TRD based on highly segmented solid-state detectors

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R&D on innovative TRDs: physics goals and group composition

- Physics motivations:
  - Development of new type of detectors combining precise tracking and particle identification properties for high energy physics and cosmic-ray experiments in space
- Groups:
  - INFN Bari & Bari University (Italy)
  - CERN
  - Prague University (Czech Republic)
  - Louisiana University (USA)
  - …
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  - Mike Cherry (Lousiana Un.)
  - Anatoli Romaniouk (Innsbruck Un.)

Introduction

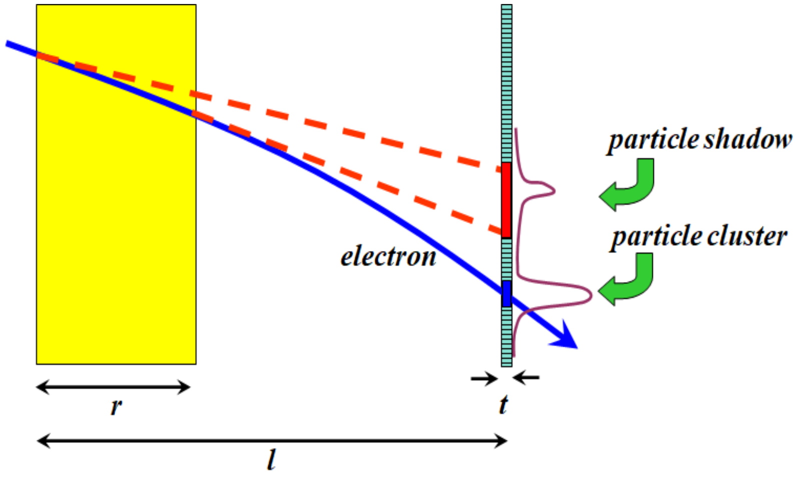
- Transition radiation detectors (TRDs) used as high energy particle identification (PID)
  - Usually used as threshold devices due to the threshold Lorentz factor for the emission of Transition Radiation (e.g. electron/hadron separation)
  - TRDs equipped with gaseous detectors successfully used in in both accelerator and space experiments (e.g. ATLAS, ALICE, AMS-02)
  - The typical application is electron/hadron identification
- Development of new generation TRDs based on highly segmented solid state detectors
  - Combination of precise tracking and PID devices in one detector
  - Coordinate accuracy $< 10\ \mu m$
  - Enhancement of the PID properties due to:
    - Separation of transition radiation and particle dE/dx
    - Simultaneous measurement of photon energies and emission angles
- Applications:
  - Electron/hadron separation
  - Hadron identification in the TeV region

Experience: TRD based of Si strip detectors (SiTRD)

- Si-StripTRD in magnetic field
  - Few beam test campaigns at the CERN PS T9 with electrons and pions up to 5 GeV/c
  - MC simulations studies
- The SiTRD combines a magnetic spectrometer with a TRD, thus allowing both particle identification and momentum measurement
  - Each SiTRD module consists of a radiator and a single side silicon strip detector operated in a magnetic field region
  - Multiple detector modules
  - Possible applications in both accelerator and in cosmic-ray experiments
  - Possible upgrades with double side strip detectors or pixel detectors

Principle of operation of Si-strip TRD in magnetic field

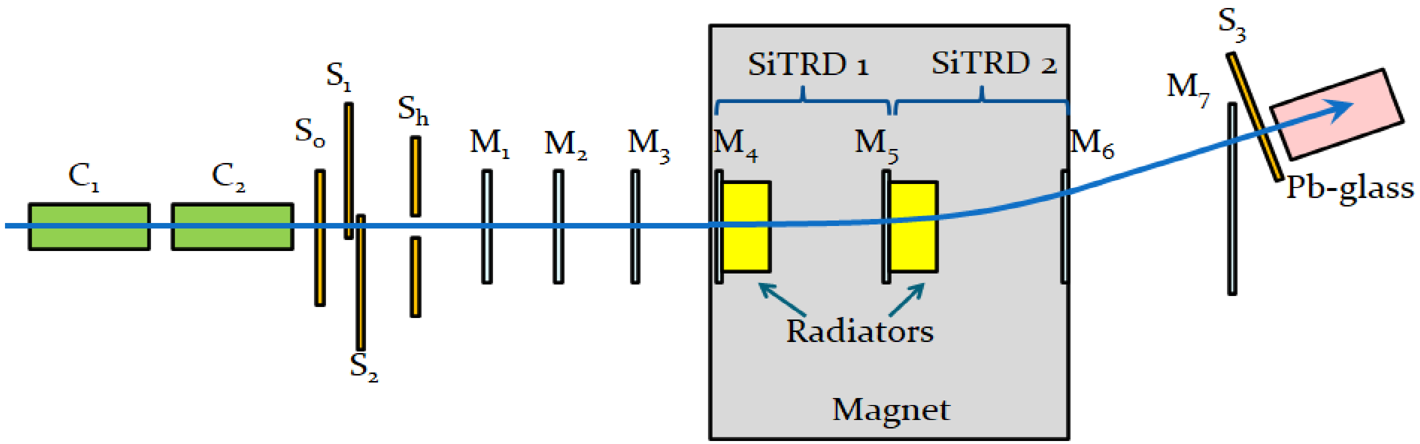
- The radiating particle is separated from the TR X-rays by the magnetic field
- The ionizing particle will induce signals on one or more strips ("particle cluster")
  - The size of the "particle cluster" will depend on the inclination of the track and on the charge sharing in the SSD
  - The ionization energy deposit of the particle is of ≈120 keV in a 400 μm thick SSD
- Absorption of TR X-rays is expected to occur in a different region ("particle shadow") from that in which the particle leaves its ionization energy deposit
  - The position of the "particle shadow" can be inferred starting from the particle track
  - The TR X-ray energy spectrum is peaked at ~10-20 keV and its tails may extend up to a few tens of keV
  - TR X-rays induce signals on one or more strips ("X-ray cluster") within the "particle shadow"
    - Since X-ray conversion is a point event, the typical size of an "X-ray cluster" is of a single strip
- A low noise electronics is required for efficient X-ray detection
  - Typical value of σ_{noise} of a few hundreds ENC

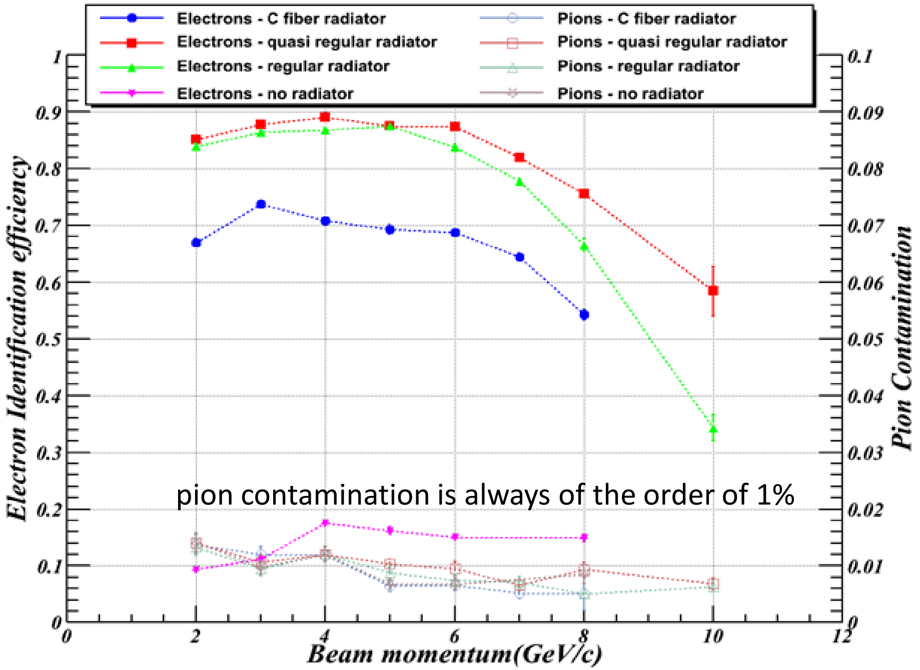


- A minimum separation of one strip is required between the "particle cluster" and the "particle shadow"
- This condition sets the momentum upper limit for the identification of radiating particles

Beam test in 2006

- Reduced scale 2-module SiTRD prototype carried out at the CERN-PS T9
  - e/π beam with momenta up to 10 GeV/c
  - MNP17 magnet: B field up to 1T
  - Length of each SiTRD module = 25cm
    - Radiator thickness = 5cm
    - 400 μm thick SSDs with a strip pitch of 228 μm

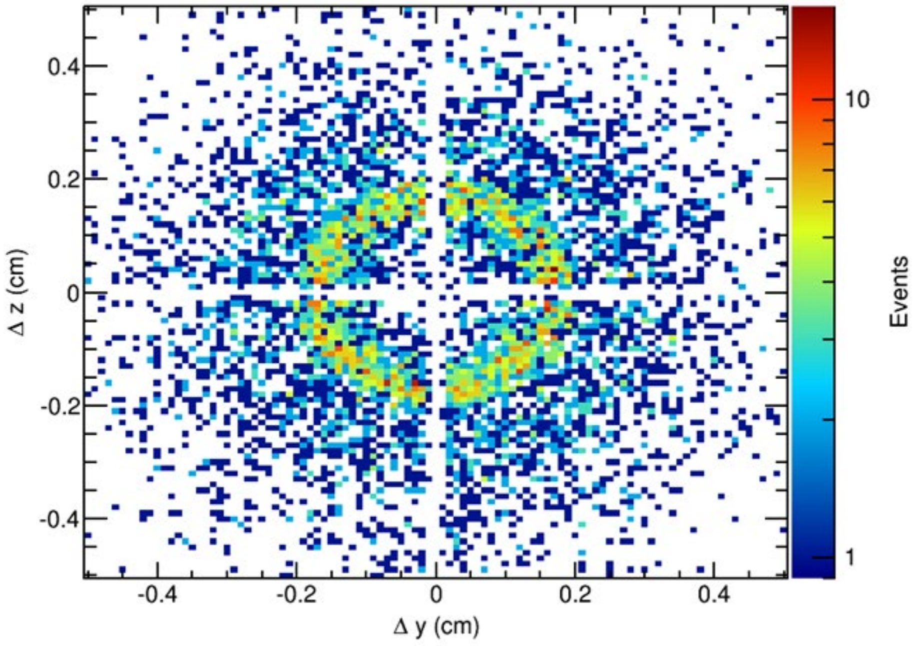




- At low momenta the “particle shadow” is well separated from the “particle cluster” and the electron identification efficiency reaches its maximum
- p > 5 GeV/c the electron identification efficiency drops because some “X-ray clusters” can be merged into the “particle cluster”

Si-strip TRD exploiting angular properties of TR

- Test beam 2017: measurements with a double sided Si-strip Detector
  - Cross section = 2×2 cm2
  - Readout strip pitch = 50 µm
  - Detector thickness = 300 µm
  - Detector noise: Average RMS = 1.3 keV / 1.7 keV (junction/ohmic side)



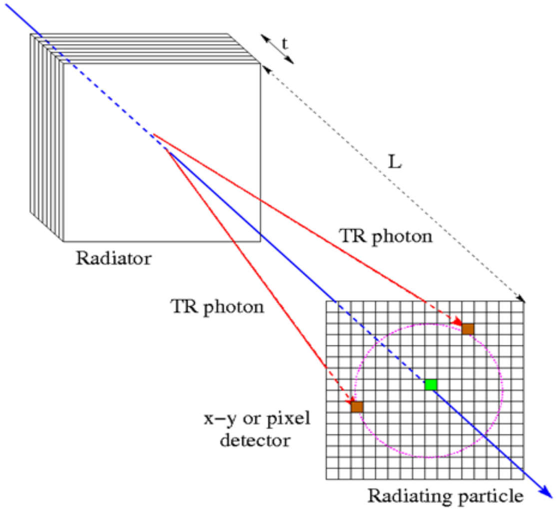
$\cancel{\theta \sim 1/\gamma}$ Commonly used relation is not accurate! $\theta \approx \sqrt{1.4\pi^2/\gamma^2_{\mathrm{sat}} - 1/\gamma^2}.$

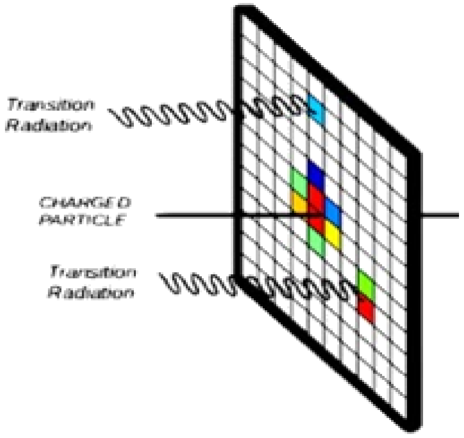
- The plot shows the relative positions of TR X-rays with respect to the radiating particle
- Data taken in a run with 290 GeV/c muons using a polypropylene/air radiator

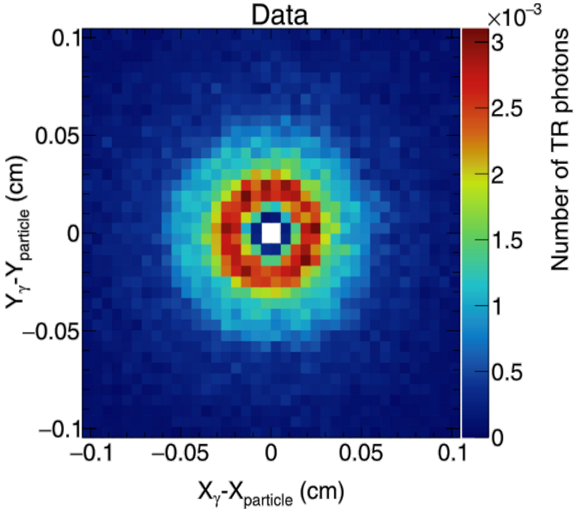
Pixel TRD

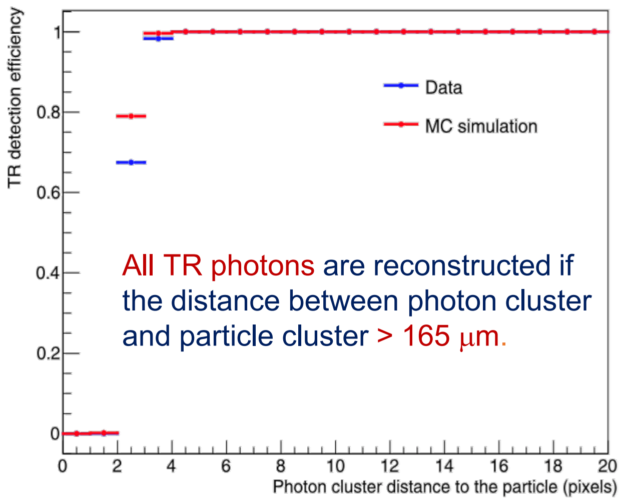
- Groups involved:
  - CERN (A. Romaniouk et al.), INFN Bari (N.M. & F.L. et al.), Prague Un. (B.Bergmann), Lousiana Un. (M. Cherry)…
- Activities started in 2017
  - Beam test campaigns performed at the SPS H8 line and at DESY
  - Different radiators tested
  - Tests with strip and pixel detectors
    - Si and GaAs detectors used
    - Pixel detectors equipped with Timepix3 chips
  - Simulation studies

Pixel TRD (Ring TRD)

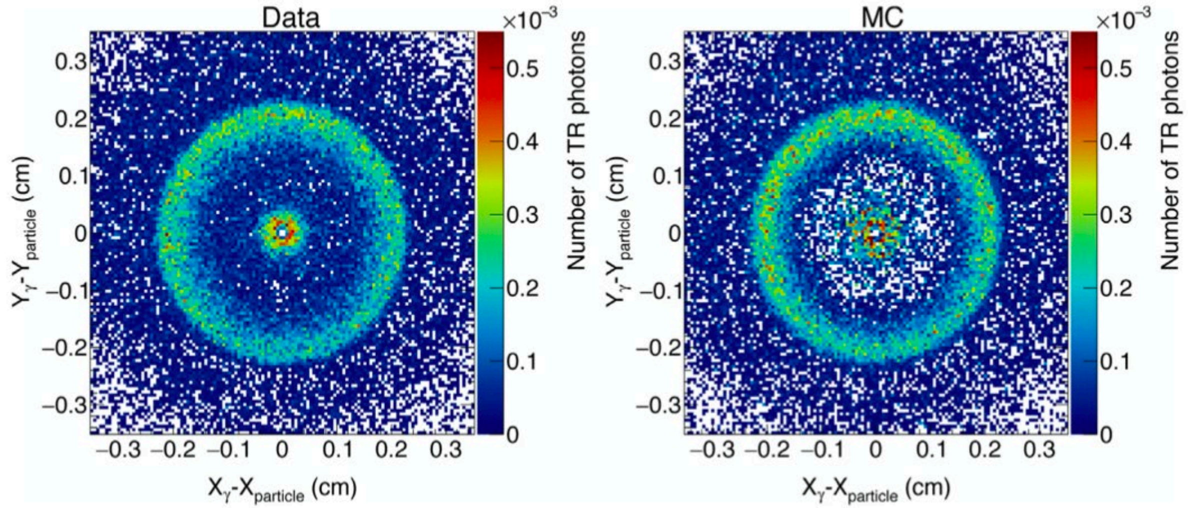




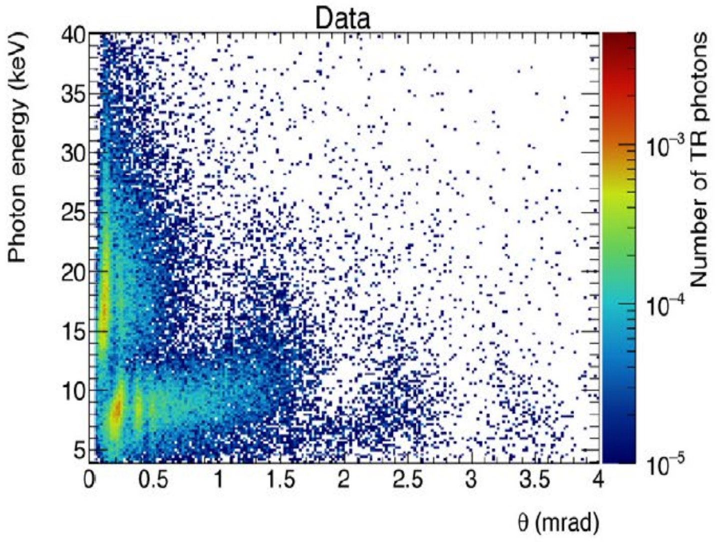


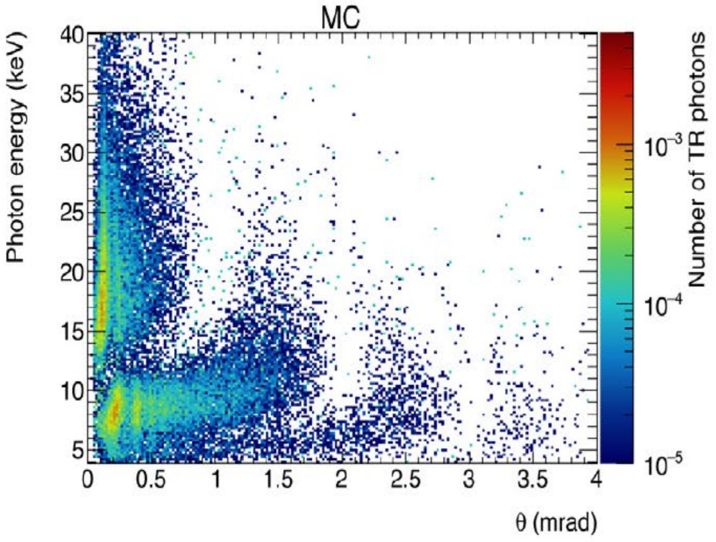


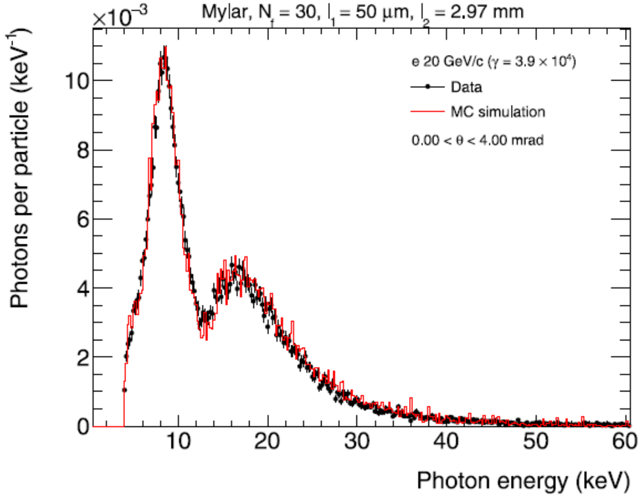
- Test beam 2018
  - 480 μm thick silicon sensor bonded to a Timepix3 chip
  - 256×256 pixels with 55μm pitch
  - Different radiators tested
- MC simulations reproduce TR properties with high accuracy

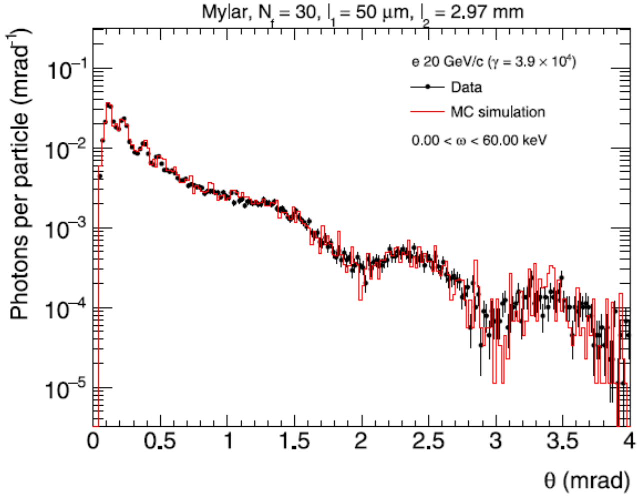


Measurements with a silicon pixel detector





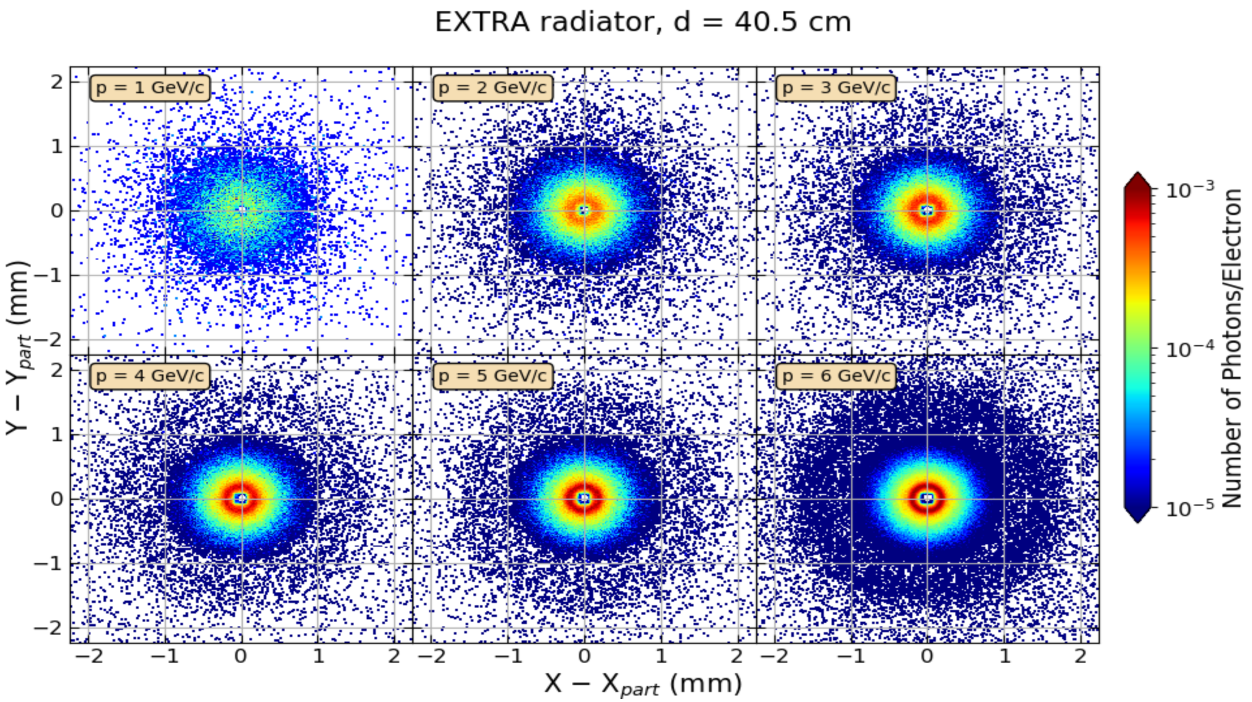


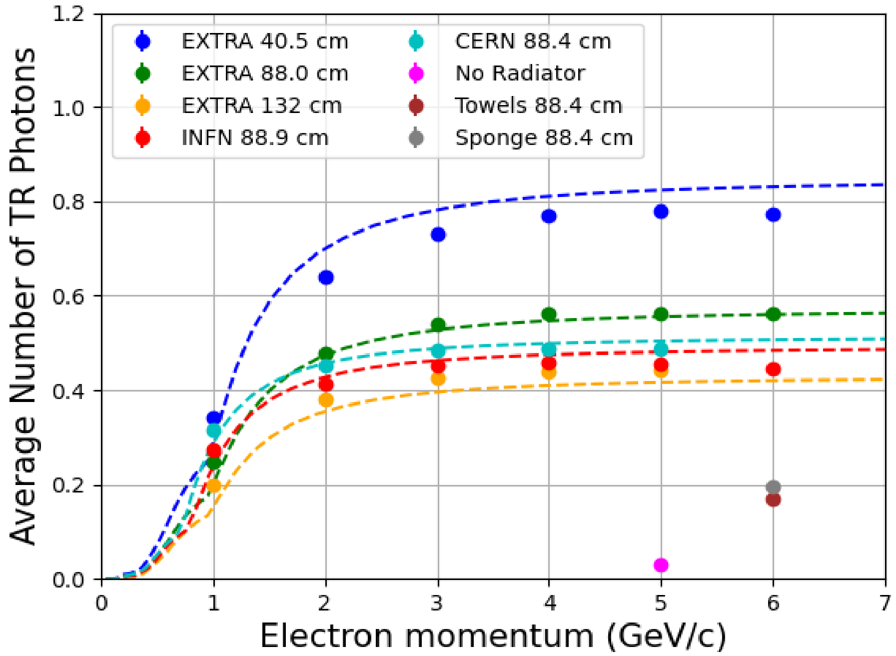


- The plots show the measured and simulated energy-angle distribution of TR X-rays produced by 20 GeV/c electrons crossing a mylar/air radiator
- Data are well reproduced by MC simulation

Further measurements with silicon pixel detectors

- Measurements performed at the DESY II Beam Test Facility in the framework of an experiment winning the BL4S competition
- Silicon pixel detector, 100 µm thickness, 55 µm pitch readout with a Timepix3 chip

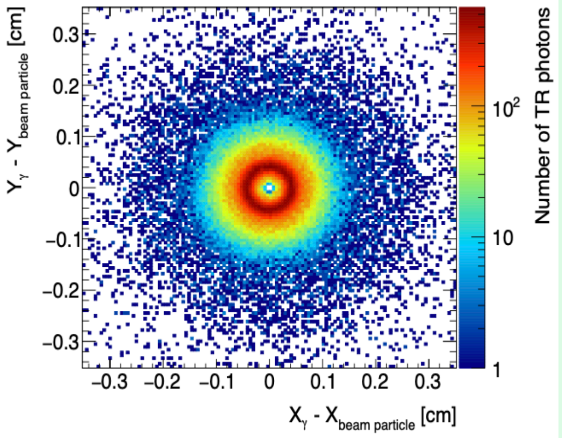




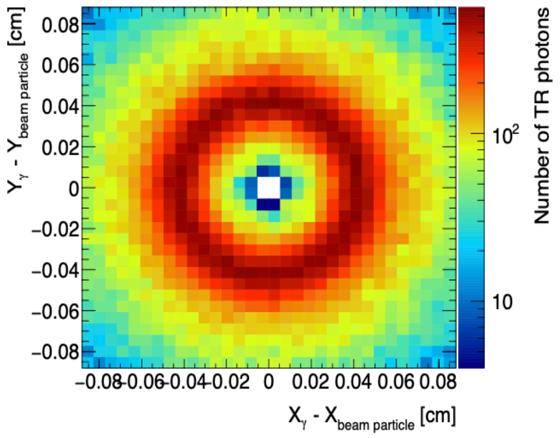
Electron/pion separation using GaAs sensor

Electrons

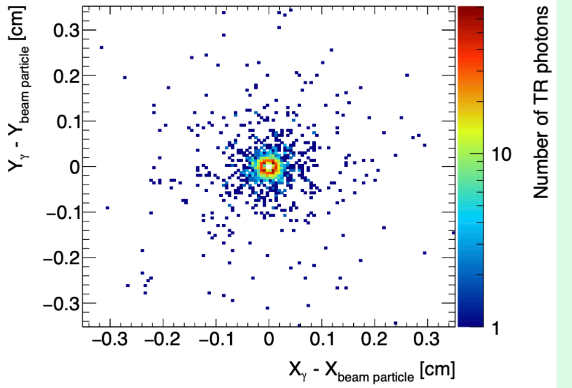
TR cluster distributions around particle cluster



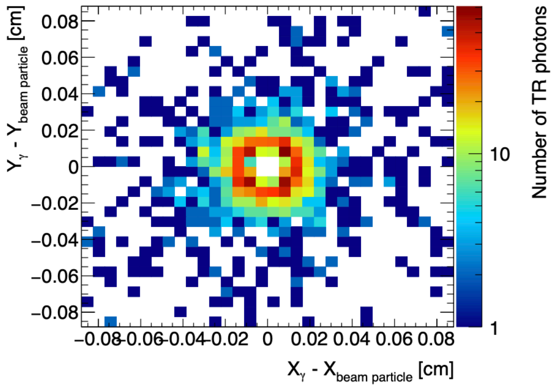
Expanded view



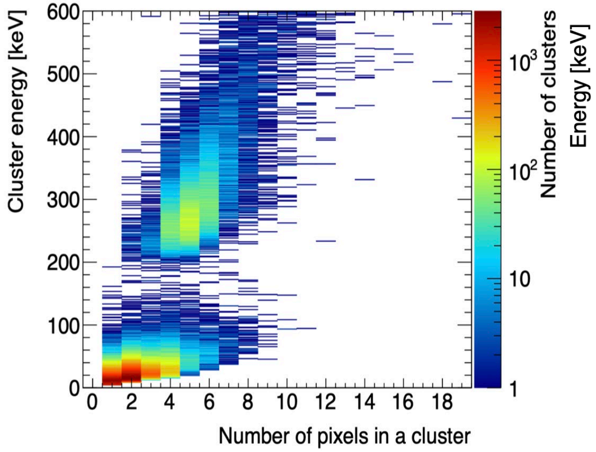
Pions



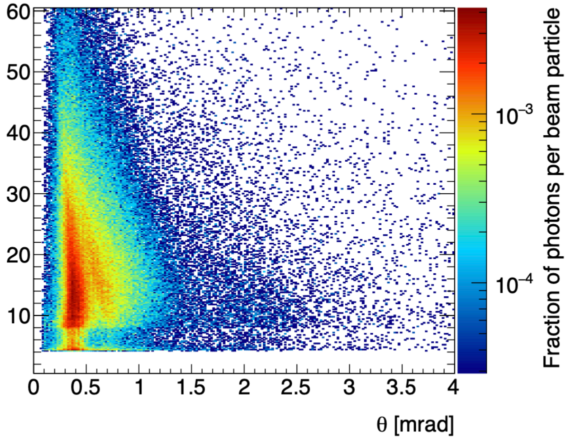
Expanded view



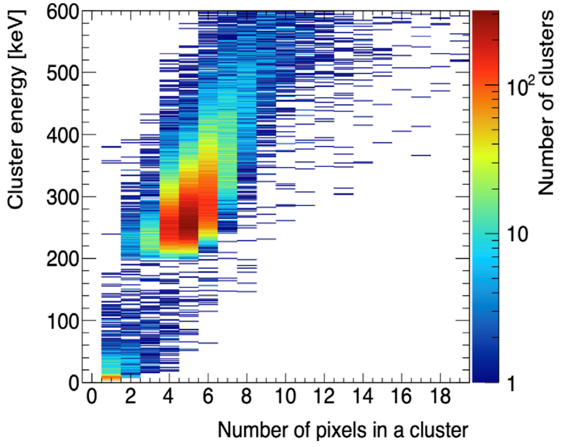
Cluster energy VS number of pixels



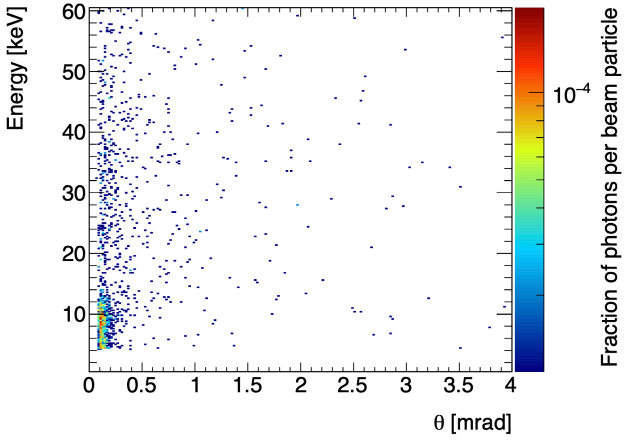
TR cluster distributions



Cluster energy VS number of pixels

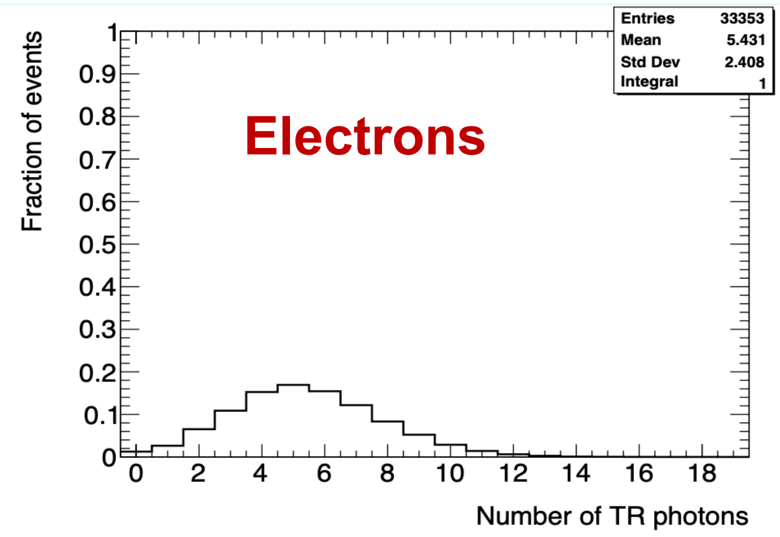


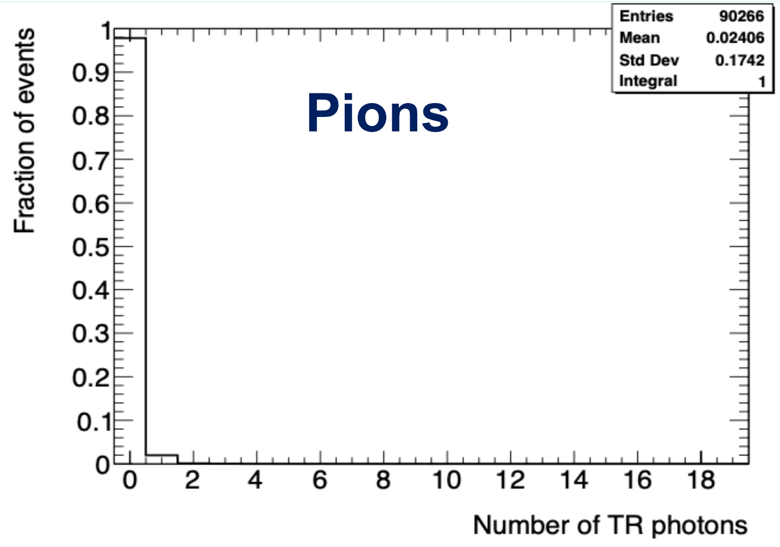
TR cluster distributions



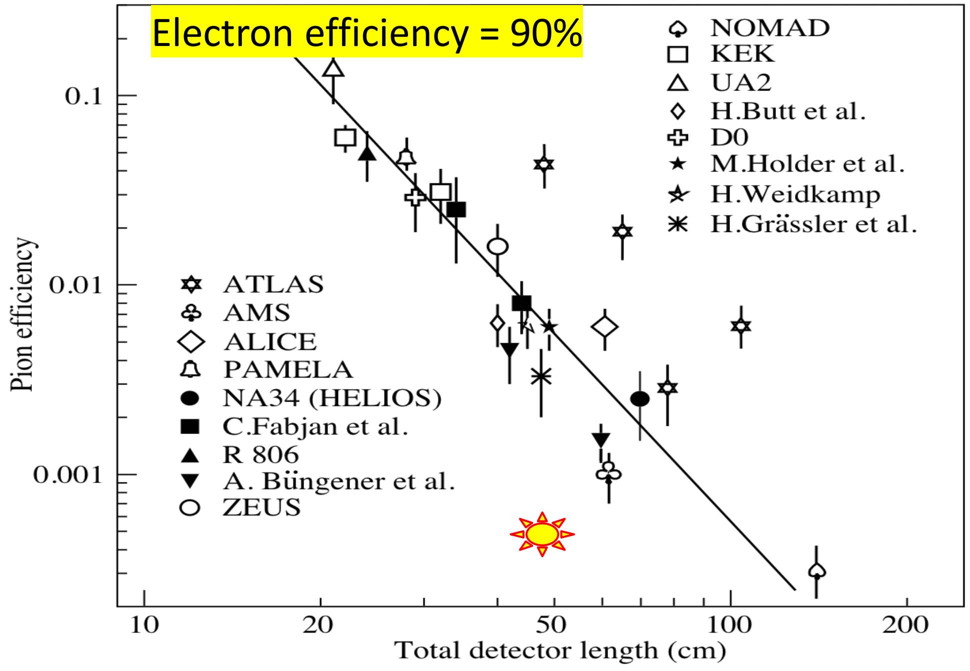
Electron/pion separation with GaAs detector with the length of 50 cm (not optimized!)

Distribution of a number of photon clusters in event





- Requirement at least one TR clusters to be present reduces pion misidentification **down to 2×10^{-2} at 98% electron efficiency**
- Requirement of more than two TR clusters to be present reduces pion misidentification **down to 4.5×10^{-4} at 90% electron efficiency**



Conclusions

- Modern technology of semiconductor detectors offers new opportunities of combining precise tracking and particle identification devices in one detector
- Preliminary studies show that separation of TR and particle dE/dX together with a simultaneous measurement of TR production energy and emission angles significantly enhances particle identification power
- Further R&D:
  - Detailed studies of the TRD based on the GaAs and other types of sensors
  - Development MC models of the TRDs based on semiconductor detectors
  - Developments of the new separation techniques with such detectors
  - Prototyping, test beam studies and data analysis
  - Detector optimization for different applications
  - ……

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