TRD technique overview

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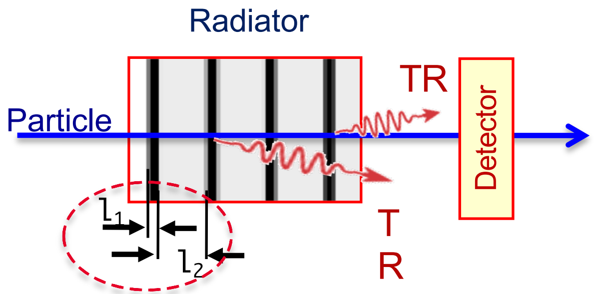
RD51 Workshop on Gaseous Detector Contributions to PID , Feb. 17th, 2021

Transition radiation: basic principles

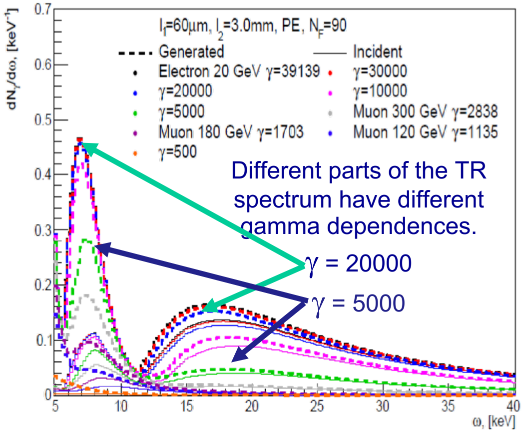
In TR of X-ray energy range is used for PID.



TR production depends on the radiator properties. For foil radiator those are:

- Radiator material (foil) thickness - **l_1**
- Distance between foils - **l_2**
- Plasma frequency ω_i which is $\sim\sqrt{\rho}$, where ρ is the material density and symbol **i** is **1** for the radiator material **2** for the gap material.

Varying these parameters one obtains different gamma-factor dependences.

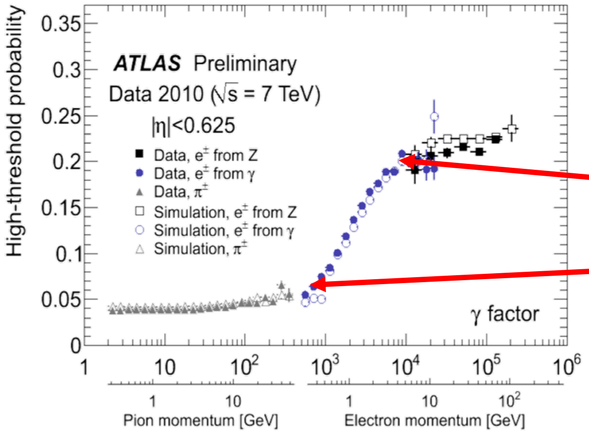


Different parts of the TR spectrum have different gamma dependences.

γ = 20000

γ = 5000

TR x-ray spectrum.



Number of X-ray TR photons VS gamma-factor.

For Air between foils main TR characteristics can be estimated using relations:

$$\omega_{max} = 0.65\,\ell_1\omega_1^2$$

$$\gamma_{\,sat} \sim 3\times10^3\ \omega_1\sqrt{\ell_1\ell_2}$$

$$\gamma_{thr} \sim 3\times10^3\ \omega_1\ell_1$$

$$\theta \approx \sqrt{1.4\pi^2/\gamma_{\,sat}^{\,2} - 1/\gamma^2}.$$

θ in mrad, ω_1 in eV, ω_{max} in keV and l_1 and l_2 in mm

NIM, A 961 (2020) 163681

Transition radiation: basic principles

TR theory well developed. One of the approach often used described in M. Cherry et al. Phys. Rev. D 10 (1974) 3594.

One foil

Interference term for N foils

$$\frac{d^2N_{gen}}{d\theta d\omega} = \boxed{4\frac{d^2N_0}{d\theta d\omega}\sin^2\left(\frac{l_1}{Z(\omega_1)}\right)}\boxed{\frac{\sin^2\left(N\left(\frac{l_1}{Z(\omega_1)}+\frac{l_2}{Z(\omega_2)}\right)\right)}{\sin^2\left(\frac{l_1}{Z(\omega_1)}+\frac{l_2}{Z(\omega_2)}\right)}},$$

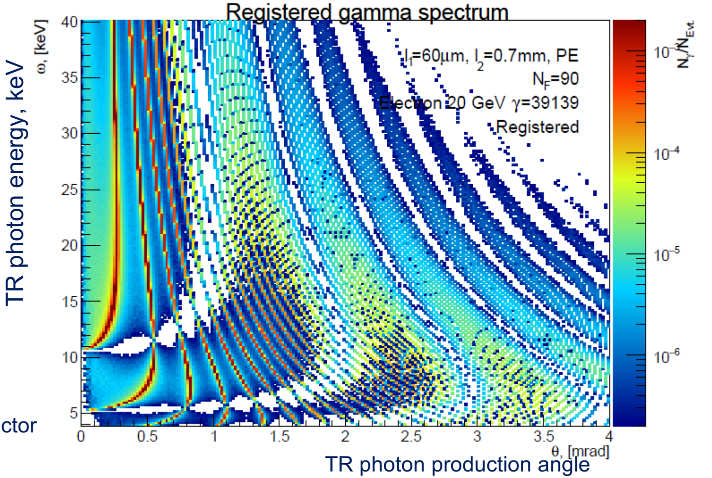
One boundary

$$\frac{d^2N_0}{d\theta d\omega} = \frac{1}{c}\left(\frac{qe}{4\pi c}\right)^2\theta^3\omega\left(Z(\omega_1)-Z(\omega_2)\right)^2$$

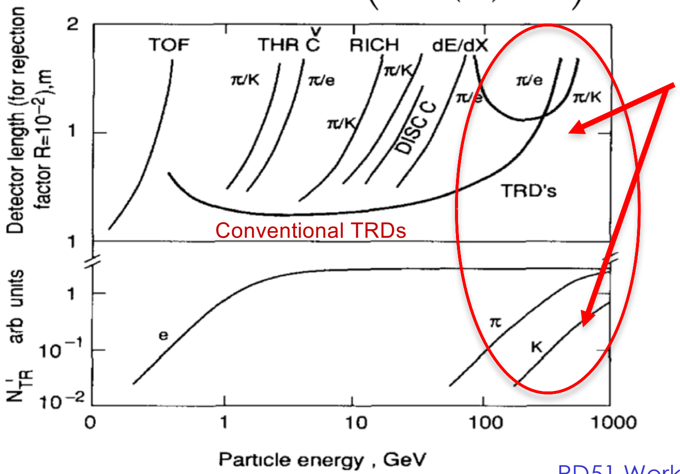
For irregular radiators:
NIM, 125 (1975) 133–137

TR formation zone

$$Z(\omega_i) = Z(\theta,\omega,\omega_i) = \frac{4c}{\omega\left(\gamma^{-2}+\left(\frac{\omega_i}{\omega}\right)^2+\theta^2\right)}.$$



TRDs have the largest gamma factor range.



Mainly used well for separation of particles up to gamma factors few*10³.
But it is not a limit!

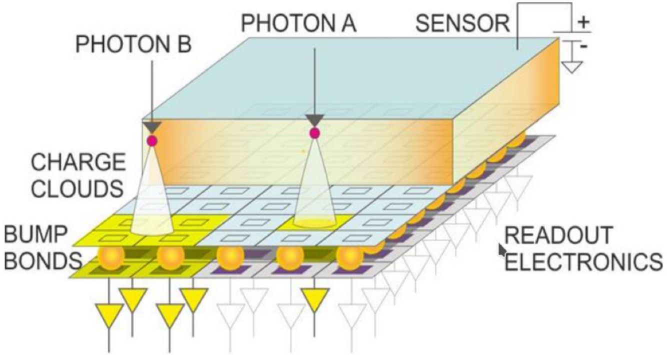
Main TR parameters its energy and production angle. TRT production angle depends on gamma-factor and may bring an additional PID information.
One or more photons are generated by in 30 foils the main questions are:
how to avoid their absorption in the radiator and how to detect them?

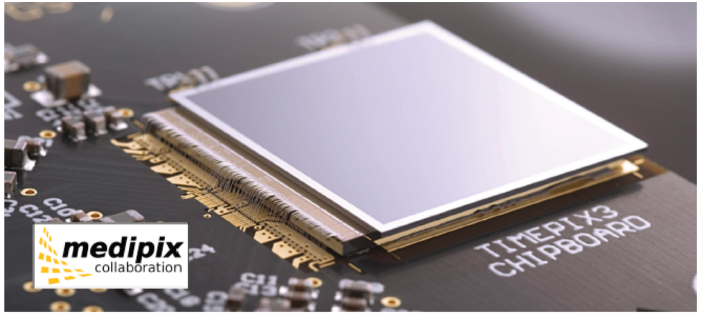
TRD reviews:
NIM, A326 (1993) 434–469
NIM, A666 (2012) 130–147
Review of Particle Physics, PTEP, v. 2020 issue 8.

Basic approach for any detector:

Theory → Simulation model → Prototype → Corrections of the detector model → Detector optimization, design and production.

How well TR can be simulated?





Beam tests wth TimePix3 front-end chip attached to Si or GaAs sensors.

NIM, A 961 (2020) 163681
J. Phys.: Conf. Ser.,1690 (2020), 012041

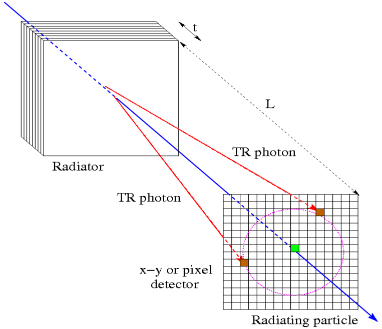
Timepix3 front-end hybrid pixel readout chip:

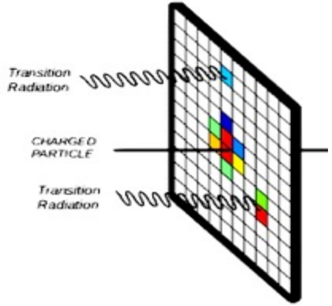
- Various sensor materials possible.
- Simultaneous per-pixel measurement of a time-of-arrival (ToA) and the time-over-threshold (ToT).
- Time resolution of 1.56ns and
- Spatial resolution of ~16µm
- 256 x 256 pixel matrix with 55 x 55 µm2 pitch
- throughput of up to 40 Mhits/s/cm2

TimePix4 with improved time measurements is coming soon (see later)

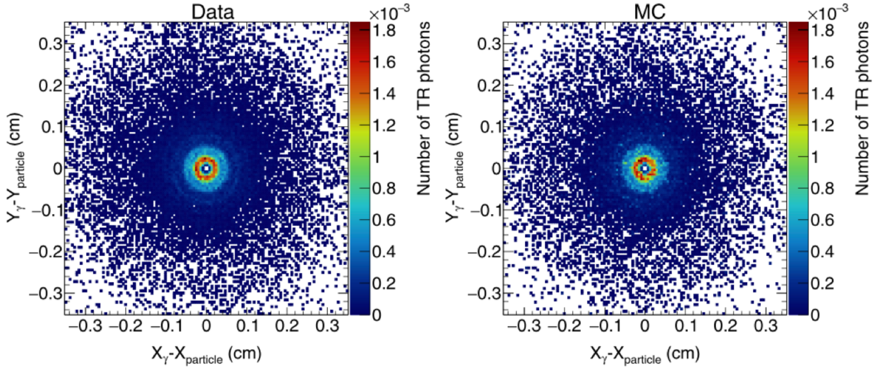
Data/MC comparison. Si sensor. Electrons 20 GeV.

NIM, A 961 (2020) 163681

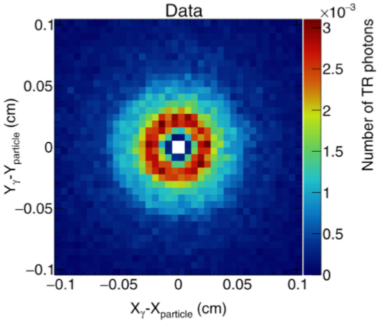


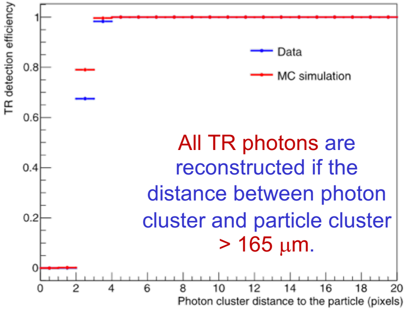


Mylar radiator 50 μm, 2.97 mm spacing, 30 foils

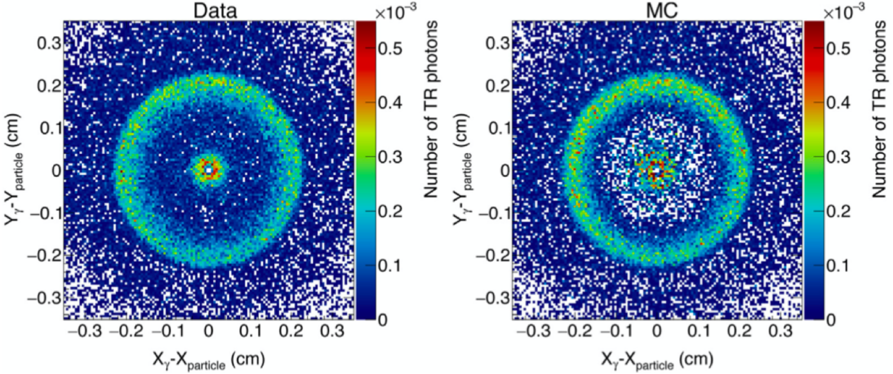


PE radiator 15.5 μm, 222 (±13%) μm spacing, 180 foils





All TR photons are reconstructed if the distance between photon cluster and particle cluster > 165 μm.



Data/MC comparison. Si sensor.

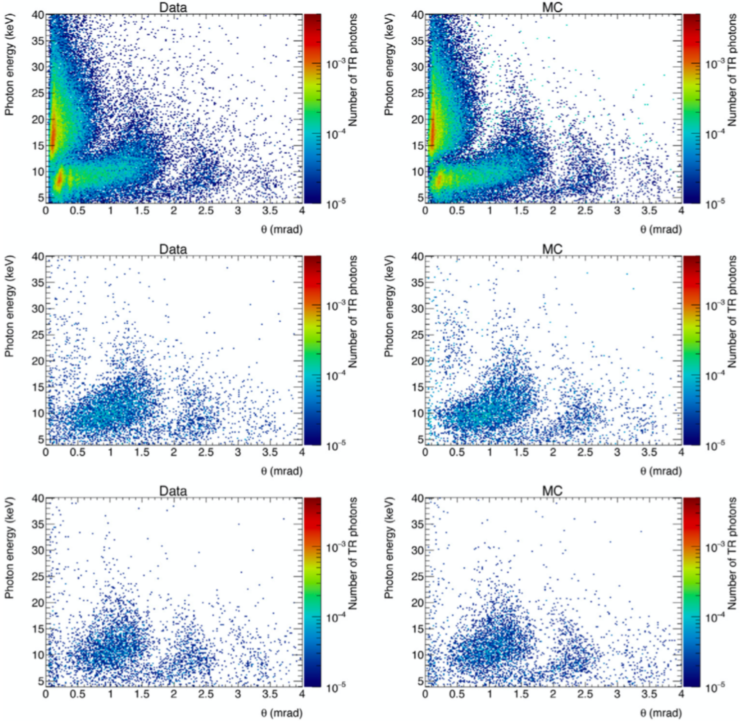
NIM, A 961 (2020) 163681

Electrons
20 GeV

Muons
180 GeV

Muons
120 GeV

Mylar radiator 50 μm, 2.97 mm spacing, 30 foils



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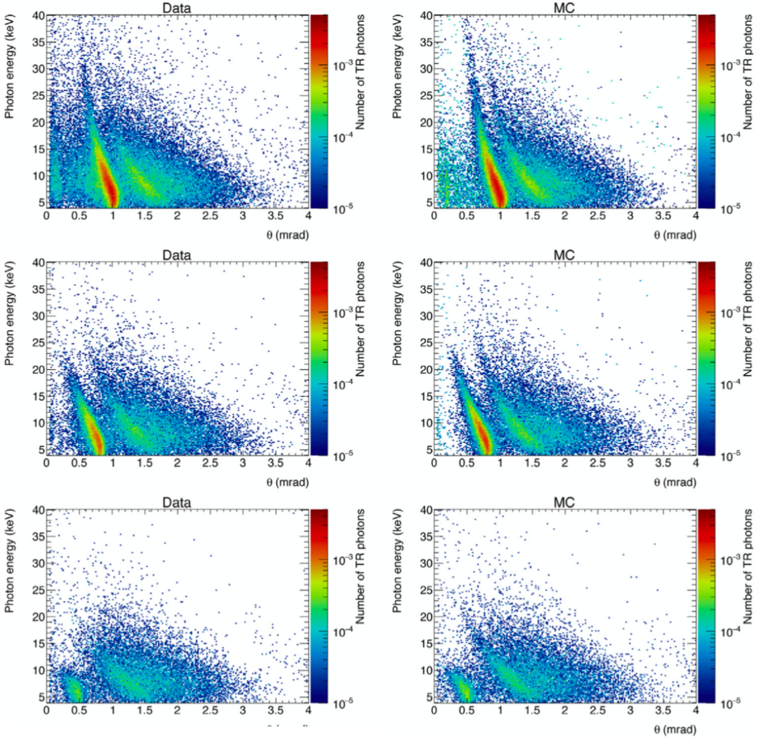
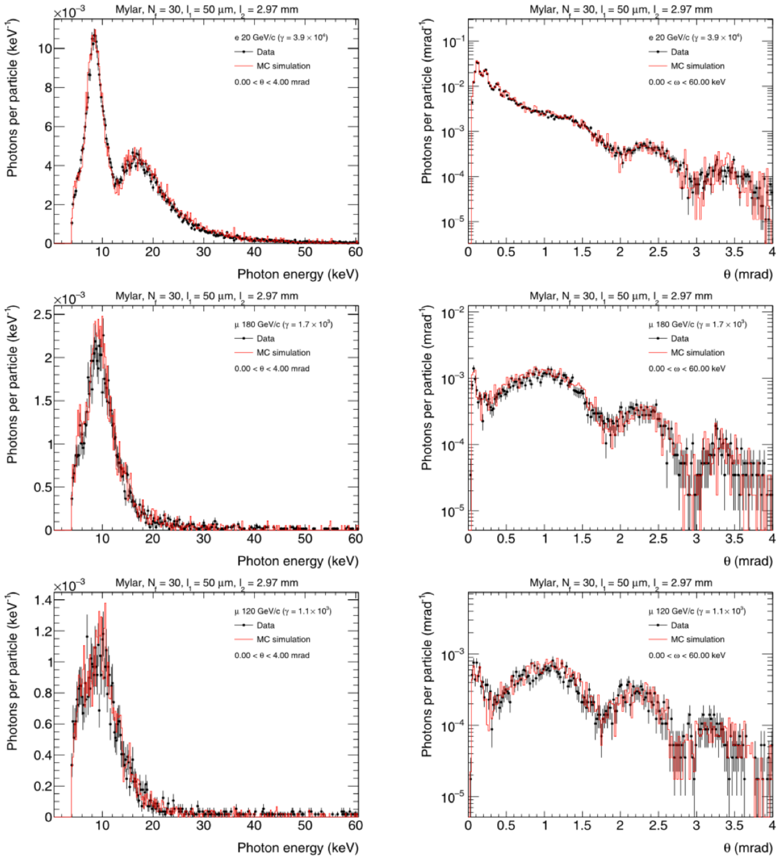


Two-dimensional distributions of TR photon energy (Y) VS production angle

Data/MC comparison. Si sensor.

NIM, A 961 (2020) 163681

Mylar radiator 50 μm, 2.97 mm spacing, 30 foils



Electrons
20 GeV

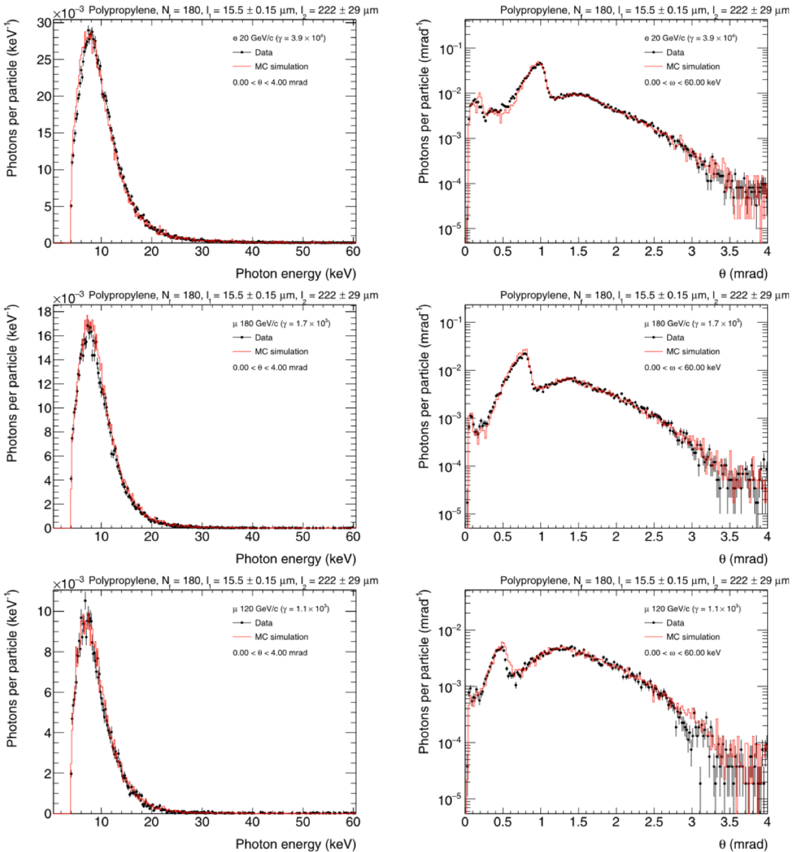
Muons
180 GeV

Muons
120 GeV

Energy spectra of TR photons.

Angular distribution of TR photons.

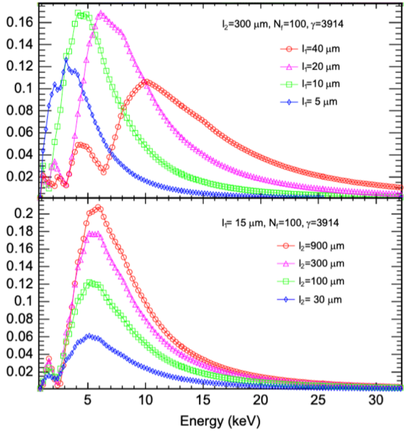
PE radiator 15.5 μm, 222 (±13%) μm spacing, 180 foils



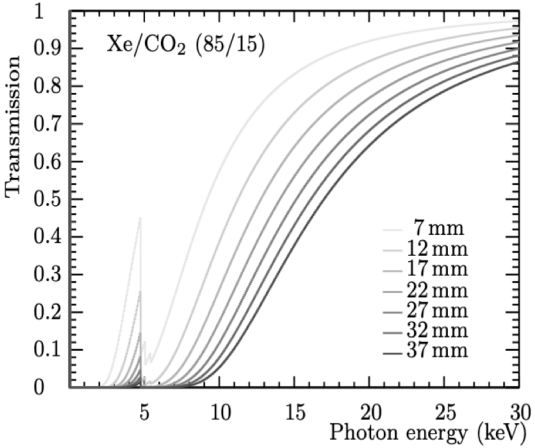
Energy spectra of TR photons.

Angular distribution of TR photons.

Gas based TRDs: concepts

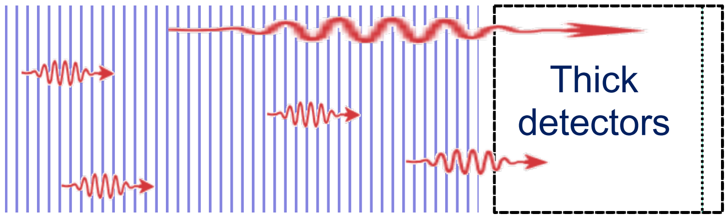


TR photon spectrums for different radiator parameters



Fraction for photons passed through the detectors with different gas thicknesses as a function of photon energy.

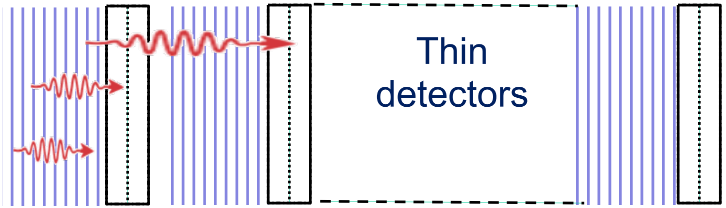
- *The TR and dE/dX losses are overlapped.*
- *dE/dX measurements improve PID at low momentums.*
- *All modern TRDs provide also tracking information.*
- *Both types of doctors are used in the accelerator and cosmic-ray experiments*



In “thick” detectors the radiator, optimized for a minimum total radiation length at maximum TR yield and total TR absorption in the detector. Radiator usually consists of few hundred foils or equivalent material.

Most of the soft TR photons are absorbed in the radiator itself and spectrum is shifted to higher energies.

e.g.UA2, NA34, ALICE …



Fine granular radiator/detector structure exploits the soft part of the TR spectrum more efficiently. Radiator usually consists of few dozens of foils or equivalent material.

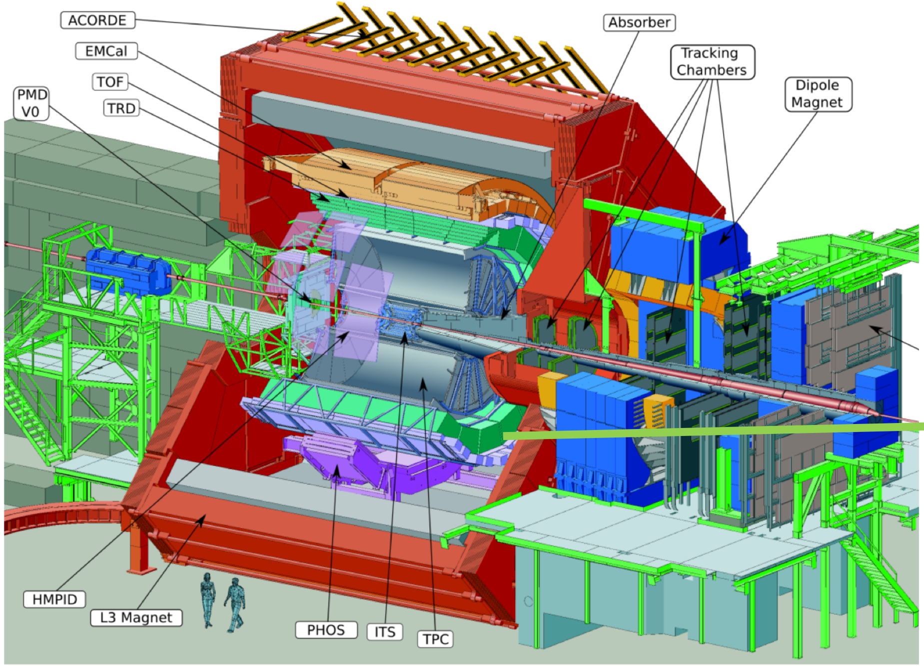
TR can be registered by several consecutive detector layers. Walls of the detector layers are made from thing foils and also produce TR.

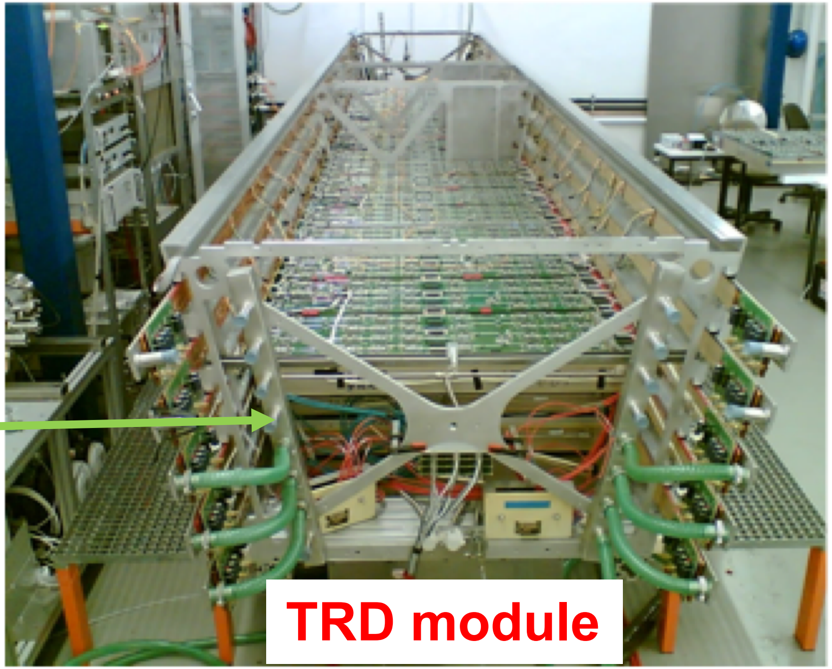
ATLAS, AMS-2, TRD for Pamela experiment

ALICE experiment

Dedicated for heavy-ion studies at LHC.

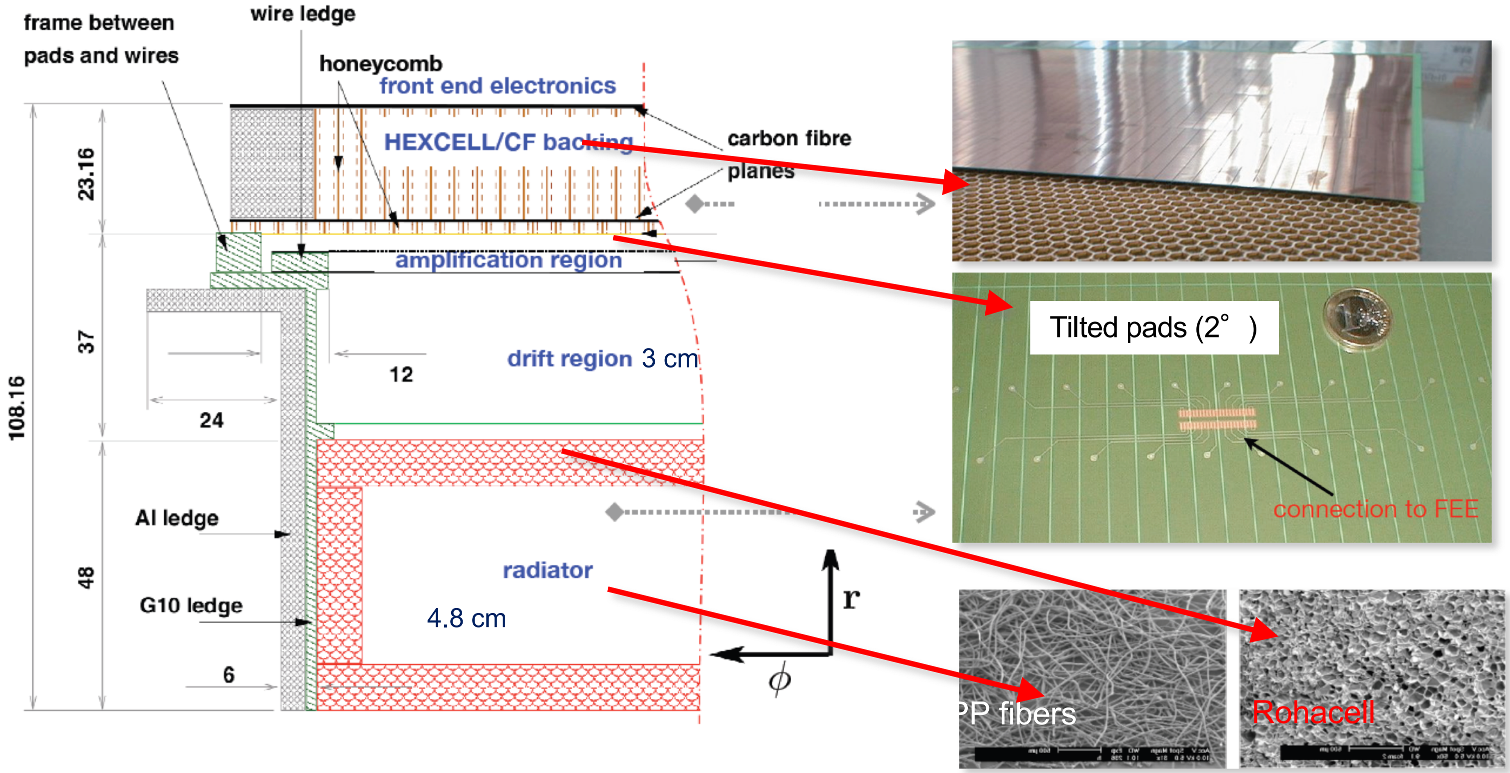
Optimized or Pb-Pb collisions. Particle identification in relatively low particle momentums.




TRD module

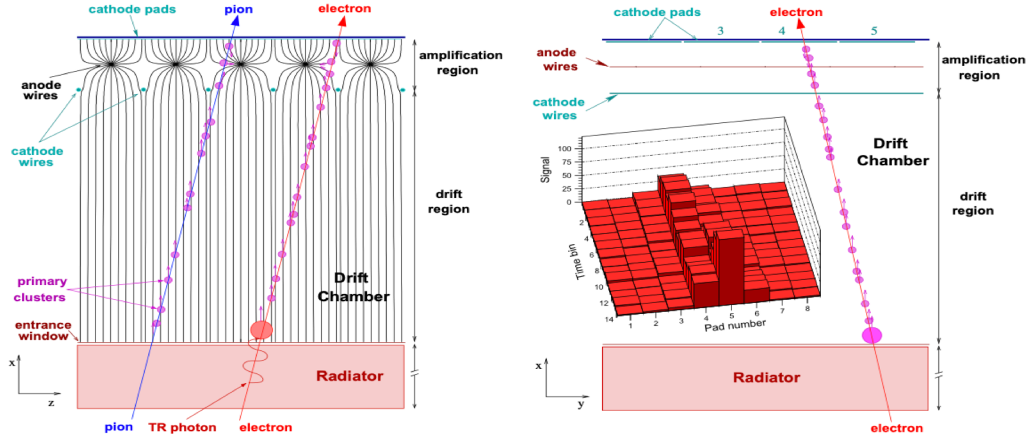
ALICE TRD: thick detector concept

6 TRD layers. Pad readout.

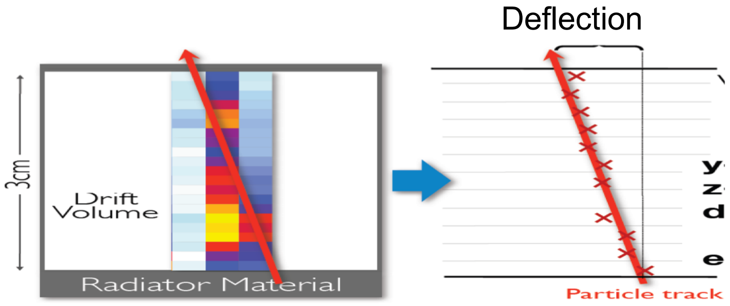


ALICE TRD: thick detector concept

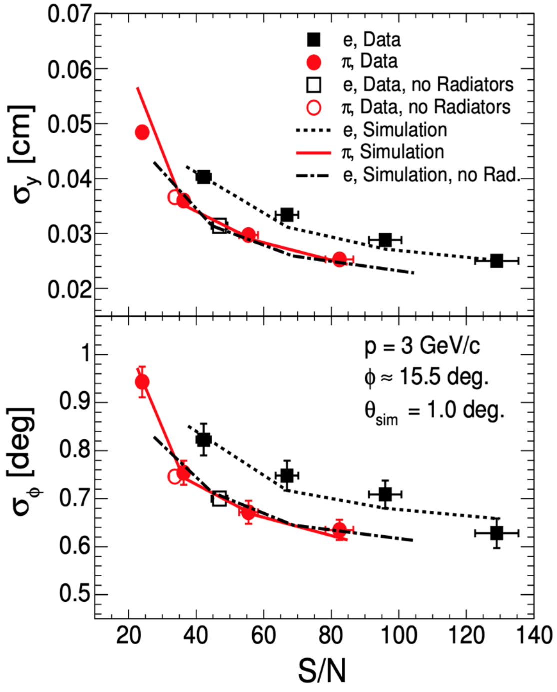
*ALIICE: NIM, A*881 (2018) 89-127



Drift space 3 cm, pad-readout



Signal amplitude on pads for different time bins.



Track position and track angle accuracies as a function signal to noise ratio.

ALICE TRD: thick detector concept

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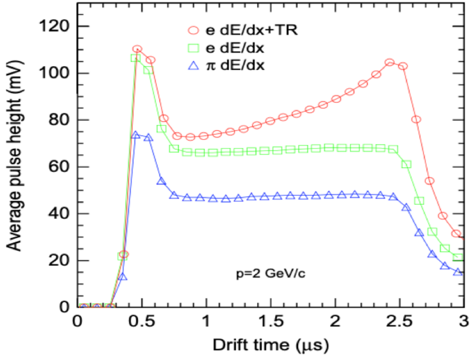
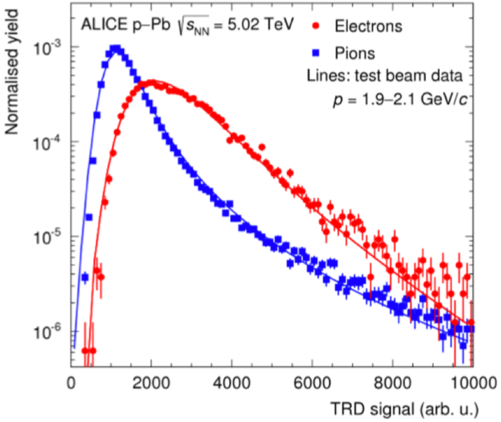
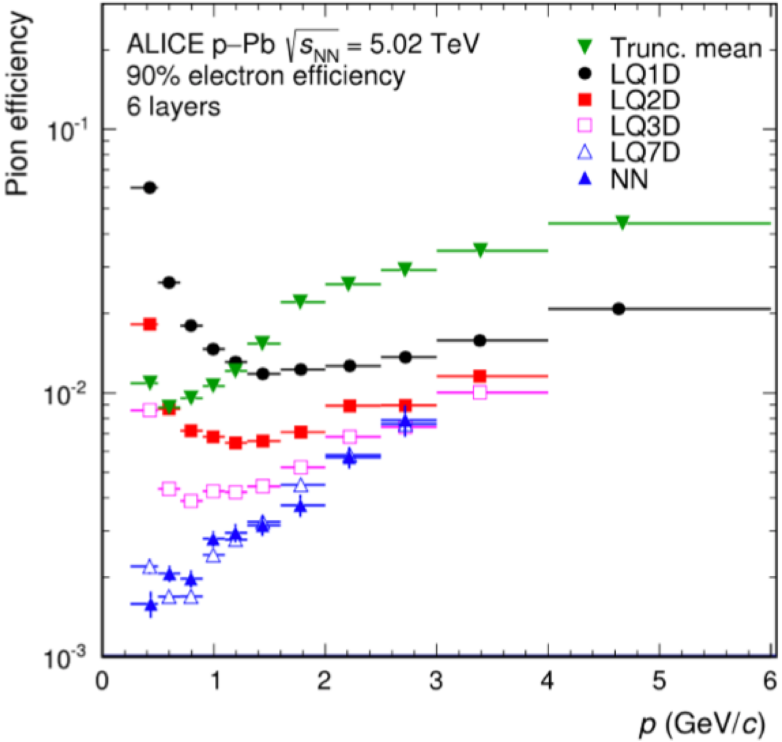


Averaged signal amplitude as a function of time.

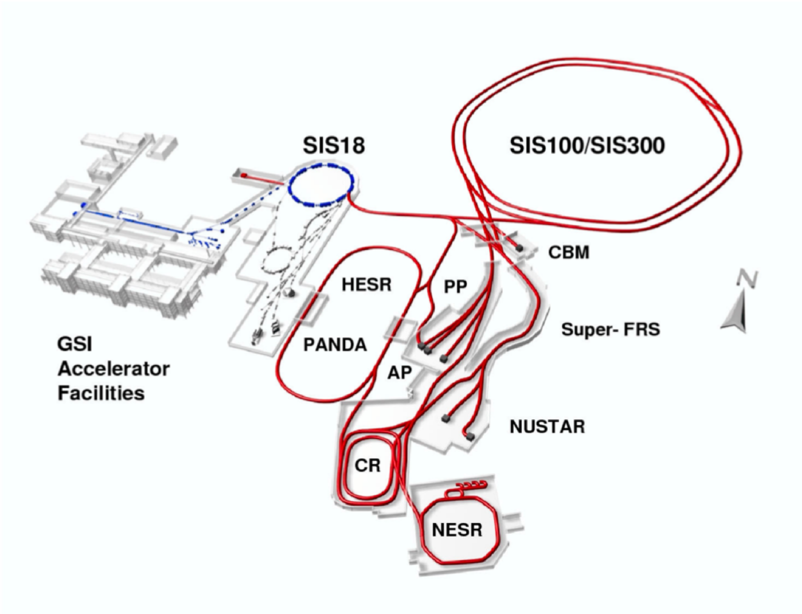


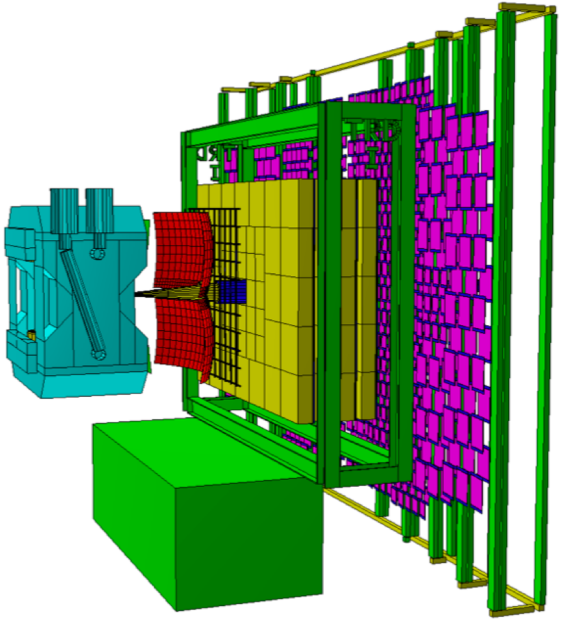
TRD signal distribution in one layer for different particle type



Pion efficiency as a function of particle momentum using different analysis methods.

TRD CBM (FAIR)



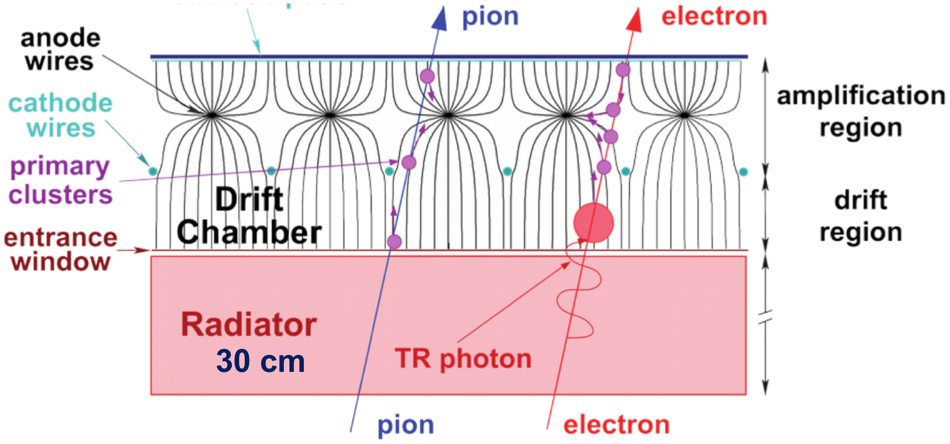


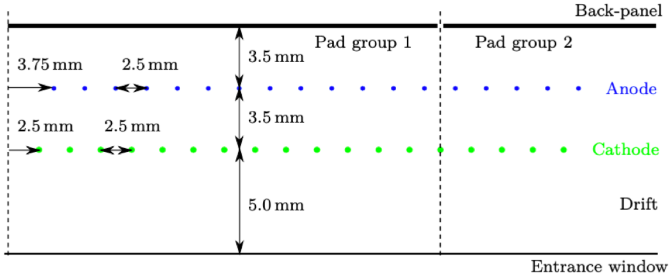
CBM: NIM, A 732 (2013) 375-379
CMB TRD TDR: DOI:10.15120/GSI-2018-01091

TRD for CMB: intermediate detector concept

High rate application. Drift distance reduced to 5 mm.

Pad readout. Total energy is counted

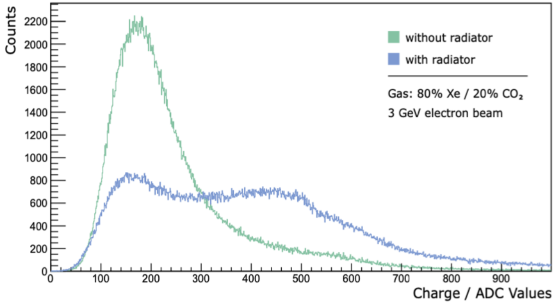




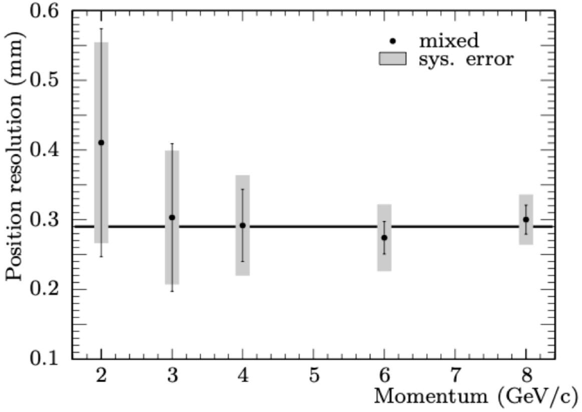
Test beam prototype of large chambers.
4 TRD layers

TRD for CMB: intermediate detector concept

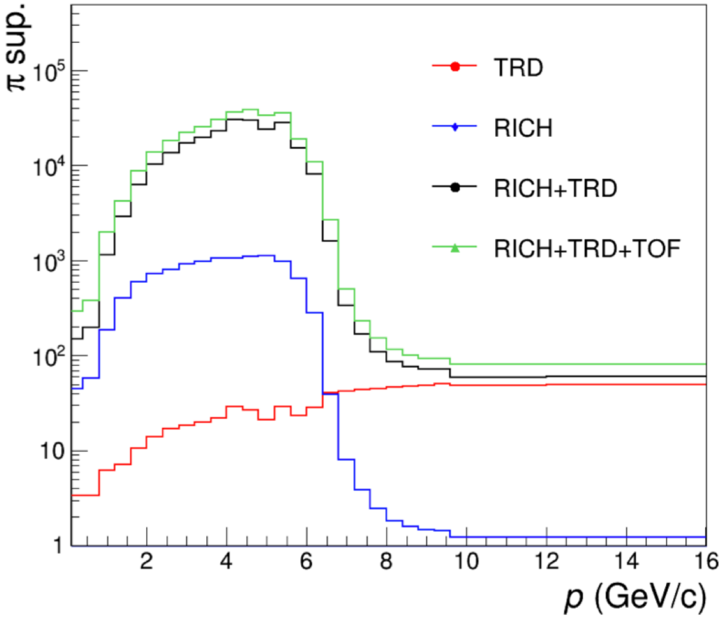
Performance.



Signal amplitude for electrons with and without radiator.

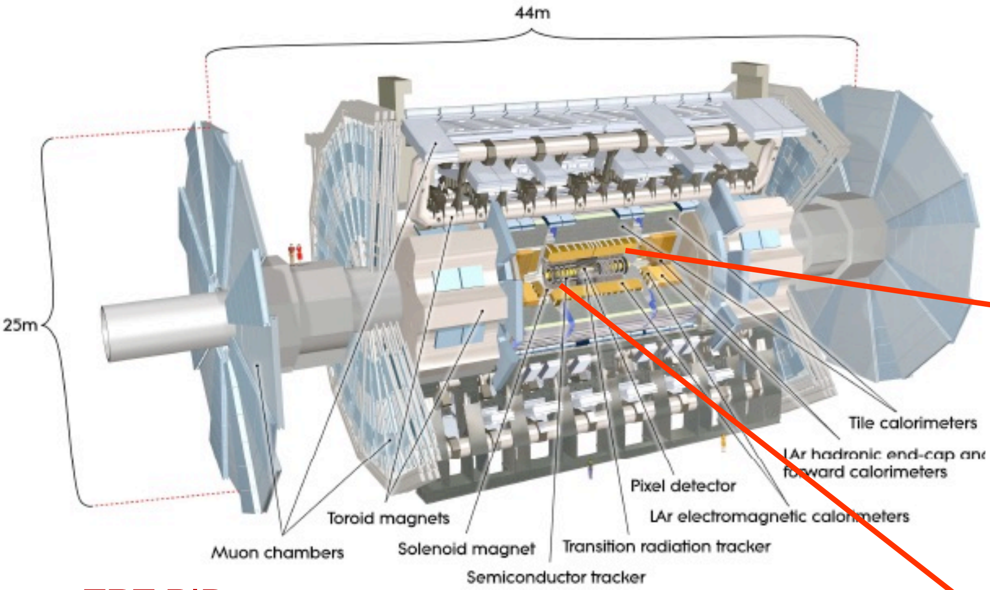


Track position and track angle as a function signal to noise ratio. Pad width 6.8mm.



Pion suppression factor as a function of particle momentum.

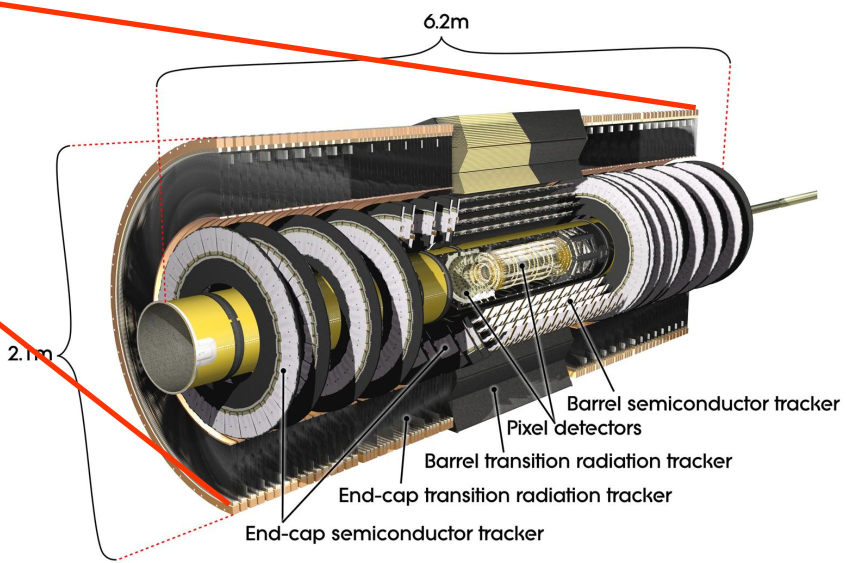
ATLAS TRD: thin detector concept



ATLAS ID consists of Pixel detectors, Semiconductor Tracker and **Transition Radiation Detector (TRT)**

TRT:

- **Electron identification** for particles with $|\eta|<2$ and $0.5 < p_T < 150$ GeV
- Continuous tracking.
- Particle momentum measurements.

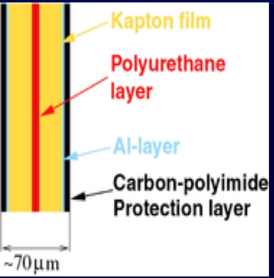


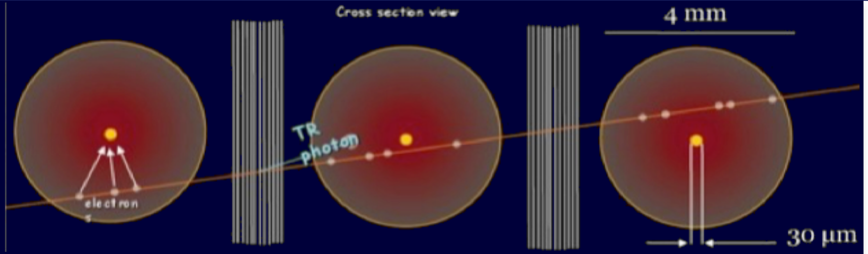
TRT PID:

- Electron identification
  - HL trigger
  - Offline
- Conversion reconstruction
- Electron veto for hadronic τ-decays

Normally, use of the TR Techniques uses 90% electron efficiency criteria. But for physics more often softer criteria are used. In The ATLAS that is 95% so called tight cut and 98% so called medium CUT

TRT – Straw based detector





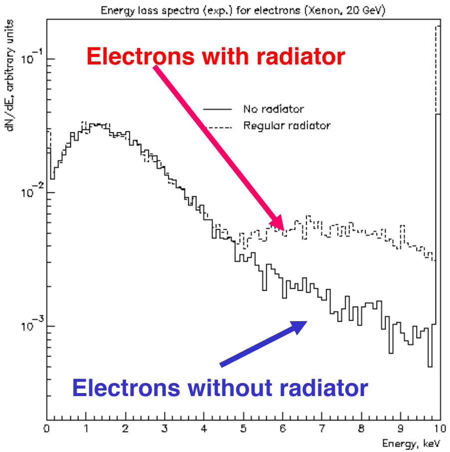
Signal in the detector is a superposition of dE/dX and TR

"Mutually contradictory requirements":

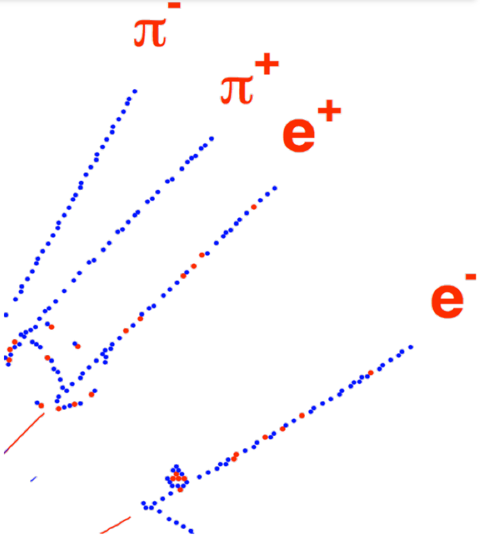
- *Should have no material (TR).*
- *No cathode résistance (fast signal)*
- *Survive at any conditions (sLHC)*
- *Be a part of the mechanical support (real detector.*

Operation conditions:

- *Particle rate – up 20 MHz*
- *Particle density up to 500 kHz/cm*
- *Accumulated charge up to 10 C/cm of*
- *Current up to 10 μA per wire*
- *Ionization current density ~015 μA*
- *Total ionization current ~ 3 A*
- *TRT ionization current power ~5 kW*



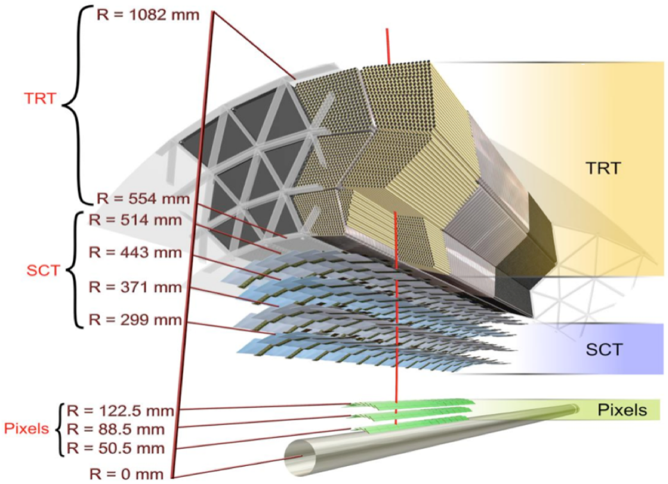
Differential spectrum of the energy loss in the straw.



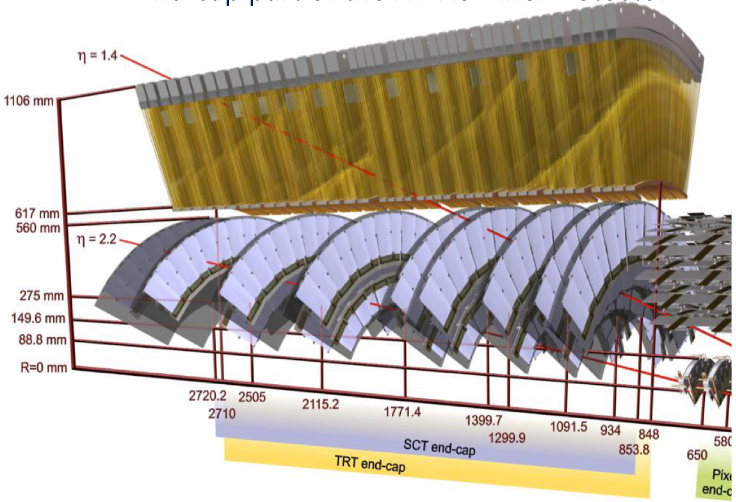
ATLAS TRD: thin detector concept

Two different detector design for the Barrel and End-Caps

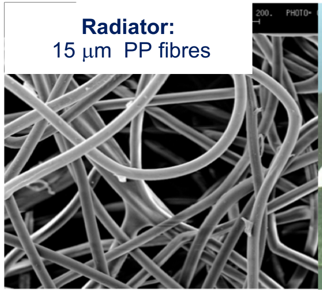
Barrel part of the ATLAS Inner Detector

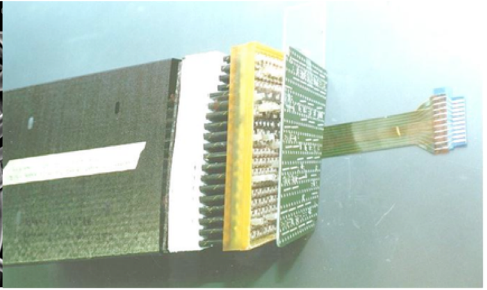


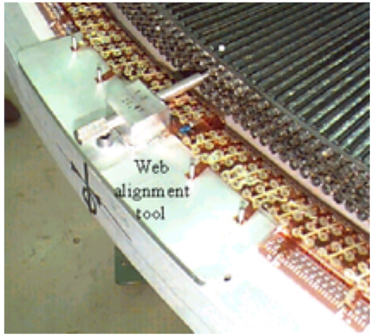
End-cap part of the ATLAS Inner Detector

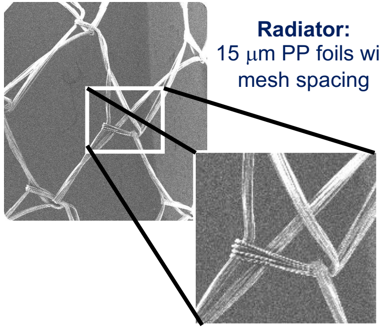


Radiator:
15 μm PP fibres



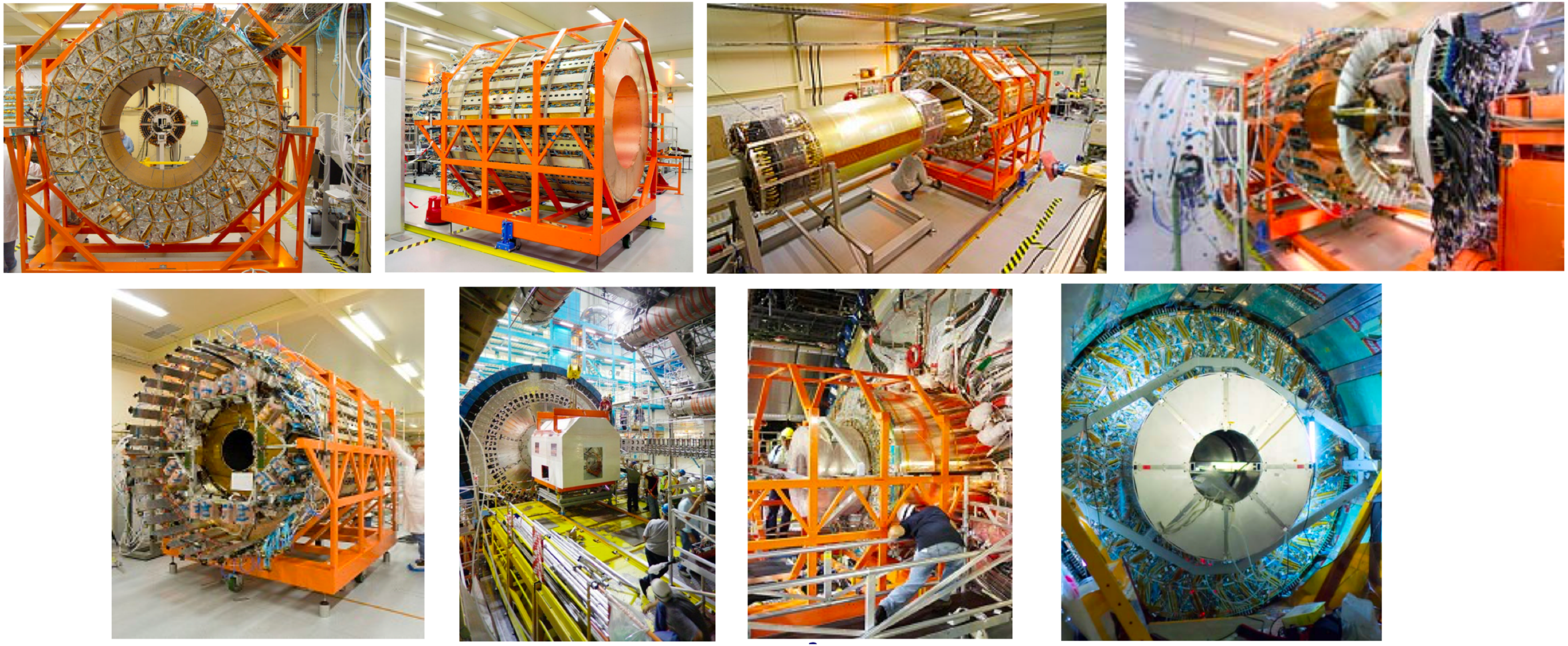






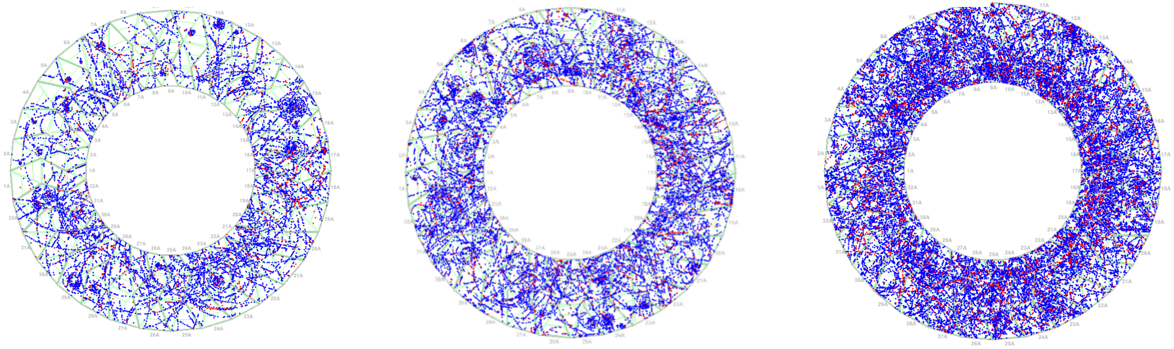
Radiator:
15 μm PP foils with
mesh spacing

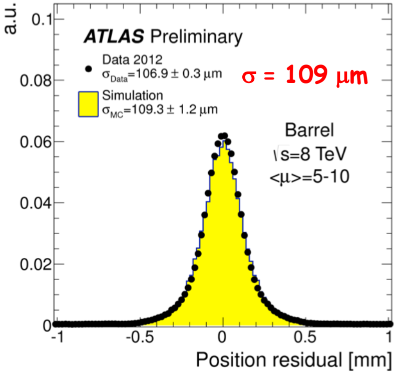
ATLAS TRD: thin detector concept



TRT Tracking performance.

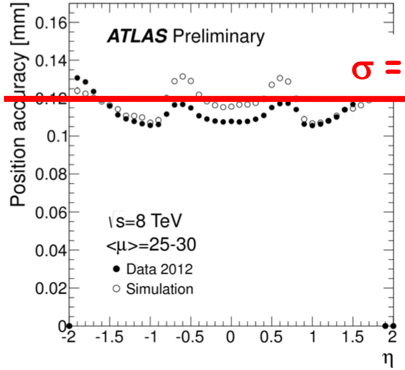
Track in the TRT crosses ~ 30 straws. TRT occupancy is one of the problems





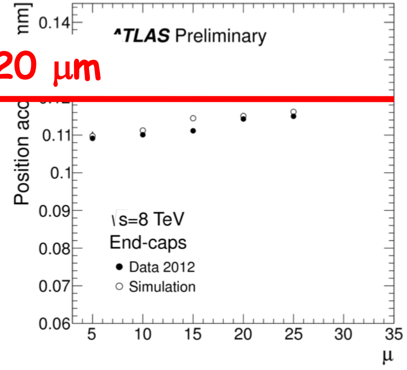
σ = 109 μm

Track to drift-radius residual distribution



σ = 120 μm

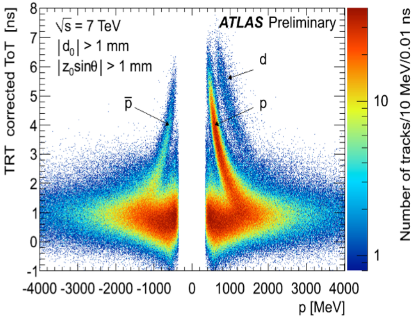
TRT straw position measurement accuracy as function of pseudorapidity



TRT straw position measurement accuracy as function average number of interactions per bunch

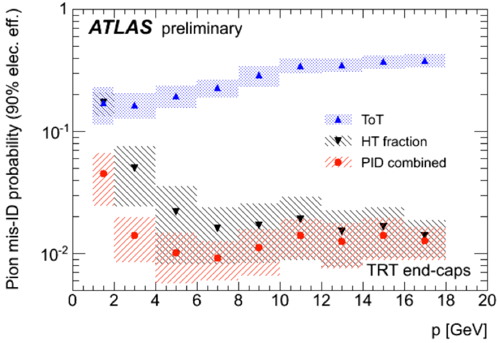
TRT performance: PID

Additional e/pion separation in time-over-threshold for low momentum particles

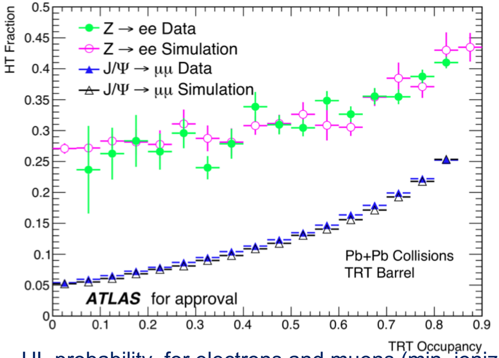


dE/dx performance using time-over-threshold

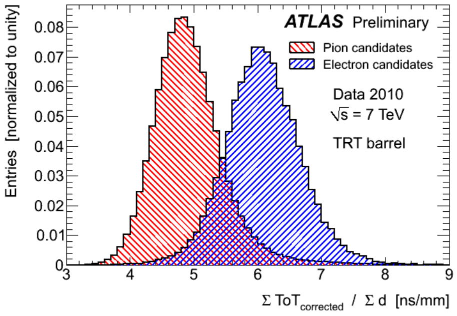
dE/dX + TR



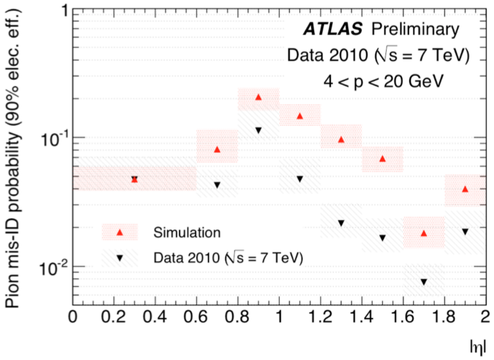
Pion misidentification as a function pion momentum



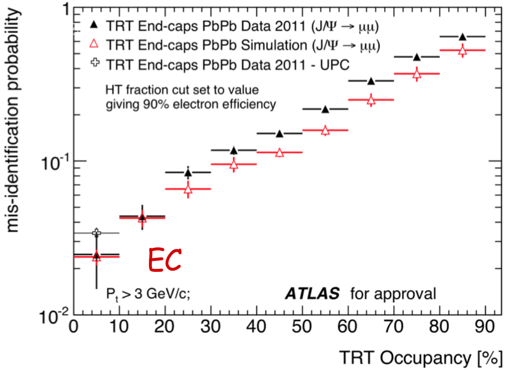
HL probability for electrons and muons (min. ionizing particles) as function of TRT occupancy



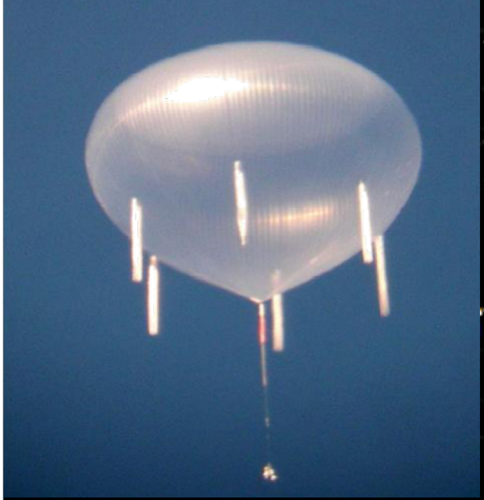
Electron/pion separation using only ToT method.



Pion misidentification as a function of ETHA



Pion misidentification as a function of TRT occupancy



TRDs for space applications.

Most often case: ELECTRONS AND POSITRONS separation from pion and proton background

Expected relative abundances:

- ***$e^-/p \leq 10^{-2}$***
- ***$e^+/p \sim 10^{-4}$***

Required discrimination at least 10^{-3} to 10^{-5}

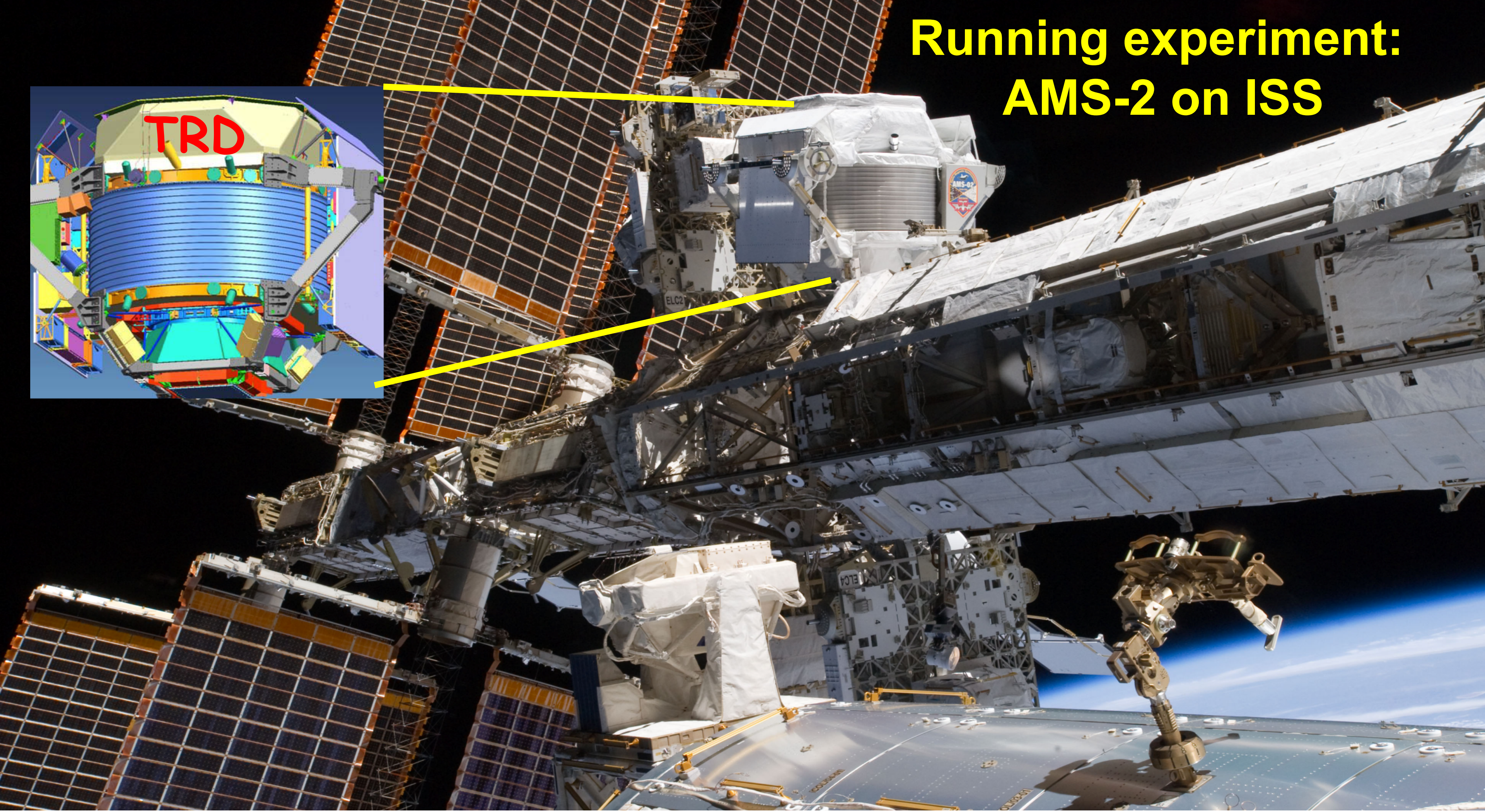
TRD:

e-p rejection requirement ***10^2 to 10^3***

Threshold TRD’s: Electron and Positron Measurements (TREE, HEAT, AMS)

TRD’s for Energy Measurements of Cosmic-Ray Nuclei (CRN, TRACER, CREAM)

Running experiment: AMS-2 on ISS

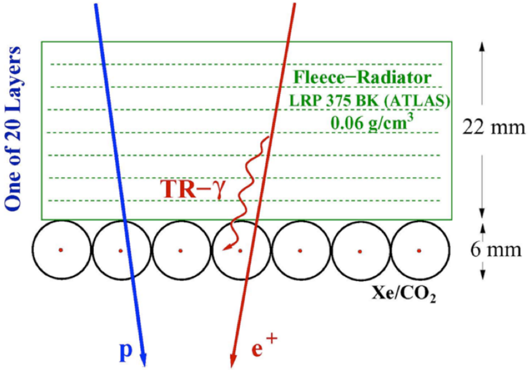


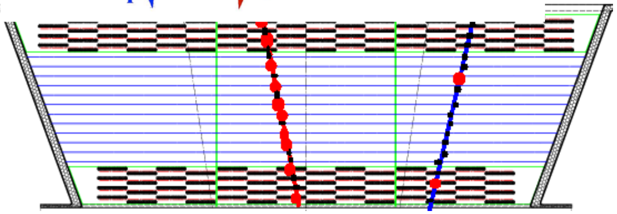
AMS-02 TRD: Thin detector concept

NIM. A706, 2013, 43-47

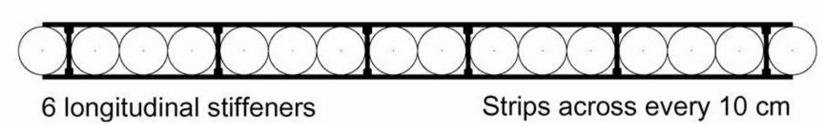
Straw tube proportional counter modules:

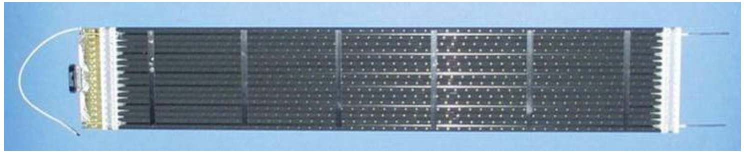
- Straw tubes: 72 μm multilayer aluminium kapton foil,
  Ø 6 mm , 0.8 ÷ 2.0 m length
- Wire: tungsten anode wire, 30 μm Ø, tension ≈ 100 g
- Gas mixture: Xe / CO_2 (80% / 20%) → to be optimized
- Operating HV ~ 1460 V → Gasgain of ~ 3000
- 1 Module → 16 Straws, 100 μm mechanical accuracy
- 328 Modules → 5248 Straws





Straws and radiators from the TRT developments





Chosen configuration for 60 cm height:

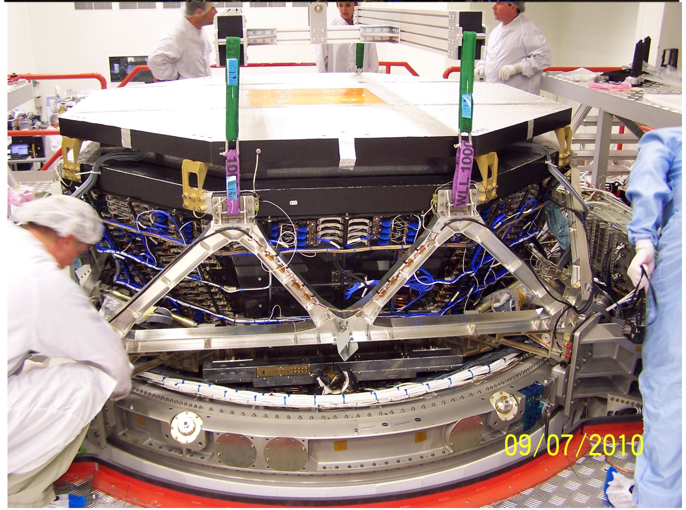
20 Layers each existing of:

- 22 mm fibre fleece
- Ø 6 mm straw tubes (Xe/CO_2 80%/20%)

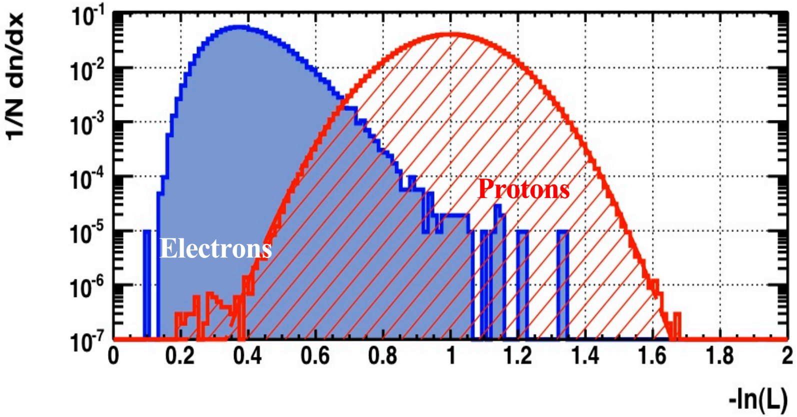
Non-bending plane: 2x4 layers

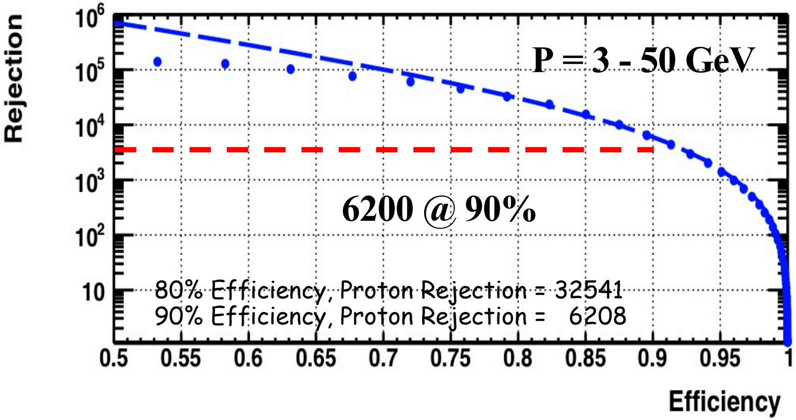
Bending plane: 12 layers

AMS-02 TRD: Thin detector concept



Straws and radiators from the TRT developments



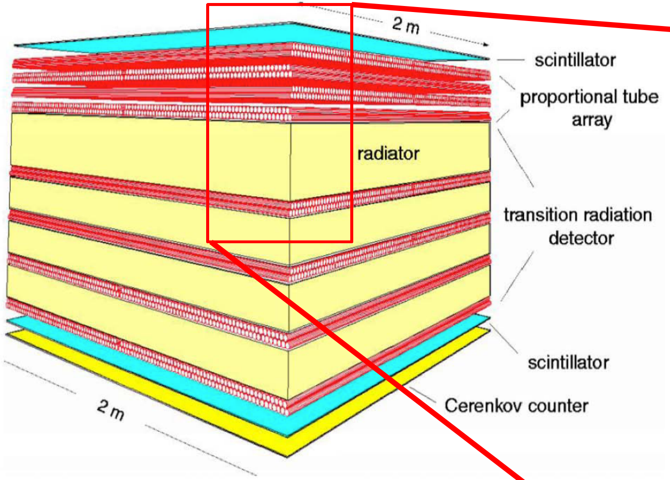


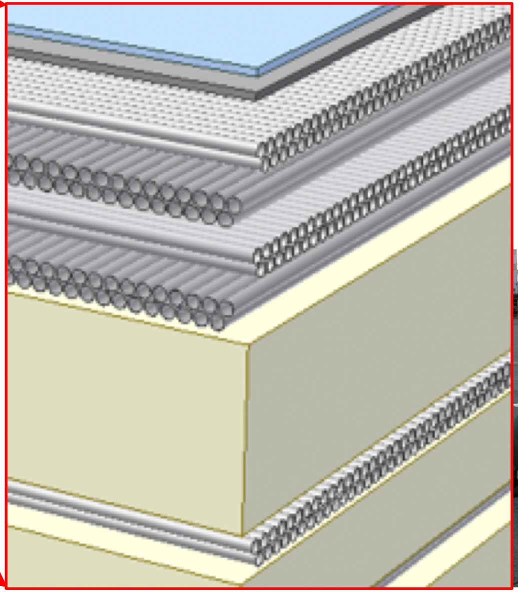
TRACER - balloon experiment : intermediate detector concept

TRDs: Lorentz factor measurements.

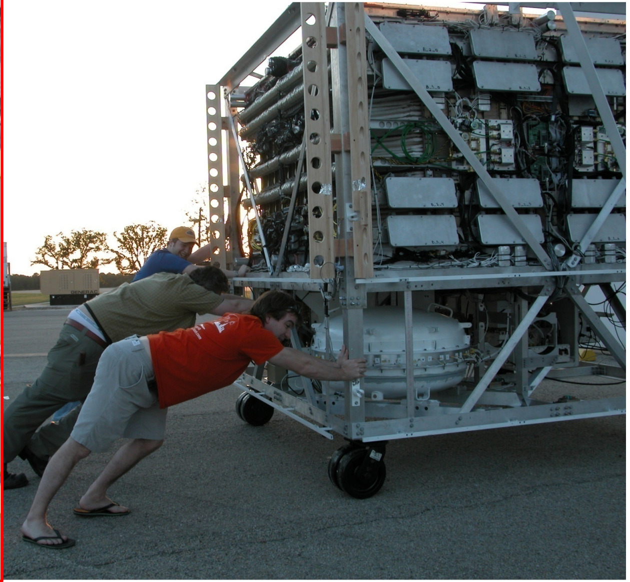
$N_{TR} \sim Z^2$ particle

TRACER Detector System
“Transition Radiation Array
for Cosmic Energetic





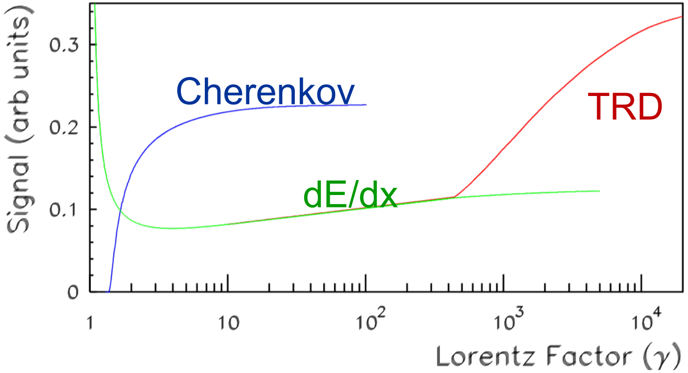
TRACER IS BIG:
5 m^2 area - the largest balloon-borne cosmic-ray detector

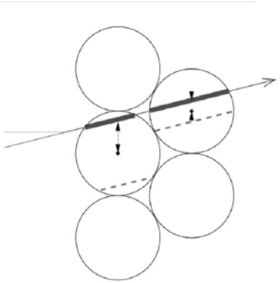


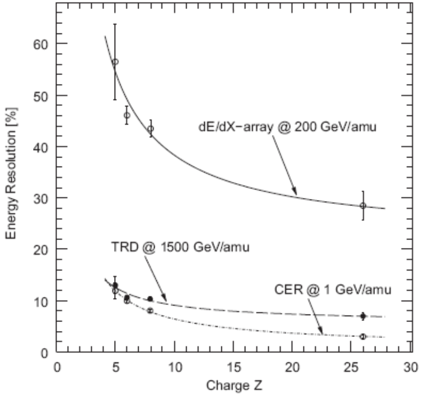
TRACER has 16 layers Mylar straws of 20 mm diameter, 8 for dE/dx measurement,
and 8 for dE/dx+TR

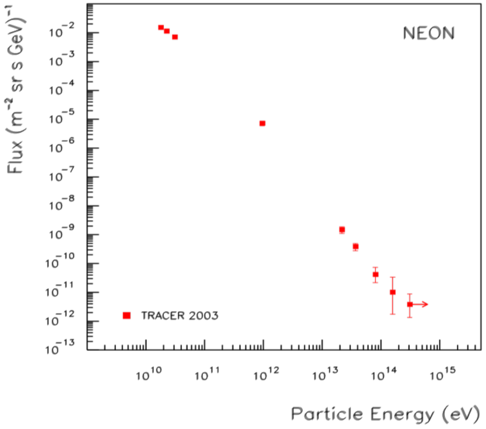
TRACER - balloon experiment : intermediate detector concept

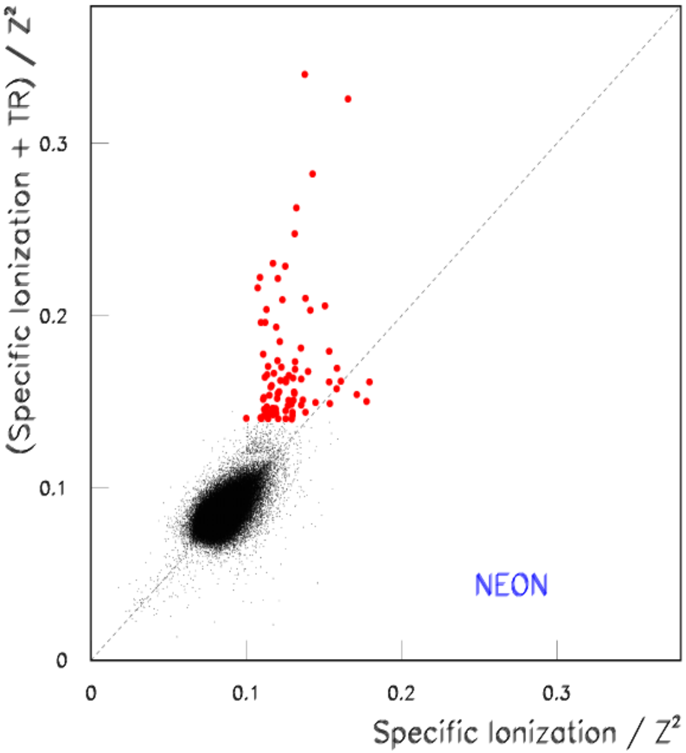
TRDs: Lorentz factor measurements.



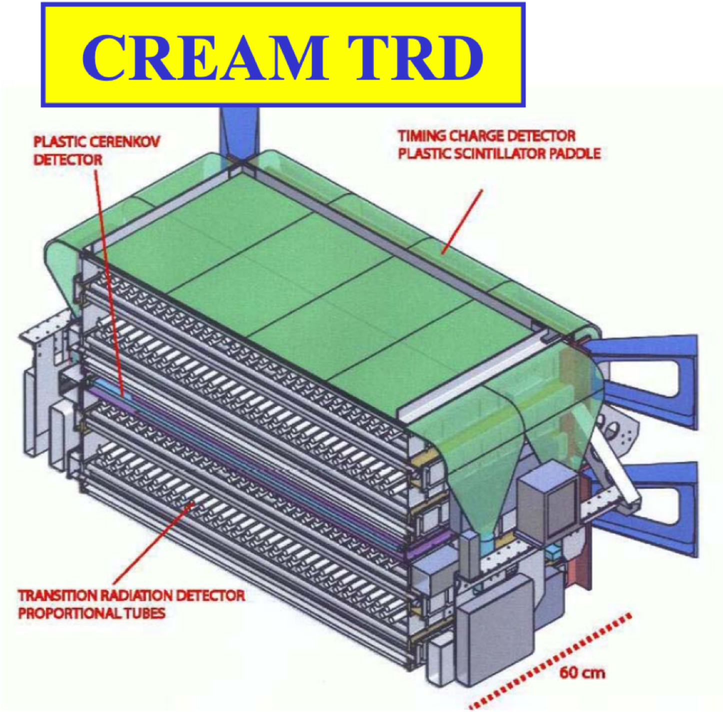








CREAM - balloon experiment : intermediate detector concept



:

Detector: array of Mylar straws of 20 mm diameter.

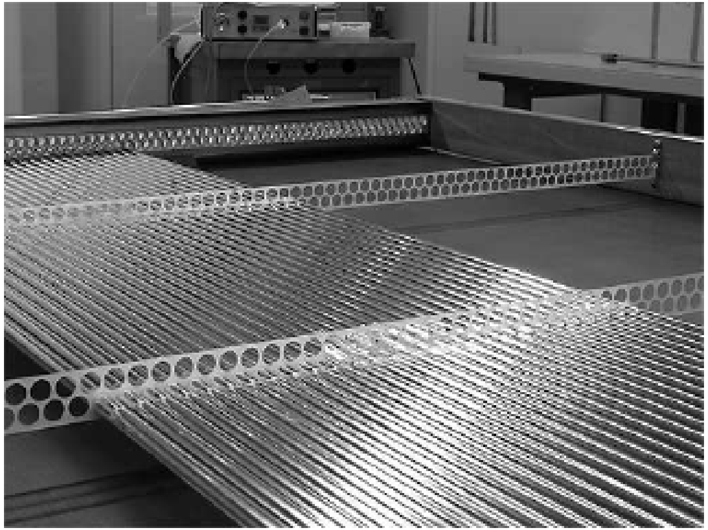
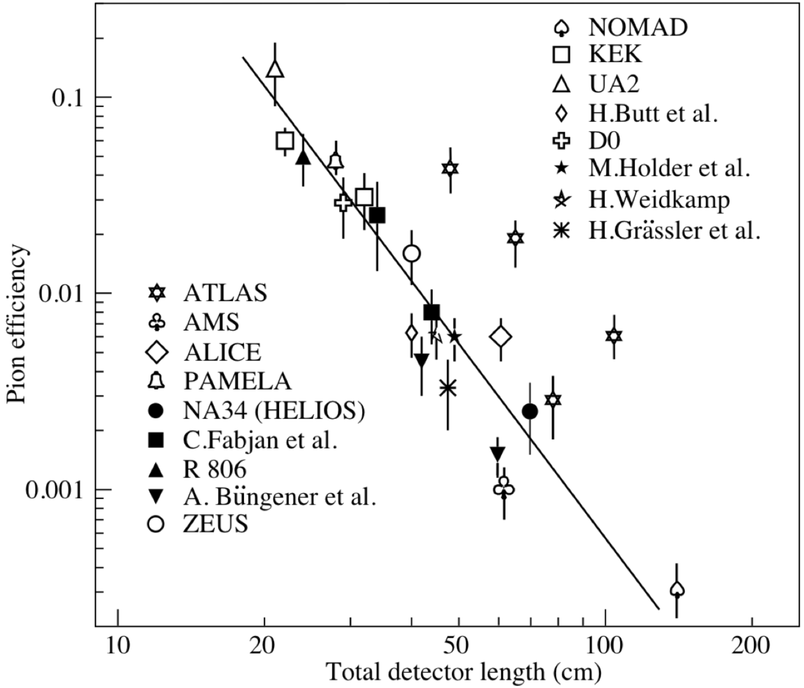


Fig. 10: Production of the TRD modules

TRD scaling Low



- *TR radiators occupy largest space* -> New Radiators!?
- *Better TR detection efficiency and better separation from particle ionization* -> New Detectors?

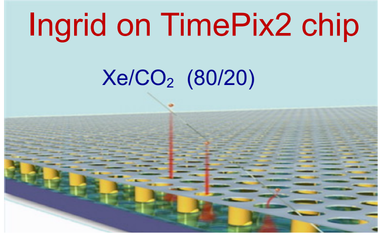
What was good yesterday

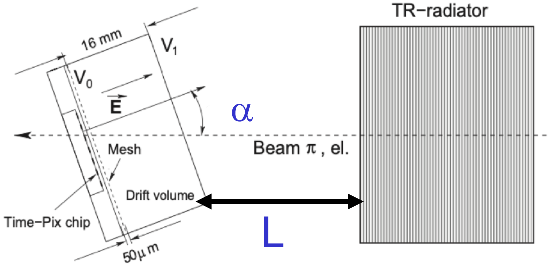
Isn't necessarily good today

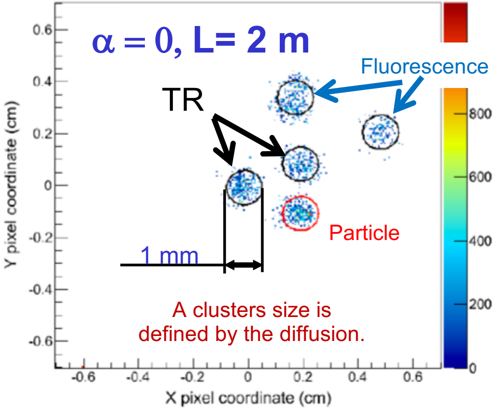
New approaches in the TRD development.

Micropattern detectors based TRDs: *Ingrid technology*

Ingrid on TimePix2 chip



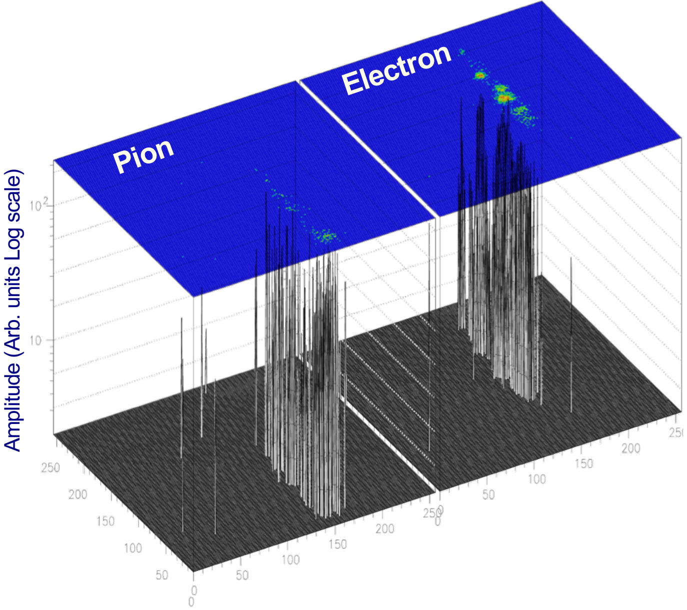




A clusters size is defined by the diffusion.

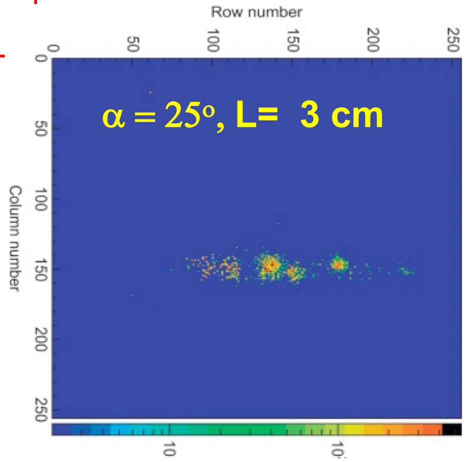
J. Phys. : Conf. Ser. 934 (2017) 012049

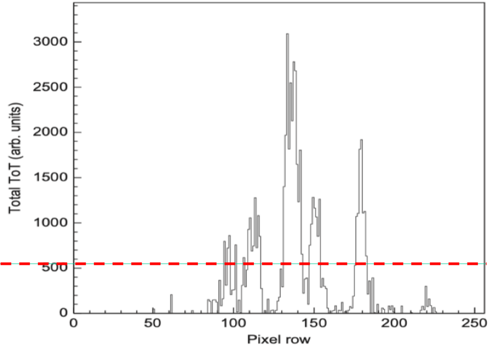
α = 25°, L= 3 cm
For close radiator position the TR and dE/dX losses cannot be separated!



Count energy in clusters above the threshold or take a total energy?

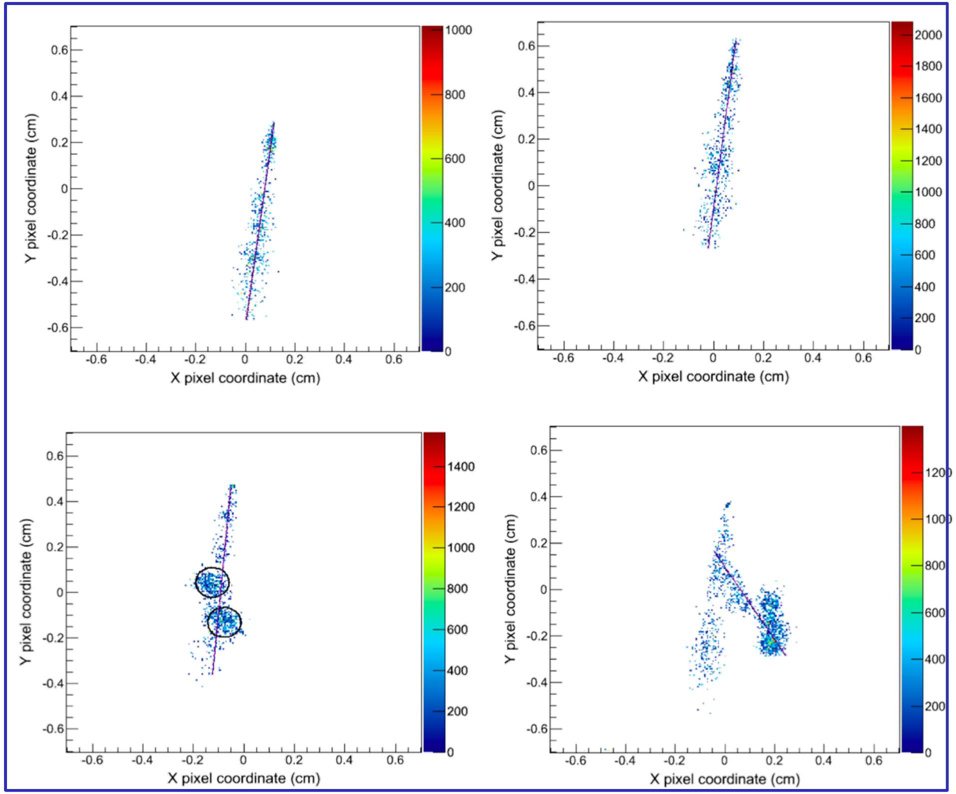
MIM, A 706 (2013) 59–64



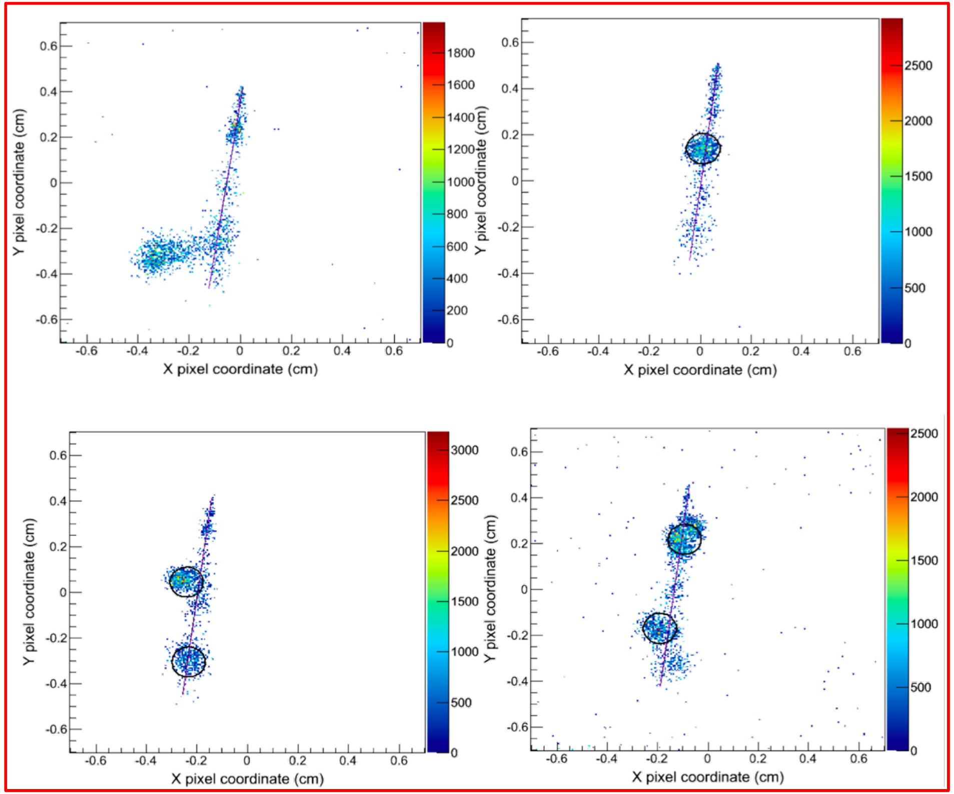


Two TRD concepts

Pion event displays



Electron event displays

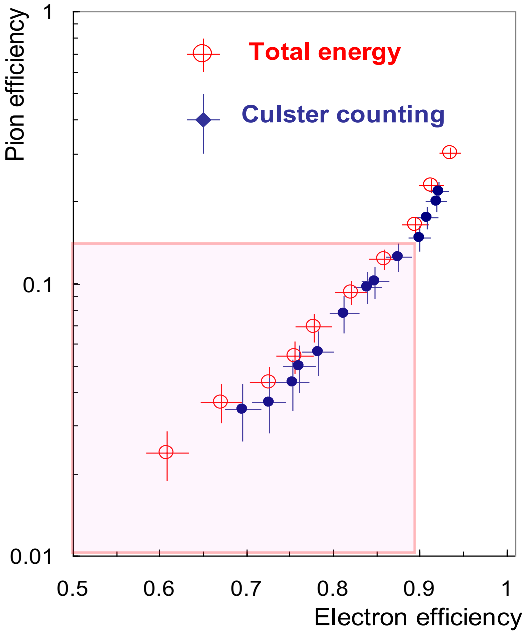


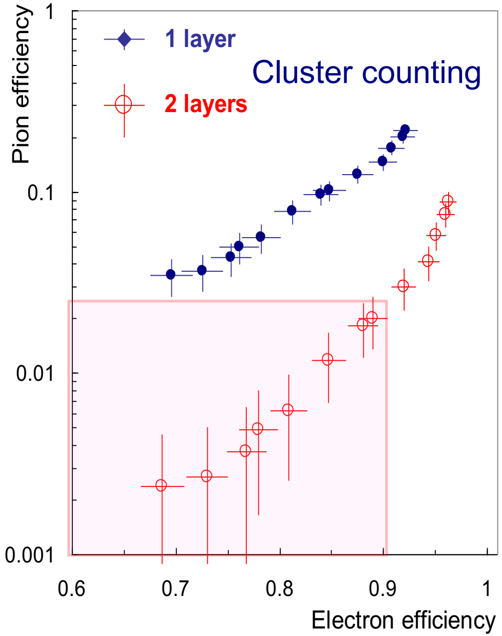
Delta-electron and photo-electron signatures cannot be separated!
However low energy part of the dE/dX can be selected and used as an additional information.

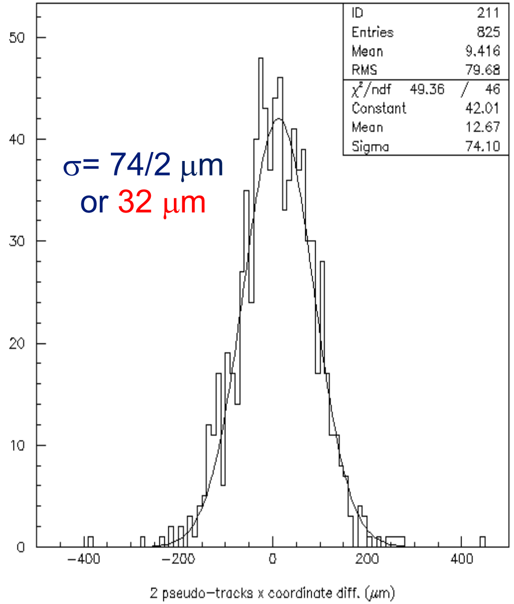
Particle Identification. Ingrid based detector.

MIM, A 706 (2013) 59–64

16 mm detector







Pion registration efficiency as a function of electron efficiency for the total energy method and Cluster counting method.

Cluster counting method has a bit larger rejection power. For 90% electron efficiency pion rejection factor is ~8.

Pion registration efficiency as a function of electron efficiency for 1 and 2 layers of the detector. Cluster counting method.

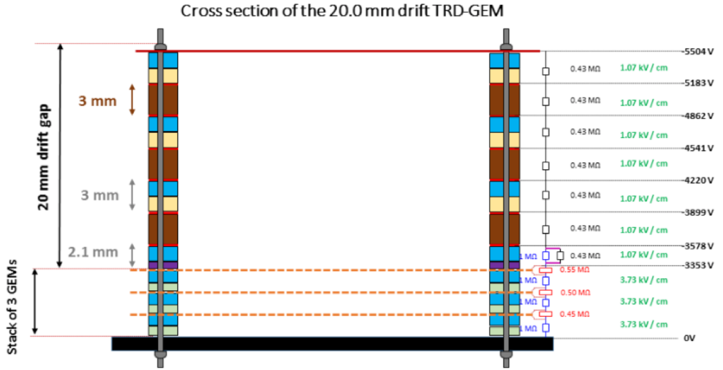
TRD with two detector layers (total thickness ~ 40 cm) allows to achieve rejection factor of ~ 50 for 90% electron efficiency.

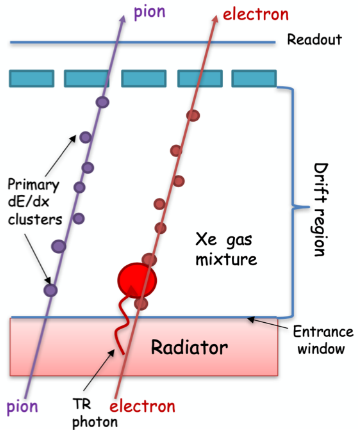
Track position accuracy on the chip plane. Combines tracking and PID properties. Vector tracking.

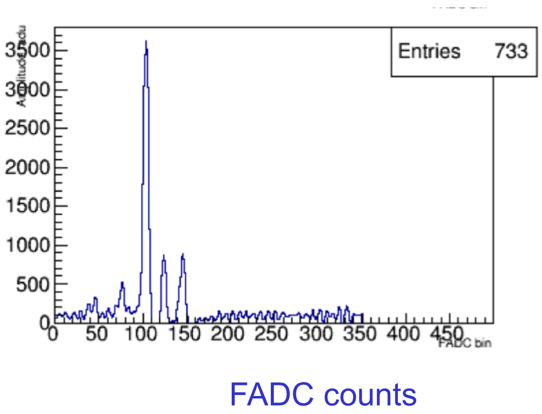
Big amount of information to be extracted! → require a special electronics for a real detector

GEM TRD for Electron-Ion Collider (EIC)

NIM, A 942, (2019) 162356





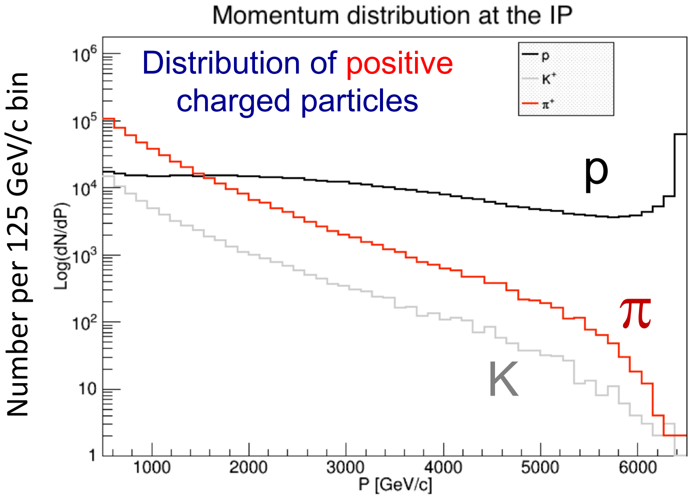


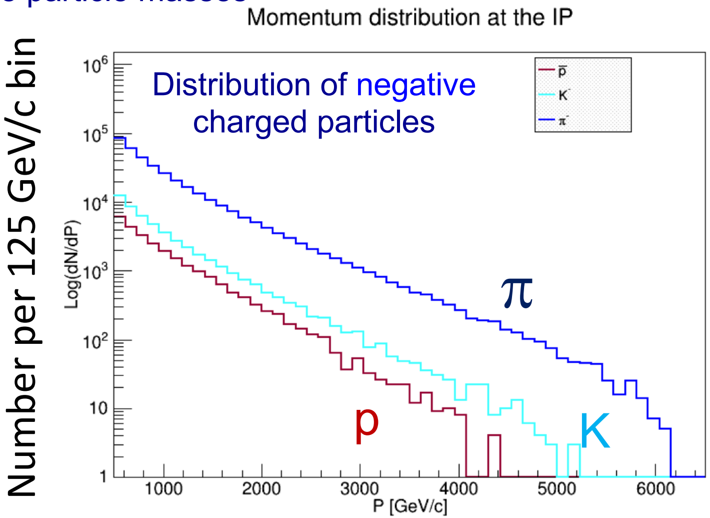
Approach similar to the ALICE TRD.
Drift distance is divided on 10 slices.

TRD for FHS (Forward Hadron Spectrometer) at LHC

J. Phys.: Conf. Ser. 1390 (2019) 012126, J. Phys.: Conf. Ser. 1690 (2020) 012043

The goal is a hadron reconstruction in 1-6 TeV energy range.
The difficulty is close particle masses

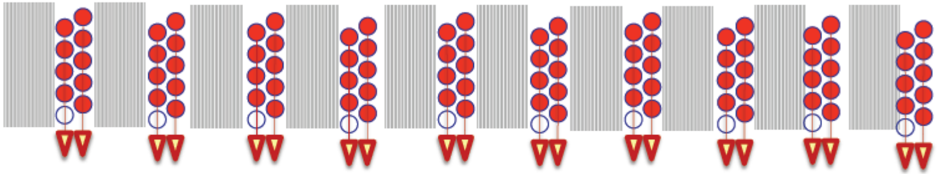




Fine grained structure which allows to work with **soft** and **hard** parts of the TR spectrum (different gamma dependences).

Advantages:

- Use of two TR energy ranges with different gamma dependencies
- Straw walls are a part of the radiator (they produce TR in in the same energy range) => no dead material, only radiator and gas.



Disadvantages:

- TR and dE/dx cannot be decoupled.

TRD for FHS (Forward Hadron Spectrometer) at LHC

For precise measurements it is very important to know exact response of the detector.
There are two few caveats here: Space charge effect and photo electron pass in the working volume

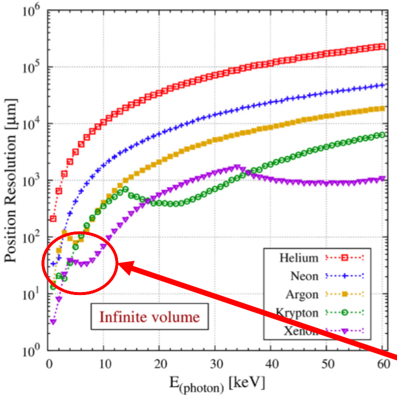
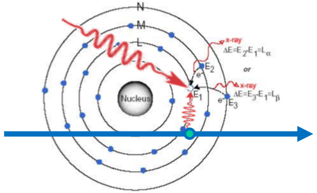


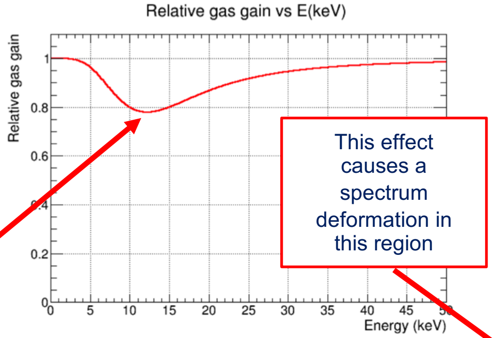
Fig. 5. Position resolution as a function of the photon energy for an “infinite” geometry.

Charge density on the wire is maximal in a photon energy range of 8-14 keV. This causes a drop of the gas gain known and a space charge effect. This must be taken into account in simulations.

90% auger electron probability

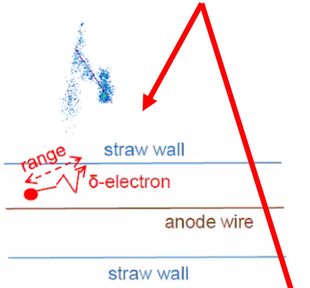


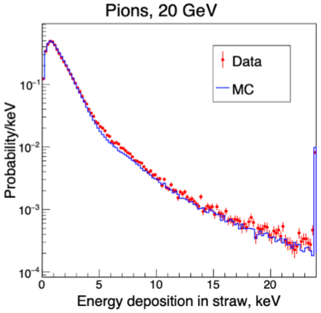
Photon of 10 keV:
Photoelectron ~5 keV
Auger electrons: ~4 keV + 1 keV the rest

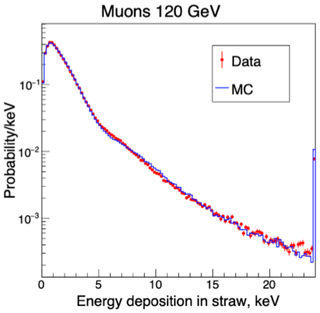


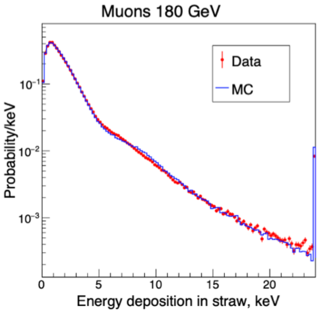
This effect causes a spectrum deformation in this region

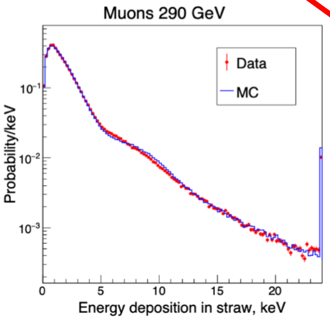
δ-electrons of high energy have a significant pass in the gas and can go out from the working volume. This affect the spectrum shape and must be taken into account

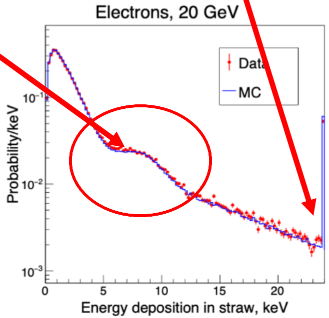






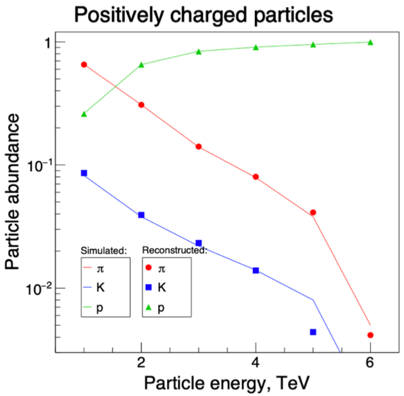


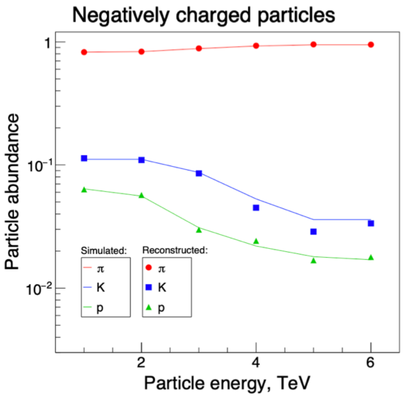




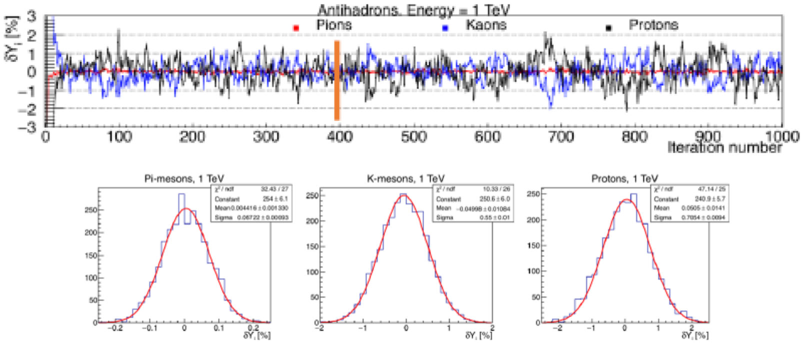
Expected and reconstructed particle composition for FHS@LHC

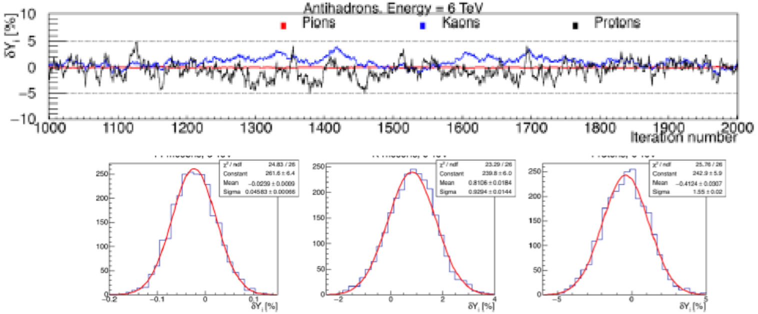
Iterative Bayesian approach.





What reconstruction accuracy can be reached after many iterations? Negatively charged particles



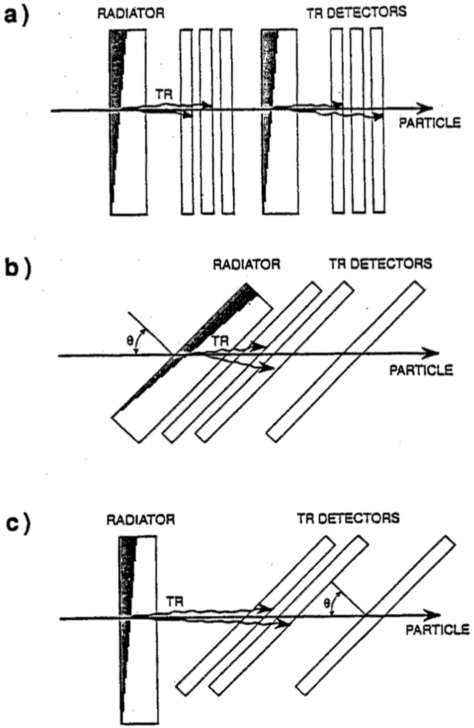


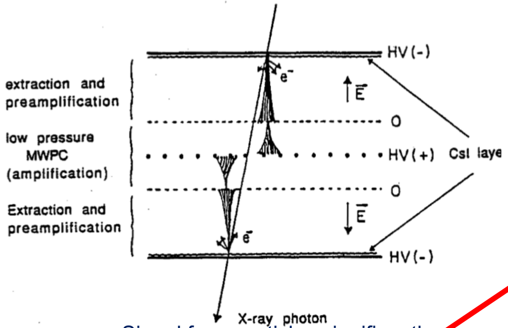
A new idea is well forgotten the old one!?

Transition Radiation Imaging Detectors with CsI Convertors

R. Chechik, A. Breskin et al. IEEE Trans. Nucl. Sc. v39, V. 4 (1992) 728

Method based on the absorption of X-ray photons in thin CsI convertors and the detection of secondary emitted electrons in low-pressure (~20 mbar) multistage electron multipliers.





Signal from particles significantly suppressed

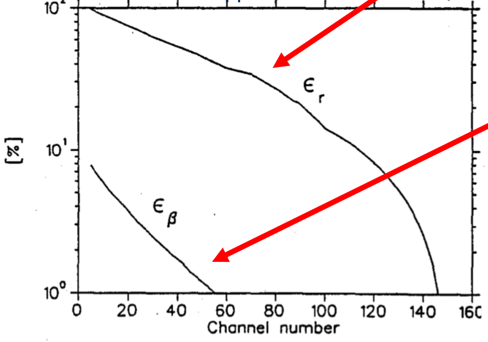
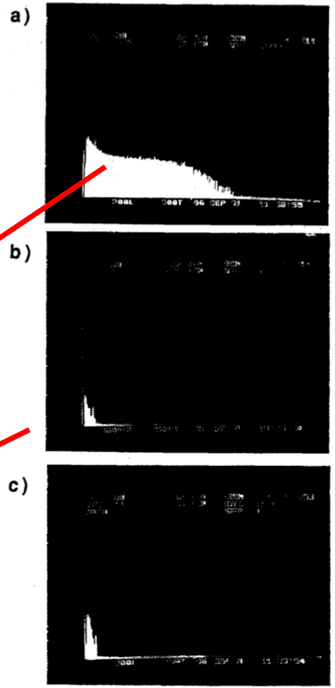


Fig.16 Measured relative X-ray detection efficiency ($\mathcal{E}_r$) and absolute β-ray detections efficiency ($\mathcal{E}_\beta$), as function of the "threshold", for a 300 nm thick CsI absorber. Isobutane, 17 Torr.



The main advantages.

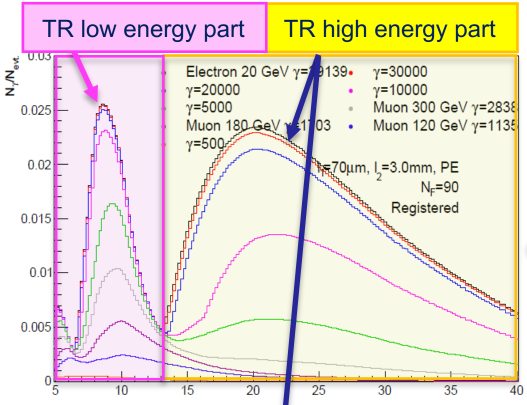
High position accuracy
< 0.2 mm FWHM

Very fast timing
<1 ns.

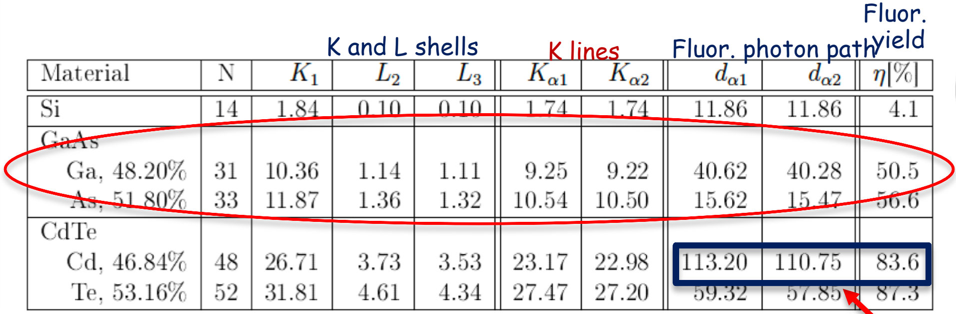
The detection efficiency strongly depends on the impact angle of photons and very little for charged particles

Solid state TRDs

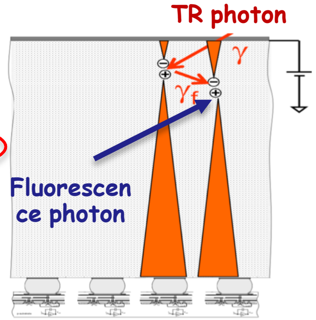
Semiconductor based detectors.

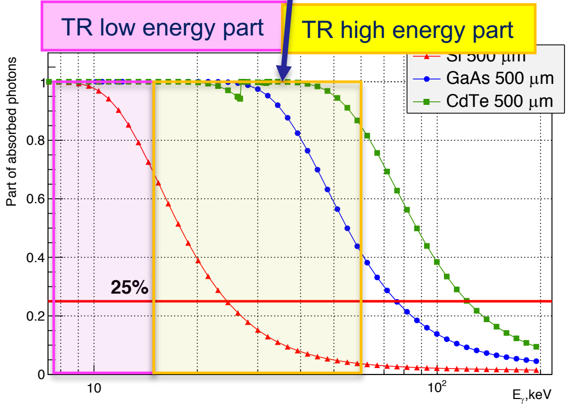


TR spectra for different particles produced in PE radiator with 70 µm foil thickness and 3 mm spacing.



Material	N	K_1	L_2	L_3	$K_{\alpha1}$	$K_{\alpha2}$	$d_{\alpha1}$	$d_{\alpha2}$	η[%]
Si	14	1.84	0.10	0.10	1.74	1.74	11.86	11.86	4.1
GaAs									
Ga, 48.20%	31	10.36	1.14	1.11	9.25	9.22	40.62	40.28	50.5
As, 51.80%	33	11.87	1.36	1.32	10.54	10.50	15.62	15.47	56.6
CdTe									
Cd, 46.84%	48	26.71	3.73	3.53	23.17	22.98	113.20	110.75	83.6
Te, 53.16%	52	31.81	4.61	4.34	27.47	27.20	59.32	57.85	87.3



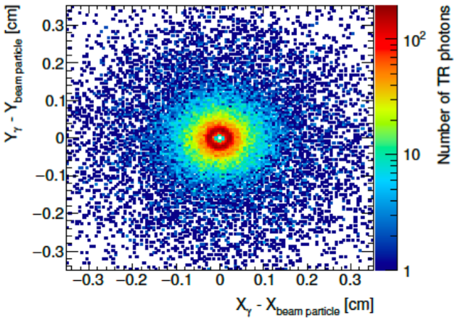


Fraction of photons absorbed in 500 µm sensor.

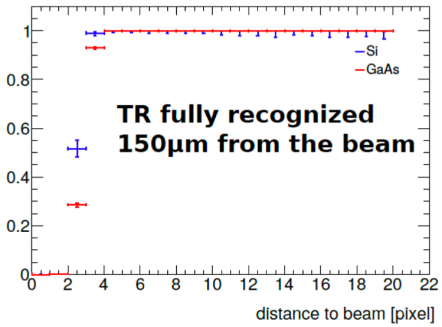
- **CdTe** can be the best but it has big fluorescent yield (84%) and fluorescence photons have a large mean path in the detector (110 µm).
- **Si detectors** are very good but for low energy part of TR spectrum.
- **GaAs material is the optimum one** for low and high energy part of TR spectrum. Fluorescence photons have small mean path (**15.5 and 40** µm).
- **GaAs sensor** can be produced up to 1 mm think.

Si and GaAs sensors on TimePix3 chips

NIM, A 961 (2020) 163681,   J. Phys.: Conf. Ser.,1690 (2020), 012041, NIM, A 958 (2020) 162037

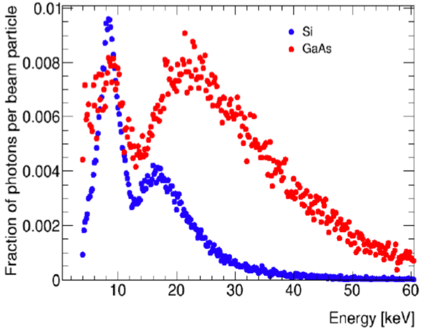


Angular distribution of TR photons.

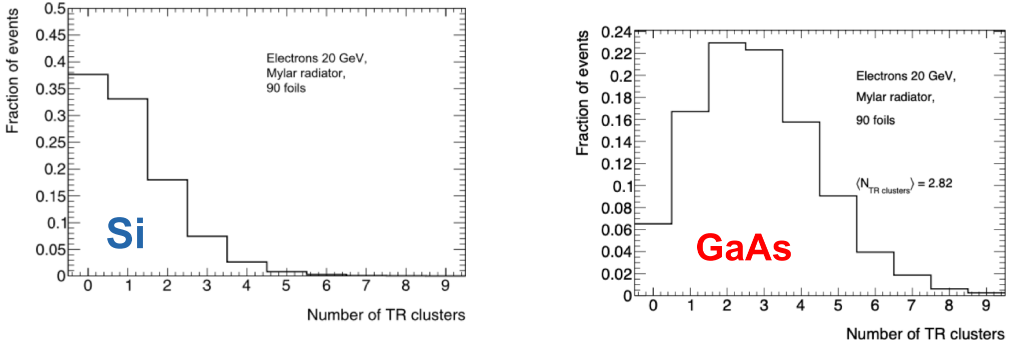


TR fully recognized 150μm from the beam

TR photon efficiency registration as a function of the distance from a particle impact point.



Energy spectra of TR photons from 50 μm thick foil Mylar radiator.

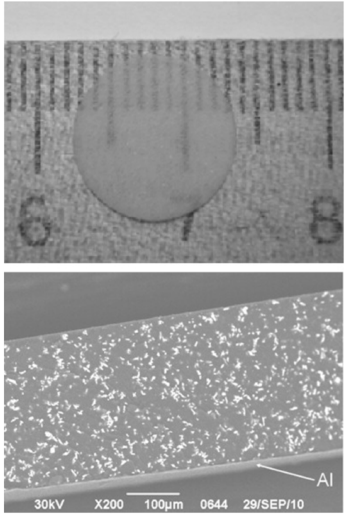


Number of TR photons form 90 foils Mylar radiator dby Si and GaAs detectors.

Heavy scintillator based detectors

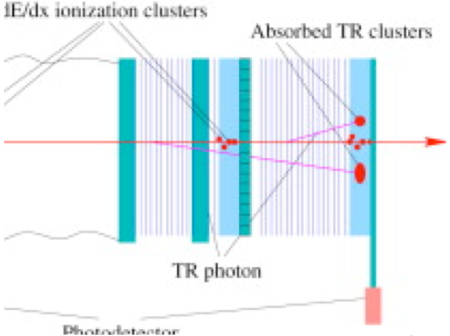
NIM, A706 (2013), 65

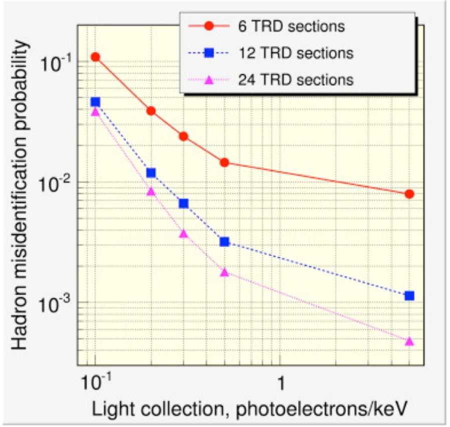
Very thin layers of heavy scintillator can be good candidates for the TR detectors



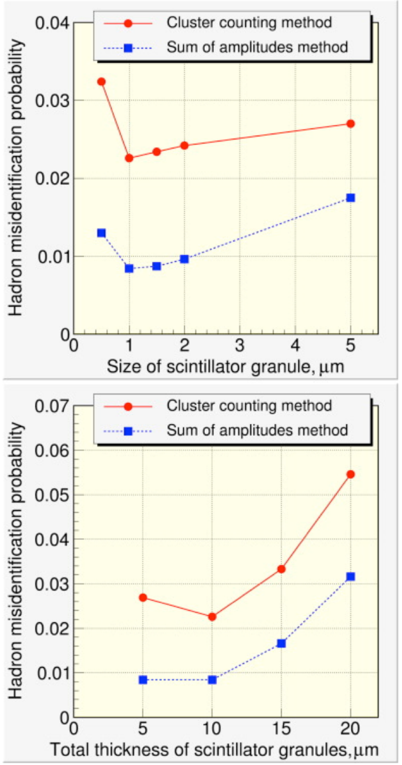
Small crystals of LSO scintillator imbedded to transparent epoxy.

High efficiency photon detectors are required





Probability for pion to be detected as electron as a function detected number of photons per 1 keV.



Probability for pion to be detected as electron as a function of LSO parameters.

The End