Detector and Physics Studies for High Energy Lepton Colliders with ILCroot Simulation Framework

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Outline

- Lepton Collider Physics
- Lepton Collider Proposals
- Lepton Collider Experiment Challenges
- ILCroot framework
  - Architecture
  - Virtual Montecarlo
  - Interface to MARS framework
- ILC studies
  - Jet reconstruction
  - Physics benchmarks
- MuC studies
  - Tracking in the MuC background

Lepton Collider Physics

LHC will produce new results soon...

then the Lepton Collider physics program can be sharpened

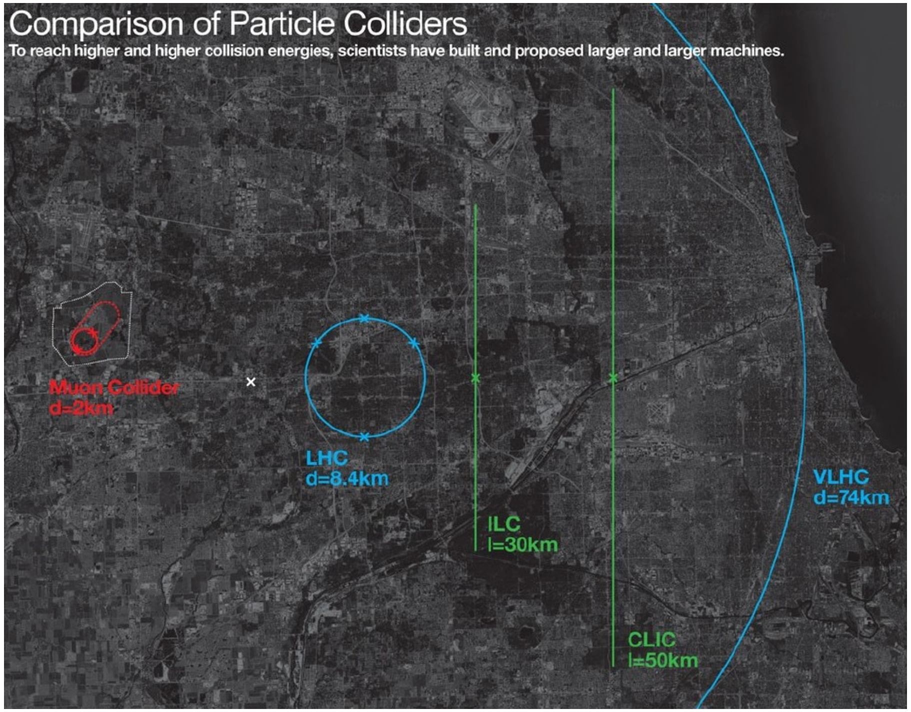
- Establish the mechanism for EWSB

  does Higgs boson have Standard Model properties? – or NOT?
- Establish the nature of physics beyond the SM

  such as SUSY, extra dimensions, ...
- Open new windows for discovery at the precision frontier
- Increase sensitivity to new physics which might be lost in hadron collider – eg. invisible decays or trigger losses

Lepton Collider Proposals

- ILC: 0.5-1.0 TeV e+e- linear collider
  - Superconducting RF accelerating cavities
  - Physics/Detectors well studied
- CLIC: up to 3 TeV e+e- linear collider
  - Two beam acceleration with warm RF
  - R&D underway
- MuC: up to 4 TeV μ+μ- storage ring
  - Fermilab's Muon Accelerator Proposal will study technical feasibility and cost of the machine



Each of them presents a set of challenges

Lepton Collider Experiment Challenges

- Physics and Detectors
  - Develop a detector technology adequate for the physics goals
  - Study the detector performance at different physics benchmarks
  - Understand the detector response in the machine's environment

- Software
  - Need new simulation frameworks for the next generation of HEP experiments
  - Implement the new detector technologies in simulations
  - Compare results obtained by different Montecarlo packages

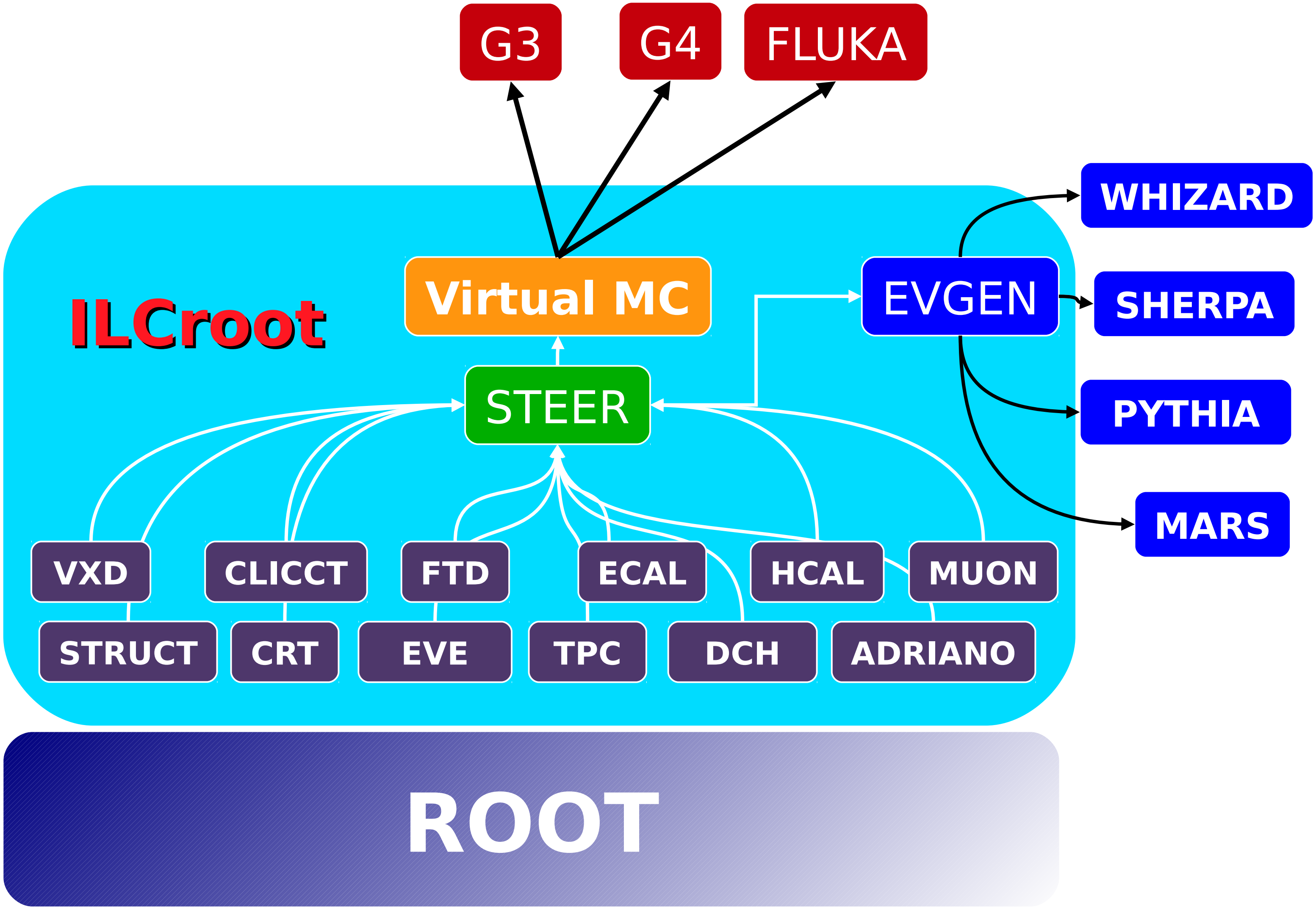
This presentation will cover most of the above issues in ILC and MuC

ILCroot: root Infrastructure for Large Collider

- **CERN** architecture (based on Alice's Aliroot)
- Uses ROOT as infrastructure
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
  - Growing number of experiments have adopted it: Alice, Opera, Panda, 4th Concept, LheC, T1015
- Include interfaces to read external event generator outputs (Pythia, Whizard, Sherpa) and MARS generator for the Muon Collider background
- Virtual Geometry Modeler (VGM) for geometry
- Virtual Montecarlo allows to use several MonteCarlo (Geant3, Geant4, Fluka)
- Six MDC have proven robustness, reliability and portability
- Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!

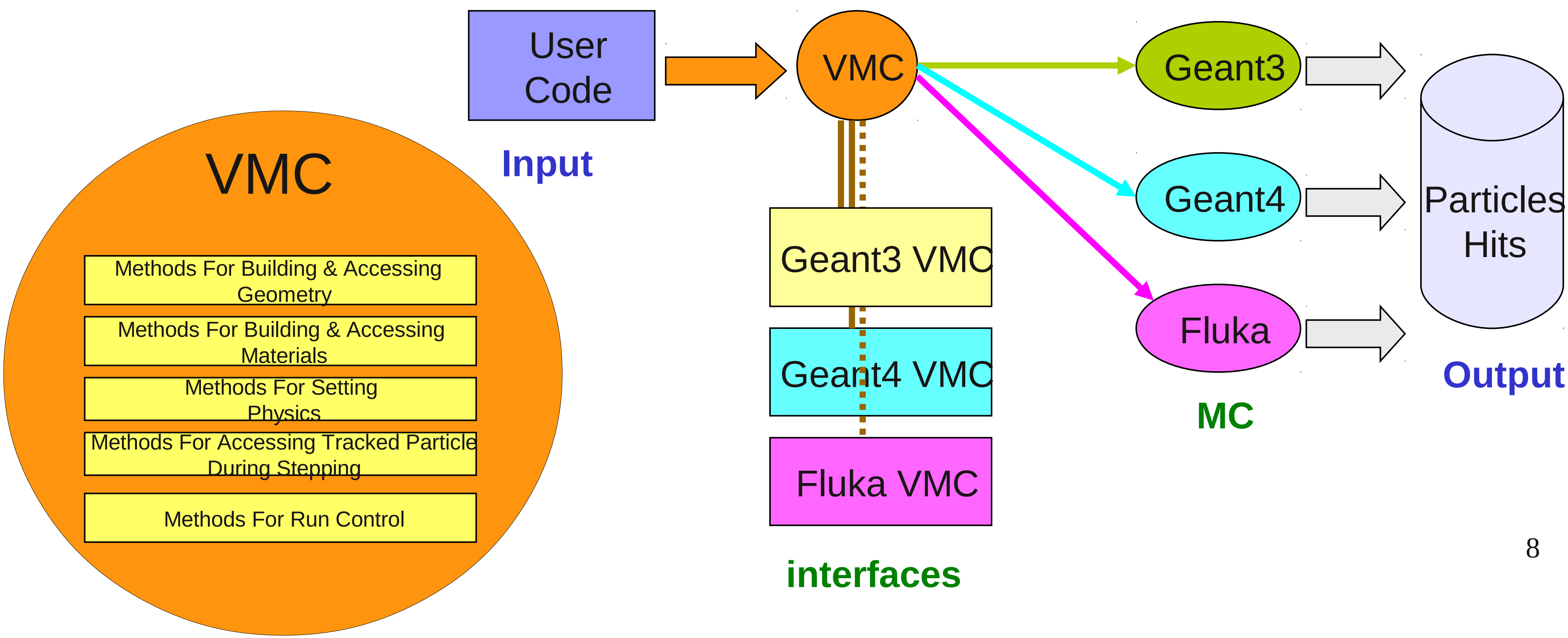
All the studies presented in this talk have been performed with ILCRoot

ILCroot: Architecture

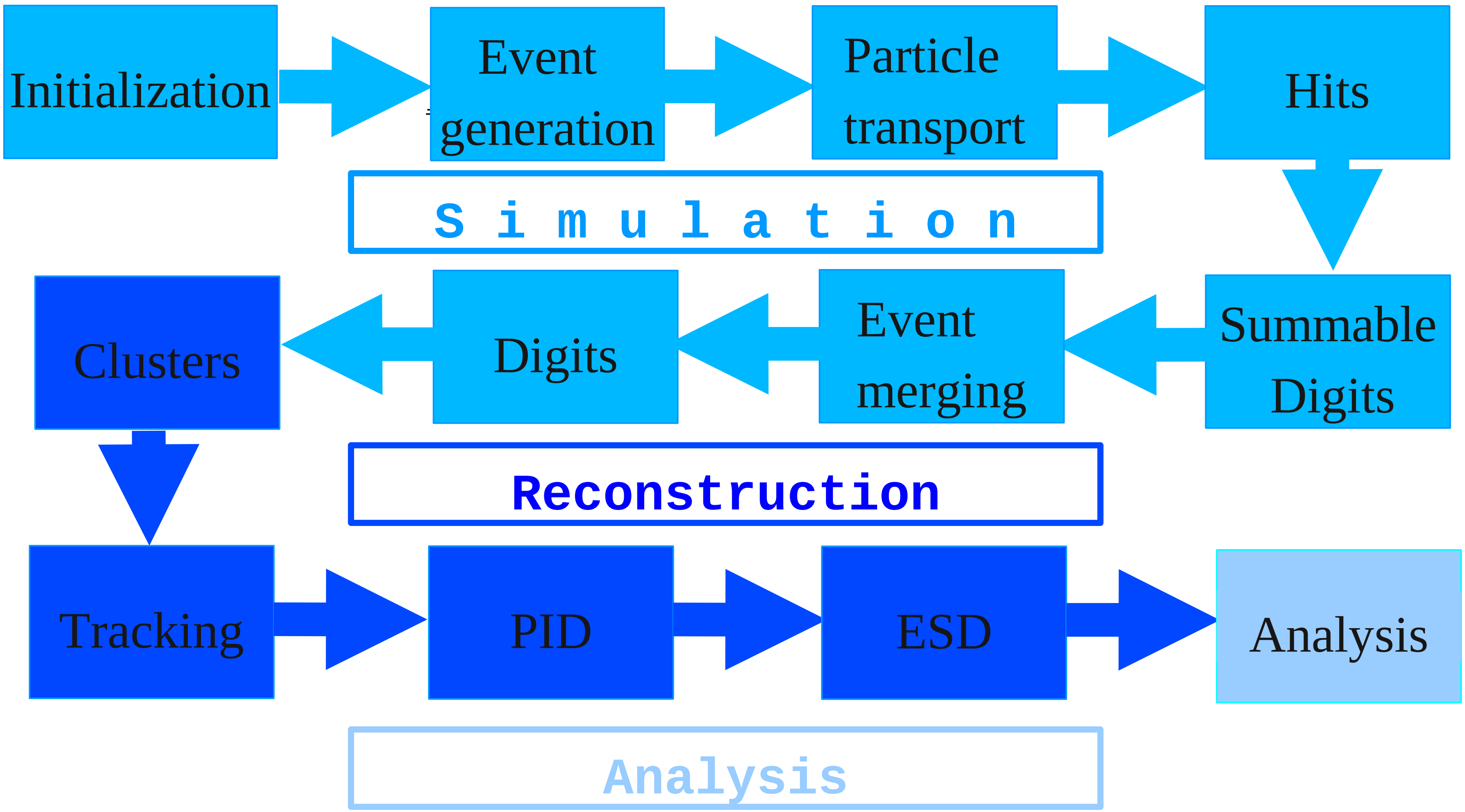


ILCroot:
Virtual MonteCarlo

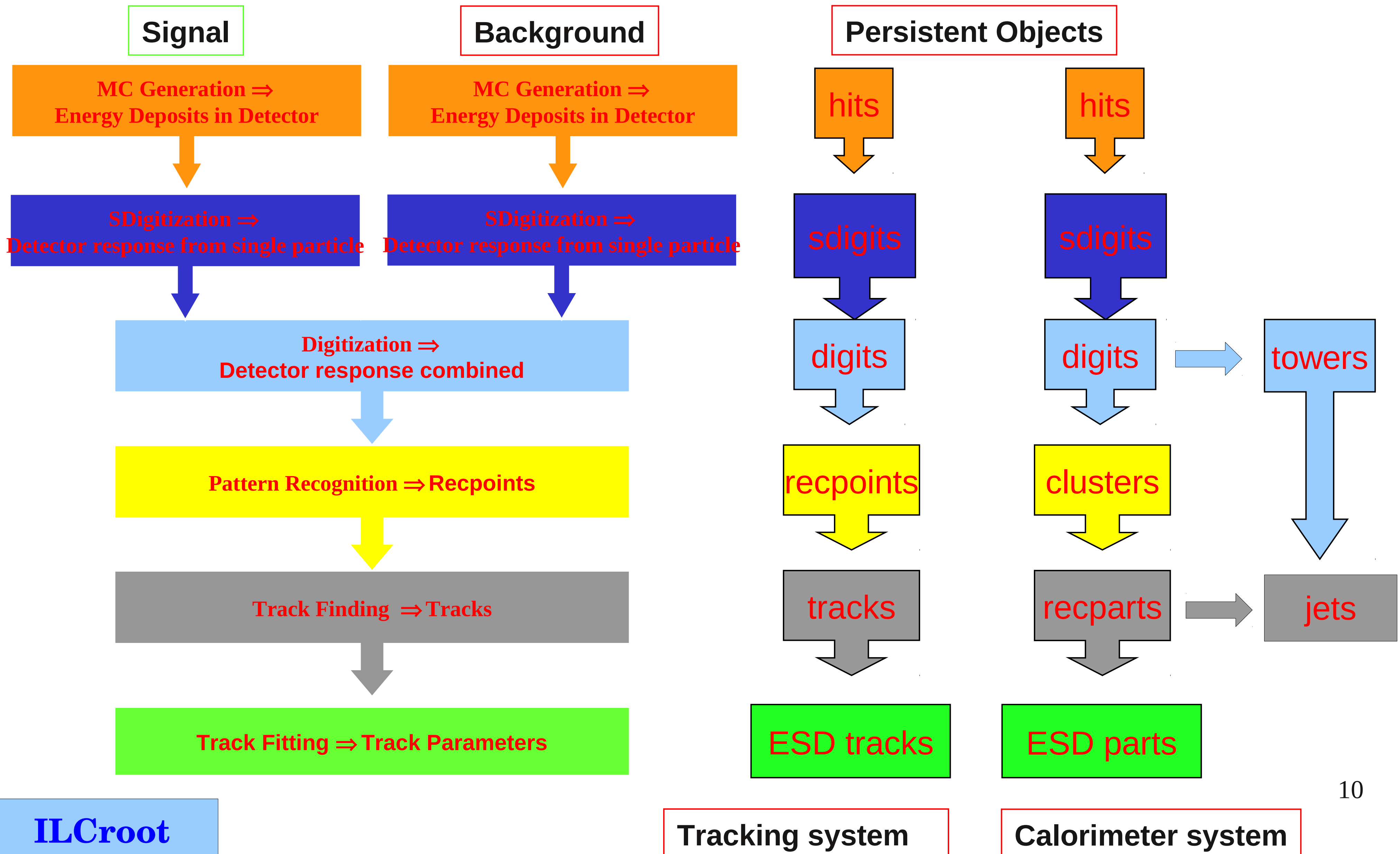
- The Virtual MC provides a virtual interface to transport MC programs
- It allows to run the same user application with all supported Montecarlo's
- The MC (Geant3, Geant4, Fluka) is selected and loaded at run time without changing any line of the code and therefore the geometry definition, the detector response simulation, or input and output formats



ILCRoot: Flow Control

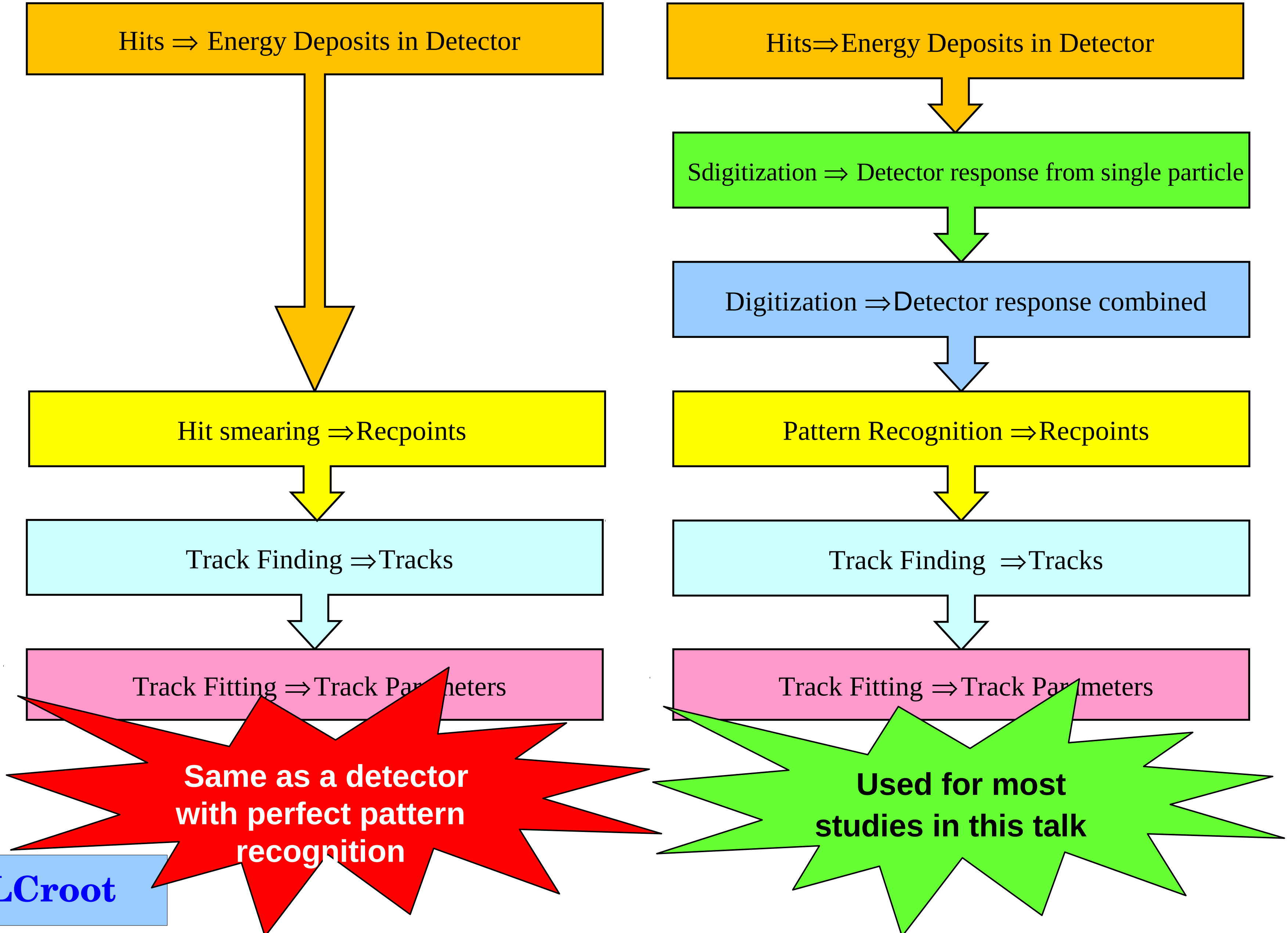


ILCroot:
Simulation and Reconstruction steps



ILCroot

ILCroot:
Fast vs Full Simulation



ILCroot:
Fast Simulation and/or Fast Digitization

- Fast Simulation = hit smearing
- Fast Digitization = full digitization with fast algorithms
- Do we need fast simulation ?

  Yes!

  - Calorimetry related studies do not need full simulation/digitization for tracking
  - Faster computation for quick answer to response of several detector layouts/shielding
- Do we need full simulation?

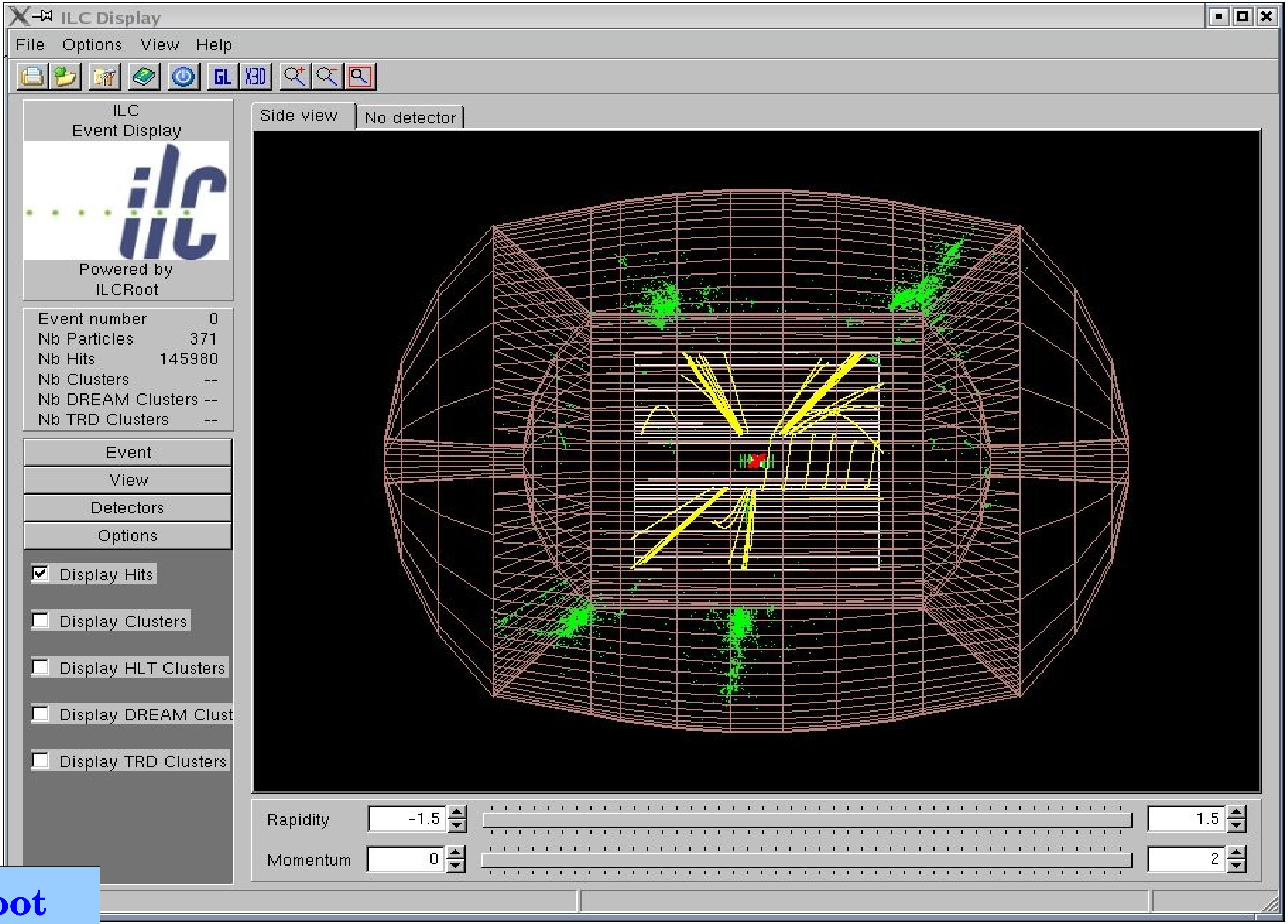
  Yes!

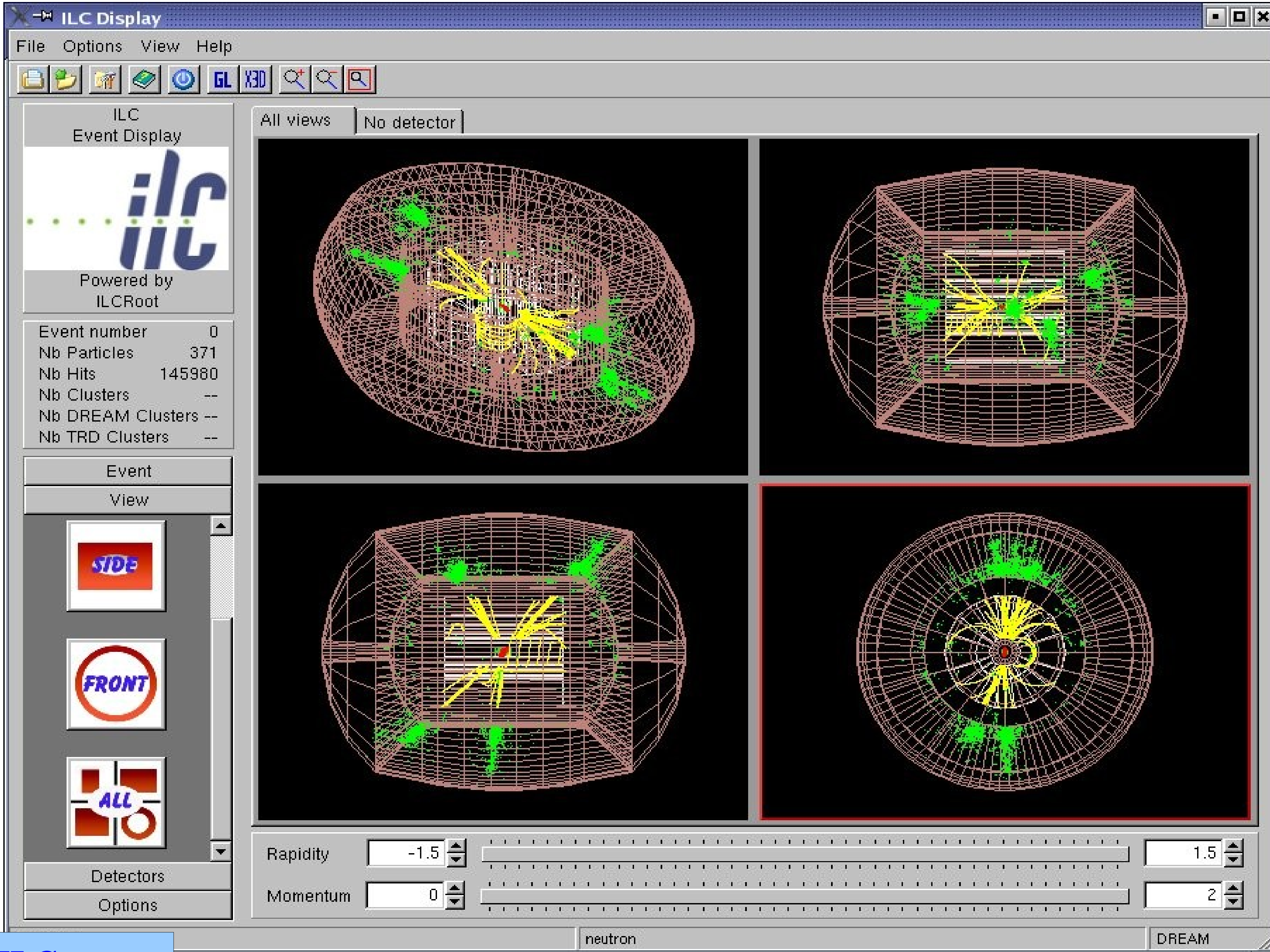
  - Fancy detector and reconstruction needed to be able to separate hits from signal and background

ILCroot:
Interface to MARS framework for MuC studies

- **MARS**
  - MARS is the framework for simulation of particle transport and interactions in accelerator, and shielding components.
  - The new release of MARS15 is available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS)
  - Among new features are:
    - Refined MDI(Machine Detector Interface) with a 10^{o} forward shielding (“nozzle”)
    - Significant reduction of particle statistical weight variation
    - Background is provided at the surface of MDI (10^{o} nozzle + walls)
- **MARS-to-ILCroot interface**
  - The ILCroot interface to MARS is implemented in ILCGenReaderMARS class.
  - ILCGenReaderMARS reads the list of particles provided by MARS with a weight W.
  - ILCGenReaderMARS feeds the Montecarlo with W particles smeared according the azimuthal simmetry

ILCroot:
Event Display




ILC Display
File
Options
View
Help
GL
X3D
All views
No detector
ILC
Event Display
ilc
Powered by
ILCRoot
Event number 0
Nb Particles 371
Nb Hits 145980
Nb Clusters --
Nb DREAM Clusters --
Nb TRD Clusters --
Event
View
SIDE
FRONT
ALL
Detectors
Options
Rapidity
-1.5
1.5
Momentum
0
2
neutron
DREAM

ILCroot

Studies for the International Linear Collider

Detector Requirements

Experimental conditions at ILC provide an ideal environment for precision studies and offer a clean and well-defined initial conditions to recognize new phenomena.

To fully exploit the physics opportunities ILC detectors must fulfill very demanding requirements pushing the actual technologies :

- Excellent jet energy resolution

  For the unambiguous identification of multi-jet decays of Z's, W's, top, H's, χ's

$$\sigma(E_j)/E_j = 30/\sqrt{E_j(GeV)}$$

- Superb tracker momentum resolution

  For Higgs recoil mass and χ decay endpoint measurements

$$\sigma(p_t)/p_t^2 = 5\times 10^{-5}(GeV/c)^{-1}$$

- Precise impact parameter resolution

  For the flavor identification and quark charge determination of heavy quarks

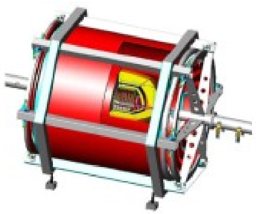
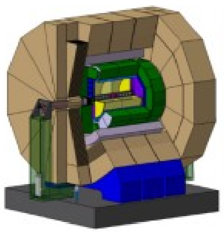
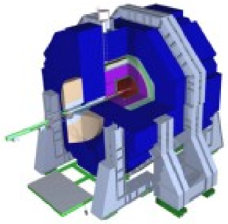
$$\sigma_{IP} = 5 \oplus 10/p\beta\sin^{3/2}\theta(\mu m)$$

- As hermetic as possible

  For the identification and the measurement of missing energy, eliminating SM backgrounds to SUSY

$$\theta_{min} = 5\,mrad$$

Three Detectors Proposed at ILC

Detector	4^{th}	ILD	SiD
Premise	Multiple Readout	PFA + TPC	PFA + Si Trkr
Vertex Detector	5-layer silicon pixel	5/6-layer silicon pixel	5-layer silicon pixel
Tracking	CluCou drift chamber	MPGD-TPC + Si	Silicon strips
EM calorimeter	BGO	Silicon-Tungsten	Silicon-Tungsten
Hadron Calorimeter	Dual/triple-readout Cu-scint/clear fibers	Analog- scintillator	Digital Steel - RPC
Solenoid	3.5 Tesla	3.5 Tesla	5 Tesla
Muon	Iron free dual solenoid with He drift tubes	Instrumented flux return	Instrumented flux return RPC
Forward Cal	Si-W	Si-W	Si-W

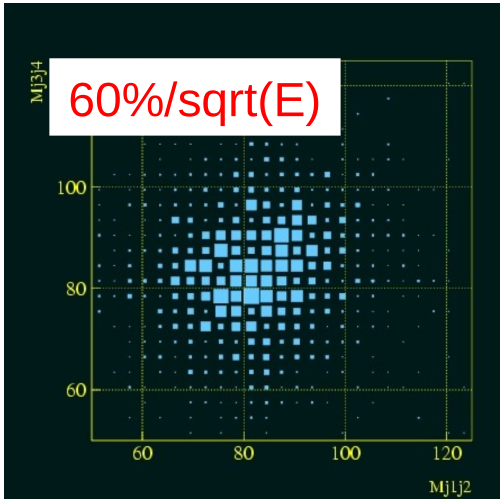
Main difference:
Approach to jet reconstruction

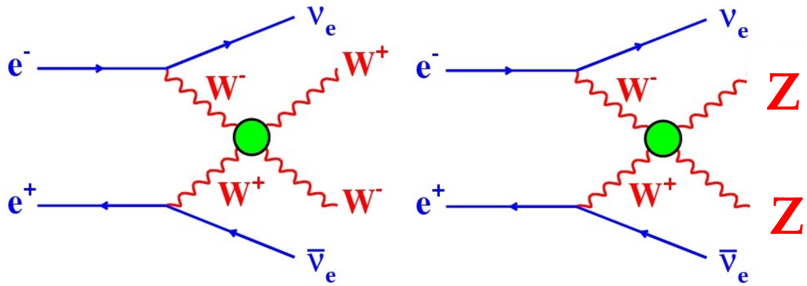
Main Physics Issue at ILC: Jet Reconstruction

Many interesting ILC physics processes have multi-jets in the final state

Jet energy resolution is the key in the ILC physics

Main Detector Issue at ILC: Calorimeter Performance

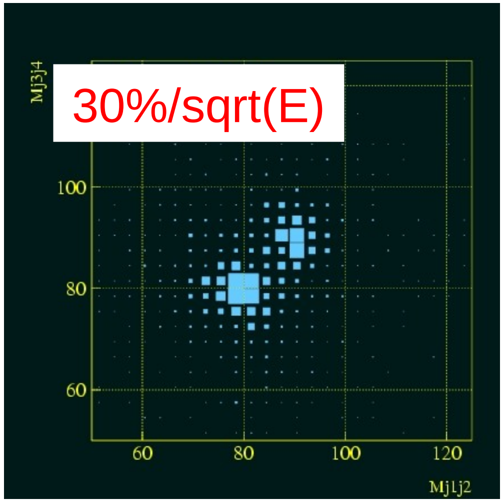




Z/W→ jj can be reconstructed and separated if

$$\sigma_E / E = 30\% / \sqrt{E(\mathrm{GeV})}$$

the performance goal
for the jet energy resolution



Such a resolution represents a considerable technical challenge for ILC detectors.
The limiting factor is represented by the performance of the hadronic calorimeter.

Approaches in ILC community

Two different approaches have been considered to reconstruct jets with high resolution

1) Imaging calorimetry: Particle Flow Analysis (PFA)

Combine the information from a tracking system and a fine segmented calorimeter as jets at ILC experiments contain:

SiD **ILD**

- Charged particles (~60%) reconstructed in tracking systems
- Photons (~30%) reconstructed in ECAL
- *Neutral hadrons (~10%) reconstructed in ECAL + HCAL*

2) *Compensating calorimetry: Multiple-Readout Calorimeter*

4th

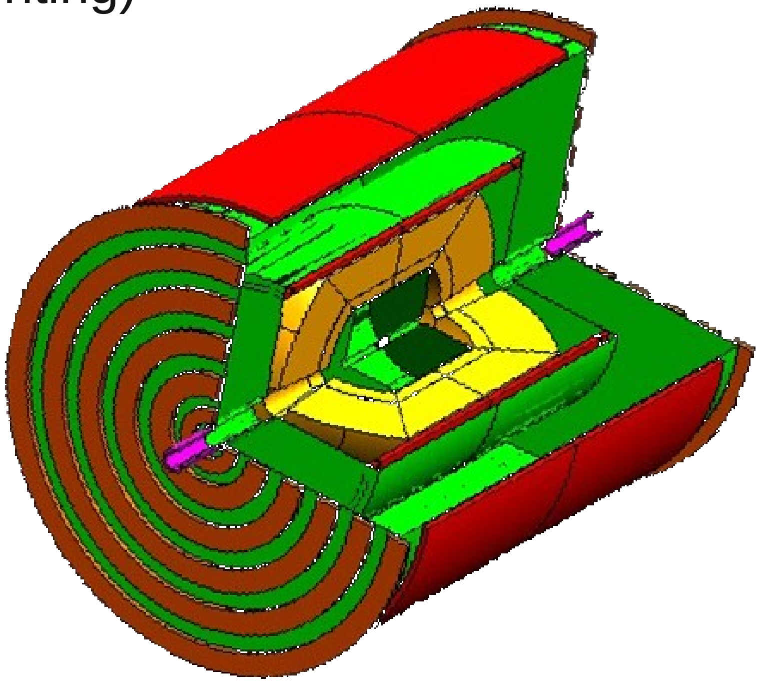
Reduce/eliminate the (effects of) fluctuations that dominate the calorimeter performance through the:

- Compensation of the f_{em} fluctuations event by event by measuring the detector response to the em and had component of the shower (Dual-Readout)
- Compensation of the neutron fluctuations event by event by measuring the neutron component of the shower (Triple-Readout)

Baseline Detector for ILC Studies presented in this talk

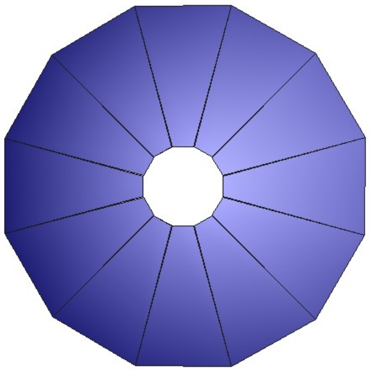
4^{th} Concept Detector

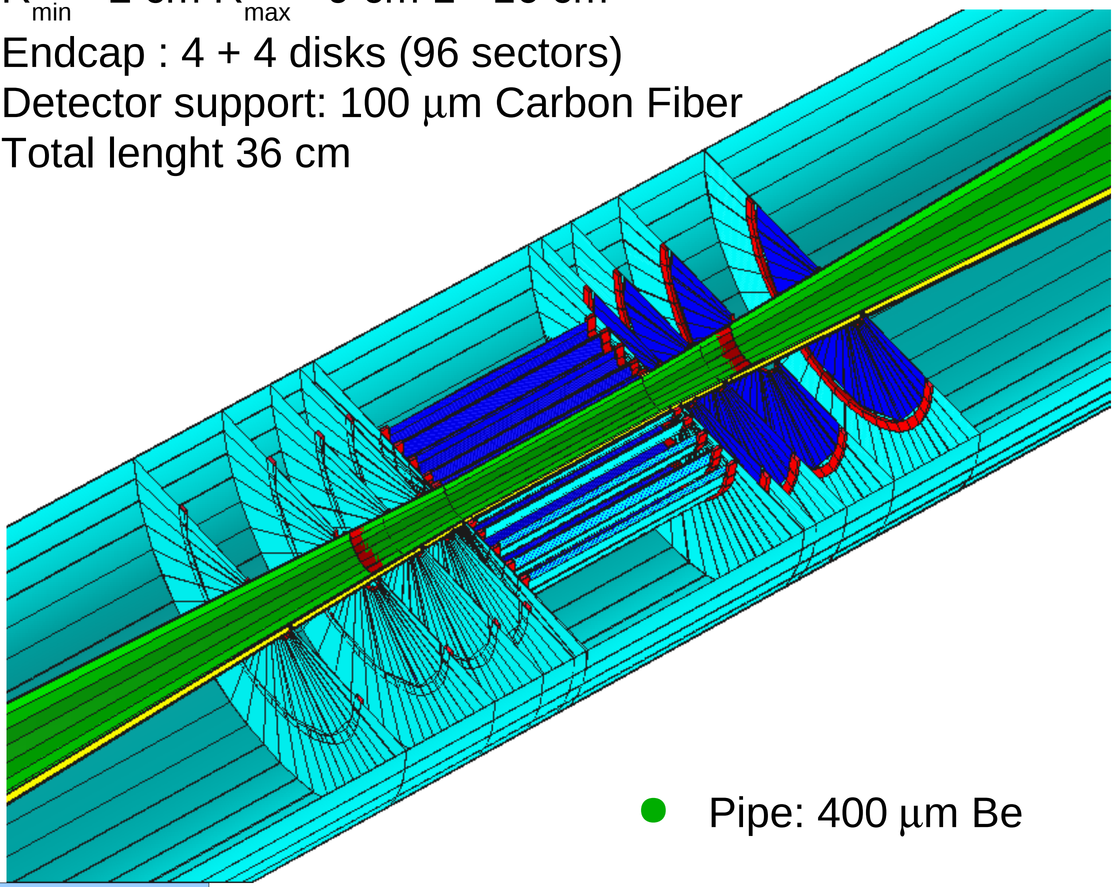
- Vertex Detector (Si-pixel)
- Drift Chamber (He based with cluster counting)
- Triple Readout Hadron Calorimeter
- Dual Readout EM Calorimeter
- Muon Spectrometer in Dual Solenoid

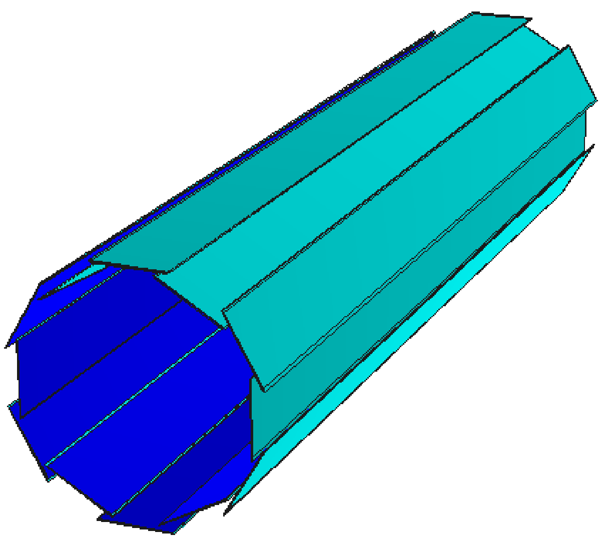


ILC Studies: Vertex Detector

- 100 µm thick Si layers
- 15 µm x 15 µm Si pixel
- Total 4.3×10^9 pixels
- Barrel : 5 layers (96 ladders)
- R_{min} = 2 cm R_{max} ~ 9 cm L~ 16 cm
- Endcap : 4 + 4 disks (96 sectors)
- Detector support: 100 µm Carbon Fiber
- Total lenght 36 cm





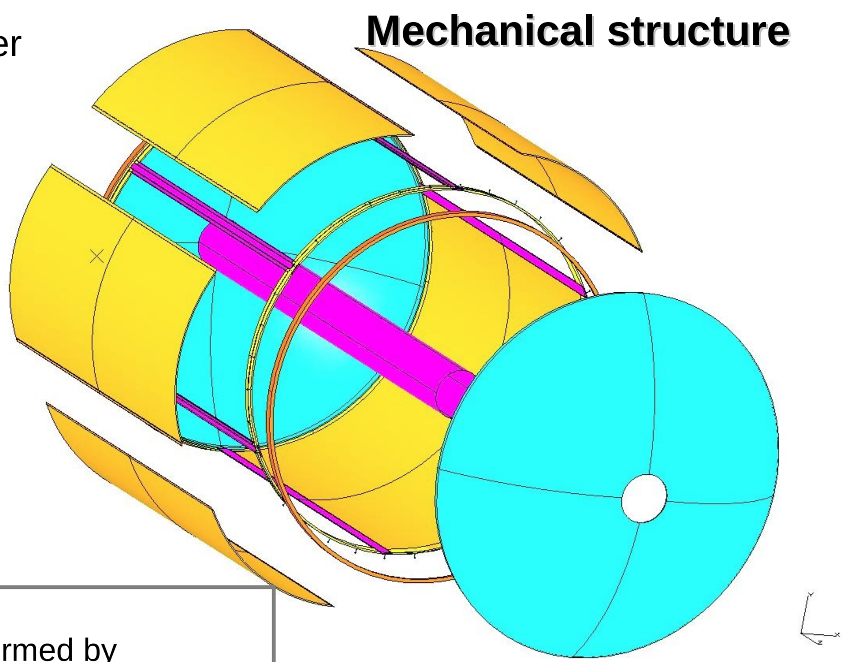


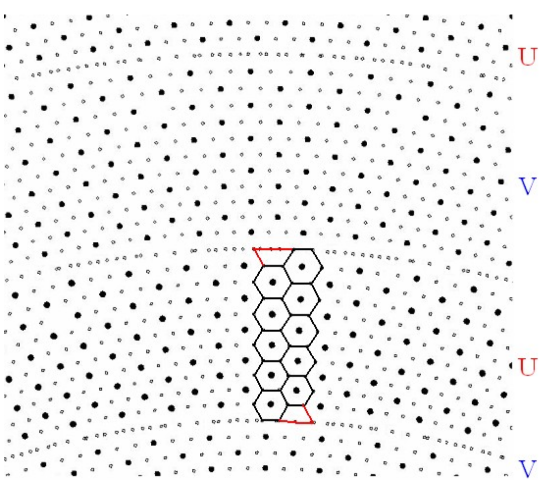
- Pipe: 400 µm Be

Very thin Si pixel to achieve the best IP resolution

ILC Studies: Central Tracker

- general layout based on successful operation of KLOE drift chamber
- all stereo, cluster timing drift chamber
- light He based gas mixture (90% He – 10% iC_4H_{10})
- mechanical structure entirely C-fibre
- max drift time contained in one BX
- total tracking volume (inner wall,gas and wires) < 0.5% X_0





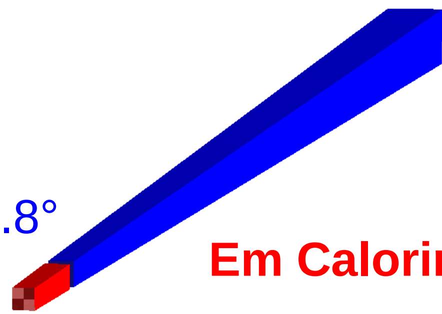
Basic building block: hexagonal cell formed by

- 6 field wires (25 μm Al) and a sense wire (25 μm W)
- 66000 sense w. 20 μm W
- 150000 field w. 80 μm Al
- cell height: 1.00 ÷ 1.20 cm
- cell radius: 4.5 ÷ 6.00 mm
- 24 superlayers, in 240 rings
- 10 cells each (7.5 in average)
- at alternating stereo angles from 55 mrad to 220 mrad

Very light device to reduce the multiple scattering

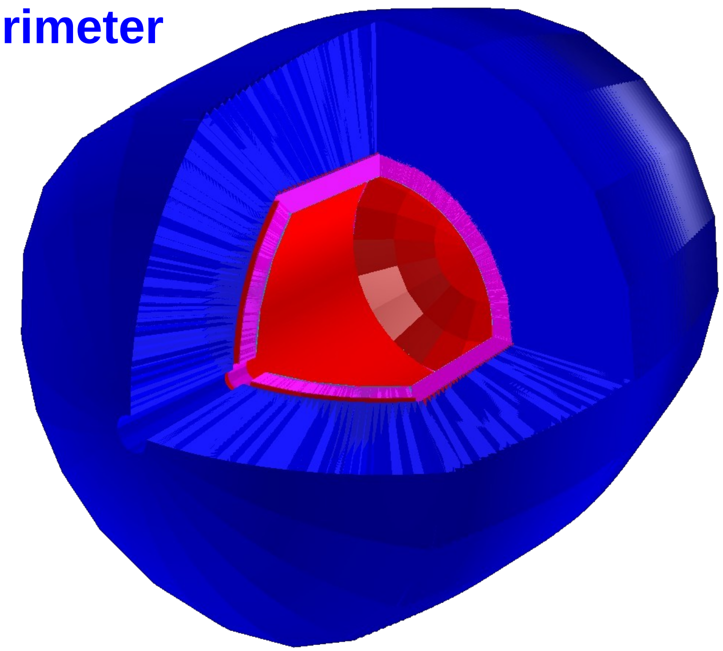
ILC Studies: Triple Readout Had Calorimeter

- Cu + scintillating fibers+ Čerenkov fibers
- ~1.4° tower aperture angle
- 150 cm depth
- ~ 7.3 λ_I depth
- Fully projective geometry
- Azimuth coverage down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers



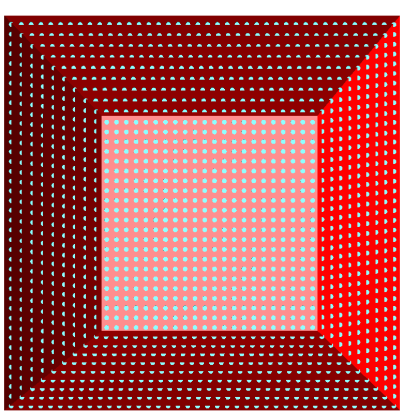
Had Calorimeter

Em Calorimeter



Hadronic calorimeter tower

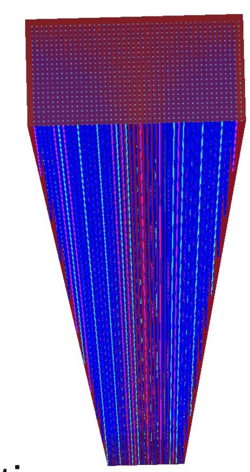
Bottom view of a tower



- 500 μm radius plastic fibers
- Fiber stepping ~2 mm
- Number of fibers inside each tower: ~1600 equally subdivided between Scintillating and Čerenkov

Each tower works as two independent towers in the same volume

Prospective view of a tower

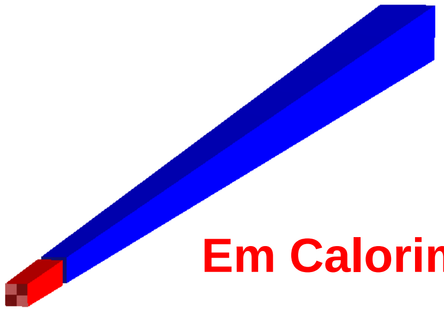


- Top tower size: ~ 8.1 × 8.1 cm^2
- Bottom tower size: ~ 4.4 × 4.4 cm^2
- Tower length: 150 cm

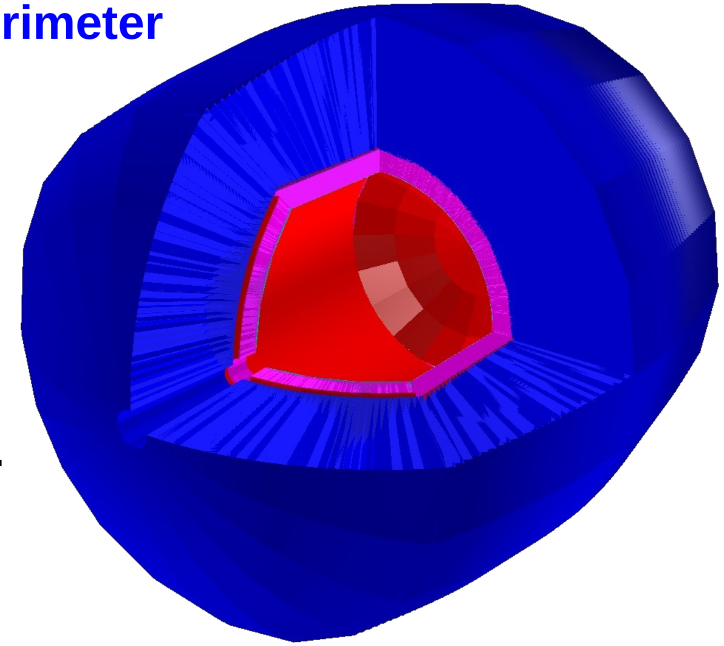
Multiple-readout calorimeter to achieve the best energy resolution

ILC Studies: Dual Readout EM Calorimeter

- BGO crystals for scintillating and Čerenkov light
- 25 cm depth
- ~22.7 X_0 depth and ~ 1 λ_I depth
- 2x2 crystals for each HCAL
- Fully projective geometry
- Azimuth coverage down to ~
- Barrel: 65536 crystals
- Endcaps: 29800 crystals



Electromagnetic calorimeter tower



- Array of 2x2 crystals
- Crystal size ~ 2x2x25 cm^3
- Each crystal is used to read scintillating and Čerenkov light
- Each crystal works as two independent cells in the same

- Top tower size: ~ 4.3 × 4.3 cm^2
- Bottom tower size: ~ 3.7 × 3.7 cm^2
- Crystal length: 25 cm

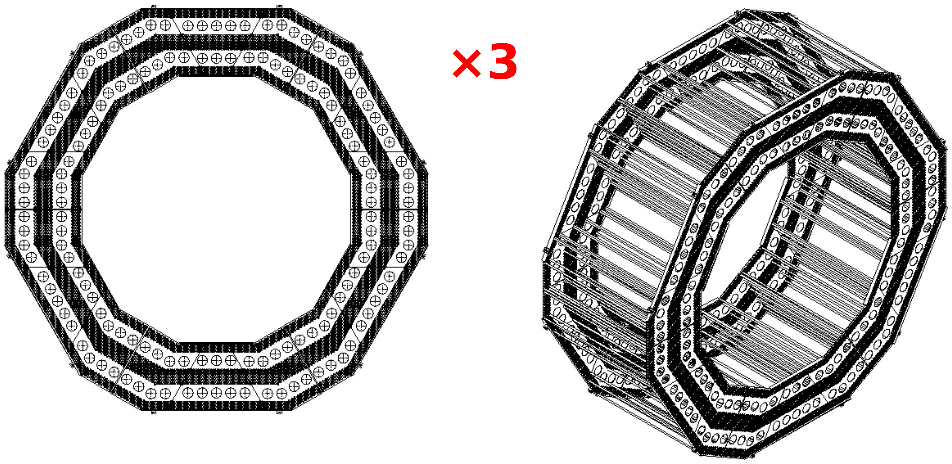
Prospective view of BGO tower array

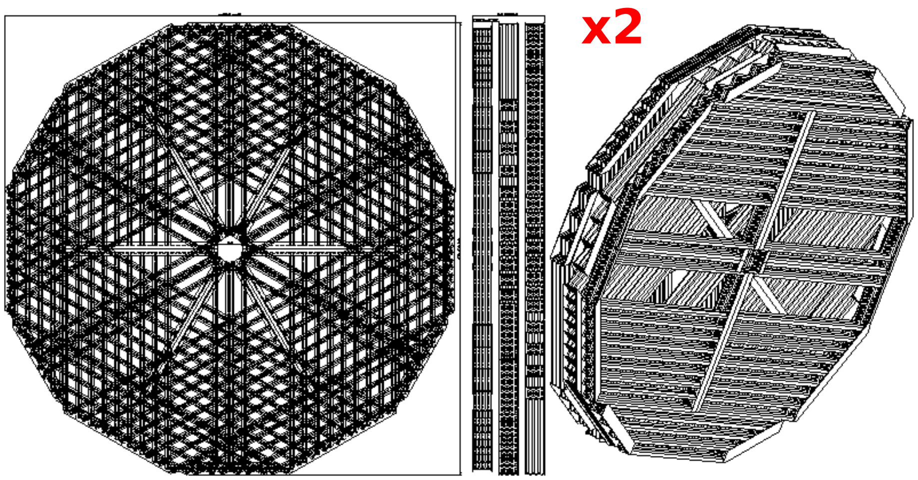
Multiple-readout calorimeter to achieve the best energy resolution

ILC Studies: Muon Spectrometer

Basic building block: 4.6 cm drift Al tube
filled with gas mixture 90% He – 10% $iC_4H_{10}0$

Layout of one stave of Muon barrel
each containing 20 layers of tubes





Layout of 3 planar sector of Muon endcap
each containing 20 planes of tubes

Muon spectrometer to achieve 1/1000 momentum resolution

Jet Studies at ILC:

Dual Readout Calorimeter and Durham Jet Finder Algorithm performance for Di-Jet Events

First step

Study

Calorimeter performance

for di-jet events

- Total Reconstructed Energy
- Energy Response
- Total Energy Resolution

How

dual readout calorimeter performs

Second step

Study

Jet Reconstruction Performance

for di-jet events

- Jet Reconstructed Energy
- Jet Energy Resolution

How

jet finder algorithm performs on

the reconstructed energy

Third step

Study

Jet Reconstruction Performance

at Z Pole (91 GeV)

- Z Mass Resolution

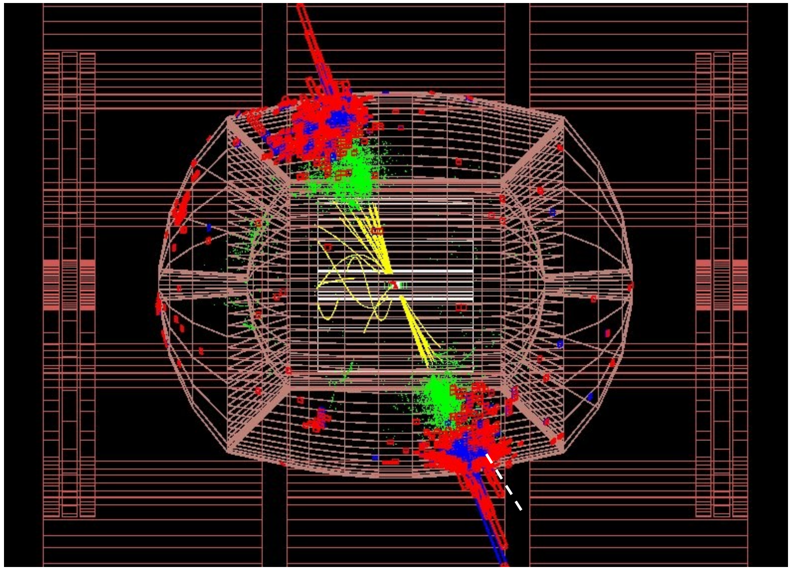
How

jet finder algorithm performs on

the reconstructed mass

Jet Studies at ILC:
Di-Jet Event Simulation and Reconstruction

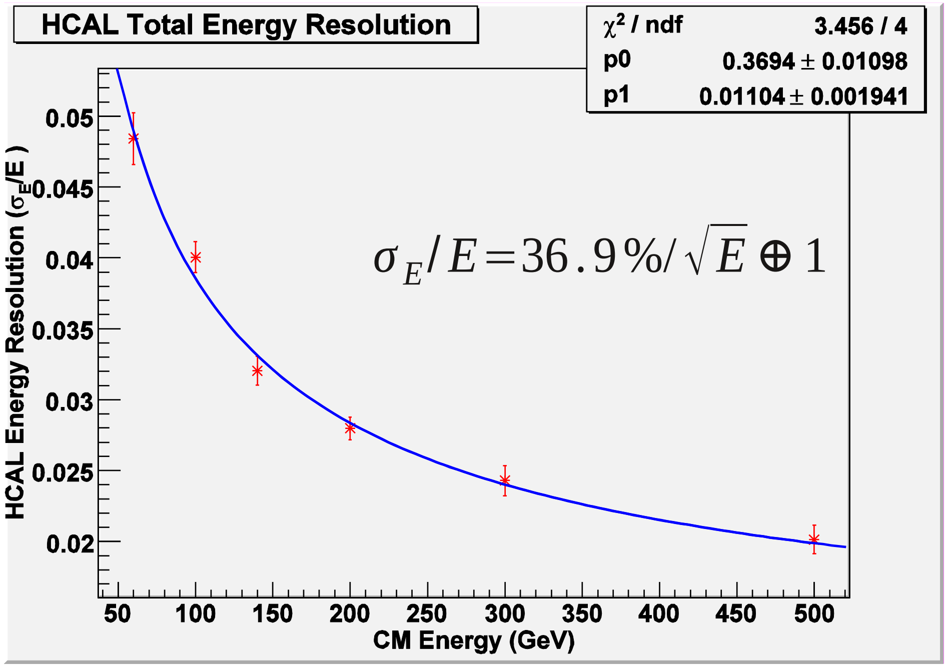
500 GeV di-Jet ILCroot event display

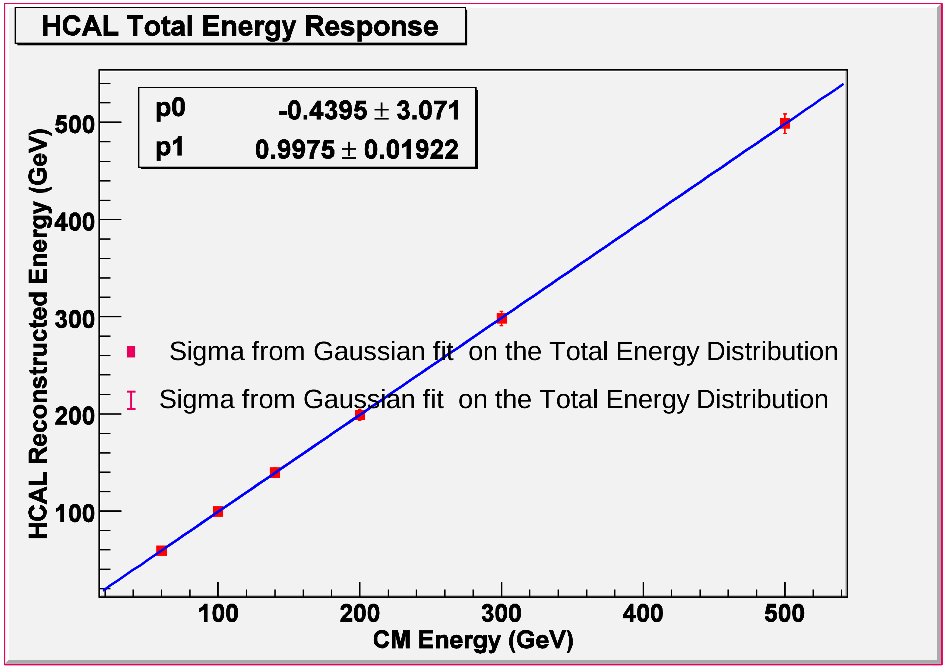


- ILCroot framework
- 4th Concept Detector (No ECAL)
- Pandora-Pythia to generate
  - $e^+e^- \rightarrow qq$ (q=uds) @ 60, 100, 140, 200, 300, 500 GeV
  - $e^+e^- \rightarrow Z \rightarrow qq$ (q=uds) @ 91 GeV
- Fluka to track particles in the detectors
- Full Digitization/Clusterization for VXD, DCH, and HCAL
- Full pattern recognition
  - Clusterization = collection of nearby "digits"
  - Unfolding of overlapping showers through Minuit fit to shower shape
- Fast rec-points (gaussian smearing of hits) for MUON spectrometer
- Durham algorithm to reconstruct jets

Jet Studies at ILC:
Dual Readout Calorimeter Performance

Study: Energy Response and Energy Resolution
with the Total Reconstructed Energy

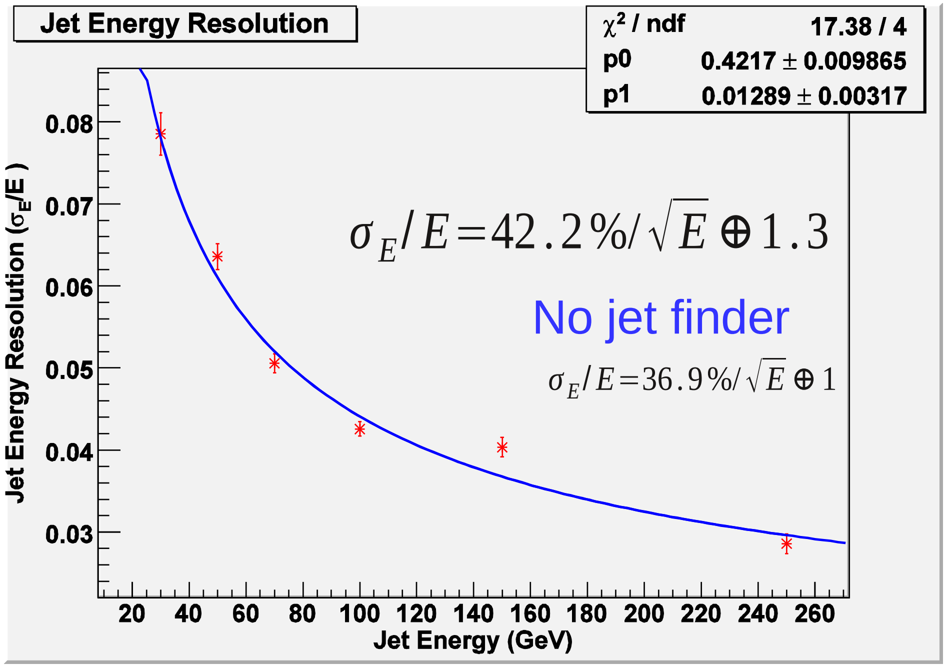


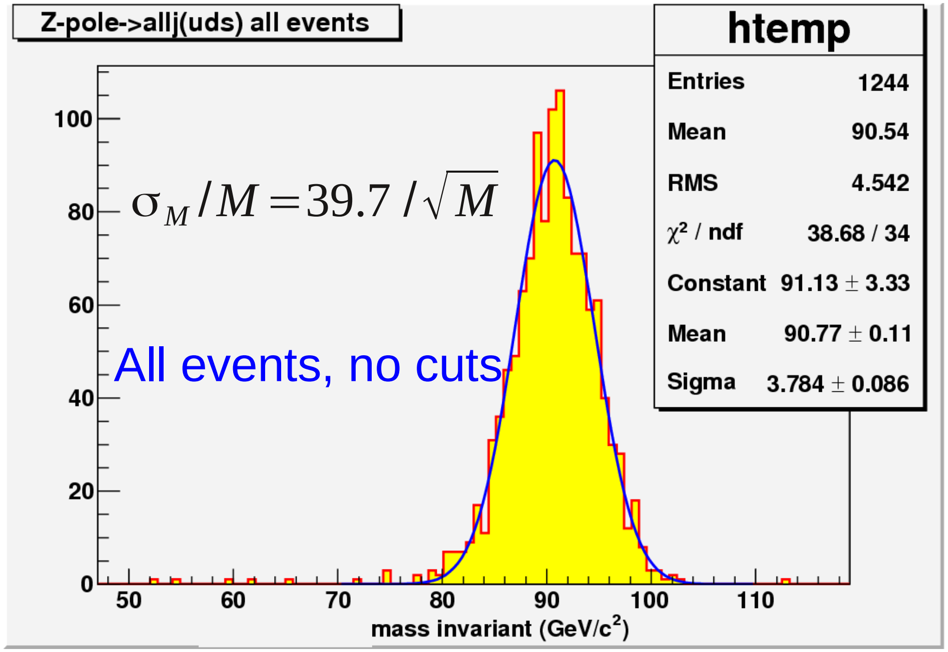


Jet Studies at ILC:

Jet Reconstruction Performance for di-jet events and at Z Pole (91 GeV)

Study: Energy Resolution and Z Mass Resolution with the Jet Reconstructed Energy



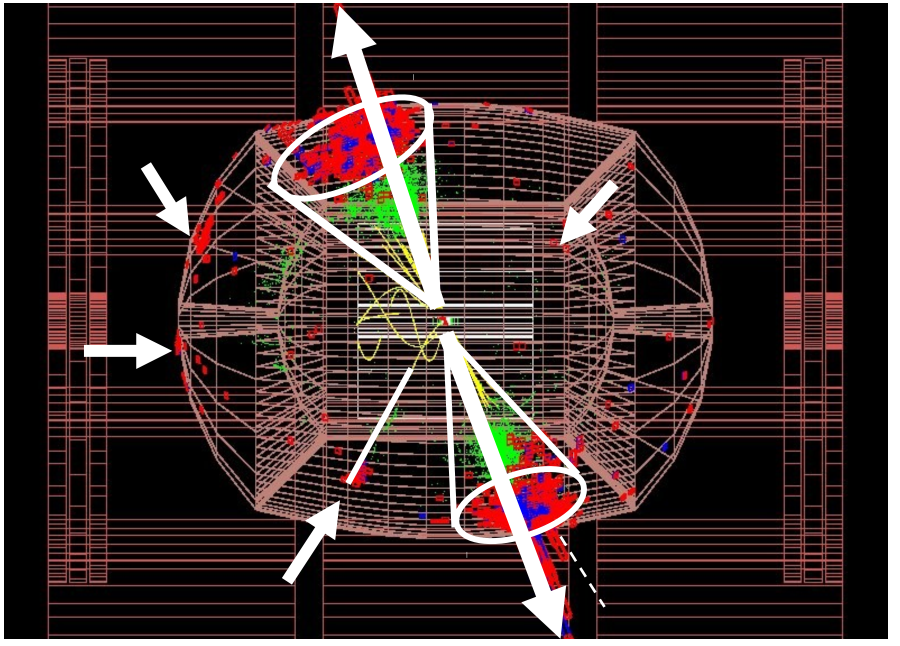


See also A. Mazzacane presentation at ALCPG07

Jet Studies at ILC:
Strategies to improve Jet Energy and Mass Reconstruction

I have developed the following jet reconstruction algorithm

- Assume the jet is spread across 2 non-overlapping regions
  - Core: region of the calorimeter with overlapping showers
  - Outliers: hit towers separated from the core
- Measure the Core energy
  using information from the calorimeter
- Measure the Jet axis
  using information from the tracker detectors
- Reconstruct Outliers individually
  tracking and/or calorimetry
  charge of the particle
- Add reconstructed muons by the muon detector



25 GeV Muon

Jet Studies at ILC:

Performance of Jet Reconstruction Algorithm for Di-Jet and Four-Jet Events

Physics events

- qq (q=uds) @ 91GeV
- WWνν @ 500 GeV
- ZZνν @ 500 GeV
- ZH(120)→νν cc @ 250 GeV
- ZZ→νν qq @ 250 GeV

Detector & framework

- 4th Concept detector
- IlcRoot framework

Jet algorithm

- Existing algorithm (Durham)
- Combine informations from tracking and calorimetric objects
- Add reconstructed tracks in the muon spectrometer

Jet Studies at ILC:

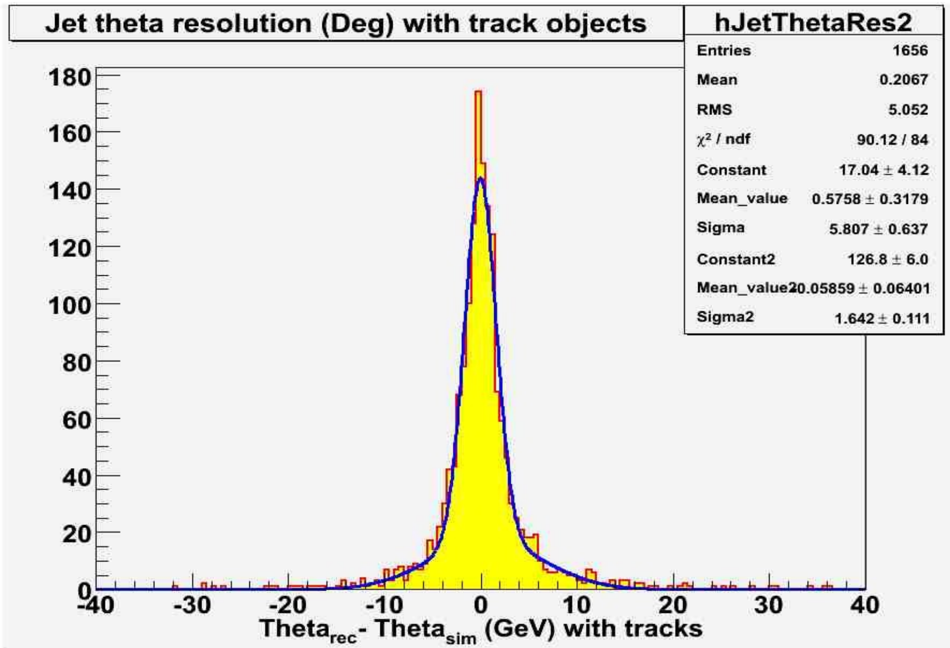
Simulation Details of Di-jet and Four-jet events

- ILCroot framework
- 4^{th} Concept Detector (No ECAL)
- Generated events:
  - $e^+e^- \rightarrow Z \rightarrow qq$ (q=uds) @ 91 GeV (Pandora-Pythia) with ISR
  - $e^+e^- \rightarrow ZH \rightarrow \nu\nu\, cc$ @ 250 GeV
  - $e^+e^- \rightarrow ZZ \rightarrow \nu\nu\, qq$ @ 250 GeV
- Fluka to track particles in the detectors
- Full Digitization/Clusterization for VXD, DCH, and HCAL
- Fast rec-points (gaussian smearing of hits) for Muon detector
- Full parallel Kalman Filter for track reconstruction
- Single tower informations for the Calorimeter

Jet Studies at ILC:

Jet Reconstruction Performance at Z^0-Pole (di- jets events)

Study: Theta and Phi Resolutions

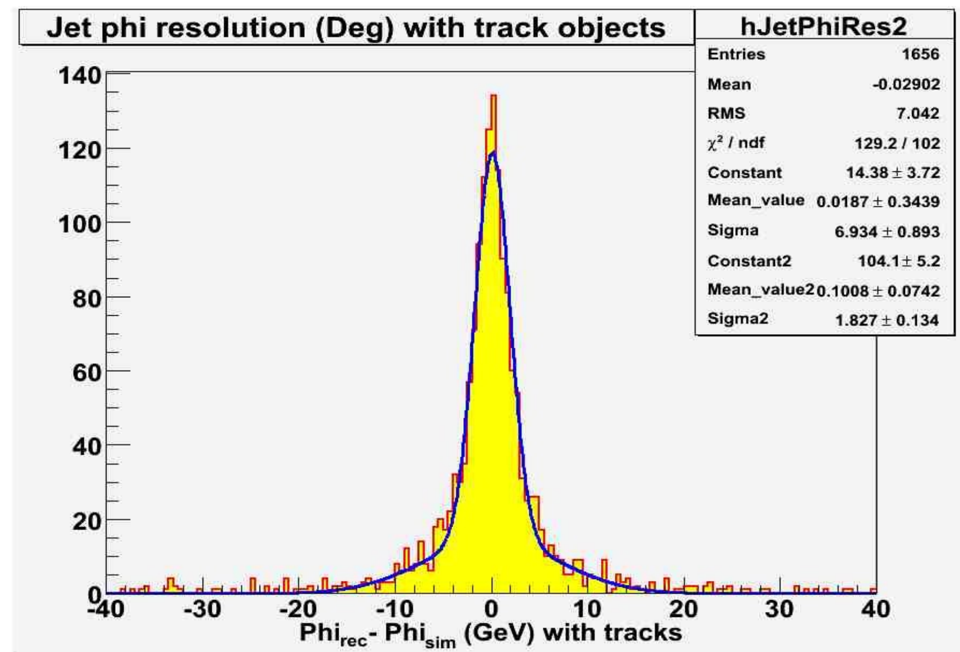


Find 2 jets from reconstructed tracks

$(\theta_{rec} \quad \phi_{rec})$

Find 2jets from generated particles

$(\theta_{sim} \quad \phi_{sim})$



Jet axis resolution

$\sigma_\theta = 1.6°$

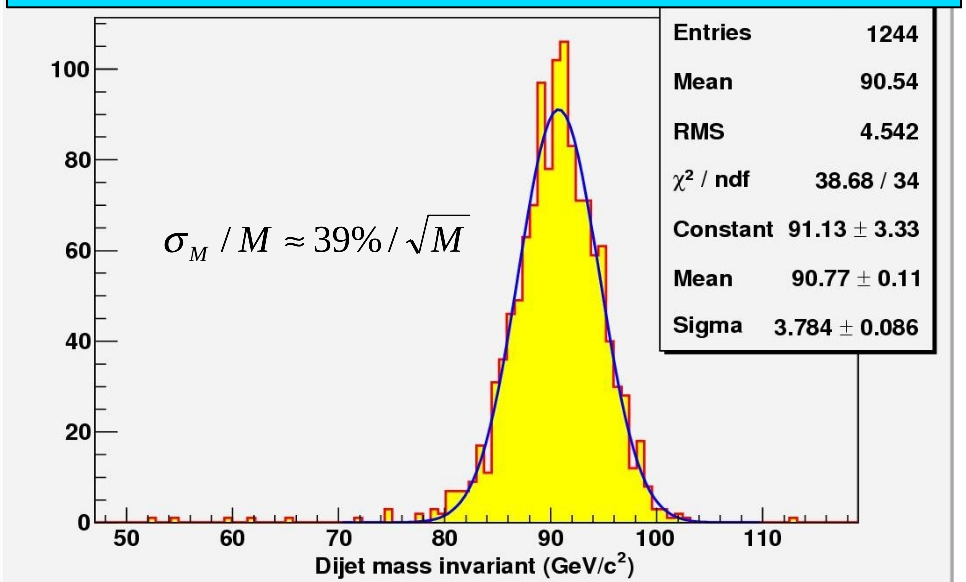
$\sigma_\phi = 1.8°$

Jet Studies at ILC:

Jet Reconstruction Performance at Z^0-Pole (di- jets events)

Study: Z^0 Mass Resolution

Dual Readout Calorimeter



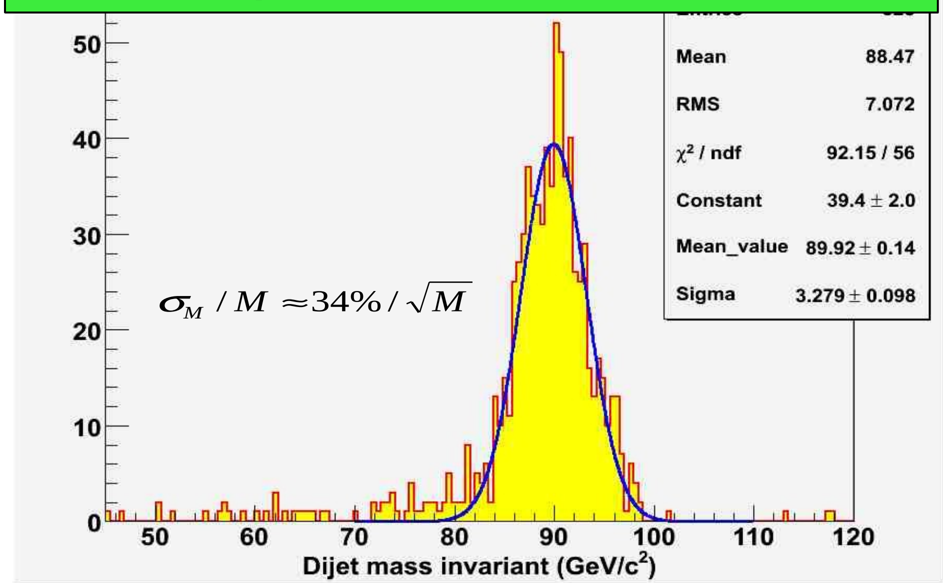
Reconstruted 2 jets from track objects

Reconstruted 2 jets from tower objects

E_{tower}>100 MeV

no cut on theta

Triple Readout Calorimeter



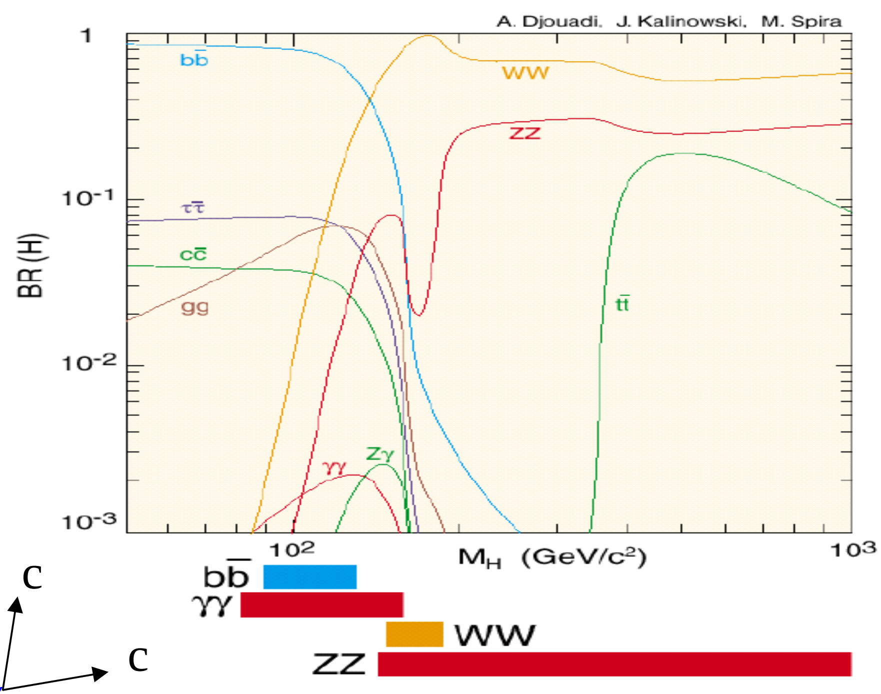
Combine jet energy from calorimeter

and jet axis from trackers

Physics studies at ILC:
$ZH \to \nu\nu cc$

- One of the benchmark reaction for ILC
- To be tested:
  - Multi jet final state
  - Heavy flavour tagging, secondary vertex

For $M_H \leq 140$ GeV, large variety of channels decays for the Higgs: O(80%) bb, O(5%) cc

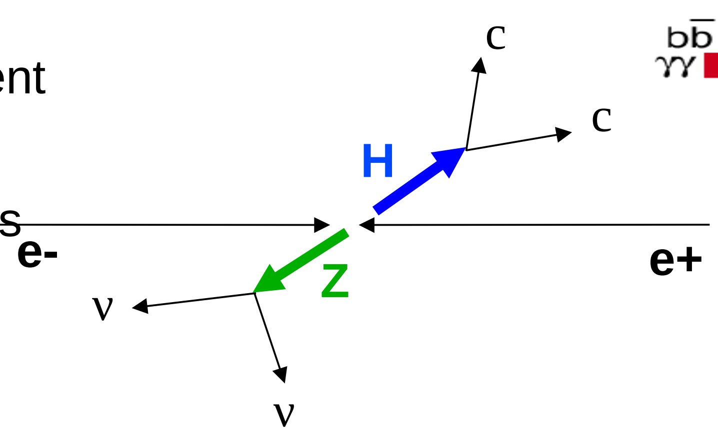


Simulation:

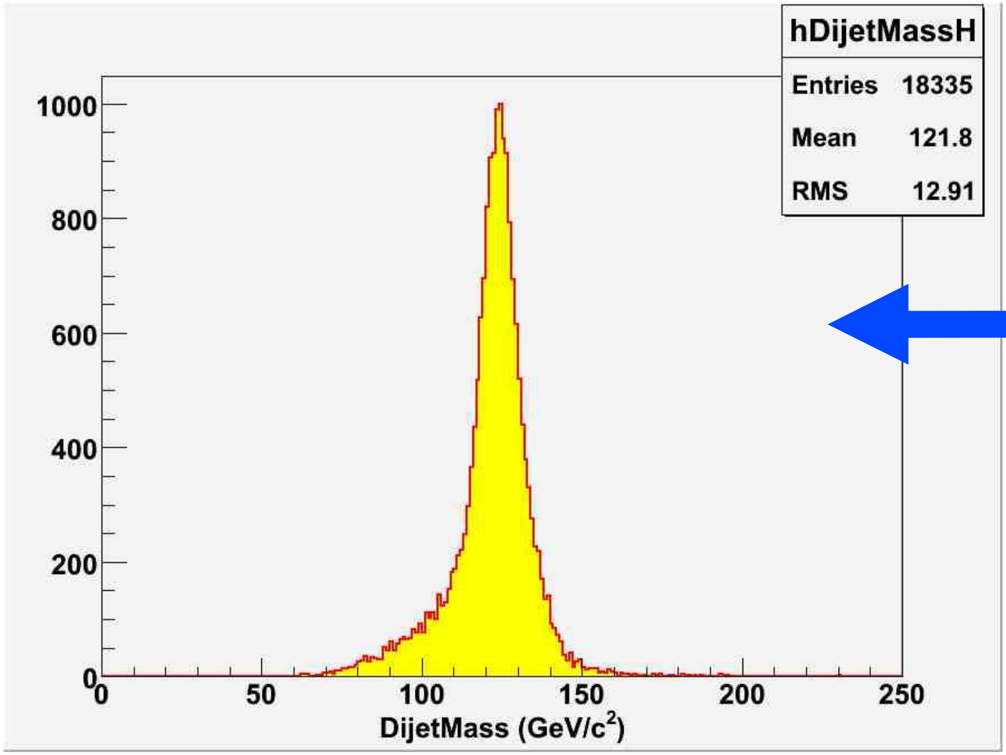
- Full sim/rec 22960 events for the signal
- Full sim/rec 15998 events for the background ($ZZ \to \nu\nu cc$ only)

Event selection:

- Look for 2 jets in the event
- E_{vis}>130.0 GeV
- NO cut on the recoil mass
- NO flavour tagging

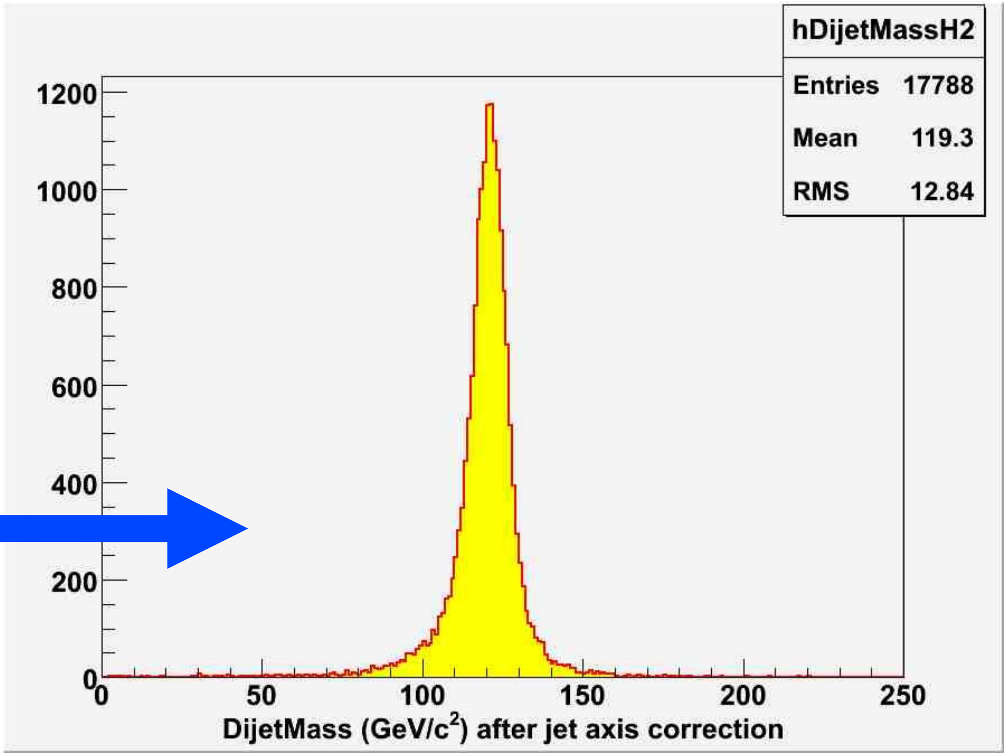


Physics studies at ILC: $ZH \rightarrow \nu\nu cc$



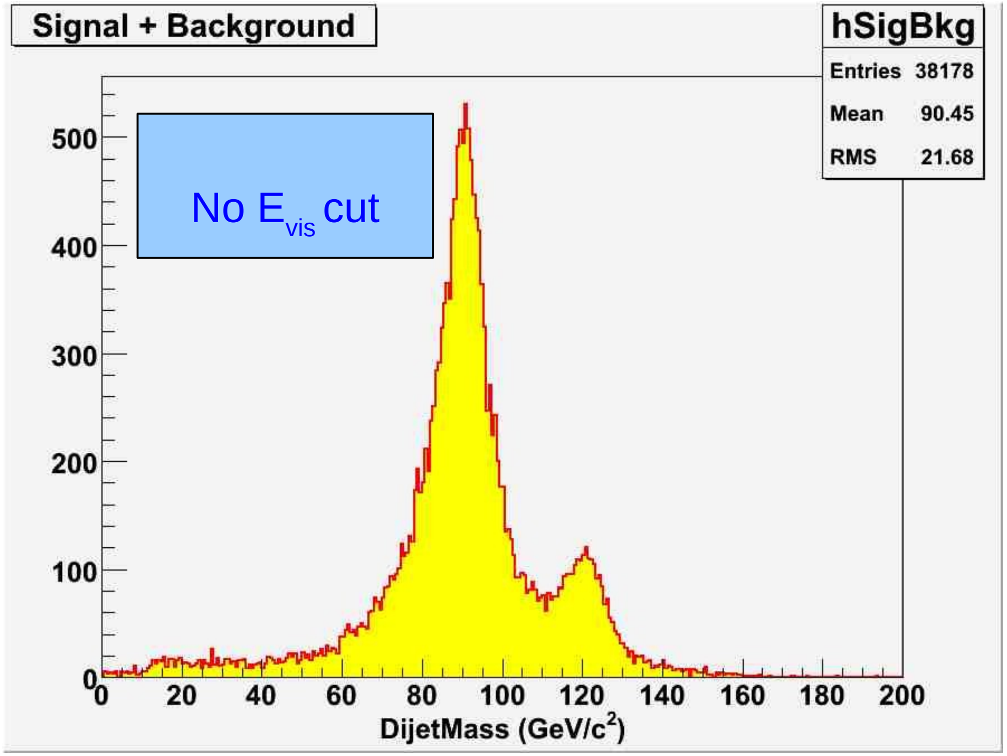
Results from jet finder with calorimeter only

After correction from tracker informations



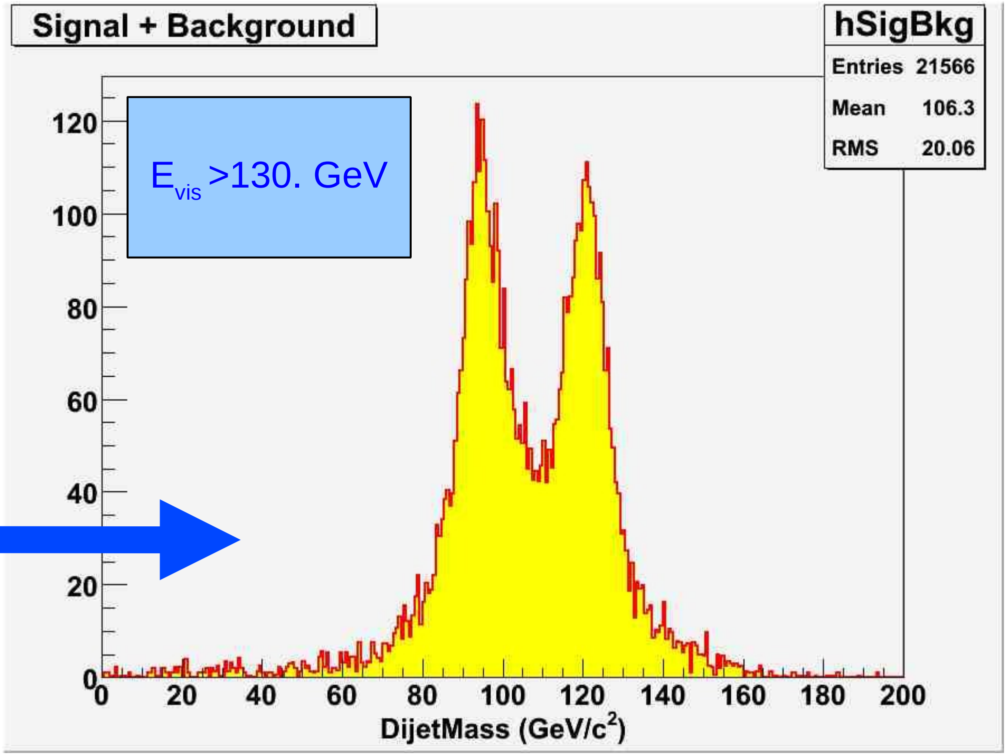
ILC Studies

Physics studies at ILC: $ZH \rightarrow \nu\nu cc$



Improving signal/background ratio

with E_{vis} cut



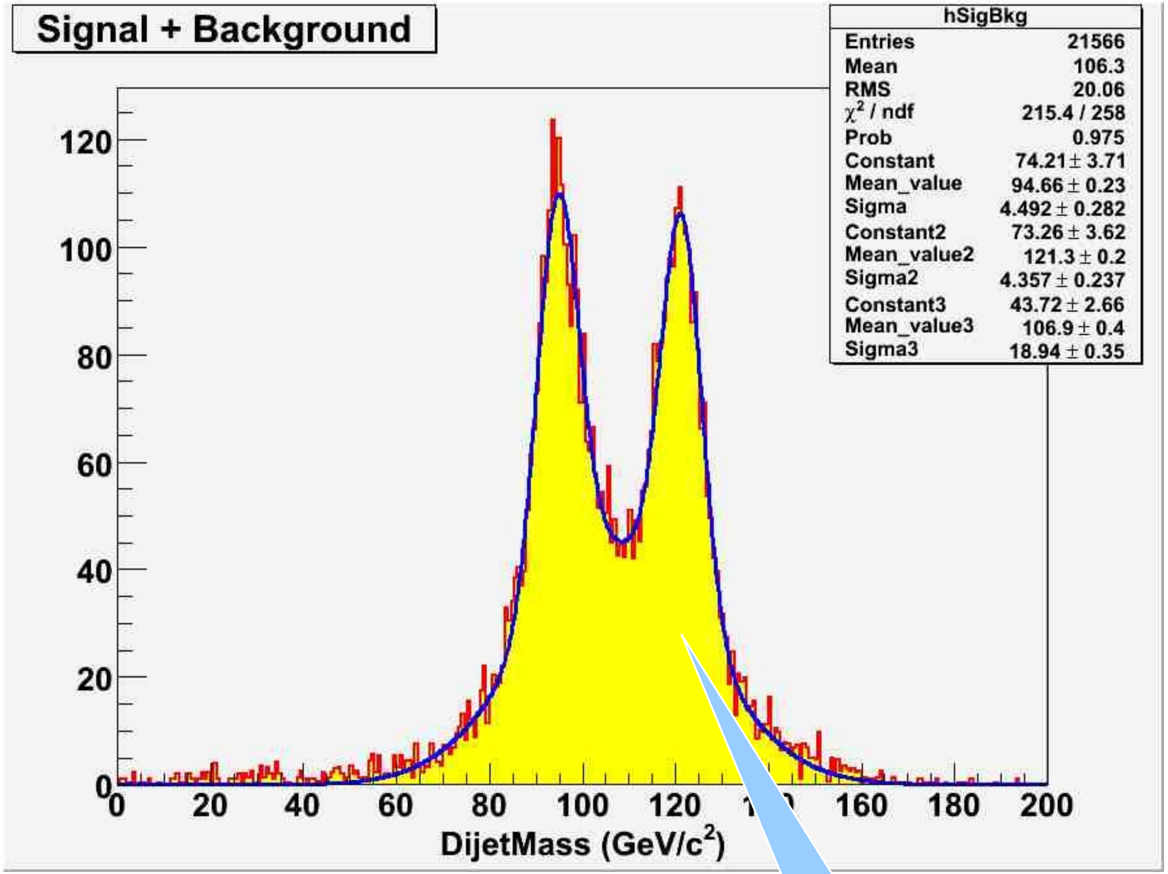
ILC Studies

Physics studies at ILC: $ZH \rightarrow \nu\nu cc$

2-jets finding efficiency: 96.6%

E_{vis} cut efficiency: 82.2%

Total selection efficiency: 77.4%



UIC
University of Illinois at Chicago

See also A. Mazzacane plenary presentation at LCWS08

1% Error on the Higgs mass

Physics studies at ILC:

Chargino/Neutralino

$$e^+e^- \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow W\tilde{\chi}_1^0\, W\tilde{\chi}_1^0 \rightarrow q\bar{q}'\,\tilde{\chi}_1^0\, q\bar{q}'\,\tilde{\chi}_1^0$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0\, Z\tilde{\chi}_1^0 \rightarrow q\bar{q}\,\tilde{\chi}_1^0\, q\bar{q}\,\tilde{\chi}_1^0$$

- One of the benchmark process analyzed for the LoI's.
- The masses of charginos and neutralinos are important parameters in supersymmetry which can be measured at ILC with high precision.
- The signature (hadronic W/Z decays) is 4 jets + missing energy.
- The separation of W and Z bosons through their hadronic decay products requires excellent jet resolution and it is a good benchmark of the detector performance.
  (established good jet finder algorithm and best pair jet association)
- Analysis is complicated by the fact that the $\tilde{\chi}^0_2\,\tilde{\chi}^0_2$ cross section is only 10 % of that for $\tilde{\chi}^+_1\,\tilde{\chi}^-_1$

Physics studies at ILC:
Chargino/Neutralino

Event simulation :

- 250 fb^{-1} at 500 Gev with Whizard
- Full simulation (ILCroot framework)
- All 2f $\rightarrow$ 2f, 4f, 6f and some 8 fermions processes in the e^+e^-, $e\gamma$, $\gamma\gamma$ included

Event reconstruction :

- Full reconstruction (ILCroot framework)
- List charged traks from trackers
- List of HCAL towers and ECAL cells with E >10 MeV after calorimeters calibration

Jet reconstruction :

- Durham algorithm
- Combined tracking and calorimeter informations

Jet pairing :

- min $|m_1 - m_2|$
- To further reduce background:
  $|m_1 - m_2| < 5$ GeV/c^2

WW/ZZ selection :

- Fit on dijet-mass invariant distribution

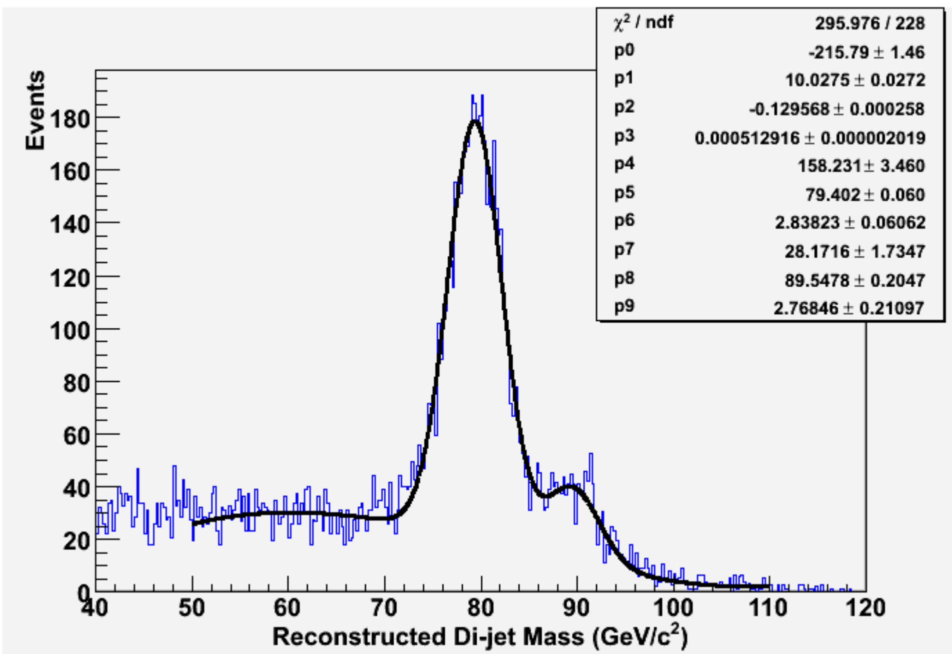
Event selection :

- Events forced into 4jets (Durham)
- $E_{jet} \geq$ 5 GeV
- $|\cos\theta_{jet}| <$ 0.99
- $N_{total\ lcharged\ tracks\ \ in\ jet} \geq 2$
- $N_{total\ charged\ tracks} \geq 20$
- $Y_{cut} > 0.001$
- 100 GeV < E_{vis} < 250 GeV
- $|\cos\theta_{miss\ P}| < 0.8$
- $M_{miss} >$ 220 GeV/c^2
- No lepton with $E_{lepton} >$ 25 GeV

Physics studies at ILC:

Chargino/Neutralino

THE UNIVERSITY of NEW MEXICO



See also A. Mazzacane plenary presentation at ALCPG09

Fitted distribution (double gaussian plus 3rd order polynomial)

M_W = 79.40 ± 0.06 GeV/c^2

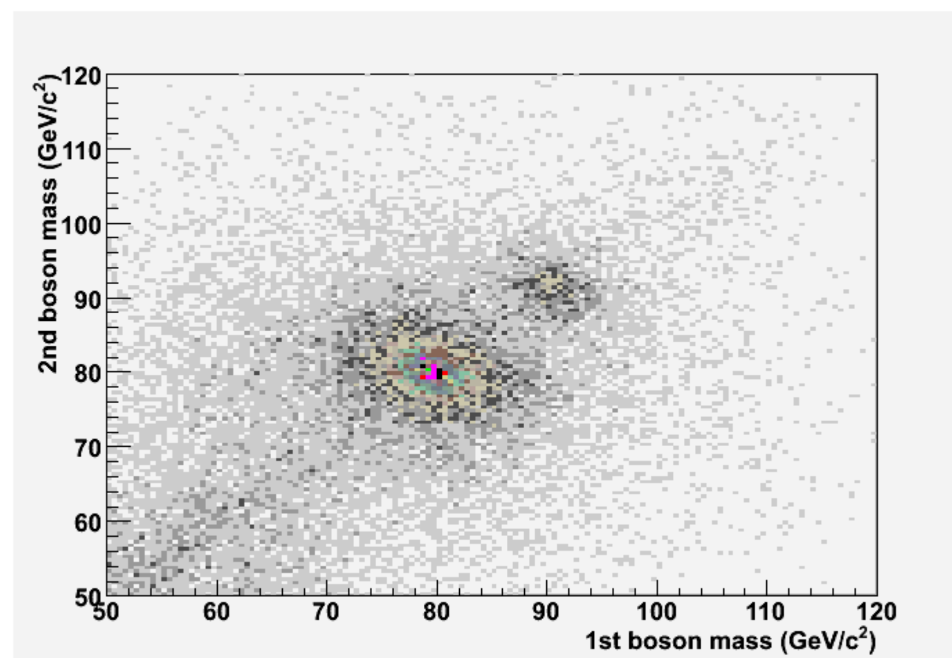
σ_W = 2.84 ± 0.06 GeV/c^2

M_Z = 89.55 ± 0.20 GeV/c^2

σ_Z = 2.77 ± 0.21 GeV/c^2

$\varepsilon_{chargino}$ = 30.3% $\varepsilon_{neutralino}$ = 28.6%

Reconstructed masses after selection cuts and jet pairing



ILC Studies

Summary of the studies at ILC

- Triple Readout calorimeter improves physics performance compared to Dual Readout
- Jet reconstruction algorithm improves di-jet mass resolution
- $\sigma/M \cong$ 34% / $\sqrt{M}$ Z^0-Pole mass resolution
- M_H precision ($ZH \rightarrow \nu\nu cc$) $\cong 1\%$
- W/Z mass well separeted (chargino/neutralino)

Tracking Studies for the Muon Collider

Muon Collider Motivation

If we can build a muon collider, it is an attractive multi-TeV lepton collider option because muons don't radiate as readily as electrons (m_μ / m_e ~ 207):

- COMPACT
  Fits on laboratory site

- NARROW ENERGY SPREAD
  Precision scans, kinematic constraints

- TWO DETECTORS (2 Ips)

- ΔTbunch ~ 10 μs … (e.g. 4 TeV collider)
  Lots of time for readout
  No background pile up

- $(m\mu/me)^2$ = ~40000
  Enhanced s-channel rates for Higgs-like particles

Muon Collider Challenges

- Muons are produced as tertiary particles.
- Muons decay
- Muons are born within a large 6D phase-space.
- After cooling, beams still have relatively large emittance.

Detector Challenges

- One of the most serious technical issues in the design of a Muon Collider experiment is the machine background reaching the detector region
- The major source is from muon decays:

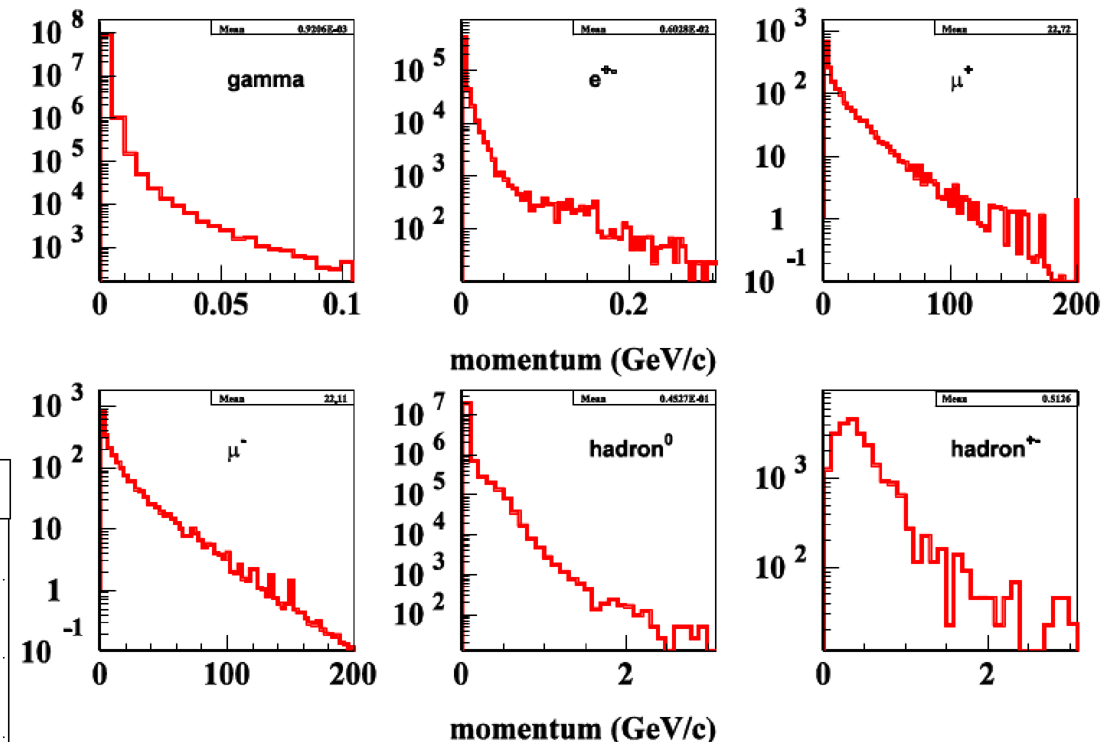
  Ex.: for 750 GeV muon beam with $2*10^{12}$ muons/bunch ~ $4.3*10^{5}$ decays/m

- The backgrounds can spoil the physics program
- The Muon Collider physics program and the background will guide the choice of technology and parameters for the design of the detector.

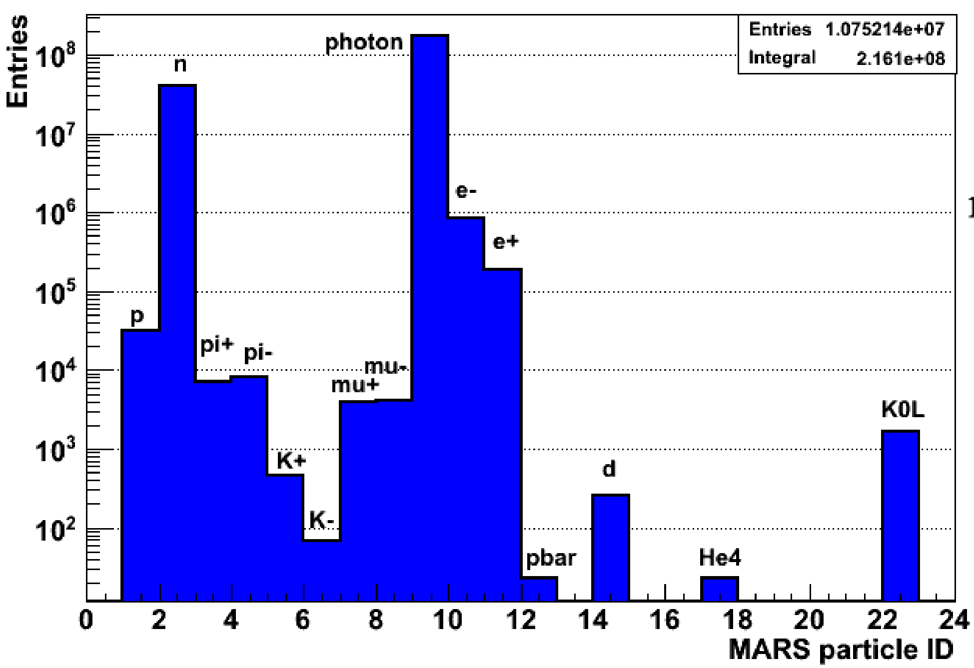
Muon Collider Background

Most of the background are low momenta photons and neutrons

Energy spectra entering the detector

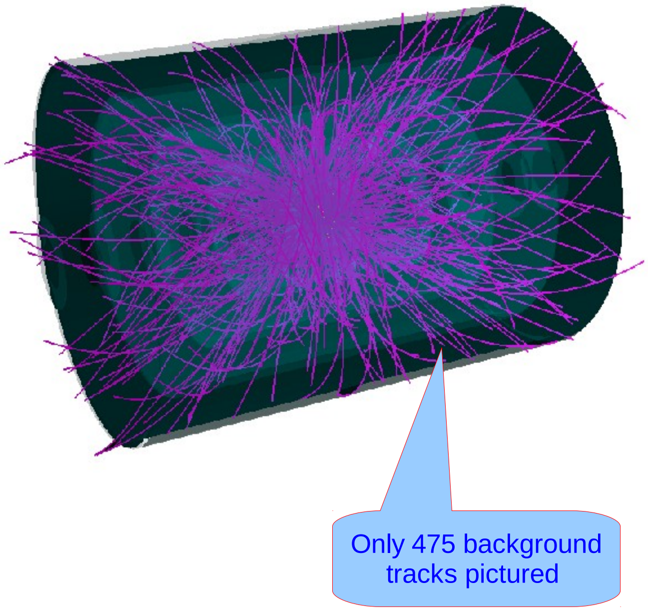


Particles species entering the detector



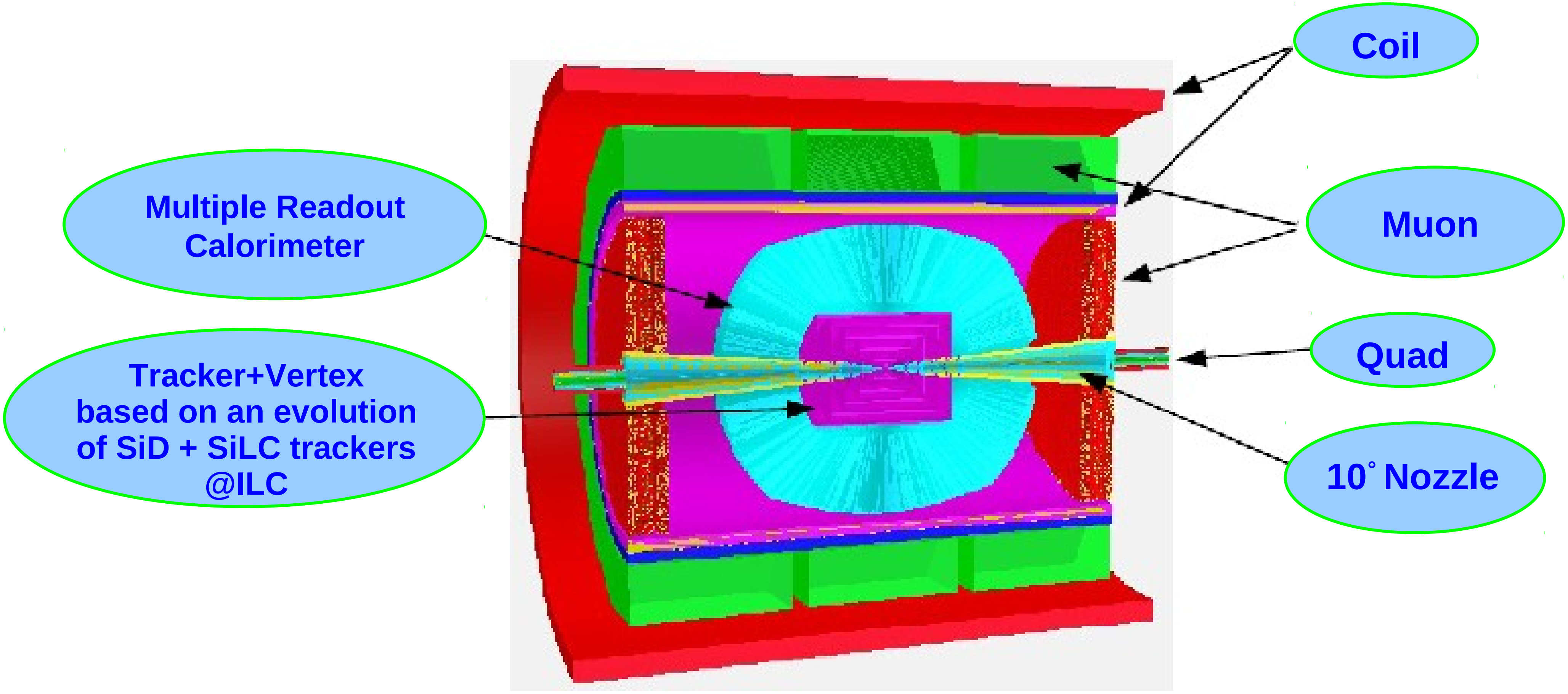
See also N. Terentiev and S. Striganov Presentation at TIPP11

Rationale



- Large background is expected in the tracking detectors at a MuC experiment
  - Pepper-like bkg (mostly from photons)
  - Real tracks trough the detector:
  - (beware of muons from outside)
- Proposed collimating nozzle in the detector to suppress the machine background
- In MARS15 simulation showed a reduction of the machine background ~ 3 orders of magnitude (depends on the nozzle angle)
- What matters is **NOT** the total amount of background but, rather, the ability to reconstruct tracks in a dense environnment of spurious hits
- Two strategies have been implemented in ILCroot for MuC-related studies:
  - Detector layout with extra redundancy in forward region (Forward Tracking Detector)
  - Full parallel Kalman Filter

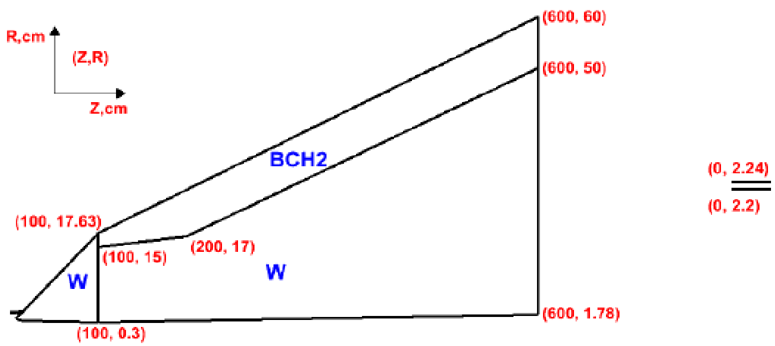
Baseline Detector for MuC Studies presented in this talk

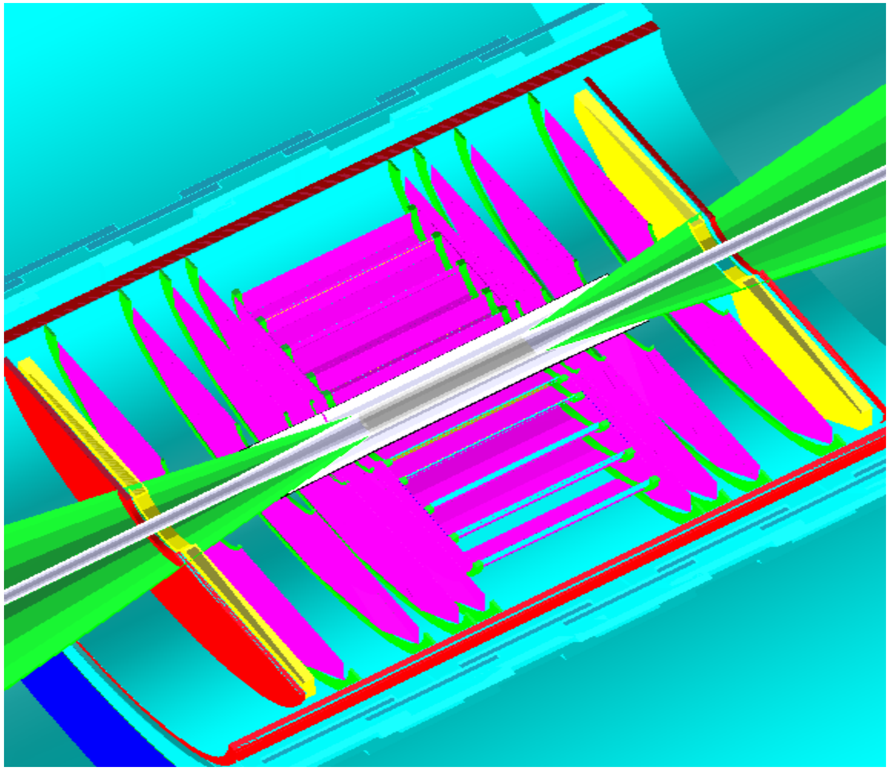


MuC Studies:
Vertex Detector (VXD)
10°Nozzle and Beam Pipe

VXD

- 100 μm thick Si layers Si pixel
- 20 μm x 20 μm Si pixel Si pixel
- Barrel : 5 layers subdivided in 12-30 ladders
- R_{min}~3 cm R_{max}~13 cm L~13 cm
- Endcap : 4 + 4 disks subdivided in 12 ladders
- Total lenght 42 cm





FORWARD SHIELDING (NOZZLE)

- W - Tungsten
- BCH2 – Borated Polyethylene

PIPE

- Be – Berylium 400 μm thick
- 12 cm between the nozzles

MuC Studies:

Silicon Tracker (SiT) and

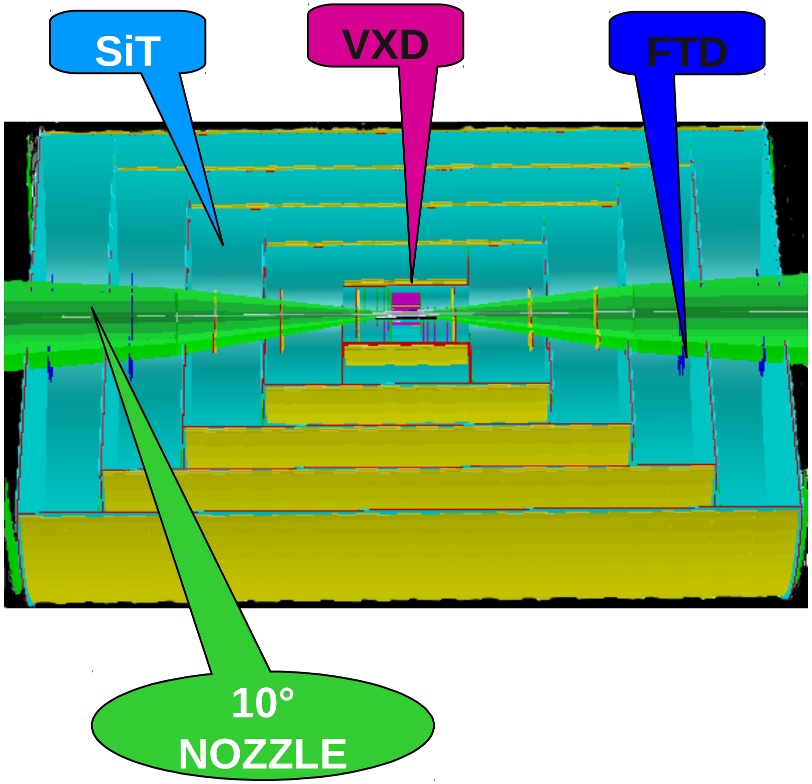
Forward Tracker Detector (FTD)

SiT

- 100 µm thick Si layers
- 50 µm x 50 µm Si pixel
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+2) + (4+2) disks subdivided into ladders
- R_{min}~20 cm R_{max}~120 cm L~330 cm

FTD

- 20 µm x 20 µm Si pixel
- Endcap : 3 + 3 disks
- Distance of last disk from IP = 190 cm

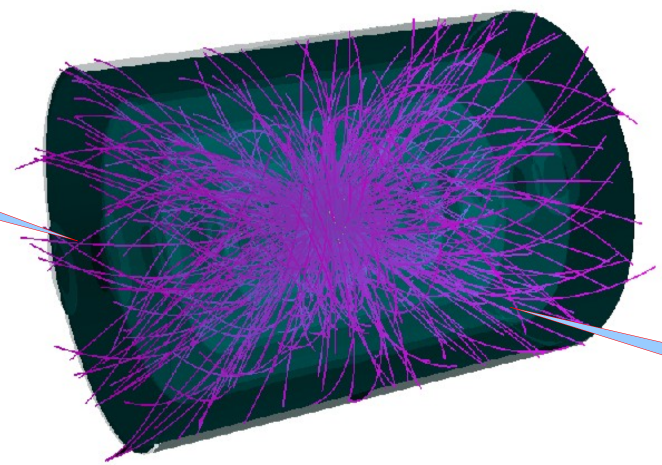


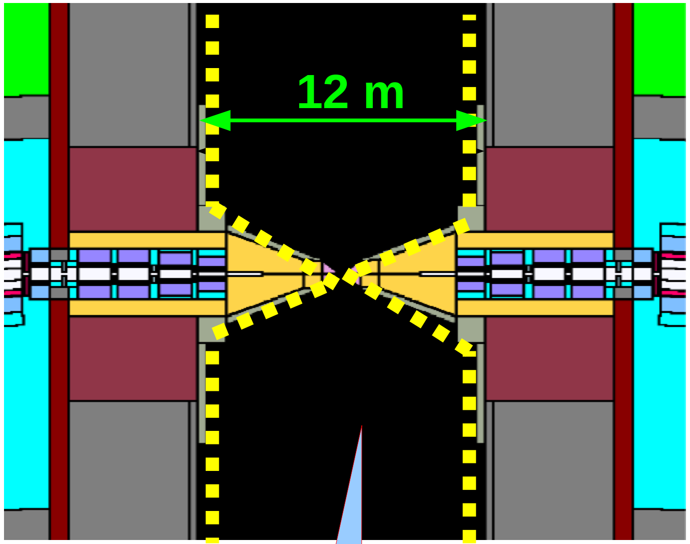
- Silicon pixel for precision tracking amid up to 10^5 hits
- Tungsten nozzle to suppress the background

Tracking Studies at MuC: Ingredients

- MARS background provided at the surface of MDI (10^0 nozzle + walls)
- GEANT4 simulated particles in the detector

  (background + single muons from the I.P.)





- Reconstructed tracks from a parallel Kalman Filter in a 3.5 T B-field
- Studies performed in ILCroot framework

Tracking Studies at MuC:
Nozzle Effects on Tracking Performance

Reconstruction Efficiency & Resolutions

$$\epsilon_{tot} = \frac{reconstructed\ \ tracks}{generated\ \ tracks} = \epsilon_{geom} * \epsilon_{track}$$

$$\epsilon_{geom} = \frac{good\ \ tracks}{generated\ \ tracks}$$

$$\epsilon_{track} = \frac{reconstructed\ \ tracks}{good\ \ tracks}$$

Defining “good tracks” (candidate for reconstruction)

DCA(true) < 3.5 cm

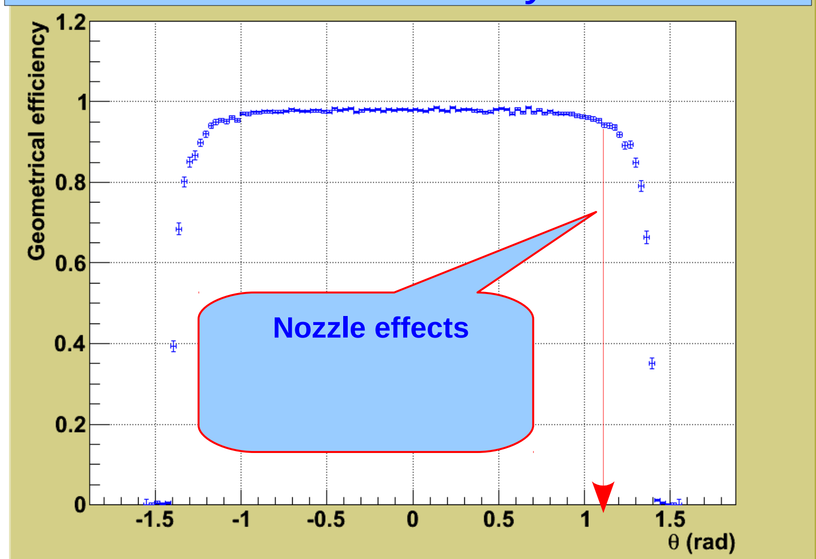
AND

at least 4 hits in the detector

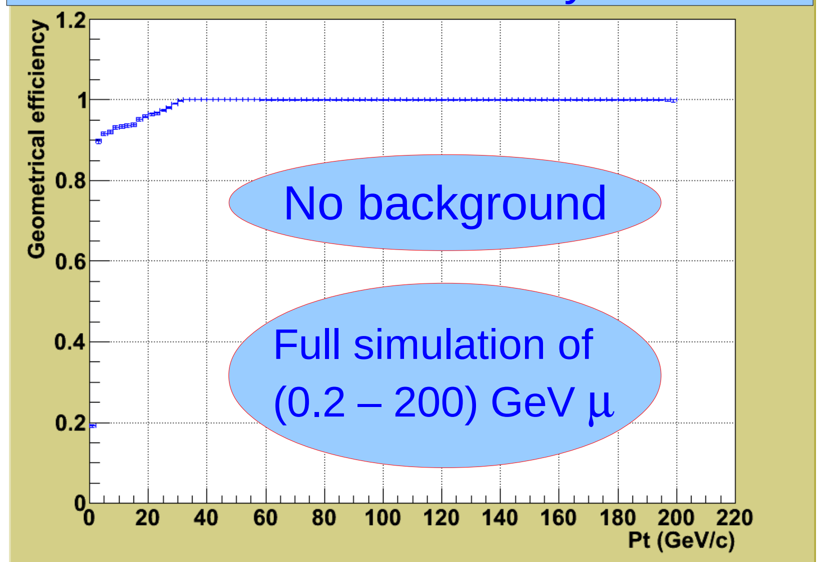
Tracking Studies at MuC:

Reconstruction Efficieny for Single Muons

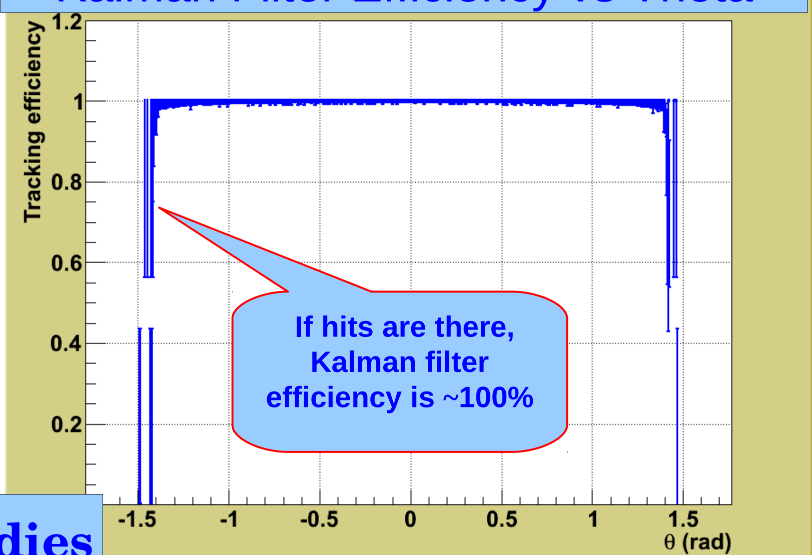
Geometrical Efficiency vs Theta



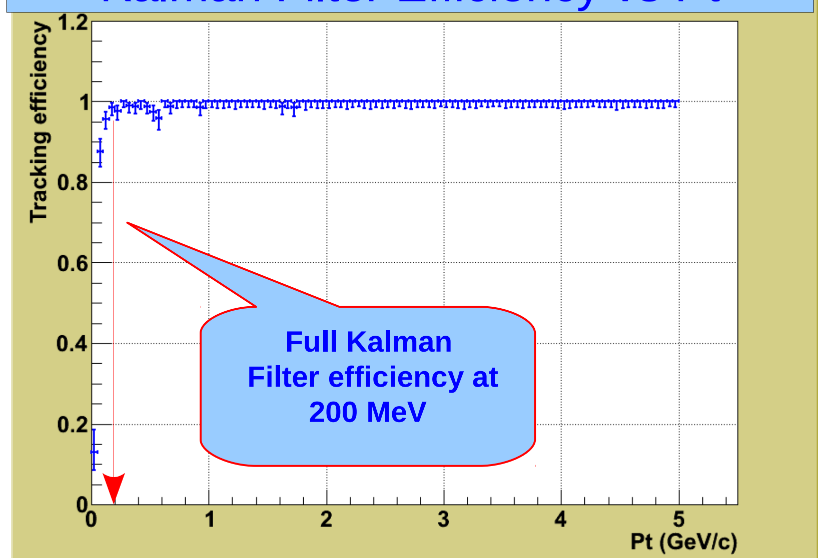
Geometrical Efficiency vs Pt



Kalman Filter Efficiency vs Theta



Kalman Filter Efficiency vs Pt

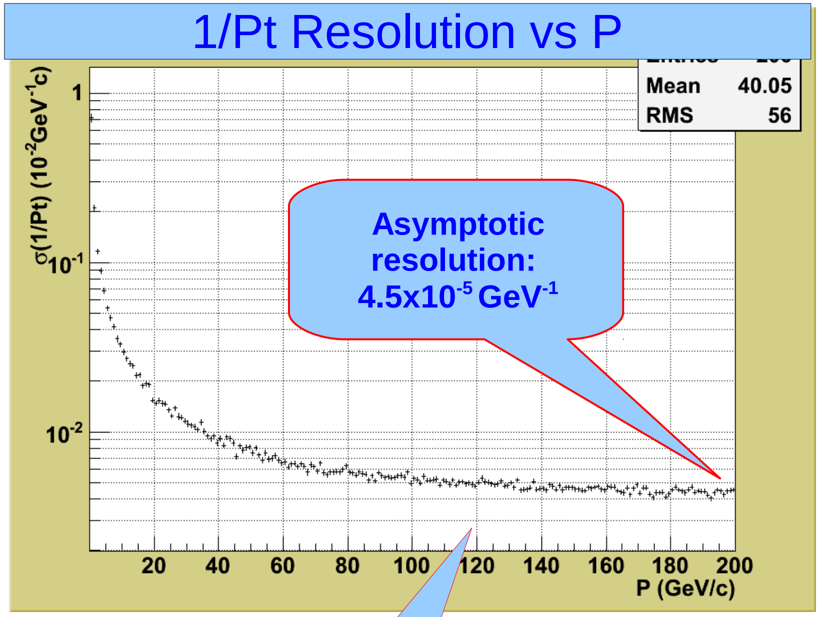


MuC Studies

Tracking Studies at MuC:

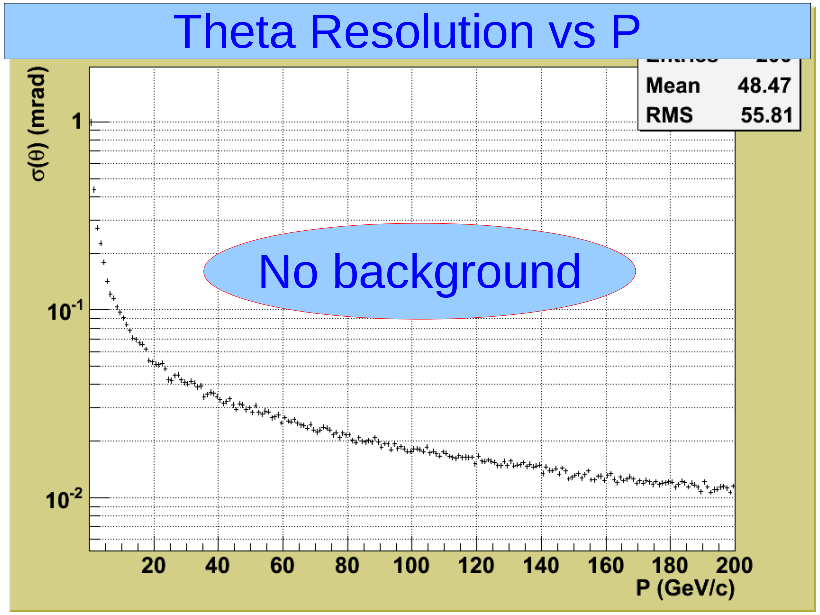
Resolutions for single muons

1/Pt Resolution vs P



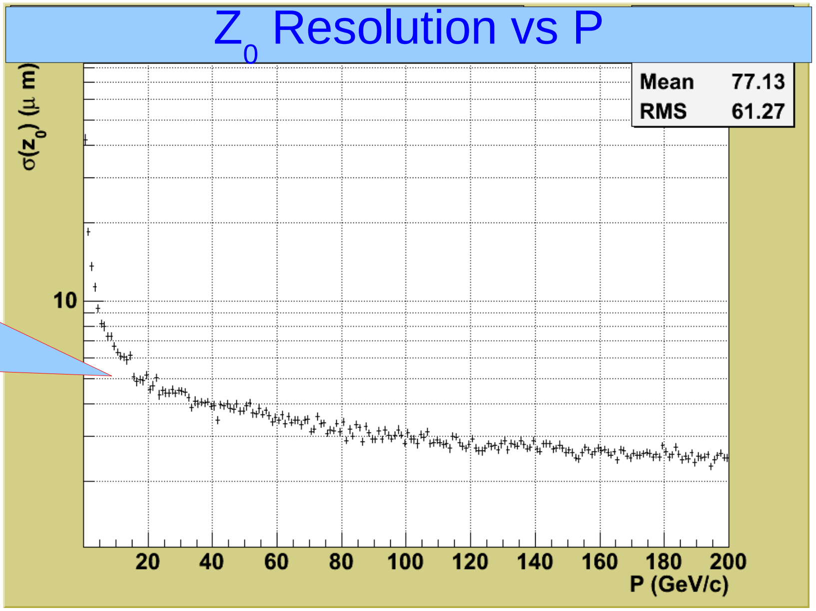
Asymptotic resolution: 4.5×10^{-5} GeV^{-1}

Theta Resolution vs P



No background

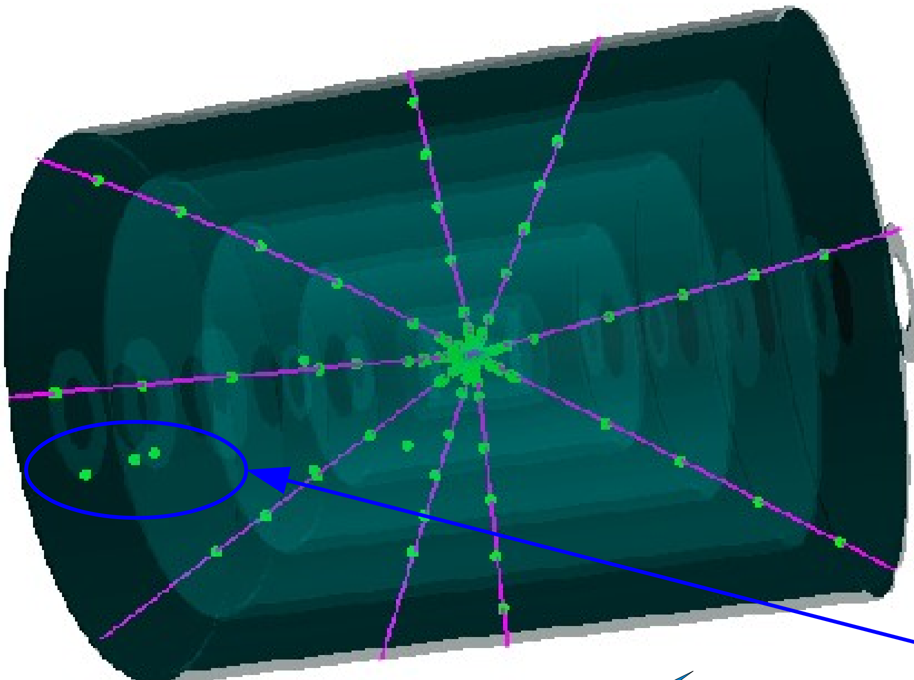
Z_0 Resolution vs P



Well within requirements for precision physics

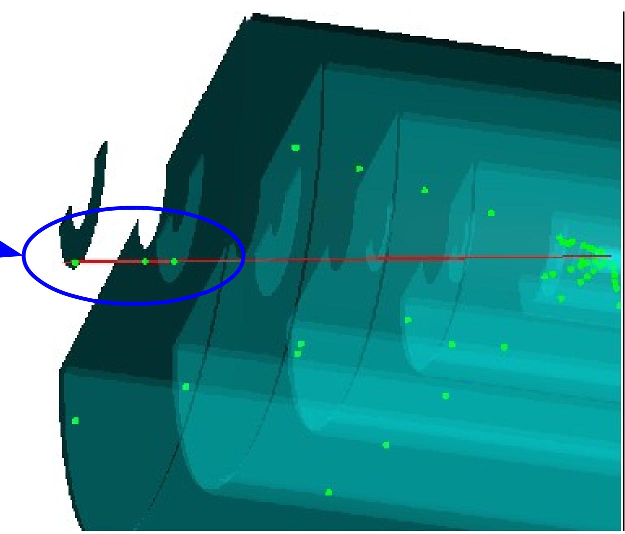
Full simulation of (0.2 – 200) GeV μ

Tracking Studies at MuC: Effect of the 10° nozzle



ILCroot event display
for 10 muons up to 200 GeV

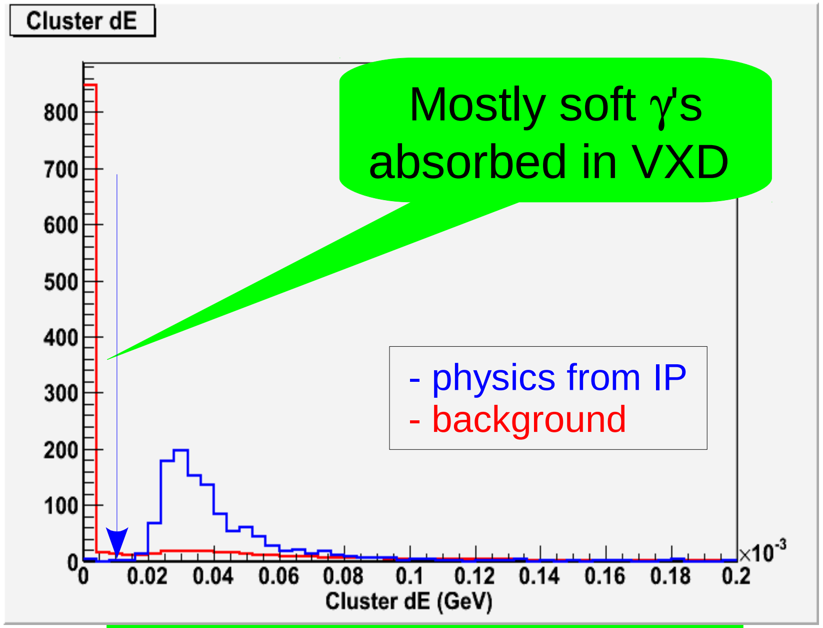
- green - hits
- purple – reconstructed tracks
- red – MC particle



10 generated muons
9 reconstructed tracks

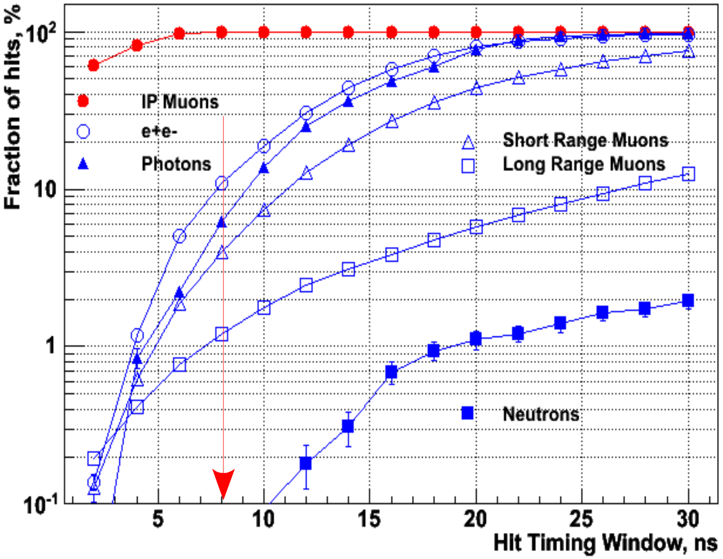
Tracking Studies at MuC:
Strategies to reduce clusters in the tracking system produced by the background

	Kalman Reconstruction	Clusters
Physics: 100 μ (0.2–200)GeV/c	92 (include geom. eff.)	1166
Machine Background	-	4 x 10^7



ΔE threshold 10 KeV (2400 e-)

From N. Terentiev's studies



Hits timing cut:: 7ns

Tracking Studies at MuC: Timing

- Simulated in ILCroot four detectors with different timing capabilities:
  - Det. A – No time information (integrates all hits)
  - Det. B – Acquires data in a fixed 7 ns time gate (minimal timing capabilities)
  - Det. C - Acquires data in a 3 ns time gate tuned to distance from IP (advanced timing capabilities)
  - Det. D - Acquires data in a 1 ns time gate tuned to pixel distance from IP (extreme timing capabilities)

Tracking Studies at MuC:
Reconstructed Background Tracks (from Kalman filter)

Full vs fast simulation of the bkg

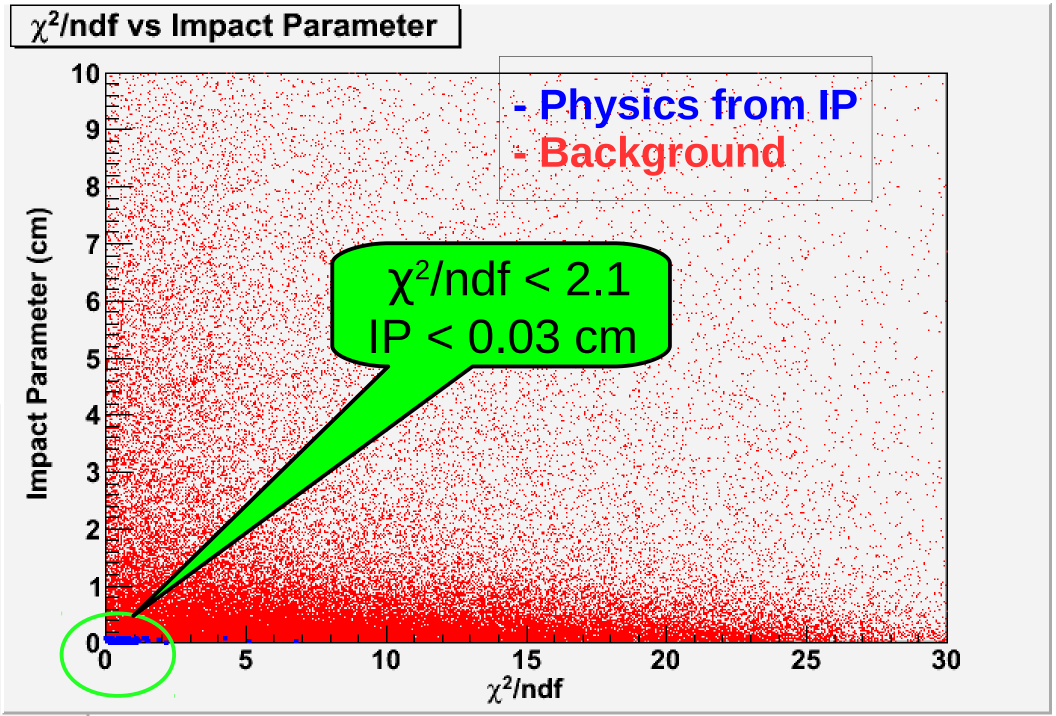
Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	75309	64319
Det. C (3 ns adjusteble gate)	6544	4639
Det. D (1 ns adjusteble gate)	1459	881

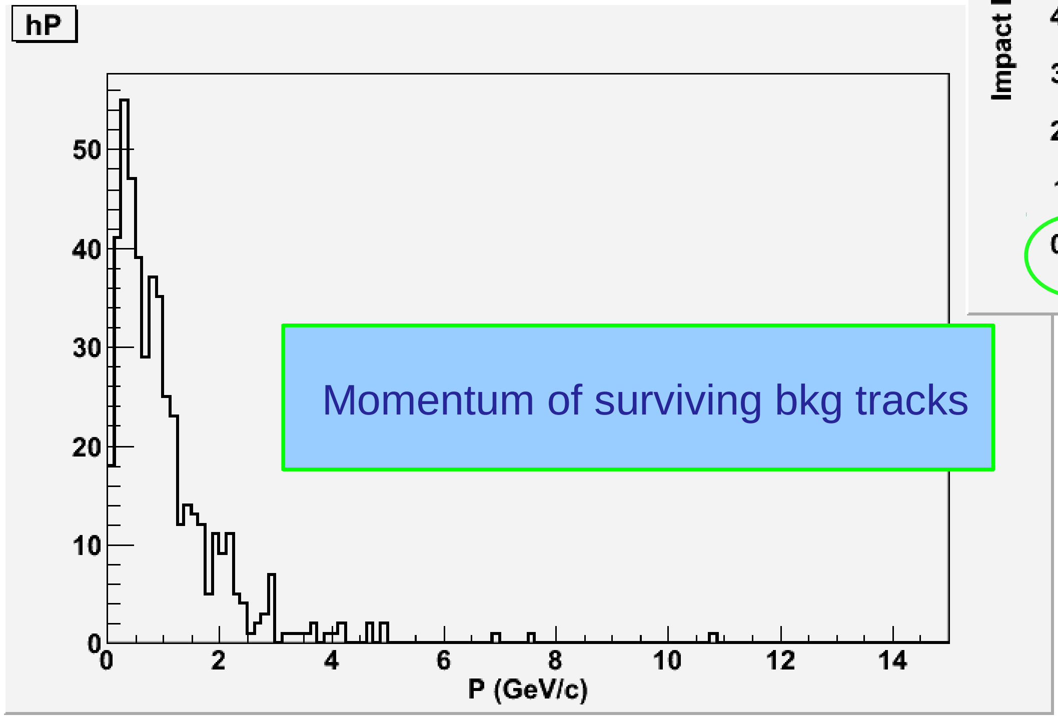
Full reconstruction is paramount when combinatorics is relevant

Tracking Studies at MuC:

Physics vs Background in Det. B:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg



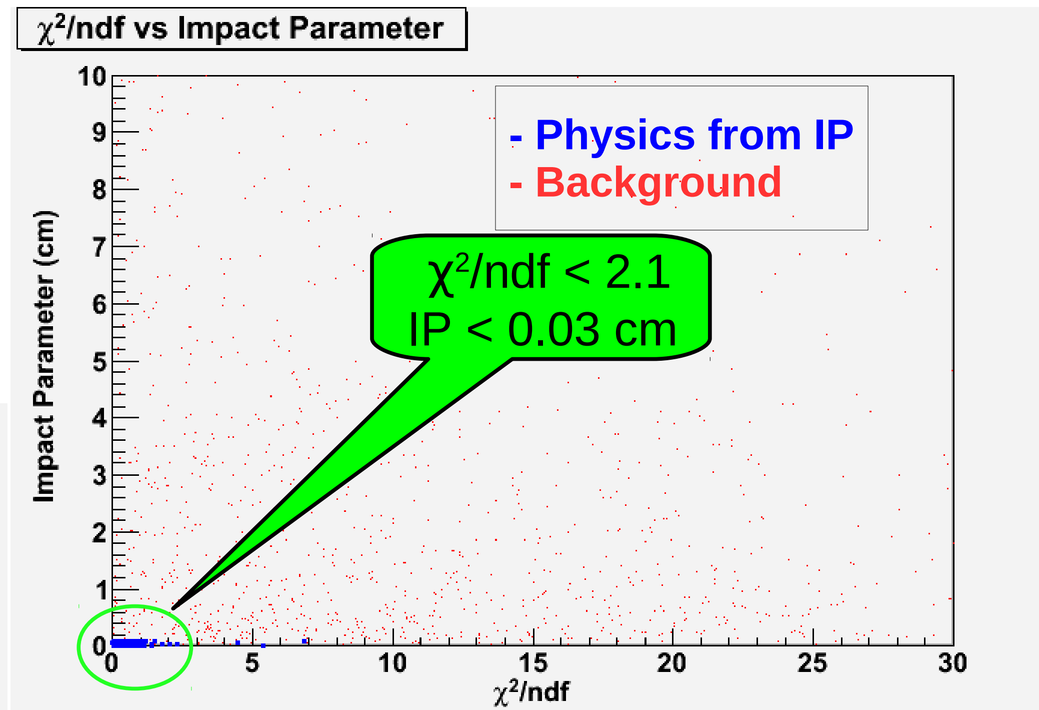


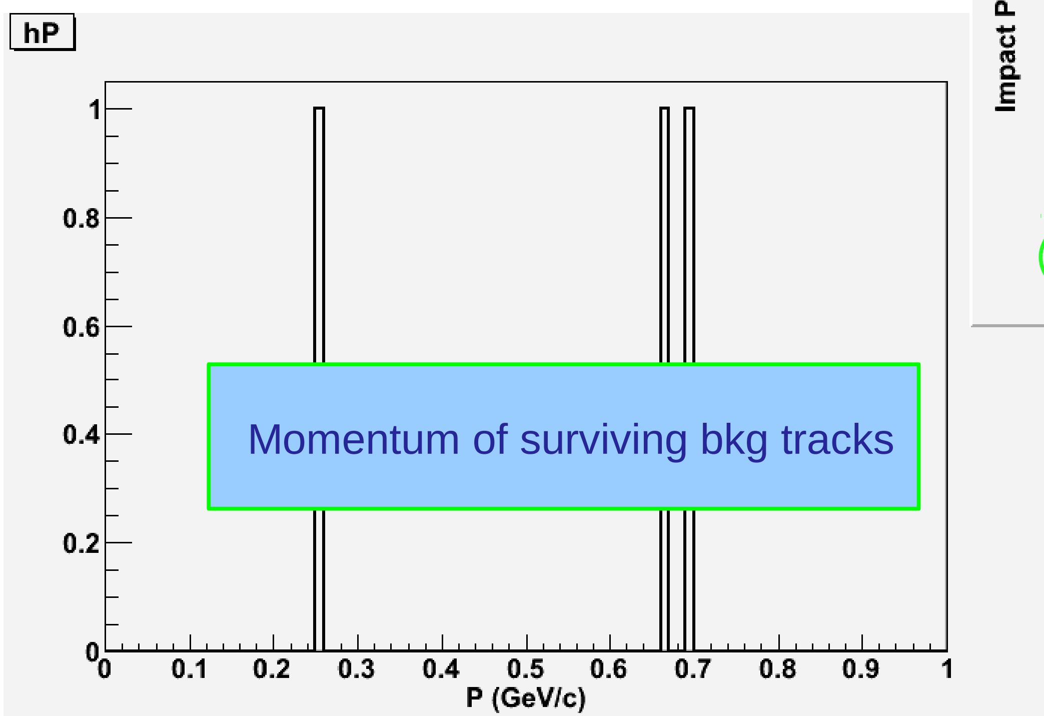
Momentum of surviving bkg tracks

Tracking Studies at MuC:

Physics vs Background in Det. D:
A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg





MuC Studies

Tracking Studies at MuC:
Reconstructed Background Tracks (from Kalman filter) after χ^2 and IP cuts

Full vs fast simulation of the back

Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	475	405
Det. C (3 ns adjusteble gate)	11	8
Det. D (1 ns adjusteble gate)	3	1

See also A. Mazzacane presentation at TIPP11

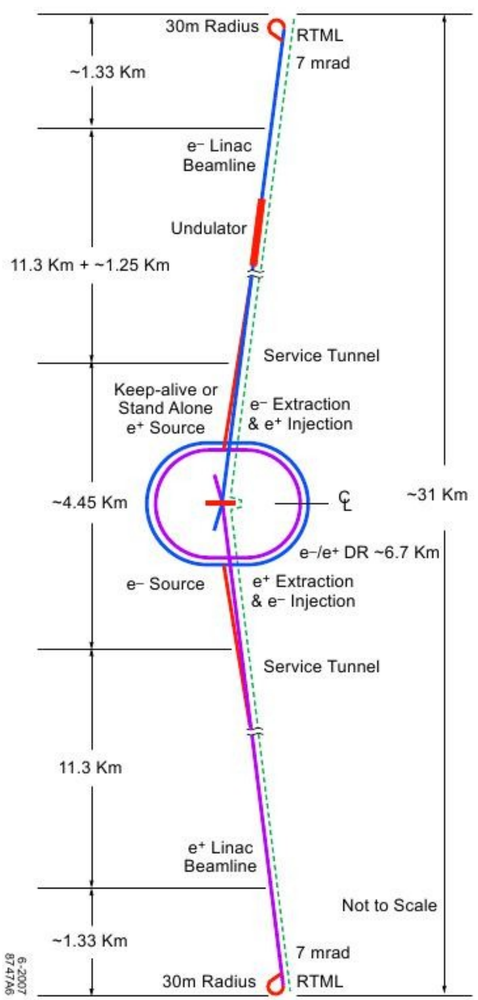
Summary of the studies at MuC

- The baseline detector configuration for Muon Collider studies performs well without background
- The background is very nasty, but fully understood
- Timing is important at a Muon Collider
- The simulated timing for the Si detectors is at the limit of current pixel devices (power consuption-cooling, material budget)
- A second generation of detector and algorithm are being considered:
  - 3-D Si-pixel with precision timing
  - 4-D Kalman filter

Backup slides

International Linear Collider

- Next big project in Particle Physics after LHC (Φ~27 km, E_{cm}=14 TeV)
- Electron - positron collider
- Linear instead of ring to avoid synchrotron loss (~31 Km long)
- Super – high – tech machine
- Accelerate beam to 250 GeV (E_{cm}= 500 GeV)
- Upgradeable to 1 TeV (~50 Km long)
- Focus beam down to a few nm in height (few hundreds in width)
- Peak luminosity $L = 2\text{x}10^{34}\,cm^{-2}s^{-1}$ (>1000xLEP)
- One interaction point, two detectors ("push-pull" system)
- Host country not chosen yet



ILC Studies

ILCroot:
Full Simulation of Si Detectors

SDigitization

- Follow the track in steps of 1 μm
- convert the energy deposited into charge
- spreads the charge asymmetrically (B-field) across several pixels:

- Parameters used:
  - Eccentricity = 0.85 (fda)
  - Bias voltage = 18 V
  - cr = 0% (coupling probability for row)
  - cc = 4.7% (coupling probability for column)
  - threshold = 3000 electrons
  - electronics noise = 0 electrons
  - T° = 300 °K

Charge pile-up is automatically taken into account

• Digitization

- Merge signals belonging to the same channel (pixel)
  - Add threshold
  - Add saturation
- Add electronic noise
- Save Digits over threshold
  - threshold = 3000 electrons
  - electronics noise = 0 electrons

Cluster Pattern recognition

- Create a initial cluster from adjacent pixels (no for diagonal)
- Subdivide the previous cluster in smaller NxN clusters
- Get cluster and error matrix from coordinate average of the cluster
- Kalman filter picks up the best Recpoints

ILCroot

VXD Simulation and Reconstruction

- Init

  Define Model: Silicon Pixel, Silicon Strip, Silicon Drift (at run-time)

  Define Segmentation (at run-time)
- Hits

  Produced by MC (G3,G4,Fluka)
- SDigits

  Simulate detector response for each Hit

  add pixel coupling
- Digits

  merge from several files of SDigits

  add electronic noise
- Recpoints (local reconstruction)

  Clusterize nearby Digits

  Unfold overlapping clusters
- Recparticles (global reconstruction)

  Kalman Filter

SDigitization

- Define Segmentation (at run-time)
- Define Model: Silicon Pixel, Silicon Strip, Silicon Drift (at run-time)
- Add background hits from file (optional)
- Step into materials (min. Step = 1μm)
  - Convert energy deposited by MC into charge
  - Spread charge in asymmetric way (ExB effect)

    $D(x,z)=Erfc(x,z,\sigma_z,\sigma_x)$

    $\sigma_z = sqrt(2k/e \times T^\circ \times (thickness/bias\ V) \times step)$

    $\sigma_x = asymm \times \sigma_z$
  - Add pixels to list
- Add coupling between nearby pixels
- Remove dead pixels (optional)

Digitization

- Read SDigits from several files
  (produced by different generators
  and/or MC)
- Add electronic noise
- Cut signal + electronic noise < threshold
- Zero suppression

Clusterization

- Create a initial cluster from adiacent
  pixels (no for diagonal)
- Subdivide the previous cluster in smaller
  NxN clusters (default 3x3)
- Kalman filter picks up the best clusters

Parameters List

- Size Pixel X = 20 μm
- Size Pixel Z = 20 μm
- Eccentricity = 0.85 (fda)
- Bias voltage = 100 V volts
- cr = 0% (coupling probability for row)
- cc = 4.7% (coupling probability for column)
- threshold = 3000 Electrons
- electronics = 0 (elettronic noise)

Solutions to f_{em} *fluctuations*

Several ways to deal with problem 1:

- *Compensating calorimeter* (design to have e/h=1) fluctuations in f_{em} eliminated by *design*
- *Off-line compensation* (signals from different longitudinal sections weighted)
- *Measurements of* f_{em} *event by event by comparing two different signals from scintillation light and Ĉerenkov light in the same device*(through spatial profile of developing shower)

Detectors: Calorimeters

- Detectors measuring energy of particles and jets by total absorption (calorimeters) **crucial** in HEP experiments

  - The performance of the calorimeter improves with the energy:

$$\text{if} \quad E \propto signal\, quanta\, n \rightarrow \sigma(E) \propto \sqrt{n} \rightarrow \frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{n}} \propto \frac{1}{\sqrt{E}}$$

  - In an ideal calorimeter the energy resolution scales with E-1/2

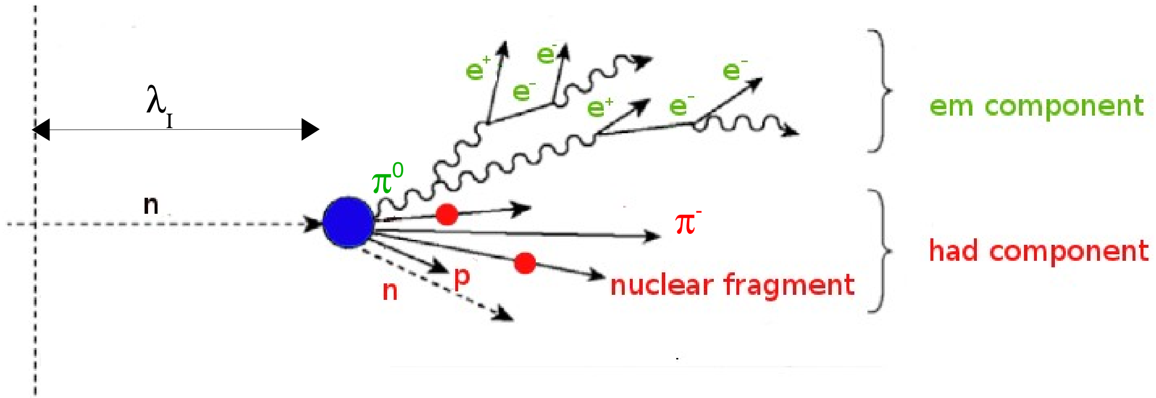
- But
  - Whereas em calorimeter are very precise ➡ detection of em interacting particles is performed with high precision
  - Hadron calorimeters are far from ideal
    - response function non-Gaussian
    - signals not linear
    - poor energy resolution

Detectors: Hadron Calorimeters

- A hadronic shower consists of two components:

- Electromagnetic component
  - Photons
  - Electrons
  - Neutral pions → 2 gammas

- Hadronic component
  - Charged hadrons ($\pi^{\pm}$, $k^{\pm}$) (20%)
  - Neutrons (15%)
  - Nuclear fragments (*p*) (25%)
  - Break up of nuclei (*invisible*) (40%)



- The calorimeter response to the two shower component is not the same ($e/h \neq 1$)
- Large and non-Gaussian fluctuations in energy sharing e/h
- Large and non-Gaussian fluctuations in "invisible" energy losses

LESSONS FROM 25 YEARS OF R&D → Energy resolution determined by fluctuations

- Fluctuations in the em shower fraction, f_{em}
- Fluctuations in visible energy (nuclear binding energy losses)

How Dual Readout Works

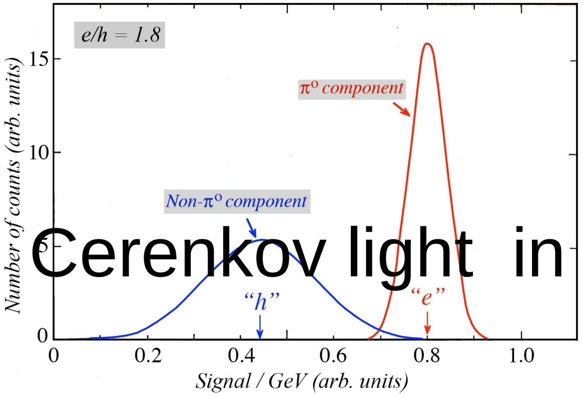
$$S = E\left[\frac{1}{\eta_S}\left(1 - f_{em}\right) + f_{em}\right]$$

$$C = E\left[\frac{1}{\eta_C}\left(1 - f_{em}\right) + f_{em}\right]$$

$$E = \frac{S - \zeta C}{1 - \zeta}$$

$$\eta_S = \left(e/h\right)_S \qquad \eta_C = \left(e/h\right)_C \qquad \zeta = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$

$f_{em} = em \;\; fraction \;\; of \;\; the \;\; hadronic \;\; shower$



scintillation light and Cerenkov light in the sa

Dual Readout Calorimeter Calibration

Calibrate with single 45 GeV e^-

➡ S and C

Calibrate with single 45 GeV π

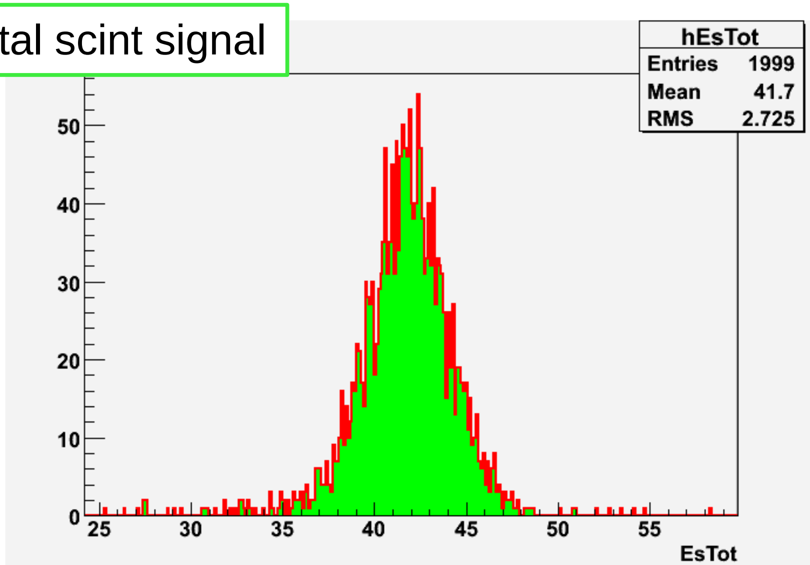
➡ η_S and η_C

Once calibrate, hadron calorimeter energy

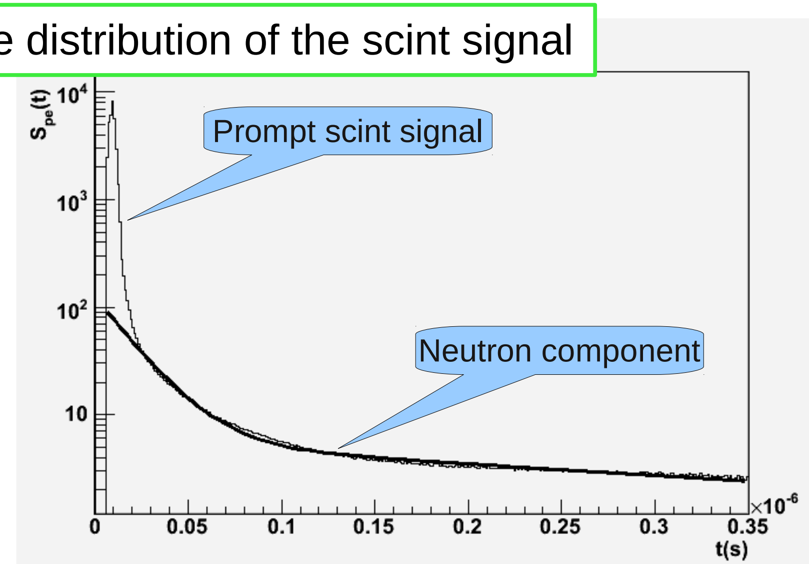
$$E_{HCAL} = \frac{\eta_S \cdot E_S \cdot (\eta_C - 1) - \eta_C \cdot E_C \cdot (\eta_S - 1)}{\eta_C - \eta_S} + \eta_N \cdot E_N$$

Separation of the neutron component in the scintillation signal

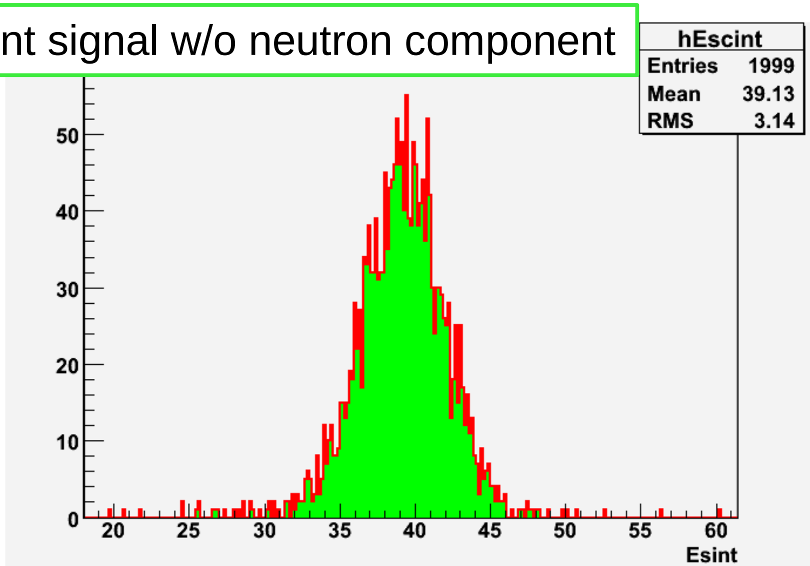
Total scint signal



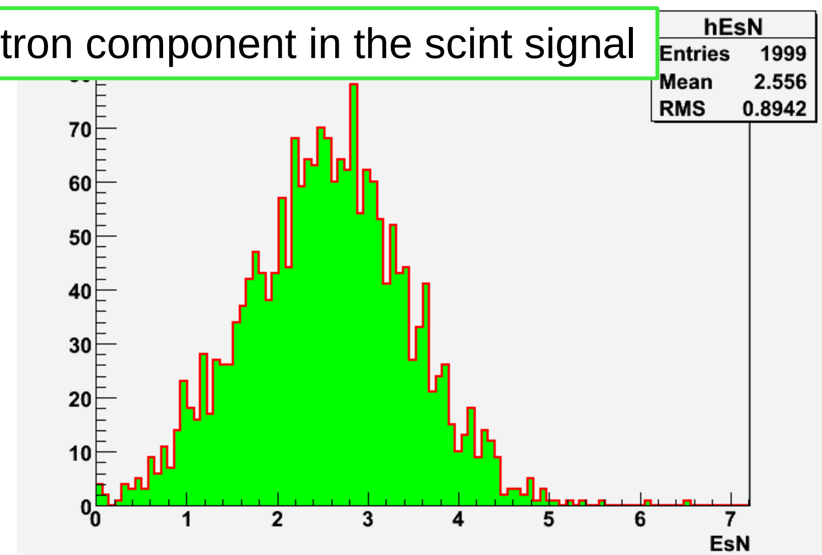
Time distribution of the scint signal

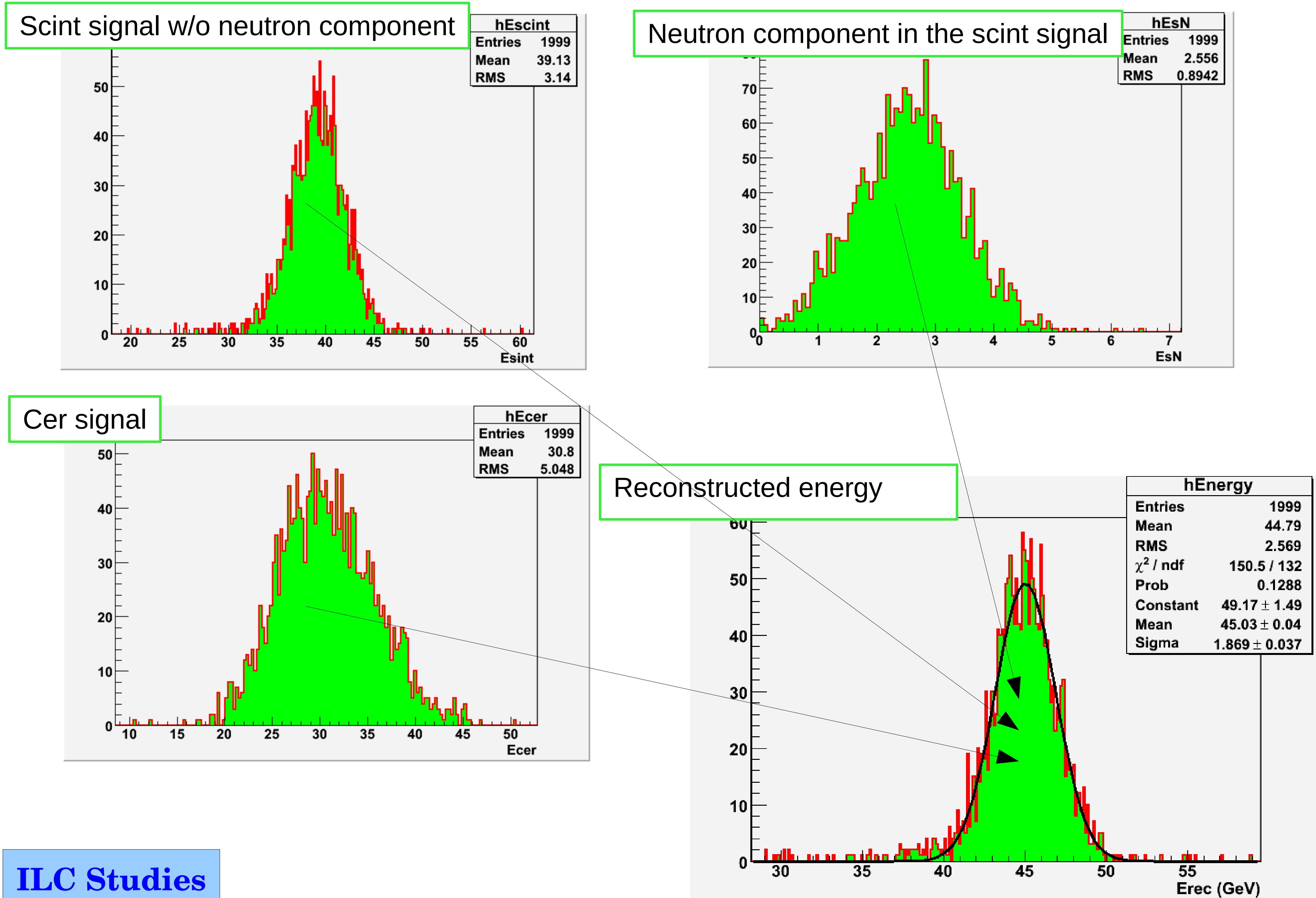


Scint signal w/o neutron component



Neutron component in the scint signal




Scint signal w/o neutron component
hEscint
Entries 1999
Mean 39.13
RMS 3.14
Esint
Neutron component in the scint signal
hEsN
Entries 1999
Mean 2.556
RMS 0.8942
EsN
Cer signal
hEcer
Entries 1999
Mean 30.8
RMS 5.048
Ecer
Reconstructed energy
hEnergy
Entries 1999
Mean 44.79
RMS 2.569
χ² / ndf 150.5 / 132
Prob 0.1288
Constant 49.17 ± 1.49
Mean 45.03 ± 0.04
Sigma 1.869 ± 0.037
Erec (GeV)

ILC Studies

Jet Studies at ILC:

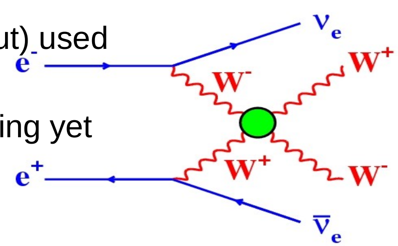
WWνν and ZZνν @ 500 GeV (four–jet events)

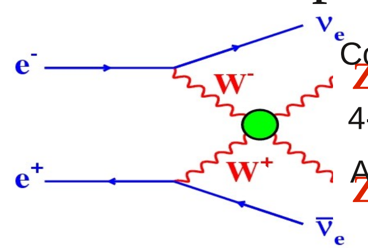
Study: W/Z Mass Separation

One of the goal of ILC is to distinguish WW from ZZ, using M_{jj}

One of the benchmarks to evaluate calorimeter performance

- Simple Durham jet-finder (fixed YCut) used for this analysis
- No combined information with tracking yet
- 4-jets finding efficiency: 95%
- Choose best pair combination

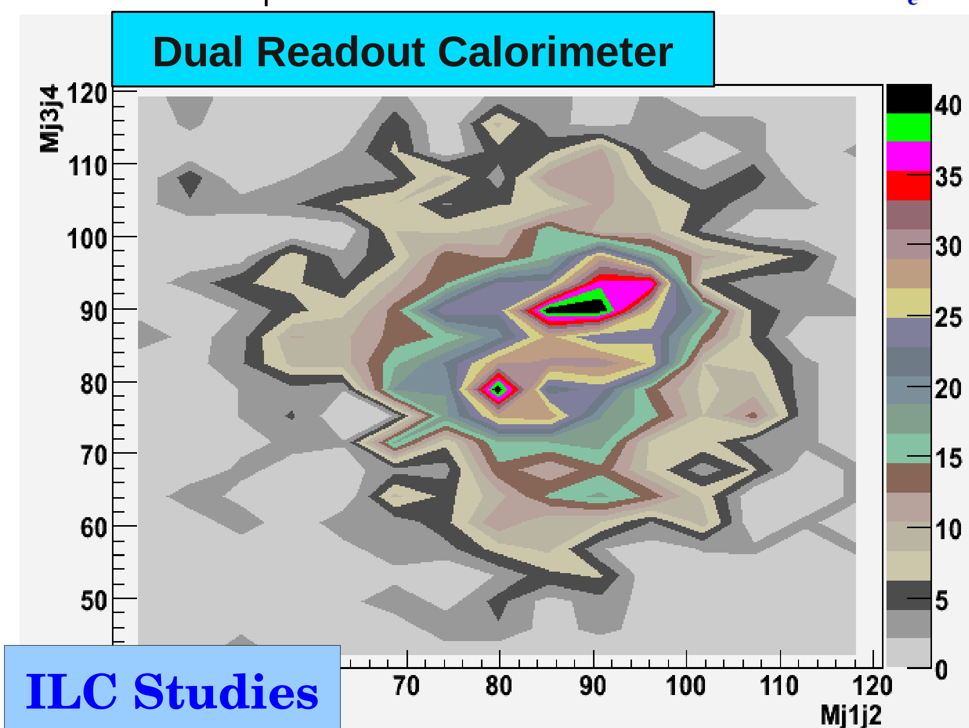


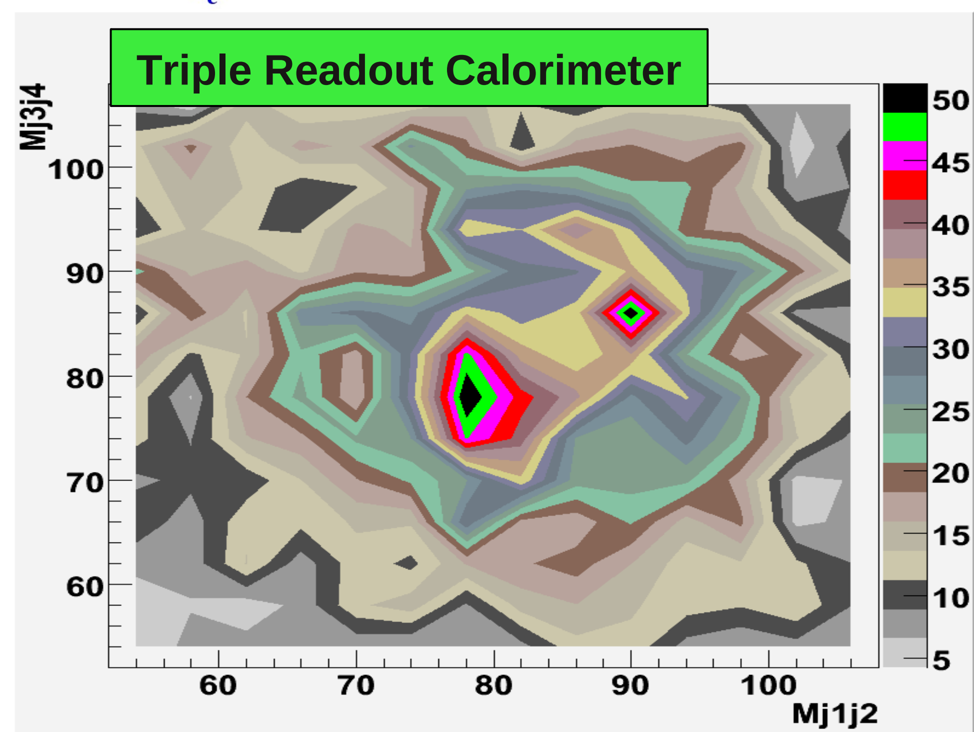


Combined informations with tracking

4-jets finding efficiency: 67.2%

All combinations plotted (6 events/event)





ILC Studies