Projectile Spectator Detector (PSD) at NA61

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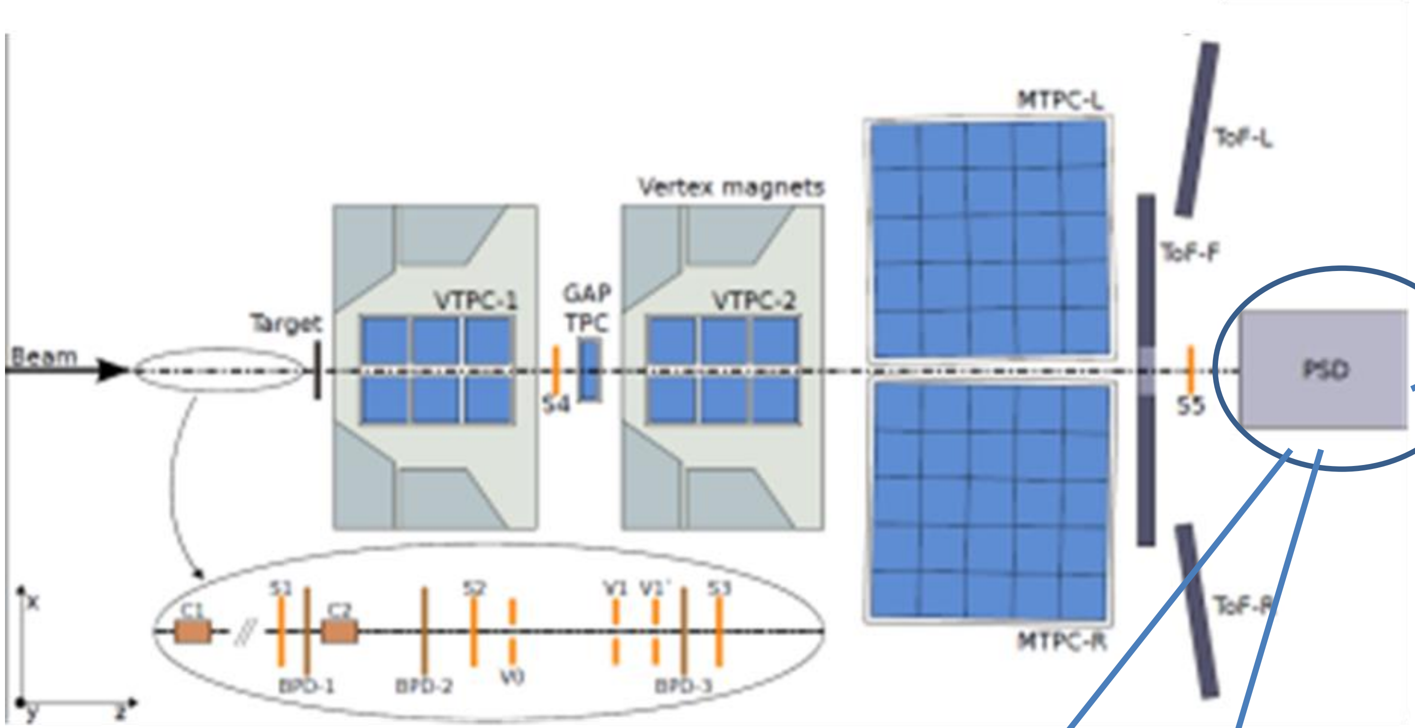
PSD in NA61



Previous PSD

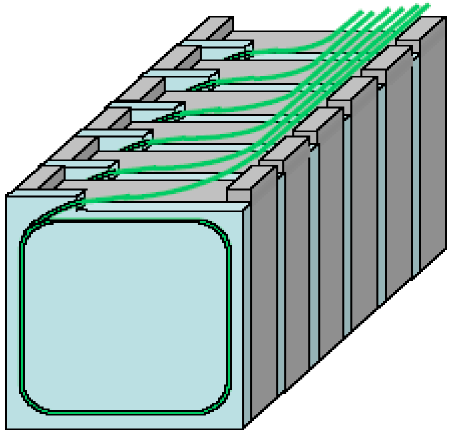
~20 tons of lead with a small amount of sensitive components: scintillators, WLS-fibers and SiPMs.

New PSD

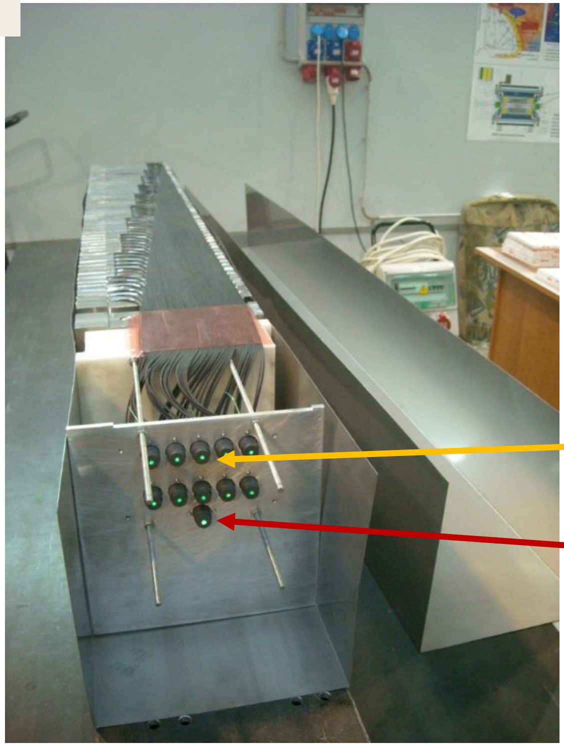
PSD modules

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Below we will explain all these unclear words.

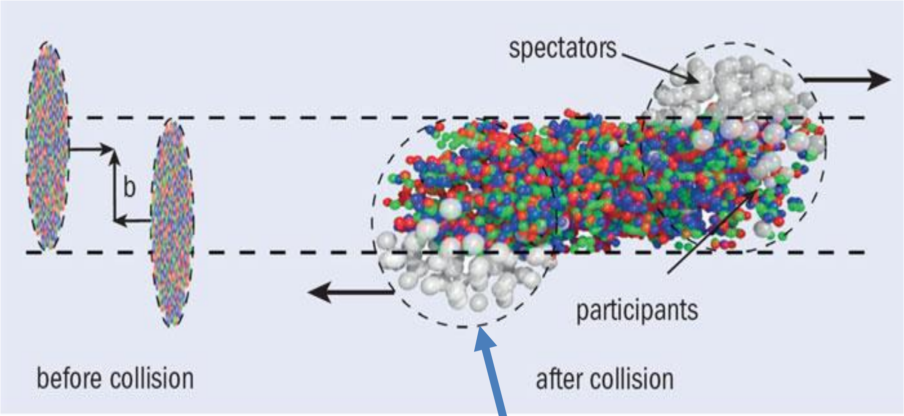


- Compensating ratio 4:1 Pb (16 mm) : scintillator (4 mm);
- 60 sandwiches in one module;
- Dimensions of modules 20 x 20 x 165 cm^3;
- Length - 5.6 λ_{int} (interaction lengths);
- Weight – 500 kg;
- WLS-fiber light readout;
- 10 individual longitudinal sections;
- 10 photodetectors (SiPM's) per module.

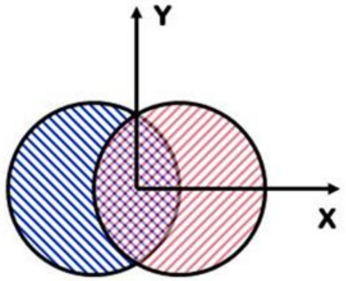


Connector for LED of monitoring system

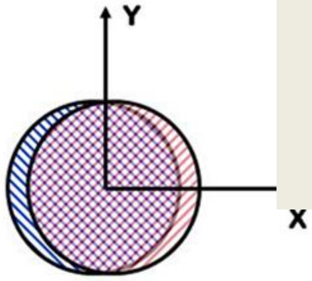
What are spectators?



spectators



Peripheral Collision



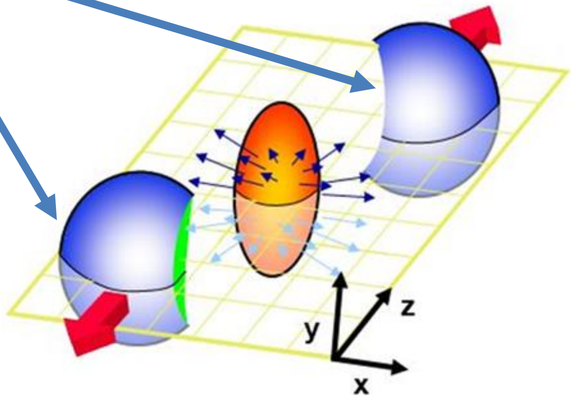
(near) Central Collision

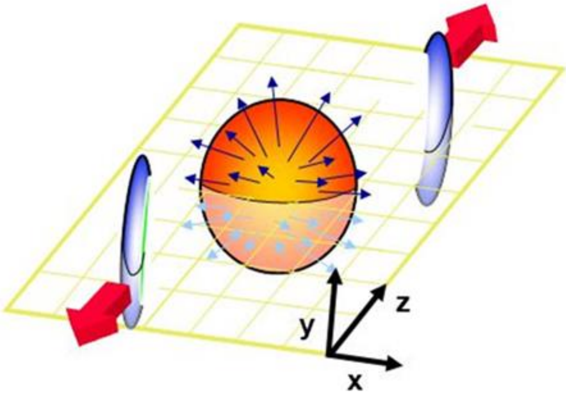
<u>Projectile Spectator</u> Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Spectators – non-interacting nuclear fragments.

Reaction plane:
plane of ***b*** and ***Z***
(beam).

Free spectators – protons and neutrons.
Bound spectators - A>1.

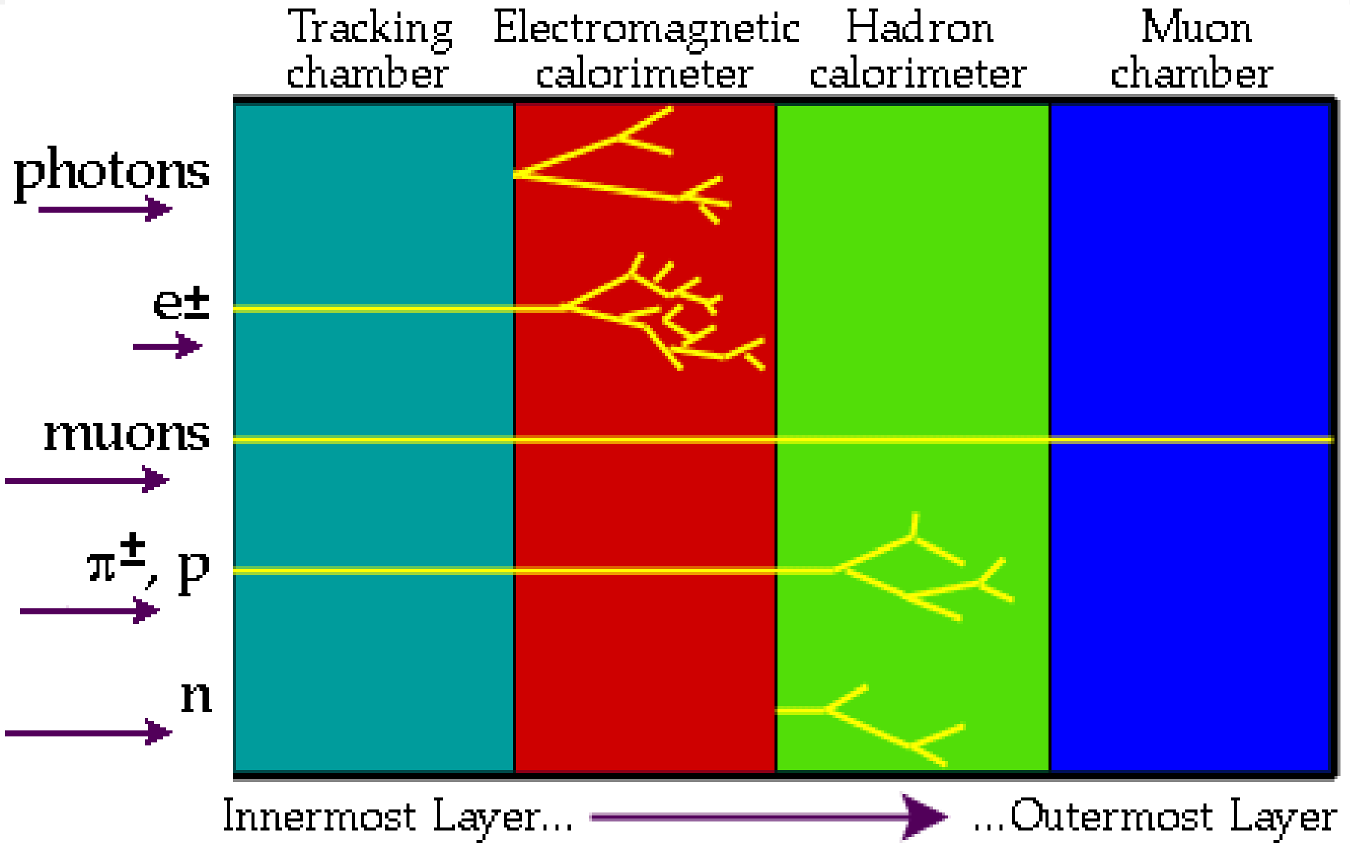




Spectators are effective tool in the measurements of centrality and the reaction plane of collisions.

Calorimeters in High Energy Physics

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.



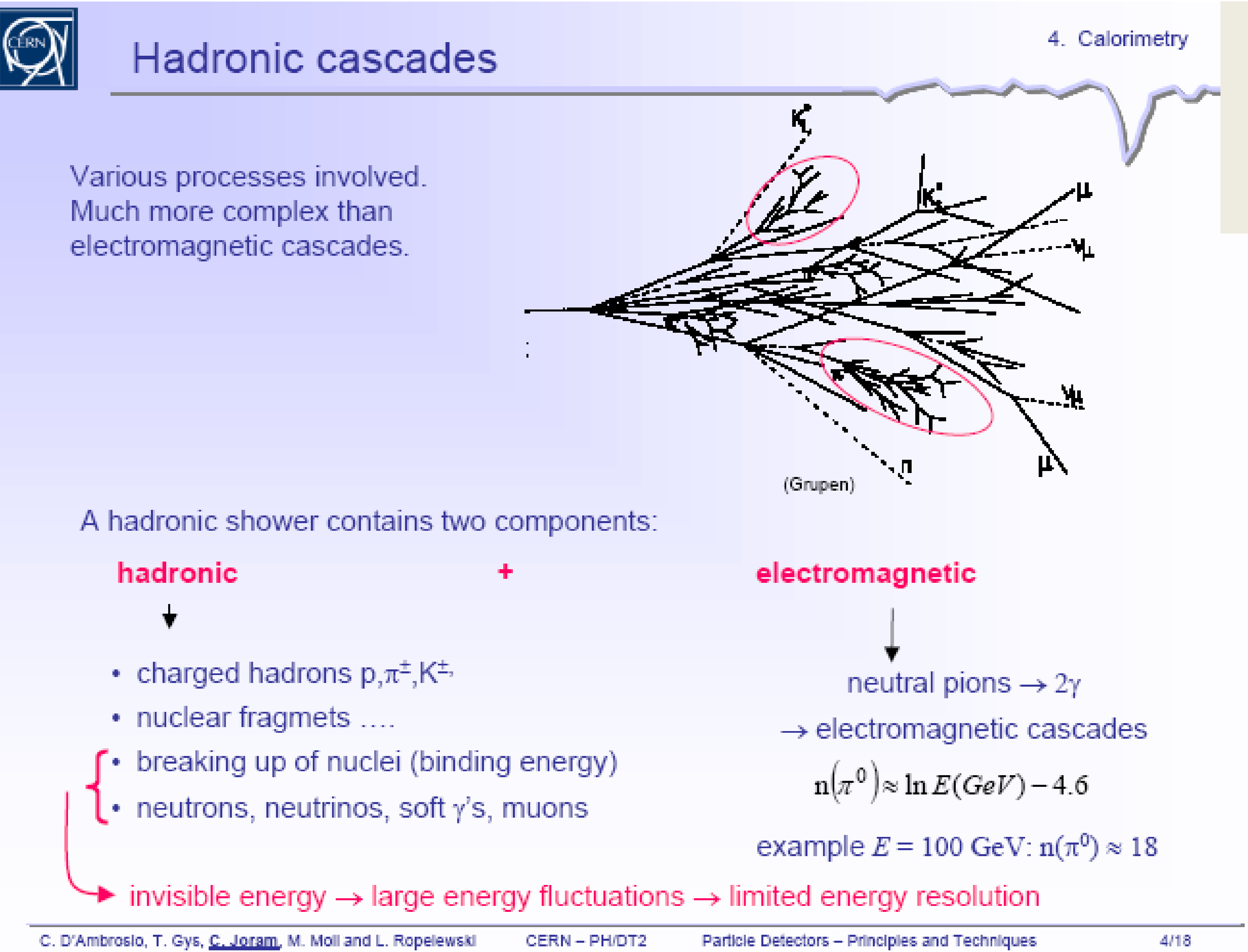
Electrons (or positrons) and photons
- Electromagnetic shower
- Electrons (positrons) and photons lose energy due to Bremsstrahlung and pair creation

Hadrons
- Hadronic shower
- Charged and neutral hadrons undergo nuclear and subsequent electromagnetic interaction

Muons
- No or almost no showering, mainly minimum ionizing (but: high energy muons may generate Bremsstrahlung, resulting in an electromagnetic shower)

Particles are detected via their interaction with matter.

Many types of interactions are involved, mainly electromagnetic.
In the end, always rely on ionization and excitation of matter.



Hadronic cascades

Various processes involved.
Much more complex than
electromagnetic cascades.

(Grupen)

A hadronic shower contains two components:

hadronic + **electromagnetic**

- charged hadrons p,$\pi^{\pm}$,$K^{\pm}$,
- nuclear fragmets ….
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ's, muons

neutral pions → 2γ

→ electromagnetic cascades

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example $E = 100$ GeV: $n(\pi^0) \approx 18$

invisible energy → large energy fluctuations → limited energy resolution

CERN Academic Training Programme 2004/2005

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Hadronic cascades

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

The concept of compensation

A hadron calorimeter shows in general different efficiencies for the detection of the hadronic and electromagnetic components ε_h and ε_e.

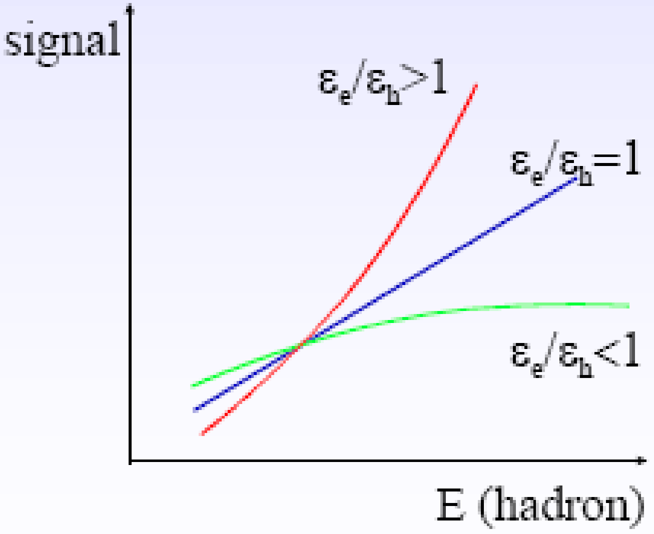
$$R_h = \varepsilon_h E_h + \varepsilon_e E_e$$

ε_h: hadron efficiency
ε_e: electron efficiency

The fraction of the energy deposited hadronically depends on the energy (remember n(π^0))

$$\frac{E_h}{E} = 1 - f_{\pi^0} = 1 - k \ln E \quad (GeV) \qquad k \approx 0.1$$

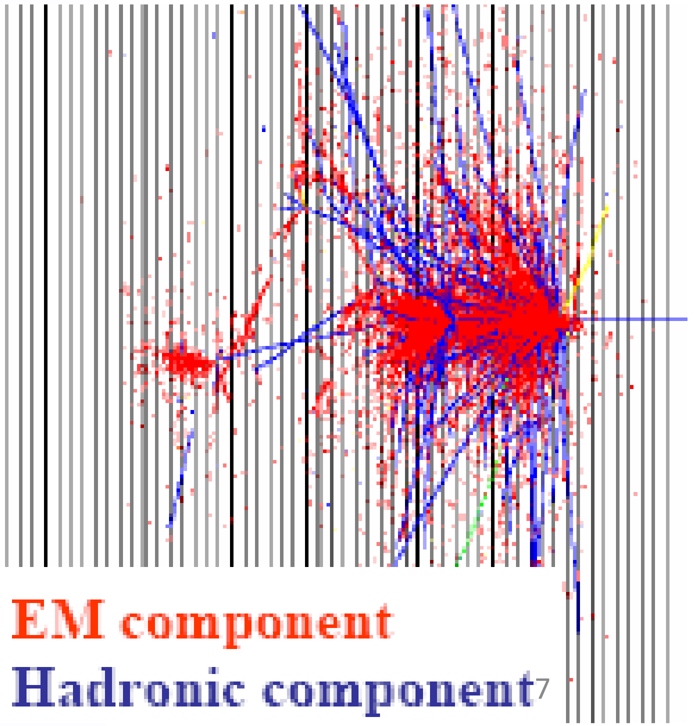
→ Response of calorimeter to hadron shower becomes non-linear



Energy resolution degraded !

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b \cdot \left| \frac{\varepsilon_e}{\varepsilon_h} - 1 \right|$$

(Schematically after Wigmans   R. Wigmans NIM A 259 (1987) 389)



Hadronic Calorimeter

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Fluctuations

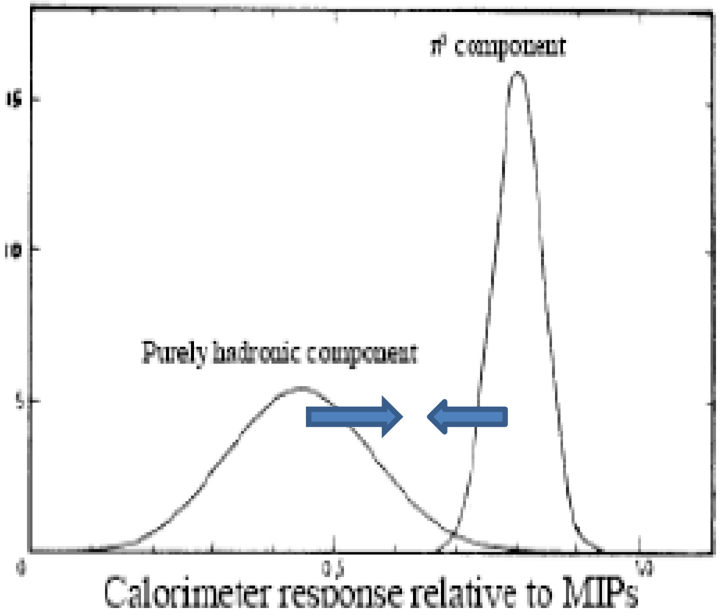
Sampling fractions

→ Ideally, one wants

$$\boxed{\frac{e}{h} = 1}$$

→ But in general:

$$\boxed{\frac{e}{h} > 1}$$

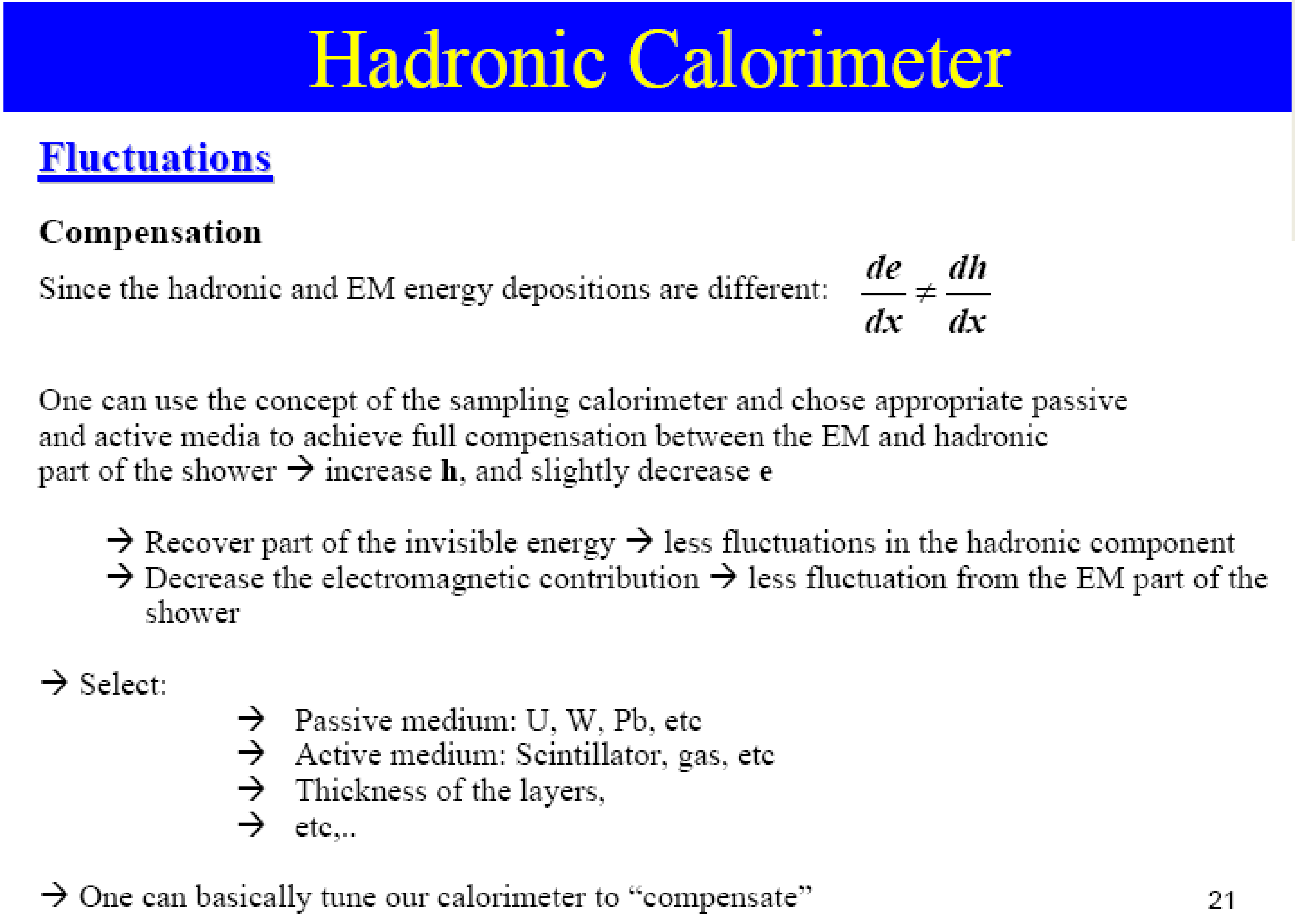


because not all available hadronic energy is sampled:

- → Lost nuclear binding energy
- → neutrino energy
- → Slow neutrons, …

Remember, in lead (Pb):
Nuclear break-up (invisible) energy: 42%
Ionization energy: 43%
Slow neutrons ($E_K \sim 1$ MeV): 12%
Low energy λ's ($E_\gamma \sim 1$ MeV): 3%

→ We should find a way of increasing h
and at the same time decrease the EM fluctuations → decrease e



Hadronic Calorimeter

Fluctuations

Compensation

Since the hadronic and EM energy depositions are different: $$\frac{de}{dx} \neq \frac{dh}{dx}$$

One can use the concept of the sampling calorimeter and chose appropriate passive and active media to achieve full compensation between the EM and hadronic part of the shower → increase **h**, and slightly decrease **e**

→ Recover part of the invisible energy → less fluctuations in the hadronic component
→ Decrease the electromagnetic contribution → less fluctuation from the EM part of the shower

→ Select:
- → Passive medium: U, W, Pb, etc
- → Active medium: Scintillator, gas, etc
- → Thickness of the layers,
- → etc,..

→ One can basically tune our calorimeter to "compensate"

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Hadronic Calorimeter

Hadronic Calorimeter (HCAL)

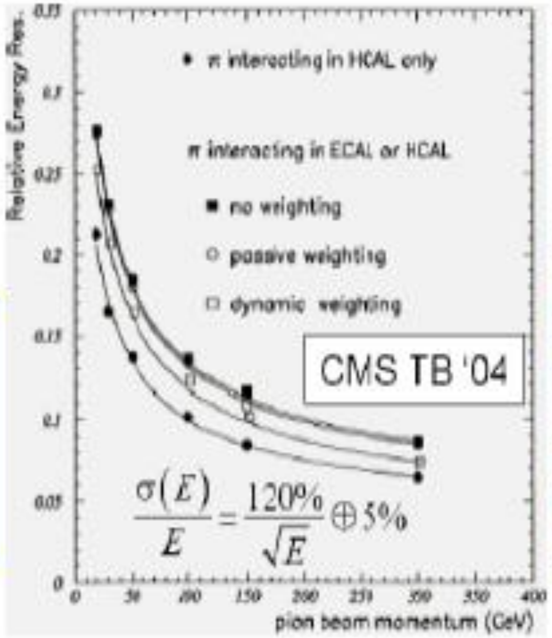
→ CMS hadron calorimeter

→ 16 scintillator 4 mm thick plates (active material)
Interleaved with 50 mm thick plates of brass

→ Energy resolution:

$$\boxed{\frac{\sigma(E)}{E} \propto \frac{(120\%)}{\sqrt{E}} \oplus 5\%}$$

Hadronic energy resolution compromised in favor of a much higher EM energy resolution

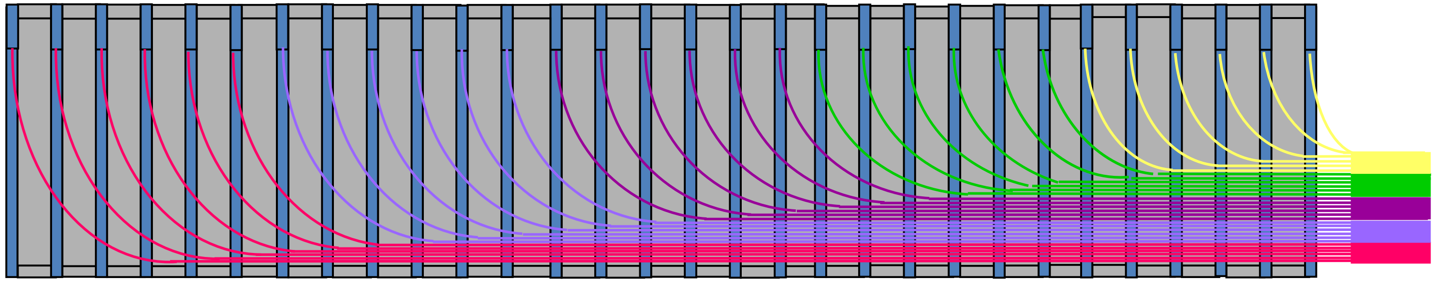


The HCAL being inserted into the solenoid

http://www.flickr.com/photos/naezmi/365114338/

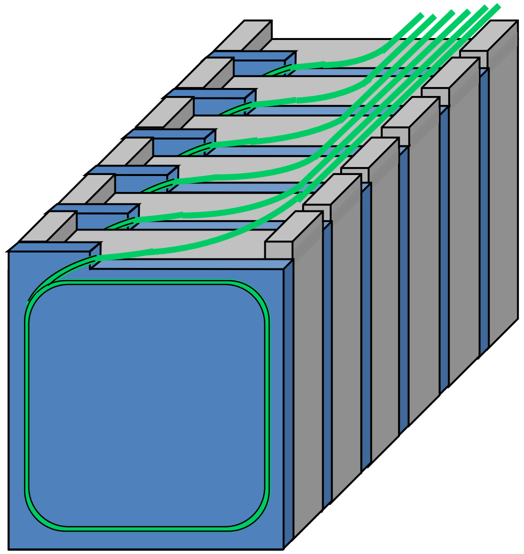
PSD: light readout with WLS-fibers from scintillators

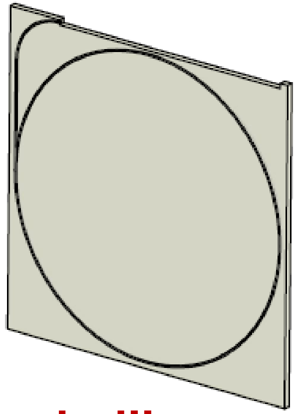
Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.



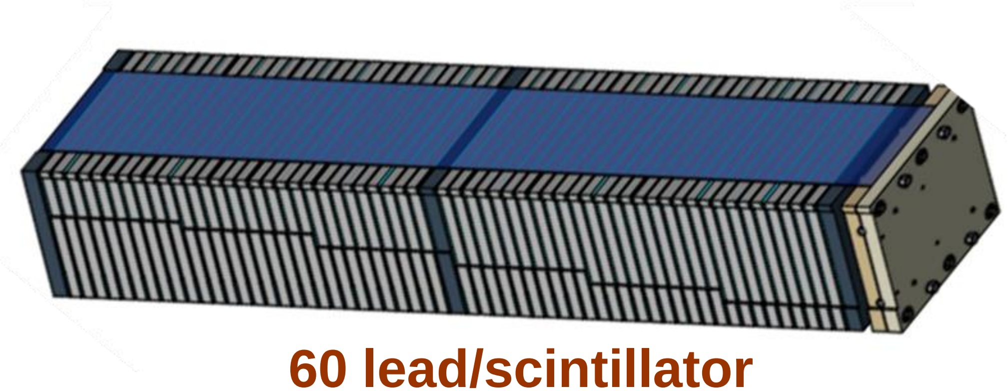
6 fiber/SiPM
10 SiPMs/module

Half of module.





scintillator



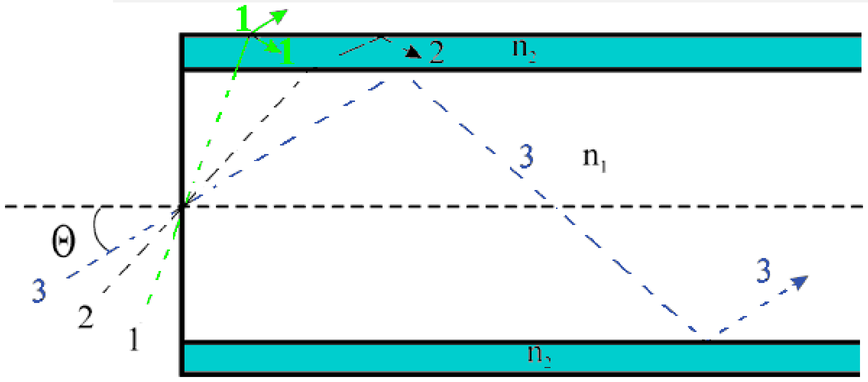
60 lead/scintillator sandwiches.

Compensating ratio:
Lead/Scintillator 4:1.
Lead- 16 mm; scintillator – 4 mm

Wave-Length-Shifting (WLS)-fibers

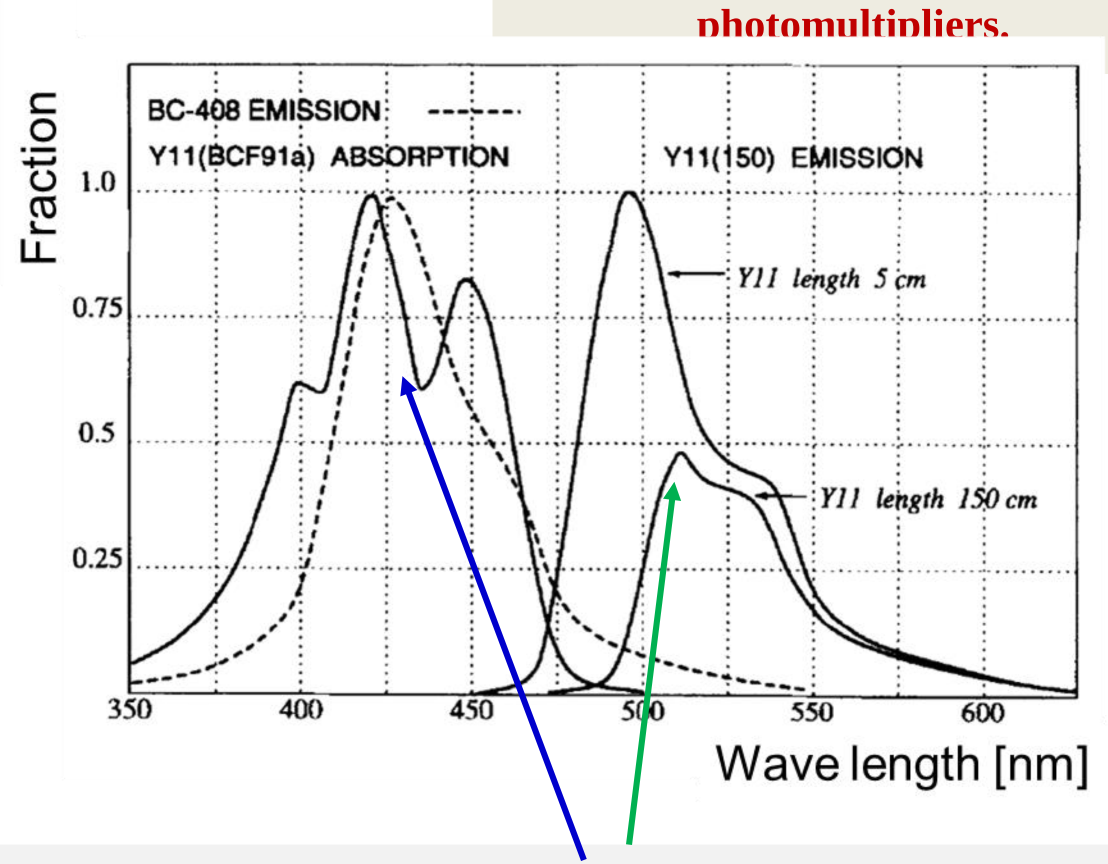
Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Principle – total inner reflection of the light.



WLS-fibers.

Optical connectors.



Core of WLS-fiber contains shifter – remittance of blue light to green one. Only 5-7% of initial light is captured by fiber (solid angle of fiber).

Signal readout by photodectors

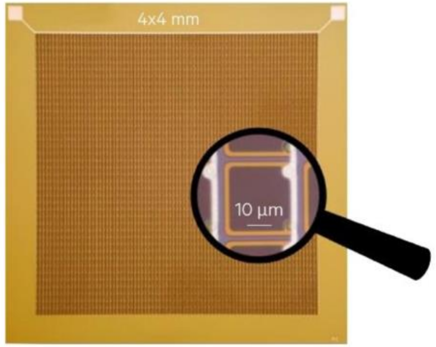
Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Photomultipliers (PM‘s) have been developed during 100 years. The first photoelectric tube was produced by Elster and Geiter 1913. RCA made PM‘s a commercial product in 1936. Single photons can be detected with PM‘s.
The high price, the bulky shape and the sensitivity to magnetic fields of PM‘s forced the search for alternatives.

PIN photodiodes are very successful devices and are used in most big experiments in high energy physics (CLEO, L3, BELLE, BABAR, GLAST) but due to the noise of the neccessary amplifier the minimal detectable light pulses need to have several 100 photons.

Avalanche photodiodes have internal gain which improves the signal to noise ratio but still some 20 photons are needed for a detectable signal. The excess noise, the fluctuations of the avalanche multiplication limits the useful range of gain. CMS is the first big experiment that uses APD’s.

Geiger-APD‘s (**silicon photomultipliers, SiPM**s) can detect single photons. They have been developed since the beginning of this millennium.



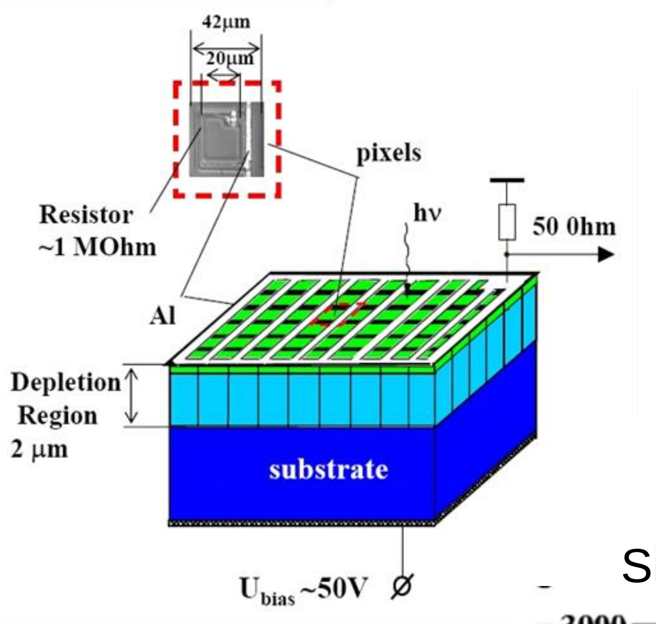
Silicon photomultipliers (SiPM's)

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

combine many small APD pixels onto the same substrate with a common anode

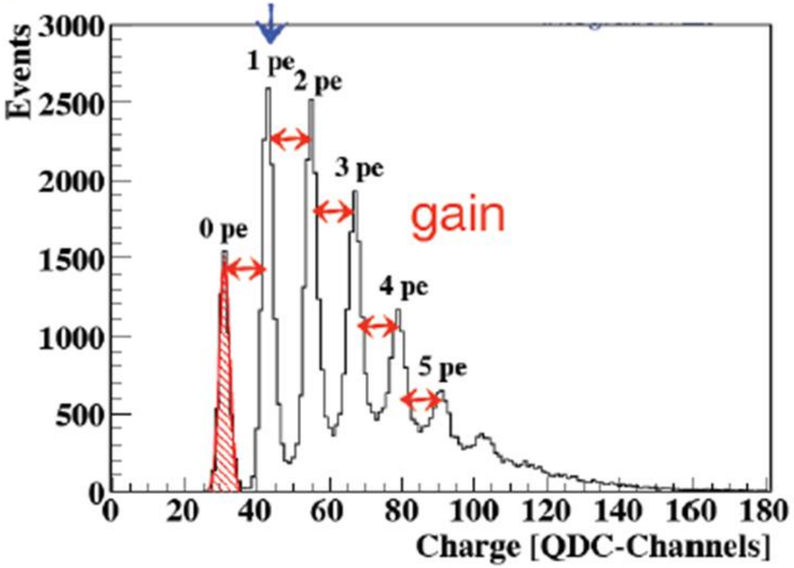
Fully digital device – number of pixels determines the dynamic range:

$$N_{fired} = N_{total}\left(1 - e^{\frac{-N_{photons} PDE}{N_{total}}}\right)$$

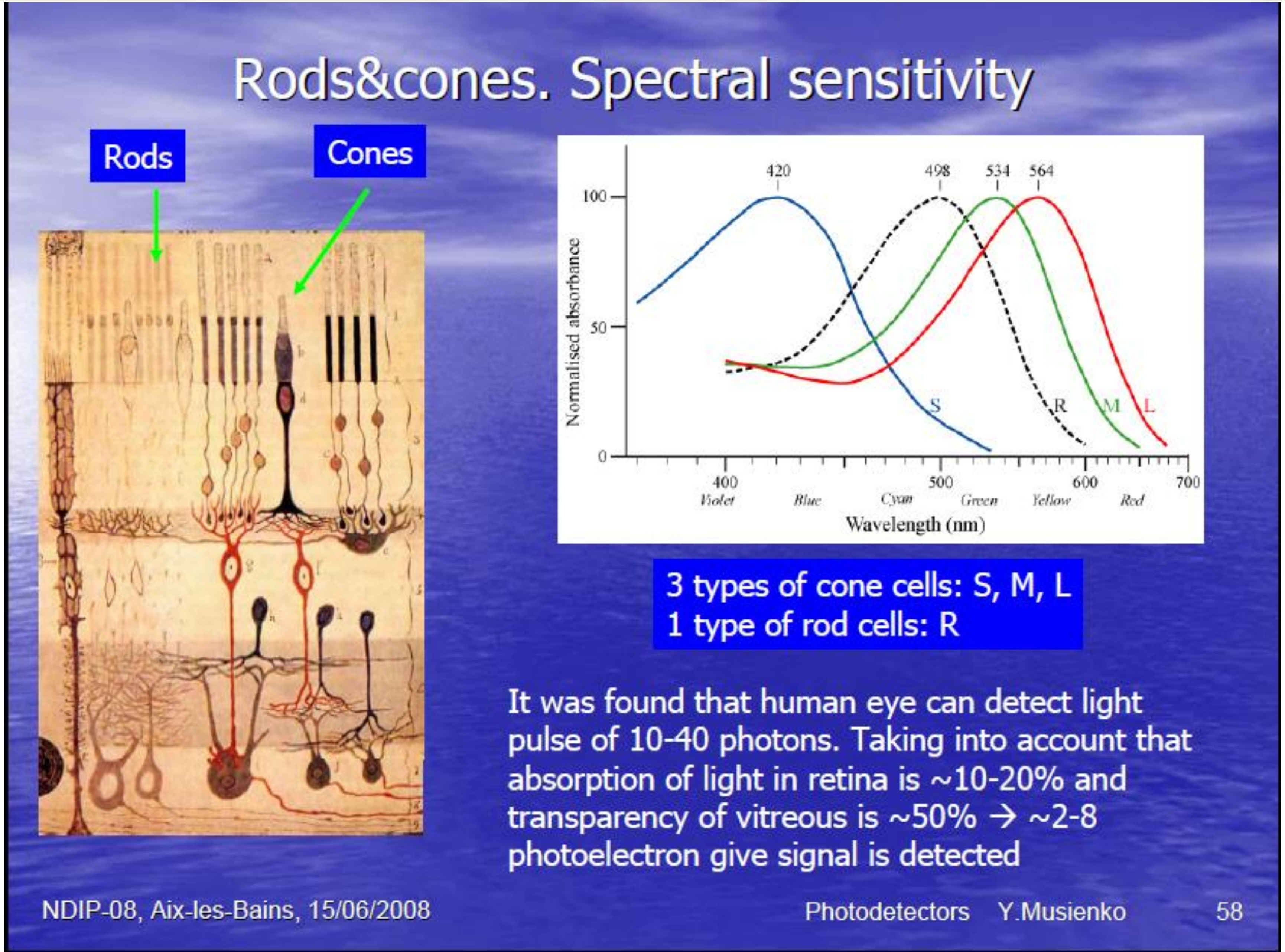


- •SiPM's work at low bias voltage (~50 V),
- •have low power consumption (< 50 µW/mm^2),
- •are insensitive to magnetic fields up to 15 T,
- •are compact and rugged,
- •have a very small nuclear counter effect (sensitivity to charged particles),
- •have relative small temperature dependence,
- •tolerate accidental illumination
- •and are cheap. They are produced in a standard MOS process

SiPM can count a single photons.



The best (color) photodetector is human eye!



Rods&cones. Spectral sensitivity

3 types of cone cells: S, M, L
1 type of rod cells: R

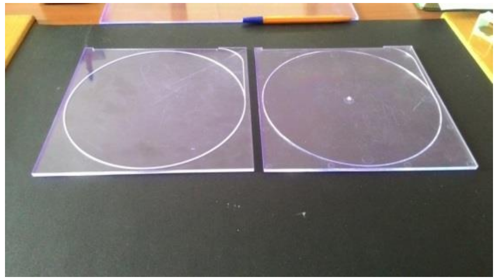
It was found that human eye can detect light pulse of 10-40 photons. Taking into account that absorption of light in retina is ~10-20% and transparency of vitreous is ~50% → ~2-8 photoelectron give signal is detected

NDIP-08, Aix-les-Bains, 15/06/2008 Photodetectors Y.Musienko 58

There are no color SiPM's in Projectile Spectator Detector.

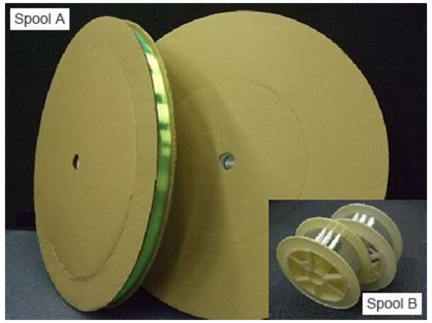
Main PSD module components

About 3000 scintillator plates (200 x 200 x 4mm^3) with WLS fiber glued into grove were produced.

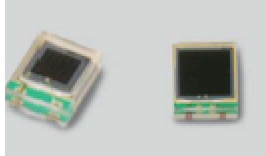


About 3000 lead / antimony (3%) absorbers have been produced.

About 5 km of WLS-fibers were used.

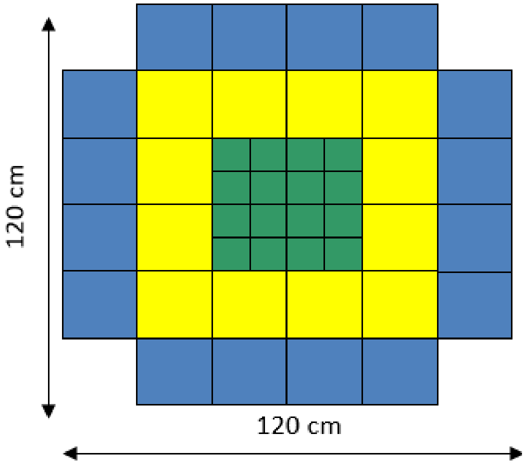


About 500 SiPM’s are used



Previous and new configurations of PSD

Previous configuration



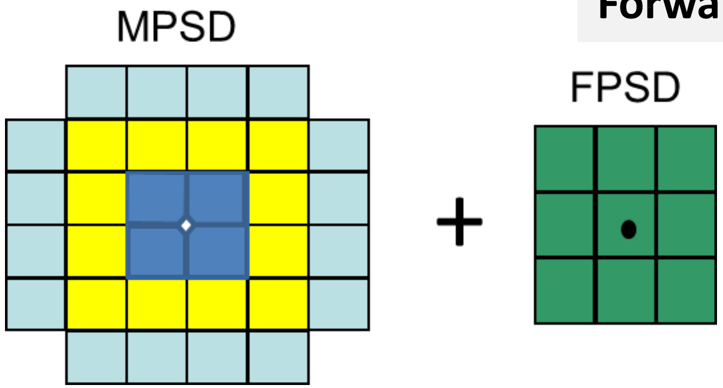
Previous PSD:

44 modules:
16 central (small),
28 outer (large) modules.

New configuration

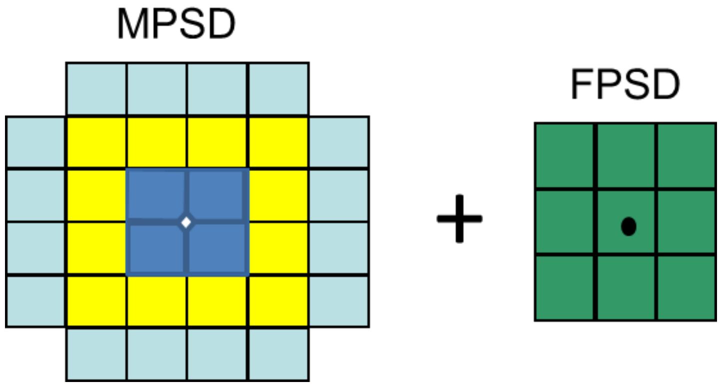
Main PSD: 32 modules.

Forward PSD: 9 modules



Why we need new configuration of PSD?

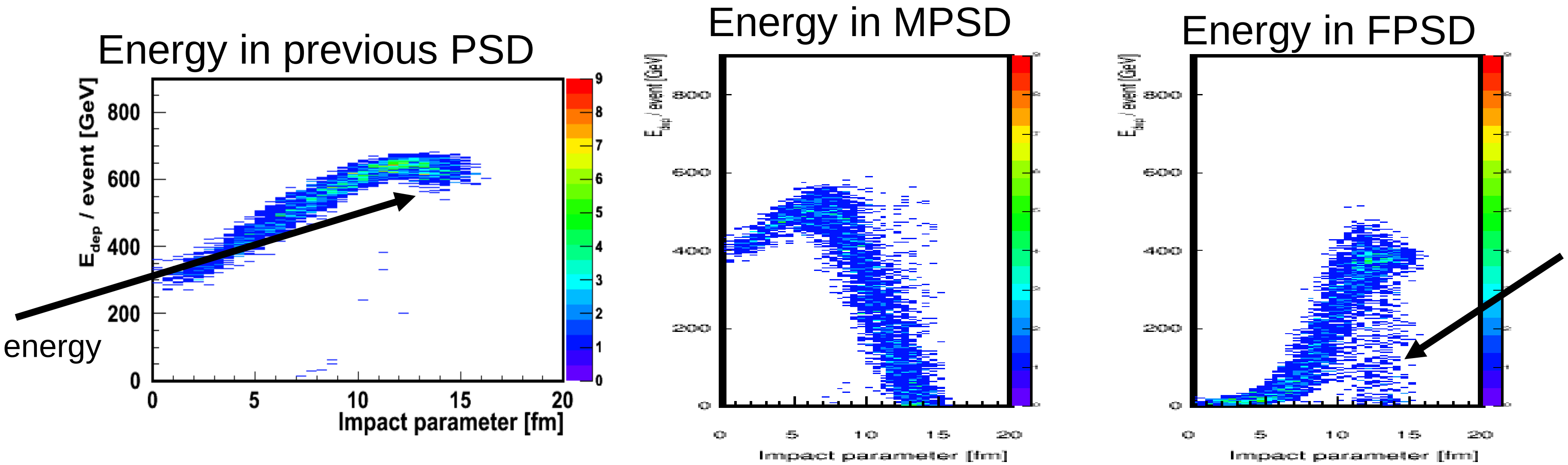
At one order higher beam intensity the scintillators will not survive in the center. Beam hole is needed!



Main PSD: 32 modules.

Forward PSD: 9 modules

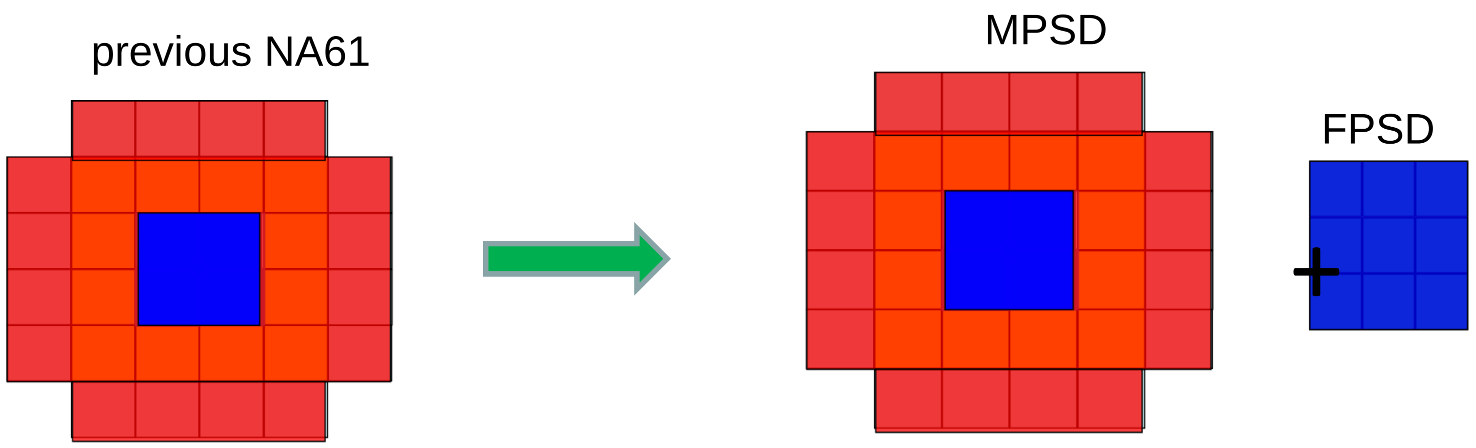
Simulation of Pb+Pb@150 AGeV with QGSM model



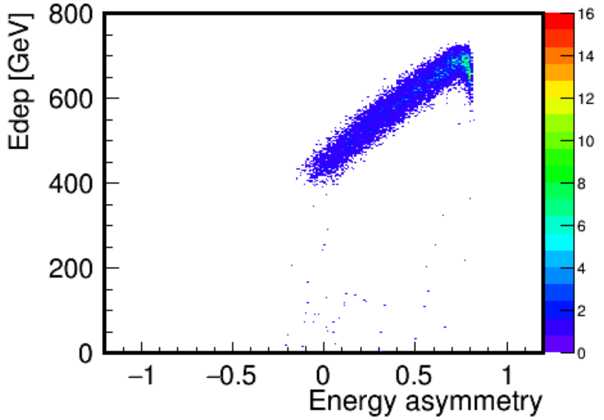
Leak of energy

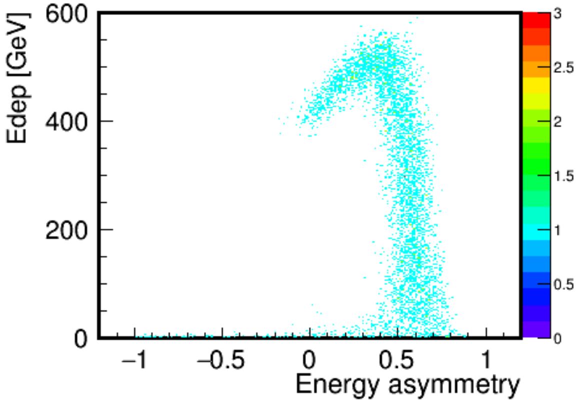
Effect of 4 cm hole in scintillators in FPSD

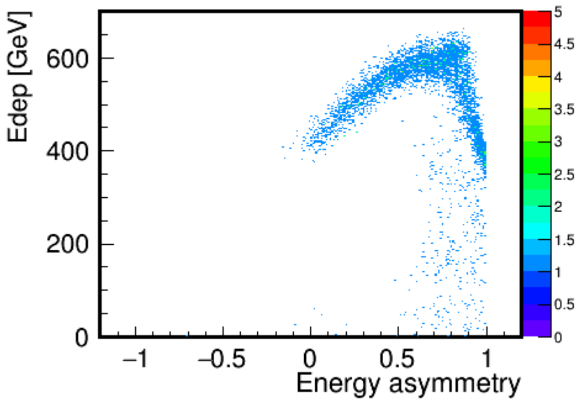
New observables can be constructed additional to the energy



Energy asymmetry = $(E_{blue}-E_{red}) / (E_{blue}+E_{red})$


previous PSD


MPSD

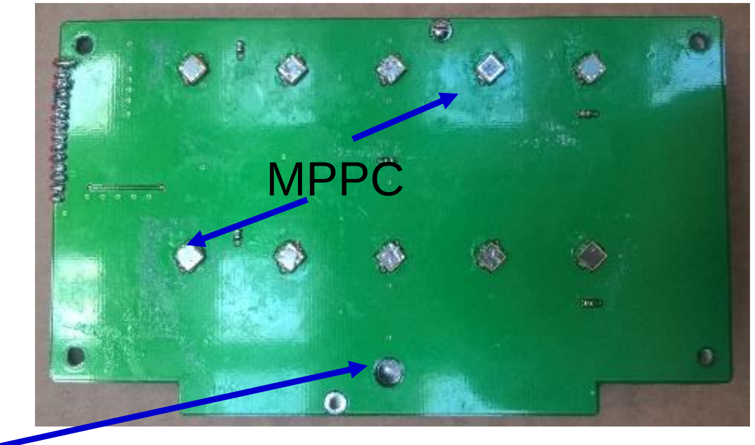

MPSD+FPSD

The centrality classes can be constructed from above two-dimensional plots.

Other approaches (ML) are under development.

Front-End-Electronics for PSD.

Two boards with SiPM’s and analog electronics are installed in each module.



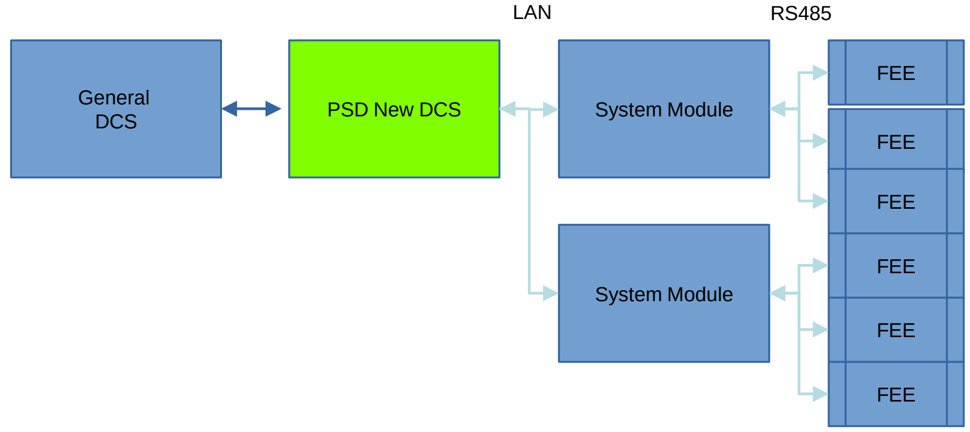
MPPC

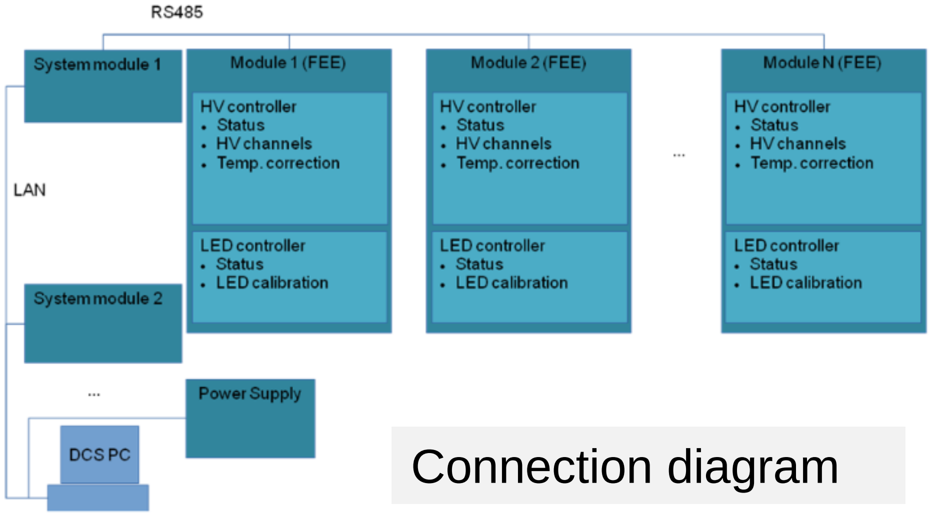
LED source

Hamamatsu S12572-010P
Sensitive area - 3 x 3 mm^2
Number of pixels - 90 000
nominal gain - 1 x 10^5,
Gain ~1% /1^{o}C
Pixel recovery time - 10 ns
PDE -12%

- Amplifiers,
- Power sources,
- Control for SiPM parameter (HV, Temperature, Gain)
- Stabilized light source.

Detector Control System for PSD



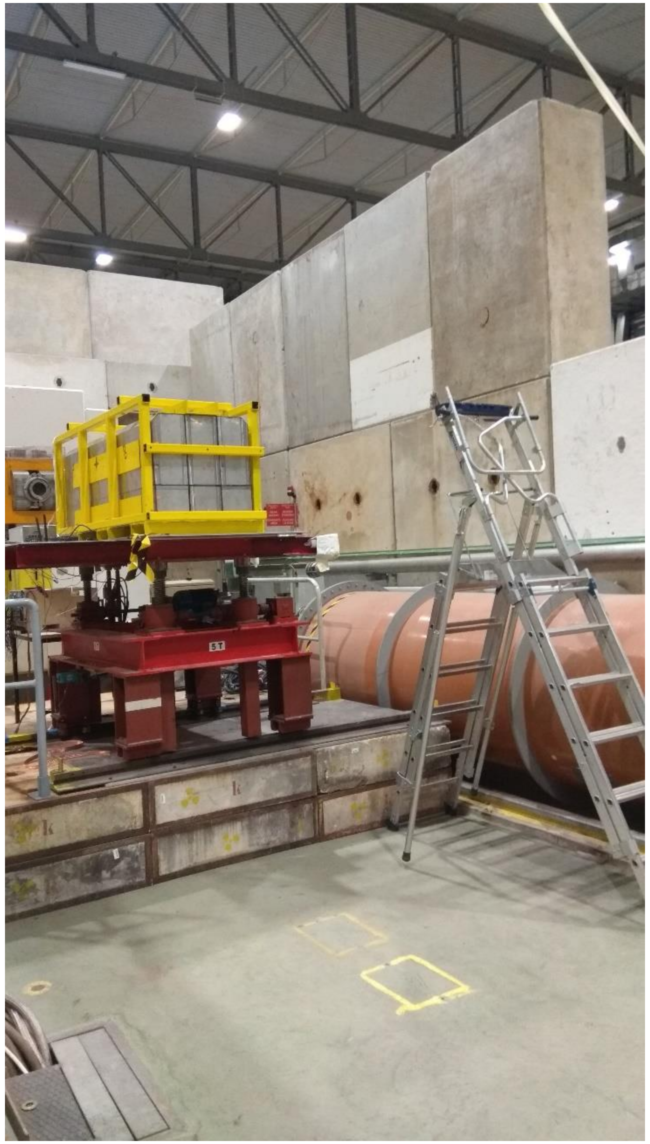


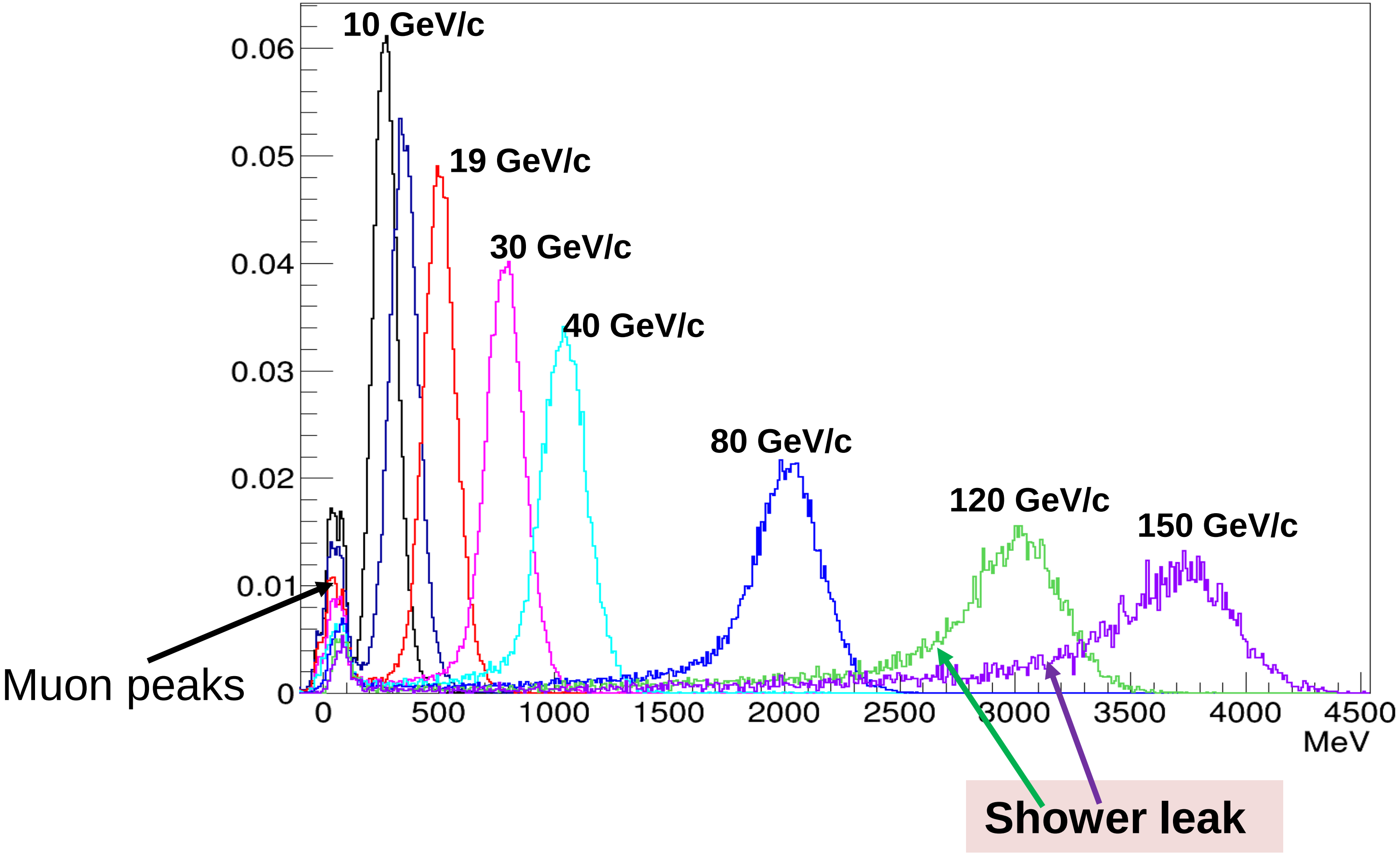
Connection diagram

DCS Tasks:

- **Control of HV at photodetectors (MPPC's);**
- **Temperature control of photodetectors;**
- **Compensation of temperature drift of MPPC gain;**
- **Monitoring of MPPC gain with stabilized light source.**

Energy spectra in F-PSD for different beam energies

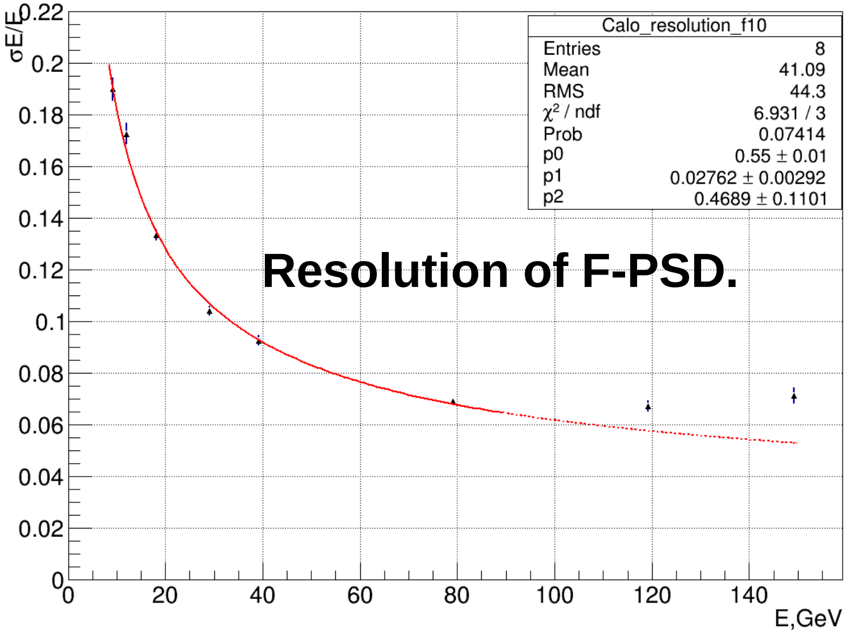




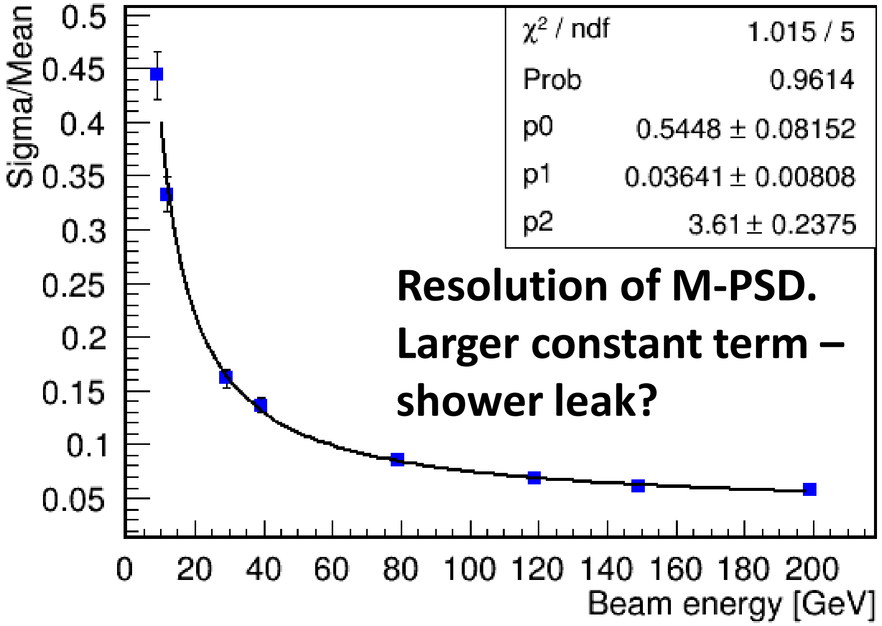
Fit of these spectra gives the energy resolution of F-PSD.

Energy resolution of F-PSD at high (10-150 GeV/c) beam momenta

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \mathrm{b} \oplus \frac{c}{E}$$



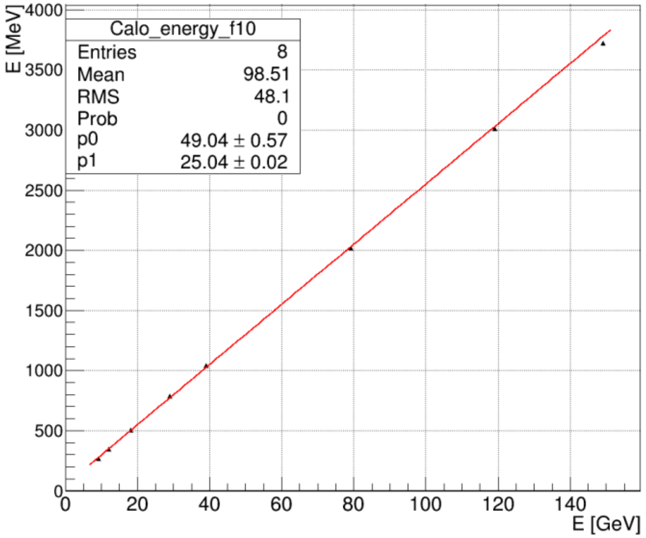
Resolution of F-PSD.



Resolution of M-PSD.
Larger constant term –
shower leak?

The fit is nice up to 80 GeV/c.
At higher energies the significant discrepancy is observed.
Shower leak!

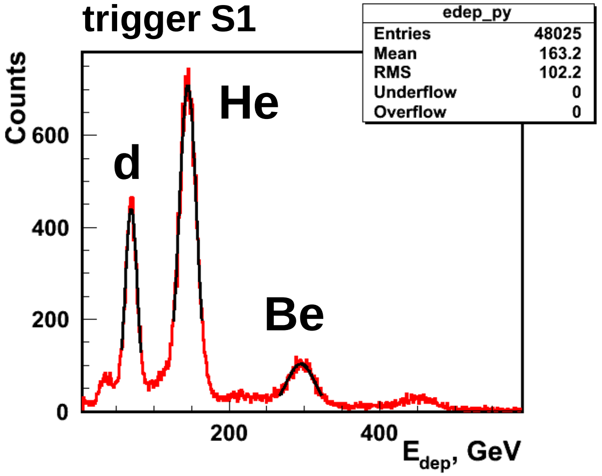
The **stochastic term of ~56%.**
Good agreement with MC results.
Constant term is about 2.8%.
The noise term is rather small.



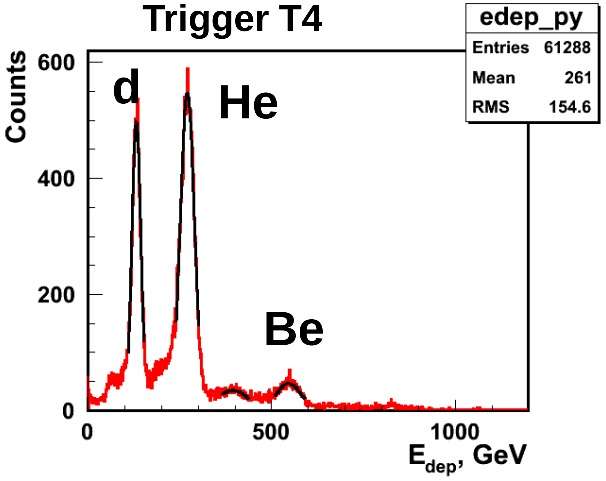
Linearity of response is good excepting 150 GeV.

Energy in PSD on-line for first ^{7}Be-run (no energy calibration)

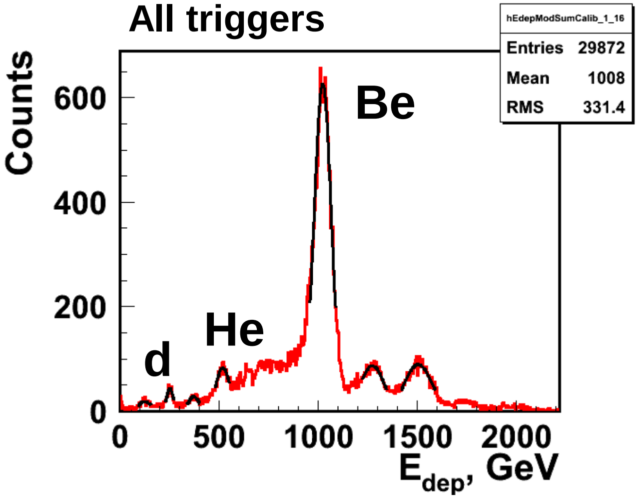
40 AGeV
Run 15258 special, target IN
trigger S1



75 AGeV
Run 15161, target IN
Trigger T4



150 AGeV
Run 14946, target OUT
All triggers



Beam energy (AGeV)	40		75		150	
	E_{total} (GeV)	Resol. (%)	E_{total} (GeV)	Resol. (%)	E_{total} (GeV)	Resol. (%)
^{2}H	80	11.8	150	9.2	300	6.6
^{4}He	160	8.1	300	7.0	600	6.7
^{7}Be	280	6.4	525	6.1	1050	4.1

The PSD on-line resolution ~90%/sqrt(E) is about 1.5 times worse of expected one. Further improvement needs the accurate energy calibration.

History of PSD operation

- **The concept of PSD was developed in 2007-2010 when the very first commercial SiPM’s appeared at market.**
- **It was designed for the energy below 100 GeV where the critical point was expected that time.**
- **The length of PSD modules was chosen to fit this energy that lead to the shower leak for higher energies.**
- **Hadron shower leak was observed in the past physical program at beam energies higher then 100 GeV.**
- **This problem will accompany us in future program too ☹.**
- **PSD is the first operational calorimeter with SiPM readout in the world!**
- **But first SiPM’s were not ideal. Our experience with SiPMs was not ideal too.**
- **Significant temperature drifts of SiPM’s gain was discovered in the first beam runs.**
- **Long recovery time of SiPM’s pixels was an unexpected discovery in Ar-runs.**
- **The problems were fixed hastily.**
- **New SiPM’s are excellent devices with the reliable performance.**

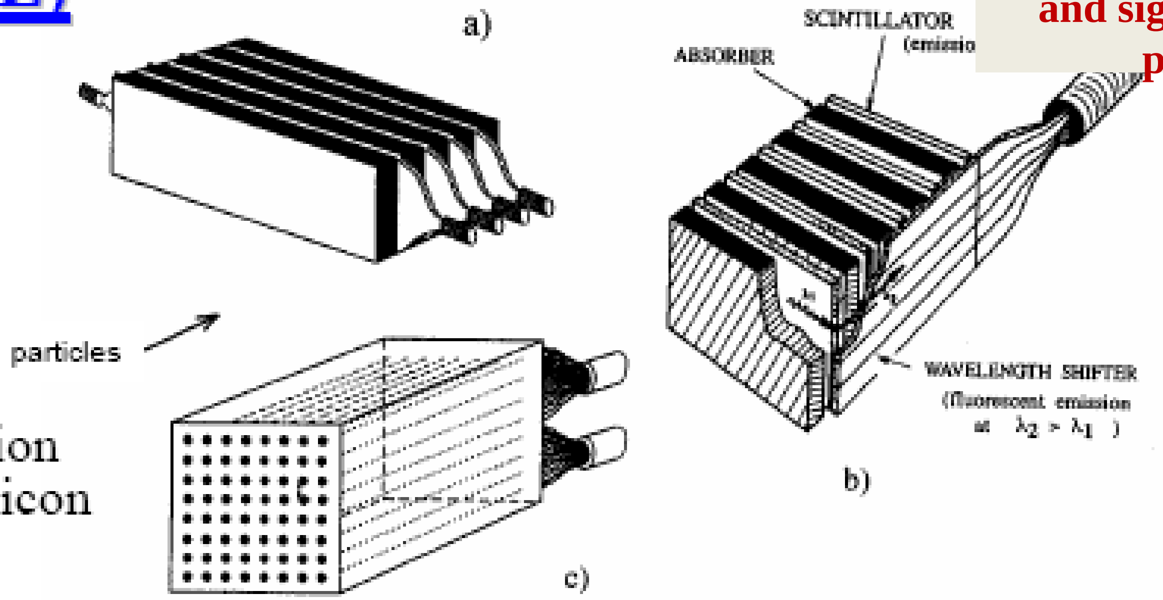
Let’s discover not only the problems with PSD but great effects in nuclear collision!

Thank you!

Hadronic Calorimeter

Projectile Spectator Detector is a lead/scintillator sampling compensating hadron calorimeter with light readout by WLS-fibers and signal readout by silicon photomultipliers.

Hadronic Calorimeter (HCAL)



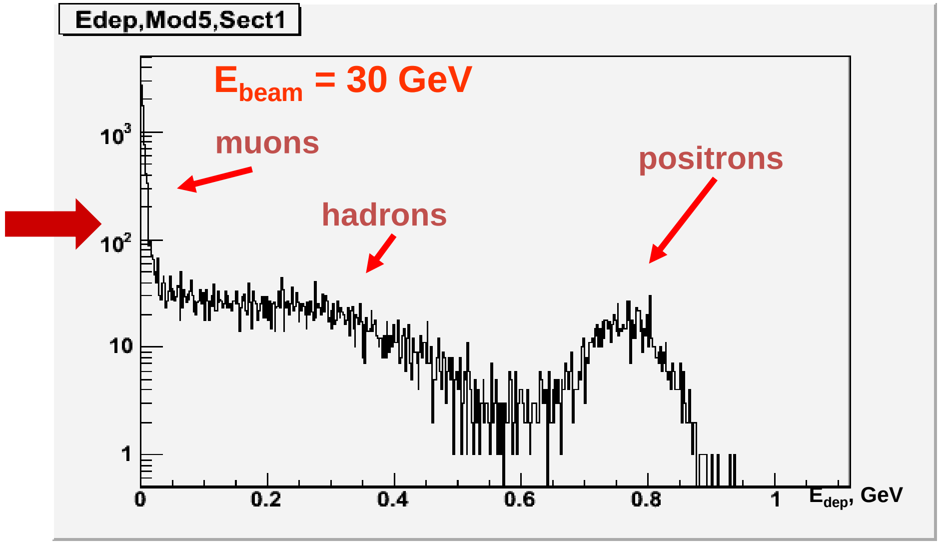
- → Hadronic calorimeters are usually sampling calorimeters
- → The active medium made of similar material as in EM calorimeters:
  - → Scintillator (light), gas (ionization chambers, wired chambers), silicon (solid state detectors), etc
- → The passive medium is made of materials with longer interaction length λ_I
  - → Iron, uranium, etc
- → Resolution is worse than in EM calorimeters (discussion in the next slides), usually in the range:

$$\frac{\sigma(E)}{E} \propto \frac{(35\% - 80\%)}{\sqrt{E}} \longrightarrow$$

Can be even worse depending on the goals of an experiment and compromise with other detector parameters

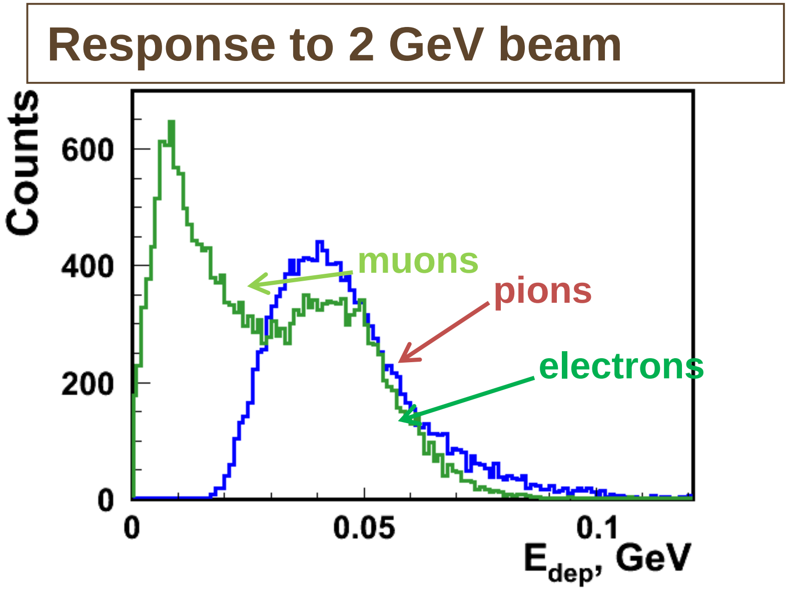
Study of e/h ratio

Good identification/separation of muons, pions and electrons at high energies in <u>first section:</u>



Muons and pions are badly separated at low energies (E<4 GeV)

According to simulation e/h ~1.1 (almost compensating calorimeter)

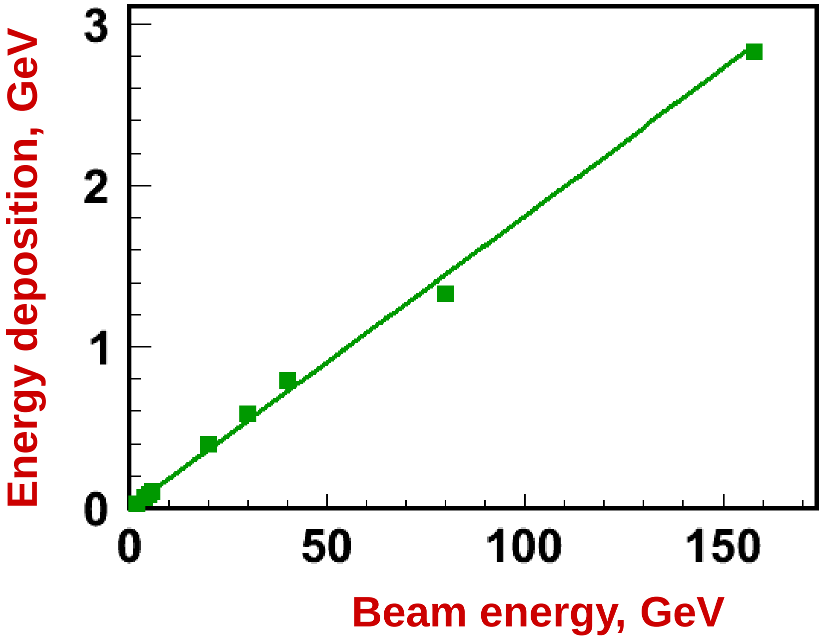


Small constant term in energy resolution is expected.

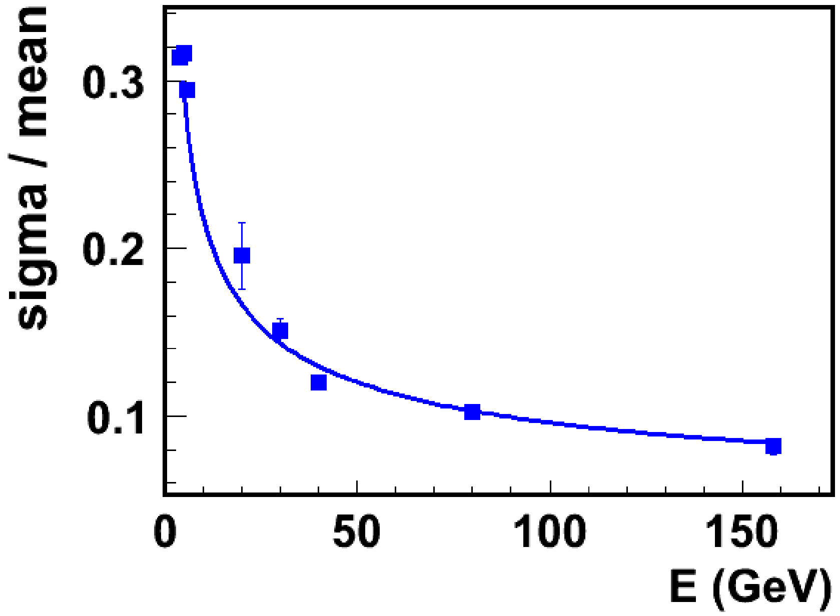
Calorimeter response to pions (linearity and energy resolution)

Good linearity in range 4-158 GeV.

No signal saturation, good e/h compensation



Energy resolution v.s. beam energy in range 4-158 GeV



$\sigma(E)/(E) = 56.1\%/\sqrt{E(\text{GeV})} + 2.1\%$

$+16\%/\sqrt[4]{E(\text{GeV})}$

Constant term is essential only for energy measurement of single particle. It is not important in case of measurement of total energy from many particles with the same energy:

$$\frac{\sigma(E)_N}{E_N} = \frac{\sqrt{\Sigma_i \sigma(E)_i^2}}{E_N} = \frac{\sqrt{N}\sigma(E)_1}{NE_1} = \frac{1}{\sqrt{N}} \otimes \frac{\sigma(E)_1}{E_1}$$