Dual Readout Calorimetry in ILCroot

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INFN Lecce and Università del Salento

Muon Collider Physics Workshop, Fermilab

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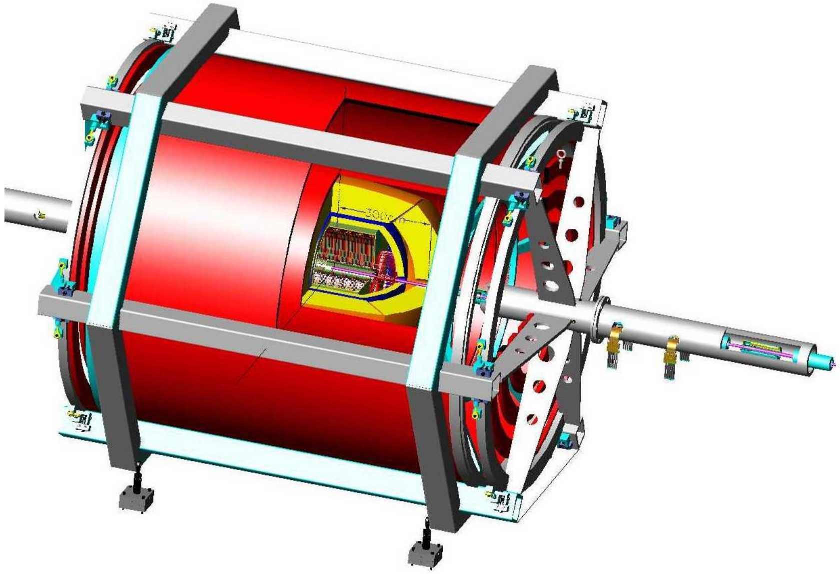
Outline

- The 4th Concept Detector
- ILCroot Offline Framework
- Calorimeter layout
- Calibration studies and calorimeter performances
- Impact of the MuonCollider background on the Calorimeter
- Comparison of DREAM data with ILCroot simulation
- Conclusions

"The 4th Concept" Detector

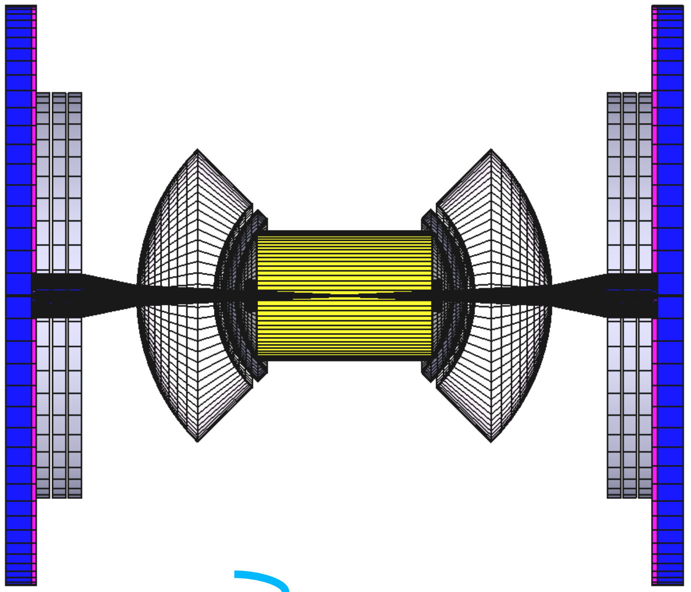
@ILC



- VXD (SiD Vertex)
- DCH (Clu Cou)
- ECAL (BGO Dual Readout)
- HCAL (Fiber Multiple Readout)
- MUDET (Dual Solenoid, Iron Free, Drift Tubes)

"The 4th Concept" Detector

@μCollider



- VXD (SiD Vertex)
- Silicon Pixel Tracker (SIPT)
- Forward Tracker Disks (preliminary version) (FTD)
- ECAL (BGO Dual Readout)
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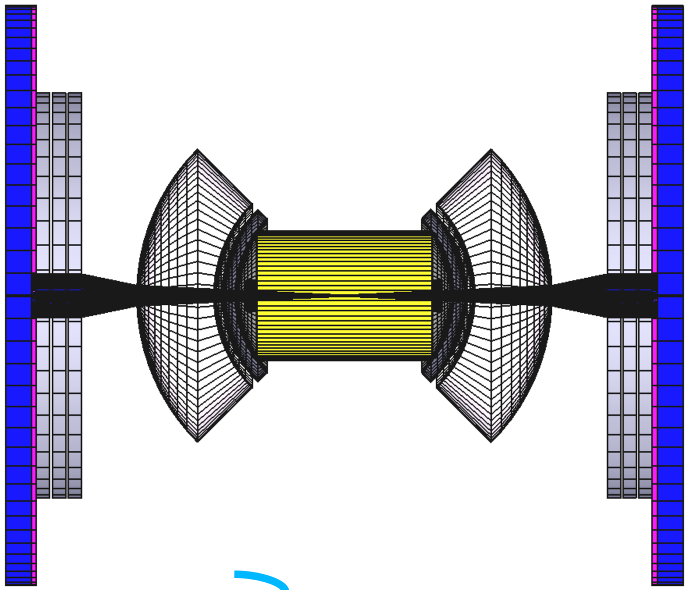
- Inner Tungsten nose + Borate Polyethylen and Tungsten walls

} Replace the DCH

"The 4th Concept" Detector



@μCollider

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} Replace the DCH

ILCRoot: summary of features

- Software architecture based on root, VMC & Aliroot
- Uses ROOT as infrastructure
  - All ROOT tools are available (I/O, graphics, PROOF, data structure, etc)
  - Extremely large community of users/developers
- Include an interface to read MARS output to handle the MuonCollider background
- Single framework, from generation to reconstruction through simulation. Don't forget analysis!!!
- It is Publicly available at FNAL on ILCSIM since 2006

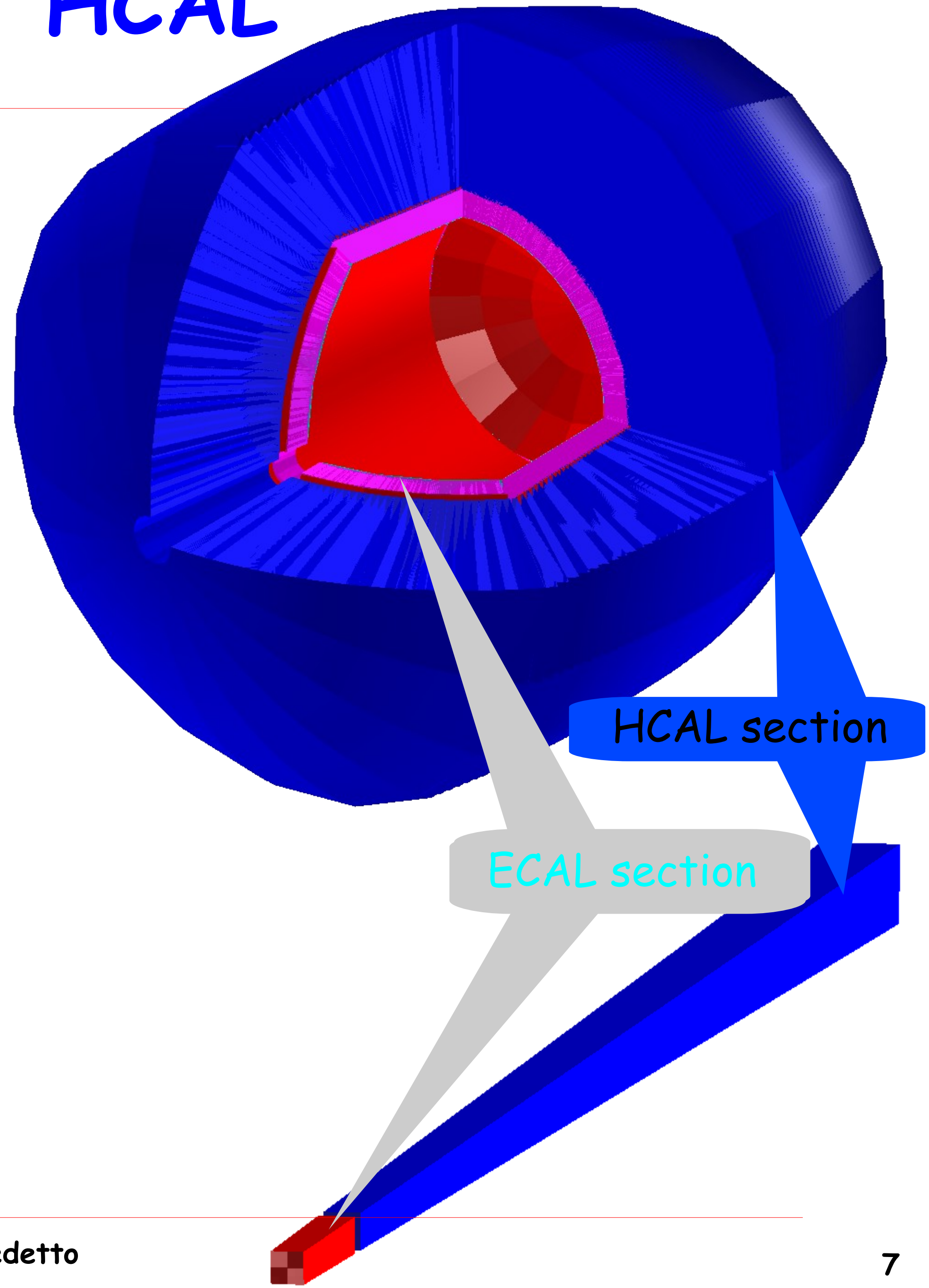
All the studies presented are performed by ILCRoot

The 4th Concept HCAL

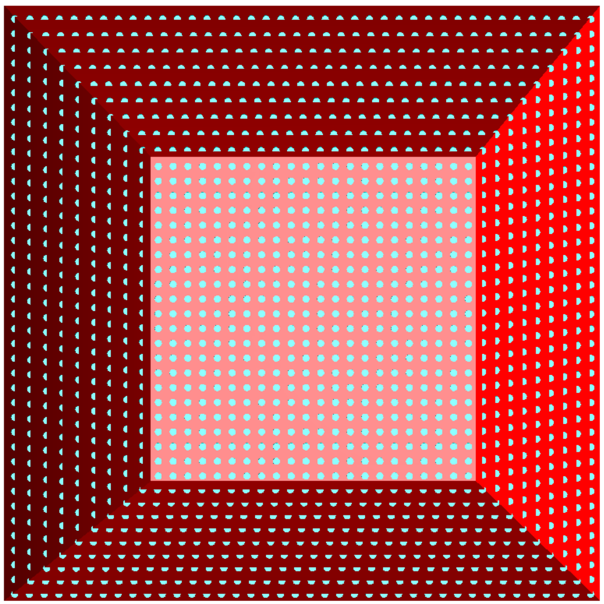
- Cu + scintillating fibers

  + Čerenkov fibers
- ~1.4° tower aperture angle
- 150 cm depth
- ~ 7.3 λ_{int} depth
- Fully projective geometry
- Azimuth coverage

  down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers



Hadronic Calorimeter Towers

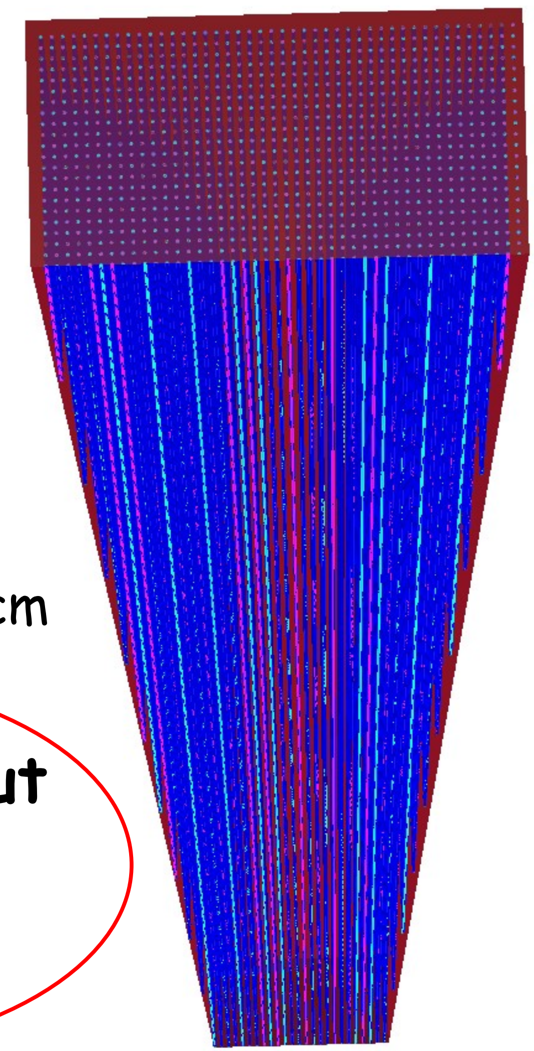


Bottom view of single tower

Top tower size: ~ 8.1 × 8.1 cm²

Bottom tower size: ~ 4.4 × 4.4 cm²

Prospective view of clipped tower



Quite the same absorber/fiber ratio as DREAM

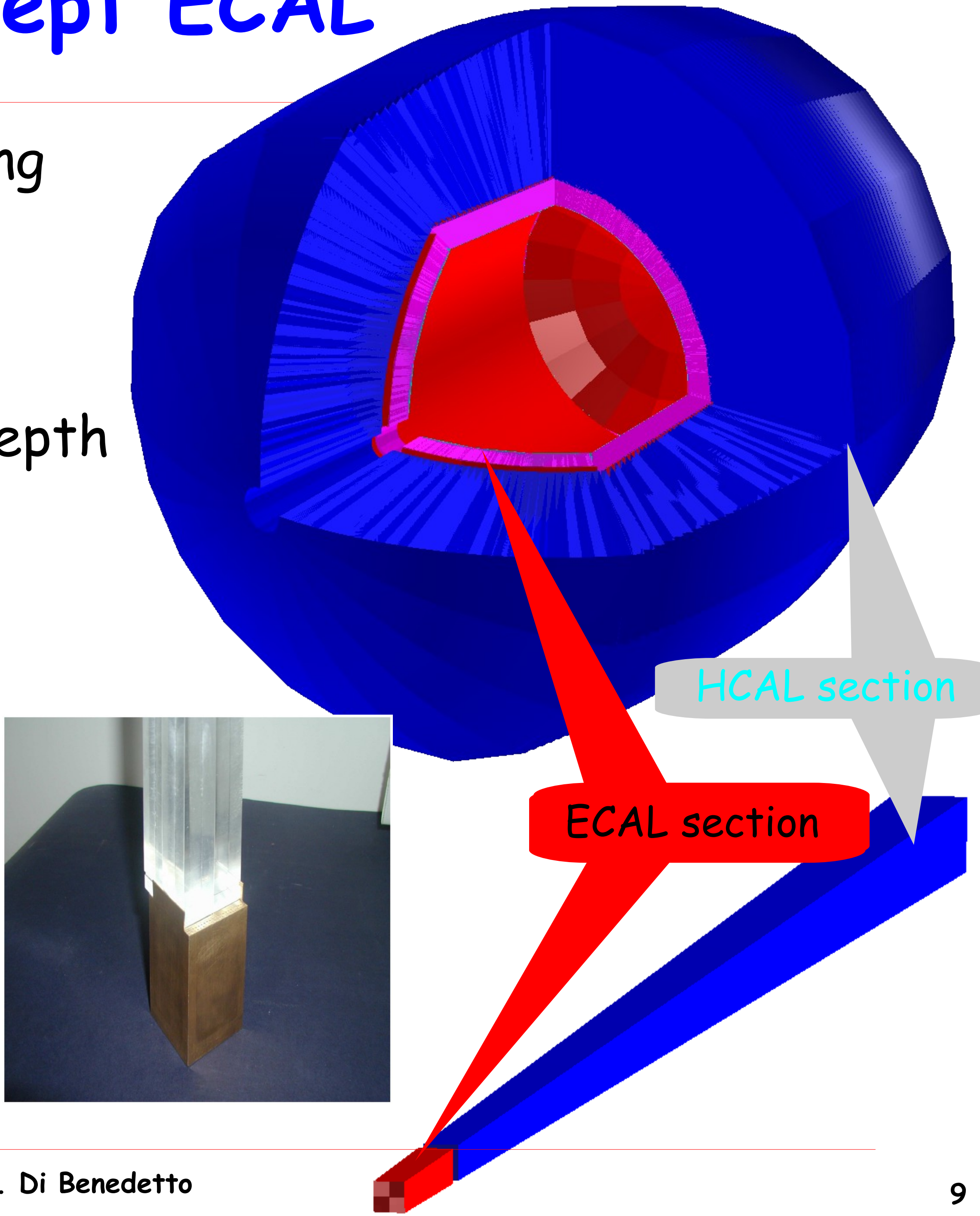
- 500 μm radius plastic fibers
- Fiber stepping ~2 mm
- Number of fibers inside each tower: ~1600 equally subdivided between Scintillating and Čerenkov
- Each tower works as two independent towers in the same volume

Tower length: 150 cm

Multiple Readout Fibers Calorimeter

The 4th Concept ECAL

- BGO crystals for scintillating and Čerenkov light
- 25 cm depth
- ~22.7 X_0 depth and ~ 1 λ_{int} depth
- 2x2 crystals for each HCAL tower
- Fully projective geometry
- Azimuth coverage down to ~2.8°
- Barrel: 65536 crystals
- Endcaps: 29800 crystals



Electromagnetic Calorimeter Cells

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

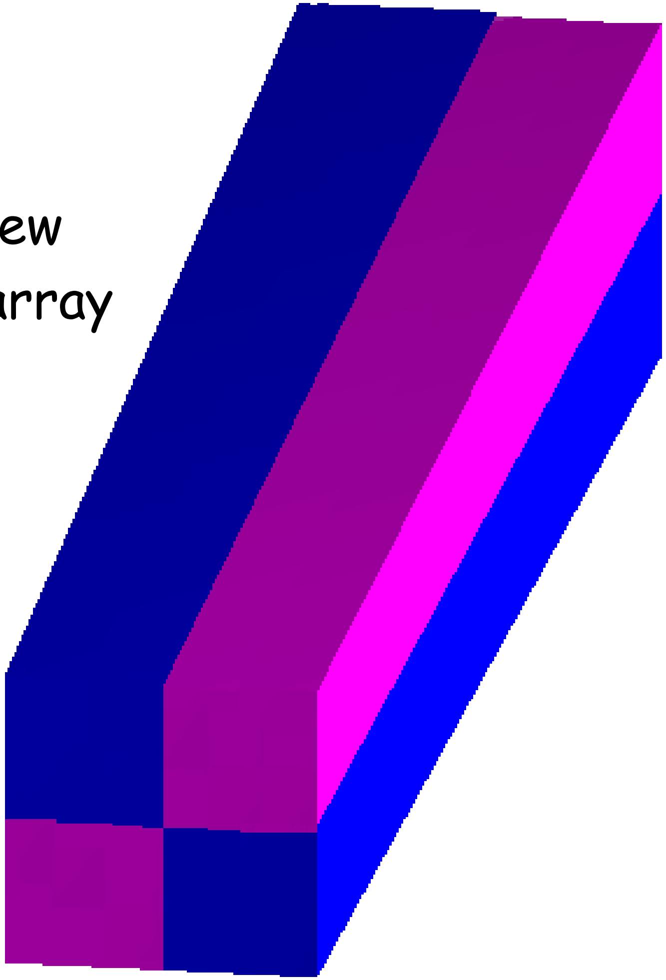
Dual Readout BGO Calorimeter

Top cell size: ~ 4.3 × 4.3 cm^2

Bottom cell size: ~ 3.7 × 3.7 cm^2

Prospective view of BGO cells array

crystal length: 25 cm



MonteCarlo

- ROOT provides the Virtual MonteCarlo (VMC) interface
- VMC allows to use several MonteCarlo (Geant3, Geant4, Fluka)
- The user can select at run time the MonteCarlo to perform the simulations without changing any line of the code

The results presented here have been simulated using Fluka

The geometry used include all the fibers
Each photon is tracked in the fibers and converted into the photo-detector

How Dual Readout works

$$E_{Cal} = \frac{S_e - \lambda C_e}{1 - \lambda}$$

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

How Dual Readout works

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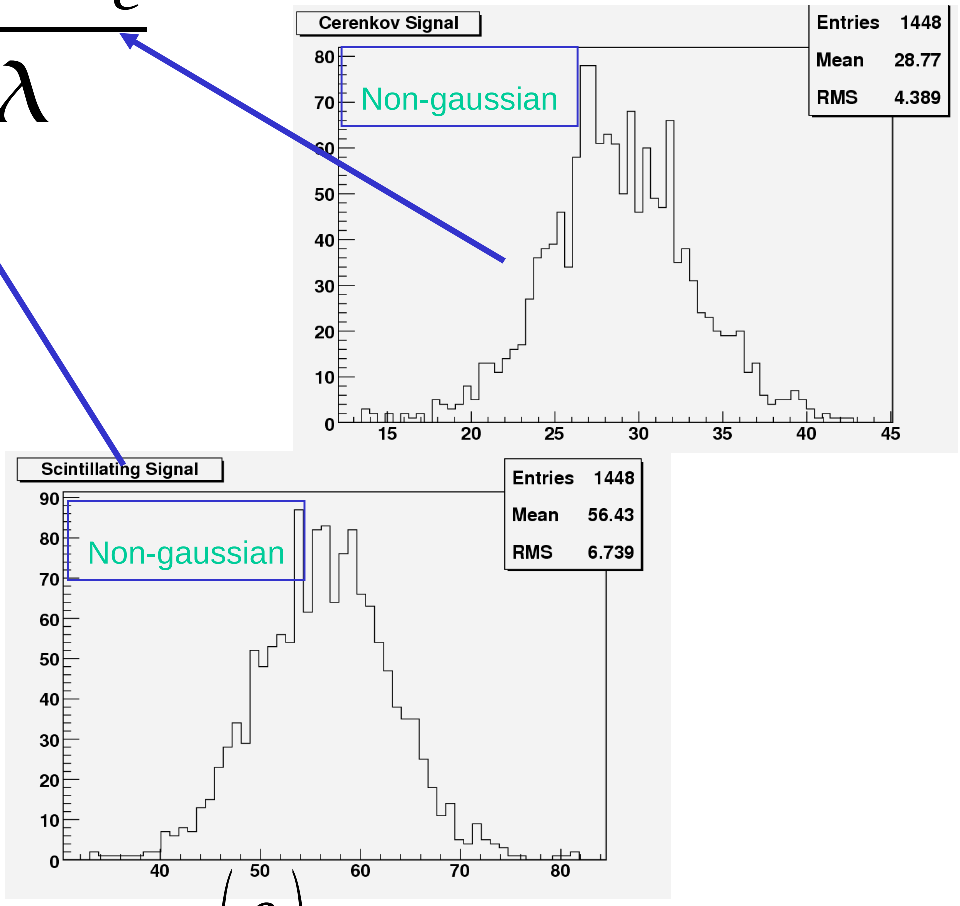

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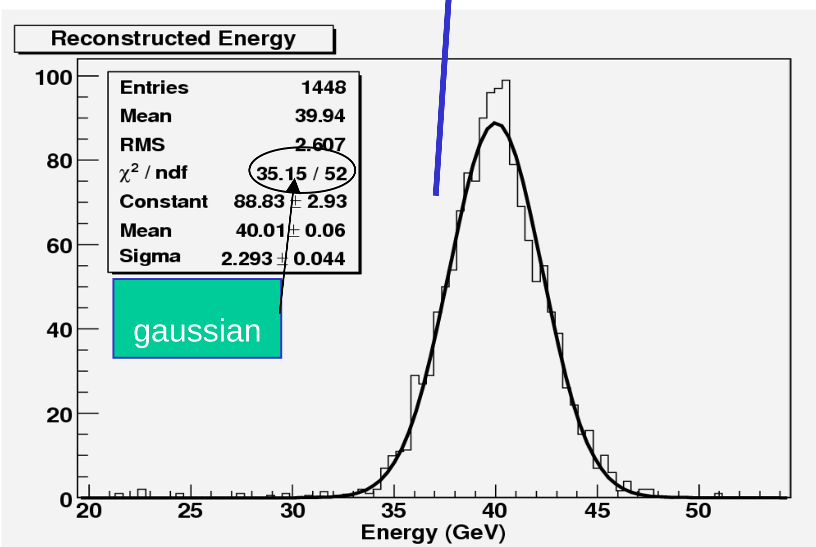
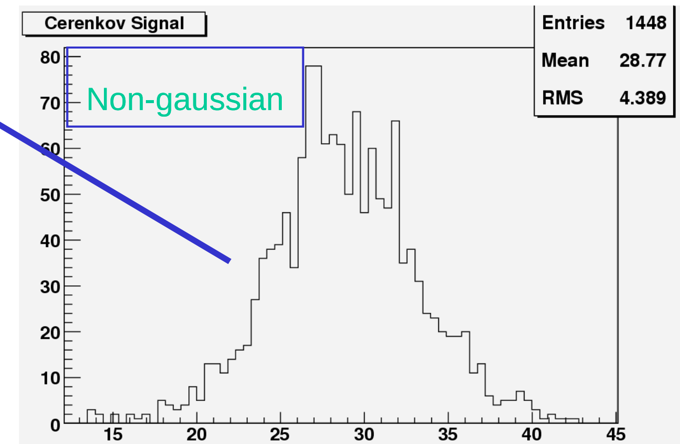
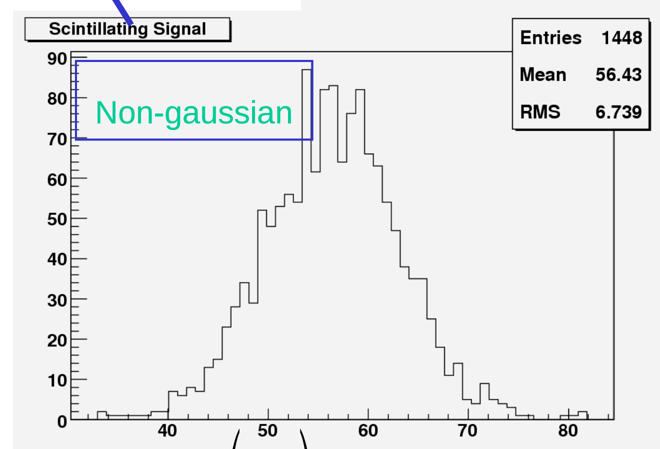






$$\lambda = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$

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

Calibration

The energy of HCAL is calibrated in 2 steps:

- Calibrate with single 45 GeV e^-

➡ raw S_e and C_e

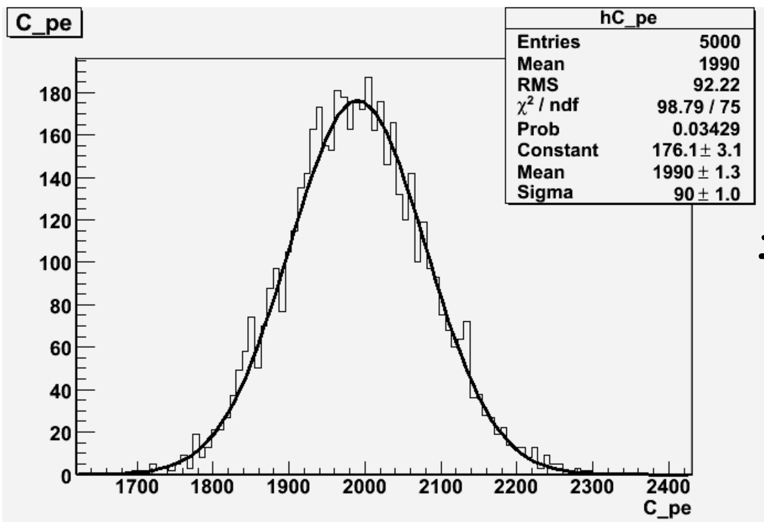
- Calibrate with single 45 GeV π^- and/or di-jet @ 91.2 GeV

➡ η_c , η_s

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

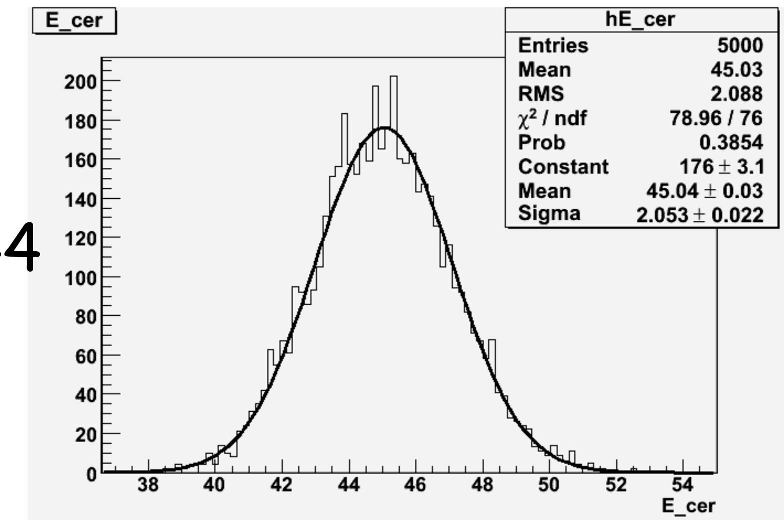
First step calibration

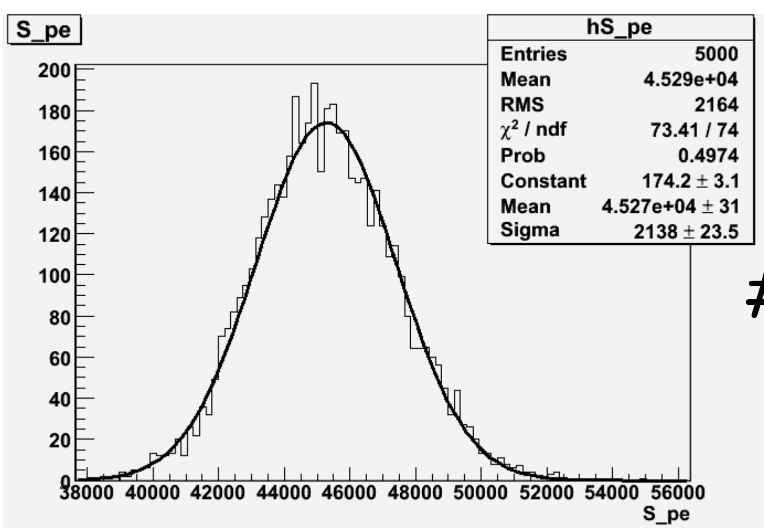
Beam of 45 GeV e^-



Cer

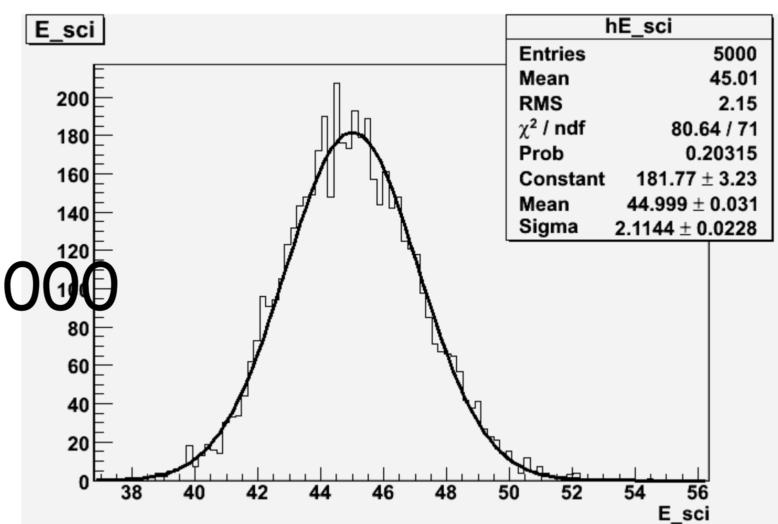
#pe/GeV ≈ 44





Scint

#pe/GeV ≈ 1000



How Triple Readout works

$$R(f_{em}) = f_{em} + \frac{1}{\eta}(1 - f_{em})$$

$$R = \frac{E_{RAW}}{E}$$

f_{em} = em fraction of the hadronic shower

η = em fraction in the fibers

hadronic energy:

$$E_{Cal} = \frac{S_e - \lambda C_e}{1 - \lambda} + \eta_n Sn_e$$

$$\lambda = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$

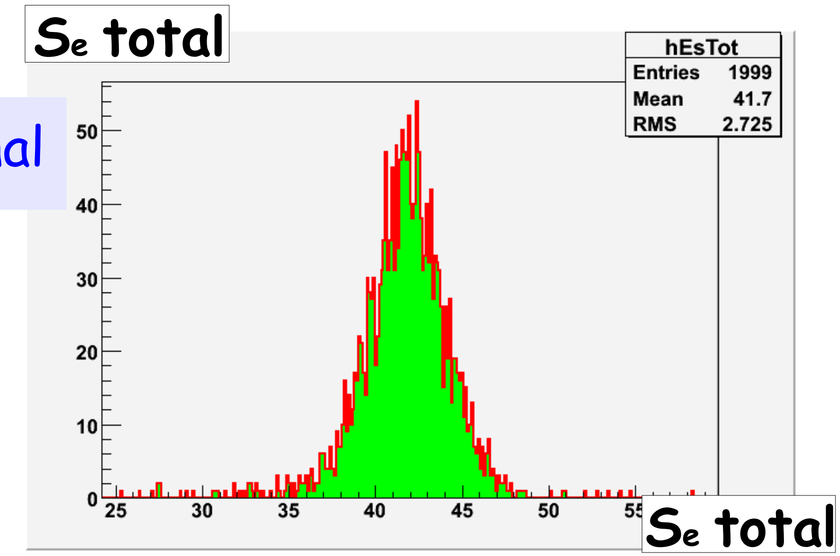
Dual Readout

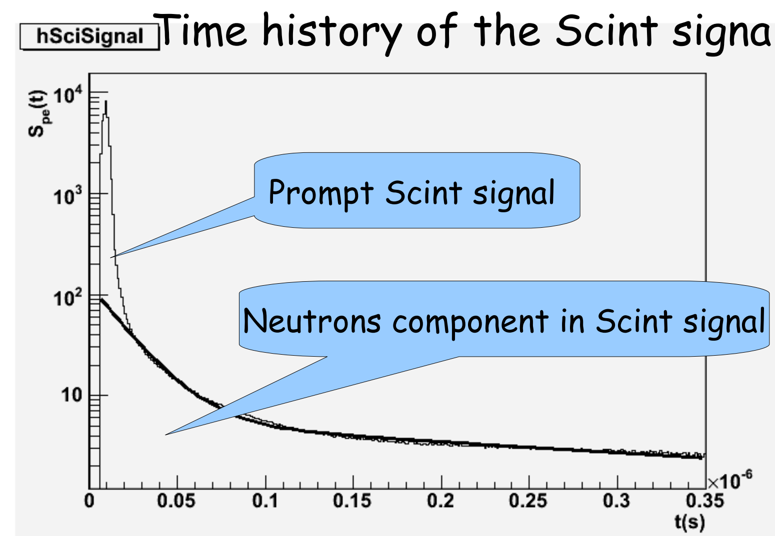
Triple Readout with time history

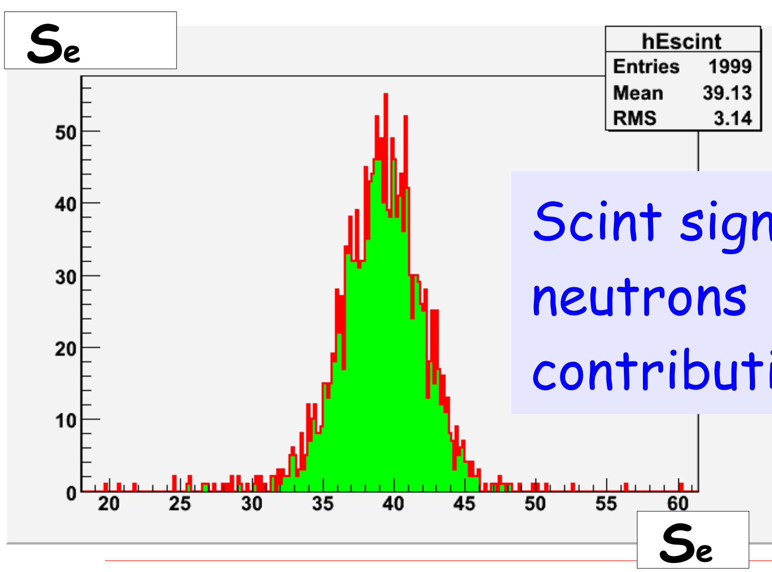
How Triple Readout works

Separation of the neutron component in the scintillation signal

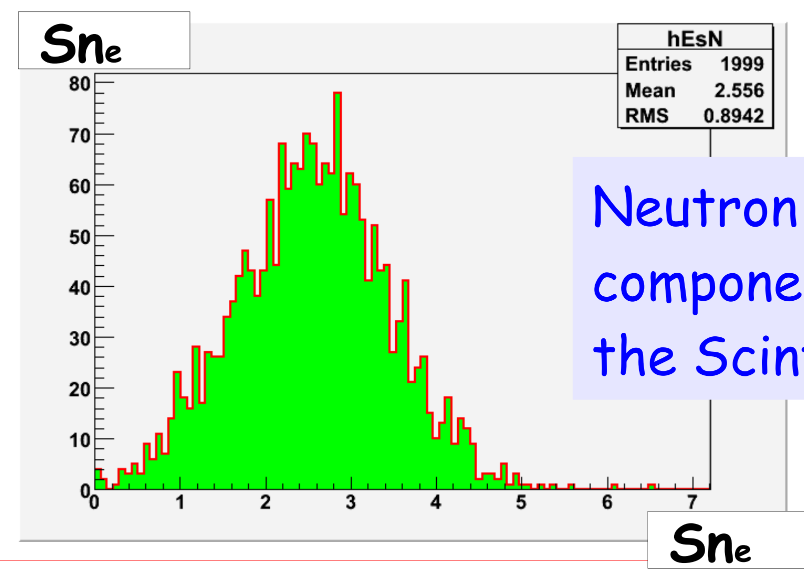
Full Scint signal





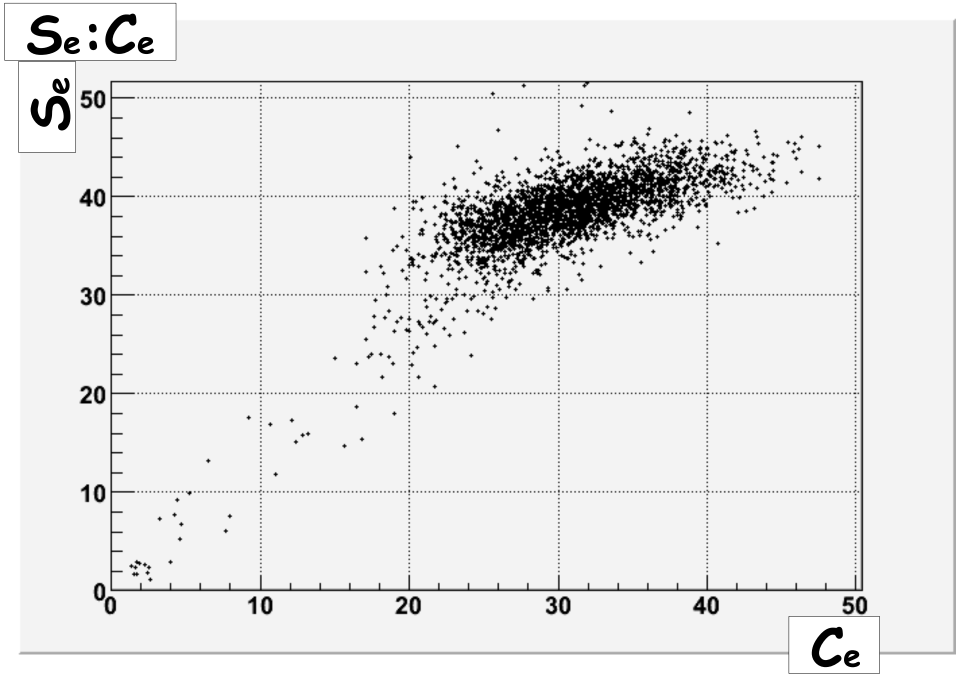


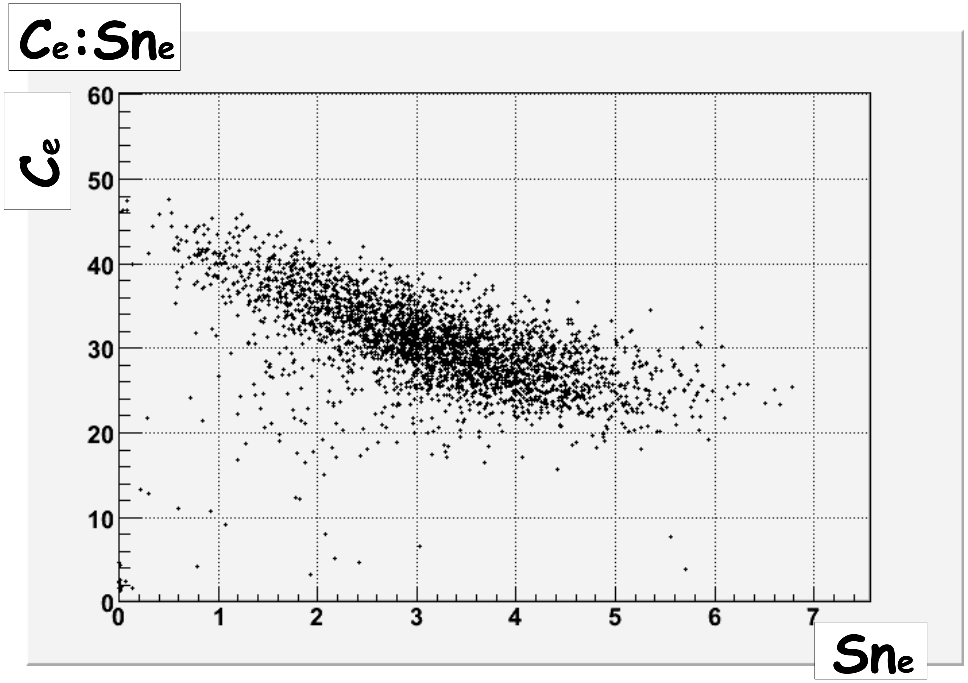
Scint signal w/o neutrons contribution

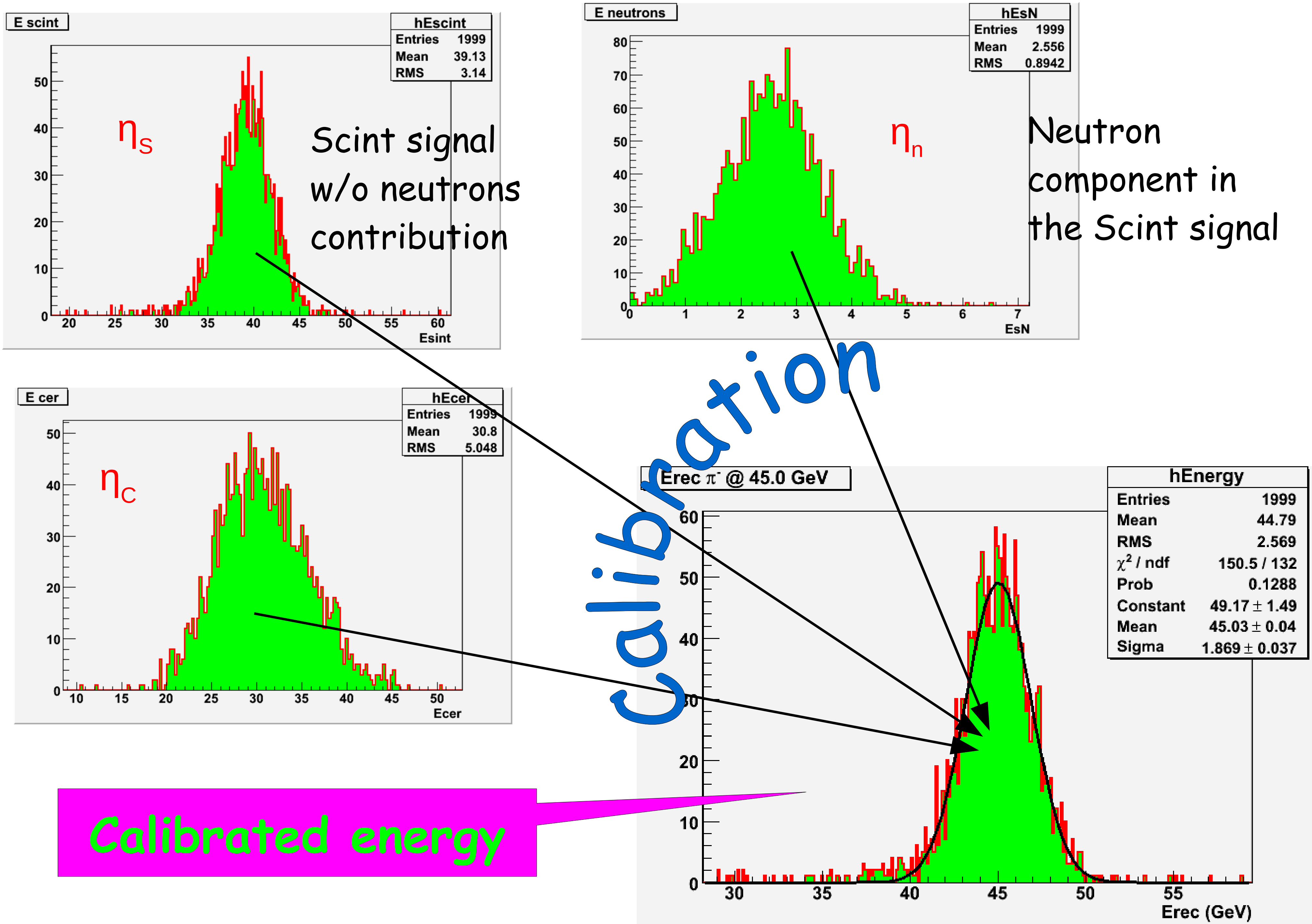


Neutron component in the Scint signal

Correlation between calorimeter signals



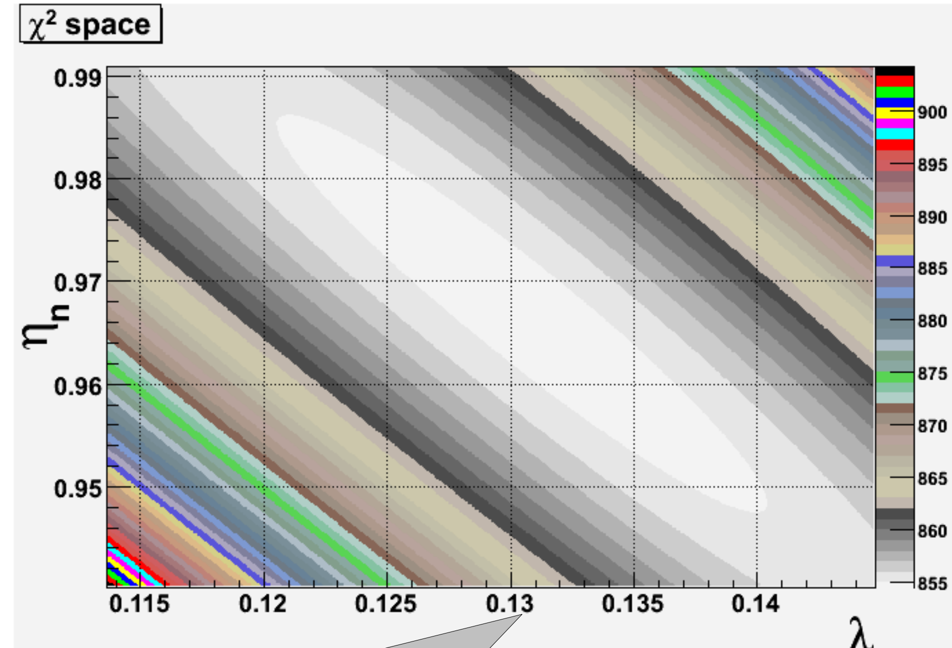



E scint
hEscint
Entries 1999
Mean 39.13
RMS 3.14
η_S
Scint signal
w/o neutrons
contribution
Esint
E neutrons
hEsN
Entries 1999
Mean 2.556
RMS 0.8942
η_n
Neutron
component in
the Scint signal
EsN
E cer
hEcer
Entries 1999
Mean 30.8
RMS 5.048
η_C
Ecer
Calibration
Erec π^- @ 45.0 GeV
hEnergy
Entries 1999
Mean 44.79
RMS 2.569
χ^2 / ndf 150.5 / 132
Prob 0.1288
Constant 49.17 ± 1.49
Mean 45.03 ± 0.04
Sigma 1.869 ± 0.037
Erec (GeV)
Calibrated energy

Second step calibration di-jet @ 91.2 GeV case

$$E_{Beam} = \frac{E_S - \lambda E_C}{1-\lambda} + \eta_n E_n$$

$$\lambda = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$

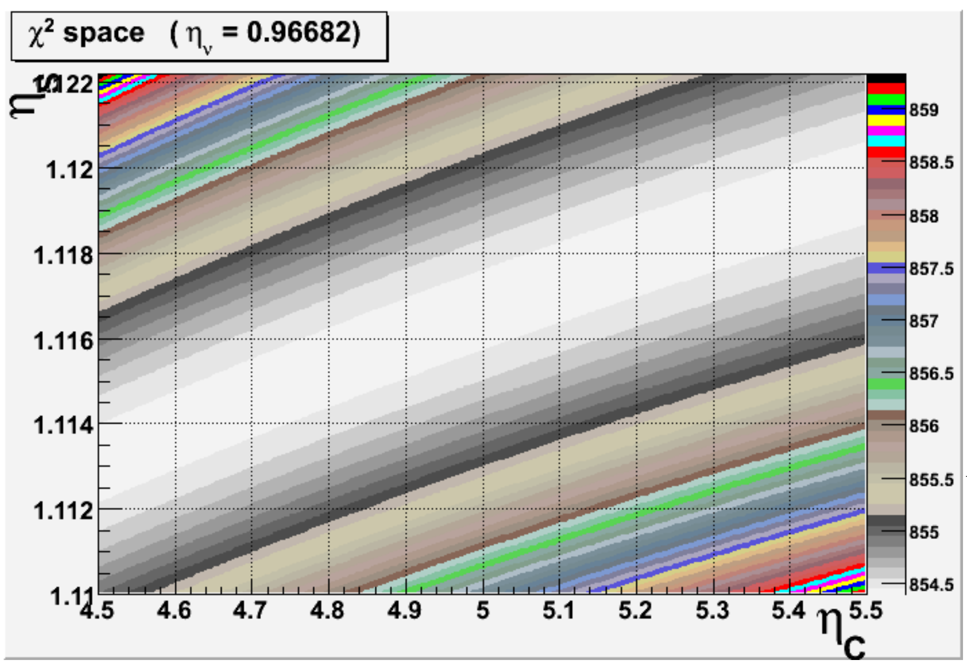


$\eta_n = 0.967$ $\lambda = 0.130$

#events = 744

$\chi^2 = 854.39$

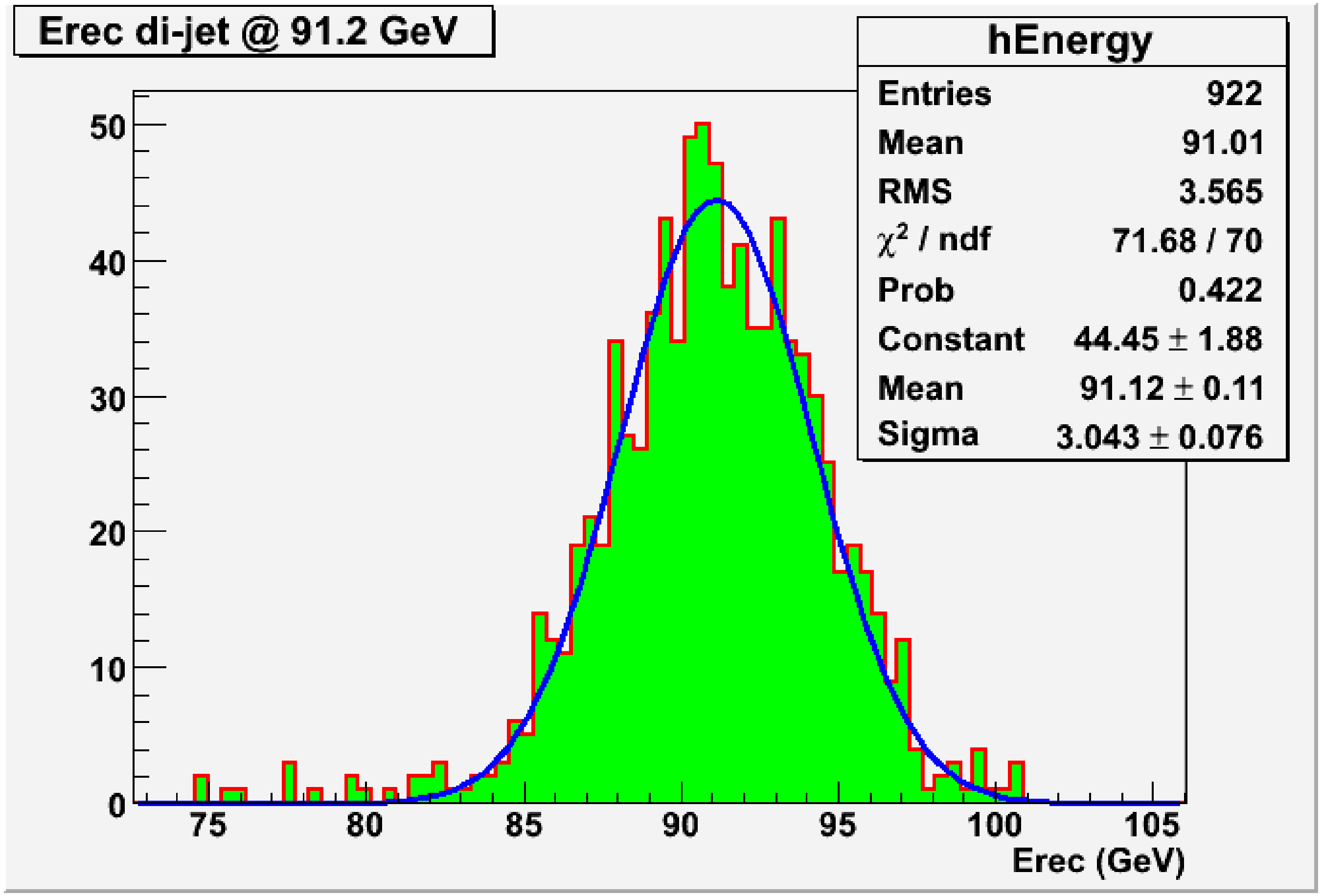
$\chi^2/ndf = 1.15$



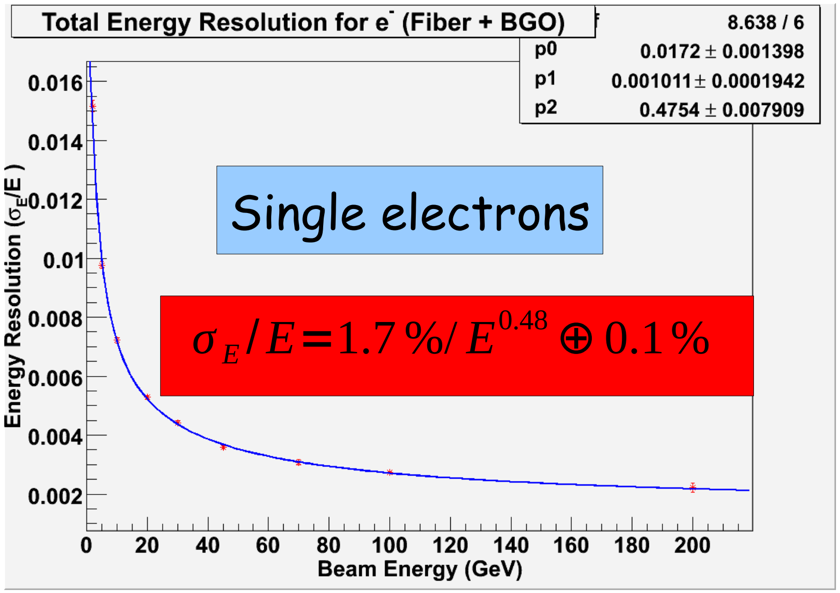
$\eta_c = 4.665$ $\eta_S = 1.114$

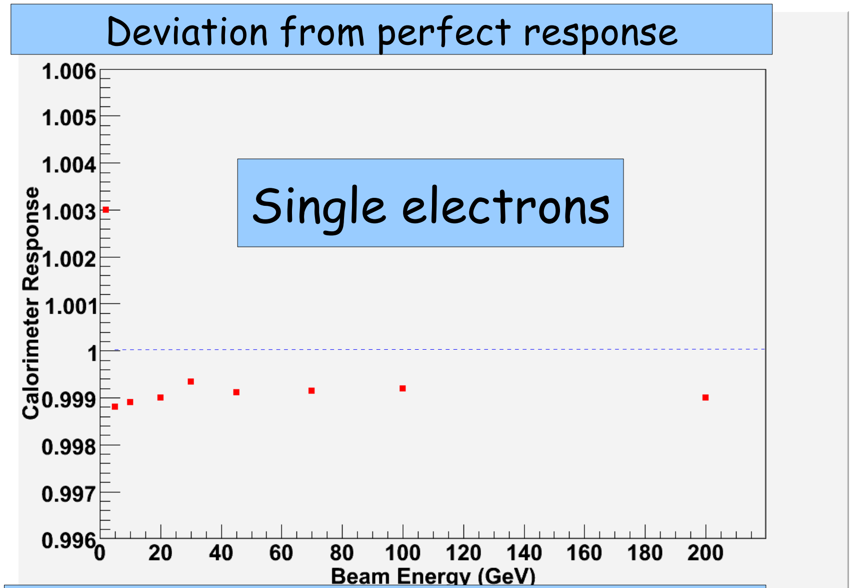
Calibrated energy: di-jet @ 91.2 GeV case using Triple Readout

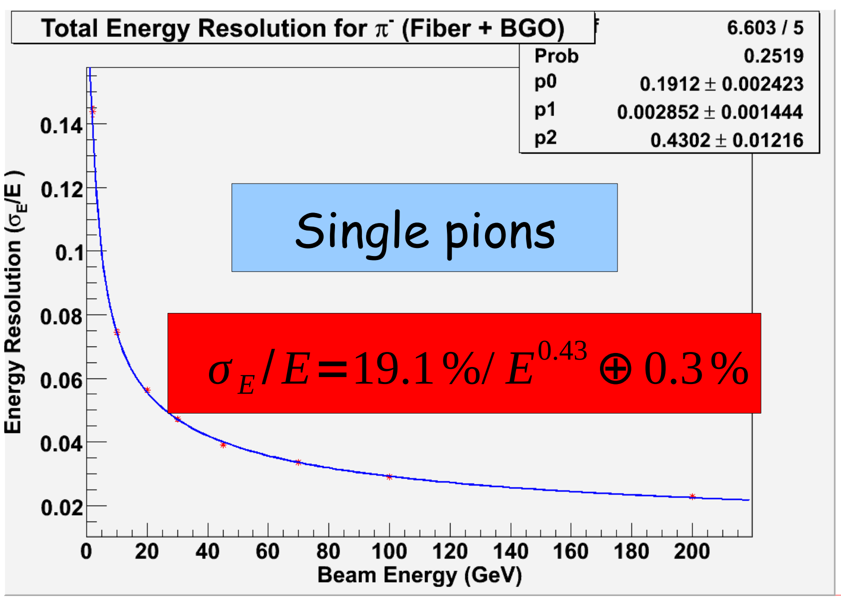
$$E_{HCAL} = \frac{E_S - \lambda E_C}{1-\lambda} + \eta_n E_n$$

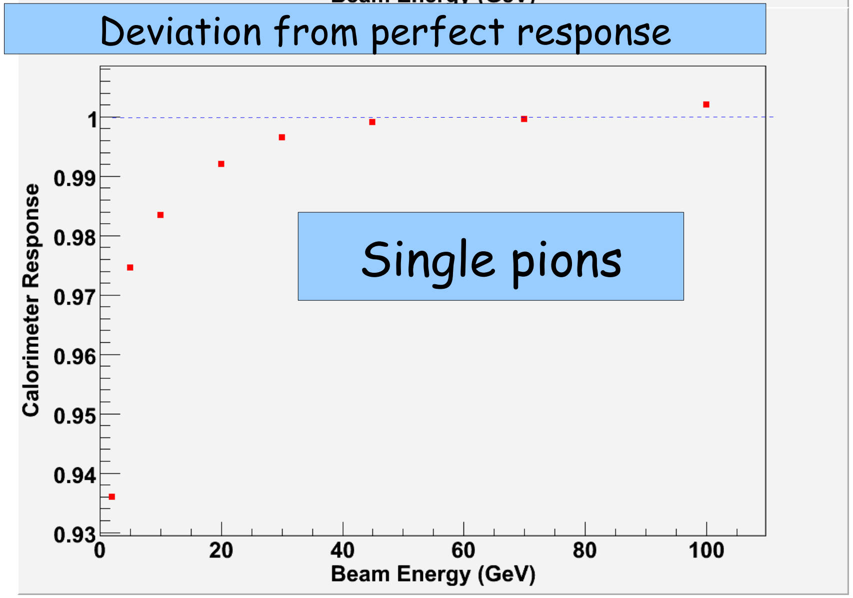


HCAL + ECAL resolution (single particles)

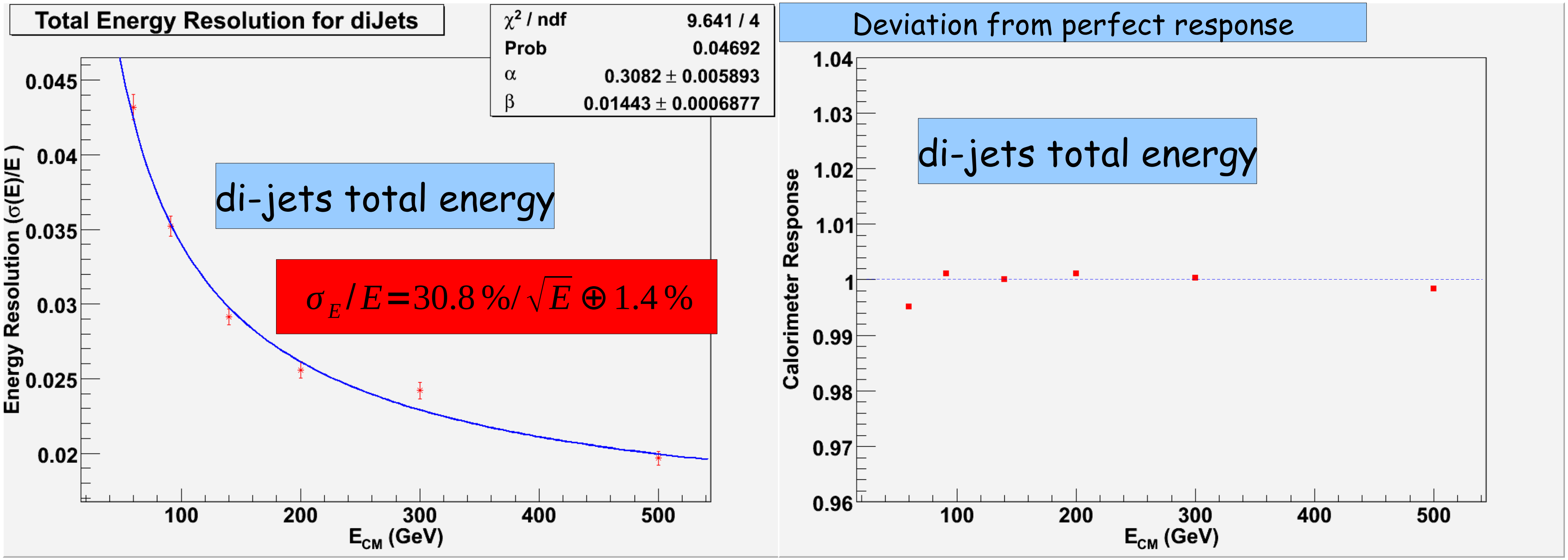








HCAL + ECAL resolution (di-jets)



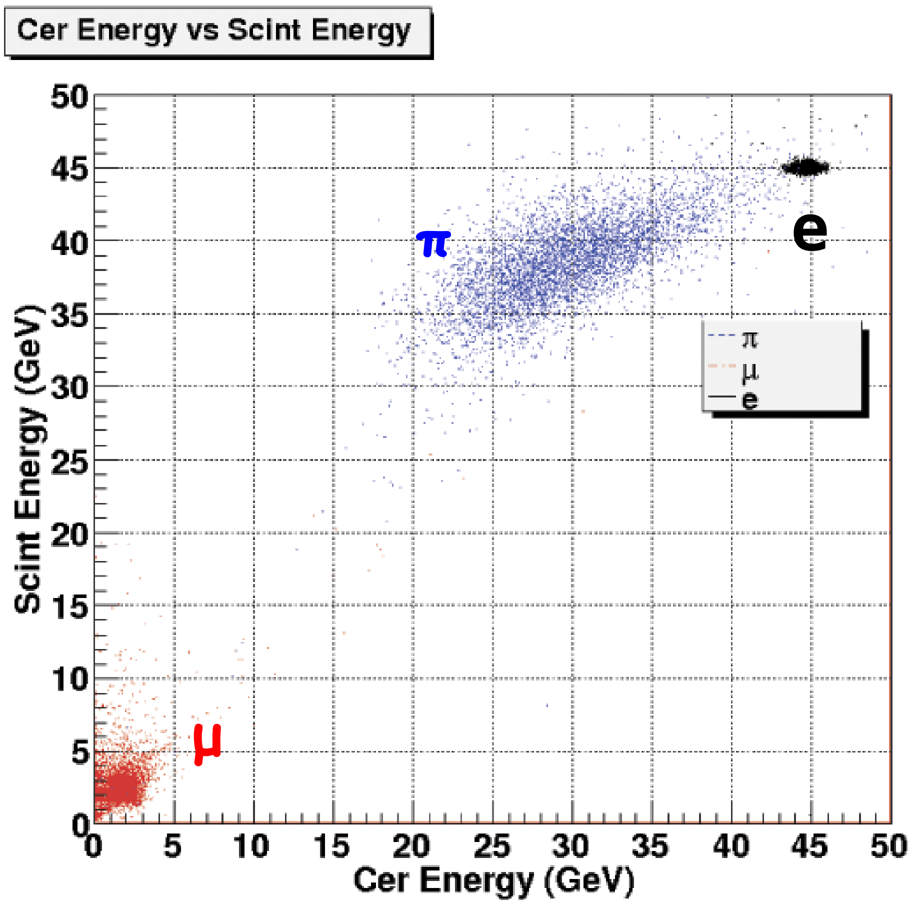
HCAL + ECAL resolution: summary

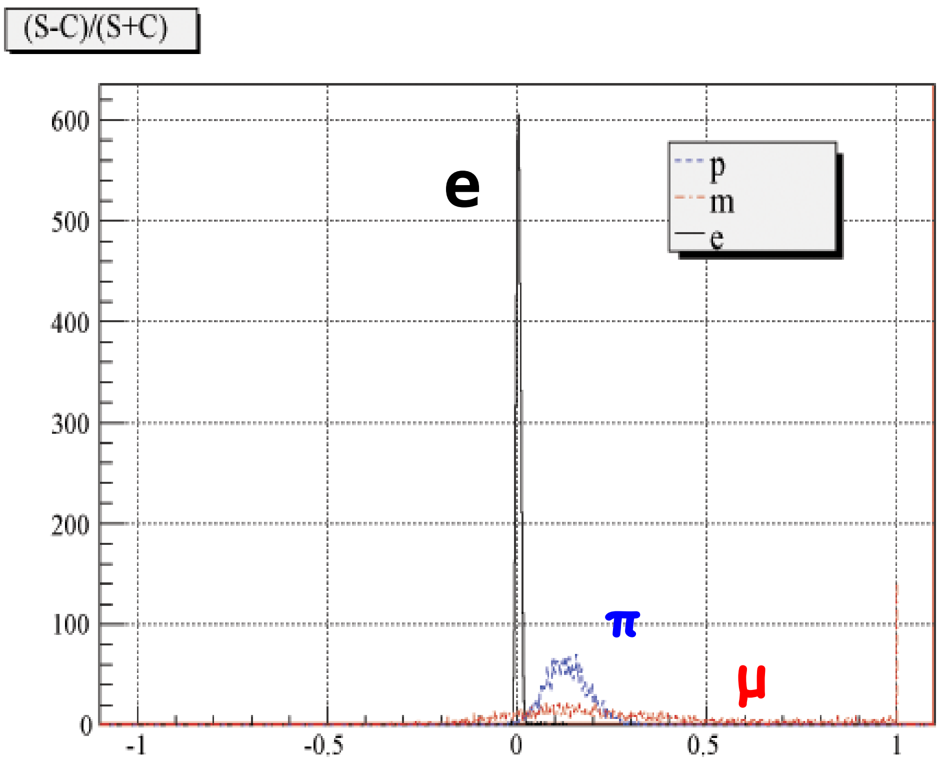
Triple readout HCAL	Gaussian resolution stocastic term	constant term
π^-	$25.6\%/\sqrt{E}$	1.5%
di-jet	$29\%/\sqrt{E}$	1.2%

Triple readout ECAL + HCAL	Gaussian resolution stocastic term	constant term
e^-	$1.7\%/E^{0.48}$	0.1%
π^-	$19.1\%/E^{0.43}$	0.3%
di-jet	$30.8\%/\sqrt{E}$	1.4%

Particle Identification with Triple Readout

45 GeV particles





How the mass reconstructions of Physics particles is affected by the calorimeter performances?

2 jets	$e^+e^- \rightarrow Z^0H^0$; $Z \rightarrow \nu\underline{\nu}$; $H \rightarrow q\underline{q}$	M_{Higgs} = 119.60 ± 0.07 GeV/c^2 σ_{Higgs} = 3.83 ± 0.07 GeV/c^2	**35%/√M**	HCAL
4 jets	$e^+e^- \rightarrow Z^0H^0$; $Z \rightarrow u\underline{u}$; $H \rightarrow c\underline{c}$	M_{Higgs} = 117.9 ± 1.2 GeV/c^2 σ_{Higgs} = 4.48 ± 1.6 GeV/c^2	**41%/√M**	HCAL
4 jets	e^+e^- -> $\chi_1^+\chi_1^-$ -> $\chi_1^0\chi_1^0 W^+W^-$	M_W = 79.40 ± 0.06 GeV/c^2 σ_W = 2.84 ± 0.06 GeV/c^2	**31%/√M**	HCAL + ECAL
4 jets	e^+e^- -> $\chi_2^0\chi_2^0$ -> $\chi_1^0\chi_1^0 Z^0Z^0$	M_Z = 89.55 ± 0.20 GeV/c^2 σ_Z = 2.77 ± 0.21 GeV/c^2	**29%/√M**	HCAL + ECAL
6 jets	e^+e^-->tt ->W^+bW^-b ->qqbqqb	M_{top} = 174 .21 ± 0.06 GeV/c^2 σ_{top} = 4.65 ± 0.06 GeV/c^2	**35%/√M**	HCAL

Benchmark Physics studies presented in the LOI @ILC

Calibration issue

- The calibration scheme need the that the ECAL and HCAL response have to be measured independently
- It is in progress a new calibration scheme

New calibration approach (1)

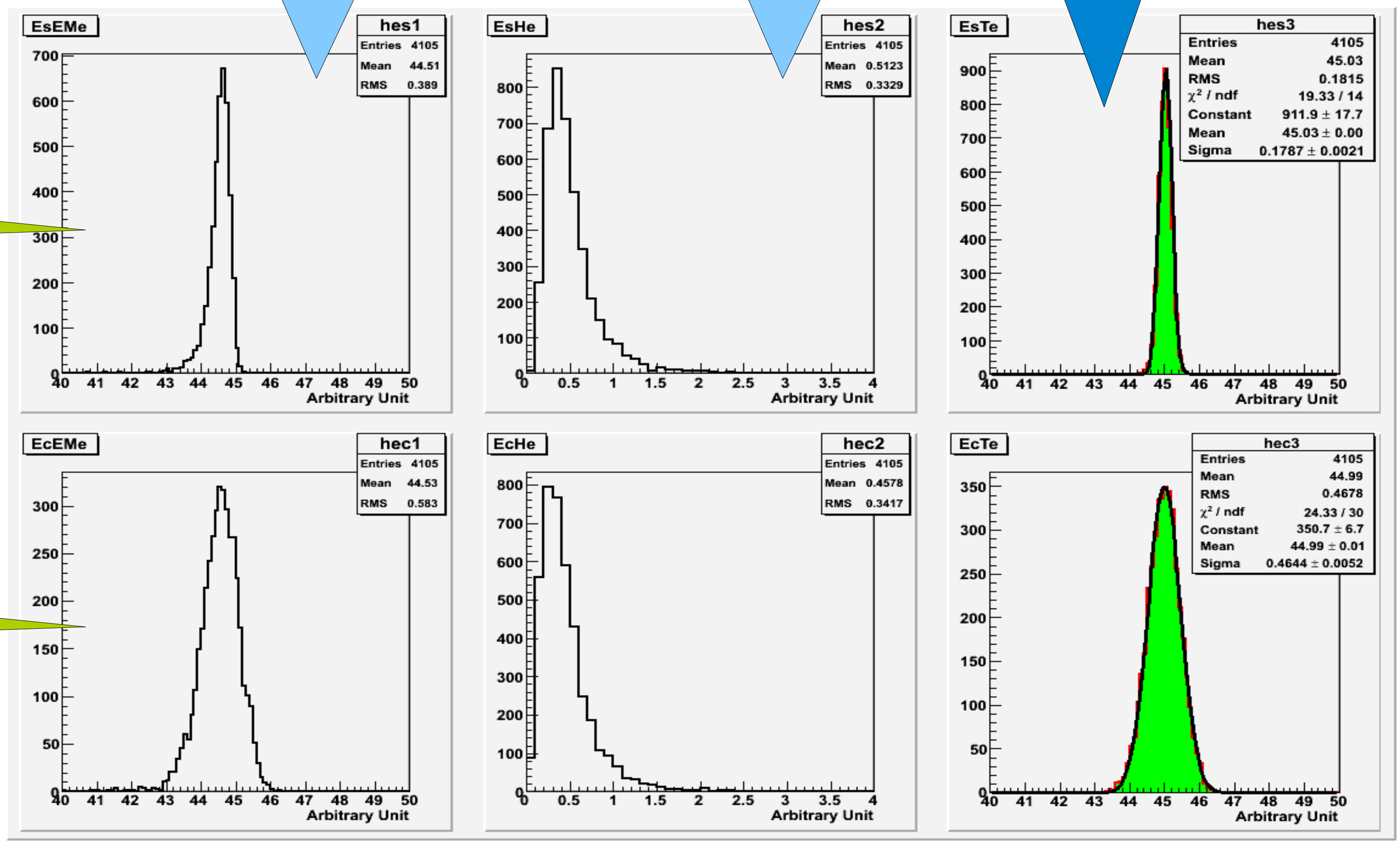
Preliminary

45 GeV e⁻

ECAL section | HADR section | Sum

Scint signal

Čer signal

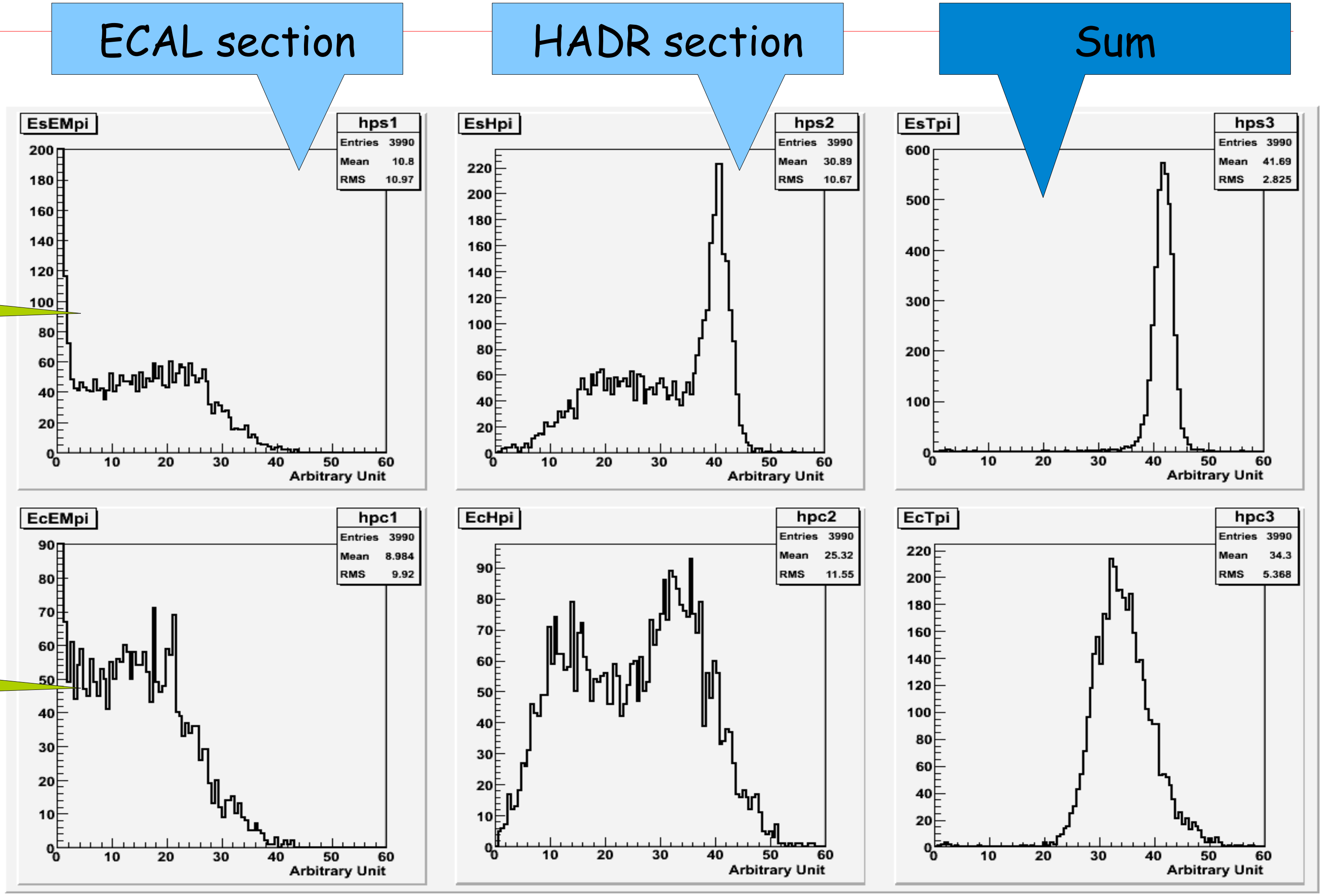


One electron beam can allow to evaluate the response for both ECAL and HCAL

New calibration approach (2)

Preliminary

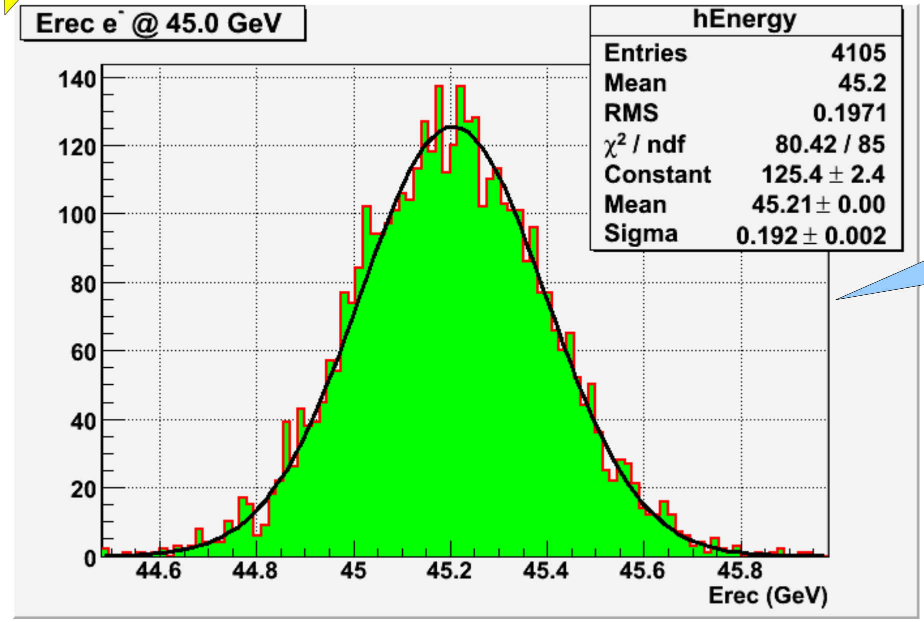
45 GeV π^-



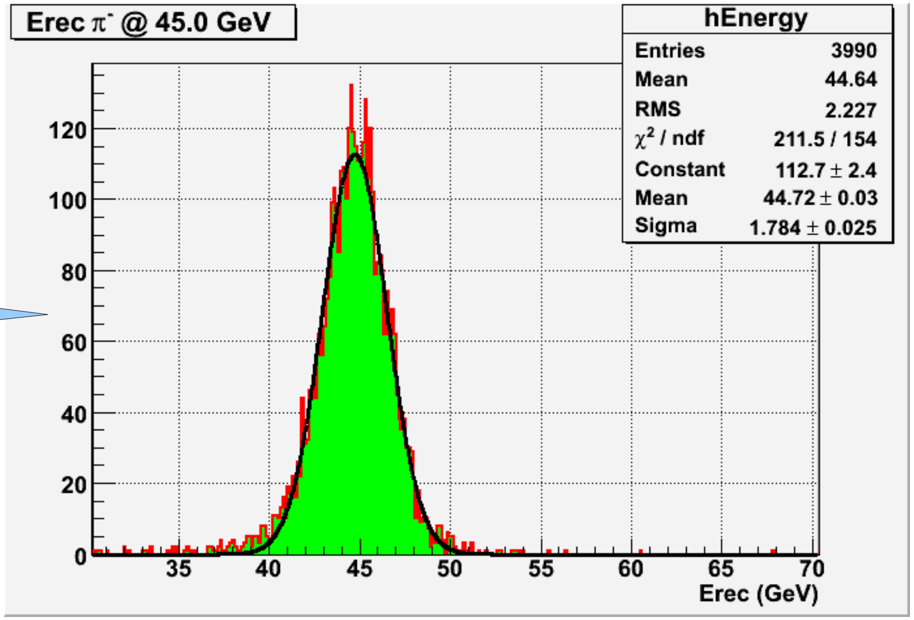
Combining the Scint and Cer signal of ECAL and HCAL allow to evaluate calibration parameters

New calibration approach (3)

Preliminary

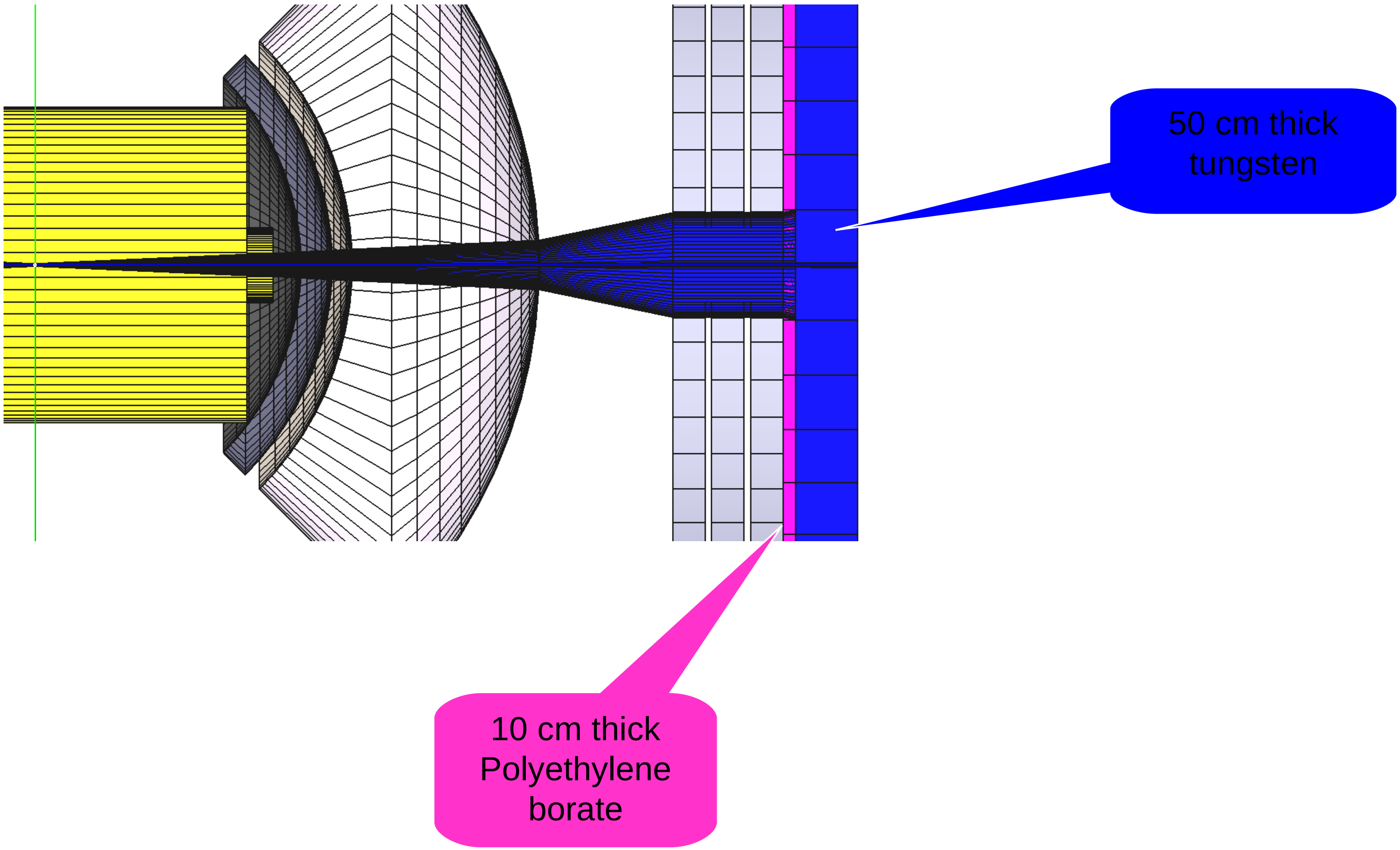


electrons
resolution 2.9% / √E



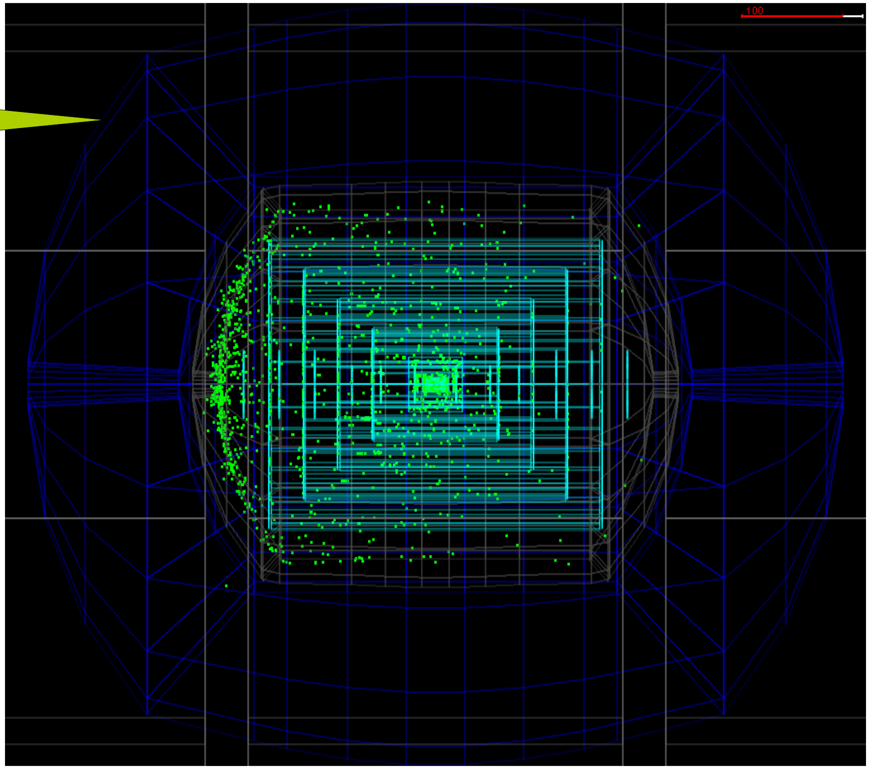
pions
resolution 26.7% / √E

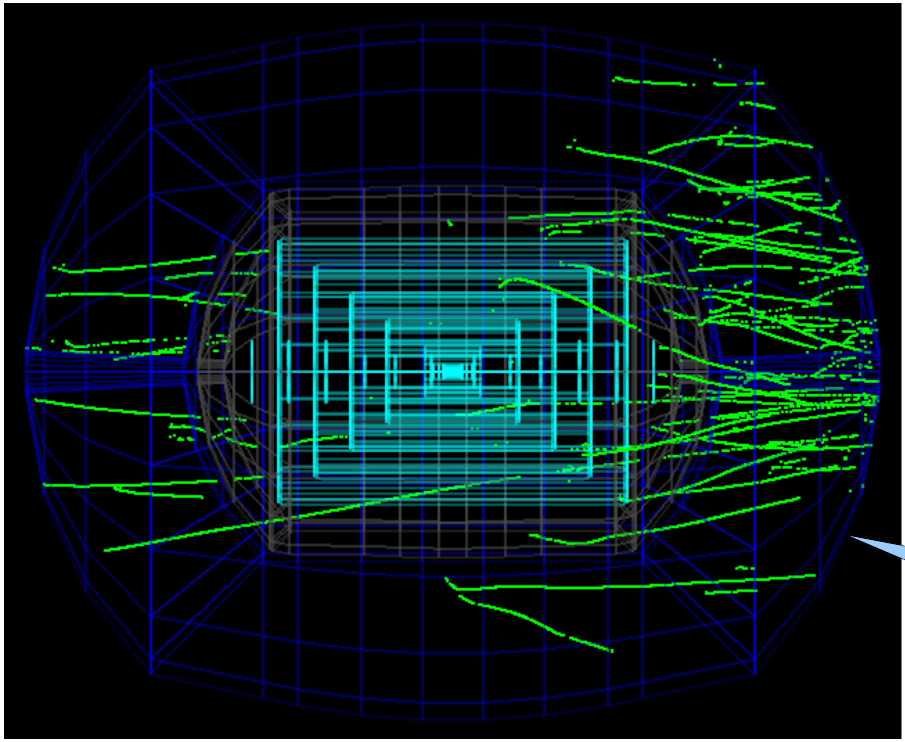
Shielding



beam background effect in HCAL and ECAL

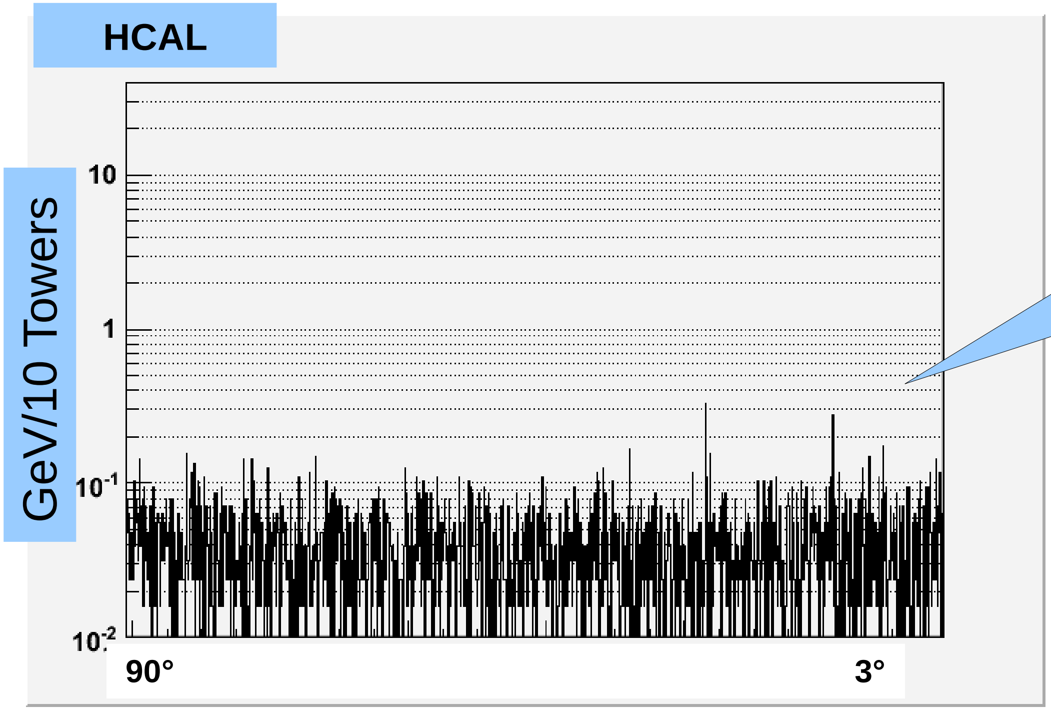
electrons background effect



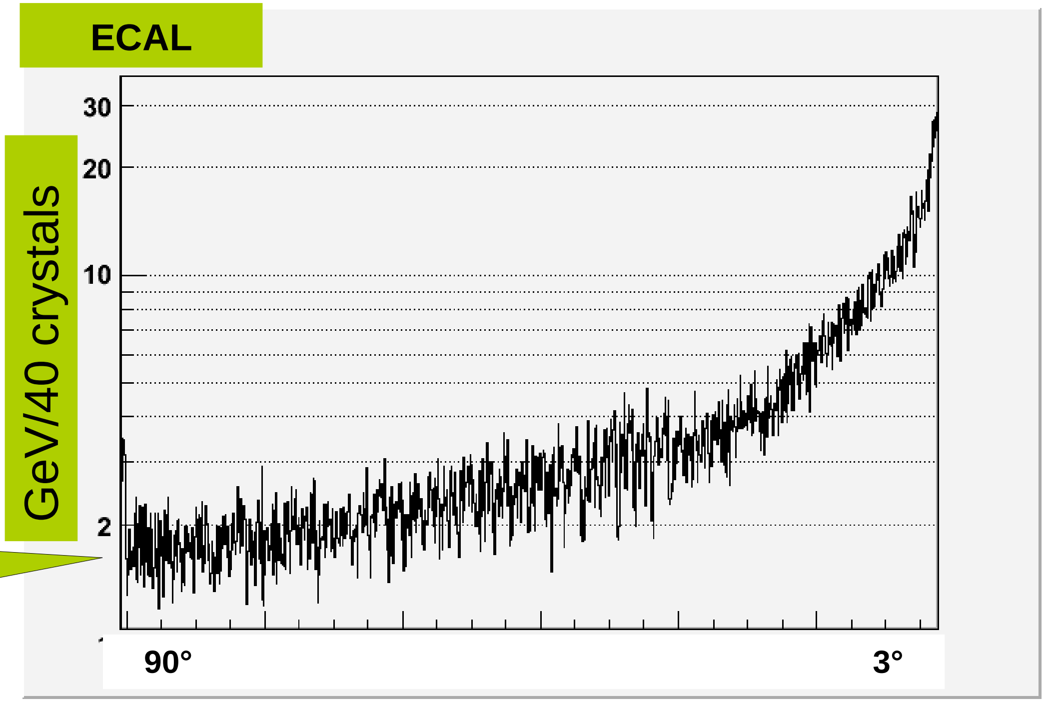


muons background effect

Estimate beam background in HCAL and ECAL

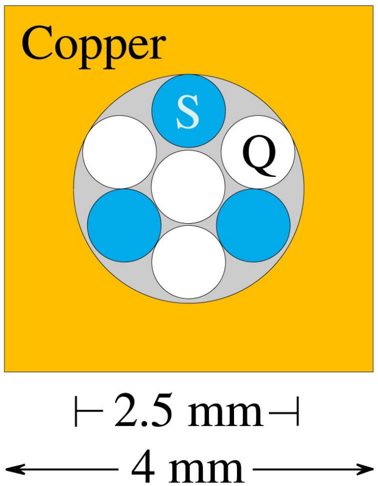


The HCAL background is mostly induced by muons

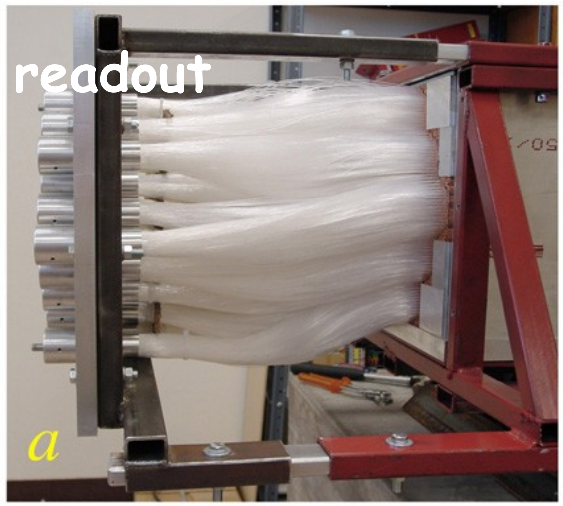


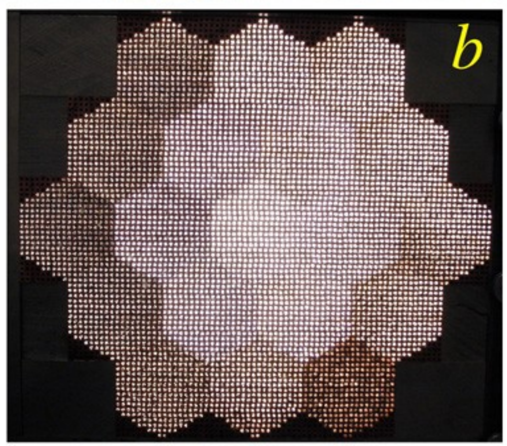
The ECAL background is mostly induced by electrons

DREAM beam test setup



Unit cell

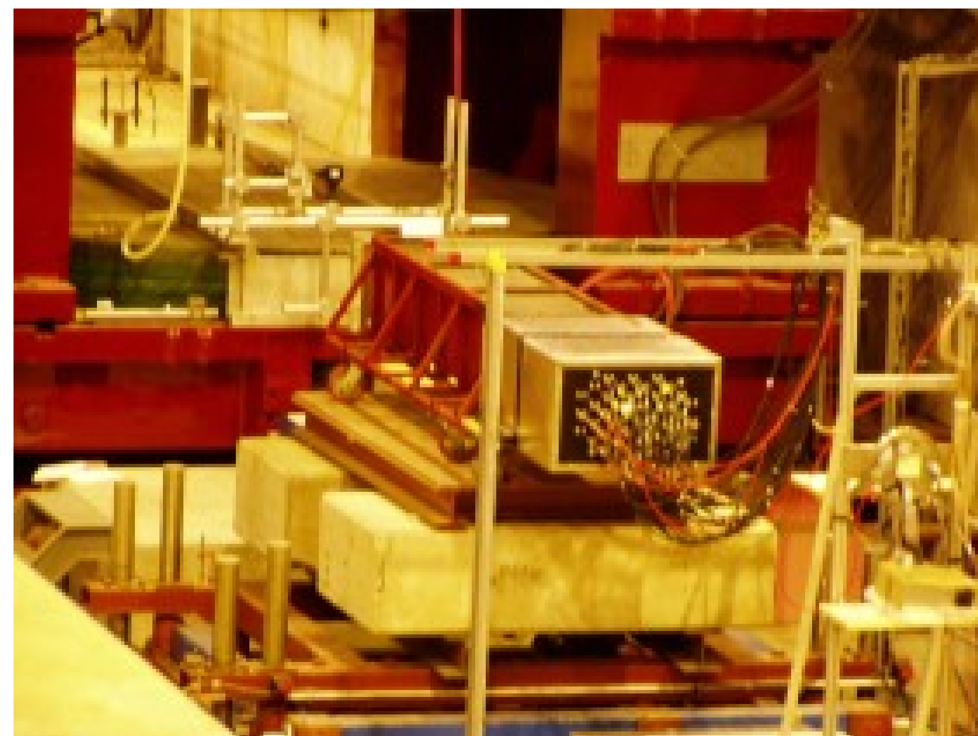




Channels structure

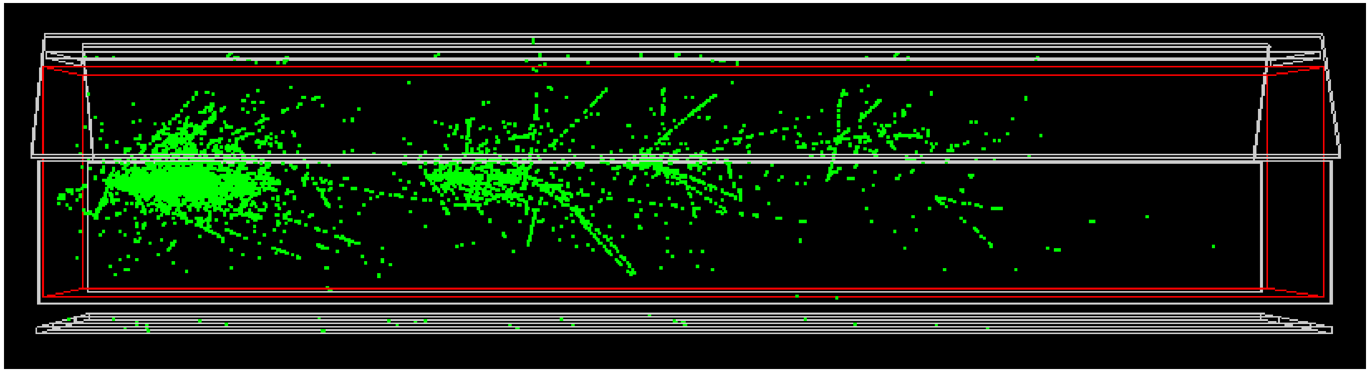
Look at the John Hauptman and Nural Akchurin talks in the Calorimetry session

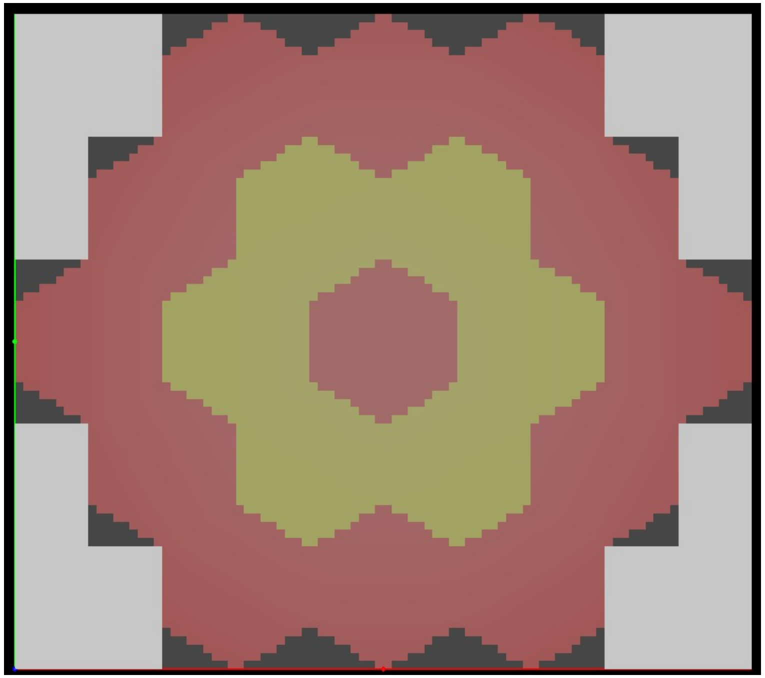
DREAM



DREAM simulated in ILCroot

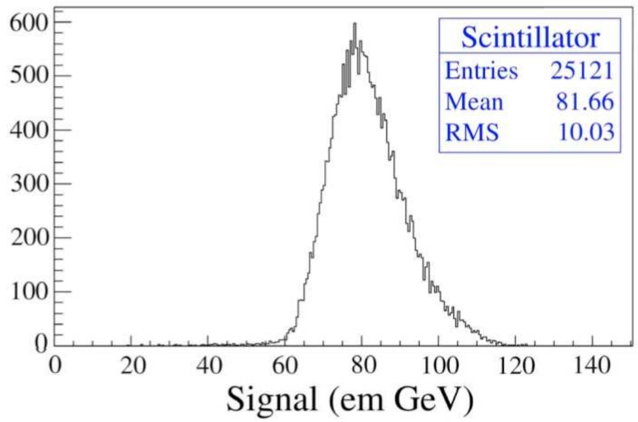
100 GeV π^- shower

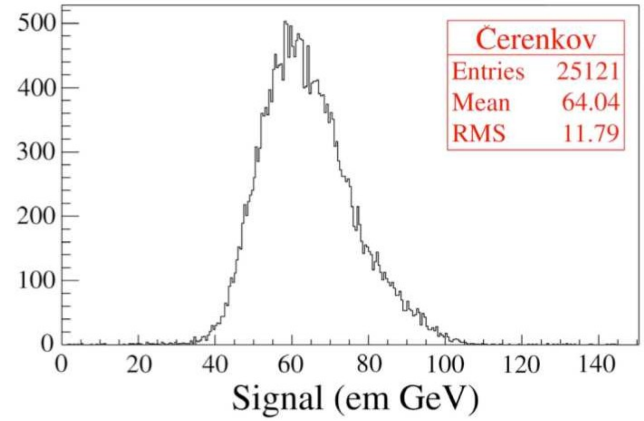




Front view of the DREAM module in the simulation

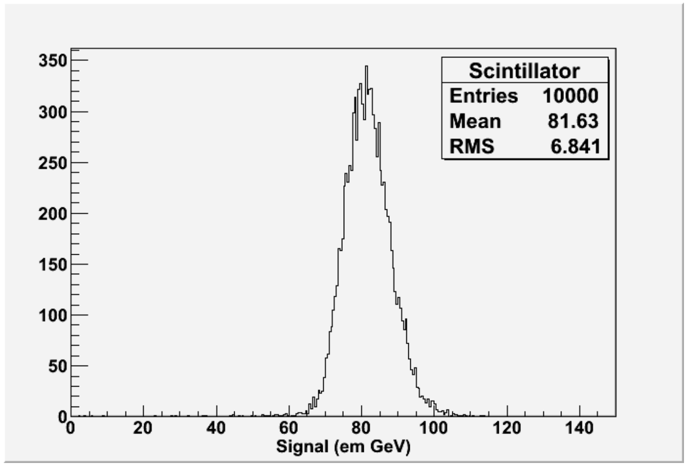
Scintillation and Cerenkov signal distributions for 100 GeV pions

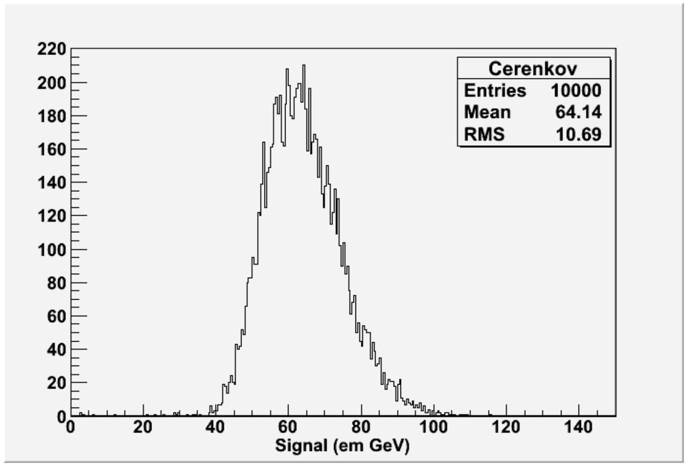




DREAM data

(raw signals)

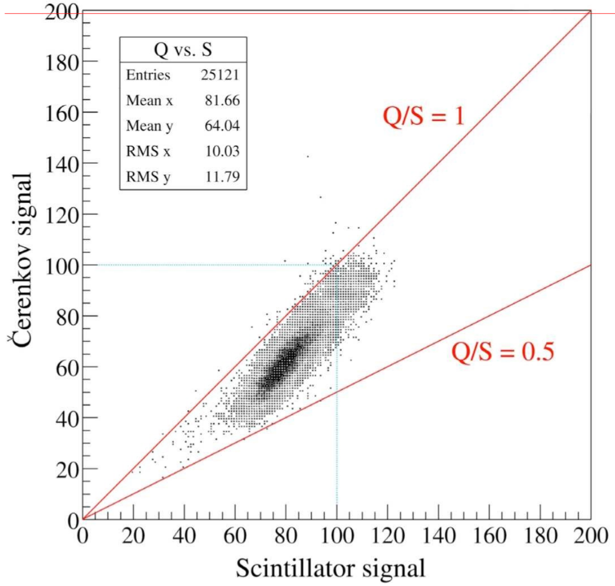


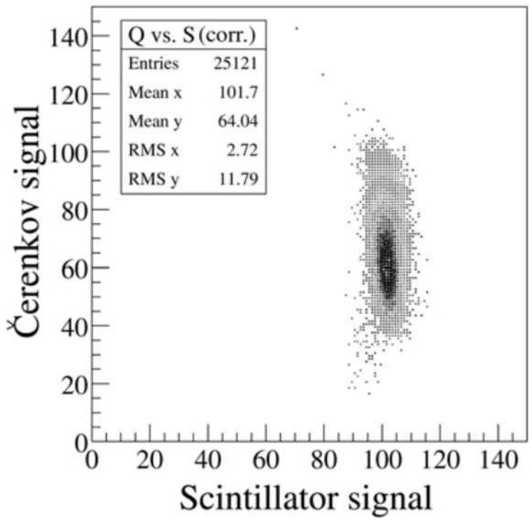


ILCroot simulation

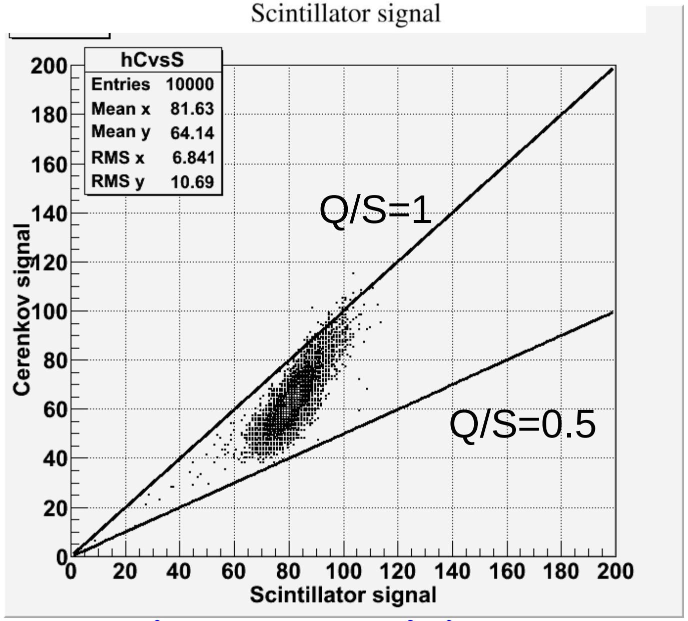
Note: DREAM integrate the signal in 80 ns, in the ILCroot simulation I integrate the signal in 350 ns

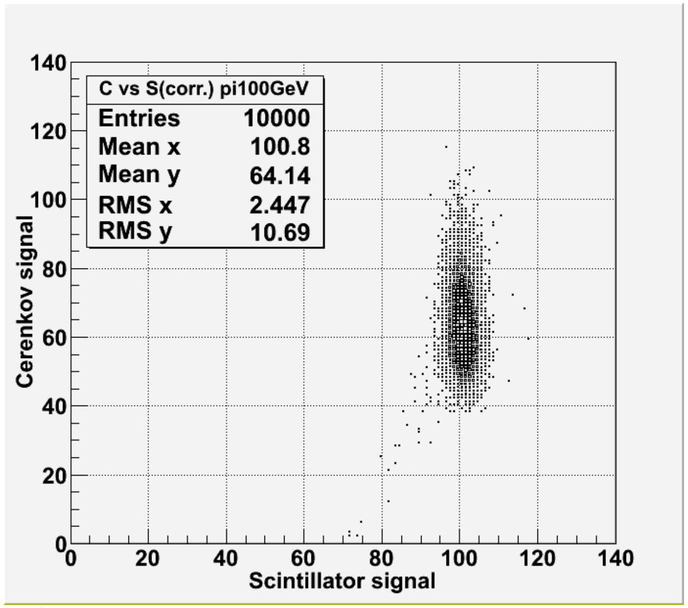
Scintillation signal vs. Cerenkov signal for 100 GeV pions





DREAM data



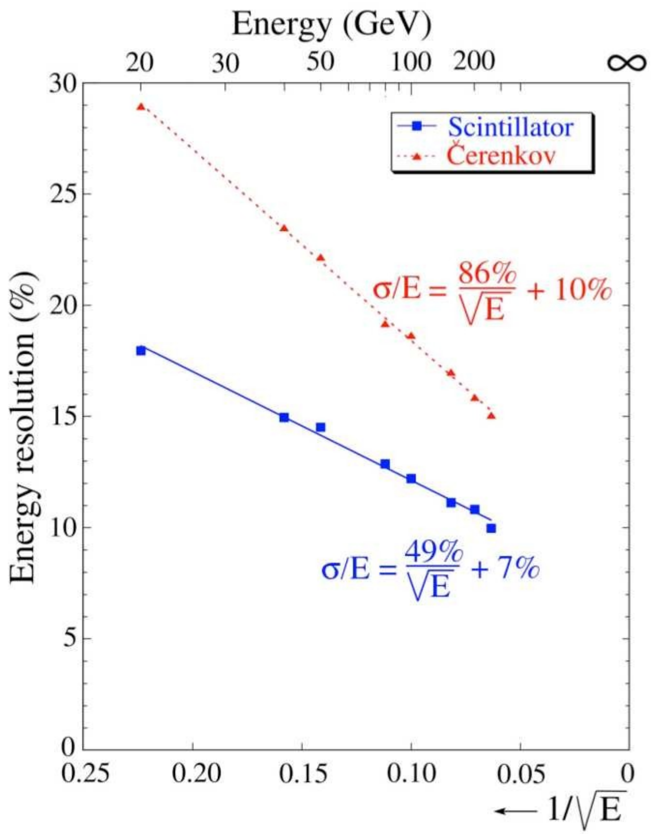


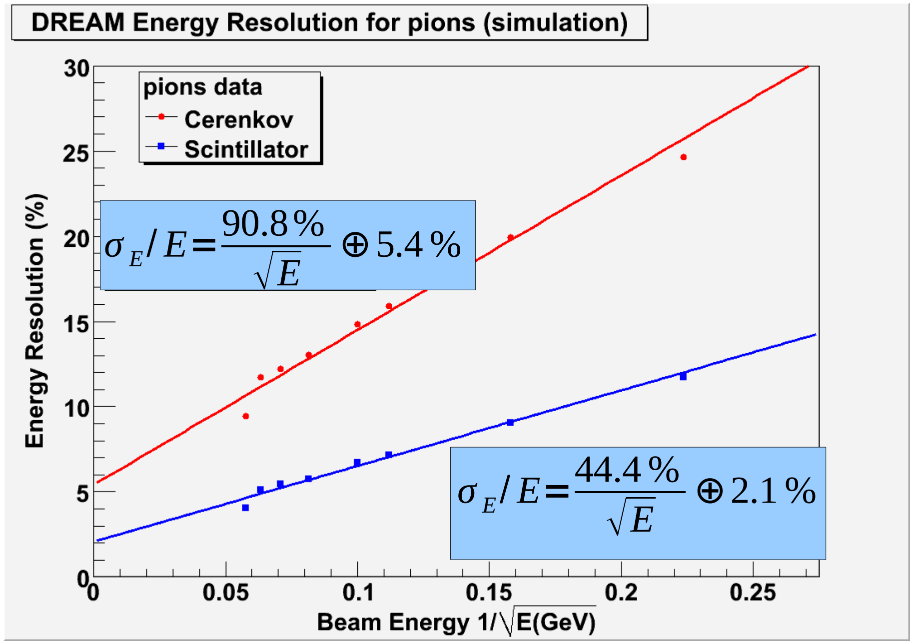
ILCroot simulation

(raw signals)

(raw Cer, corrected Scint)

Individual resolutions for pions in the scintillation and Cerenkov signals



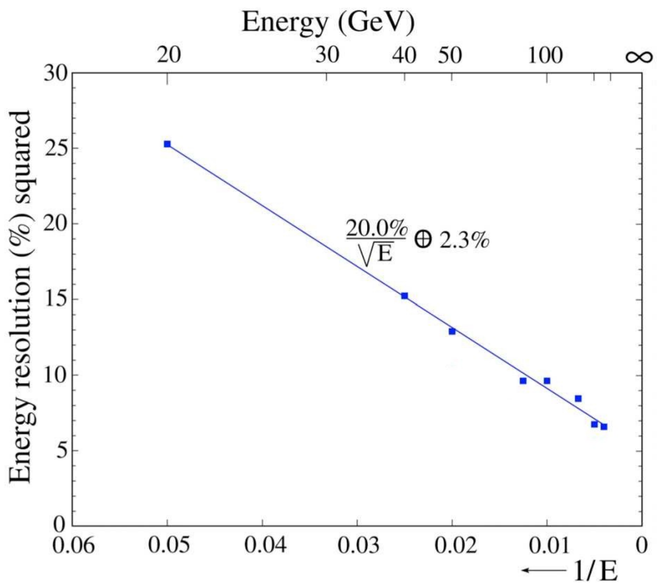


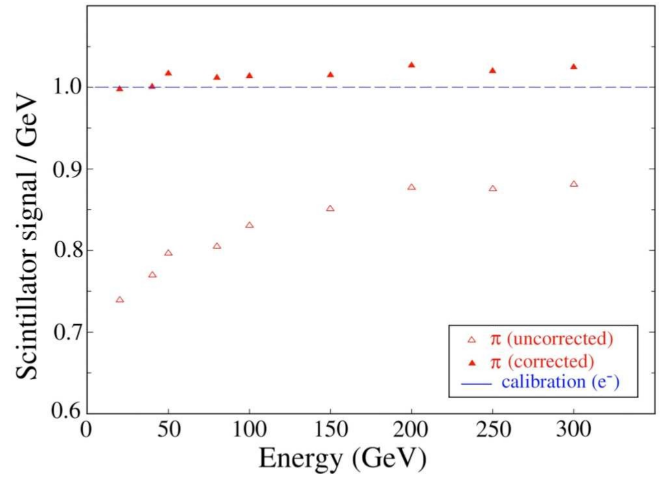
DREAM data

(raw signals)

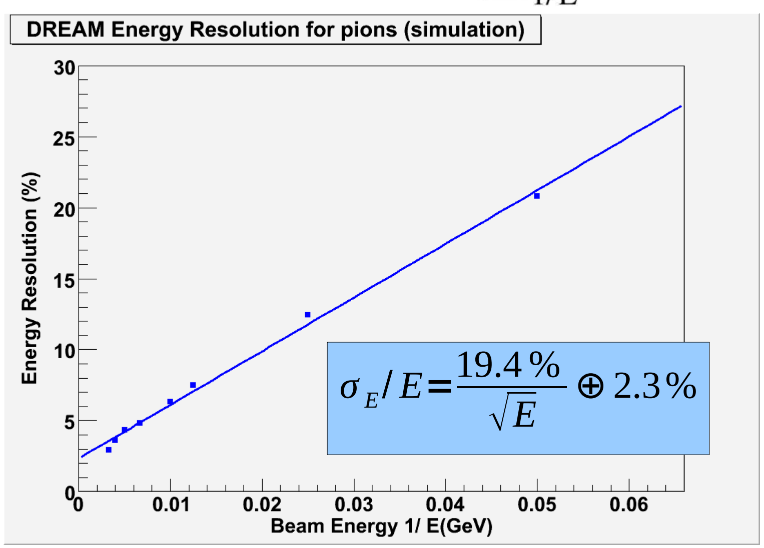
ILCroot simulation

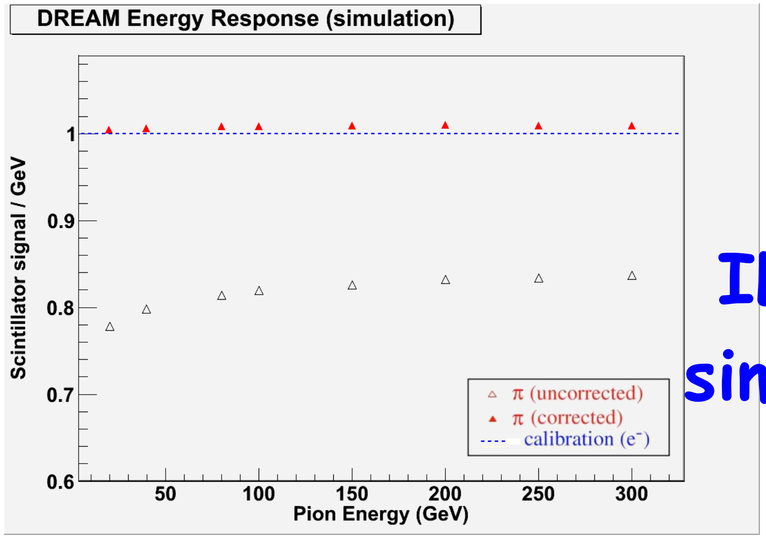
Energy resolutions for pions (calibrated energy)





DREAM data





ILCroot simulation

The algorithm used for the reconstructed energies are not the same but equivalent

Comparison studies issue

In the comparison studies there is some issue, but it is understood and I'll reprocess the data to overcome this issue

Conclusion

- Dual/Triple Readout calorimetry are being studied since 4 years in ILCroot
- In ILCroot there are implemented two HCAL versions and two ECAL varsions
- We used FLUKA and Geant4 as MonteCarlo, it looks like Geant4 has some problems with neutrons
- The Dual/Triple Readout calorimetry is performing very well with data and simulations
- Effect on the Physics is well understood
- Comparison of ILCroot simulations with DREAM test beam is very good, there is some issue, but it is understood
- Working in progress to understand the MuonCollider background impact

Conclusion

All the machinery is ready to perform a very large number of Physics and performances studies at the MuonColider taking into account the machine background