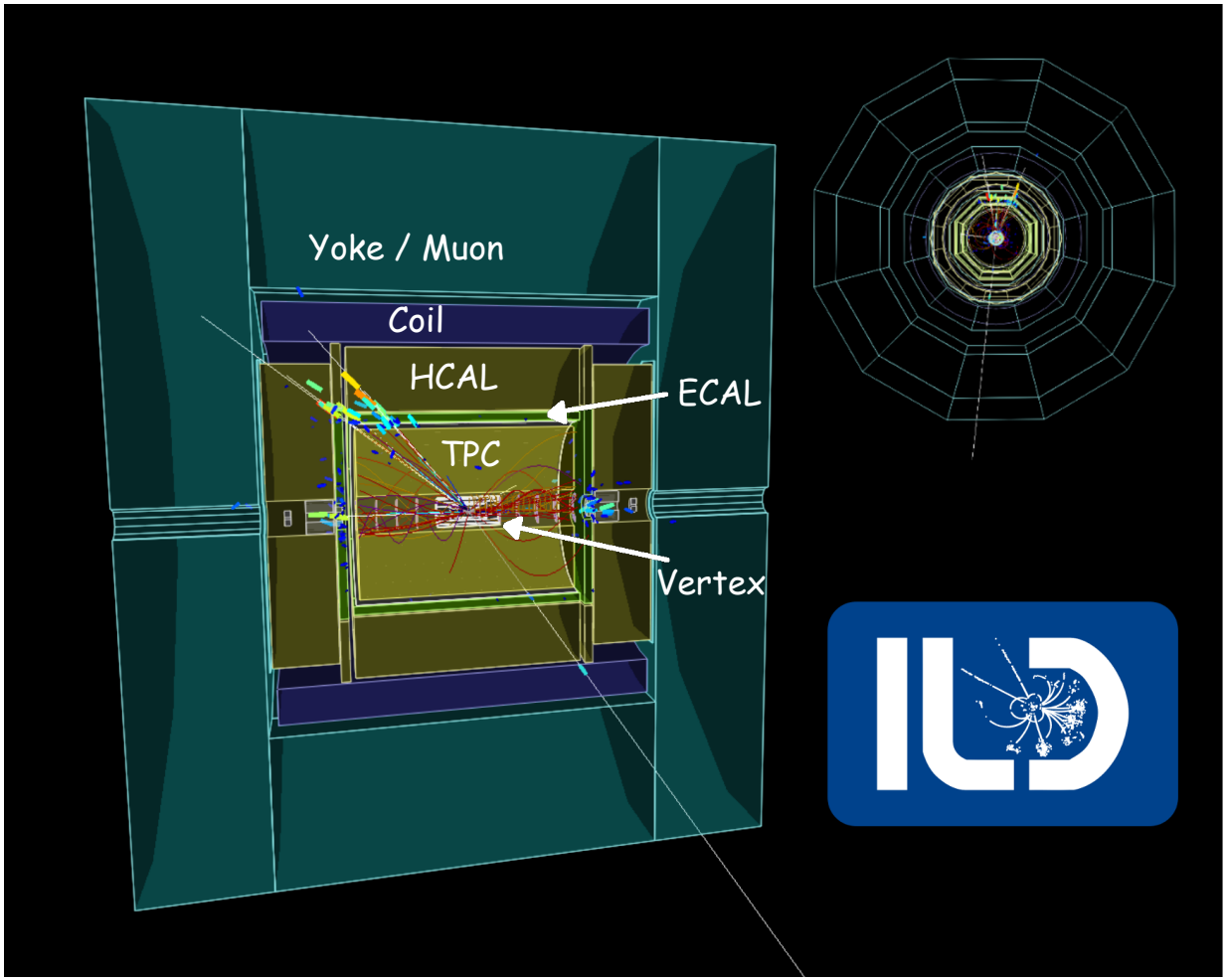


Figure : $\mu\mu + 2$ jets event in the ILD detector.

- 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

- $BR(W/Z \rightarrow \text{hadrons}) \sim 70\%$
  $\rightarrow$ in hadron colliders inaccessible due to pile-up
- In lepton colliders clean event and jet reconstruction
  $\Rightarrow$ **Hadronic boson decay modes accessible**
- Want to separate W and Z by invariant dijet mass
  $\rightarrow$ Requirement:

  Jet energy resolution $\sigma_E/E \sim 3-4\%$

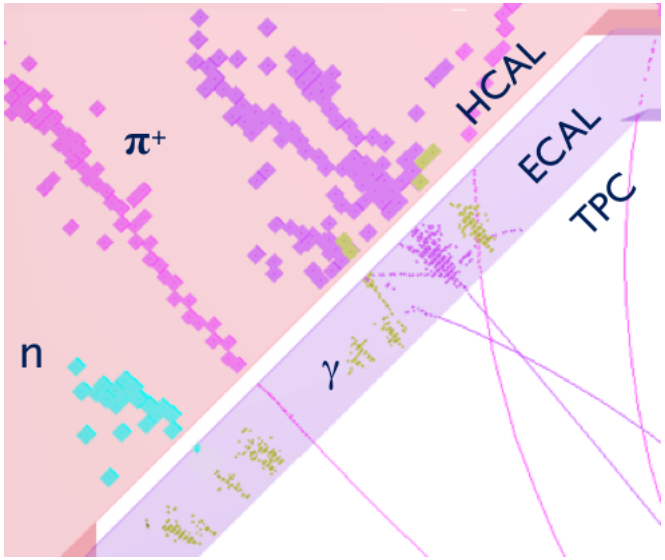
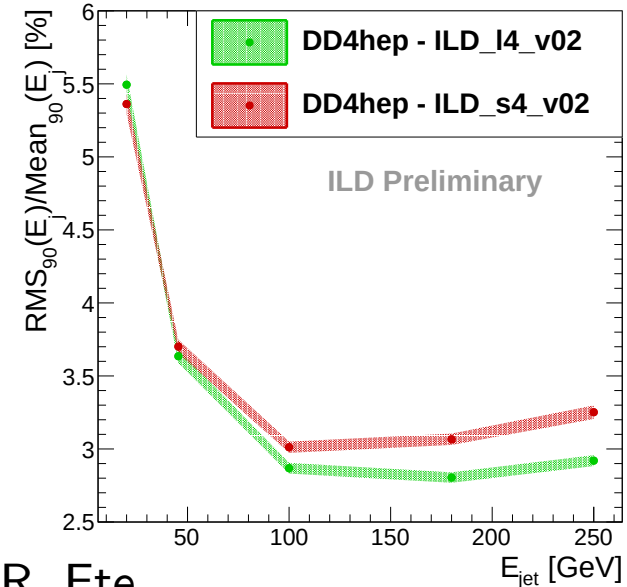


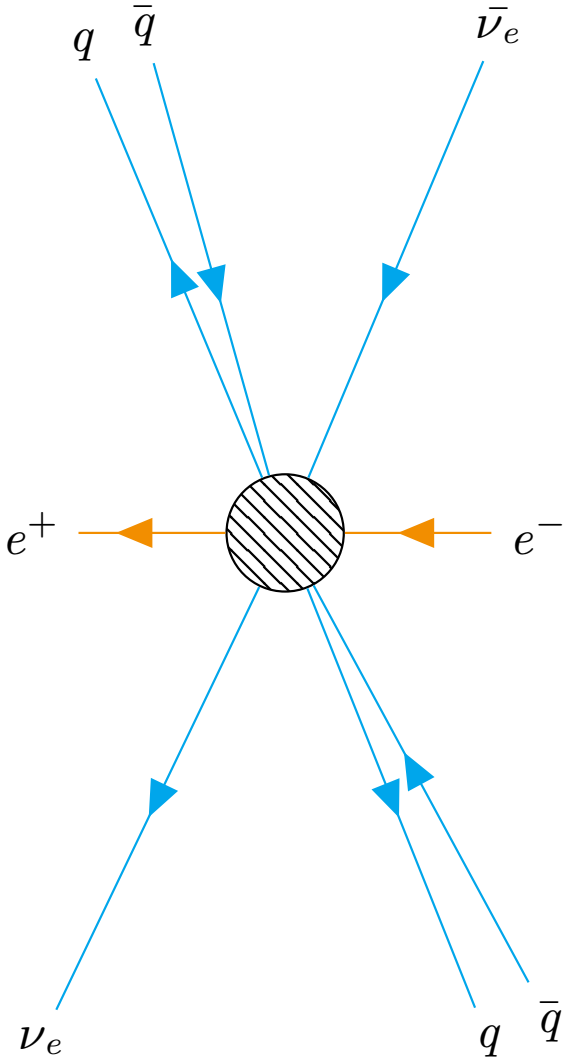
Figure : 250 GeV jet in the ILD



- Benchmark achievable with current technology
  $\Rightarrow$ Test ILD potential in hadronic physics channels

R. Ete

$e^+e^- \longrightarrow \nu\nu q\bar{q}q\bar{q}$ to demonstrate ILD potential



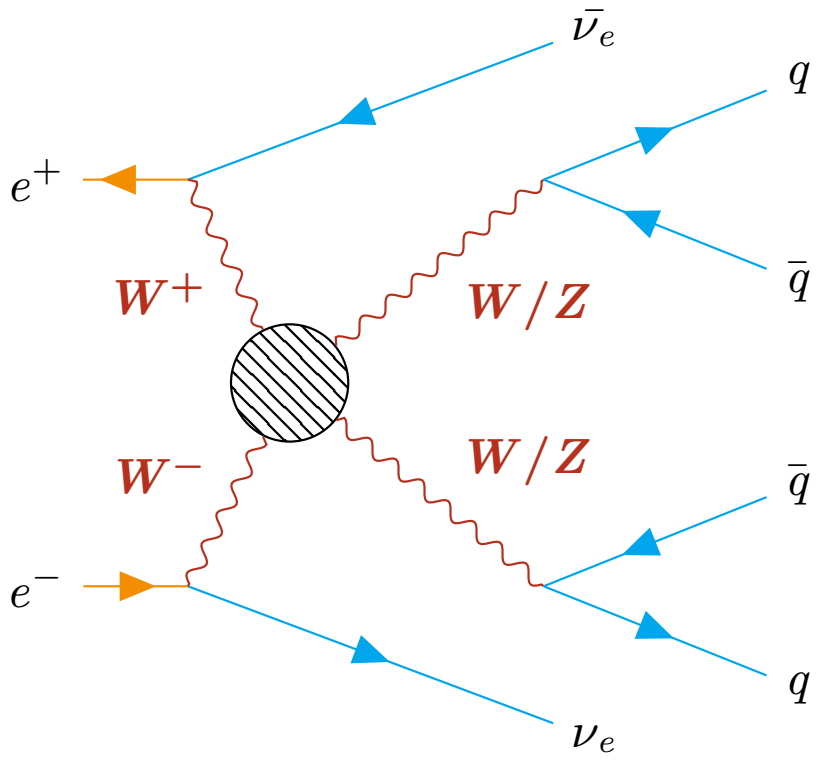
Choose final state: $\nu\nu q\bar{q}q\bar{q}$

$\Rightarrow$ Demonstrates full potential of ILC + ILD:

- Reconstructing particles from 4 jets accurately requires:
  - Separation of individual particles
    $\longrightarrow$ **Granularity**
  - Precise reconstruction software
    $\longrightarrow$ **Particle Flow**
- ν reconstruction requires:
  - Precise initial state knowledge
    $\rightarrow$ **No PDFs in initial state**
  - Full event reconstruction
    $\rightarrow$ **Full angular coverage**
- (Differential) Cross-section highly dependent on **beam polarisations**

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

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



- In SM w/o Higgs: $WW \to WW/ZZ$ scattering ME diverges at $\sqrt{s} \geq 1.2\,\text{TeV}$
  $\Rightarrow$ Higgs restores unitarity
- If Higgs not SM-like:
  Scenarios of delayed unitarity restauration
  $\to$ Test for BSM physics
- Requires high $\sqrt{s}$
  $\Rightarrow$ Studies in this talk at $\sqrt{s} = 1\,\text{TeV}$

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

Basic setup

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

Find W/Z invariant masses

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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
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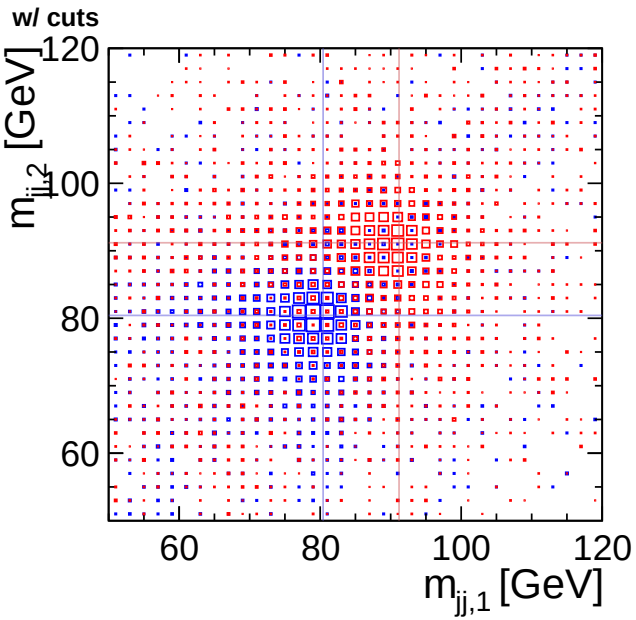
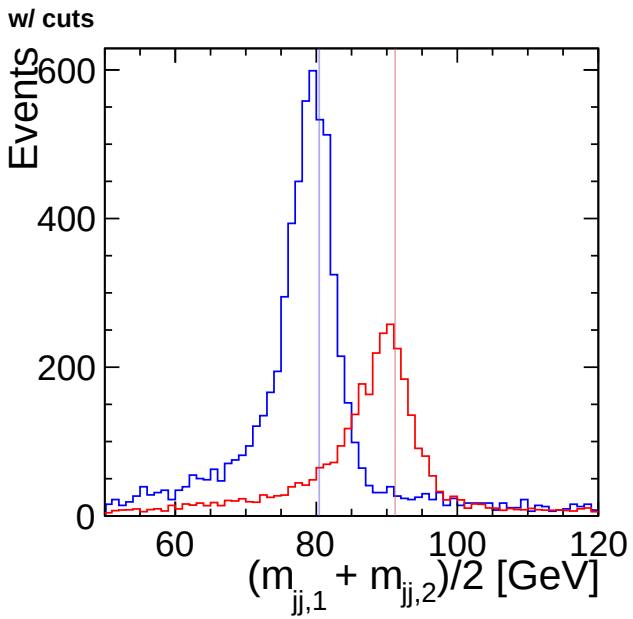
   - Plot boson masses m_{jj} for (WW) and (ZZ) events



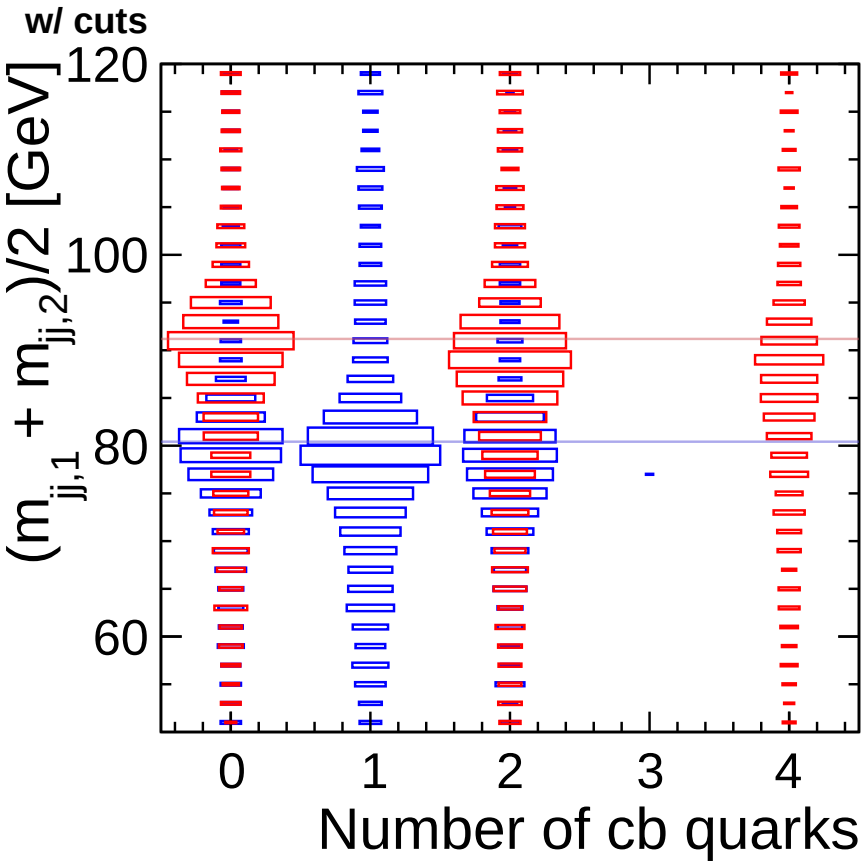


- Lumi: $\mathcal{L} = 1\,\text{ab}^{-1}$
- Good separation of WW and ZZ peaks.
- Shifted mass peaks wrt. boson masses $\rightarrow$?
- Long tails to high and low m_{jj} $\rightarrow$?

Influence of heavy quarks

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

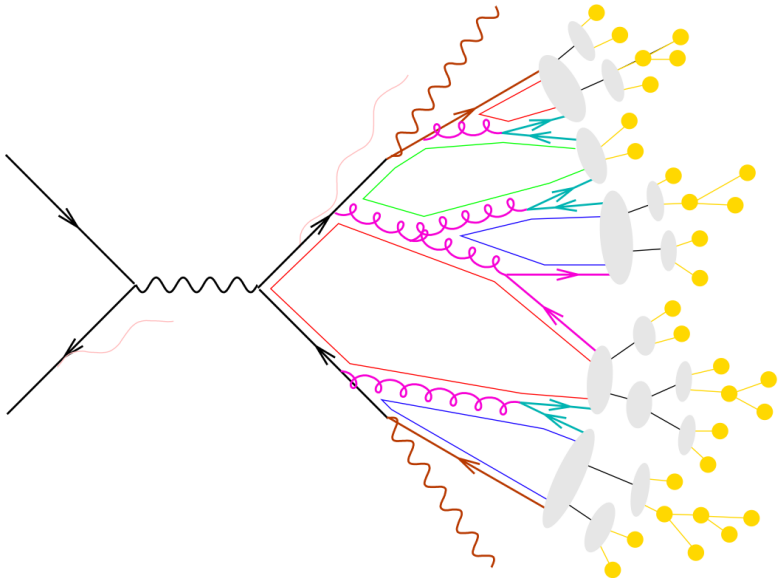
$\longrightarrow$ Test influence of number of c and b quark on reconstructed m_{jj} distributions



- Heavy quarks shift mass peaks
  $\Rightarrow$ Further investigation!
- Even without heavy quarks tail remains

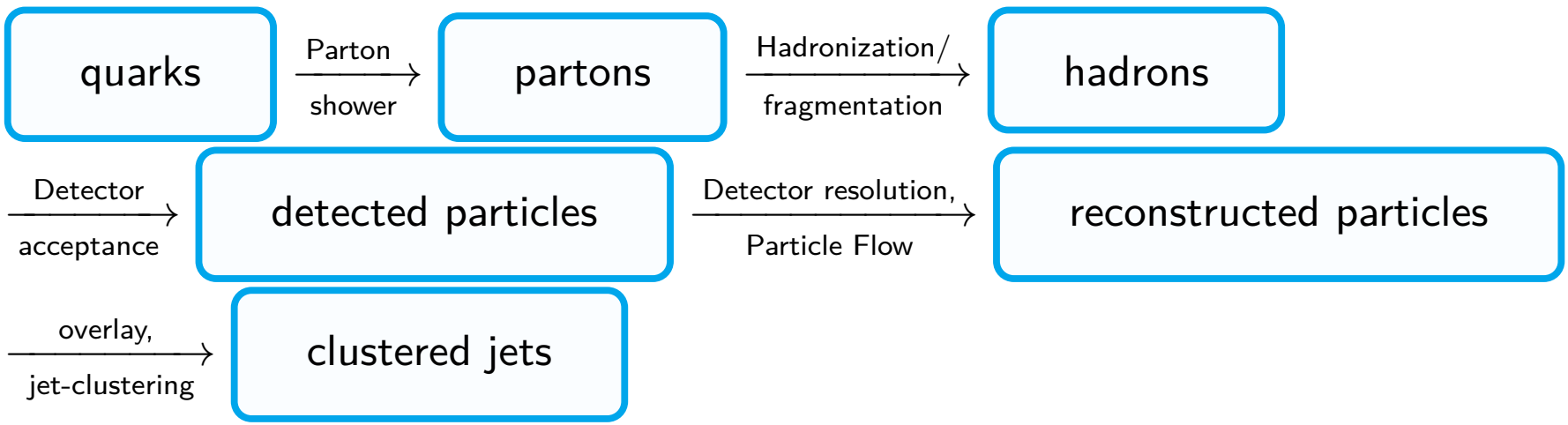
Figure : Averaged reconstructed V mass against number of c and b quarks on generator level. Color indicates generator level definition: WW, ZZ.

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

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

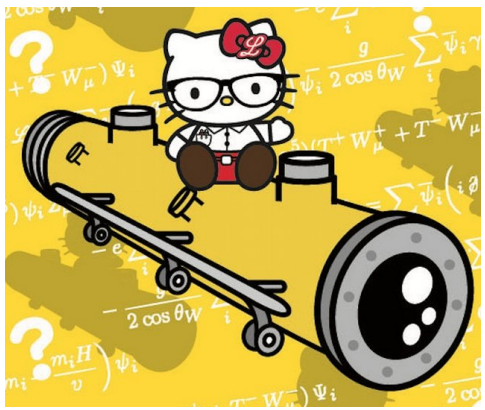


$\Rightarrow$ Distinguish clustering, detector resolution, detector acceptance, ...

Conclusion and outlook

- ILC: Future linear e^+e^- collider with $\sqrt{s} = 250\,\text{GeV}$ (...1 TeV)
- Investigating $\nu\nu q\bar{q}q\bar{q}$ final state using the ILD
  $\rightarrow$ Demonstrates potential of lepton machine
  $\rightarrow$ Interesting channels for Higgs-related BSM physics
- Can achieve separation of WW and ZZ events using invariant mass
- Found issue in heavy quark jet reconstruction
  $\rightarrow$ Now using TrueJet tool to investigate jet corrections

Thanks for your attention!



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BACKUP

WW/ZZ event definition

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:

   $\to$ Want events with $q\bar{q}q\bar{q}$ from $WW \to WW/ZZ$, but samples use full $\nu\nu q\bar{q}q\bar{q}$ ME

   $\to$ Define $WW \to WW/ZZ$ 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)
   - $|m^1_{qq} - m^2_{qq}| \leq 20.0\text{GeV}$
   - $m_{\nu_e\bar{\nu}_e} \geq 100.0\text{GeV}$

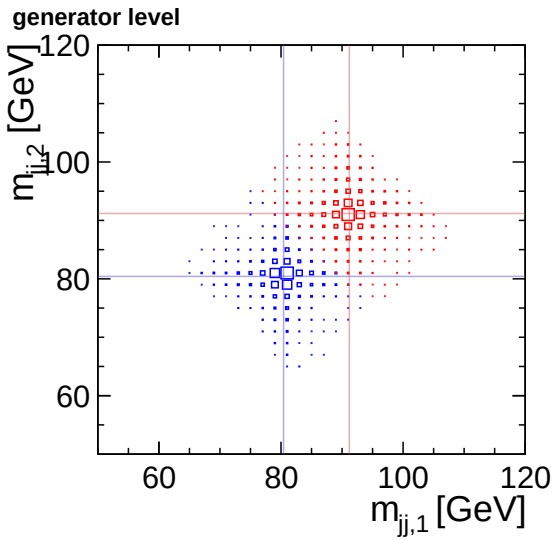


Figure : 2D di-quark mass distributions for events classified as WW or ZZ (normalized).

2. Detector simulation & event reconstruction using *iLCsoft*
3. Apply preselection for SM background reduction:
4. Find invariant masses of the W/Z candidates:

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*
3. Apply preselection for SM background reduction:

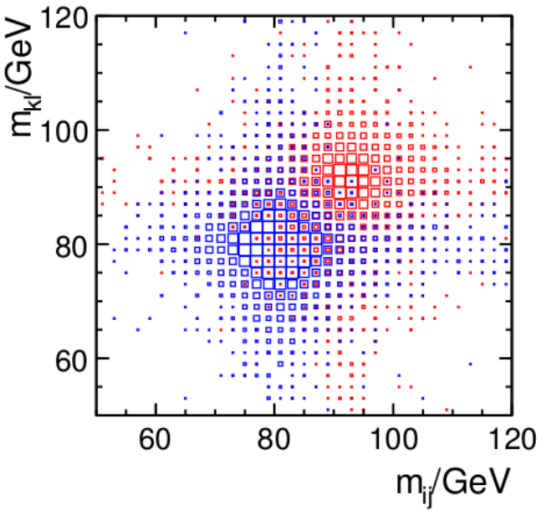
   $\to$ apply cuts as in previous work (ILD Letter of Intent arXiv:1006.3396):
   - Cuts on jet content to reject $t\bar{t}$ events
   - $Y_{34} > 0.0001 \to$ Event does not have less than 4 jets
   - Suppress 2- and 4-fermion and $ZWW/ZZZ(, Z \to \nu\nu)$ background using $m_{missing}$, $E_{T,visible}$ and $p_{T,visible}$
   - Missing momentum not from particles going to beam pipe
   - Suppress ISR-γ $\to$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:

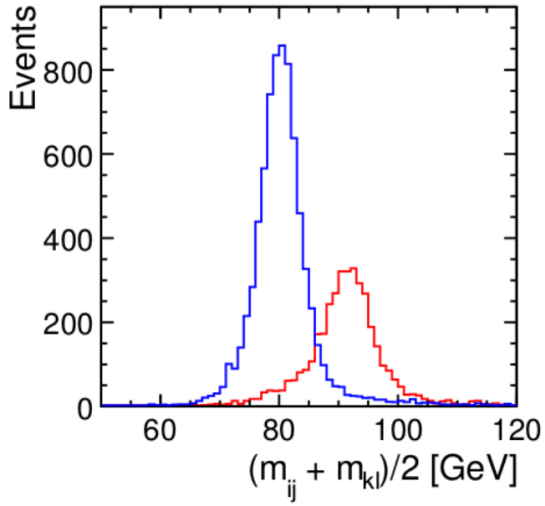
LoI preselection

Reject events with SM-background-like signatures:

- Jets must have ≥ 2 particles and ≥ 3 charged particles
  $\rightarrow$ reduce $t\bar{t}$ events with isolated leptons
- $Y_{34} > 0.0001 \rightarrow$ Event does not have less than 4 jets
- To suppress 2- and 4-fermion and $ZWW(, Z \rightarrow \nu\nu)$ background require:
  - $m_{recoil} = \sqrt{E_{miss}^2 - p_{miss}^2} > 200\,\text{GeV}$
  - $E_{T,visible} \geq 150\,\text{GeV}$
  - $p_{T,visible} \geq 40\,\text{GeV}$
- Missing momentum not from particles going to beam pipe:
  $\rightarrow |\cos(\theta_{miss})| < 0.99$
- To suppress ISR$\rightarrow$hadrons bkg: $\rightarrow |\cos(\theta)| < 0.99$ for highest energetic track
- To reject $t\bar{t} \rightarrow b\bar{b}q\bar{q}l\nu$:
  $\rightarrow 10^\circ$ cone around most energetic track: $E_{cone} \geq 2.0\,\text{GeV}$

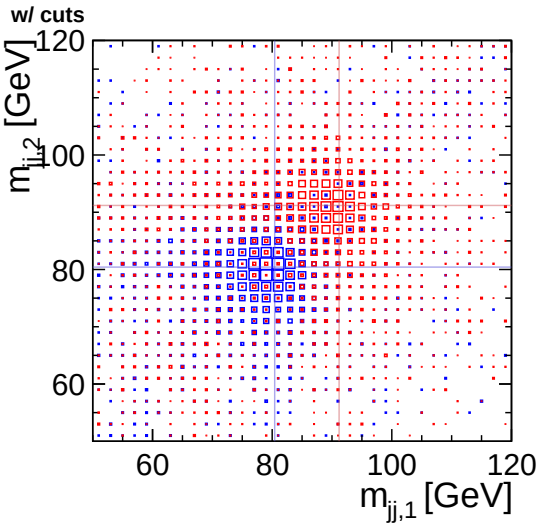
Recreation of performance plots

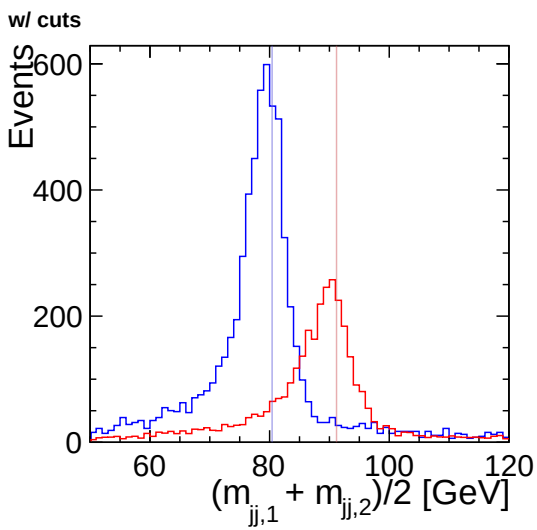




Letter of Intent

- Well-separated and resolved WW and ZZ peaks





Own analysis

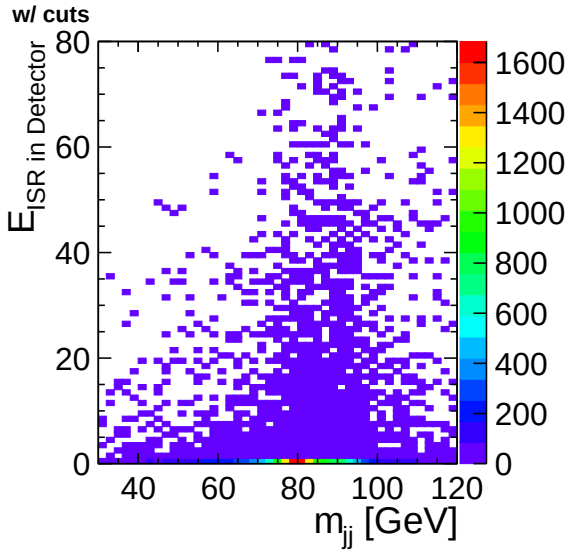
- Distribution tails (not observed in LoI)
- Mass peaks shifted wrt. boson masses

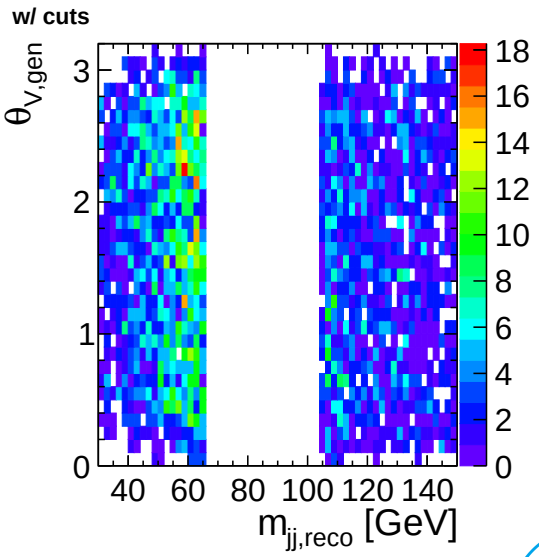
Performance plots - Tail regions

Investigated 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





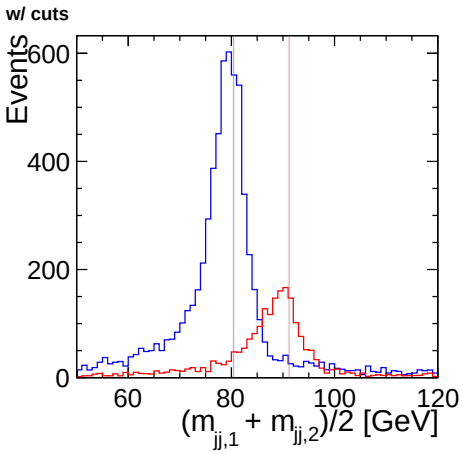


Figure : Using own pairing method.

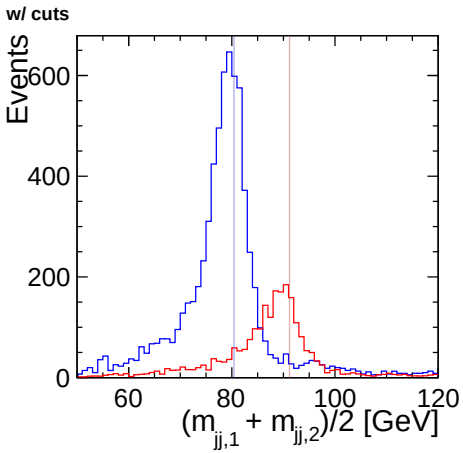


Figure : Using LoI pairing method.

Generator Level - LoI and own results

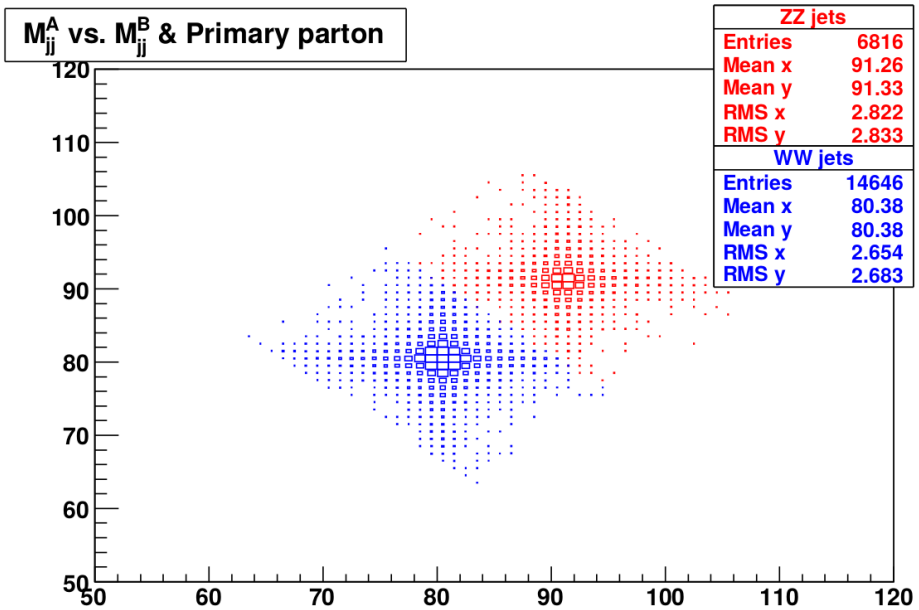


Figure : LoI

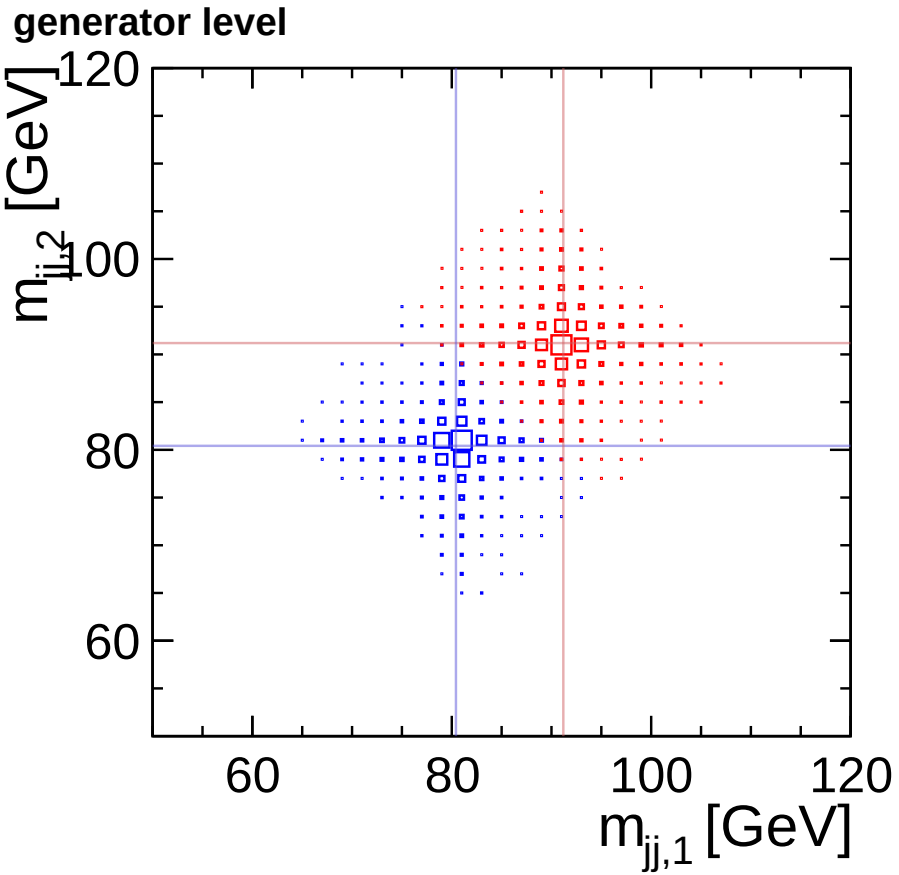
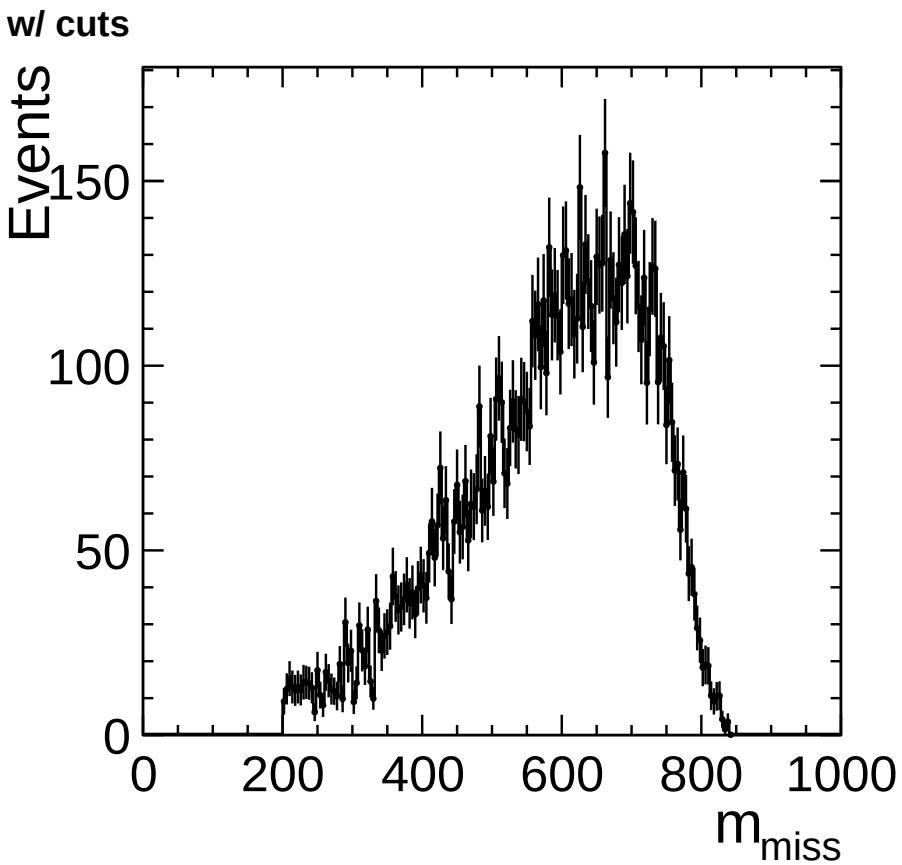
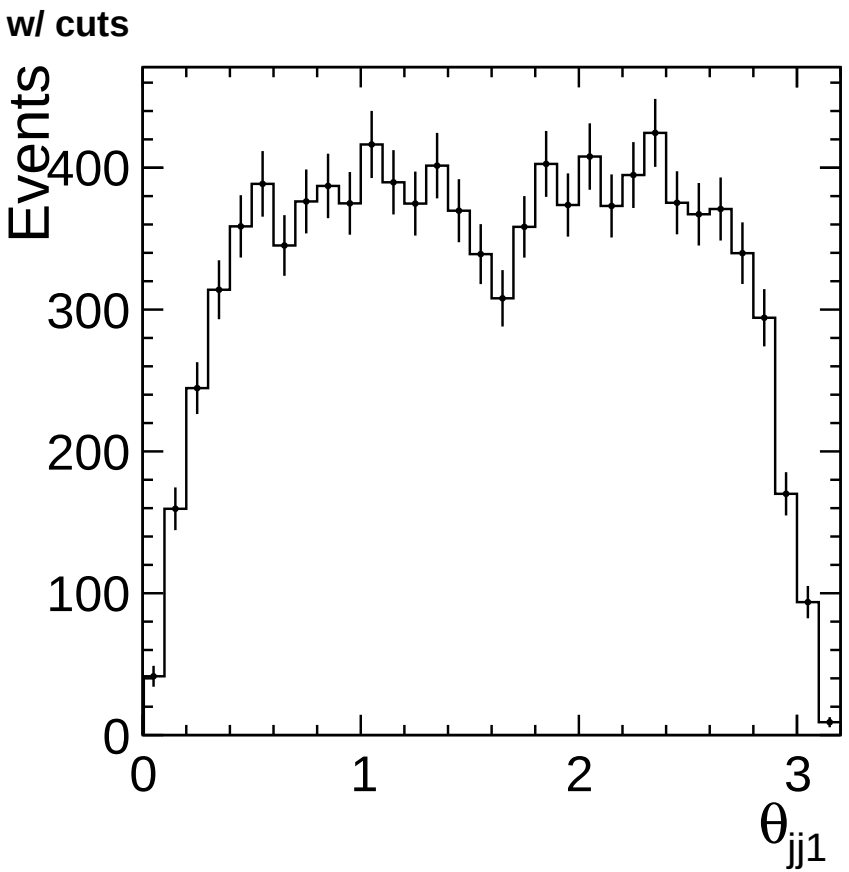


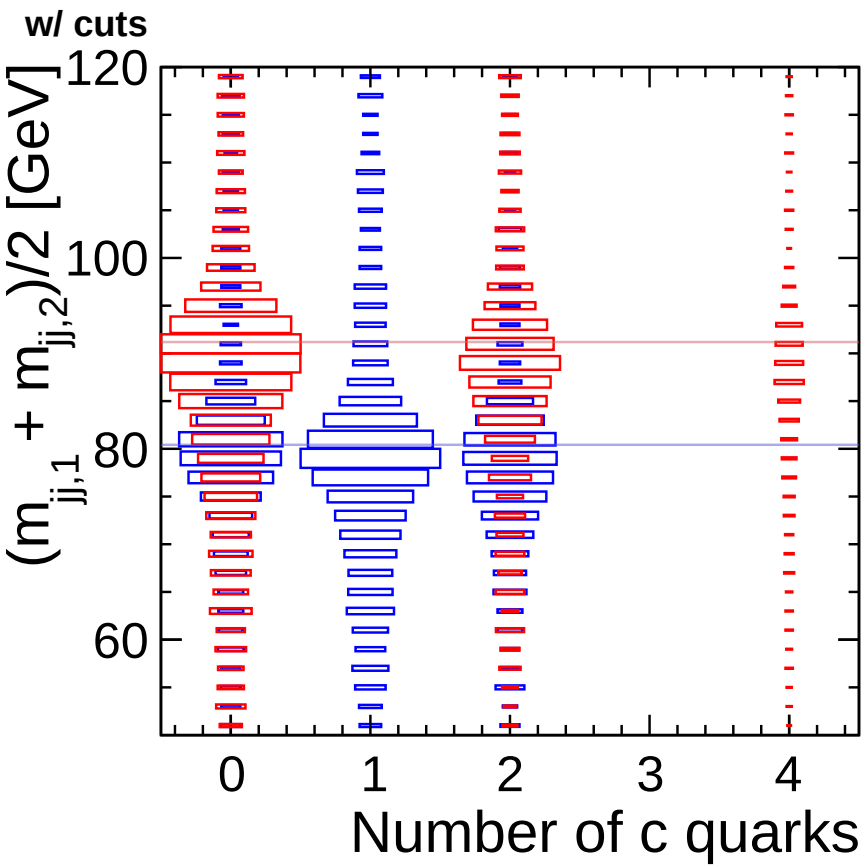
Figure : own results

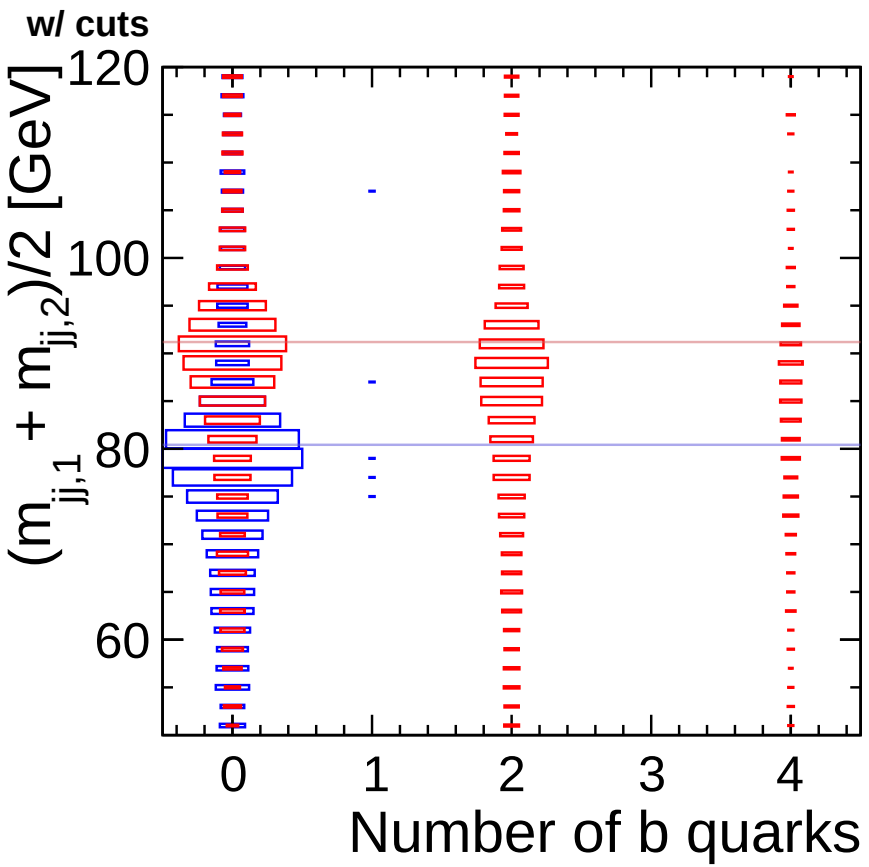
Event shape


w/ cuts
Events
150
100
50
0
0
200
400
600
800
1000
m_miss


w/ cuts
Events
400
300
200
100
0
0
1
2
3
θ_jj1

Mass shift - separately c and b

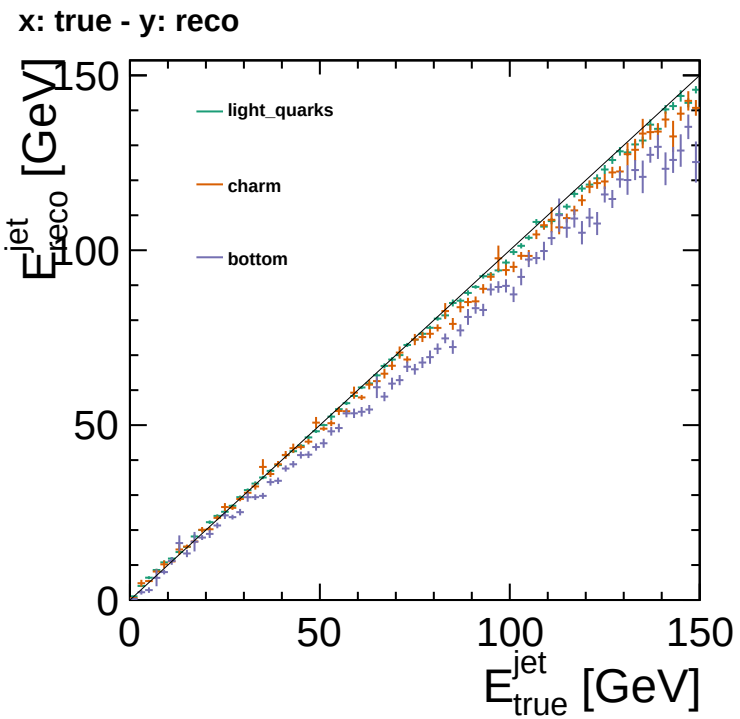




Using TrueJet for jet corrections

Goal: Use TrueJet to identify possible corrections for each step in jet measurement

- Example: Reconstructed energy of jet VS true energy of jet origin



- Correctly clustered jets
- Differentiate between jet origins
- All jets need Jet Energy Scale!
  $\rightarrow$ b jets stronger mismeasured
  $\Rightarrow$ Possibility: Search for leptons and infer neutrino

- Next step: Detailed analysis of each step

$\Longrightarrow$ Jet 4-momentum corrections