Muon Collider Tracking Studies in ILCroot

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Muon Collider 2011
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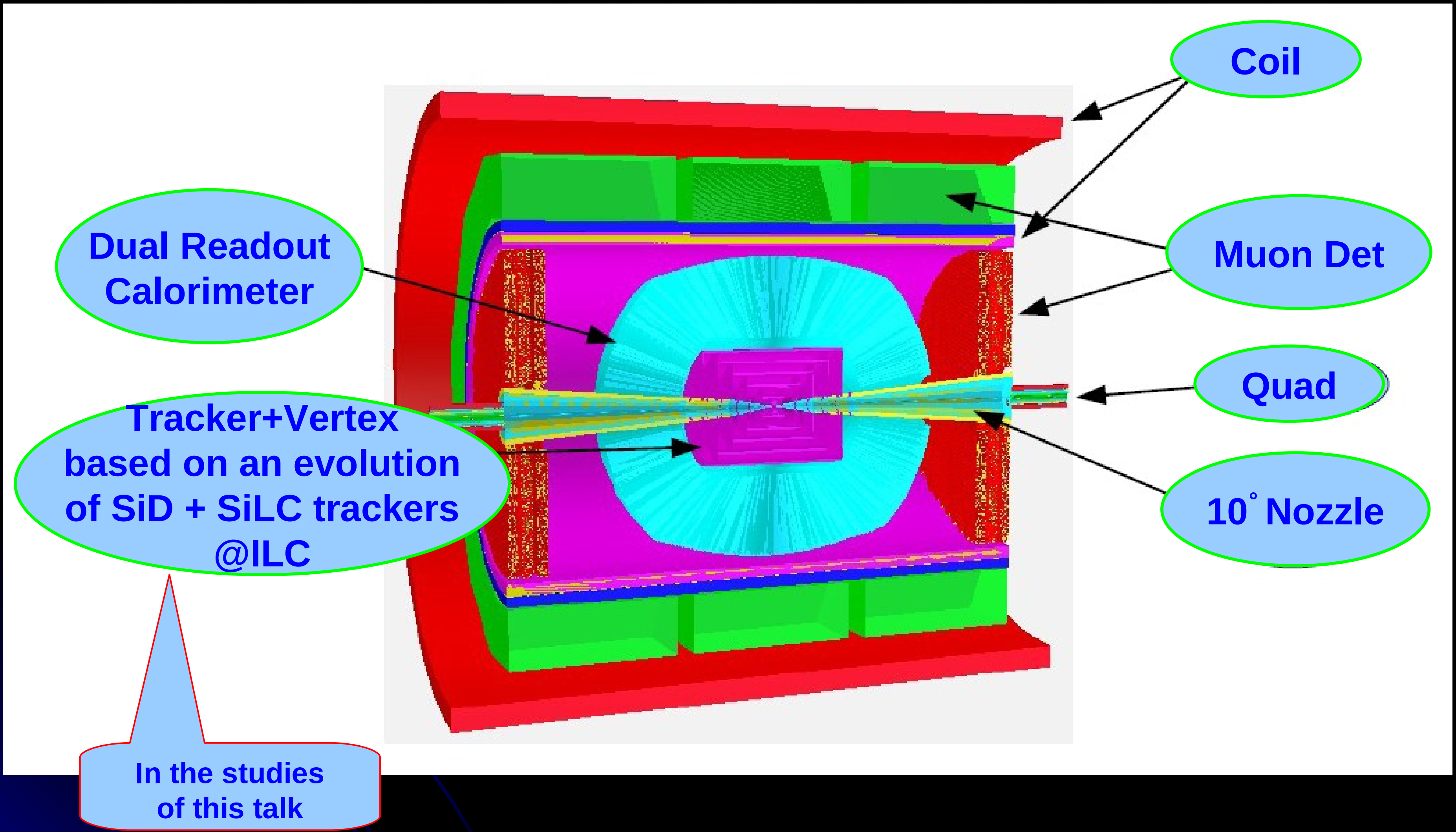
Main Detector Challenges

- 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



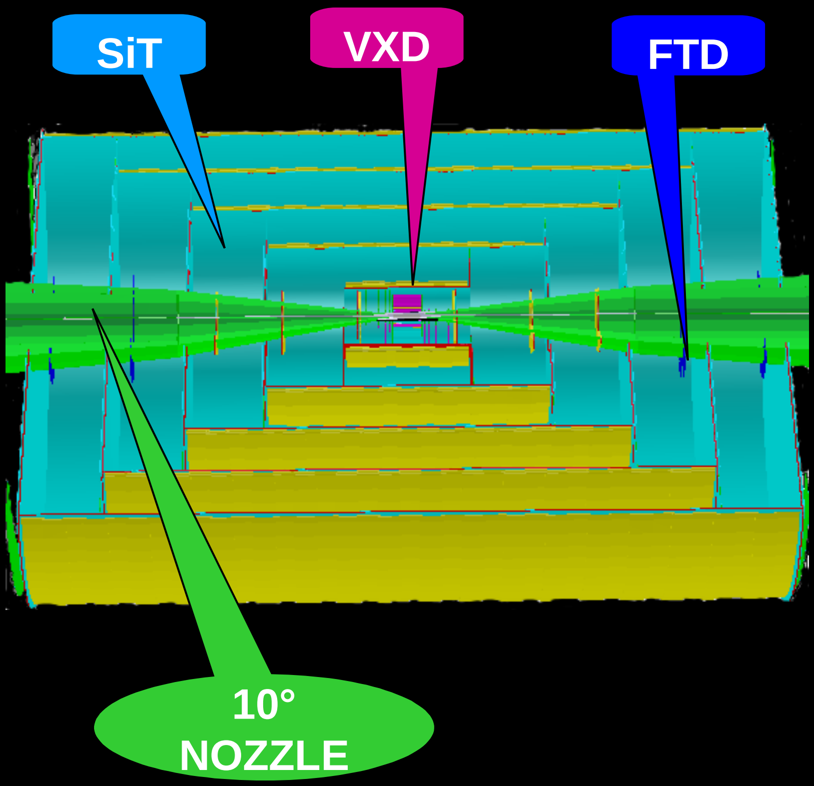
Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

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+3) + (4+3) disks subdivided in ladders
- R_{min}~20 cm R_{max}~120 cm L~330 cm

FTD

- 50 μm x 50 μm Si pixel
- Endcap : 3 + 3 disks
- Distance of last disk from IP = 190 cm

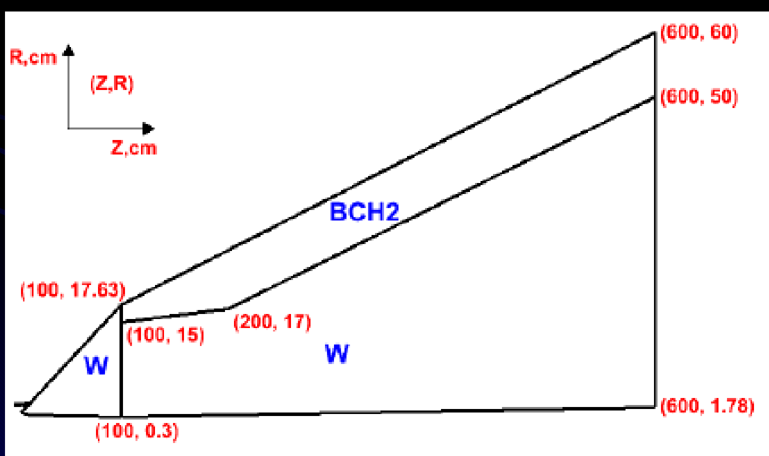


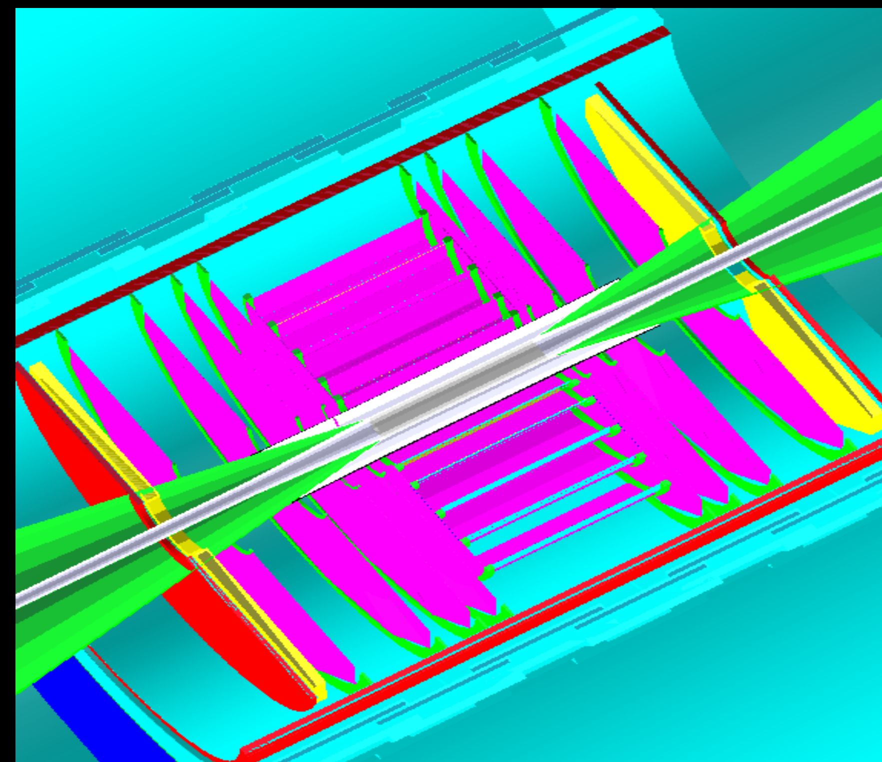
- Silicon pixel for precision tracking amid up to 10^5 hits
- Tungsten nozzle to suppress the background

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

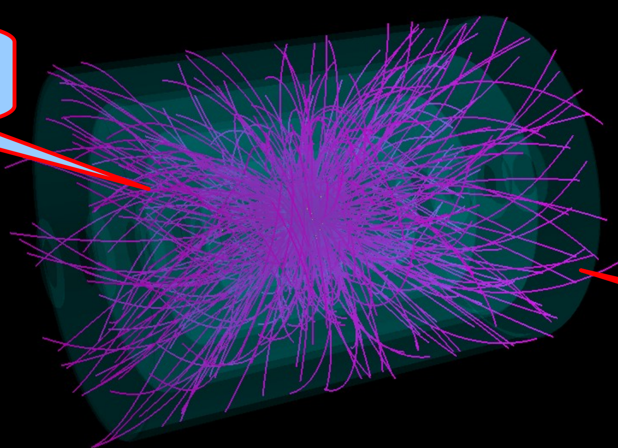
- W - Tungsten
- BCH2 – Borated Polyethylene

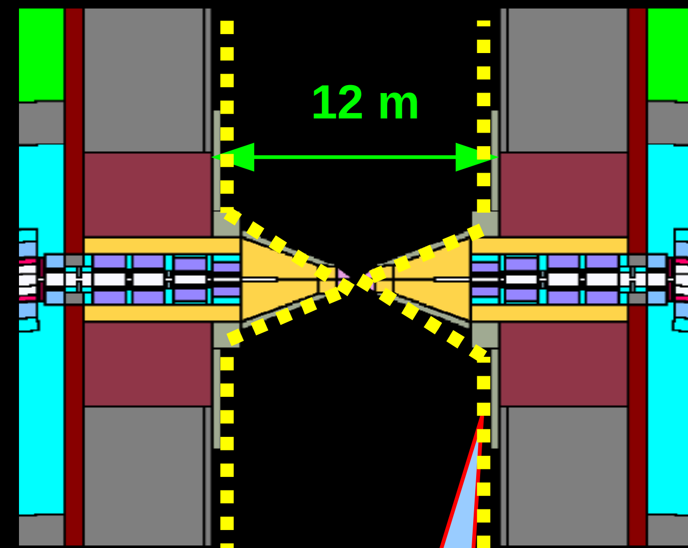
PIPE

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

Ingredients for these Studies

- MARS background provided at the surface of MDI (10^o 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
- ILCroot framework

MARS and ILCroot Frameworks

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

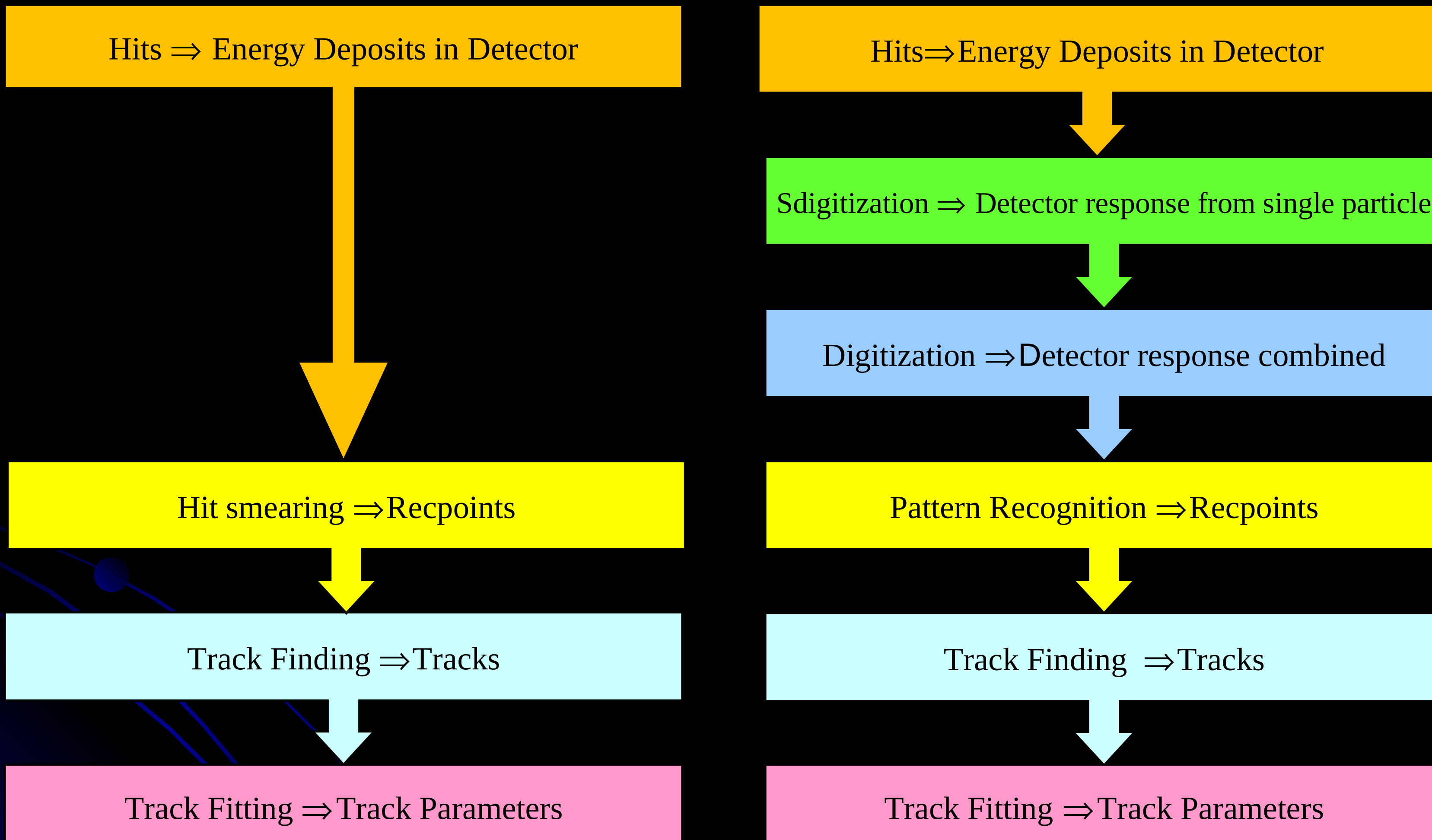
- New release of MARS15 available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS)
- Among new features:
  – Refined MDI (Machine Detector Interface) with a 10^{o} nozzle
  – Significant reduction of particle statistical weight variation
  – Background is provided at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

ILCroot - Software architecture based on ROOT, VMC & Aliroot

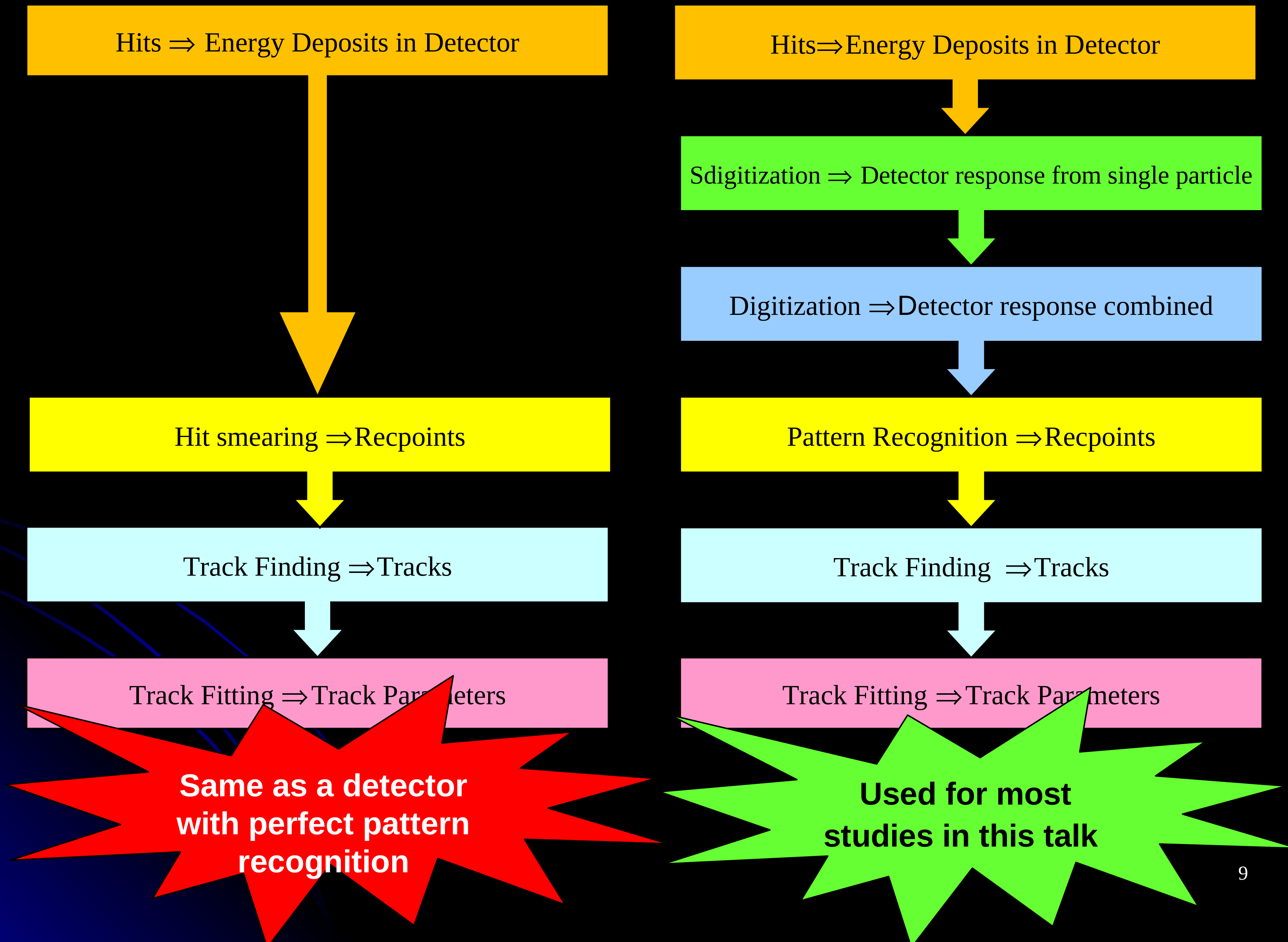
- All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
- Extremely large community of ROOT users/developers

- 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 (4^{th} Concept, LHeC, T1015, SiLC)
- It is publicly available at FNAL on ILCSIM since 2006

Fast vs Full Simulation



Fast vs Full Simulation



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:

$$f(x,z) = Errf(x_{step}, z_{step}, \sigma_x, \sigma_z)$$

$$\sigma_x = \sqrt{T \cdot k / e \cdot \Delta l / \Delta V \cdot step}$$

$$\Delta l = Si\,tickness, \quad \Delta V = bias\,voltage, \quad \sigma_x = \sigma_z \cdot fda$$

- 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)

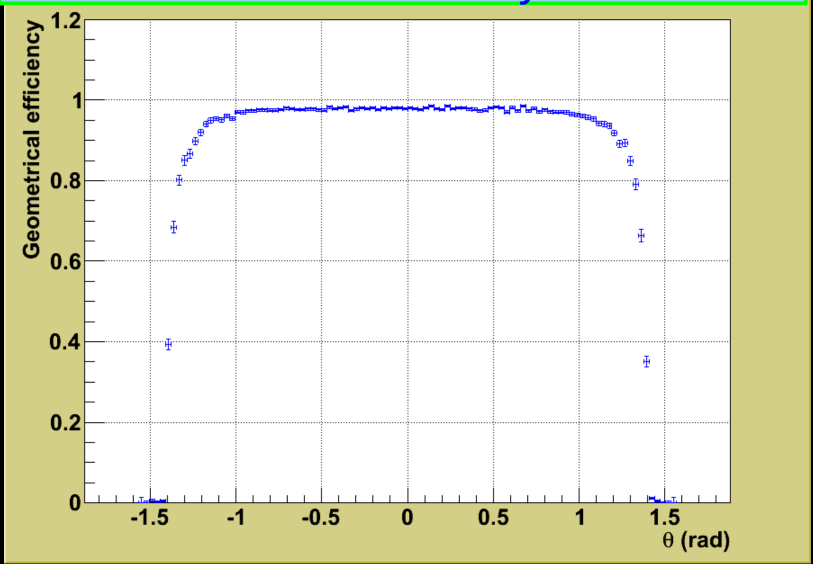
- Add threshold
- Add saturation
- Add electronic noise
- Save Digits over threshold
  - threshold = 3000 electrons
  - electronics noise = 0 electrons

Cluster Pattern recognition

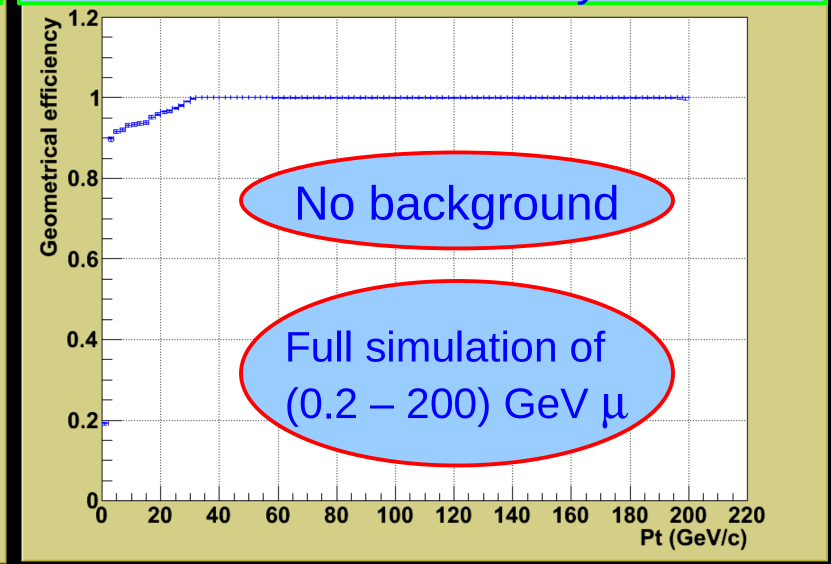
- Create a initial cluster from adjacent pixels (no for diagonal)
- Subdivide the previous cluster in smaller NxN clusters
- Get cluster and error matrix from coordinate average of the cluster
- Kalman filter picks up the best Recpoints

Reconstruction Efficieny for Single Muons

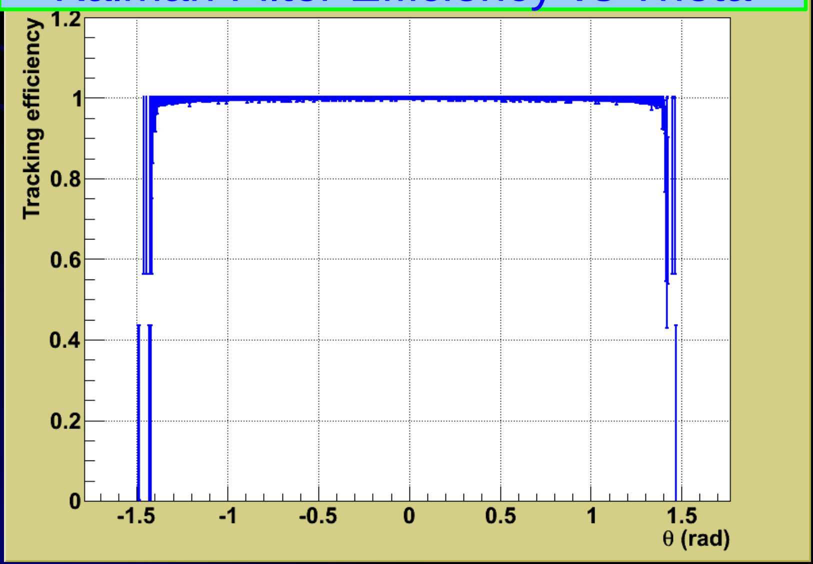
Geometrical Efficiency vs Theta



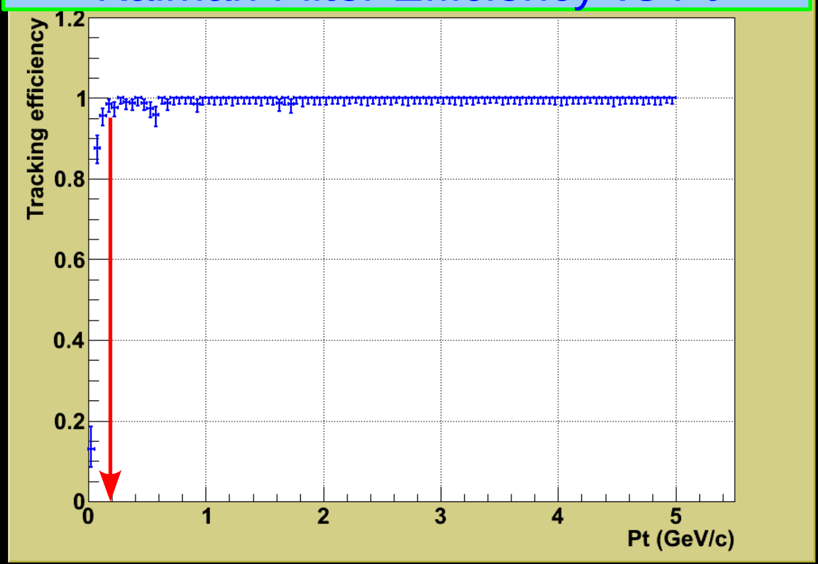
Geometrical Efficiency vs Pt



Kalman Filter Efficiency vs Theta

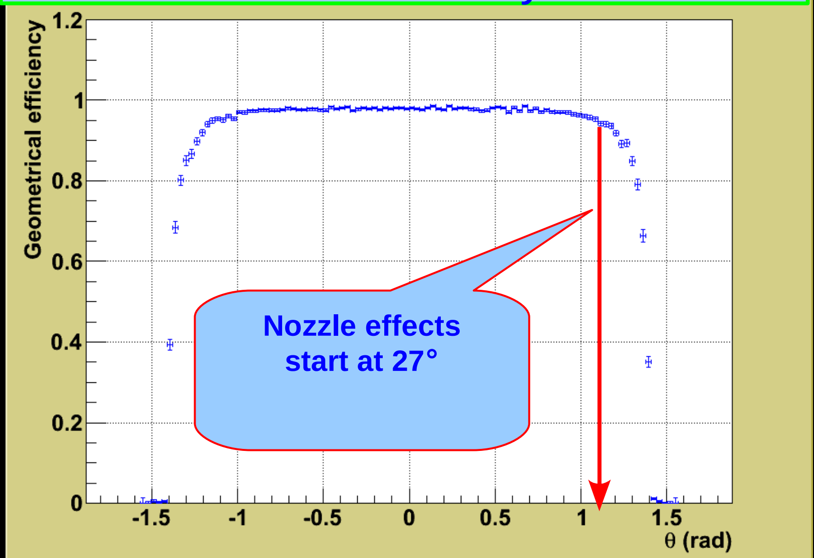


Kalman Filter Efficiency vs Pt

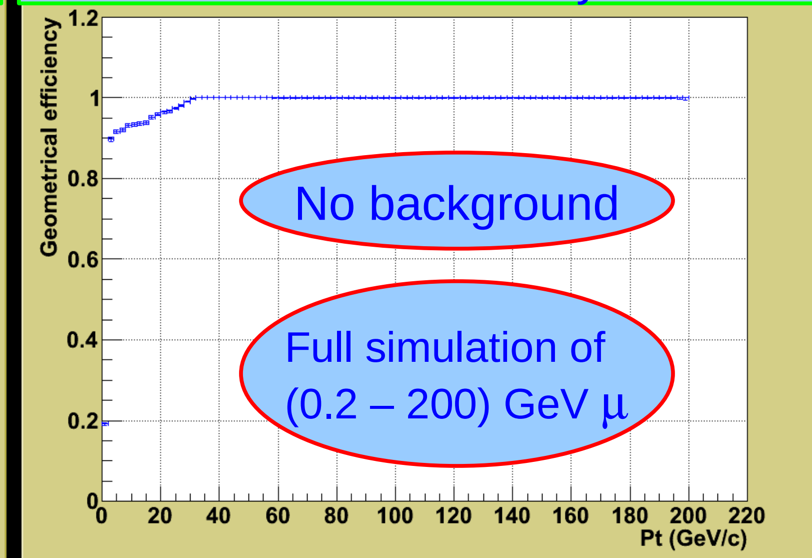


Reconstruction Efficieny for Single Muons

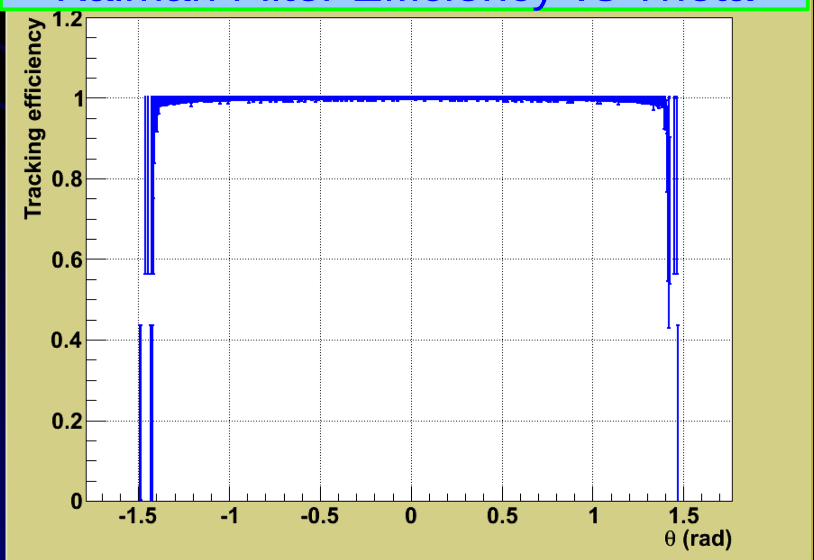
Geometrical Efficiency vs Theta



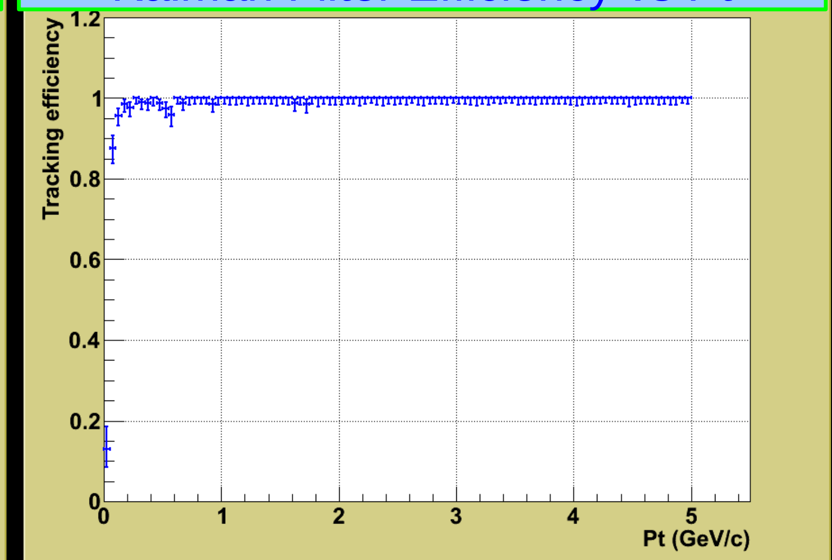
Geometrical Efficiency vs Pt



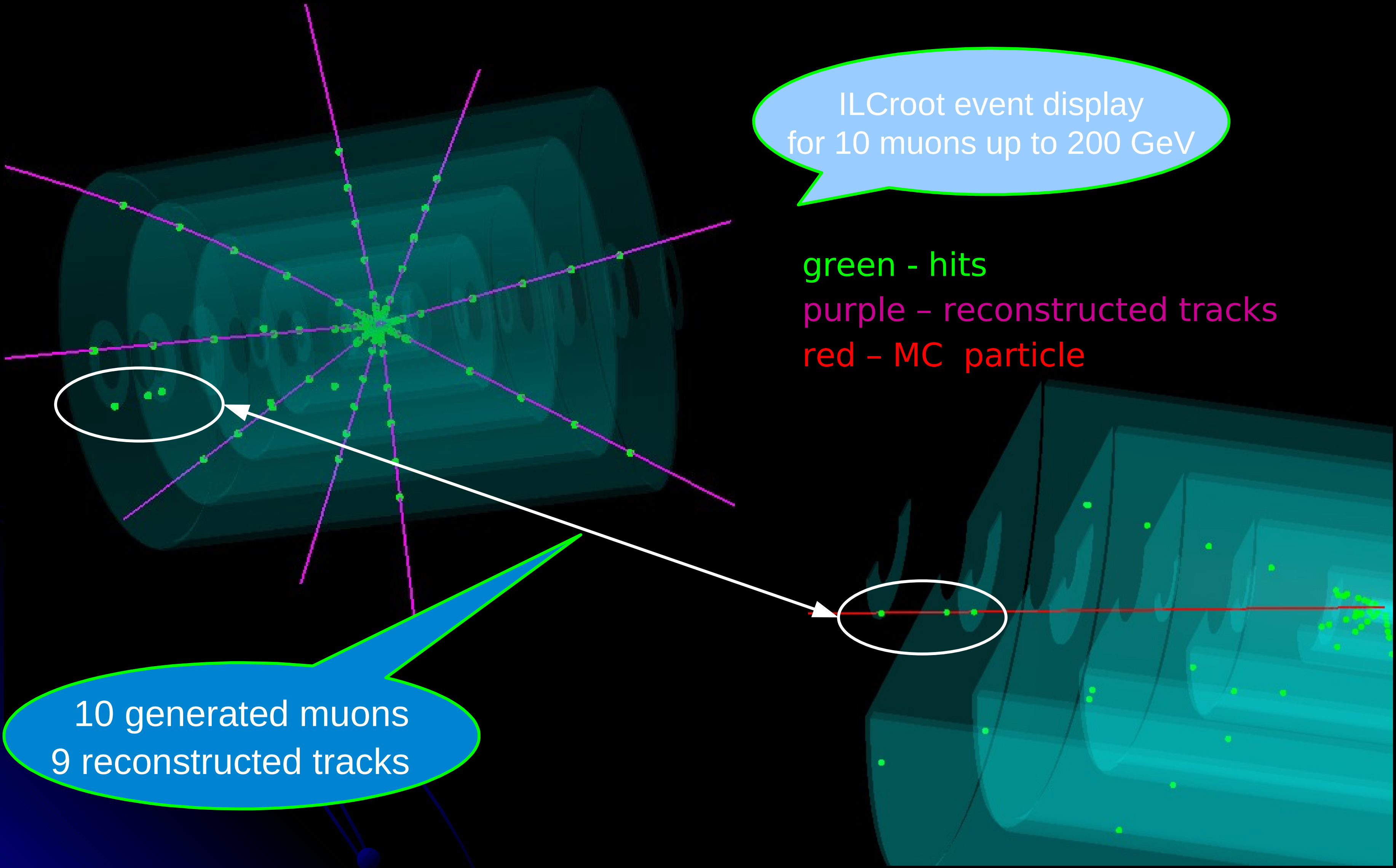
Kalman Filter Efficiency vs Theta



Kalman Filter Efficiency vs Pt

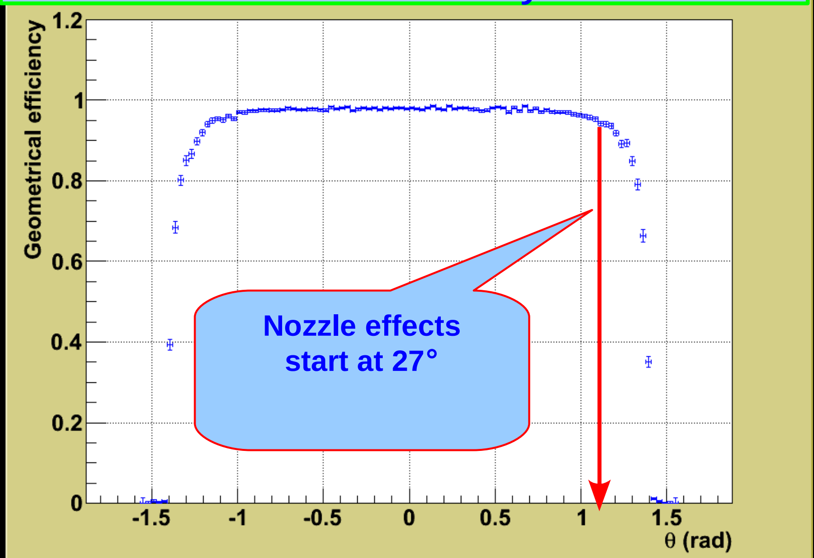


Effect of the 10° nozzle

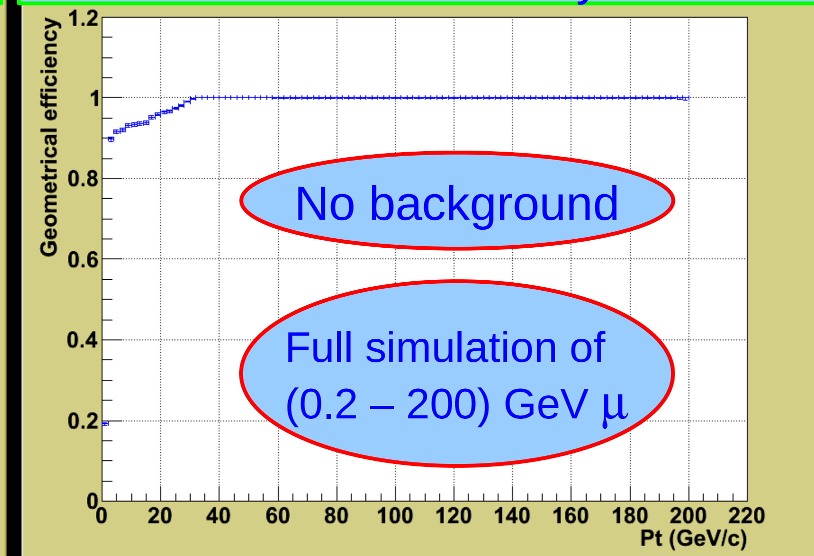


Reconstruction Efficieny for Single Muons

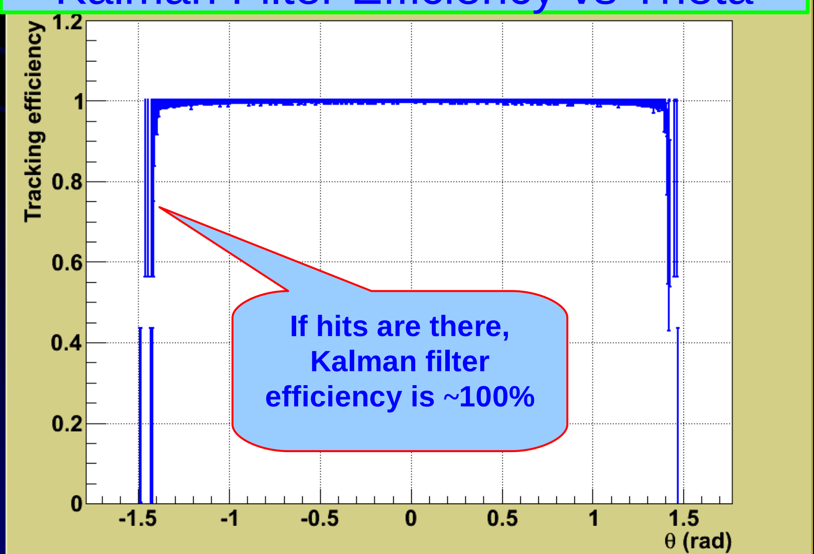
Geometrical Efficiency vs Theta



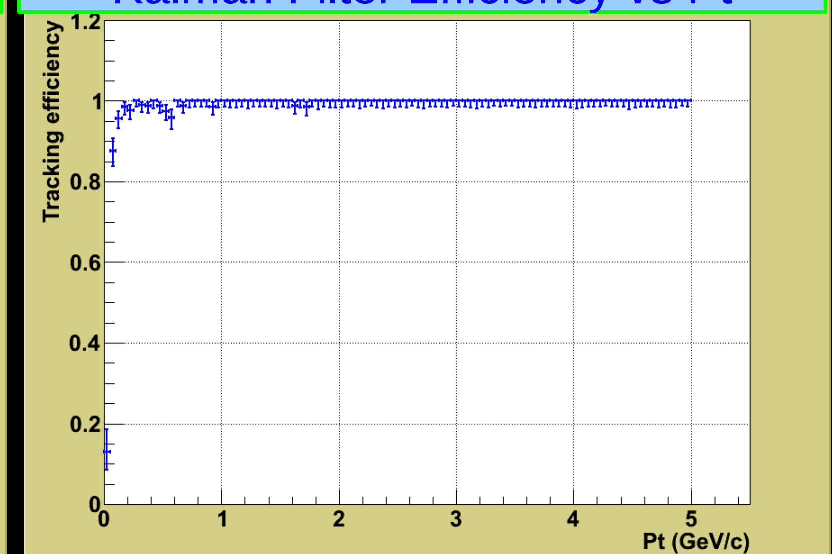
Geometrical Efficiency vs Pt



Kalman Filter Efficiency vs Theta

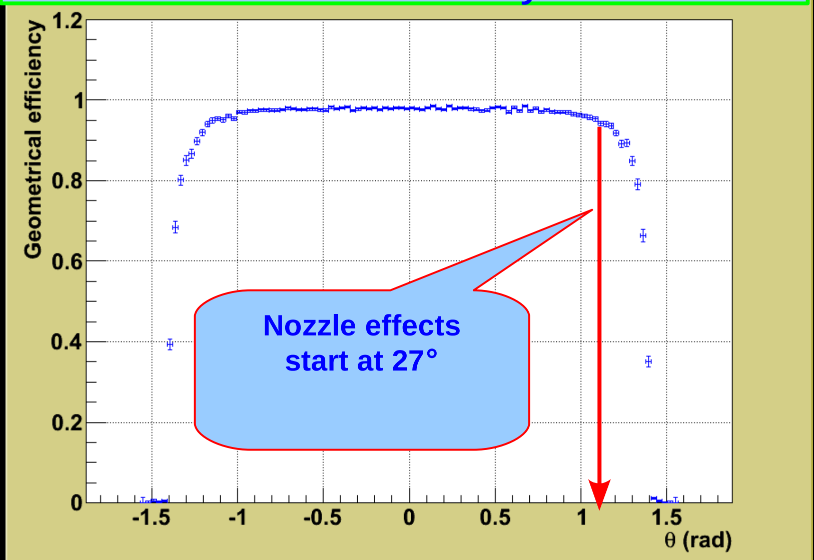


Kalman Filter Efficiency vs Pt

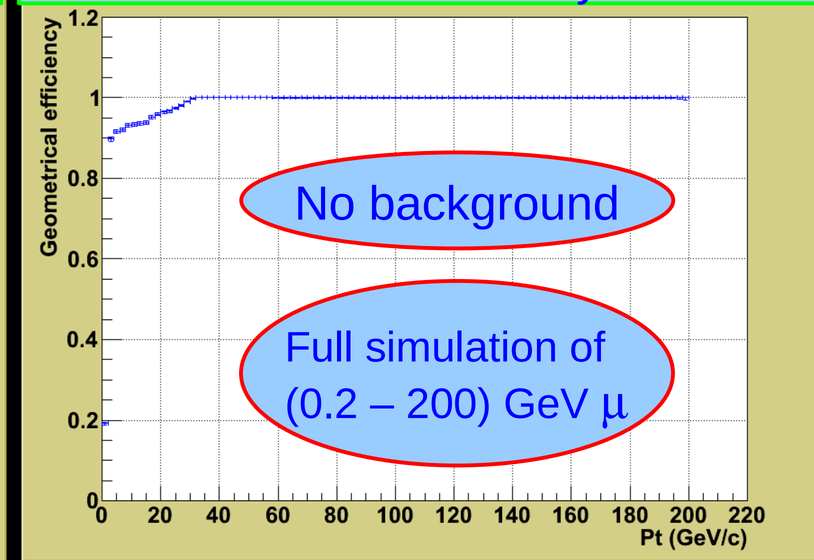


Reconstruction Efficieny for Single Muons

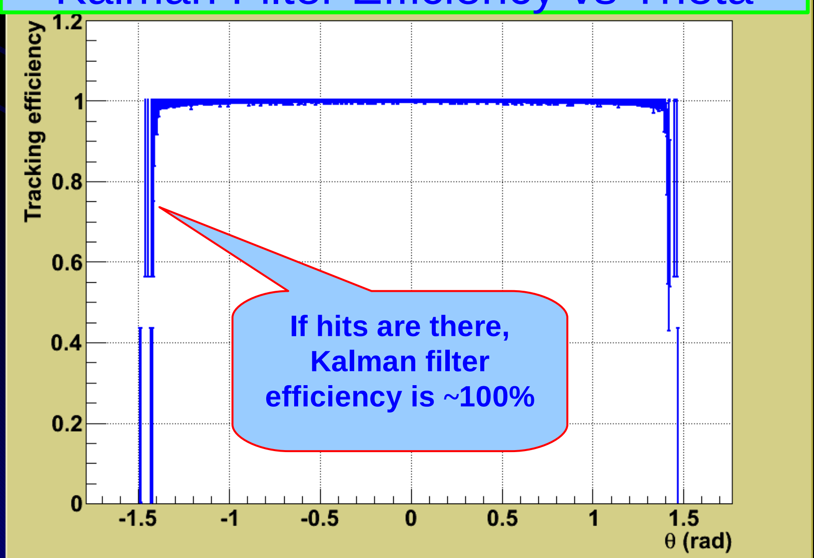
Geometrical Efficiency vs Theta



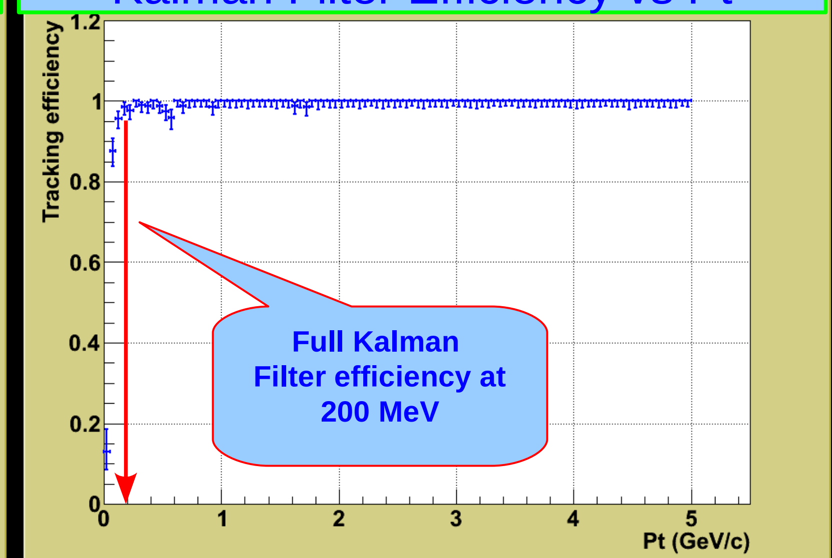
Geometrical Efficiency vs Pt



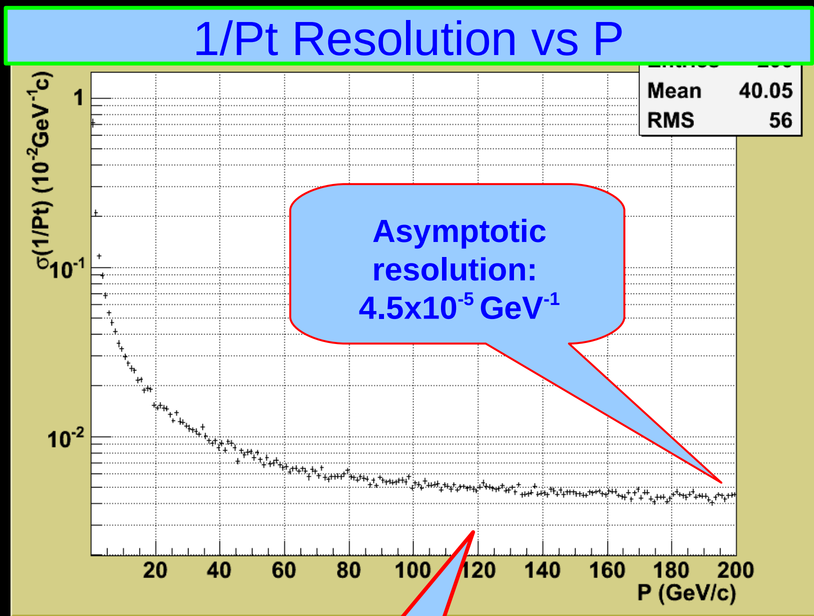
Kalman Filter Efficiency vs Theta

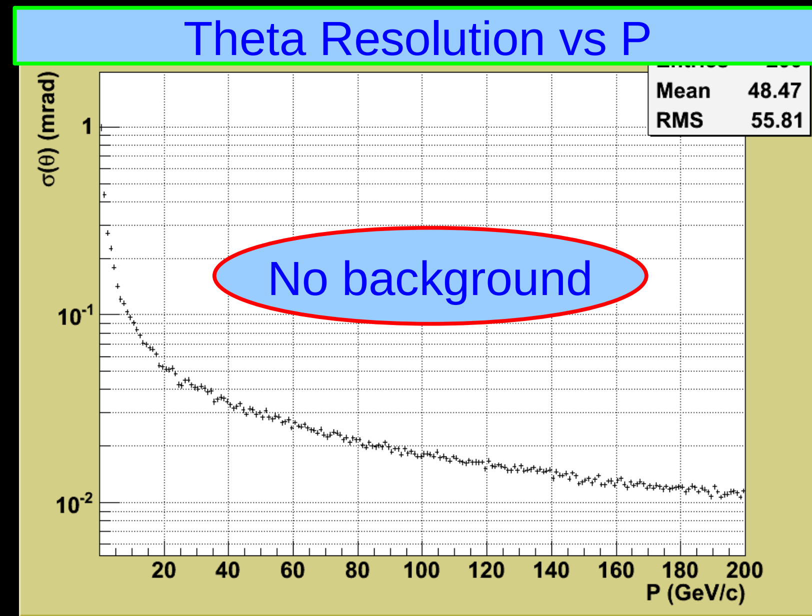


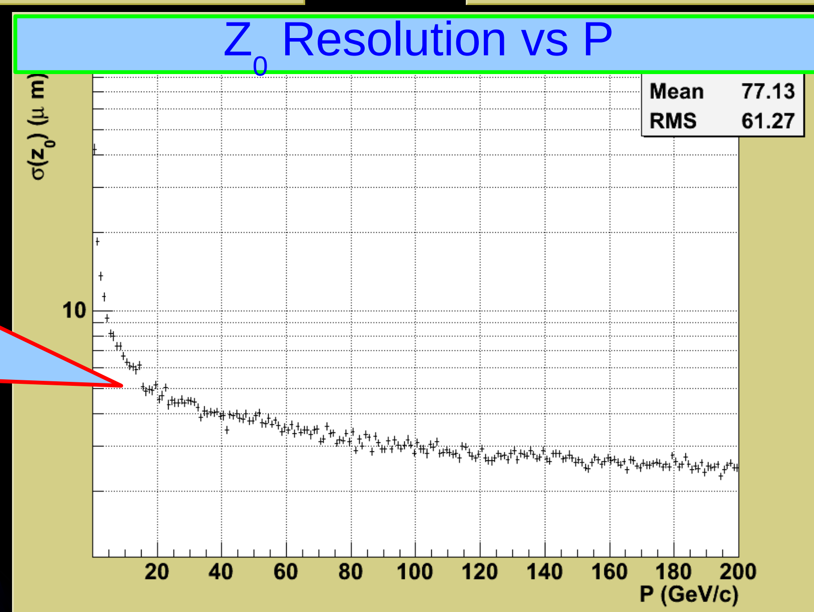
Kalman Filter Efficiency vs Pt



Resolutions for single muons







Well within requirements for precision physics

Full simulation of (0.2 – 200) GeV μ

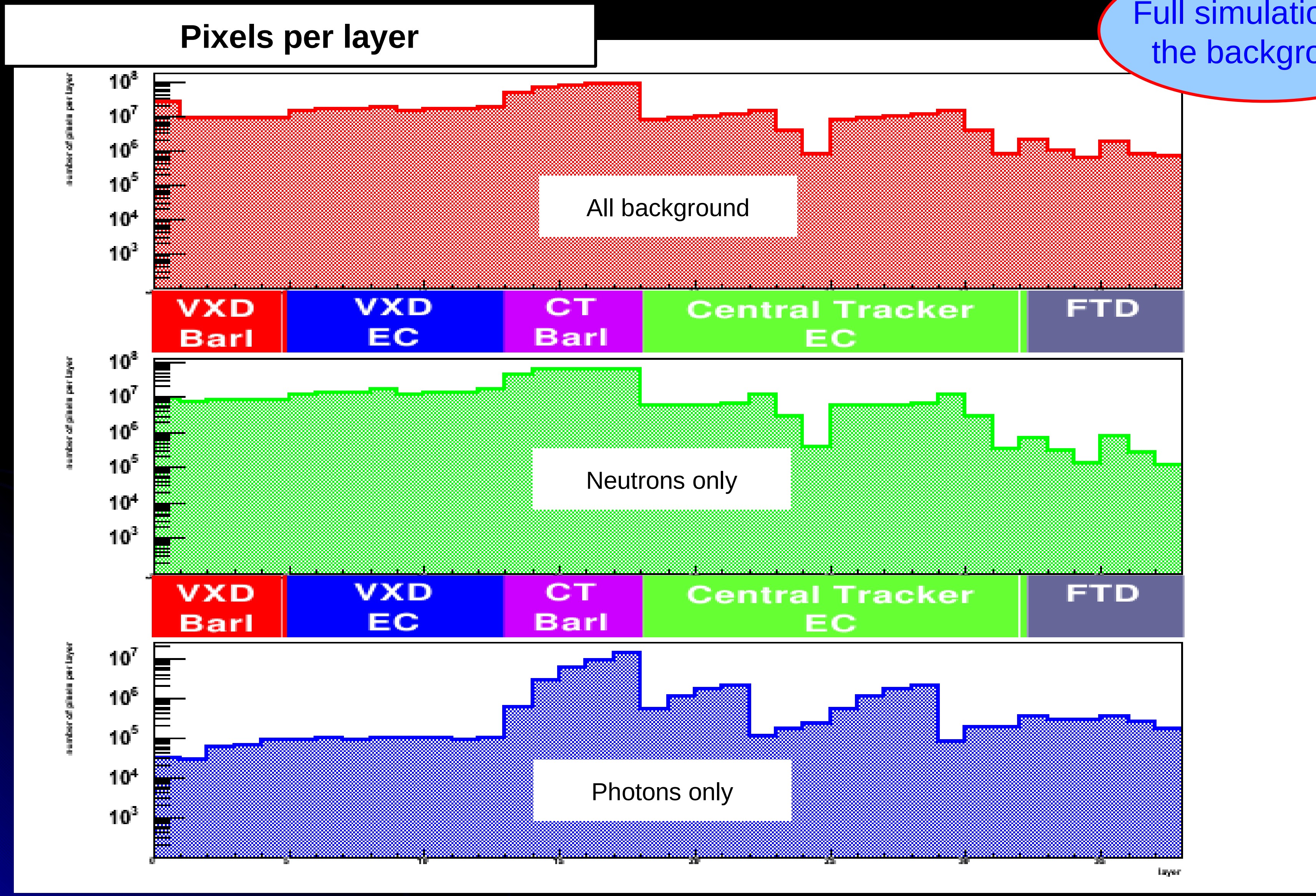
Beam Background Studies

- Simulated in ILCroot 4 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)

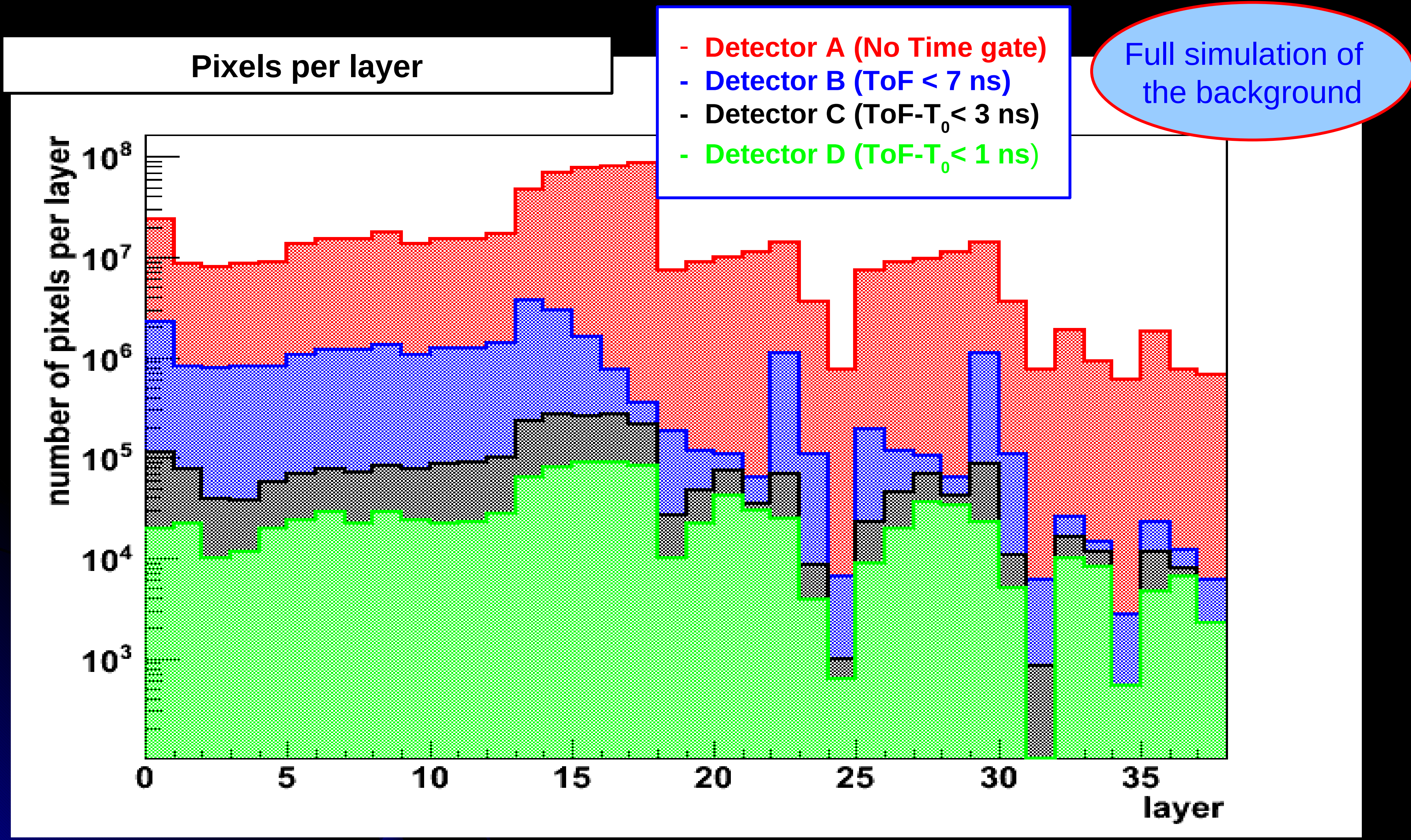
See also N. Terentiev 's talk

Pixels occupancy in detector A (no timing) vs PID

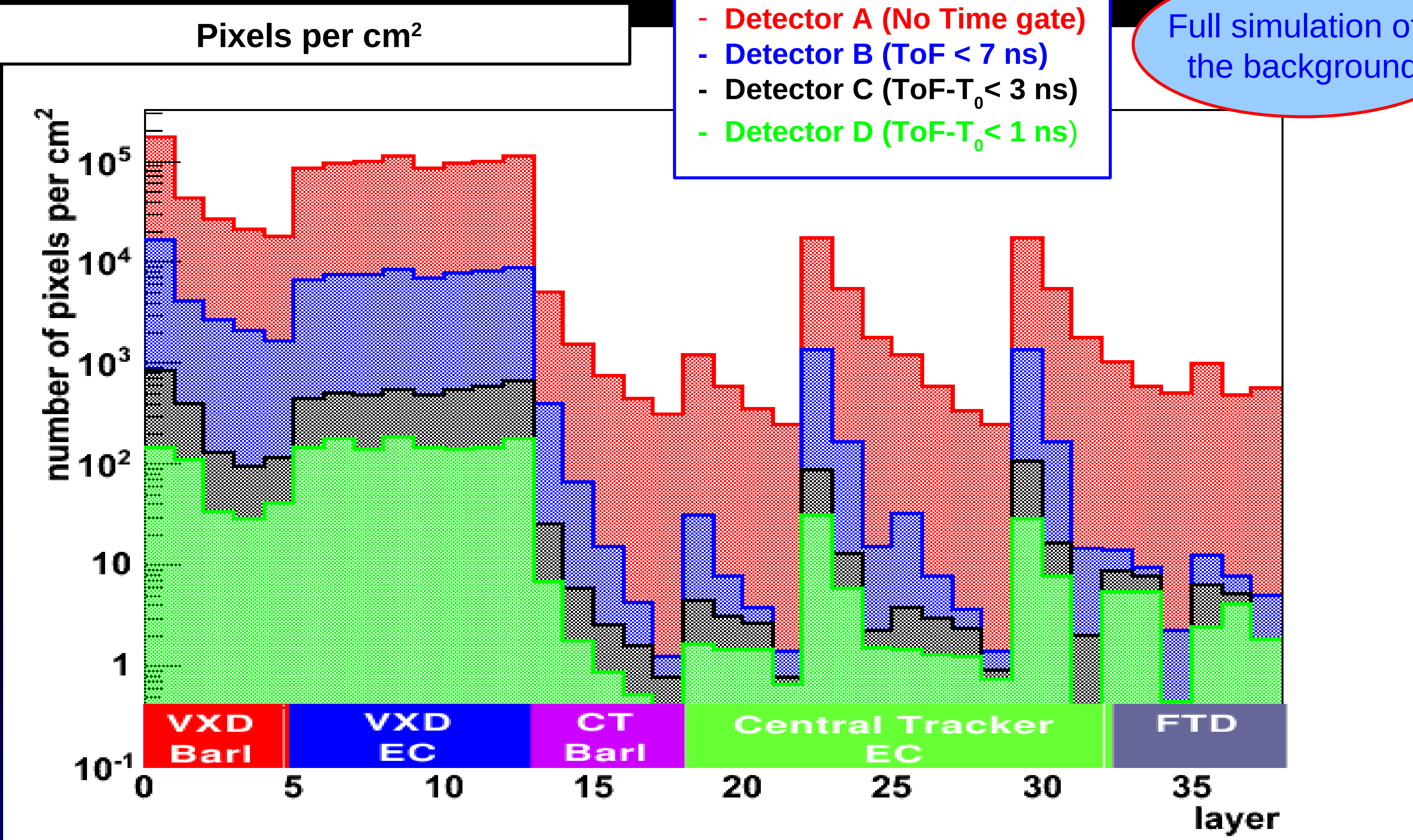
Full simulation of the background



Pixels Occupancy for 4 detectors



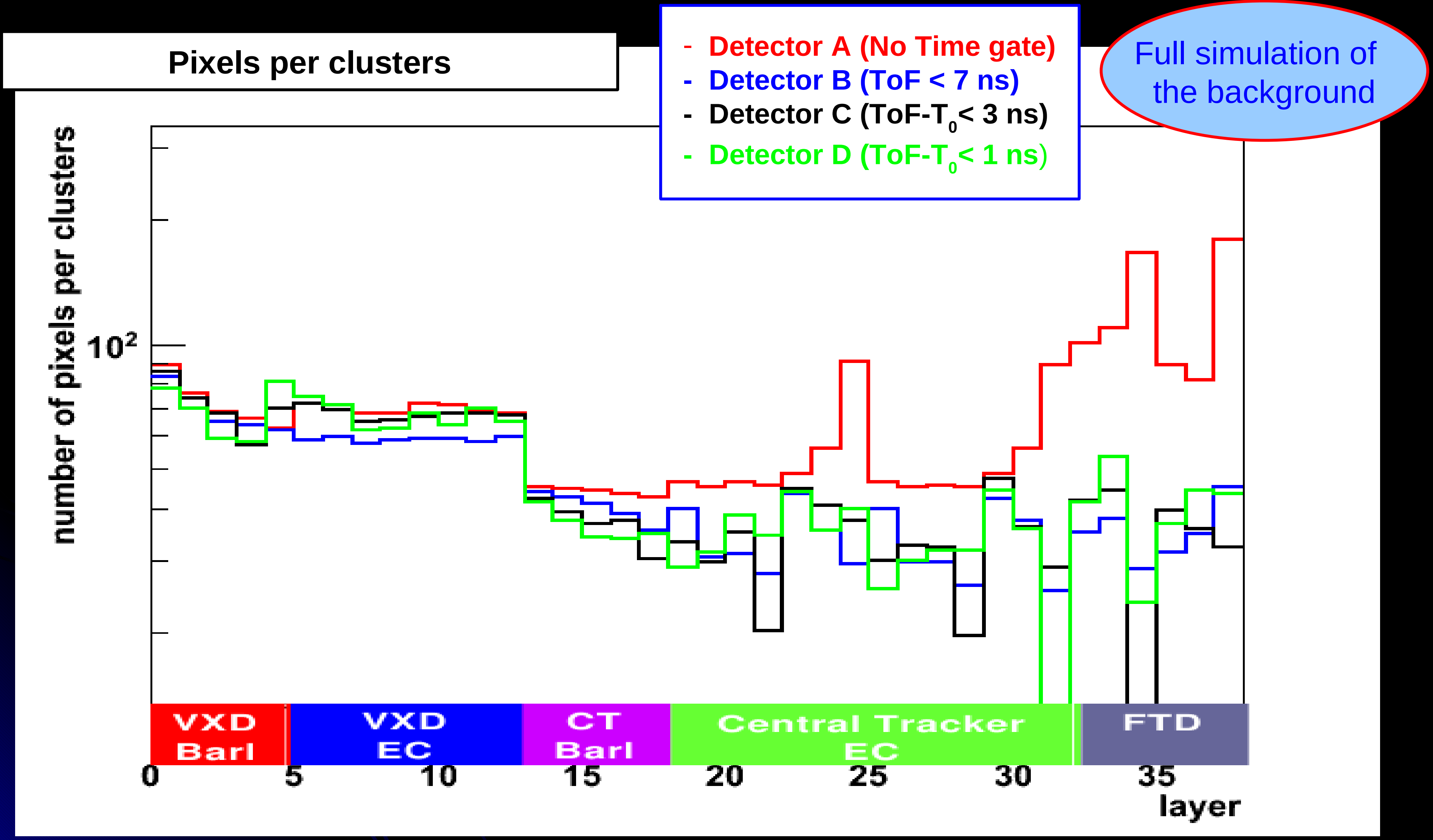
Pixels Occupancy for 4 detectors



- Detector A (No Time gate)
- Detector B (ToF < 7 ns)
- Detector C ($ToF-T_0 < 3$ ns)
- Detector D ($ToF-T_0 < 1$ ns)

Full simulation of the background

Pixels Occupancy for 4 detectors



Reconstructed Background Tracks (from Kalman filter)

Full vs fast simulation of the back

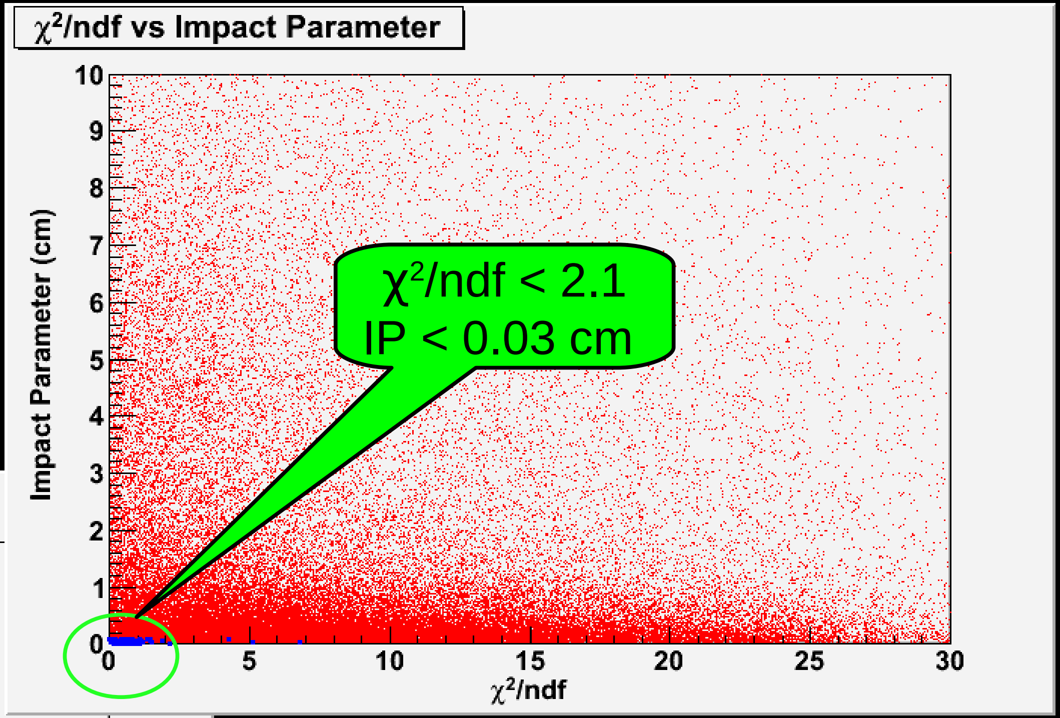
Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	75309	64319
Det. C (3 ns adjusteble gate)	6544	4639
Det. D (1 ns adjusteble gate)	1459	881

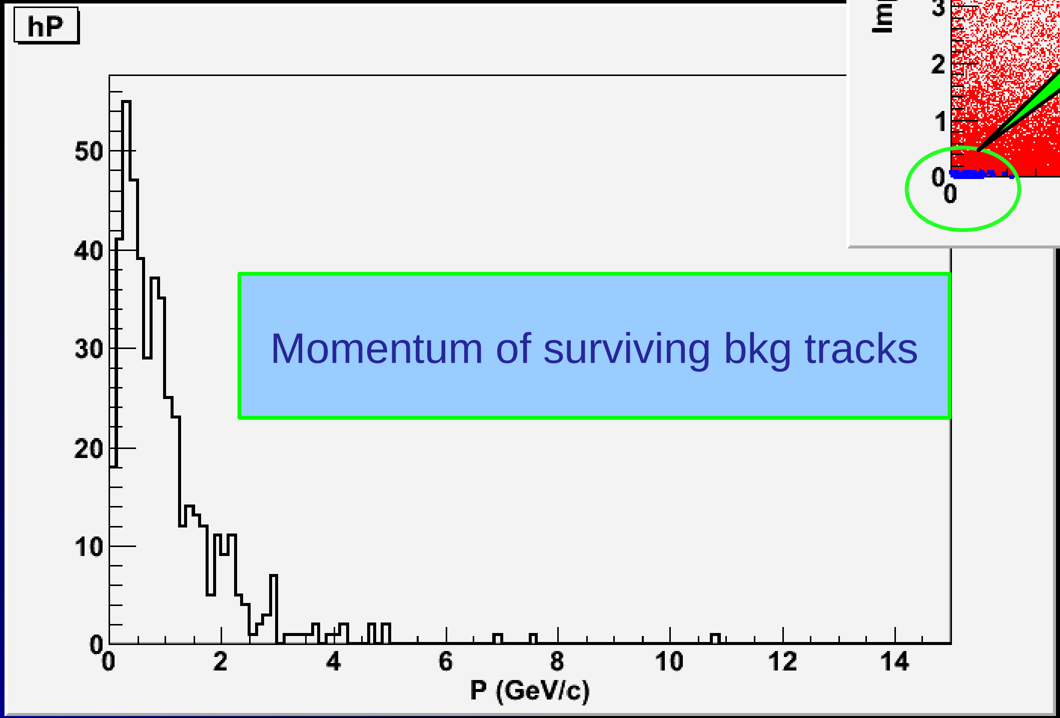
Full reconstruction is paramount when combinatorics is relevant

Physics vs Background in Det. B:

A strategy to disentangle reconstructed tracks from IP

Full simulation of physics + bkg

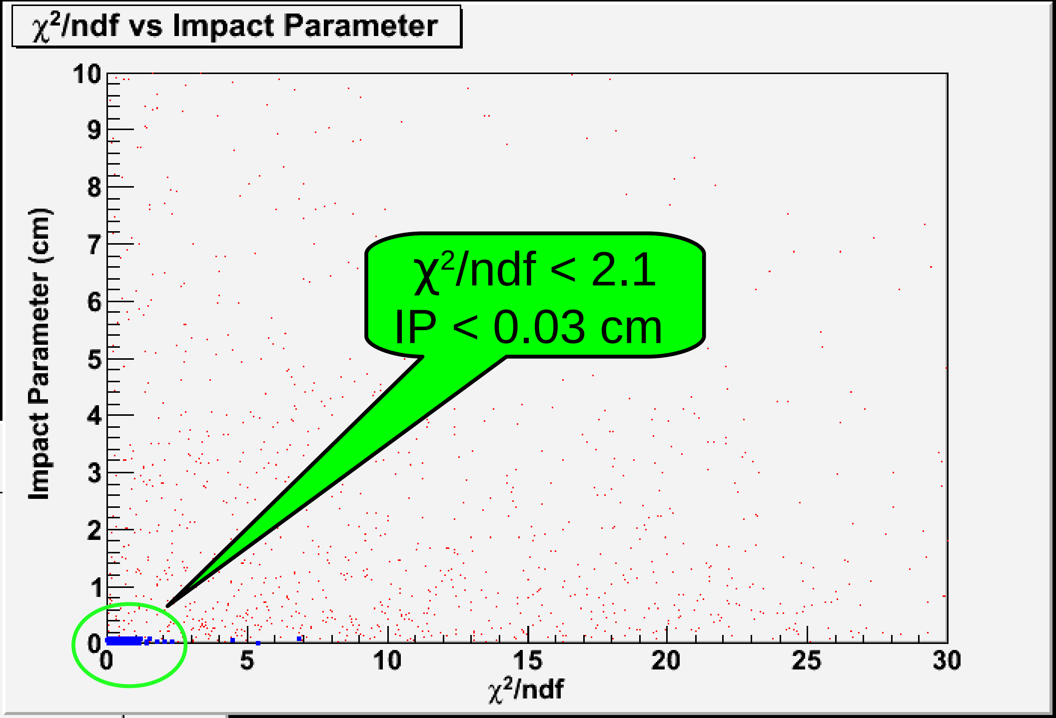


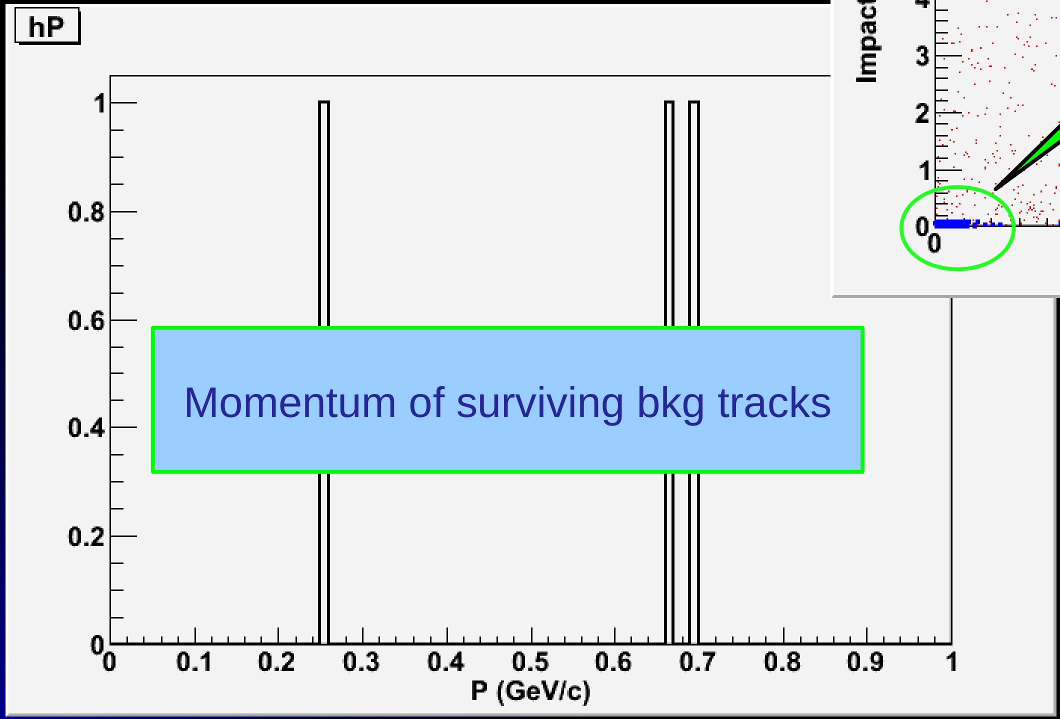


Momentum of surviving bkg tracks

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

Full simulation of physics + bkg





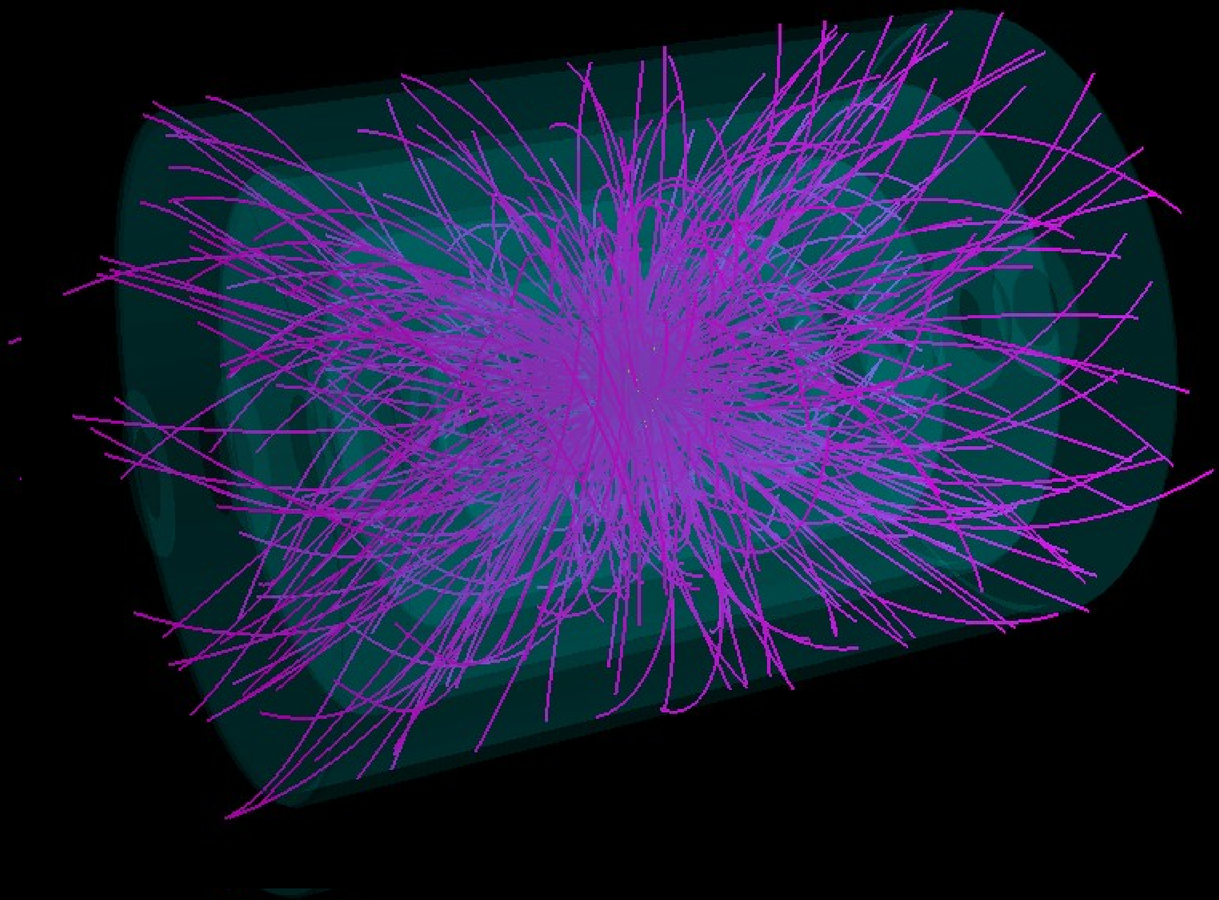
Reconstructed Background Tracks (from Kalman filter) after χ^2 and IP cuts

Full vs fast simulation of the back

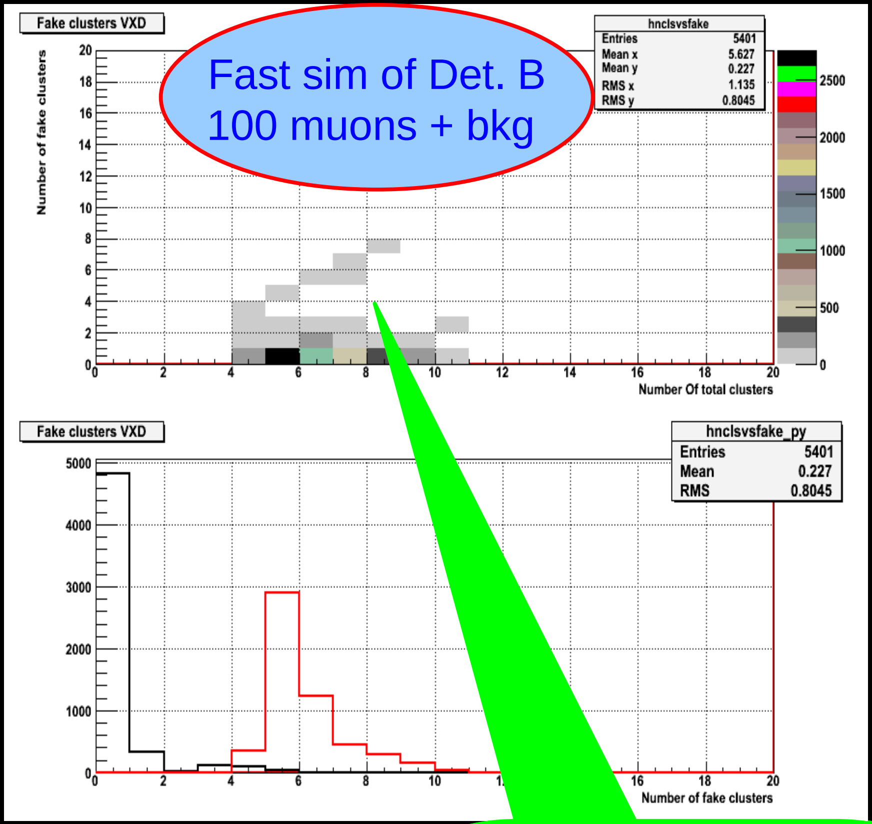
Detector type	Reconstructed Tracks (full simu)	Reconstructed Tracks (fast simu)
Det. A (no timing)	Cannot calculate	Cannot calculate
Det. B (7 ns fixed gate)	475	405
Det. C (3 ns adjusteble gate)	11	8
Det. D (1 ns adjusteble gate)	3	1

Full reconstruction is paramount when combinatorics is relevant

Event Display of Surviving Background tracks



Effects of background Hits on Physics



no fake cluster

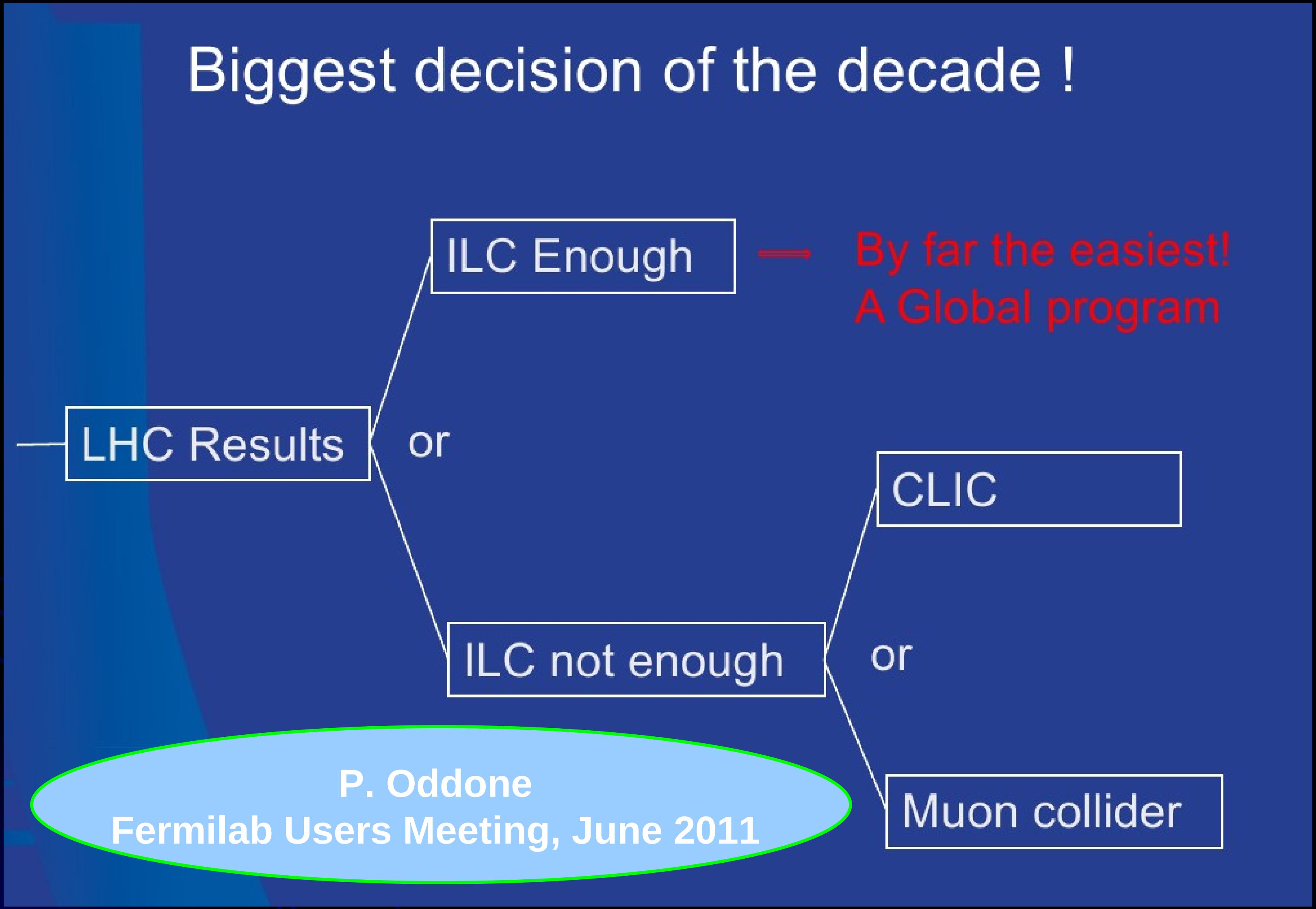
< 5% of tracks have > 1 fake cluster

Effects on track parameter resolution are unaffected by background

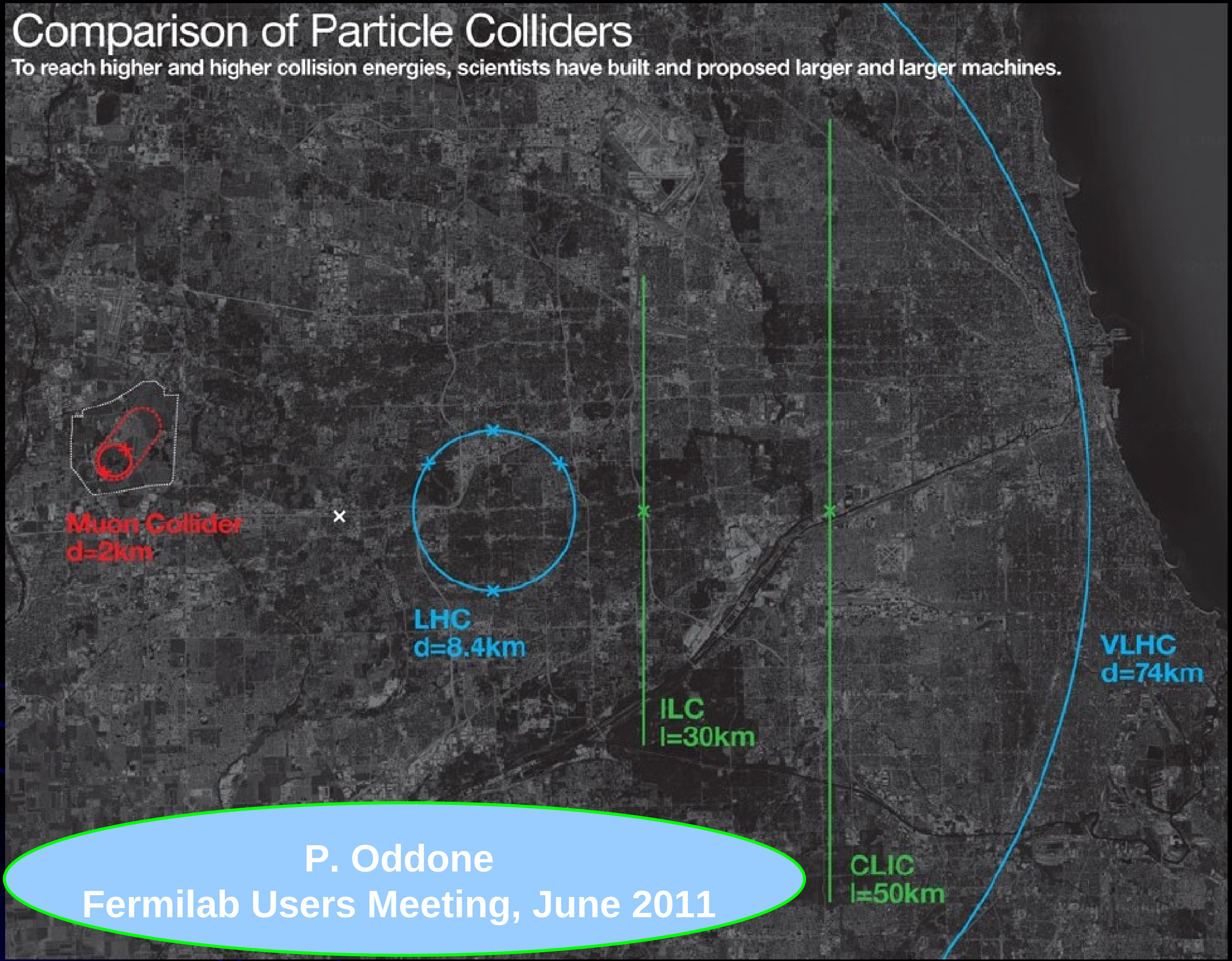
Conclusions

- A full simulation and reconstruction of Si-tracking detectors is implemented in ILCroot framework (There is the experience of 4 years of work in ILC R&D studies and a LOI)
- MARS15 and ILCroot are 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
  - Background tracks are easily rejected with smart timing and efficient Kalman filter
- - Physics is mostly unaffected for $\theta > 20°$
- - For $\theta<20°$ geometrical efficiency deteriorates quickly
- **<u>Not a bad start for a baseline detector with no optimization yet</u>**

Backup slides



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.
Muon Collider
d=2km
LHC
d=8.4km
ILC
l=30km
CLIC
l=50km
VLHC
d=74km
P. Oddone
Fermilab Users Meeting, June 2011

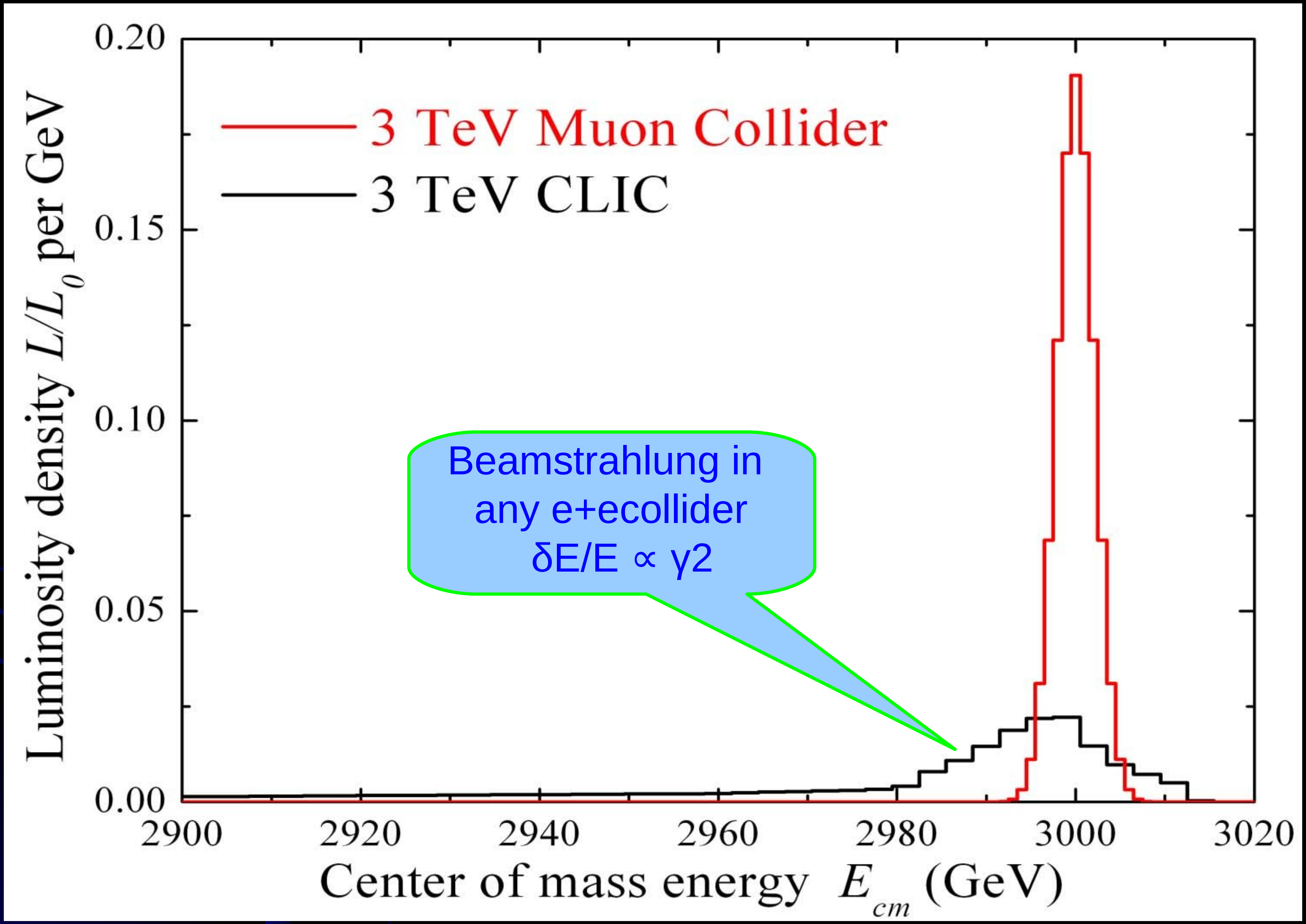
MUON COLLIDER MOTIVATION

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 ($m_\mu / m_e \sim 207$):

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)
- $\Delta T_{bunch} \sim 10\ \mu s$ … (e.g. 4 TeV collider)
  Lots of time for readout
  Backgrounds don't pile up
- $(m_\mu/m_e)^2 = \sim 40000$
  Enhanced s-channel rates for Higgs-like particles

Energy Spread



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

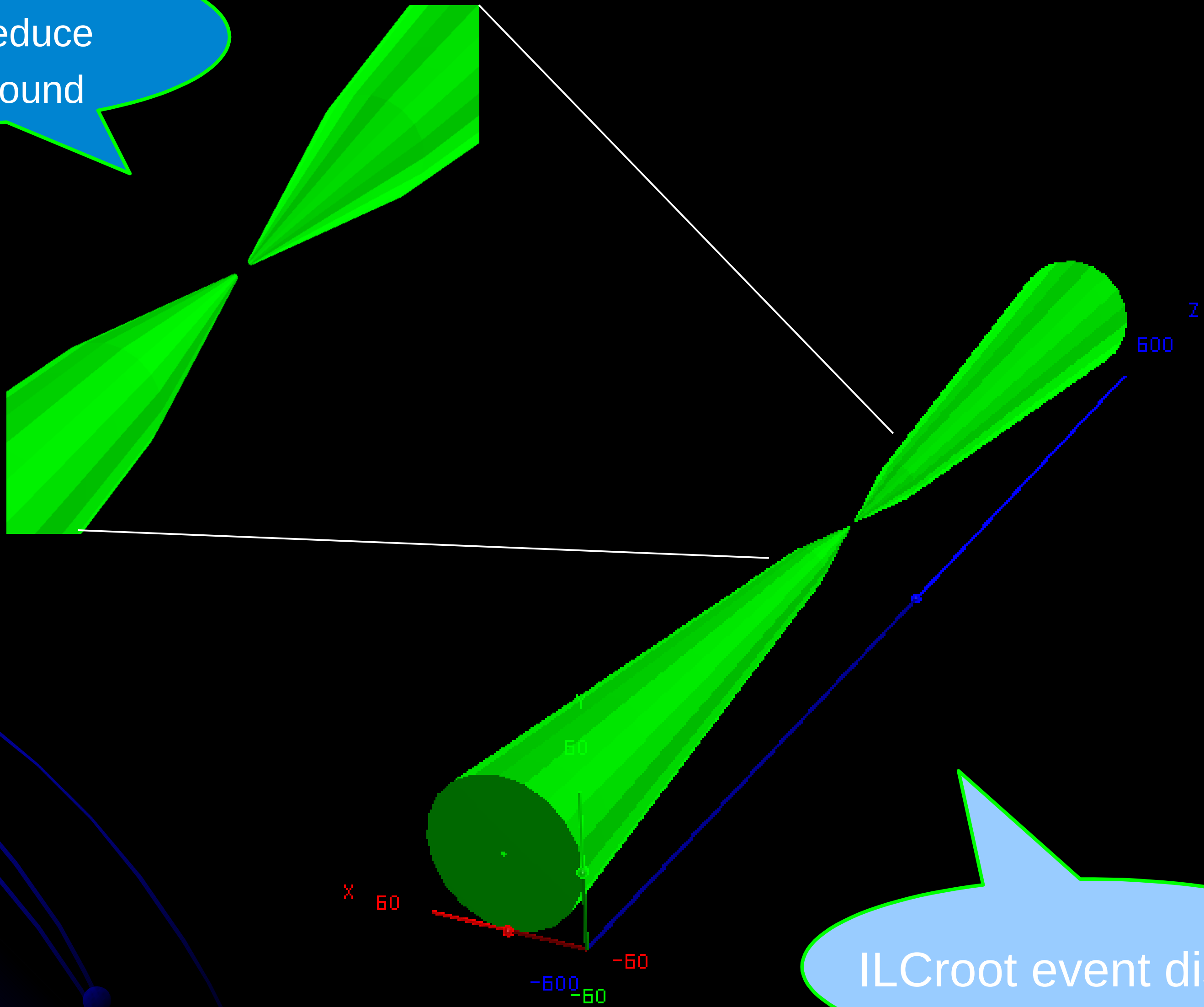
  For a MC we must cool them by O(106) before they decay ⇒ New cooling technique (ionization cooling) must be demonstrated, and it requires components with demanding performance (NCRF in magnetic channel, high field solenoids.)

- After cooling, beams still have relatively large emittance

S. Geer- Accelerator Seminar
SLAC 2011

10° Nozzle

Newer version
To further reduce
MuX background

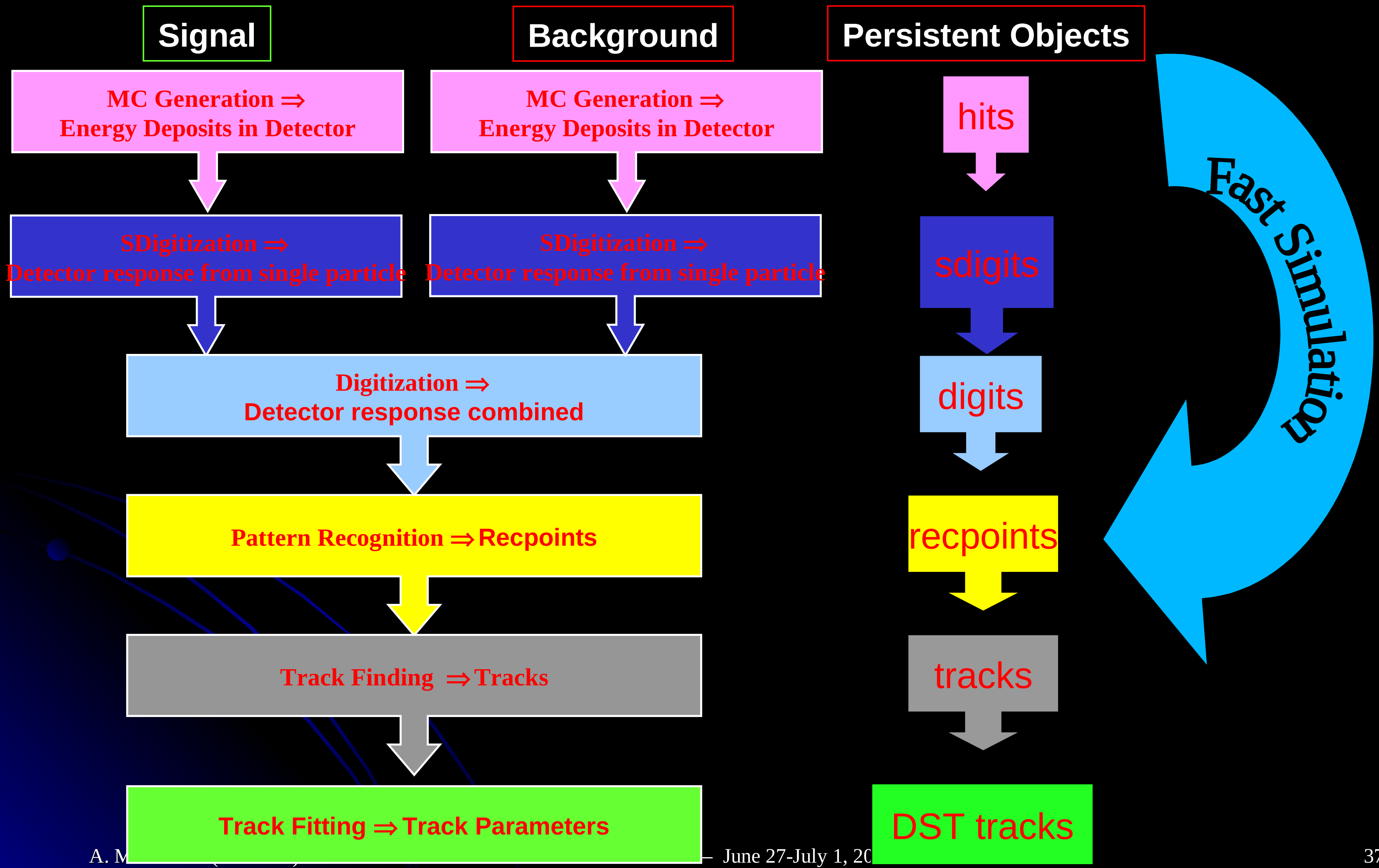


ILCroot event display

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



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-9   dV= thick/bias voltage
    - Compute charge spreading:

      σ_{xy}=sqrt(2k/e*T°*dV*L), σ_z=fda*σ_{xy}
    - Spread charge across pixels using Erfc(xy,z,σ_{xy},σ_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

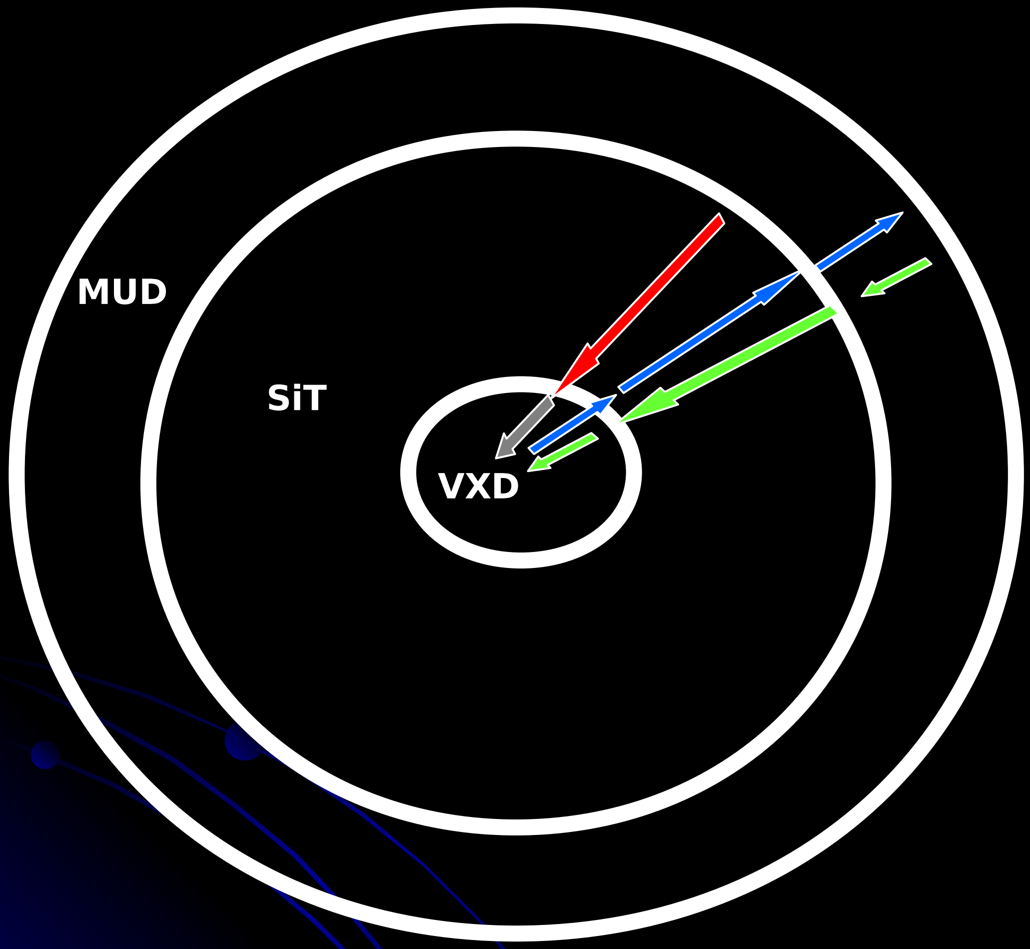
Kalman Filter (classic)

- 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

Tracking System Studies:
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