Initial studies of the top pair production

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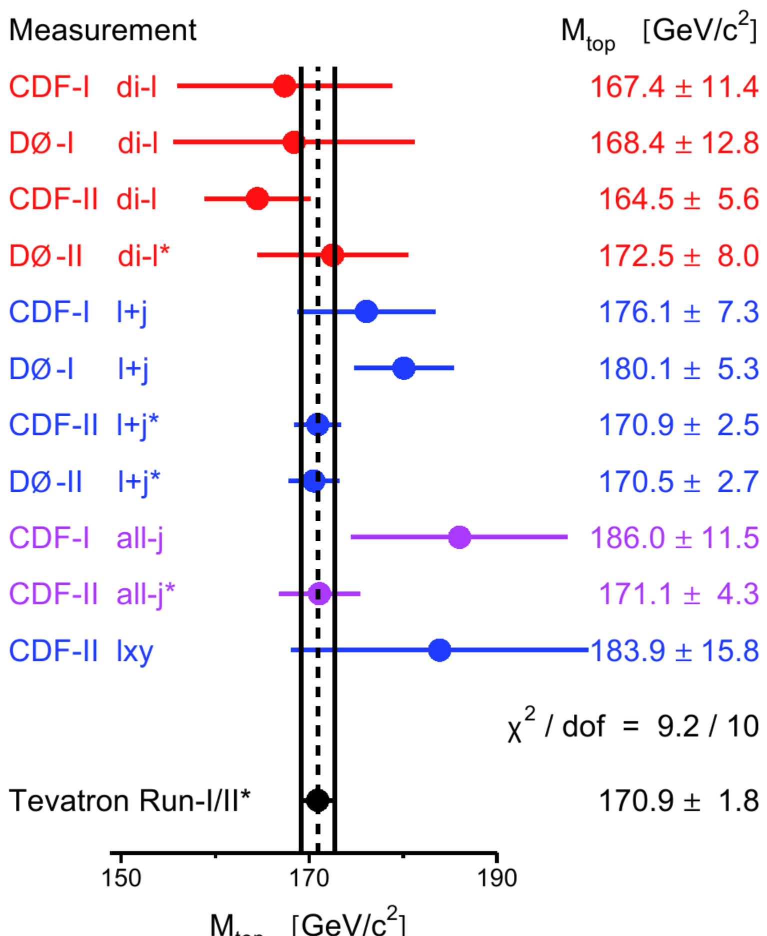
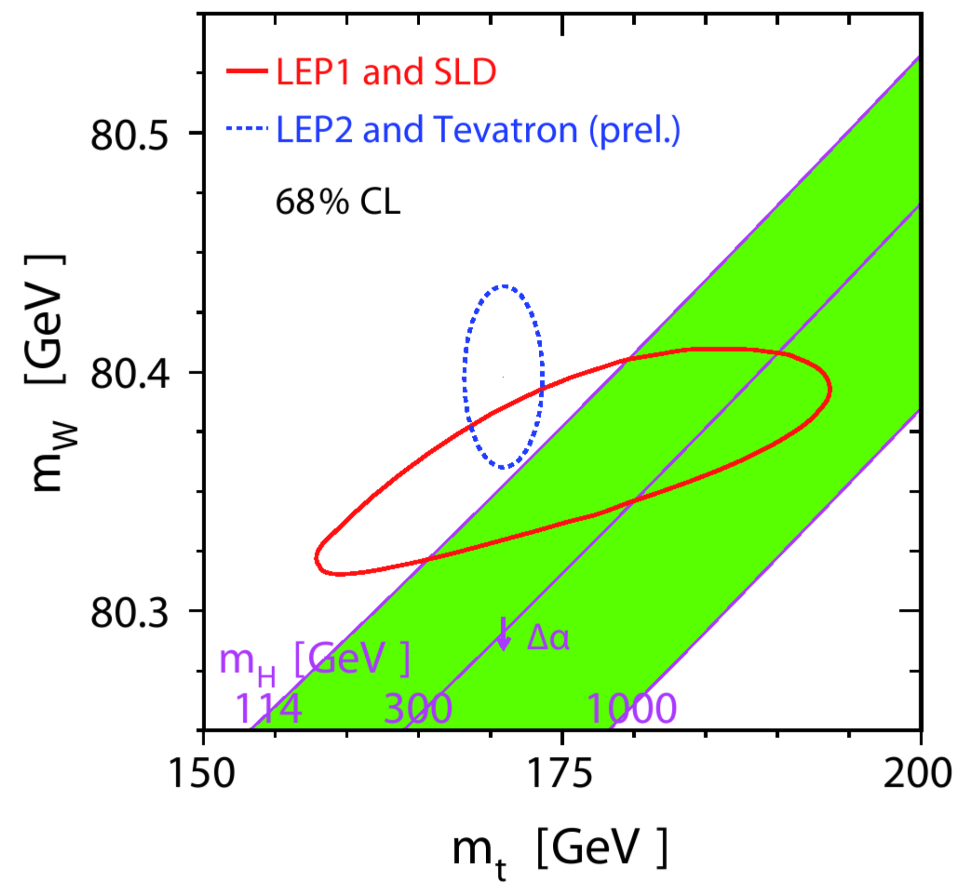
Why precise measurement of top invariant mass (m_t) ?

- m_t is free parameter of the Standard Model
- Electroweak observables including m_t depend on m_H $\sim \log(m_H^2)$

⇨ m_t sets mass constraint on mass of **Higgs** particle

World average top mass:
$m_t = 170.9 \pm 1.8\, GeV$





Pictures taken from Stefan Kasselmann

Why $t\bar{t}$ production analysis for ILC ?

- calculate accuracy for top mass measurement at ILC
- $t\bar{t}$ benchmark reaction for detector optimization
- tuning and validation of the reconstruction software

LHC:

$int.\,luminosity = 1\,fb^{-1} (startup\,of\,LHC)$

$\delta m_t(stat.) \approx 1\,GeV\,(220\,MeV\,for\,20\mathrm{fb}^{-1})$

$\delta m_t(syst.) \approx 3\,GeV$

ILC:

$int.\,luminosity = 20\,fb^{-1}$

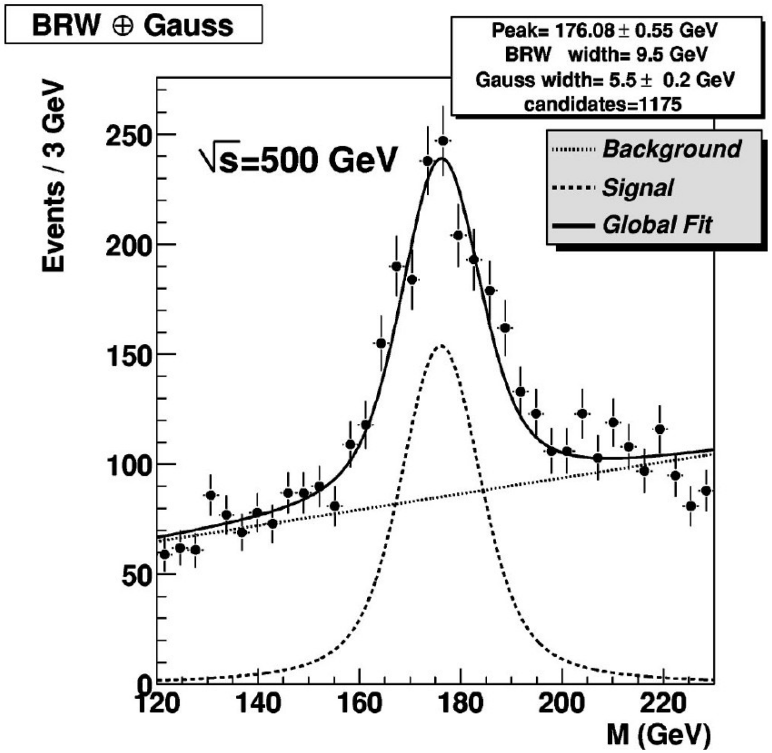
$\delta m_t(stat.) \approx\ ?$

Goal: estimate statistical error on m_t and width for ILC from direct reconstruction of t decays

The method used in this Analysis provides the consistency check and is complementary to the threshold scan technique.

S.V. Chekanov, V.L. Morgunov *Phys. Rev.* D 67, 074011 (2003)

- Detector simulation using Brahms (Fortran)
- Reconstruction optimized for TESLA design
- btag information not used
- no kinematic fits



$int. luminosity = 16\, fb^{-1}$

$\delta m_t(stat.) \approx\ 380\, MeV\ for\ \sqrt{s} = 500\, GeV$

In the meantime detector design considerably changed.

⇨ *Revision of the analysis needed.*

Tools used in this analysis:

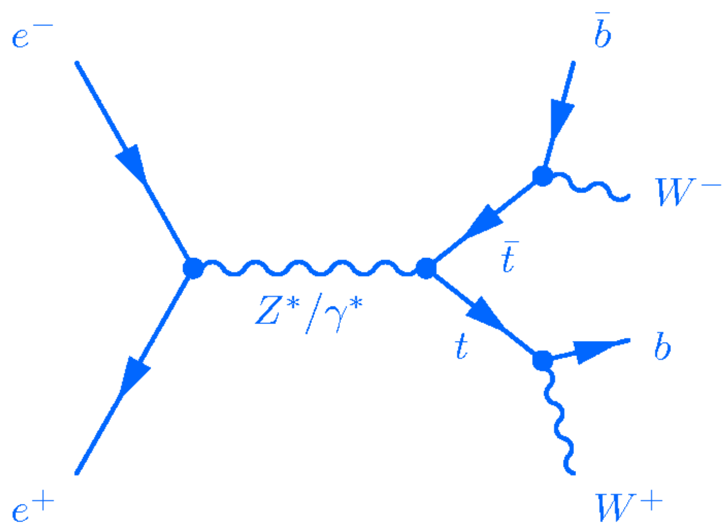
Mokka – flexible geant4 based detector simulation framework

Marlin – modular and detector independent reconstruction software

- btag information from LCFIVertex package used
- kinematic fitting applied

Studies done for center of mass energy of 500 GeV

500 GeV is the nominal energy for the first phase of ILC running (bulk of luminosity).



<table>
<tr><td rowspan="3" colspan="3">$t\bar{t} \to (W^+b)(W^-\bar{b})$</td><td colspan="9">$W^+ \to$</td></tr>
<tr><td>$e^+\nu_e$</td><td>$\mu^+\nu_\mu$</td><td>$\tau^+\nu_\tau$</td><td>$u\bar{d}$</td><td>$u\bar{d}$</td><td>$u\bar{d}$</td><td>$c\bar{s}$</td><td>$c\bar{s}$</td><td>$c\bar{s}$</td></tr>
<tr><td></td><td></td><td></td><td>$(r\bar{r})$</td><td>$(g\bar{g})$</td><td>$(b\bar{b})$</td><td>$(r\bar{r})$</td><td>$(g\bar{g})$</td><td>$(b\bar{b})$</td></tr>
<tr><td rowspan="9">$W^- \to$</td><td>$e^-\bar{\nu}_e$</td><td></td><td rowspan="3" colspan="3">9/81</td><td rowspan="3" colspan="6">18/81</td></tr>
<tr><td>$\mu^-\bar{\nu}_\mu$</td><td></td></tr>
<tr><td>$\tau^-\bar{\nu}_\tau$</td><td></td></tr>
<tr><td>$\bar{u}d$</td><td>$(r\bar{r})$</td><td rowspan="6" colspan="3">18/81</td><td rowspan="6" colspan="6">36/81</td></tr>
<tr><td>$\bar{u}d$</td><td>$(g\bar{g})$</td></tr>
<tr><td>$\bar{u}d$</td><td>$(b\bar{b})$</td></tr>
<tr><td>$\bar{c}s$</td><td>$(r\bar{r})$</td></tr>
<tr><td>$\bar{c}s$</td><td>$(g\bar{g})$</td></tr>
<tr><td>$\bar{c}s$</td><td>$(b\bar{b})$</td></tr>
</table>

fully hadronic $t\bar{t}$ decay mode used:

$$t\bar{t} \to (W^+ b)(W^- \bar{b})$$

$W \to q\bar{q}$ *branching ratio 44.4 %*

$$t\bar{t} \to 6\ jets$$

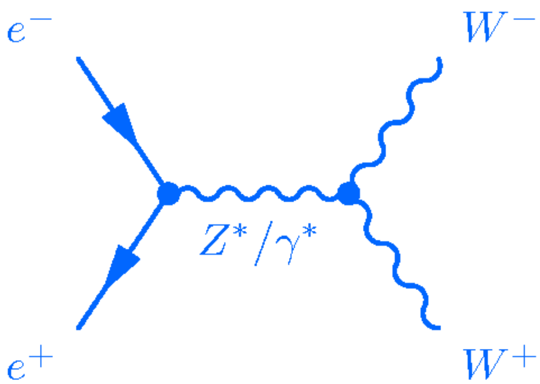
$int.\,luminosity = 20\,fb^{-1}$

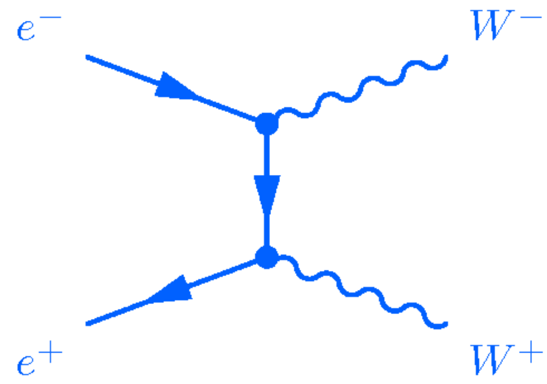
$\sigma = 3.07 \cdot 10^2\,fb \;\; (for\ \sqrt{s} = 500\ GeV)$

$\#_{events} = 6140$

Values used in event production

Picture taken from Stefan Kasselmann



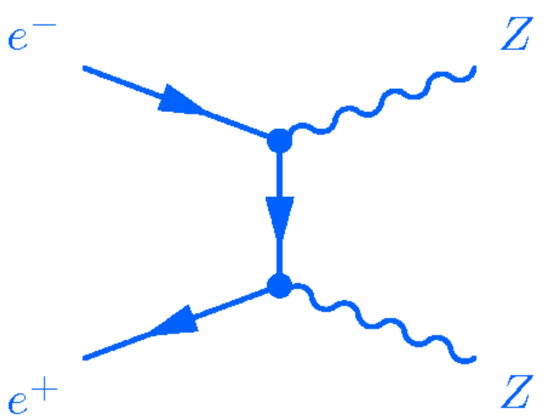


Values used in event production

$int.luminosity = 20\,fb^{-1}$

$\sigma = 4.15\cdot 10^3\,fb \quad (for\ \sqrt{s} = 500\,GeV)$

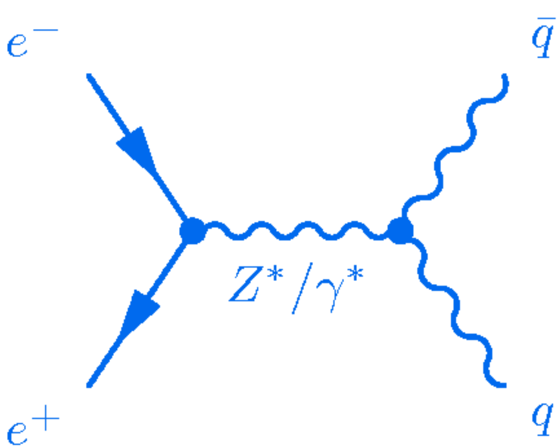
$\#_{events} = \ 8.3\cdot 10^4$



$int.luminosity = 20\,fb^{-1}$

$\sigma = 3.14\cdot 10^2\,fb \quad (for\ \sqrt{s} = 500\,GeV)$

$\#_{events} = \ 6280$



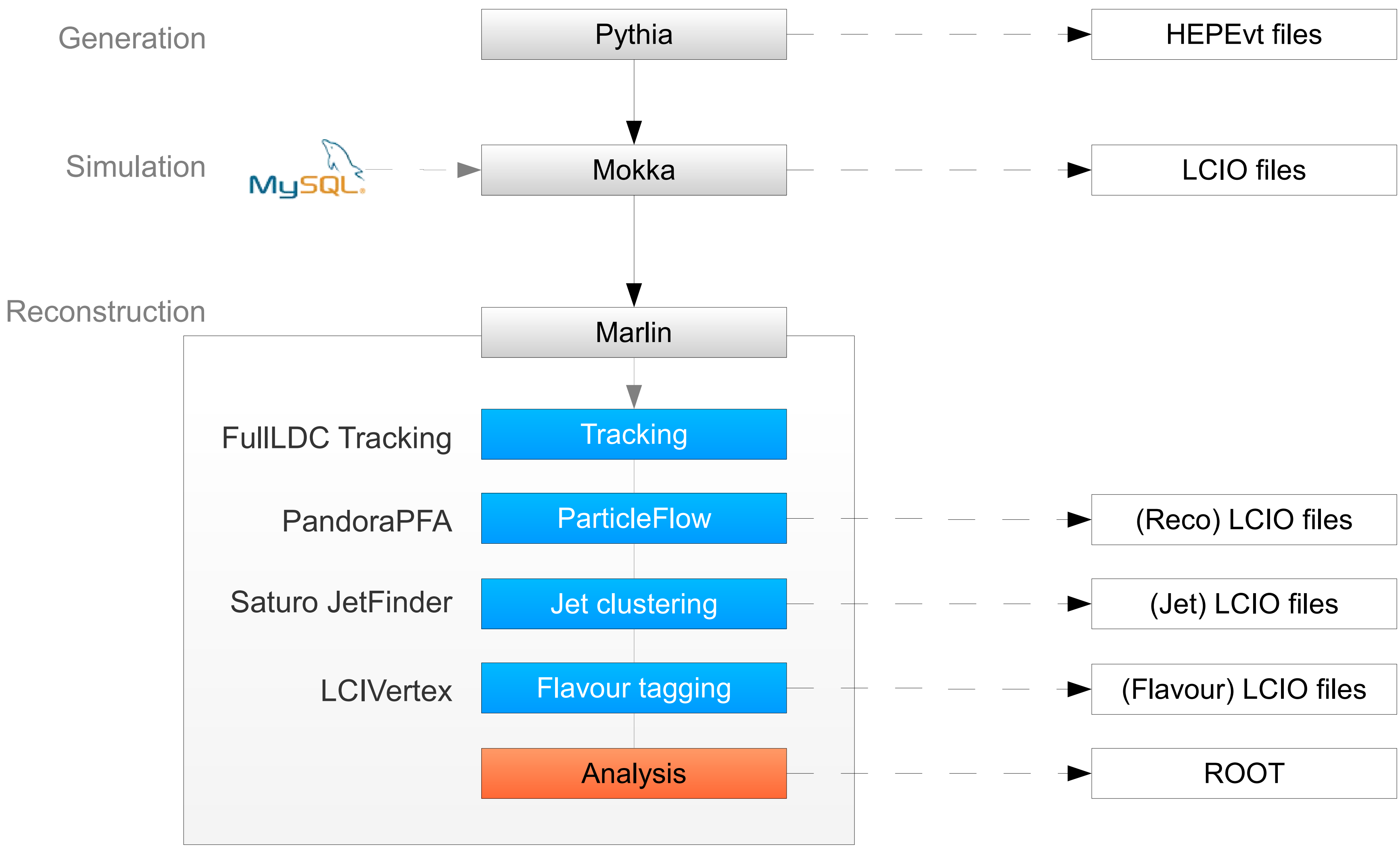
$int.luminosity = 20\,fb^{-1}$

$\sigma = 1.4\cdot 10^4\,fb \quad (for\ \sqrt{s} = 500\,GeV)$

$\#_{events} = \ 2.8\cdot 10^5$

Cuts at the generator level to reduce the number of events:

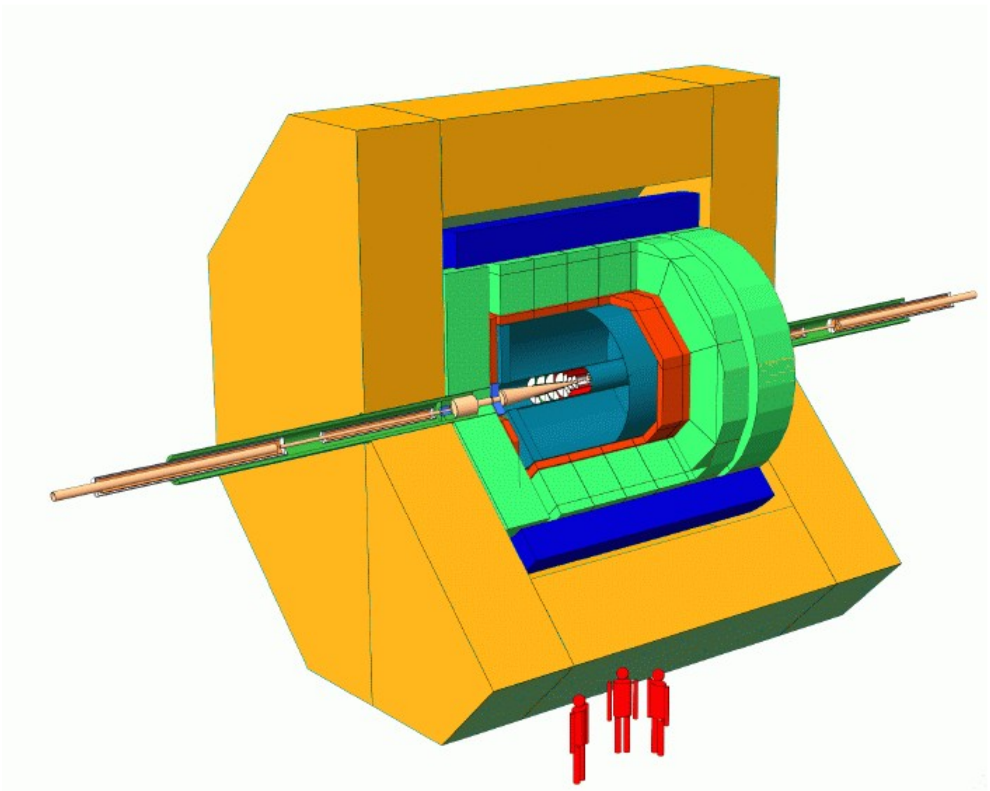
$$\left.\begin{array}{l} E_{vis} > 100\,GeV \\ N_{part} > 50 \\ \log(y_{56}) > -9.0 \end{array}\right\} \quad \#_{afterCuts} = \ 9080$$


Generation
Pythia
HEPEvt files
Simulation
MySQL
Mokka
LCIO files
Reconstruction
Marlin
FullLDC Tracking
Tracking
PandoraPFA
ParticleFlow
(Reco) LCIO files
Saturo JetFinder
Jet clustering
(Jet) LCIO files
LCIVertex
Flavour tagging
(Flavour) LCIO files
Analysis
ROOT

Mokka: geant4 based framework for full detector simulation

Detector used for simulation with Mokka: **LDCPrime_02Sc_p01**

⇒ Interpolation between the two detector concepts GLD and LDC



Magnetic field: 3.5 T

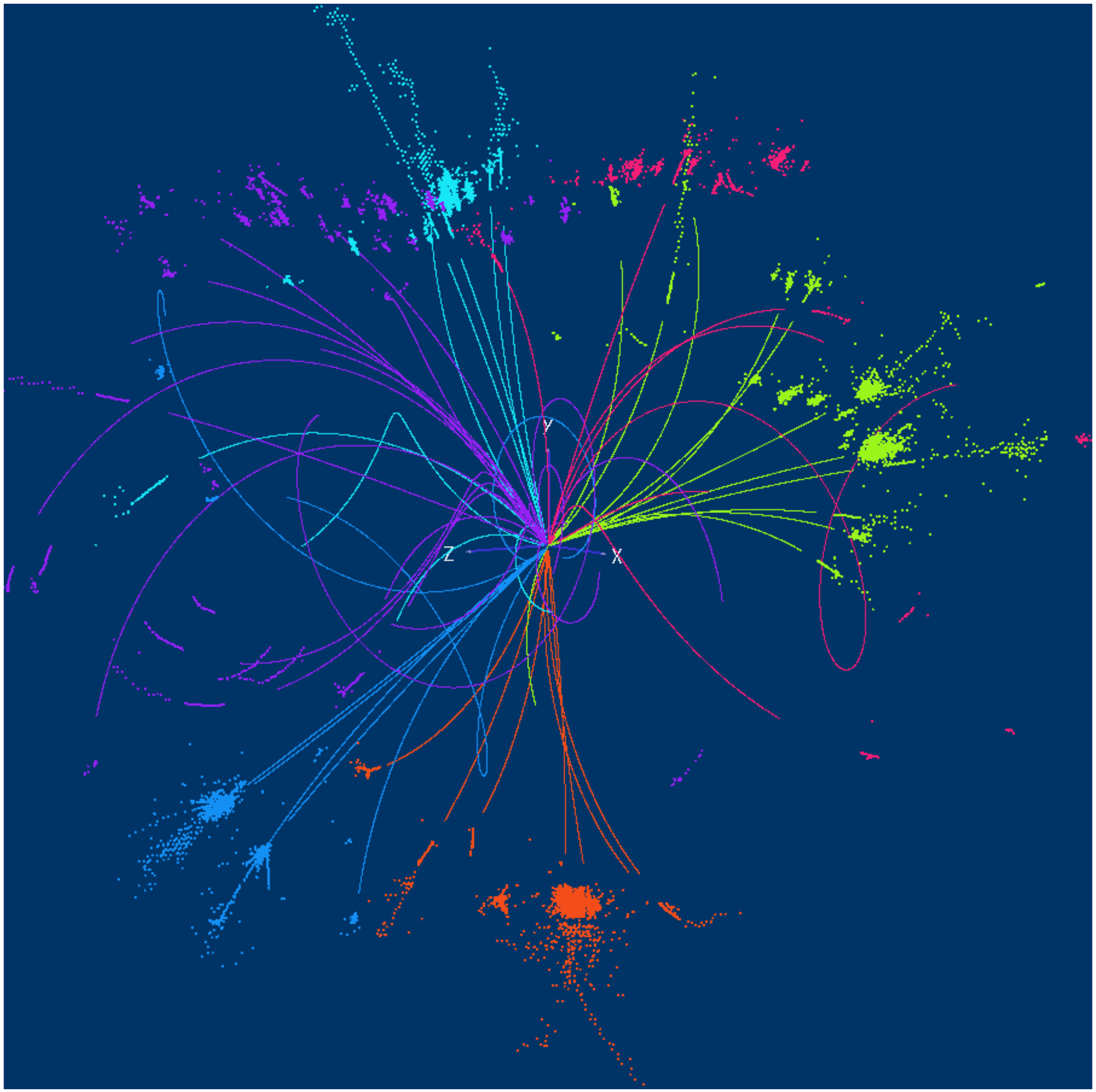
Tracking:

VTX $(inner\ radius = 1.5\,cm)$
TPC $(R = 1.7\,m, L = 4.4\,m)$
FTD *(acceptance down to 7 degrees in polar angle)*

High granularity calorimeters:

ECAL $W - Si, 23\,\chi_o, 1x1\,cm^2$
HCAL $Iron - Scintillator, \sim 4\text{-}6\,\lambda, 3x3\,cm^2$

$t\bar{t}$ 6jet Event



Event characteristics $t\bar{t}$:

- high multiplicity
- 6 jet topology
- two jets containing B-hadron decay products
- some fraction of energy is carried away by neutrinos from B-hadron decay.

defines next steps in pipeline:

Particle Flow
jet clustering
b-tagging
cuts

Particle Flow: *method to reconstruct four-momenta of all measurable particles in an event*

Tracking in VTX/TPC/SiT/FTD, **Clustering** of hits in ECAL/HCAL

charged particles (e+/-,μ+/-,h+/-):

- *Use tracker to measure p*
- *Identify particle by dE/dx, fraction energy ECAL/HCAL, cluster shapes,...*

  $\rightarrow$ *particle mass* $\rightarrow E^2 = p^2 + m^2$

► *4 - momenta reconstructed*

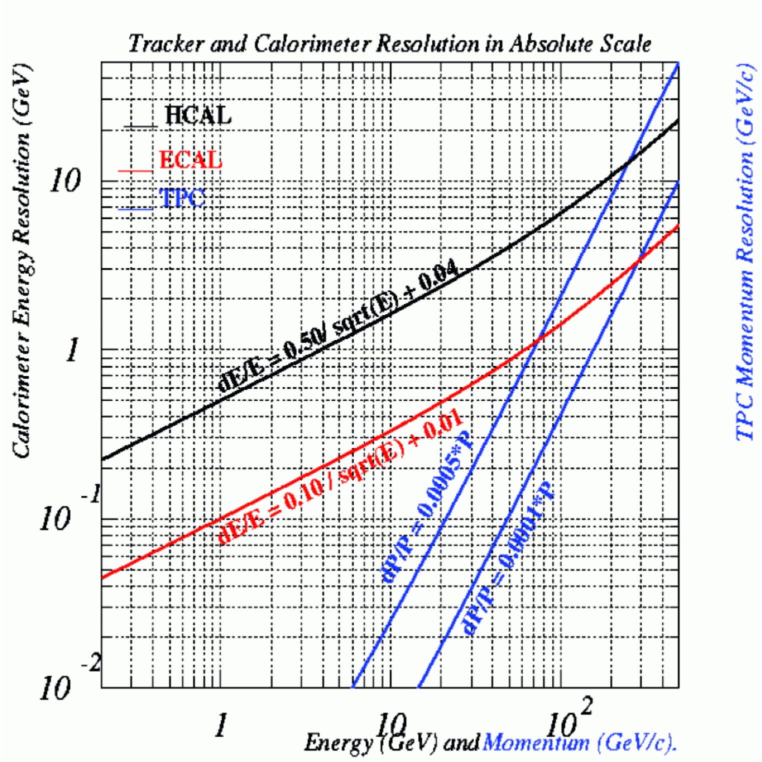
neutral particles (γ, h0):

- *Use calorimeter to measure E*
- *Identify particle by fraction energy ECAL/HCAL, cluster shapes,...*

  $\rightarrow$ *particle mass*

- *direction of p is defined by cluster position w.r.t primary interaction point*
- *value of p is then given by* $p^2 = E^2 - m^2$

► *4 - momenta reconstructed*



for < 100 GeV better resolution in tracking system

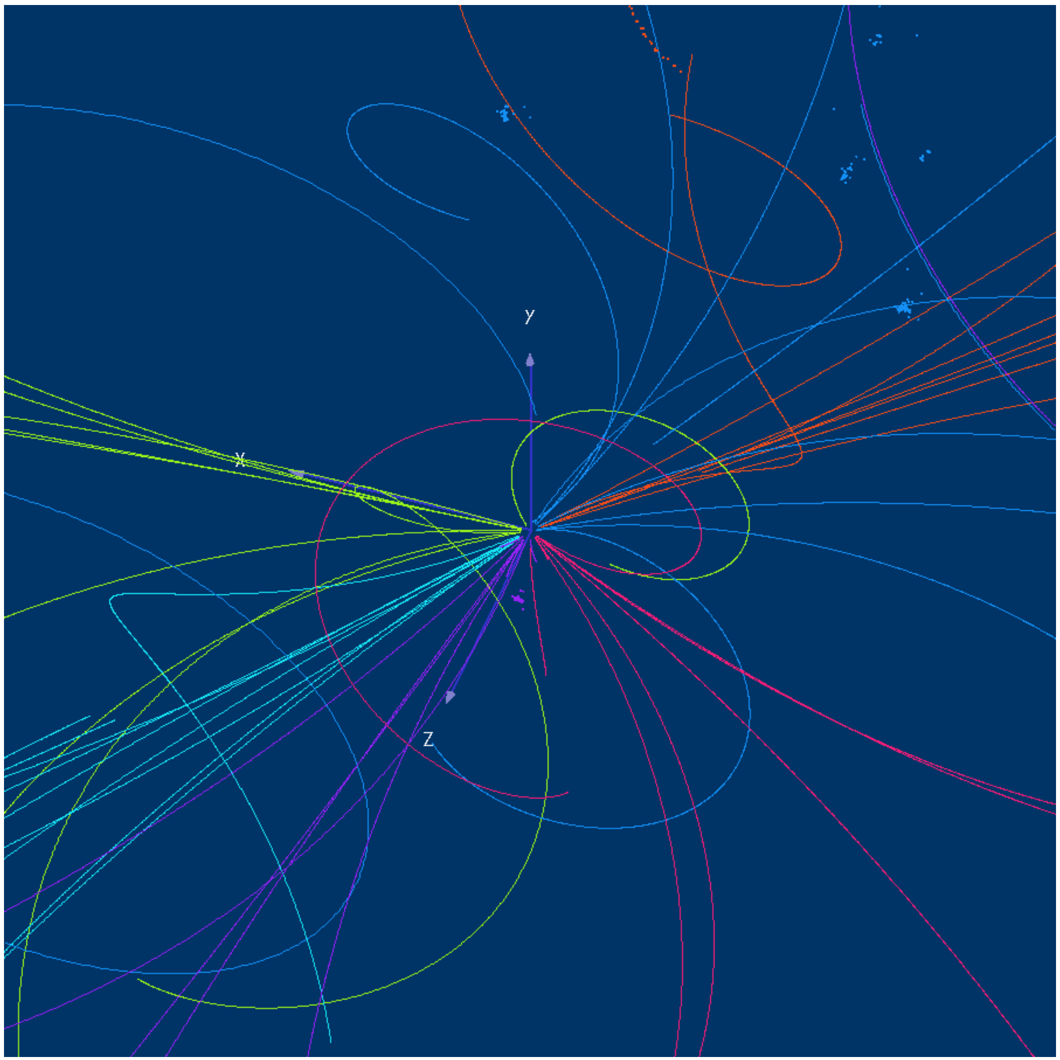
ParticleFlow algorithm used:

PandoraPFA

by Mark Thomson

Algorithm used: **DURHAM**

Cluster mode: force to 6 jets



DURHAM short summary:

- *for every pair of particles* (i, j) *compute a closeness measure* y_{ij}
- *if* $min(y_{ij}) < ycut \rightarrow$ *particles i and j should be merged*

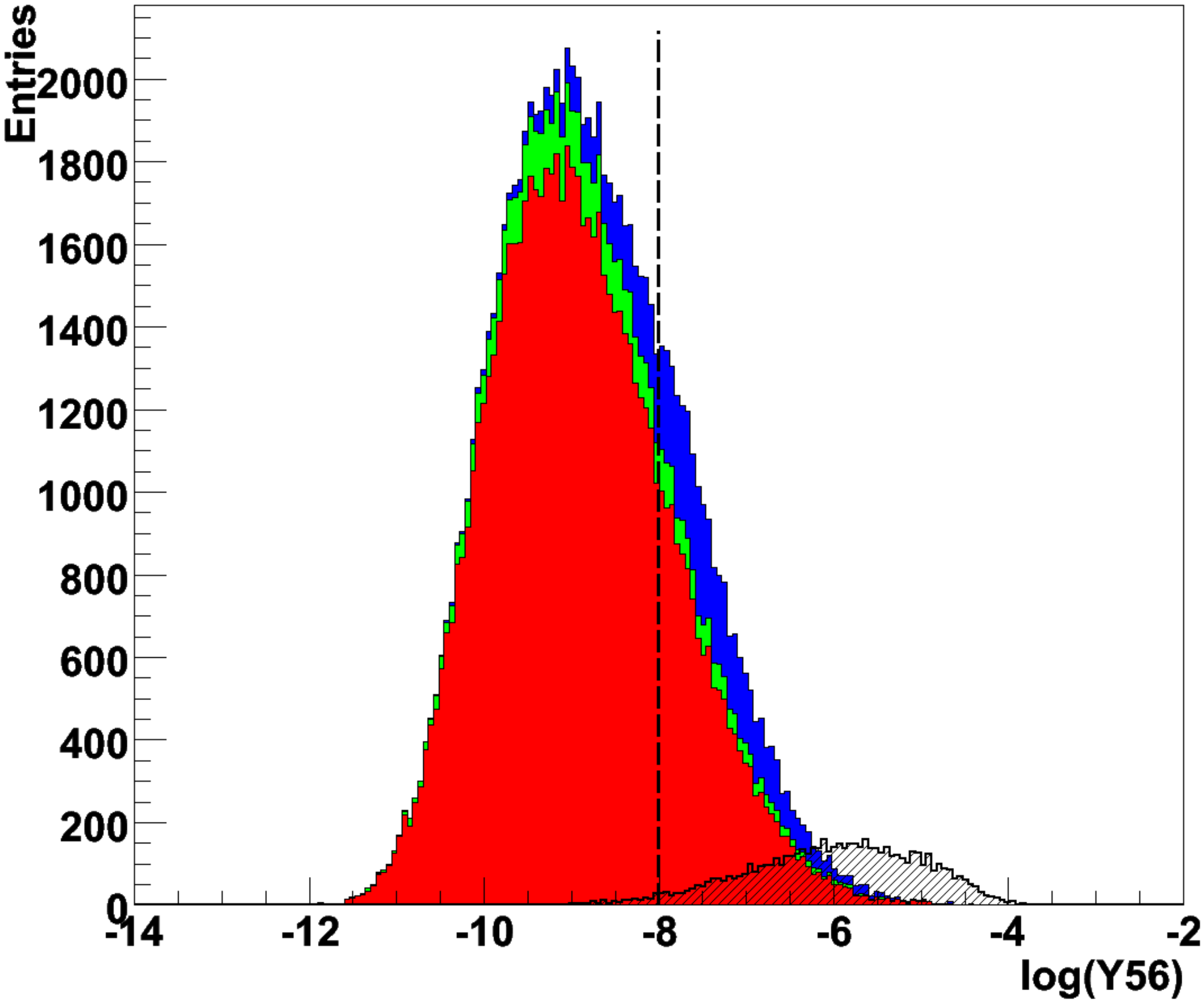
$$y_{ij} = \frac{2\,min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{E_{vis}^2}$$

$$\vec{p}_{jet} = \vec{p}_i + \vec{p}_j \qquad E_{jet} = E_i + E_j$$

y_{56} *is the jet resolution parameter for which the event is resolved from 6 to 5 jet topology.*

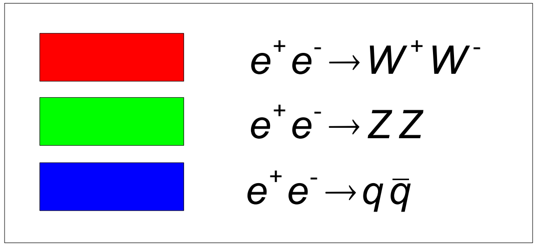
y_{56} *is used for cuts later on*

cut value log(Y56)

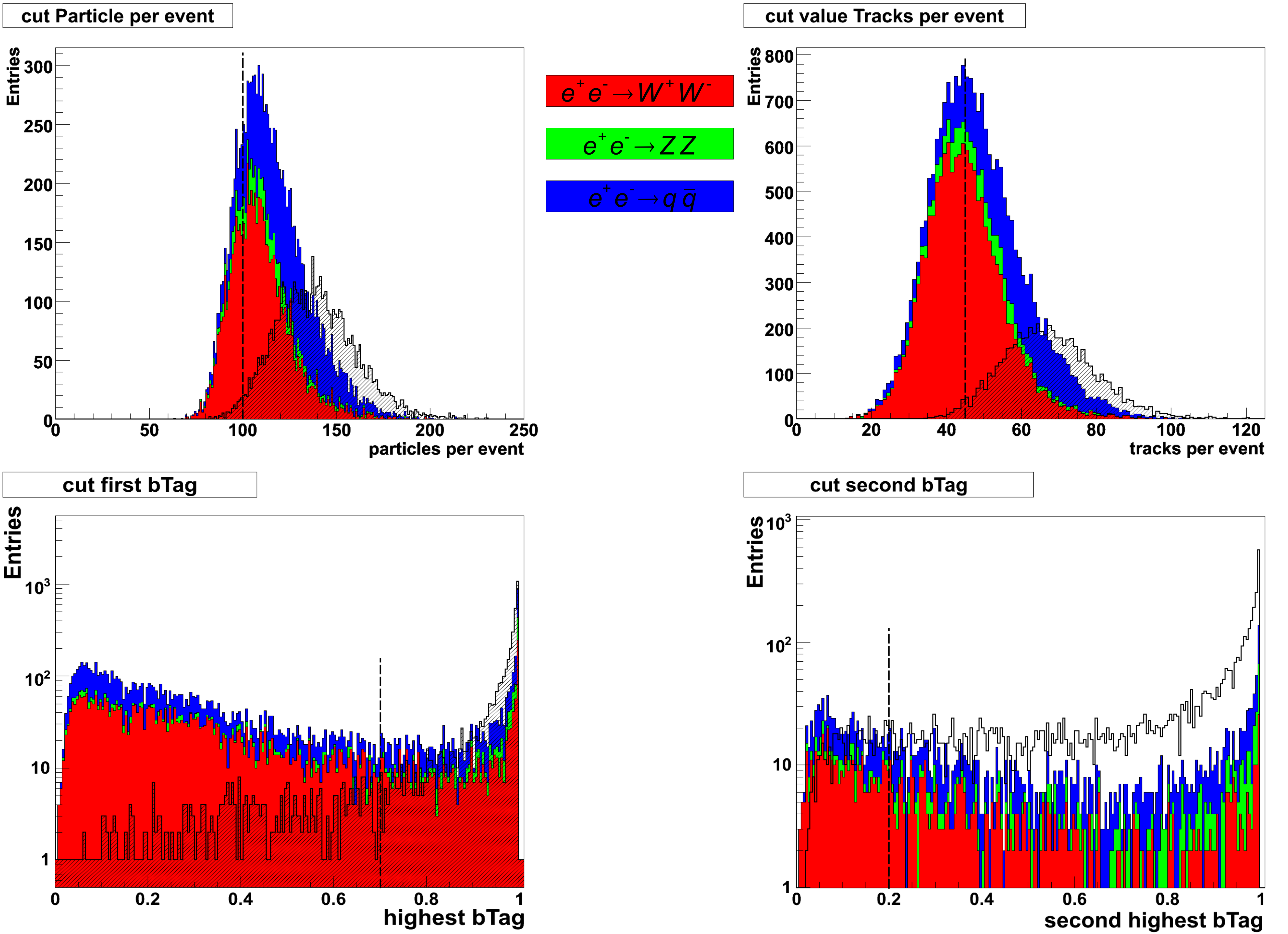


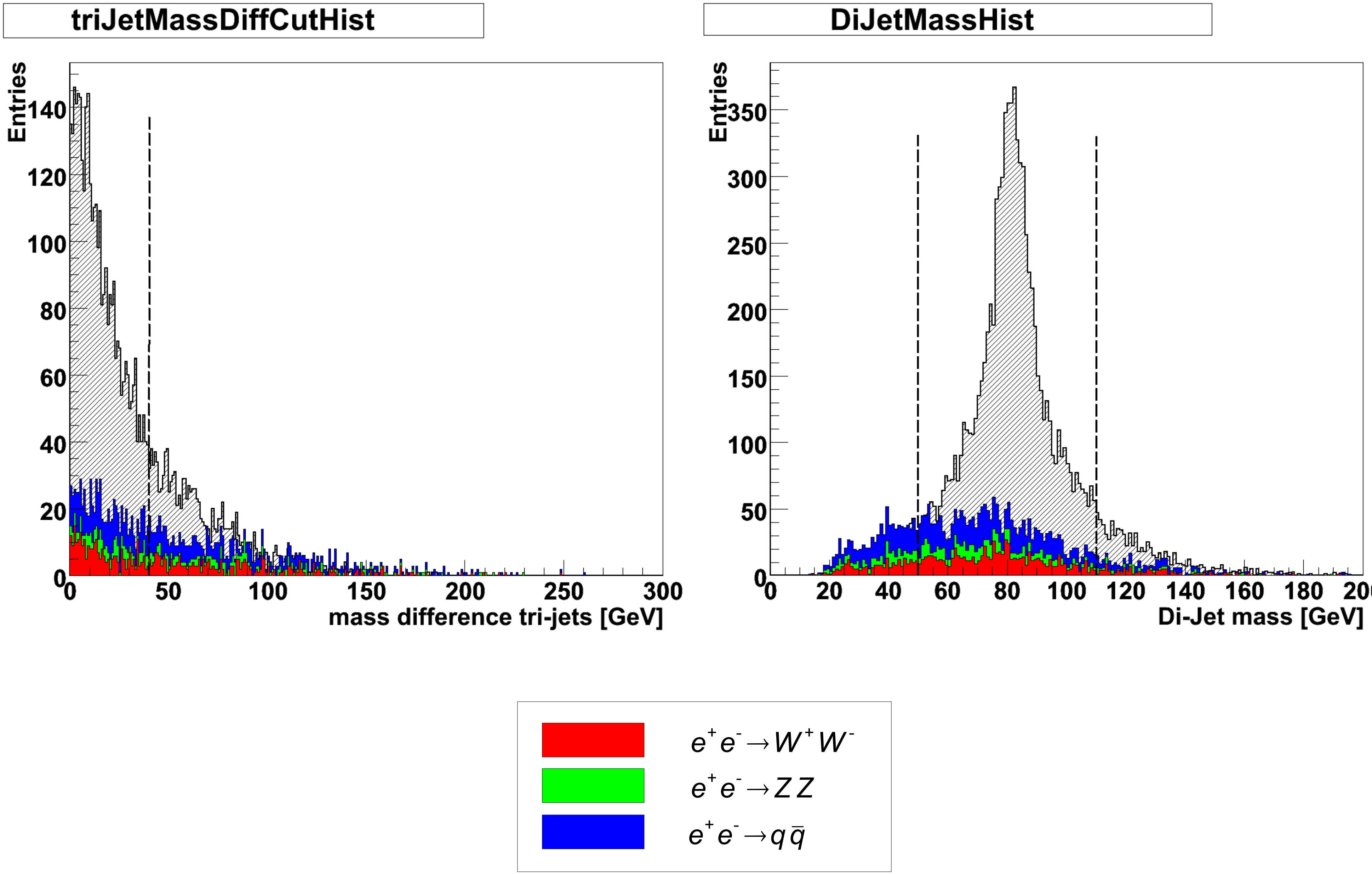
Cuts used for selection of $t\bar{t}$ events:

$\log(y_{56})$	y_{ij} *value for* 6jets $\rightarrow$ 5jets
N_{Tracks}	*total number of tracks per evt*
$N_{Particles}$	*total number of particles per evt*
$bTag_{First}$	*highest bTag value*
$bTag_{Second}$	*second highest bTag value*
Δm_{3j}	*mass difference tri – jets*
$\lvert m_{ij} - m_W \rvert$	*mass difference of W di – jet and nominal W mass*



Eliminating the background – selection cuts



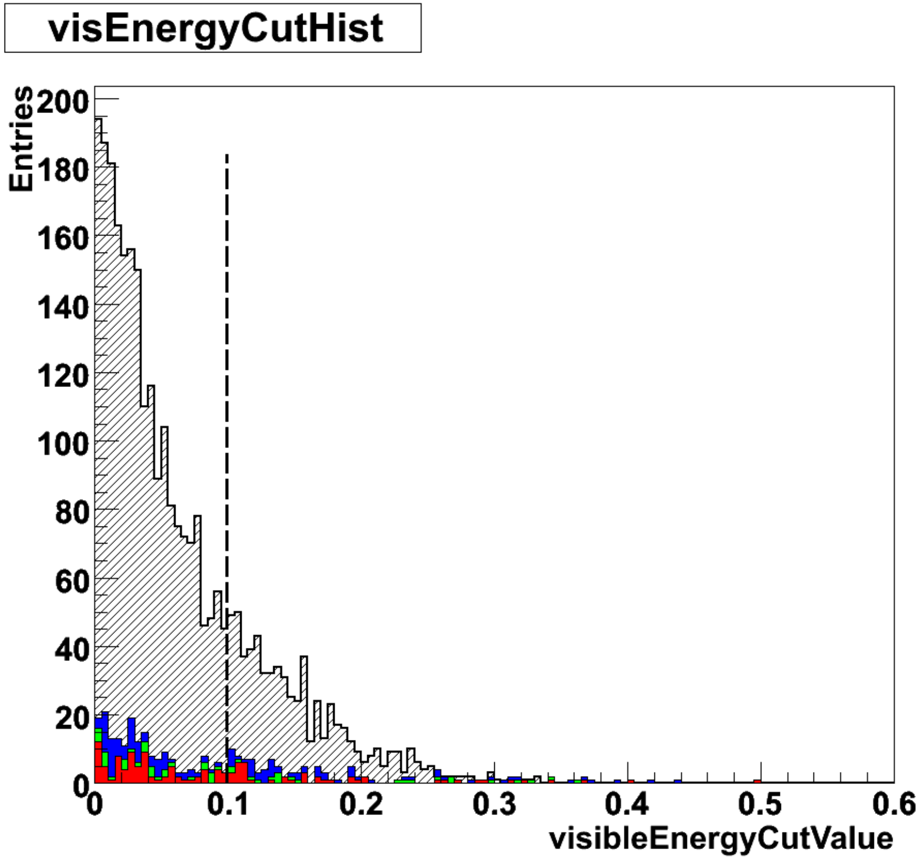

triJetMassDiffCutHist
Entries
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
mass difference tri-jets [GeV]
DiJetMassHist
Entries
0
50
100
150
200
250
300
350
0
20
40
60
80
100
120
140
160
180
200
Di-Jet mass [GeV]
$e^+e^- \to W^+W^-$
$e^+e^- \to ZZ$
$e^+e^- \to q\bar{q}$

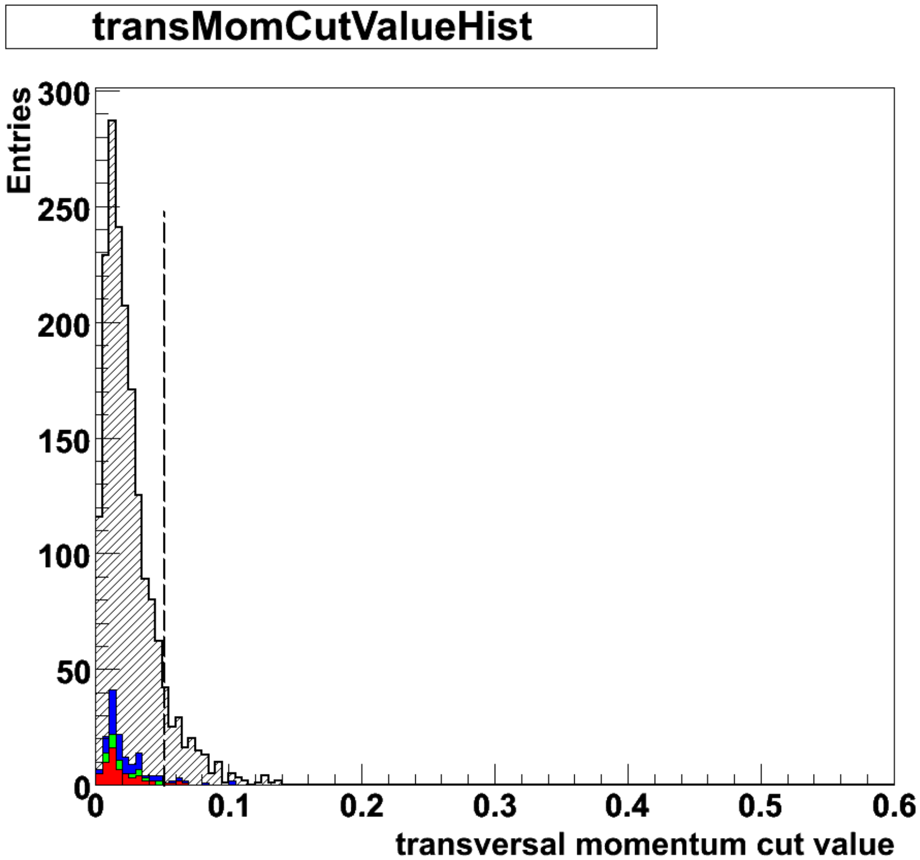
to improve quality the typical CERN $e^+ e^-$ LEP **cuts** were applied

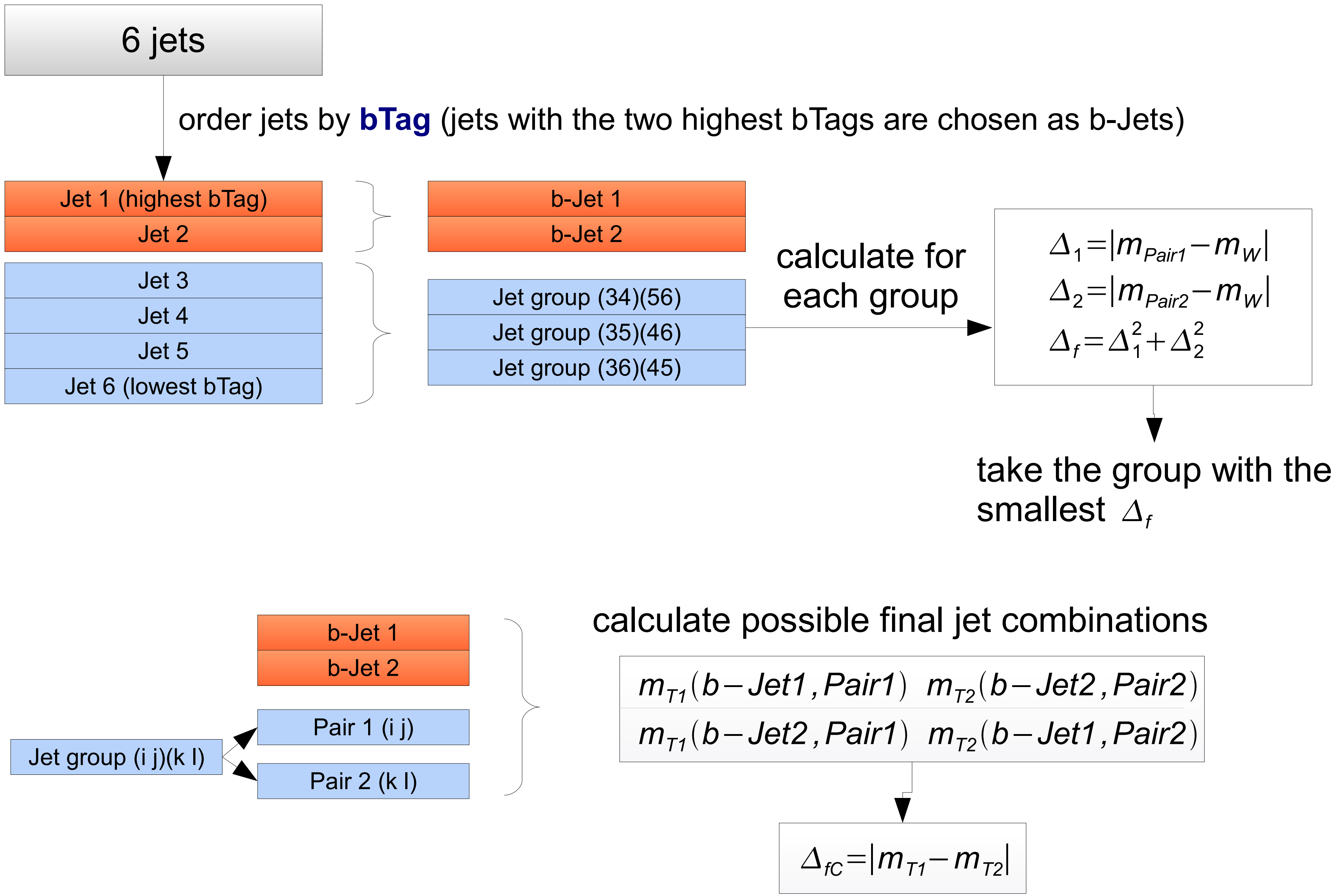
$$\left|\frac{E_{vis}}{\sqrt{s}} - 1\right| < \Delta_E \qquad \frac{\left|\sum \vec{p}_{\parallel i}\right|}{\sum |\vec{p}_i|} < \Delta_{PL} \qquad \frac{\left|\sum \vec{p}_{Ti}\right|}{\sum |\vec{p}_i|} < \Delta_{PT}$$

$t\bar{t}$	1674	27.3%	(sel. eff.)
WW	56	99.9%	(rej. eff.)
ZZ	22	99.6%	
$q\bar{q}$	63	99.3%	

Cuts removed events with large missing energy due to **neutrinos**.

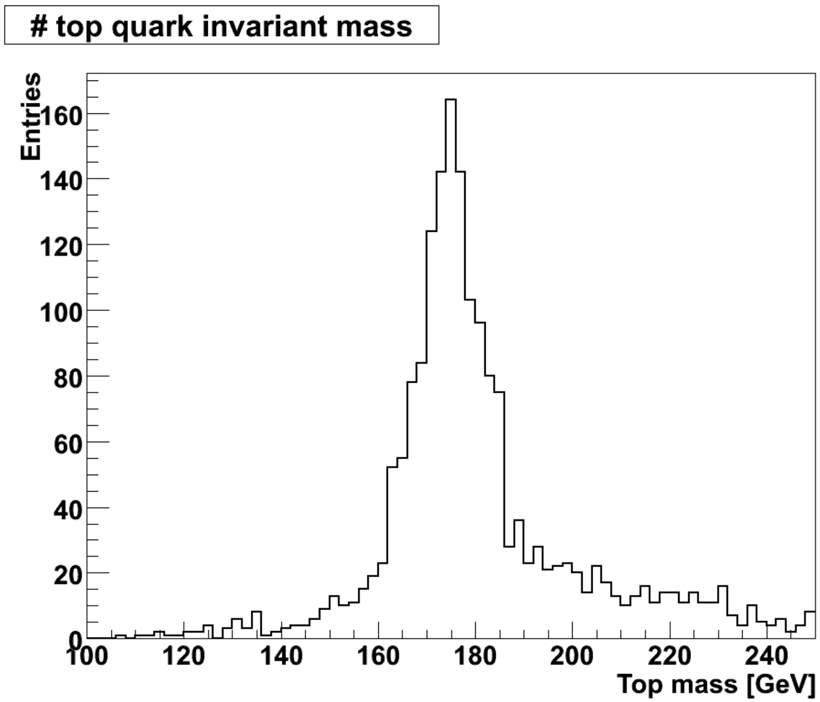


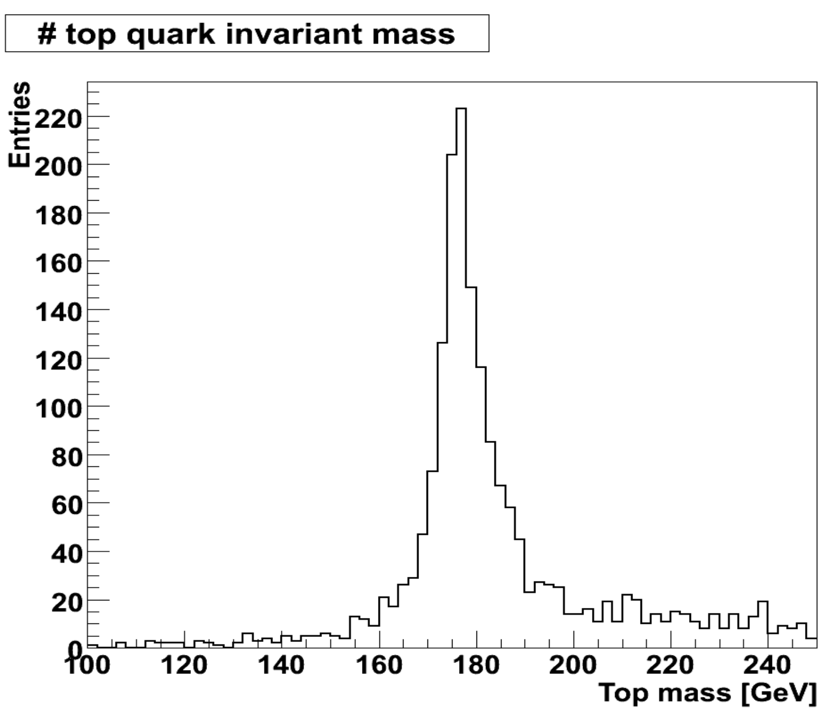




⇨ Take the Tri-Jet (b-Jet/Pair) combination with smallest Δ_{fC} as **final jet** state.

Improving further – kinematic fitting

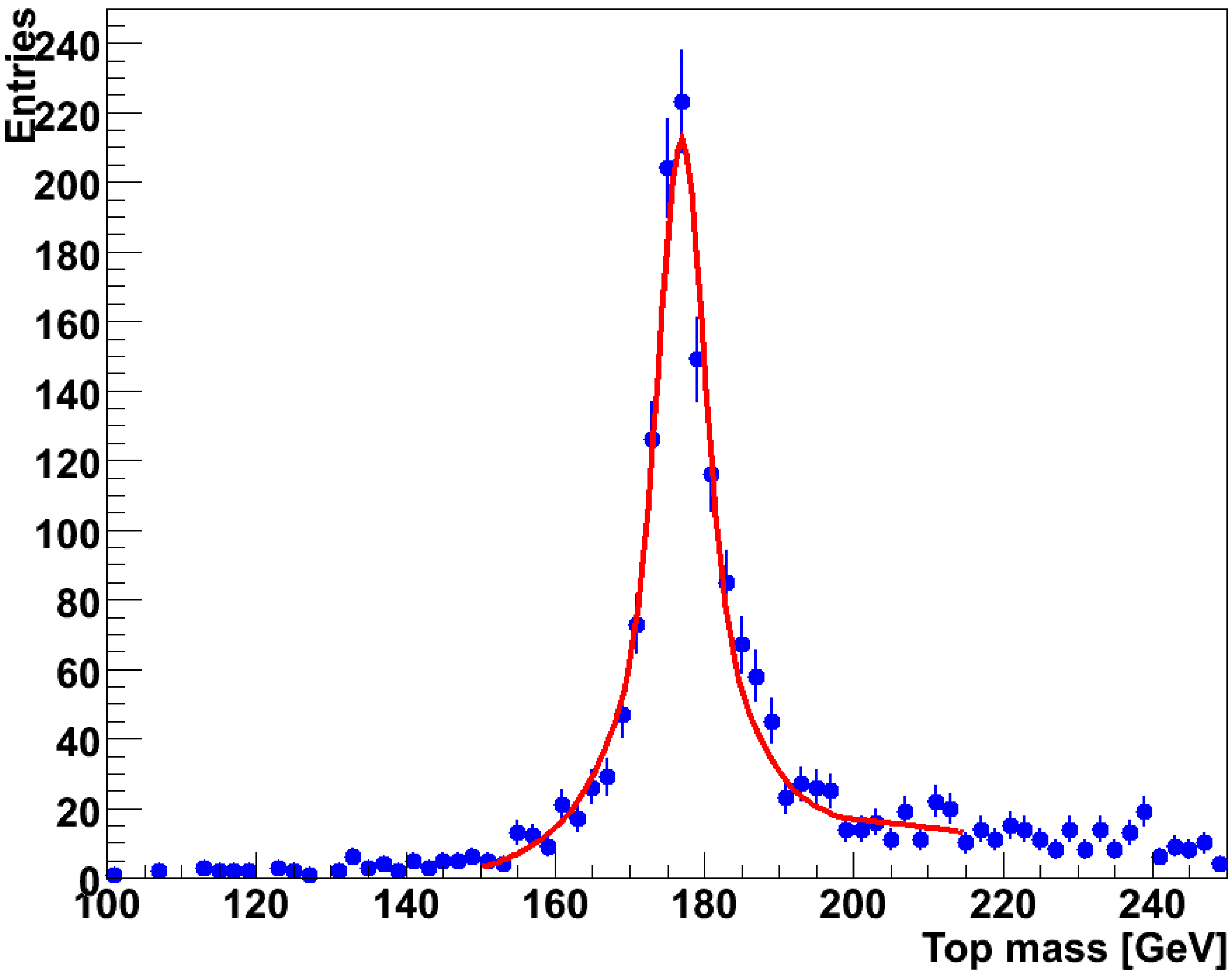




7 constraints were used for kinematic fitting:

3	$\sum_{i=1}^{6} \vec{p}_i = 0$	*momentum conservation*
1	$\sum_{i=1}^{6} E_i = \sqrt{s}$	*energy conservation*
2	$\lvert m_{ij} - m_W \rvert = 0$ $\lvert m_{kl} - m_W \rvert = 0$	*mass difference W dijet and nominal W mass*
1	$\Delta m_3 = 0$	*same mass t and $\bar{t}$*
7		

top quark invariant mass



$L = 20\,fb^{-1}$

$\langle m_t \rangle \approx 175.01 \pm 0.18 \quad GeV$

$\Gamma = 1.5 \pm 0.4 \quad GeV$

Fitting function: **Breit-Wigner** convoluted with the resolution function

Double Gaussian used as resolution function. Shape of the resolution function fixed.

Invariant mass of top quark was reconstructed using

- full ILD detector simulation
- full hadronic background
- complete reconstruction

Result of this analysis: $m_t = 175.01 \pm 0.18 (stat.) GeV \quad (for\ 20\ fb^{-1})$

Extrapolated for higher luminosity: $m_t = 175.01 \pm 0.05 (stat.) GeV \quad (for\ 300\ fb^{-1})$

Result by S.V. Chekanov and V.L. Morgunov: $m_t = 176.08 \pm 0.1 (stat.) GeV \quad (for\ 300\ fb^{-1})$

Analysis will be used for detector optimization and performance studies and is supposed to be included in the Letter of Intent for the ILD detector.

Outlook:

Include additional backgrounds involving leptons in final states:
$ZZ \rightarrow q\,q\,l^+ l^-$
$WW \rightarrow q\,q\,l\,\nu$
$W\,e\,\nu, Z\,e\,e$

⇨ Implementation of the veto on high energy isolated lepton