Recent Developments on Scintillating Crystal Fibers for Calorimetry Applications

13th Pisa Meeting on Advanced Detectors

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Outline

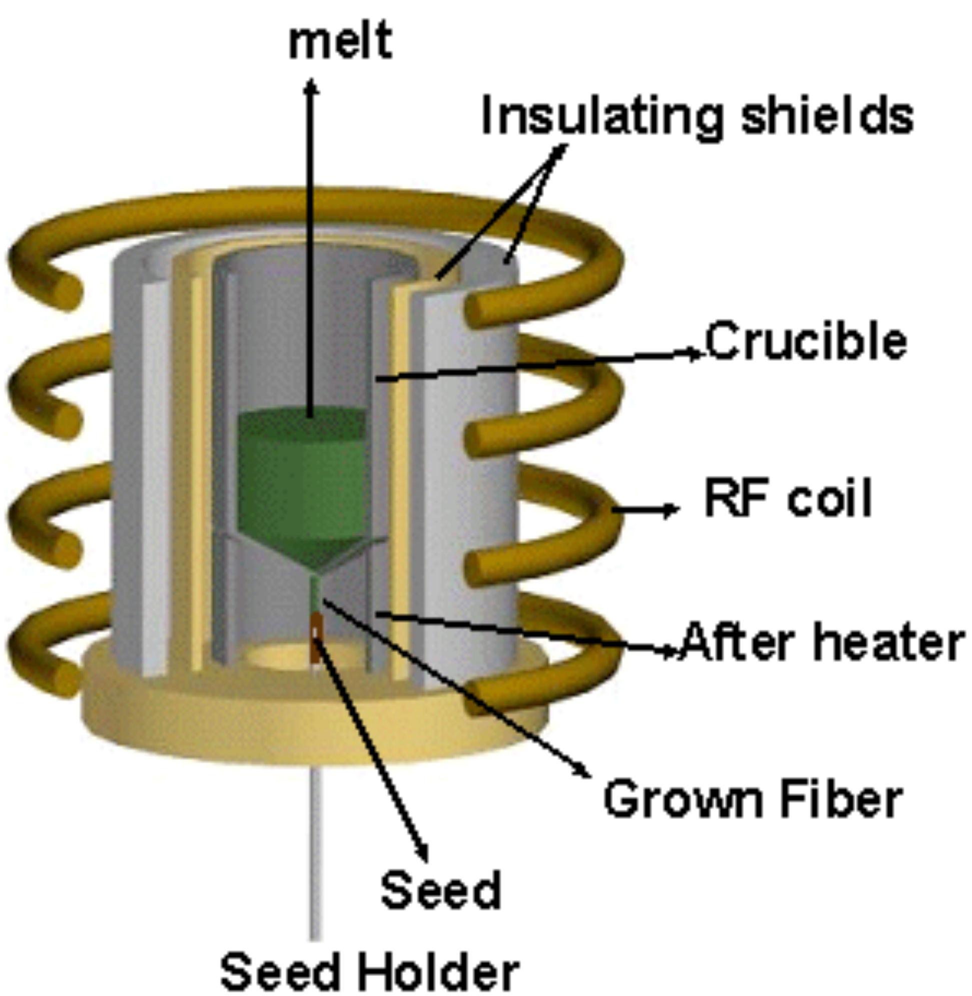
- Crystal fiber R&D: recent developments
  - LuAG:Ce: attenuation length, radiation hardness, co-doping
  - YAG:Ce crystals: attenuation length, radiation hardness
  - The need for radiation resistance and fast response

- Crystal fiber calorimeter prototypes for high-energy physics
  - the beam test at FNAL
  - the beam tests at CERN

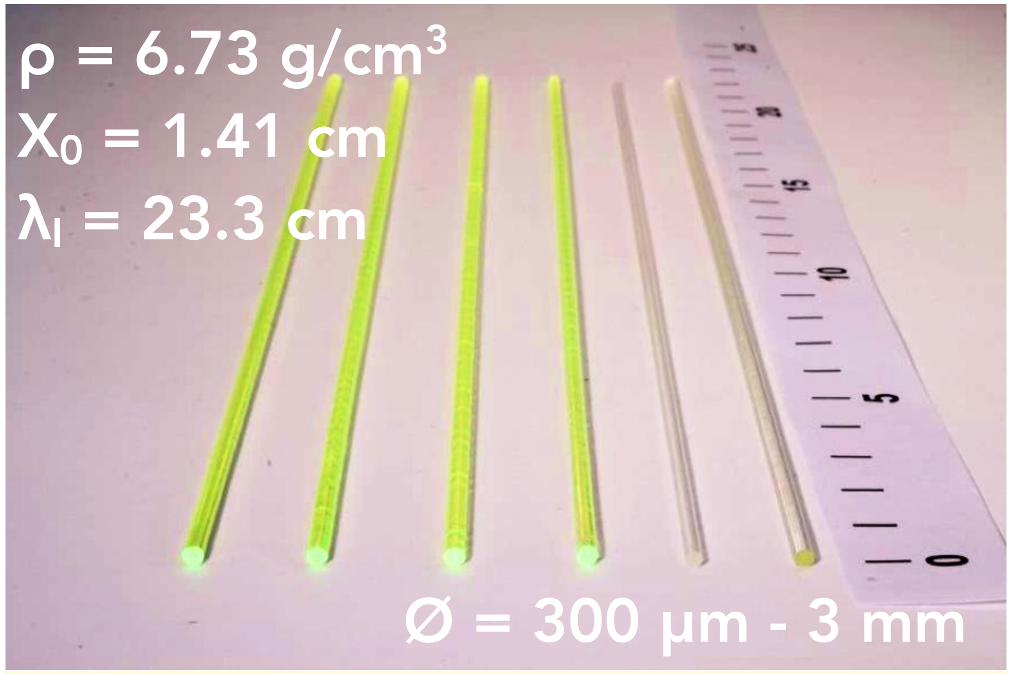
Crystal fiber R&D:
recent developments

LuAG fibers grown with μ-PD technique

- A lot of effort was spent to improve the quality of the fibers
  - **fiber growth parameters** have been widely **studied** to **improve** the **light attenuation** and the **homogeneity** of the light output



$Lu_3Al_5O_{12}$



E. Auffray et al., NSS 2009 p2245

E. Auffray et al., TNS 2010 57 (3) p1454

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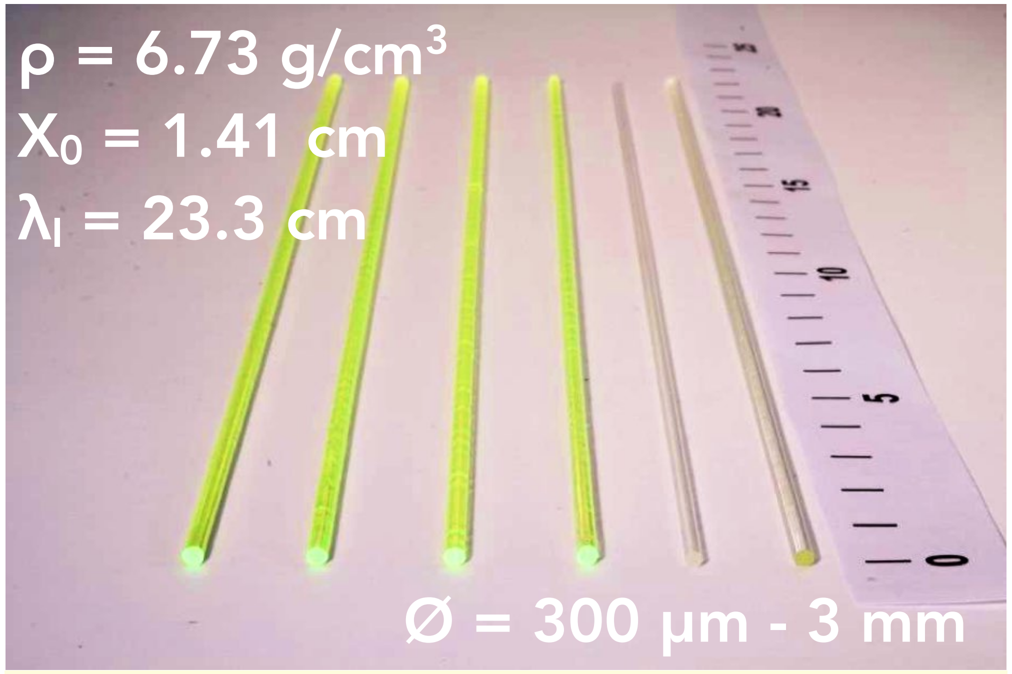

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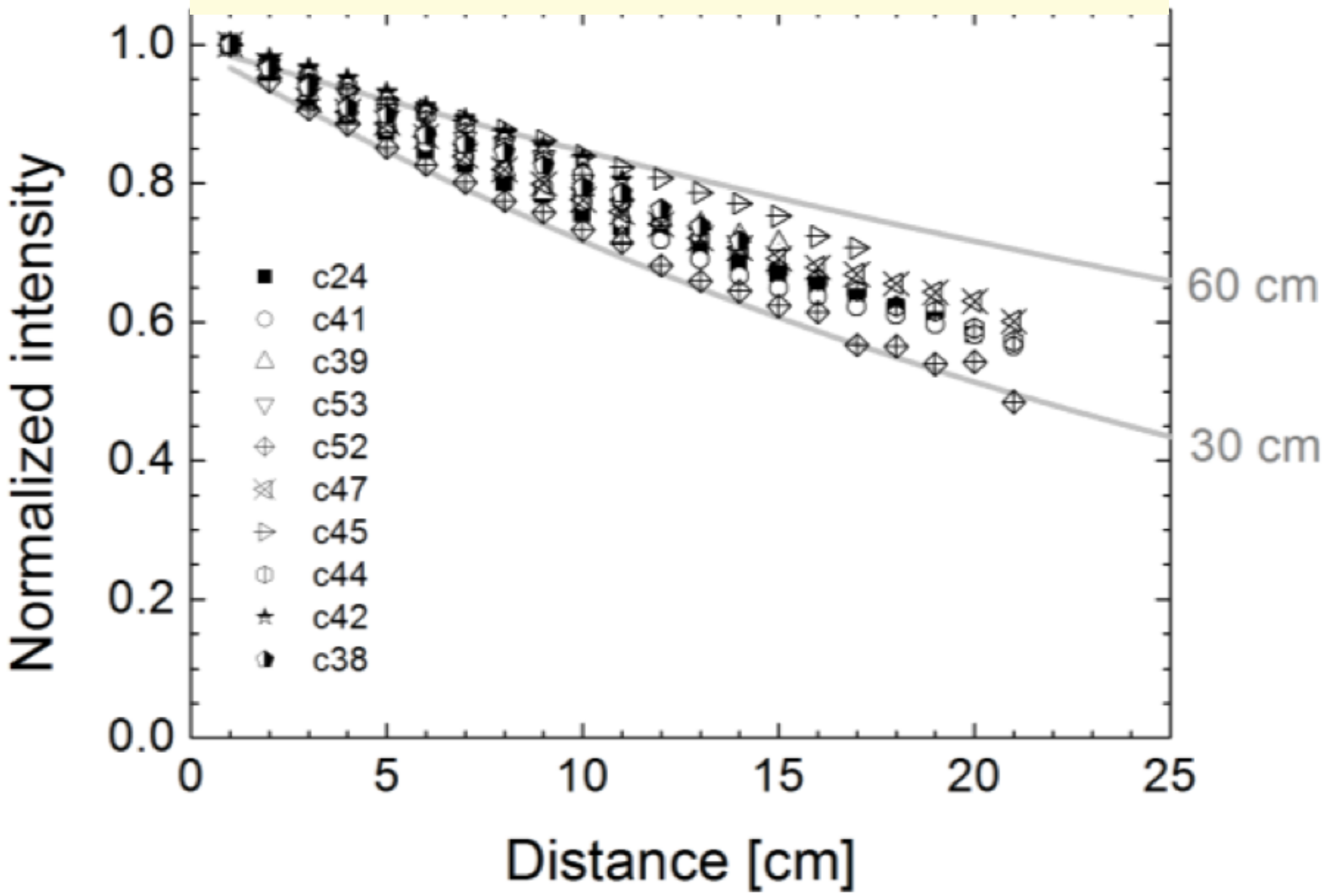
Pauwels et al. JINST 8 P09019 (2013)



good optical quality and reproducibility of fibers can now be achieved

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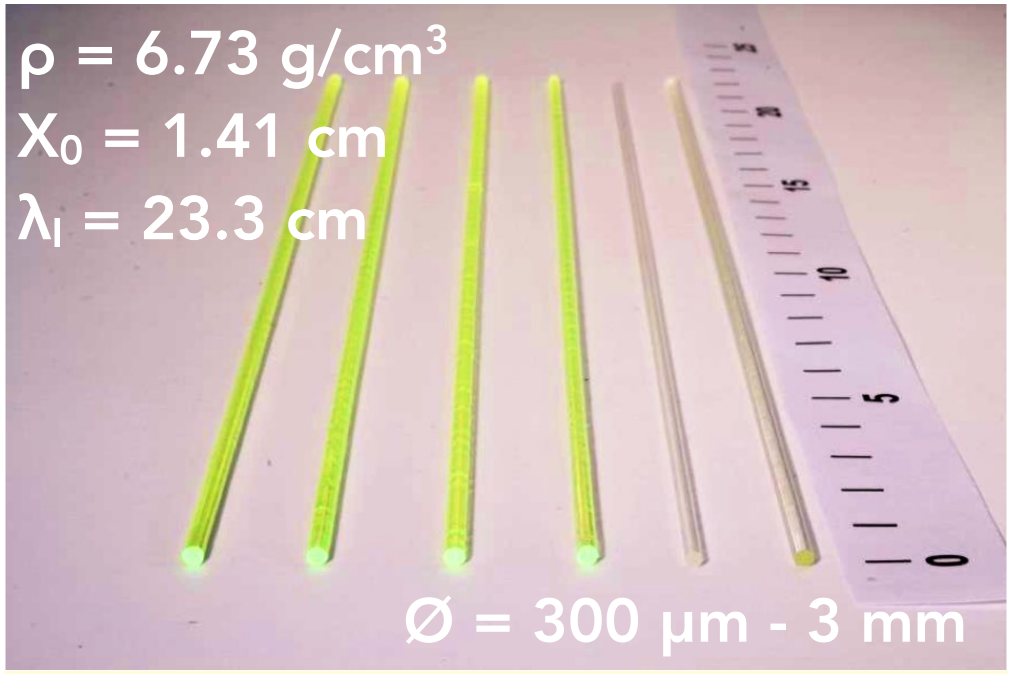

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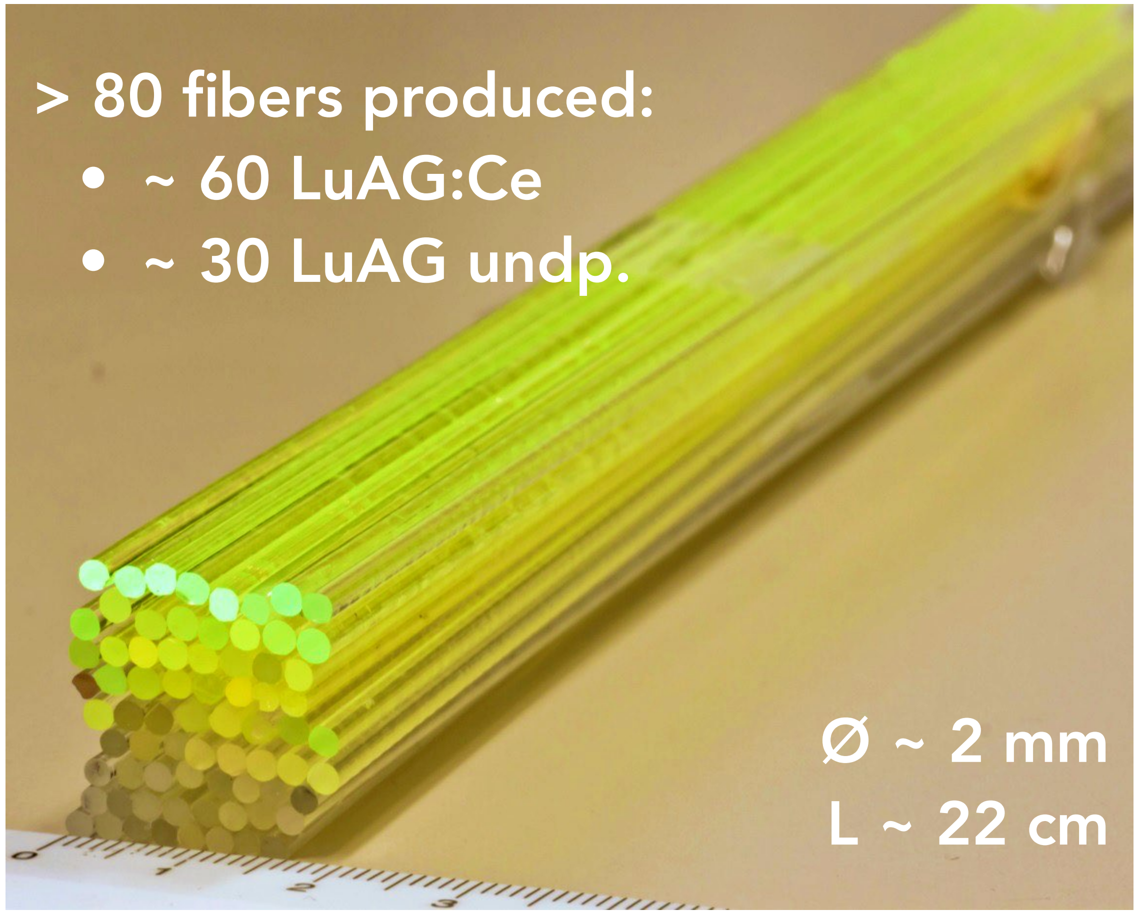
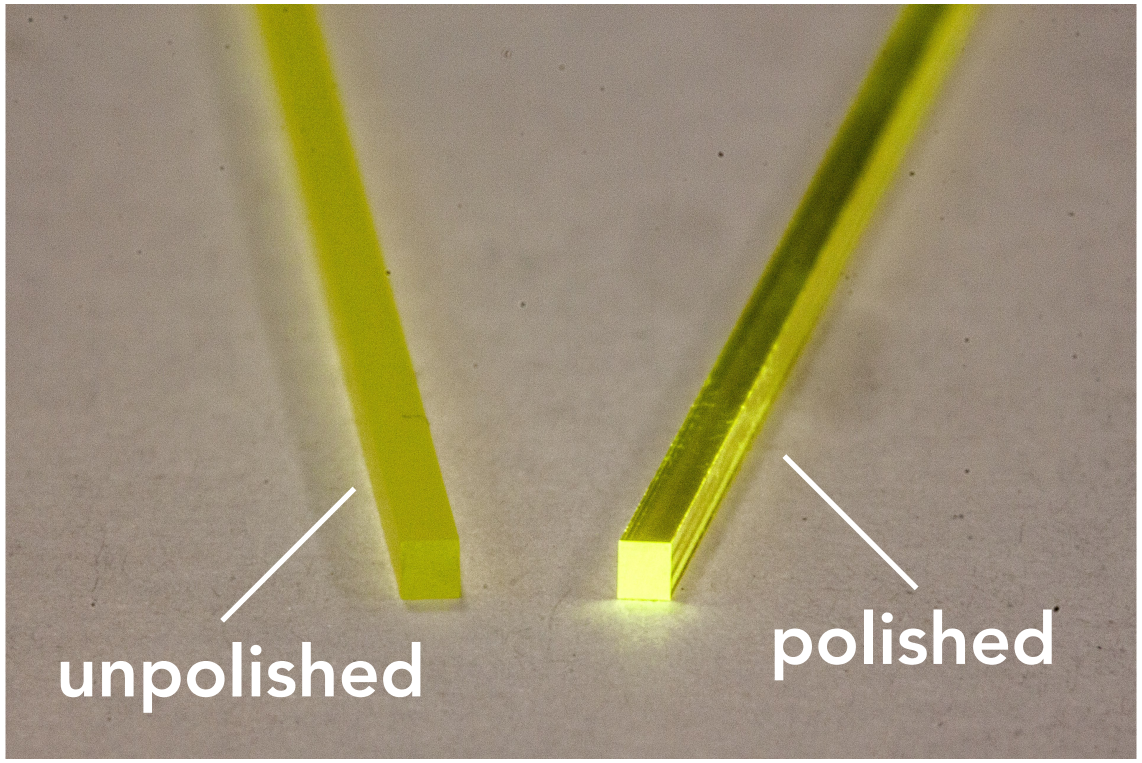


large production achieved

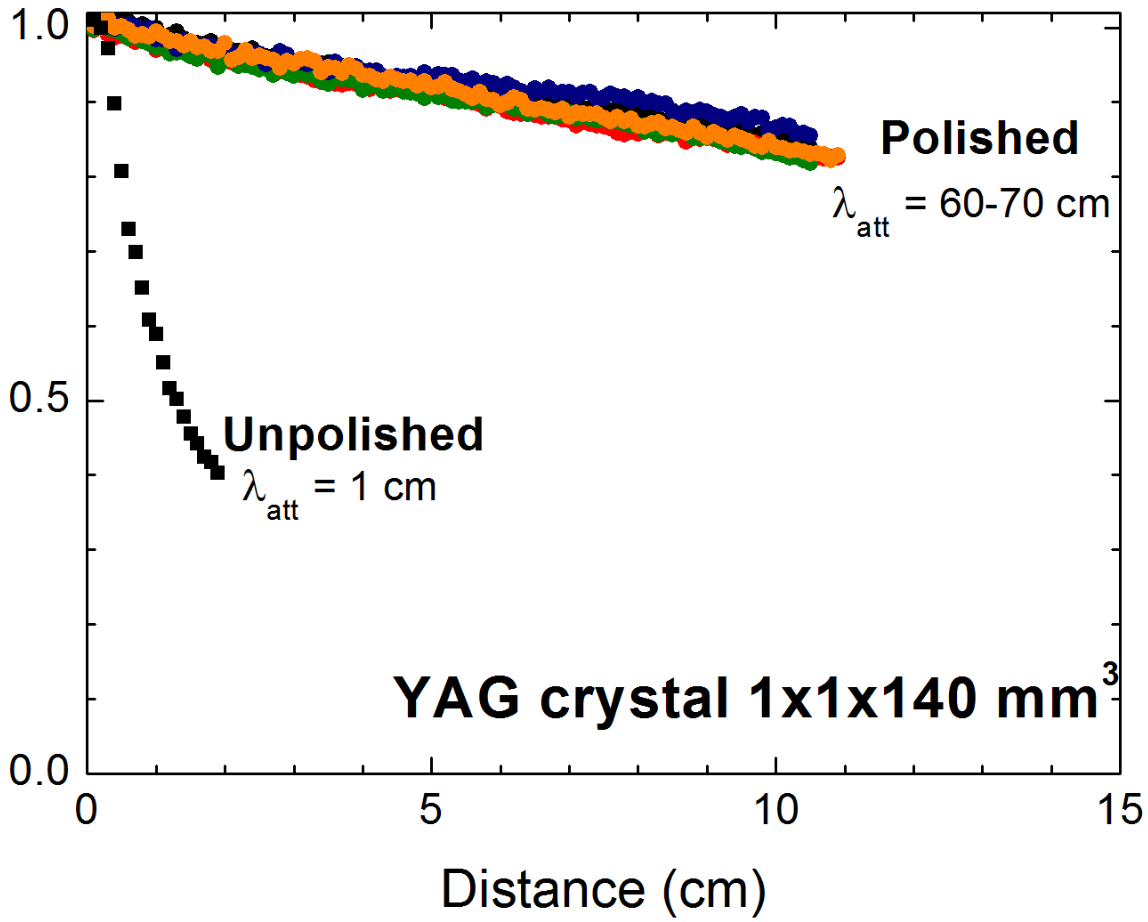
- originally produced by **University Lyon (ILM)**
- technology transfer to **commercial company (Fibercryst)**

YAG fibers grown with Czochralski method

- Square, 1x1x140 mm^3 crystal fibers **cut and polished** from standard Czochralski ingots by **Crytur**
- Promising alternative:
  - **very good optical quality** from the central part of the ingot
  - expected to be **rad-hard** (more in slide 12)
  - production **costs competitive** with μ-PD



attenuation length



The challenges for HL-HLC:
fast response and radiation resistance

- The **extension** of the **LHC** physics program until **2035** has recently been approved
  - proton **interaction rate** up to **7 times larger** than in 2012

- The **operating regime** of the new **High-Luminosity HLC**…

…will require **major upgrades** for the **CMS forward calorimeters** (~2022)

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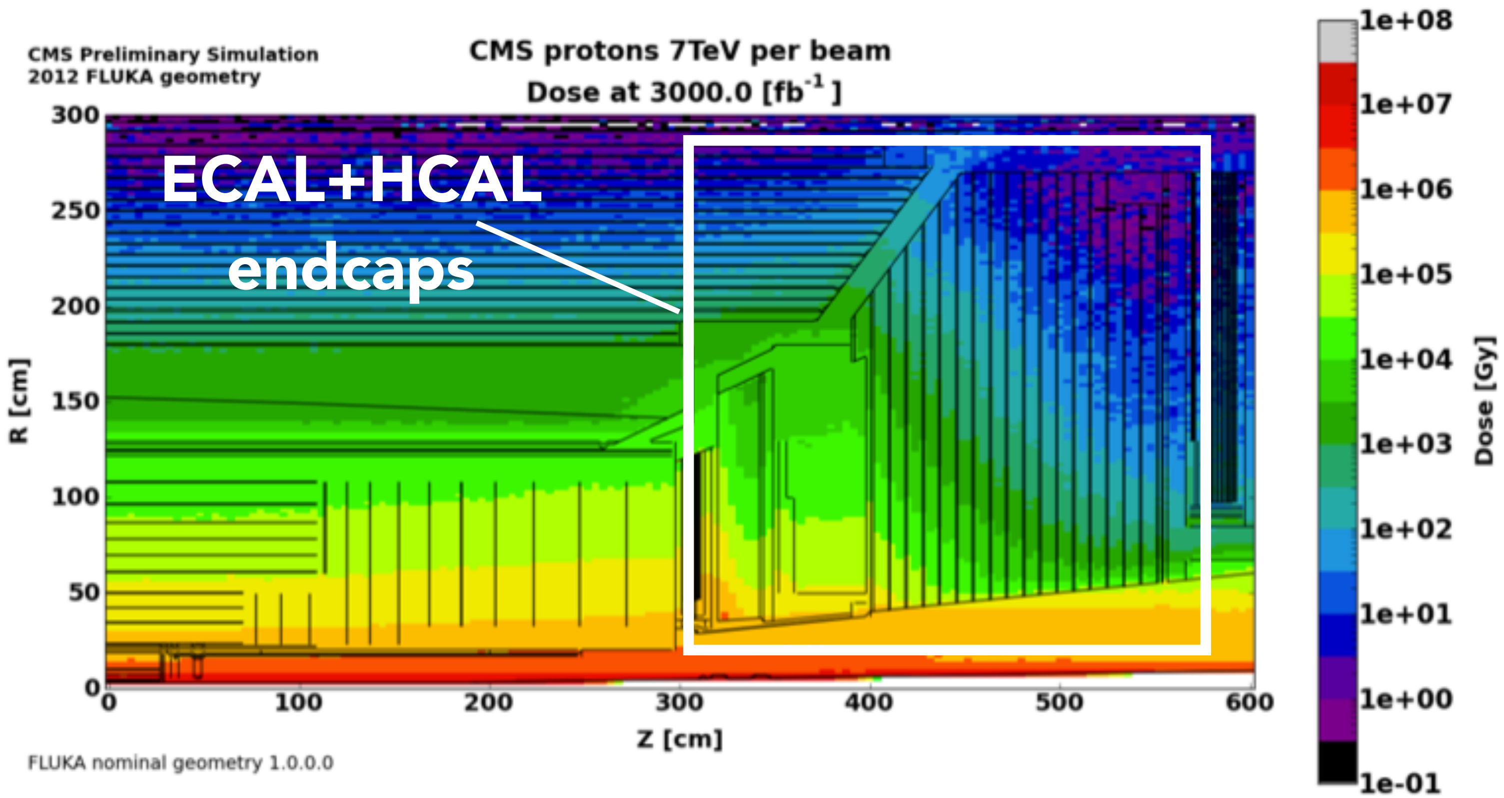
Radiation hardness



high radiation levels:

- ionizing radiation dose up to **~1 MGy**
- charged hadron fluences up to $\mathbf{2 \cdot 10^{14} cm^{-2}}$

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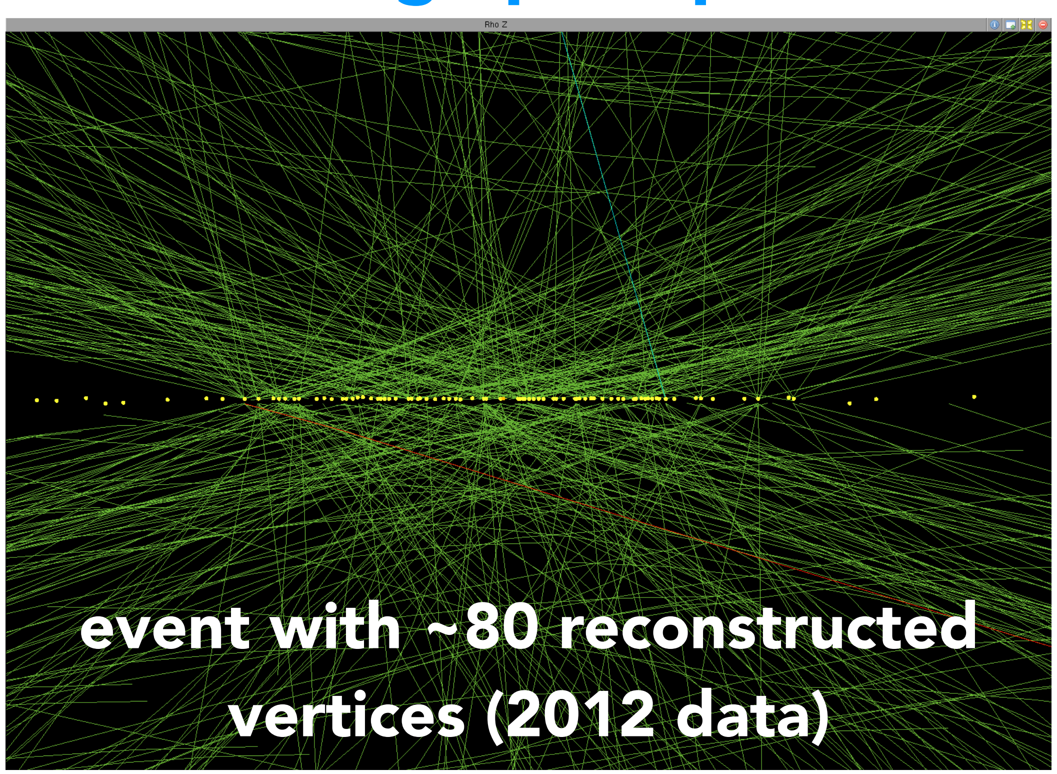
High pile-up

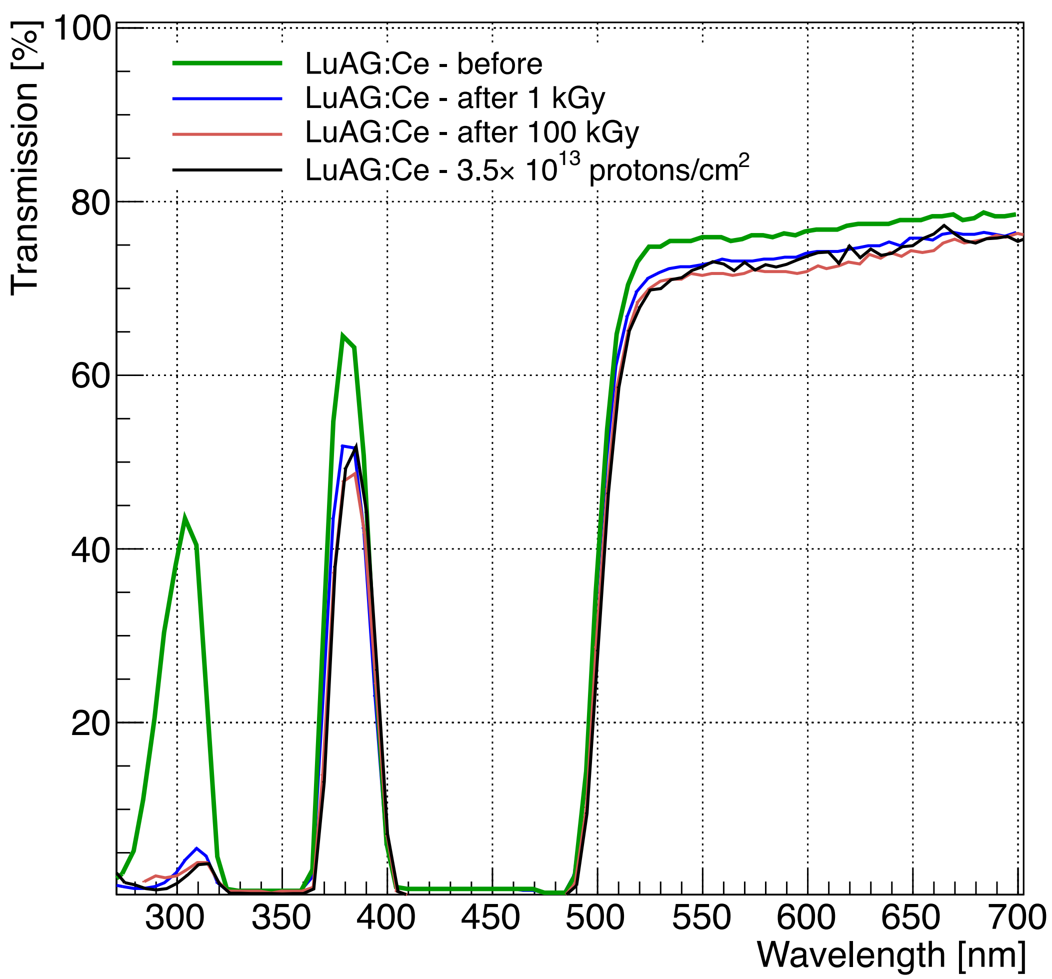


- **fast time response**
  to resolve different vertices
- i.e. scintillator decay time
  $\lesssim$ **25 ns**

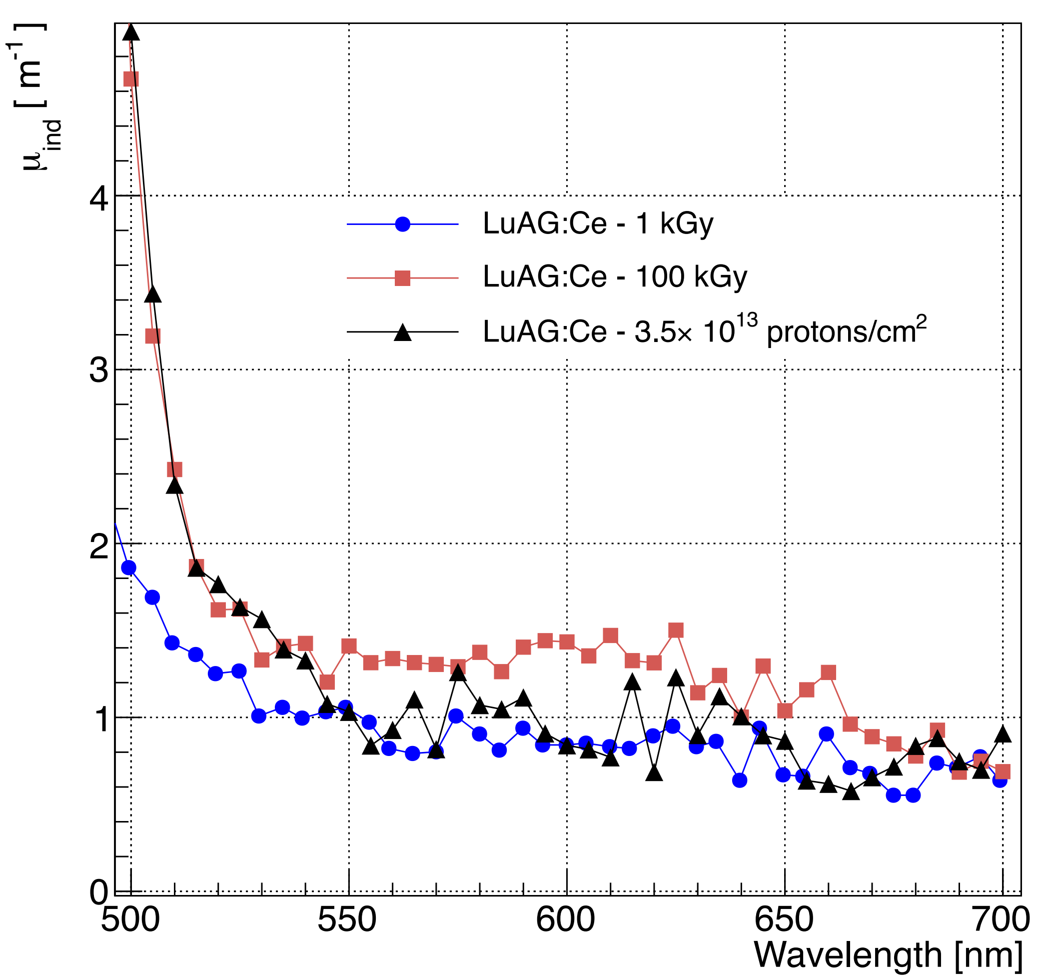
Promising radiation resistance in LuAG

- LuAG bulk material irradiated with gamma (1 kGy and 100 kGy) and protons ($3.5 \cdot 10^{13}$ protons/cm^2)
  - $0.8 \times 0.8 \times 4.2$ cm^3 samples
- Transparency loss observed to saturate after 1 kGy

transmission



μ induced

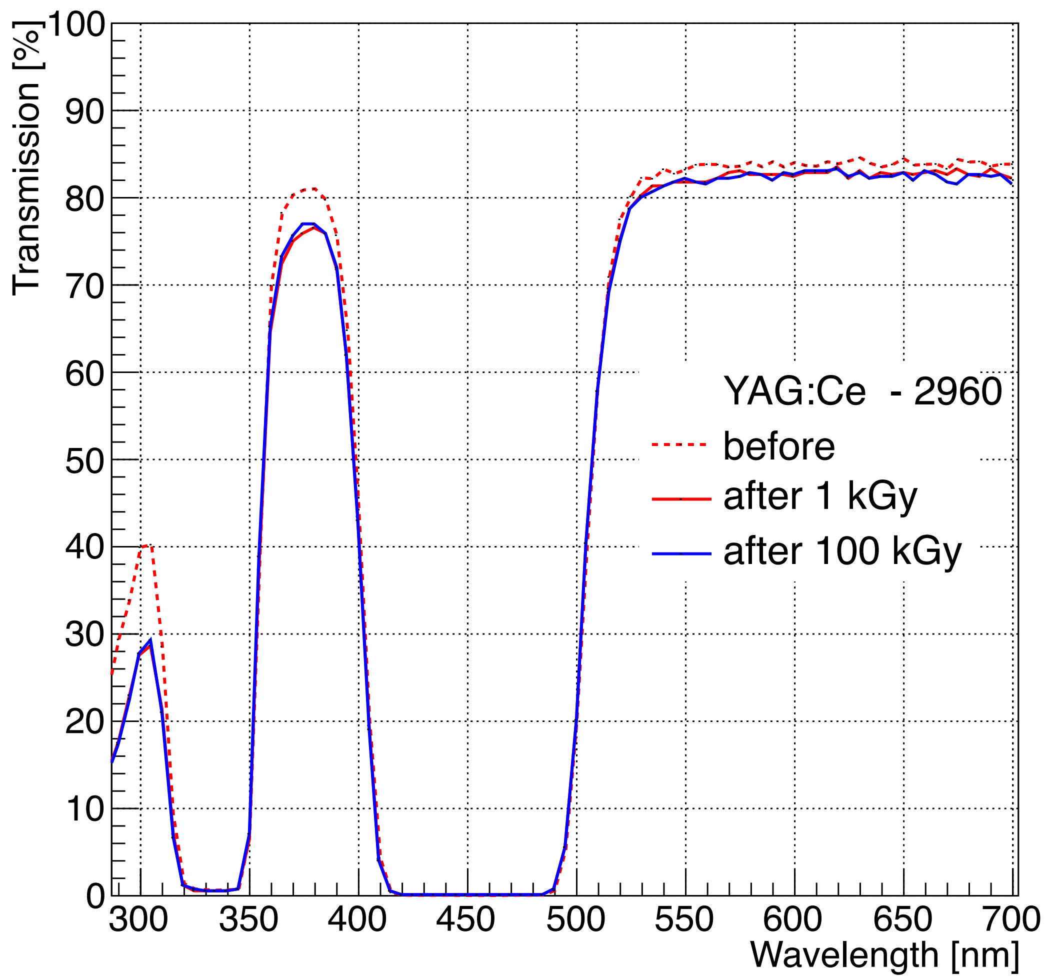


Very good radiation resistance of YAG

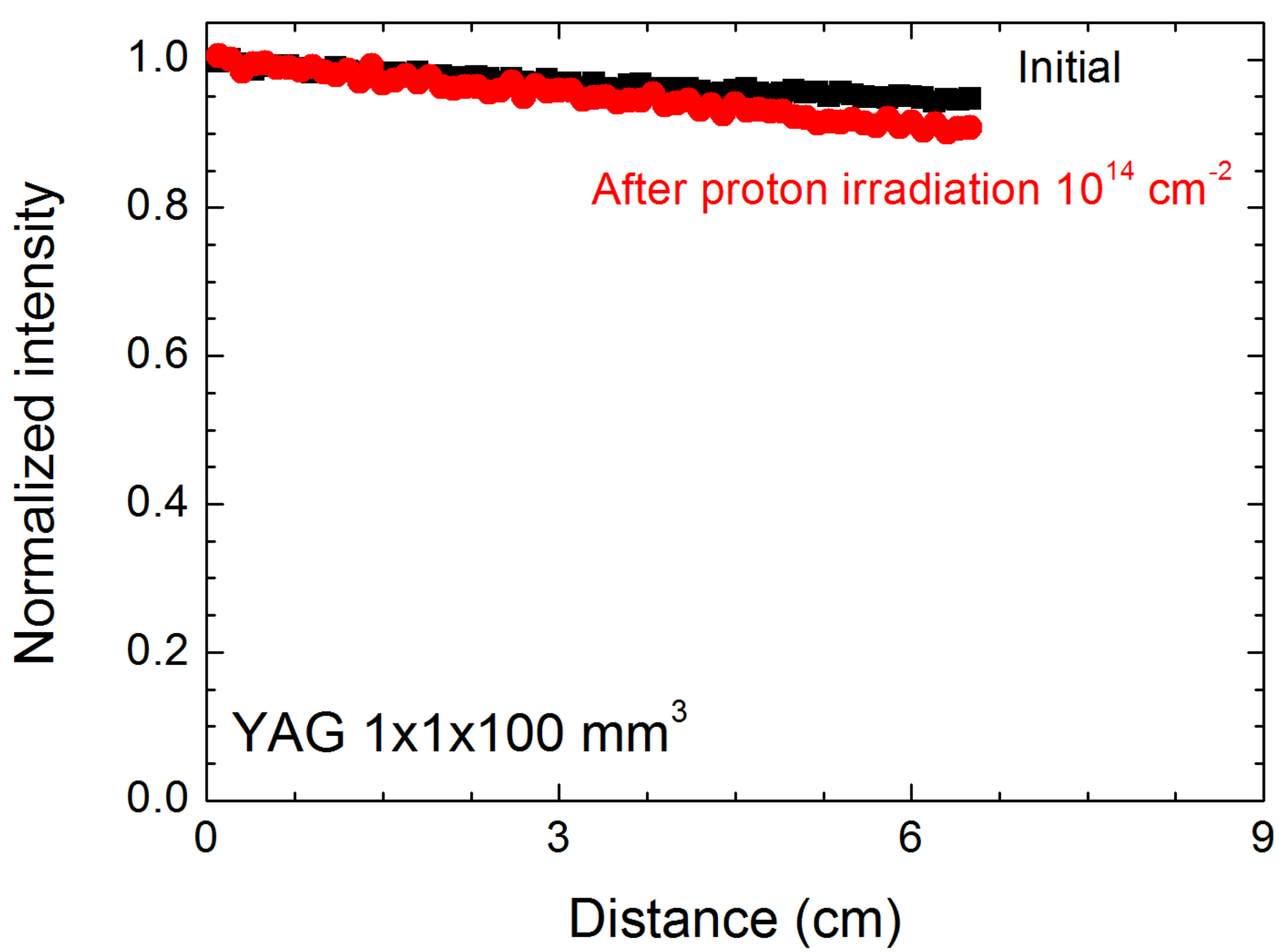
- **Bulk** material and **fibers** from **Crytur** company measured in lab before and after irradiation with gamma rays

- Transparency loss observed to saturate after 1 kGy

bulk - gamma irr.



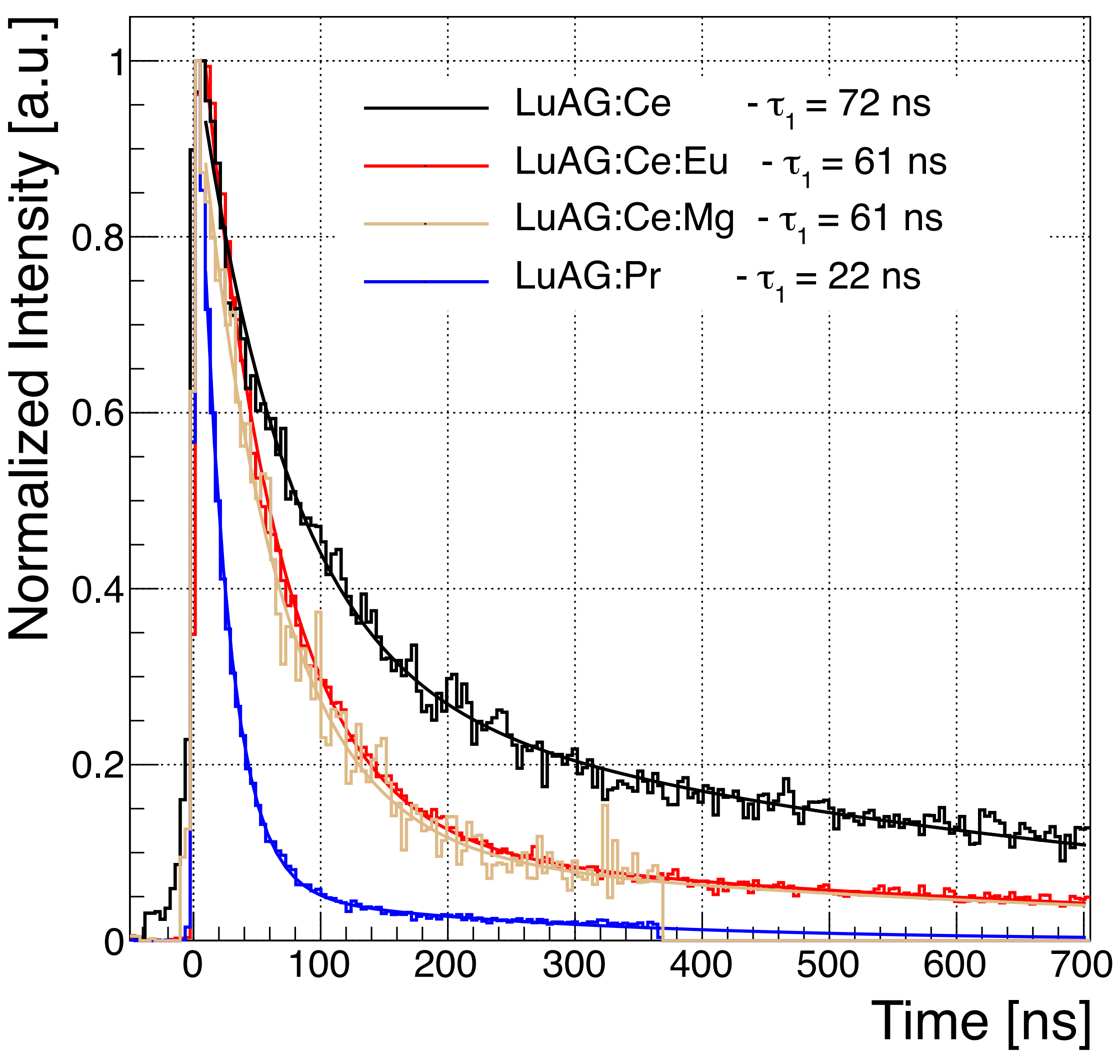
fiber - proton irr.

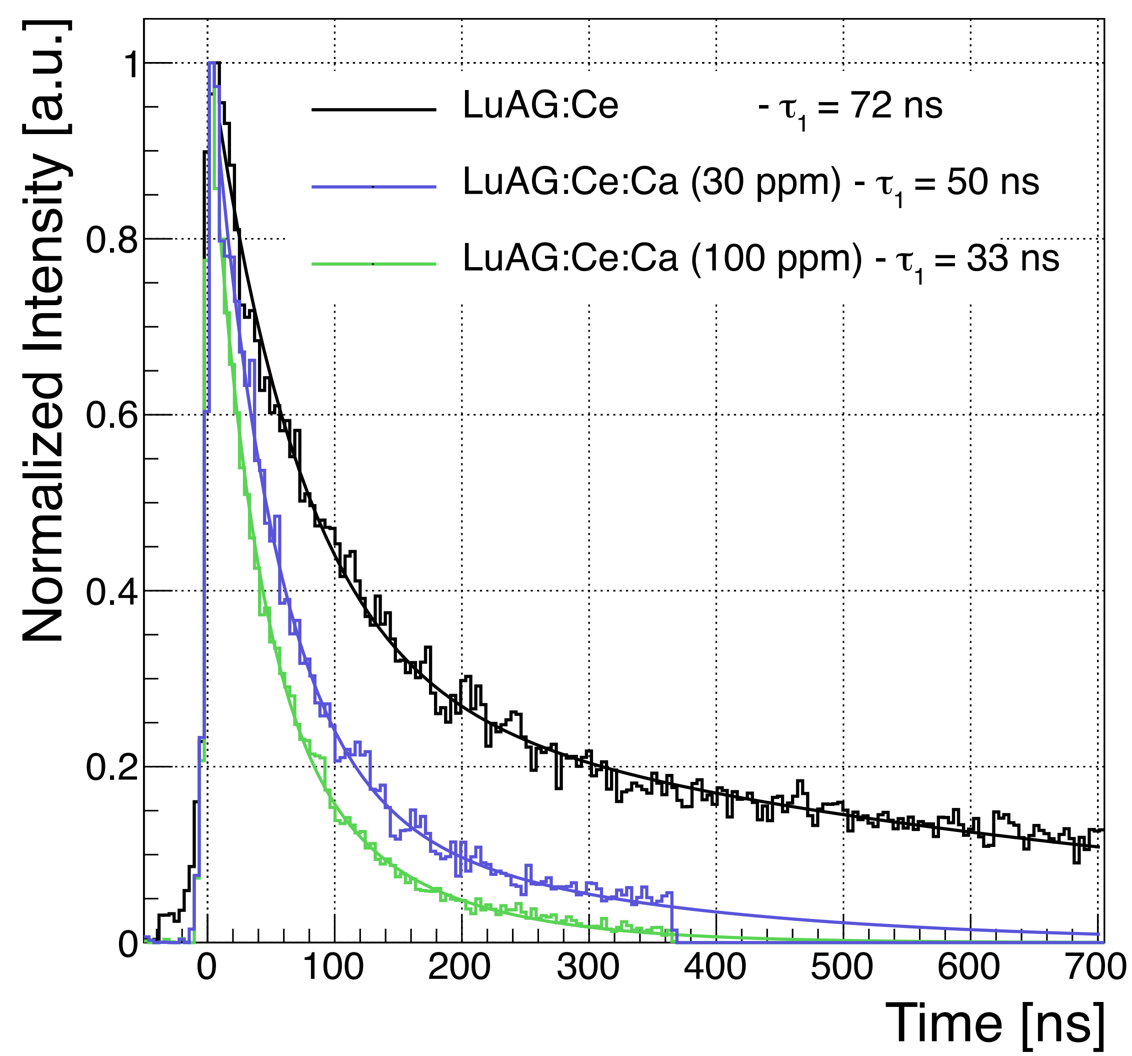


LuAG:Pr or :Ce co-doping to improve response time

- Different ways to improve **crystal response time** investigated:
  - the usage of **Praseodymium** as dopant (one fast component ~ 22 ns)
  - the usage of **co-dopants** (Ca^{2+}, Mg^{2+}) that **quench the slow component** of LuAG:Ce see e.g. Nikl M. et al., Defect Engineering in Ce-Doped Aluminum Garnet Single Crystal Scintillators

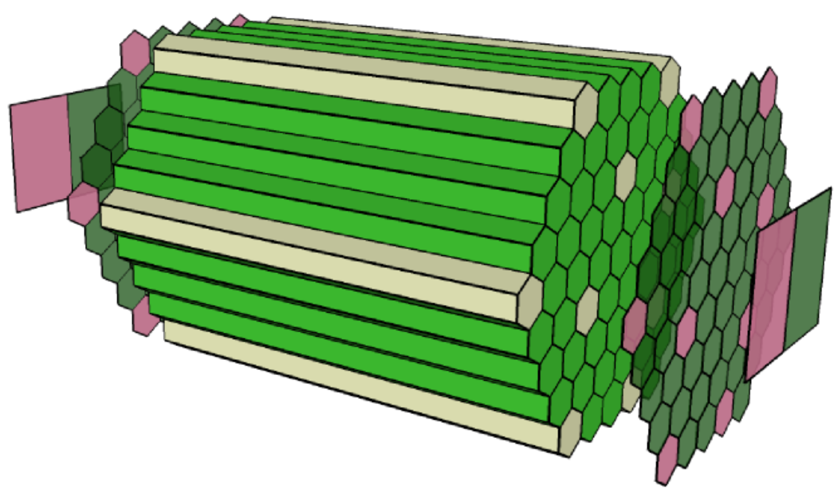
- Samples studied in the lab:



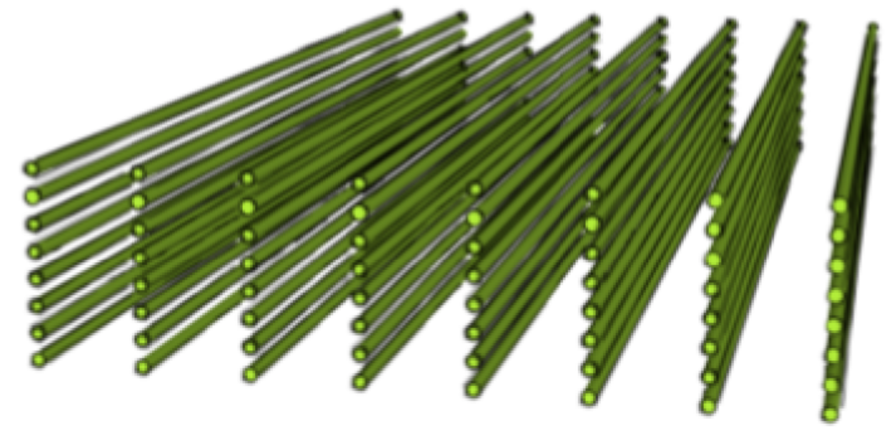


Crystal fiber calorimeter prototypes for high-energy physics

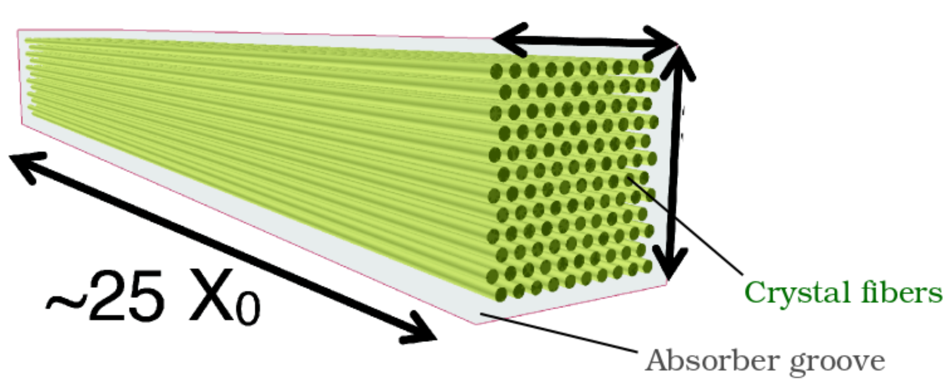
Homogeneous
Dual Read-Out Calorimeter



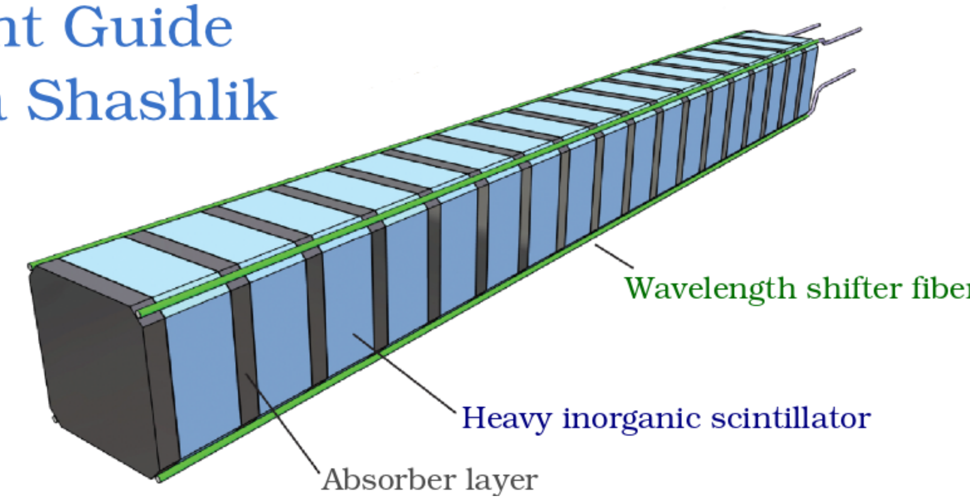
Layers of Crystal Fibers
in a sampling calorimeter



Pointing Fibers
in a Spaghetti Calorimeter

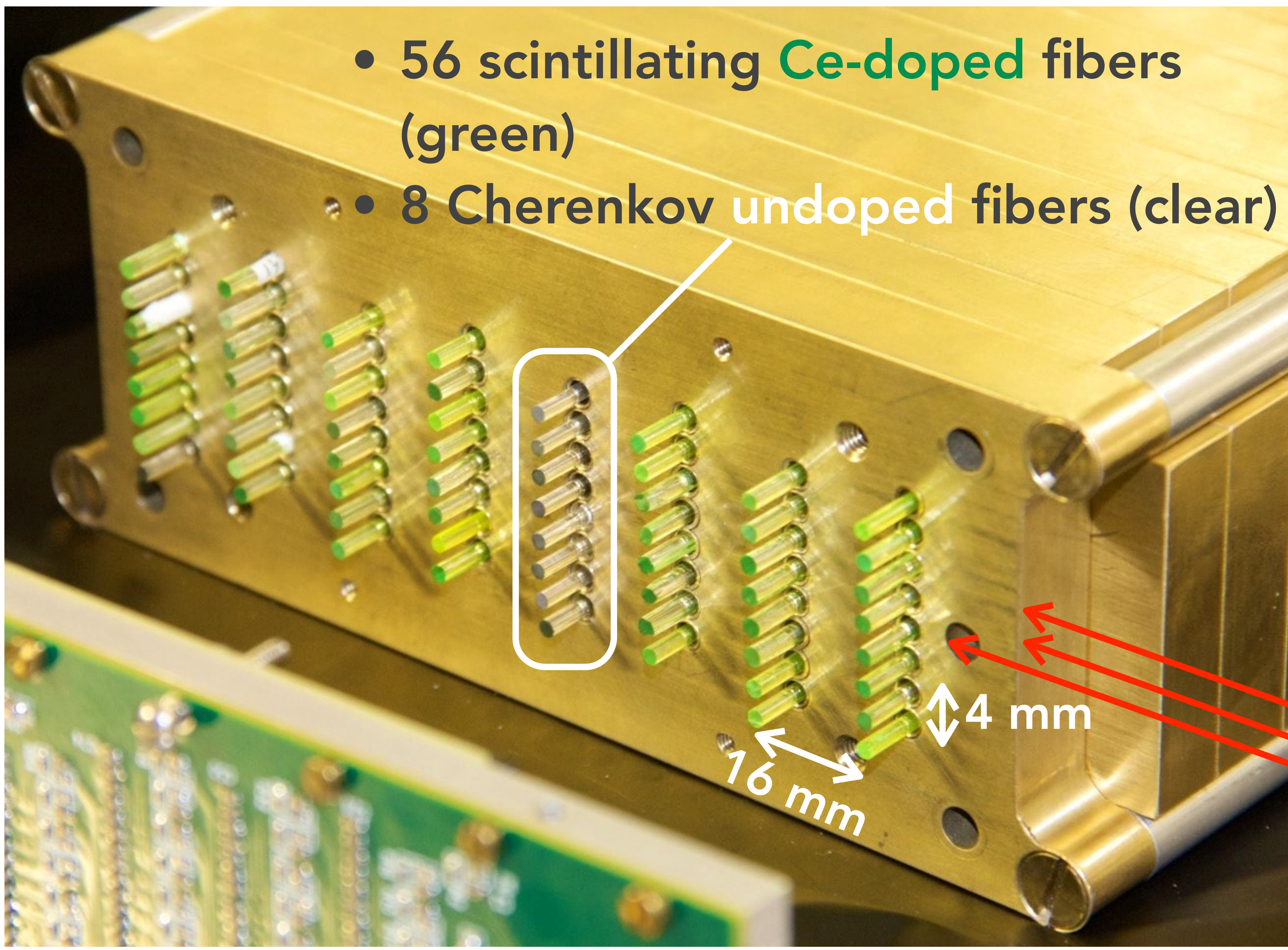


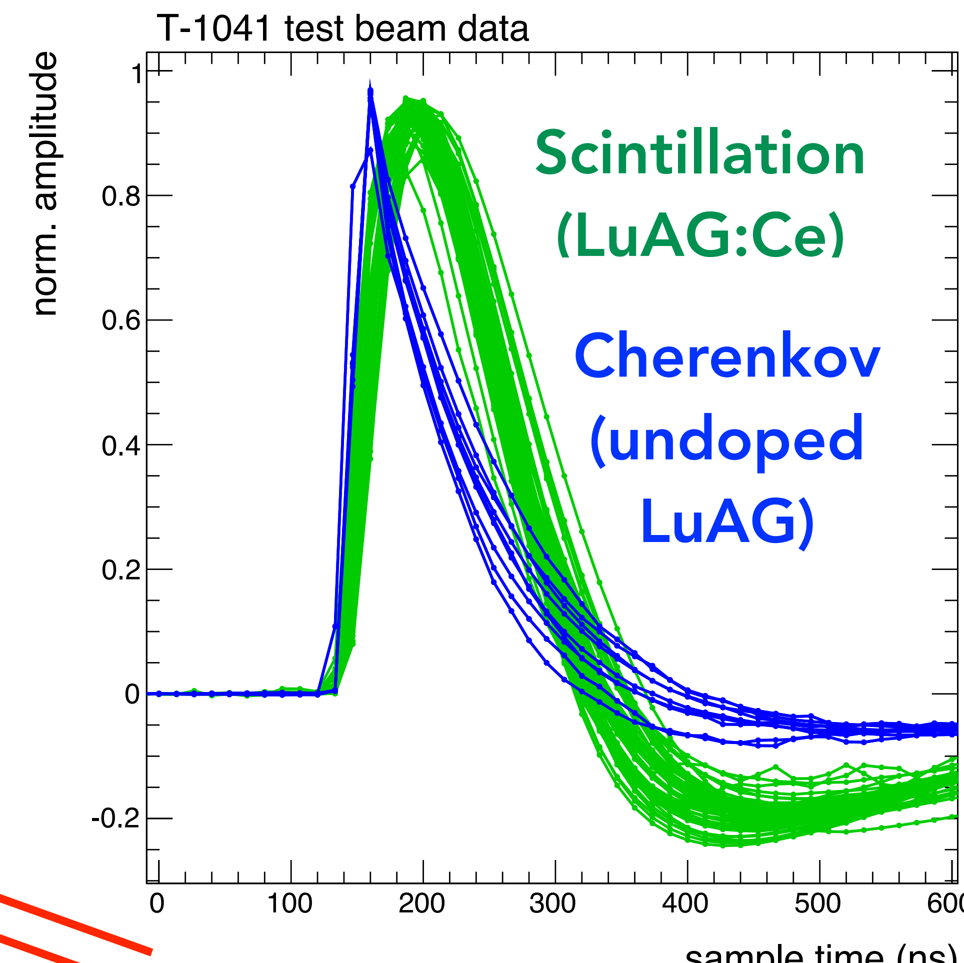
As a Wavelength Shifter
Light Guide
in a Shashlik



A Crystal Fiber Calorimeter prototype

- This **CFCal prototype** was assembled and tested with an electron beam at FNAL (March and August 2014)



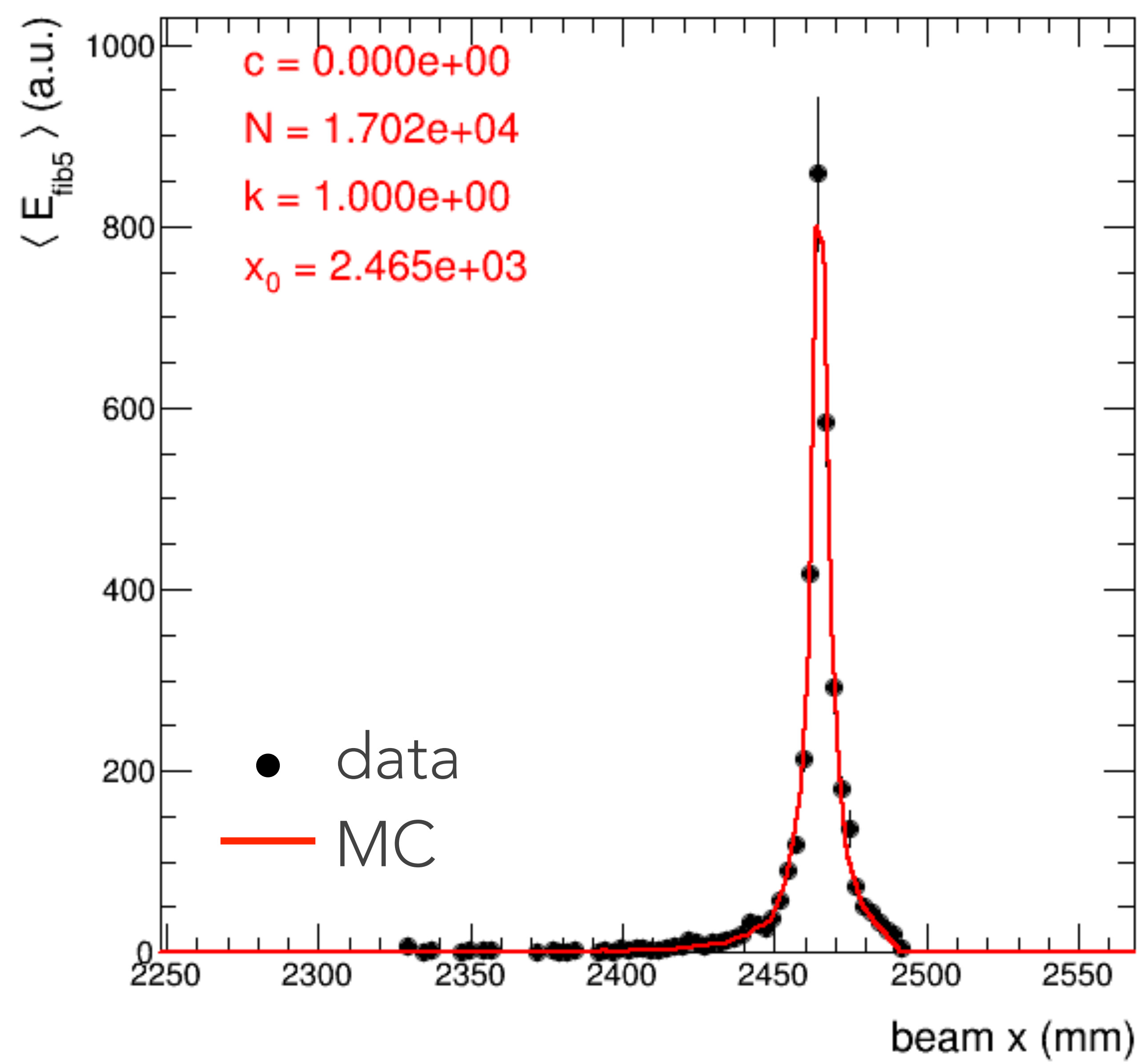


electron / pion beam

Position reconstruction

- **Position** is well reconstructed for all fibers

- fit **energy profiles** vs beam x/y coordinate using MC template



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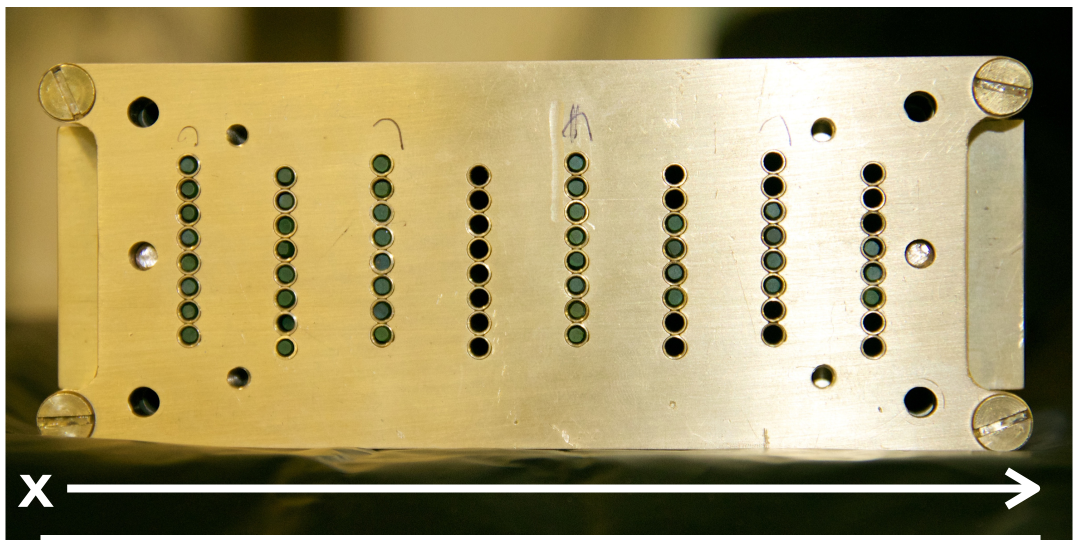
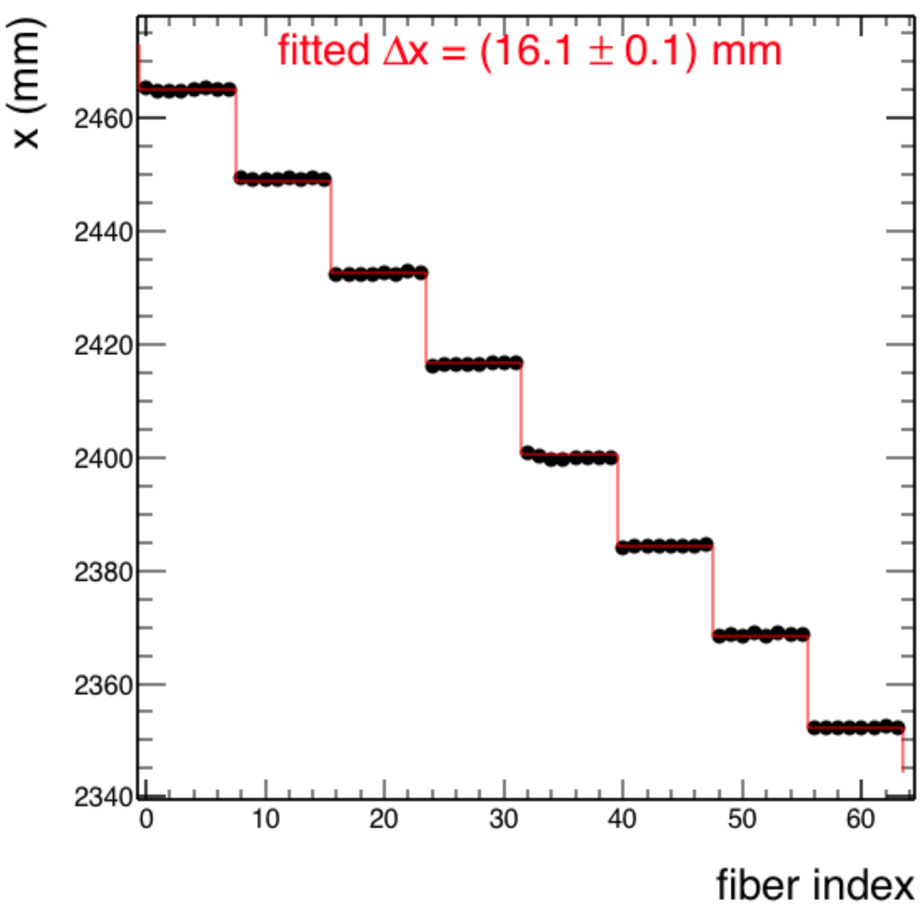
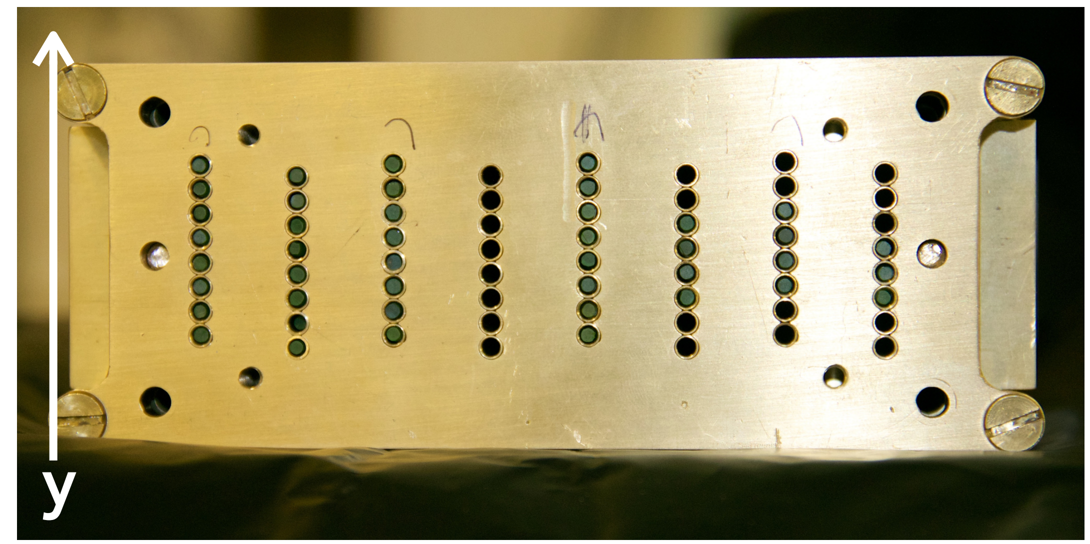
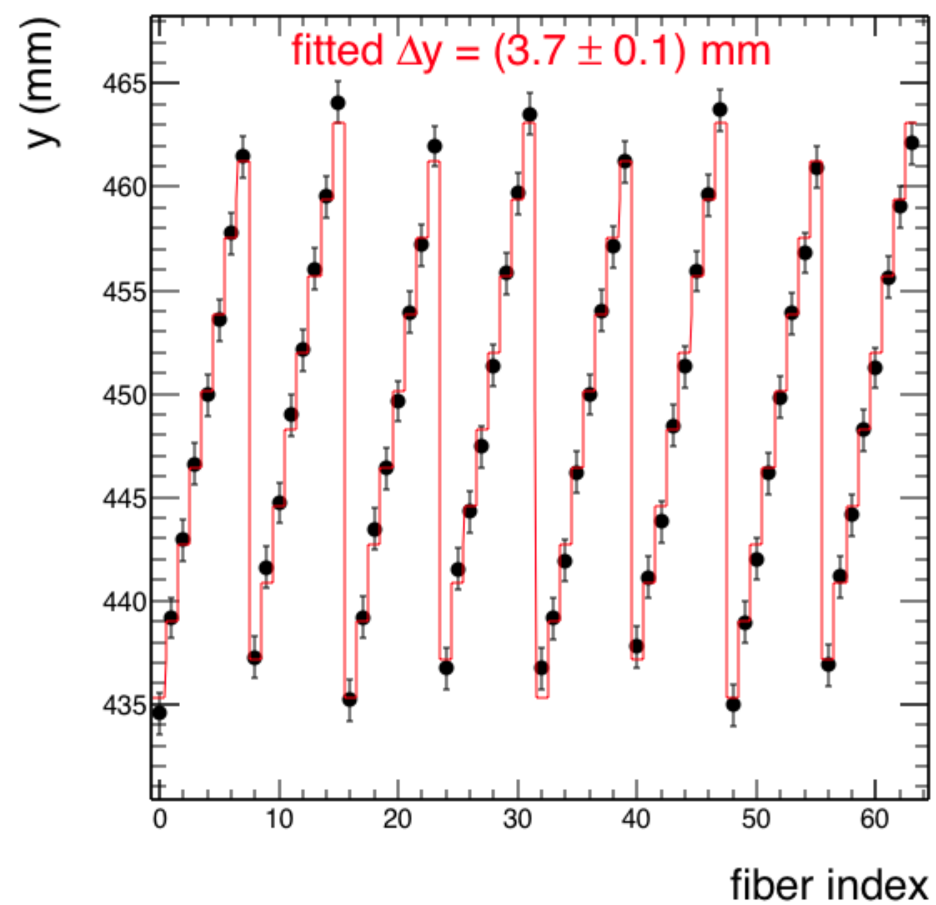


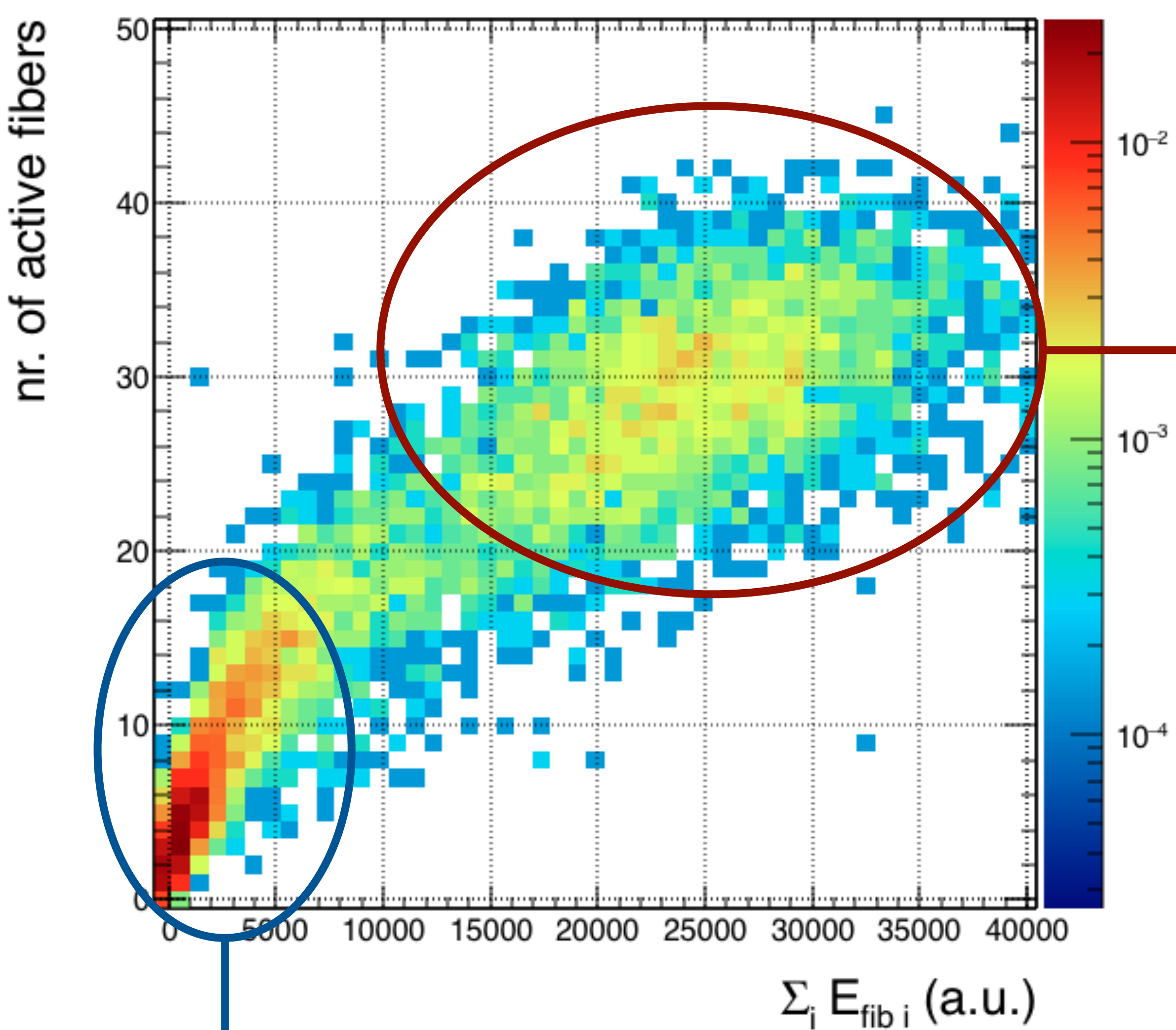






Particle identification

- **Granularity** provide a powerful tool for e/π separation



Electrons
large energy deposits
with ~30 fibers on

Pions
small energy deposits
with < 10 fibers on (mip)

Particle identification

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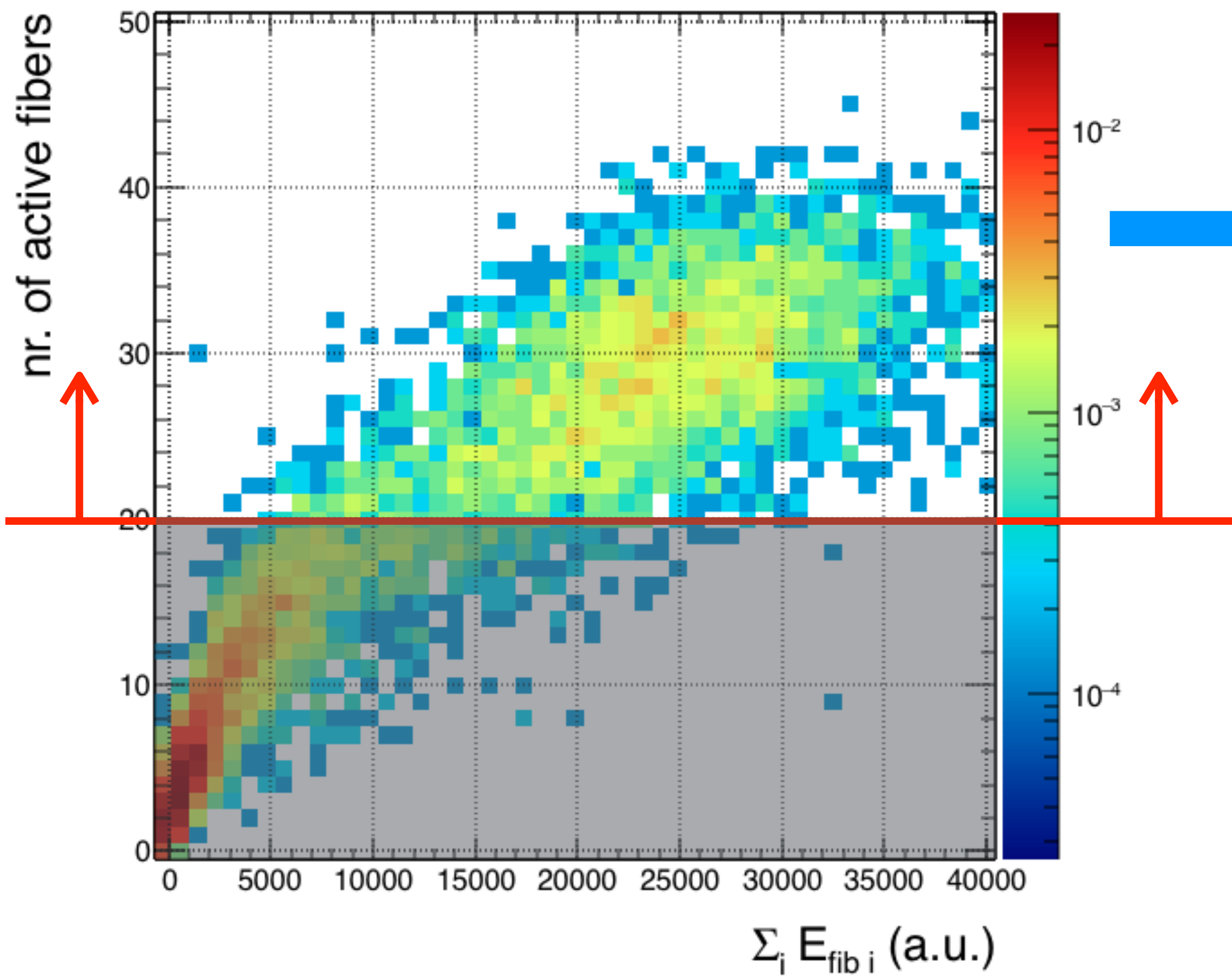
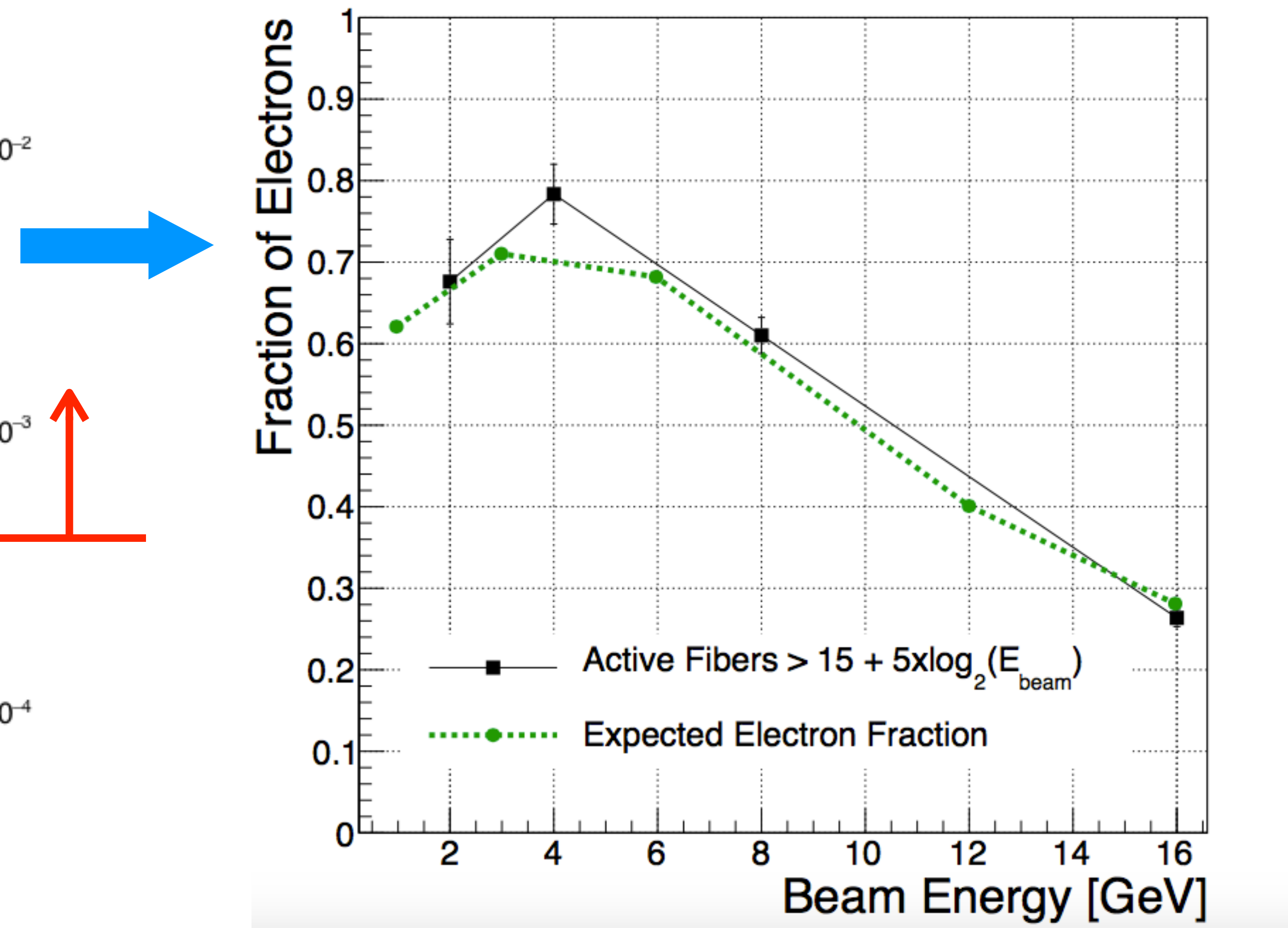
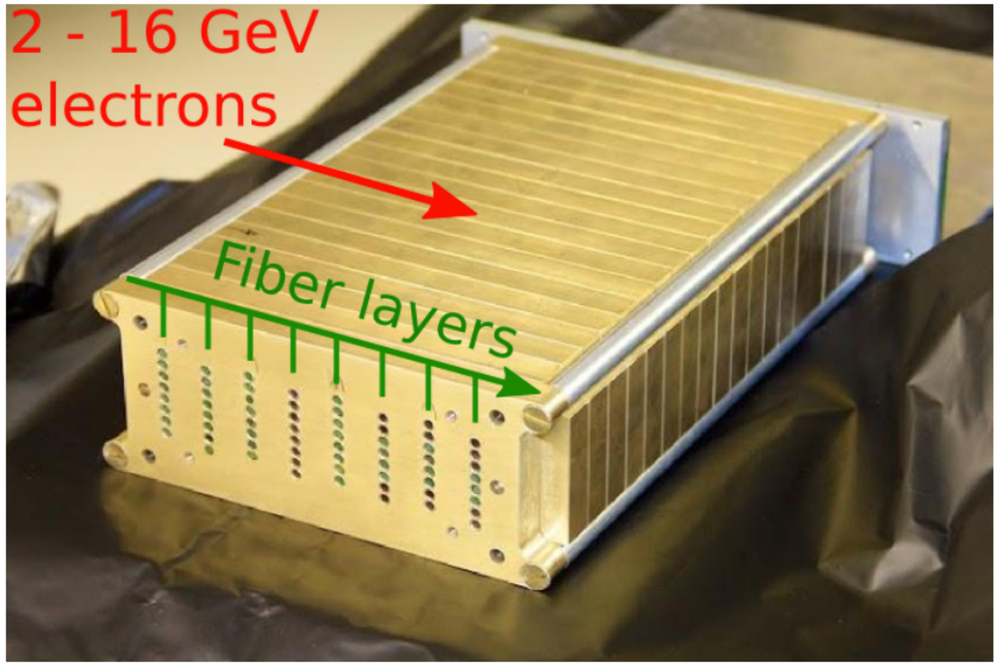




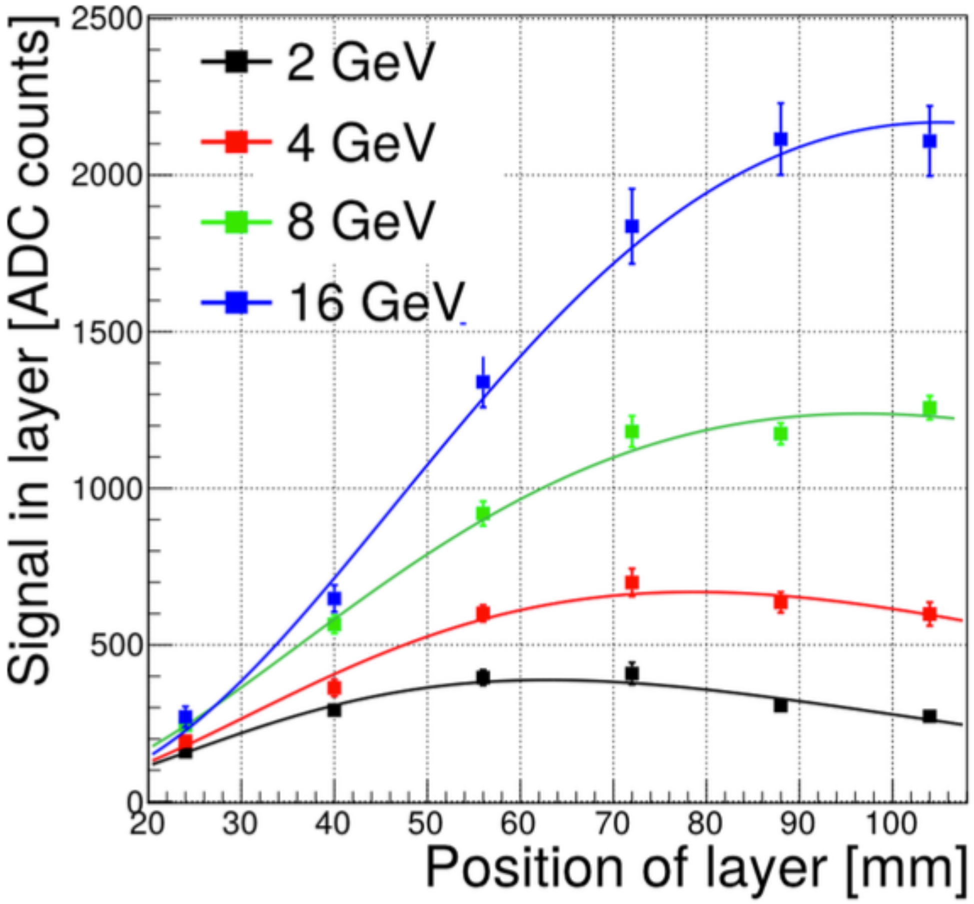
Efficient electron id

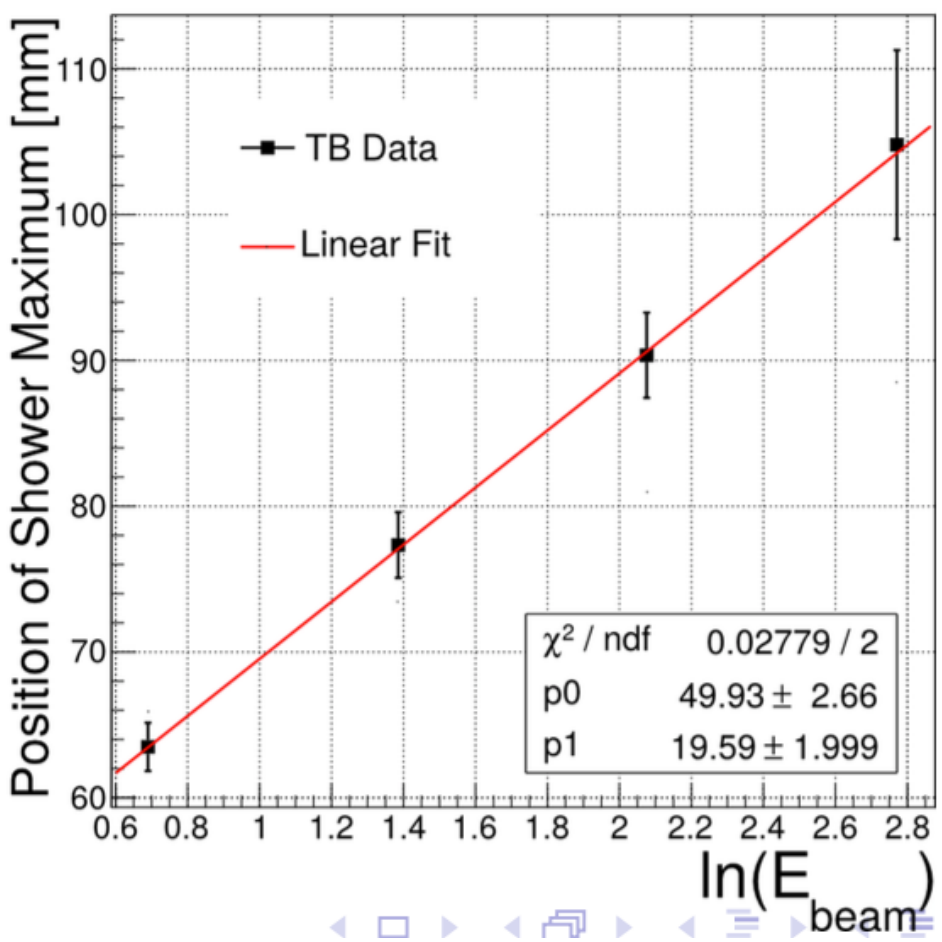
with a simple cut, the electron fraction expected from beam parameters is matched

Longitudinal shower profile



- Electron energy from 2 to 16 GeV
- Clear observation of the electromagnetic shower profile
- Shower maximum shifts proportionally to $\ln(E_{beam})$

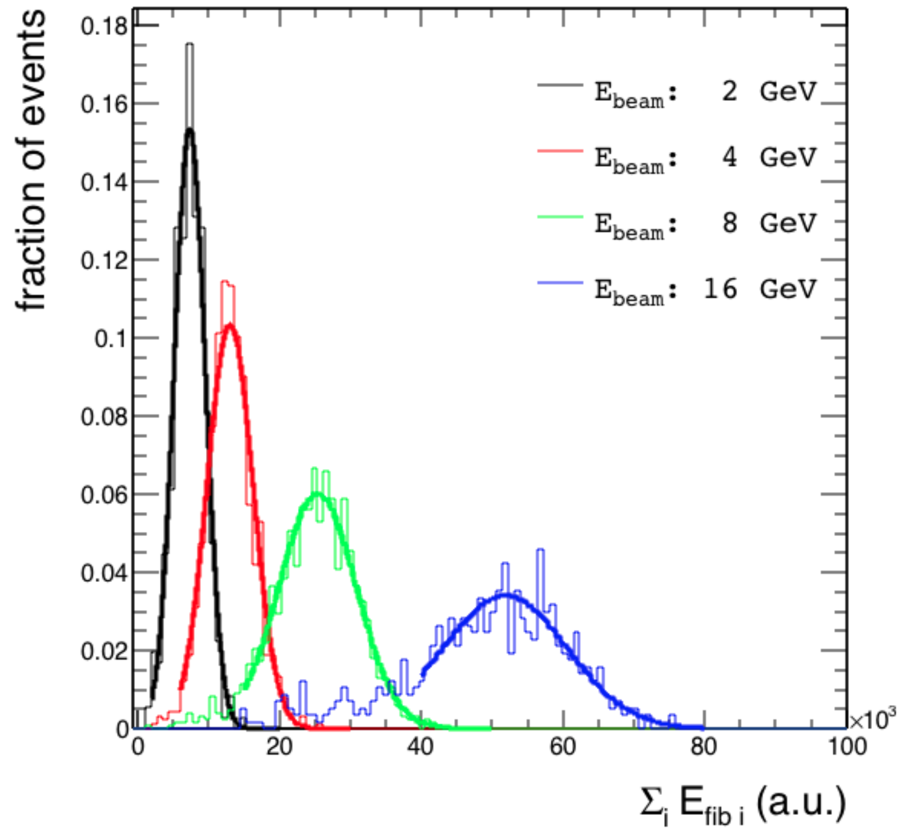


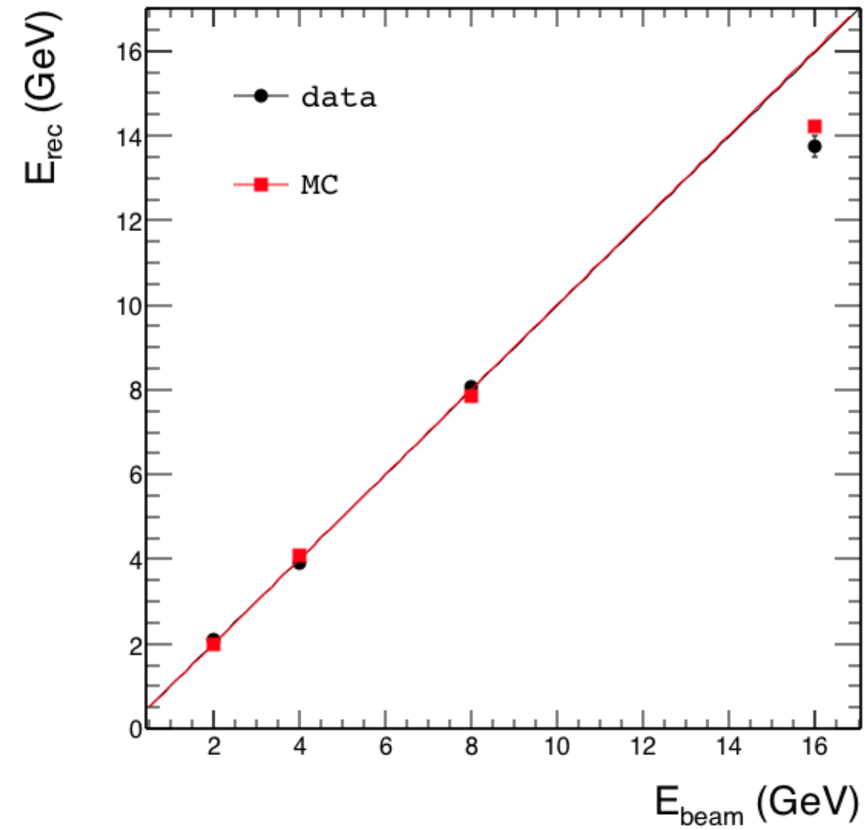


Energy reconstruction

Shooting electrons ⊥ to fibers

- beam spot selection to maximize f_S (15×50 mm^2)
- nice energy peaks observed
- non-linearity at 16 GeV expected (shower leakage)





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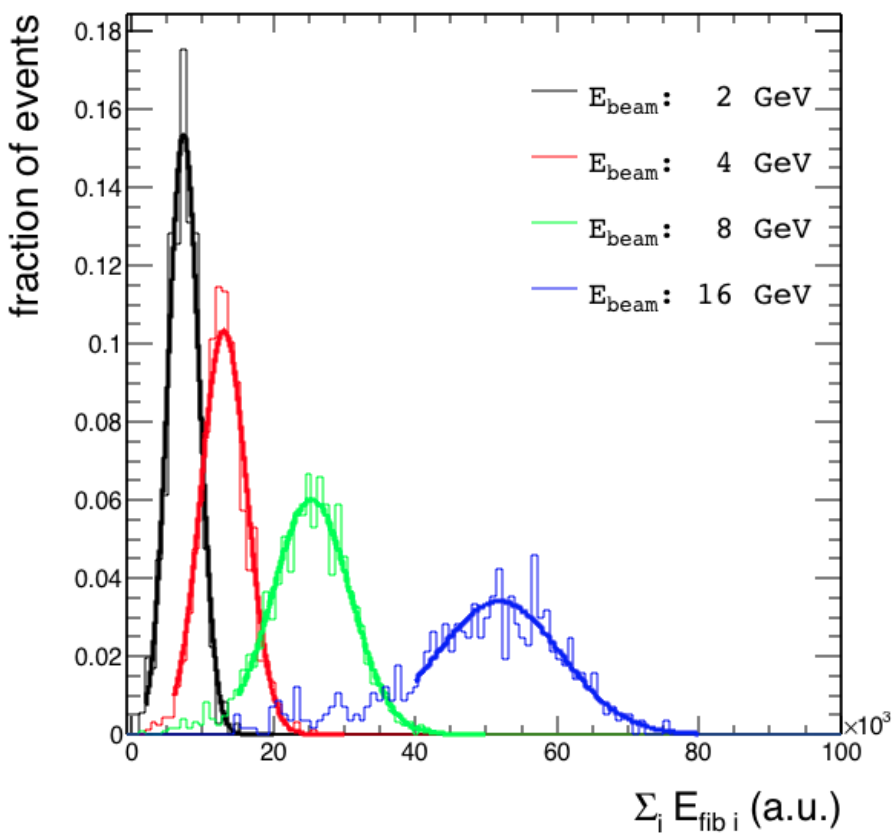

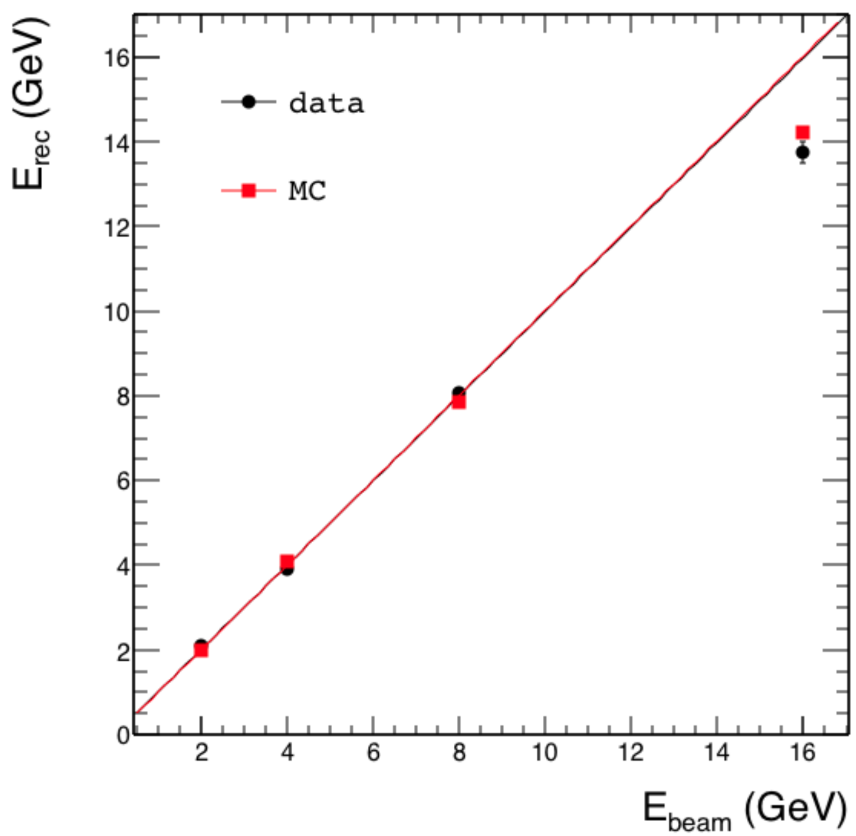

Energy resolution:

- roughly constant @ ~20% in 2-16 GeV range
- dominated by
  - shower leakage
  - fiber attenuation length
  - limited precision of inter-calibration

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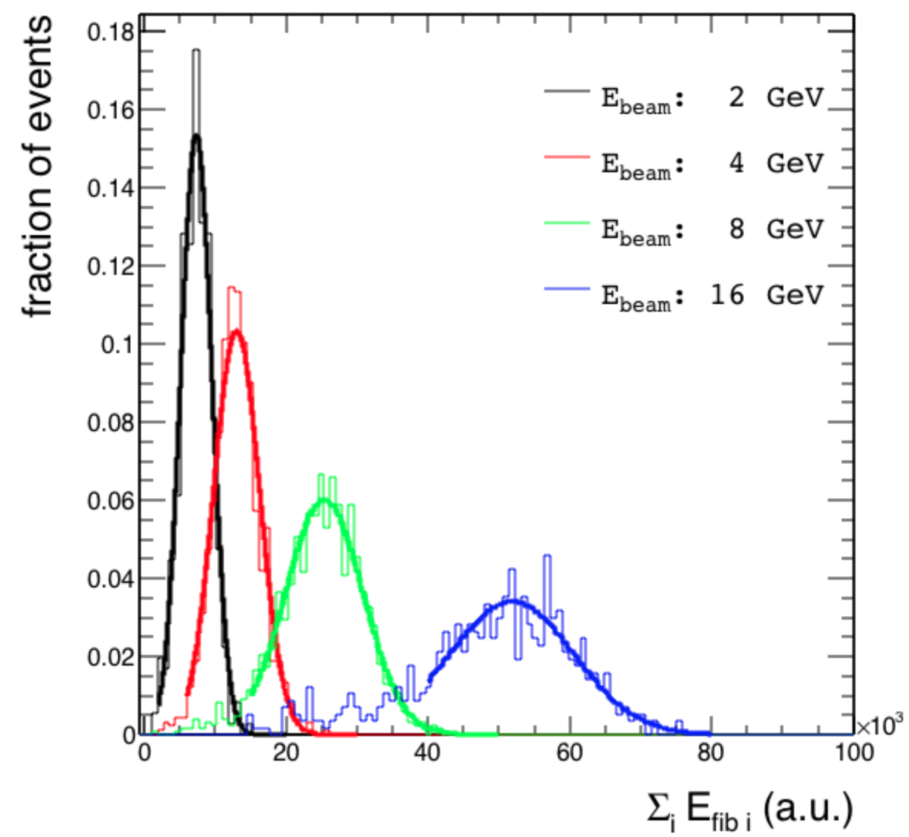
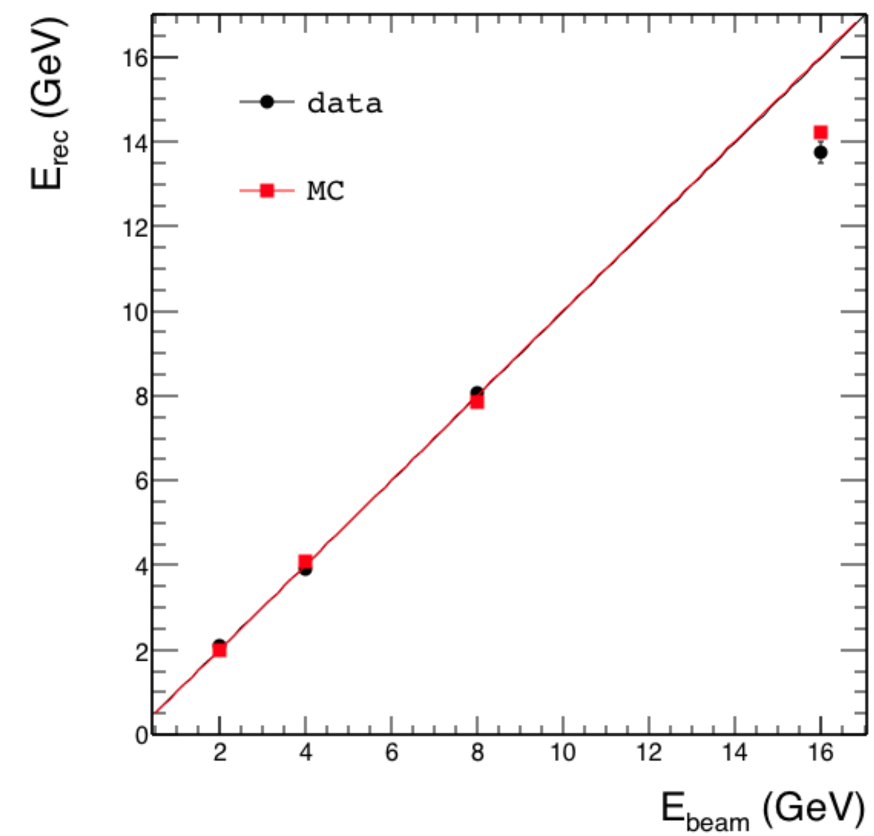
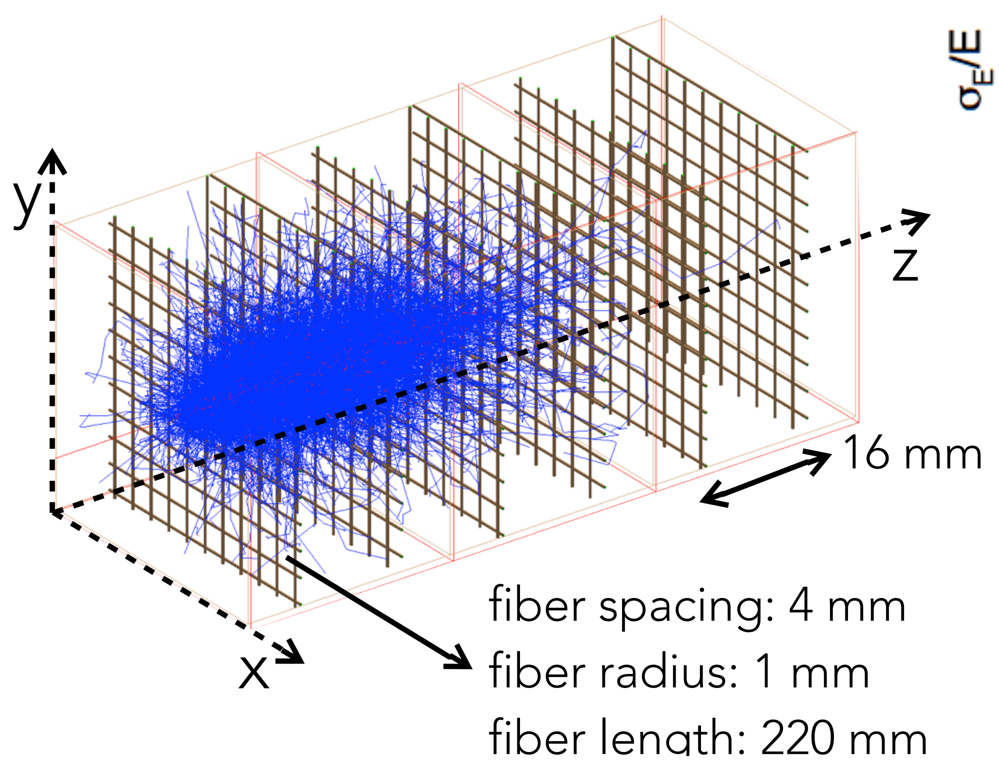
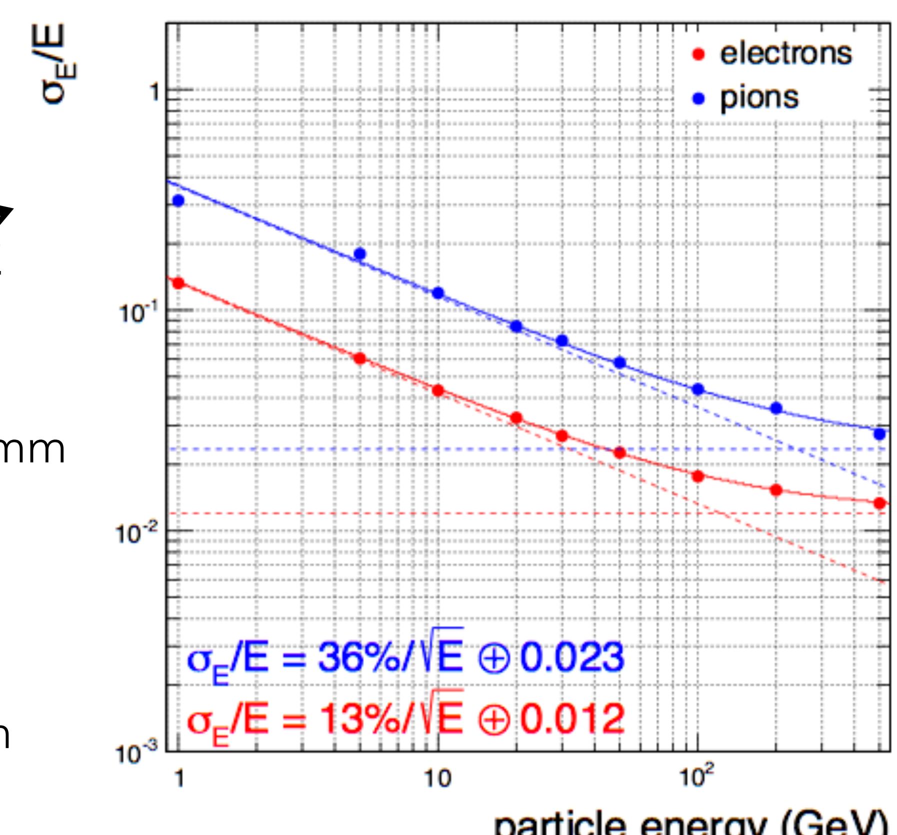




Energy resolution in a full-size fiber detector:

- estimated by means of MC simulation
- similar f_S of the tested prototype



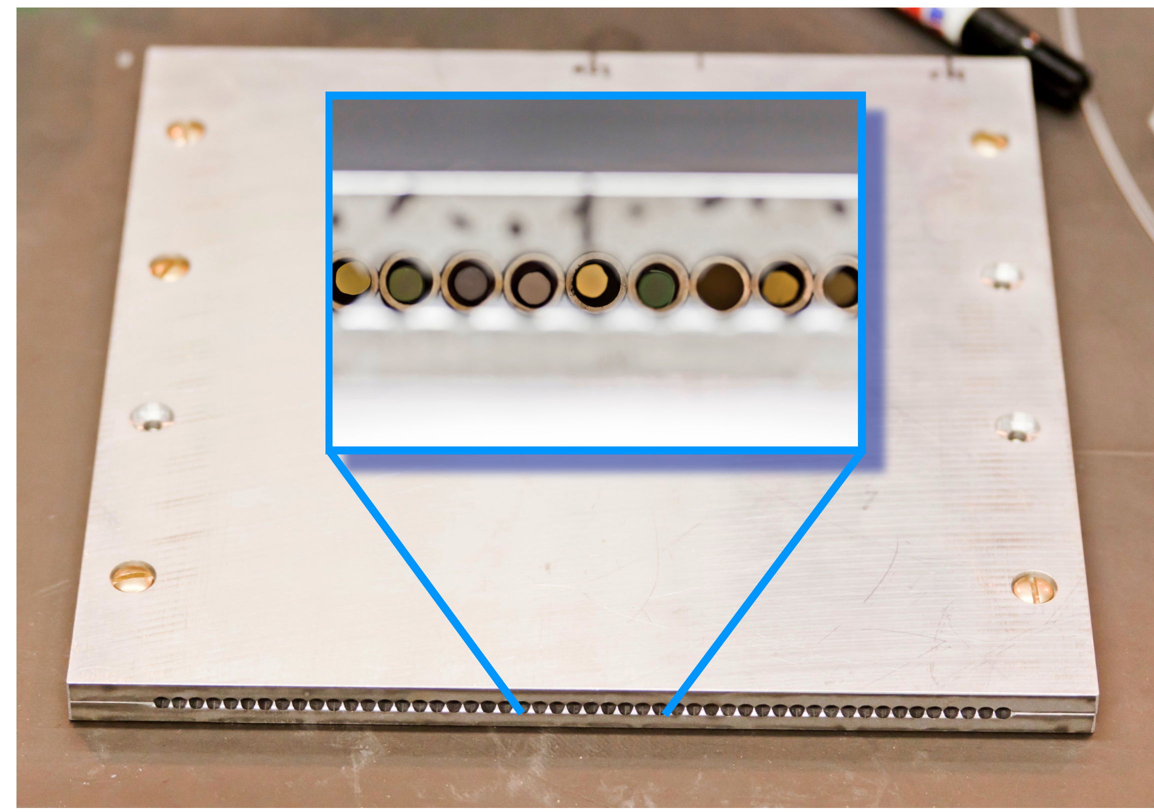


Other fiber calorimeter prototypes

pointing fibers in a **SPAghetti CALorimeter** configuration (ECAL up.)

- tested **beam** at **CERN** scheduled for Sep. 2015
- W-Cu absorber / **YAG** fibers
- could be interesting for **CMS forward ECAL upgrade**

transverse fiber in Al-tile configuration (**HCAL upgrade**)



- tested on **beam** at **CERN** on Oct. 2014
- Al absorber / **LuAG:Ce-LuAG:Pr-YAG** fibers
- **being considered for CMS forward HCAL upgrade**

Conclusions

- A lot of **improvements** have been achieved in the **quality** of the growth of crystal fibers
  - historically, experience gained with LuAG grown with μ-PD technique
  - new interesting samples studied (e.g. YAG crystals) seem promising

- **Large production** of fibers achieved as well
  - ~80 fibers tested on beam at FNAL and CERN
  - first physics results obtained

- Crucial for application for future upgrades of LHC experiments is the fiber **radiation resistance** and **response time**
  - intensive R&D is in progress

Acknowledgements

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Crystal Clear Collaboration

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