Detector and Physics studies for a 1.5TeV Muon Collider Experiment

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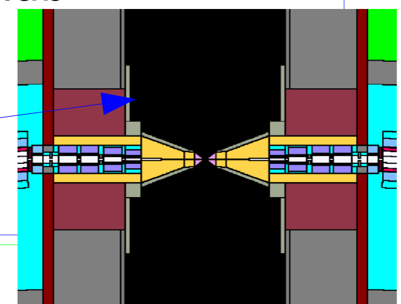
Outline

- MARS and ILCroot overview.
- Calorimeters requirements for Lepton Colliders.
- Muon Collider detector layout.
- Machine background overview and its rejection strategy (focused on calorimeter).
- Study of $\mu^+\mu^- \rightarrow W^+W^-\nu\bar{\nu}$ in 4 jets at 1.5TeV Muon Collider.
- Preliminary results for W invariant mass with machine background.
- Conclusions.

MARS and ILCroot Frameworks

- **MARS** – is the framework for simulation of particle transport and interactions in accelerator, detector and shielding components.
- New release of MARS15 is available since February 2011 at Fermilab (N. Mokhov, S. Striganov, see www-ap.fnal.gov/MARS).
- Background simulation in the studies shown in this presentation is provided at the surface of MDI (10° nozzle + walls).



- ILCroot is a 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.
- Include an interface to read MARS output to handle the MuonCollider background.
- It is a simulation framework and an offline system:
  - Single framework, from generation to reconstruction and analysis!!!
  - VMC allows to select G3, G4 or Fluka at run time (no change of user code).
- Widely adopted within HEP community (4th Concept@ILC, LHeC, T1015, SiLC, ORKA, MuC).
- It is available at FNAL since 2006.

All the studies presented are performed by ILCroot

Calorimetry performances requirements at Future Colliders

- Many interesting physics processes at TeV scale have multi-jets in the final state.
- **Jet energy resolution is the key in the future of HEP.**

Z/W→ jj can be reconstructed and separated if

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

Two approaches are pursued to reach this goal:

- **Particle Flow Analysis (PFA)**
  - Combine the information from a tracking system and a fine segmented calorimeter.
  - Charged particles are reconstructed in tracking system.
  - Neutral particles are reconstructed in calorimeter.
  - Energy resolution at high energy jets doesn't scale as 1/√E.
  - Short depth, can't contain jets at multi-TeV energy.
  - At high energy PFA -> EFA.
- **Dual Readout calorimeter**
  - Reduce/eliminate event by event the (effects of) fluctuations that dominate the calorimeter performance.
  - Has PID capability.
  - Energy resolution scales as 1/√E.

Total Active Dual-Readout

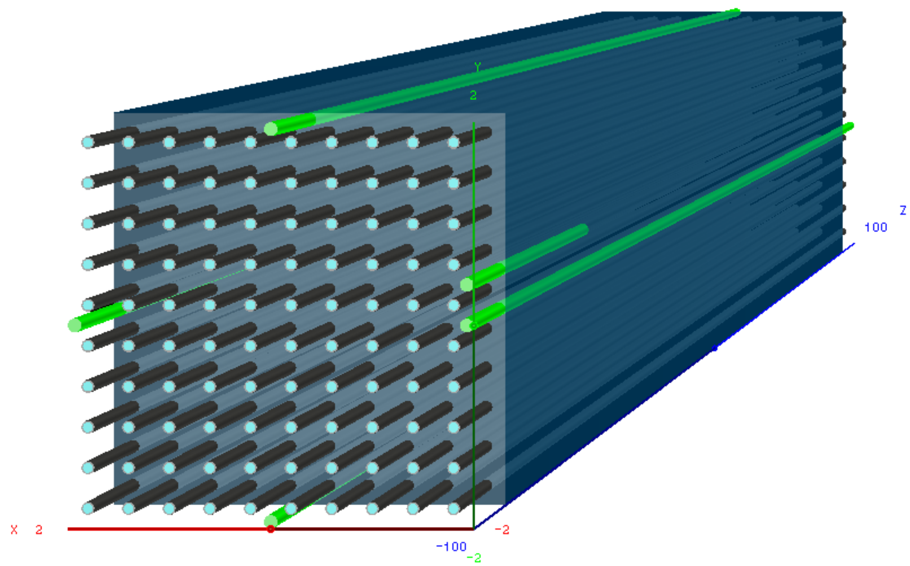
Total Active Dual-Readout (i.e. with ACTIVE absorber)

- Approach pursued by
  - **DREAM** with crystals (PbWO4, BGO, ...)
  - **T1004** with crystals (BGO, PbF2, ...)
  - **T1015** with scintillating fibers embedded in heavy glass.
- Crystals produce both scintillating and Cerenkov light.
  - Two light components have to be separated by mean of:
    - Time structure of the signals.
    - Spectrum of the signals.

not an easy task (mixing between Cer and Sci light)

- T1015 got signals separated by design.
  - Glass is much cheaper than crystals (cost factor 10^2).

ADRIANO: A Dual-Readout Integrally Active Non-segmented Option
T1015 approach

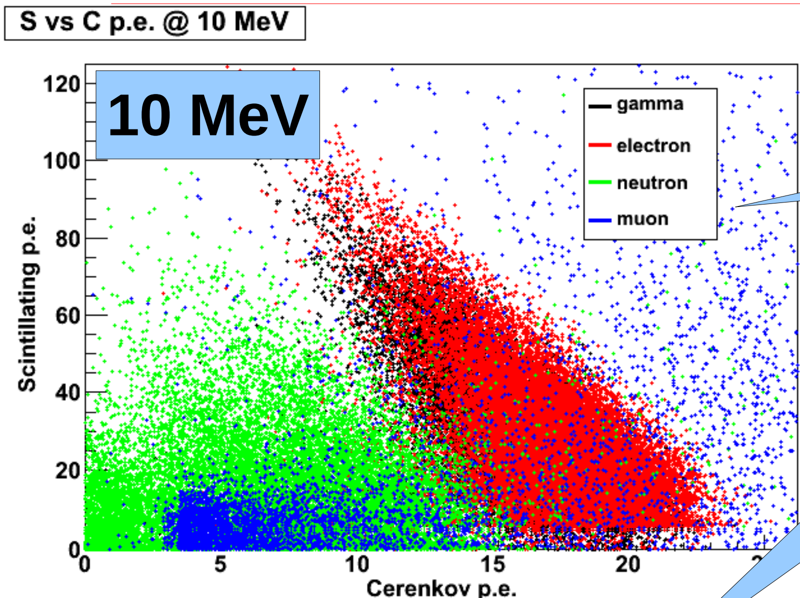


- **Cells dimensions:** 4x4x180 cm^3
- **Absorber and Cerenkov radiator:** SF57HHT (other glasses are under investigation) **no Sci light produced**.
- **Cerenkov light collection:** 10 WLS fiber/cell.
- **Scintillation region:** SCSF81J fibers, Φ 1mm, pitch 4mm (total 100/cell) **optically separated by Cer radiator**.
- **Particle ID:** 4 WLS fiber/cell (black painted except for foremost 20 cm).
- **Readout:** front and back SiPM.
- **CoG z-measurement:** light division applied to SCSF81J fibers.

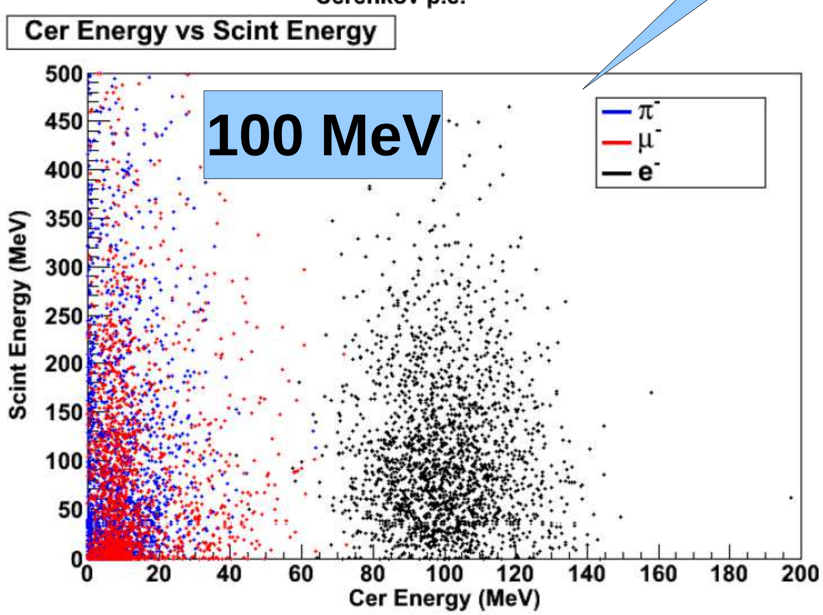
- Fully modular structure.
- Ratio photo-detectors / calorimeter surface ≈8%
- 3D with longitudinal shower CoG via light division technique.
- ADRIANO is full simulated in ILCroot with parameters taken from T1015 beam test.

ADRIANO can be operated simultaneously as EM and hadronic calorimeter

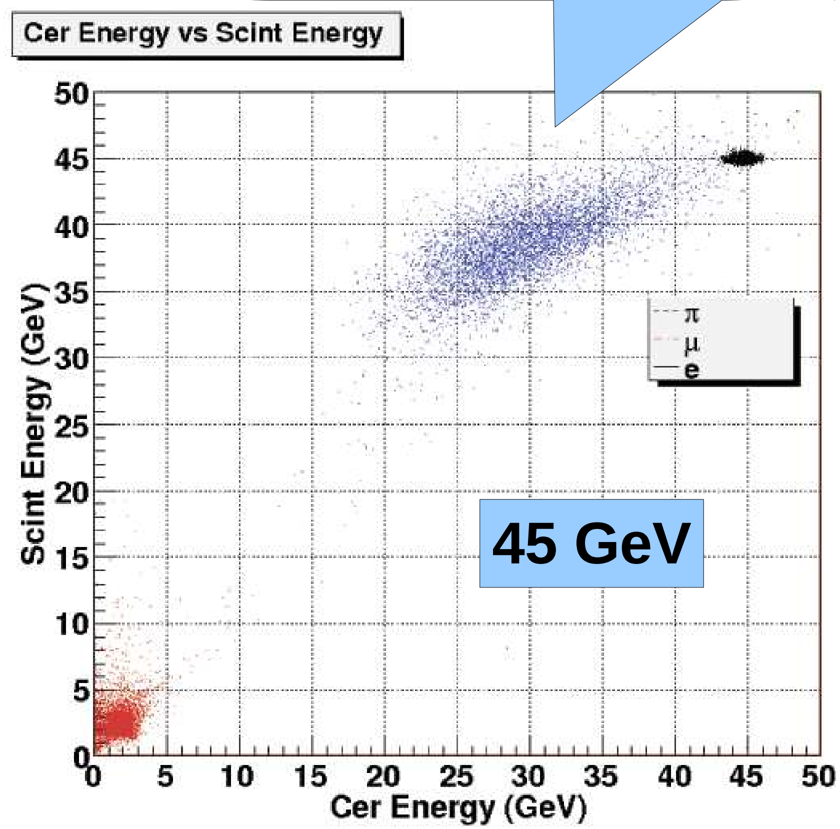
Particle ID with ADRIANO



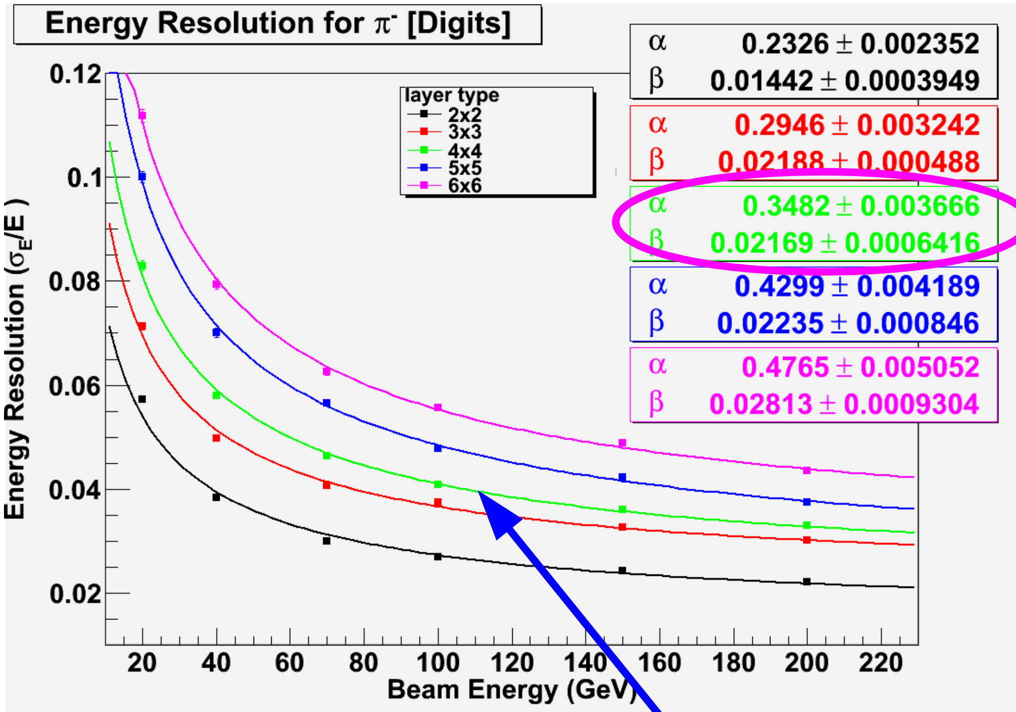
PID in ADRIANO:
low energy configuration.



PID in ADRIANO:
high energy configuration.

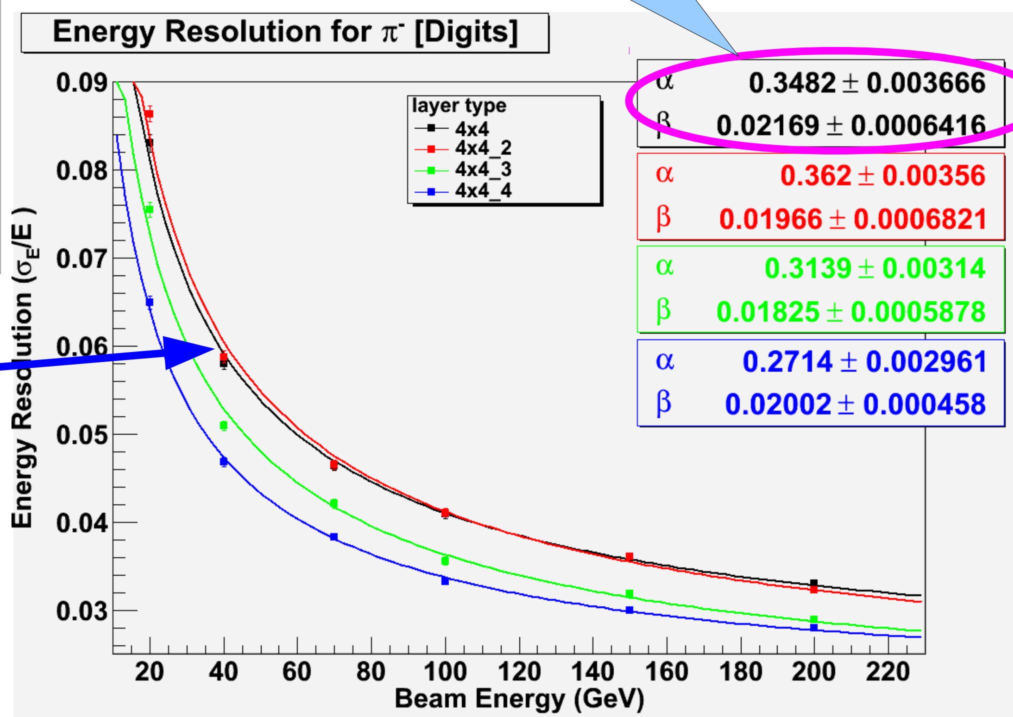


ADRIANO Energy Resolution
Dual-Readout configuration



Different fibers pitch and different fibers arrangement tested

Baseline configuration



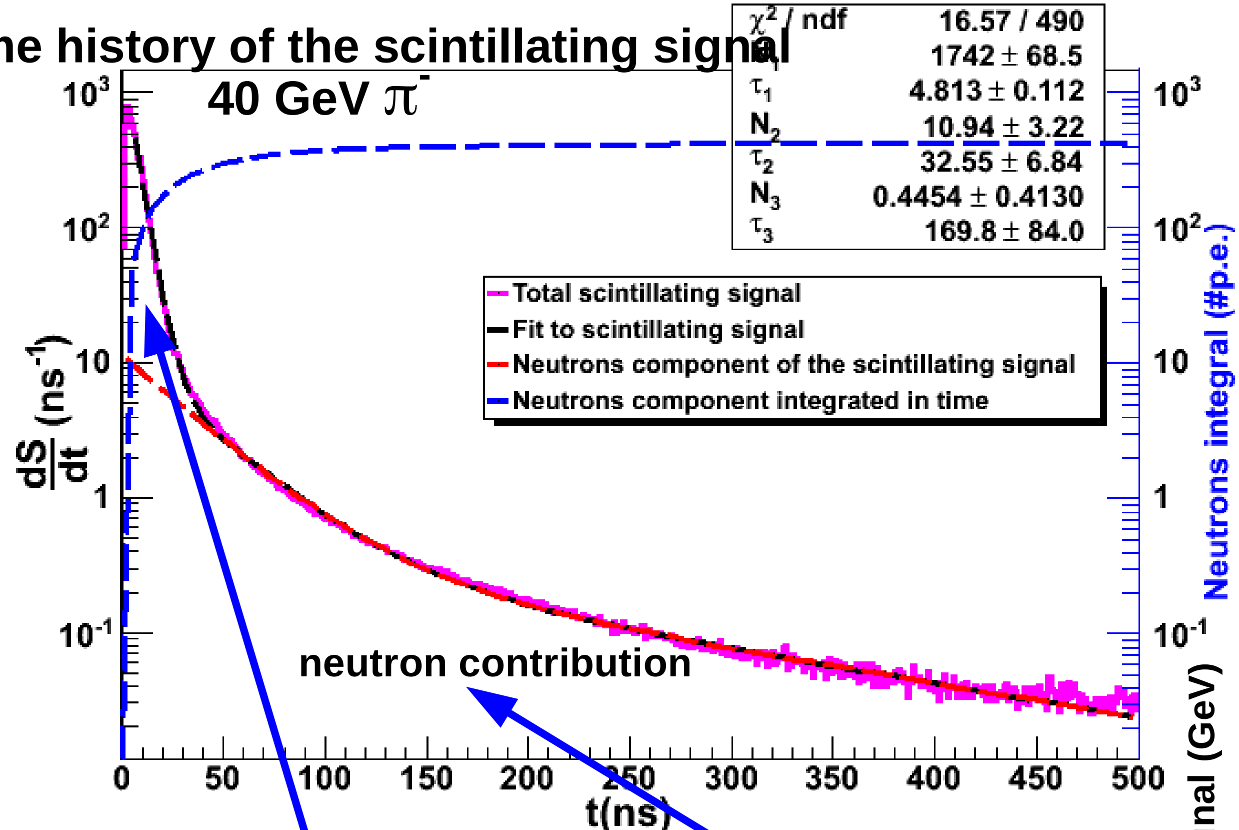
$$\frac{\sigma(E)}{E} = \frac{35\,\%}{\sqrt{E}} \oplus 2\,\%$$

From Dual to Triple Readout

measure neutron induced signal

Measure neutron induced signal helps to further reduce fluctuations and improves energy resolution.

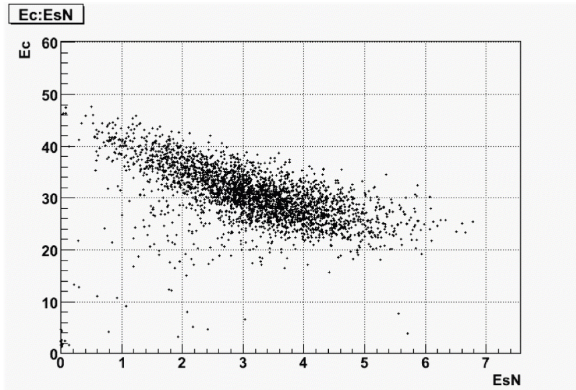
Time history of the scintillating signal



$$E_{shower} = \frac{S_{fast} - \chi C}{1 - \chi} + \xi S_{slow}$$

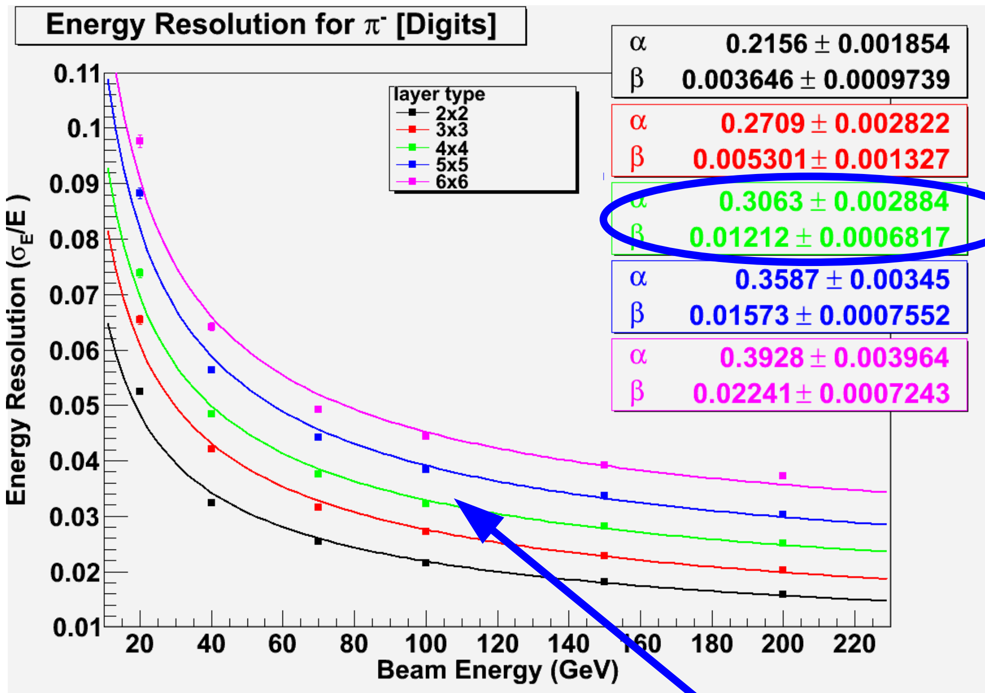
- **The distribution has been fitted with a triple exponential function.**
- **After 50 ns only neutrons contribute to the signal.**

Cerenkov signal (GeV)



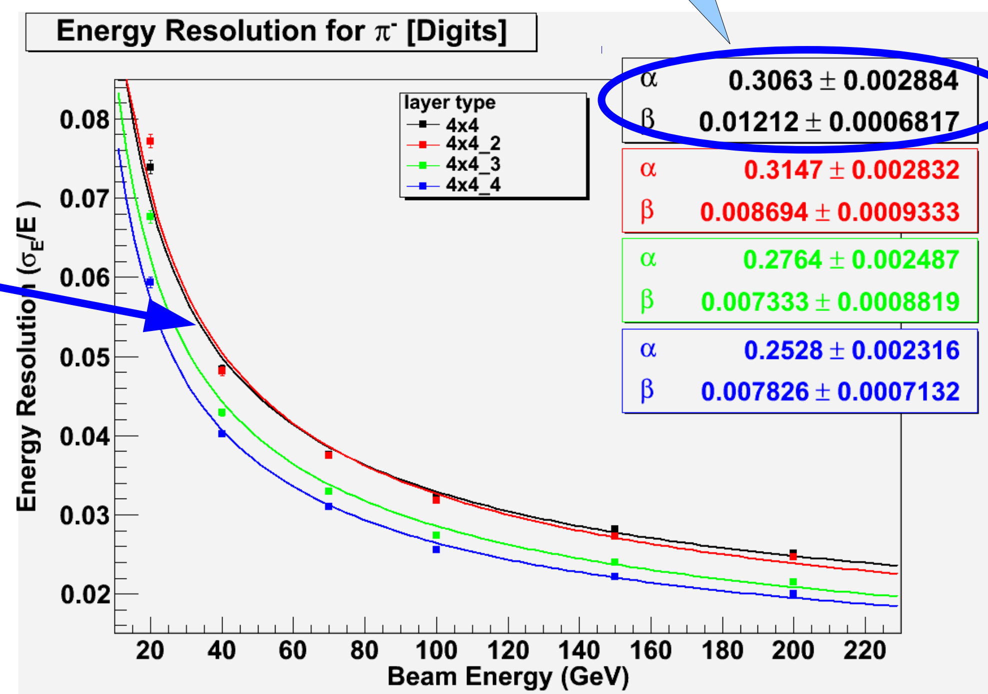
Neutron induced signal (GeV)

ADRIANO with Triple Readout



Baseline configuration

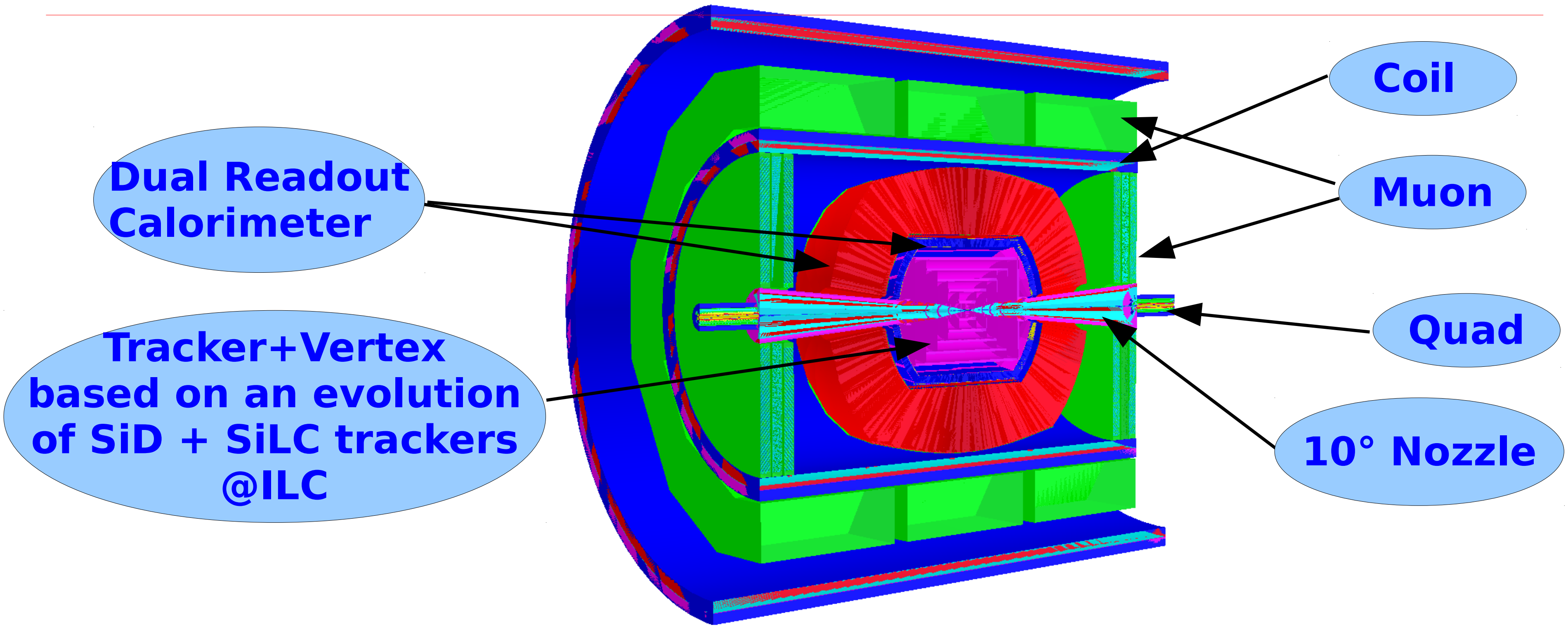
$$\frac{\sigma(E)}{E} = \frac{30.6\%}{\sqrt{E}} \oplus 1\%$$



Compare to ADRIANO in Dual Readout configuration

$$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E}} \oplus 2\%$$

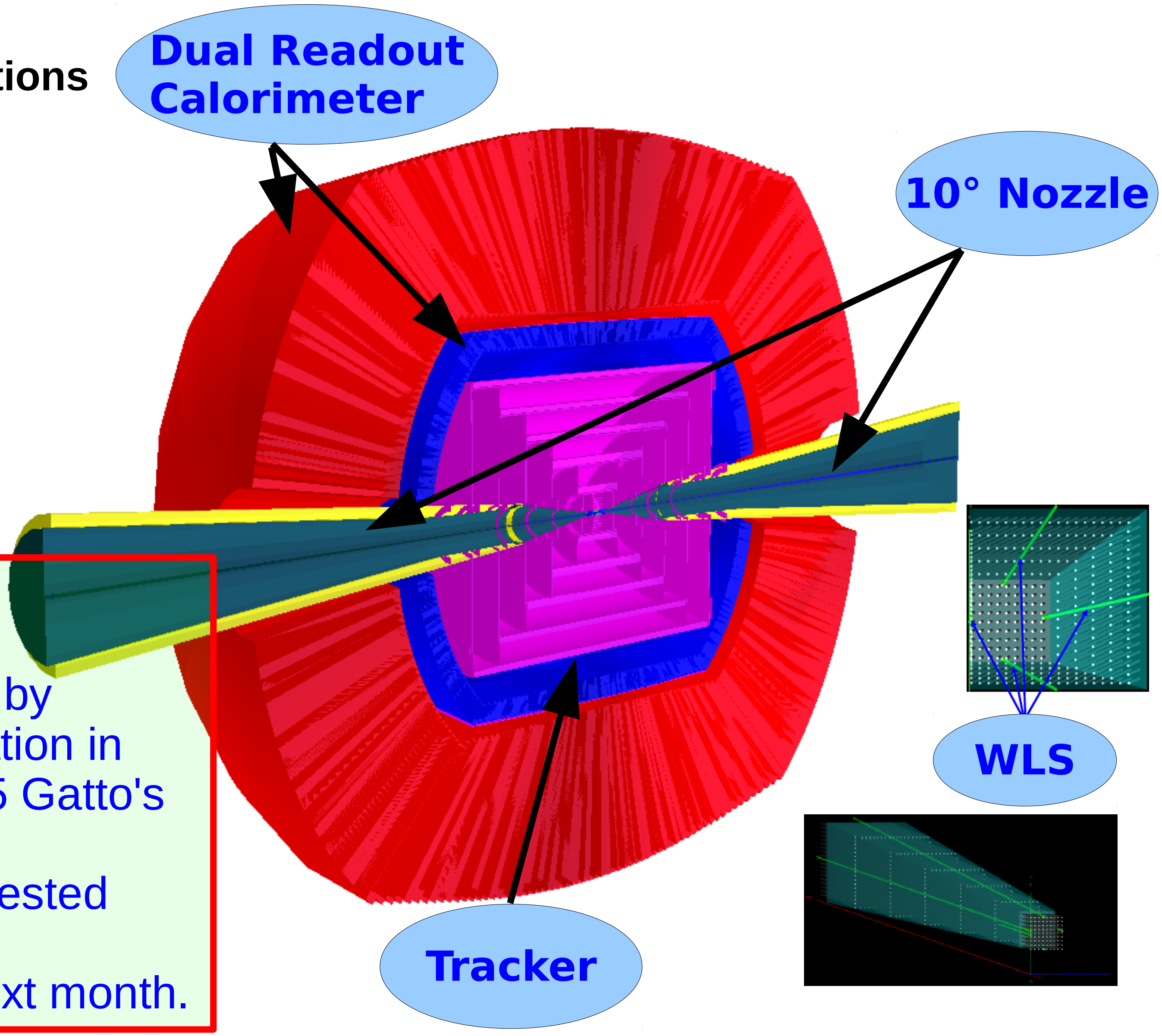
Muon Collider Detector baseline



- Detailed geometry (dead materials, pixels, fibers ...)
- Full simulation: hits-sdigits-digits. Includes noise effect, electronic threshold and saturation, pile up...
- Tracking Reconstruction with parallel Kalman Filter.
- Light propagation and collection for photon detectors.
- Jets reconstruction implemented.

Dual Readout Projective Calorimeter

- Lead glass + scintillating fibers
- ~1.4° tower aperture angle
- Split into two separate sections
- Front section 20 cm depth
- Rear section 160 cm depth
- ~ 7.5 λ_{int} depth
- >100 X_0 depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nozzle)
- Barrel: 16384 towers
- Endcaps: 7222 towers



- All simulation parameters corresponds to ADRIANO prototype #9 beam tested by Fermilab T1015 Collaboration in Aug 2012 (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested with real beam.
- New beam test coming next month.

Simulating MARS generated event with ILCroot

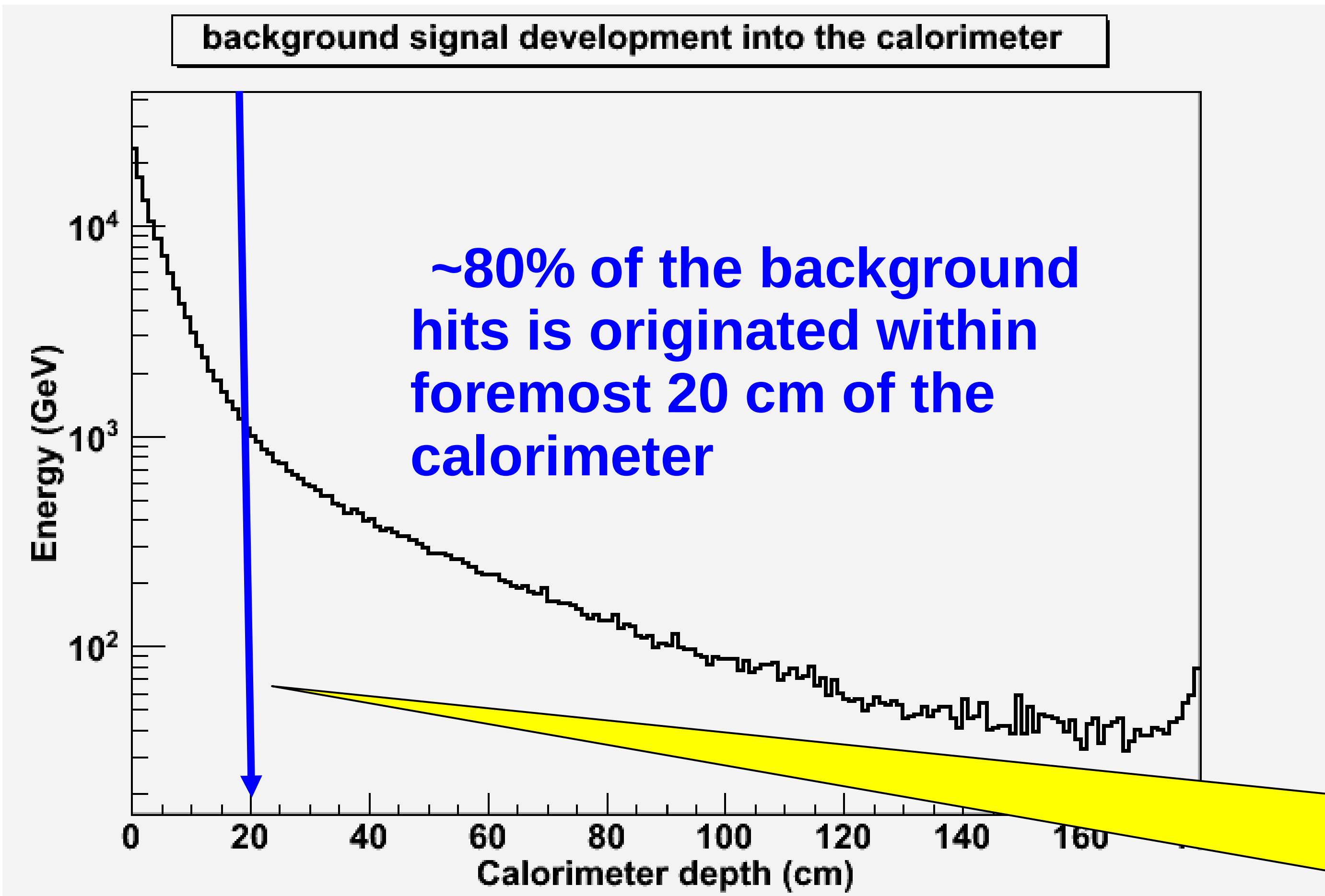
- **Simulated 1 MARS event**
  - Origin of the particles: MDI surface.
  - Background particles for μ^+ and μ^- within 25 m and beyond 25 m.
  - Particle in a MARS event ~10^8, almost all originated within 25 m (MARS particles have weight).

  - **Particles from within 25 m have weight ~ 20**
    - These particles are splitted using azimuthal symmetry.

  - **Particles from beyond 25 m have weight << 1**
    - Pick up randomly these particle and set their weight to 1, taking care the integral weight is not alterated.

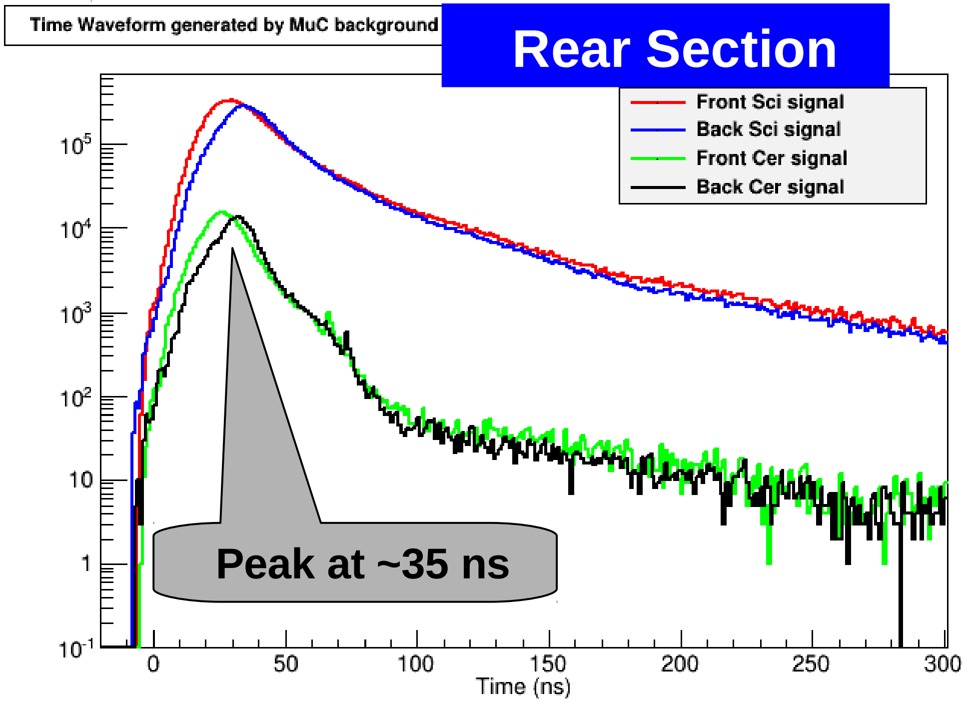
- **Results presented use only background within 25m.**

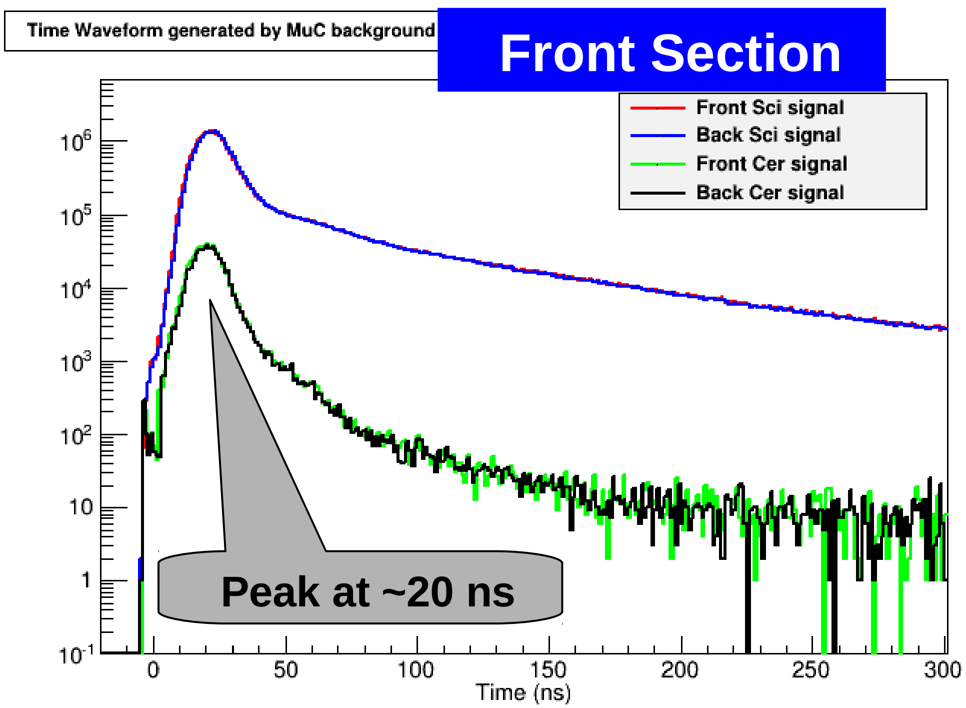
Longitudinal energy deposition in Dual-Readout calorimeter produced by 1 background event



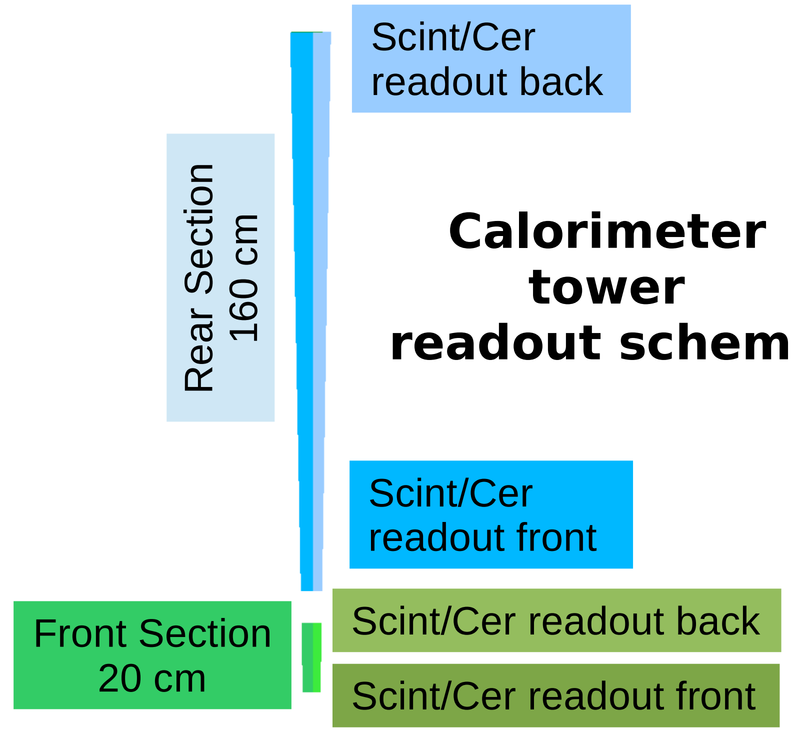
Longitudinal segmentation of the calorimeter could be beneficial

Time Waveform of the MuonCollider background





Calorimeter is split into a rear (160cm) and front (20 cm) section

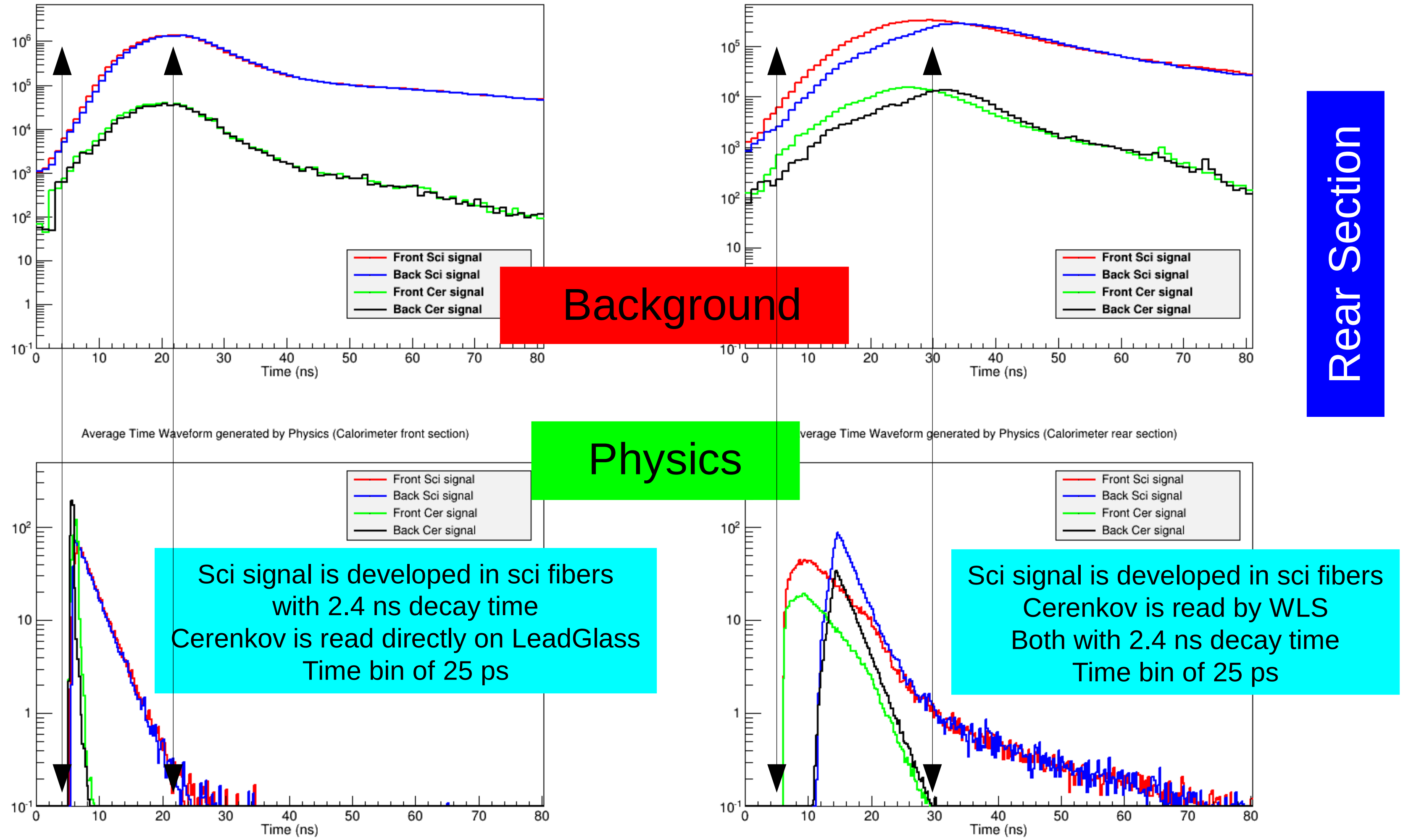


- **Light propagation in fibers and lead glass is implemented in ILCroot**
- **Time bin in calorimeter 25 ps**

Time Waveform of the MuonCollider background vs Physics (time < 80 ns)

Front section has a background signal ~x10 compared to rear section

Front Section

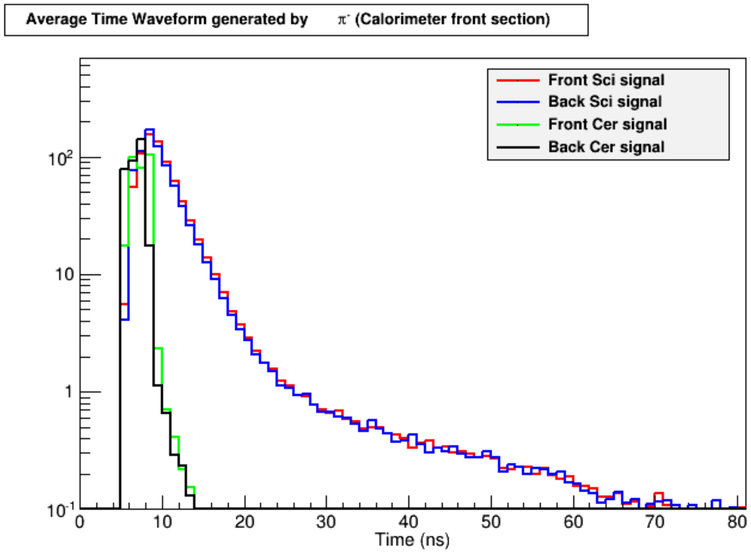


Rear Section

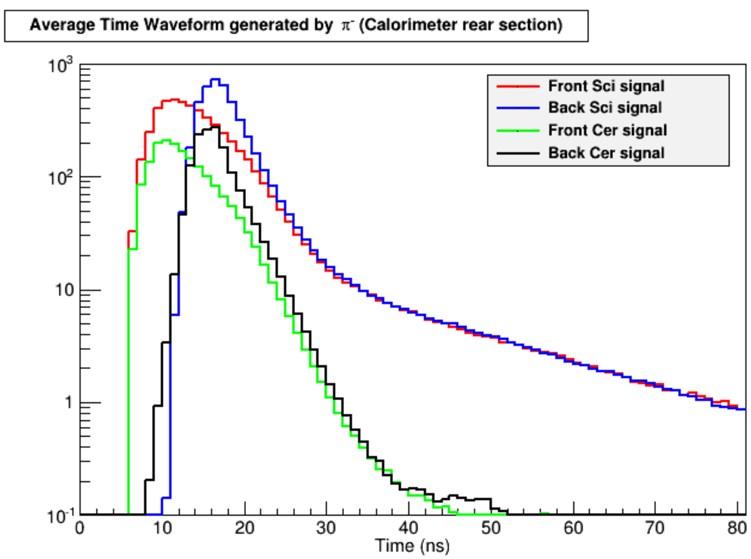
- Time is one key to suppress machine background in calorimeter

Time Waveform for IP π⁻ and time window cut

Front Section



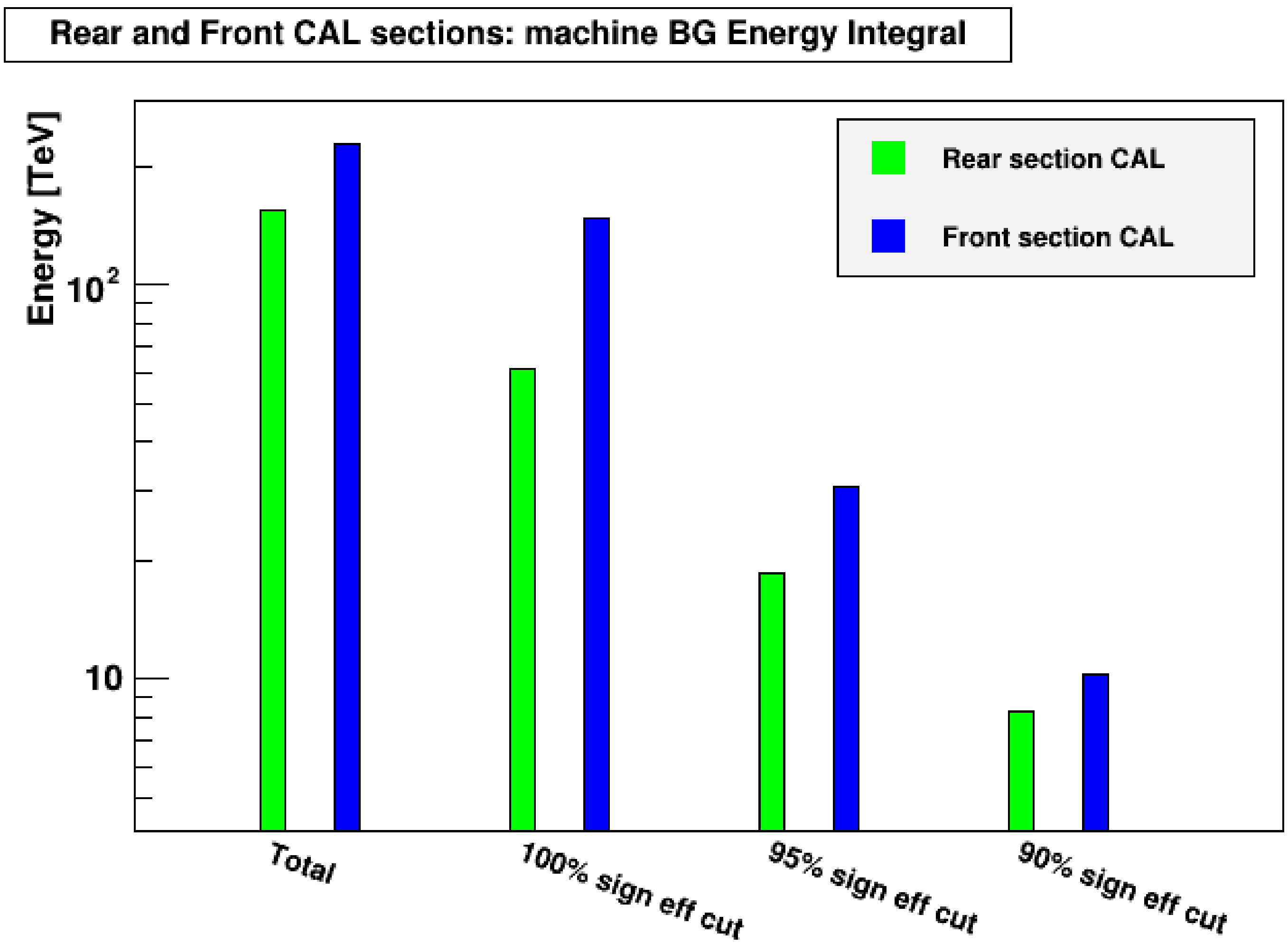
•Rear Section



Integration time gate for each section						
conf		Front Section		Rear Section		Signal efficiency
		Scint	Cer	Scint	Cer	
A	front	6÷200 ns	6÷60 ns	5÷200 ns	5÷50 ns	~100%
	back	9÷200 ns	9÷60 ns	5÷200 ns	5÷50 ns	
B	front	5 ÷ 19 ns	5 ÷ 9 ns	6 ÷ 29 ns	6 ÷21 ns	~95%
	back	5 ÷ 19 ns	5 ÷ 8 ns	12÷32 ns	12÷24 ns	
C	front	6 ÷ 15 ns	5 ÷ 9 ns	7 ÷ 23 ns	7 ÷ 19 ns	~90%
	back	6 ÷ 15 ns	5 ÷ 8 ns	13÷25 ns	12÷21 ns	

- **Front Section calo has faster Cer signal (read-out directly on glass).**
- **In conf B 95% signal collection efficiency can be a good starting point.**

Integral of the energy from machine background measured in the calorimeter sections



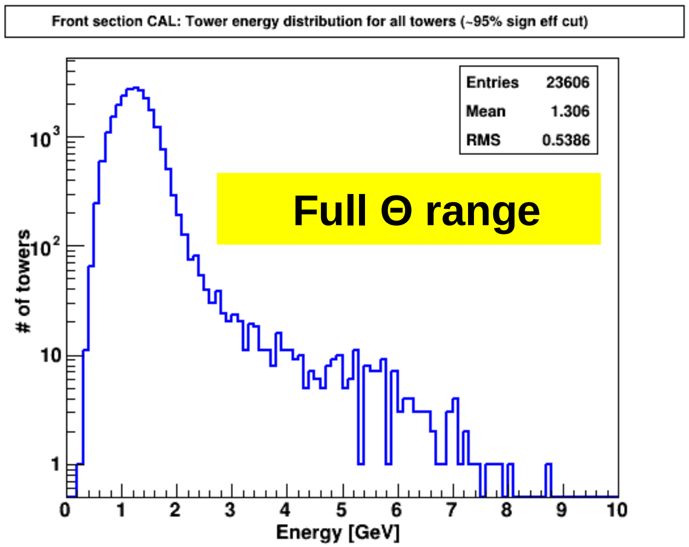
BG energy	Front Section	Rear Section
Total	228 TeV	155 TeV
100% sign eff	148 TeV	61 TeV
95% sign eff	31 TeV	19 TeV
90% sign eff	10 TeV	8 TeV

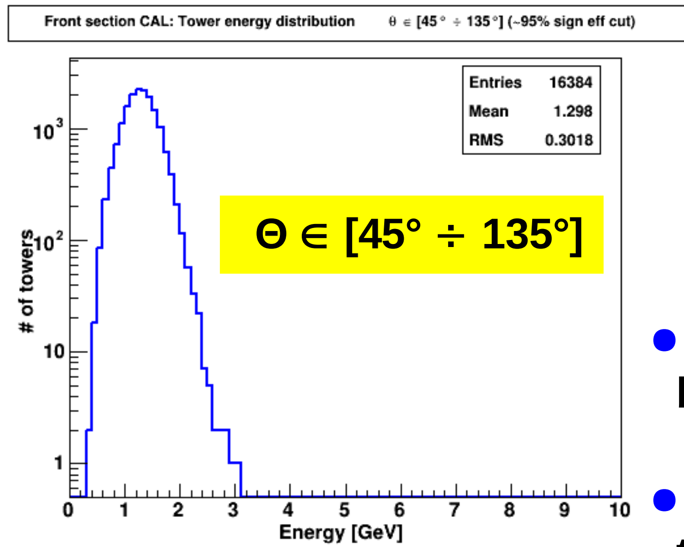
- **Relevant fraction of the BG is in the front section calorimeter**
- **95% signal efficiency config reduce BG of ~86% in front section and ~88% in rear section**

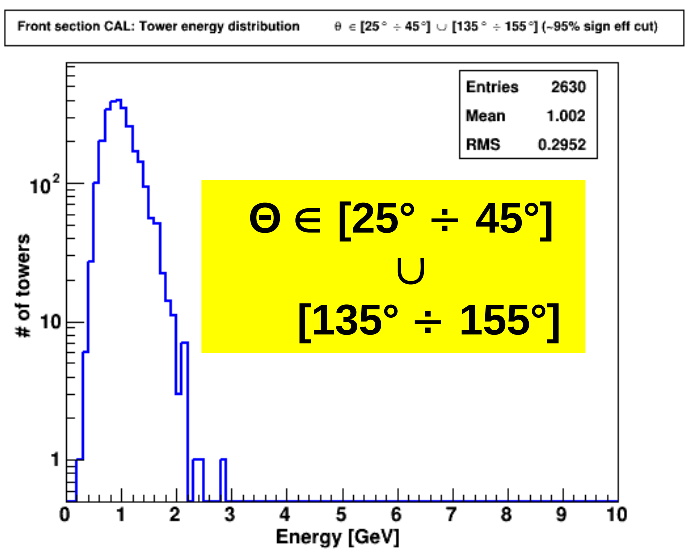
Energy distribution of background for different theta ranges

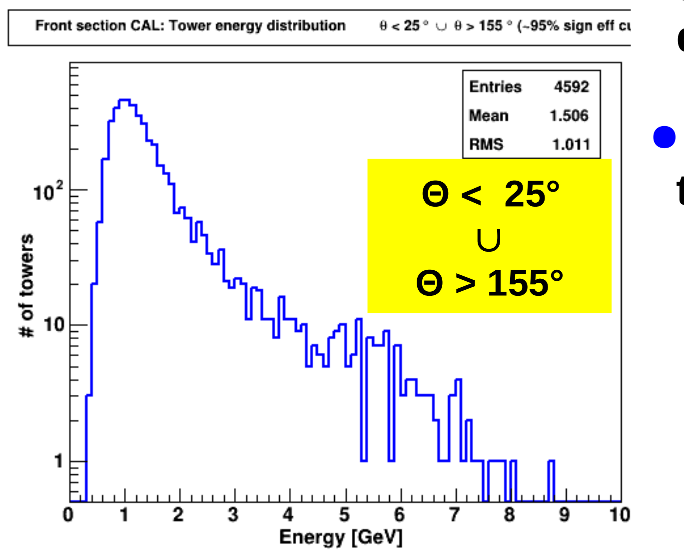
1 entry = <1 tower>

Front Section







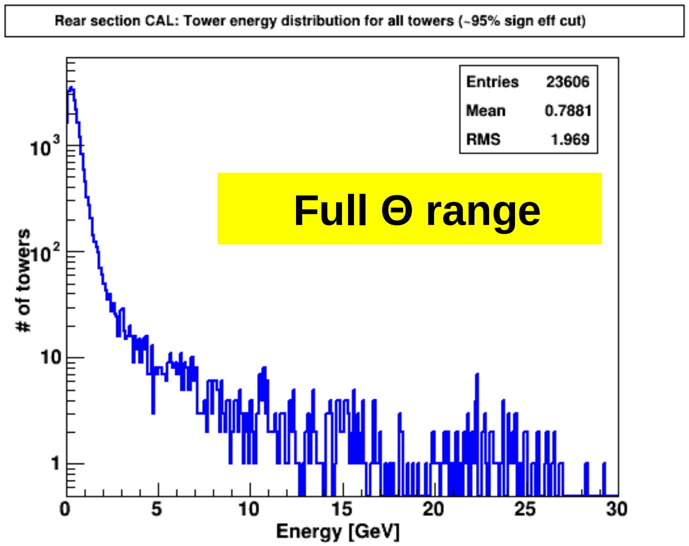


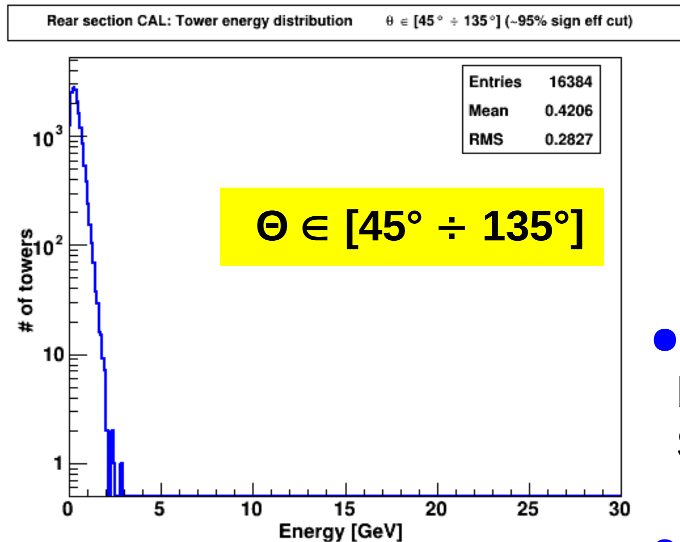
- **Energy distribution has a broad range.**
- **In barrel and mid endcap the energy distribution is quite narrow.**
- **Forward endcap can be tricky to deal with.**

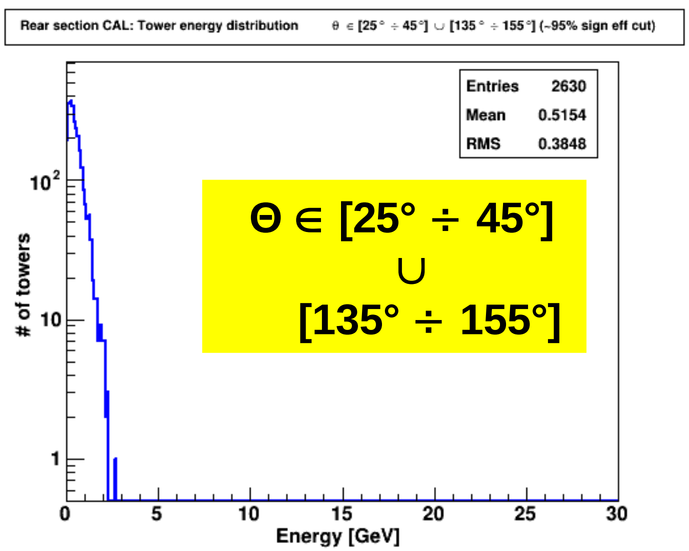
Energy distribution of background for different theta ranges

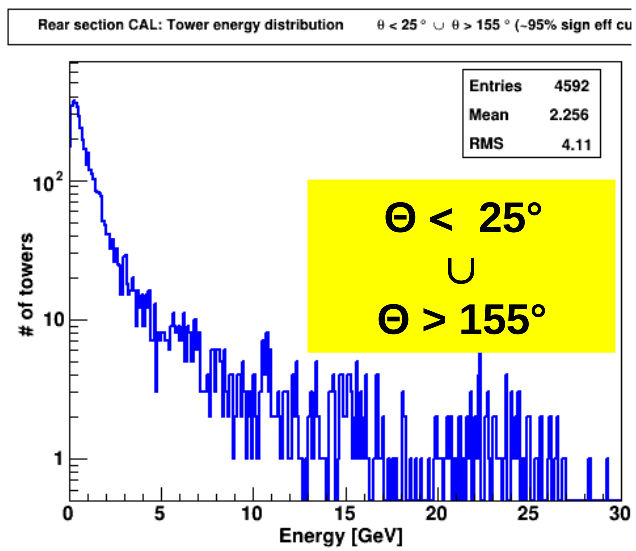
1 entry = <1 tower>

Rear Section





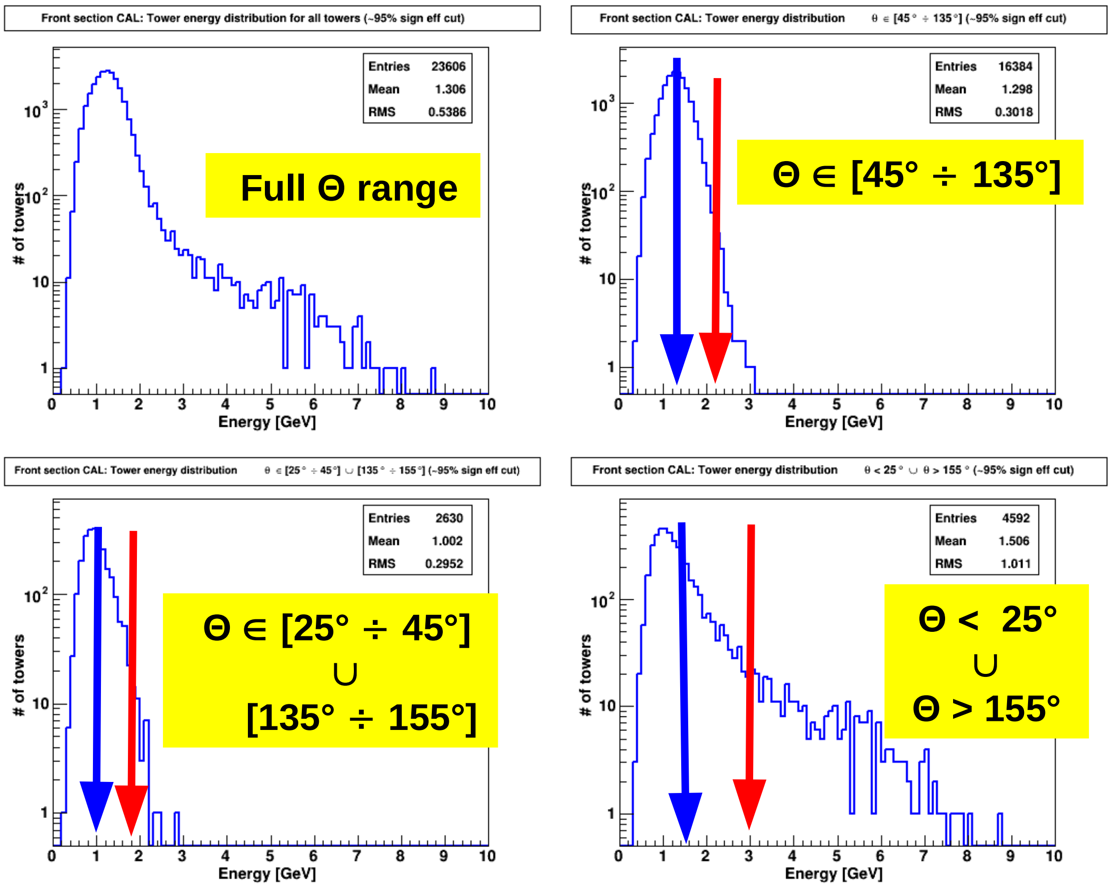




- **Energy distribution has a broader range than in Front Section.**
- **In barrel and mid endcap the energy distribution is quite narrow and lower than in Front Section.**
- **Forward endcap can be tricky to deal with.**

Machine background soppression strategy

Front Section calorimeter as an example



Soft energy cut
Hard energy cut

- First approach to remove machine background.
- Use the "mean" value of the energy distribution as "Energy subtraction" (soft cut).
- This has a concern.
  - This way remove completely the background from about half of calorimeter towers.
  - The other towers mantain an average energy due to the background of the order of the RMS of the energy distribution.
  - The remnant background energy in the calorimeter is about

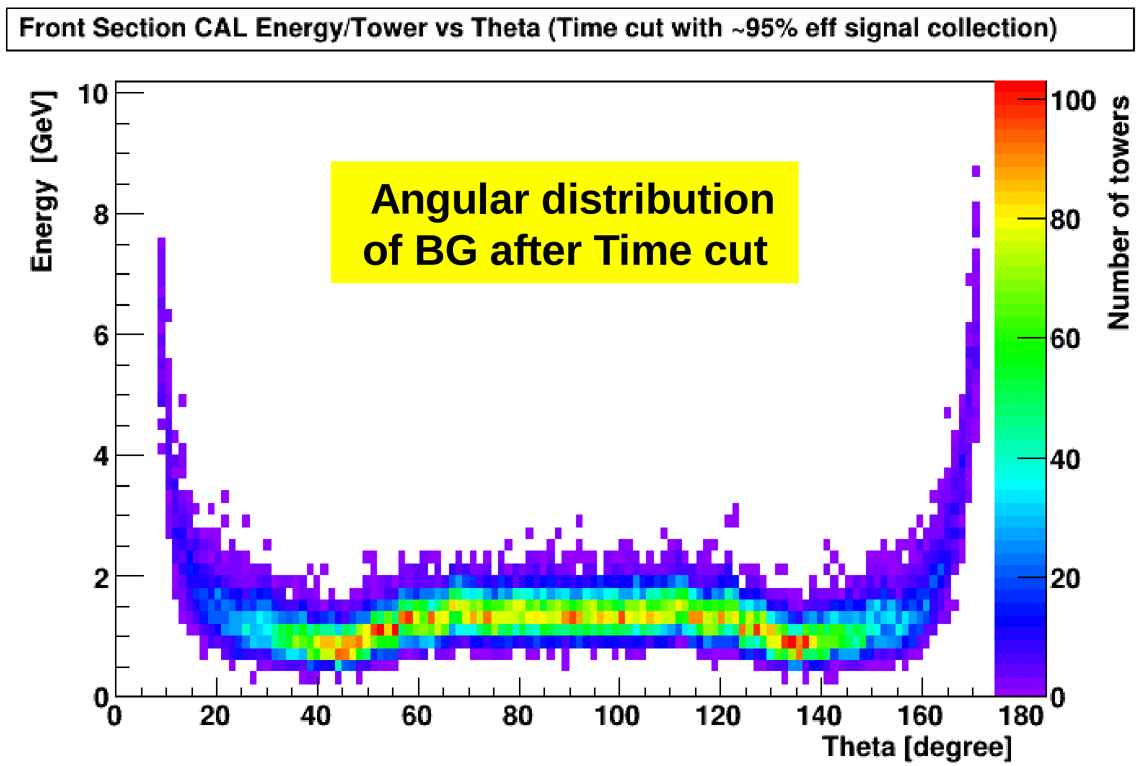
    10^4 towers X 0.1GeV/tower = 1 TeV !

- It is needed an hard cut to remove quite completely the background.
  - This can have effect on Physics.

- Forward endcap can be tricky to deal with (again).

Improved machine background suppression strategy

- An improved approach to remove machine background.
- Use the “profile” of the energy distribution vs theta and use for each theta the “mean” value of the energy distribution as “Energy subtraction”.
- This approach can be more effective for the forward endcap region.



Improved machine background suppression strategy

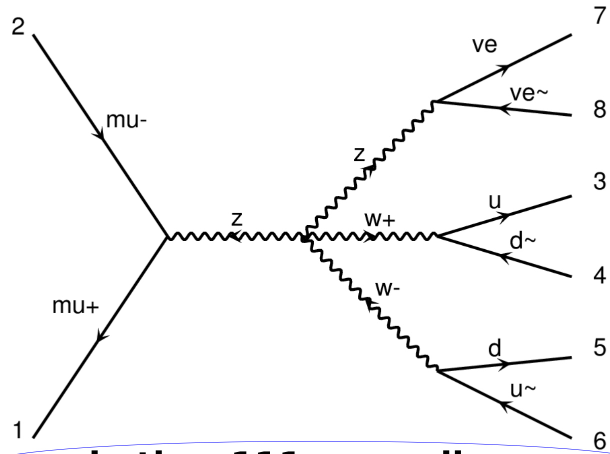
- **Further improvement to reduce the machine background.**
- **Define time gate with fix width, but start and stop are theta dependent according to the distance of the tower from the IP.**

Time gate for each section				
	Front Section		Rear Section	
	Scint	Cer	Scint	Cer
front	6.3 ns	1.5 ns	12.8 ns	10.3 ns
back	5.7 ns	0.8 ns	8.5 ns	7.0 ns
Signal efficiency	83%		76%	
BG suppression	98.5%		97.3%	

BG energy	Front Section	Rear Section
Total	228 TeV	155 TeV
100% sign eff	148 TeV	61 TeV
95% sign eff	31 TeV	19 TeV
90% sign eff	10 TeV	8 TeV
After time gate cut	3 TeV	4 TeV

- **Apply time gate cut.**
- **Individuate Region of Interest (RoI), i.e. regions where the energy is 2.5 σ above the expected background level in that region (implemented on tower by tower basis).**
- **In the RoI apply soft energy subtraction, i.e. use as energy subtraction the mean value of the background in that region**
- **In the other regions apply hard energy cut.**

Physics motivation



and other 111 more diagrams

$\mu^+\mu^- \rightarrow W^+W^-\nu\bar{\nu}$ @1.5TeV

jet,jet

jet,jet

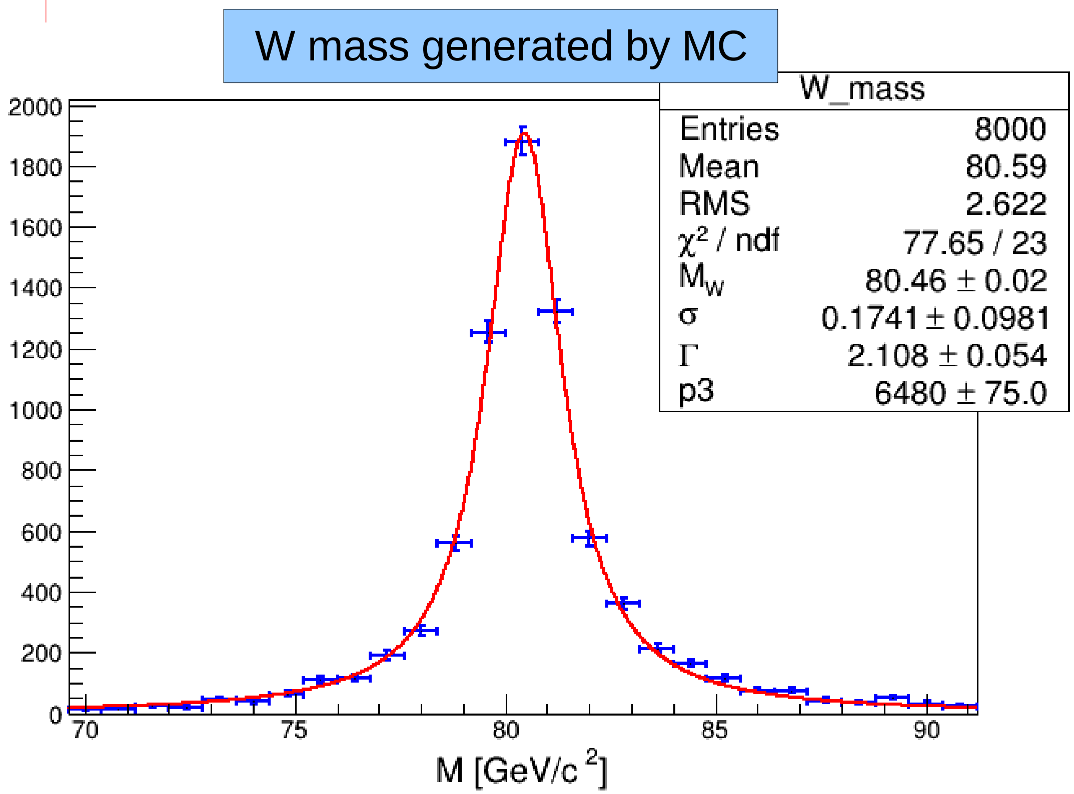
Jet's are originated by mostly light quarks (u,d,s,c)

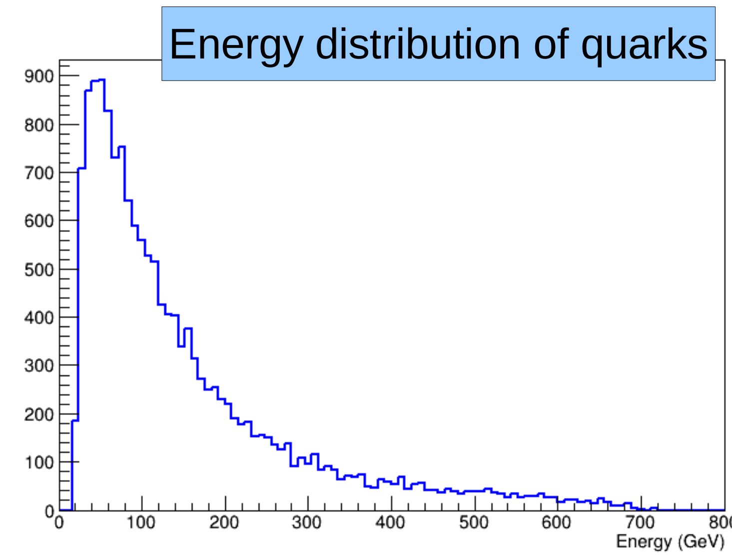
- Events generated with MadGraph5/PYTHIA 6.426
- Reconstruct W mass from a 4 jets channel.
- Stress Calorimeter energy resolution.
- Stress Tracker performances (to lesser extent).
- No constraint on ECM.
- Nozzle effect on Physics.
- **Implement/test a strategy to reject machine background in the calorimeter.**

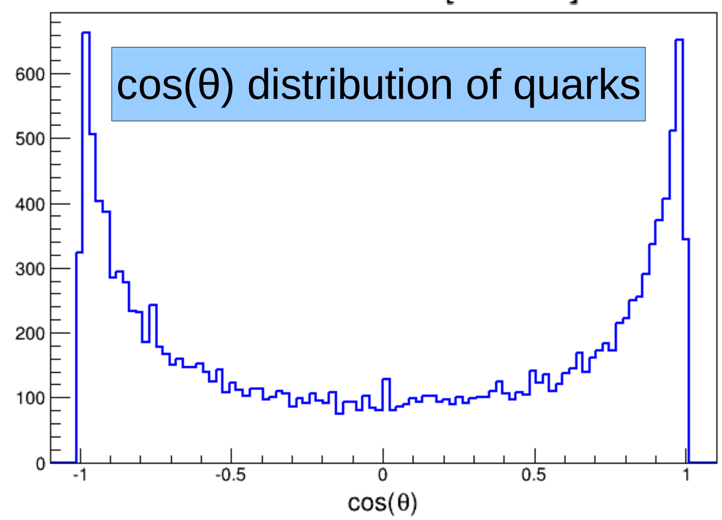
$\mu^+\mu^- \rightarrow W^+W^-\nu\bar{\nu}$ simulation @1.5TeV

- Fully simulated with track and calorimeter reconstruction in ILCroot framework 4000 of such events.
- Reconstructed 4 jets applying PFA-like jet reconstruction developed for ILC benchmark studies.
- Jets paired to get invariant mass of W^+ and W^-.
- All 3 invariant mass combinations for each event have been recorded (six entries per event).
- A Voigt function has been used to fit the invariant mass distribution.
- All of the above have been done with and without machine background
- To suppress background I have applied
  - Tracker: 3.1ns time gate with start and stop layer dependent (thanks to N. Terentiev).
  - Calorimeter: time gate as shown in previous slide + background energy subtraction on tower by tower basis.

W mass as generated by MC





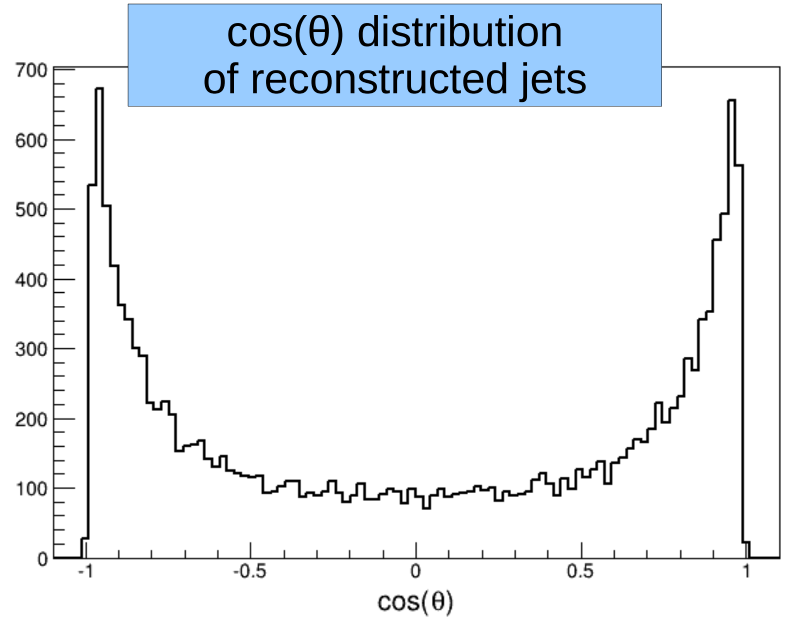


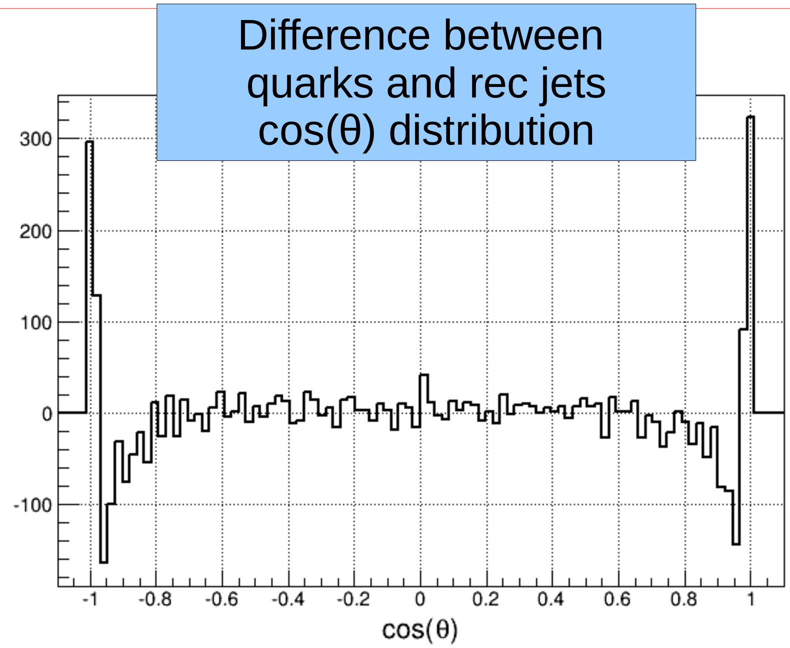
- **W mass fitted with Voigt funcion.**
- **This process has considerable number of events in forward region.**
- **The energy distribution of quarks originating jets peaks at ~100 GeV.**

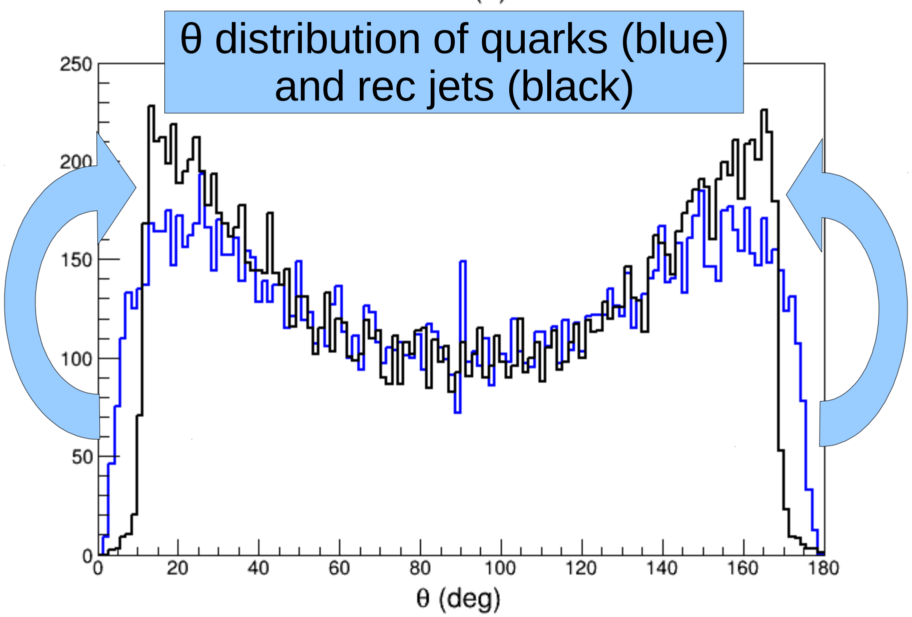
ILCRoot simulation

NO background

Reconstructed jets
Theta Rec vs Theta MC (no background)



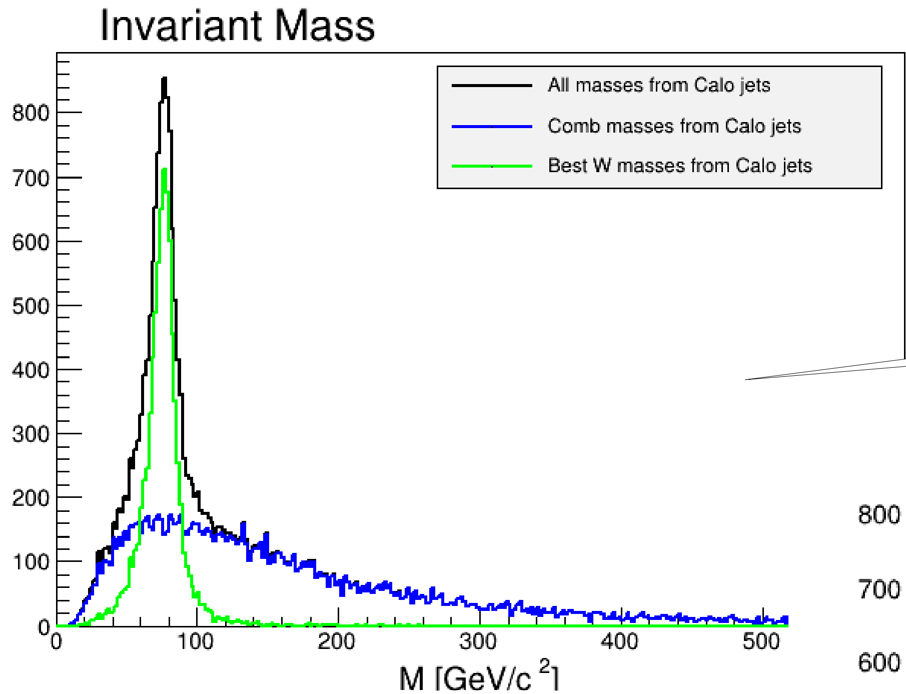




Preliminary results

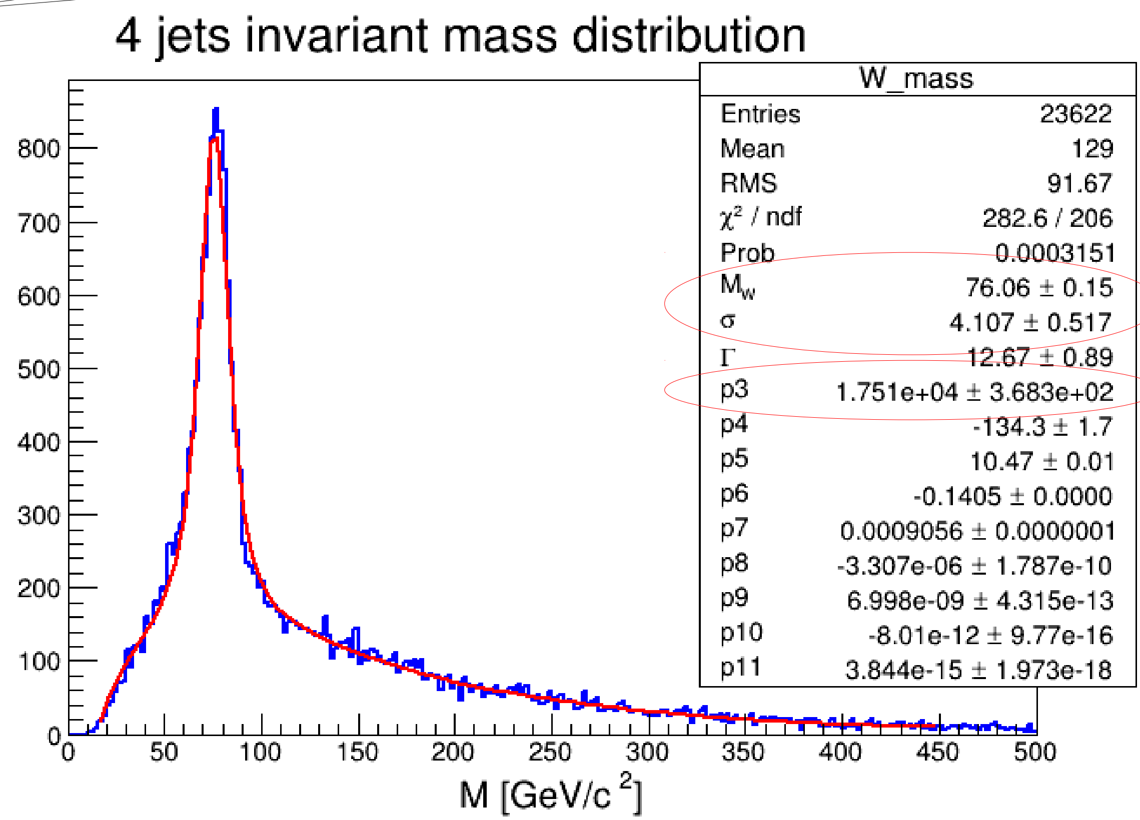
- **Nozzle effect on reconstructed jets for theta below 35°.**
- **Excess of reconstructed jets for theta between ~10° and 30°.**

W mass reconstructed (no background)



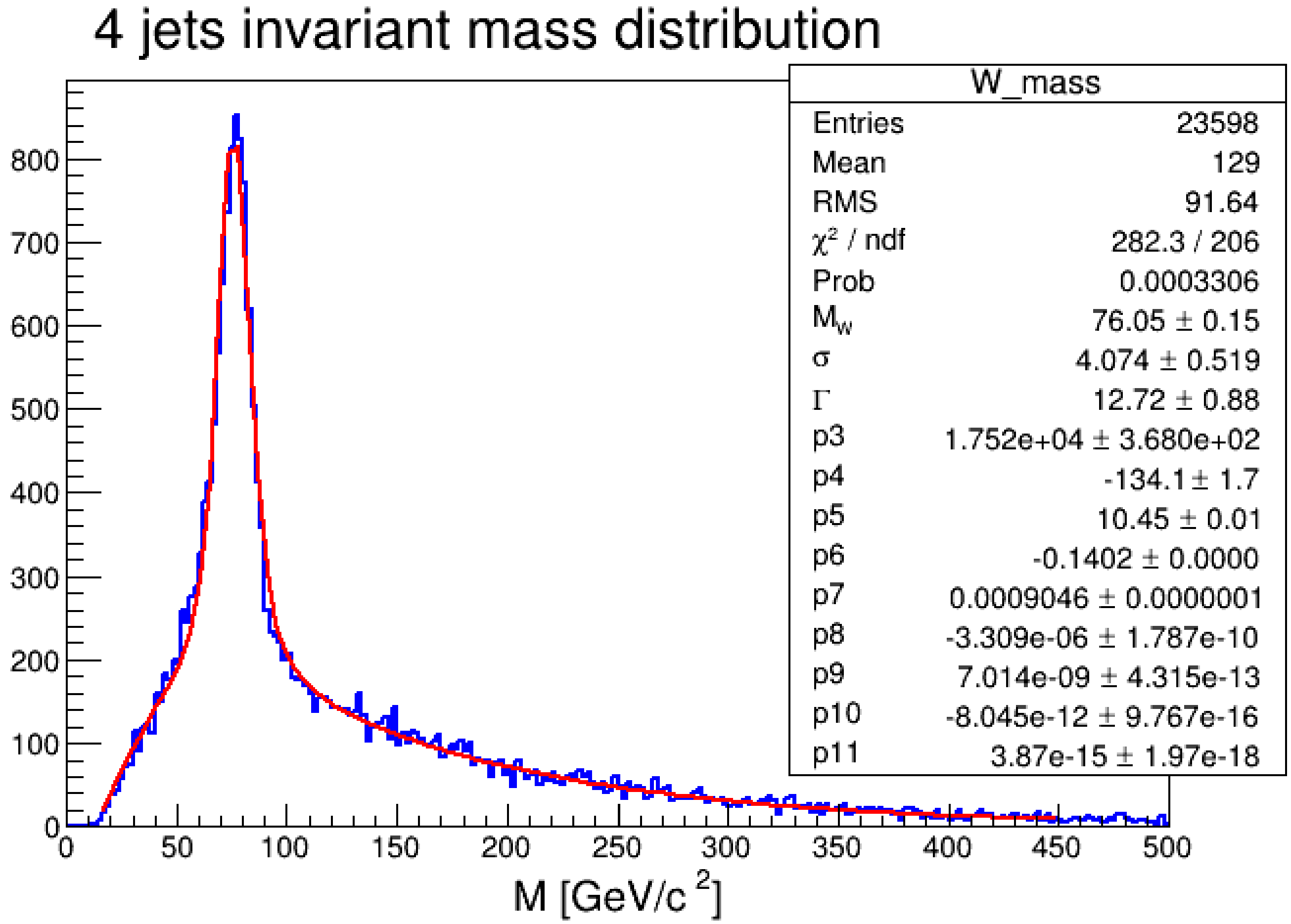
Preliminary results

Shows all invariant mass combination (black)
Best W invariant mass candidate(green)
Combinatorics (blue)



- **Fit on all invariant mass combinations with Voigt + polynomial.**
- **W mass underestimated (presence of ν's in jets).**
- **W mass resolution ~5.4%**
- **Statistical error on BR ~2%**

W mass reconstructed *with time cuts*

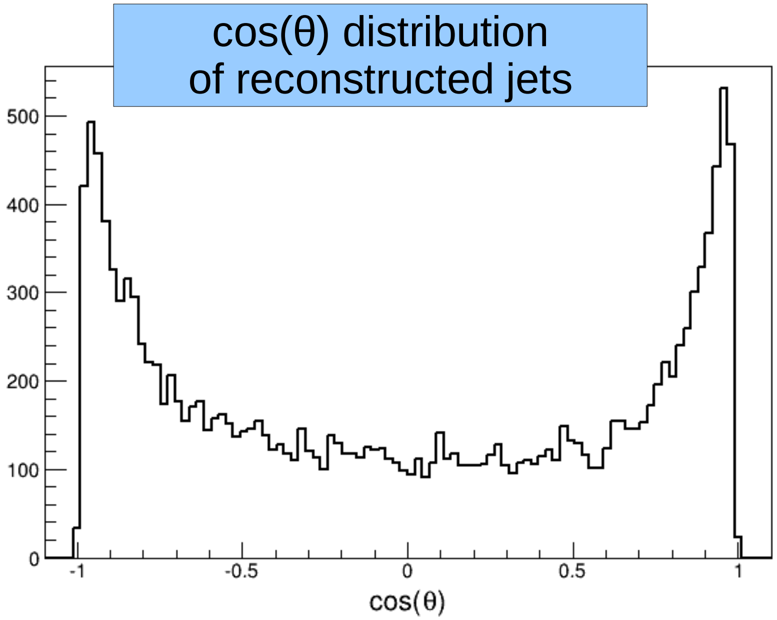


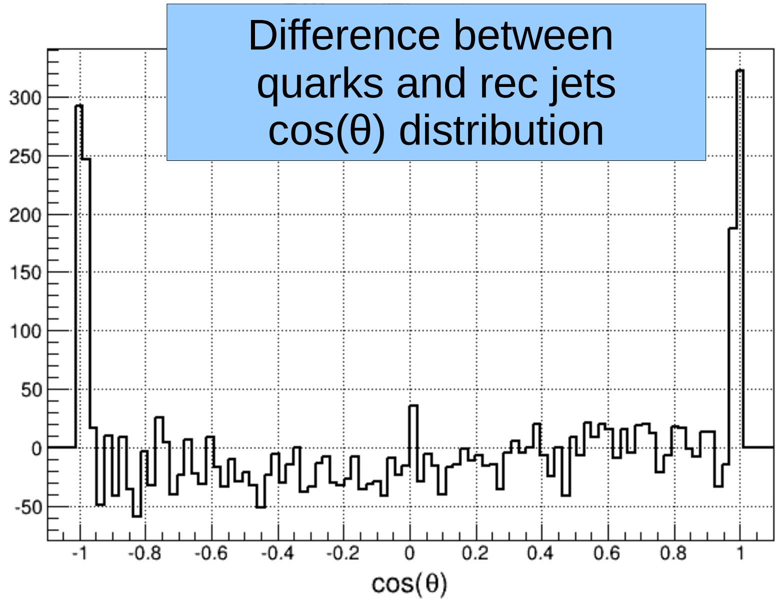
- **Fit on all invariant mass combinations with Voigt + polynomial.**
- **W mass underestimated.**
- **W mass very similar to the case without time cuts and without background.**

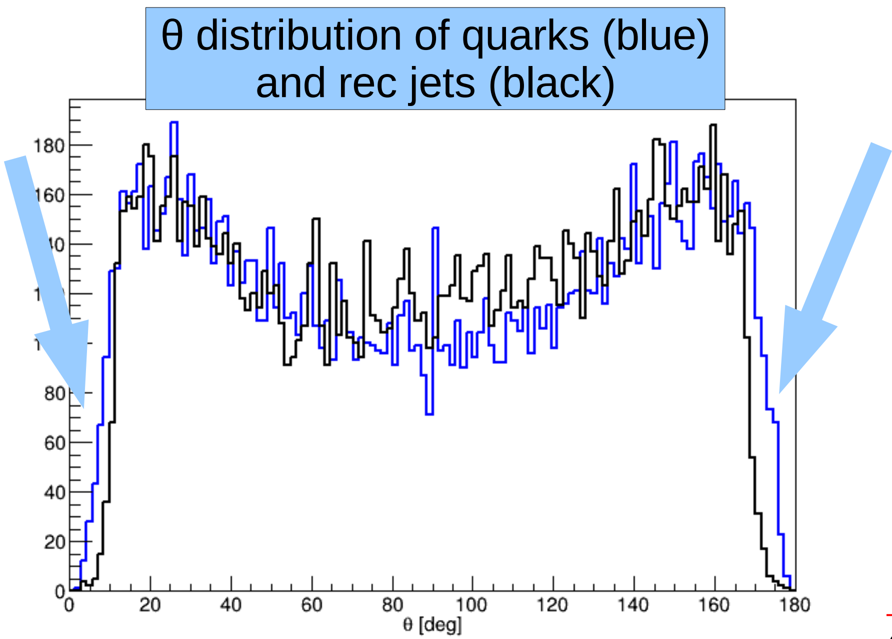
ILCRoot simulation

WITH background

Reconstructed jets
Theta Rec vs Theta MC *with background*

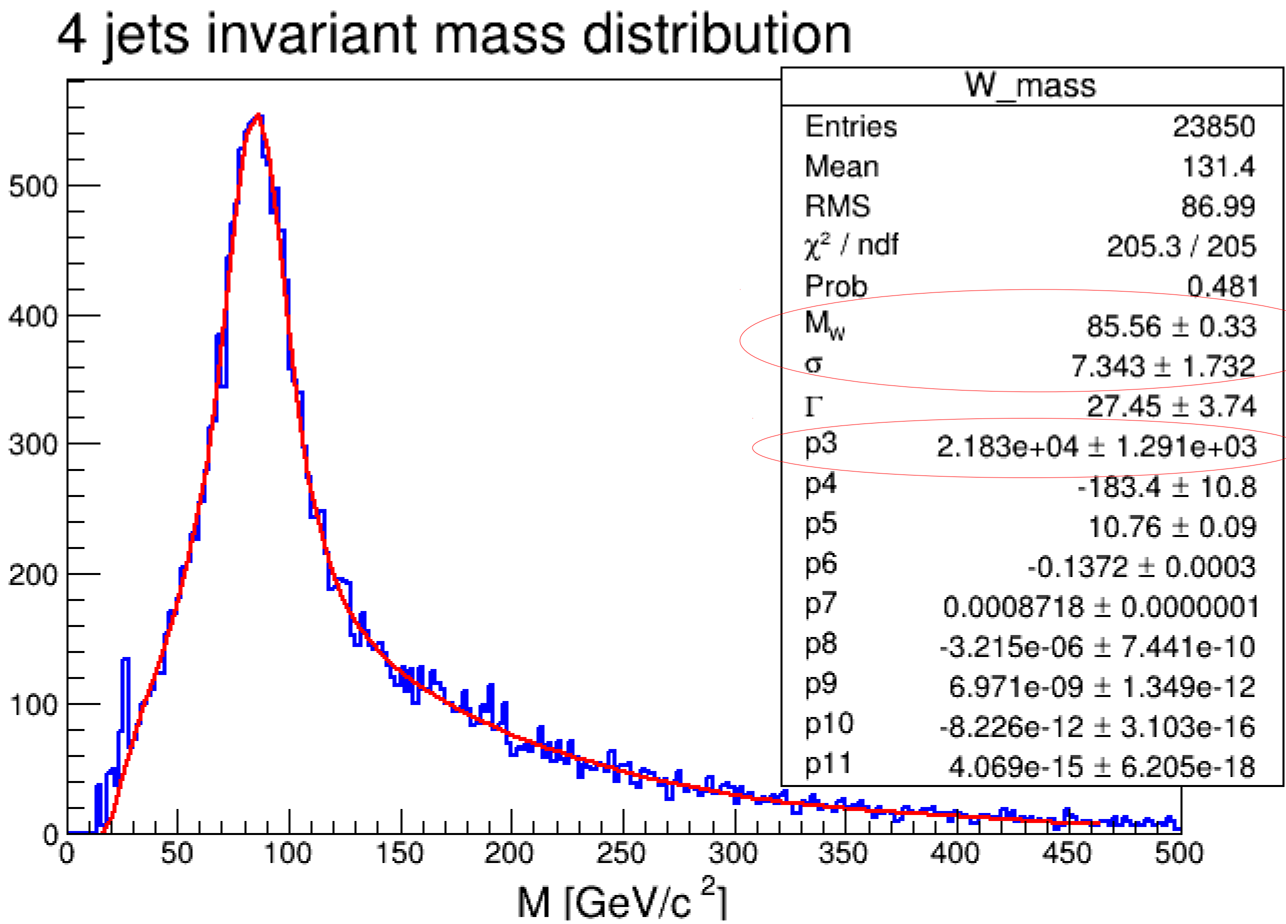






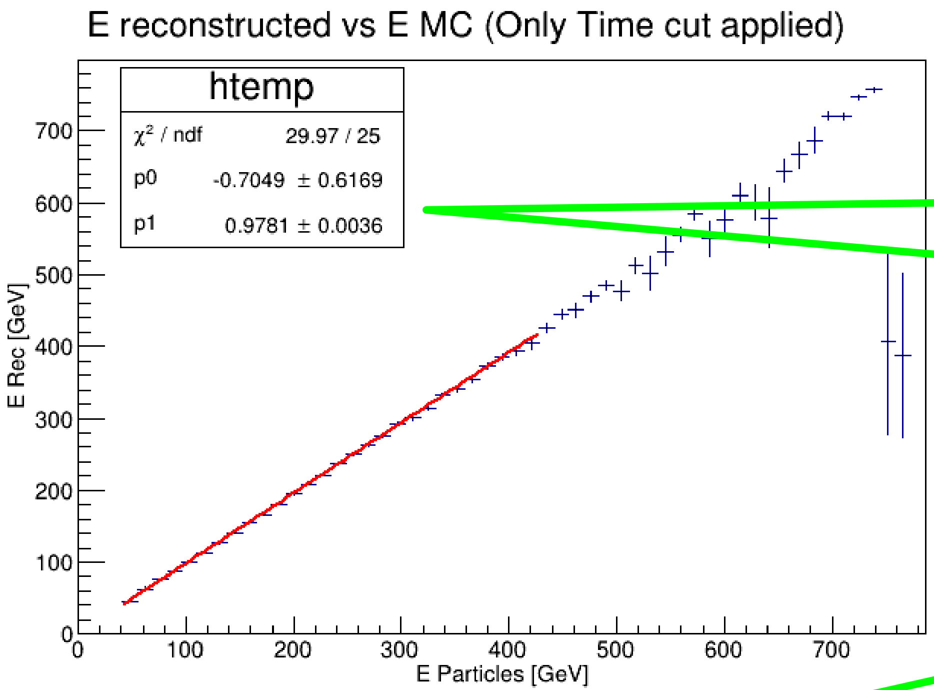
- **Nozzle effect on reconstructed jets still visible on very forward region, but almost masked by background effect.**
- **To be understand what happen to events in very forward region.**

W mass reconstructed ***with background***



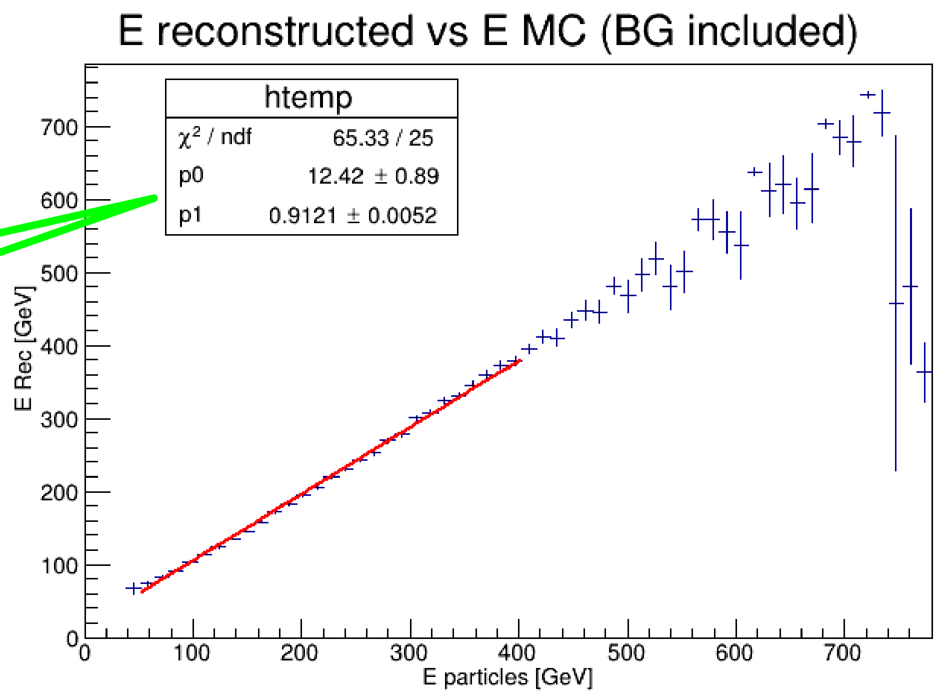
- **Fit on all invariant mass combinations with Voigt + polynomial.**
- **W mass overestimated.**
- **W mass resolution ~8.5%**
- **Statistical error on BR ~6%**

Calorimeter energy response with time cuts and with background



Try to understand the W mass shift

After time cuts the calorimeter energy is recovered quite well. (In MC particles ν's are discarded)



After background subtraction there is some residual energy ~12 GeV and an average energy oversubtracted of ~9% (In MC particles ν's are discarded)

W mass reconstruction summary

- $\mu^+\mu^- \rightarrow W^+W^-\nu\bar{\nu}$ in 4 jets has considerable number of jets in the forward region.
- Nozzle has some effect on Physics.
- Without bakground:
  - W mass resolution ~5.4%
  - Statistical error on BR ~2%
- With Background:
  - W mass resolution ~8.5%
  - Statistical error on BR ~6%
- The strategy to reject background need some improvement.

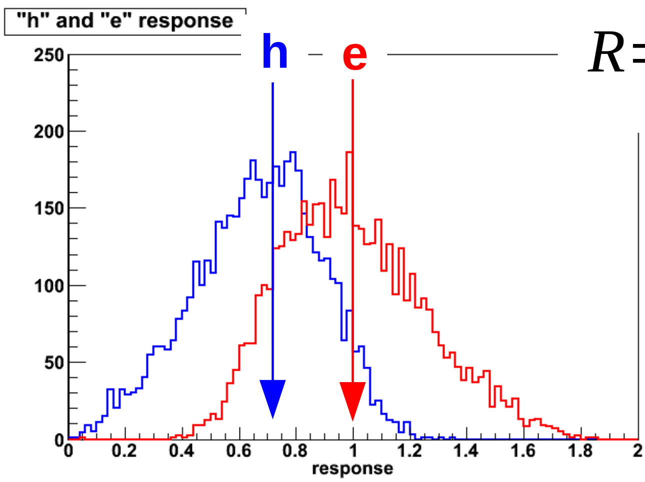
Conclusions

- **Background in calorimeter is high.**
- **We are on the right way to handle this background.**
- **Background rejection strategy is working quite fine.**
- **Still some improvement needed to have more accurate background rejection in calorimeter.**
- **Preliminary study of the process $\mu^+\mu^- \rightarrow W^+W^-\nu\bar{\nu}$ in 4 jets has been presented.**
- **W invariant mass reconstructed is quite good.**
- **Statical error on BR measure is few %.**
- **This machinery can be used also for all 4 jets final state processes.**

Back-up slides

Hadronic calorimetry fluctuations

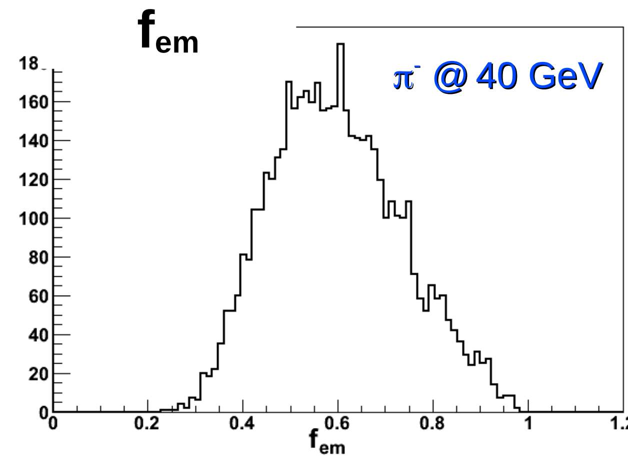
- Fluctuations in hadronic shower properties hamper the calorimeter resolution
- The most important fluctuation is in the shower em fraction f_{em} (mainly due to π^0 production in hadronic interactions)



$$R=\frac{E_{measured}}{E_{shower}}=e\,f_{em}+h\,(1-f_{em})$$

e = calorimeter response to EM shower component
h = calorimeter response to non-EM shower component

e≠h ⇨ R depends on f_{em}



- To improve hadronic calorimeter performance: reduce/eliminate the (effects of) fluctuations that dominate the performance
- E_{shower} and f_{em} can be evaluated by measuring the shower energy with two independent calorimeters that share the same volume and differs for (*e/h*)

Principle of Dual Readout Calorimetry

Energy calibration scheme with π^- @ 40 GeV

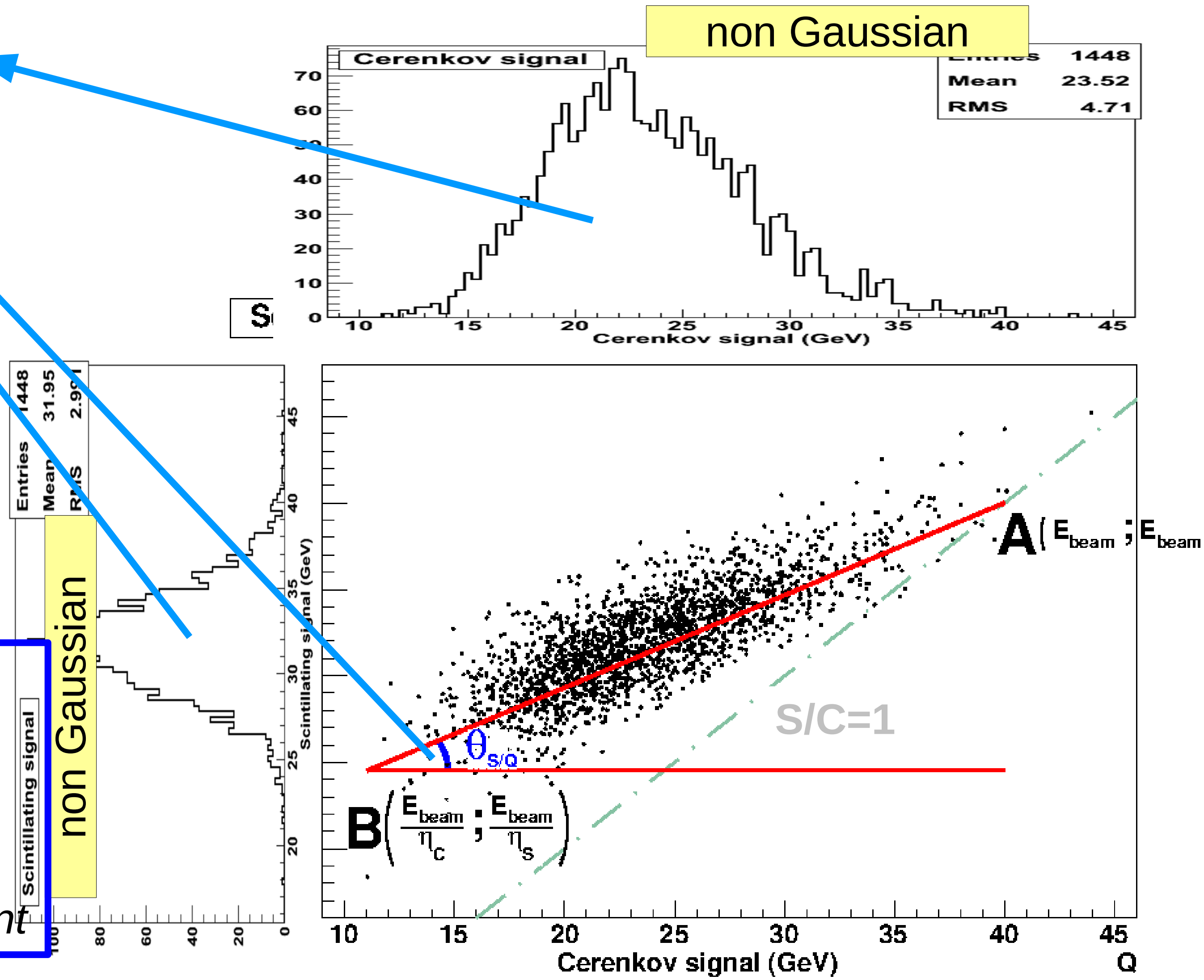
$$E_{shower}=\frac{S-\chi C}{1-\chi}$$

$$\chi=\tan(\theta_{S/Q})$$

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

$$\eta=\left(\frac{e}{h}\right)$$

A = pure EM shower
B = pure non-EM shower
e = calorimeter response to EM shower component
h = calorimeter response to non-EM shower component



Principle of Dual Readout Calorimetry

Energy calibration scheme with π^- @ 40 GeV

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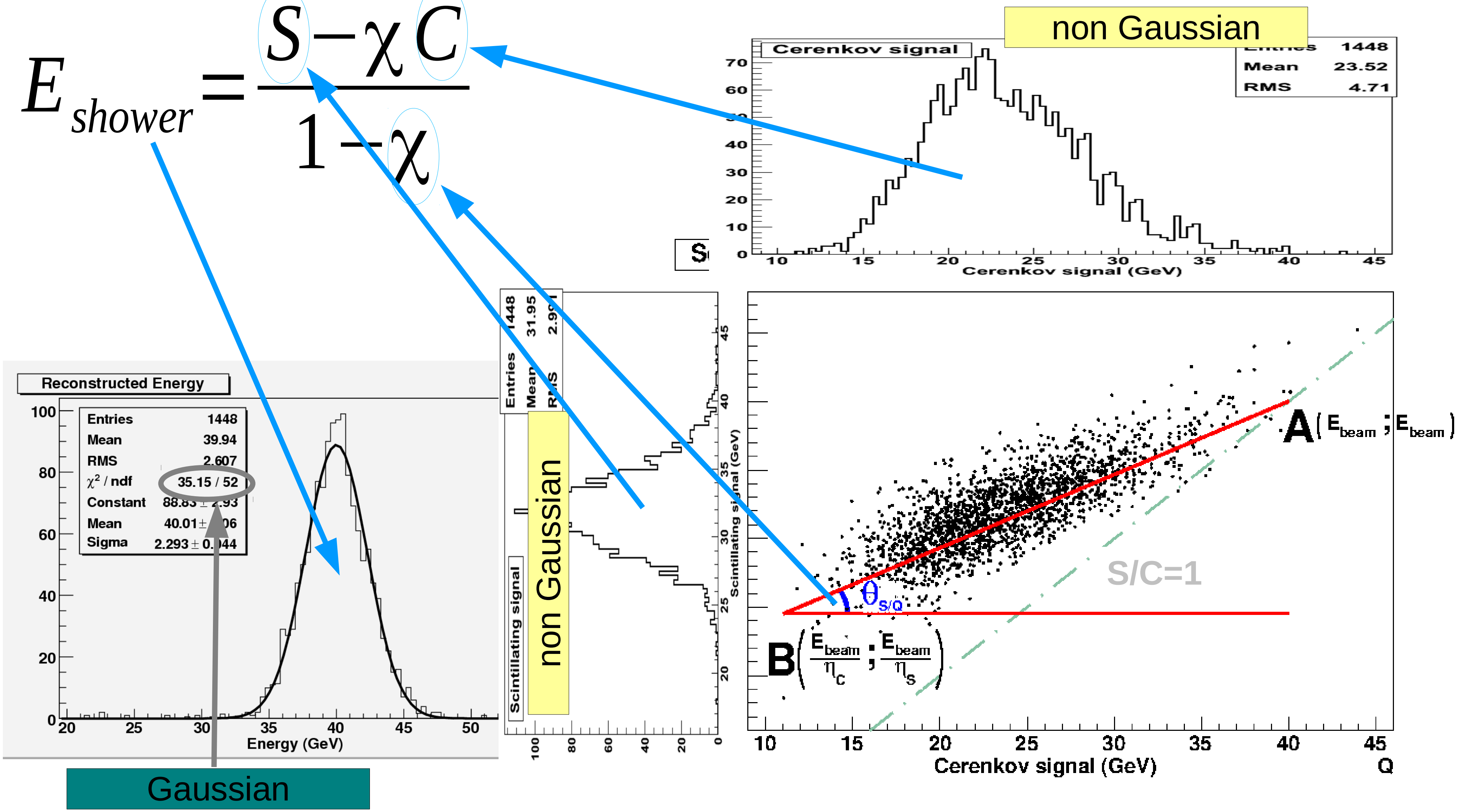


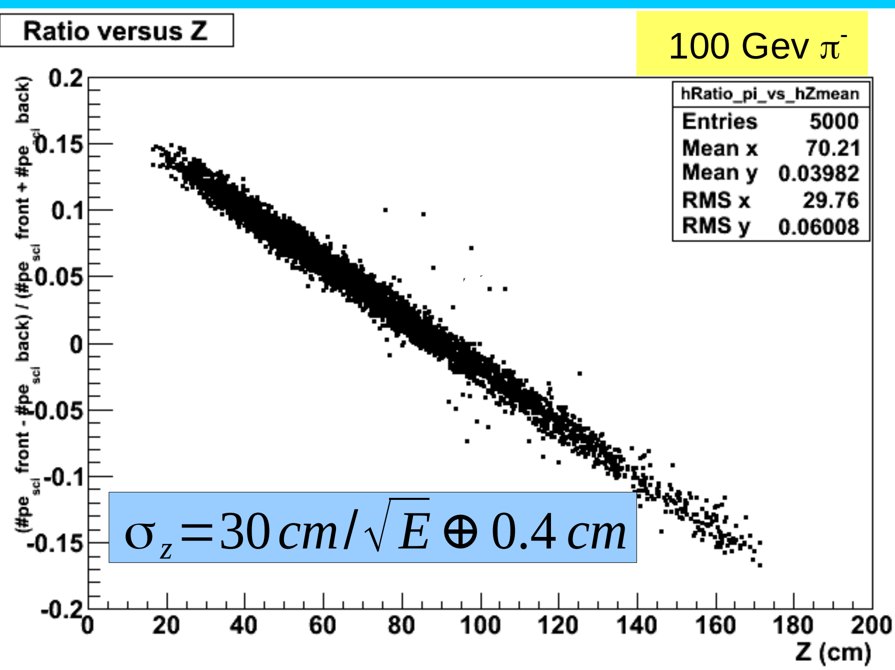
Adding the 3rd Dimension info with light division methods

- Determine Center of Gravity of showers by ratio of front vs back scintillation light
- It works because $\lambda_{SCSF-81J} = 3.5$ m
- Similar to charge division methods in drift chambers with resistive wires
- A technique already adopted by UA1 and ZEUS

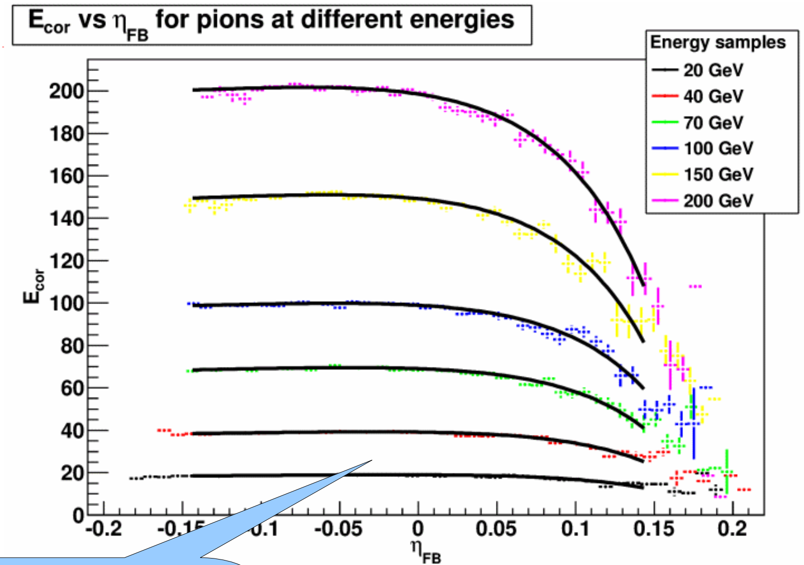
Instrumental effects included in ILCroot :

- SiPM with ENF=1.016
- Fiber non-uniformity response = 0.6% (scaled from CHORUS)
- Threashold = 3 pe (SiPM dark current < 50 kHz)
- ADC with 14 bits
- Constant 1 pe noise.

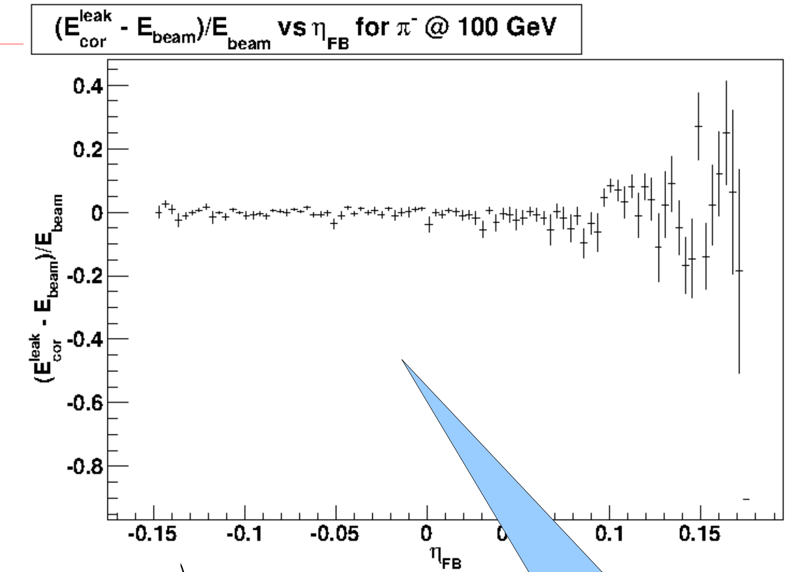
Front-Back Scintillation light vs true shower CoG



Leakage correction in 180 cm long *ADRIANO* module

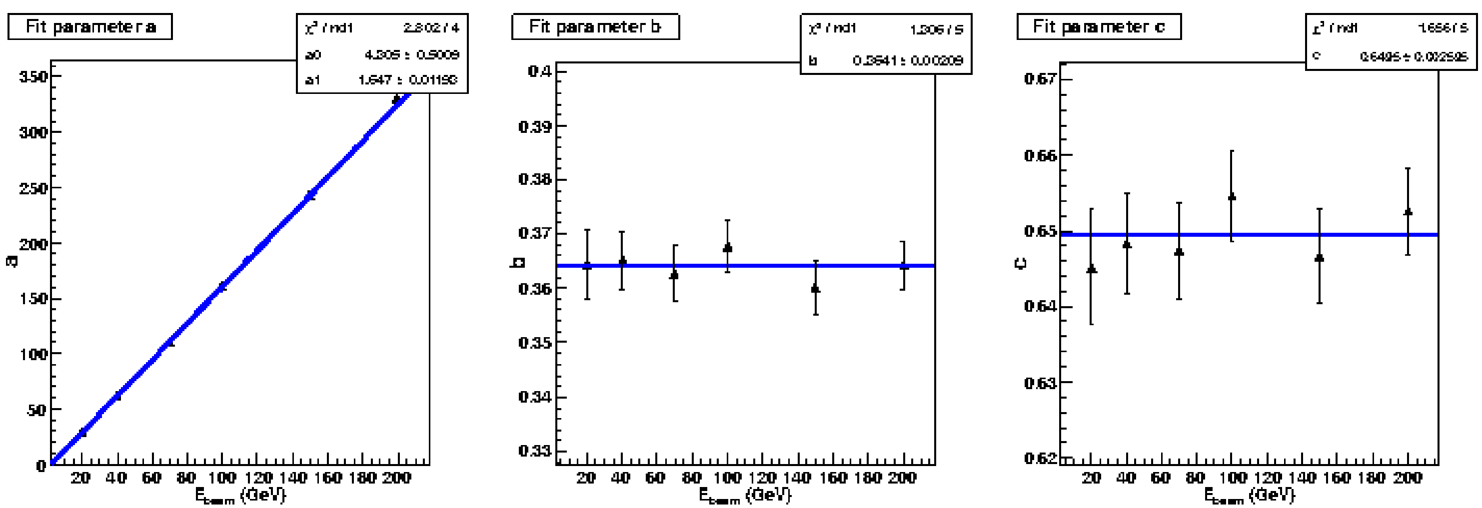


Before correction



After correction

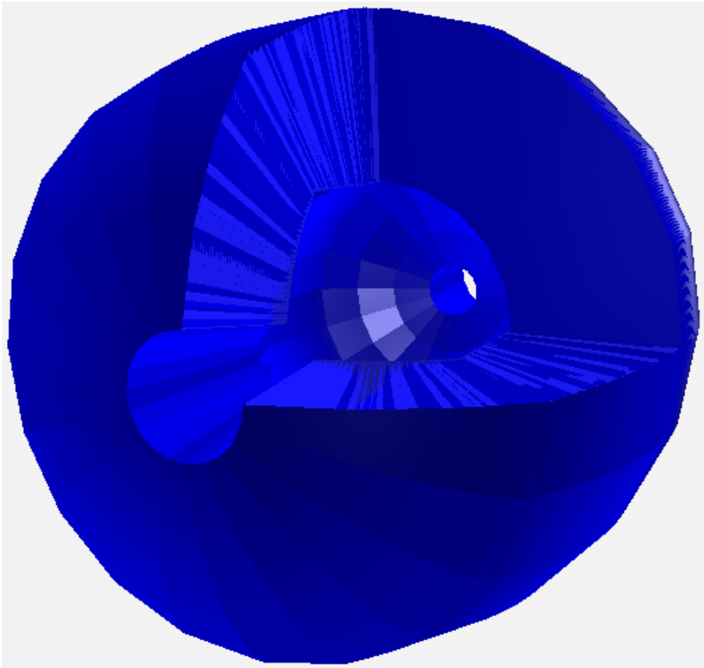
$$E_{cor} = a\left(1 + \frac{1}{(\eta_{FB} - b)} + \frac{1}{(\eta_{FB} - c)^2}\right)$$

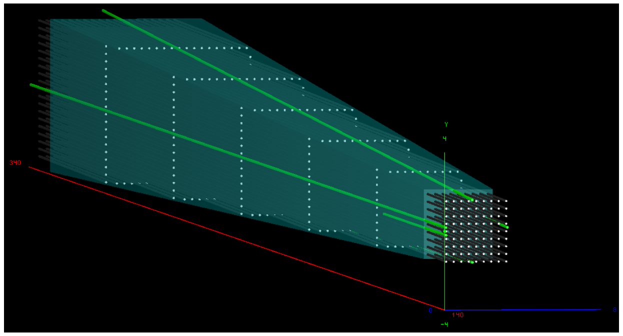


Detector baseline

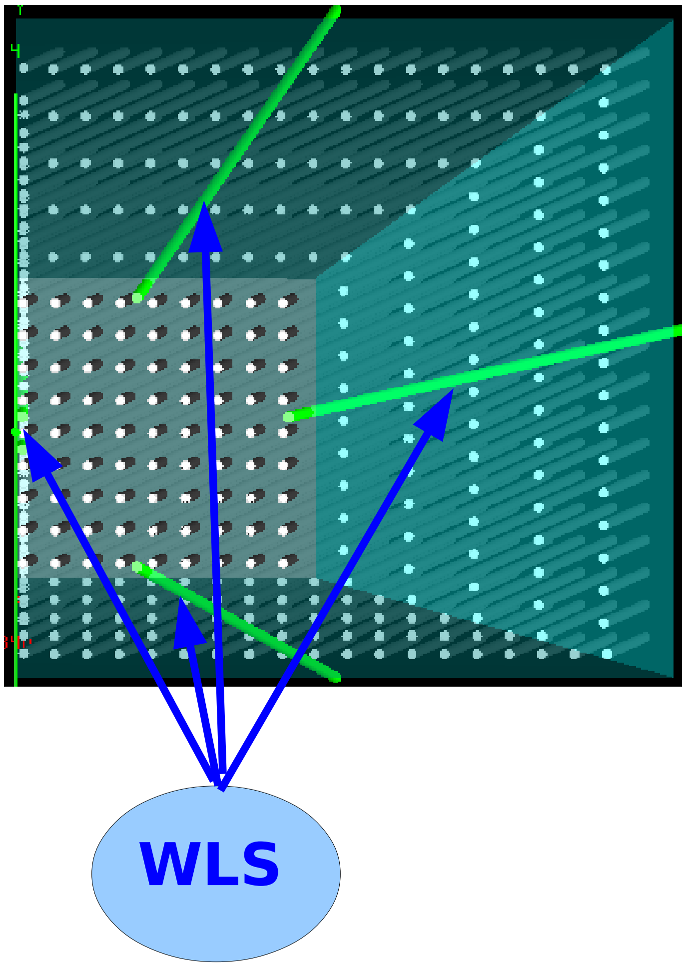
ADRIANO Calorimeter

- Lead glass + scintillating fibers
- ~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





Detector baseline



- WLS's collect Cerenkov photons generated in lead glass (front and back readout)
- Scint fibers generate and collect scintillating photons (front and back readout for fibers in the core of the tower; only back readout for the other fibers)
- Simulation include:
  - SiPM with ENF=1.016
  - Fiber non-uniformiti response = 0.8% (scaled from CHORUS)
  - Threshold = 3 p.e. (SiPM dark current< 50 kHz)
  - ADC with 14 bits
  - Gaussian noise with σ= 1 p.e.