A new Transition Radiation Detector based on GEM technology

VCI2019 – The 15th Vienna Conference on Instrumentation

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on behalf of GEM-TRD working group

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Outline

- Introduction
- Motivation
- Detector concept
- MC studies
- Test beam results
- Summary

Electron-Ion Collider (EIC)

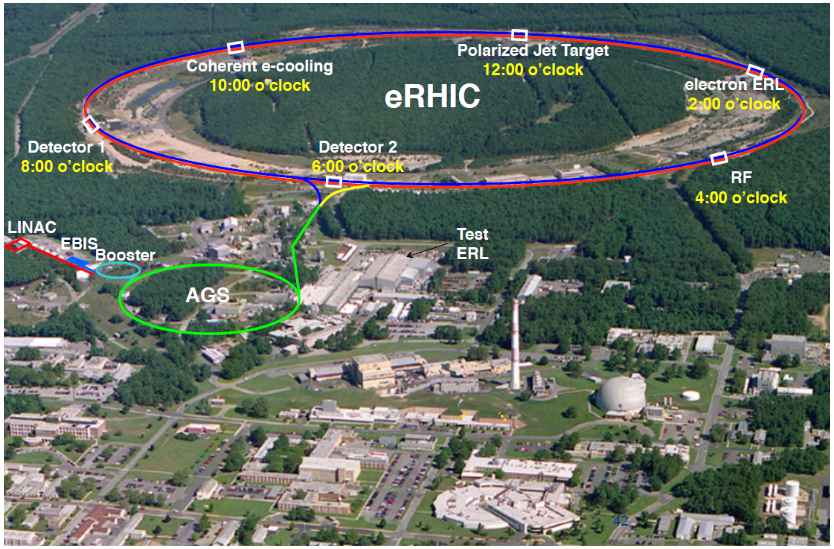
EIC is a proposed QCD facility to study a structure and dynamics of matter (our world):

- ✓ Property of Hadrons (Mass, Spin)
- ✓ Structure or Imaging of Hadrons (PDF, TMD, GPD)
- ✓ QCD at Extreme Parton Densities
- ✓ Emergence of hadrons

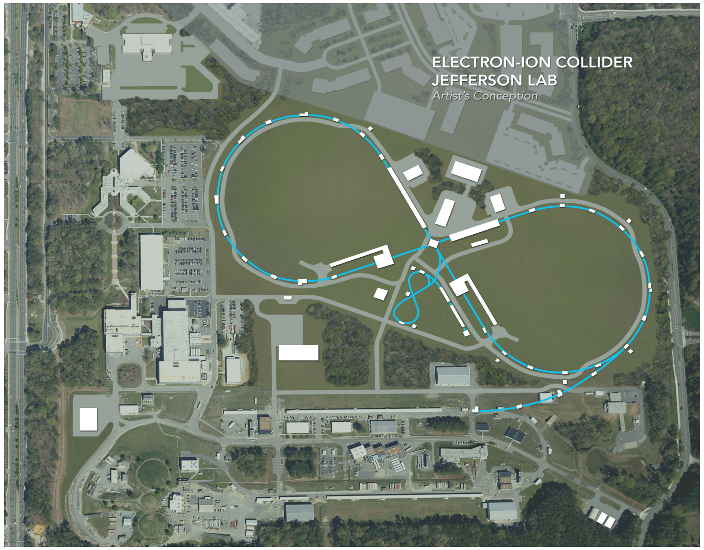
EIC:
Wide range of nuclei
CM energy $\sqrt{s}(eN) \sim 20\text{–}140$ GeV
Luminosity L ~ 10^{34} cm−2 s−1
Polarized beams (both)
Next generation of detectors

Two sites proposed their design:

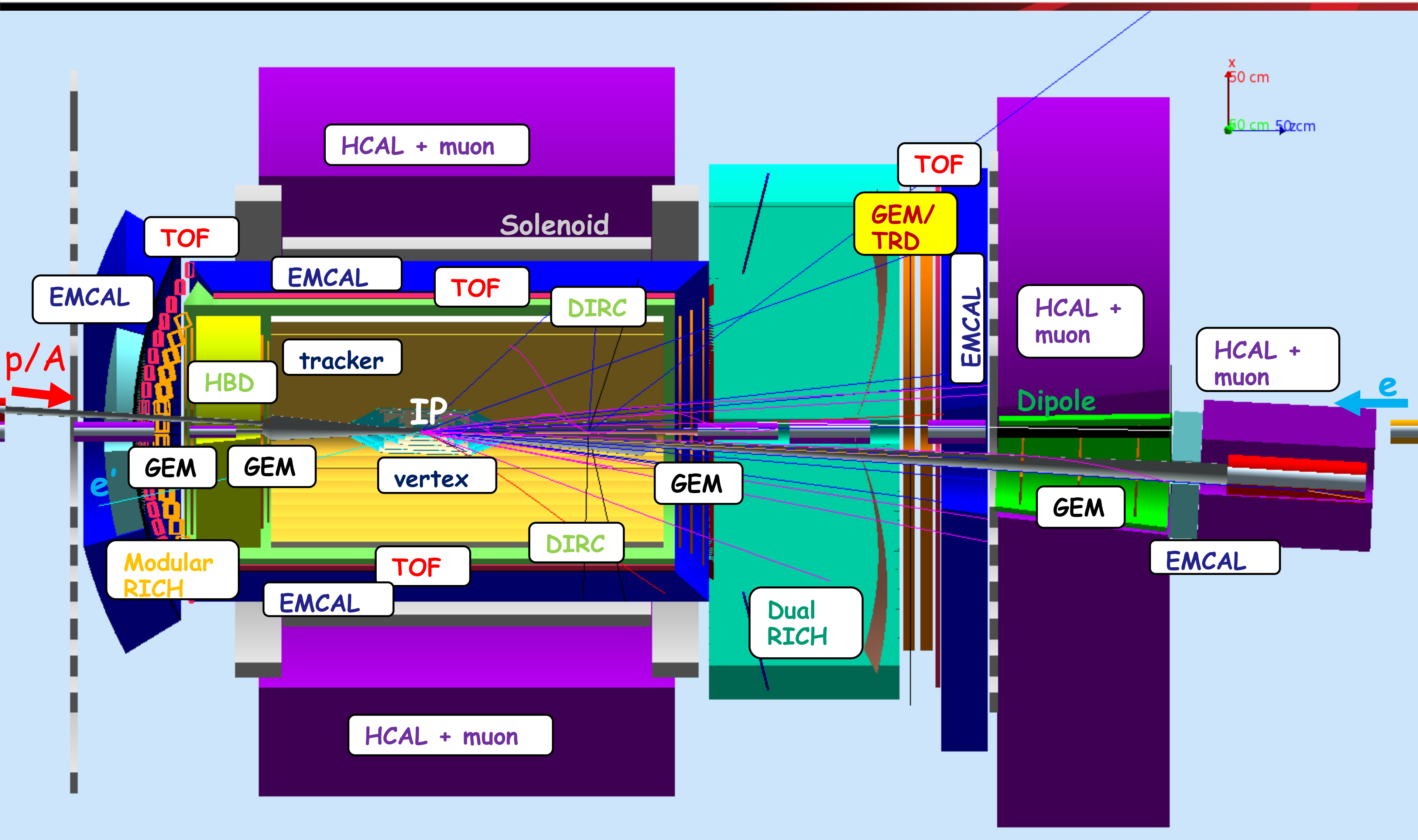
Brookhaven Lab, Long Island, NY



Jefferson Lab, Newport News, VA



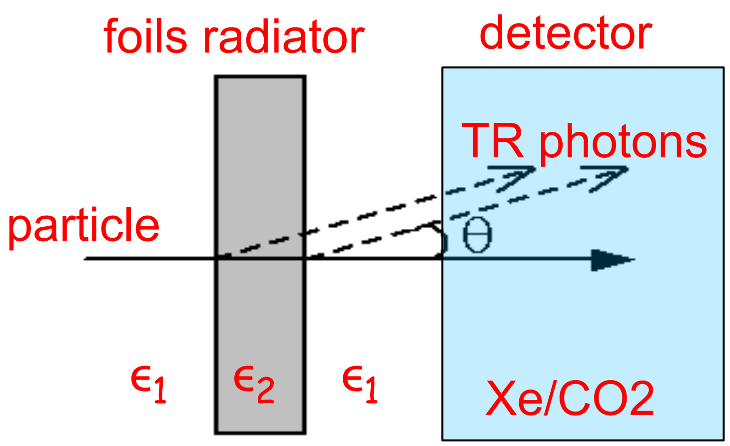
EIC detector designed by JLab



Modular design of the central detector

Transition Radiation intro

- Transition radiation is produced by a charged particles when they cross the interface of two media of different dielectric constants ϵ_1 ϵ_2



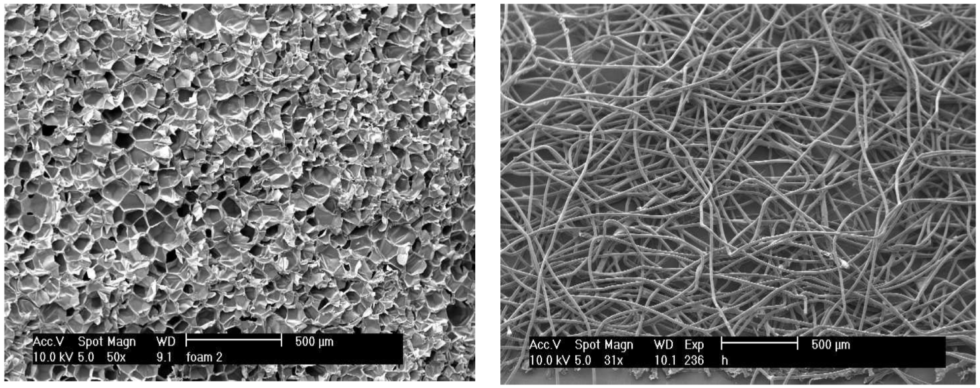


Figure 2: Electron microscope images of a polymethacrylimide foam (Rohacell HF71)(left) and a typical polypropylene fiber radiator (average diameter ≈ 25 μm) (right) [52].

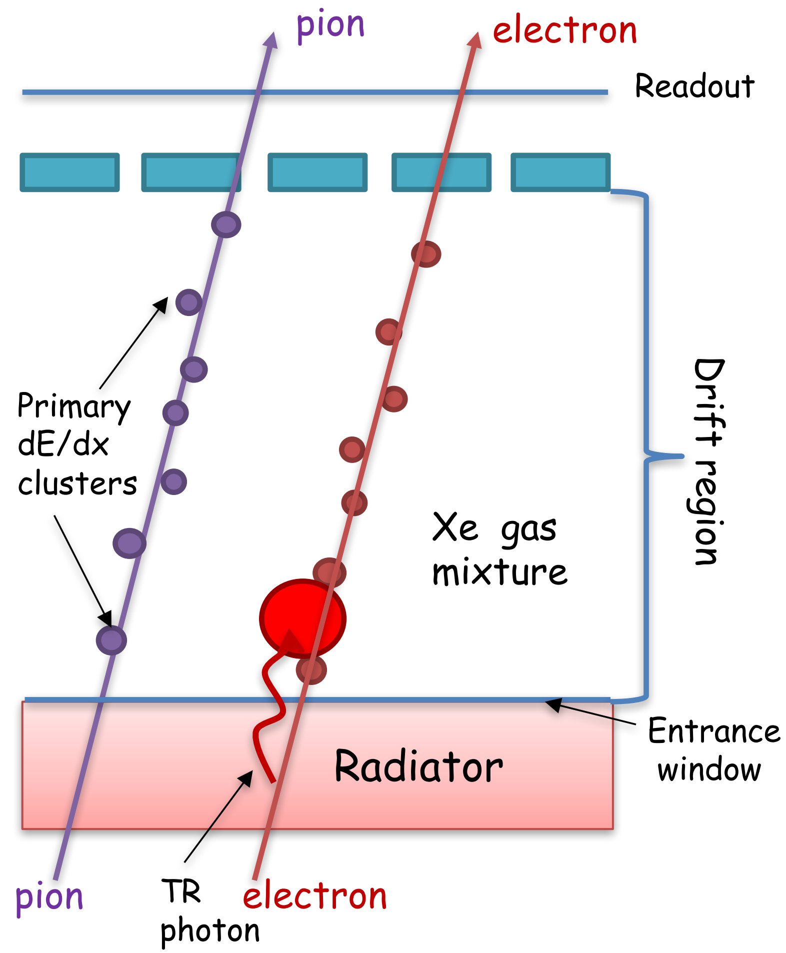
[52] A. Andronic et al. (ALICE collaboration), Nucl. Instr. and Meth. in Phys. Res. A **558**, 516 (2006).

- the probability to emit one TR photon per boundary is of order α~1/137. Therefore multilayer dielectric radiators are used to increase the transition radiation yield, typically few hundreds of Mylar foils with air gaps.
- TR in X-ray region is extremely forward peaked within an angle of $1/\gamma$
- Energy of TR photons are in X-ray region (2 - 40 keV)
- Total TR Energy is proportional to the γ factor of the charged particle
- TRD can separate charged particles by their gamma-factor

More details about TRD: B. Dolgoshein, Transition radiation detectors, 1993 Nucl. Instr. and Meth. A 326 434-469.

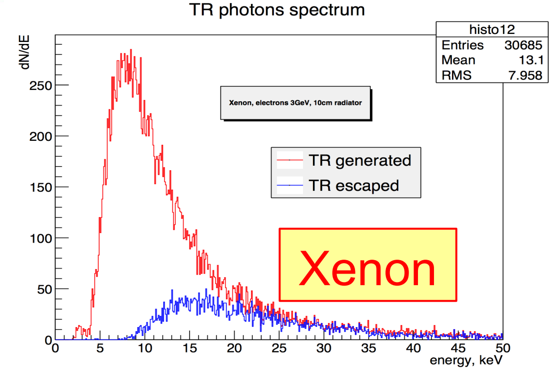
GEM as transition radiation detector

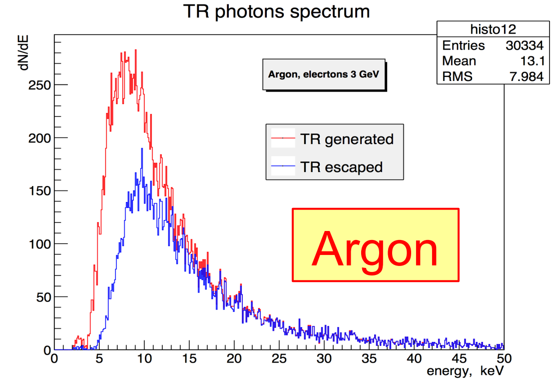
- GEM is high resolution tracker (strip pitch 400 μm).
- Low material budget detector
- To convert GEM tracker to TRD:
  - ➢ Add a radiator in the front of each chamber (radiator thickness ~5-10cm)
  - ➢ Change gas mixture from Argon to Xenon (TRD uses a heavy gas for efficient absorption of X-rays)
  - ➢ Increase drift region up to 2-3 cm (for the same reason).
- Single module could provide e/pi rejection factor of ~10 and electron efficiency ~90%
- For higher rejection, several such modules (radiator+detector) can be installed.



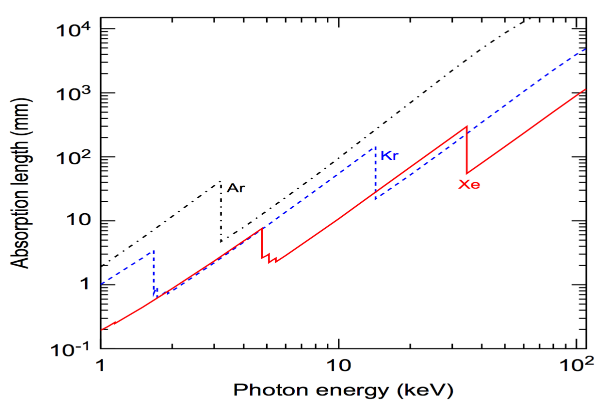
Select working gas

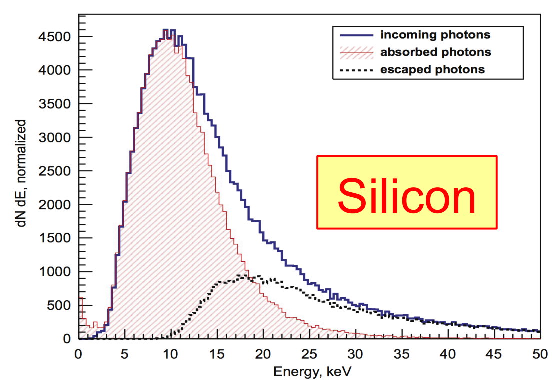
- GEM tracker uses Argon mixture, while TRD needs heavy gas to efficiently absorb X-rays (TR photons), typically Xenon based mixture.
- Plots on the right compare noble gases and silicon in terms of efficient absorption of TR photons : red – incoming (incident photon spectrum), blue – escaped TR-photons.
    - Gas thickness 20mm, silicon thickness 500 um
- The bottom left plot represents absorption length versus photons energy, and reflects a shell structure of atoms.

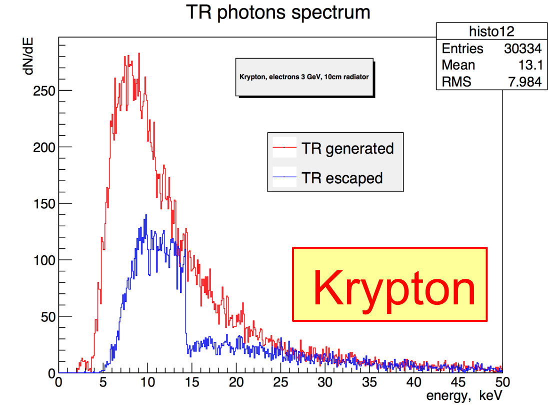




in Physics Research A 666 (2012) 130–147



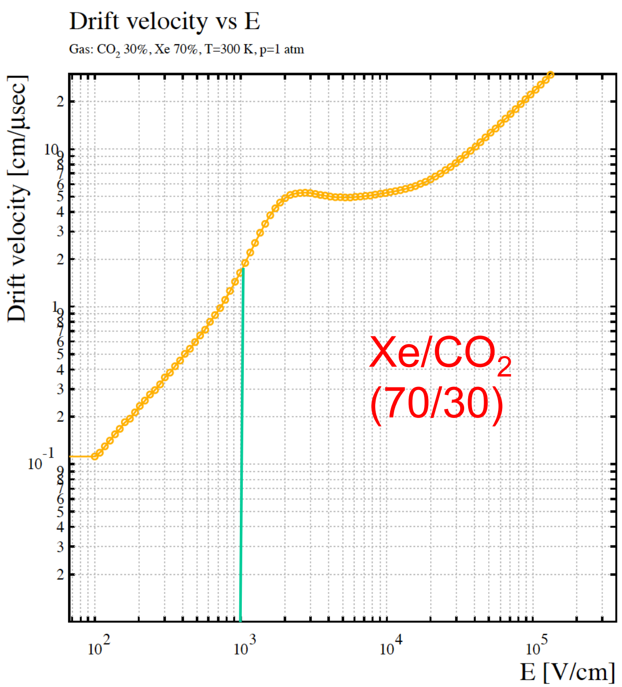


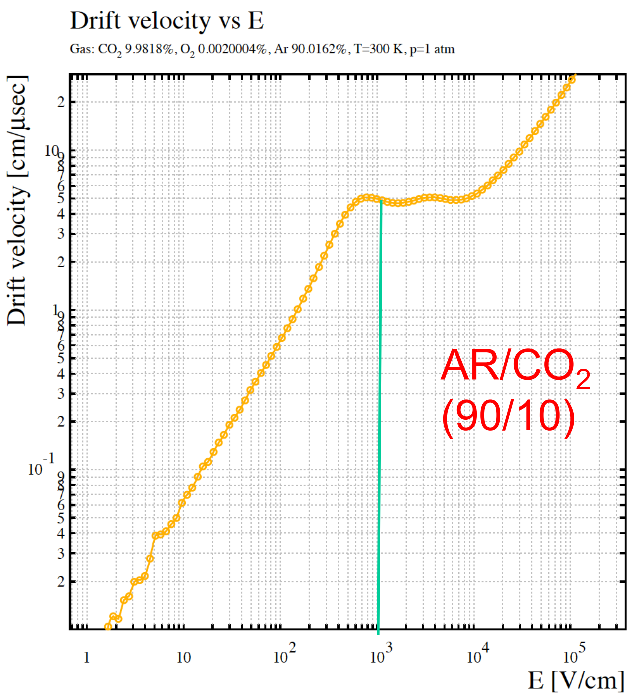


Xenon based gas mixture

- Xenon mixture differs from Argon mixture in two aspects:
  - ✓ In order to have similar to Argon drift velocity, one need to apply higher electric field in Xenon mixture: ~2000 V/cm (for 2.1 cm drift distance ~4400 V.)
  - ✓ Xenon is expensive gas (~$20/l) , hence we need a closed loop gas system with recirculation, recuperation and purification ability

Garfield + Magboltz





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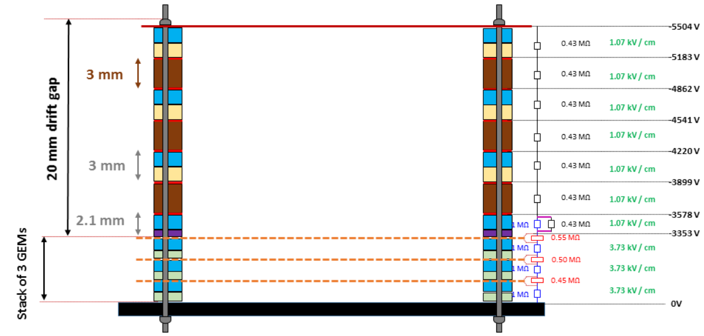
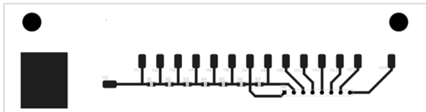
GEM-TRD prototype

- A test module was built at the University of Virginia
- The design includes modification needed for TRD operation:
  - Drift distance increased to 21 mm
  - Added a side field cage with dividers to have uniform drift field in whole volume.
  - The gas gap between the entrance window and the cathode is reduced to 400 μm, because it is a dead volume that absorbs photons
  - New GEM HV divider to be able to control the gas gain and drift field independently.

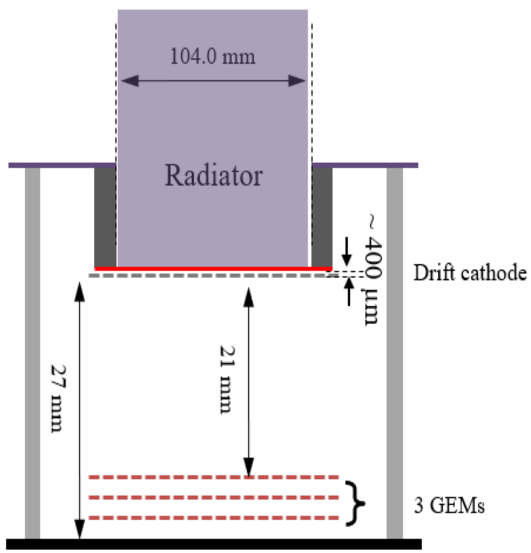
Cross section of the 20.0 mm drift TRD-GEM



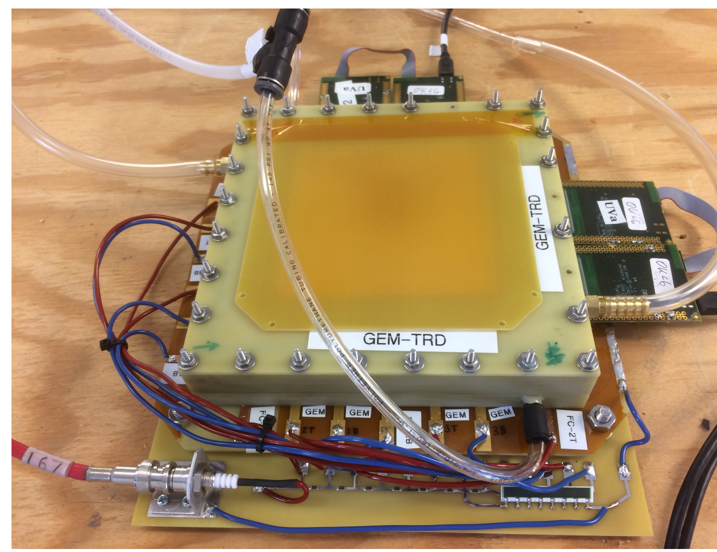
Drawing for the resistive divider



HV 5504 V,
Resistive Divider = 7.404 MΩ,
Max current = 747.3 μA



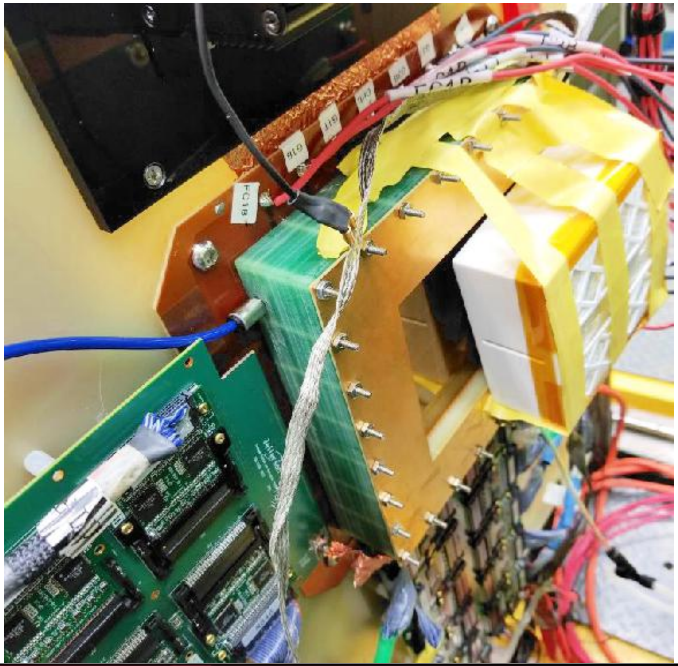
New GEM-TRD: proto II



Radiator for TR

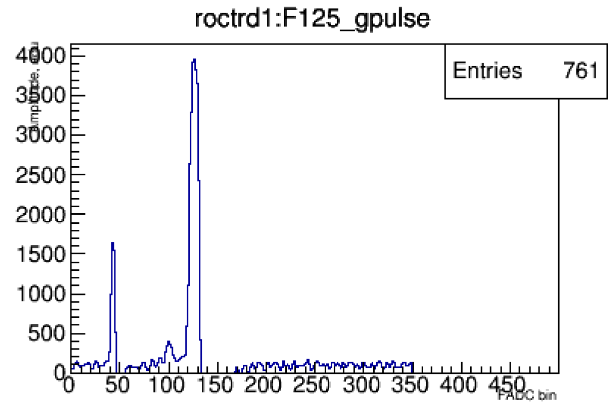
- The theory of transition radiation predicts that the best radiator is a stack of regular foils:
  - 20-30μ mylar foils and 200-300μ air gap.
- ATLAS use foils and spacer between foils to provide an air gap.
- ZEUS and many other experiments use fleece radiators.
- Bottom pictures show GEM-TRD test module with regular and fleece radiators in front

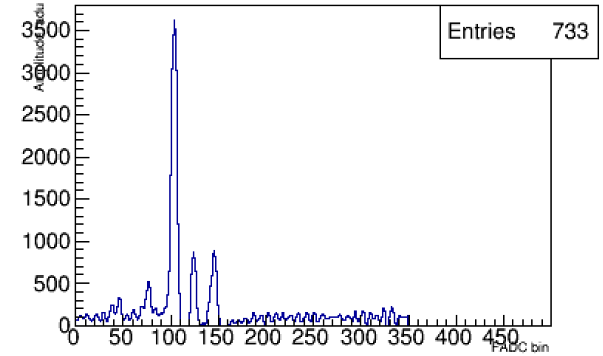
Atlas spacer

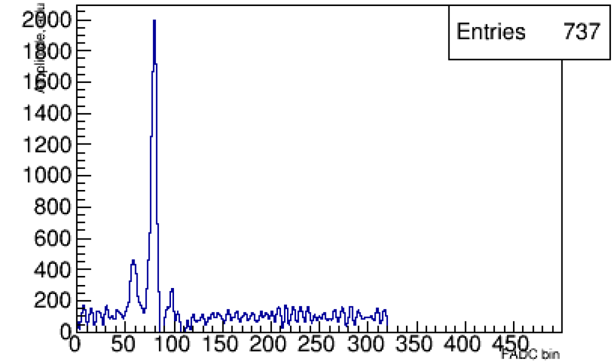


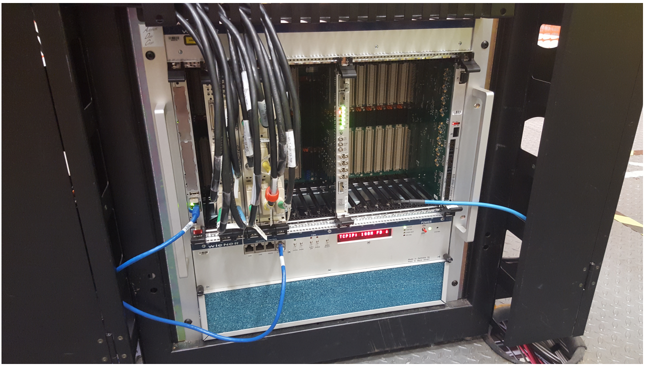
Readout electronics for GEM–TRD

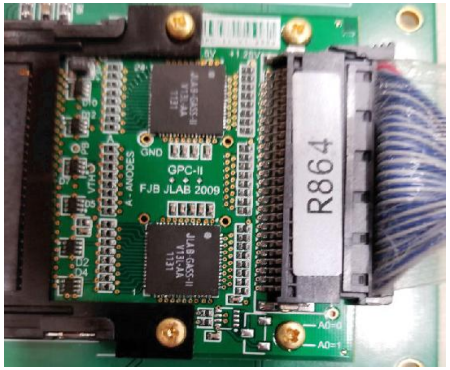
- The standard tracking GEM readout is usually based on an APV25 chip and measures peak amplitude
- TRD needs information about ionization along the track, to discriminate TR photons from energy loss of the particle.
- For the TRD test we used a precise 125 MHz, 14 bit flash ADC, developed at JLAB with VME readout.
    - FADC readout window (pipeline) up to 8 μs
- Pre-amplifier has GAS-II ASIC chips, provides 2.6 mV/fC amplification and has a peaking time of 10 ns.





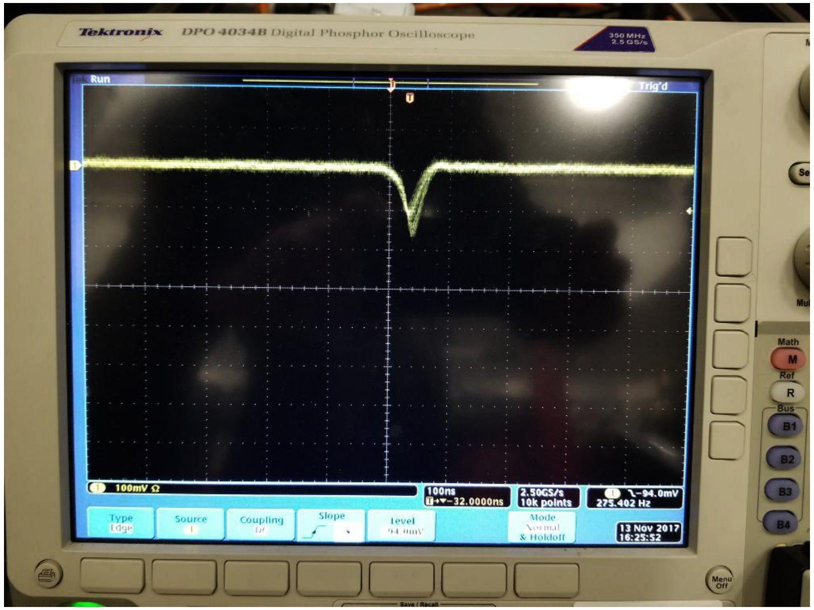


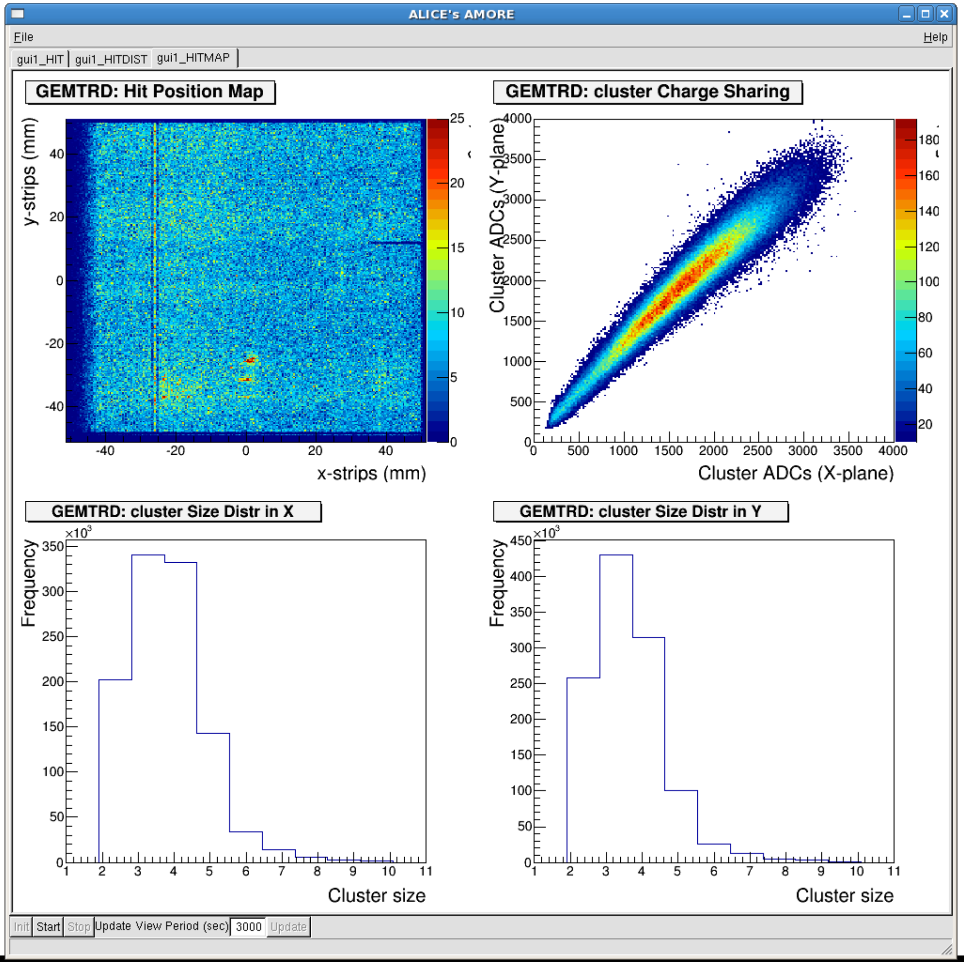




X-ray and ^{55}Fe test

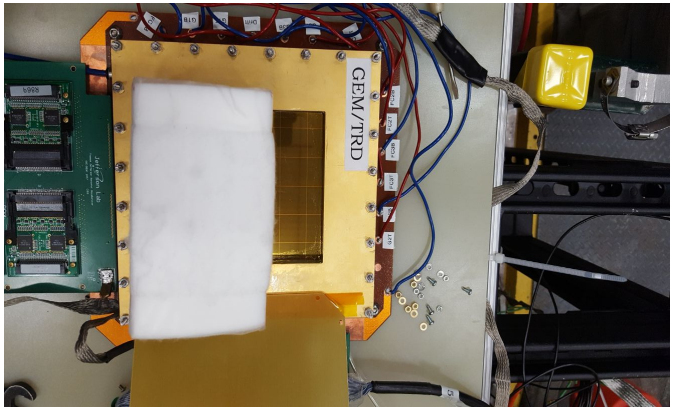
- X-ray uniformity test was performed using the APV25 for readout
- The HV and gas gain was tested with ^{55}Fe source for Argon and Xenon gas mixtures.

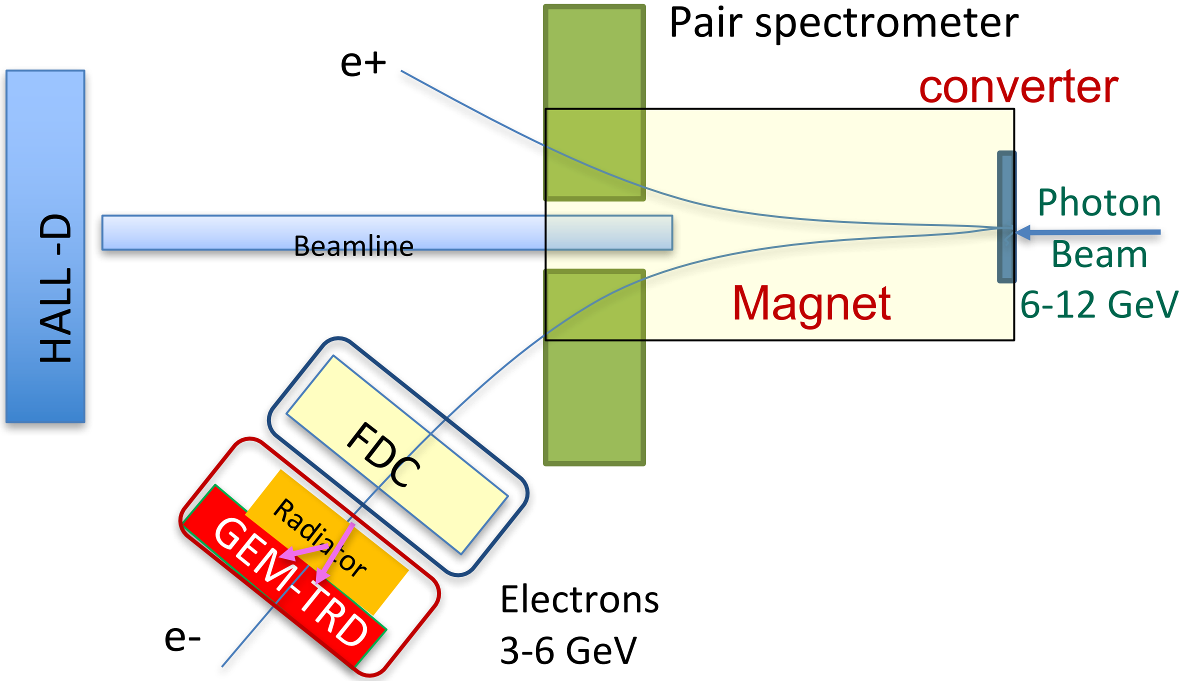




Beam setup at JLab Hall-D

- The tests were carried out using electrons with an energy of 3-6 GeV, produced in the converter of a pair spectrometer.
- The electron energy is known from the pair spectrometer.
- The radiator is mounted in front of the GEM-TRD and covers about half of the sensitive area.
- We do not have hadron beam in this setup:
  - ✓ The effect of TR is evaluated by comparison of data from electrons with radiator and electrons without radiator.



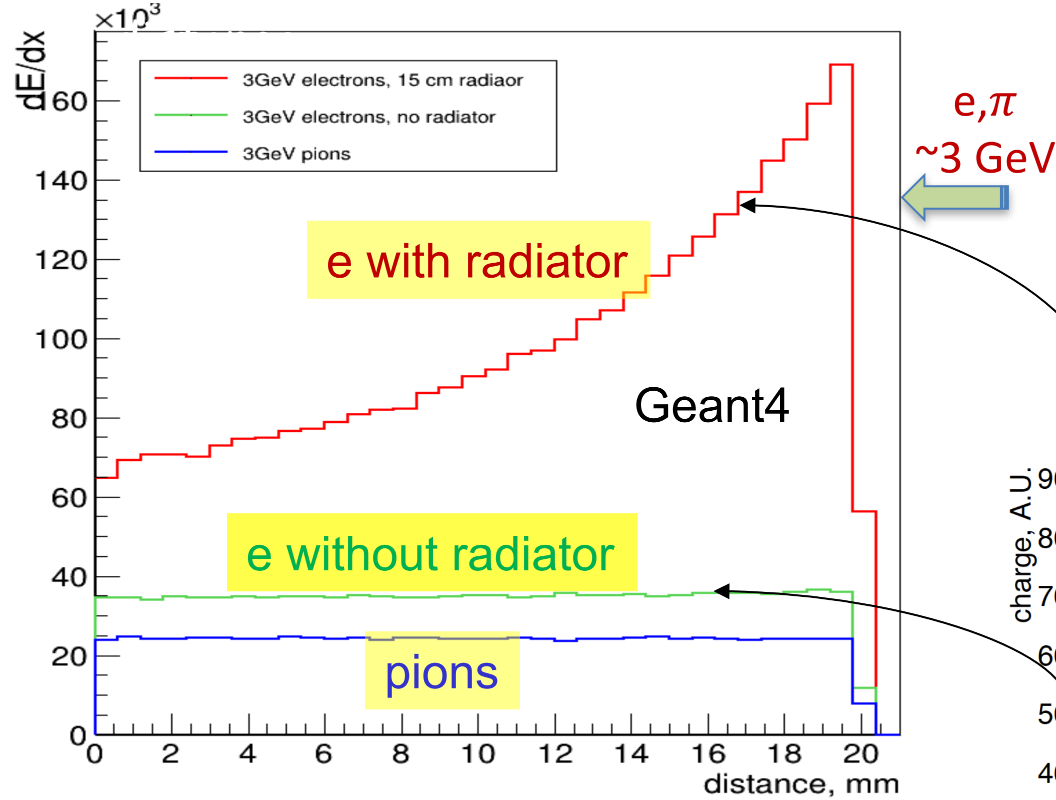


Data analysis

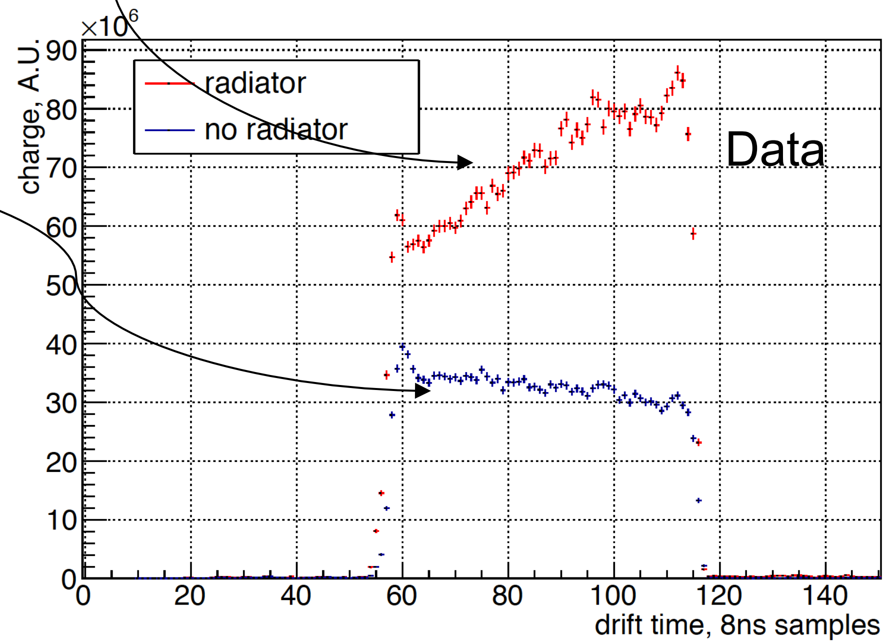
- TR photons move forward at a small angle within $1/\gamma$, practically along the path of the original particle, and are detected together with dE/dx from the particle..
- There are several methods that are used to discriminate TR photons and dE/dx from particle
  1. Cluster counting method
     - use one threshold on ionization amplitude (just above average dE/dx), assuming that energy deposition from TR photons is a point like and produces cluster with high amplitude. Method is widely used with straw based TRD.
  2. Total energy deposition
  3. Separation in space
     - Require high resolution detector (silicon pixels) to see natural angular distribution of TR photons, or magnetic field to deflect particle from TR photons.
  4. In case of measurements of ionization along the track, the likelihood or neural network methods can be used for separation of electrons and pions.
- For this test we used ionization along the track and neural network.

Ionization along the particle track

Energy deposition (dE/dx + TR) vs drift distance

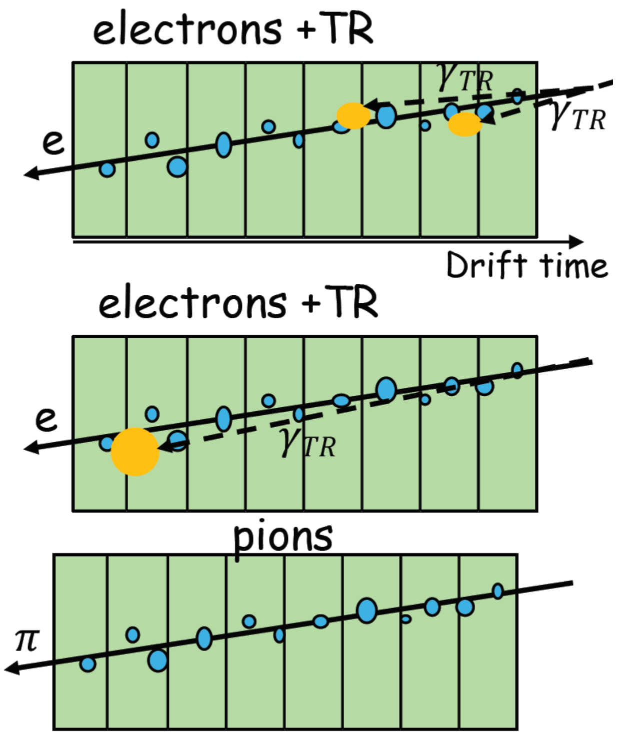


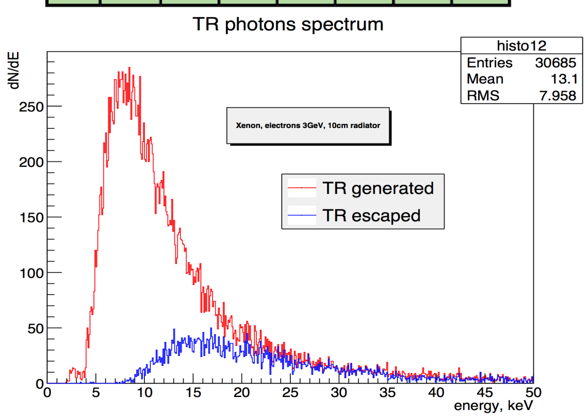
- Measured dE/dx profile is in good agreement with MC.
- The presence of TR photons is clearly visible in the data with radiator
- The slope for electrons without a radiator in the data is not reproduced in the current MC, and can be explained by diffusion and relatively high threshold.



- Note that ionization from 3 GeV pions is less than from 3 GeV electrons, so rejection for electrons without radiator can not be directly compared with pions rejection.

Absorption regions





Soft TR-photons:

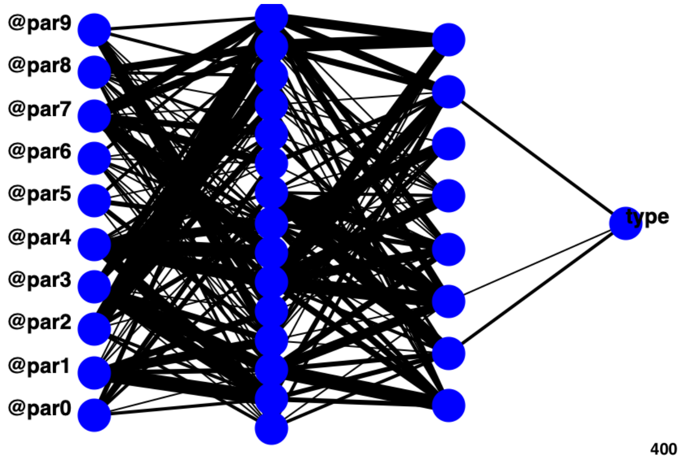
- absorbs near entrance window, therefore have largest drift time
- sensitive to dead volumes, like Xe-gap, cathode material.
- Increasing the length of the radiator thickness does not lead to increase of number of soft-photons (radiator self-absorption)

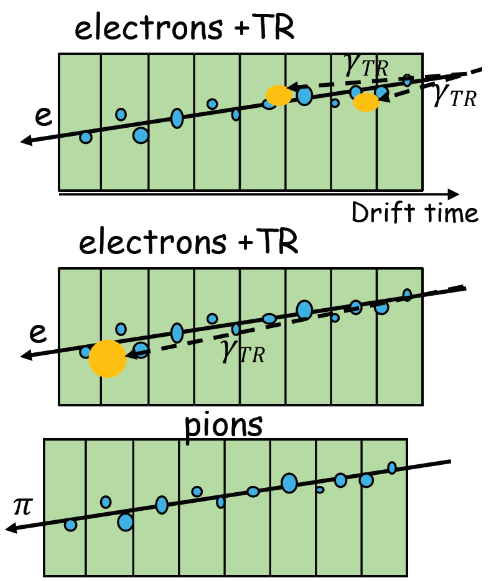
Hard TR-photons:

- Depending on energy of TR-photons, could escape detection (depends on detection length)
- Increasing the length of the radiator leads to an increase of hard TR spectra.
- Need thick detector to absorb

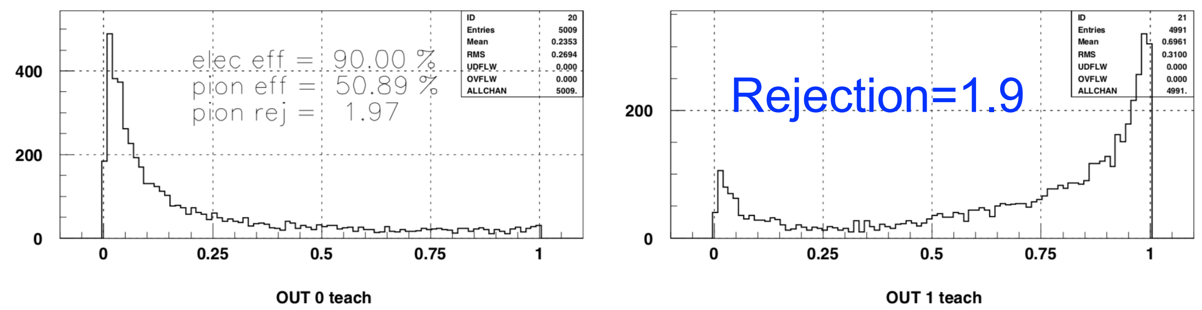
MC test of machine learning technique

- Drift distance is divided into 10 slices
  Energy deposition in slices used as input for NN
  Used different methods/programs (JETNET, Root based-TMVA, etc) for cross-check.

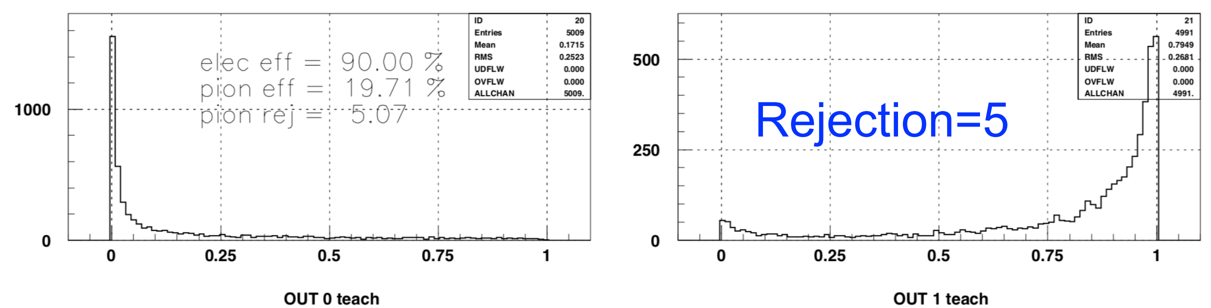




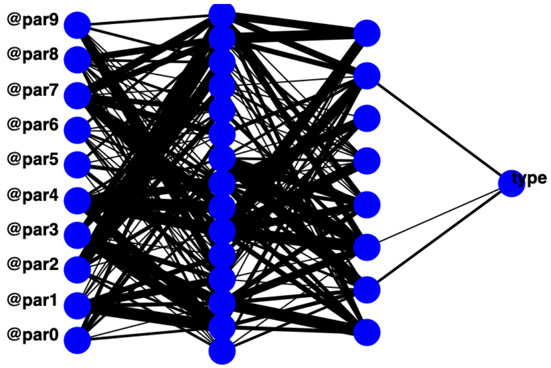
Neural network output for e/e with radiator and without radiator

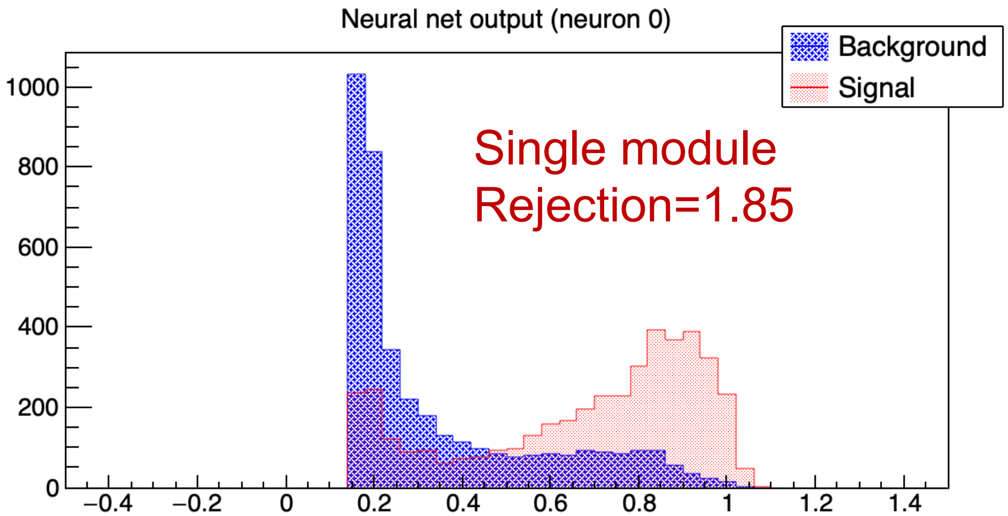


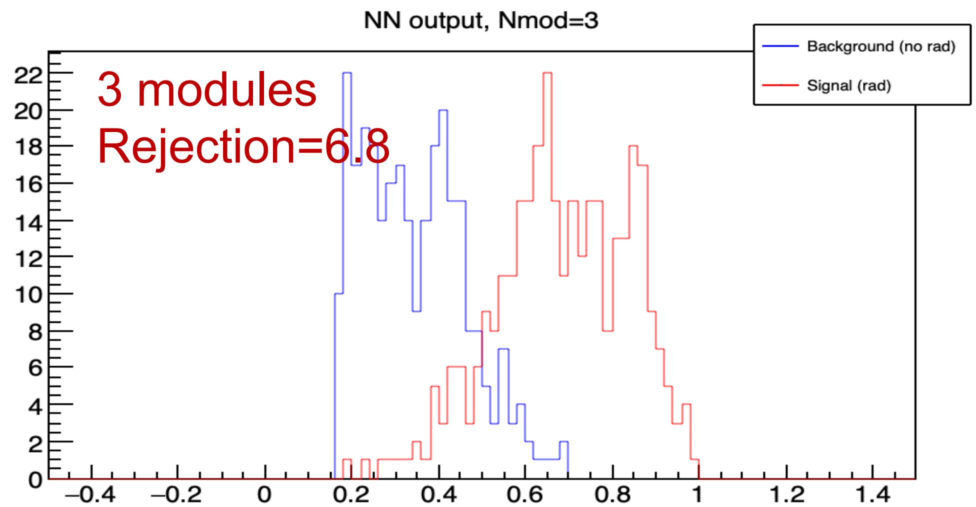
Neural network output for e/π identification



Machine learning in the data analysis



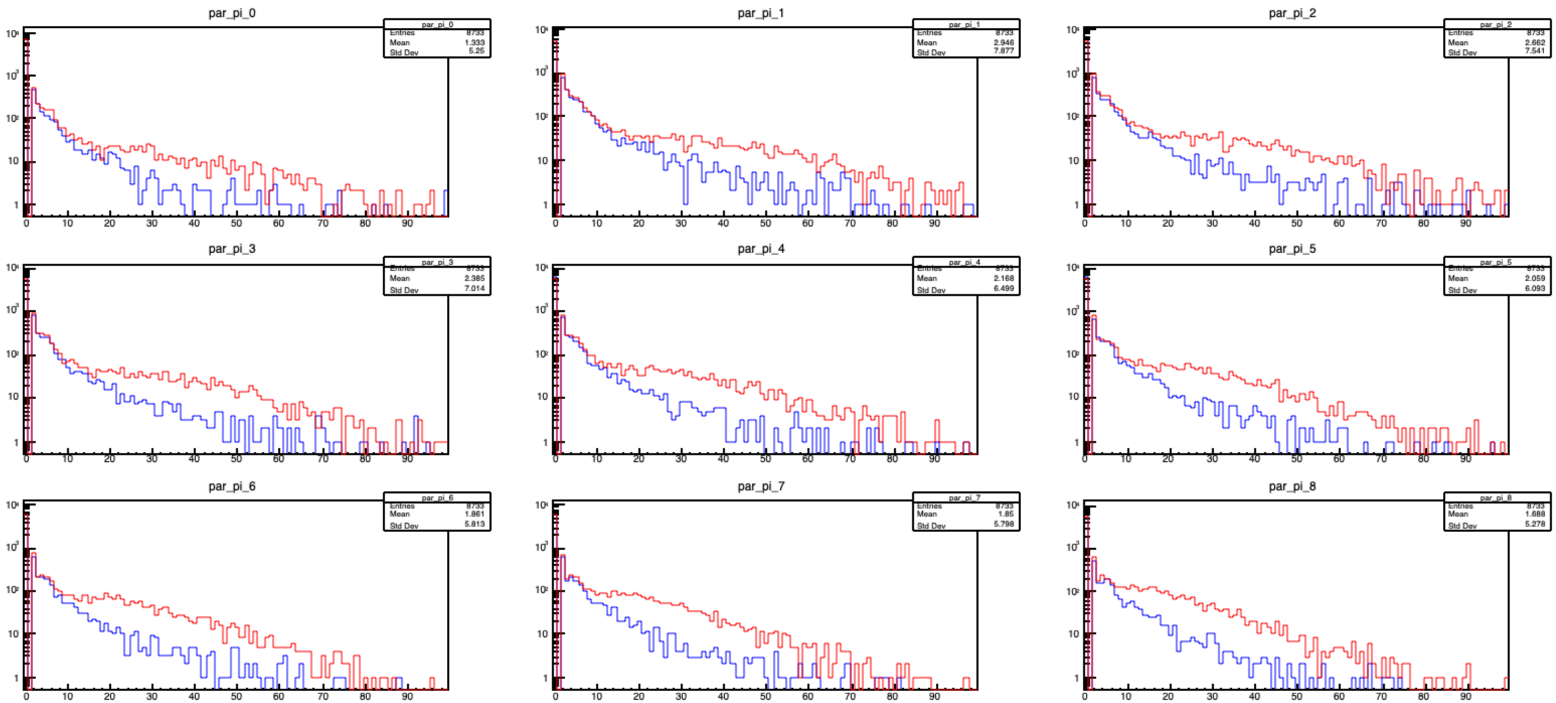


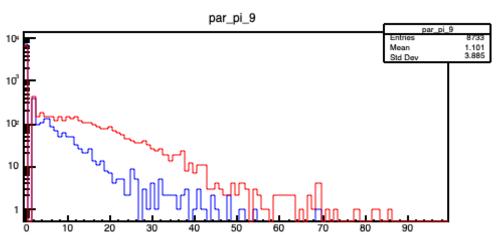


- For data analysis used the same method as for Monte Carlo
- All data was divided into 2 samples:
  - Training and test samples
- Top right plot shows neural network output for single module:
  - Red - electrons with radiator
  - Blue – electrons without radiator
- Bottom right plot is NN output extrapolated for 3 GEM-TRD modules.

NN input parameters distribution

Distribution of energy deposition in each of 10 time slices.

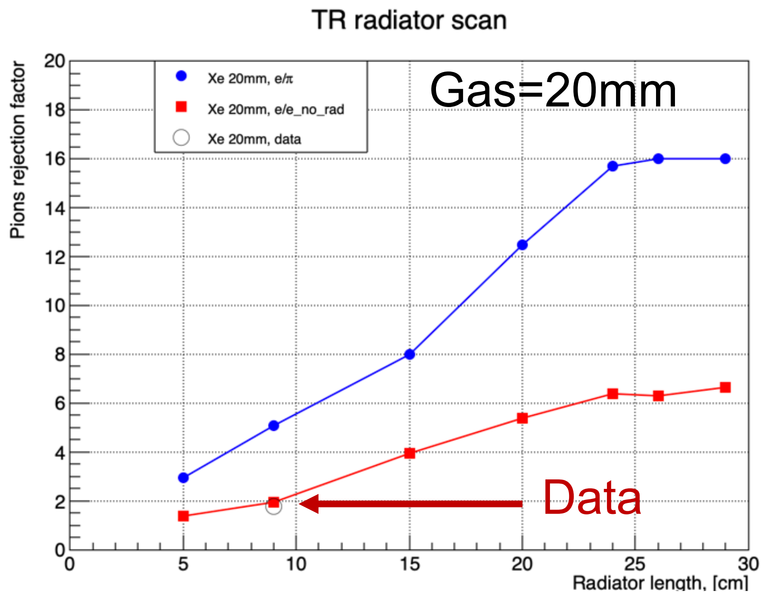


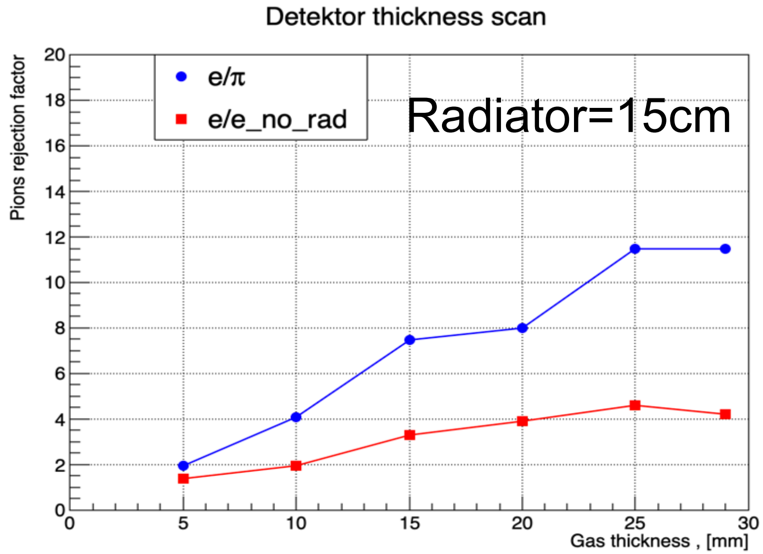


The last histogram represents the first time bin after entrance window with the most soft TR photons spectrum.

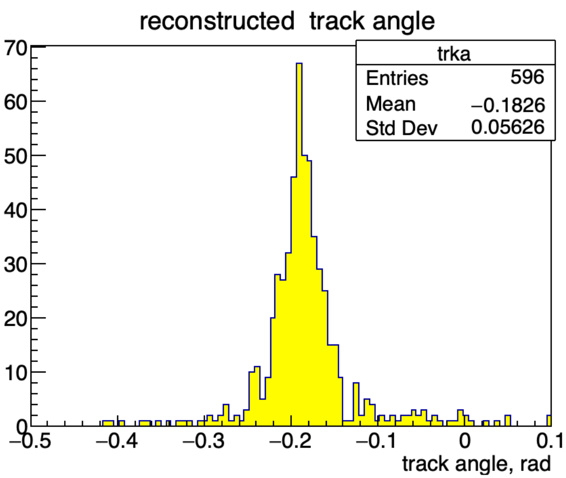
Comparison Data with MC

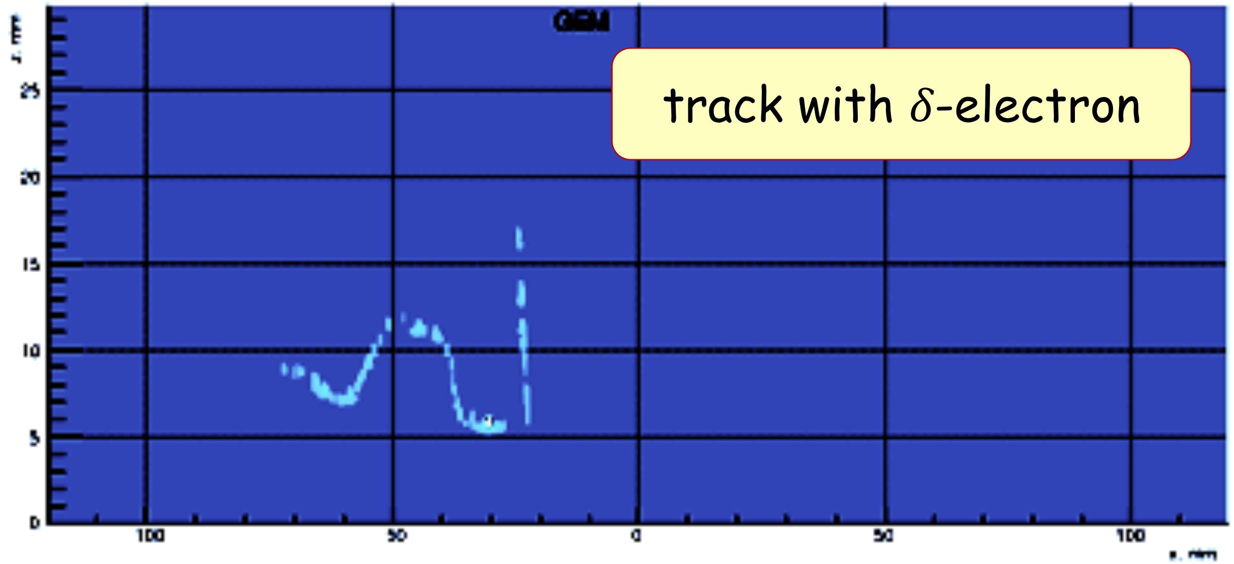
- GEM-TRD was tested with ~9cm radiator, and has ~21mm drift gap
- To understand how far the detector parameters are from the optimal, two Monte Carlo scan were performed:
  1. Fixed gas thickness at 20mm and radiator length varied from 5cm to 30cm
  2. Fixed radiator length at 15cm and gas thickness varied from 5mm to 30mm
- The data point was found in good agreement with Monte Carlo
- From MC scans one can predict:
  1. The current setup is able to separate e/π with pion rejection factor of ~5.5
  2. The detector gas thickness is optimal
  3. With radiator length of 25cm e/π rejection will be 16 for a single module.



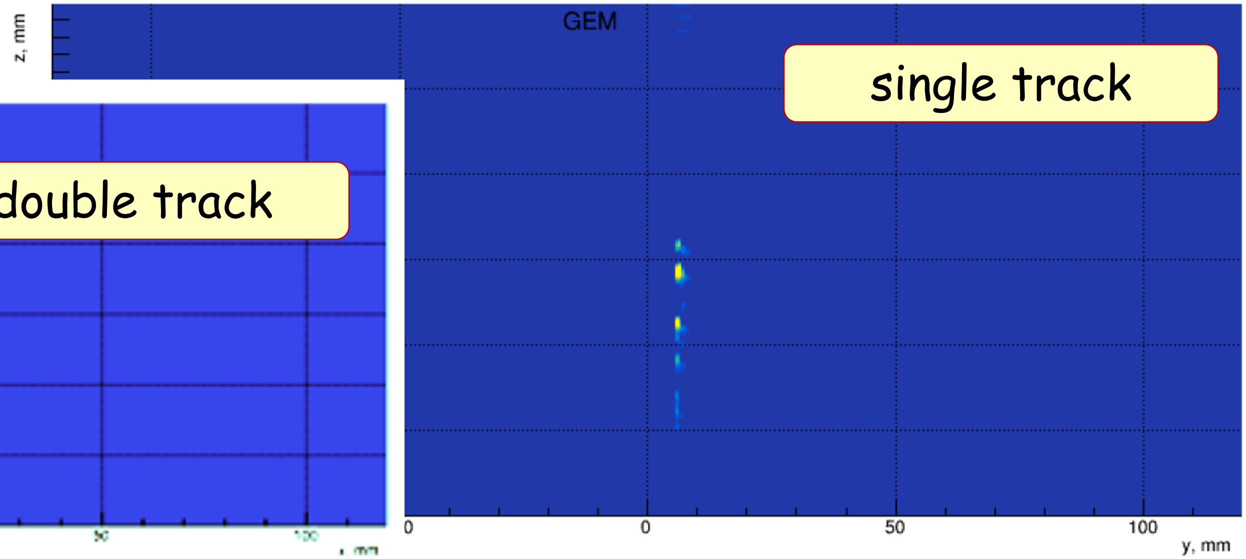


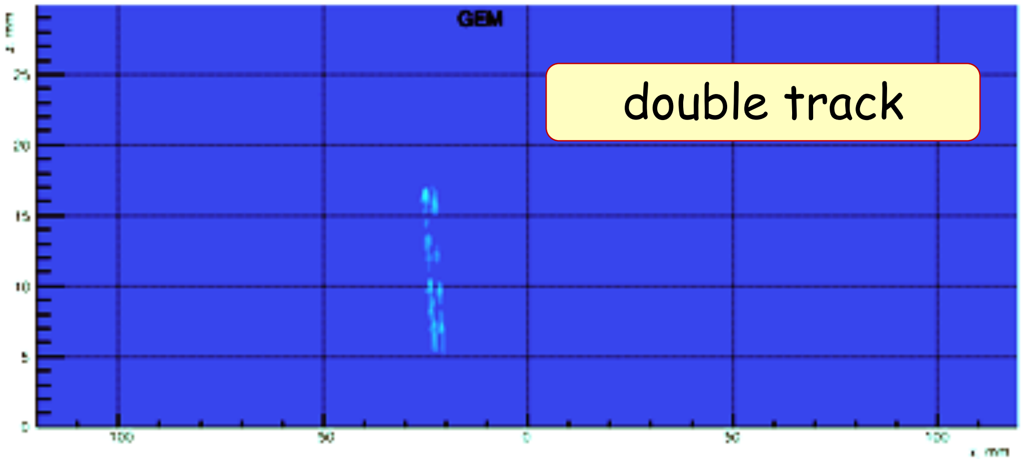
Tracking with GEM-TRD





GEM-TRD can work as mini TPC, providing 3D track segments





Discussion of results

- High granularity TRDs are interesting for modern physics with higher energy and luminosity and are actively developing at the present time.
- Our results in a good agreement with other high granularity TRD project (GasPixel + TimePix chip)
  - F. Hartjes et al. / Nuclear Instruments and Methods in Physics Research A 706 (2013) 59–64
- The advantage of GEM-TRD with a strip readout is the price
  - ➢ The price of electronics grows linearly with increasing detector size.
- Due to a large drift gap and FADC readout, GEM-TRD is able to reconstruct 3D track segments like mini TPC.
- Xenon gas mixture produces a higher ionization density on the track, which also improves tracking accuracy.

Summary

- Electron identification is very important for EIC physics. Due to a large hadron background expected in the forward (Hadron-endcap) region, a high granularity tracker combined with TRD functionality could provide additional electron identification - GEM-TRD/T

- GEANT4 simulation of GEM-TRD has been performed

- First test beam measurement has been performed and showed good agreement with MC simulation.

- e/π rejection factor of 5 can been achieved with a single module
  - can be up to 16 in case of using radiator with length of 25cm

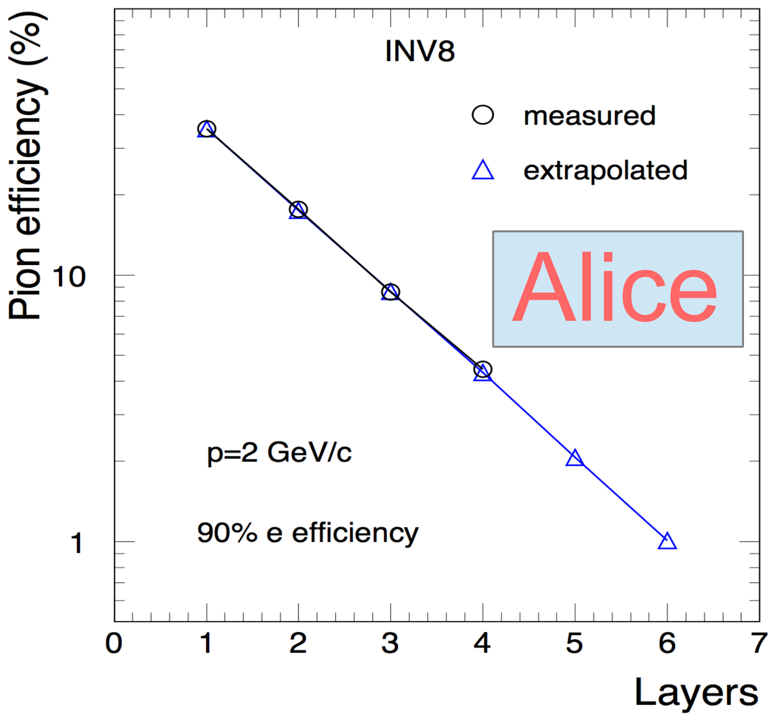
- GEM-TRD provides better tracking functionality, compared to the standard GEM tracker.

Thank you!

Backup slides

What rejection we can expect ?

- Performance of TRD can be parametrized as a function of a detector length.



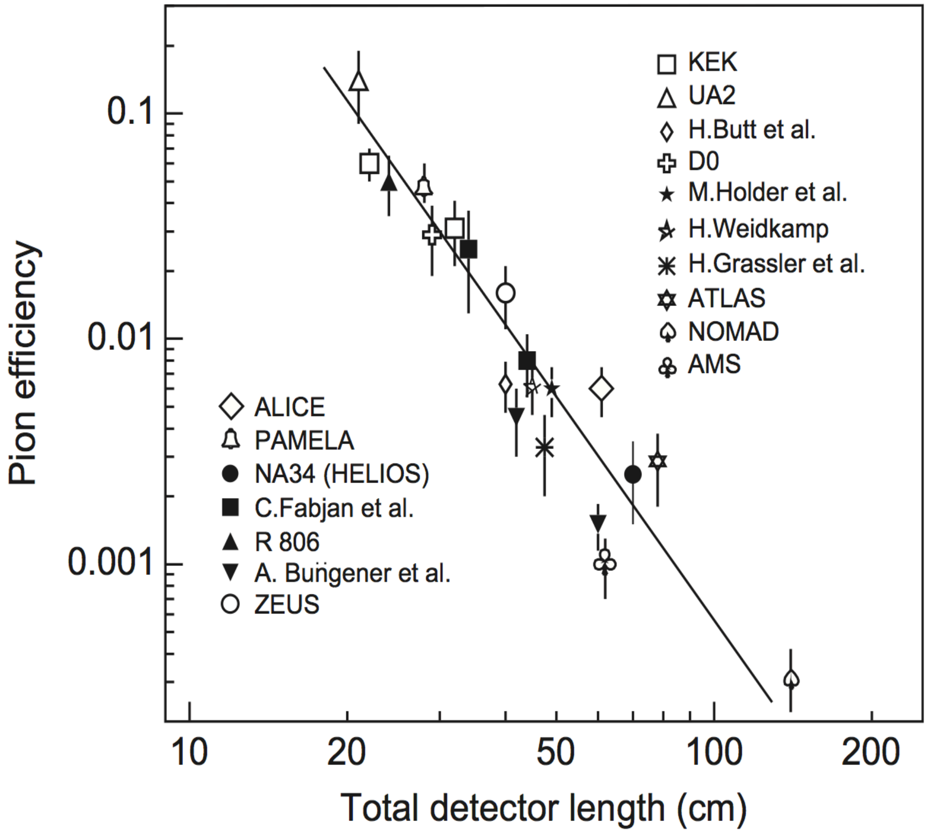


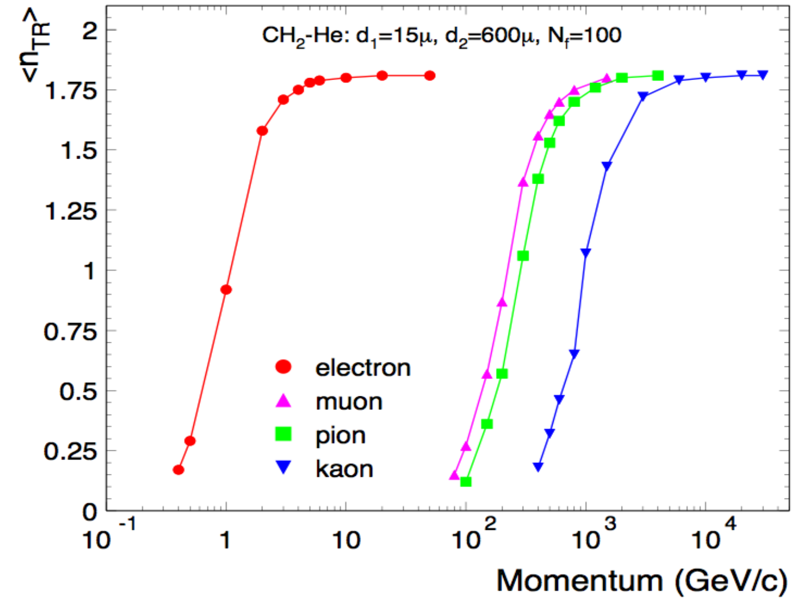
Fig. 11. TRD rejection power as a function of the total length of the detector for various high-energy (astro-)particle experiments (figure from [46]). The line is drawn to guide the eye.

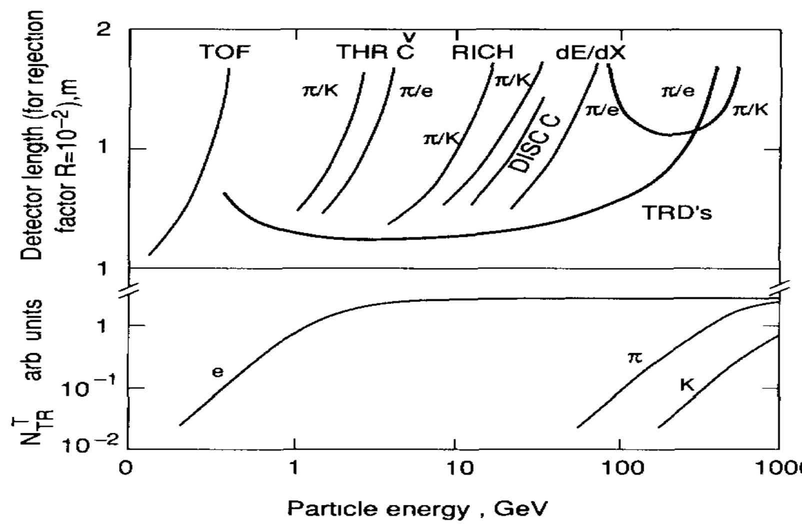
[46] K. Nakamura, et al., Particle Data Group, Journal of Physics G 37 (2010) 075021.

Motivation / detector

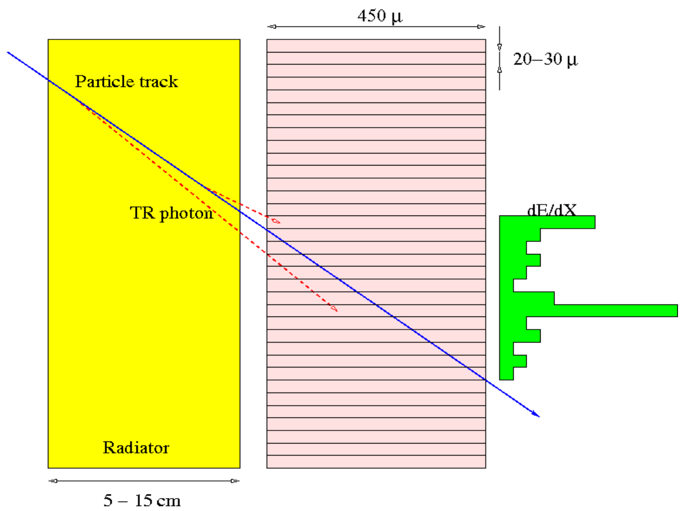
- Transition Radiation Detectors (TRD) has the attractive features of being able to separate particles by their gamma factor.
- e/π separation in high γ region, where other methods are not working anymore.
- Identification of the charged particle "on the flight": without scattering, deceleration or absorption.
- Application of TRD in physics experiments:

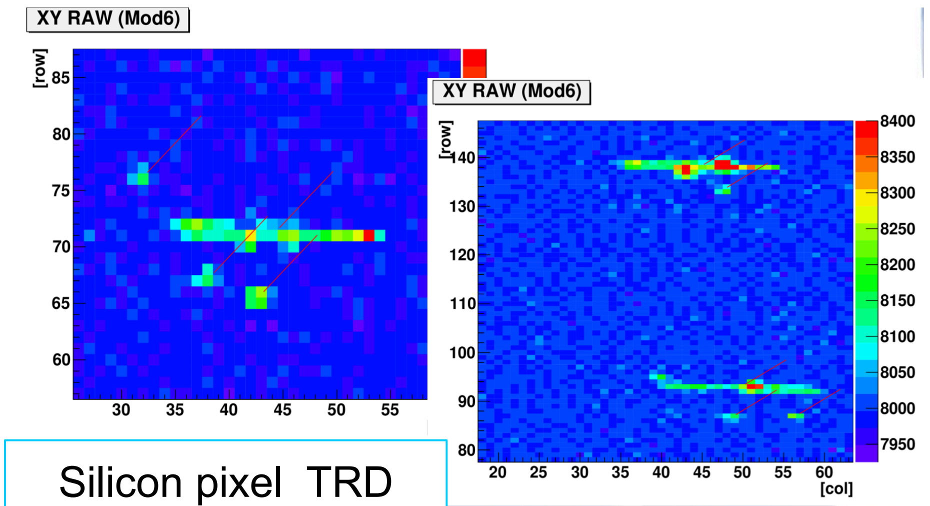
  ZEUS, H1, HERMES at HERA (DESY), D0, PHENIX, ATLAS, ALICE...
- TRD in space missions – AMS, PAMELA.



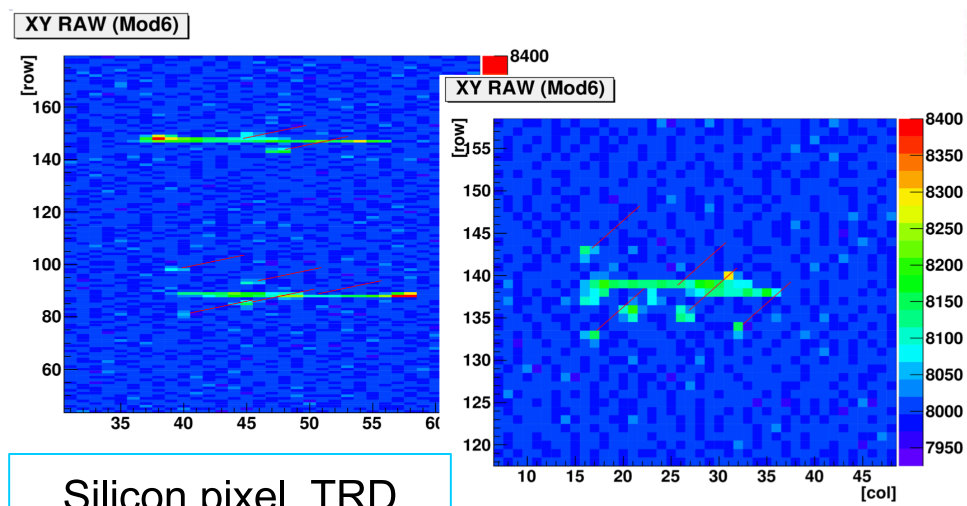


Silicon TR detection (DEPFET)





Silicon pixel TRD

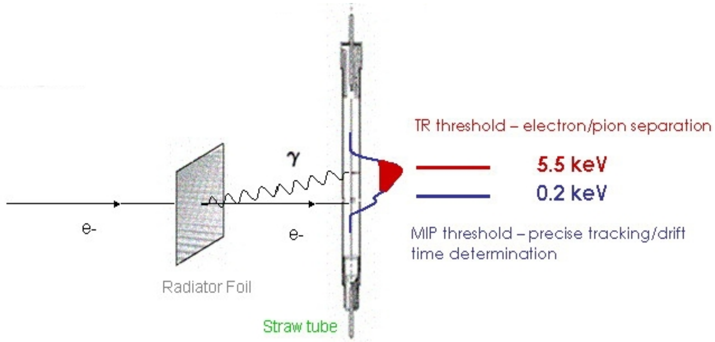


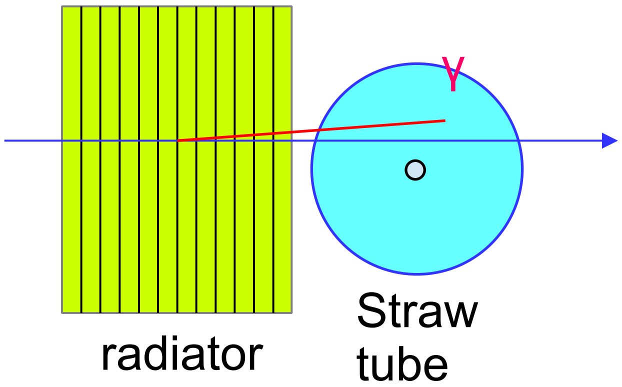
Silicon pixel TRD

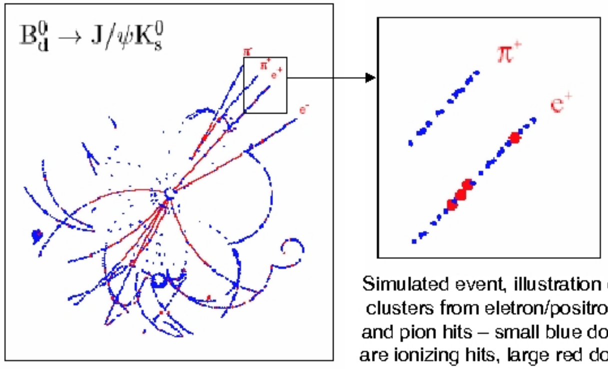
- Silicon pixel detector , 450 μ thick. (pixel size – 20x20μ)
- The electrons energy is 5 GeV (DESY testbeam)
- Radiator thickness 15 cm (fleece)
- TR photons are clearly visible and separated from track by a few pixels !
  - red lines shows the center of found TR clusters

TRD principle : ATLAS

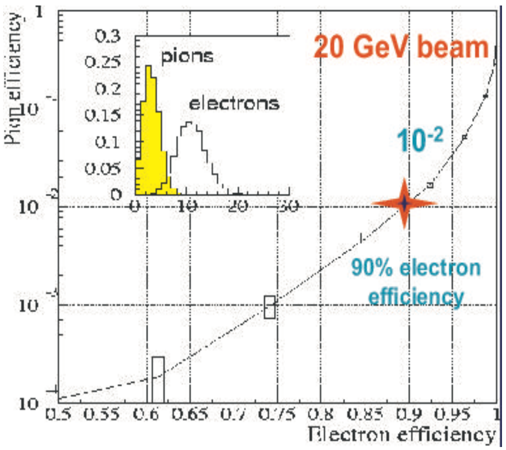
- Typically in high energy physics TRD are used for electron identification and to reject hadron background.
- ATLAS TRT uses proportional gas chambers (straws) filled with Xenon gas mixture:
  - dE/dx +TR, Cluster discrimination by threshold method.







Simulated event, illustration of clusters from eletron/positron and pion hits – small blue dots are ionizing hits, large red dots are TR hits



TRD in experiments

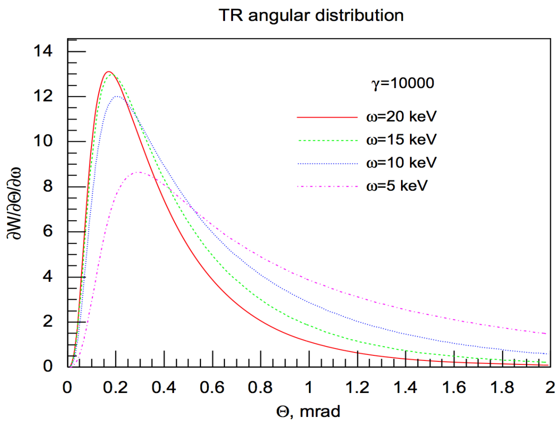
Experiment	Radiator (x,cm)	Detector (x,cm)	Area (m^2)	N	L (cm)	N. chan.	Method	π_{rej}
HELIOS	foils (7)	Xe-C_4H_{10} (1.8)	0.5	8	70	1744	N	2000
H1	foils (9.6)	Xe-He-C_2H_6 (6)	1.8	3	60	1728	FADC	10
NA31	foils (21.7)	Xe-He-CH_4 (5)	4.5	4	96	384	Q	70
ZEUS	fibres (7)	Xe-He-CH_4 (2.2)	3	4	40	2112	FADC	100
D0	foils (6.5)	Xe-CH_4 (2.3)	3.7	3	33	1536	FADC	50
NOMAD	foils (8.3)	Xe-CO_2 (1.6)	8.1	9	150	1584	Q	1000
HERMES	fibres (6.4)	Xe-CH_4 (2.54)	4.7	6	60	3072	Q	1400
kTeV	fibres (12)	Xe-CO_2 (2.9)	4.9	8	144	~10 k	Q	250
PAMELA	fibres (1.5)	Xe-CO_2 (0.4)	0.08	9	28	964	Q,N	50
AMS	fibres (2)	Xe-CO_2 (0.6)	1.5	20	55	5248	Q	1000
PHENIX	fibres (5)	Xe-CH_4 (1.8)	~~50~~	~~6~~	~~4~~	~~43 k~~	~~FADC~~	~~~300~~
ATLAS	fo/fi (0.8)	Xe-CF_4-CO_2 (0.4)	31	36	51-108	425 k	N,ToT	100
ALICE	fi/foam (4.8)	Xe-CO_2(3.7)	**126**	6	52	**1.2 mil.**	FADC	200

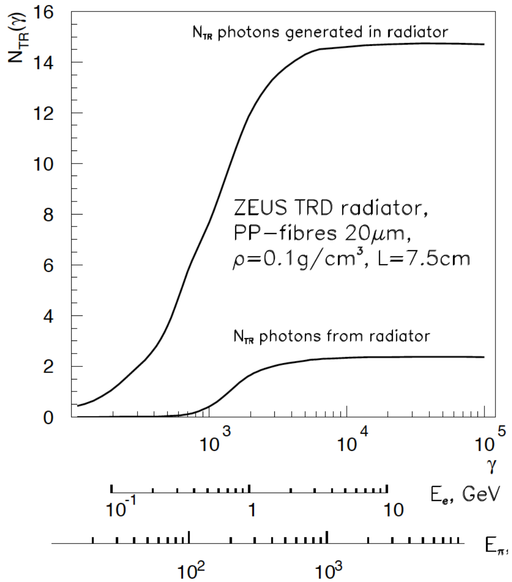
?

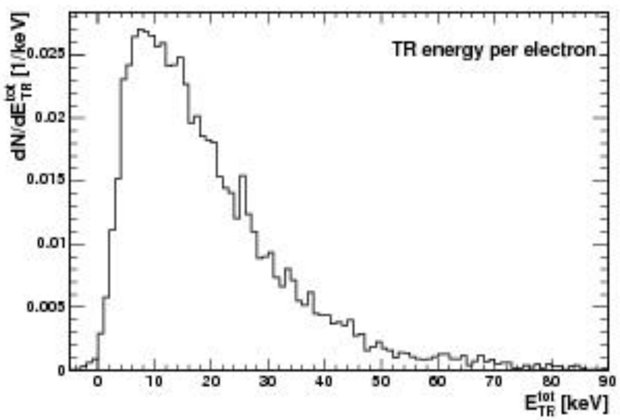
all radiator material CH_2

TR features

- X-ray TR has remarkable features:
- TR in X-ray region is extremely forward peaked within an angle of 1/γ
- Energy of TR photons are in X-ray region (2 - 40 keV)
- Total TR Energy ETR is proportional to the γ factor of the charged particle







e/e efficiency with radiator vs without rad.