The Mu2e Calorimeter

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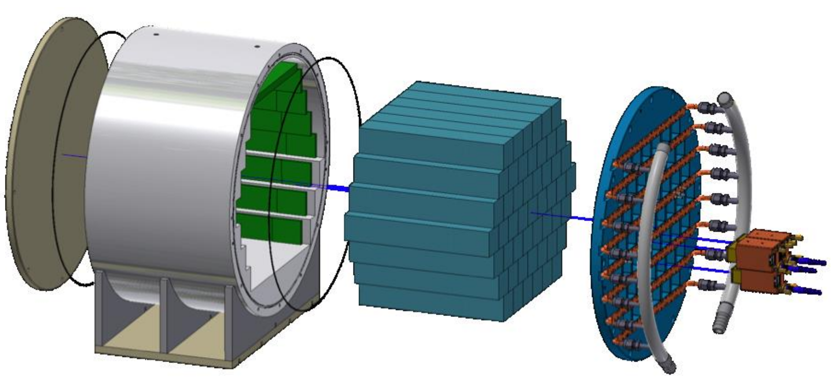
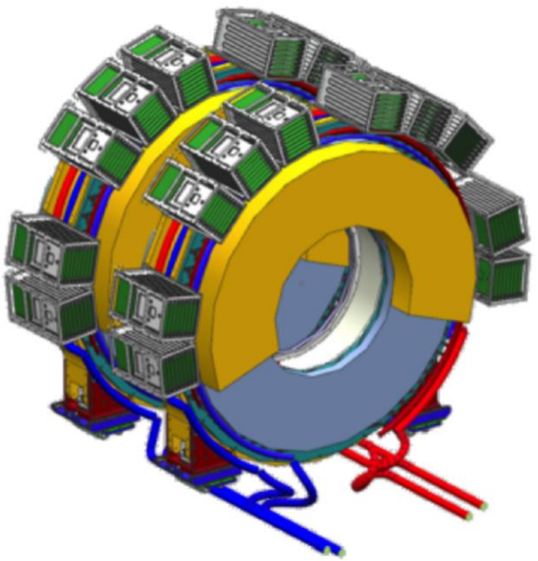




Outline

- Calorimeter principles
- Scintillation & Photodetectors
- The Mu2e calorimeter
- Conclusions

What is a calorimeter? (1)

- A calorimeter measures the particle energy

- The measurement process is a destructive process
  → particles are no longer available

- What kind of particle can be measured?
  - em calorimeter (photon, electrons, π^0)
  - hadron calorimeter (neutrons, protons, $\pi^{+/-}$, K, jets…)

- Basic assumption : linearity

  Calorimeter signal = (Constant) x (particle energy)

What is a calorimeter? (2)

- Calorimetry is a widespread technique in particle physics:
  - instrumented targets
    - neutrino experiments
    - proton decay / cosmic ray detectors
  - shower counters
  - 4π detectors for collider experiments

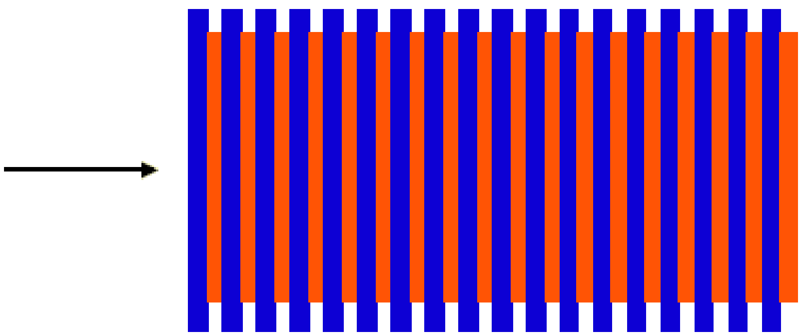
- Calorimetry makes use of various detection mechanisms:
  - Scintillation
  - Cherenkov radiation
  - Ionization

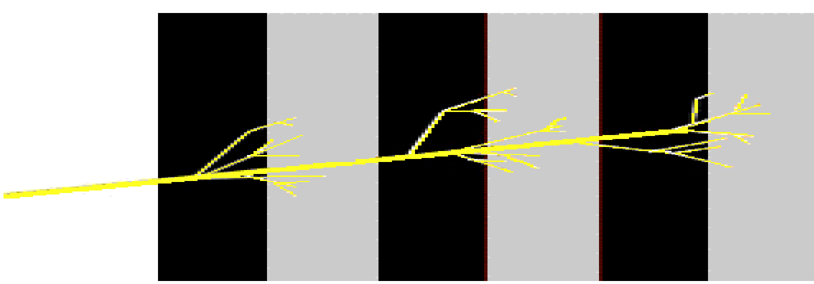
- Calorimeter can be extremely fast
  → recognize and select events in real time (*trigger*)

Calorimeter types

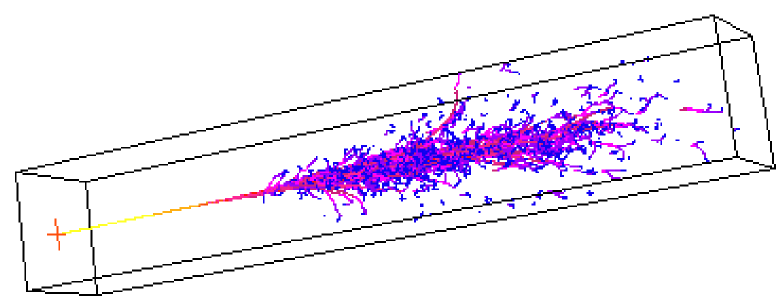
Two different calorimeter by construction:

- **Heterogeneous calorimeter**
  Layers of passive absorber alternate with active detector layers





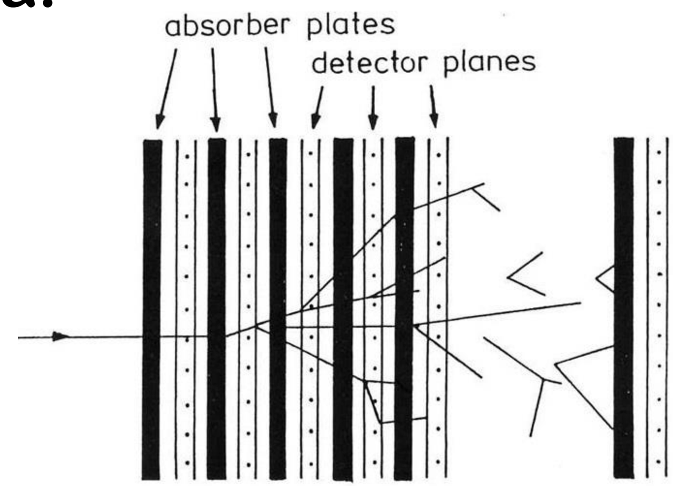
- **Homogenous calorimeter**
  A single medium serves as both absorber and detector



Heterogeneous calorimeter

These calorimeters use different media:

- High density absorber
- Interleaved with active readout devices
- Most common used : sandwich structure



Advantages:

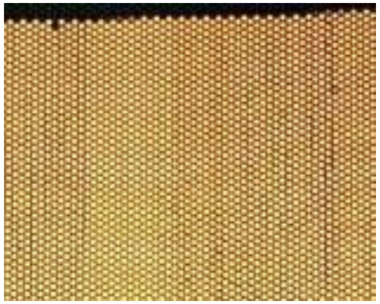
- Cost
- Transverse and longitudinal segmentation

Disadvantages:

- Only part of shower seen
- Bad energy resolution (sampling fluctuations)

Example:

- ATLAS ECAL
- KLOE

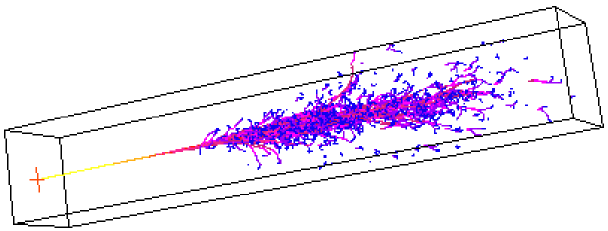


KLOE calorimeter:
Lead and Scintillating fibers

Homogenous calorimeters

One block of material serves as absorber and active medium at the same time

- Scintillating crystals → scintillation
- Lead glass → Cherenkov light
- Liquid noble gasses → ionization



Advantages:

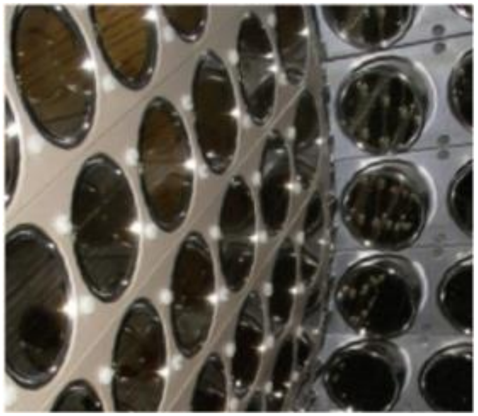
- Best energy resolution
- Good linearity

Disadvantages:

- Expensive
- Limited segmentation

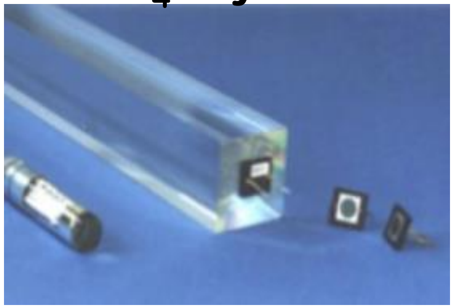
Example:

- CMS ECAL
- MEG ECAL



MEG:
Liquid Xenon
+ PMTs

CMS:
$PbWO_4$ crystals



Electromagnetic shower

Dominant processes at the high energies (E > few MeV)

Photons: pair production

$$\sigma_{\rm pair} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$

$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

Absorption coefficient:

$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\rm pair} = \frac{7}{9}\frac{\rho}{X_0}$$

X_0: radiation length [g/cm^3]

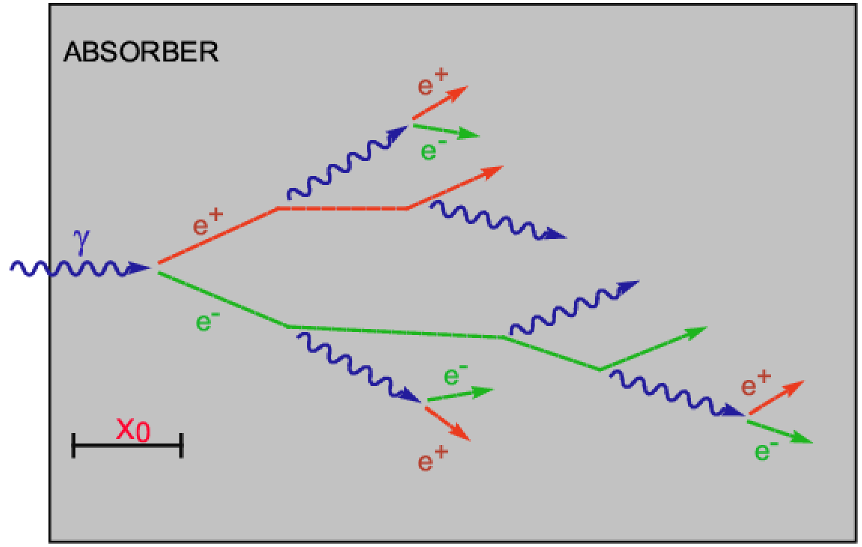
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}}$$

Electrons: Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A}r_e^2\cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

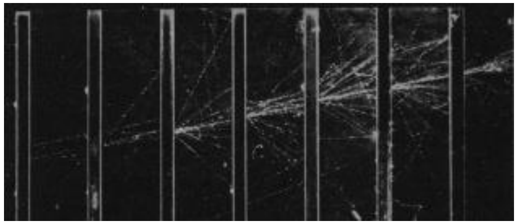
$$\rightarrow E = E_0 e^{-x/X_0}$$

After passage of one X_0 electron has only (1/e)$^{\rm th}$ of its primary energy ...
[i.e. 37%]



Analytic shower model

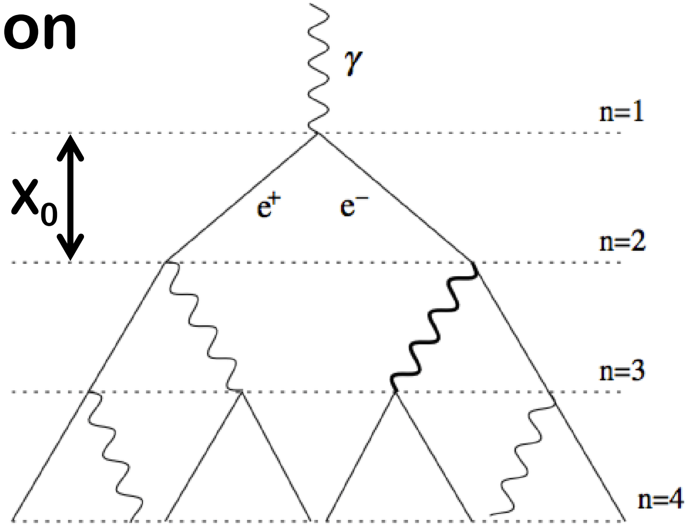
An alternating sequence of interactions creates a cascade



Simplified shower model [*Heitler*]:

- $E > E_c$: shower development governed by X_0
  - e^- loses energy 63% of energy in 1 X_0 via Bremsstrahlung
  - γ pair production with mean free path 9/7 X_0
- N. particle doubles every X_0 of material
- Energy reduced by 2 @ each iteration
- Shower stops if $E < E_c$
- Number of particles $N = E_0/E_c$
- Maximum @ $n_{max} = \ln(E_0/E_c)/\ln 2$

$$E_c = \frac{610\ MeV}{Z + 1.24}$$



Signal generation

- A particle deposits its **full energy** in the calorimeter media
- The energy is converted into a **measurable signal** (charge / light / sound / heat)

The most used materials are:

- **Semiconductors**: dE/dx or photon absorption + **drift of e-h**
  eV per e-hole pair
- **Gases**: dE/dx or photon absorption + **charge diffusion**
  20-40 MeV per e-ion pair
- **Scintillators**: dE/dx or photon absorption + **light emission**
  400-1000 eV per photon

Generated charges or photons yields the measurable signals

Energy resolution

The energy resolution is parametrized as

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2}$$

- **Stochastic term a**

  $E \propto N \rightarrow \sigma \propto 1/\sqrt{N}$: all statistical effects contribute (intrinsic statistical shower fluctuations, sampling fluctuations, signal quantum fluctuation)

- **Noise term b**

  Electronic noise, radio-activity, pile-up fluctuations (relevant at low energy)

- **Constant term c**

  Inhomogeneities, calibration uncertainties, radiation damage (dominant at high energy)

Outline

- Calorimeter principles
- **Scintillation & Photodetectors**
- The Mu2e calorimeter
- Conclusions

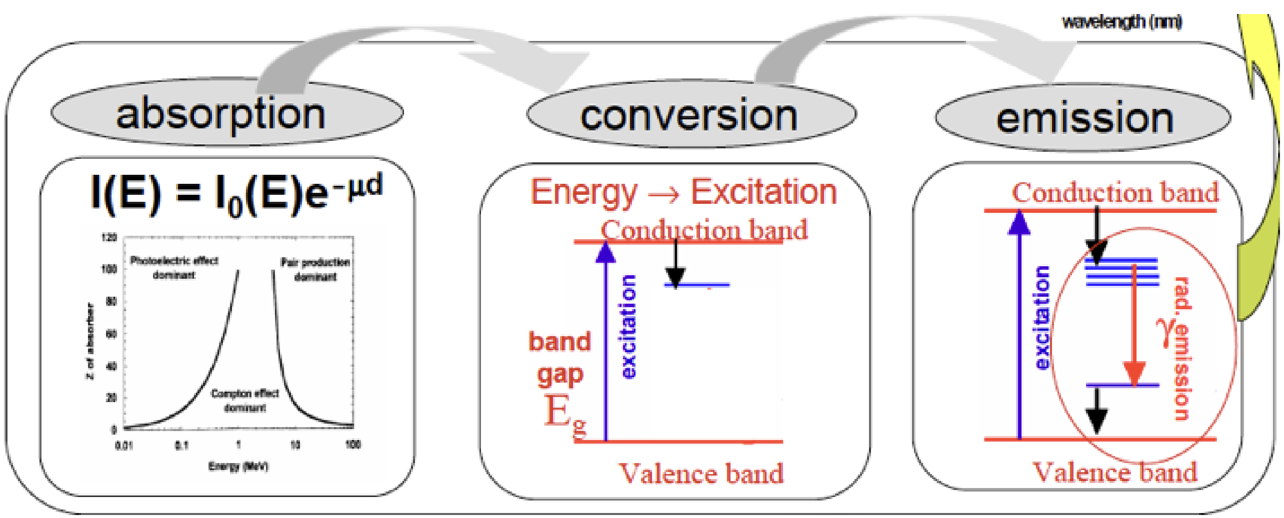
Scintillation process

A charged particle crossing a scintillator loses energy, exciting atoms or molecules of the material

→photon emission (UV-visible) follows

Light emission:

- **Can be instantaneous (<10^{-8} s) or delayed (ms to hours)**
- **Has one or two exponential decay time t_D (fast, fast/slow)**



$\lambda_{em} > \lambda_{ex}$

Scintillators: characteristics

- **Light Yield** (LY): number od photons produced for a given absorbed energy
- **Transparency** to the emitted radiation
- **Spectral emission** compatible with light detectors (photo sensors), where light is collected and then converted into electrons via photoelectric effect
- **Linearity of response**
- **Time response**
- **Density**, X_0

Types of scintillators

- **Organic scintillators**

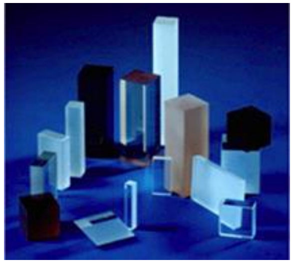
  Complex organic molecules where UV light is emitted after excitation of molecular levels. Other molecules are then added to transfer light into visible radiation

  - Fast emission time (2.5-10 ns)
  - Low scintillation efficiency (< 2k photons /MeV)
  - Low density (1 g/cm^3)
  - Can be easily machined to any shape (fibers)

- **Inorganic scintillators**

  Crystals, usually doped with impurities uniformly dispersed throughout the crystal lattice

  - High scintillation efficiency (10-70 k photons /MeV)
  - Slow emission time (100-600 ns)
  - High density (4-7 g/cm^3)



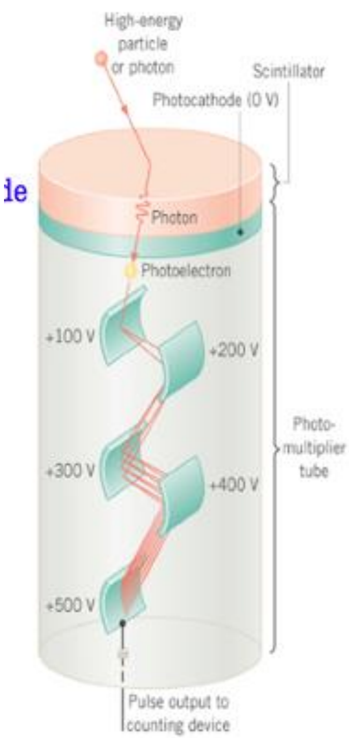
Detecting the light: photosensors

Light is guided to a photo-detector and converted into charge:

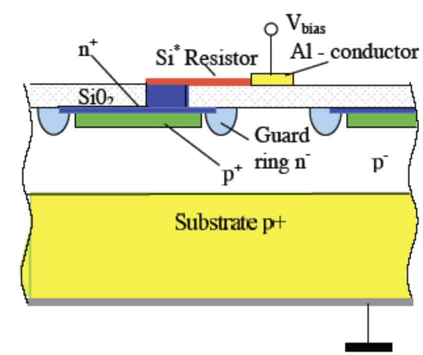
- **Conversion of a photon into electrons** via photo-electric effect
- **Amplification of the electron signal** by factor $10^5 – 10^6$ via secondary emission on dynodes or avalanche multiplication in silicon

Photo-detector requirements:

- Cover a large range of wave lengths (UV to IR)
- Good efficiencies (single photon detection possible)
- Cover large active areas



Source: Cutnell and Johnson, 7th edition image gallery



Silicon photosensors

A silicon photo-sensor is a reverse Silicon N-P junction with a photo sensitive layer where 'photo electrons' are extracted

The reverse bias helps to create a large depleted region and reduces to negligible values the 'dark current', i.e. the current seen with any signal in input

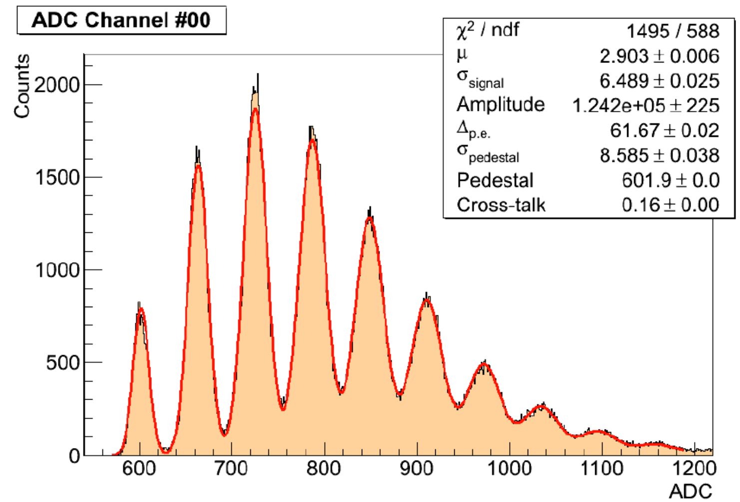
Three work regimes:

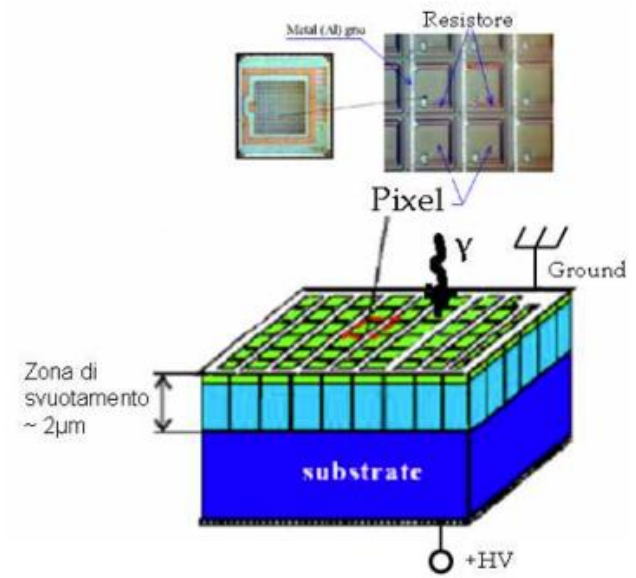
- Photodiode (G=1): all e- produced in the photosensitive layer are collected at the anode
- APD (G=50-2000), or Avalanche Photodiode, working in proportional regime
- Geiger APD ($G=10^5$-10^6) working in Geiger mode

Silicon Photomultipliers (SiPM)

The basic SiPM element (pixel) is a combination of Gaiger-APD and quenching resistor

- **A large number of pixels are electrically connected and arranged in two dimension**
- **Each pixel generates a pulse of the same amplitude when it detects a photon**
- **The output signal from multiple pixels is the superimposition of single pixel pulses**





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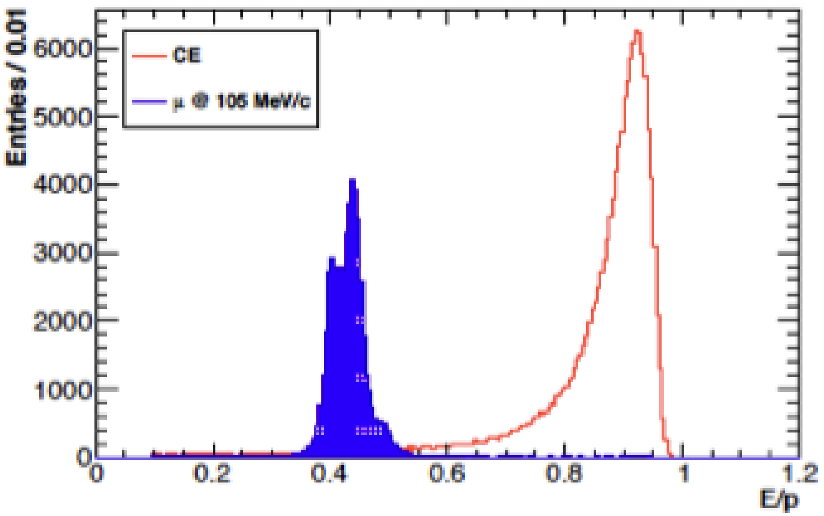
- **The Mu2e calorimeter**
- Conclusions

Calorimeter requirements

The electromagnetic calorimeter should provide high acceptance for reconstructing energy, time and position of CEs for:

- PID: e/μ separation
- EMC seeded track finder
- Standalone trigger

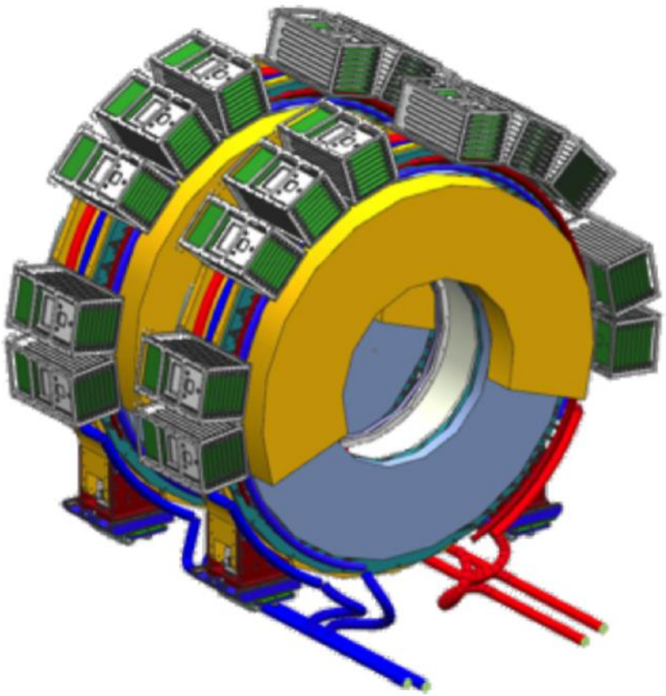


Requirements @ 105 MeV/c:

- $\sigma_E/E = O(5\%)$ for CE
- $\sigma_T < 500$ ps
- $\sigma_{X,Y} < 1$ cm

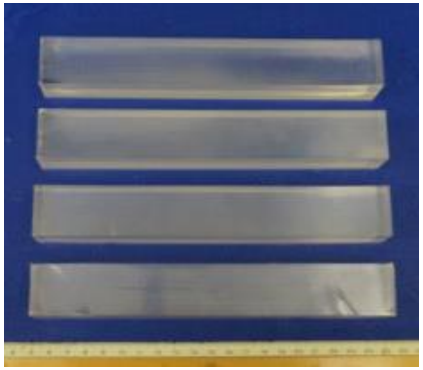
- Work in vacuum
- Survive the harsh radiation environment
- Limited access

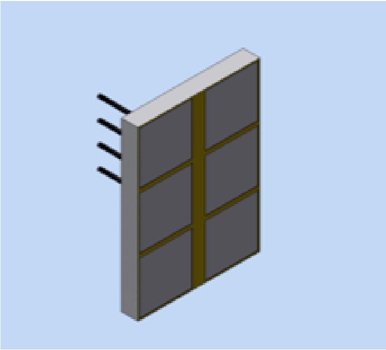
Calorimeter design



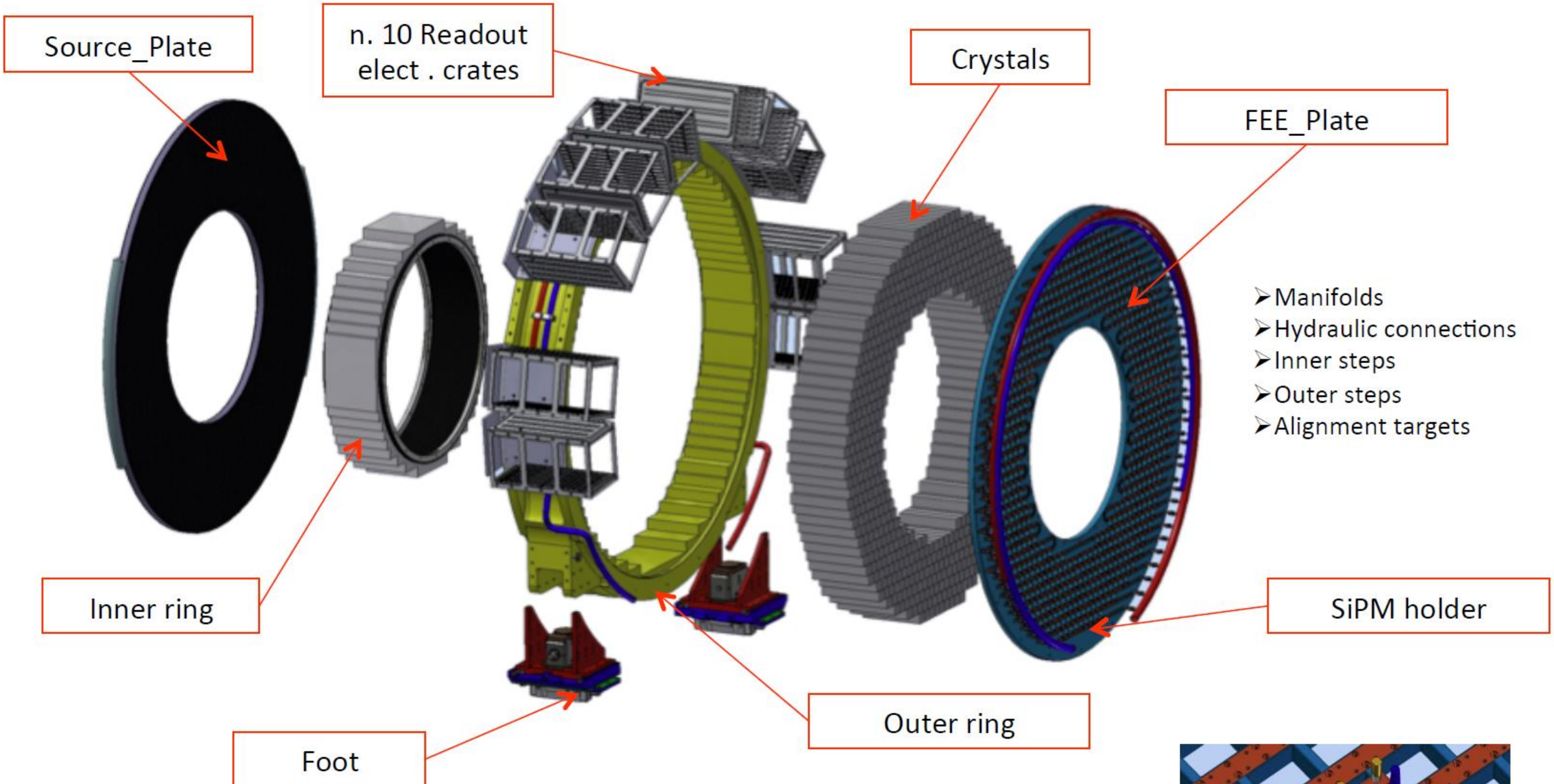
2 annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals/each disk

- R_{in} = 347 mm, R_{out} = 660 mm
- Each crystal is readout by two large area UV extended SiPM's (14x20 mm^2)
- Analog FEE is on the SiPM and digital electronics is located in near-by electronics crates
- Radioactive source and laser system provide calibration and monitoring capability



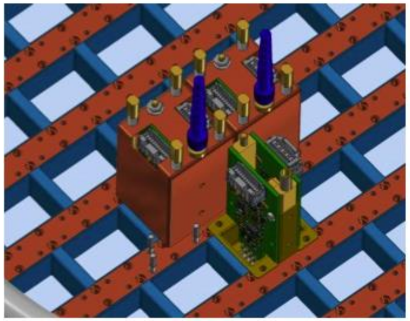


Engineering design

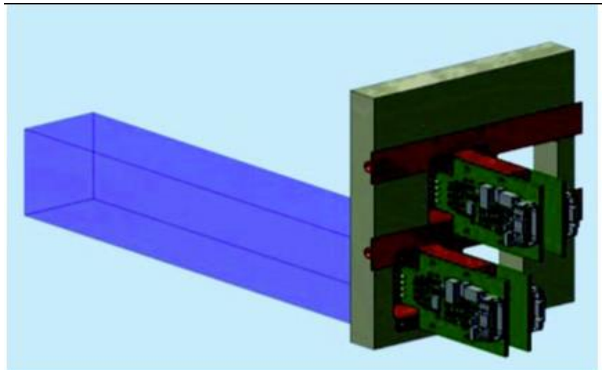


- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets

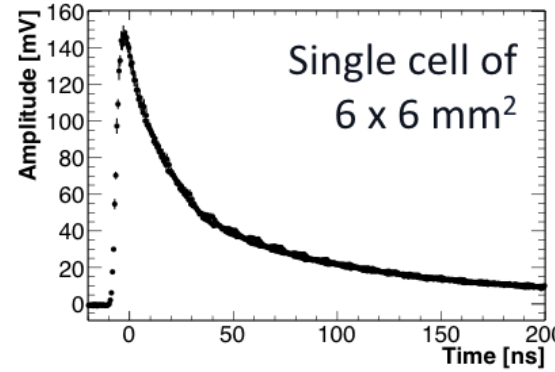
Zoom of SiPM/FEE disk and holders



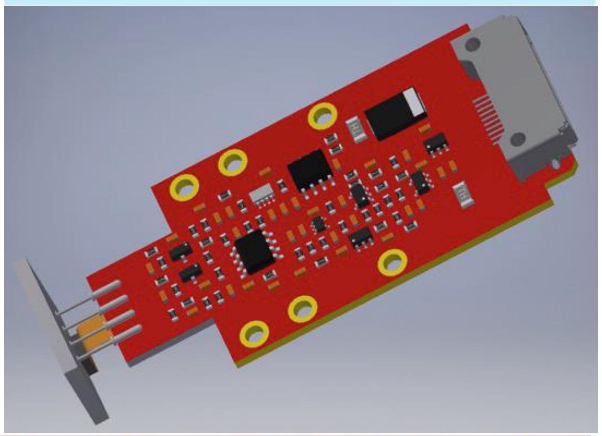
Calorimeter readout electronics



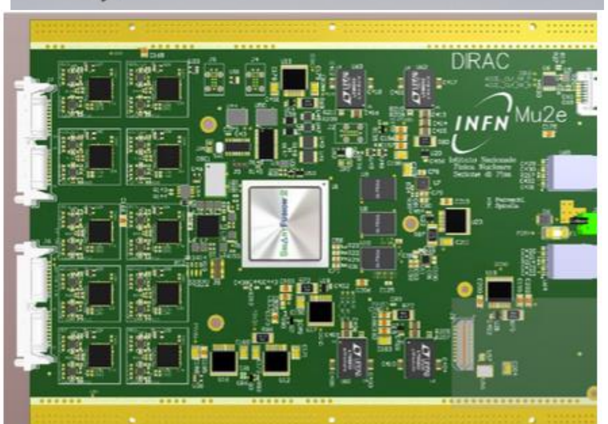
2 SiPM/crystal
1 FEE board/array



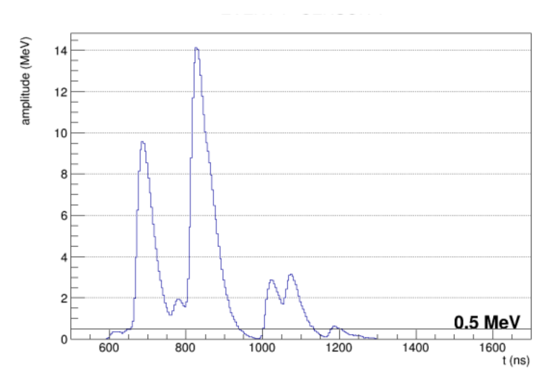
Decay time of the SiPM



FEE board:
- Amplification
- Shaping
- Voltage regulation



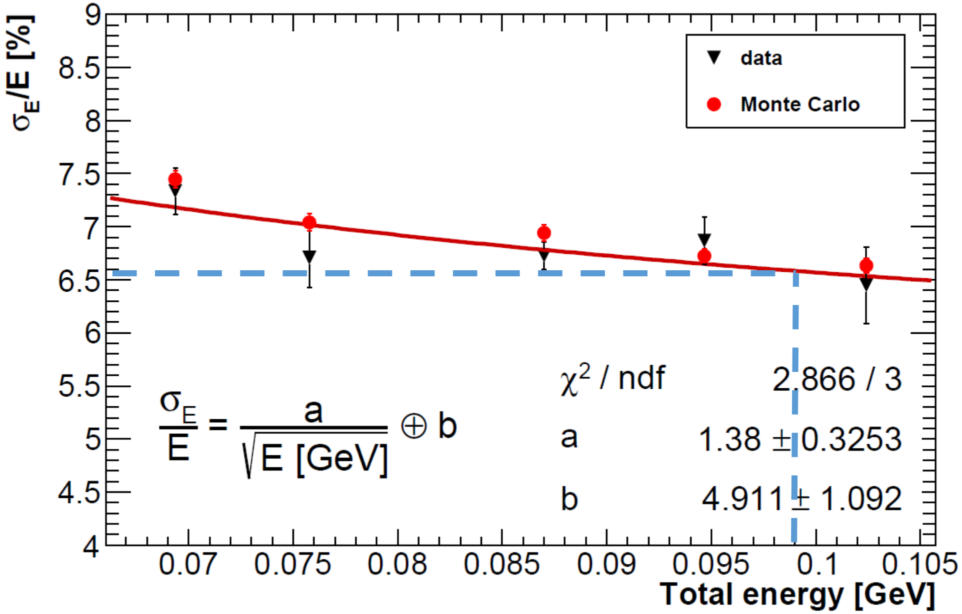
Waveform digitizer:
reads 20 channels at
200 MHz
(1 sample each 5 ns)

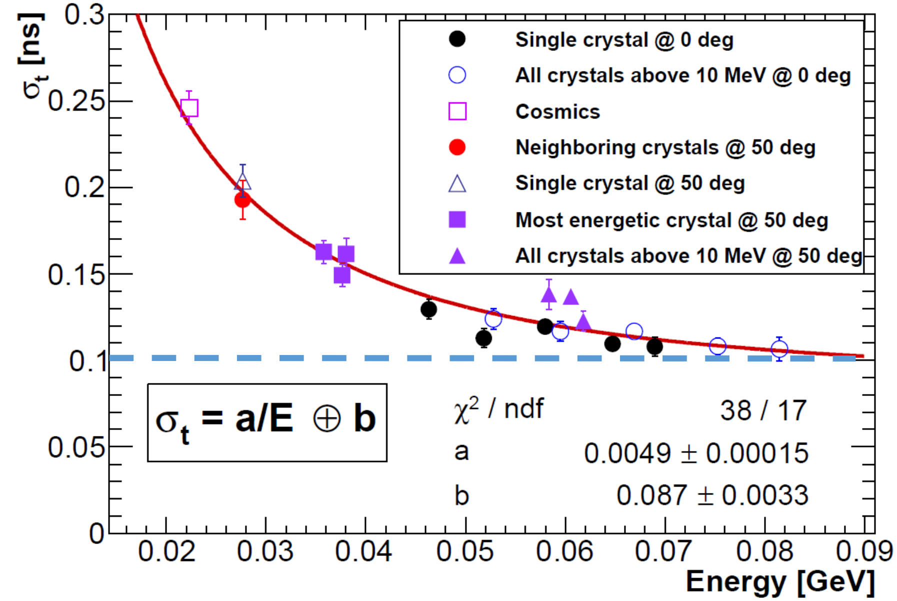


Example of front end output

Small prototype 3x3 tested @ BTF (Frascati) in April 2015, 80-120 MeV e⁻

JINST 12 (2017) P05007





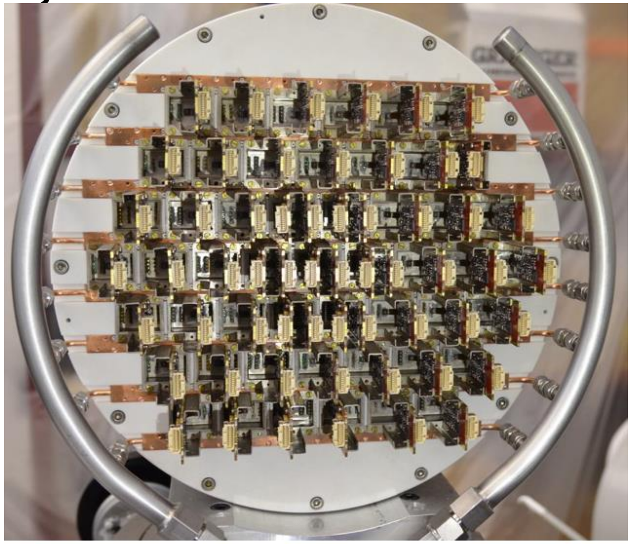
$$\sigma_E/_E \sim 6.5 \text{ @ } 100\ MeV$$

$$\sigma_T \sim 110\ ps \text{ @ } 100\ MeV$$

Significant leakage contribution due to block dimensions w.r.t. the shower

Module 0

Large ECM prototype: 51 crystals, 102 SiPM

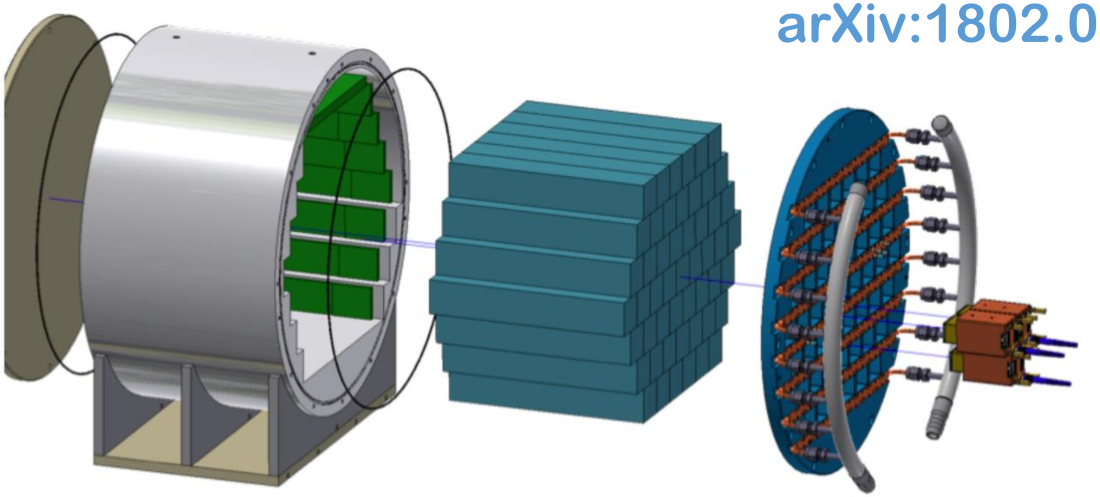


Mechanics and cooling system similar to the final ones!

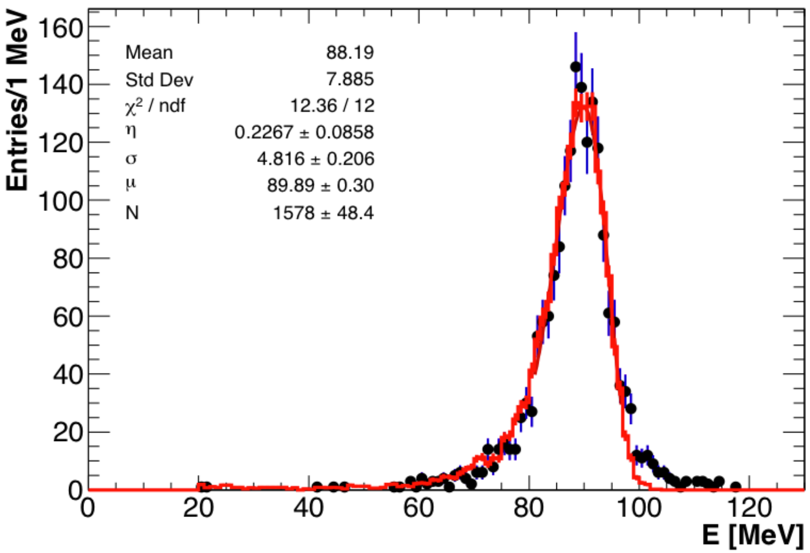
Goals:

- Integration and assembly procedures
- Test beam, 60 – 120 MeV
- Work under vacuum, low temperature, irradiation test

arXiv:1802.06346

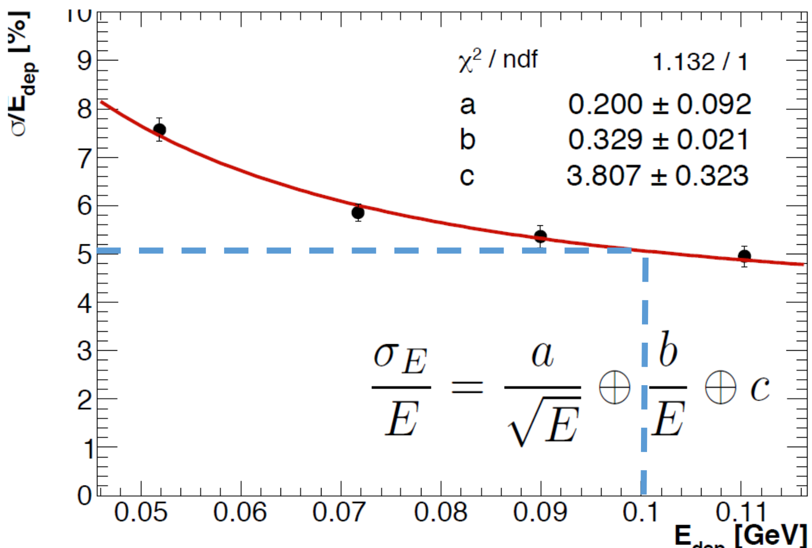


Module 0 - Results



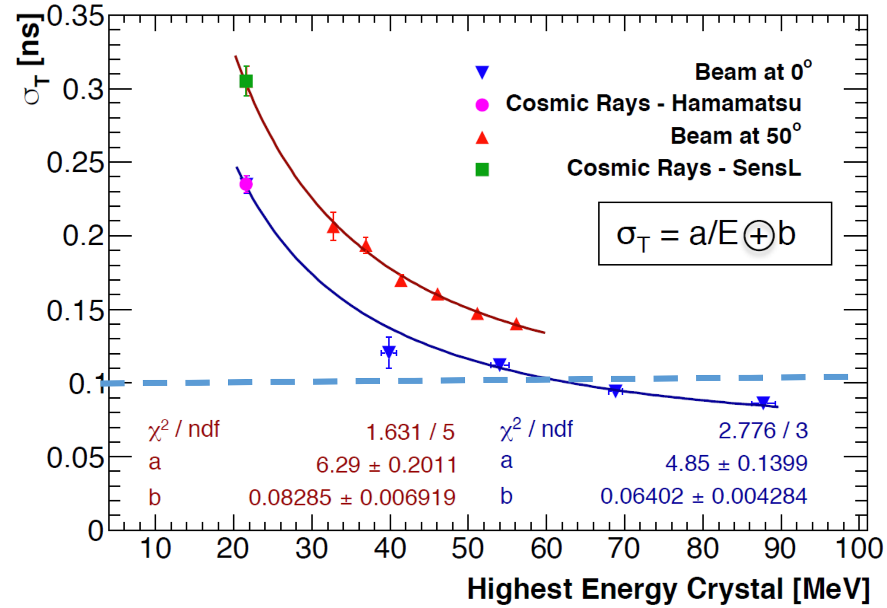
Energy distribution obtained summing up the charge of all calorimeter channels with an energy deposition above the noise threshold

Good agreement Data - MC



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

$\sigma_E/_E \sim 5\%$ @ $100\ MeV$



$\sigma_T < 100\ ps$ @ $100\ MeV$

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Conclusions

- **A calorimeter is essential in a particle physics experiment. Its function is to measure particle energy**

- **The energy deposited in the calorimeter is converted in a measurable signal (charge/light/sound/heat)**

- **A charged particle crossing a scintillator loses energy, exciting atoms or molecules of the material and a photon emission follows. A photo-sensor converts photons in electrons and amplifies the electron signal**

- **Mu2e calorimeter is a crystal calorimeter with excellent energy (5%) and timing (500 ps) resolution**

- **Mu2e calorimeter prototypes have been tested with e^- beam → good time and energy resolution achieved @100 MeV**

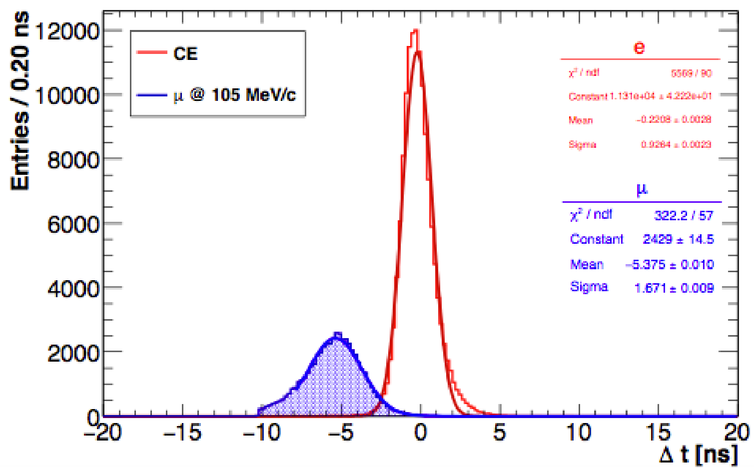
Spares

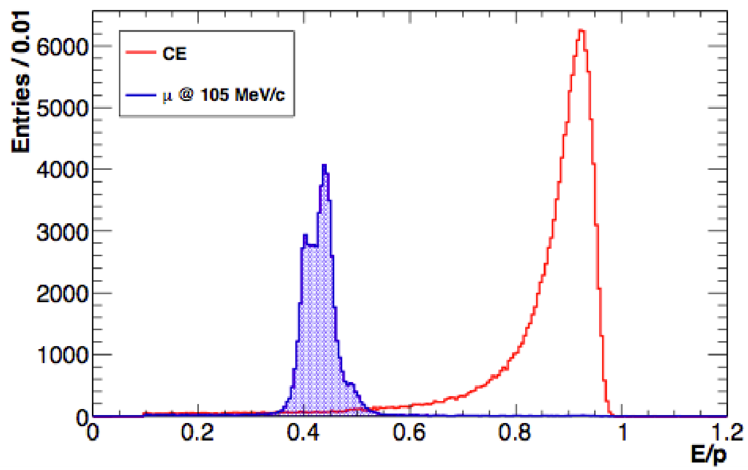
PID calorimeter-tracker – basic idea

$$\beta = \frac{p}{E} \sim 0.7 \qquad E_{kin} = E - m \sim 40\ MeV$$

Compare the reconstructed track and calorimeter information:

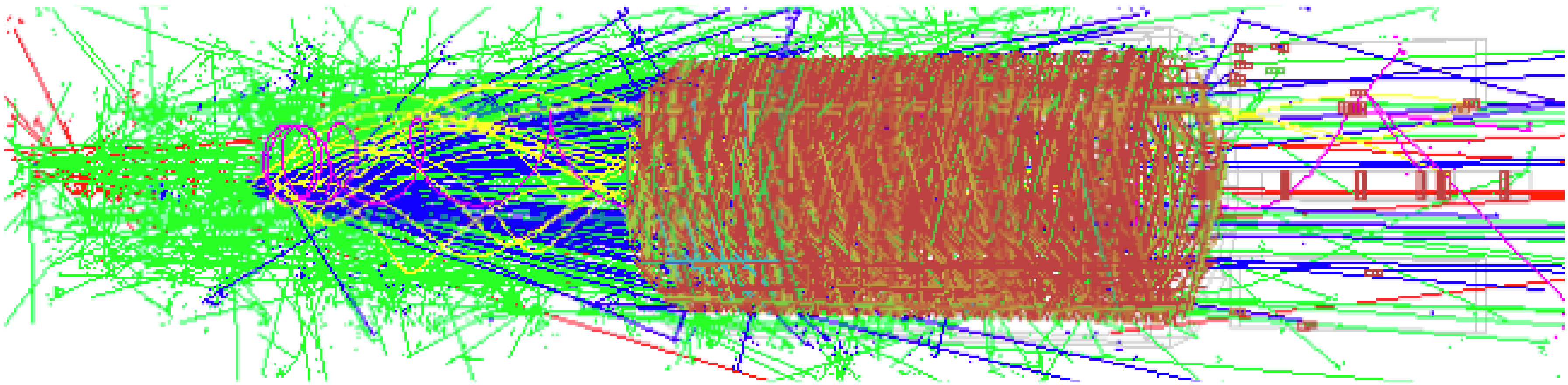
- **$E_{cluster}/p_{track}$ & $\Delta t = t_{track} - t_{cluster}$**
- **Build a likelihood for e^- e μ^- using distribution on E/p and Δt**

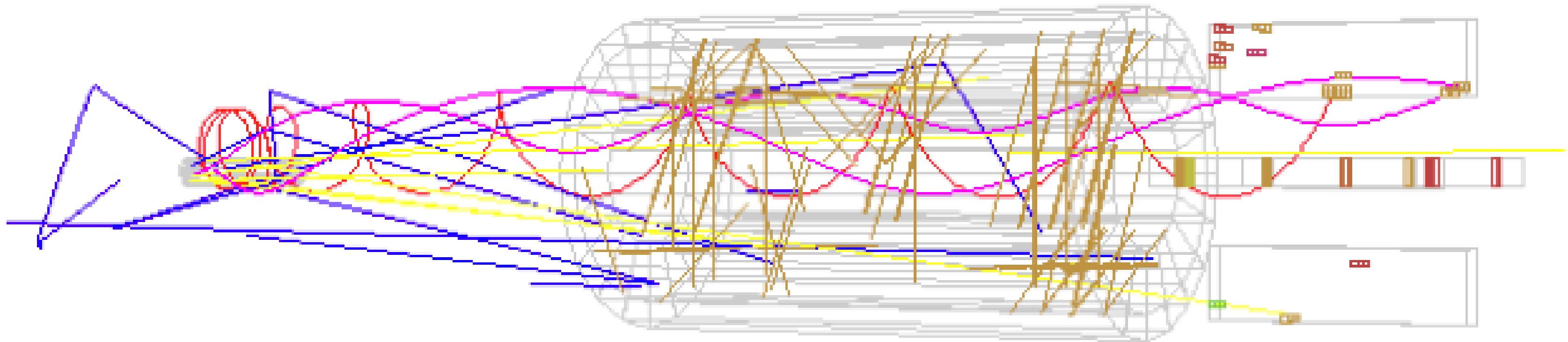




Very high efficiency (>95%) with rejection factor >200

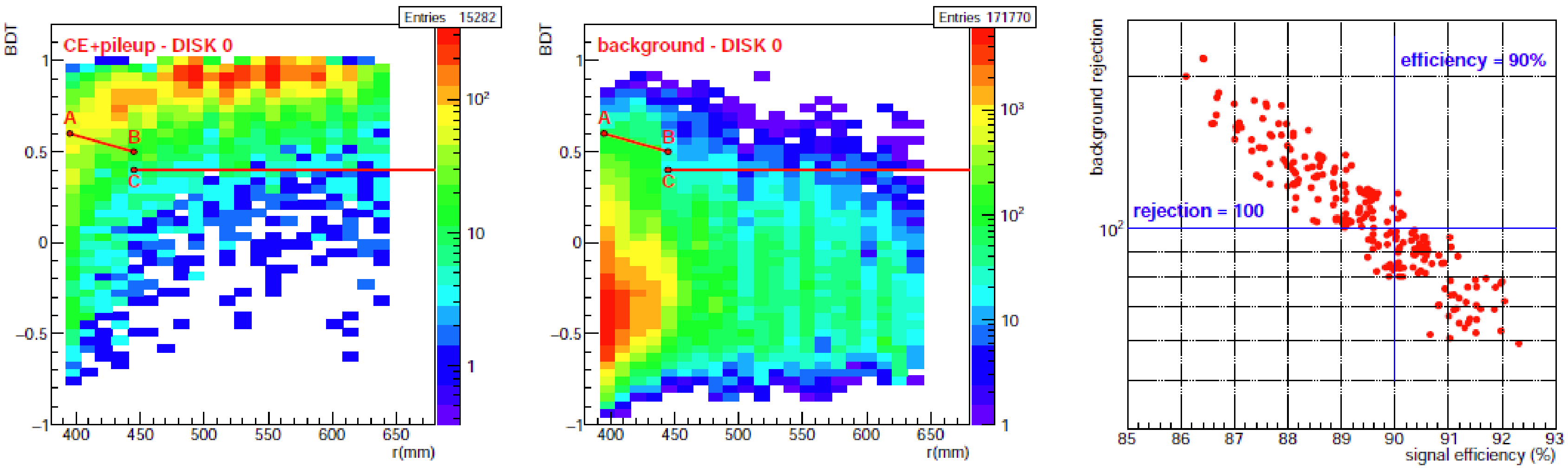
EMC based track seeding





The speed and efficiency of tracker reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta T| < 50$ ns) and azimuthal angle of calorimeter clusters → simplification of the pattern recognition

Calorimeter-based trigger



- **Acceptance > 90% of events with good tracks have a cluster E > 60 MeV**
- **Standalone calorimeter-based online trigger needed**
  - **Tracker momentum calibration (i.e. $\pi \rightarrow e\ \nu$)**
  - **Measurement of tracking efficiency**
  - **DAQ storage limitations → 100 times reduction of background events**
  - **Fast algorithm**

Crystal Choice

	~~LYSO~~	~~BaF_2~~	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**R&D APD**	SiPM
Wavelength [nm]	402	**220**/300	310

LYSO

CDR

- Radiation hard, not hygroscopic
- Excellent LY
- Tau = 40ns
- Emits @ 420 nm,
- Easy to match to APD.
- High cost > 40$/cc

Barium Fluoride (BaF_2)

BASELINE-TDR

- Radiation hard, not hygroscopic
- very fast (220 nm) scintillating light
- Larger slow component at 300 nm. should be suppress for high rate capability
- Photo-sensor should have extended UV sensitivity and be "solar"-blind
- Medium cost 10$/cc

CsI(pure)

FINAL CHOICE

- Not too radiation hard
- Slightly hygroscopic
- 15-20 ns emission time
- Emits @ 320 nm.
- Comparable LY of fast component of BaF_2.
- Cheap (6-8 $/cc)

Mu2e SiPMs design

2 arrays of 3 6x6 mm² UV-extended SiPMs for a total active area (12x18) mm²

The series configuration reduces the overall capacity and allows to generate narrower signals