Muon Collider Detector Studies

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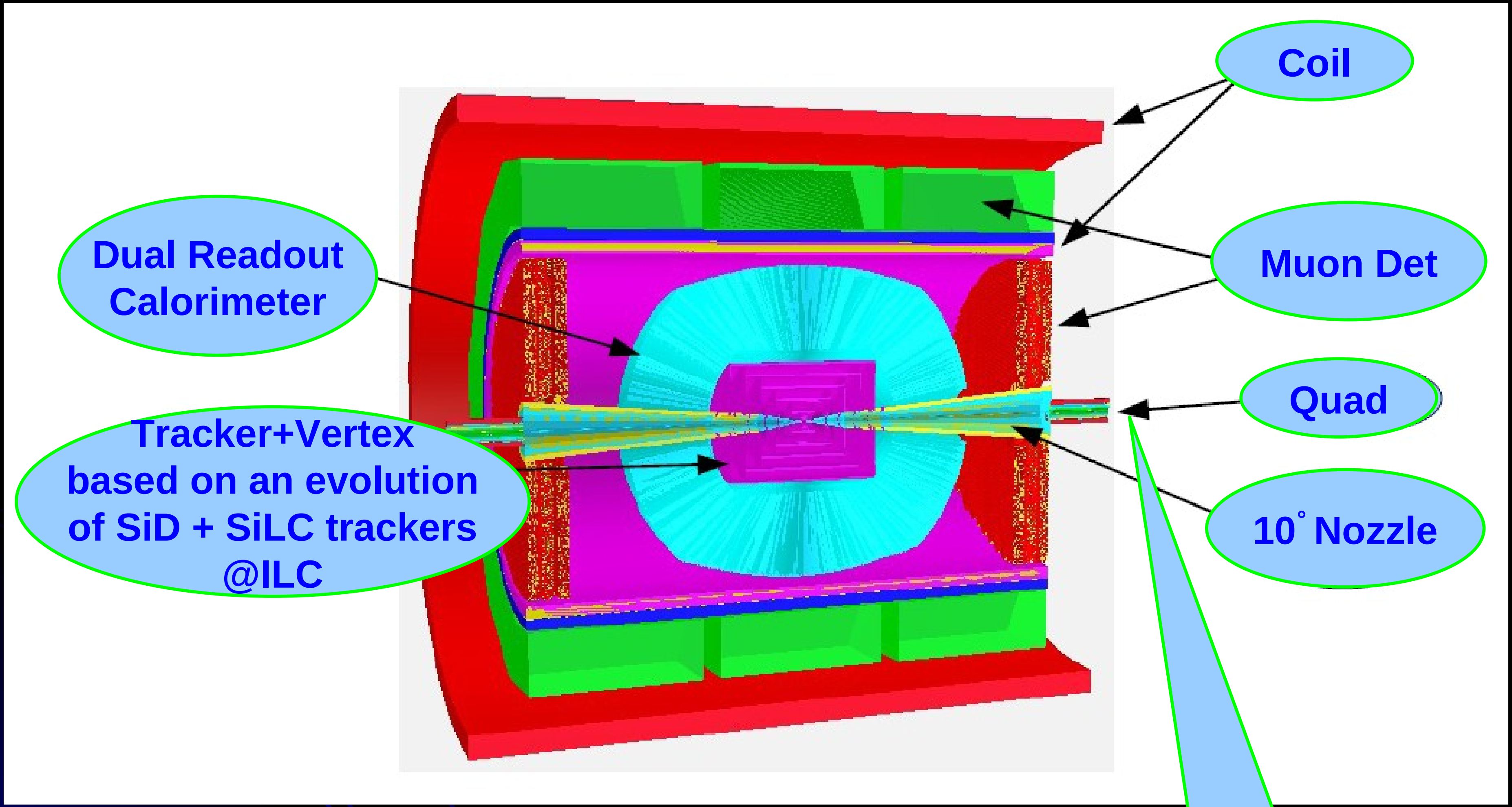
Main Detector Challenges

- If we can build a Muon Collider, it will be a precision machine!
- One of the most serious technical issues in the design of a Muon Collider experiment is the background
- The major source come from muon decays:

  for 750 GeV muon beam with $2*10^{12}$ muons/bunch ~ $4.3*10^{5}$ decays/m
- Large background is expected in the detector
- 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.

Baseline Detector for Muon Collider Studies



Coil

Dual Readout Calorimeter

Muon Det

Quad

Tracker+Vertex based on an evolution of SiD + SiLC trackers @ILC

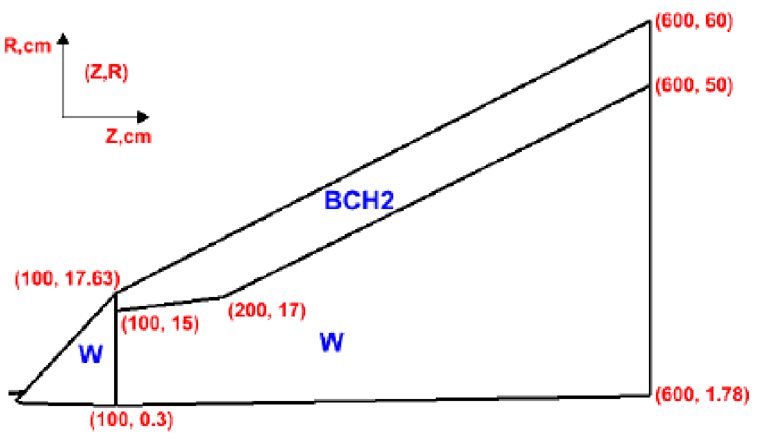
10° Nozzle

See S. Striganov's talk

Vertex Detector (VXD)
10°Nozzle and Beam Pipe

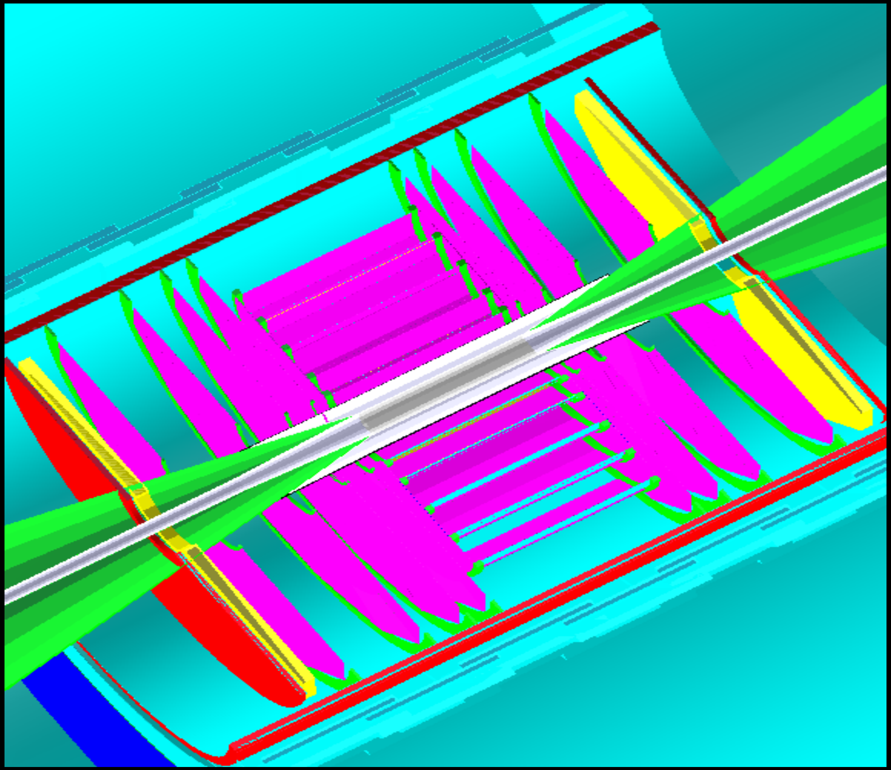
VXD

- 100 µm thick Si layers
- 20 µm x 20 µm 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



NOZZLE

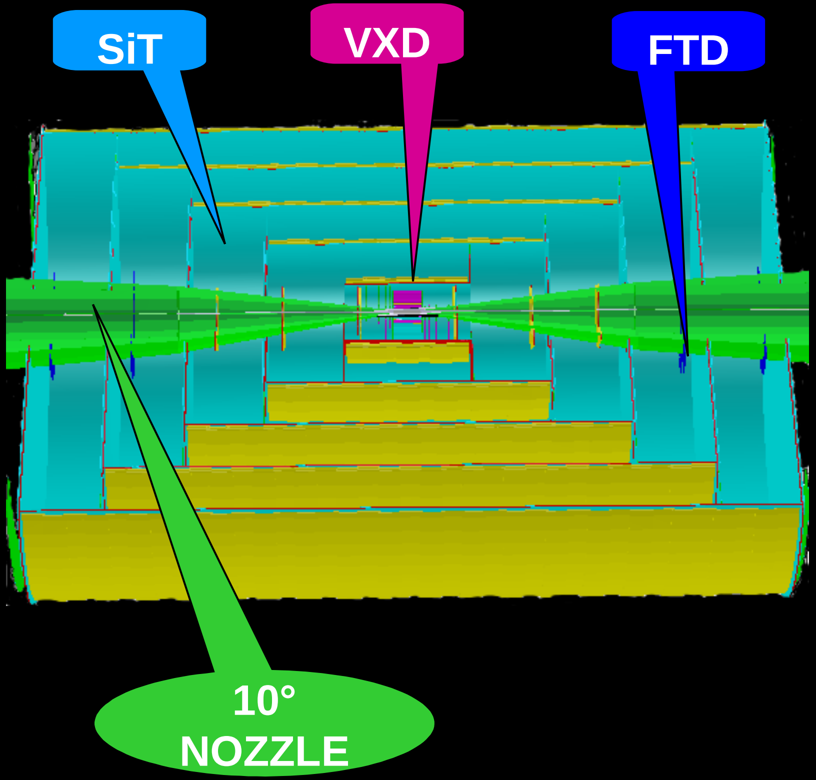
- W - Tungsten
- BCH2 – Borated Polyethylene



PIPE

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

Silicon Tracker (SiT) and Forward Tracker Detector (FTD)



SiT

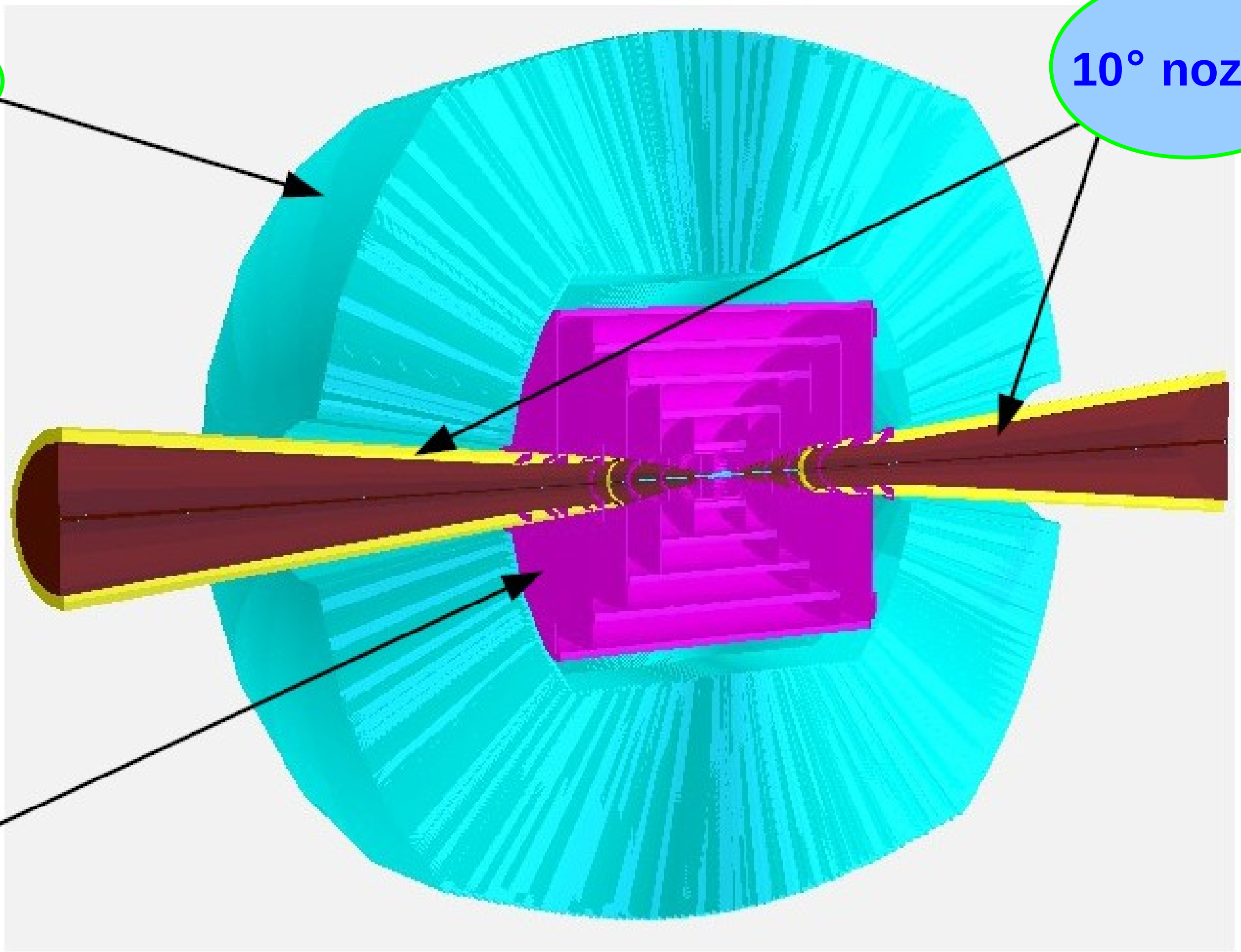
- 100 µm thick Si layers
- 50 µm x 50 µm Si pixel (or Si strips or double Si strips available)
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+2) + (4+2) disks subdivided in ladders
- R_{min}~20 cm R_{max}~120 cm L~330 cm

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

Dual-Readout Projective Calorimeter



- ~1.4° tower aperture angle
- 180 cm depth
- ~ 7.5 λ_{int} depth
- >100 X_0 depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nose)
- Barrel: 16384 towers
- Endcaps: 5544 towers

Energy resolution: < 30%/sqrt(E)

MARS and ILCroot Frameworks

MARS – the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.

- New release of MARS15 available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS)
- Among new features:
  - Refined MDI (Machine Detector Interface) with a 10° nozzle
  - Significant reduction of particle statistical weight variation
  - Background is provided at the surface of MDI (10° nozzle + walls)

ILCroot - Software architecture based on ROOT, VMC & Aliroot

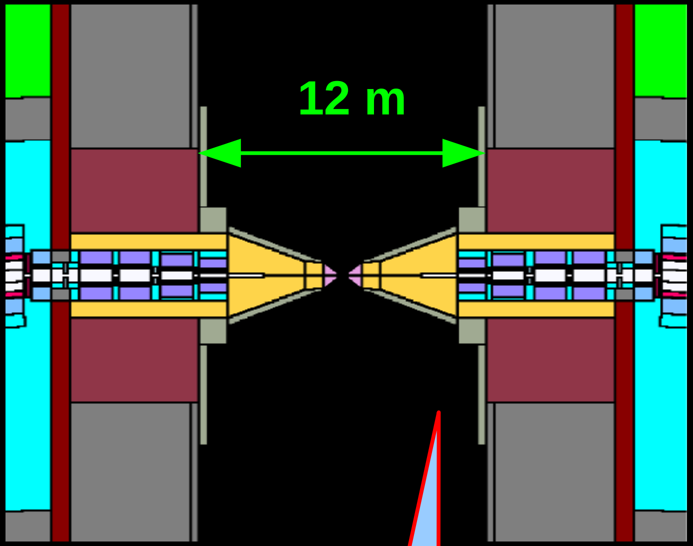
- All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
- Extremely large community of ROOT users/developers

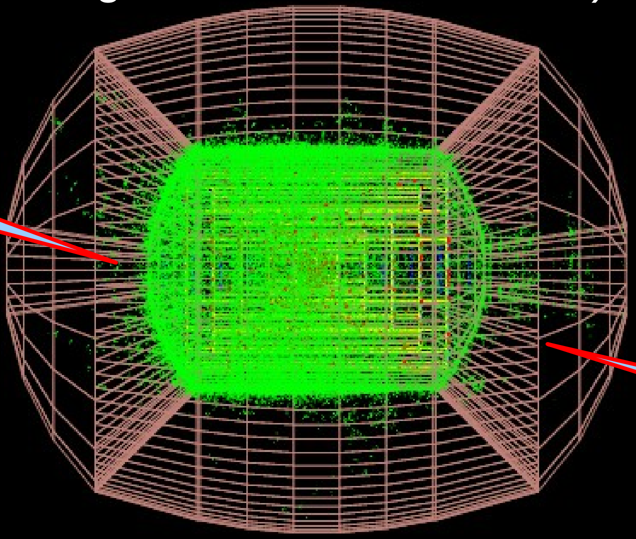
- It is a simulation framework and an offline system:
  - Single framework, from generation to reconstruction and analysis!!
  - Six MDC have proven robustness, reliability and portability
  - VMC allows to select G3, G4 or Fluka at run time (no change of user code)
- Widely adopted within HEP community (4th Concept, LHeC, T1015, SiLC)
- It is publicly available at FNAL on ILCSIM since 2006

Ingredients for these Studies

- MARS background provided at the surface of MDI (10° nozzle + walls)

- GEANT4 /fluka simulated particles in the detector (background + single muons from the I.P.)





Only 4% background pictured

Hits in the calorimeter

- Reconstructed tracks from a parallel Kalman Filter in a 3.5 T B-field

- Reconstructed energy towers from a Dual Readout calorimeter

Source term at black hole to feed detector simulation

Tracking System Studies:
Nozzle Effects on Tracking Performance

Hits densities in the vertex and the tracker detector

See N. Terentiev's talk

Reconstruction Efficiency & Resolutions

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

$$\epsilon_{geom} = \frac{good\ tracks}{generated\ tracks} \qquad \epsilon_{track} = \frac{reconstructed\ tracks}{good\ tracks}$$

Defining “good tracks” (candidate for reconstruction)

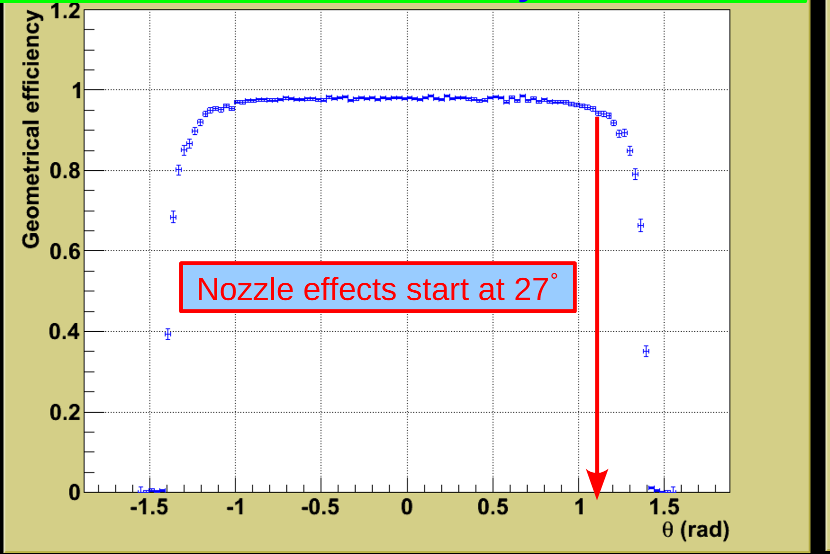
DCA(true) < 3.5 cm

AND

at least 4 hits in the detector

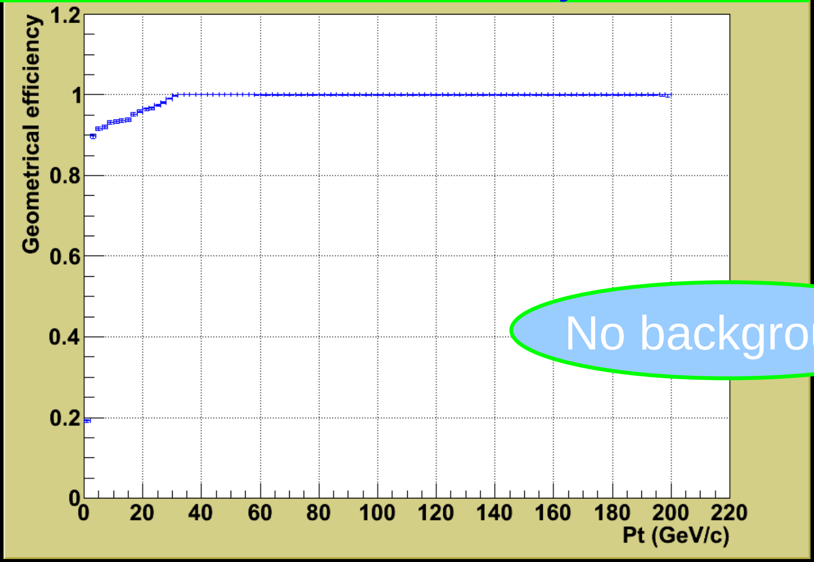
Reconstruction Efficieny for Single Muons

Geometrical Efficiency vs Theta



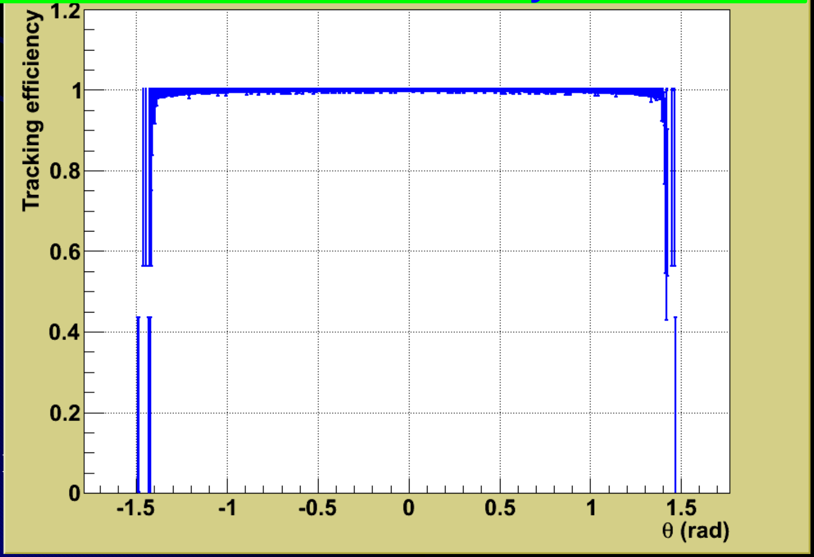
Nozzle effects start at 27˚

Geometrical Efficiency vs Pt

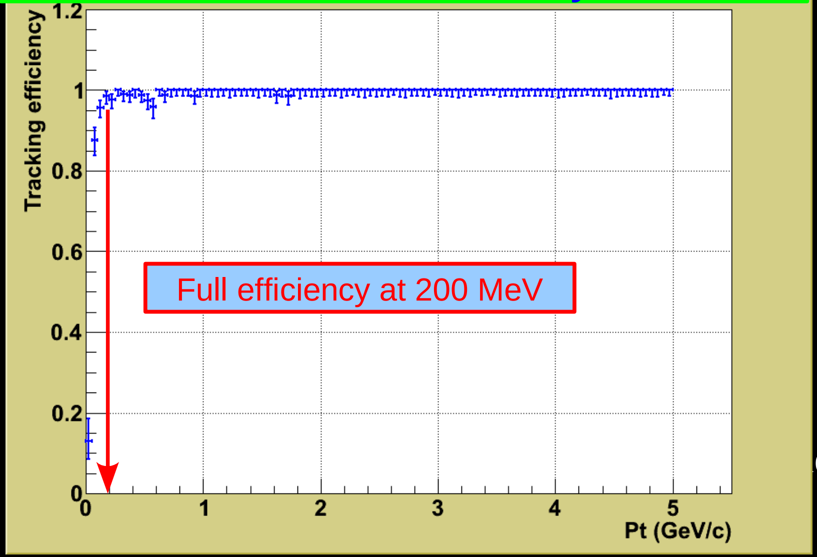


No background

Kalman Filter Efficiency vs Theta



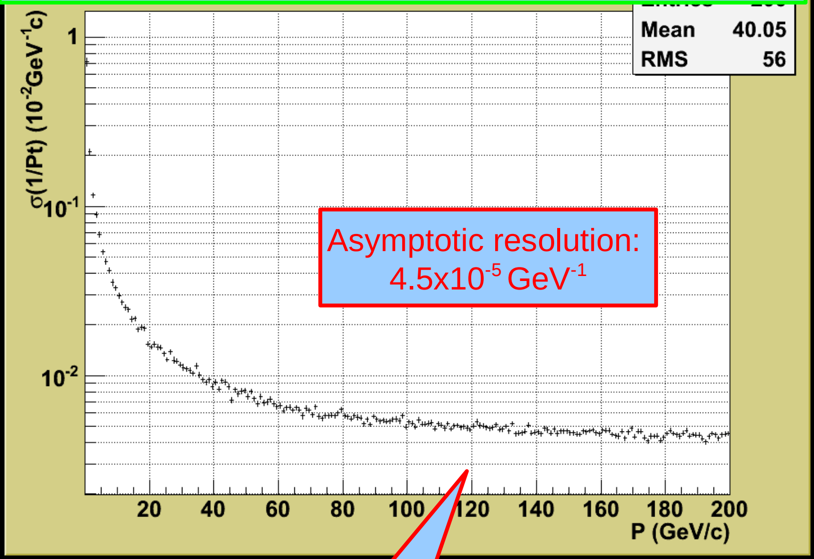
Kalman Filter Efficiency vs Pt



Full efficiency at 200 MeV

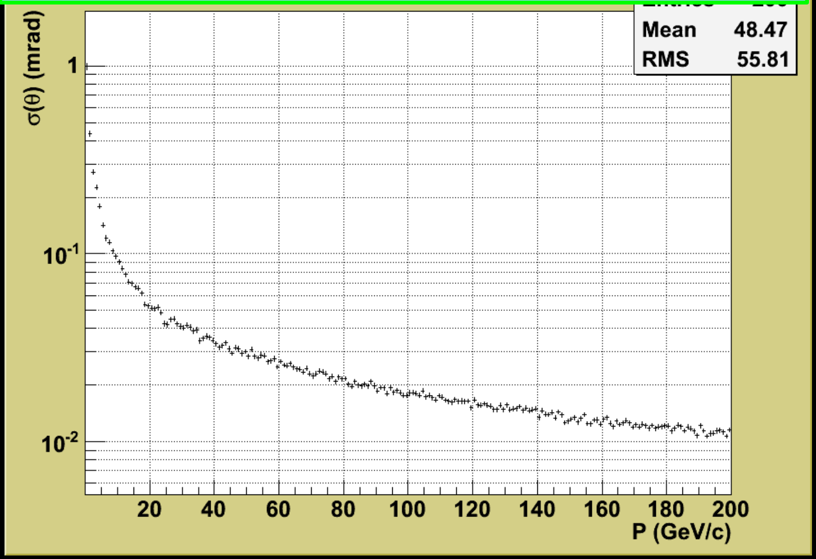
Resolutions for single muons

1/Pt Resolution vs P

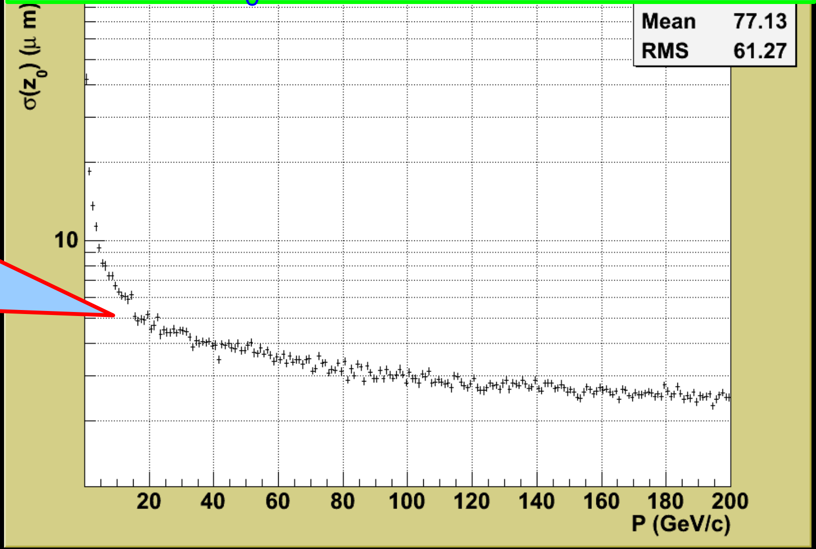


Asymptotic resolution: 4.5×10^{-5} GeV^{-1}

Theta Resolution vs P



Z_0 Resolution vs P



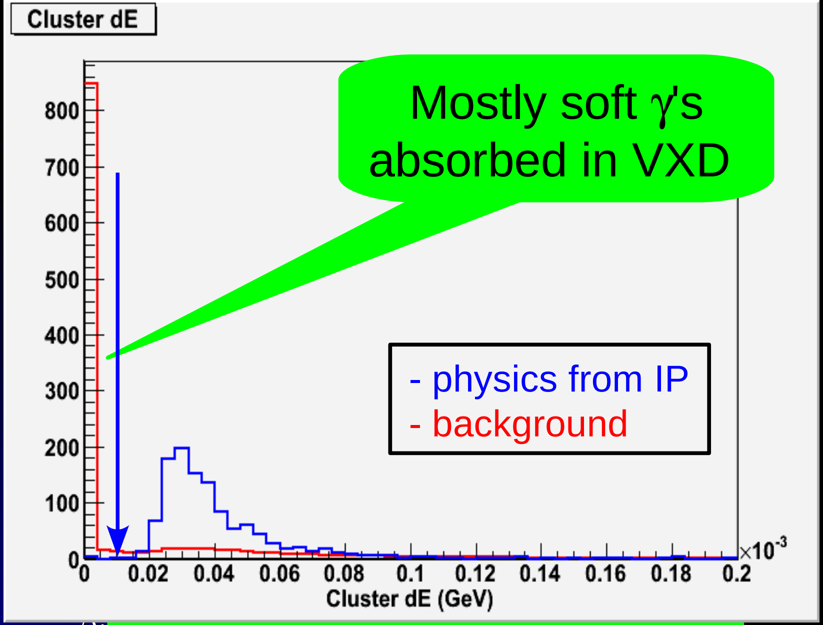
Well within requirements for precision physics

No background

Strategies to reduce clusters in the tracking system produced by the background

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

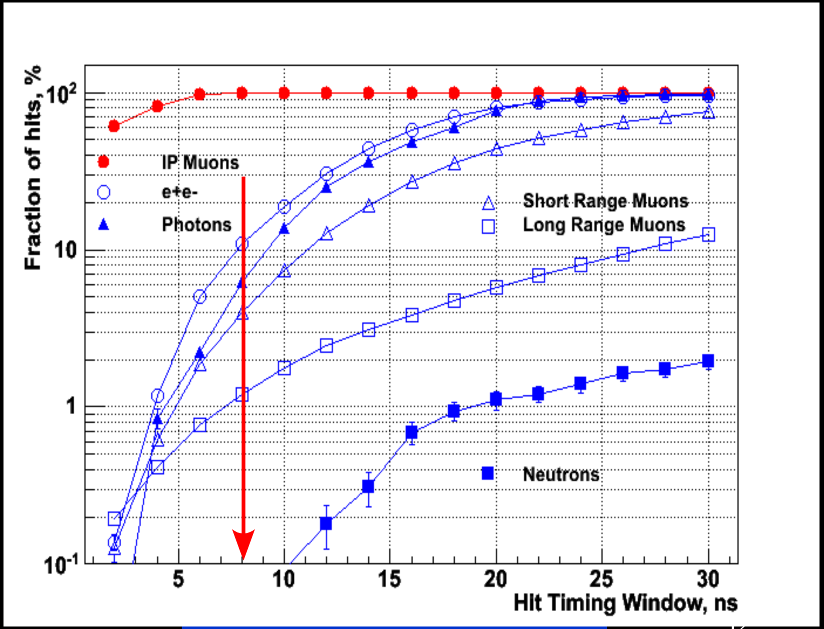
See N. Terentiev's talk



Mostly soft γ's absorbed in VXD

- physics from IP
- background

ΔE threshold 10 KeV (2400 e-)

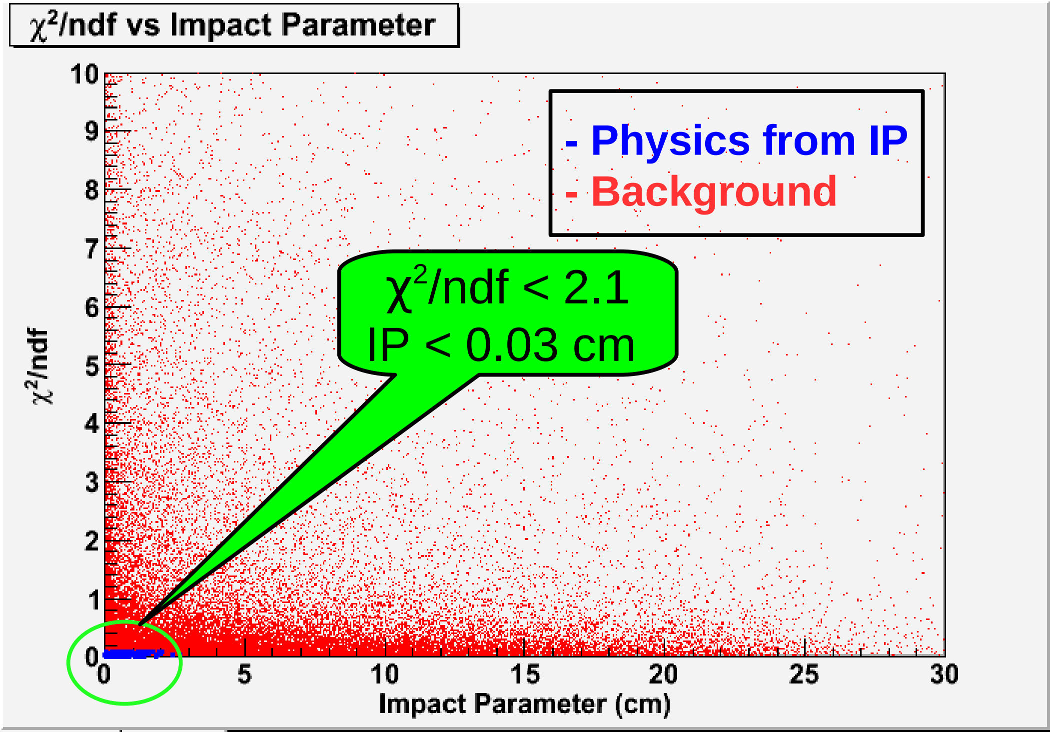


Cluster timing cut:: 7ns

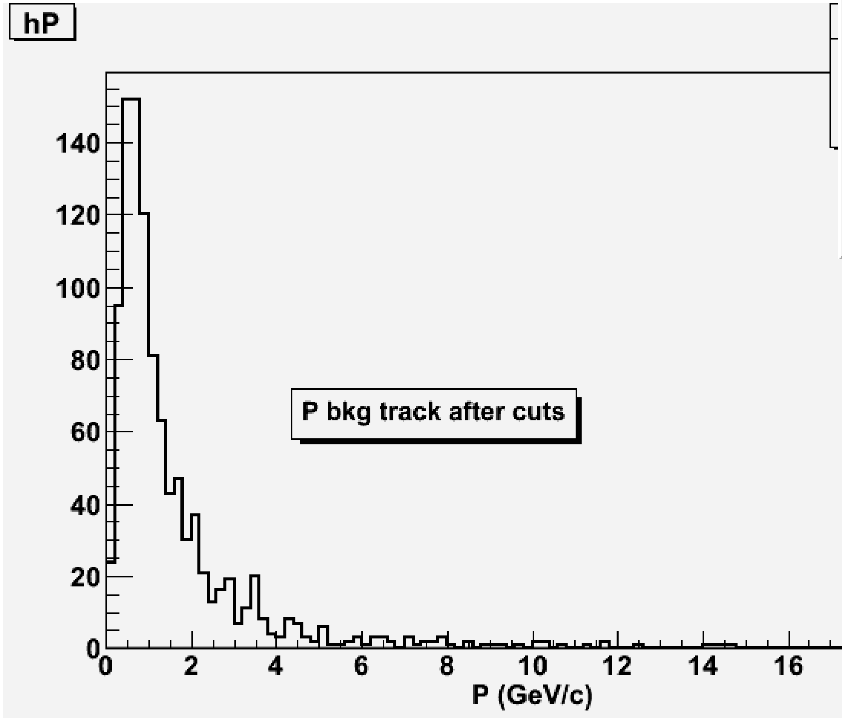
Physics vs Background:

a strategy to disantangle reconstructed tracks from IP

Studies based on half background



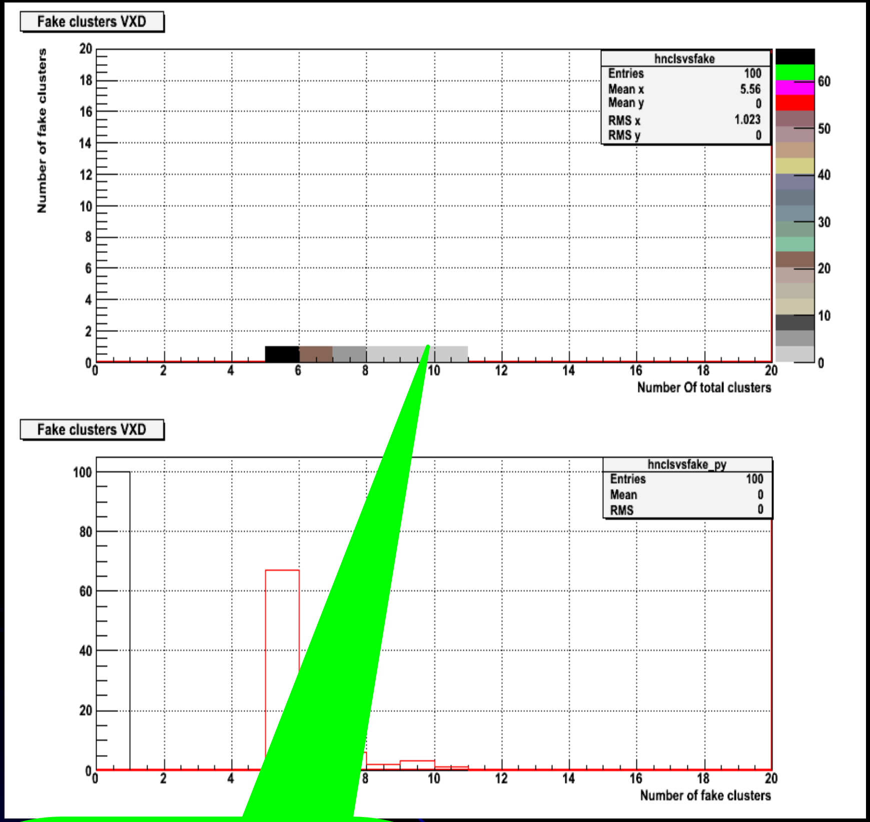
χ^2/ndf < 2.1
IP < 0.03 cm

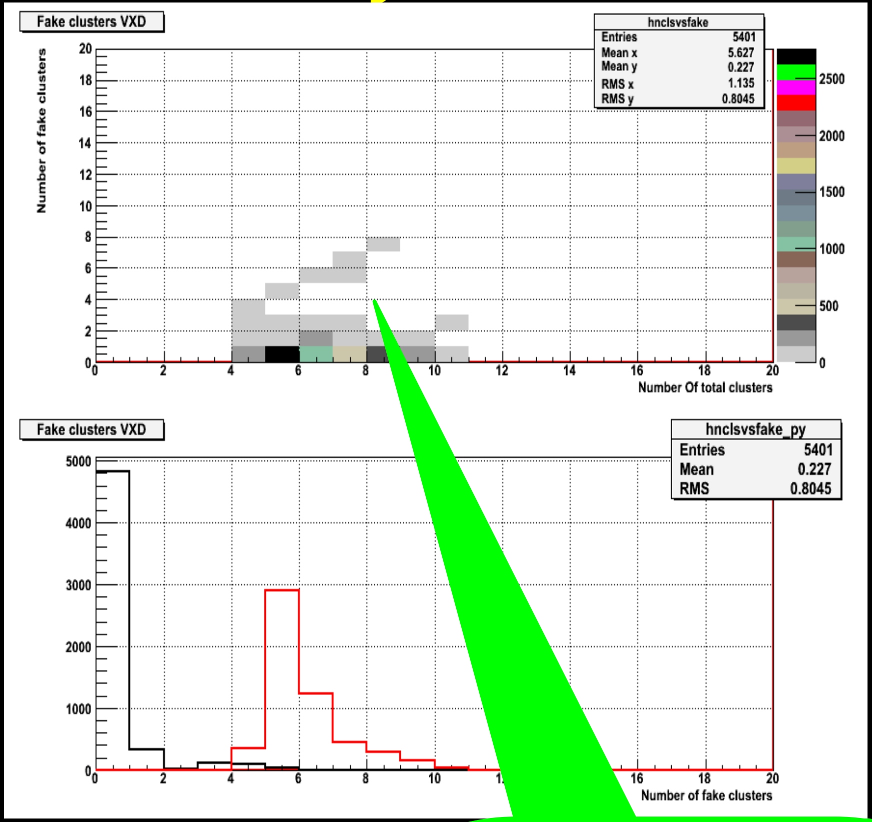


	Surviving tracks
Physics: 100 μ	89
Machine background	2110

3 lost

Effects of background Hits on the Reconstruction of Physics





no fake cluster

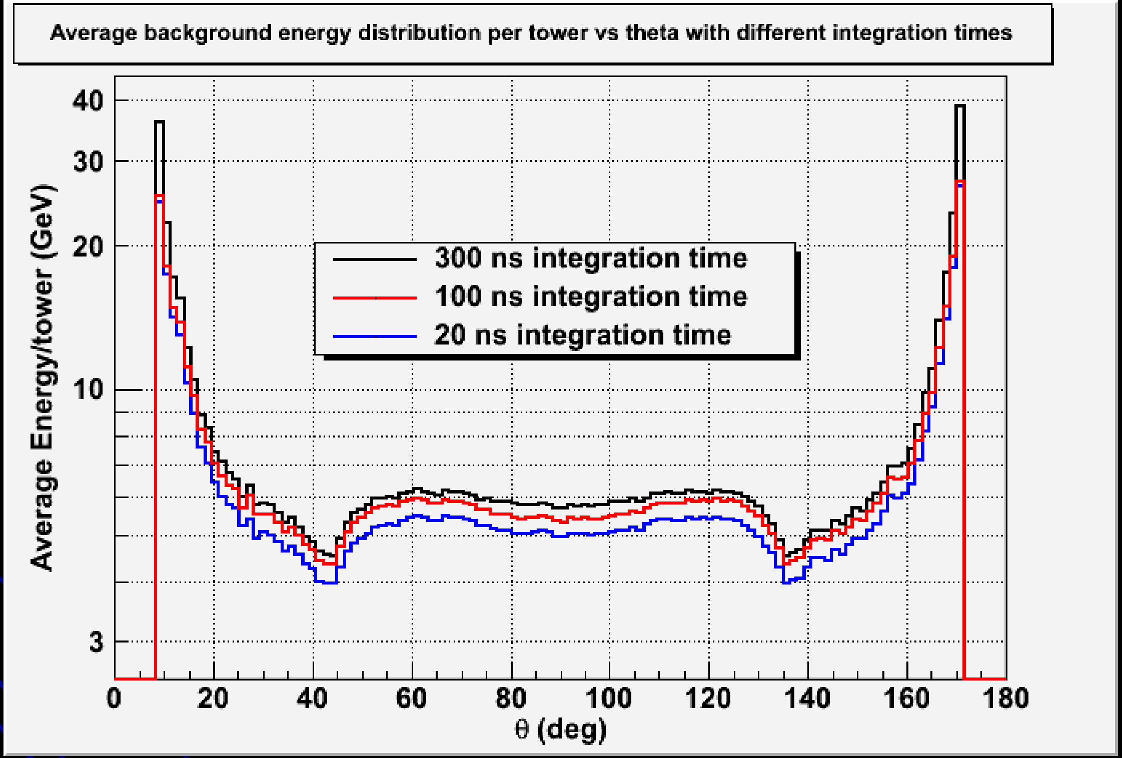
1 physics event = 100 muons

< 5% of tracks have > 1 fake cluster

Effects on track parameter resolution are under study

Calorimetric Studies

Average background energy in a calorimeter tower produced in one bunch crossing



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Integration time has little effect on visible energy

Background in the calorimeter for different particle species originating within 25 m from IP

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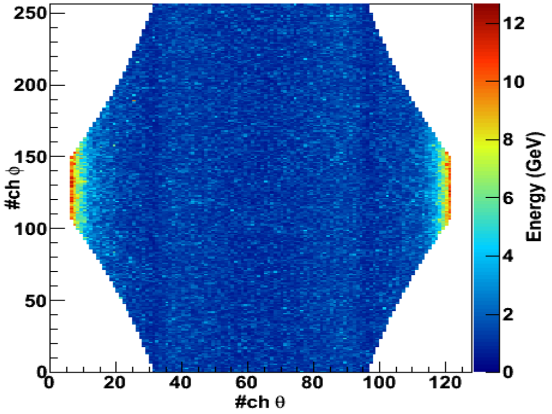
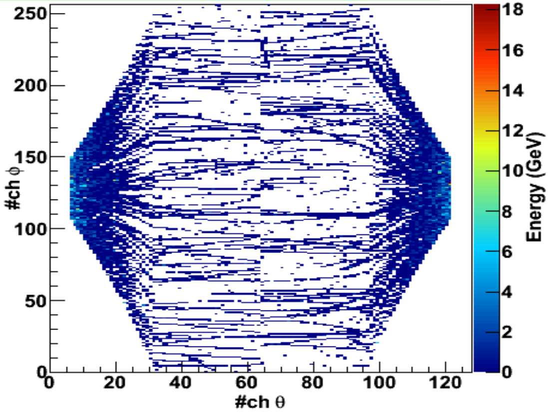
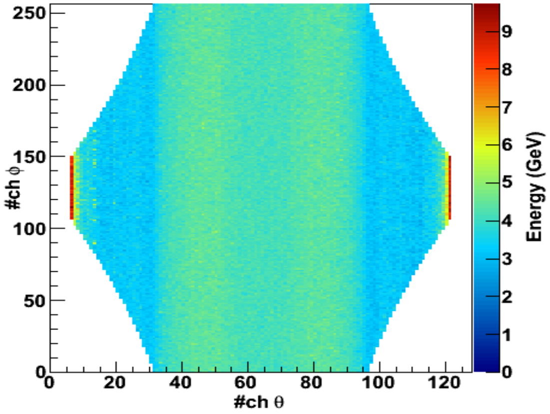
Neutrons



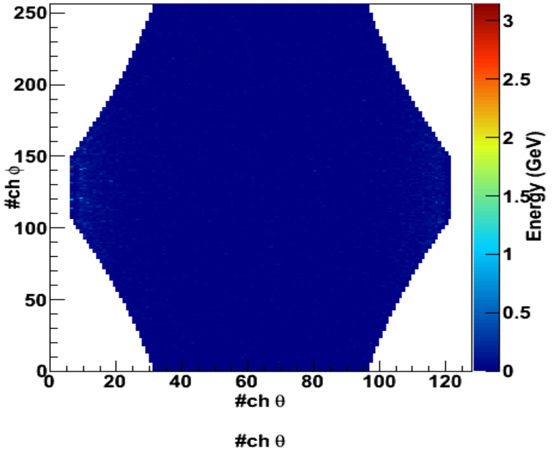
Muons



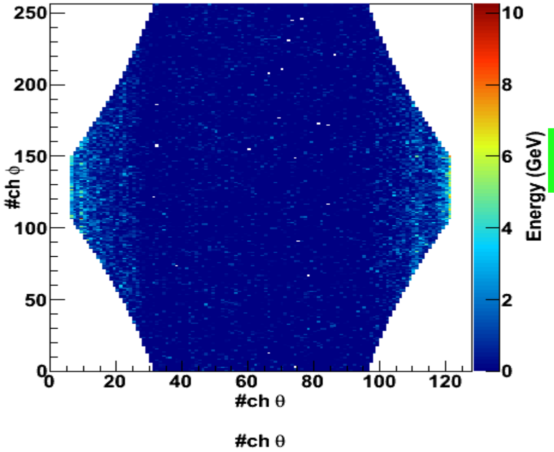
Photons



Neutrons



Others



1 bin = 1 calorimeter cell

[5ns-105ns] integration time

Mostly neutrons and photons contribute to the energy into the calorimeter

Background in the calorimeter for different particle species originating beyond 25 m from IP

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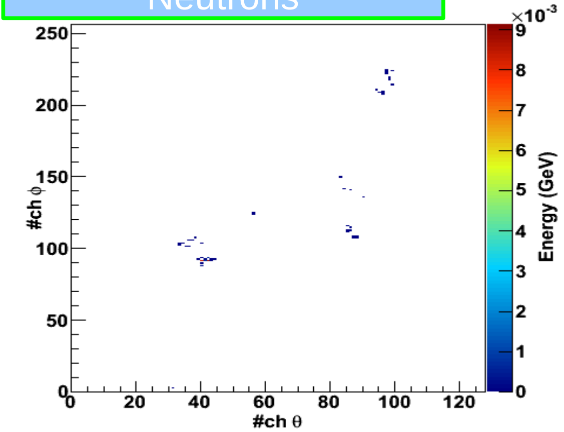
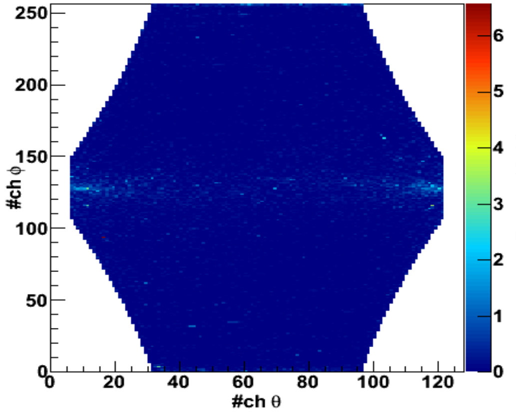
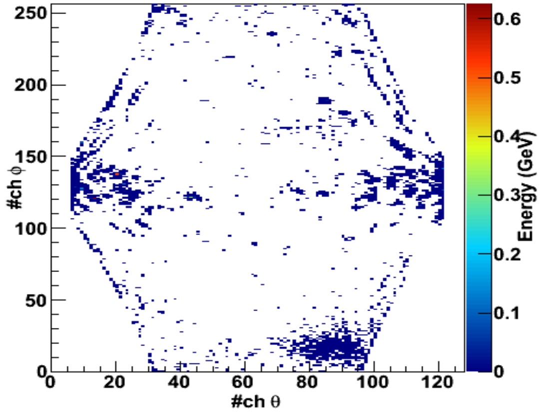
Neutrons



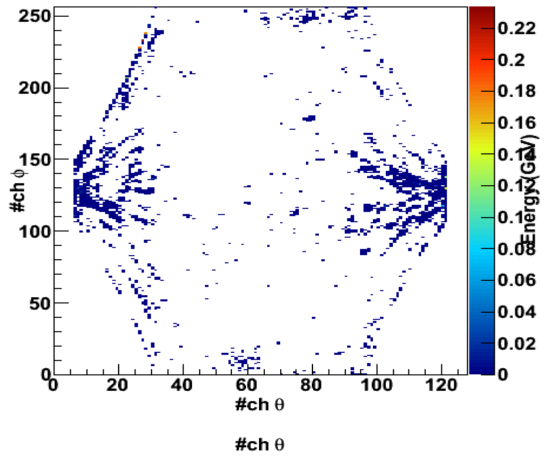
Muons



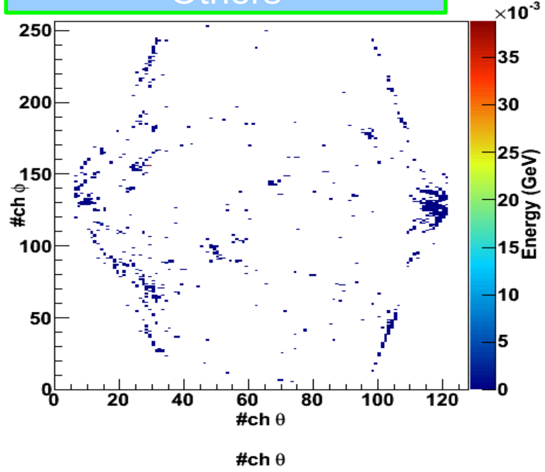
Photons



Neutrons



Others



1 bin = 1 calorimeter cell

[5ns-105ns] time gate

Only muons contribute significantly to the energy into the calorimeter

Background Energy Fluctuation in the Calorimeter

Central barrel (45° <θ< 135˚)
Fluctuations are ΔE/E~12%/cell
and ΔE ~ 3 GeV for a jet involving ~25 cells

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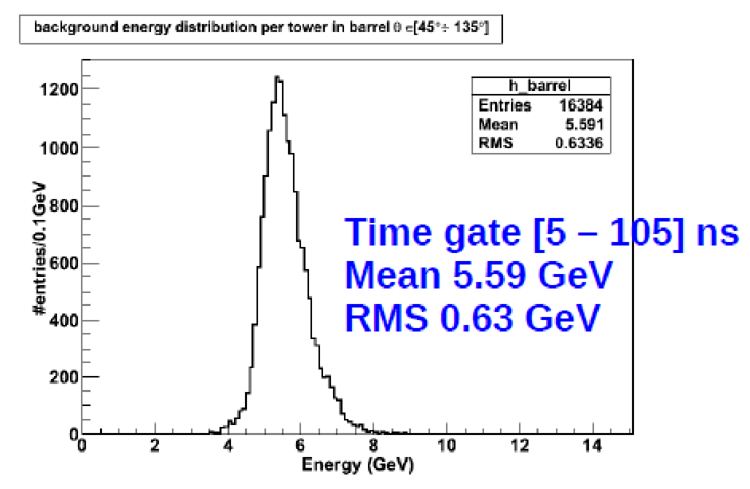
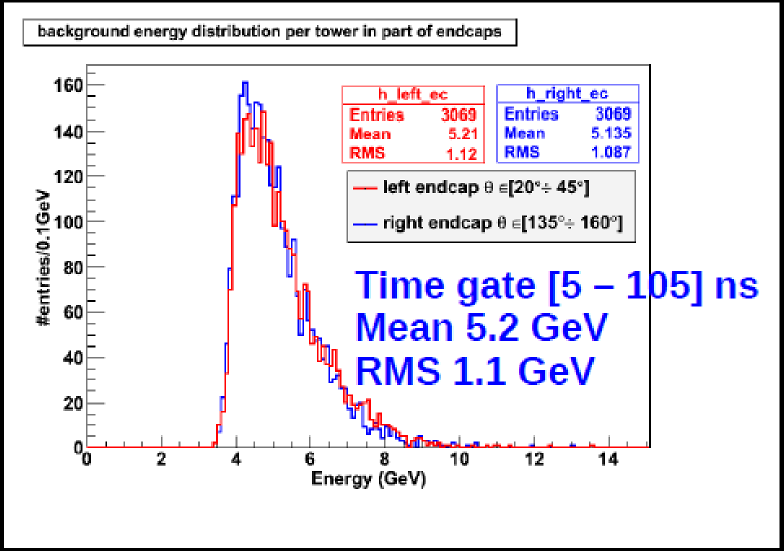
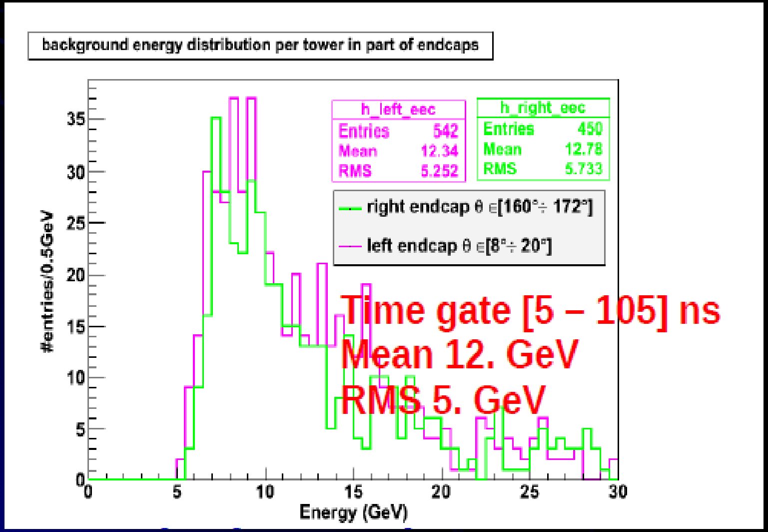


Time gate [5 – 105] ns
Mean 5.59 GeV
RMS 0.63 GeV

Large angle endcap (20° <θ < 45°)
Fluctuations are ΔE/E~20%/cell
and ΔE ~ 6 GeV for a jet involving ~25 cells



Time gate [5 – 105] ns
Mean 5.2 GeV
RMS 1.1 GeV

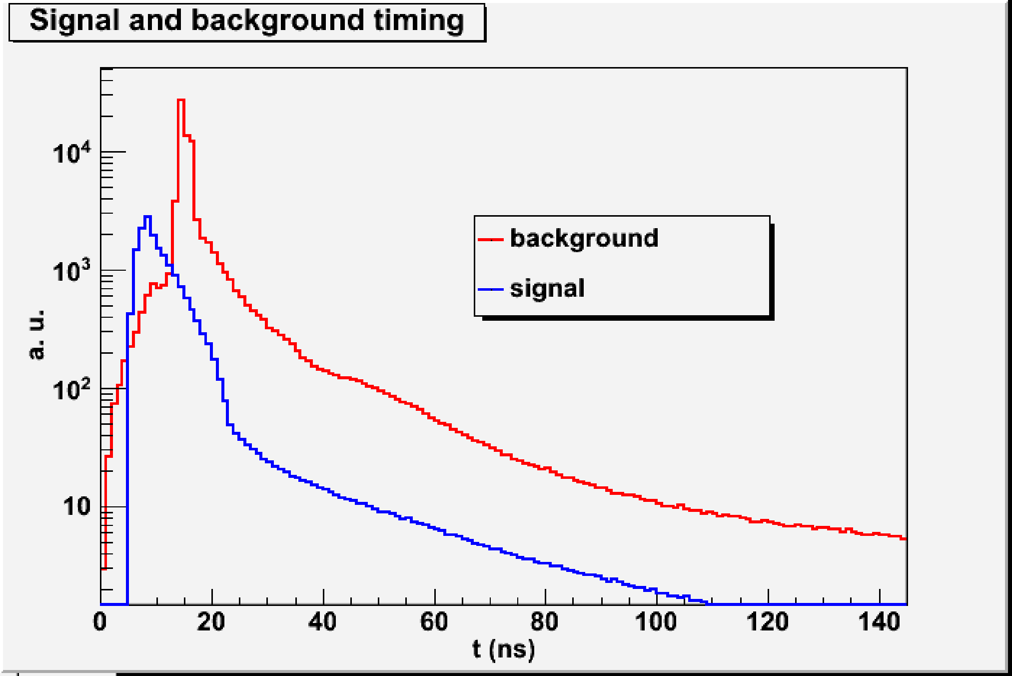


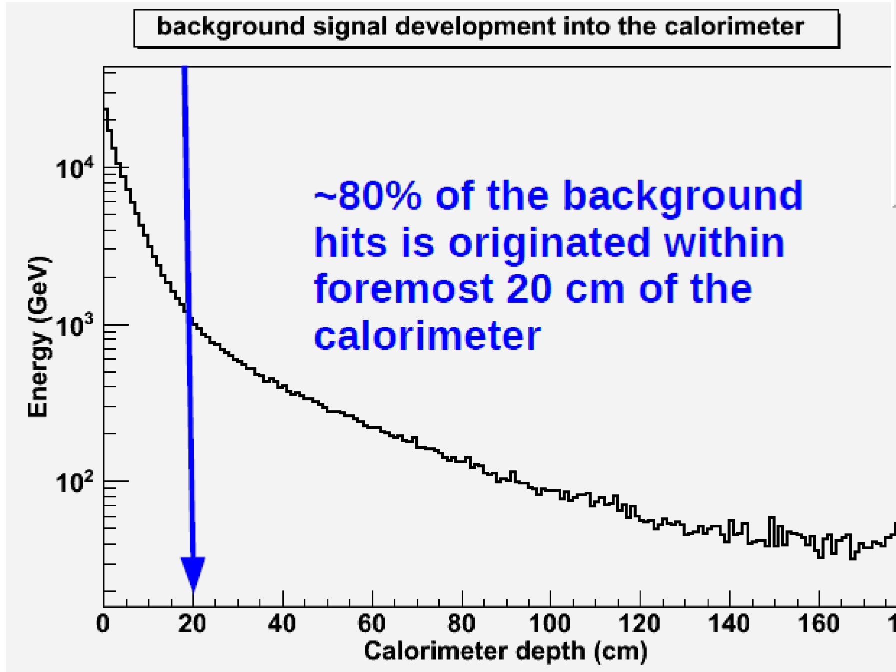
Time gate [5 – 105] ns
Mean 12. GeV
RMS 5. GeV

Small angle endcap (8° <θ< 20°)
Fluctuations are ΔE/E~40%/cell
and ΔE ~ 20-25 GeV for a jet involving ~25 cells

Properties of Visible Energy in the Calorimeter

ILCroot simulation
Signal timing from calorimeter:
Bkg vs $\mu^+\mu^-$ -> ν_μ $\underline{\nu}_\mu$ + Z_o -> 2-jets





~80% of the background hits is originated within foremost 20 cm of the calorimeter

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Preliminary Physics Studies

- Production of a single Z_o in a fusion process:

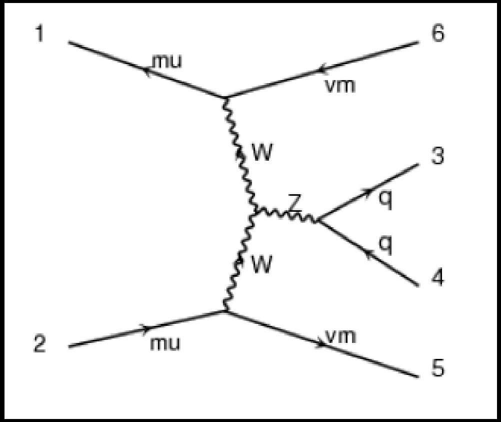
$$\mu^+\mu^- \to \nu_\mu\ \underline{\nu}_\mu + Z_o \to \text{2-jets}$$

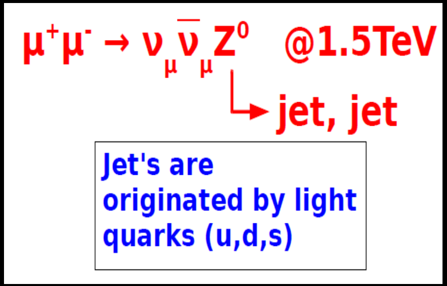
- How well can the invariant mass of the Z_o be reconstructed from its decay into two jets?
- In particular, could the Z_o be distinguished from a $W^\pm$ decaying into two jets in the process

$$\mu^+\mu^- \to \mu^-\ \underline{\nu}_\mu + W^+$$

if the forward μ^- is not tagged?

- Madgraph and MARS15 as event generators
- ADRIANO calorimeter used in this study
- Recursive jet finder (from ILC studies)
- **Full simulation, digitization and reconstruction**





$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu Z^0$ @1.5TeV

↳ jet, jet

Jet's are originated by light quarks (u,d,s)

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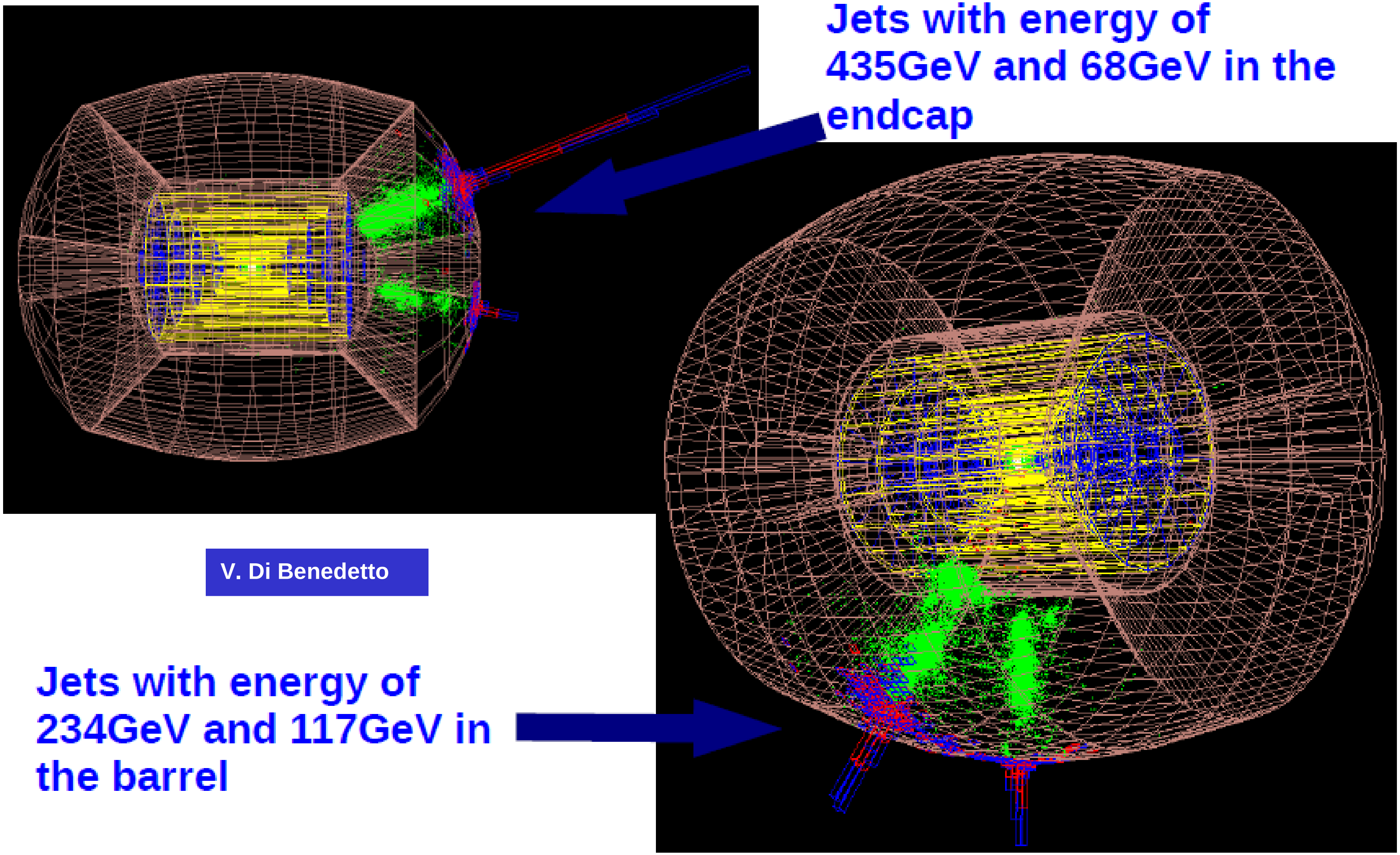
Some jet event display



Jets with energy of 435GeV and 68GeV in the endcap

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Jets with energy of 234GeV and 117GeV in the barrel

Jets Reconstruction

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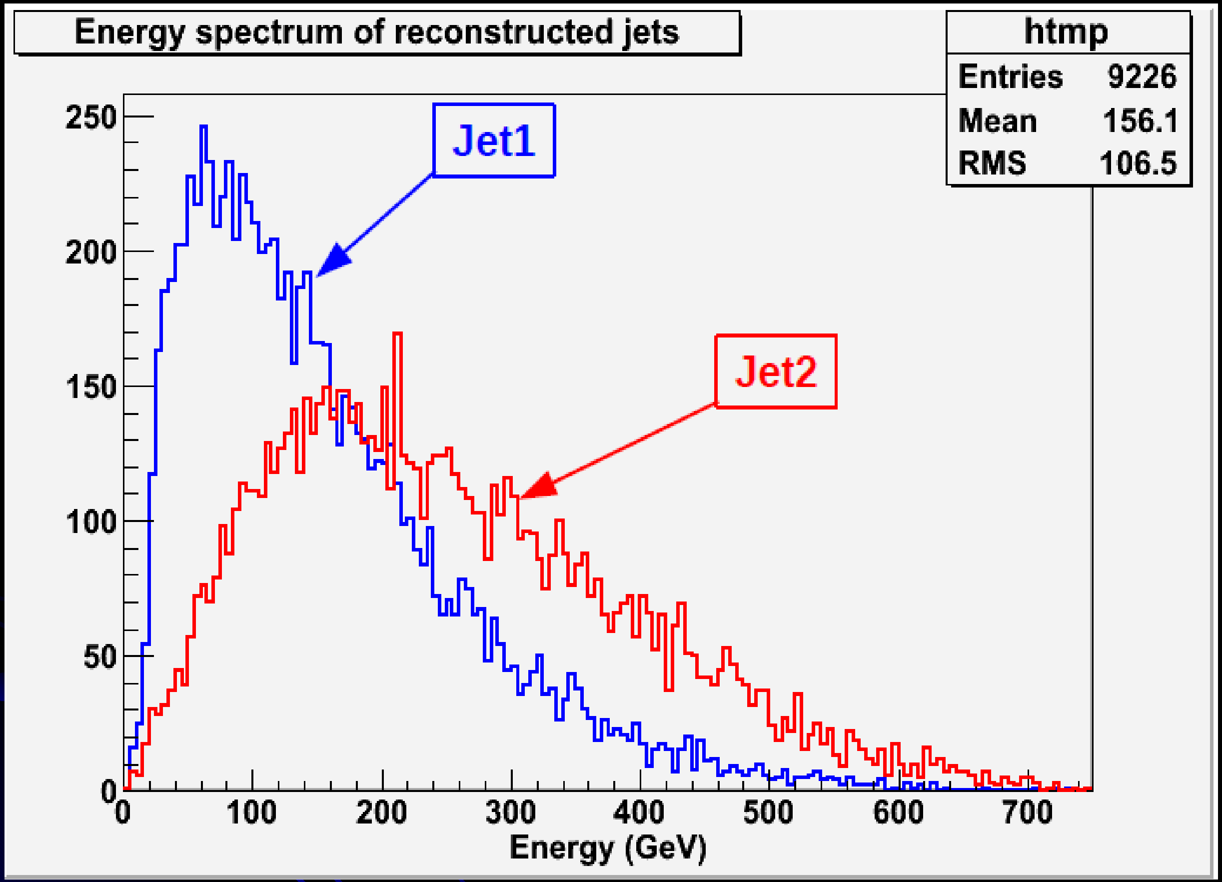
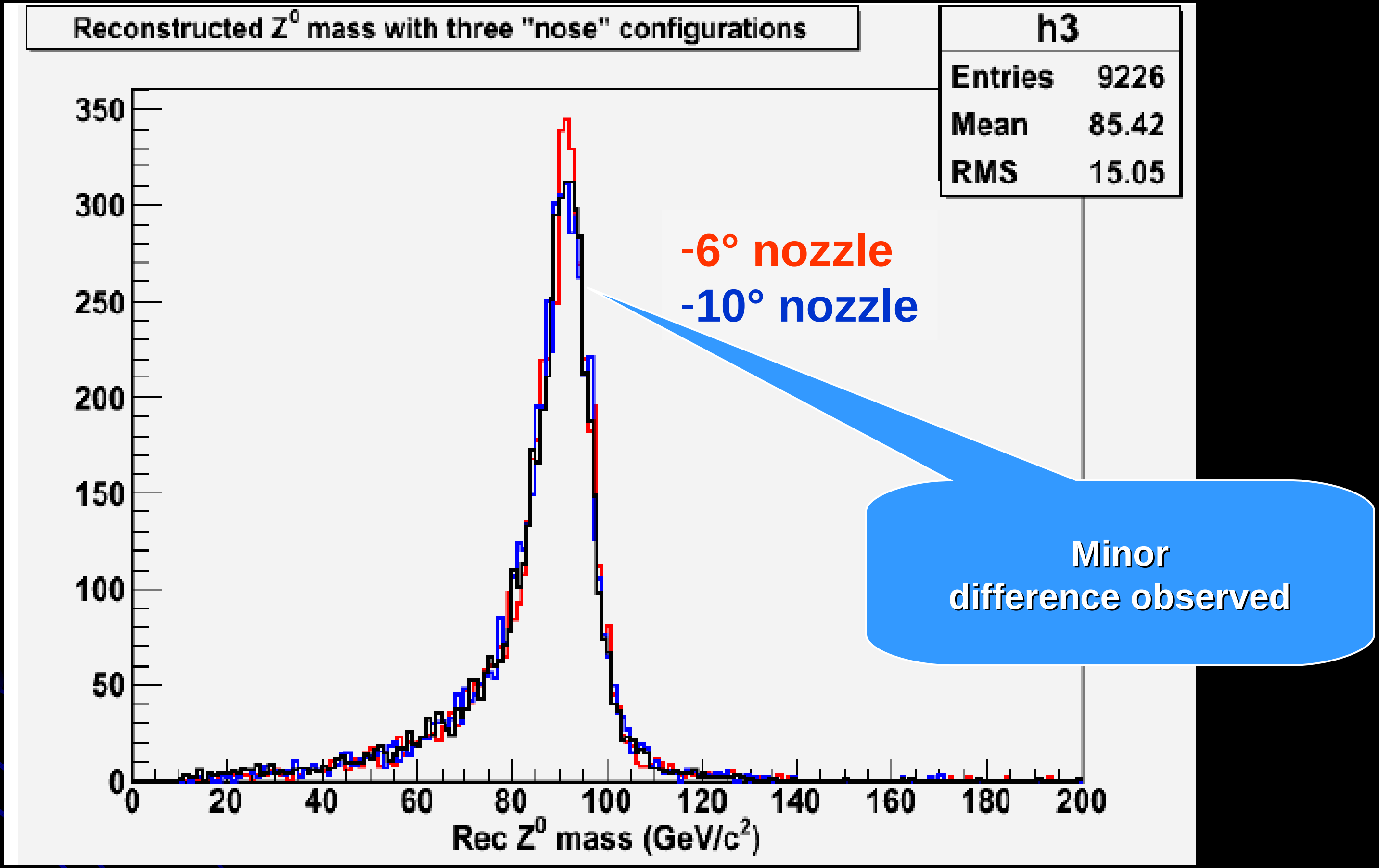


Reconstructed Jet energy spectrum
No cuts applied
1 bin = 5 GeV

Jet finder algorithm

- Divide jet in 2 non-overlapping regions:
  - **Core: region of the calorimeter with nearby clusters**
  - **Outliers: isolated clusters**
- Identify the core energy:
  - **using calorimetric informations**
- Identify the jet axis:
  - **using infos from the tracking systems**
- Reconstruct Outliers individually using:
  - **trackers if calo and trackers have match clusters**
  - **Calo for neutral outliers**
- Recursive algorythm

Zo Mass with Different Nozzles



Minor difference observed

Fully reconstructed
Z° mass (bin=1GeV)
No cuts applied
No leakage corrections

Merging Signal + Background

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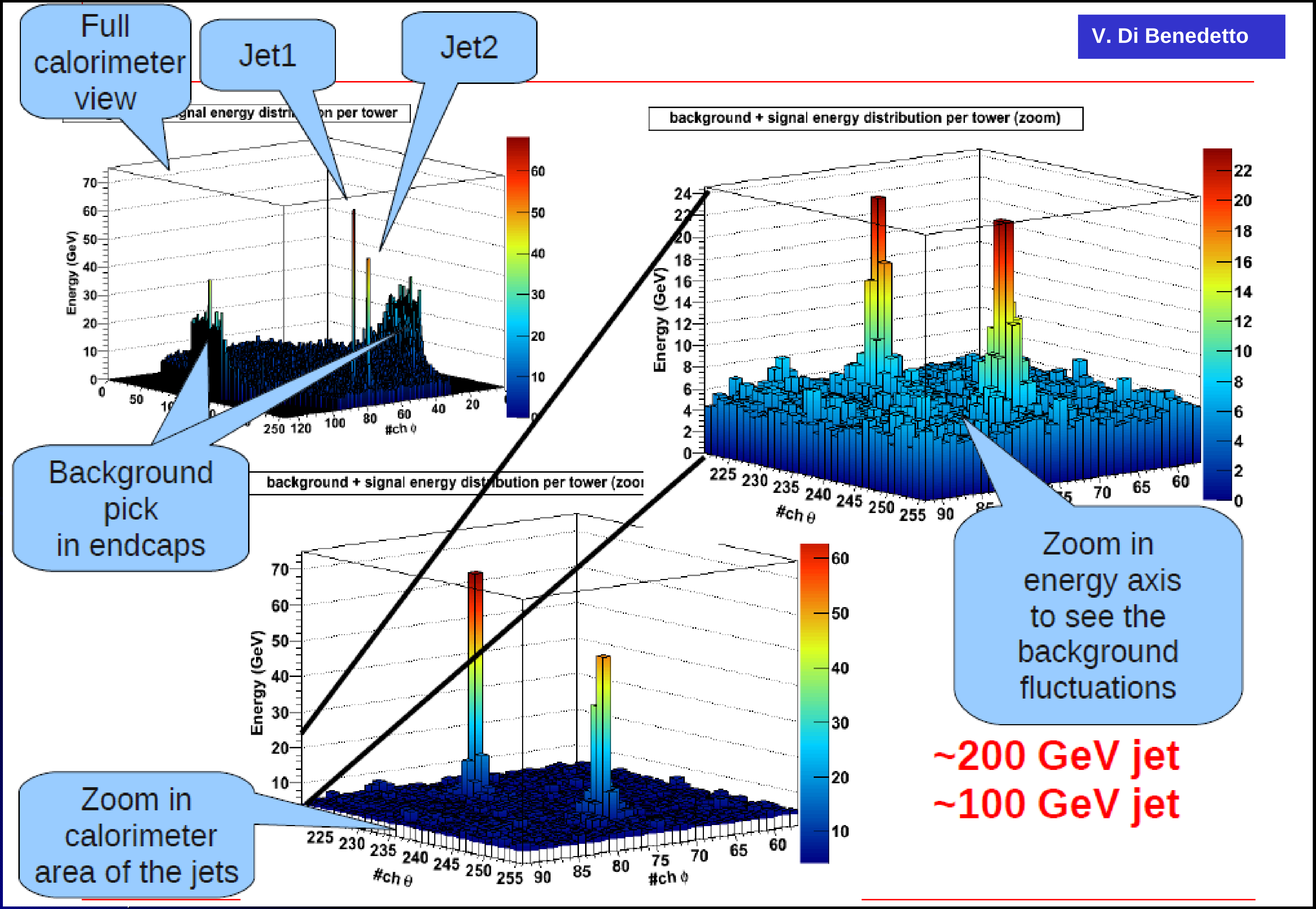


Full calorimeter view

Jet1

Jet2

Background pick in endcaps

Zoom in energy axis to see the background fluctuations

Zoom in calorimeter area of the jets

~200 GeV jet

~100 GeV jet

Future Prospects

- The baseline detector configuration for Muon Collider studies performs well without background
- Background is very nasty even with 10° tungsten nozzle, but fully understood
- A second generation detector is being considered:
  - 3-D Si-tracker with precision timing
  - Two-section calorimeter with sophisticated time gate
  - 4-D Kalman filter

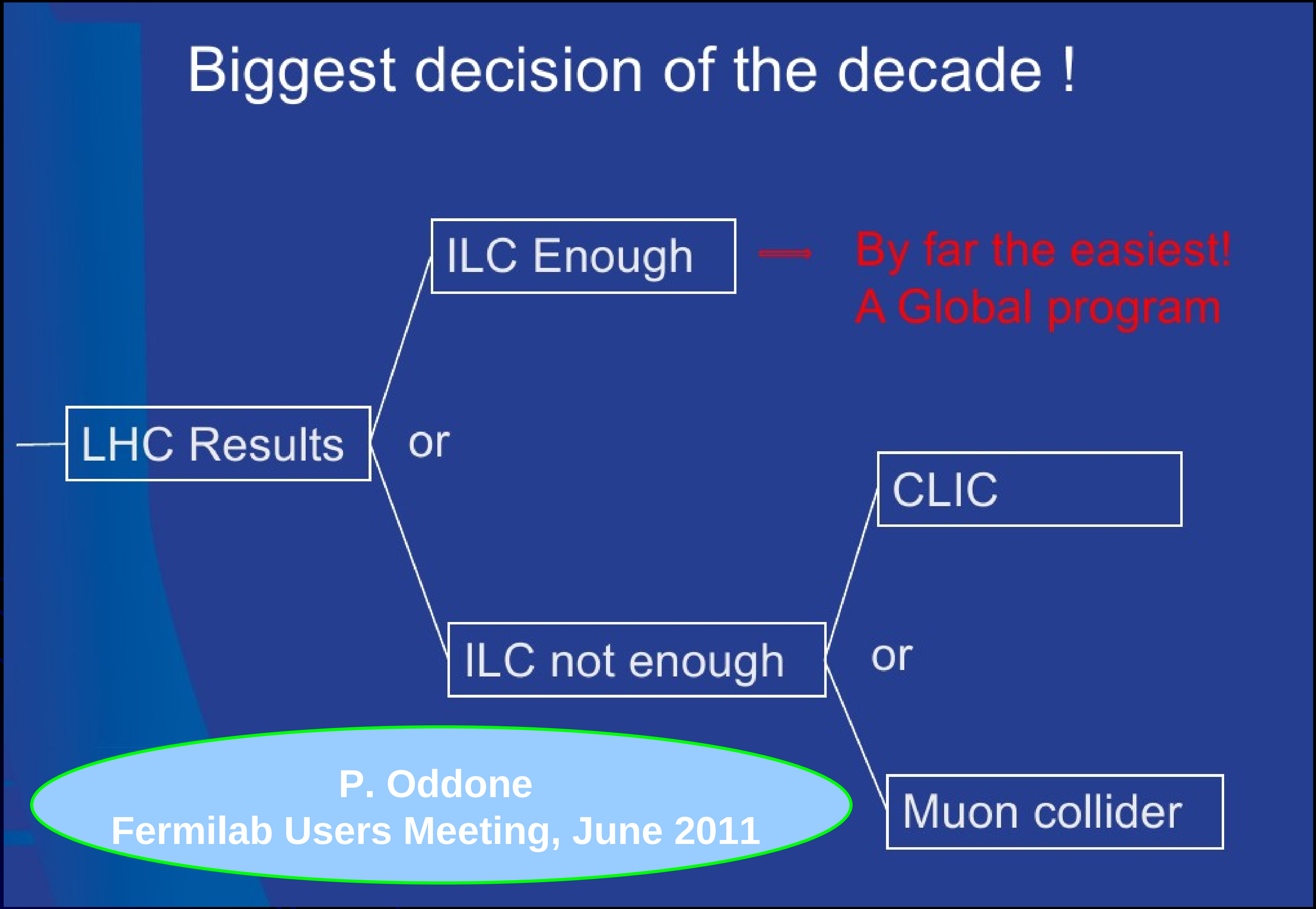
Timing is important at a Muon Collider!

Conclusions

- A full simulation and reconstruction of Si-tracking detectors and a dual-readout calorimeter is implemented in ILCroot framework
- MARS15 and ILCroot ares stable and continuosly improoved for μCollider physics and detector studies (and much more!)
  - Synergies between MARS an ILCroot working groups are excellent
  - The machinery work smoothly for fast and full simulations
- Detector performance studies with and without background are well under way
  - Track reconstruction is expected to be only slightly affected by large background ...but, up to 10^6 real tracks from the background could be fully reconstructed
  - Background in the calorimeter is under control for θ > 20°
- Preliminary physics studies are ongoing:
  - Physics is mostly unaffected for θ > 20°
  - For θ<20° jet energy uncertainties need to be improoved

Not a bad start for a baseline detector with no optimization yet

Backup slides



Biggest decision of the decade !

LHC Results

or

ILC Enough ⟹ By far the easiest!
A Global program

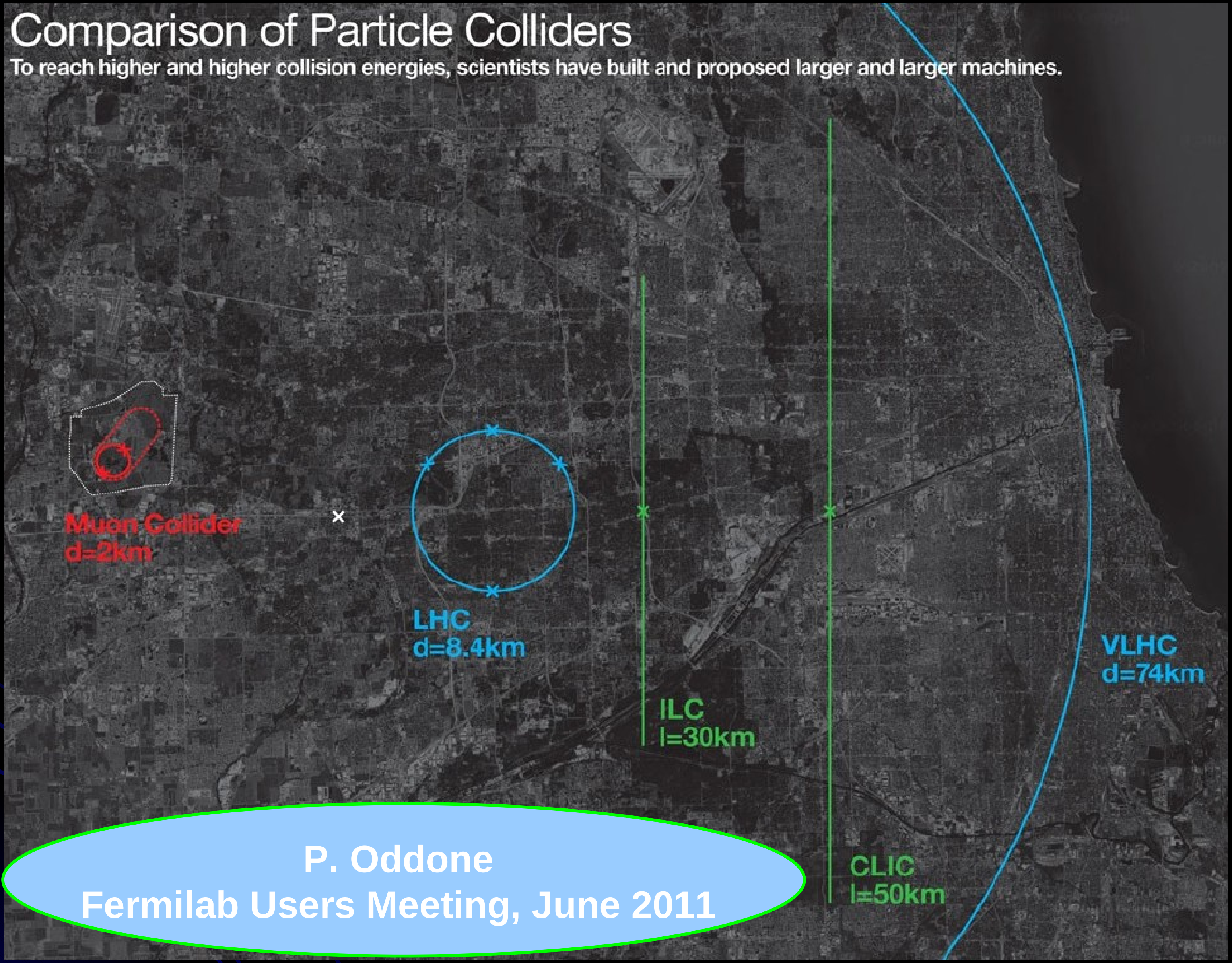
ILC not enough

or

CLIC

Muon collider

P. Oddone
Fermilab Users Meeting, June 2011



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.

P. Oddone
Fermilab Users Meeting, June 2011

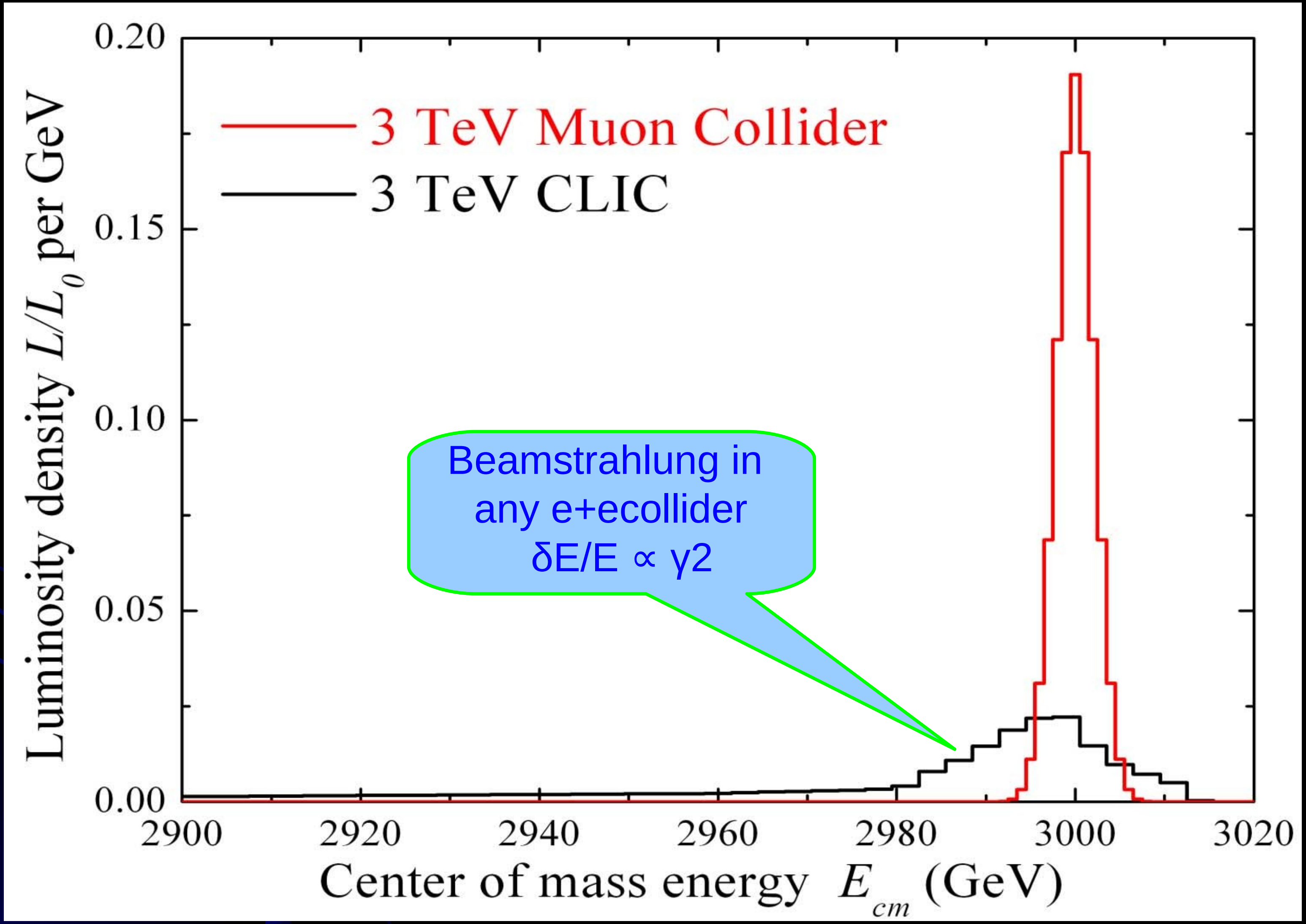
MUON COLLIDER MOTIVATION

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 / me ~ 207):

S. Geer- Accelerator Seminar SLAC 2011

- COMPACT
  Fits on laboratory site
- MULTI-PASS ACC
  Cost Effective operation & construction
- MULTIPASS COLLISIONS IN A RING (~1000 turns)
  Relaxed emittance requirements
  & hence relaxed tolerances
- NARROW ENERGY SPREAD
  Precision scans, kinematic constraints
- TWO DETECTORS (2 IPs)
- ΔTbunch ~ 10 μs … (e.g. 4 TeV collider)
  Lots of time for readout
  Backgrounds don't pile up
- $(m_\mu/me)^2$ = ~40000
  Enhanced s-channel rates for Higgs-like particles

Energy Spread



Beamstrahlung in any e+ecollider δE/E ∝ γ2

Challenges

- Muons are produced as tertiary particles⌟

  To make enough of them we must start with a MW scale proton source & target facility.
- Muons decay

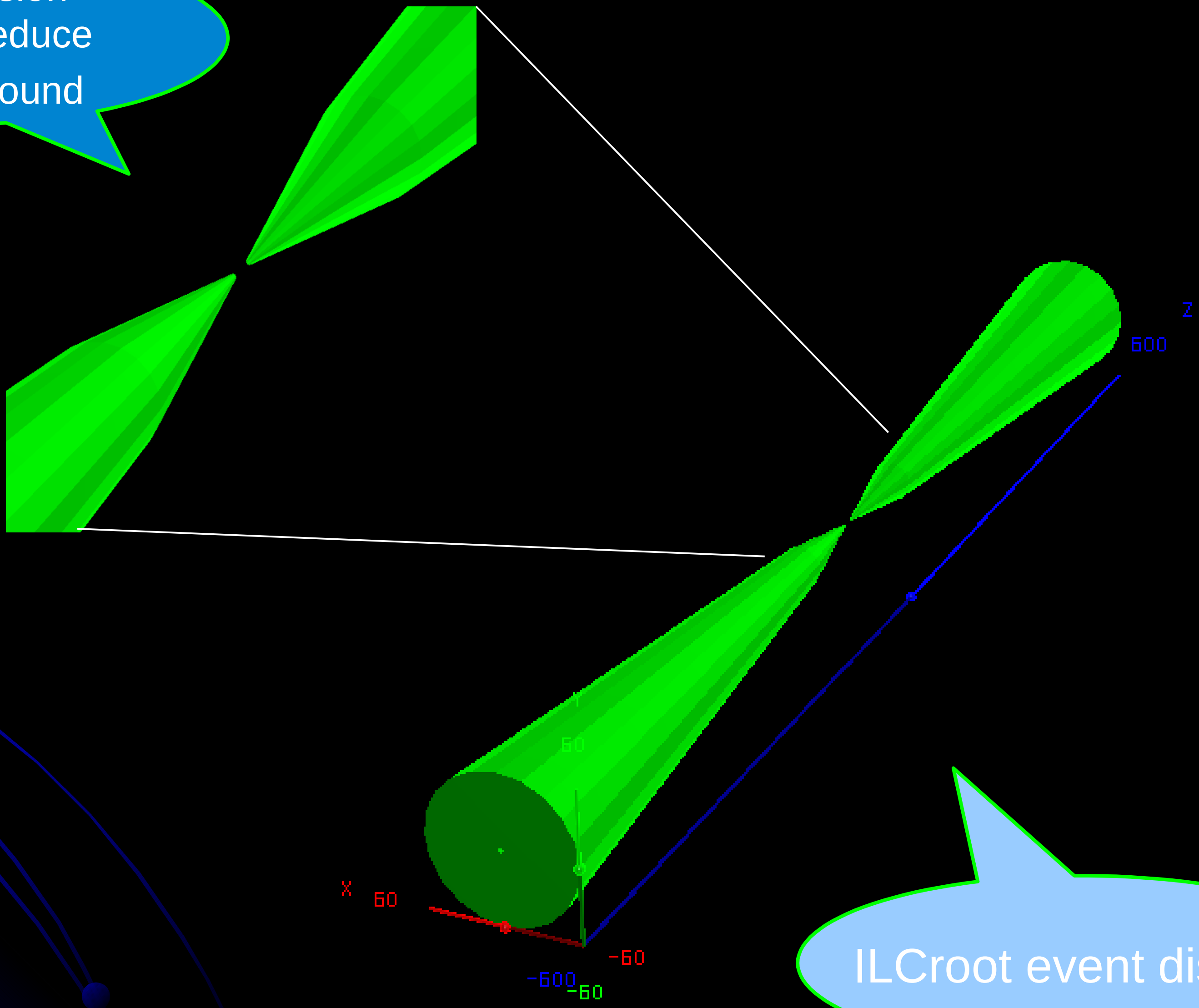
  Everything must be done fast and we must deal with the decay electrons (& neutrinos for CM energies above ~3 TeV).
- Muons are born within a large 6D phase-space⌟

  For a MC we must cool them by O(106) before they decay ⊏ New cooling technique (ionization cooling) must be demonstrated, and it requires components with demanding performance (NCRF in magnetic channel, high field solenoids.)
- After cooling, beams still have relatively large emittance⌟
-

S. Geer- Accelerator Seminar
SLAC 2011

10° Nozzle

Newer version
To further reduce
MuX background

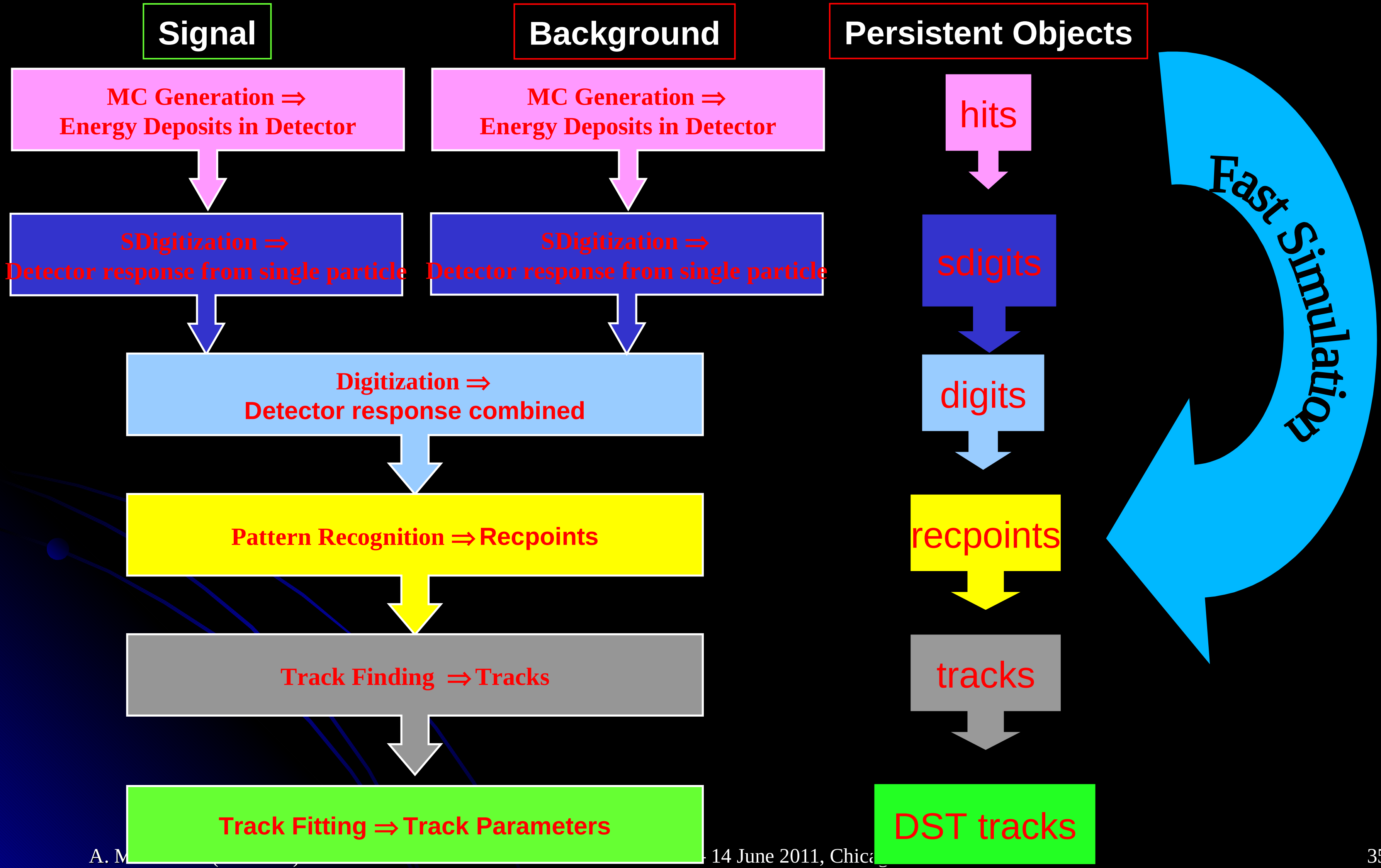


ILCroot event display

ILCroot: root Infrastructure for Large Colliders

- **Software architecture based on root, VMC & Aliroot**
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- **Re-allignement with latest Aliroot version every 1-2 years (v4.17 release)**
- **It is a simulation framework and an Offline Systems:**
  - **Single framework, from generation to reconstruction through simulation. Don’t forget analysis!!!**
  - It is immediatly usable for test beams
  - Six MDC have proven robustness, reliability and portability
- **Main add-ons Aliroot:**
  - Interface to external files in various format (STDHEP, text, etc.)
  - Standalone VTX track fitter
  - Pattern recognition from VTX (for si central trackers)
  - Parametric beam background (# integrated bunch crossing chosen at run time
- Growing number of experiments have adopted it: Alice (LHC), Opera (LNGS), (Meg), CMB (GSI), Panda(GSI), 4th Concept, (SiLC ?) and LHeC
- **It is Publicly available at FNAL on ILCSIM since 2006**
- **Used for ILC, CLIC and Muon Collider studies**

Simulation steps in ILCroot: Tracking system



Signal

Background

Persistent Objects

MC Generation ⇒
Energy Deposits in Detector

MC Generation ⇒
Energy Deposits in Detector

SDigitization ⇒
Detector response from single particle

SDigitization ⇒
Detector response from single particle

Digitization ⇒
Detector response combined

Pattern Recognition ⇒ Recpoints

Track Finding ⇒ Tracks

Track Fitting ⇒ Track Parameters

Fast simulation and/or fast digitization also available in ILCroot for tracking system

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

  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 in tracking studies?

  Yes!

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

Digitization and Clusterization of Si Detectors in Ilcroot: a description of the algorithms available for detailed tracking simulation and studies

Technologies Implemented

- 3 detector species:
  - Silicon pixels
  - Silicon Strips
  - Silicon Drift

Used for VXD SiT and FTD
in present studies

- Pixel can have non constant size in different layers
- Strips can also be stereo and on both sides
- Dead regions are taken into account
- Algorithms are parametric: almost all available technologies are easily accomodated (MAPS, 3D, DEPFET, etc.)

SDigitization in Pixel Detector (production of summable digits)

- Summable digit = signal produced by each individual track in a pixel
- Loop over the hits produced in the layer and create a segment in Si in 3D
  - Step (from MC) along the line >1 µm increments
    - Convert GeV to charge and get bias voltage:

      $q = dE*dt/3.6e\text{-}9 \quad dV = \text{thick/bias voltage}$
    - Compute charge spreading:

      $\sigma_{xy}=\mathrm{sqrt}(2k/e*T°*dV*L), \quad \sigma_z=fda*\sigma_{xy}$
    - Spread charge across pixels using $\mathrm{Erfc}(xy,z,\sigma_{xy},\sigma_z)$
  - Charge pile-up is automatically taken into account

SDigitization in Pixels (2)

- Add couplig effect between nearby pixels row-wise and column-wise (constant probability)
- Remove dead pixels (use signal map)

Digitization in Pixels

Digit = sum of all sdigit corresponding to the same pixel

- Load SDigits from several files (signal or multiple background)
- Merge signals belonging to the same pixel
  - Non-linearity effects
  - Saturation
- Add electronic noise
- Save Digits over threshold

Clusterization in Pixel Detector

Cluster = a collection of nearby digit

Create a initial cluster from adjacent pixels (no for diagonal)

Subdivide the previous cluster in smaller NxN clusters

Reconstruct cluster and error matrix from coordinate average of the cluster

Kalman filter picks up the best cluster

Parameters used for the pixel tracking detectors in current MuX studies

Size Pixel X = 20 µm (VXD and FTD), 50 µm (SiT)

Size Pixel Z = 20 µm (VXD and FTD), 50 µm (SiT)

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

Clusterization in Strip Detector

- Create a initial cluster from adjacent strips (no for diagonal)
- Separate into Overlapped Clusters
  - Look for through in the analog signal shape
  - Split signal of parent clusters among daugheter clusters
- Intersect stereo strips to get Recpoints from CoG of signals (and error matrix)
- Kalman filter picks up the best Clusters

SDigitization in Strips Detector

- Get the Segmentation Model for each detector (from IlcVXDSegmentationSSD class)
- Get Calibration parameters (from IlcVXDCalibrationSSD class)
- Load background hits from file (if any)
- Loop on the hits and create a segment in Si in 3D
  - Step along the line in equal size increments
    - Compute Drift time to p-side and n-side:

      `tdrift[0] = (y+(seg->Dy()*1.0E-4)/2)/GetDriftVelocity(0);`

      `tdrift[1] = ((seg->Dy()*1.0E-4)/2-y)/GetDriftVelocity(1);`
    - Compute diffusion constant:

      `sigma[k] = TMath::Sqrt(2*GetDiffConst(k)*tdrift[k]);`
    - integrate the diffusion gaussian from -3σ to 3σ
  - Charge pile-up is automatically taken into account

SDigitization in Strips (2)

- Add electronic noise per each side separately

```
// noise is gaussian
   noise  = (Double_t) gRandom->Gaus(0,res->GetNoiseP().At(ix));

   // need to calibrate noise
                              noise *= (Double_t) res->GetGainP(ix);

   // noise comes in ADC channels from the calibration database
   // It needs to be converted back to electronVolts
   noise /= res->GetDEvToADC(1.);
```

- Add coupling effect between nearby strips
  - different contribution from left and right neighbours
  - Proportional to nearby signals

- Remove dead pixels (use signal map)

- Convert total charge into signal (ADC count)

```
     if(k==0) signal /= res->GetGainP(ix);
     else signal /= res->GetGainN(ix);
// signal is converted in unit of ADC
     signal = res->GetDEvToADC(fMapA2->GetSignal(k,ix));
```

The Parameters for the Strips

- Strip size (p, n)
- Stereo angle (p-> 7.5 mrad, n->25.5 mrad)
- Ionization Energy in Si = 3.62E-09
- Hole diffusion constant (= 11 cm^2/sec)
- Electron diffusion constant (= 30 cm^2/sec)
- v^P_{drift}(=0.86E+06 cm/sec) , v^N_{drift}(=2.28E+06 cm/sec)
- Calibration constants
  - Gain
  - ADC conversion (1 ADC unit = 2.16 KeV)
- Coupling probabilities between strips (p and n)
- σ of gaussian noise (p AND n)
- threshold

Track Fitting in ILCRoot

- Track finding and fitting is a global tasks: individual detector collaborate
- It is performed after each detector has completed its local tasks (simulation, digitization, clusterization)
- It occurs in three phases:
  1. Seeding in SiT and fitting in VXD+SiT+MUD
  2. Standalone seeding and fitting in VXD
  3. Standalone seeding and fitting in MUD
- Two different seedings:
  - A. Primary seeding with vertex constraint
  - B. Secondary seeding without vertex constraint

Not yet implemented

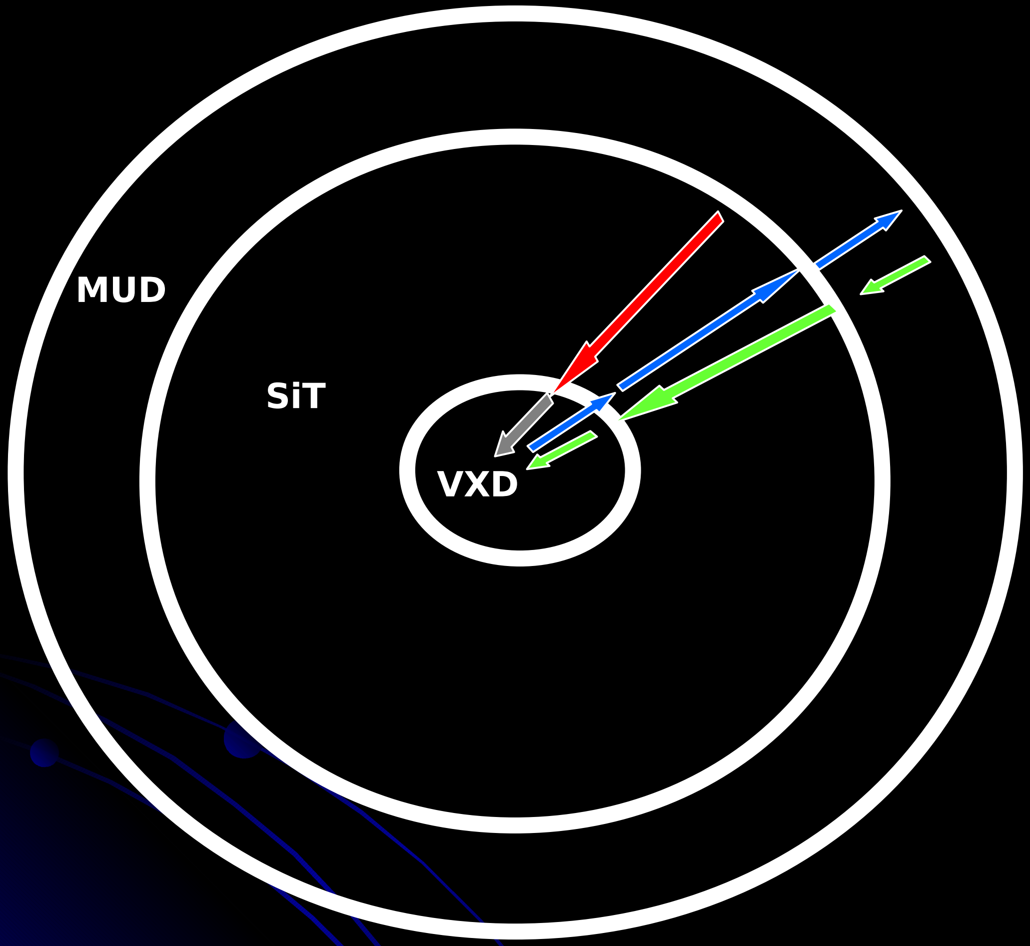
Kalman Filter (classic)

- Recursive least-squares estimation.
- Equivalent to global least-squares method including all correlations between measurements due to multiple scattering.
- Suitable for combined track finding and fitting
- Provides a natural way:
  - to take into account multiple scattering, magnetic field inhomogeneity
  - possibility to take into account mean energy losses
  - to extrapolate tracks from one sub-detector to another

Parallel Kalman Filter

- Seedings with constraint + seedings without constraint at different radii (necessary for kinks and V0) from outer to inner
- Tracking
  - Find for each track the prolongation to the next layer
  - Estimate the errors
  - Update track according current cluster parameters
  - (Possible refine clusters parameters with current track)
- Track several track-hypothesis in parallel
  - Allow cluster sharing between different track
- Remove-Overlap
- **Kinks and V0** fitted during the Kalman filtering

Tracking Strategy – Primary Tracks



- Iterative process
  - Seeding in SiT
  - Forward propagation towards to the vertex

    SiT → VXD
  - Back propagation towards to the MUD

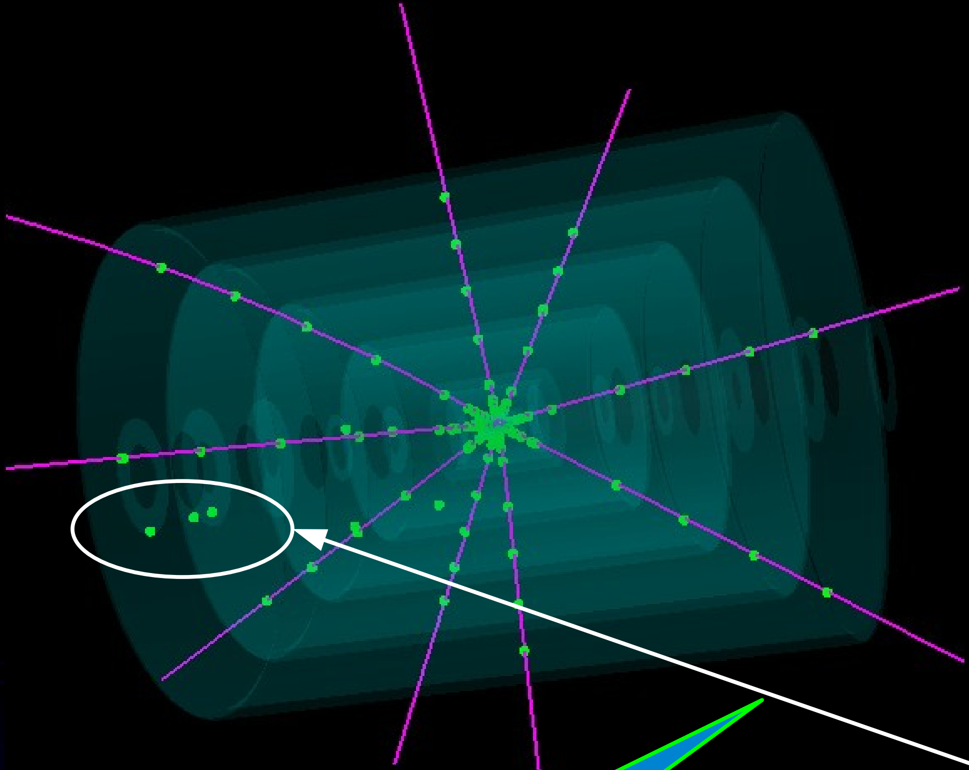
    VXD → SiT → MUD
  - Refit inward

    MUD → SiT → VXD
- Continuous seeding –track segment finding in all detectors

VXD Standalone Tracking

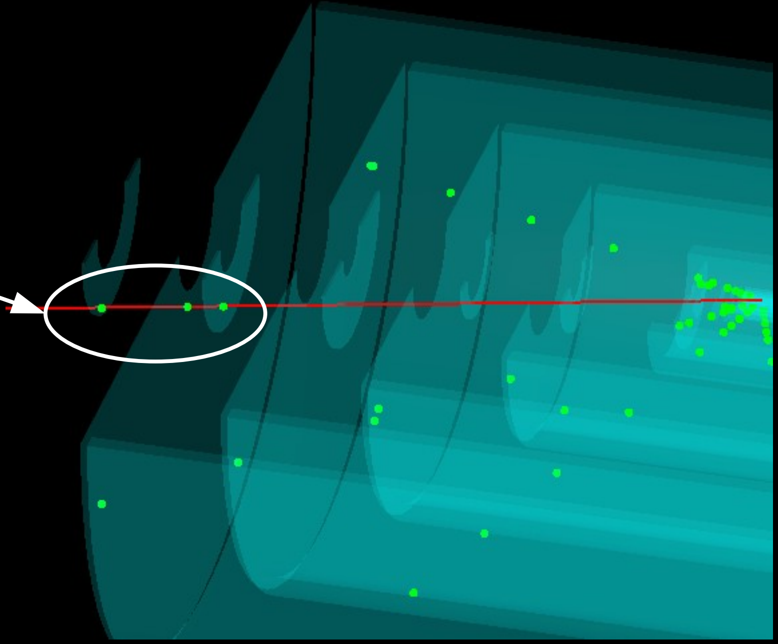
- Uses Clusters leftover in the VXD by Parallel Kalman Filter
- **Requires at least 4 hits to build a track**
- Seeding in VXD in two steps
  - Step 1: look for 3 Clusters in a narrow row or 2 Clusters + IP constraint
  - Step 2: prolongate to next layers each helix constructed from a seed
- After finding Clusters, all different combination of clusters are refitted with the Kalman Filter and the tracks with lowest χ^2 are selected
- Finally, the process is repeated attempting to find tracks on an enlarged row constructed looping on the first point on different layers and all the subsequent layers
- In 3.5 Tesla B-field P_t > 20 MeV tracks reconstructable

Event Display



ILCroot event display
for 10 muons up to 200 GeV

green - hits
purple – reconstructed tracks
red – MC particle



10 generated muons
9 reconstructed tracks

Effects on Track Resolution

Background in the calorimeter for different particle species originating within 25 m from IP

Background in the calorimeter for different particle species originating in [25-200] m from IP

Future Prospects

Conclusions

Backup slides