TRD development for hadron identification in multi-TeV energy range.

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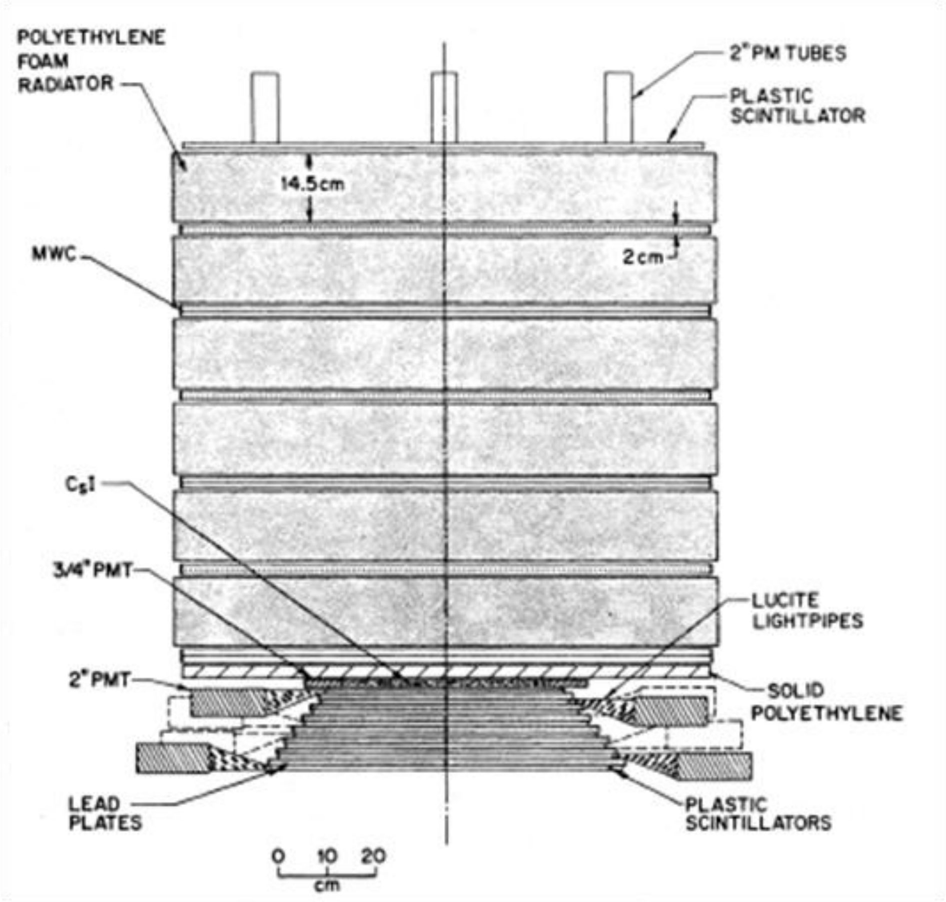
With thanks to A. Romaniouk and the ATLAS TR group

Forward Multiparticle Spectrometer meeting, CERN
M. Cherry, 4/17/2020

TR used in cosmic ray experiments to separate e, p:

TREE balloon instrument (Chicago 1970s) measured cosmic ray $e^+ + e^-$



Transition Radiation Detector (TRD):
Proton rejection 100

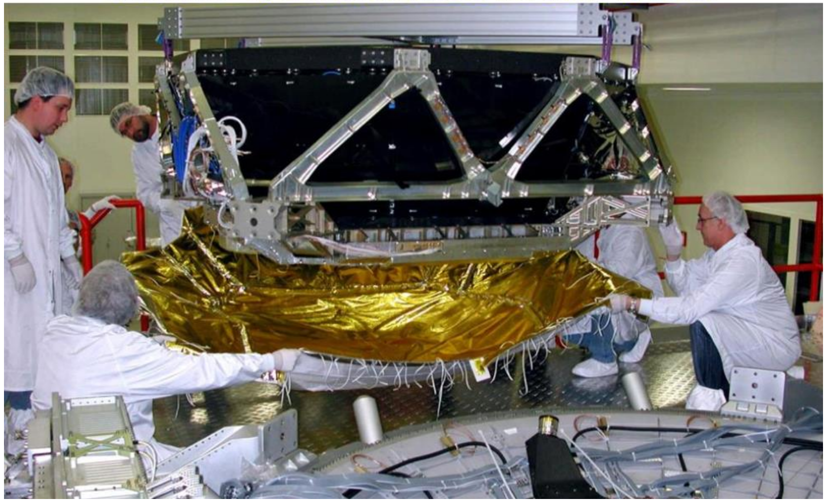
Shower Counter (longitudinal profile)
Proton rejection 100

AMS – 02

Identifies $e^{\pm}$ vs protons on Intl. Space Station

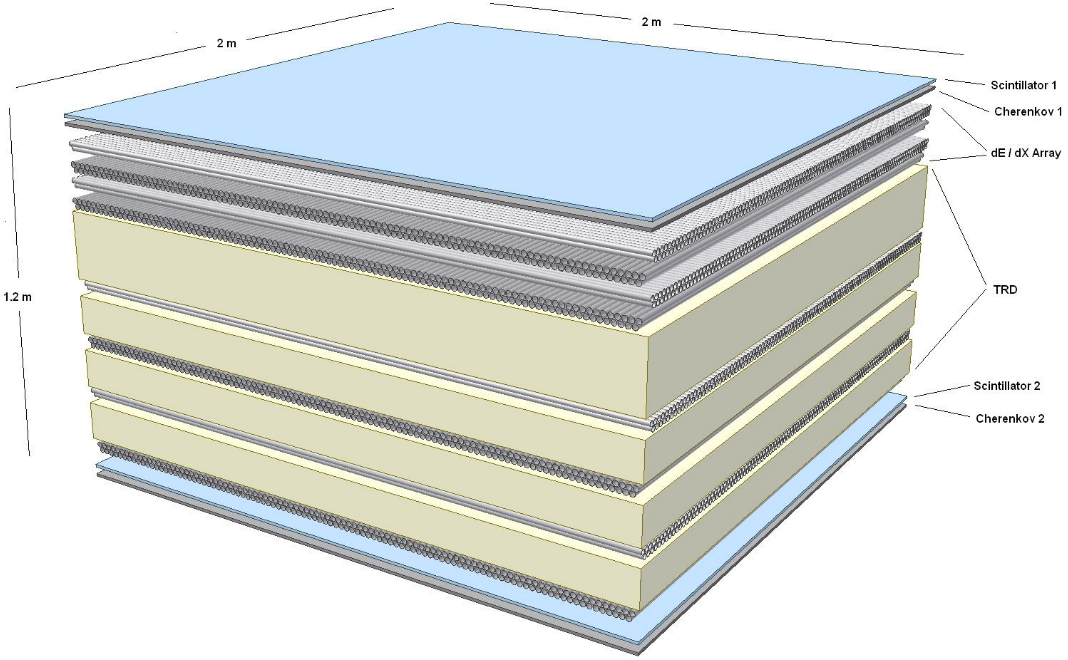
Transition Radiation Detector (TRD)

Identifies $e^{\pm}$ by transition radiation and Nuclei by dE/dX

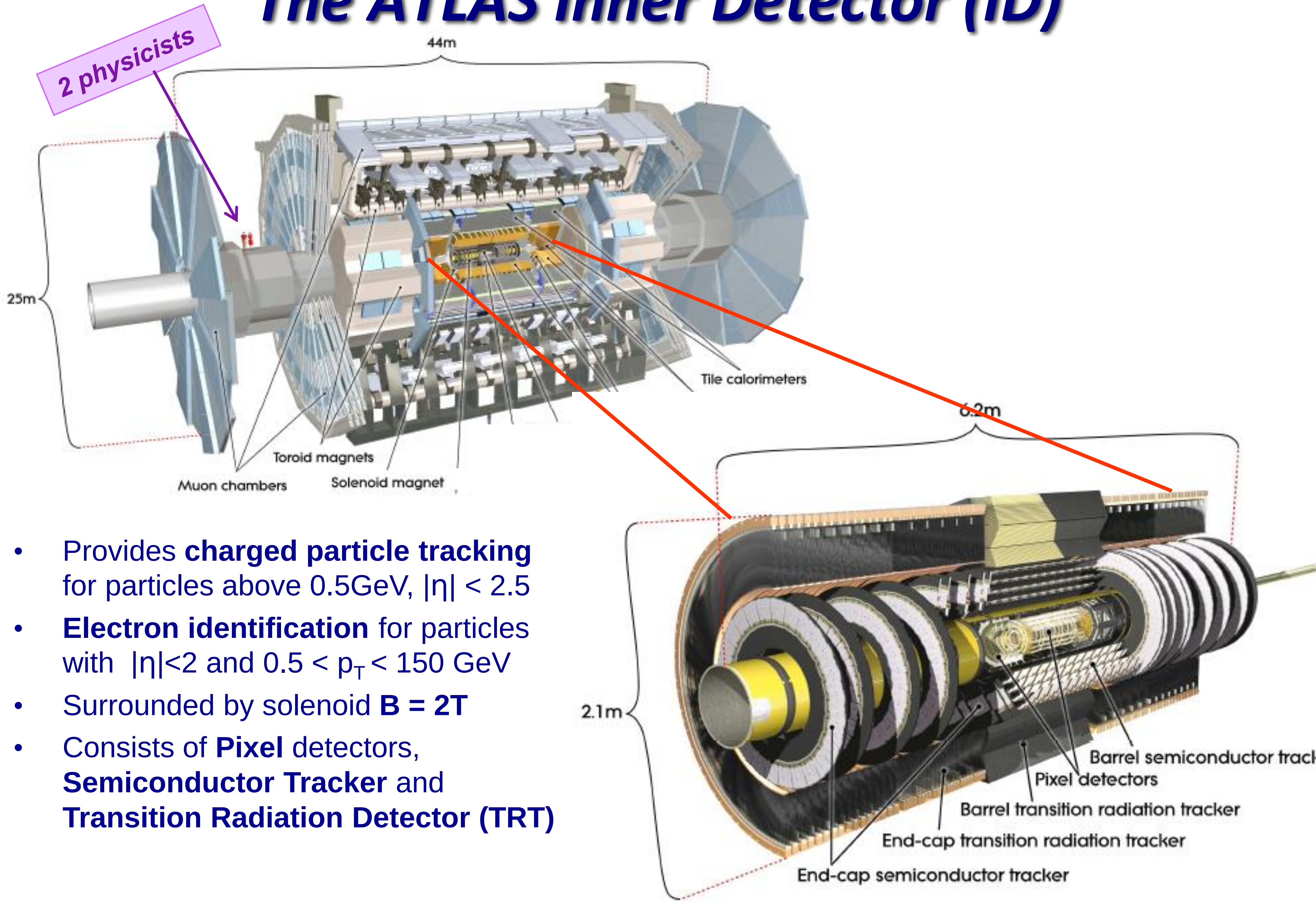


TRACER -- *Transition Radiation Array for Cosmic Energetic Radiation*

Measured energy spectra of cosmic ray nuclei on balloon



The ATLAS Inner Detector (ID)



- Provides **charged particle tracking** for particles above 0.5GeV, $|\eta| < 2.5$
- **Electron identification** for particles with $|\eta|<2$ and $0.5 < p_T < 150$ GeV
- Surrounded by solenoid **B = 2T**
- Consists of **Pixel** detectors, **Semiconductor Tracker** and **Transition Radiation Detector (TRT)**

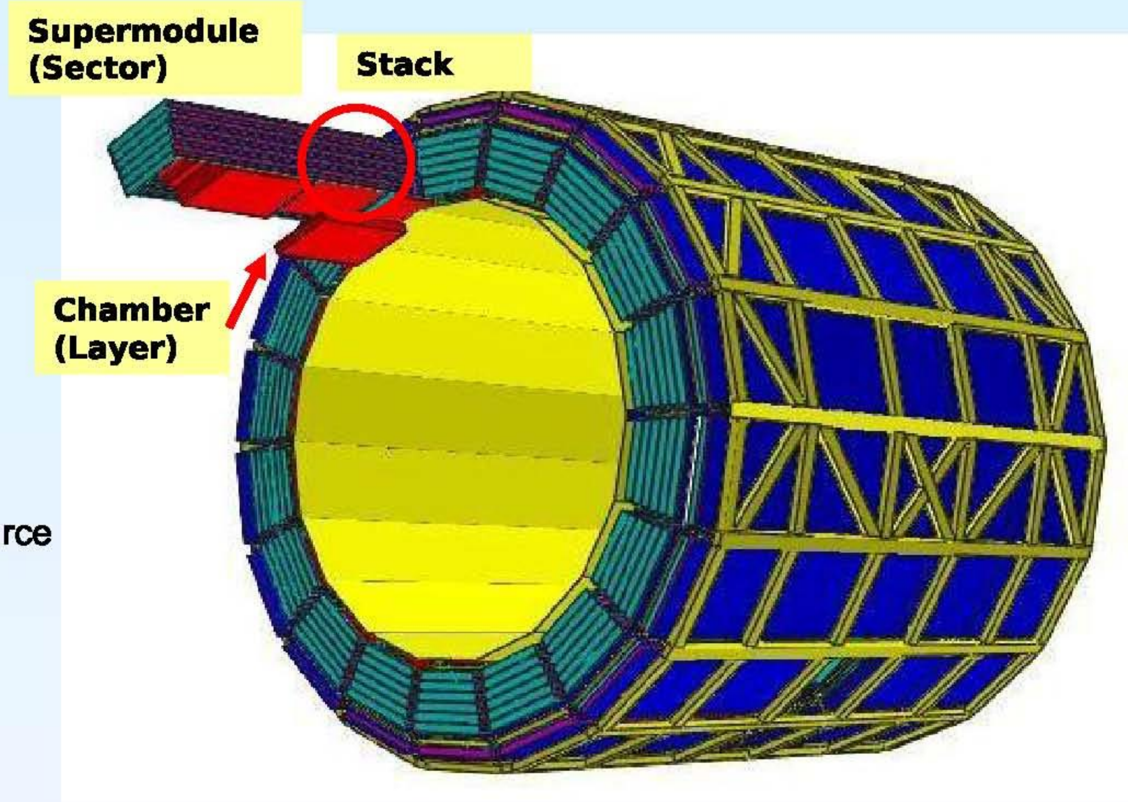
Transition Radiation Detector (TRD)

- **Parameters :**
  - Radial position: 2.9 < r < 3.7 m
  - $|\eta| < 0.9$, $0 < \phi < 2\pi$
  - 522 modules (18 super-modules) → ~675 m^2
  - ~25 m^3 Xe/CO2 (85:15)
  - 1.15 M readout channels
    - Gain Calibration with Krypton source

→ J. Stiller

  - ≈ 25% X_0
  - weight ~ 30 t
  - total power: up to 65 kW
  - Detector Control System

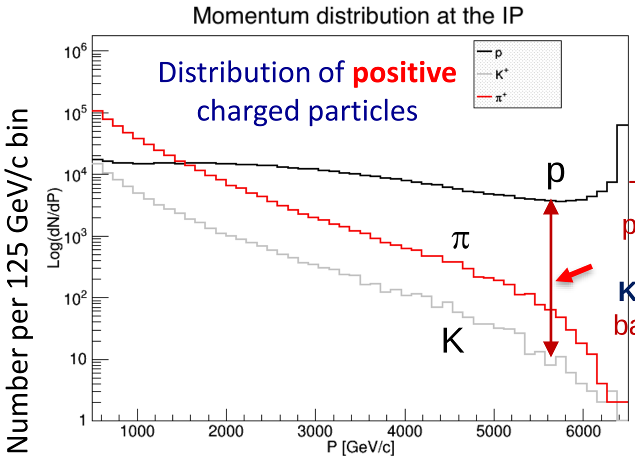
→ O. Busch



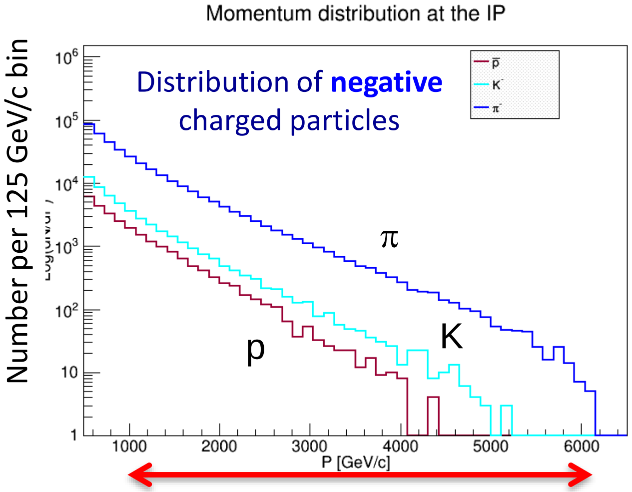
ALICE designed to operate at 10 kHz Pb-Pb, few hundred kHz p-p, up to 8000 particles per event

Hadron identification at energies above 1 TeV.

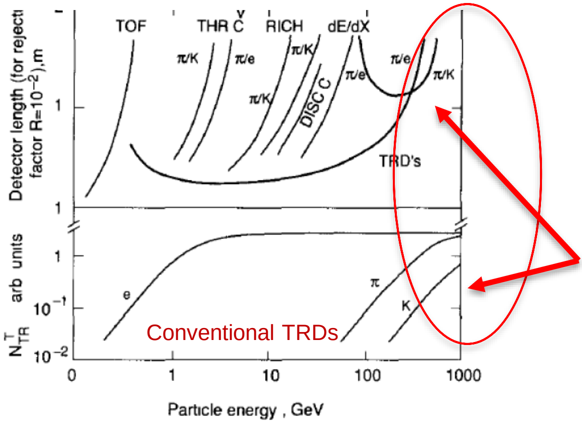
Expected hadron spectrum in FHS experiment.



The biggest problem is to separate **Kaons** at this background of **protons**.



Particle momentum 1-6 TeV/c

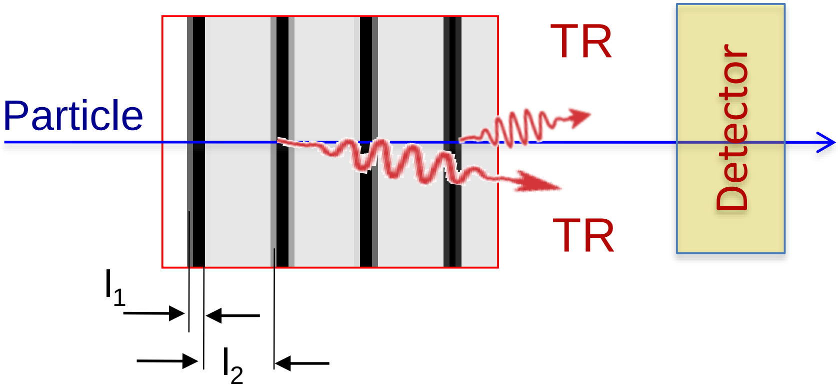


https://doi.org/10.1016/0168-9002(93)90846-A

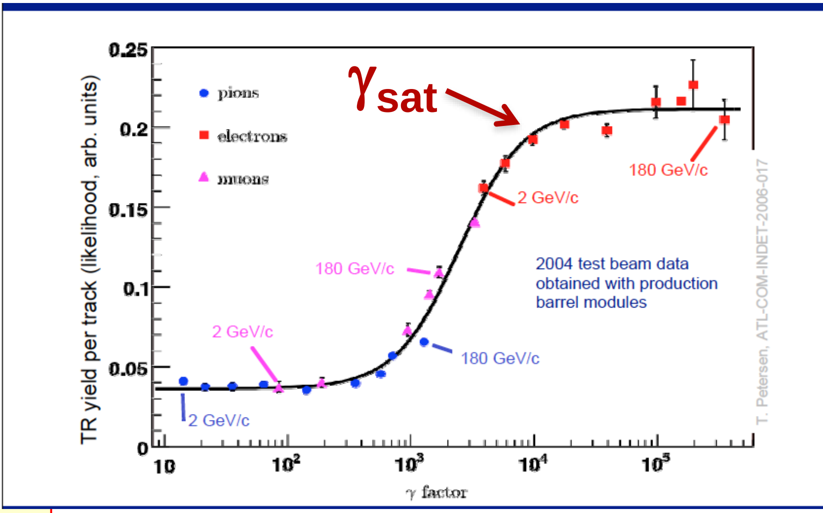
Gamma factor range to be covered 10^3 to $4*10^4$

TRD has the largest gamma factor range.
But it usually works well for separation of particles up to gamma factors few*10^3.

TR: Tuning performance with detector parameters



In X-ray energy range

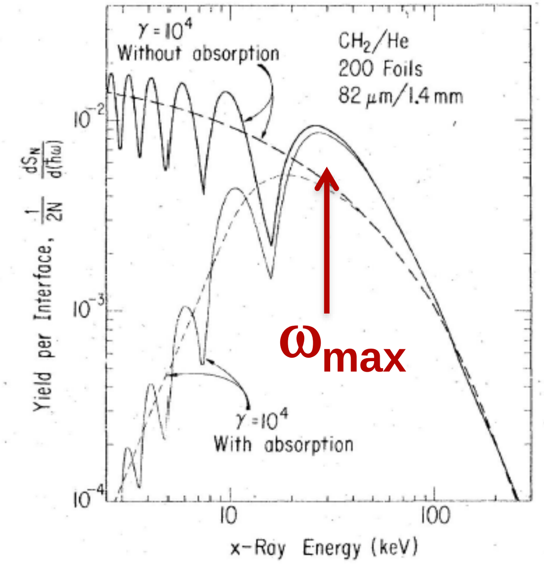


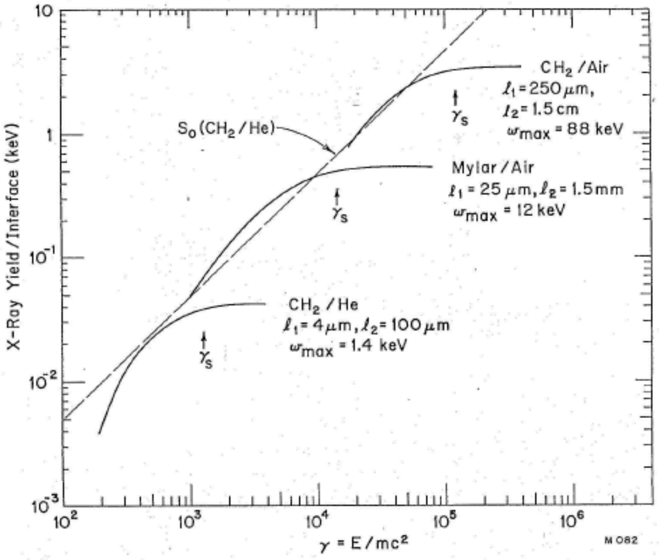
Intensity ~ difference in plasma frequencies $\omega_1^2 - \omega_2^2$

Characteristic X-ray energy $\omega_{max} \sim \omega_1^2\ l_1$

TR saturation $\gamma_{sat} = 0.6\ \omega_1\sqrt{l_1 l_2}/c$

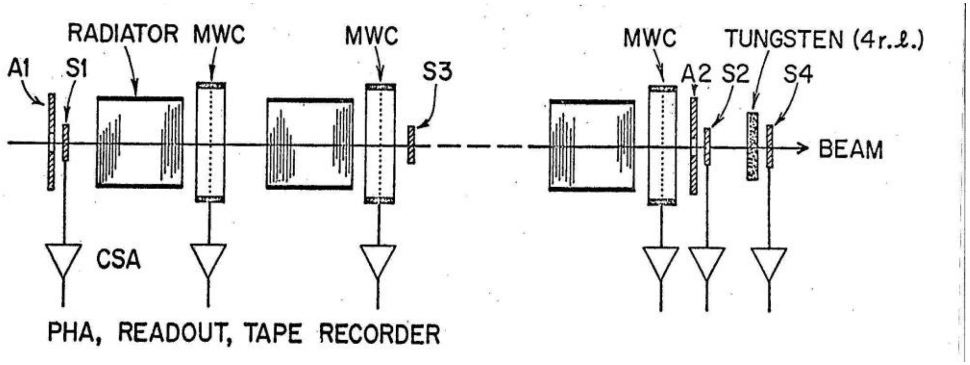
Modifying parameters l_1, l_2 and ρ (ω_1) one obtains different gamma factor dependences.

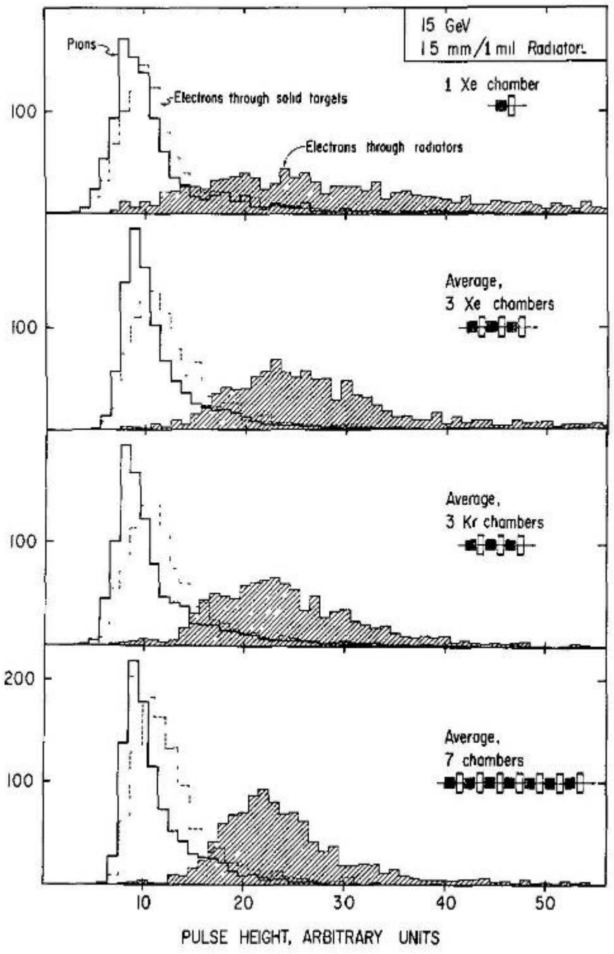




Particle id at accelerators: Yerevan, BNL, SLAC, CERN, DESY, …

Separating e^-/π
at SLAC, 1973:



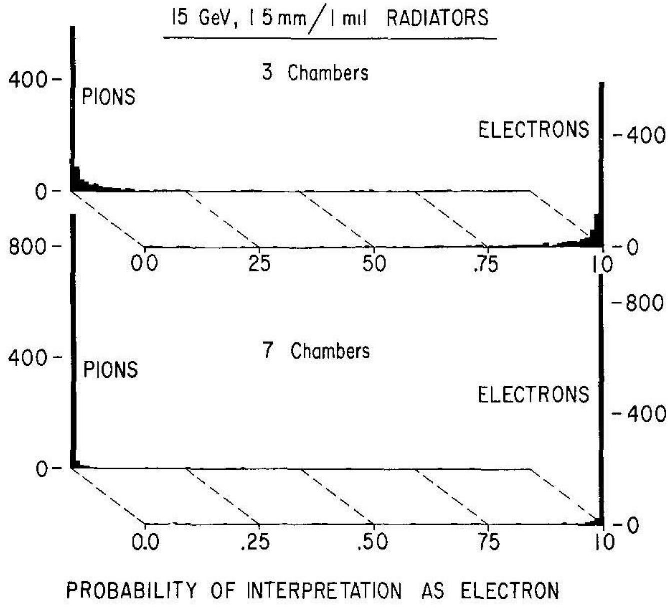


Prob. of “e- or π-like” distribution in 7 detectors:

$$P_1 = P_e^1 \bullet P_e^2 \bullet\bullet\bullet P_e^7 \qquad P_2 = P_\pi^1 \bullet P_\pi^2 \bullet\bullet\bullet P_\pi^7$$

Likelihood of event being e or π:

$$L_e = P_1/(P_1+P_2) \qquad L_\pi = P_2/(P_1+P_2) = 1 - L_e$$

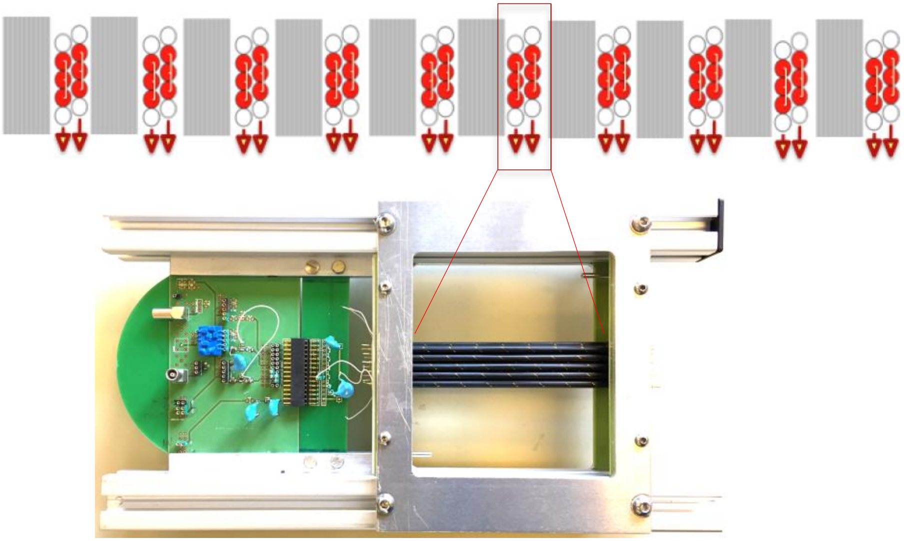


SAS_TRD: Test beams 2017, 2018

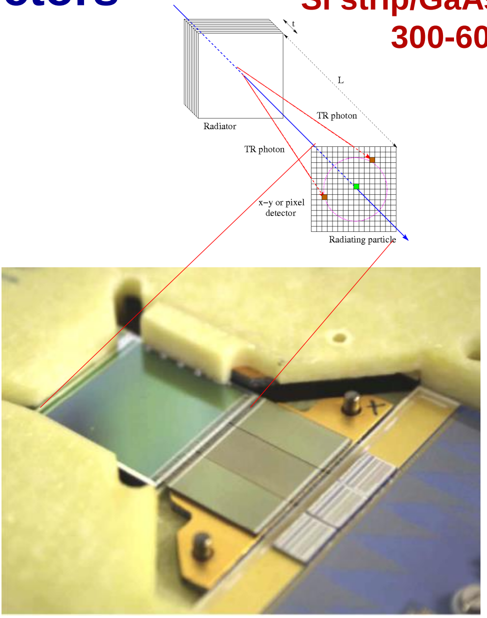
*Major **goal: to verify MC models of TR production** as function of gamma factors: spectra and angular distributions*

Two types of the detectors

Straw based with Xe gas

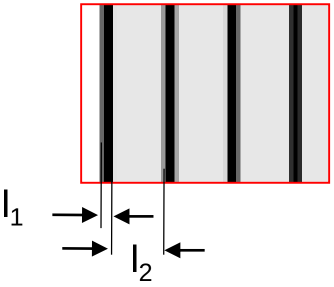


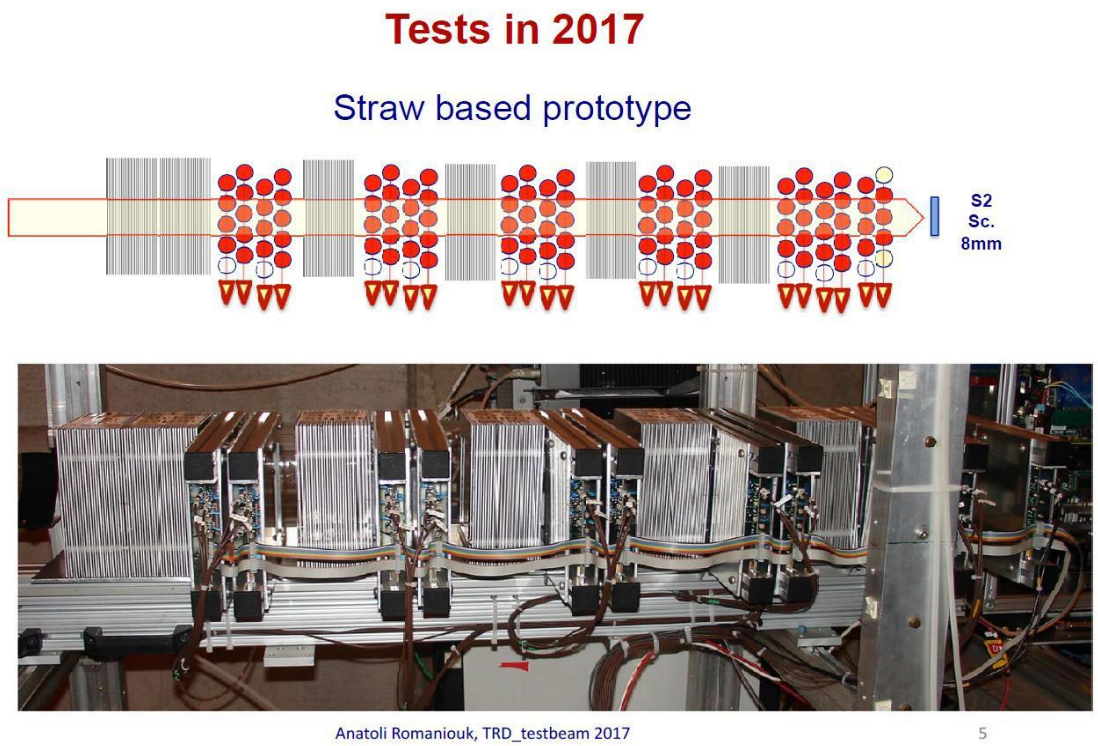
Si strip/GaAs pixel detectors 300-600 μm thick



Few types of radiators:

Different parameters l_1 and l_2 will be used





Tests in 2017

Straw based prototype

Anatoli Romaniouk, TRD_testbeam 2017

5

External detectors (not shown here): scintillator multiplicity counter, Cherenkov counter, pre-shower and leadglass calorimeter were used to select and purify the identification of the beam particle sort.

- Prototype with 4 mm diameter straws and Xe-based gas mixture (71.8% Xe, 25.6% CO_2, 2.6% O_2)
- Four or five straws in one layer were jointly connected to readout. Note: everywhere in the text below “straw number” really means “straw layer number”.
- Each straw layer (column on the picture) was shifted in vertical direction with respect to each other to minimize fluctuations of the active gas thickness crossed by the beam particles.
- 8 mm scintillator to trigger beam particles.
- Beam particles: 20 GeV pions, 20 GeV electrons, 120 GeV muons, 180 GeV muons, 290 GeV muons
- Radiators:

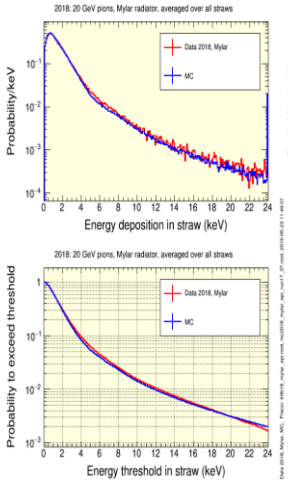
30 foils in each radiator block (55 foils in very first block)

- ✓ Mylar 50 μm foils, 3 mm gap
- ✓ Polyethylene (PE) 270 μm/3.3mm
- ✓ Polypropylene (PP): 62 μm foil / 2.2 mm gap (NB: Compound foils in this radiator made from four 15 μm foils)

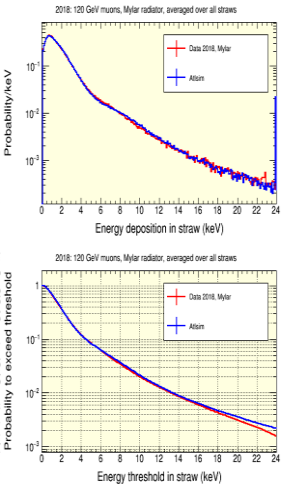
Data/MC comparison: Mylar radiator, different particles.

Differential (top row) and Integral (bottom row) energy spectra in straws.
Mylar radiator 50 um 15 foils

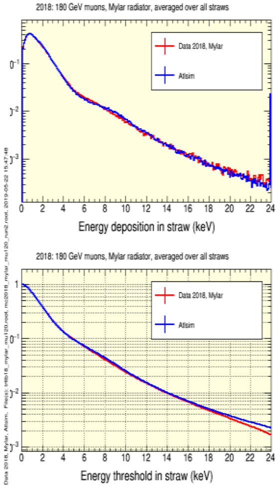
Pions 20 GeV
γ=143



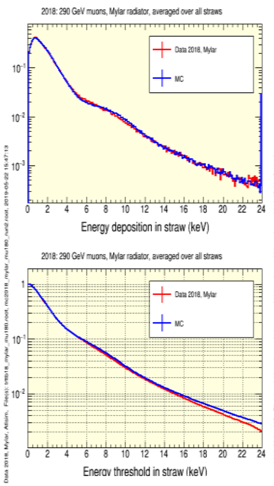
Muons 120 GeV
γ=1136



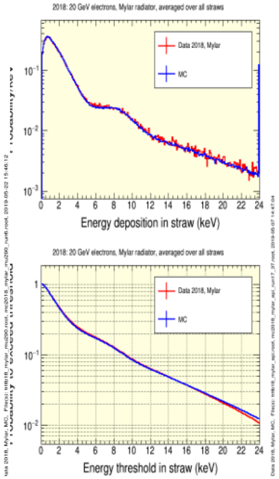
Muons 180 GeV
γ=1700



Muons 290 GeV
γ=2746



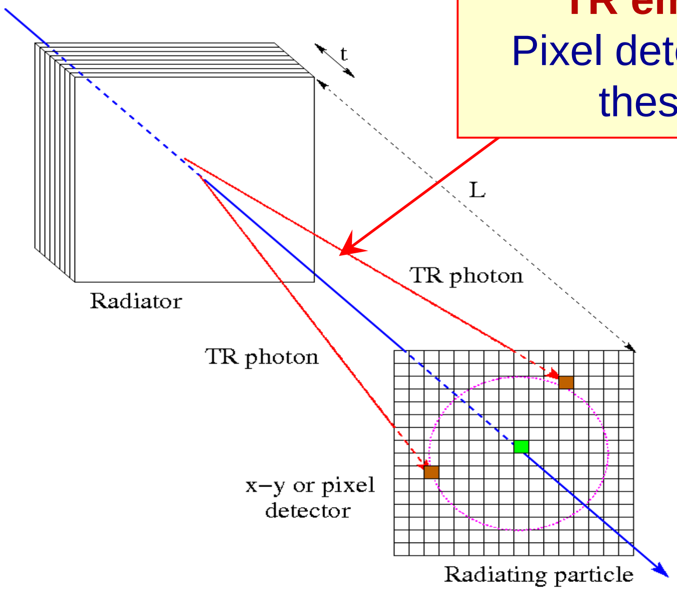
Electrons 20 GeV
γ=39139

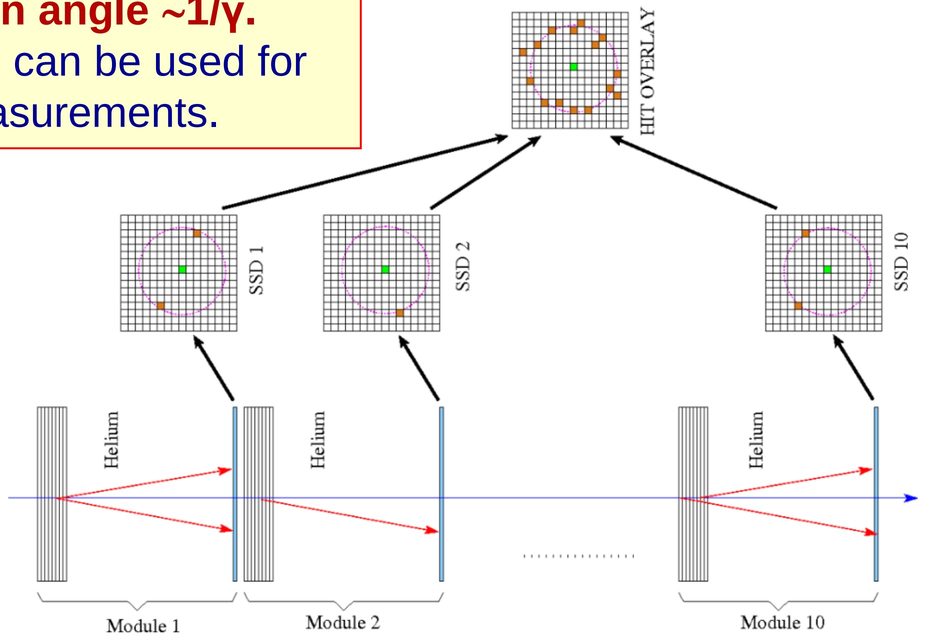


MC reproduces γ-dependence very well on the range of γ–factors
10^2 - 4*10^4

Angle TRD: concept

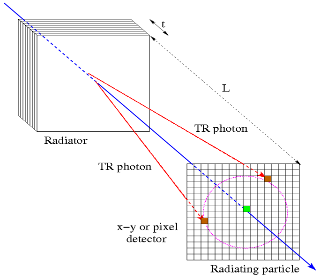
Concept is based on the fact that
TR emission angle ~1/γ.
Pixel detectors can be used for
these measurements.



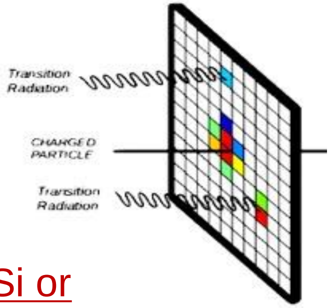


Advantages:

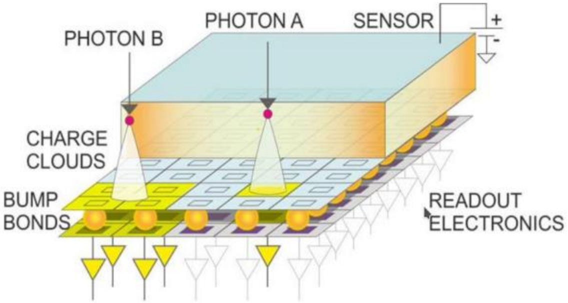
- Combination angle and TR energy information would significantly improve identification power of such kind detectors.
- This approach would allow to minimize material budget
- It combines tracking and TRD functions in one detector

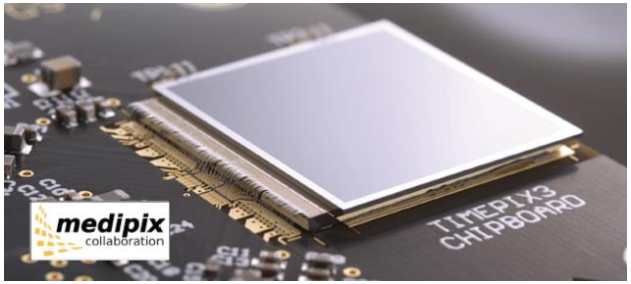


II. TRD based on high granular semiconductor technology.



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





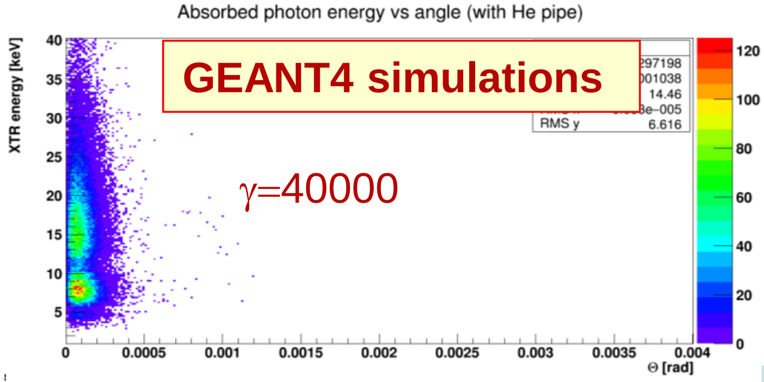
Timepix3 front-end hybrid pixel readout chip:

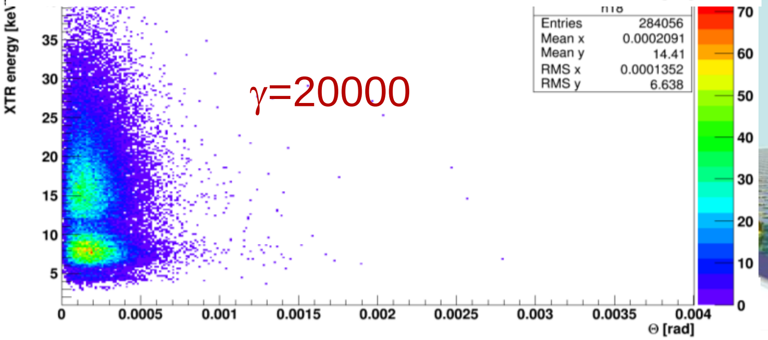
- Various sensor materials possible.
- Simultaneous per-pixel measurement of a time-of-arrival (ToA) and an energy (time-over-threshold - technique).
- Time resolution of 1.56ns
- Spatial resolution of ~16μm
- 256 x 256 pixel matrix with 55 x 55 μm2 pitch
- throughput of up to 40 Mhits/s/cm2

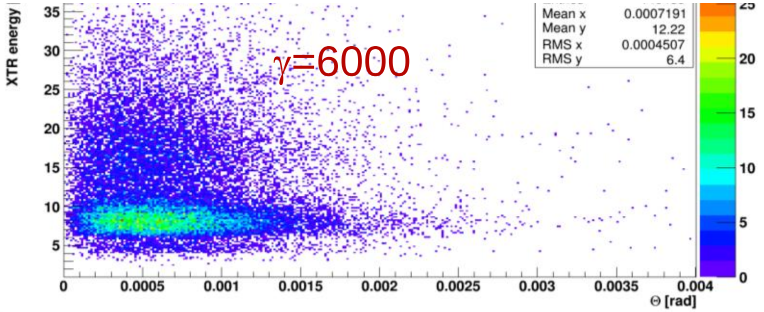
TimePix4 with improved time measurements is coming soon (see later)

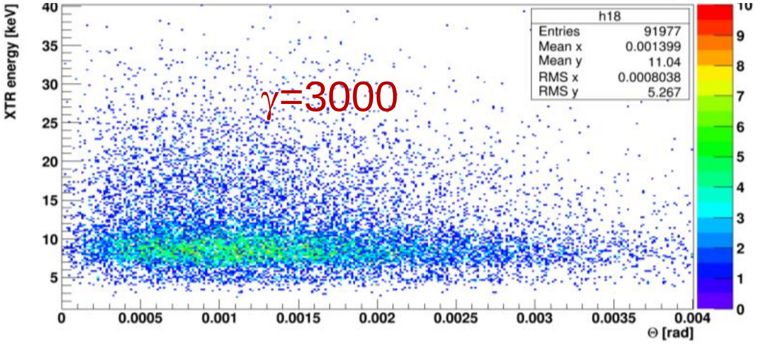
First measurements of angular and spectrum distributions

GEANT4 simulations







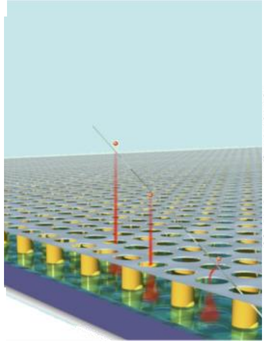


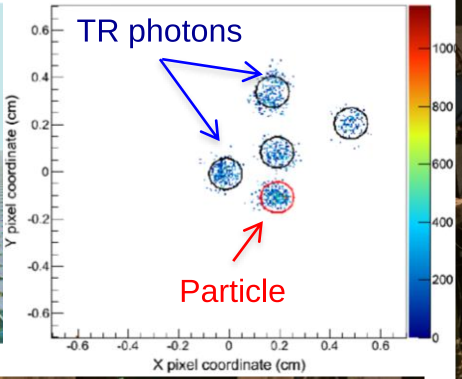
Radiator

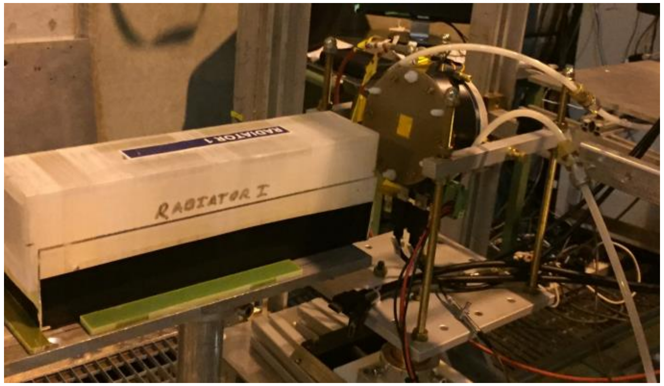
2m He pipe

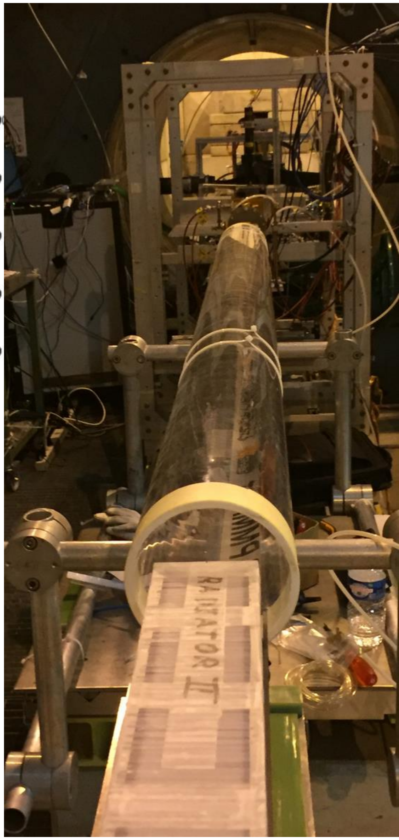
3 cm Xe/CO2 + Pixels

Beam is perpendicular to the pixel plane









First detailed studies of TR energy/angle spectra with silicon Timepix3 detector –

Schioppa et al. NIM A 936, 523 (2019)

Dachs et al., NIM A 958, 162037 (2020)

Alozy et al, NIM A 961, 163681 (2020)

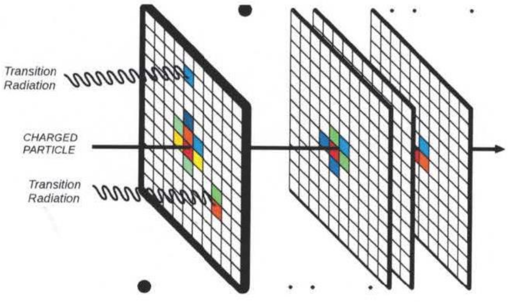


Figure 3: Sketch of a Transition Radiation event in the Timepix3 system.

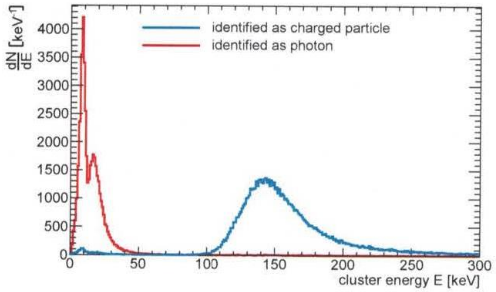


Figure 4: Distributions of energy for all the clusters identified as the charged particle (blue) and as transition radiation (red) in events with an electron trigger.

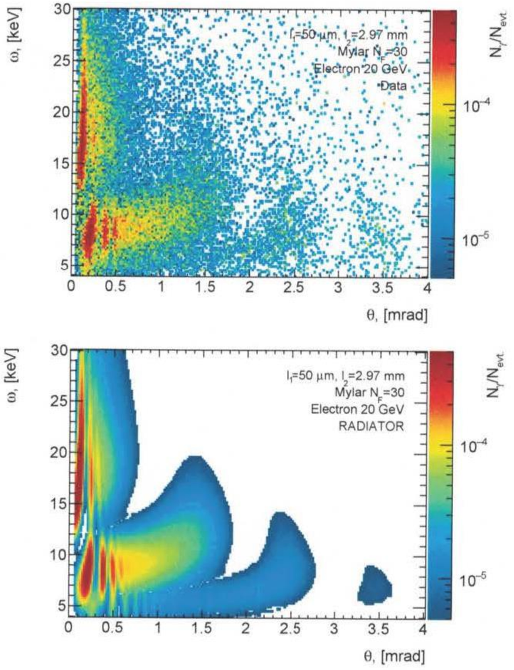
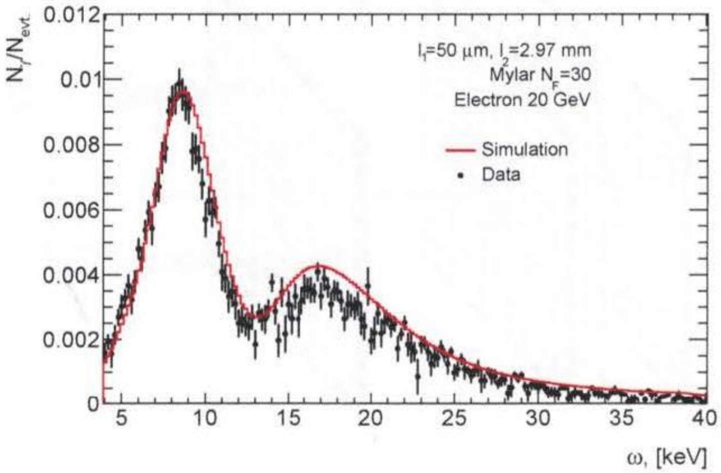
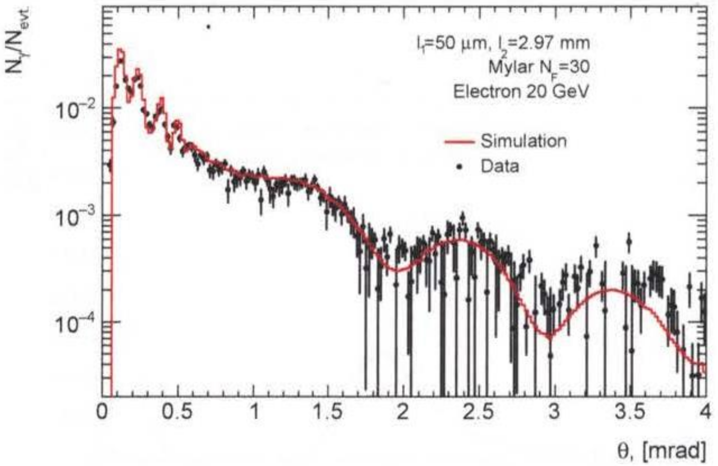


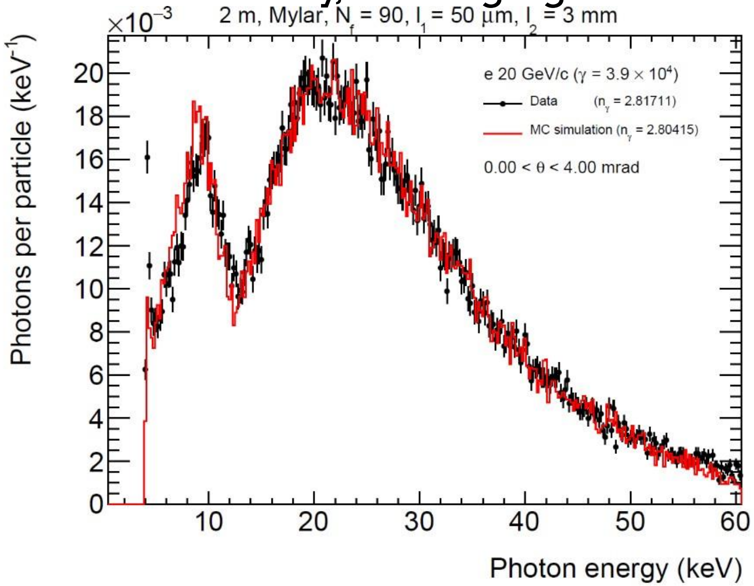
Figure 5: Energy versus angle distribution of TR photons for Mylar radiator consisting of 30 foils of 50 μm thick sparated by 2.97 mm: data (top) and simulation (bottom)



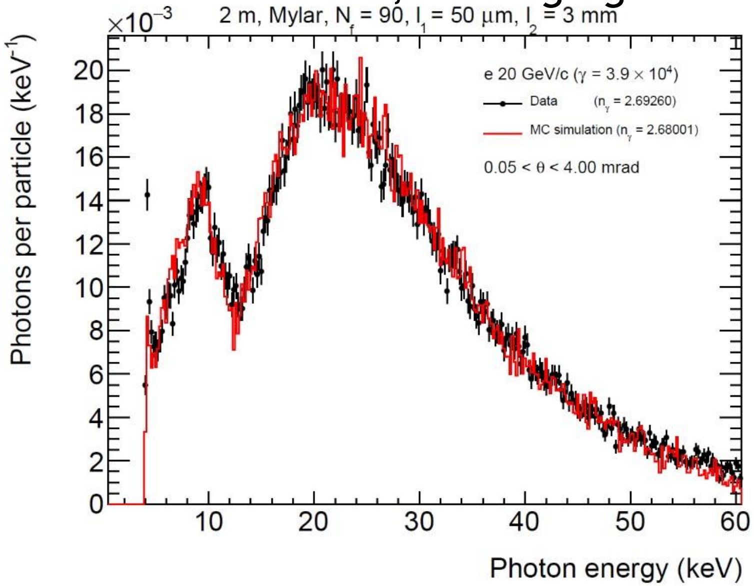


ENERGY SPECTRA

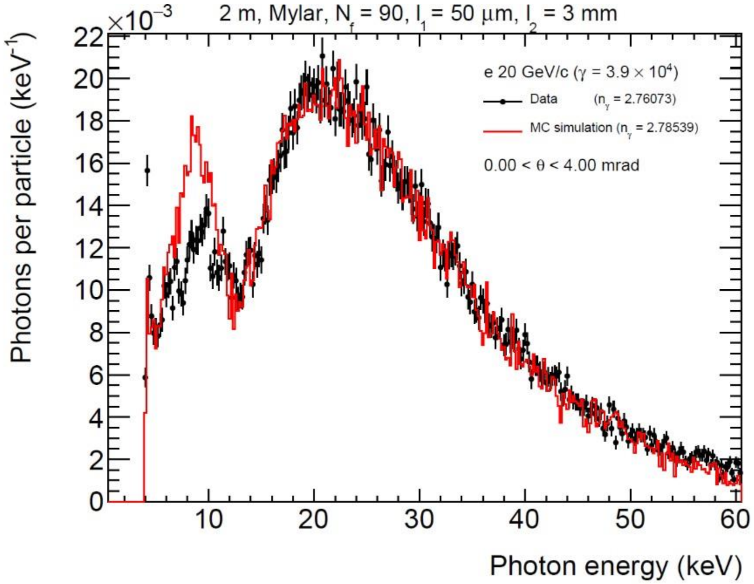
Side only, FL merging OFF



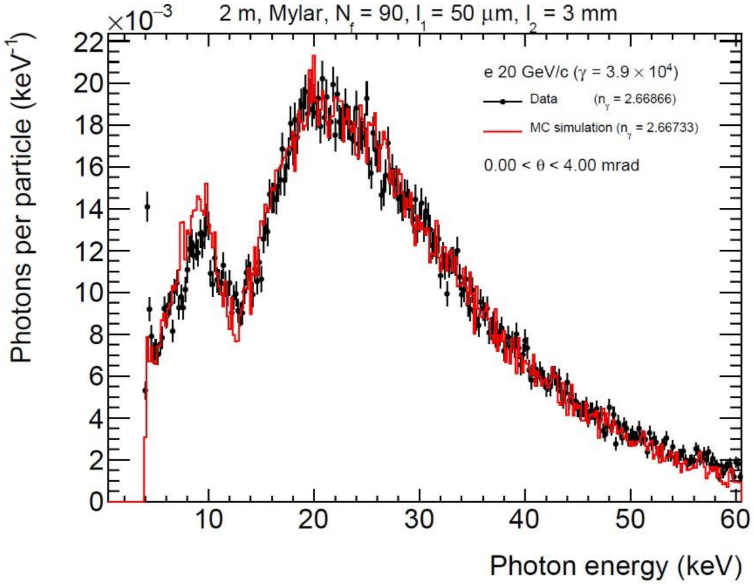
Side + corners, FL merging OFF



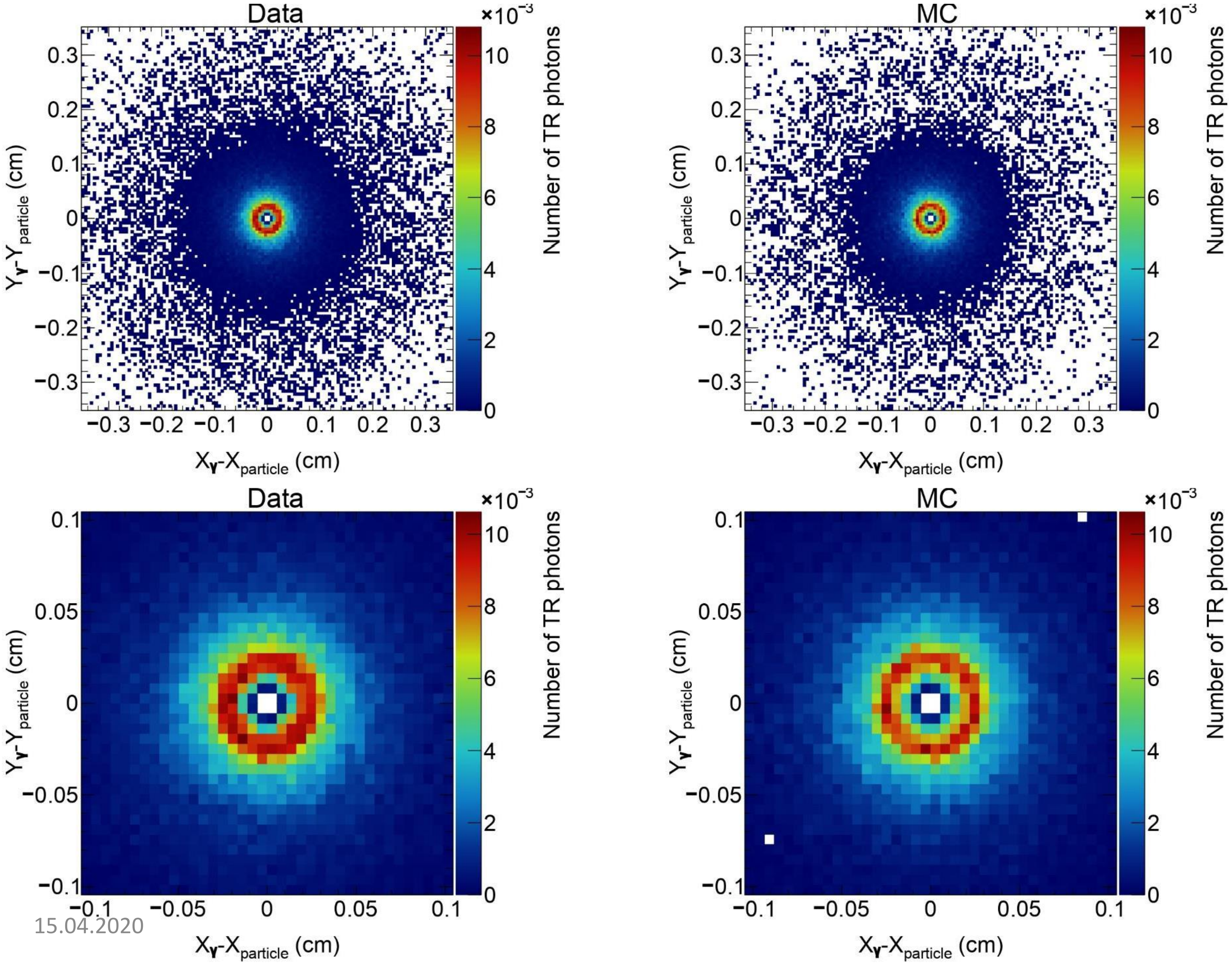
Side only, FL merging ON

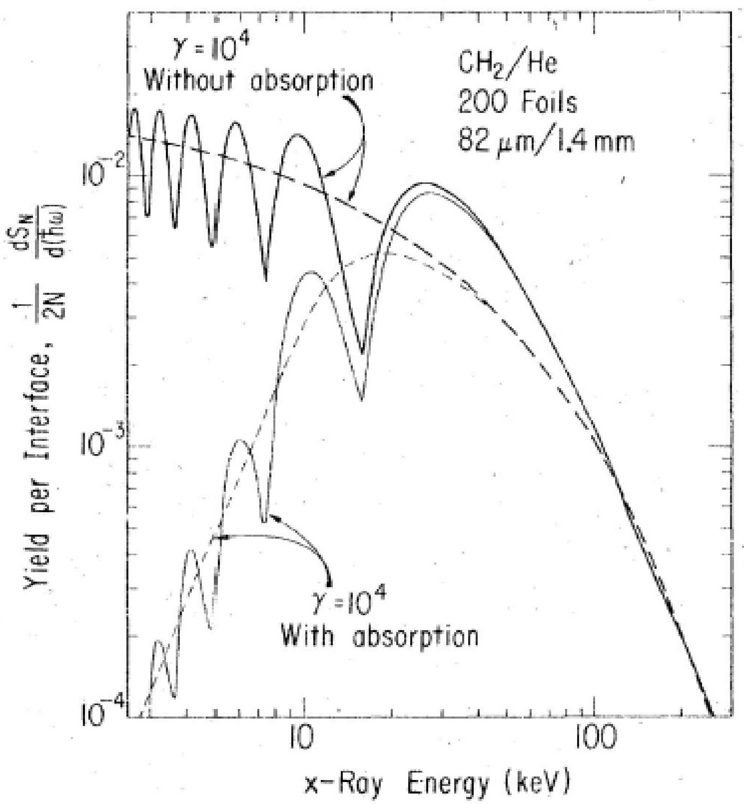


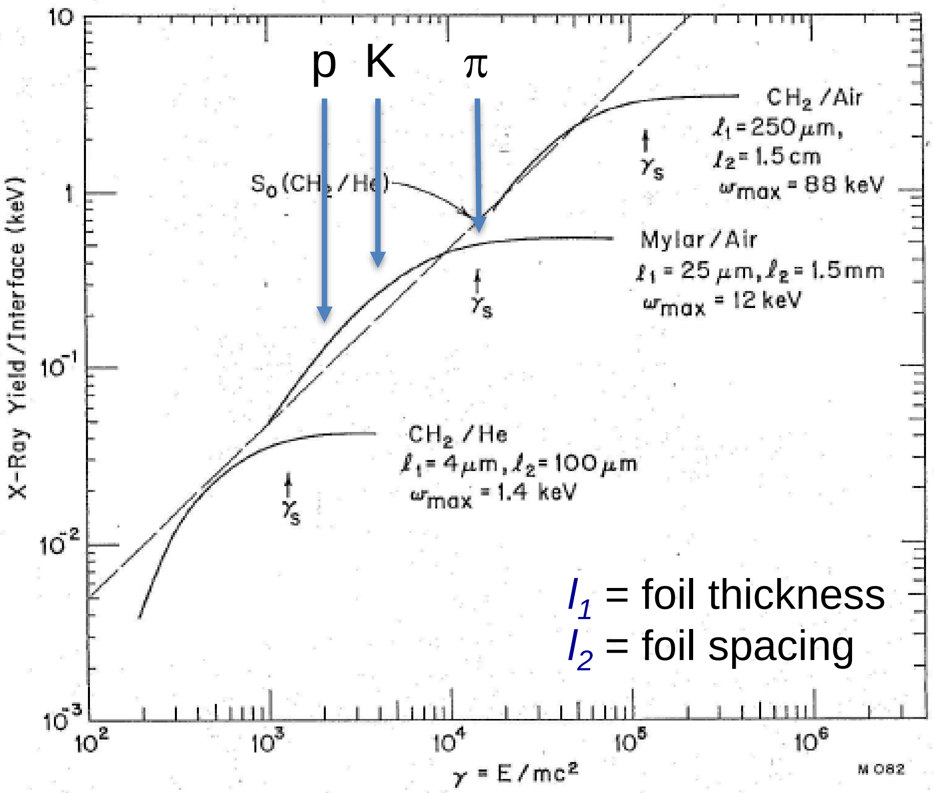
Side + corners, FL merging ON



THE RING


Data
MC
Data
MC
$\times10^{-3}$
Number of TR photons
$Y_\gamma - Y_{particle}$ (cm)
$X_\gamma - X_{particle}$ (cm)
−0.3 −0.2 −0.1 0 0.1 0.2 0.3
−0.1 −0.05 0 0.05 0.1
0 2 4 6 8 10





l_1 = foil thickness
l_2 = foil spacing

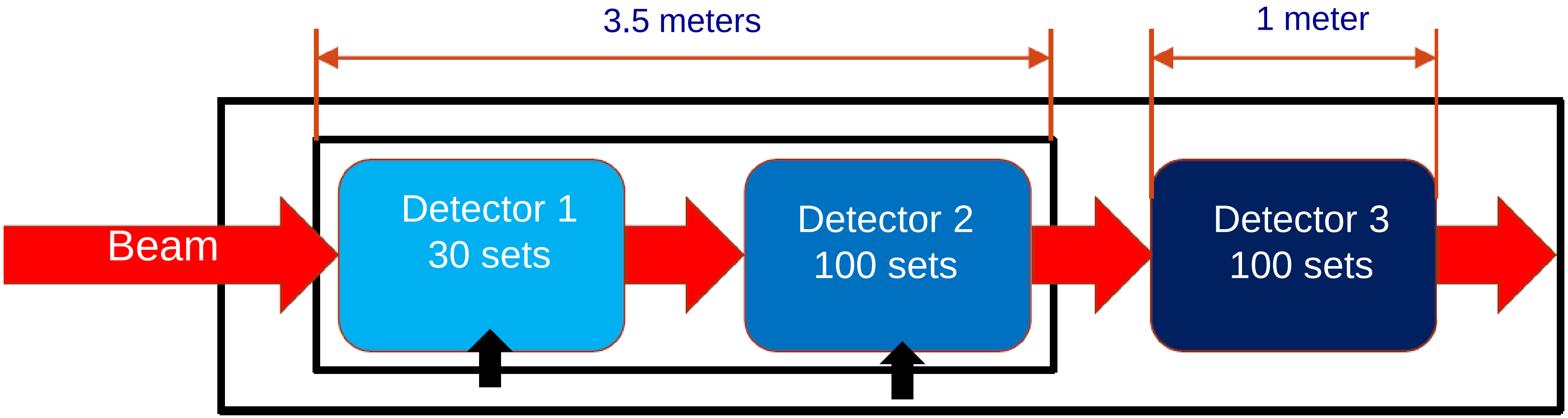
TR saturation $\gamma_s \sim 0.6\, \omega_1 \sqrt{l_1 l_2}\ /\ c$

Characteristic X-ray energy $\omega_{max} = \omega_1^2\, l_1 / 2\pi c$

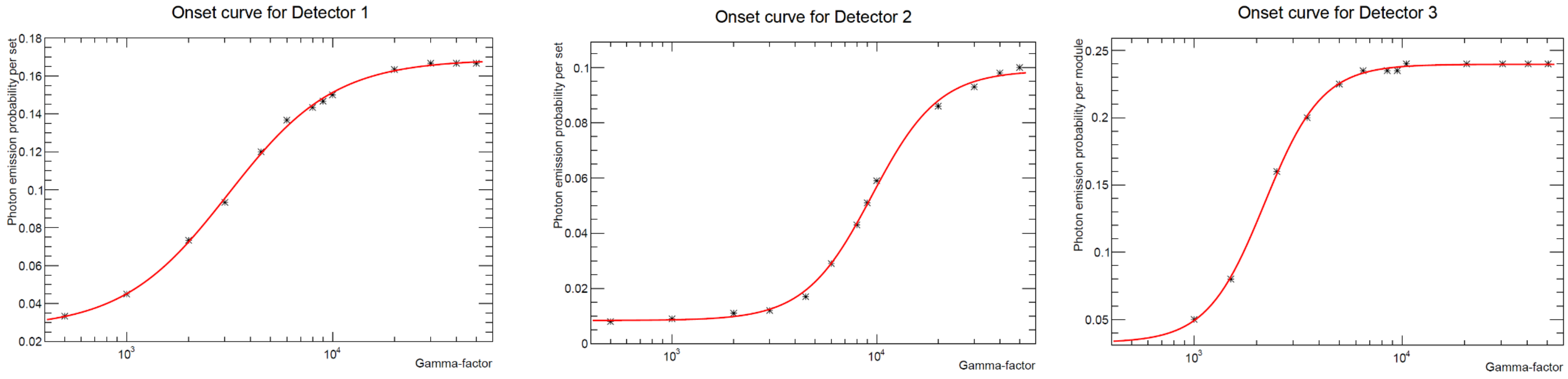
E (TeV)	γ_p	γ_K	$\gamma_{\pi\pm}$
1	1.07E+03	2.02E+03	7.16E+03
2	2.14E+03	4.04E+03	1.43E+04
6	6.40E+03	1.21E+03	4.30E+04

SAS_TRD: beam composition measurements

No optimization just some assumptions based on TR simulations (no angular information used)
Let’s suppose we have 3 types of the detectors with different gamma factors dependences



TR + dE/dx probabilities curves for one detector set.


Onset curve for Detector 1

Onset curve for Detector 2

Onset curve for Detector 3

Recent design work for Forward Scattering Spectrometer led by ATLAS TR group:

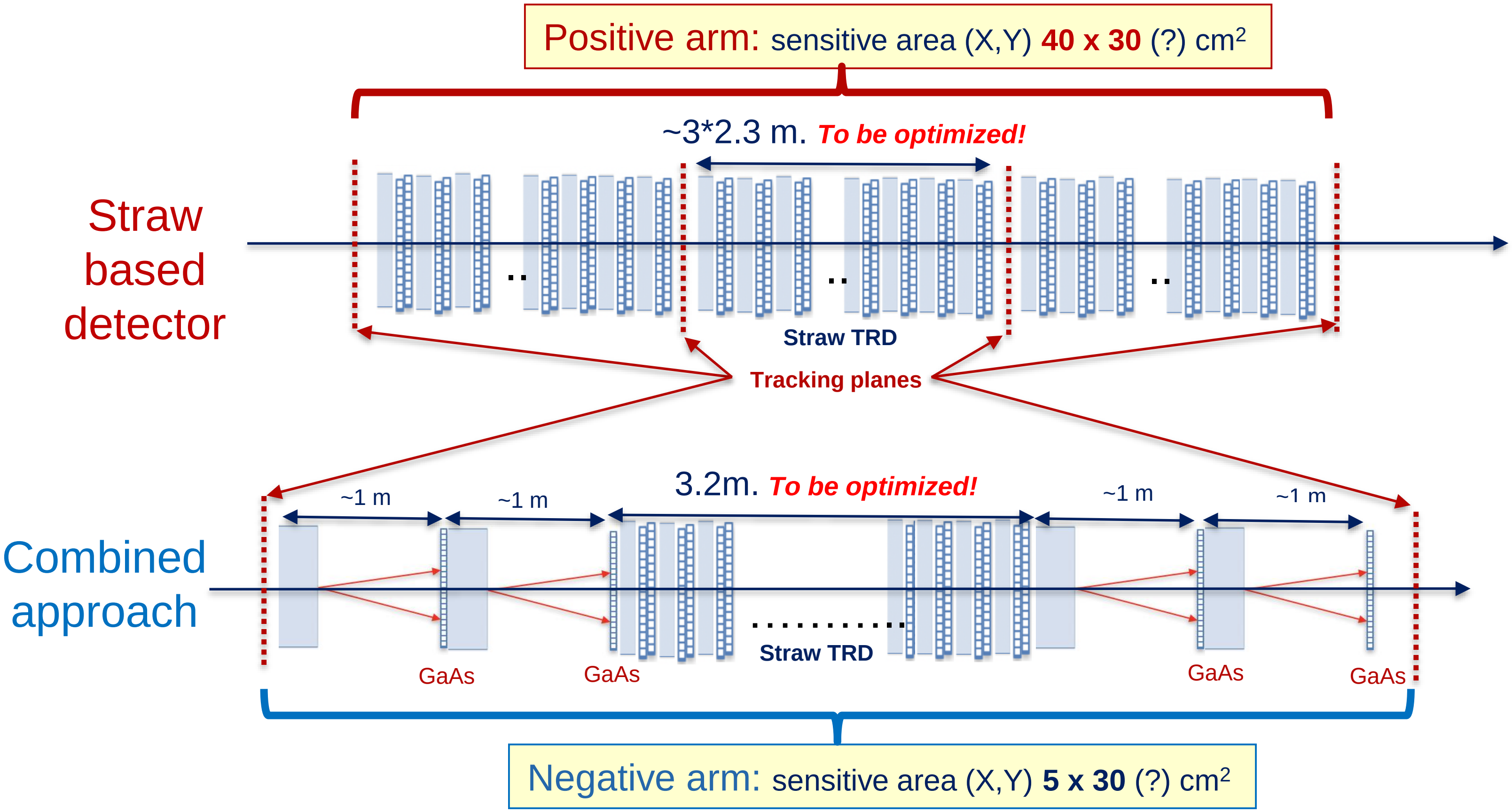
- Measurement of angular distribution
- Development of straw tubes, Si strip/GaAs pixel detectors

Final design depends on details of configuration (e.g., real estate available), but

- **we know how to tune detectors to obtain desired particle id and energy measurement**

- "Measurements of Compton Scattered Transition Radiation at High Lorentz Factors", G.L. Case et al., NIM A 524, 257 (2004).
- "Measuring the Lorentz Factors of Energetic Particles with Transition Radiation", M.L. Cherry, NIM A 706, 39 (2013).
- "First Measurements of the Spectral and Angular Distribution of Transition Radiation Using a Silicon Pixel Sensor on a Timepix3 Chip", E. J. Schioppa et al., NIM A 936, 523 (2019).
- "Identification of Particles with Lorentz factor up to 10^4 with Transition Radiation Detectors Based on Micro-strip Silicon Detectors", J. Alozy et al., NIM A 927, 1 (2019).
- "Transition Radiation Measurements with a Si and a GaAs Pixel Sensor on a Timepix3 Chip", F. Dachs et al., NIM A 958, 162037 (2020).
- "Studies of the Spectral and Angular Distributions of Transition Radiation Using a Silicon Pixel Sensor on a Timepix3 Chip", J. Alozy et al., NIM A 961, 163681 (2020).

TRD for FHS concept (2 concepts)



Positive arm: sensitive area (X,Y) **40 x 30** (?) cm^2

~3*2.3 m. ***To be optimized!***

Straw based detector

3.2m. ***To be optimized!***

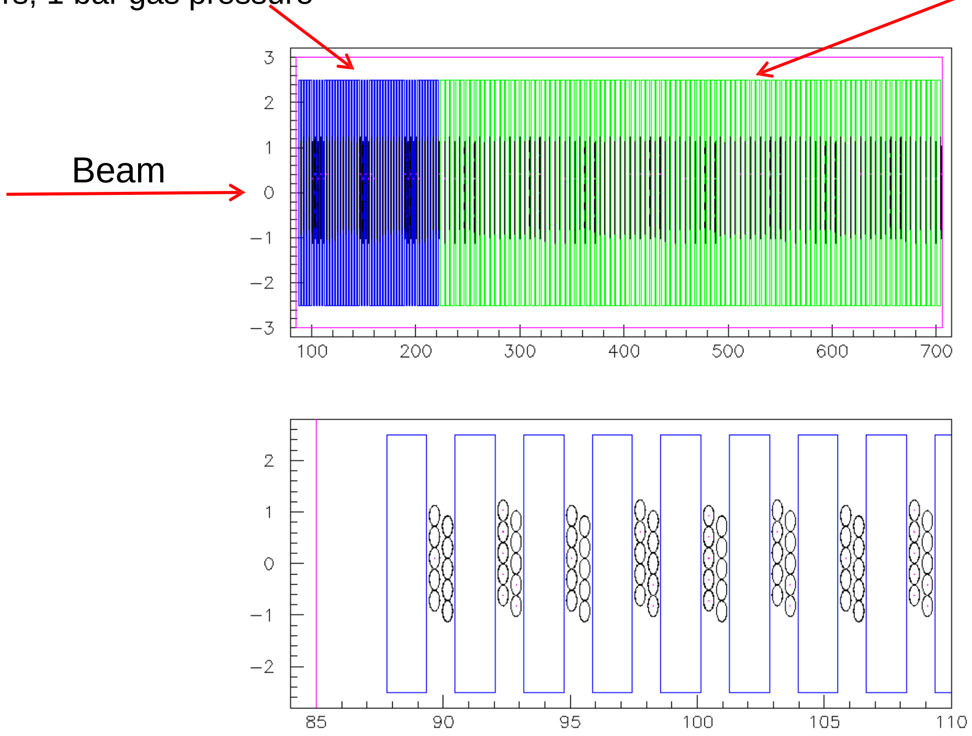
Combined approach

Negative arm: sensitive area (X,Y) **5 x 30** (?) cm^2

Detector configuration

Sub-detector 1 : PE radiator with 25 µm foils, 500 µm gap, 30 foils; 50 sections, 100 straw layers; 1 bar gas pressure

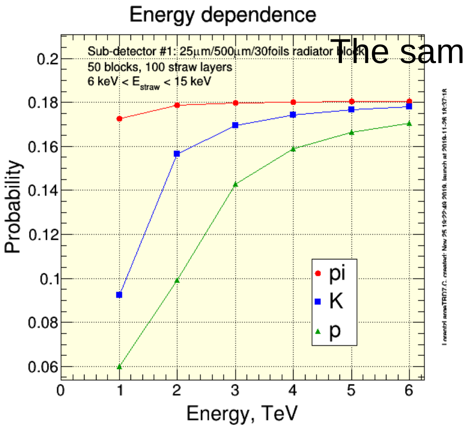
Sub-detector 2 : PE radiator with 75 µm foils, 3 mm gap, 12 foils; 100 sections, 200 straw layers; 1.5 bar gas pressure for better absorption of high-energy TR photons

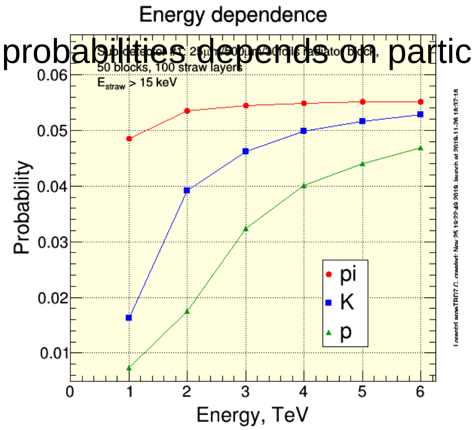


Dependencies vs particle energy

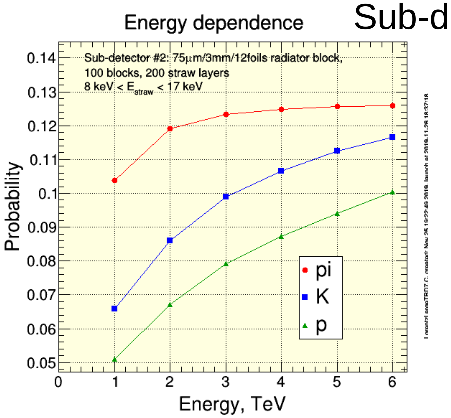
Sub-detector 1

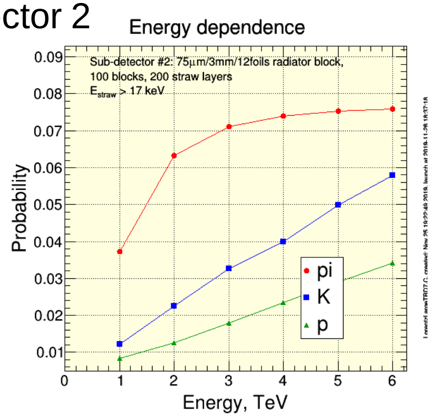
The same probabilities depends on particle energy.



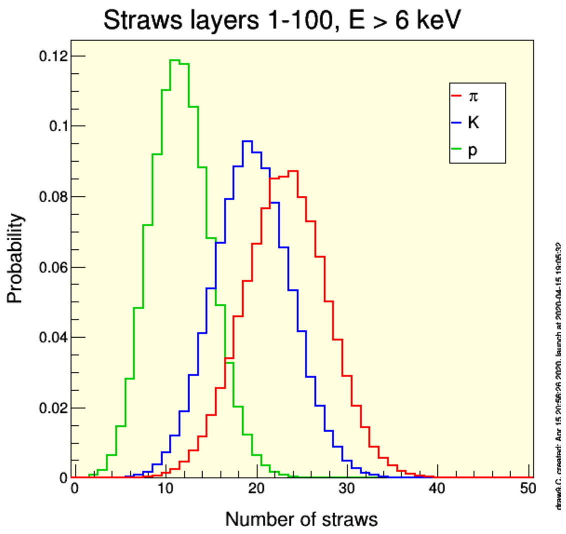


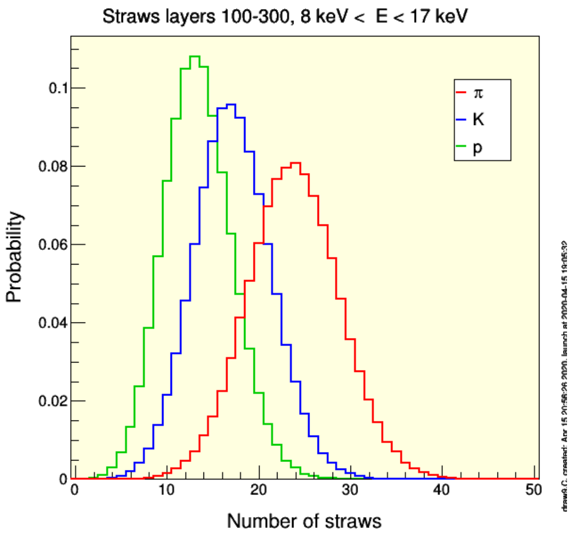
Sub-detector 2

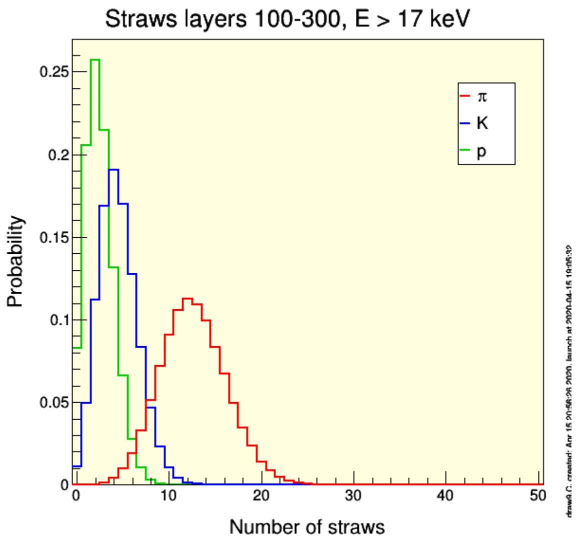




Method NOS


Straws layers 1-100, E > 6 keV


Straws layers 100-300, 8 keV < E < 17 keV


Straws layers 100-300, E > 17 keV

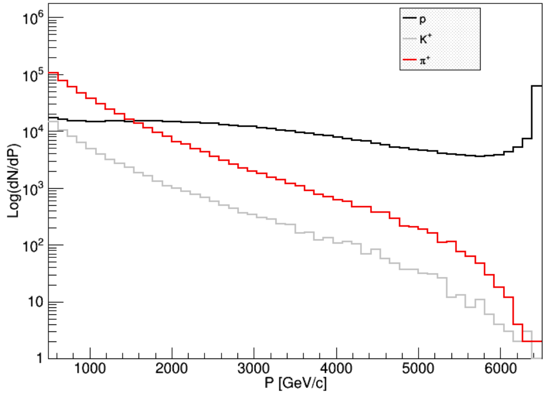
Method NOS (Number Of Straws): probability for different particle sort is estimated from number of straws in sub-detectors with certain energy deposition. When event probability is $P_i=P_{i1}*P_{i2}*P_{i3}$, where i is one of particle sort (π, K, p).

SAS_TRD: Simulation algorithm

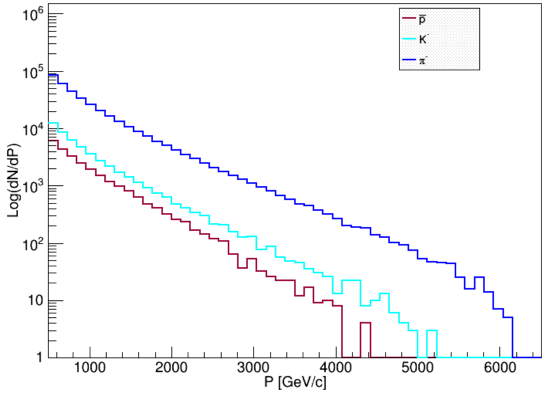
We cannot identify particles with 100% probability however we can try to reconstruct composition selecting some fraction of events in which likelihood for any particle **> X** .
This particle considered to be identified for this event.

Beam composition to be defined,.

Momentum distribution at the IP

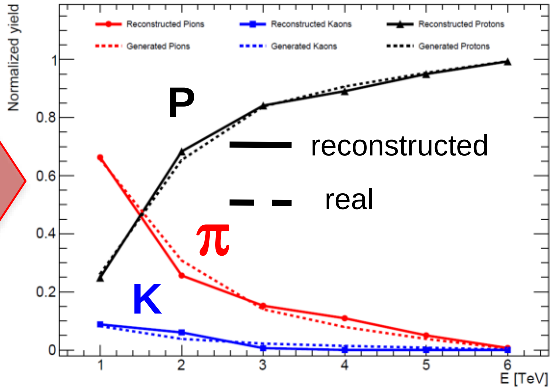


Momentum distribution at the IP

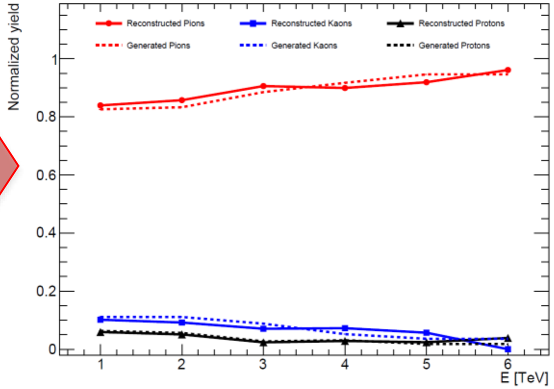


Beam composition reconstructed

PID Efficiency (LLH > 0.80), 44% of all events were accepted)

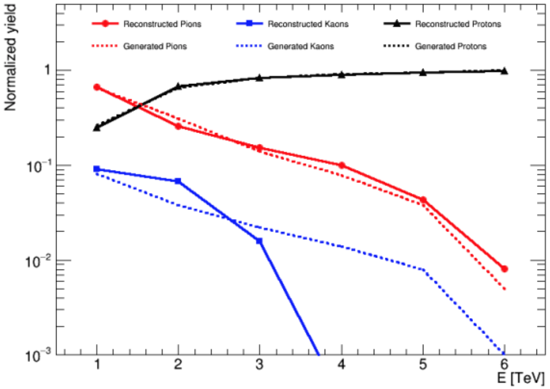


PID Efficiency (LLH > 0.80), 76% of all events were accepted)

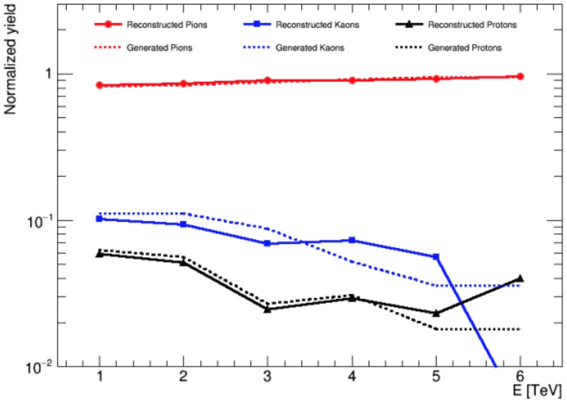


Beam composition reconstructed (LOG)

PID Efficiency (LLH > 0.77), 48% of all events were accepted)



PID Efficiency (LLH > 0.80), 76% of all events were accepted)



Compton Scatter TRD

TR x-rays emitted with angle ~ $1/\gamma$

→ difficult to spatially separate from ionization signal

Two Paths to take

1. Don’t separate:

Layer with thin gas (xenon) detector can detect photons well below ~30 keV

Detection length sufficiently thin to keep ionization signal not much larger than TR signal

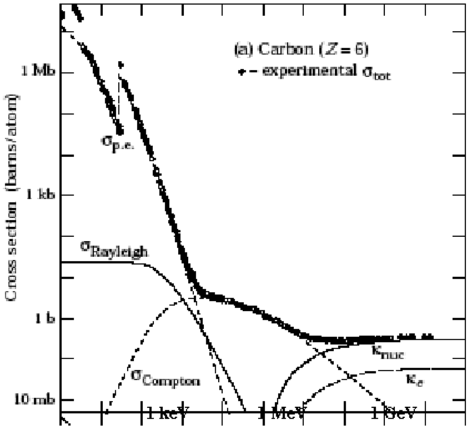
Maximal efficiency requires keeping ω’s to be low and radiator foils to be thin

2. Separate via Compton Scattering

Employ 250 μm Al foils to push TR x-ray energies > ~50 keV where Compton scattering begins to dominate

Al radiator foils can then Compton scatter TR photons, separating them from ionization deposition

Detect scattered high-energy photons with scintillator (CsI) efficiently

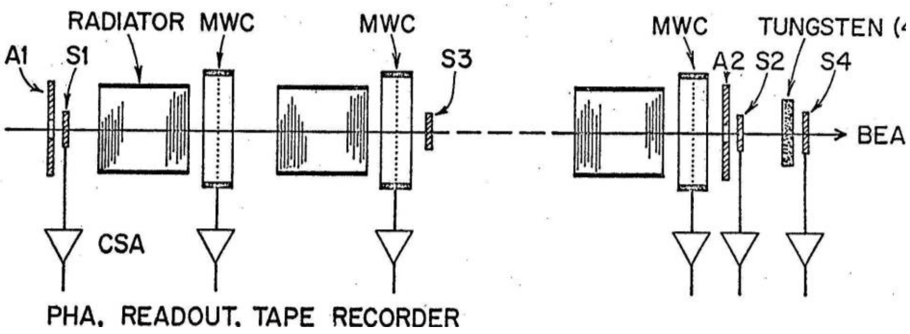


See

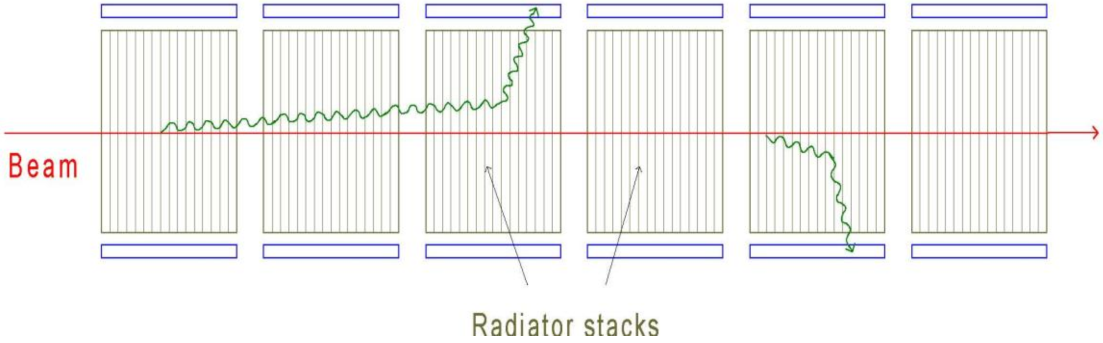
Measurement of Compton Scattered Transition Radiation at High Lorentz Factors, G. Case et al., hep-ex/0209038

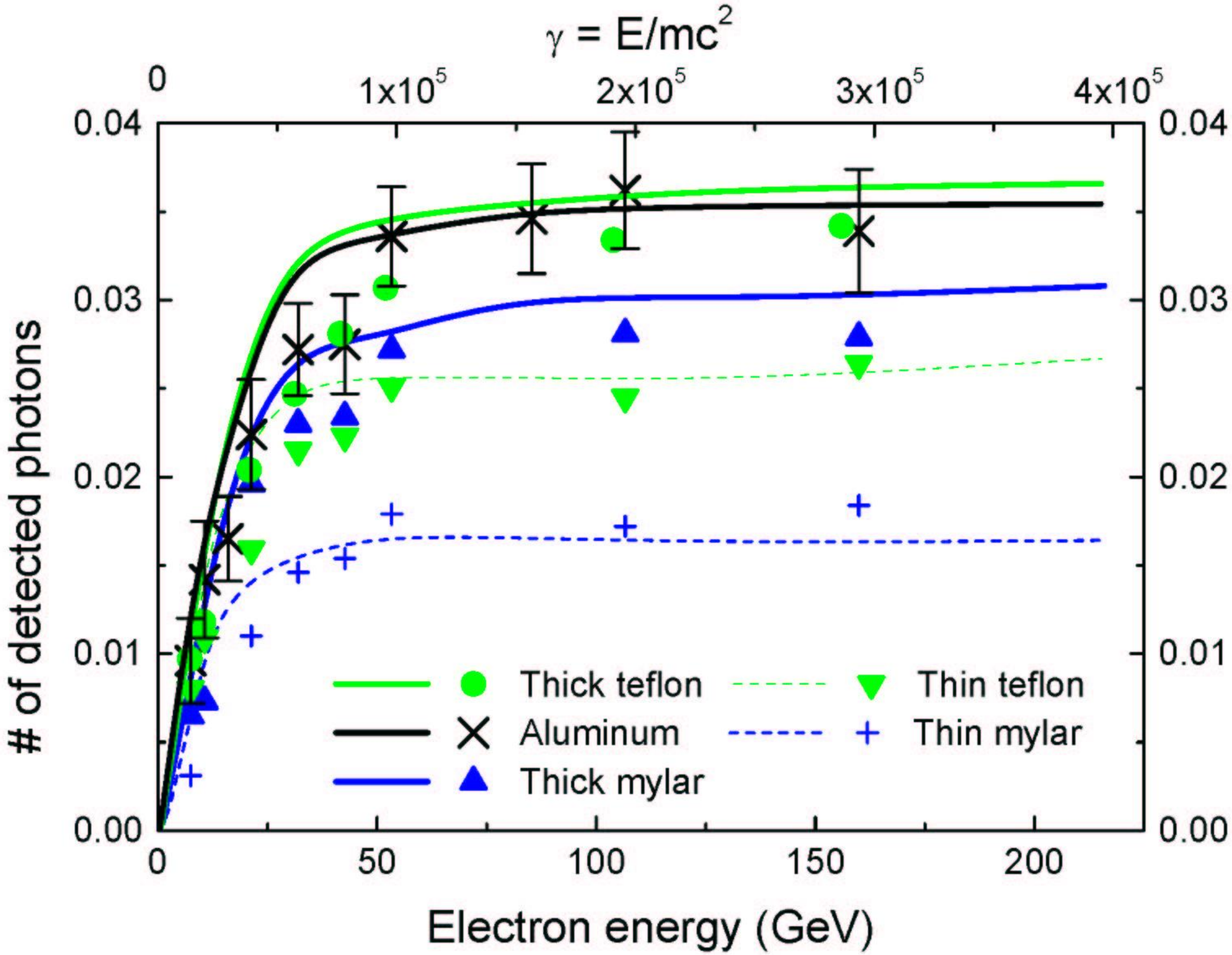
Compton Scattered Transition Radiation from Very High Energy Particles, M. Cherry & G. Case, astro-ph/02060663

“Standard” configuration – SLAC test w/plastic foils/foam, Xe



Compton scatter configuration – CERN test w/Al honeycomb, NaI





Measured 35-500 keV Compton scattered intensity

Mylar, 50 foils, l_1 = 125 and 250 μm, l_2 = 3.3 mm
Teflon, 50 foils, l_1 = 125 and 250 μm, l_2 = 3.3 mm
Al, 37 foils, l_1 = 150 μm, l_2 = 5.1 mm

Can one improve situation with more complicated radiators?

Composite radiators

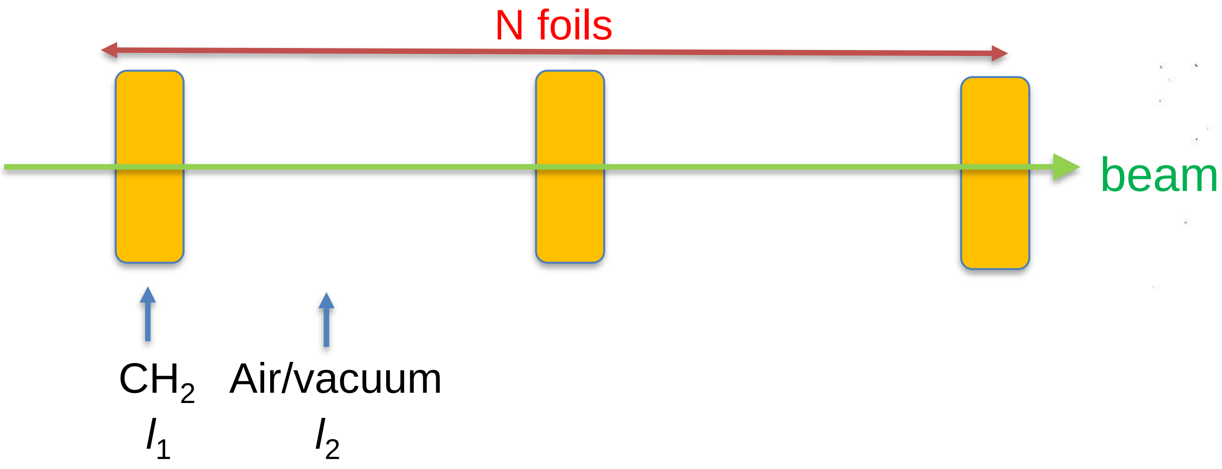
Radiators with varying foil thickness, gap lengths?

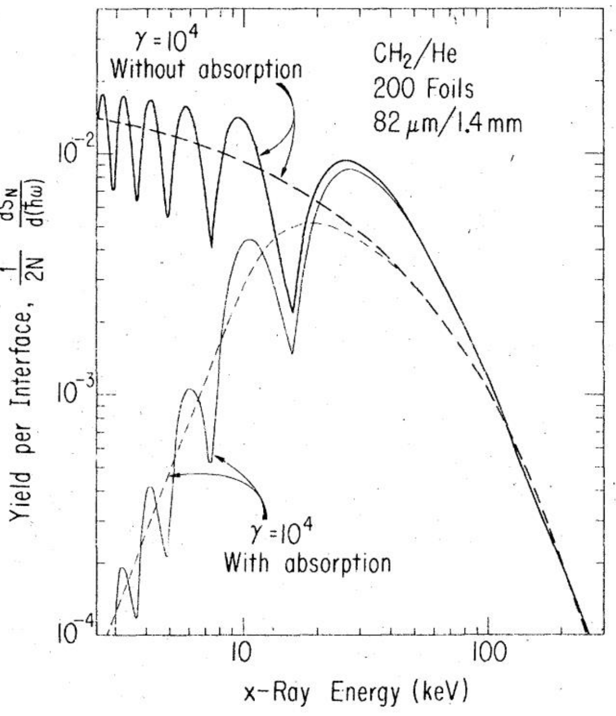
If analytic solution does not exist, one must add field amplitudes in phase.

Multi-foil yield

Single-foil yield

$$\frac{d^2S_N}{d\omega d\Omega} = \frac{d^2S_0}{d\omega d\Omega} 4\sin^2\frac{l_1}{Z_1}\frac{\sin^2 N(l_1/Z_1+l_2/Z_2)}{\sin^2(l_1/Z_1+l_2/Z_2)}$$





Here Z_i is the formation zone for medium *i* :

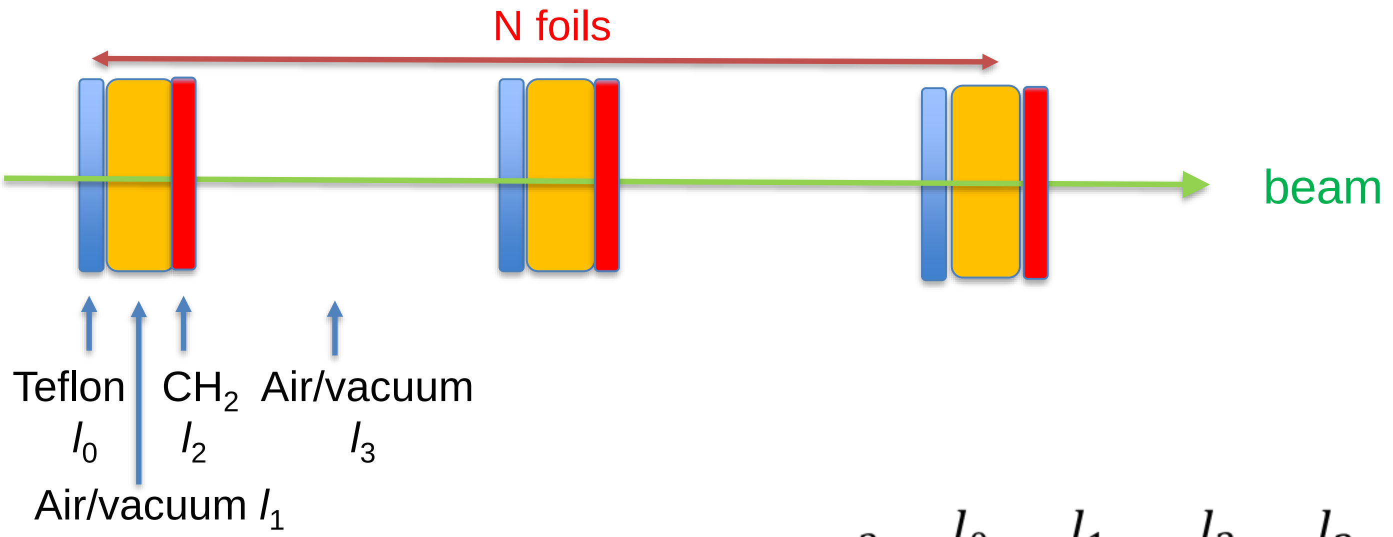
$$Z_i = \frac{4c}{\omega}/(\frac{1}{\gamma^2}+\frac{{\omega_i}^2}{\omega^2}+\theta^2)$$

Multi-foil yield

Single-foil yield

$$\frac{d^2S_N}{d\omega d\Omega} = \frac{d^2S_0}{d\omega d\Omega}\, 4\sin^2\frac{l_1}{Z_1}\, \frac{\sin^2 N(l_1/Z_1+l_2/Z_2)}{\sin^2(l_1/Z_1+l_2/Z_2)}$$

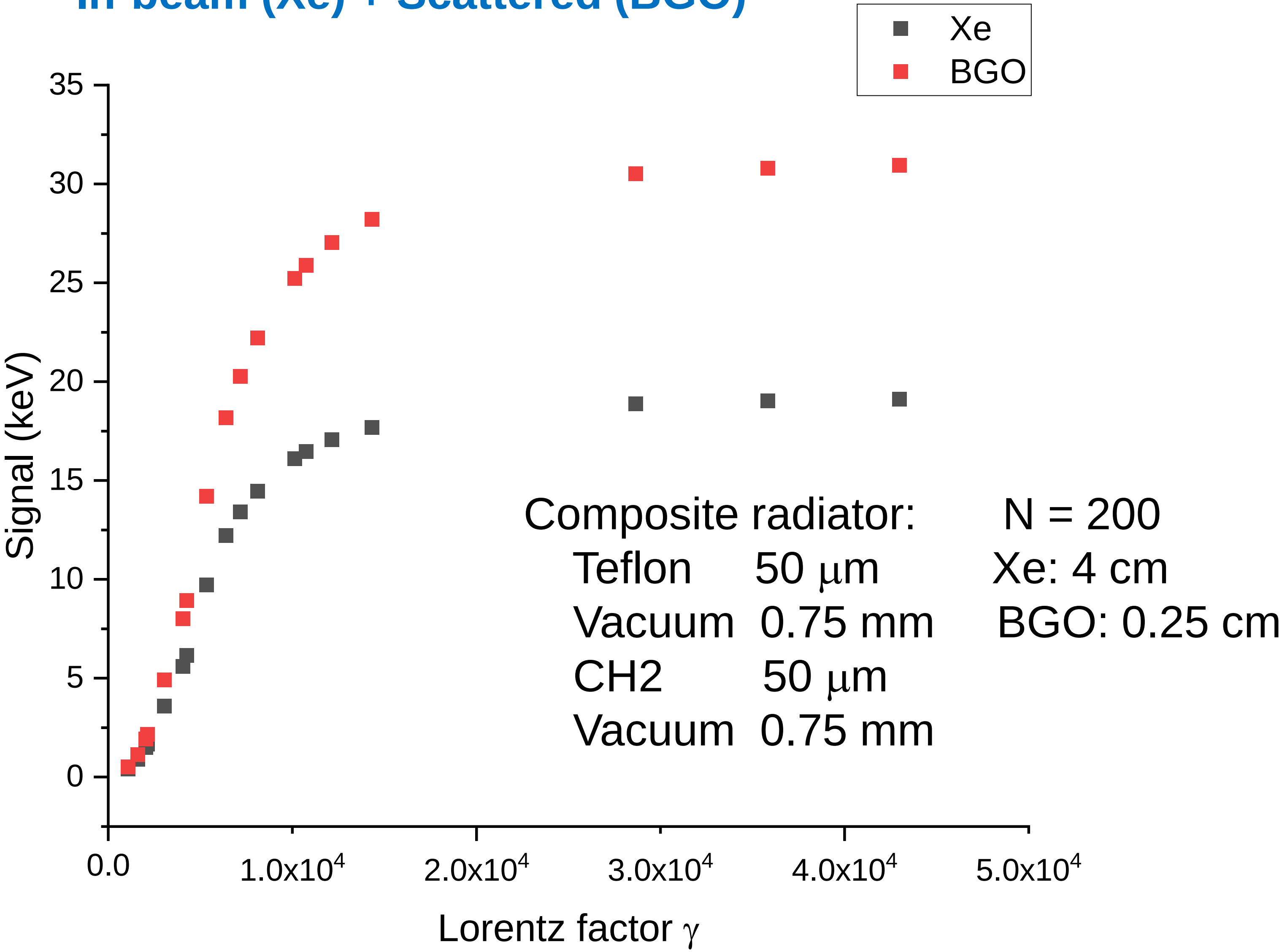
Example: Multi-layer foil



$$\frac{d^2S_N}{d\omega d\Omega} = \frac{d^2S'_0}{d\omega d\Omega}\, \frac{sin^2 N(\frac{l_0}{Z_0}+\frac{l_1}{Z_1}+\frac{l_2}{Z_2}+\frac{l_3}{Z_3})}{sin^2(\frac{l_0}{Z_0}+\frac{l_1}{Z_1}+\frac{l_2}{Z_2}+\frac{l_3}{Z_3})}$$

Multi-layer foil has similar modulation properties, potentially increases X-ray yield beyond single-layer foil.

Summed signal –
In-beam (Xe) + Scattered (BGO)



Composite radiator: N = 200

Teflon 50 μm Xe: 4 cm

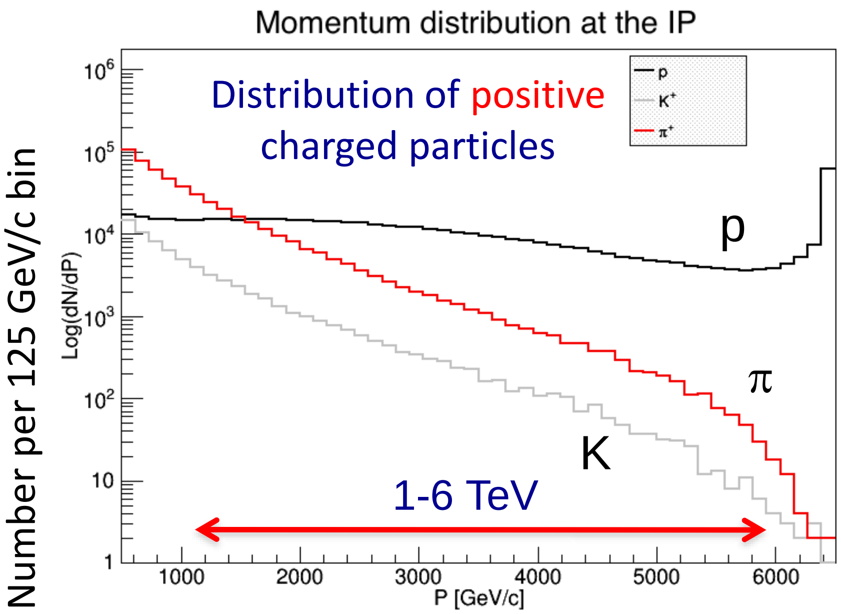
Vacuum 0.75 mm BGO: 0.25 cm

CH2 50 μm

Vacuum 0.75 mm

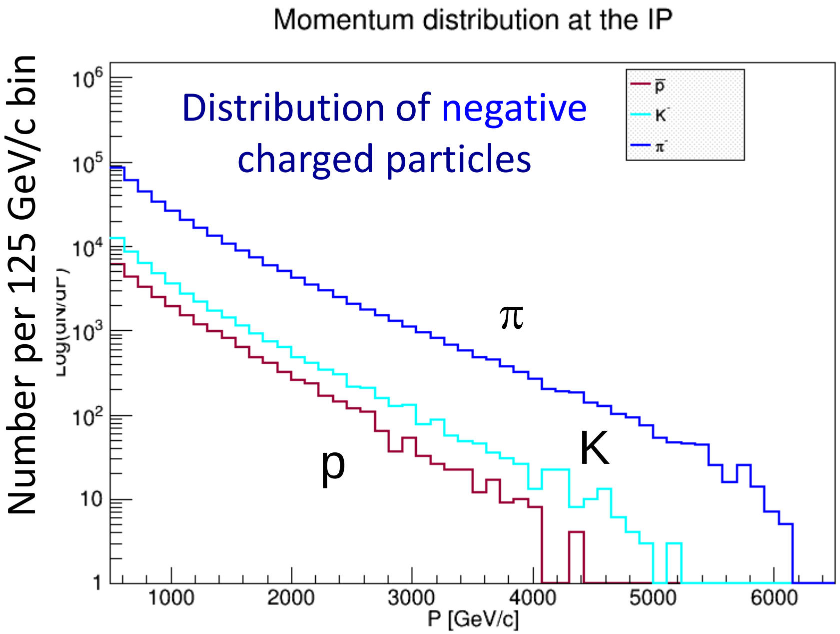
What TRD is for in this experiment?

It is assumed that electrons and muons are identified using calorimeters and muon systems.

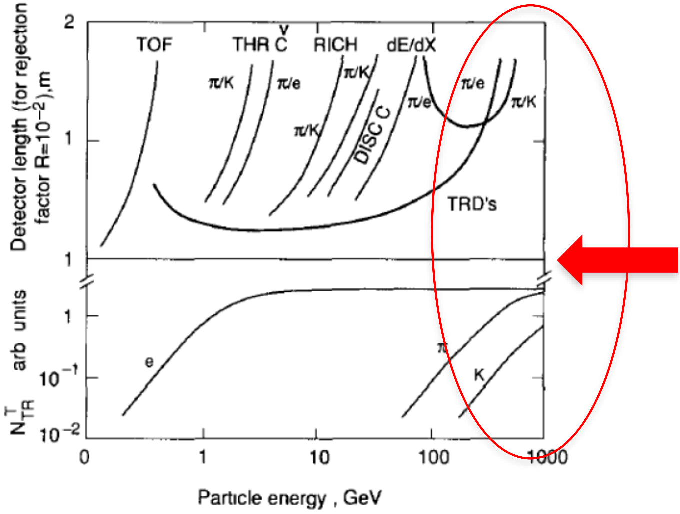


Distribution of positive charged particles

1-6 TeV



Distribution of negative charged particles



Gamma factor range to be covered
10^3 to $4*10^4$

TRD has the largest gamma factor range.
But it usually works well for separation of particles up to gamma factors few*10^3.

We have demonstrated:

- Ability to simulate details of spectra accurately
- Performance of multiple detectors (proportional chambers, straw tubes, Si/GaAs pixel detectors)
- Ability to tune radiator/detector specs to specific cases and reconstruct particle composition:

➔**Once amount of space, rates, etc. are specified, an appropriate p-K-pi id system can be designed.**