# Muon Collider Studies with MARS15 and ILCroot

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*And the ILCroot simulation group:*
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# Outline

- Beam background with MARS15
- ILCroot for μCollider
- Baseline detector for μCollider studies
- Background and MDI optimization studies
- Tracking studies
- Calorimetry studies
- Preliminary Physics studies: merging background & signal events

# MARS15 + ILCroot

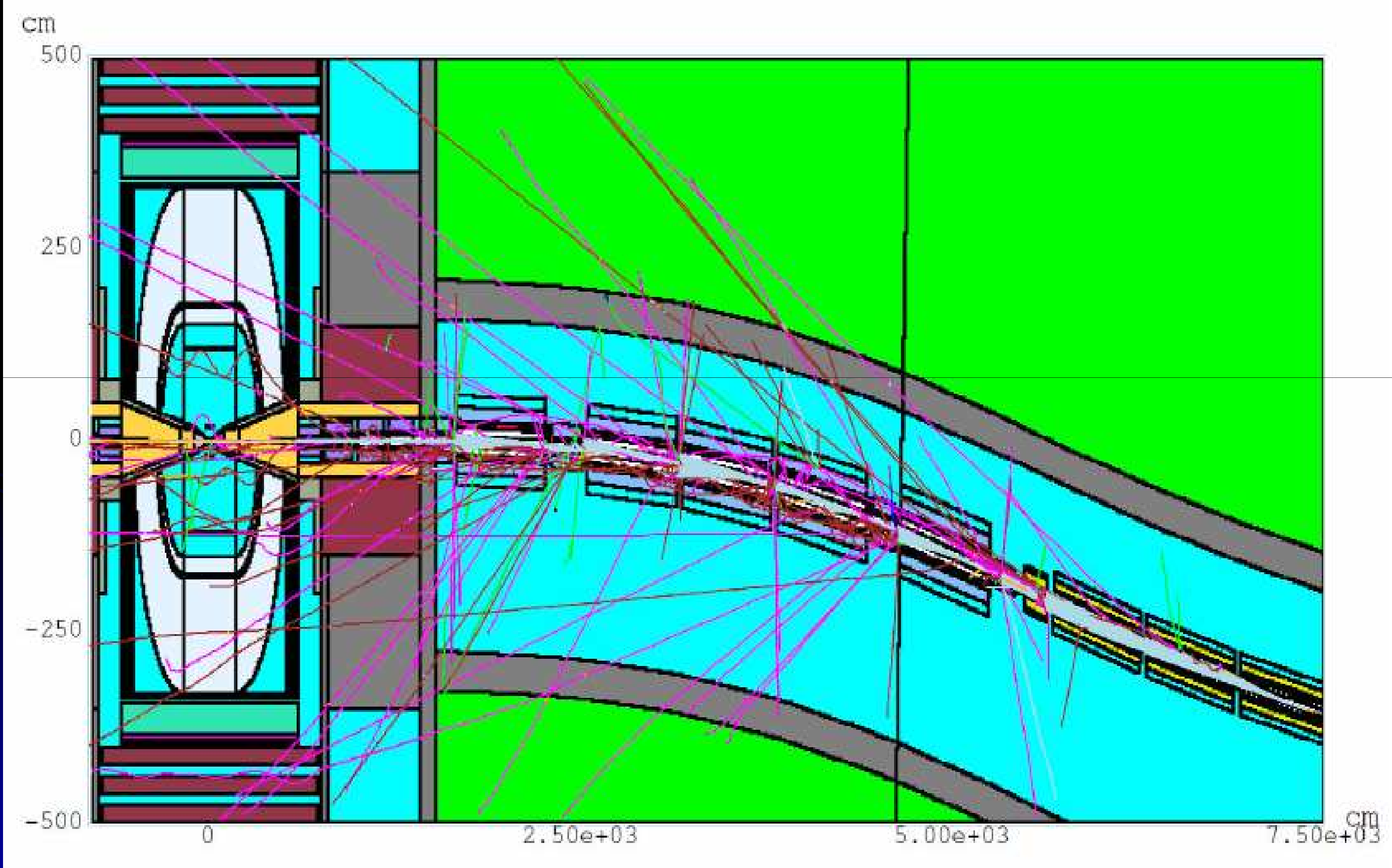
- MARS15: Montecarlo code for simulation of particle transport and interaction in accelerator, detector and shielding component
- New release available since Feb. 24, 2011
- See http://www-ap.fnal.gov/MARS
- De-facto standard at Fermilab for beam background studies and beam sensitive HEP experiment (Tevatron, LHC, μCollider, Mu2e, g-2, etc.)
- Excellent MC simulation (results comparable to Fluka) but it lacks the detector response and the event reconstruction aspects
- ILCroot takes over at MDI surface

# Simulating 1 MARS Event @ $E_{cm}$ = 1.5 TeV with $2x10^{12}$ particles

- About $1x10^8$ particles, almost all originating <25m from IP
  - Muon beam decay from beam line components and accelerator tunnel is major source of backround in the detector
  - $4.3x10^5$ decays/m/bunch Xing.
  - Incoherent $3x10^4$ $e^+e^-$ pair production per bunch Xing
- Background is split into two sources:
  - Near (< 25m)
  - Far (25m< < 200m)
- Particle at MDI interface
  - w ~ 20
- Particles from beamline
  - W << 1: need proper statistical treatement
- At large radii also:
  - Bethe-Heitler and beam-halo induced background
- Background with current shielding configuration is reduced by $\mathcal{O}(10^3)$

N. Mokhov
S. Striganov

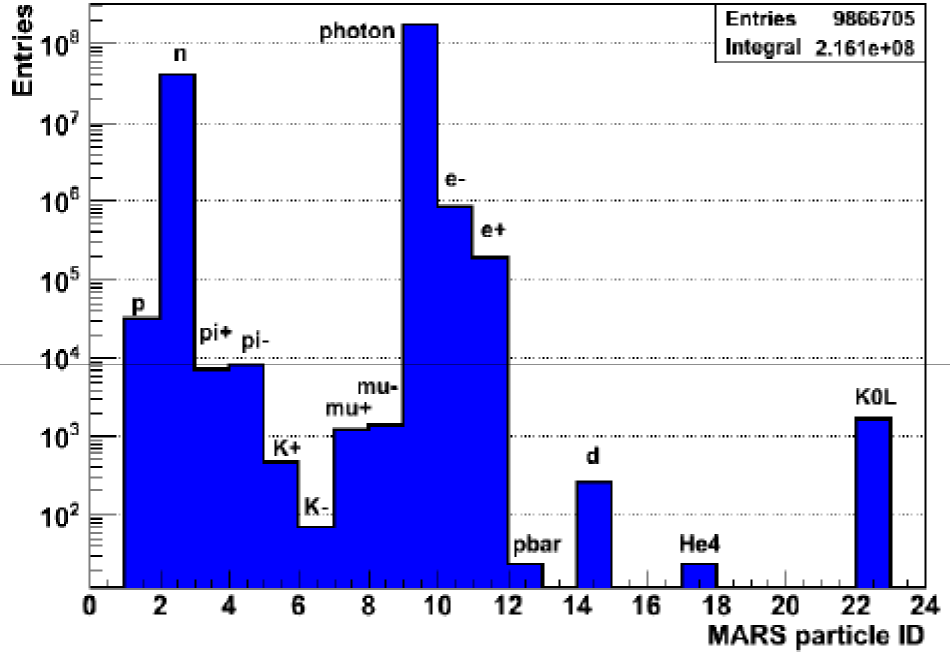
# Particle Tracks in IR (E>50MeV)



10° Nose

N. Mokhov
S. Striganov
N. Terentiev

# Background particles entering the MDI Surface @ $E_{cm}$ = 1.5 TeV




**Abs. yields/bunch (E=750 GeV, both beams, 2.0e+12 muons each, L=26 m)**

| photon | n | $e^{+-}$ | p | $\pi^{+-}$ | $\mu^{+-}$ |
|---|---|---|---|---|---|
| 1.77e+08 | 0.40e+08 | 1.03e+06 | 3.13e+04 | 1.54e+04 | 0.26e+04* |

* for "short range" source, 0.82e+04 if "long range" source is added

N. Mokhov
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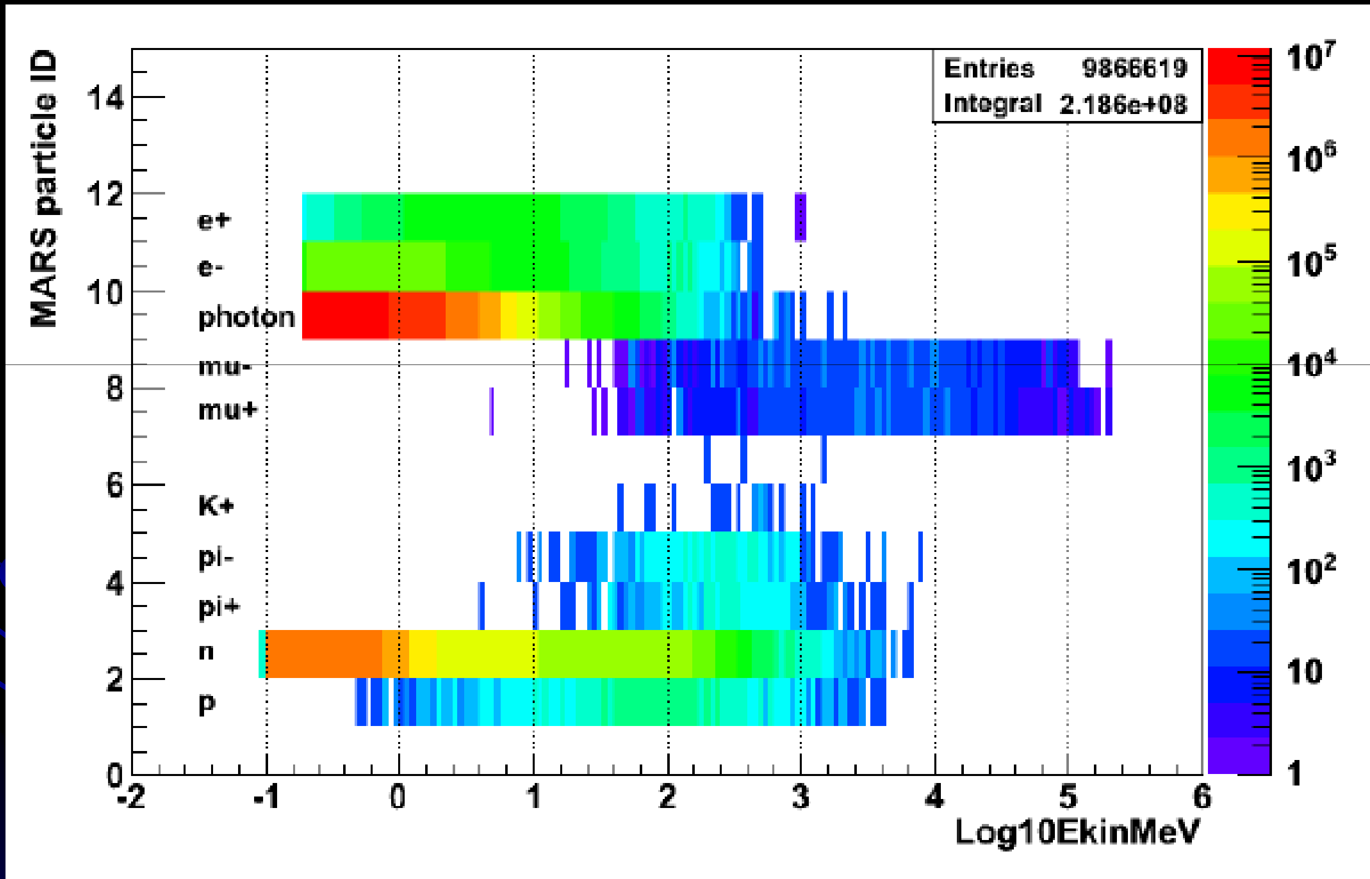
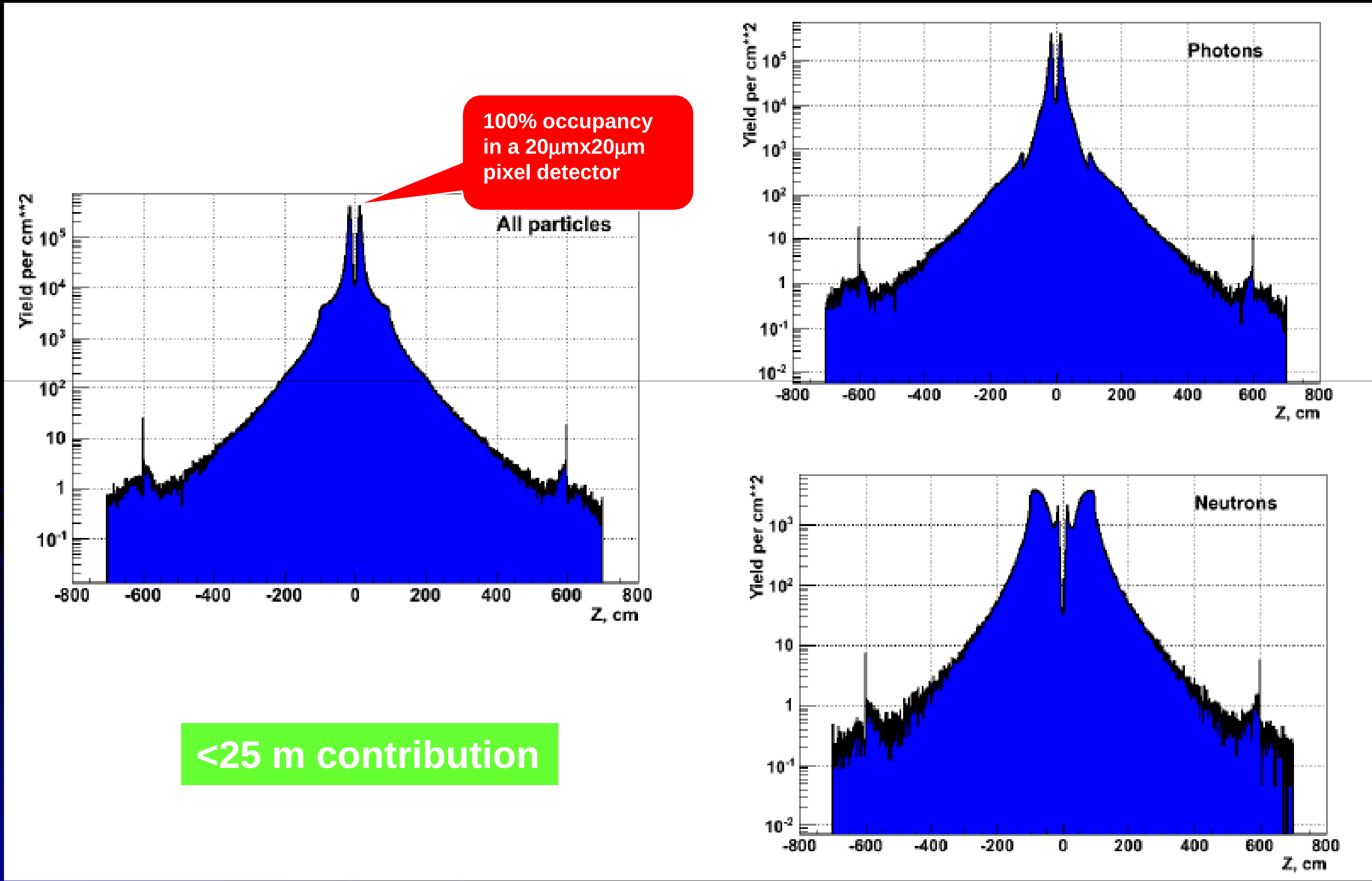
# MARS15 $E_{kin}$ vs Particle Species




**<25 m contribution**

N. Mokhov
S. Striganov
N. Terentiev

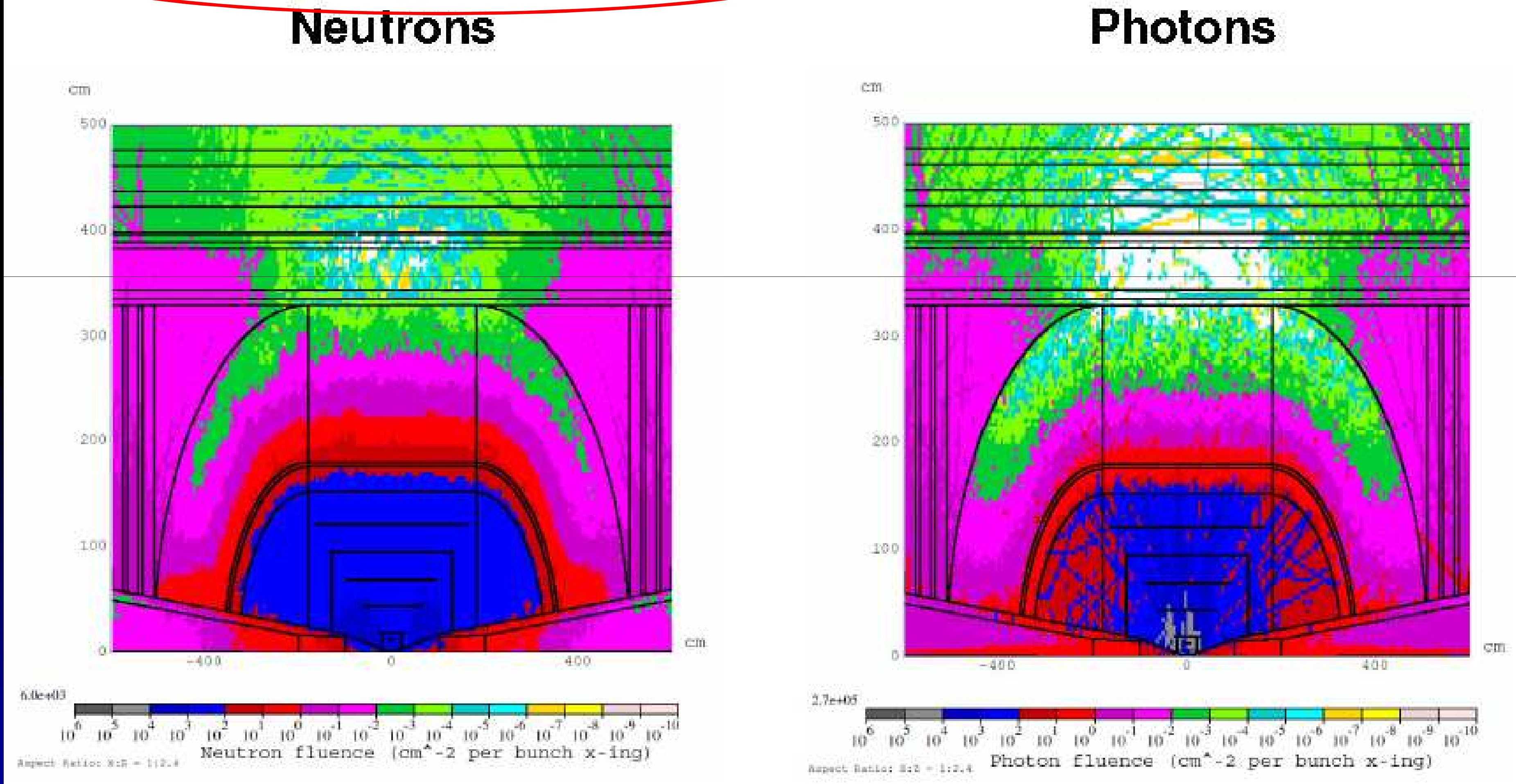
# MARS15 Background Flux vs z



N. Mokhov
S. Striganov
N. Terentiev

# Neutron and Photon Fluence

Neutron peak/yr = 0.1xLHC@$10^{34}$



# ILCroot for μ–Collider

# 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**
- **It is a simulation framework and an Offline Systems:**
  - **Single framework, from generation to reconstruction and analysis!!**
  - It naturally evolves into the offline systems of your experiment
  - Six MDC have proven robustness, reliability and portability
- ***It is Publicly available at FNAL on ILCSIM since 2006***

# The Virtual Montecarlo (VMC) Concept

- **Virtual MC provides a virtual interface to Monte Carlo**
- **It allows to run the same user application with all supported Montecarlo's**
- **The real Monte Carlo (Geant3, Geant4, Fluka) is selected and loaded at run time**

# ILCroot: essential add-ons to Aliroot

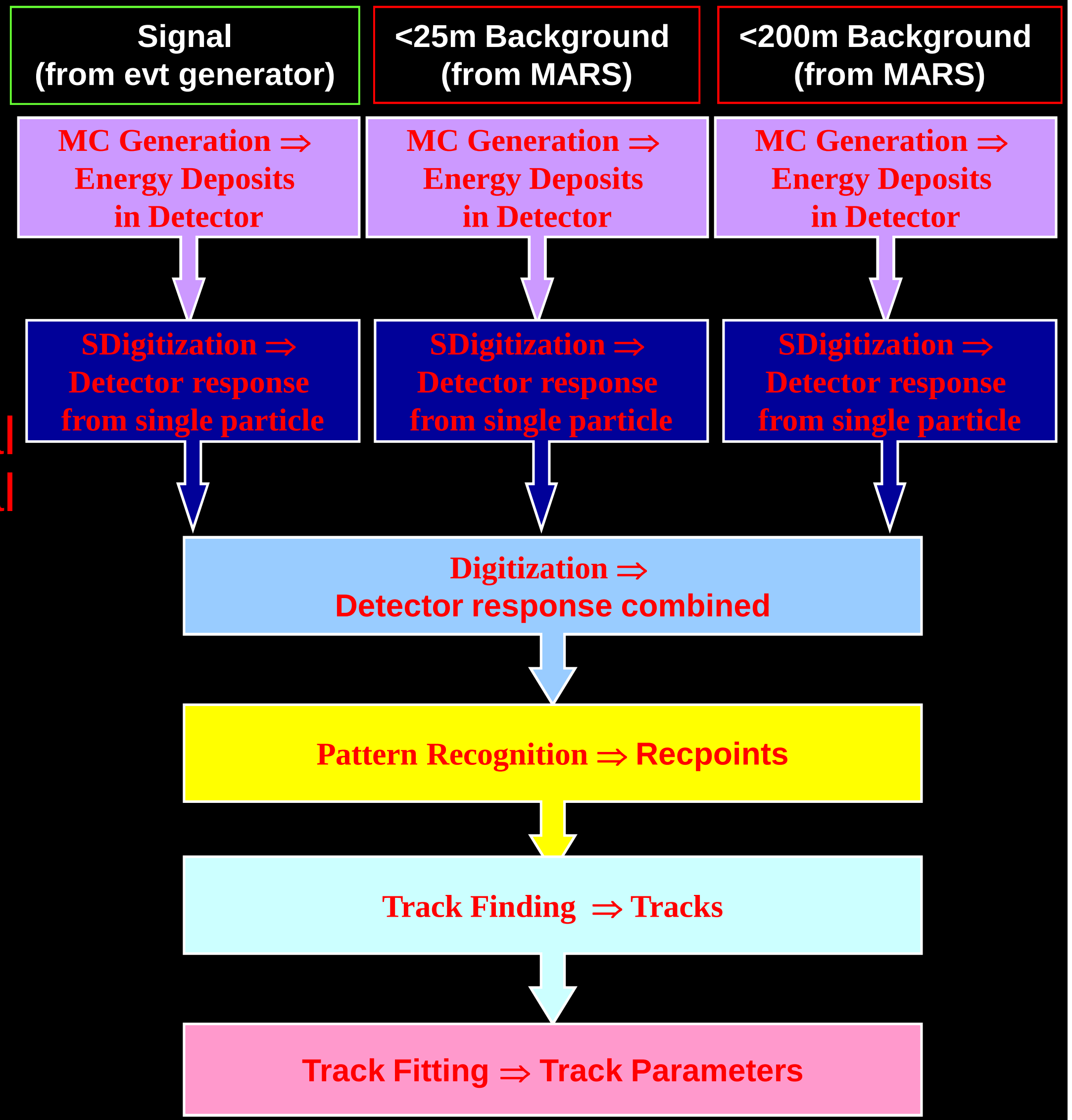
1. Interface to external files from Event Generators in various format (STDHEP, text, ***MARS***, etc.)
2. Standalone VTX track fitter
3. Pattern recognition from VTX (for Si central trackers)
4. Track fitters for different trackers technologies (Si Pixels, Si Strips, Drift Chambers, Straw Tubes, TPC's) and a ombination of them
5. Full simulation of ***Dual Readout calorimeters***
6. Parametric beam background (# integrated bunch crossing chosen at run time)

Very important for detector and Physics studies of New Projects

Growing number of experiments have adopted it: Alice (LHC), Opera (LNGS), (Meg), CMB (GSI), Panda (GSI), 4th Concept, (SiLC ?) and **LHeC**

# Processing Flow of Full Simulation: detector hits + digitization + reconstruction

- Hits: produced by MC (G3,G4,Fluka)
- SDigits: simulate detector response for each hit
- Digits: merge digit from several files of SDigits (example Signal + Beam Bkgnd)
- Recpoints: Clusterize nearby Digits
- Pattern recognition + track fit through full Parallel Kalman Filter
- Or Calorimetry shower reco



# 14 Detectors in ILCroot + 12 from Alice

| Detector | Layouts | Digit./Cluster. |
|---|---|---|
| VXD (SIDMay06) | 1 (parametric) | Full |
| FTD (SiLC) | 1 | Full |
| DCH (CluCou) | 2 | Gauss Smear. |
| TPC (Hybrid readout) | 1 | Gauss. Smear. |
| Si-Tracker (SID01-Polyhedra) | 1+1 | Full |
| μCollider/CLIC Tracker | 1 | Full |
| Hadron Calorimeter | 2 | Full |
| ***ADRIANO Calorimeter*** | **1** | **Full** |
| EM Calorimeter | 2 | Full |
| Muon Spectrometer (straw tubes) | 1 | Gauss. Smear. |

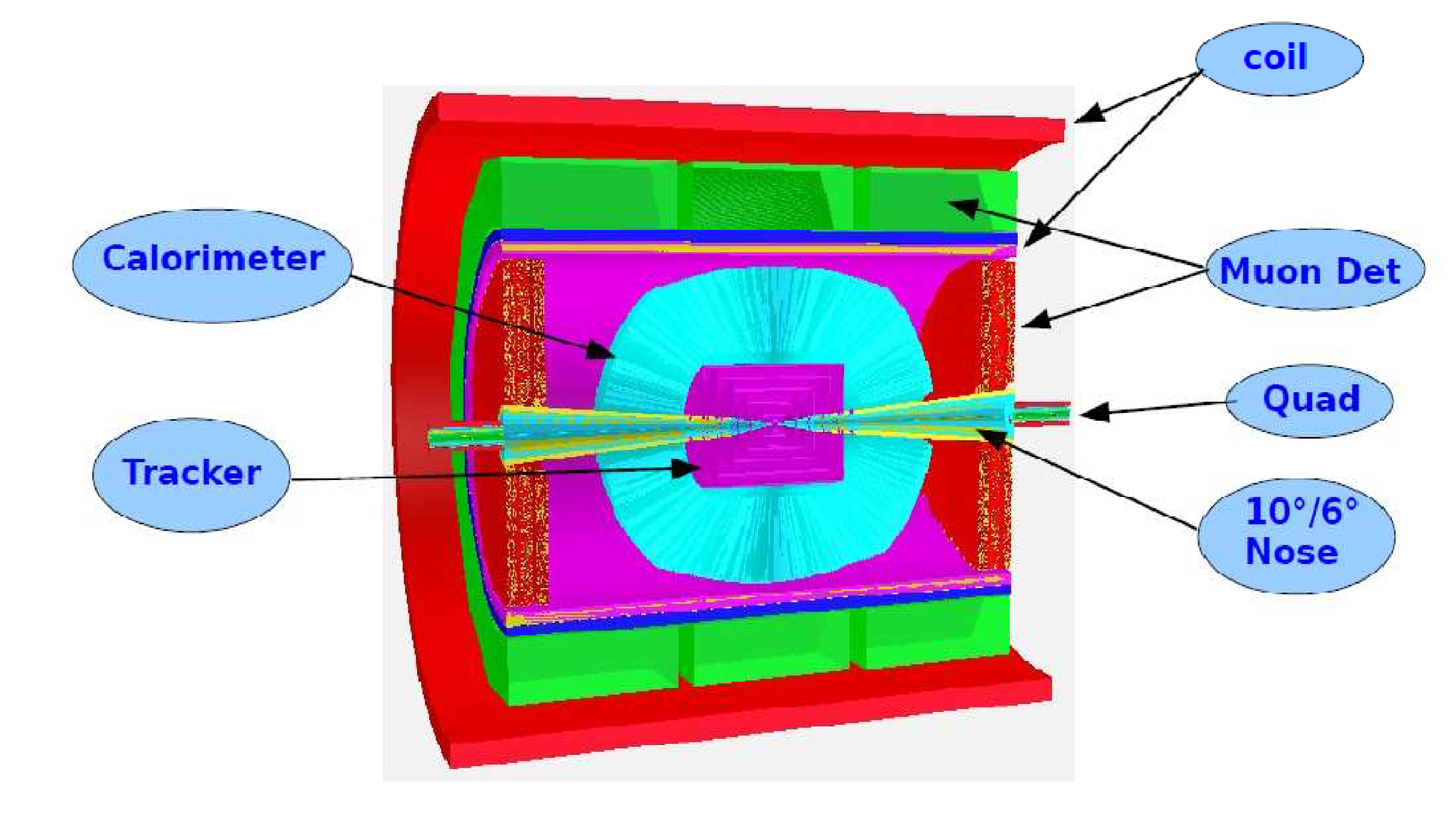
***NEW***

# MARS + ILCroot (Dedicated ILCroot framework for MUX Physics and background studies

- **The ingredients**:
  - Final Focus descripted in MARS & ILCroot
  - Detector description in ILCroot
  - MARS-to-ILCroot interface (Vito Di Benedetto)
- **How it works**
  - The interface (**ILCGenReaderMARS**) is a ***TGenerator*** in ILCroot
  - MARS output is used as a config file
  - **ILCGenReaderMARS** creates a STDHEP file with a list of particles entering the detector area at z = 7.5m
- **ILCGenReaderMARS feeds the Montecarlo with:**
  - 1 particle with corresponding weight
    - OK for calorimetric studies
  - W particles smeared according to ther origin
    - OK for detailed tracking occupancy studies
    - ...but very slow and time consuming
  - A mix of the above
    - OK for most tracking studies

# Baseline detector for μ–Collider studies

# Baseline Detector for μColl Studies

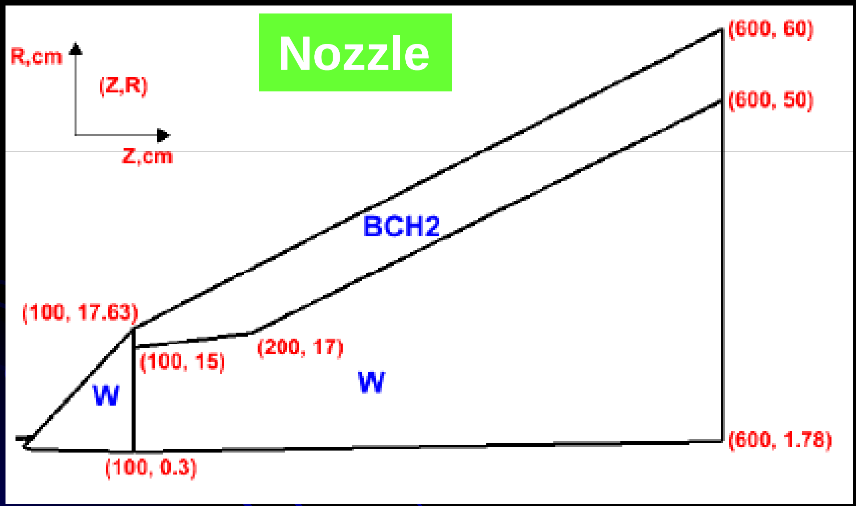


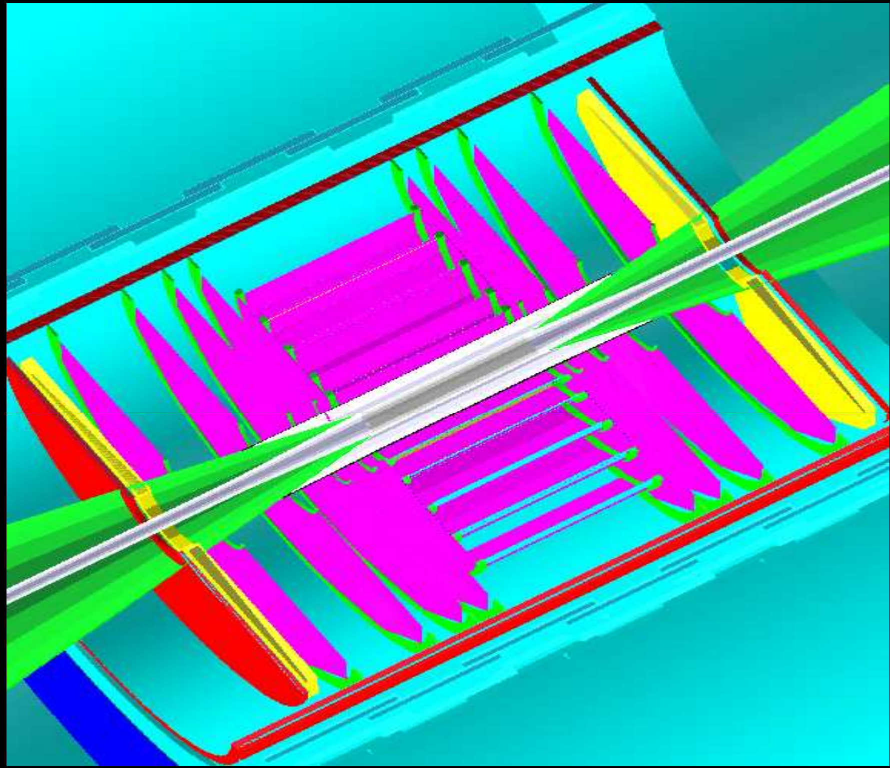

**Baseline Detector for μCollider (&CLIC) studies is SiD + FTD (from SILC) + Muon Chamber (from 4th Concept)**

**Total Active Dual Readout Calorimeter (new Concept)**

# Vertex Detector (VXD) Nozzle and Beam Pipe

- 20 µm x 20 µm
- Barrel : 5 layers subdivided in ladders
- Endcap : 4 + 4 disks subdivided in ladders



- SiD layout
- Dimensions changed from ILC (different B field = 3.5 T and worst background)
- Full parametrized geometry

# Tracking detectors for μCollider

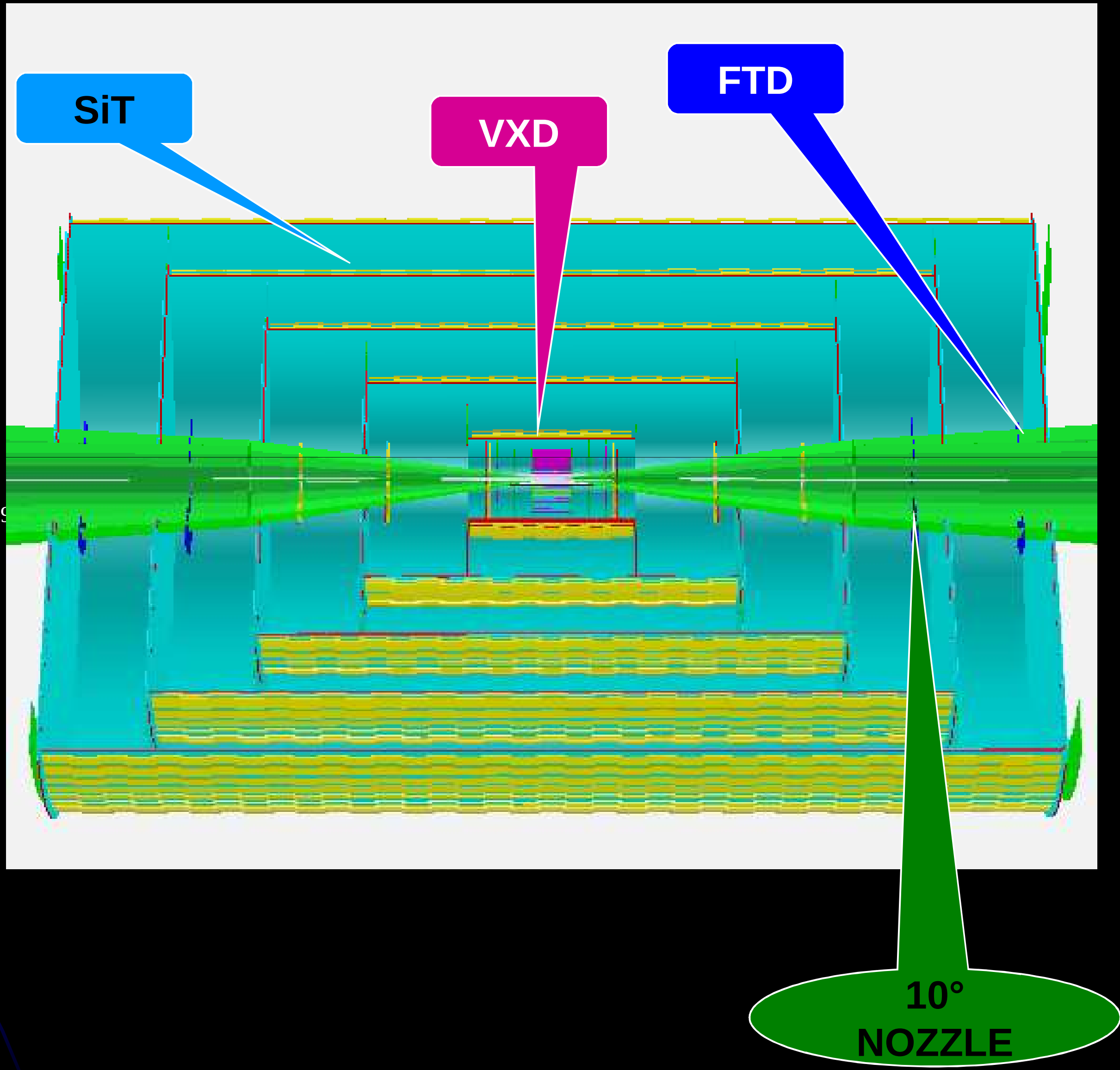
- Version SiD01-Polyhedra + SiD01
- Guard ring: mm 0.07
- Barrel Layers: 5
- Total Tiles Barrel 7312
-
- **Wafer layout**
- Strip pitch 50 μm
- Strip thickness (Si wafer) 300 μm
- Strip length 93.31 mm
- Tile width 93.531 mm
- Carbonfiber in 0.228 mm
- Rohacell tickness 3.175 mm
- Carbonfiber out 0.228 mm
- Si support 300 μm x 6.667 mm x 63.8 mm
- Kapton Layer 0.1 mm
-
- **Support layout**
- Carbon Fiber 500 μm
- Rohacell 8.075 mm
- Carbon Fiber 500 μm
-
- **Barrel Layer layout**
- Radial position (Barrel) cm 18.5-24.5; 44.1-50.1; 69
- Z-length cm 53.4; 121.6; 189.6; 257.8; 326

- **Endcap rmin rmax z position in cm**

| Endcap | rmin | rmax | z position in cm |
|---|---|---|---|
| 1 | 18.5 | 48.6 | 62.9148 |
| 2 | 18.5 | 74.1 | 96.915515 |
| 3 | 18.5 | 99.7 | 131.016285 |
| 4 | 19.5 | 125.3 | 165.117005 |
| 5 | 2.78 | 16.67 | 20.59408 |
| 6 | 7.51 | 16.67 | 54.04408 |

FTD: 3 + 3 disks Si pixel

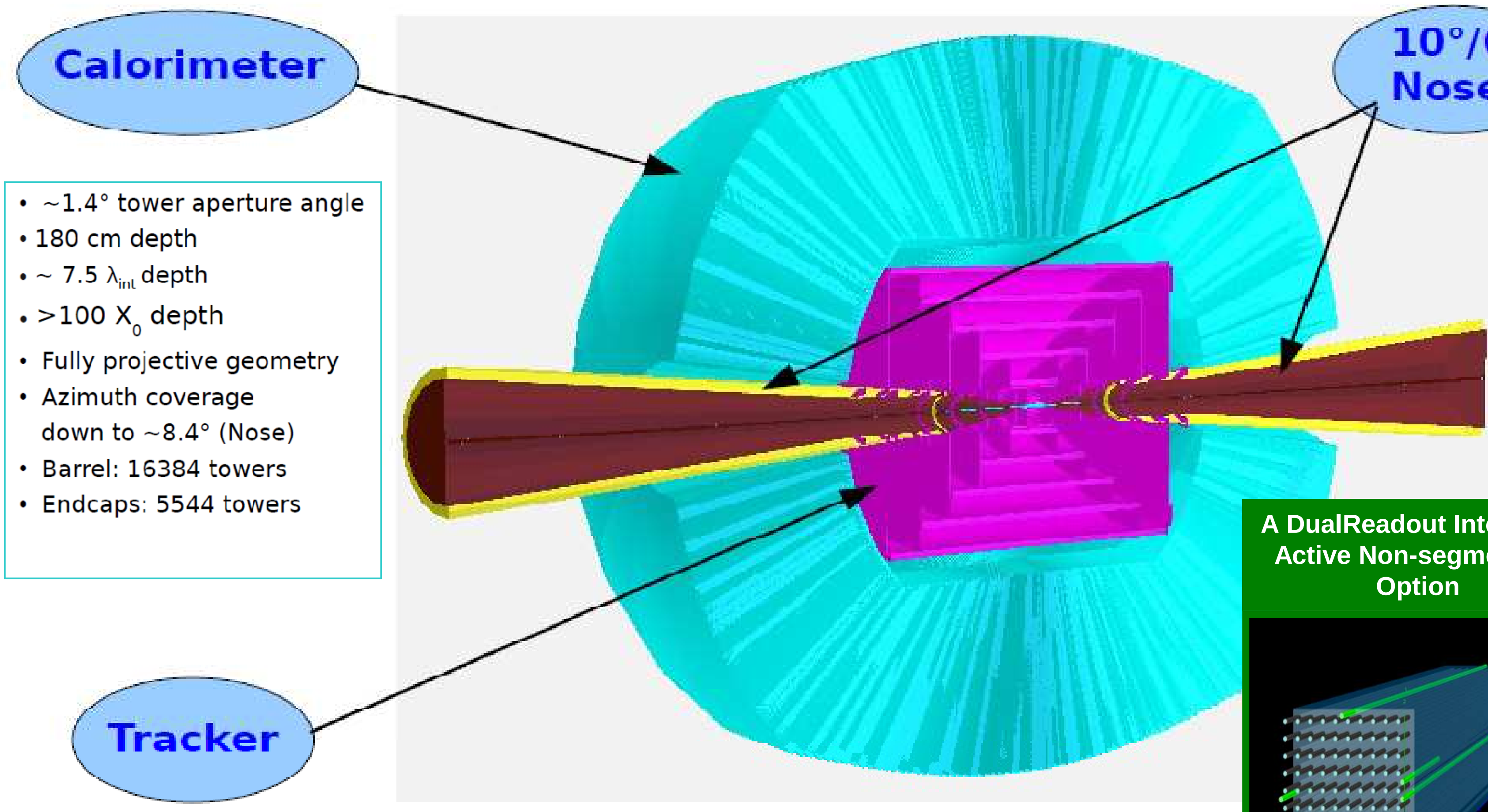
- 7 11.65 16.67 83.14408



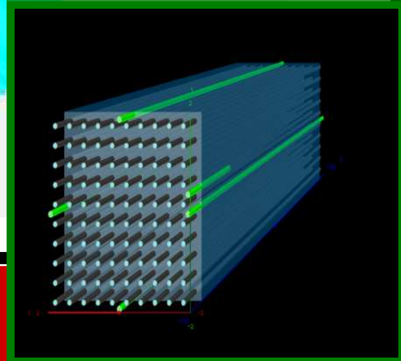

- SiT: 50 μm x 50 μm Si pixel or Si strips (1D or stereo)
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+2) + (4+2) disks Si pixel
- FTD: 20 μm x 20 μm Si pixel

# Integrally Active Dual-Readout Calorimeter

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




**A DualReadout Integrally Active Non-segmented Option**



**Two methodologies implemented:**
**- HHCAL (T1004 collaboration)**
**- ADRIANO (TWICE collaboration)**

# MDI & tracking studies

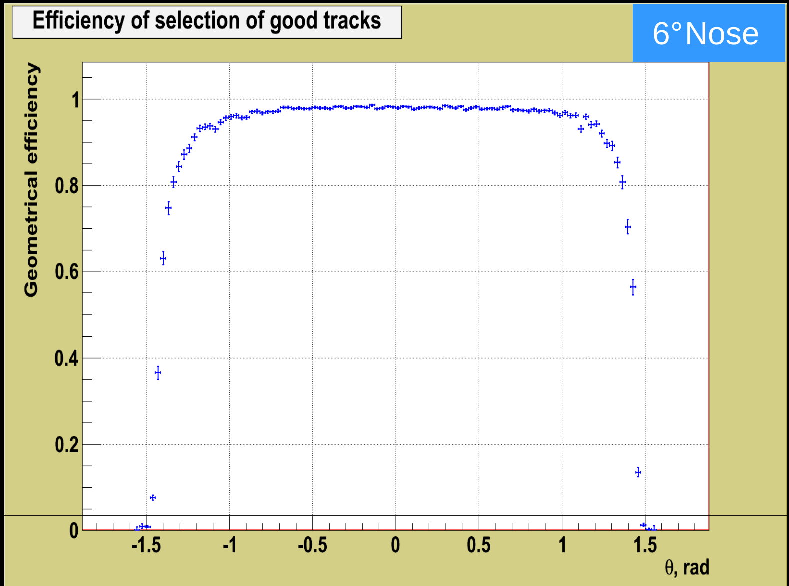
**Charged Track Geometrical Efficiency, Reconstruction Efficiency & Resolutions**

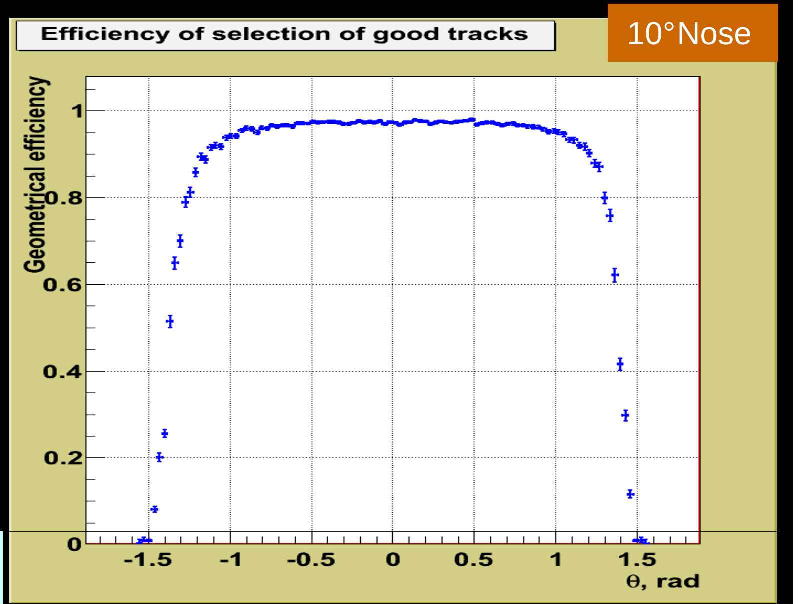
**Background Hits in Tracking Systems**

Single muons

A. Mazzacane

# Geometrical efficiency vs θ



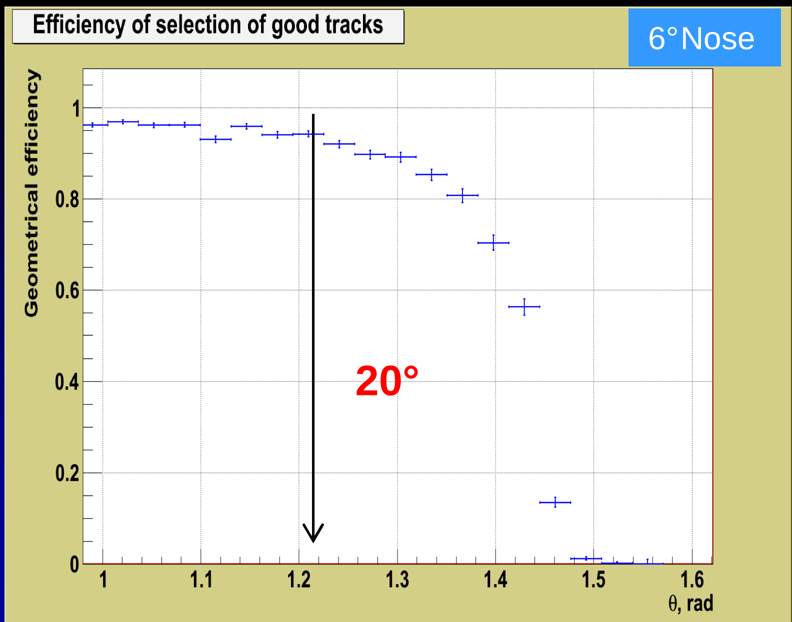

$$\varepsilon_{geom} = \frac{good\ tracks}{generated\ tracks}$$

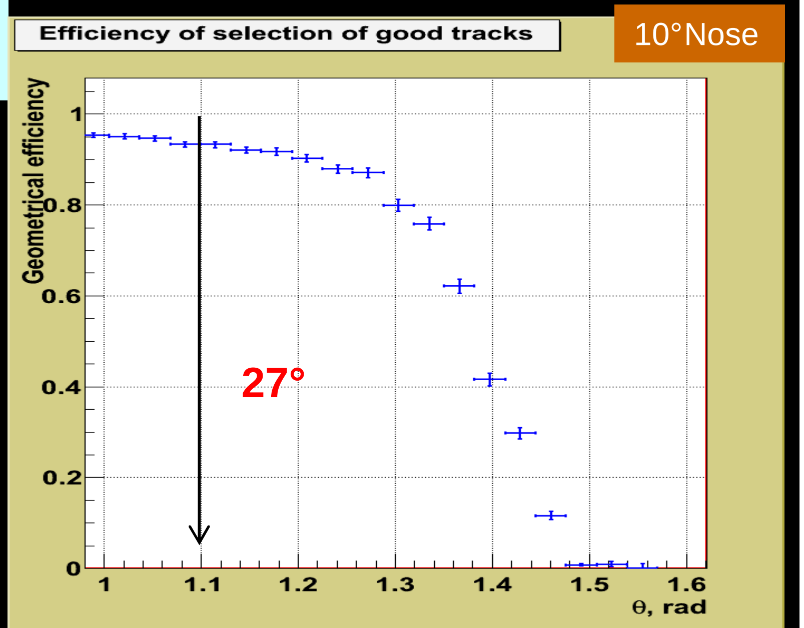
**Defining "good tracks"**

DCA(true) < 3.5 cm

AND

at least 4 hits in detector

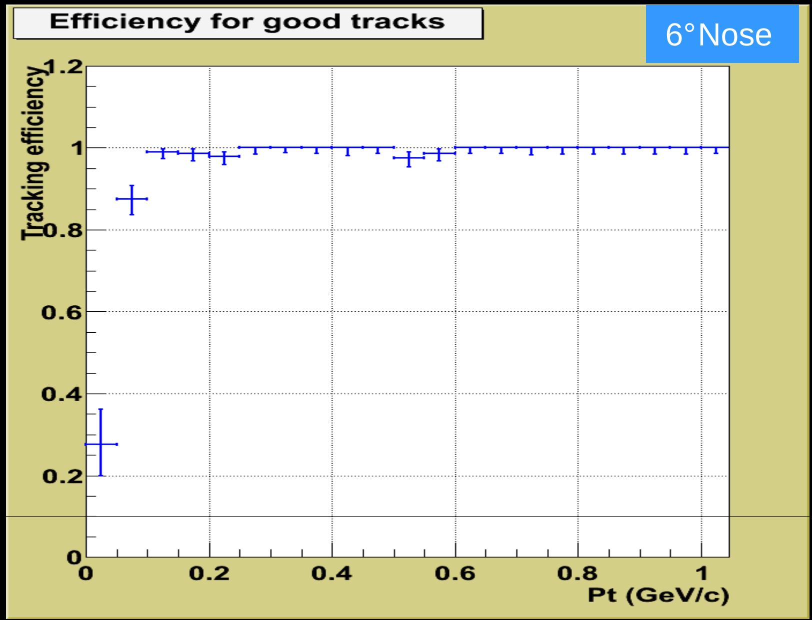


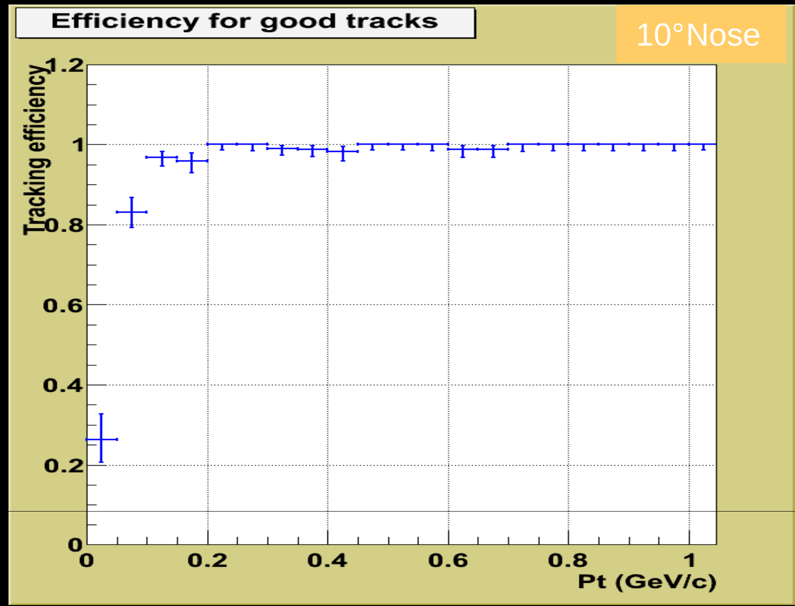



Single muons

A. Mazzacane

# Reconstruction efficiency vs $P_t$




$$\varepsilon_{reconstr} = \frac{reconstructed\ tracks}{reconstructable\ tracks}$$

**Defining "good tracks"**

**DCA(true) < 3.5 cm**

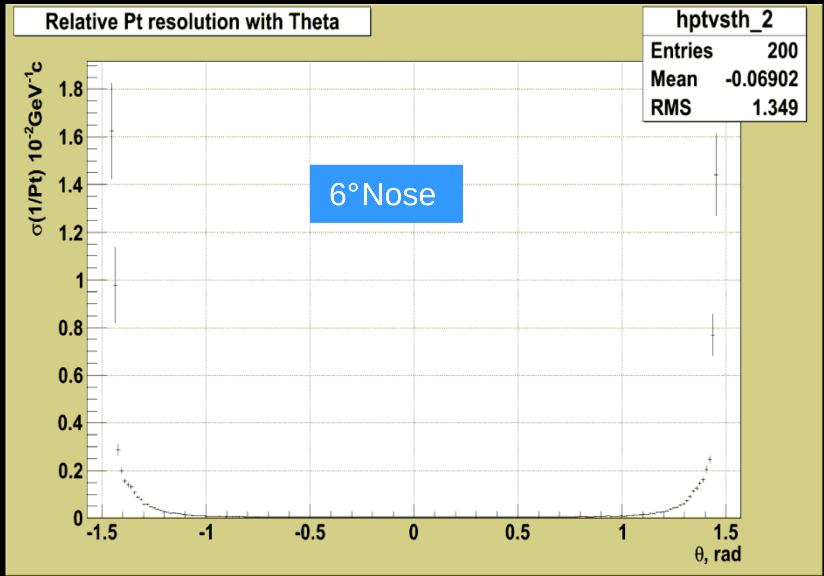
**AND**

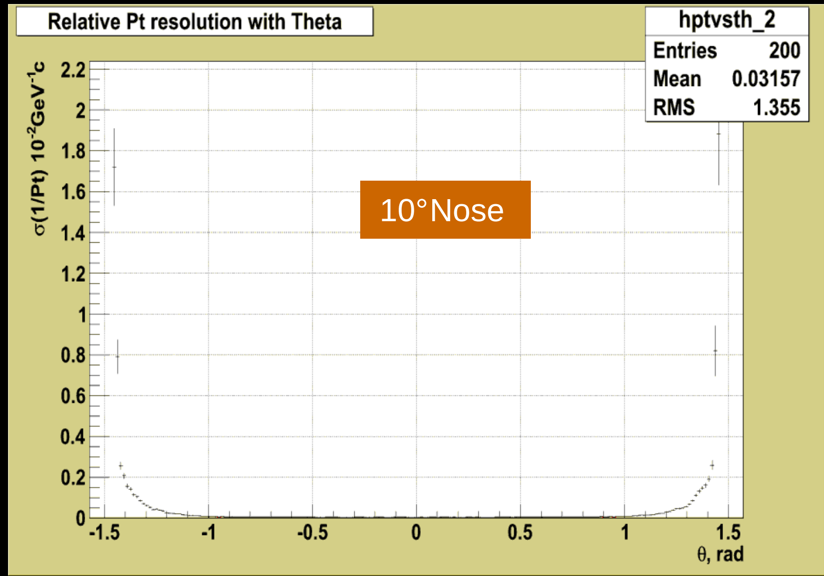
**at least 4 hits in detector**

Single muons

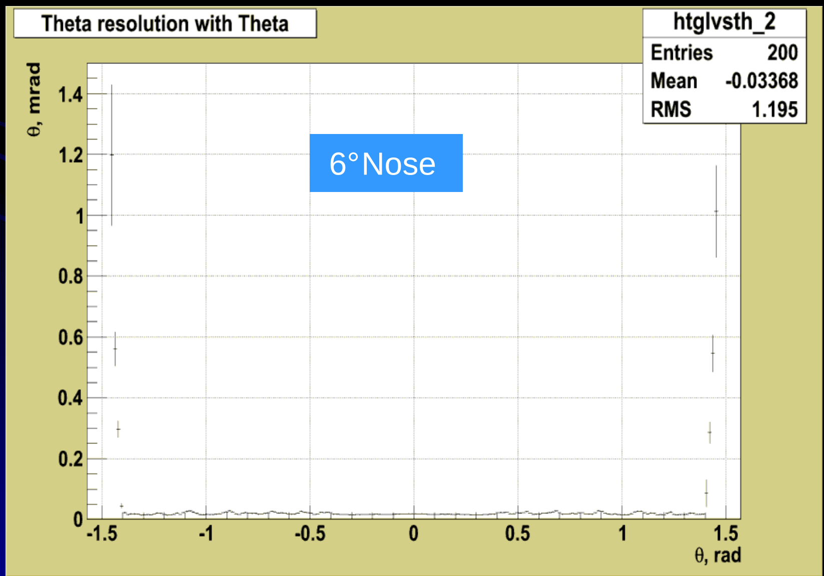
# Tracking Resolution vs θ

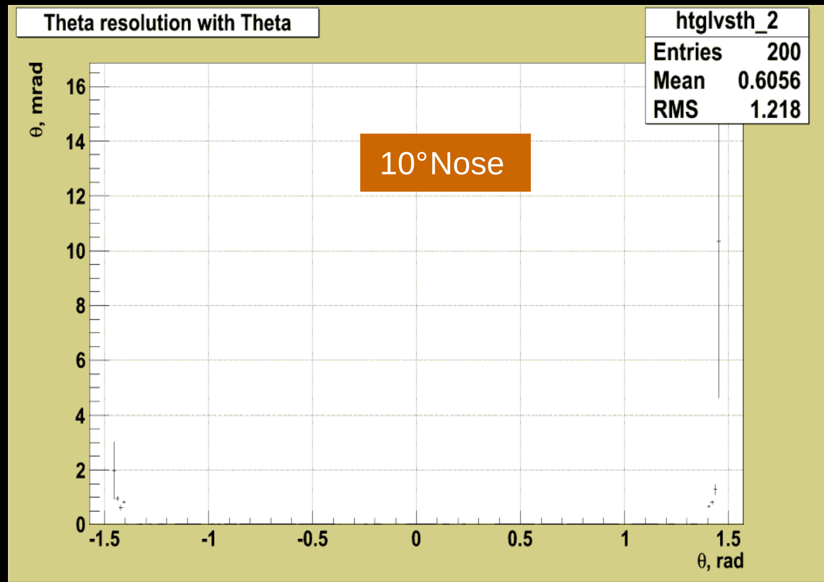
A. Mazzacane




$P_t$

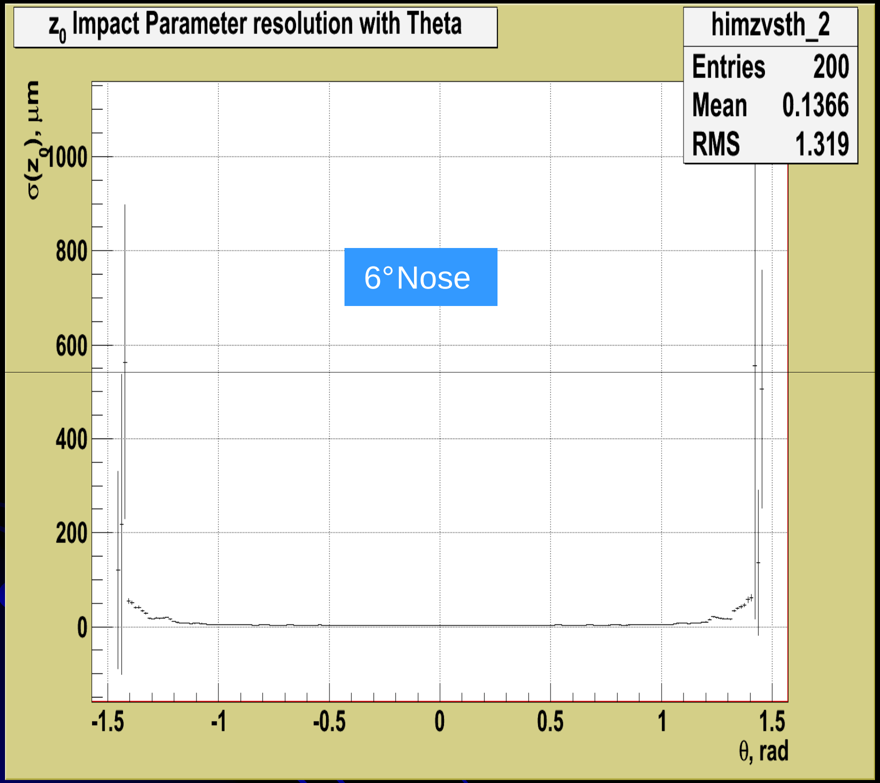


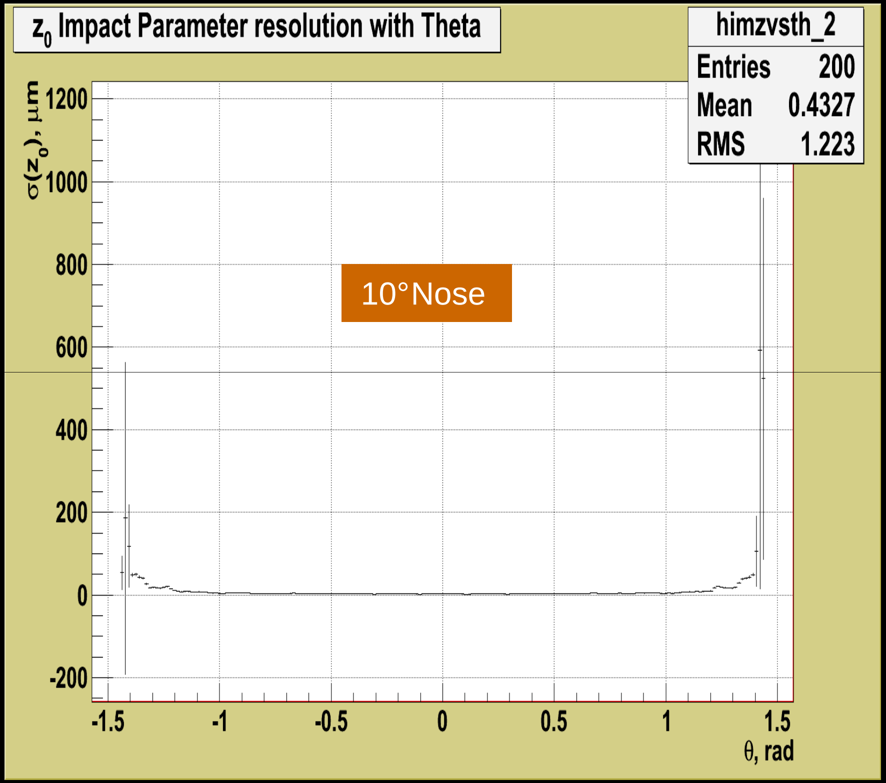




θ

A. Mazzacane

# Tracking Resolution vs θ (cont.)

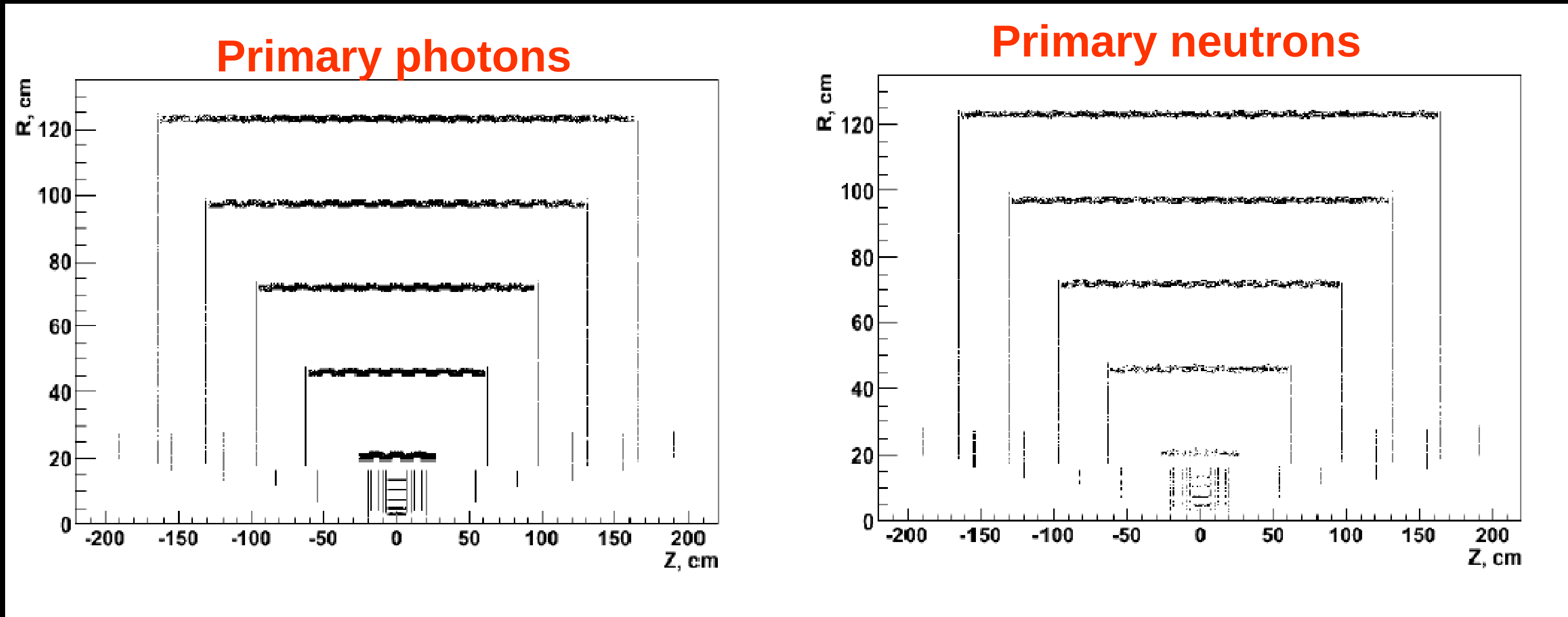


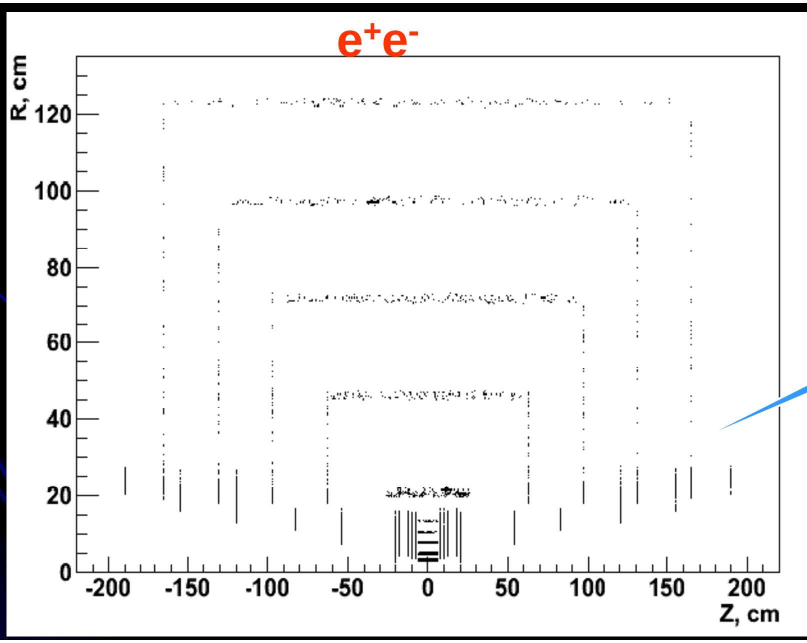




$Z_o$

N. Terentiev

# Background expected in Tracking systems

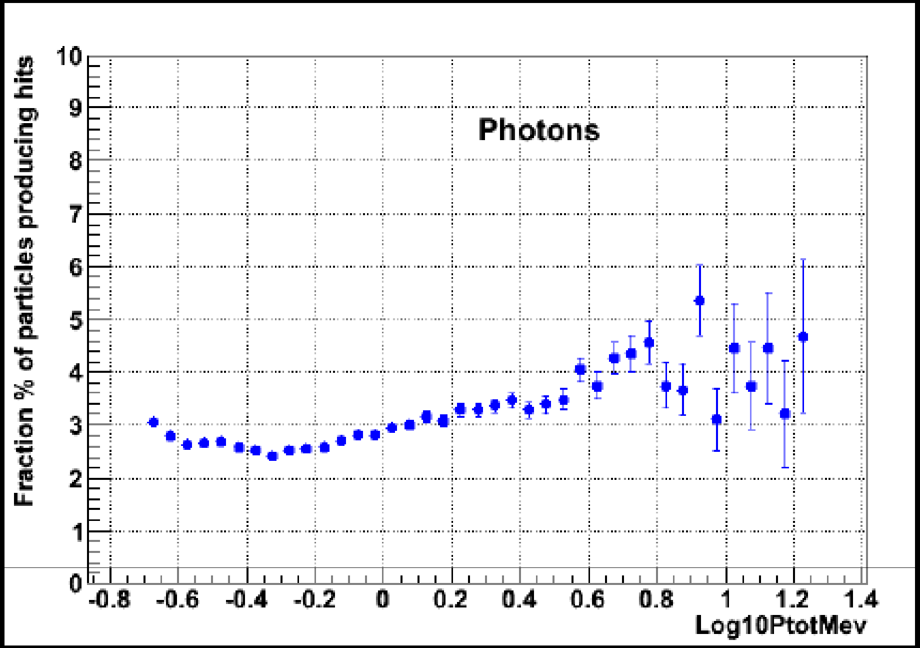


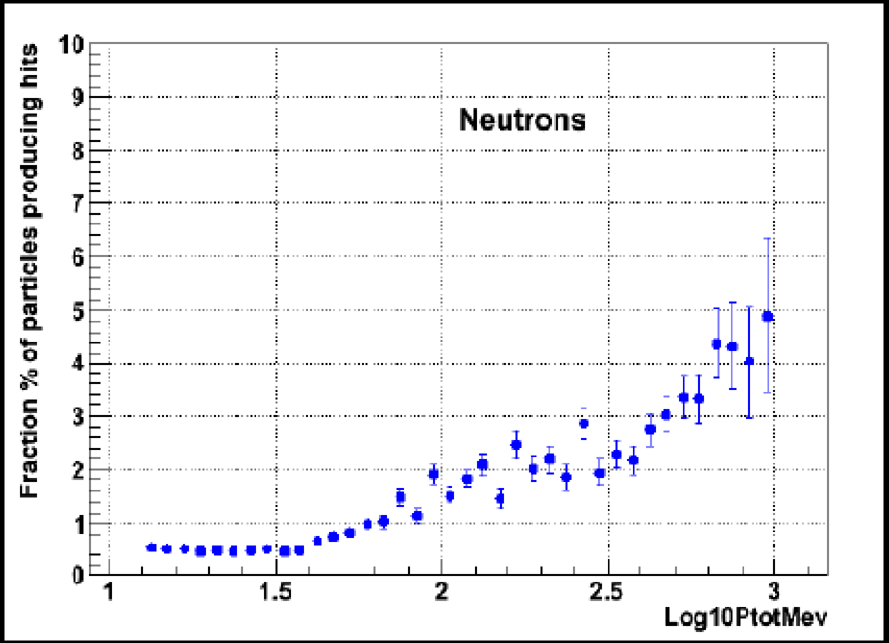



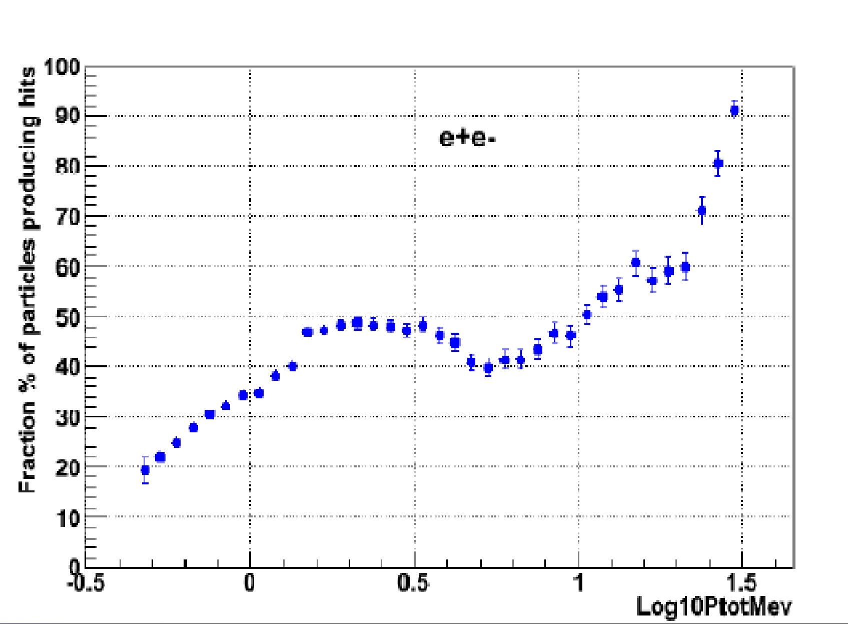

Mostly in 1st VXD layer

N. Terentiev

# Fraction of primary producing hits



N. Terentiev

# Fraction of $\gamma$'s, neutrons and $e^+e^-$ producing hits in the tracking systems

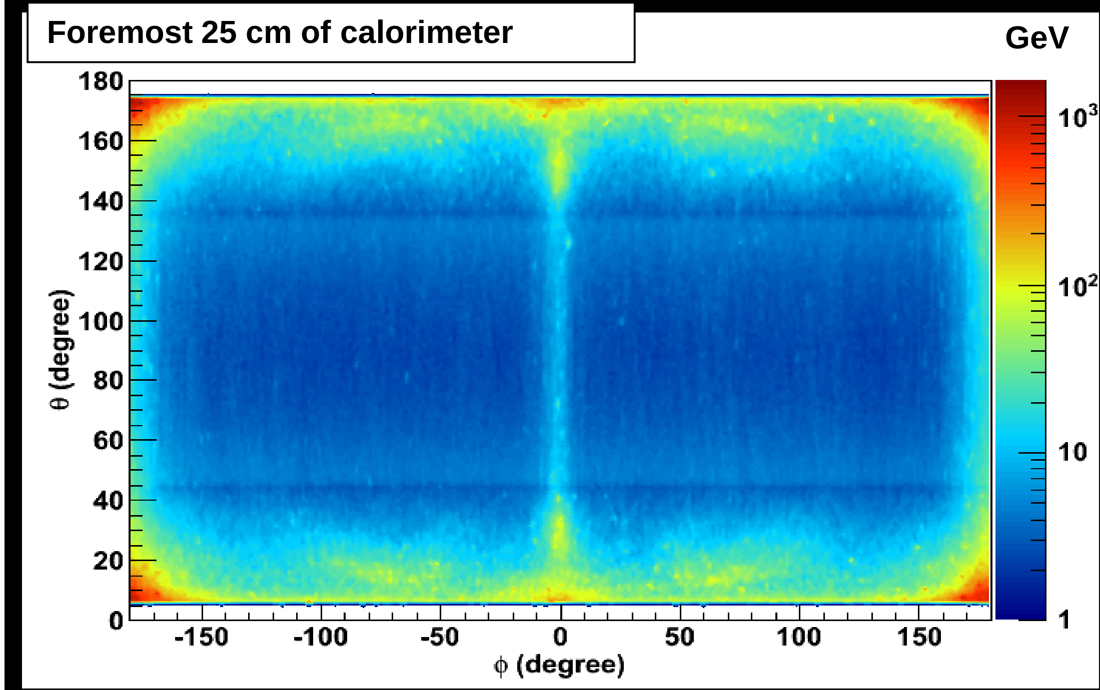
| | photons | neutrons | $e^+e^-$ |
|---|---|---|---|
| Absolute MARS yields, # of particles (weight included, both beams) | 1.77e+08 | 0.40e+08 | 1.03e+06 |
| Fraction of particles producing hits in CT sensitive volumes | ~2.8% | ~0.6% | ~43% |
| # of MARS particles "seen" | 5.0e+06 | 0.24e+06 | 0.44e+06 |

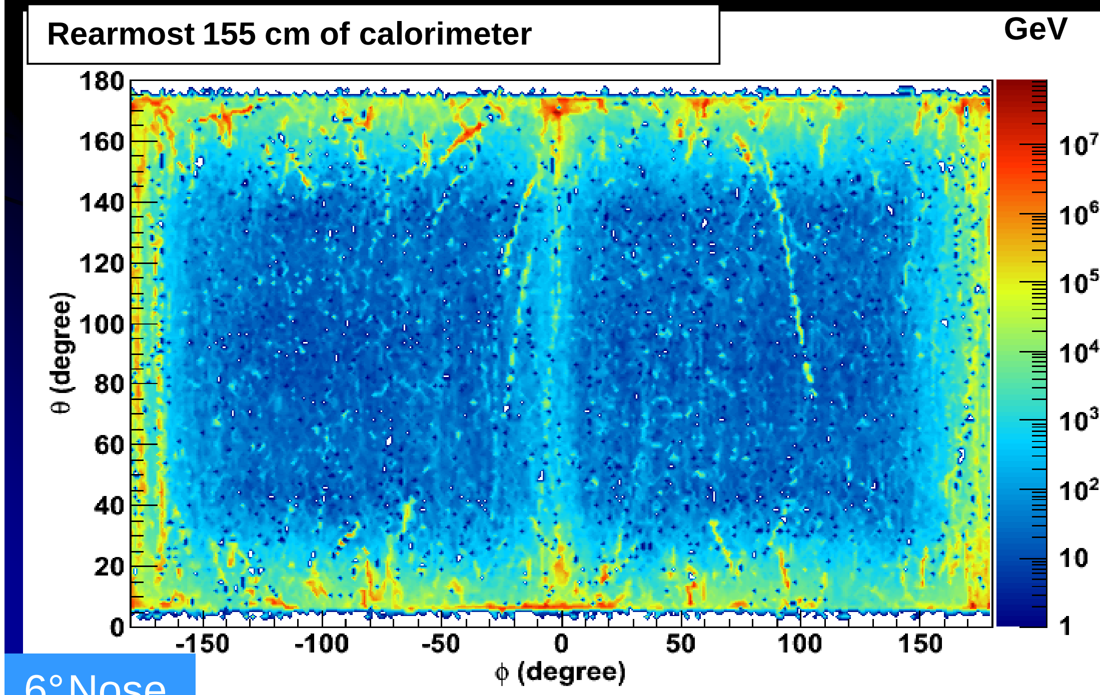
- Photons Ekin ~ 0.2 – 100 MeV
  Neutrons Ekin ~ 0.1 – 1000 MeV
  $e^+e^-$ Ekin ~ 0.2 – 100 MeV

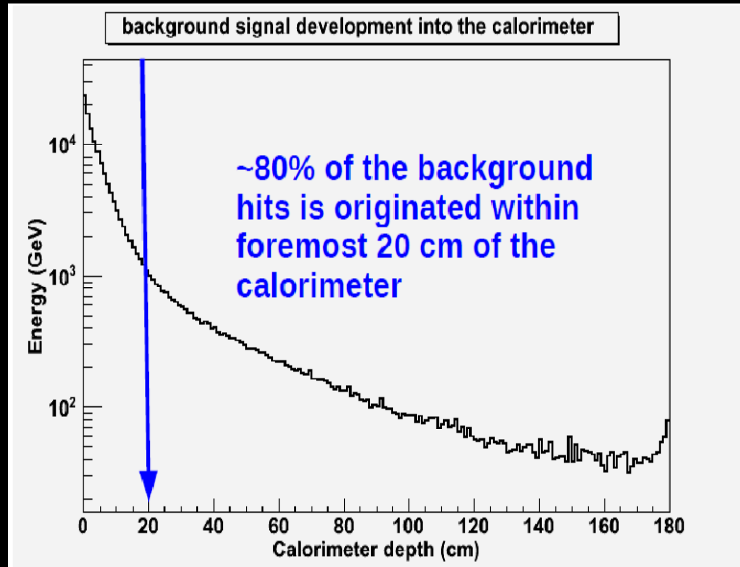
# Beam background in the calorimetry studies with different noses

V. Di Benedetto

# Integrated background in calorimeter



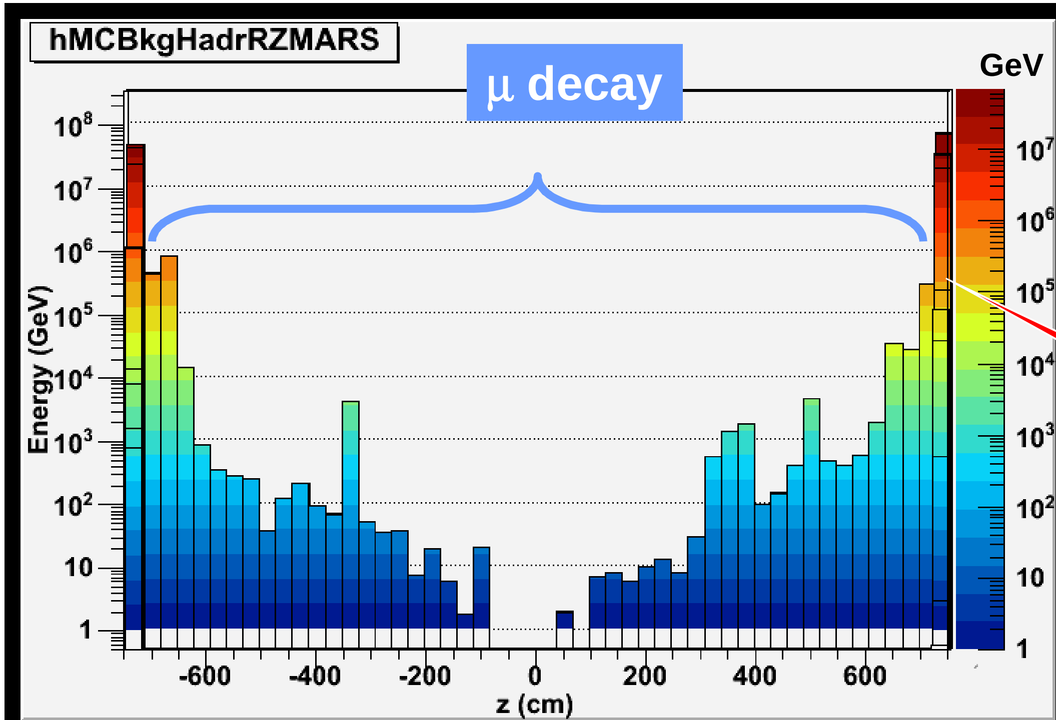



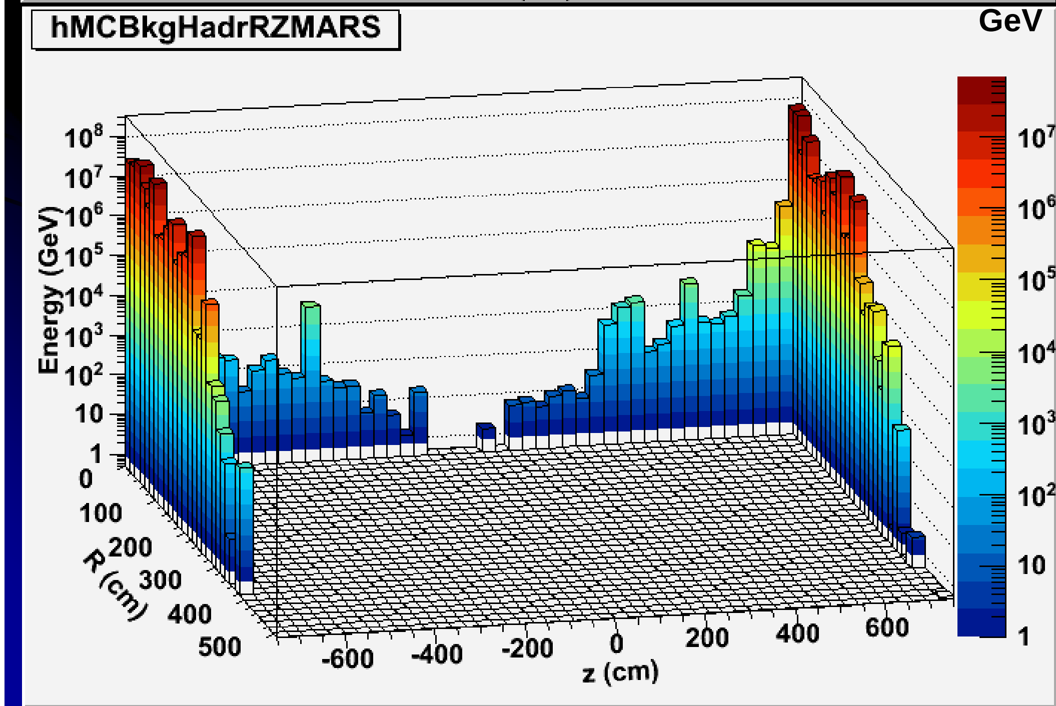




- $E_{CM}$ = 1.5 TeV
- Calorimeter coverage $6° < \theta < 174°$
- Weighted particles method
- MDI separation plane: 7.5 m from I.P.
- No pre-cuts
- Full G4 simulation
- 1 bin = 4x4 $cm^2$ projective cell

6° Nose

# Integrated background from MARS in calorimeter vs origin of particle



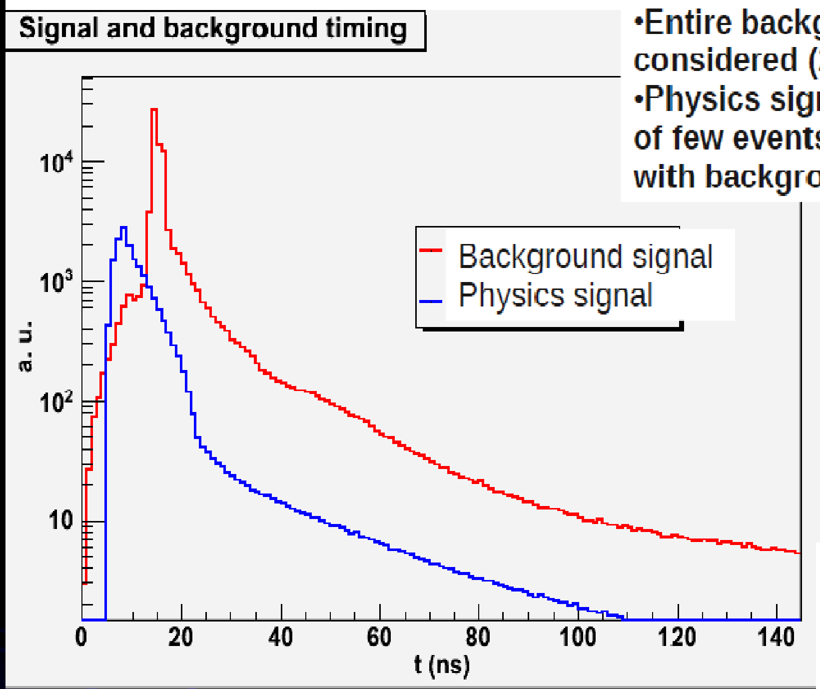

**R = $r_{xy}$ of particle origin (1bin= 30cm)**

**Z=7.5 means that the particle originated outside the MDI separation plane (1bin=16cm)**

6° Nose

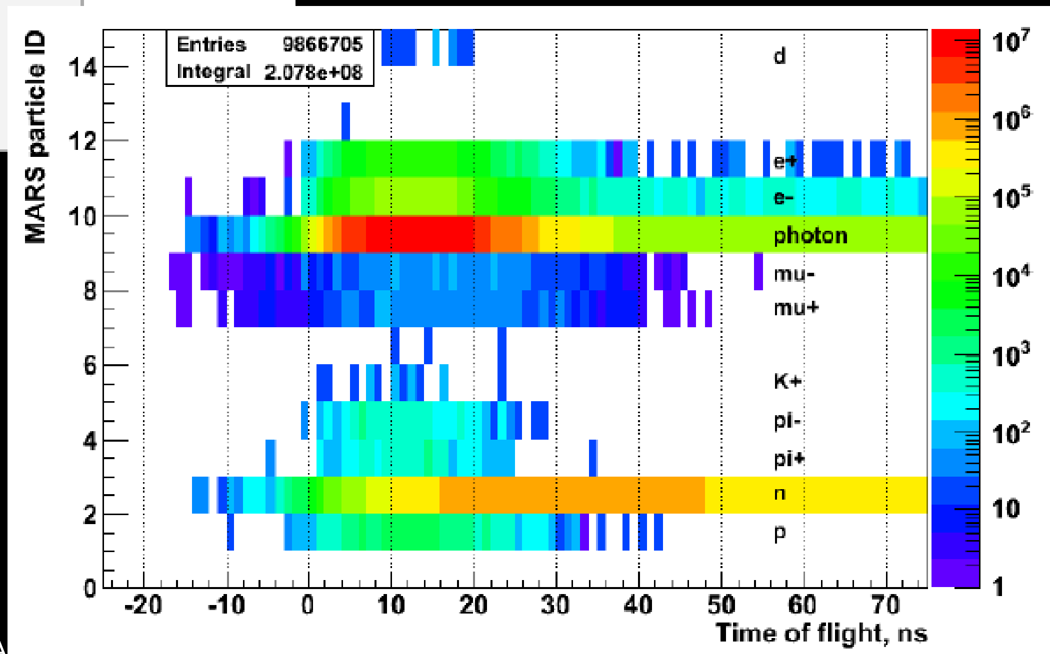
V. Di Benedetto
N. Mokhov
S. Striganov

# Background TOF properties




- Entire background considered (25 m + 250 m)
- Physics signal is an average of few events (it is not in scale with background)

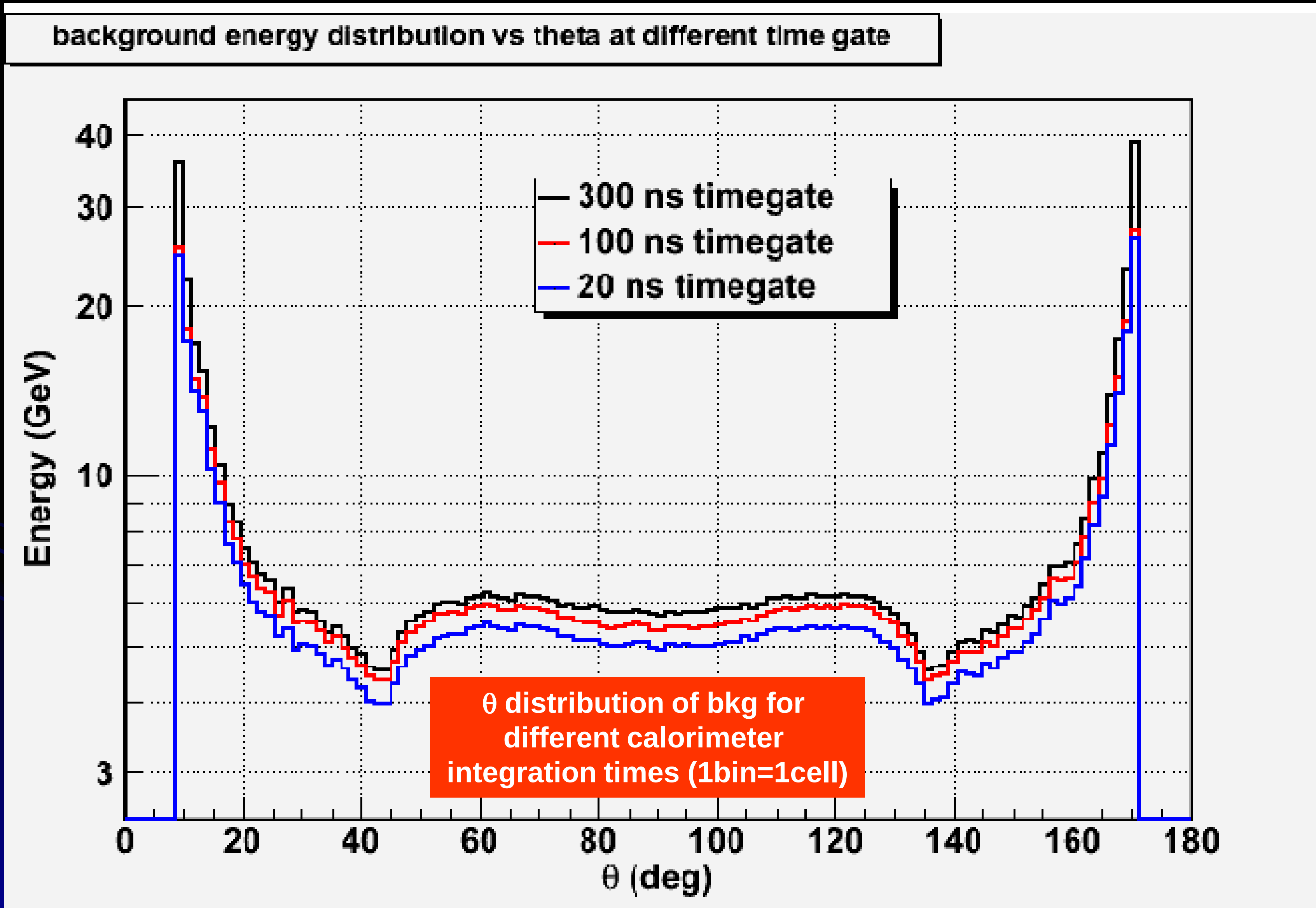
**ILCroot simulation**
Signal timing from calorimeter:
Bkg vs $\mu^+\mu^-$ -> $\nu_\mu$ $\underline{\nu}_\mu$ + $Z_o$ -> 2-jets




**MARS15 simulation**
Backgrounf ToF vs PiD
(partial event)

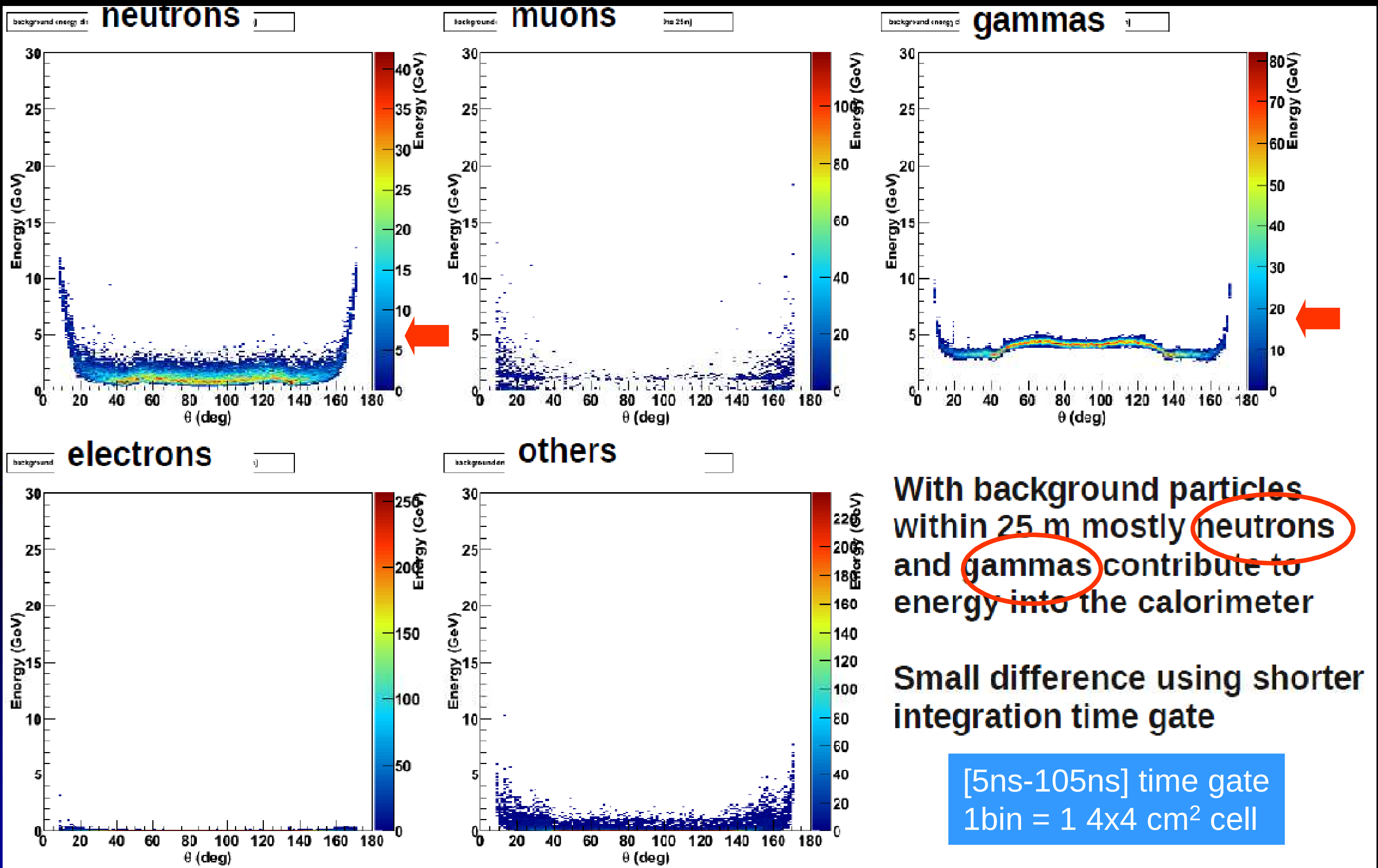
V. Di Benedetto

# Background Properties in Detectors



V. Di Benedetto

# Beam Background Originating <25m vs θ




With background particles within 25 m mostly neutrons and gammas contribute to energy into the calorimeter

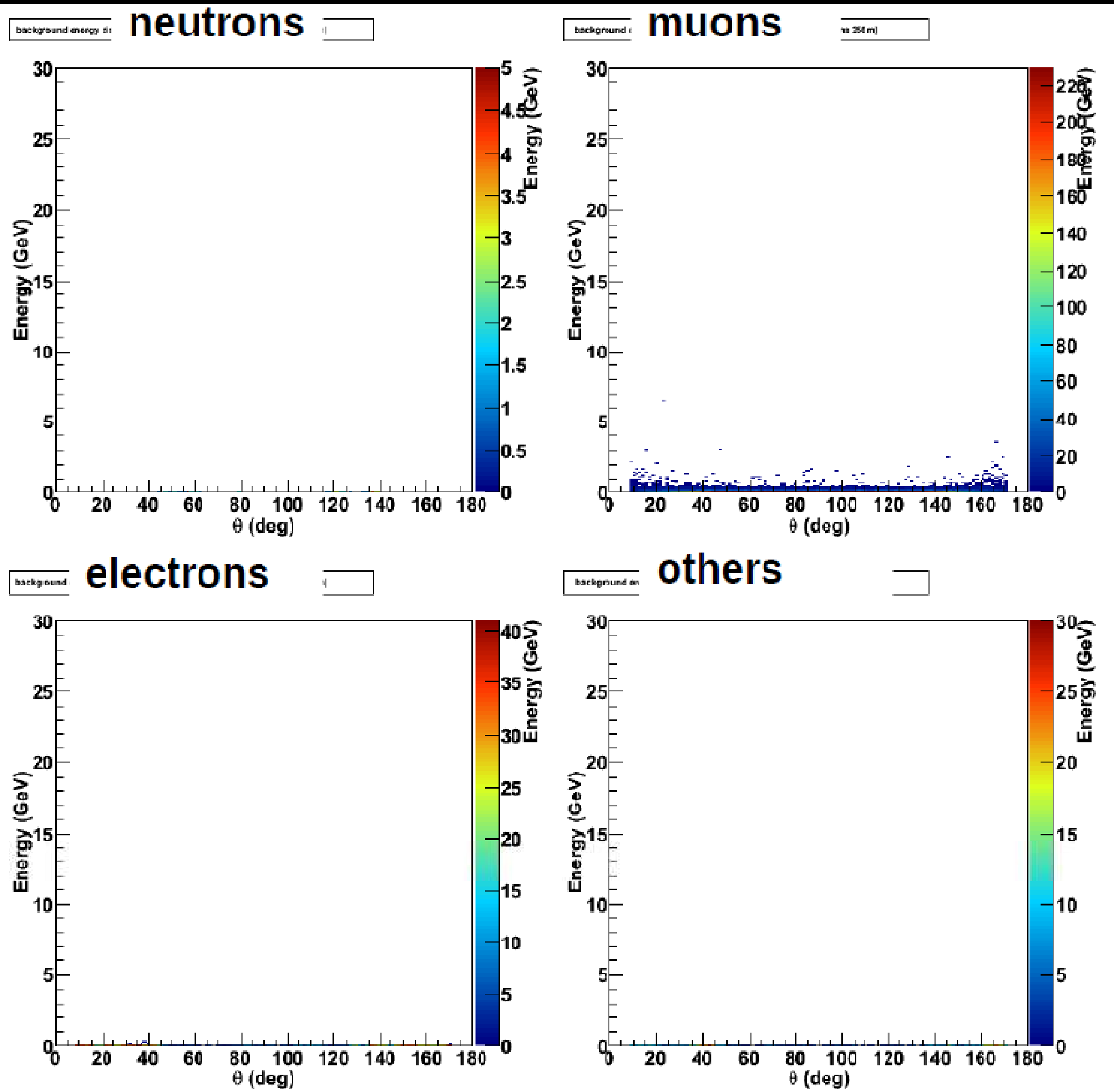
Small difference using shorter integration time gate

[5ns-105ns] time gate
1bin = 1 4x4 cm$^2$ cell

[5ns-105ns] time gate

V. Di Benedetto

# Beam Background Originating from [25-200]m vs θ




**With background particles from 250 m only muons contribute to energy into the calorimeter**

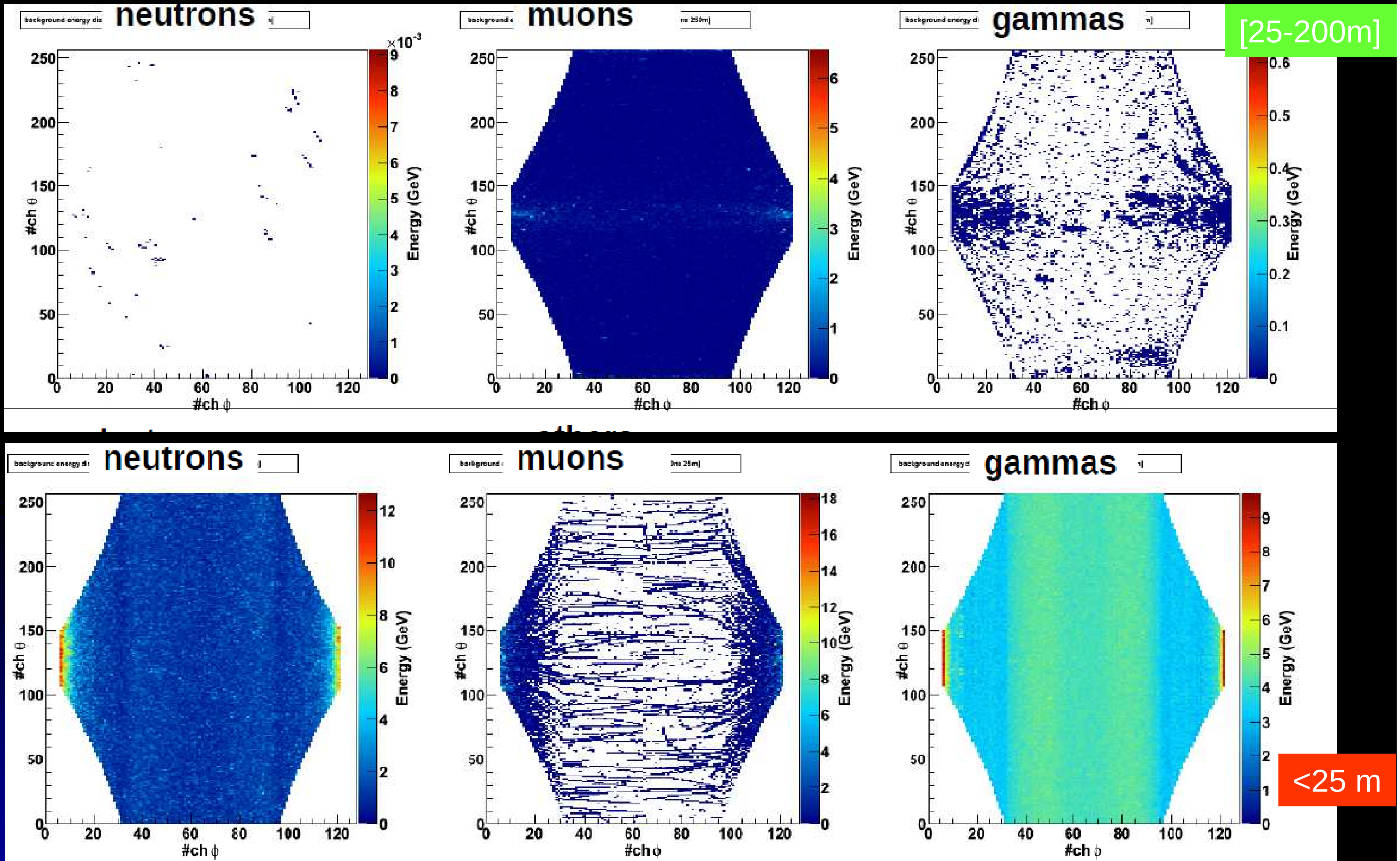
**No difference using shorter integration time gate**

[5ns-105ns] time gate
1bin = 1 4x4 $cm^2$ cell

[5ns-105ns] time gate

V. Di Benedetto

# Comparing Far vs Near Background

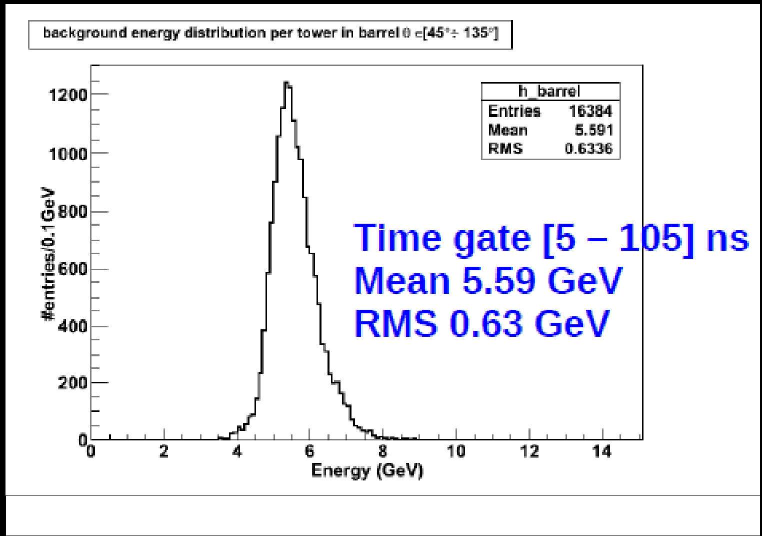



1 bin = 1 calorimeter cell

10° Nose

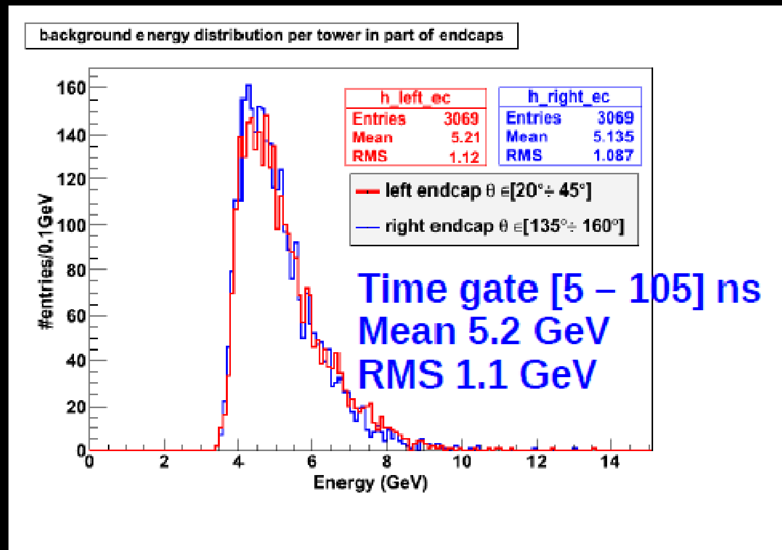
V. Di Benedetto

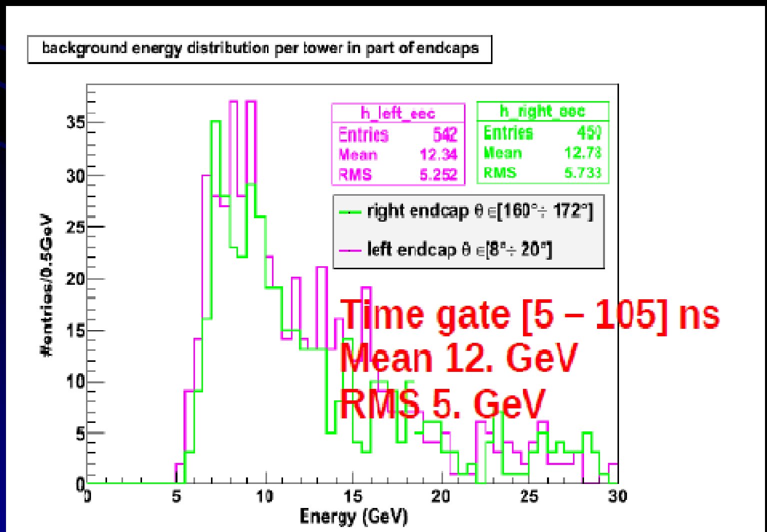
# Background Energy Distribution in ADRIANO




**Central barrel (> 45°)**
**Fluctuations are ΔE/E~12%/cell**
**and ΔE ~ 3 GeV for typical jet**

**Large angle EC (20°> > 45°)**
**Fluctuations are ΔE/E~20%/cell**
**and ΔE ~ 6 GeV for typical jet**




**Small angle EC (8°< < 20°)**
**Fluctuations are ΔE/E~40%/cell**
**and ΔE ~ 20-25 GeV for typical jet**

# Preliminary Physics Studies

# First Physics Process Study in ILCroot

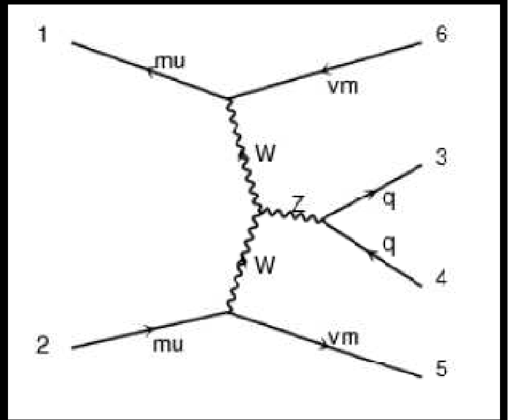
- Production of a single $Z_o$ in a fusion process:

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

- 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 $\mu^-$ is not tagged?
- Madgraph, Pythia and MARS15 as event generators
- ADRIANO calorimeter used in the study
- A. Mazzacane recursive jet finder (from ILC studies)
- **Full simulation, digitization and reconstruction**

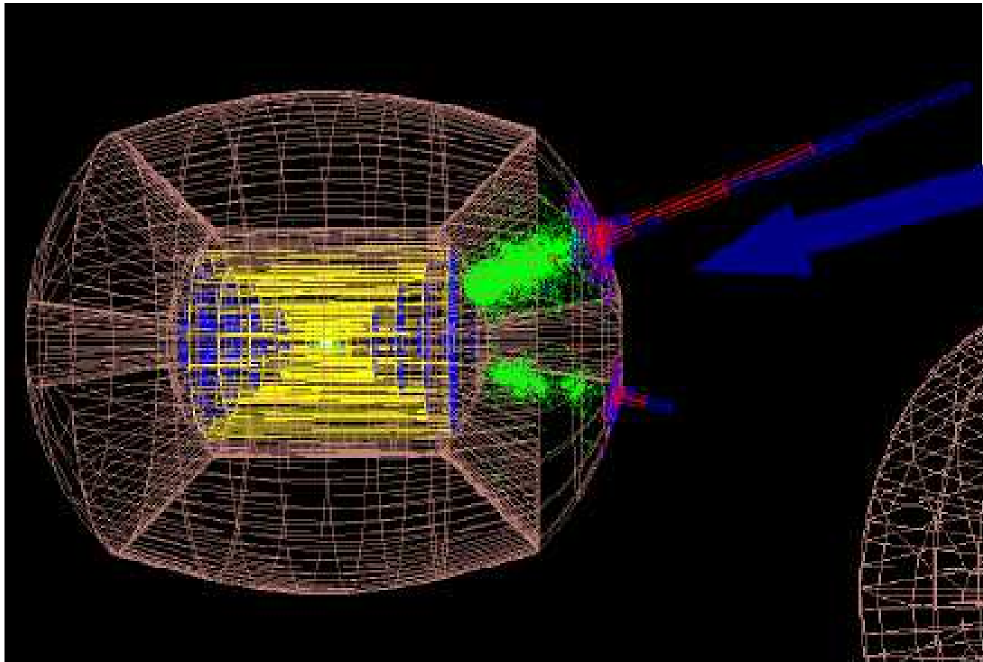



$\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu Z^0$ @1.5TeV

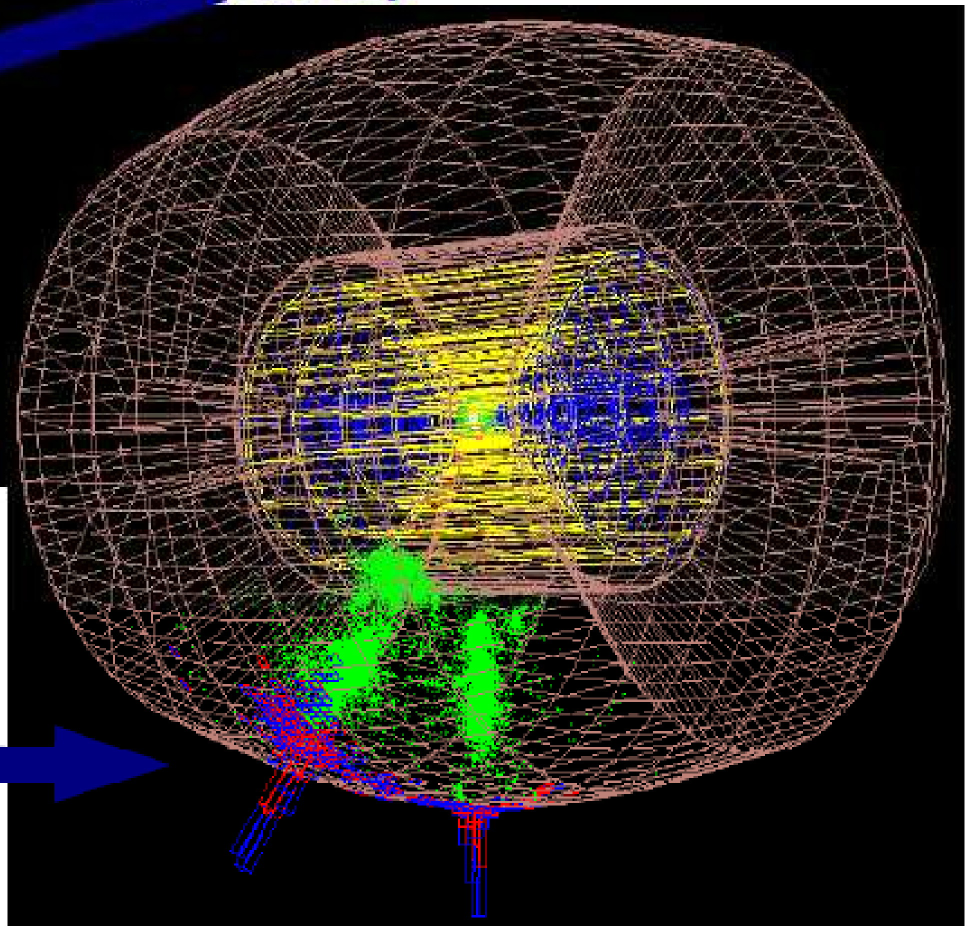
→ jet, jet

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

# Some jet event display



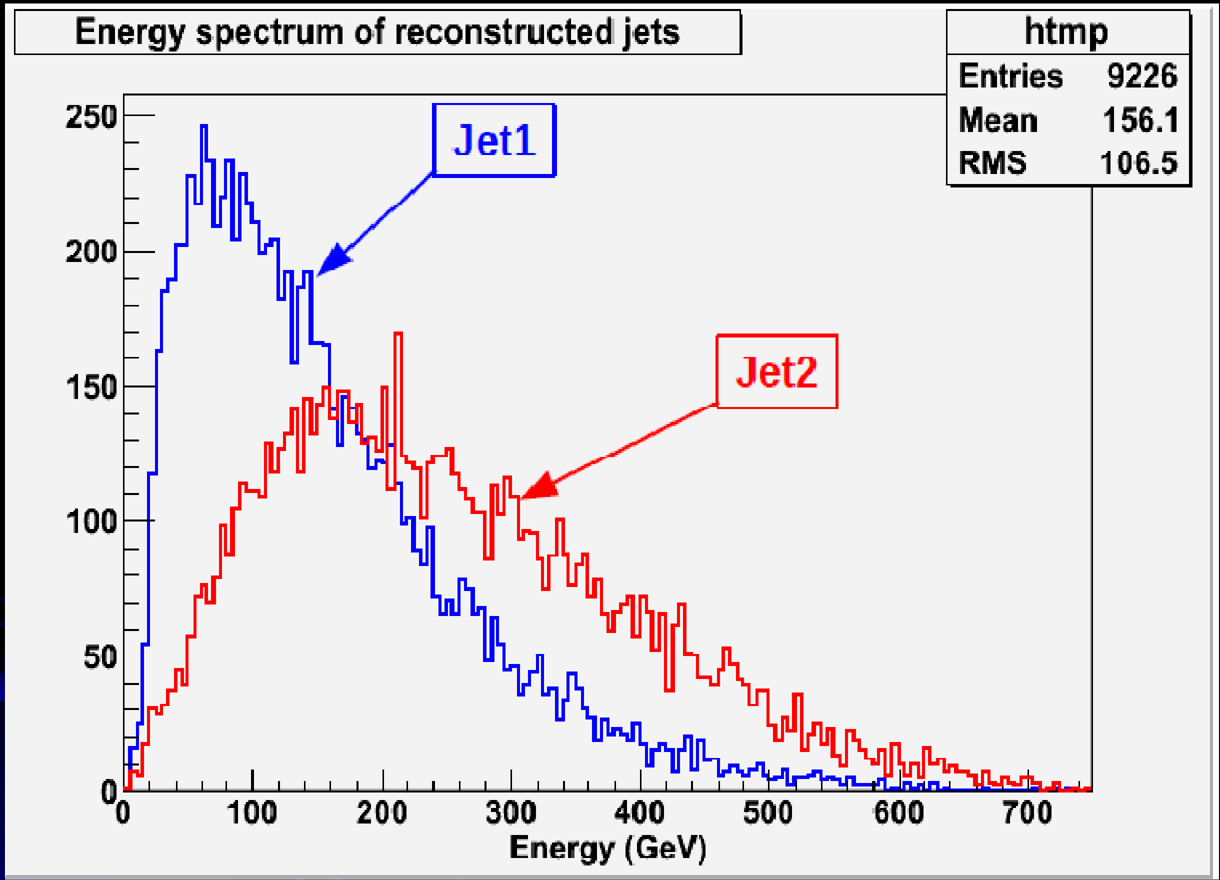
Jets with energy of 435GeV and 68GeV in the endcap



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

V. Di Benedetto
A. Mazzacane

# Jets Reconstruction




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

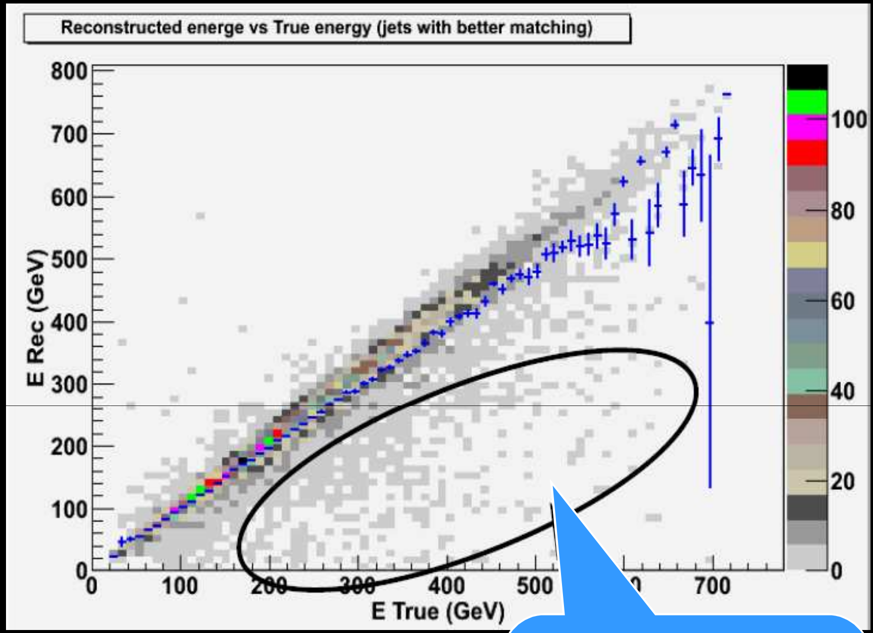
## A.M Jet finder algorithm

- 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

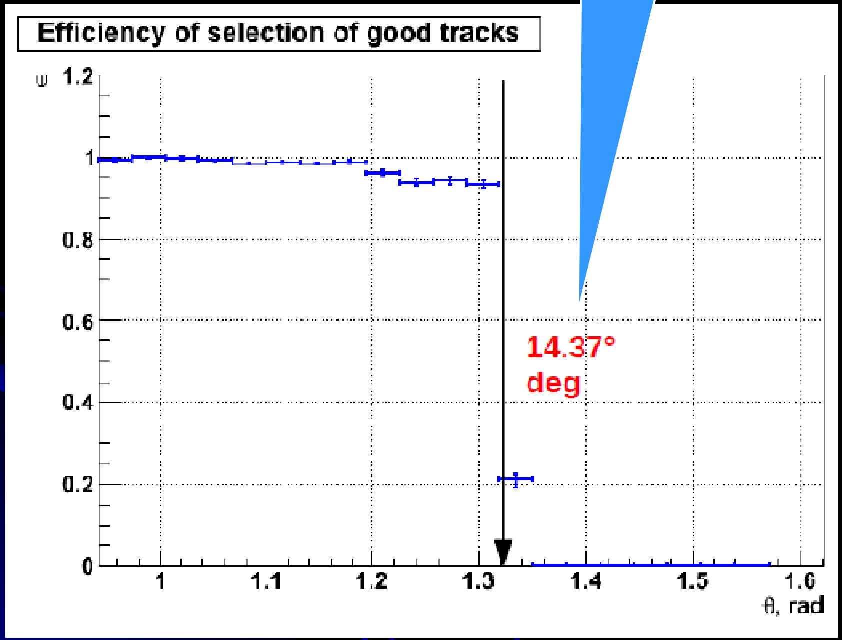
V. Di Benedetto, F. Ignatov, A. Mazzacane

# Detector Performance for $\mu^+\mu^- \to \nu_\mu \underline{\nu}_\mu + Z_o$

**Jet energy response**




**Effect of 10° nose**




**Geometrical efficiency for charged tracks**

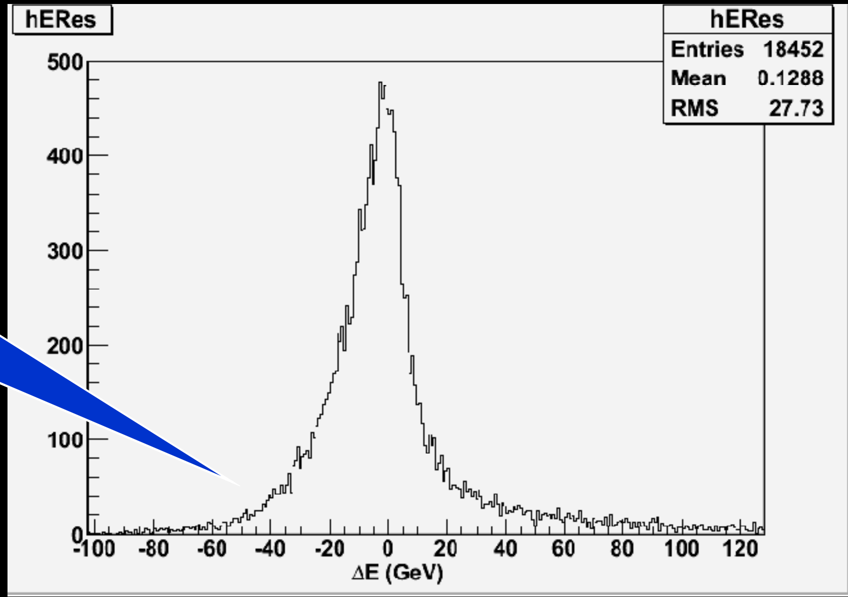
**No leakage corrections yet!**

V. Di Benedetto
A. Mazzacane

# Jet Reconstruction (no cuts applied)

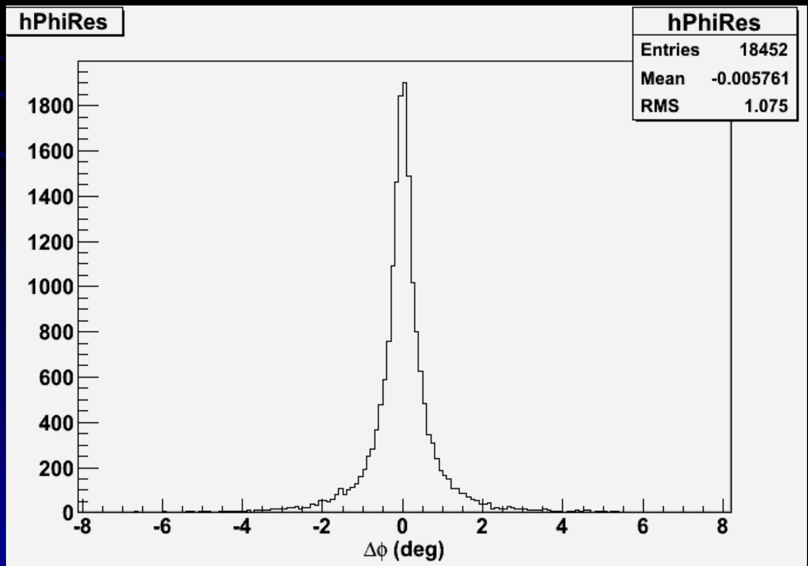
**Jet energy resolution (bin=1GeV)**

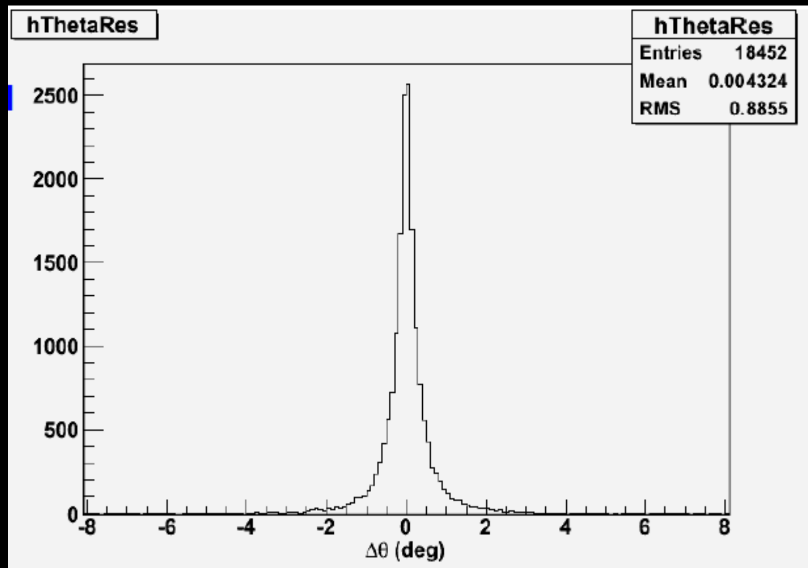
**Effect of leakage & nose**



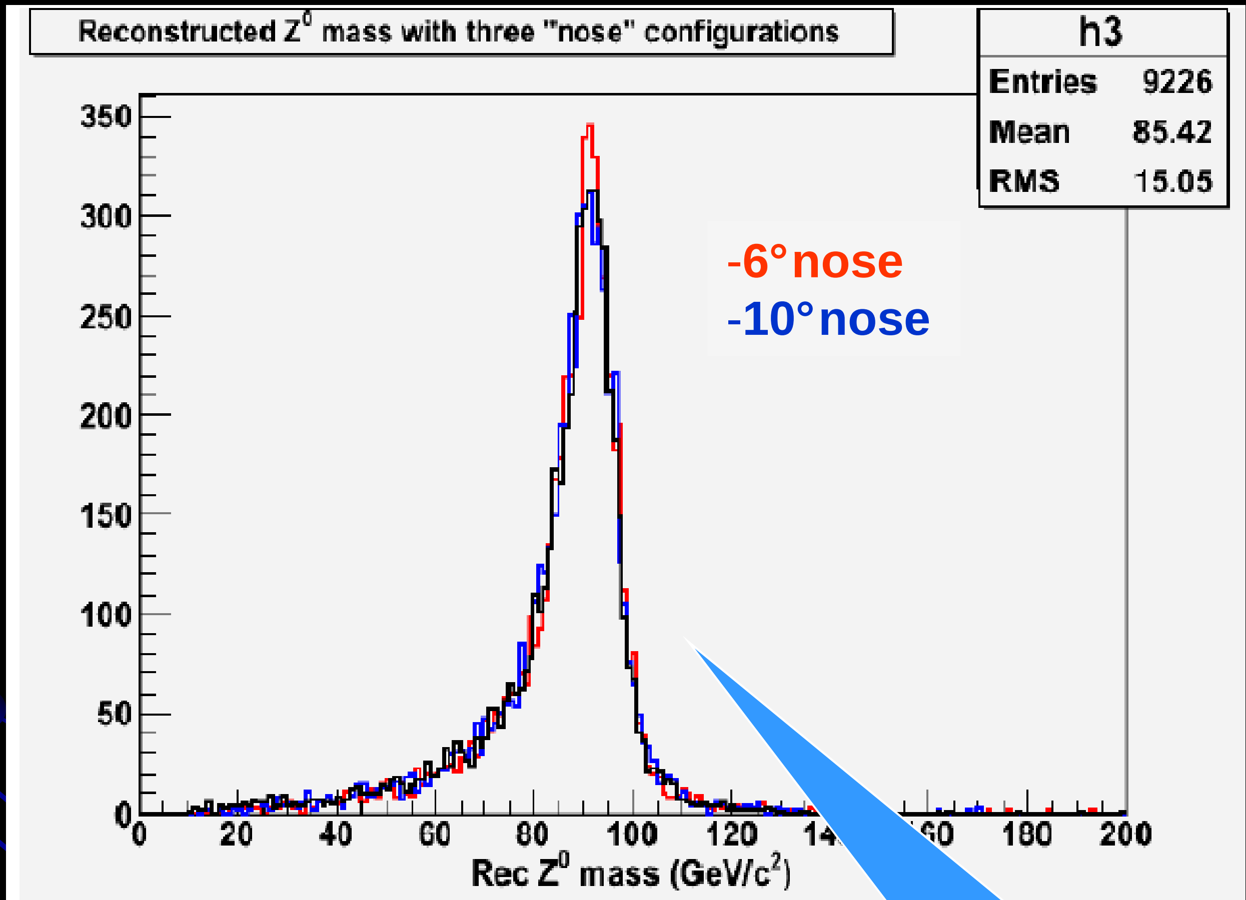

**No leakage corrections yet!**

**Angular resolution of Reconstructed jets (bin=0.1°)**



# Zo Mass with Different Noses

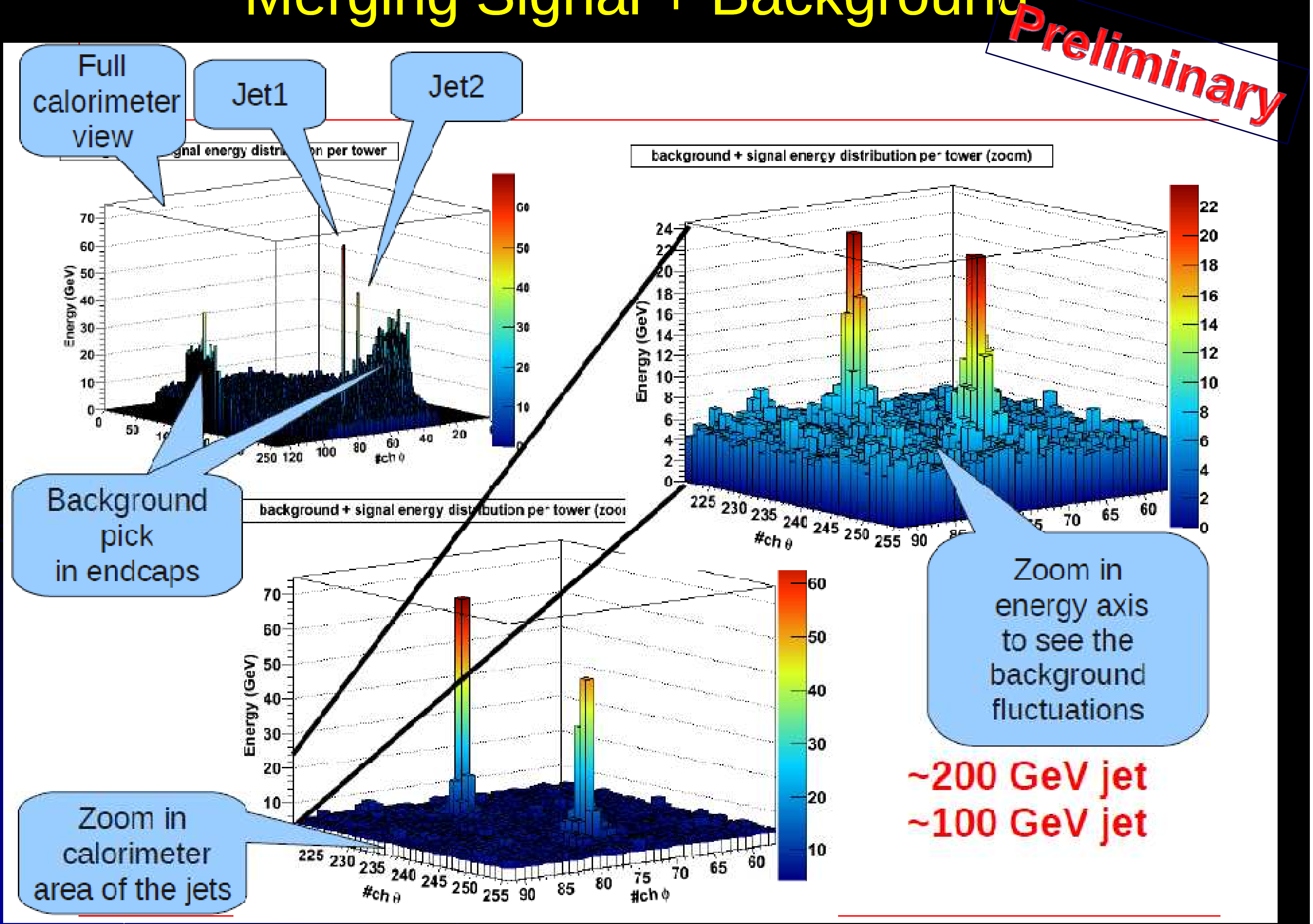



**Fully reconstructed**
**Z° mass (bin=1GeV)**
**No cuts applied**
**No leakage corrections**

**Minor difference observed**

V. Di Benedetto

# Merging Signal + Background




~200 GeV jet
~100 GeV jet

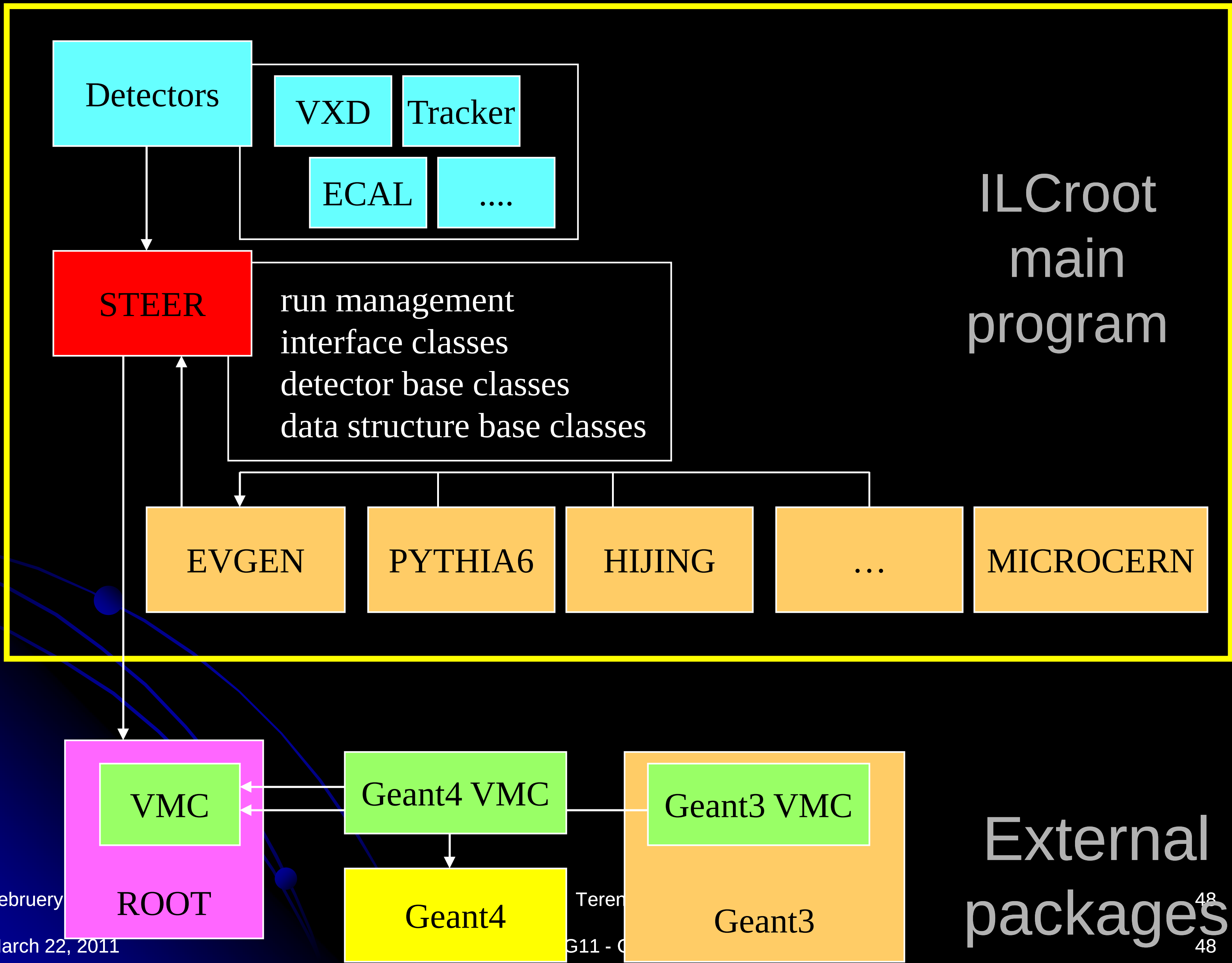
# Conclusions

- MARS15 is stable and continuosly being improoved for μCollider physics and detector studies (and much more!)
  - Synergies between MARS an ILCroot working groups are excellent
- **ILCGenReaderMARS** has been added to ILCroot framework for μCollider physics and detector studies
  - The machinery work smoothly for fast, semi-fast and full simulations
- One technical issues to resolve with charge track reconstruction
  - too many hits/track in a bkg event ( $\mathcal{O}(10^2)$ compared to Au-Au in ALICE)
  - Parallel Kalman filter can only be applied to 5% of the bkg event (about 80,000 tracks found!)
- Preliminary physics studies are ongoing:
  - Physics is mostly unaffected for θ > 20°
  - For θ<20° jet energy uncertainties have 20-25 GeV contributio n from background

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

# Backup slides

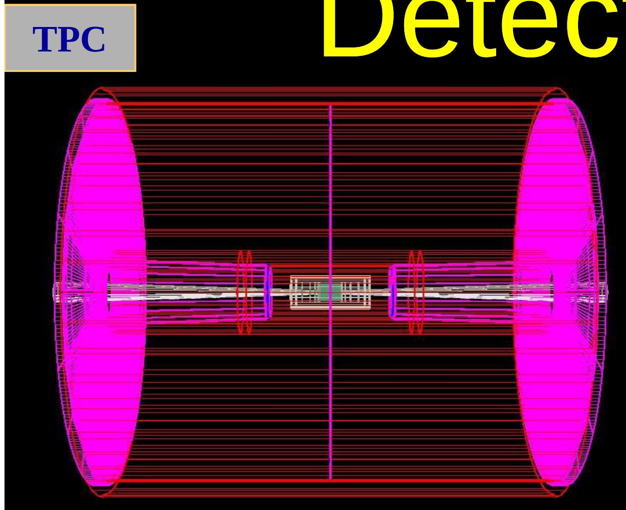
# ILCroot architecture

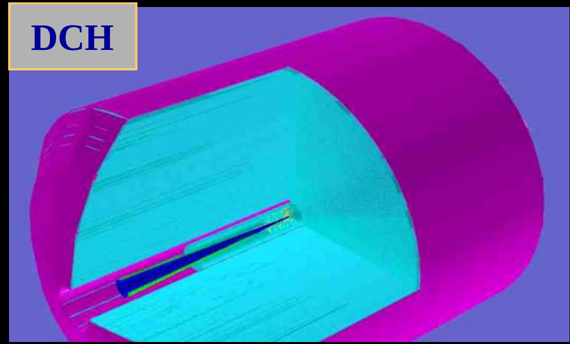


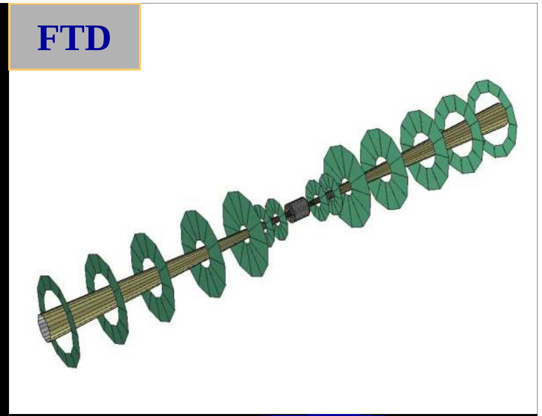
# Weights Handling in ILCGenReaderMARS

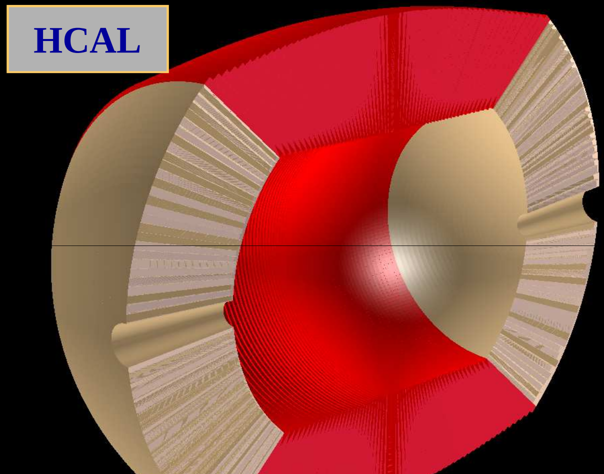
- **Weigths from MARS have different meanings**:
  - MDI surface: collection of particles with the same |P| and |r| but integrated over $2\pi$ in momentum and space coordinate
  - Along the beamline: collection of particles with the same |P| and origin but integrated over $2\pi$ in momentum space
- **ILCGenReaderMARS feeds the Montecarlo with:**
  - 1 particle with corresponding weight
    - OK for calorimetric studies
  - W particles smeared according to ther origin
    - OK for detailed tracking occupancy studies
    - ...but very slow and time consuming
  - A mix of the above
    - OK for most tracking studies

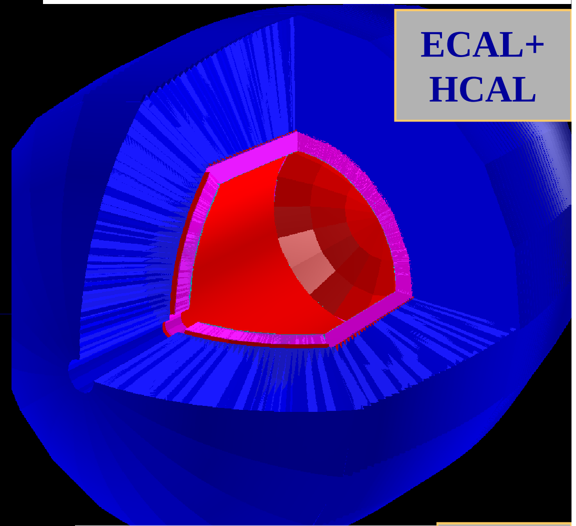
# Detectors in ILCroot

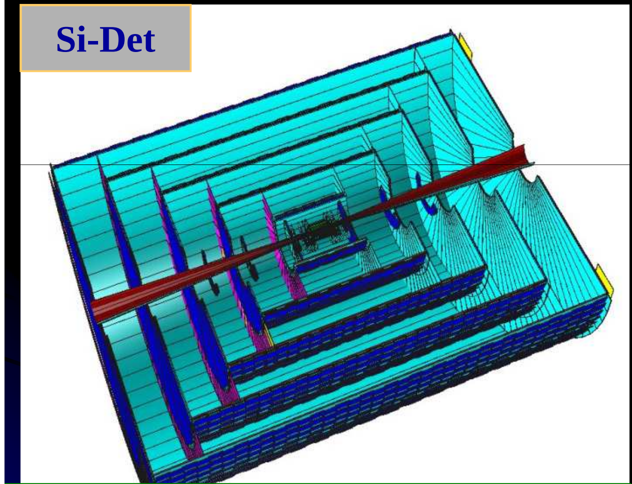


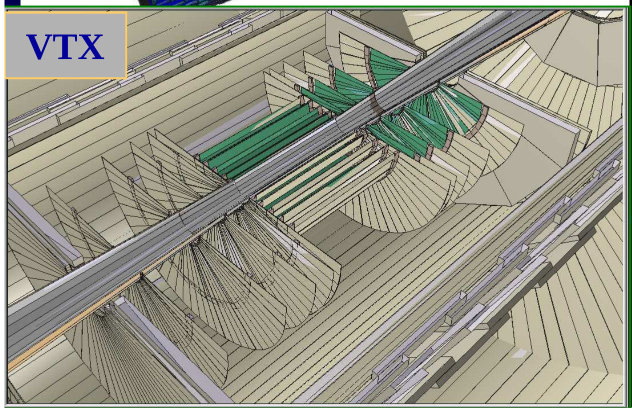



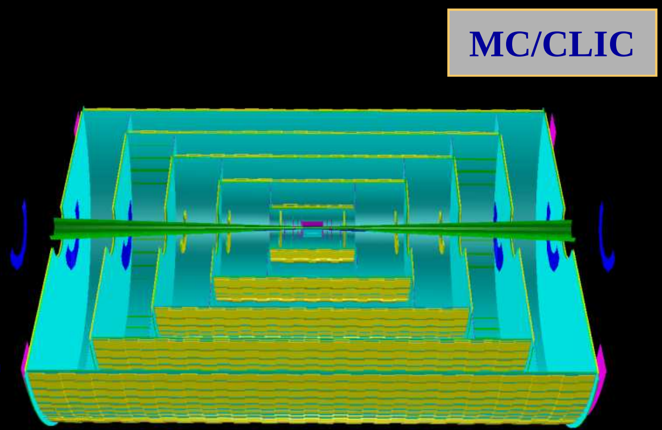



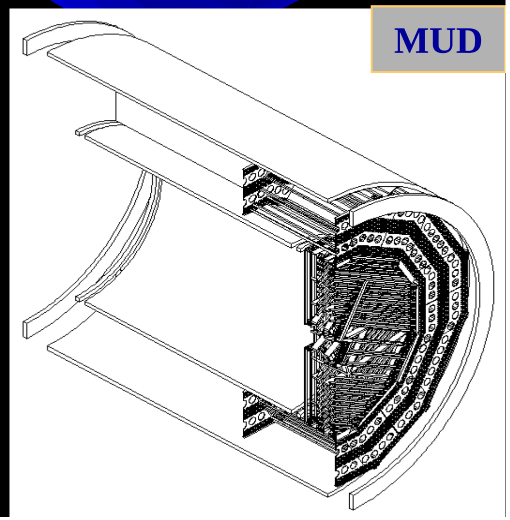



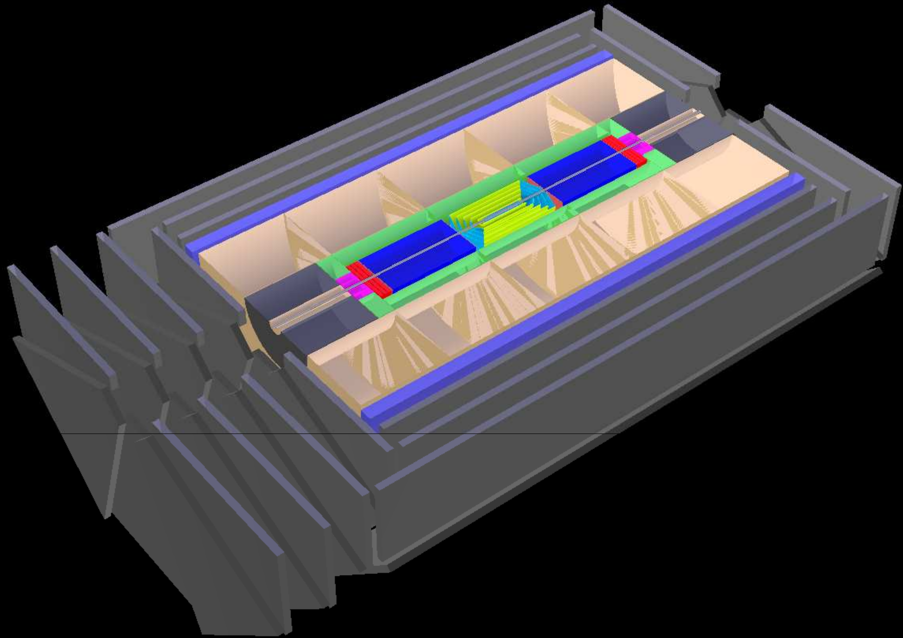



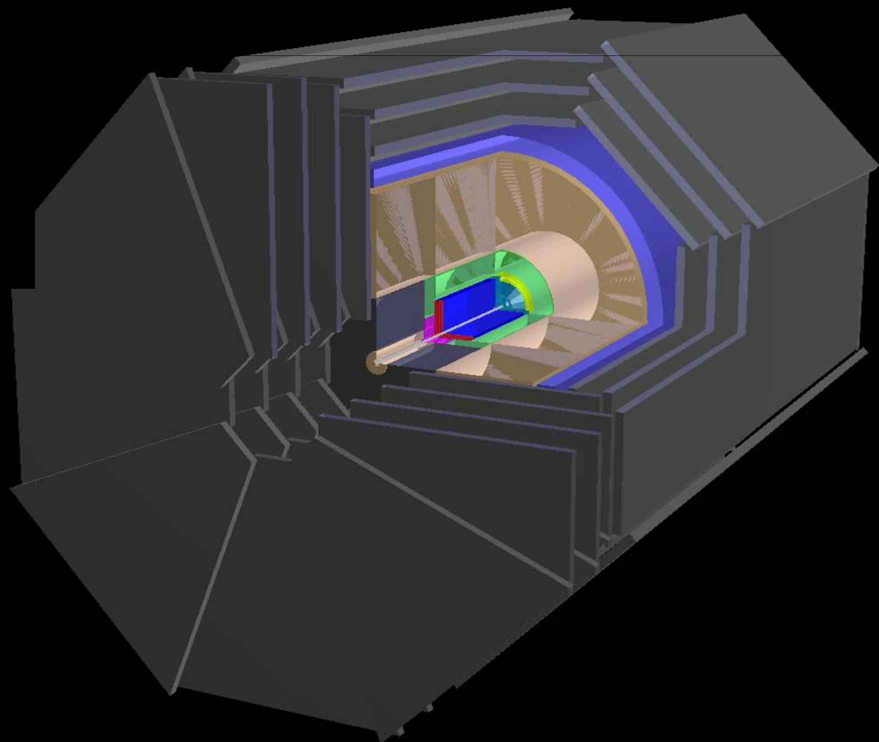



# Sharing Detectors with Other Experiments: example LHeC in ILCroot



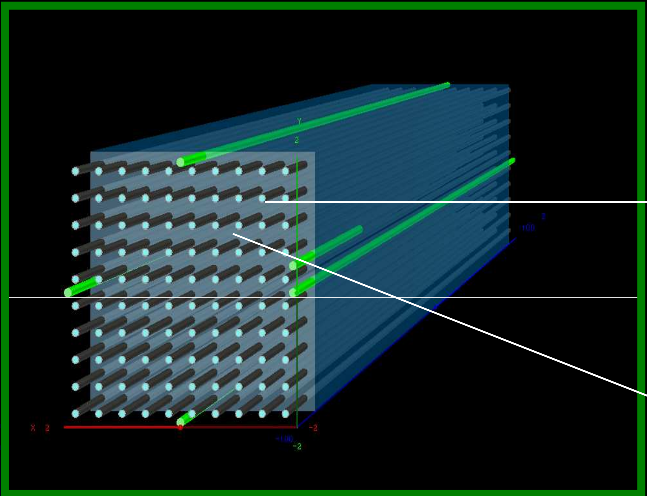


**Preparing for a DCR in 2011**

- Si VTX detector
- Si tracker
- LAr Calorimeter
- Muon Detector

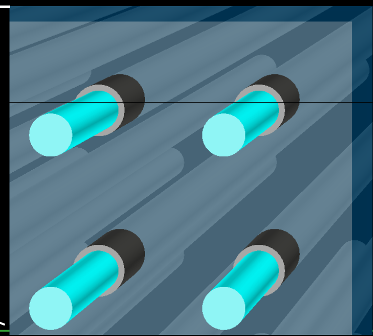
# The ADRIANO dual-readout calorimeter

- Optical SF glass as absorber, active Cerenkov radiator and mechanical structure
- Scintillating fibers matrix in glass structure



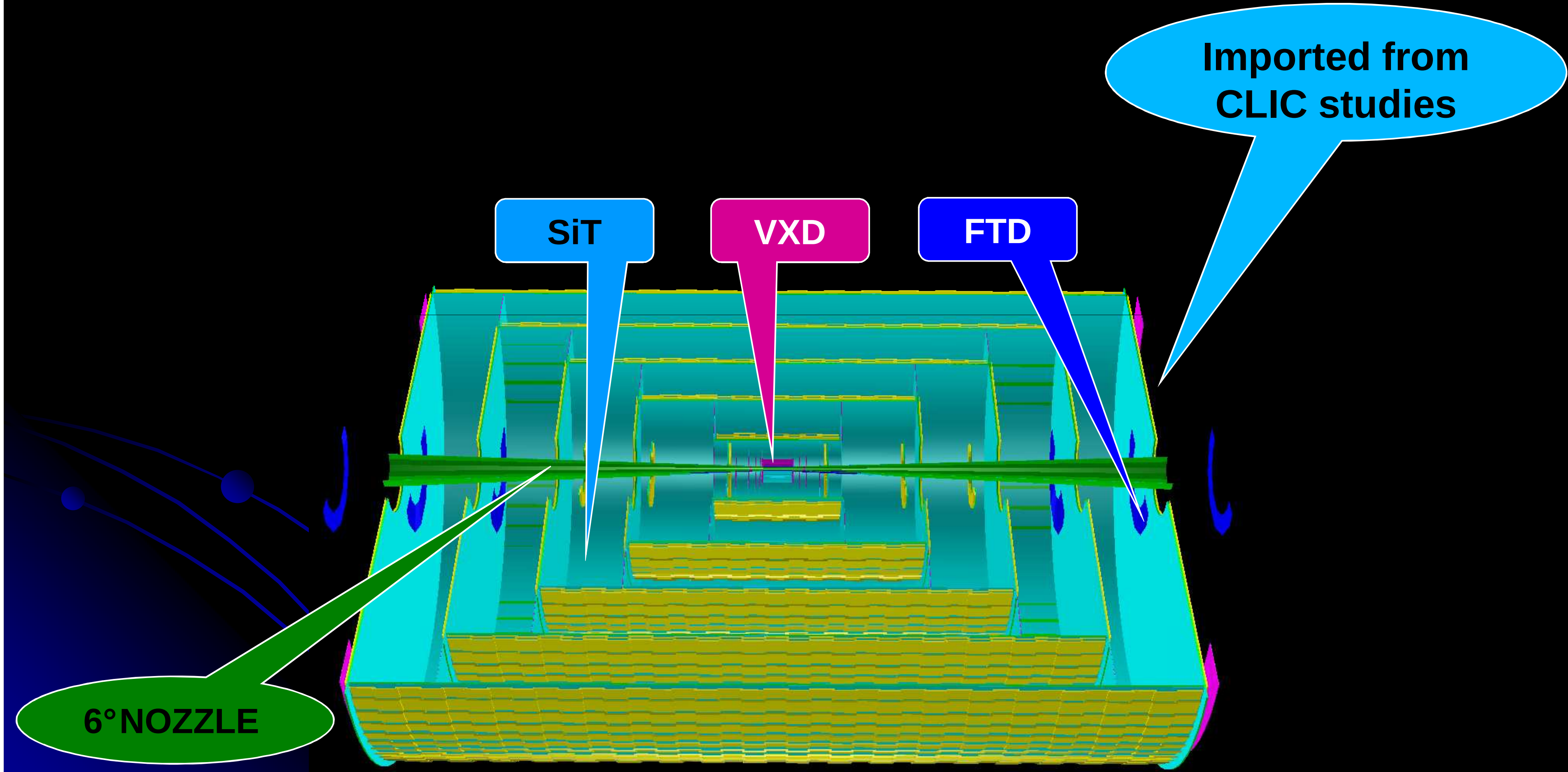
## ADRIANO cell layout

- Fully modular structure
- 2-D with longitudinal shower COG via light division techniques



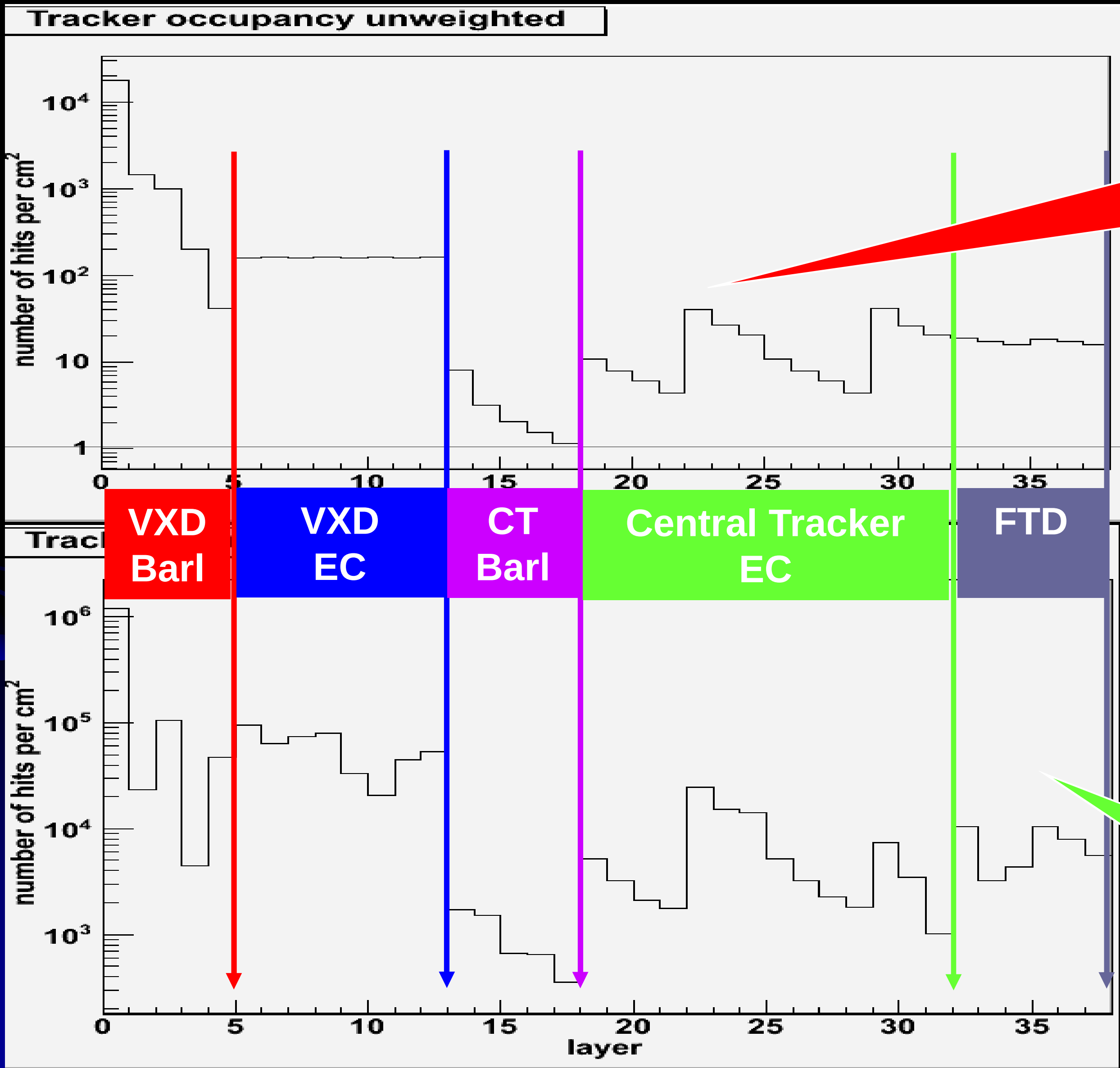
| | |
|---|---|
| Cells dimensions: | 4x4x180 $cm^3$ |
| Absorber and Cerenkov radiator: | SF57HHT |
| Cerenkov light collection: | 4 BCF92 fiber/cell |
| Scintillation region: inside 100µm thin steel capillary | SCSF81J fibers, 1mm Φ, 4mm pitch (total 100/cell) |
| Particle ID: | 1 BCF92 fiber/cell (black painted except for foremost 20 cm) |
| Readout: | front and back SiPM |
| COG z-measurement: | light division applied to SCSF81J fibers |

# Tracking detectors for MC
# VXD + SiT + FTD



F. Ignatov

# Occupancy in the Tracking Systems (from MARS+G4)




**Unweighted:**
MARS output sent to G4 disregarding the weights

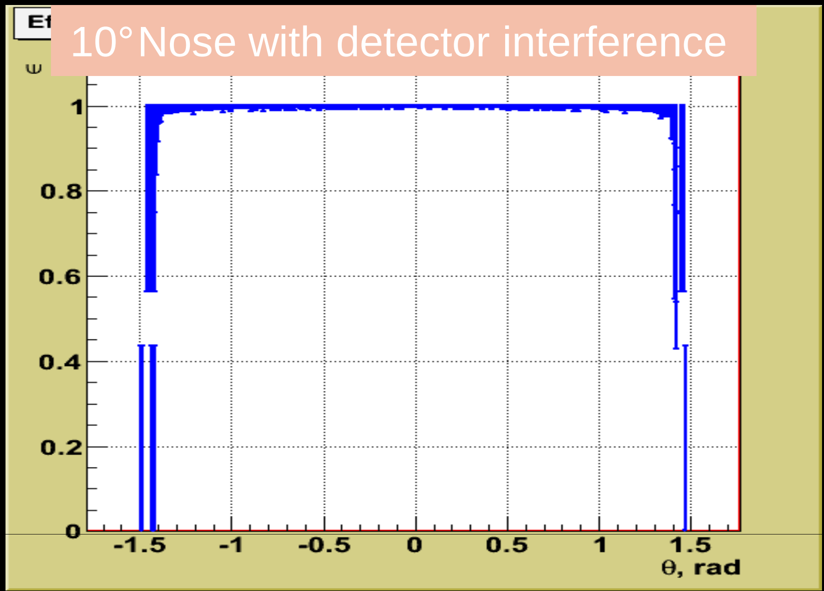
None of the two plots is fully correct

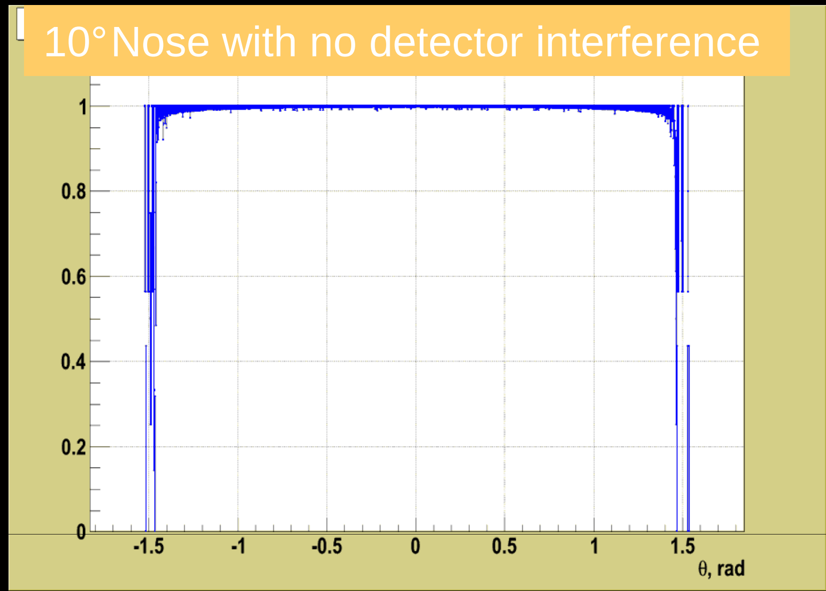
Dedicated approach is required (see later)

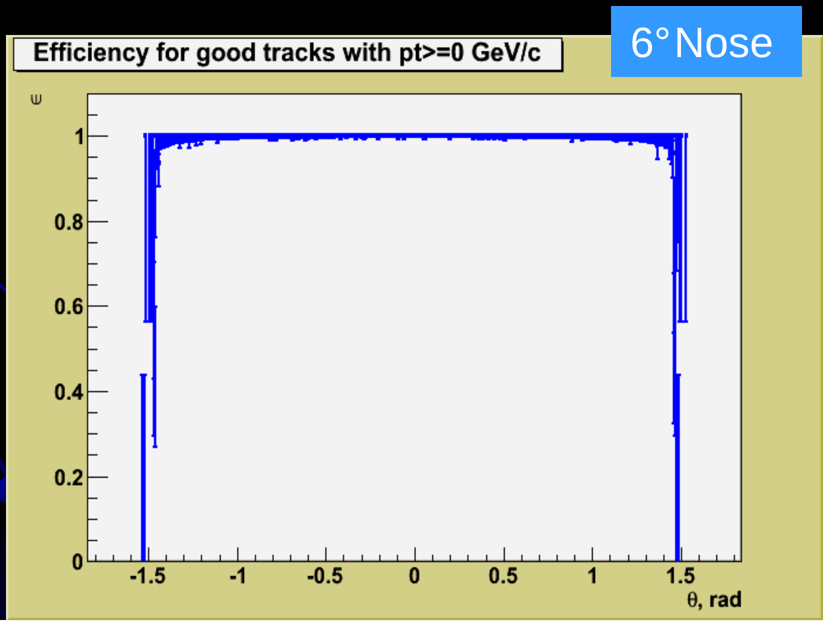
Correct occupancy is in the middle

**Weighted:**
MARS output sent to G4 multiplying by its weight

# Tracking efficiency vs $P_t$



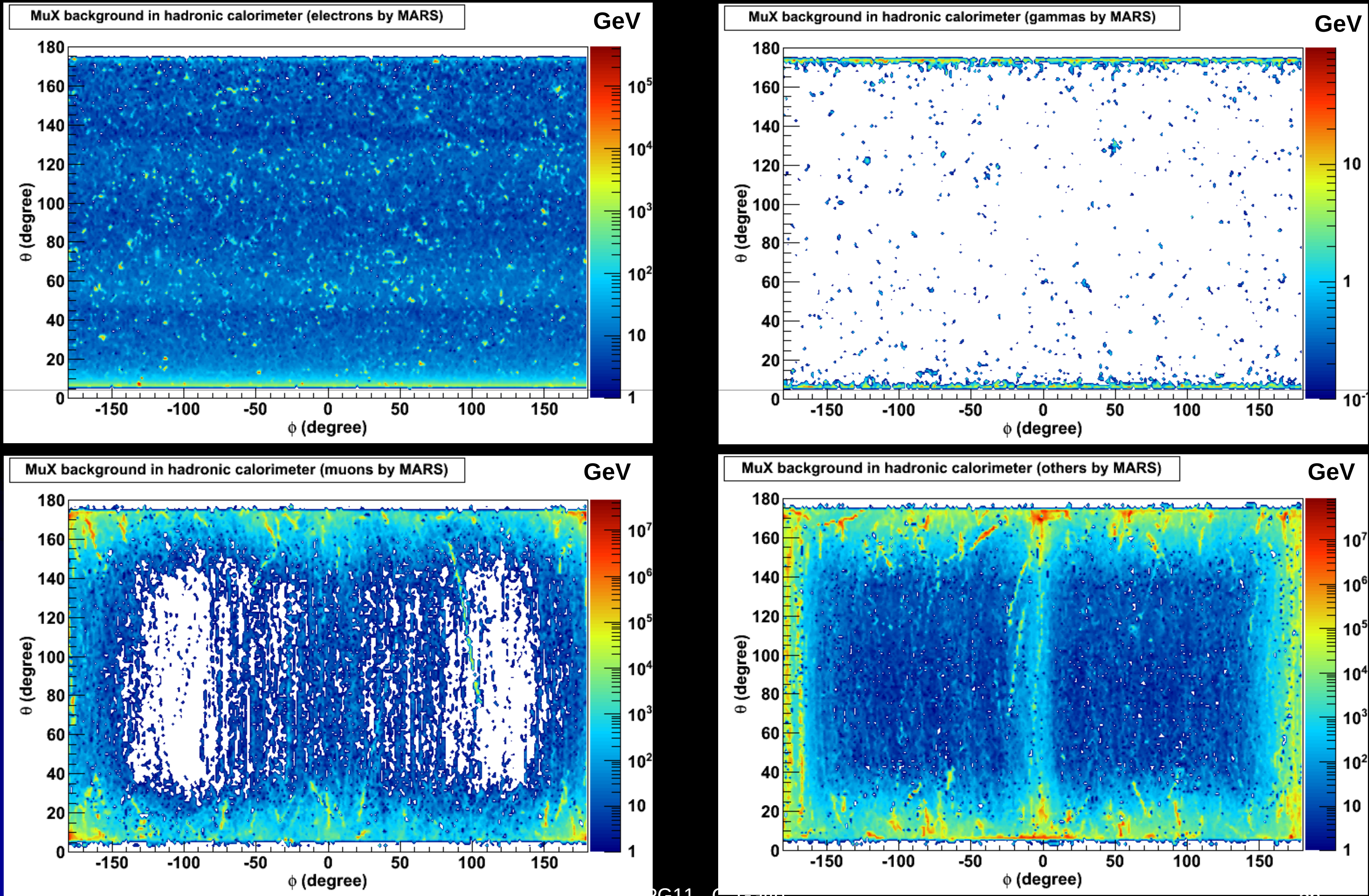




**Single muons**

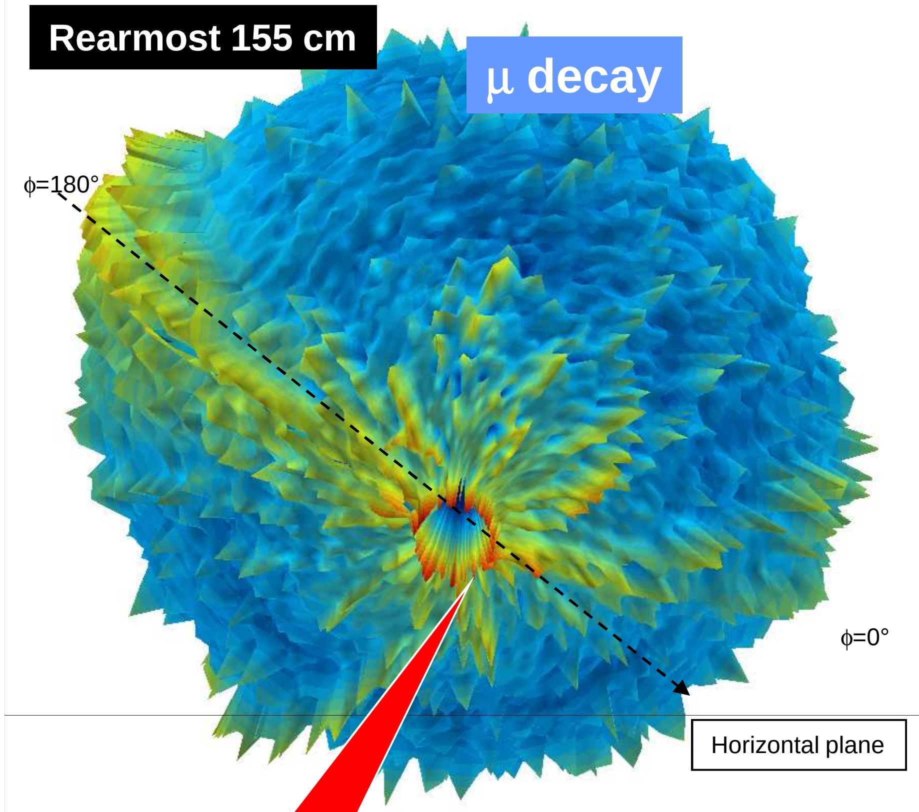
# HAD Energy/4x4cm² vs MARS particle species (MDI separation plane=7.5 m from IP)

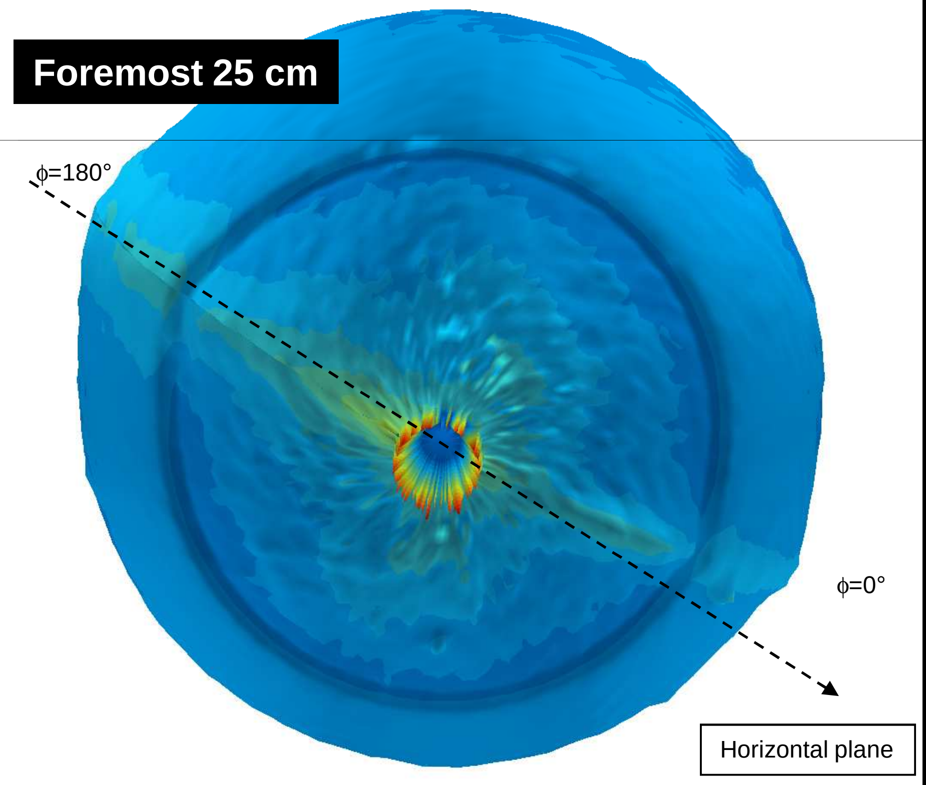
6° Nose



V. Di Benedetto

# Integrated background in foremost and rearmost calorimeter in spherical coordinates (log scale)



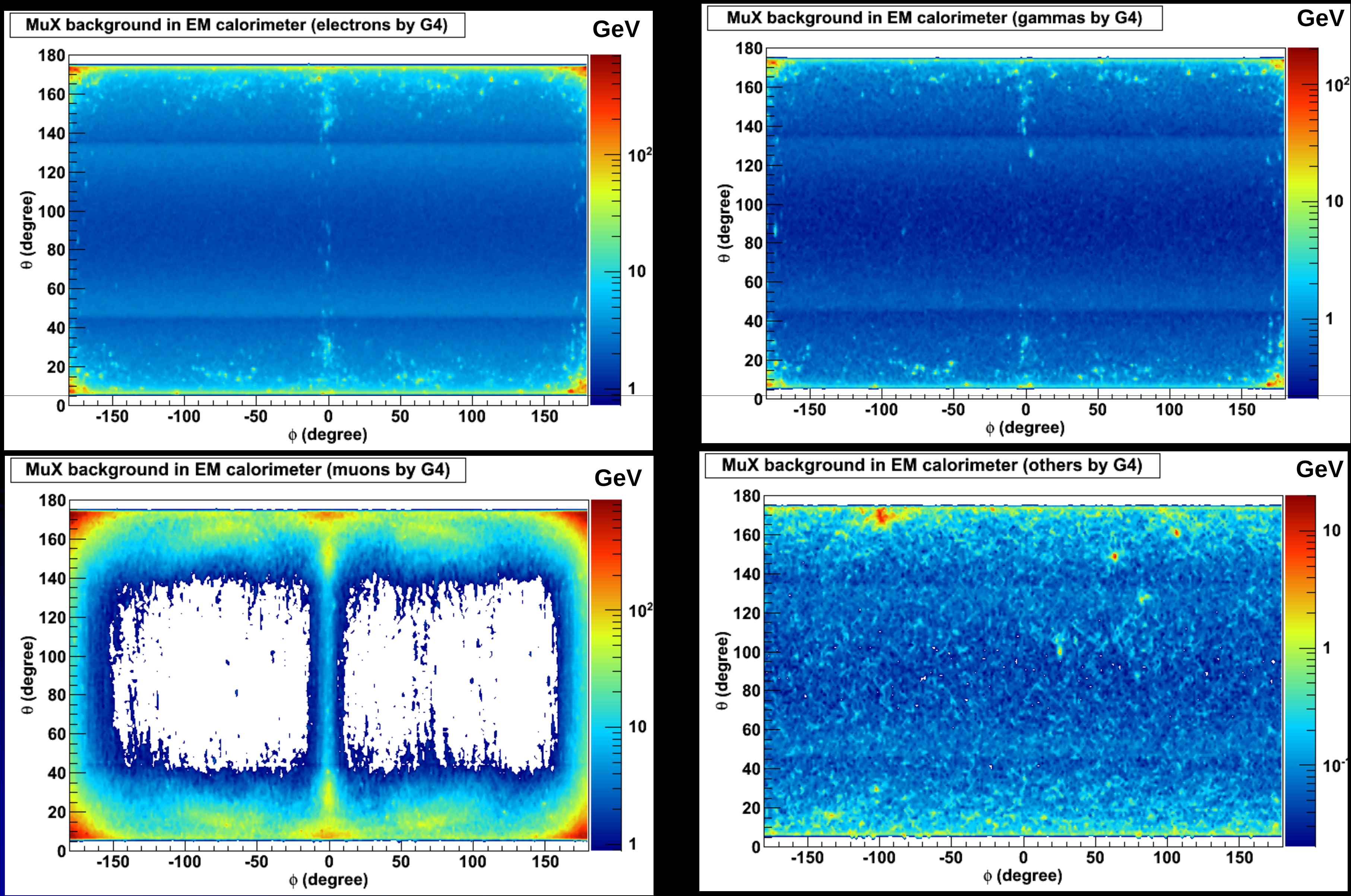

8 orders of magnitued between blue and red area)

6° Nose

**Most of background source is located in well delimited regions**

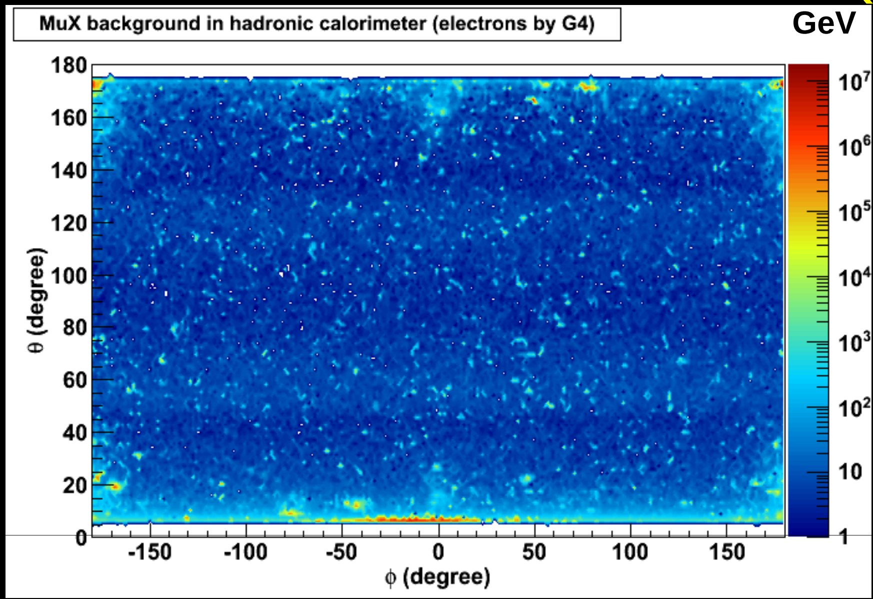
# Energy/4x4cm² vs particles entering the EM calorimeter (G4 generator)

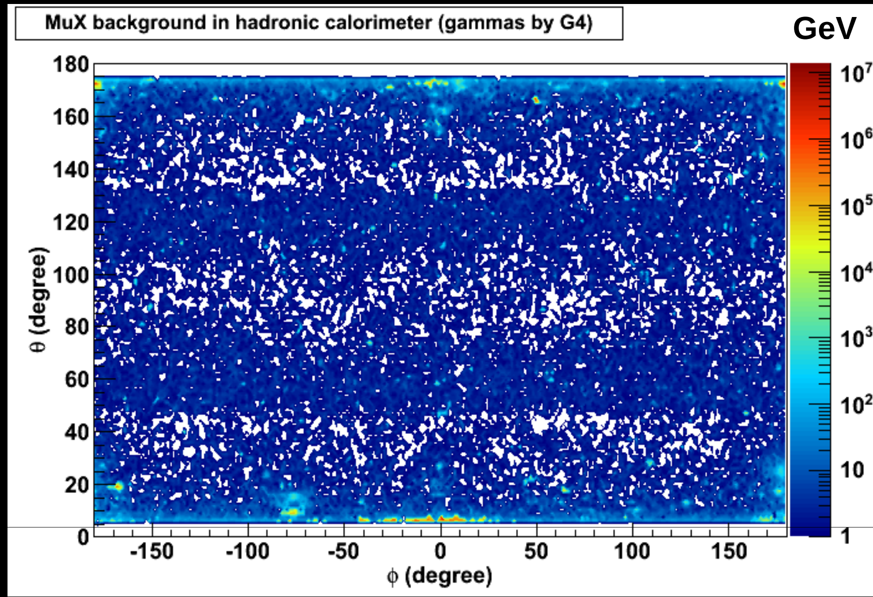
6° Nose

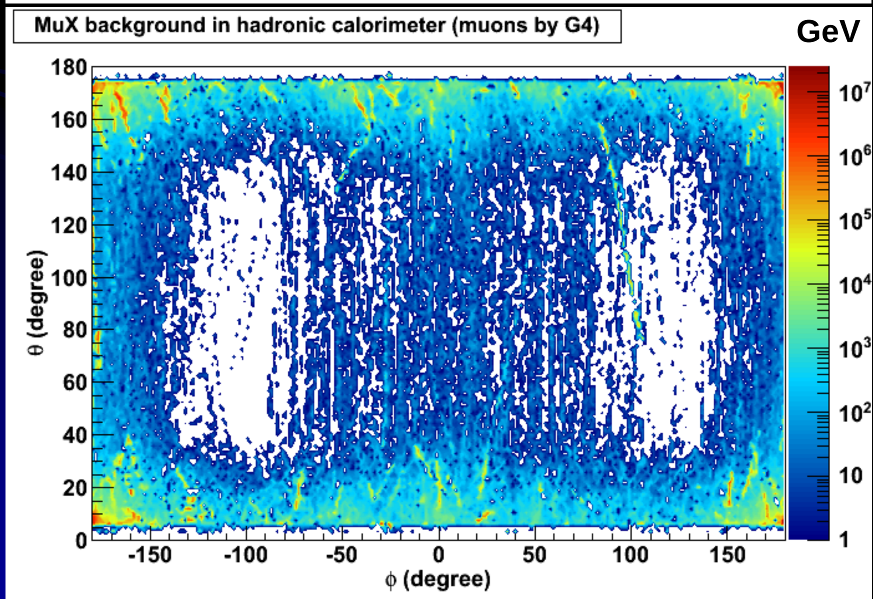


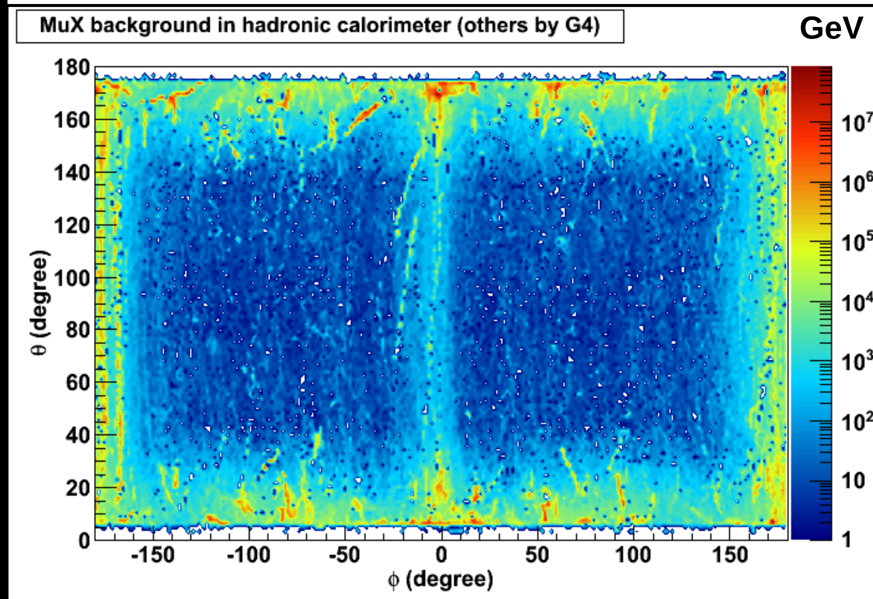
6° Nose

# Energy/4x4cm$^2$ vs particles entering the HAD calorimeter (G4 generator)



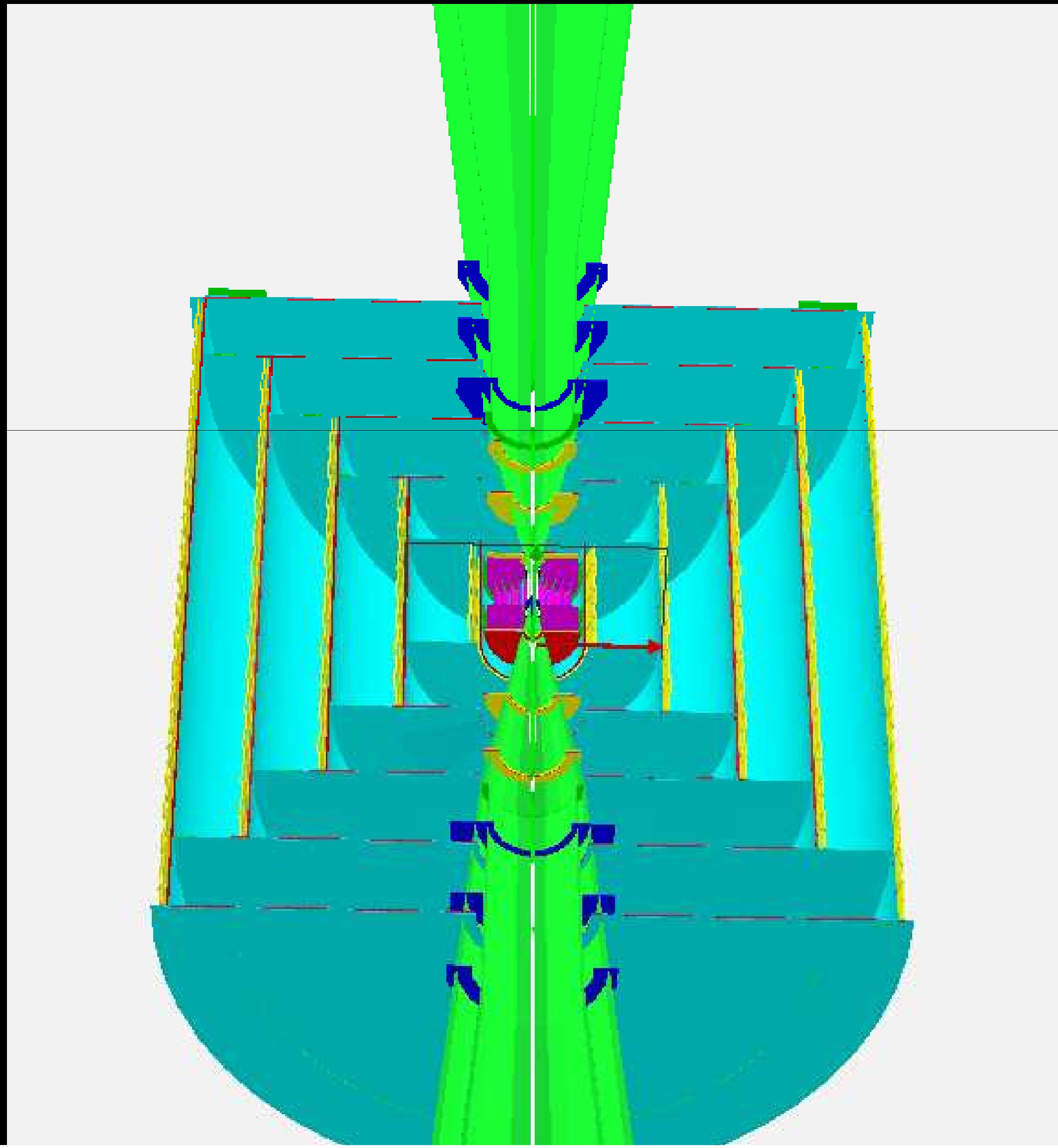



# Silicon Tracker (SiT) and Forward Tracker Detector (FTD)

- 20 µm x 20 µm Si pixel or Si strips (1D or stereo)
- Barrel : 5 layers subdivided in staggered ladders
- Endcap : (4+2) + (4+2) disks Si pixel
- FTD: 3 + 3 disks Si pixel

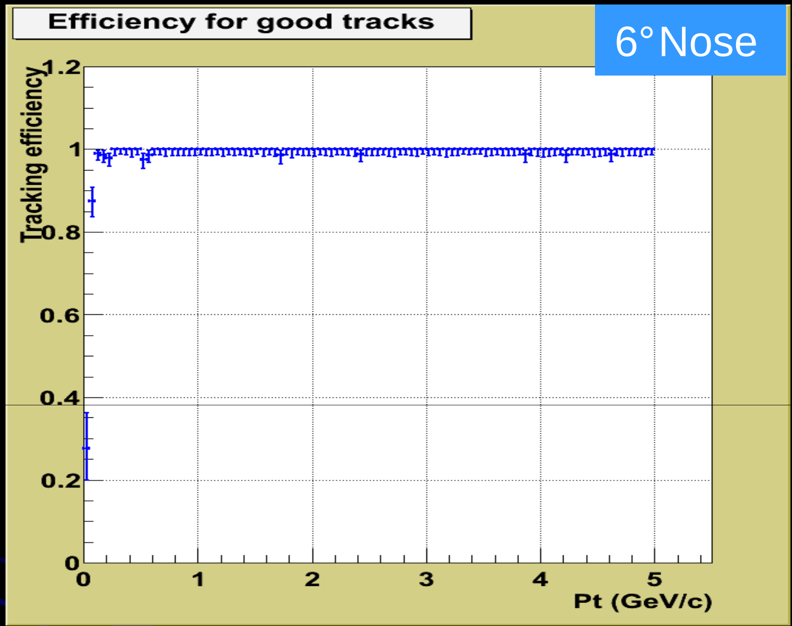
- SiD layout + FTD
- Not parametrized geometry yet

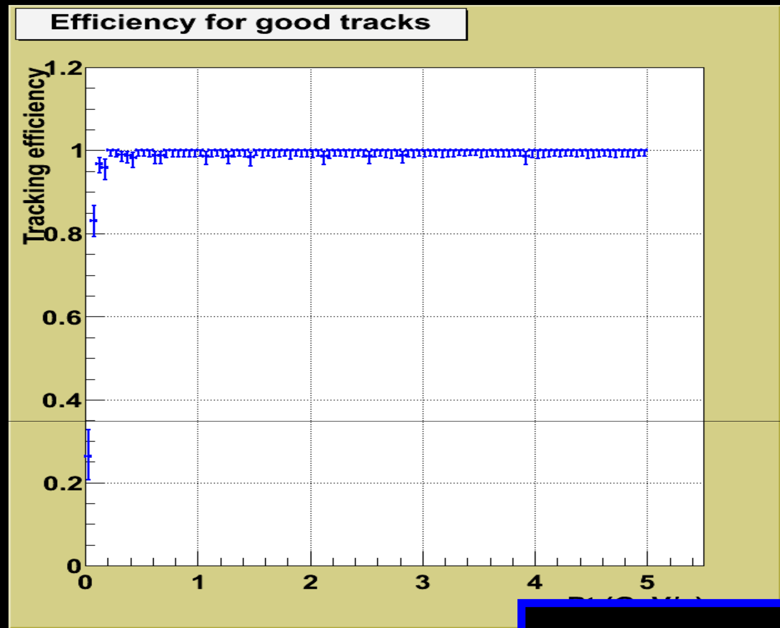


# Tracking efficiency vs $P_t$

10° Nose

6° Nose




**Single muons**

# Recent MARS modeling results

- **Available since Nov. 18, 2010**

  **(http://www-ap.fnal.gov/~strigano/mumu/mixture/)**

  - **750 GeV 2e+12 $\mu^+$ and $\mu^-$ beams**
  - **$10^0$ nozzle geometry**
  - **"Short-range" source term: 4.8e+05 simulated decays for each beam**

    **-25m < Z < 1m for $\mu^+$ beam**

    **-1m < Z < 25m for $\mu^-$ beam**

    **each source term file has about 5M particles**
  - **"Long-range" source term: 2.4e+07 simulated decays for each beam**

    **-189m < Z < -25 m for $\mu^+$ beam**

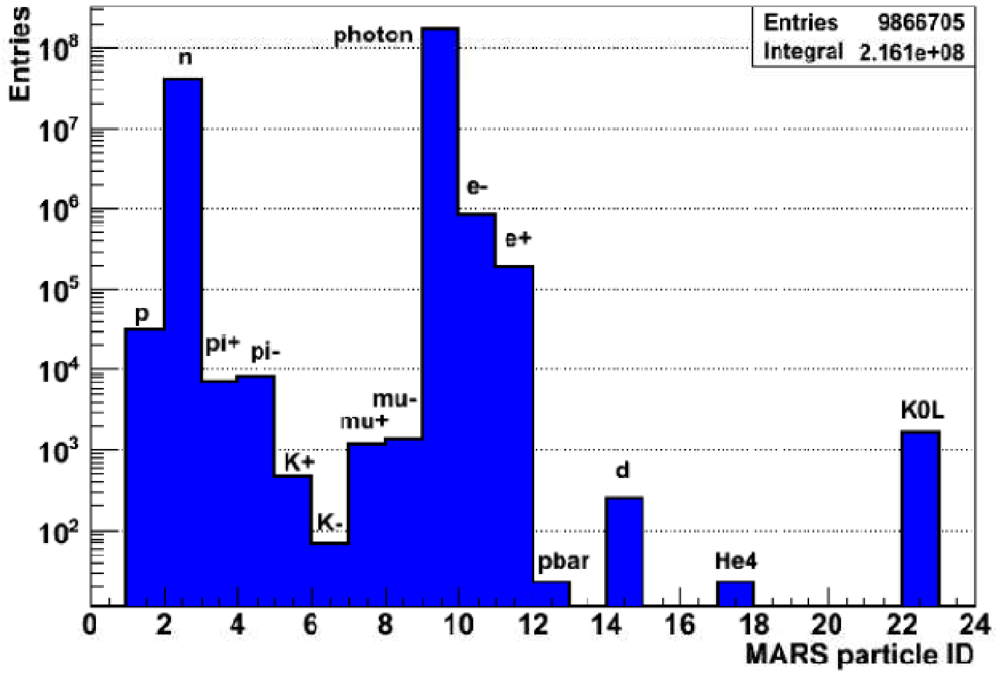
    **25m < Z < 189 m for $\mu^-$ beam**

    **each file has about 0.44M particles (mostly muons)**

# Recent MARS modeling results

Physics
Carnegie Mellon

- MARS particle ID's absolute yields (with weights) on the $10^0$ nozzle surface

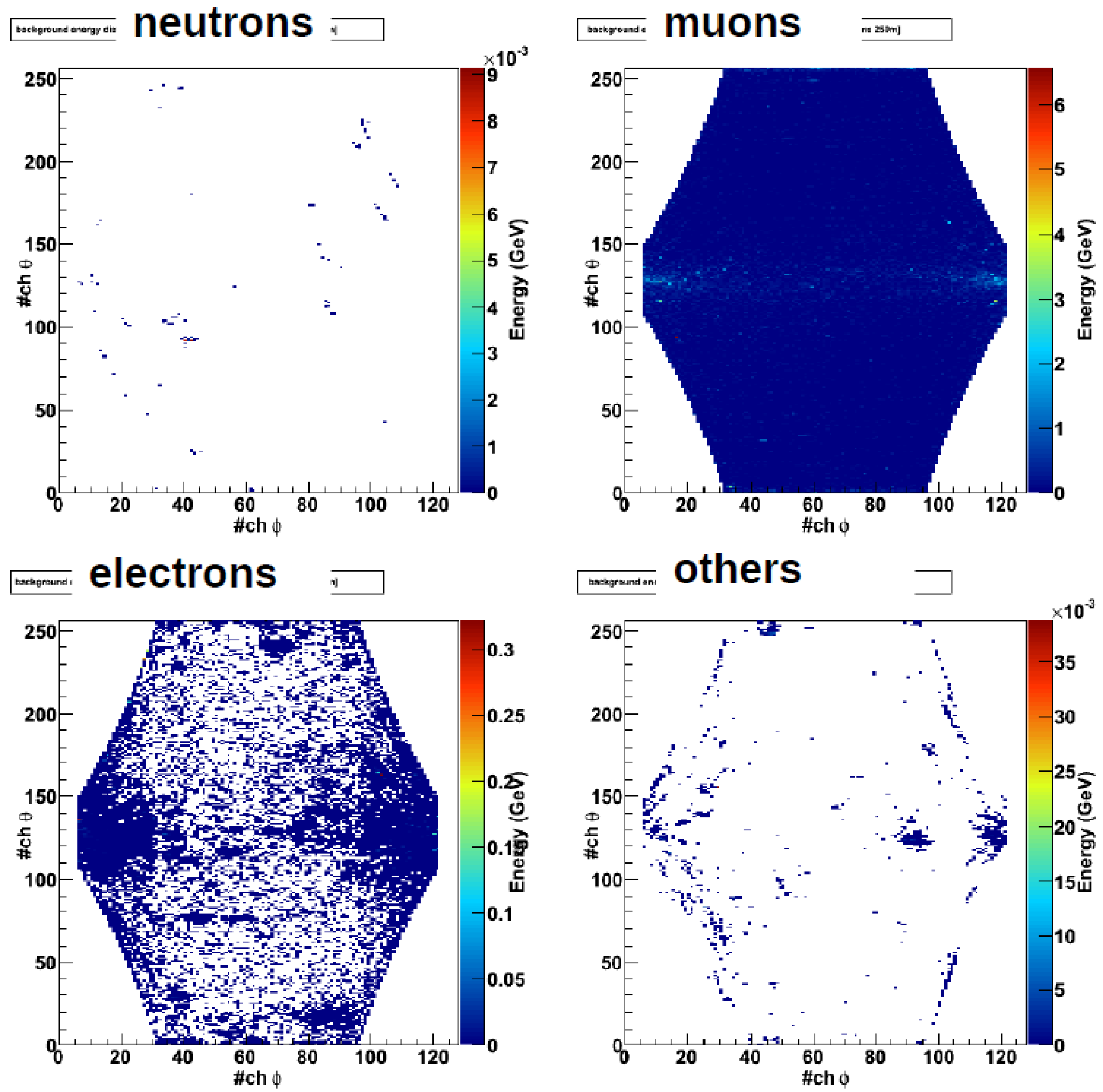



Abs. yields/bunch (E=750 GeV, both beams, 2.0e+12 muons each, L=26 m)

| photon | n | $e^{+-}$ | p | $\pi^{+-}$ | $\mu^{+-}$ |
|---|---|---|---|---|---|
| 1.77e+08 | 0.40e+08 | 1.03e+06 | 3.13e+04 | 1.54e+04 | 0.26e+04* |

* for "short range" source, 0.82e+04 if "long range" source is added

# Energy distribution per tower. MARS input file within 250 m; Integration time gate [5 – 105] ns

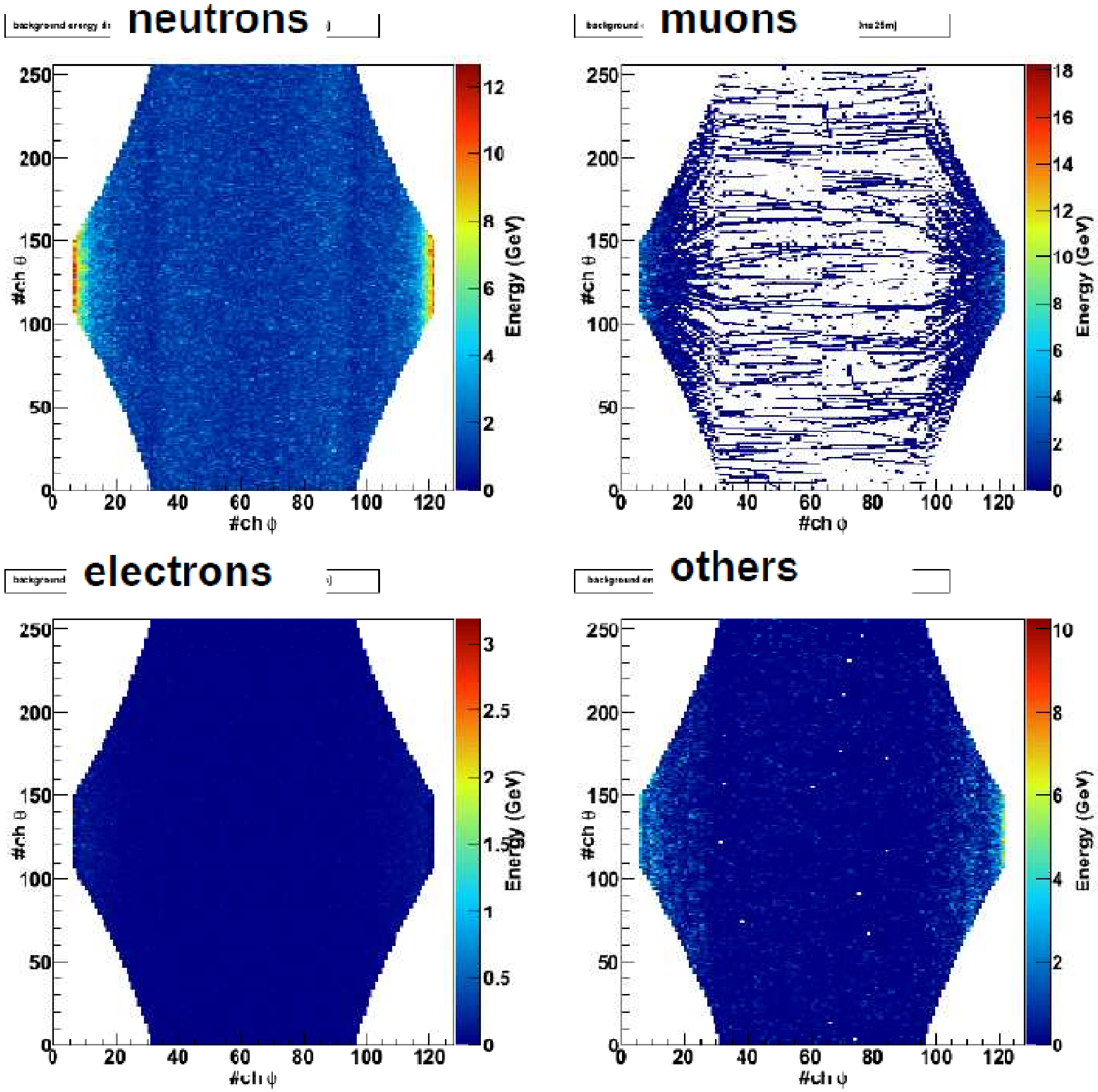



**1 entry = energy of 1 tower**

**Most of the energy is in the endcaps originated by some muons hotspot**

**No difference using shorter integration time gate**

# Energy distribution per tower. MARS input file within 25 m; Integration time gate [5 – 105] ns




**1 entry = energy of 1 tower**

**Most of the energy is in the endcaps originated by Neutrons and gammas**

**With shorter integration time gate background is reduced**