Transition Radiation Detectors

Anatoli Romaniouk

A little bit of history

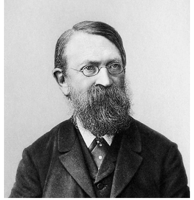
A basic question:

Is there any electromagnetic radiation coming from charged particles moving with a constant velocity?

In 1903 Arnold Sommerfeld considered a uniform motion of a charge in vacuum and came to the conclusion that it radiates at a velocity exceeding that of light (**V > C**)!

[A. Sommerfeld, Nachr.,Math.Phys.Klasse, (2) 99, (5) 363 (**1904**); (3) 201 (1905)].

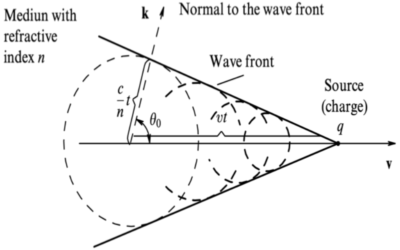
But in **1905 a special theory of relativit**y was invented which postulates the low: **V** is always **< C**. And Sommerfeld's idea was discarded at that moment because a charge cannot propagate at a speed higher than **C**.



If at that moment physicists knew that in media a phase speed of light **is less than C** the **Cherenkov radiation** could have even been predicted by a student in the last years of secondary school, familiar with the fundamentals of optics.

It follows, from Hyugens's principle according to which each point on the path of a charge moving with speed v is a source of a spherical wave emitted as the charge passes the point.

Also Mach shock waves analogs of this radiation were well known.



A little bit of history

For the first time Cherenkov radiation was observed by P Curie and M Curie in bottles with radium salt solution but it was ignored at that time.

In 1932 a PhD Pavel Cherenkov under a supervision of Sergey Vavilov (world leading physicist in a study of luminescence phenomena at that time) was intended to study of a luminescence of a uranyl salt solutions caused by gamma-irradiation (it was a subject of his PhD thesis of Pavel Cherenkov). Cherenkov happened to observe (by eye!) that the fluid (sulphuric acid) was luminous even in the absence of a solute which cause luminescence.

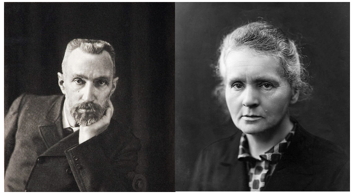
This led him to believe that his further work on should be given up as a bad job.

That was S. Vaviolov who understood that the observed radiation is something else than luminescence. Further studies proved that lead to a the discovery of a previously unknown phenomenon [Cherenkov P A ,Comptes Rendus Acad. Sciences USSR 2 451 (1934), Vavilov S I, Comptes Rendus Acad. Sciences USSR 2 457 (1934)].

That is why in Russian books this irradiation is very often called Vavilov-Cherenkov.

This discovery happened in Physics Institute of the Academy of Science (Moscow) where there was a big theory physics department with many brilliant physicists who immediately started to explore a new land of physics.

The nature of this radiation was explained in 1937 by Igor Tamm and Iliya Frank [Tamm I E, Frank I M Dokl. Akad. Nauk SSSR 14 107 (1937) [CR Acad. Sci. USSR 14 107 (1937)]



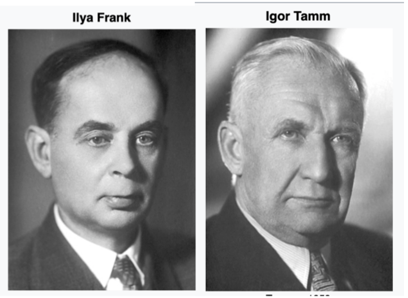
Sergey Vavilov

Pavel Cherenkov

Ilya Frank

Igor Tamm

A little bit of history



Tamm and Frank forwarded a preprint of their paper to Sommerfeld and who answered of 8 May 1937 via Austria (Nazis were already in power):

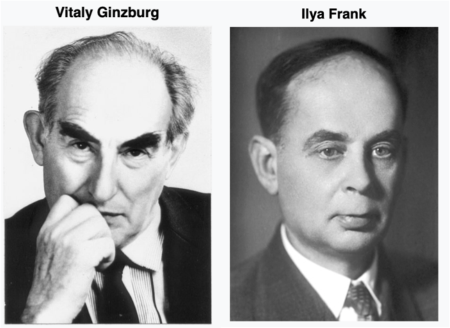
”I never thought that my calculations made in 1903 could ever have any physical implication. This confirms that the mathematical aspect of a theory outlasts changing physical concepts.”

Let’s move to <u>the translon radiation</u> now!

These studies attracted attention of young physicists **Vitaly Ginzburg** who started to ask him self “Cherenkov radiation appears when charge moves in the uniform media but what if the media is not uniform? For instances:

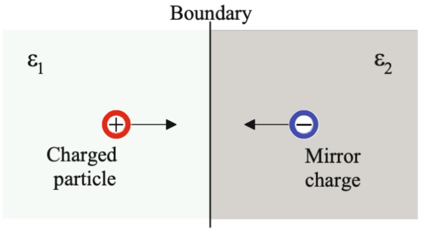
What would happen if moving charge crosses the boundary of two media with different velocities of the propagation of electromagnetic waves.

Together with Ilya Frank they considered the example of an electron moving from the vacuum into an ideal conductor.



A little bit of history

For the charge the metal is an ideal mirror.



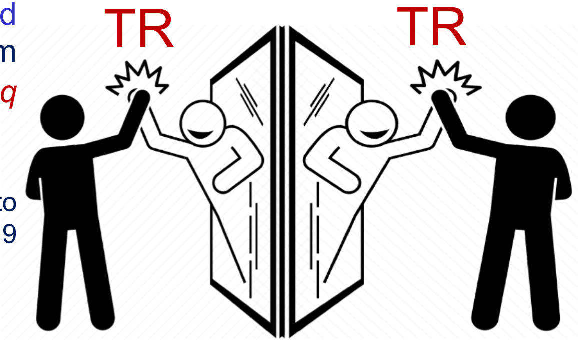
Simple considerations tell:

The field of the charge in vacuum is a sum of the fields of the charge *q* moving in the vacuum in the absence of the mirror **and** its ”image” charge –*q* moving in the mirror toward the charge *q* (i.e., with the velocity –v).

When charge *q* crosses the metal boundary, it falls into a conducting medium and ceases to produce a field in the vacuum; the image –*q* also disappears. Thus, from the viewpoint of an observer in the vacuum, the annihilation of the pair of charges *q* and –*q* occurs at the instant of crossing the boundary.

I. Ginsburg and I. Frank described this process in their work:

``Radiation of a uniformly moving electron, arising when the electron passes from one medium into another'' for publication to Ginzburg V L, Frank I M Zh. Eksp. Teor. Fiz. 16 15 (1946); J. Phys. USSR 9 353 (1945) (brief version)



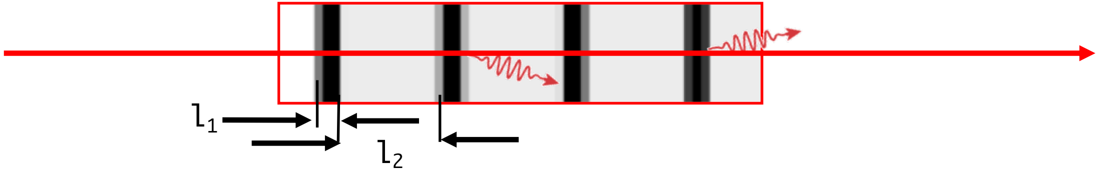
In this publication they predicted the existence of a new type of electromagnetic radiation, which they called ”Transition Radiation”

This phenomena happens at any speed of moving charge.

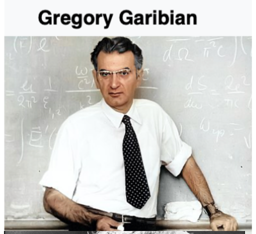
It also can be considered as a dipole which flips direction at the moment of the boundary crossing.

A little bit of history

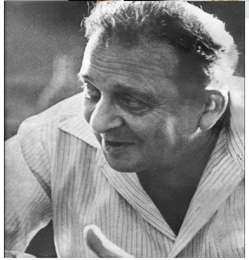
However, if you are charge or pretty enough any surface becomes a mirror!
And TR is produced at any case when boundary with different refractive indices are crossed.



The production of TR in a stack of plates was considered by G. Garibian



In 1959 it was found that, for ultra-relativistic particles, high-frequency TR (in X-ray range) is produced (that is why sometimes it is called XTR) in forward directions and its intensity strongly depends on a particle gamma factor. [G. M. Garibyan, Zh. Éksp. Teor. Fiz. 37, 527 (1959) [Sov. Phys. JETP 10, 372 (1960)]; G. M. Garibyan and Yan Shi, X-ray Transition Radiation (Akad. Nauk Arm. SSR, Yerevan, 1983)].



Artem Alikhanian and his collaborators from Armenia made first XTR observations and investigations (years 1961-70)

Transition radiation: basic principles

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

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

One boundary (surface)

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

TR formation zone

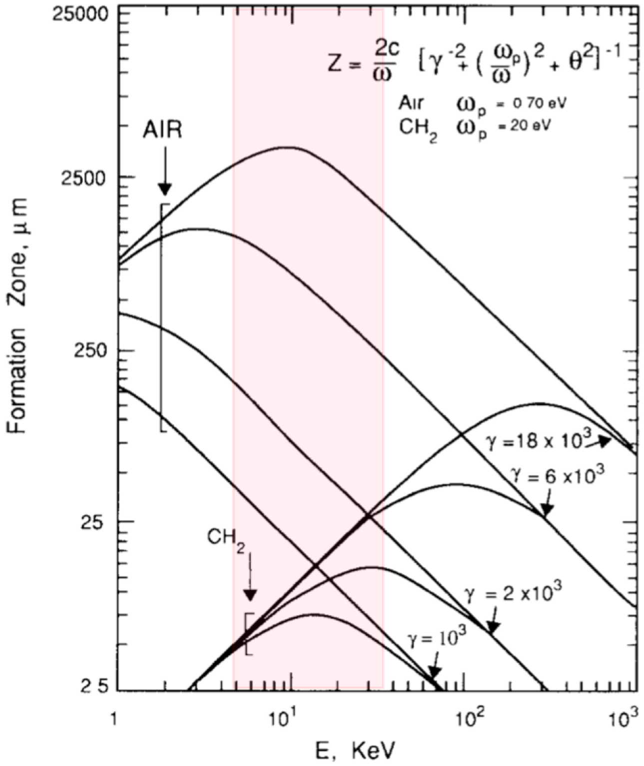
$$Z(\omega_i) = Z(\theta,\omega,\omega_i) = \frac{4c}{\omega\left(\gamma^{-2}+\left(\frac{\omega_i}{\omega}\right)^2+\theta^2\right)}$$

$$\omega_P = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \approx 28.8\sqrt{\rho\frac{Z}{A}}\,\text{eV}$$

Material	ρ, g/cm³	ω_p, eV
Polyethylene CH_2	0.925	20.9
Mylar $C_5H_4O_2$	1.38	24.4
Air	2.2×10^{-3}	0.7

ω – TR photon energy
θ - production angle
γ - particle gamma factor
Z – formation zone
θ_i – plasma frequency of a medium with index i.

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



Transition radiation: basic principles

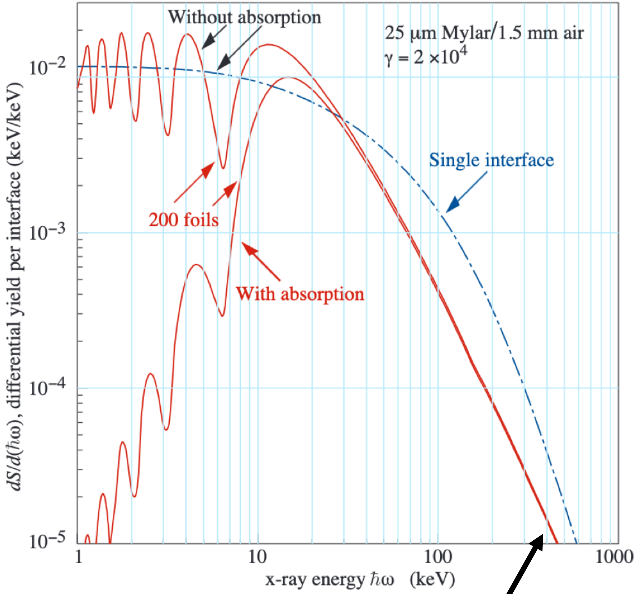
One foil

N foils (interference)

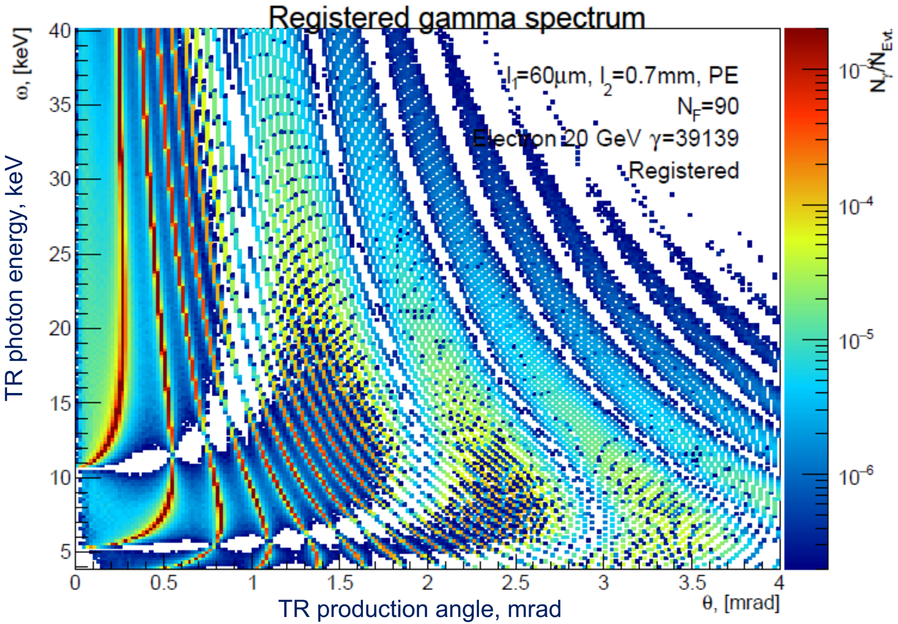
$$\frac{d^2N_{gen}}{d\theta d\omega} = \boxed{4\boxed{\frac{d^2N_0}{d\theta d\omega}}\sin^2\left(\frac{l_1}{Z(\omega_1)}\right)}\frac{\sin^2\left(N\left(\frac{l_1}{Z(\omega_1)}+\frac{l_2}{Z(\omega_2)}\right)\right)}{\sin^2\left(\frac{l_1}{Z(\omega_1)}+\frac{l_2}{Z(\omega_2)}\right)},$$

Radiator consisting on many foils:
PE, l_1=60 μm , l_2=0.7mm, N=90,

Particles: *20 GeV electrons, γ = 3.9·10^4*

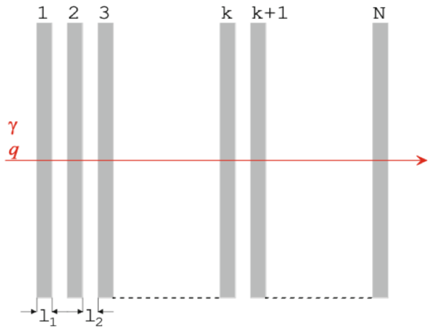


Cut off energy ~ $\omega_p \bullet \gamma$

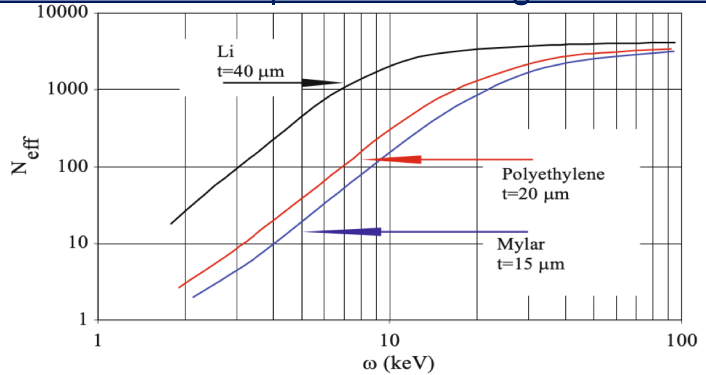


Transition radiation: TR production

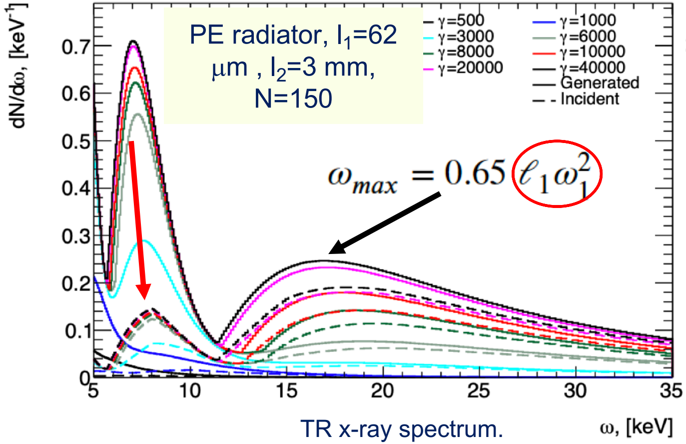
TR absorption sets a strong limit on a number of photons coming from the radiator.



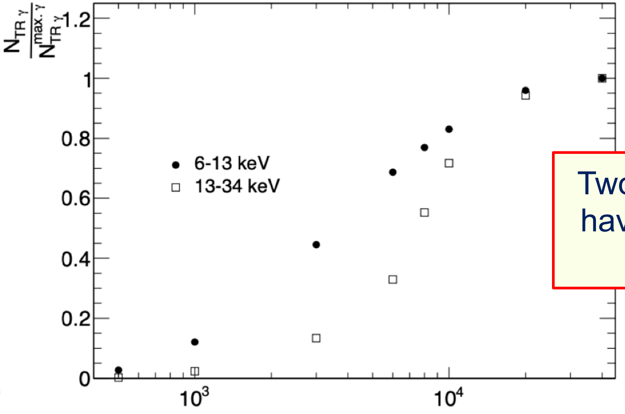
Regular radiator



Number of effectively working foils as a function of photon energy



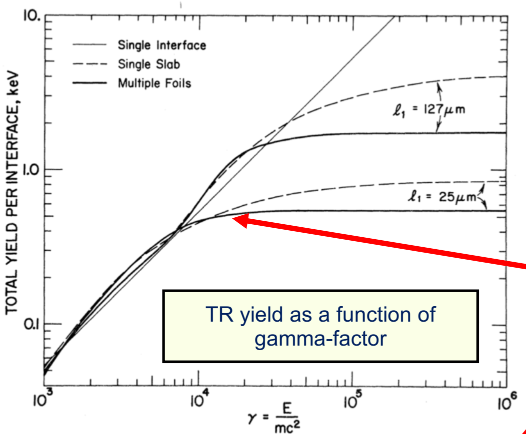
TR x-ray spectrum.



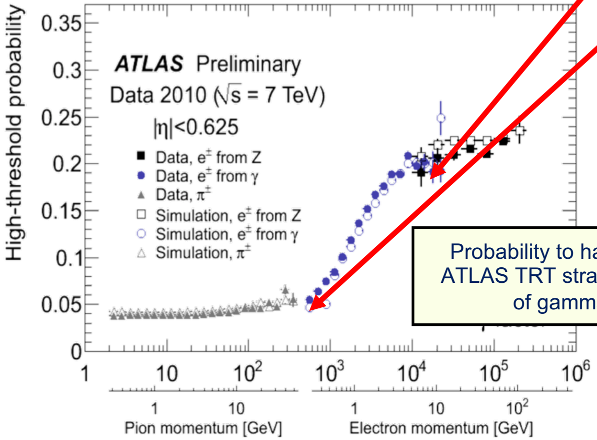
Number of X-ray TR photons VS gamma-factor. γ

Two parts of spectrum have different gamma dependencies

Transition radiation: the most important TR parameters



TR yield as a function of gamma-factor



Probability to have a hit in the ATLAS TRT straw as a function of gamma-factor

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

NIM, A 961 (2020) 163681

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

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

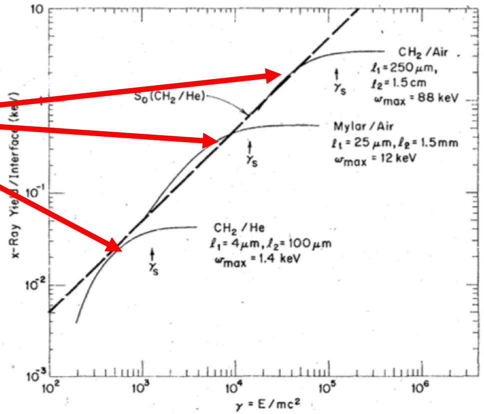
$$\gamma_{thr} \sim 3\times10^3\ \omega_1\ell_1$$

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

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

This formula is not conventional.
We will comeback to it later.

Varying radiator parameters one obtains different gamma-factor dependences.



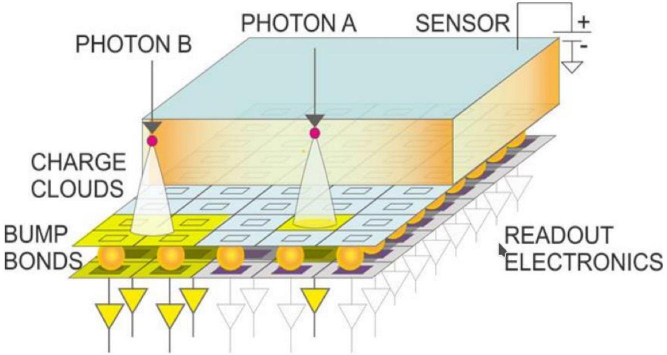
TR yield as a function of gamma-factor for different radiator parameters

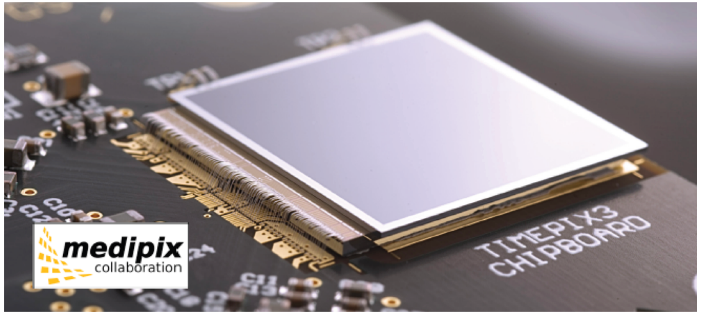
Now is a time to come down to an experimental ground.

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

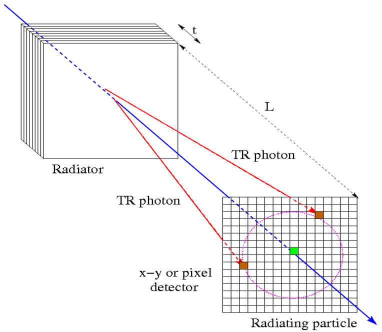
Timepix3 front-end hybrid pixel readout chip:

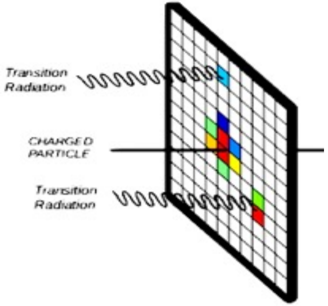
- Various sensor materials possible.
- Simultaneous per-pixel measurement of a time-of-arrival (ToA) and the time-over-threshold (ToT).
- Time resolution of 1.56ns and
- Spatial resolution of ~16µm
- 256 x 256 pixel matrix with 55 x 55 µm2 pitch
- throughput of up to 40 Mhits/s/cm2

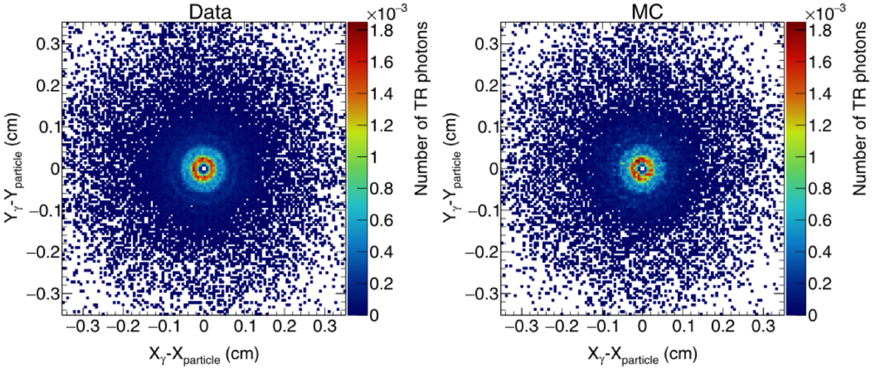
TimePix4 with improved time measurements is coming soon (see later)

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

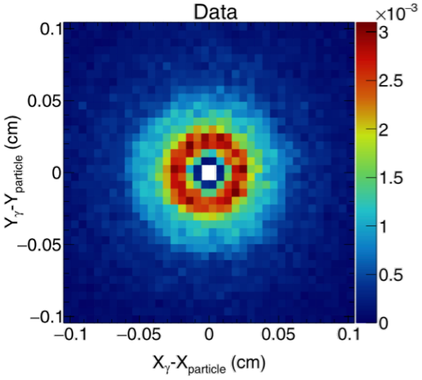
NIM, A 961 (2020) 163681

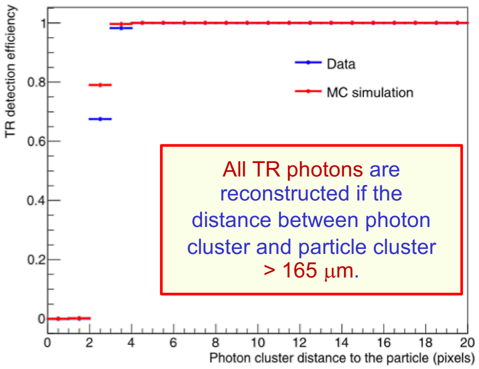




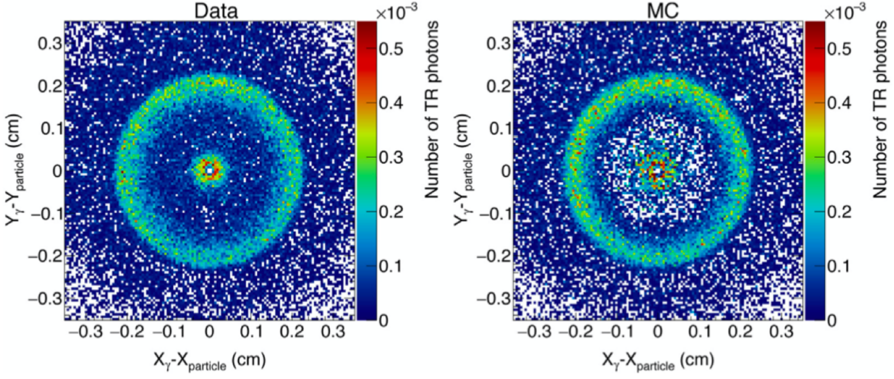


Mylar radiator 50 μm, 2.97 mm spacing, 30 foils





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



PE radiator 15.5 μm, 222 μm spacing, 180 foils

Data/MC comparison. Si sensor.

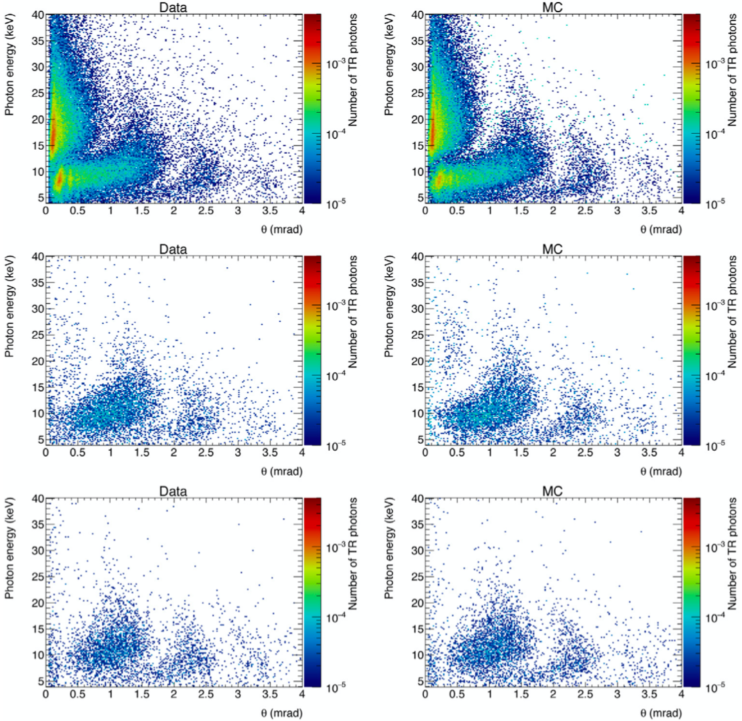
NIM, A 961 (2020) 163681

Data **MC**

Electrons
20 GeV

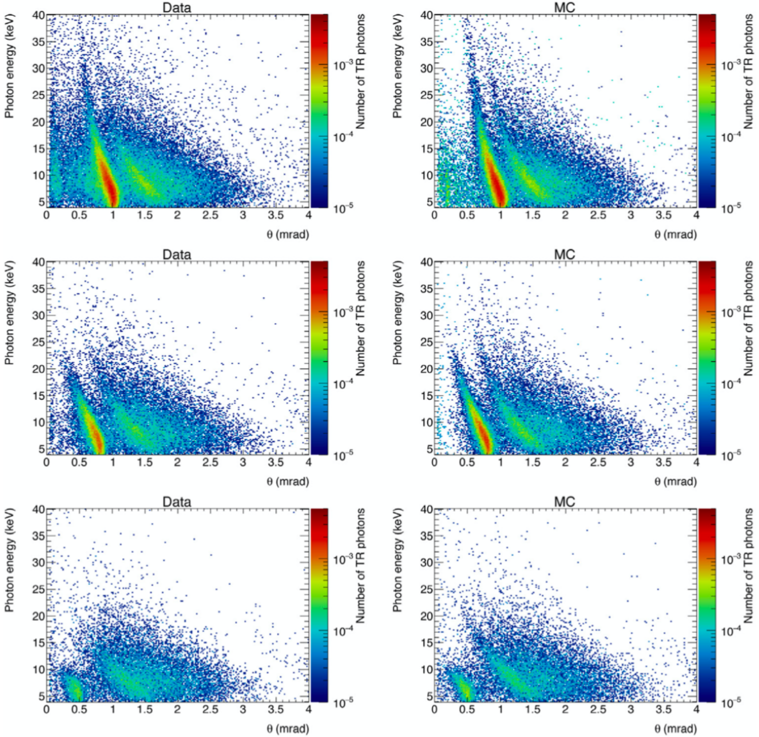
Muons
180 GeV

Muons
120 GeV



Mylar radiator 50 μm, 2.97 mm spacing, 30 foils

Data **MC**



PE radiator 15.5 μm, 222 μm spacing, 180 foils

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

Data/MC comparison. Si sensor.

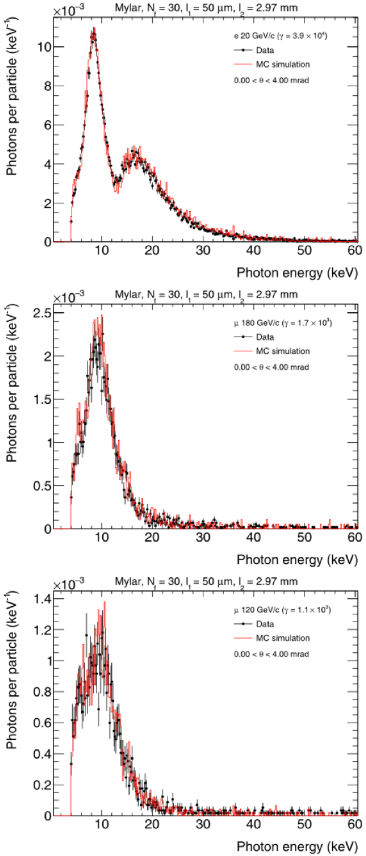
NIM, A 961 (2020) 163681

Mylar radiator 50 μm, 2.97 mm spacing, 30 foils

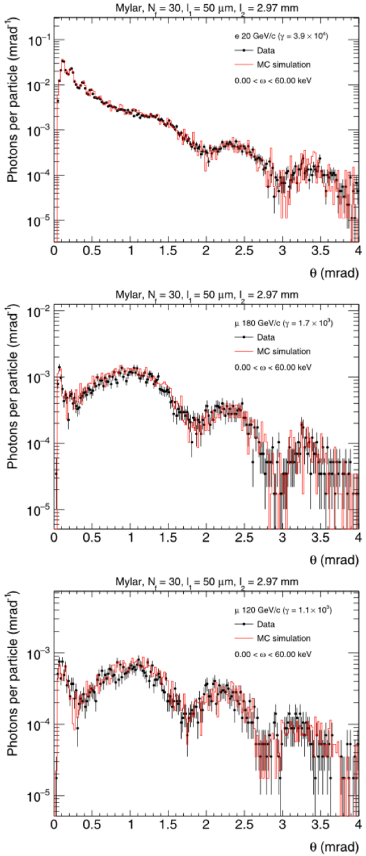
Electrons
20 GeV

Muons
180 GeV

Muons
120 GeV

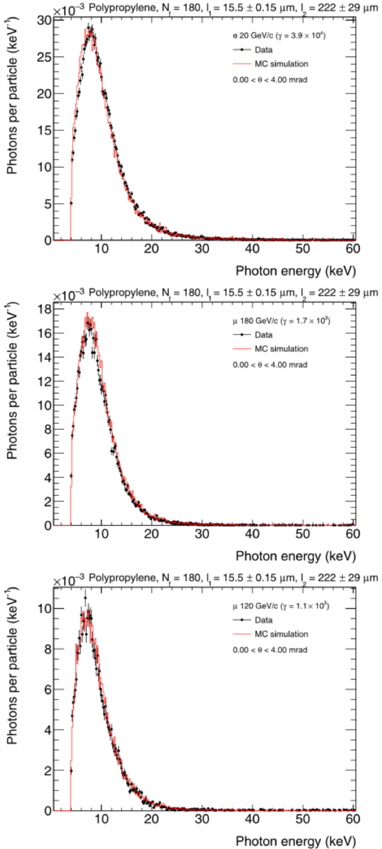


Energy spectra of TR photons.

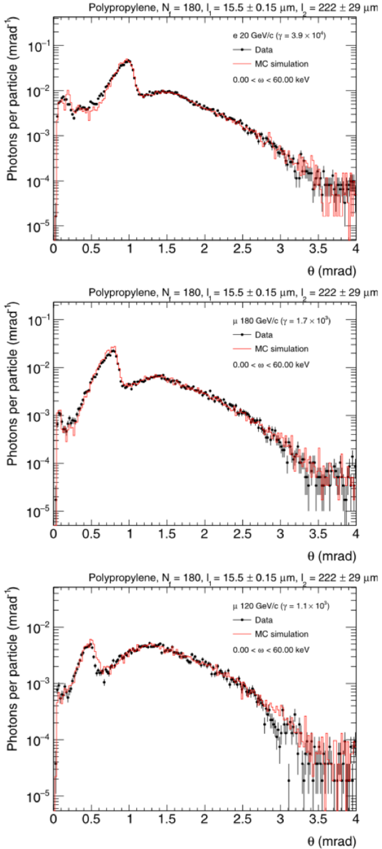


Angular distribution of TR photons.

PE radiator 15.5 μm, 222 μm spacing, 180 foils

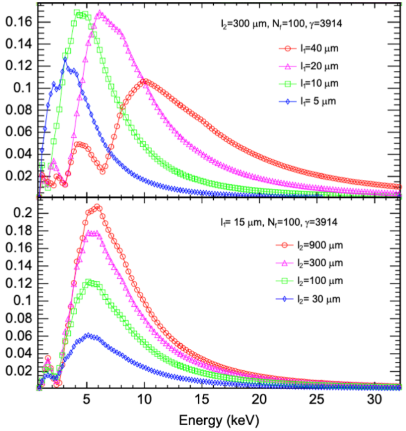


Energy spectra of TR photons.

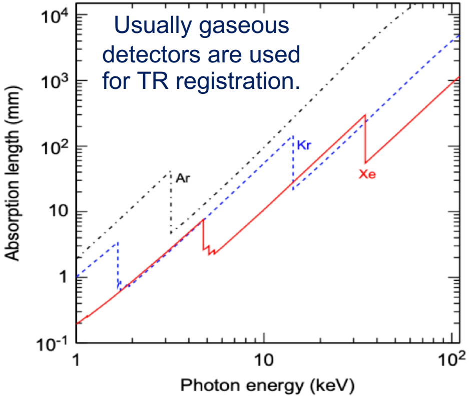


Angular distribution of TR photons.

Gas based TRDs: concepts

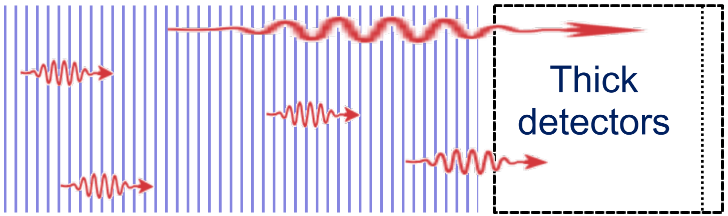


TR photon spectrums for different radiator parameters



Usually gaseous detectors are used for TR registration.

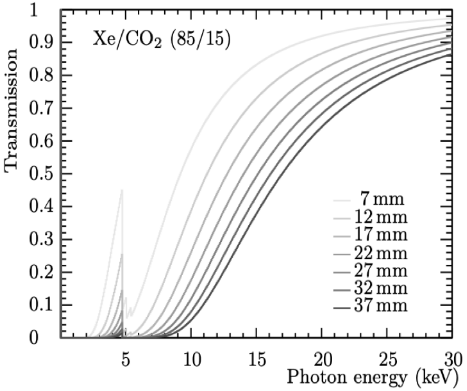
X-ray absorption length in different gases



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.

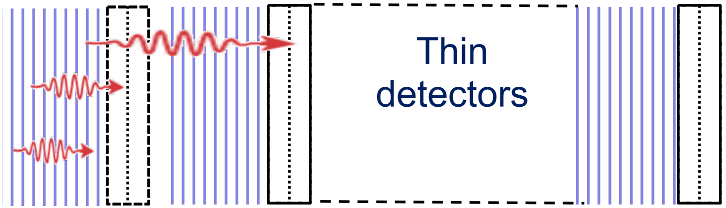
e.g.UA2, NA34, ALICE …



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

Important to NOTE:

- *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*



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.

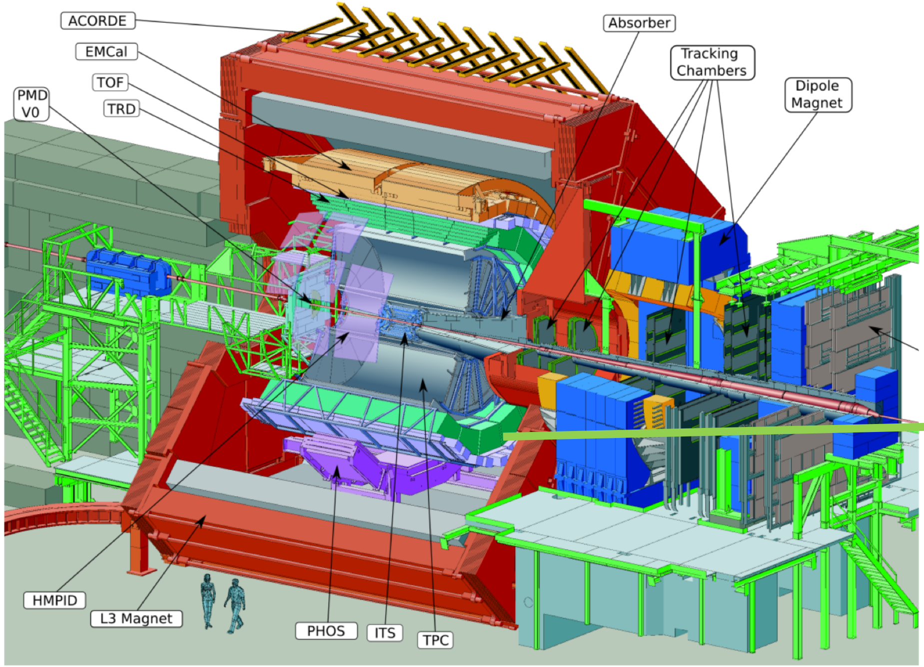
TR can be registered by several consecutive detector layers. Walls of the detector layers are made from thing foils and also produce TR.

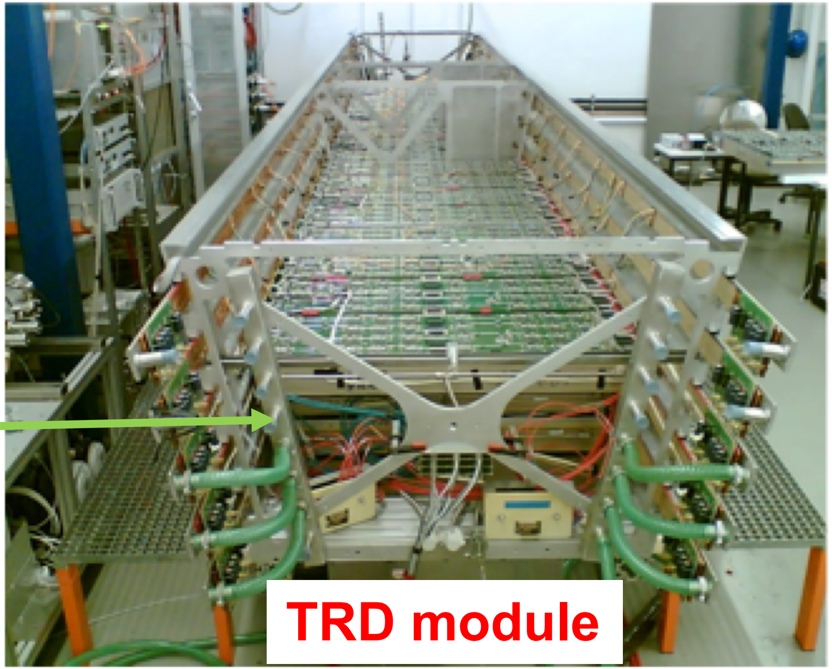
ATLAS, AMS-2, TRD for Pamela experiment

ALICE experiment

Dedicated for heavy-ion studies at LHC.

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

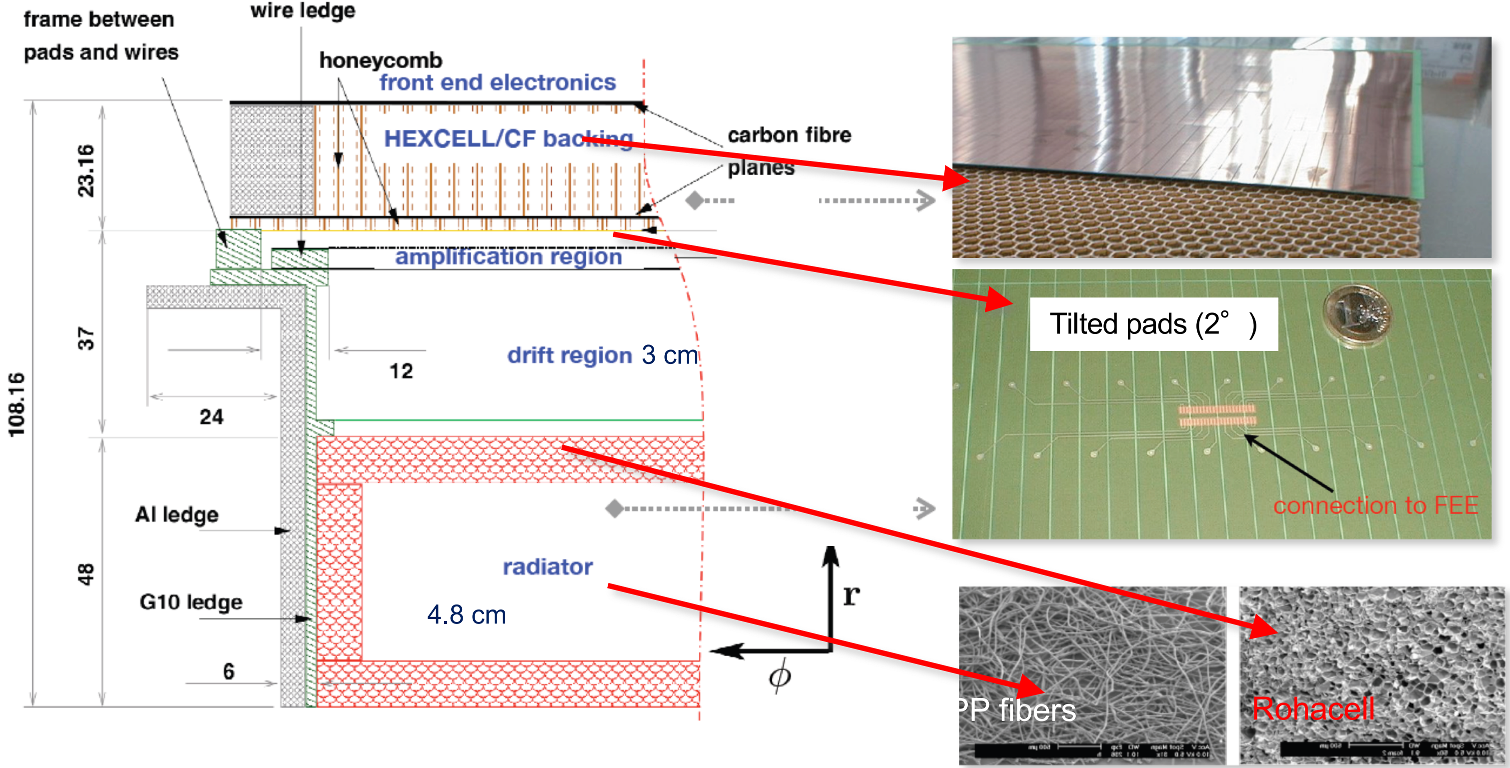




TRD module

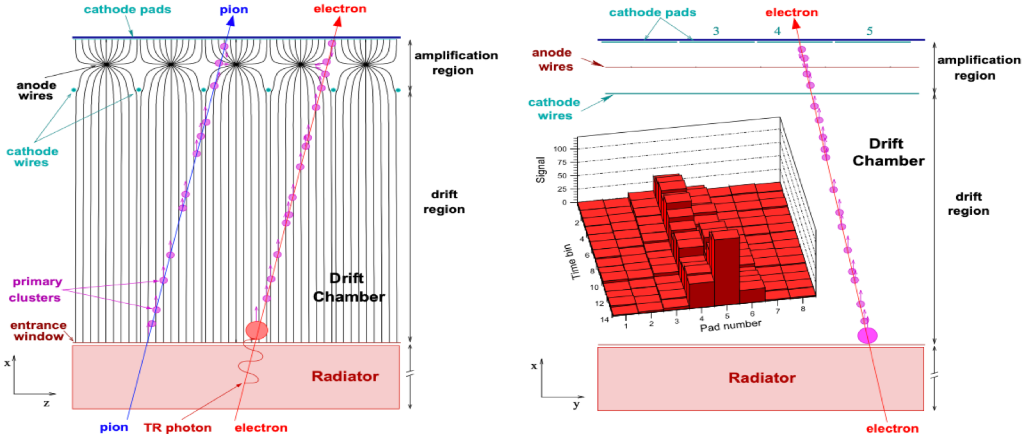
ALICE TRD: thick detector concept

6 TRD layers. Pad readout.

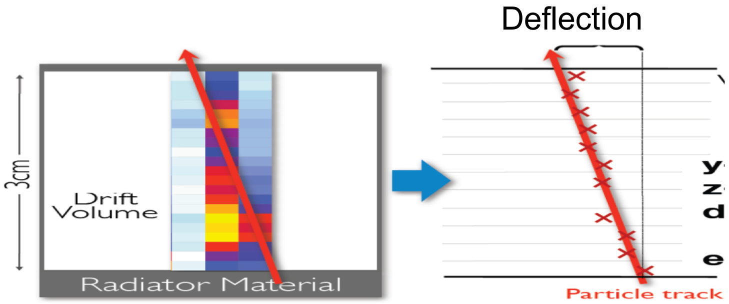


ALICE TRD: thick detector concept

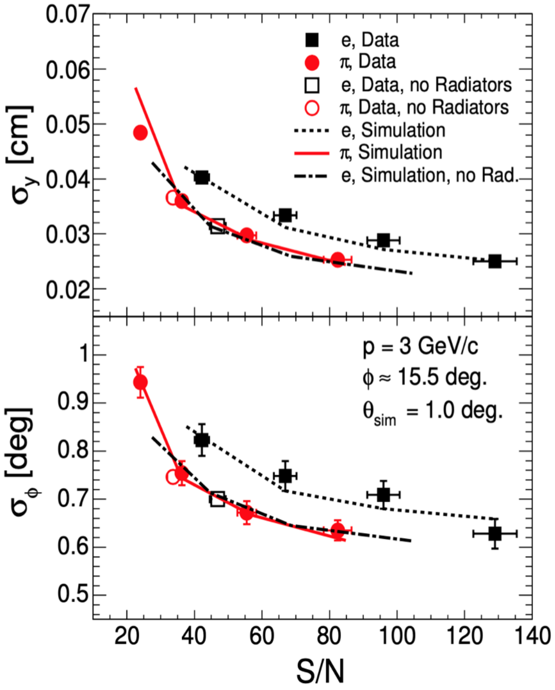
*ALIICE: NIM, A*881 (2018) 89-127



Drift space 3 cm, pad-readout



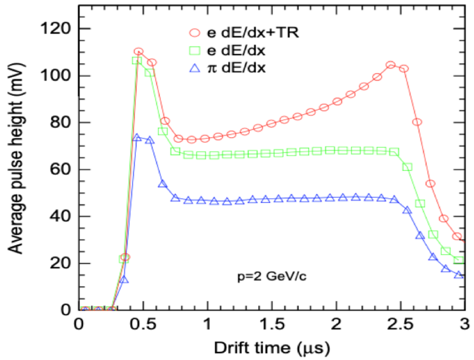
Signal amplitude on pads for different time bins.



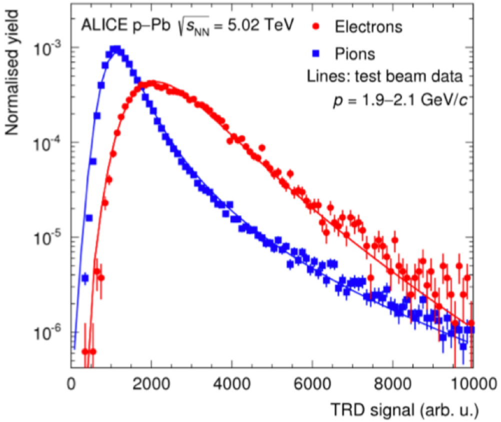
Track position and track angle accuracies as a function signal to noise ratio.

ALICE TRD: thick detector concept

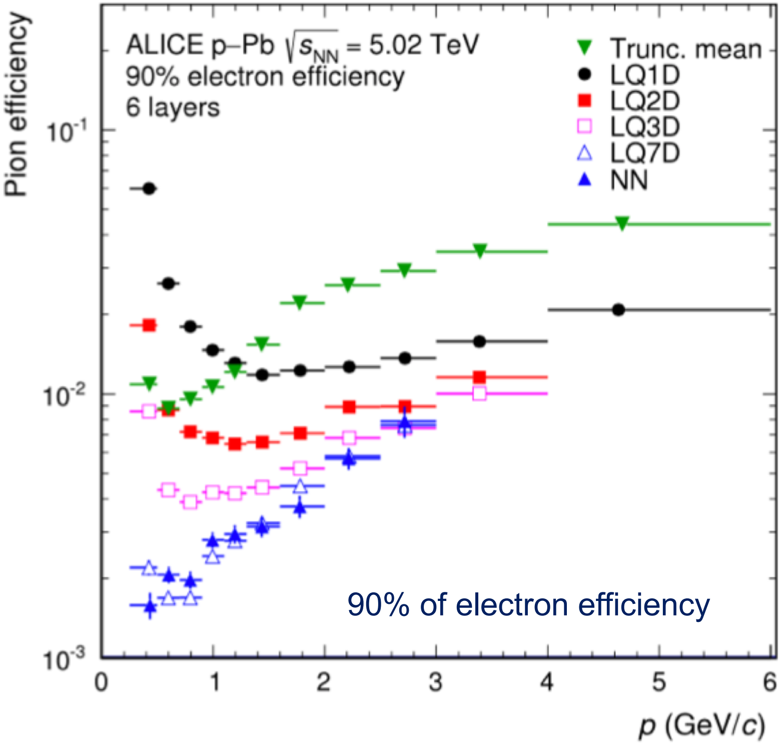
*ALIICE: NIM, A*881 (2018) 89-127



Averaged signal amplitude as a function of time.



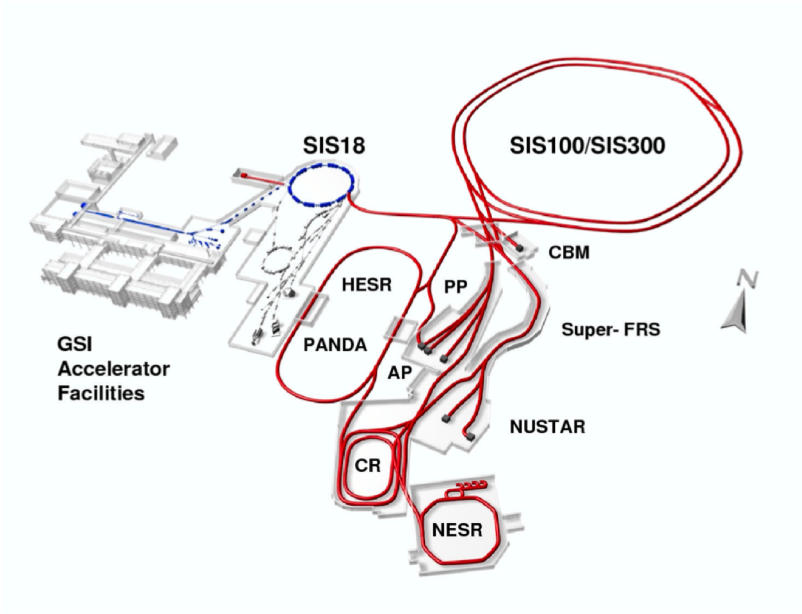
TRD signal distribution in one layer for different particle type

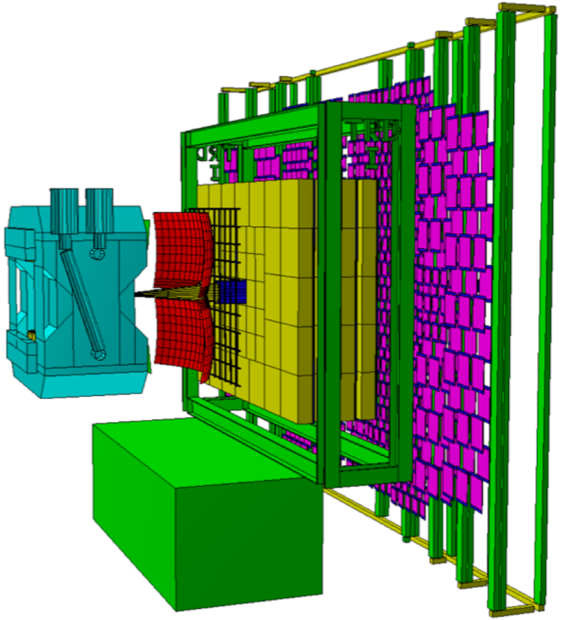


90% of electron efficiency

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

TRD CBM (FAIR)



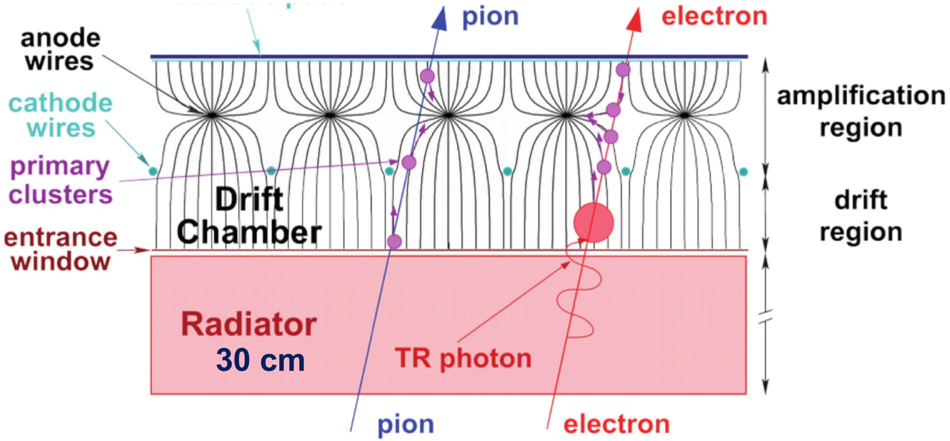


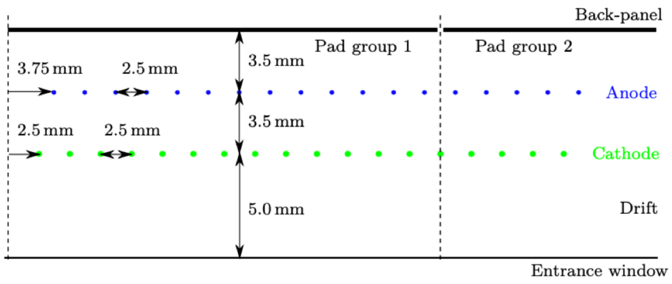
CBM: NIM, A 732 (2013) 375-379
CMB TRD TDR: DOI:10.15120/GSI-2018-01091

TRD for CMB: intermediate detector concept

High rate application. Drift distance reduced to 5 mm.

Pad readout. Total energy is counted

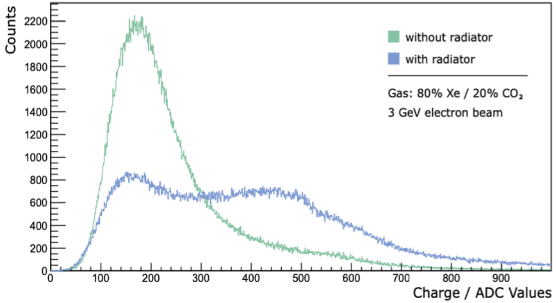




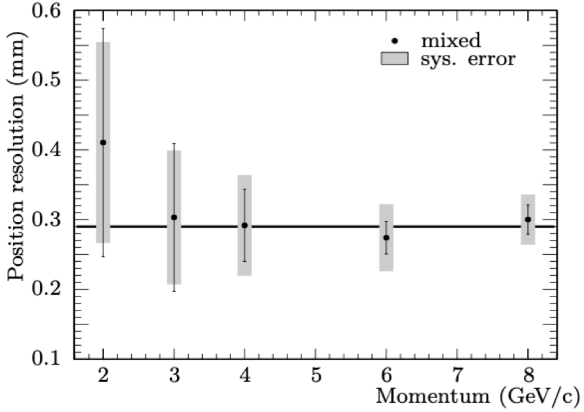
Test beam prototype of large chambers.
4 TRD layers

TRD for CMB: intermediate detector concept

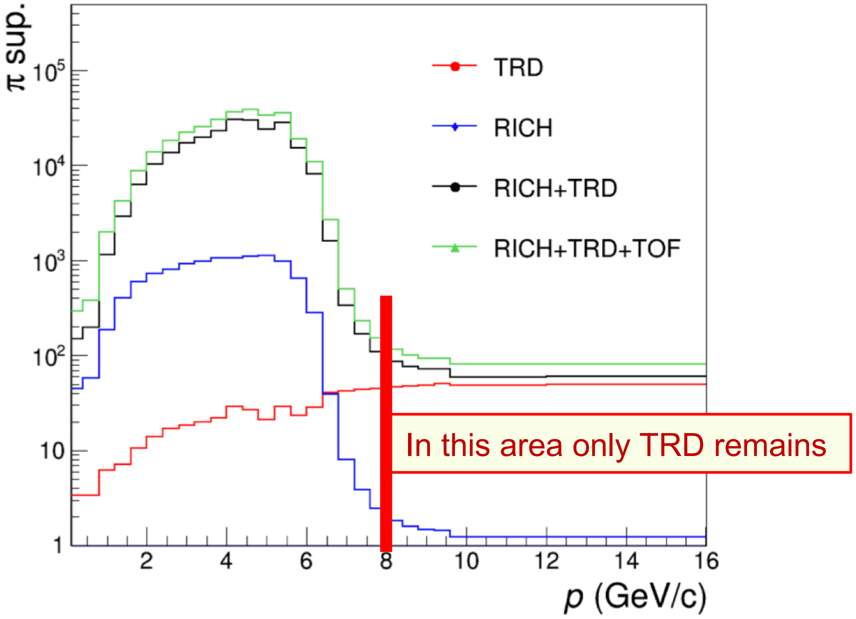
Performance.



Signal amplitude for electrons with and without radiator.



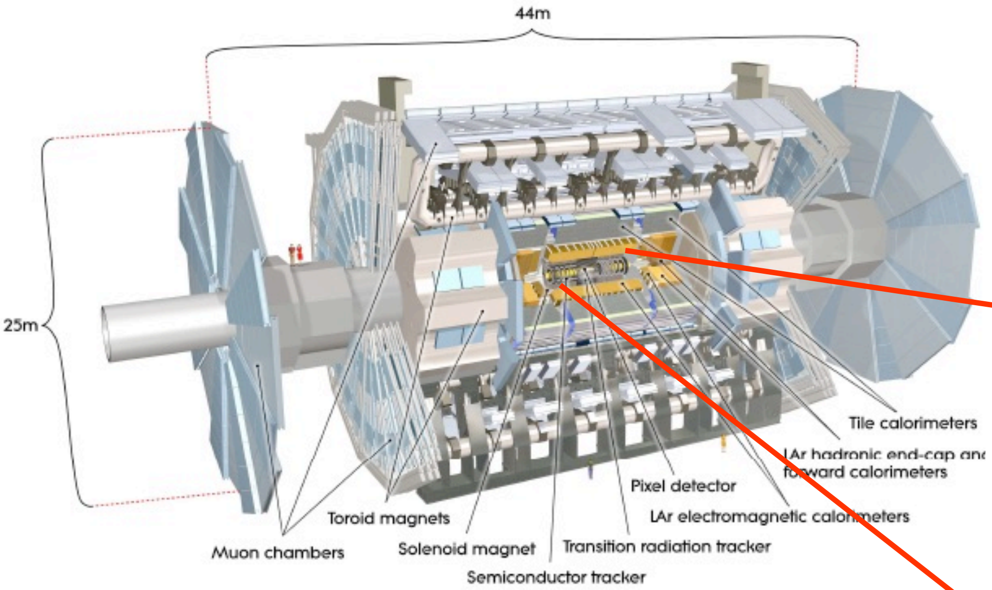
Track position and track angle as a function signal to noise ratio. Pad width 6.8mm.



In this area only TRD remains

Pion suppression factor as a function of particle momentum.

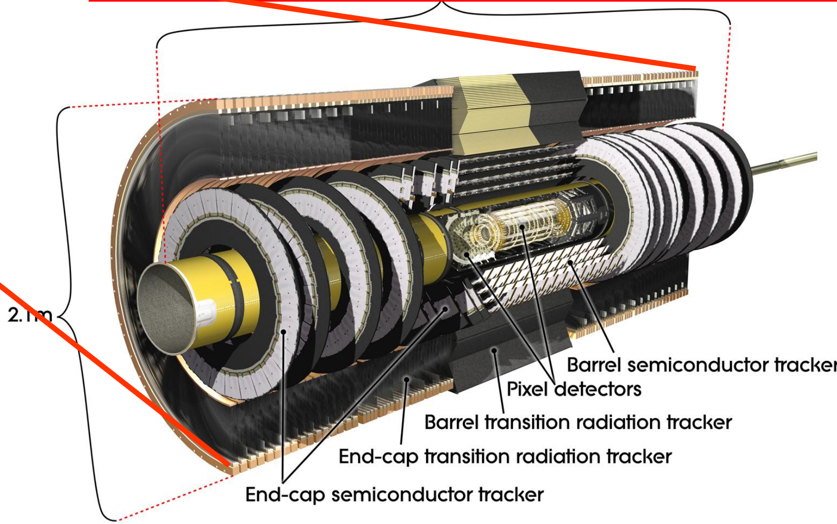
ATLAS TRD: thin detector concept



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

TRT:

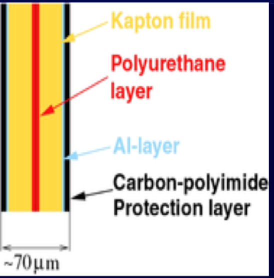
- **Electron identification** for particles with $|\eta|<2$ and $0.5 < p_T < 150$ GeV
- Continuous tracking.
- Particle momentum measurements.

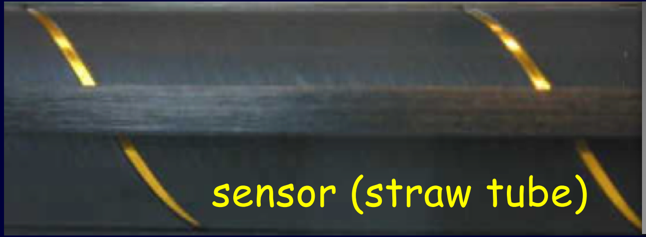


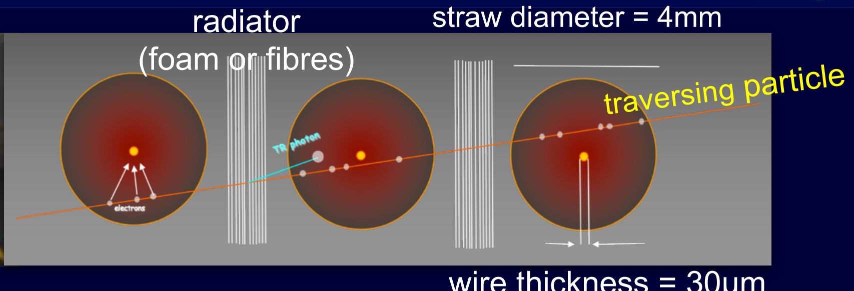
TRT PID:

- Electron identification
  - High Level Trigger
  - Offline
- Conversion reconstruction
- Electron veto for hadronic τ-decays

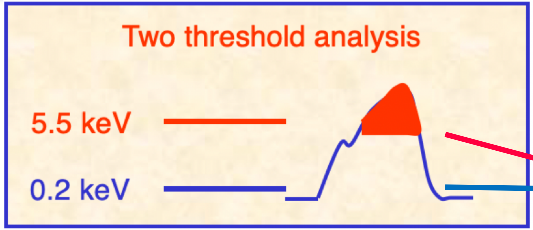
TRT – Straw based detector



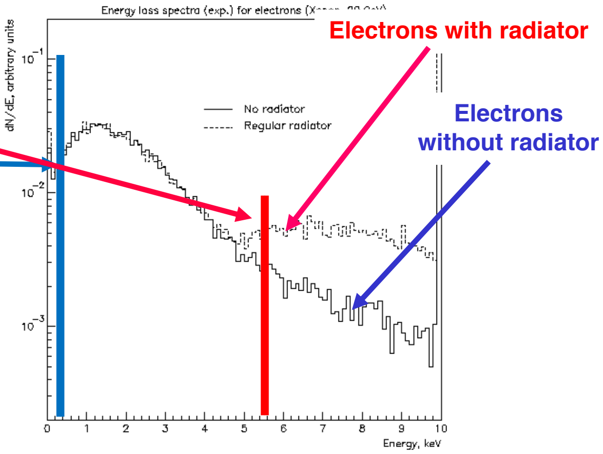




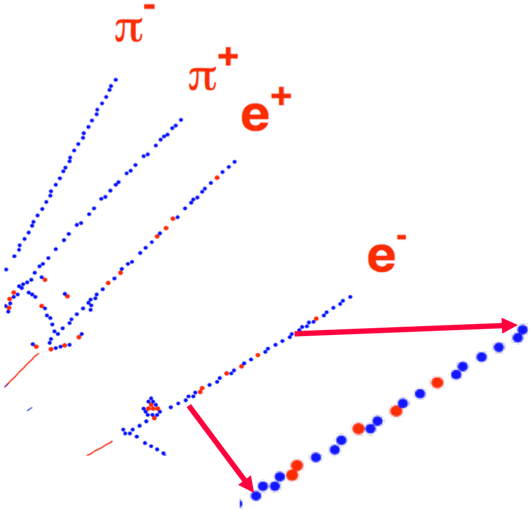
Signal in the detector is a superposition of dE/dX and TR



- 30 measurement points on track
- Space point measurement accuracy ~130 mm in each straw (Low Threshold)
- Separation of particles using High Threshold ~6keV (TR)
- Use Low Threshold information (ToT) for dE/dX measurements



Differential spectrum of the energy loss in the straw.



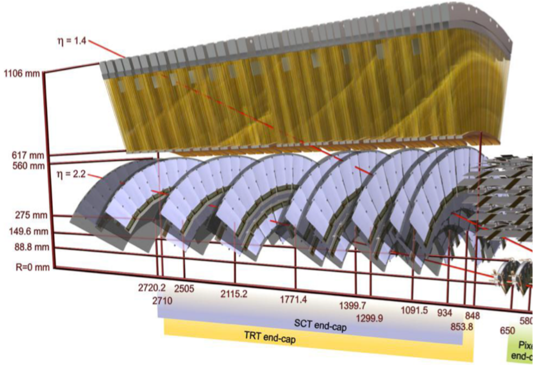
ATLAS TRD: thin detector concept

Two different detector design for the Barrel and End-Caps

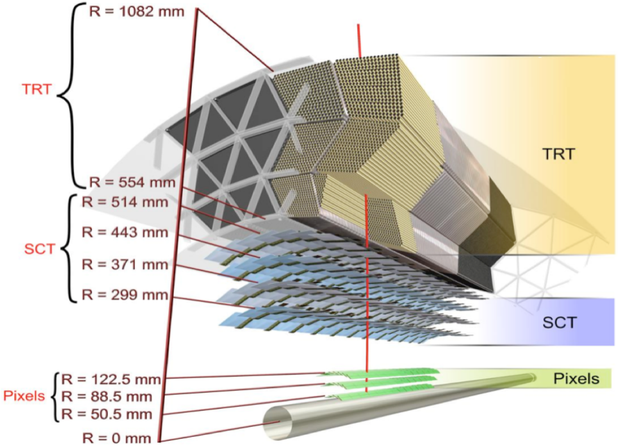
Operation conditions:

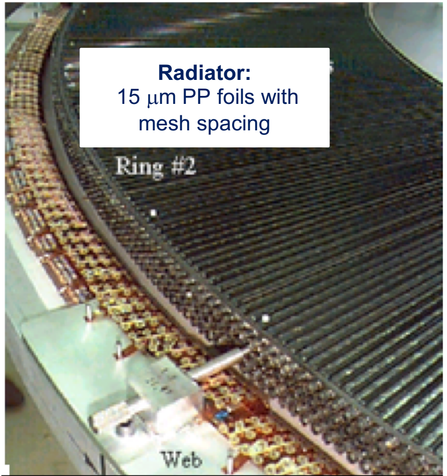
- *Particle rate – up 20 MHz*
- *Particle density up to 500 kHz/cm*
- *Accumulated charge up to 10 C/cm of*
- *Current up to 10 μA per wire*
- *Ionization current density ~015 μA*
- *Total ionization current ~ 3 A*
- *TRT ionization current power ~5 kW*

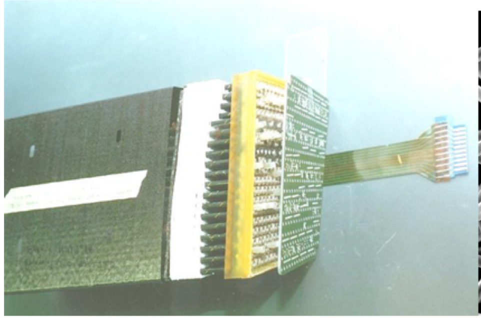
End-cap part of the ATLAS Inner Detector

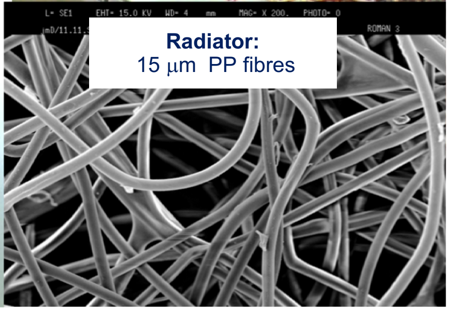


Barrel part of the ATLAS Inner Detector

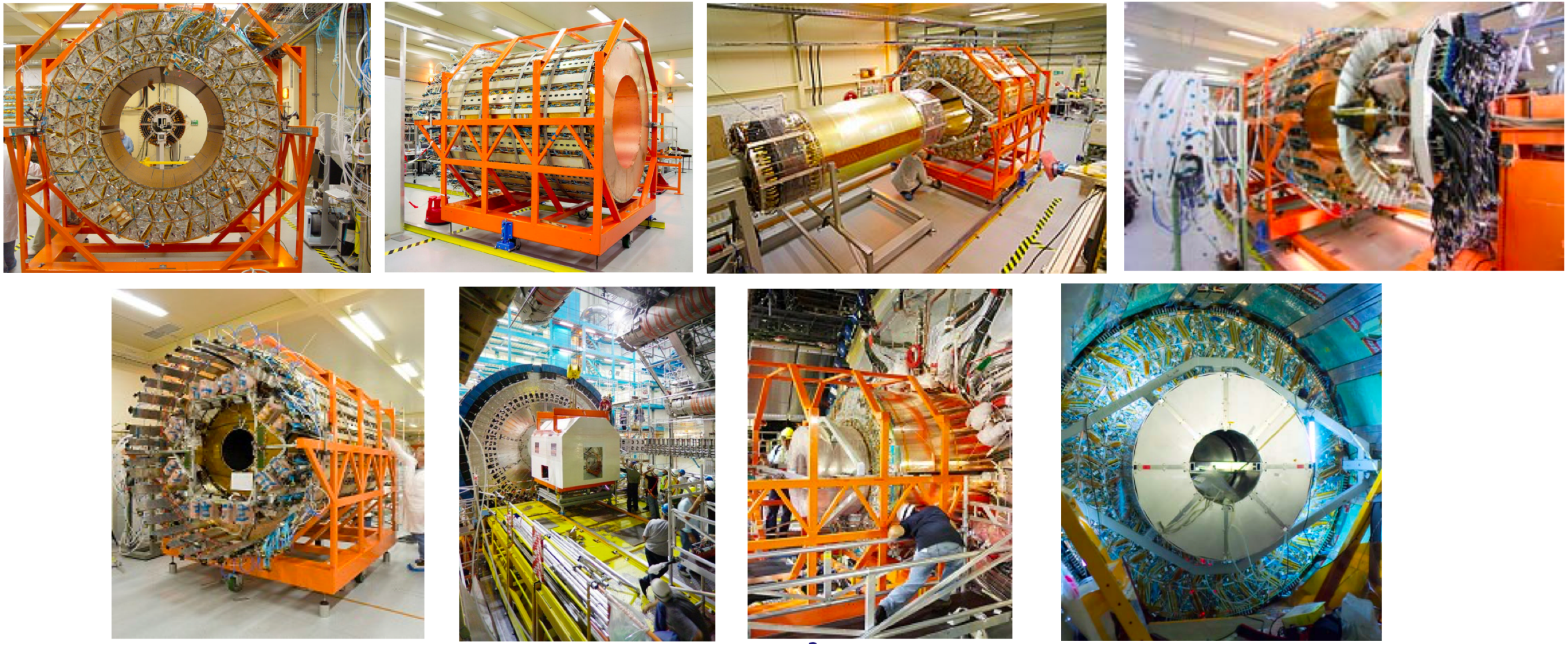



Radiator:
15 µm PP foils with
mesh spacing

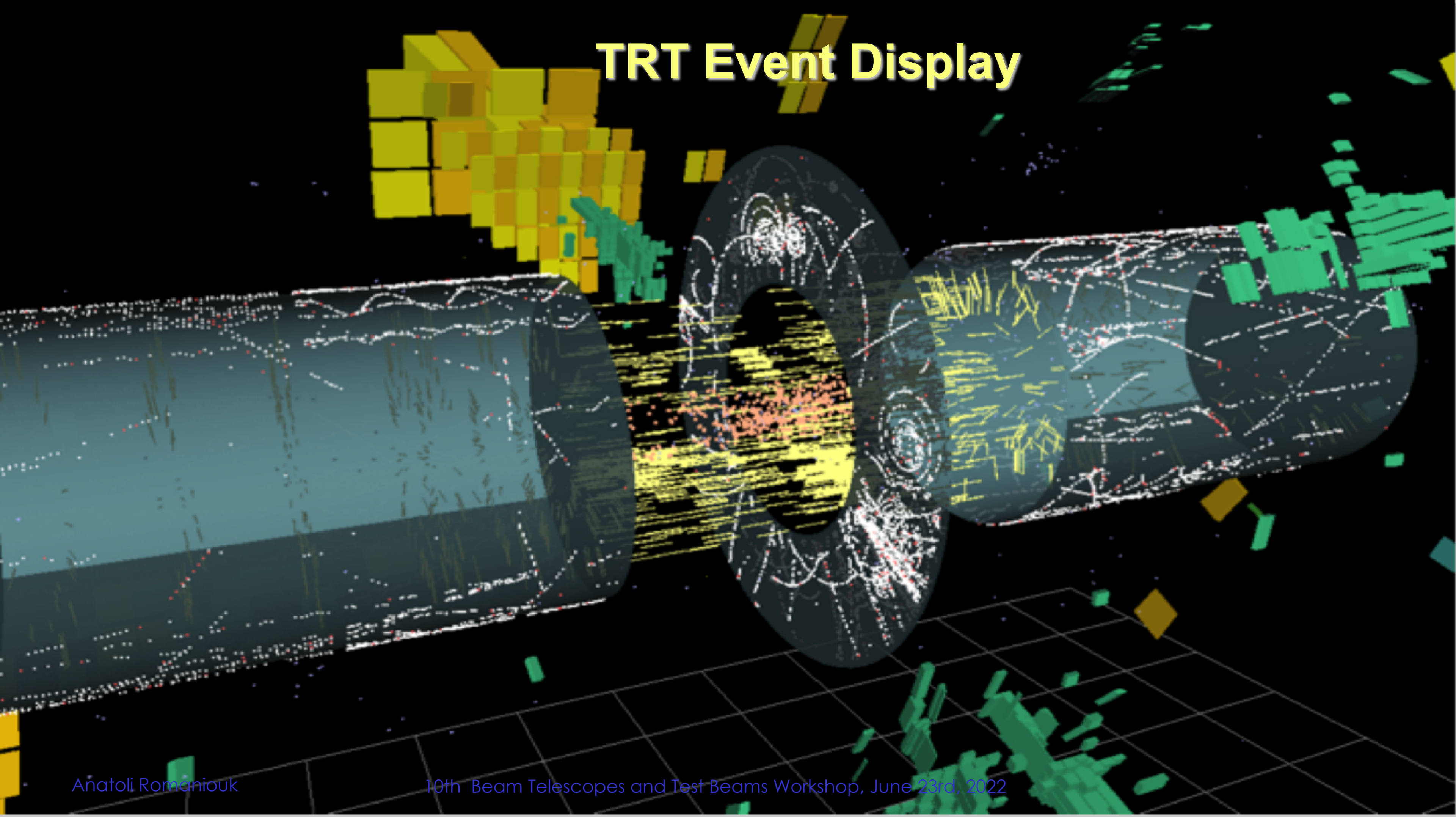



Radiator:
15 µm PP fibres

ATLAS TRD: thin detector concept

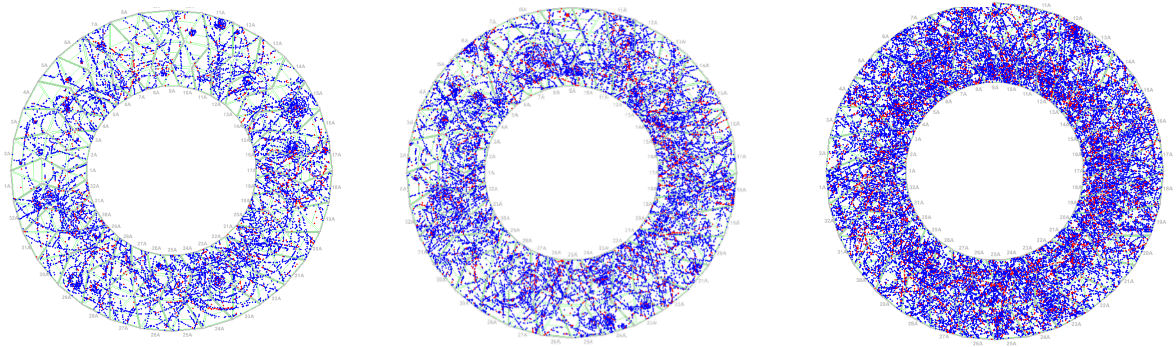


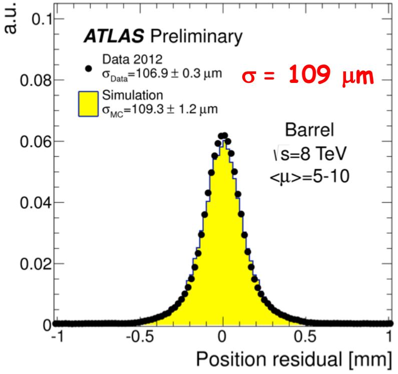
TRT Event Display



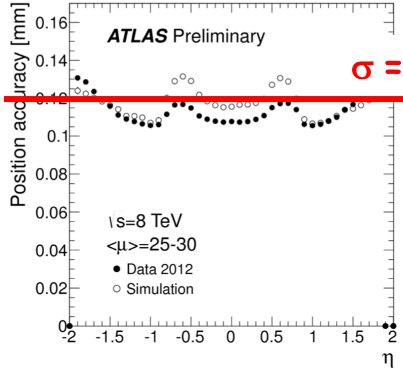
TRT Tracking performance.

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



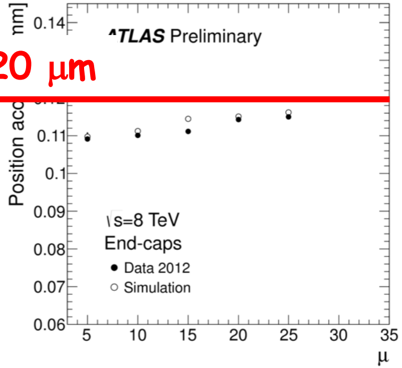


Track to drift-radius residual distribution



σ = 120 µm

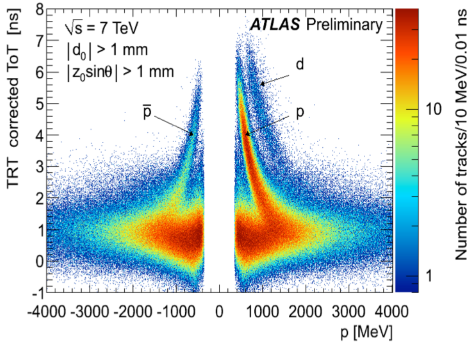
TRT straw position measurement accuracy as function of pseudorapidity



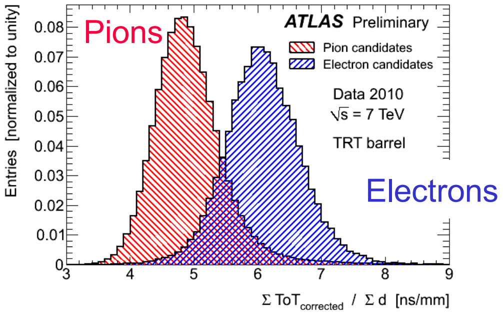
TRT straw position measurement accuracy as function average number of interactions per bunch

TRT performance: Electron/pion separation

dE/dX

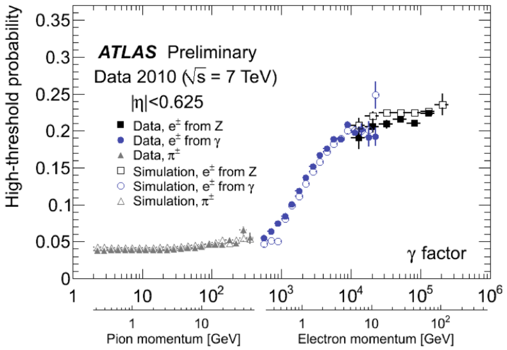


dE/dx performance using time-over-threshold

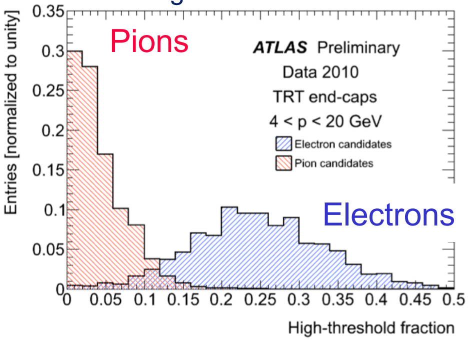


Electron/pion separation using only ToT method.

TR

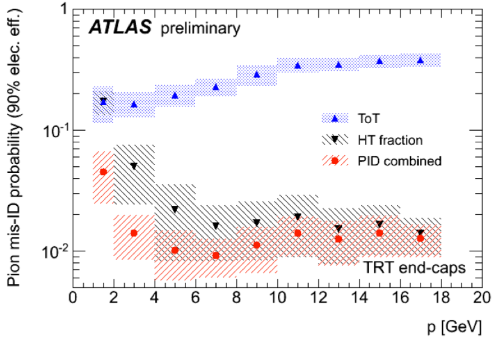


HT probability of particle gamma factor

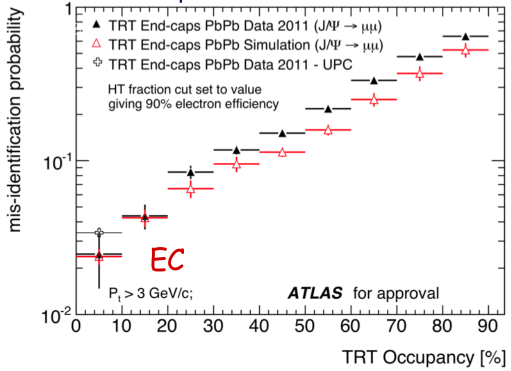


Fraction of TR hit on track for pions and electrons

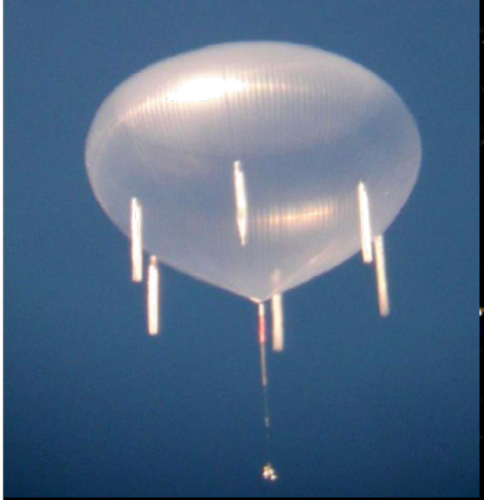
dE/dX + TR



Pion misidentification as a function pion momentum



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}

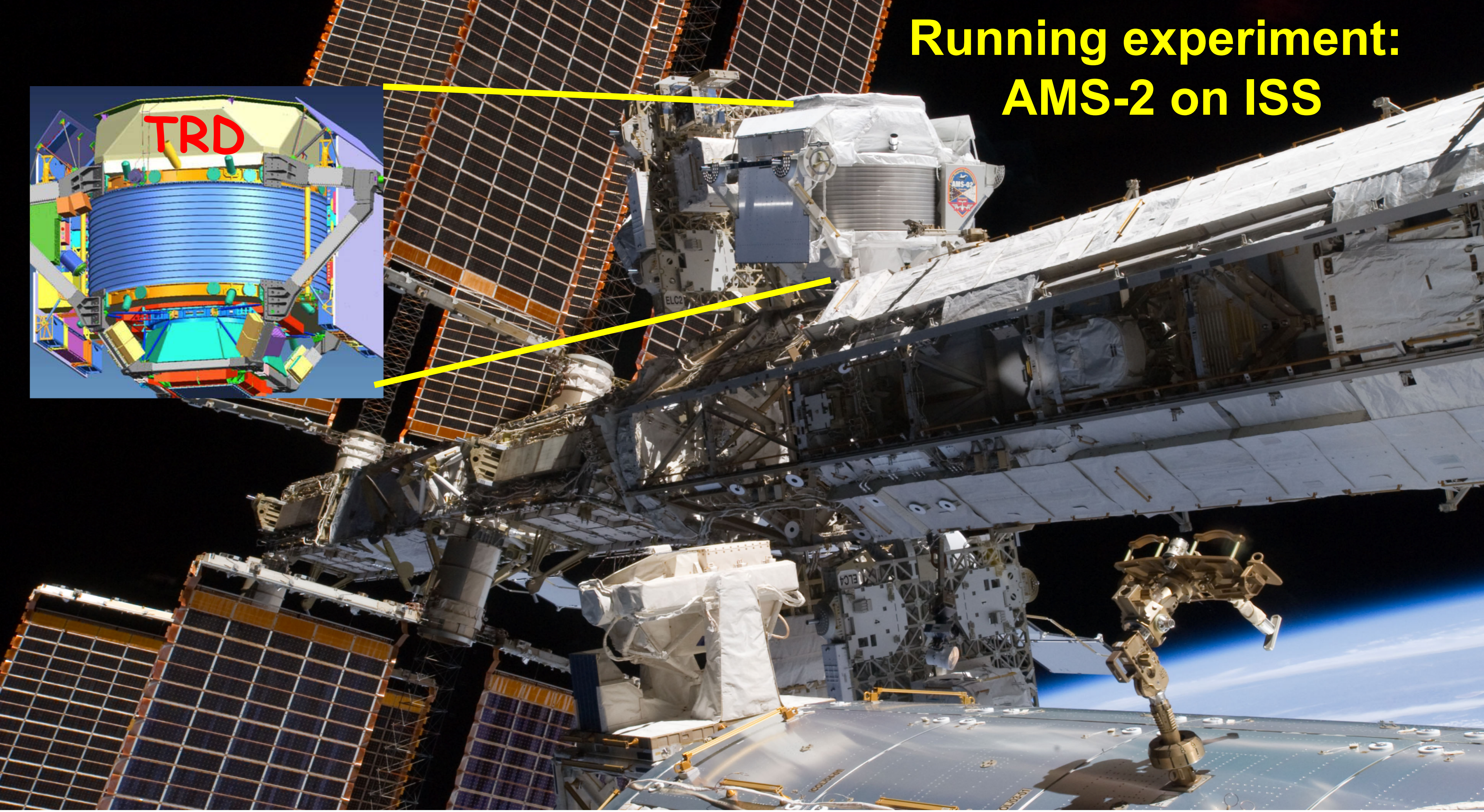
TRD:

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



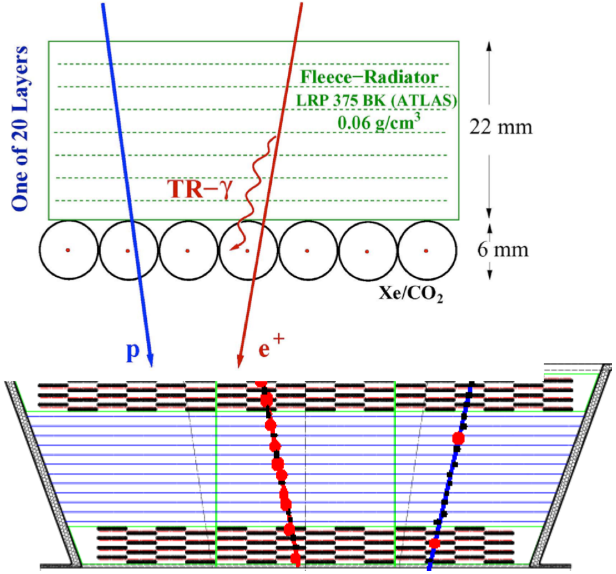
AMS-02 TRD: Thin detector concept

NIM. A706, 2013, 43-47

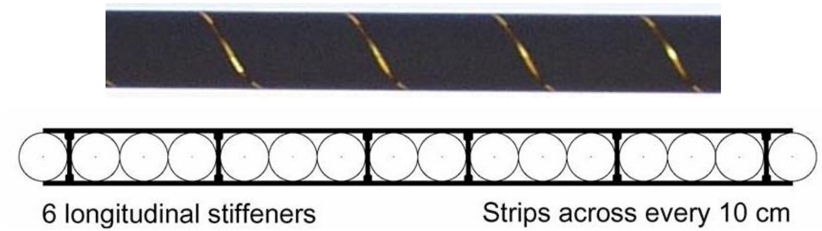
Straws and radiators from the TRT developments

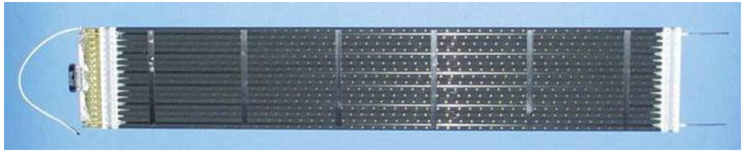
Straw tube proportional counter modules:

- 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:

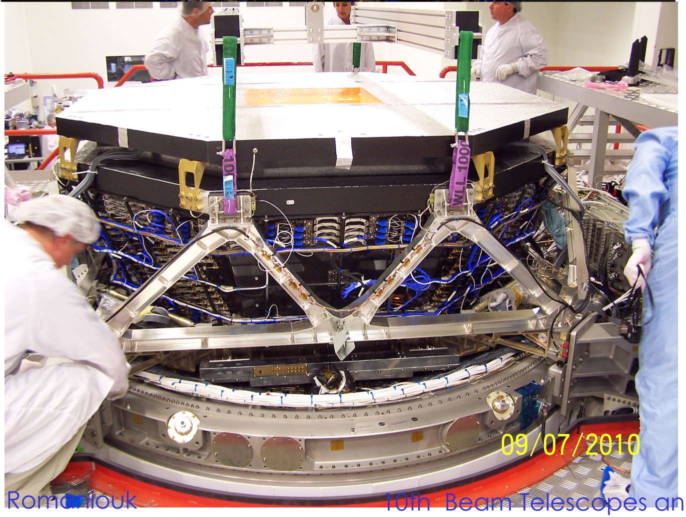
20 Layers each existing of:

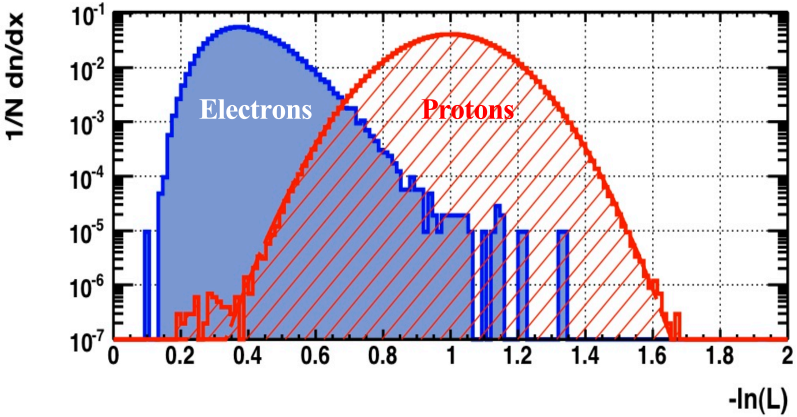
- 22 mm fibre fleece
- Ø 6 mm straw tubes (Xe/CO_2 80%/20%)

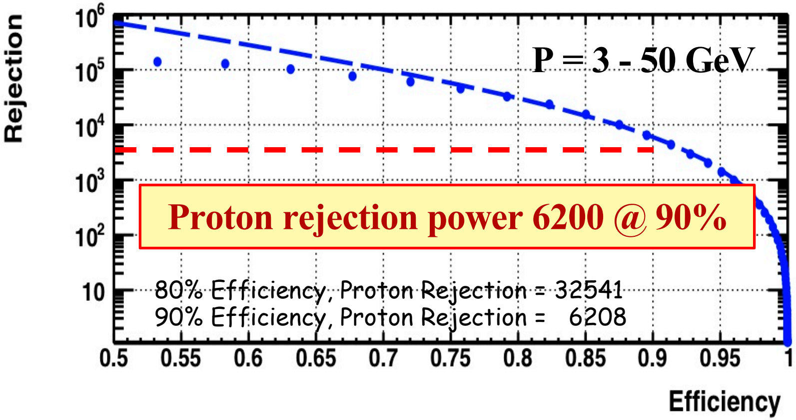
Non-bending plane: 2x4 layers

Bending plane: 12 layers

AMS-02 TRD: Thin detector concept







Proton rejection power 6200 @ 90%

80% Efficiency, Proton Rejection = 32541
90% Efficiency, Proton Rejection = 6208

TRACER - balloon experiment : intermediate detector concept

TRDs: Lorentz factor measurements.

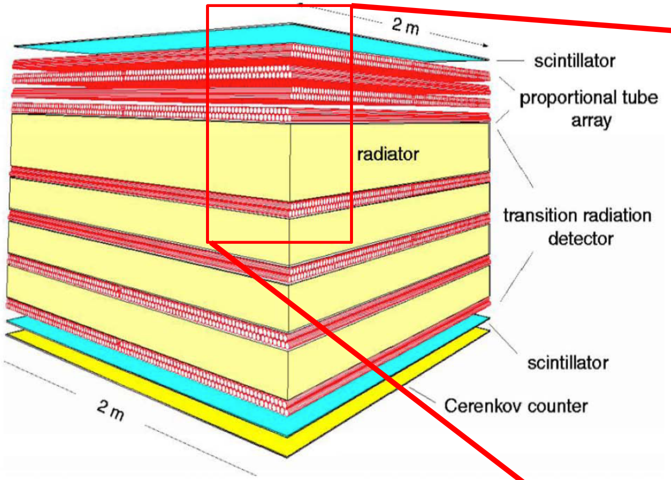
$N_{TR} \sim Z^2$ particle

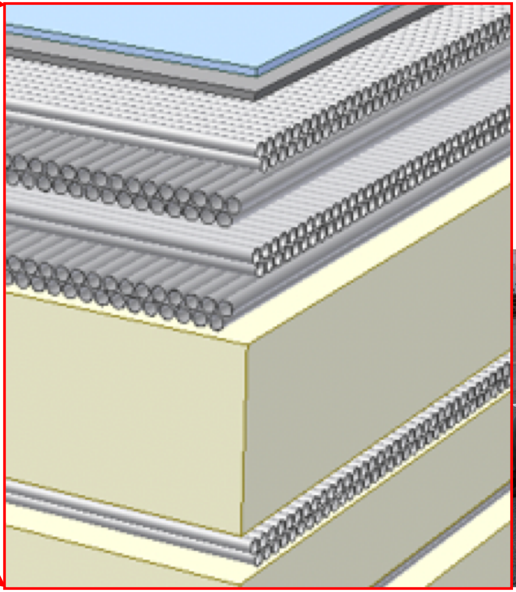
TRACER IS BIG:

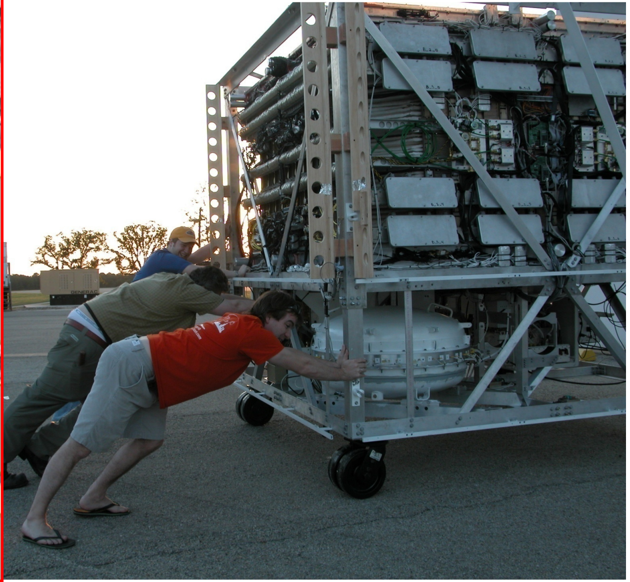
5 m² area - the largest balloon-borne cosmic-ray detector

Nucl.Instrum.Meth. A654 (2011) 140-156

TRACER Detector System
“Transition Radiation Array
for Cosmic Energetic



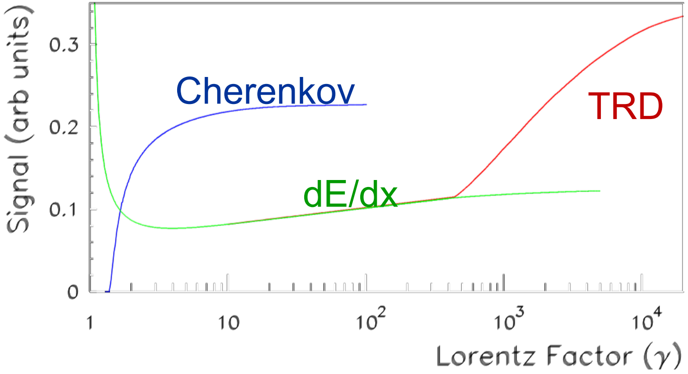


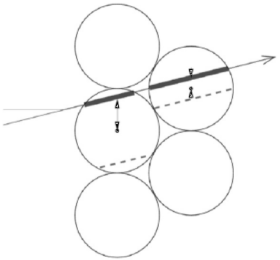


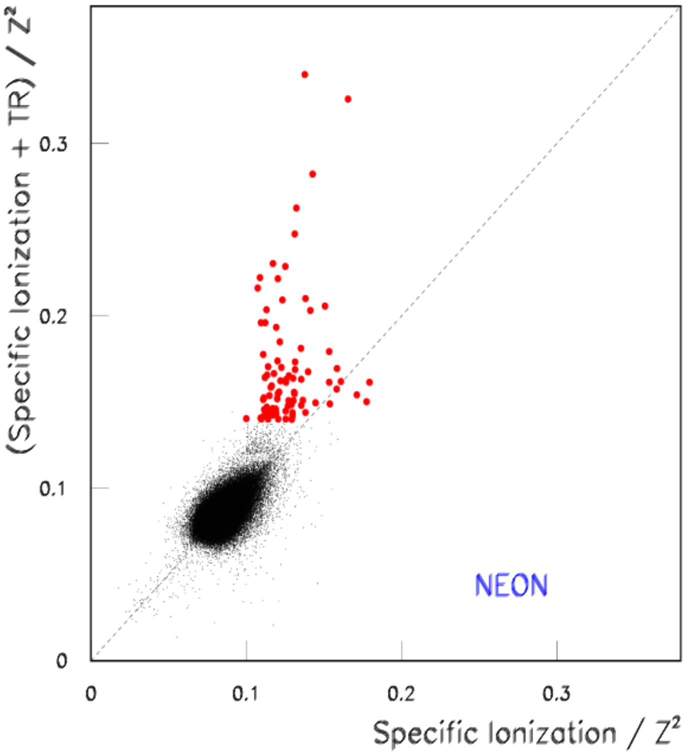
TRACER has 16 layers Mylar straws of 20 mm diameter, 8 for dE/dx measurement,
and 8 for dE/dx+TR

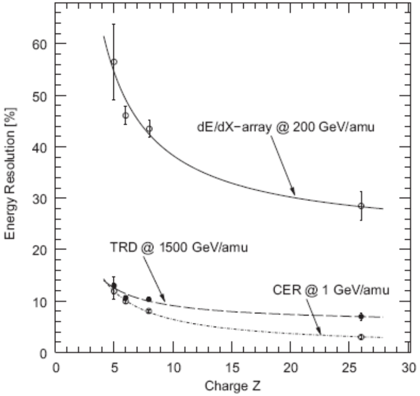
TRACER - balloon experiment : intermediate detector concept

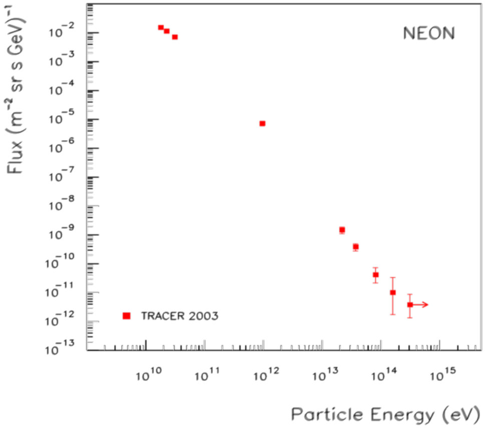
TRDs: Lorentz factor measurements.







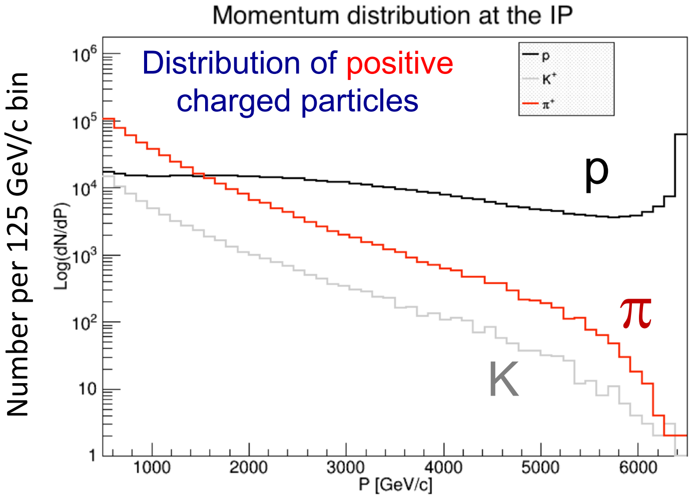


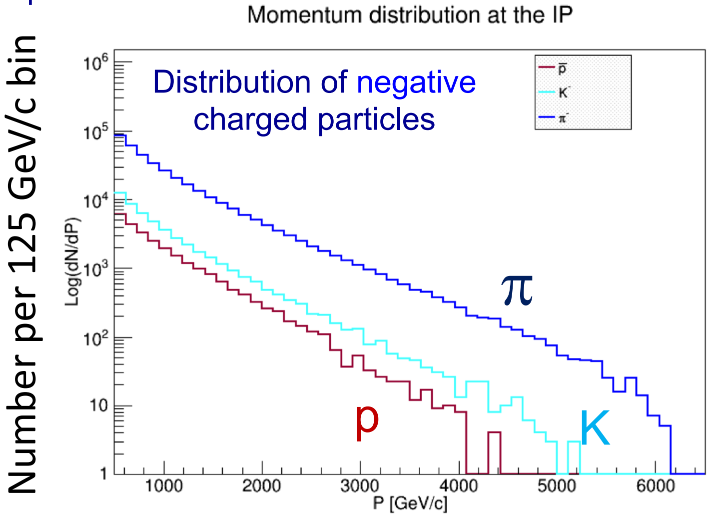


TRD for a hadron identification in a forward direction at LHC

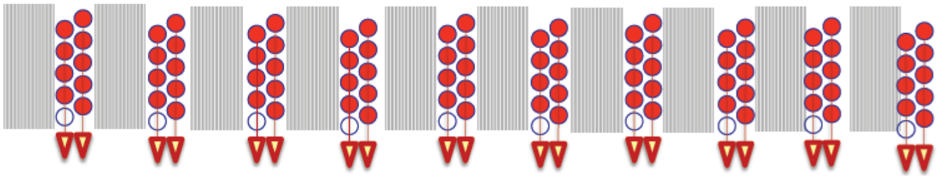
J. Phys.: Conf. Ser. 1390 (2019) 012126, J. Phys.: Conf. Ser. 1690 (2020) 012043

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).



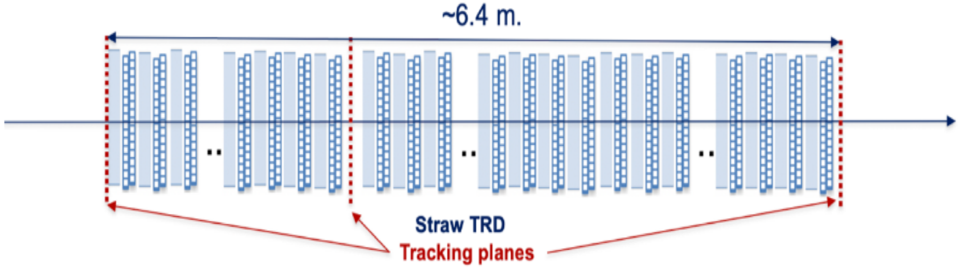
Advantages:

- 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:

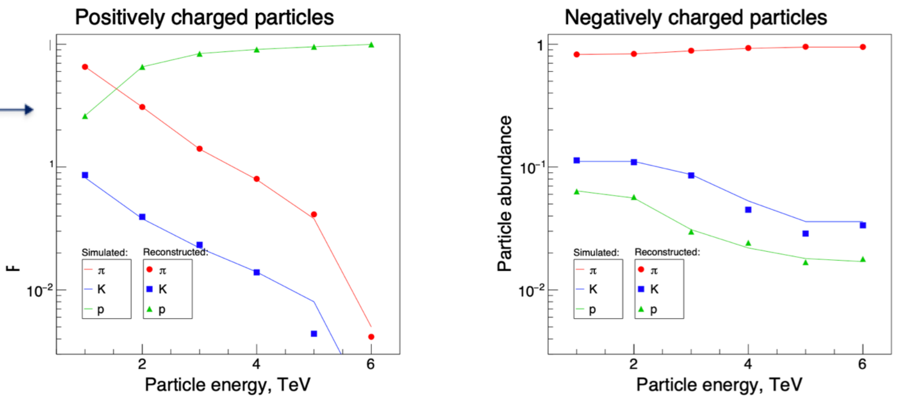
- TR and dE/dx cannot be decoupled.

TRD for a hadron identification in a forward direction at LHC

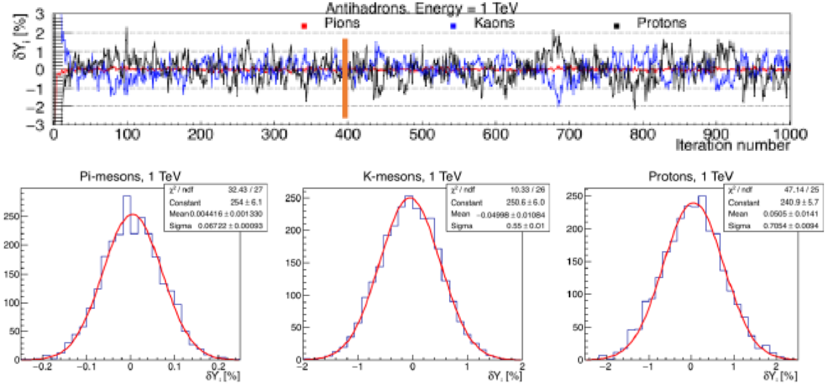


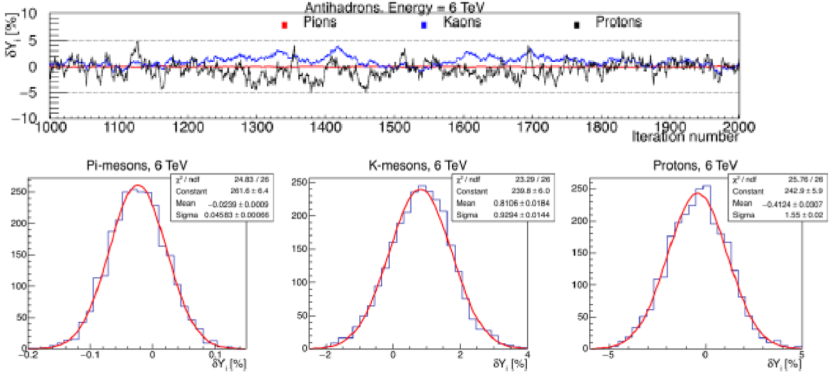
Iterative Bayesian approach:

Expected and reconstructed particle composition of hadrons.



How many iterations are required?





TRD for a hadron identification in a forward direction at LHC

All this is possible if you know exact response of the detector!

There are two few caveats here: Space charge effect and photo electron pass in the working volume

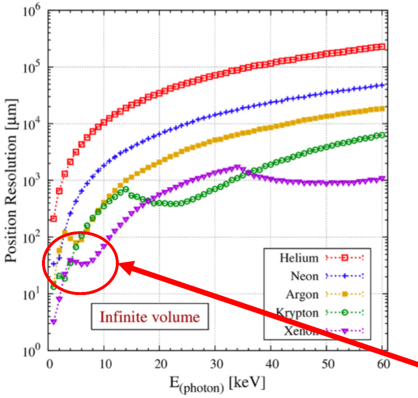
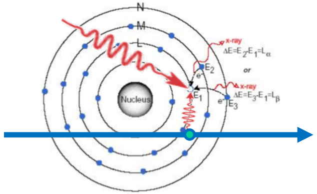


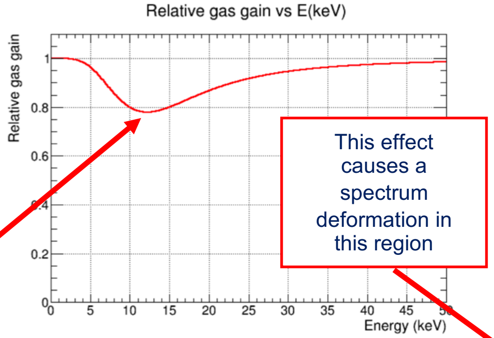
Fig. 5. Position resolution as a function of the photon energy for an "infinite" geometry.

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

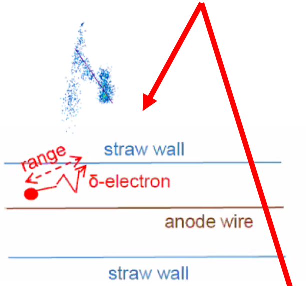


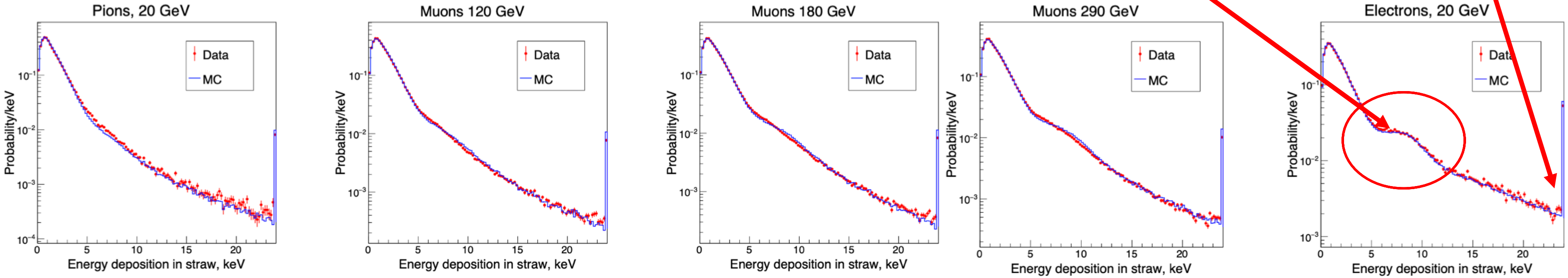
Photon of 10 keV:
Photoelectron ~5 keV
Auger electrons: ~4 keV + 1 keV the rest



This effect causes a spectrum deformation in this region

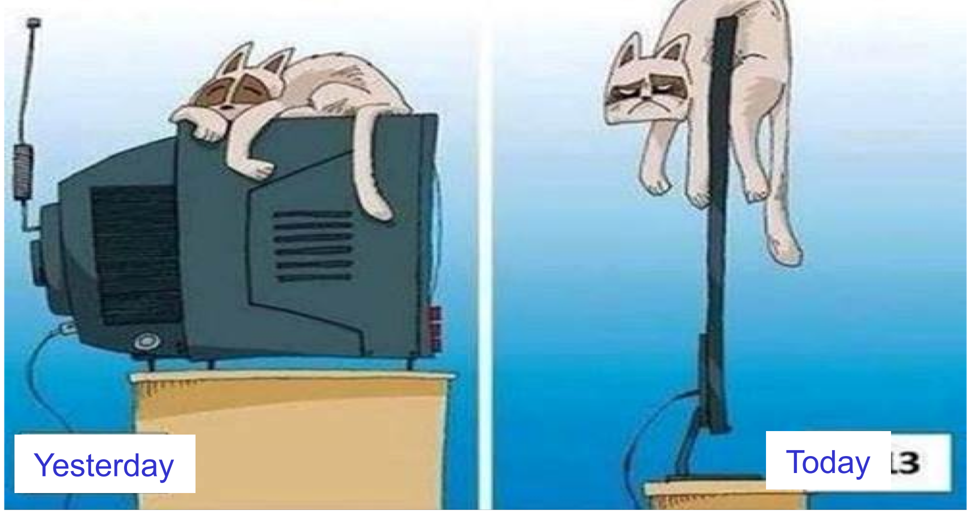
δ-electrons of high energy have a significant pass in the gas and can go out from the working volume. This affect the spectrum shape and must be taken into account





What was good yesterday

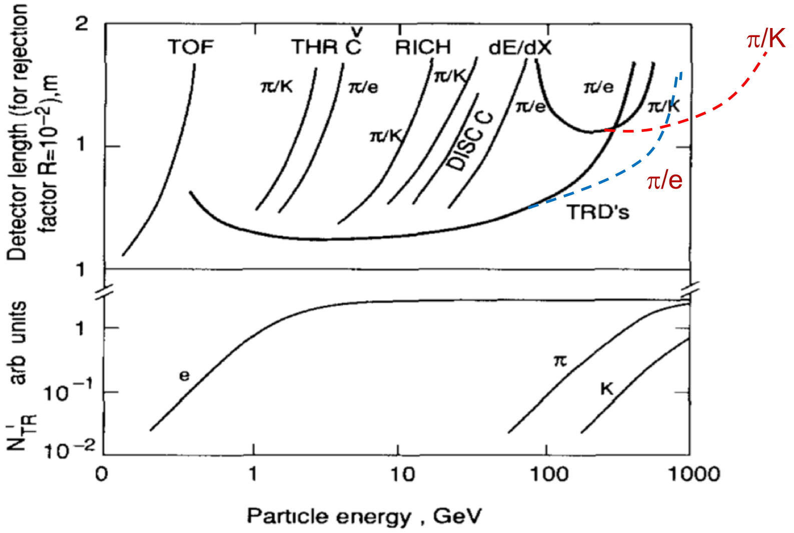
Isn't necessarily good today



New approaches in the TRD development.

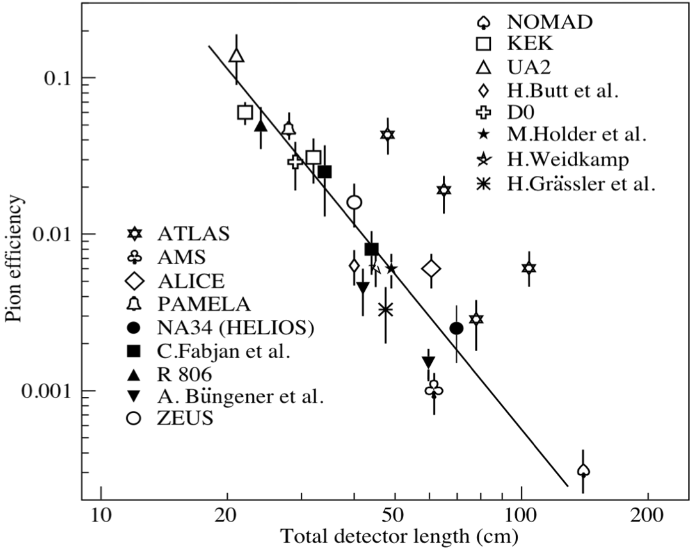
TRD: where we are now?

TRDs have the largest gamma factor range. Mainly used well for separation of particles up to gamma factors few*10^3. But it is not a limit!



TRD length is critical!

Particle Data Group, Journal of Physics G 37 (2010) 075021.

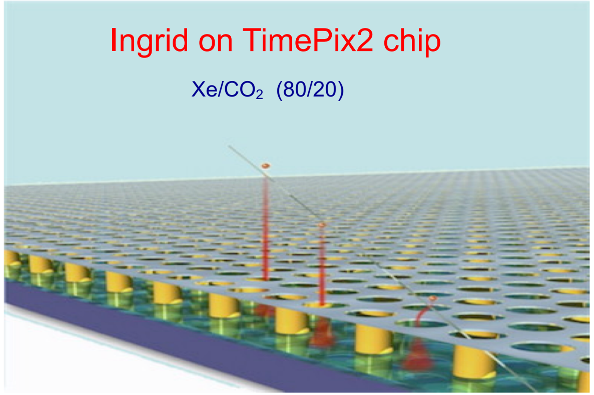


What to do?

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

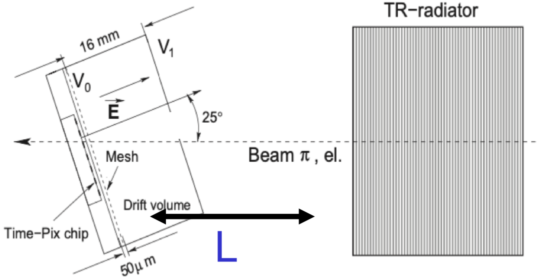
What is the limit for gaseous detectors? Track-to-TR separation limiting space.

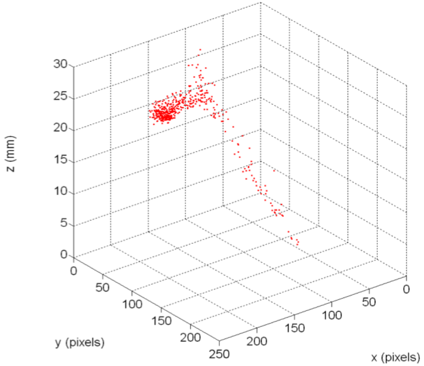
Micropattern detectors based TRDs: *Ingrid technology*

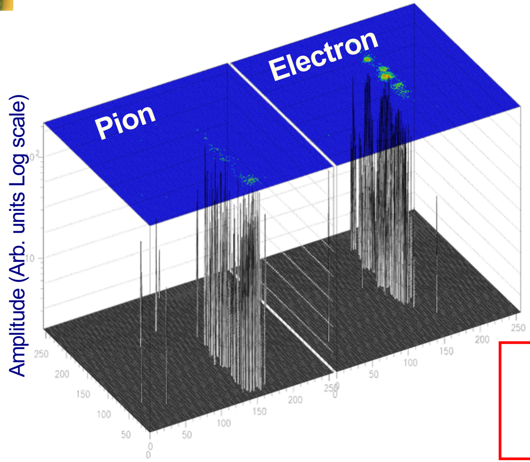

Ingrid on TimePix2 chip

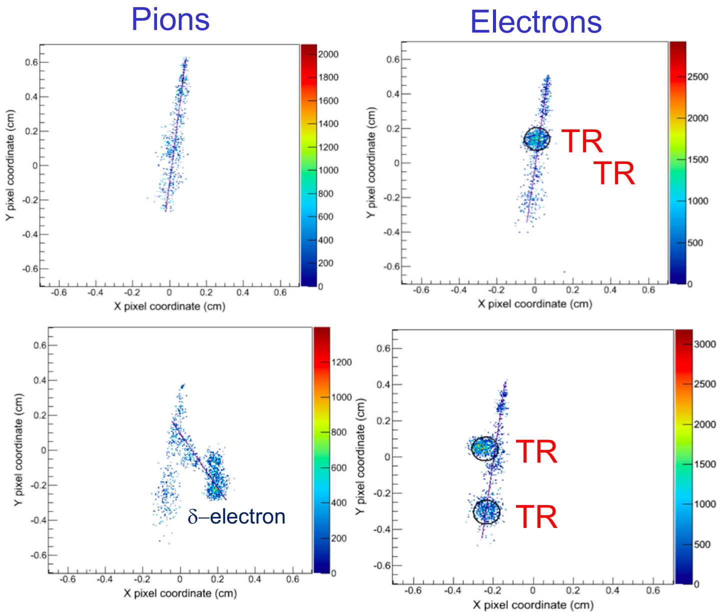
Xe/CO_2 (80/20)

MIM, A 706 (2013) 59–64



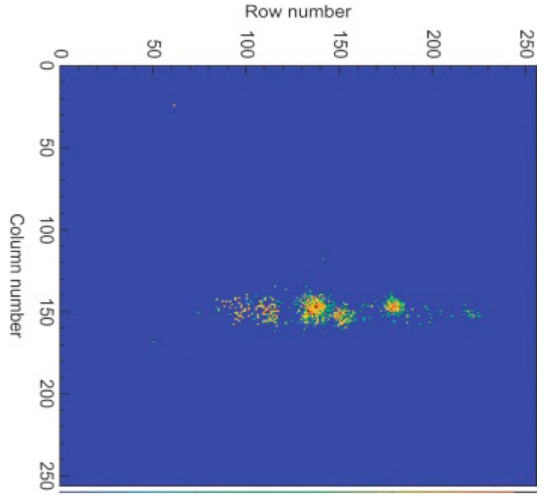


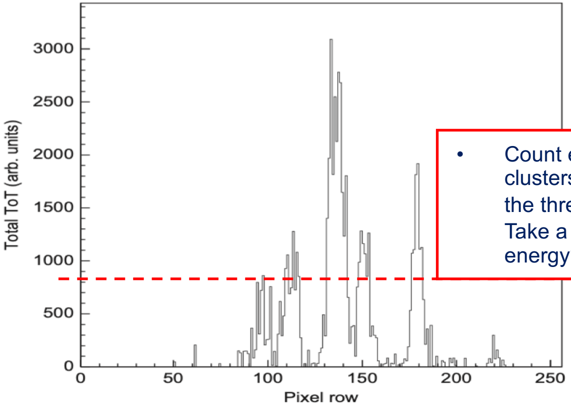




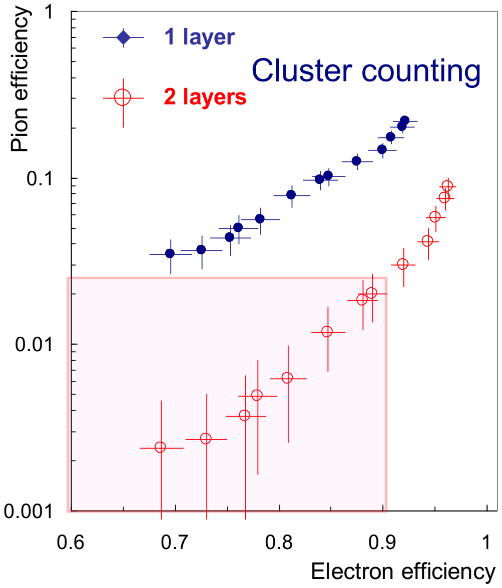
For close radiator position the TR and dE/dX losses cannot be separated but track structure is clearly seen.
The main limit is defined by delta-electrons.

Micropattern detectors based TRDs: *Ingrid technology*

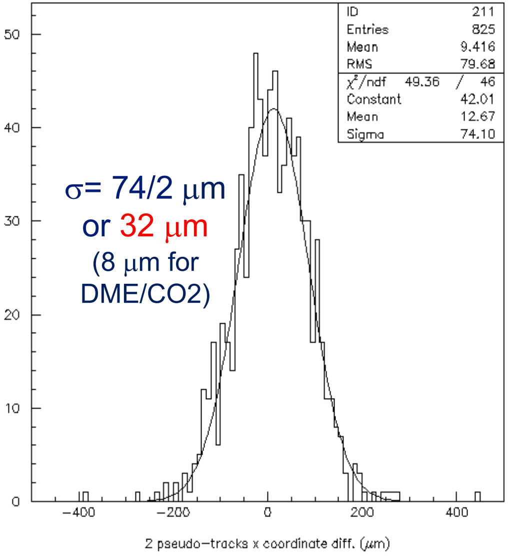




- Count energy in clusters above the threshold Take a total energy?



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



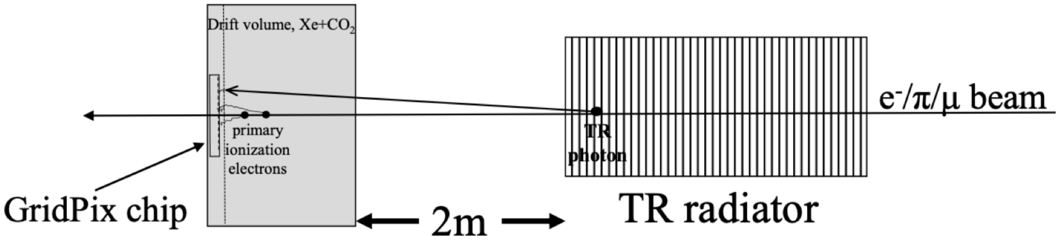
Track position residual on the chip plane.

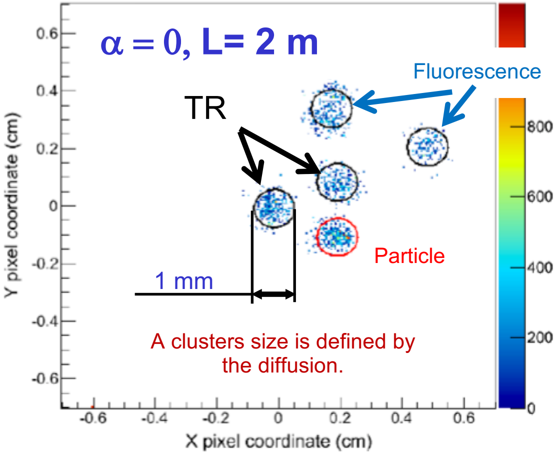
- Rejection factor of ~ 50 for 90% electron efficiency.
- Major limiting factor are delta-electrons (not removable because of the same production diagram)
- Combines tracking and PID properties.
- Vector tracking.

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

What is the limit for gaseous detectors? Track-to-TR separation using angle

Use a TR production angle?

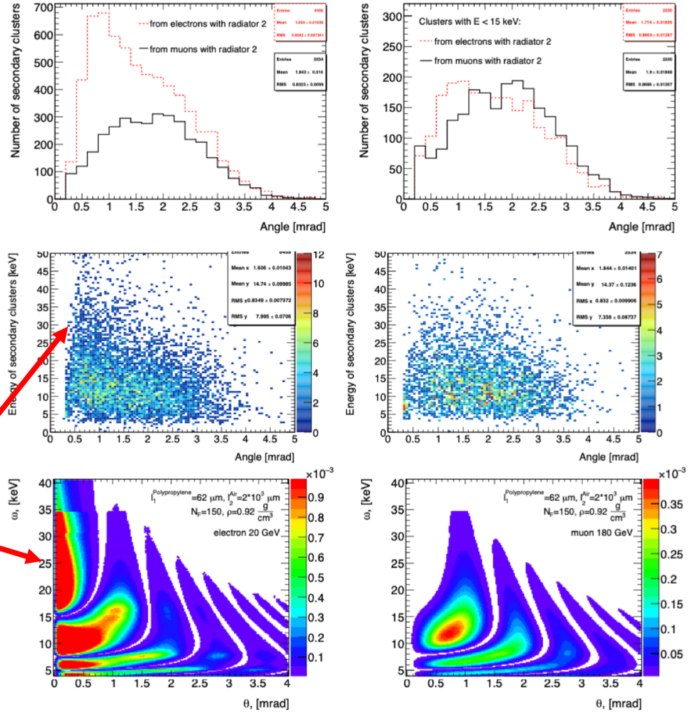




A clusters size is defined by the diffusion.

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

Angular distribution of TR



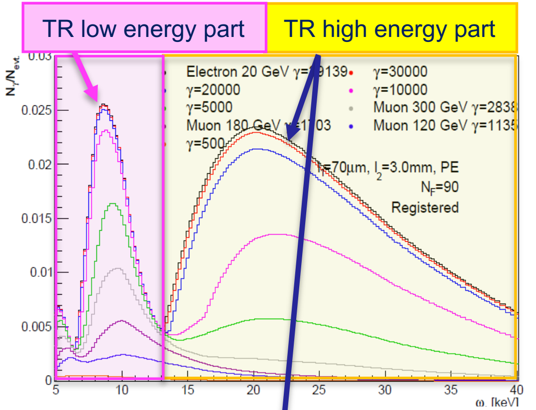
We are missing the main TR peak

Angular resolution is very much limited by **diffusion effects** even at **2 m** distance!?

TRD based on semiconductor detectors.

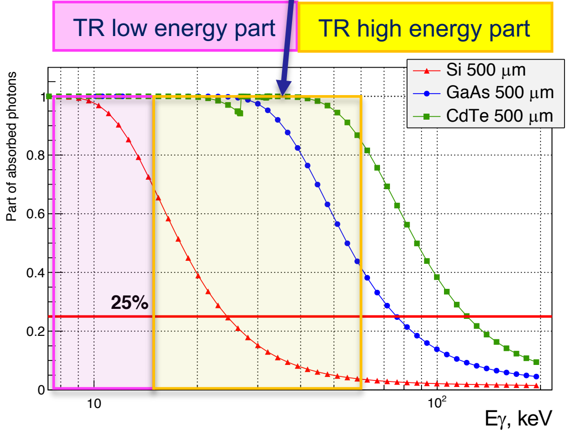
A combination of a precision tracking and a particle identification in one device!

Why GaAs sensors?

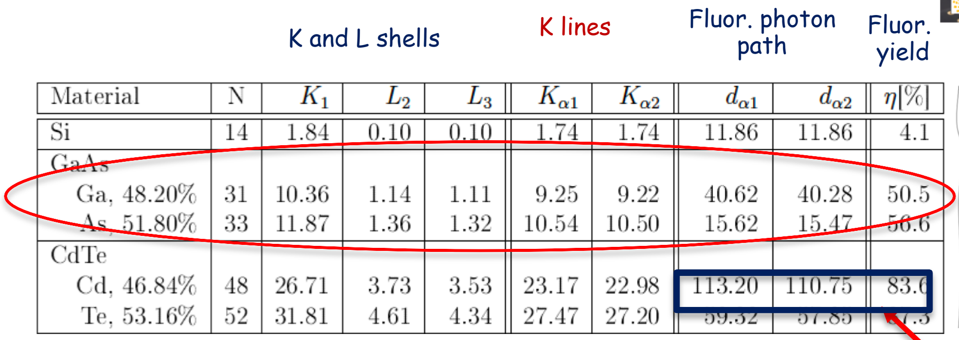


Eγ, keV

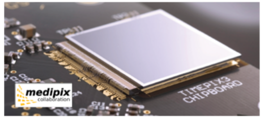
TR spectra for different particles produced in PE radiator with 70 μm foil thickness and 3 mm spacing.

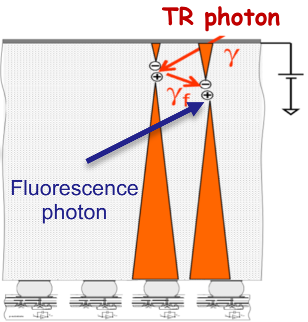


Fraction of photons absorbed in 500 μm sensor.



		K and L shells			K lines		Fluor. photon path		Fluor. yield
Material	N	K_1	L_2	L_3	$K_{\alpha 1}$	$K_{\alpha 2}$	$d_{\alpha 1}$	$d_{\alpha 2}$	$\eta[\%]$
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	87.5



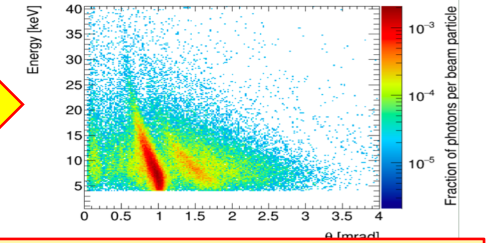


- **CdTe** can be the best but it has big fluorescent yield (84%) and fluorescence photons have a large mean path in the detector (110 μm).
- **Si detectors** are very good but for low energy part of TR spectrum.
- **GaAs material is the optimum one** for low and high energy part of TR spectrum. Fluorescence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

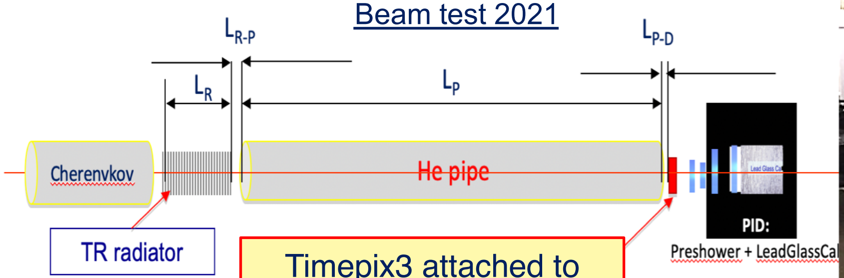
Semiconductor based detectors.

$\theta\sim\cancel{1/\gamma}$ Commonly used relation is not accurate!

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

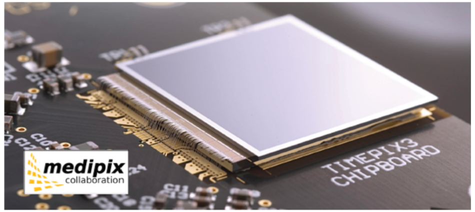


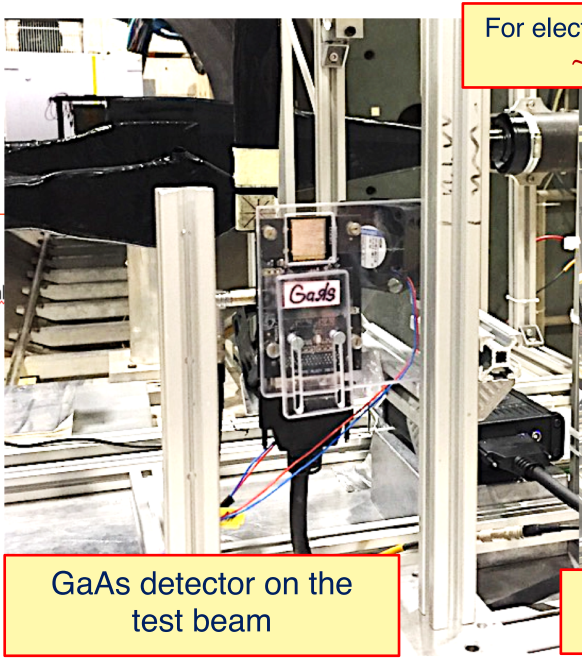
For electrons 20 GeV and specific radiator it is ~1 mrad instead of 0.025 mrad!



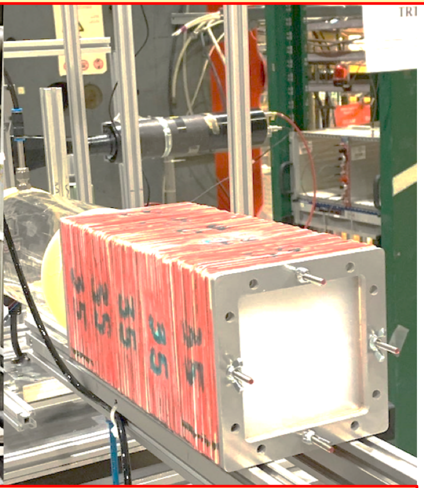
TR radiator

Timepix3 attached to 500 μm GaAs sensor





GaAs detector on the test beam

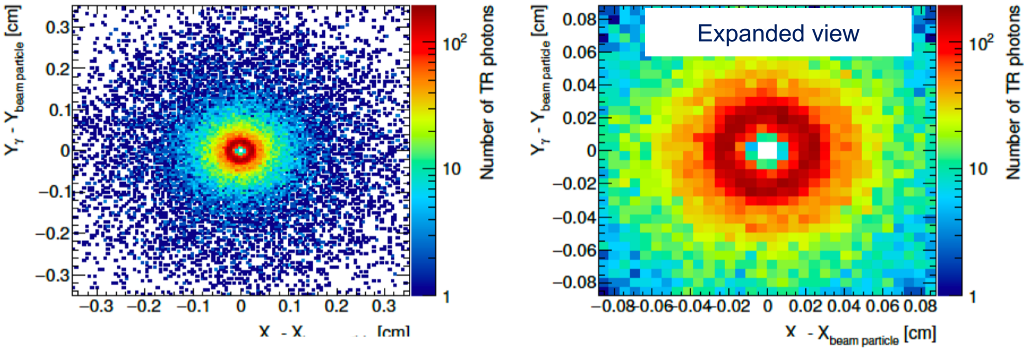


Radiator:
500 PE foils of 35 μm spaced by 0.5mm

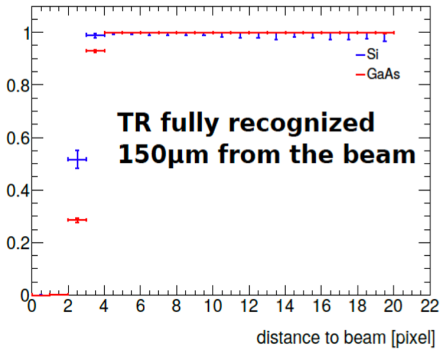
Also a tracking device! Track position accuracy ~13 μm

Si and GaAs sensors on TimePix3 chips

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

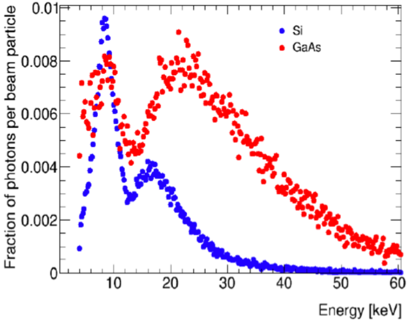


TR cluster distributions around particle cluster

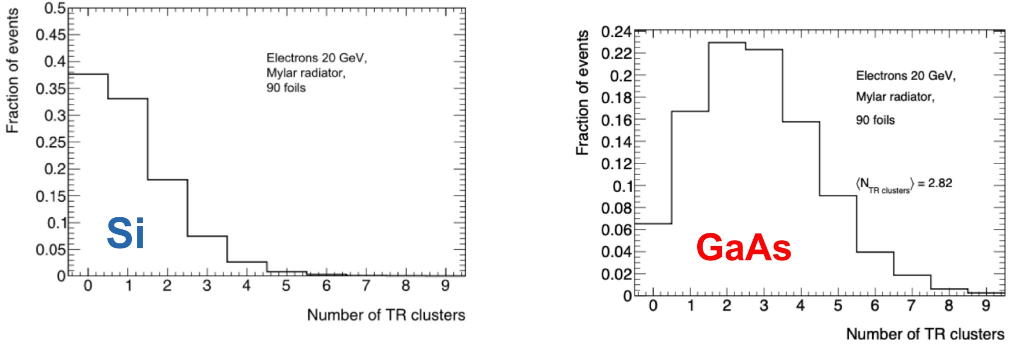


TR fully recognized 150µm from the beam

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.



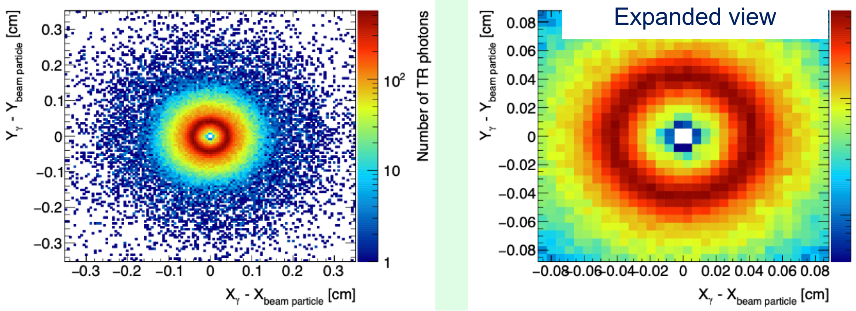
Number of TR photons form 90 foils Mylar radiator in Si and GaAs detectors.

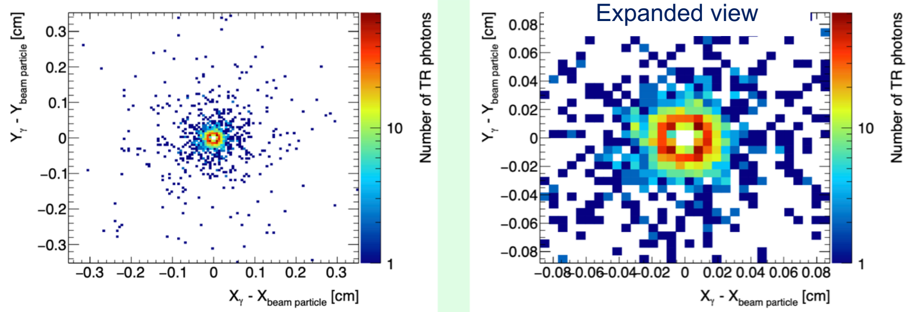
Basic distributions

Electrons

Pions

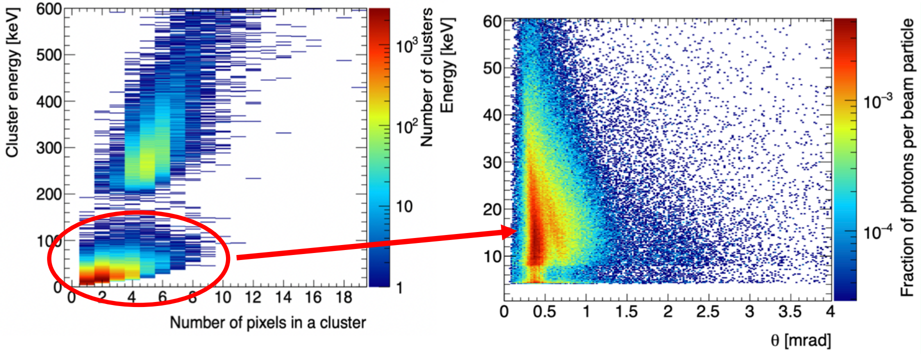
TR cluster distributions around particle cluster





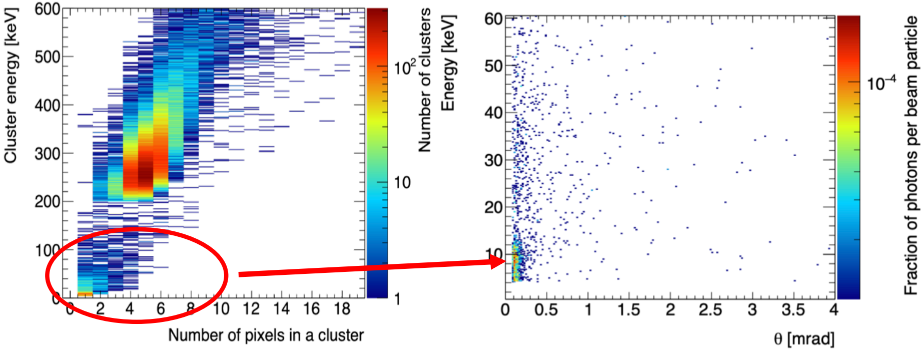
Cluster energy VS number of pixels

TR cluster distributions



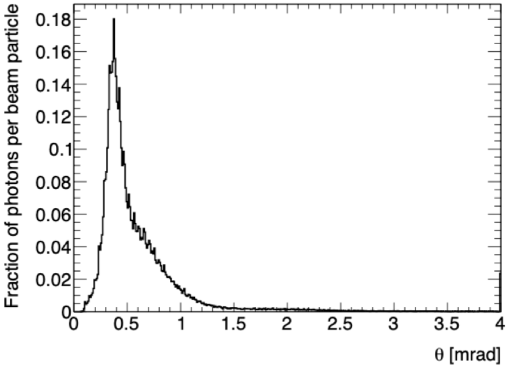
Cluster energy VS number of pixels

TR cluster distributions

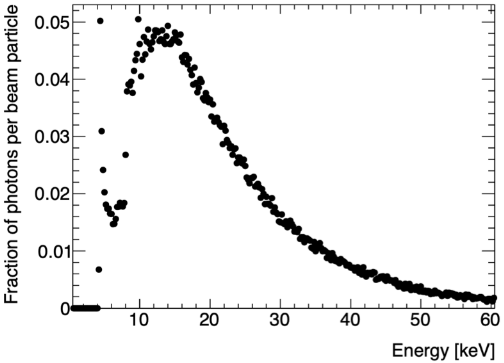


Basic distributions

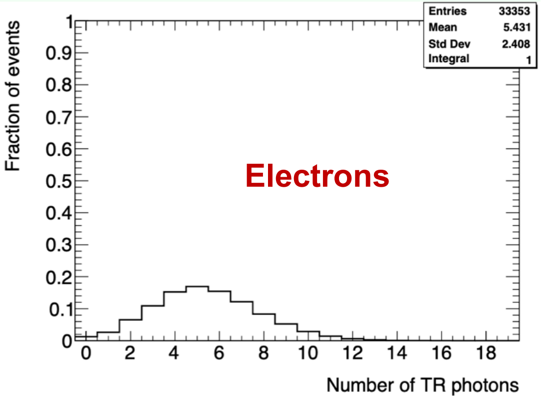
Electrons



Angular distribution of photon clusters

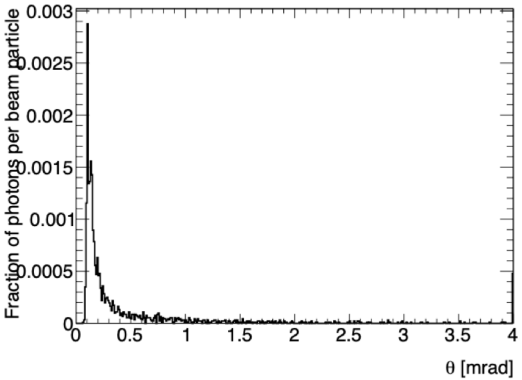


Energy distribution of photon clusters

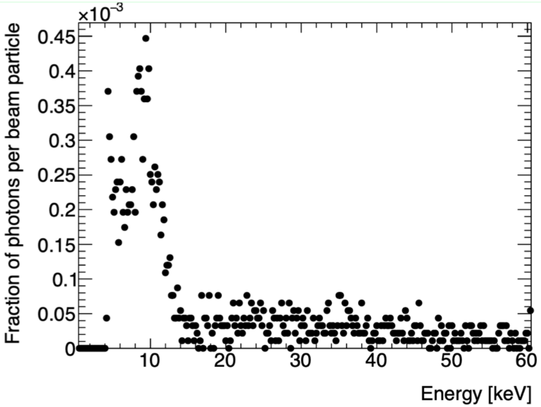


Distribution of a number of photon clusters in event

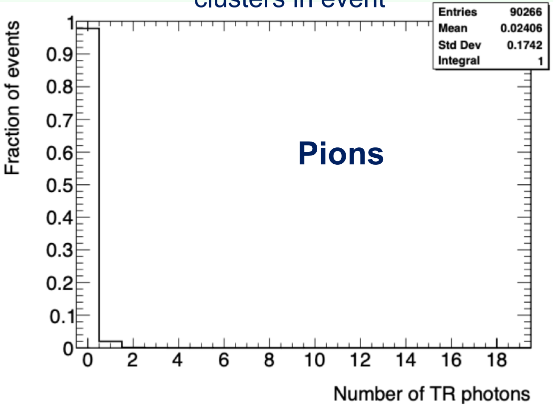
Pions



Angular distribution of photon clusters



Energy distribution of photon clusters

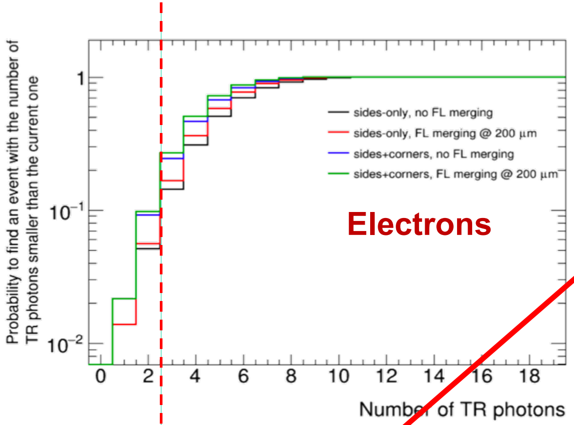


Distribution of a number of photon clusters in event

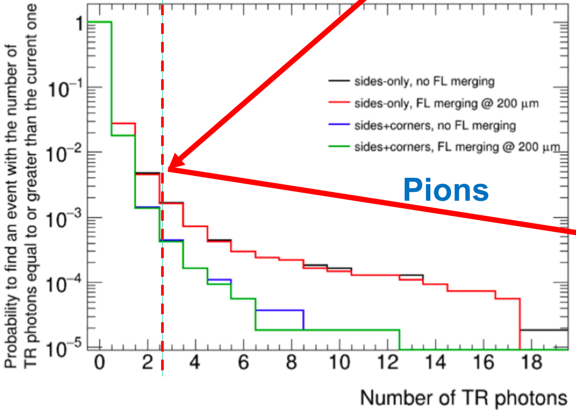
Particle identification with GaAs detector with the length of 50 cm.

Not optimized !

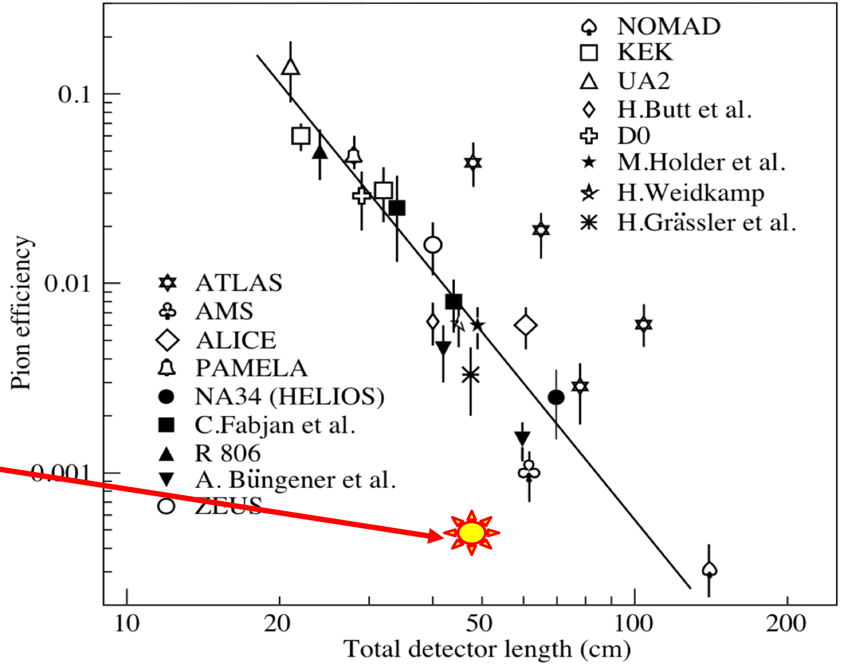
- Requirement at least one TR clusters to be present reduces pion misidentification down to **$2*10^{-2}$ at 98% electron efficiency.**
- Requirement of more than two TR clusters to be present reduces pion misidentification down to **$4.5*10^{-4}$ at 90% electron efficiency.**



Probability to find number of clusters less than the current one



Probability to find number of clusters more than the current one



The End