Transition Radiation Detectors: recent developments and outlooks

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42nd INFN ELOISATRON Workshop:
innovative detectors for super colliders

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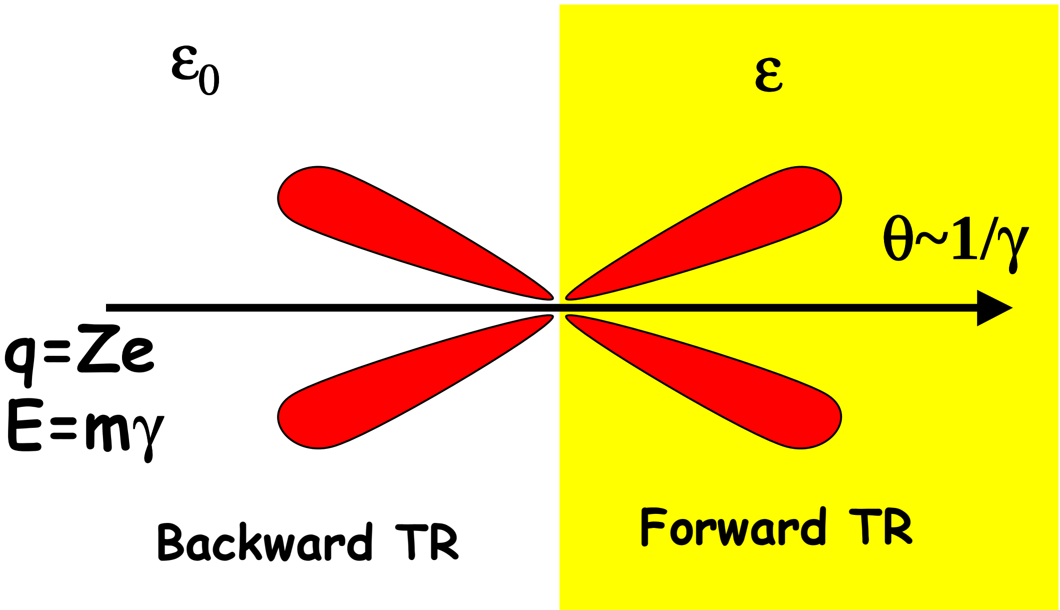
Summary

- Transition Radiation process
- Transition Radiation yield
- Signal processing
- Last generation TRDs for accelerators
- TRDs to tag high energy hadron beams
- R&D on novel TRDs
- Conclusions

Transition radiation (TR) at the interface of two different media



X-ray region

$\varepsilon \approx 1-(\omega_p/\omega)^2$

$\omega_p(eV) \approx 28.8(\rho(g/cm^2)Z/A)^{\frac{1}{2}}$

$\omega_p \approx 20$ eV

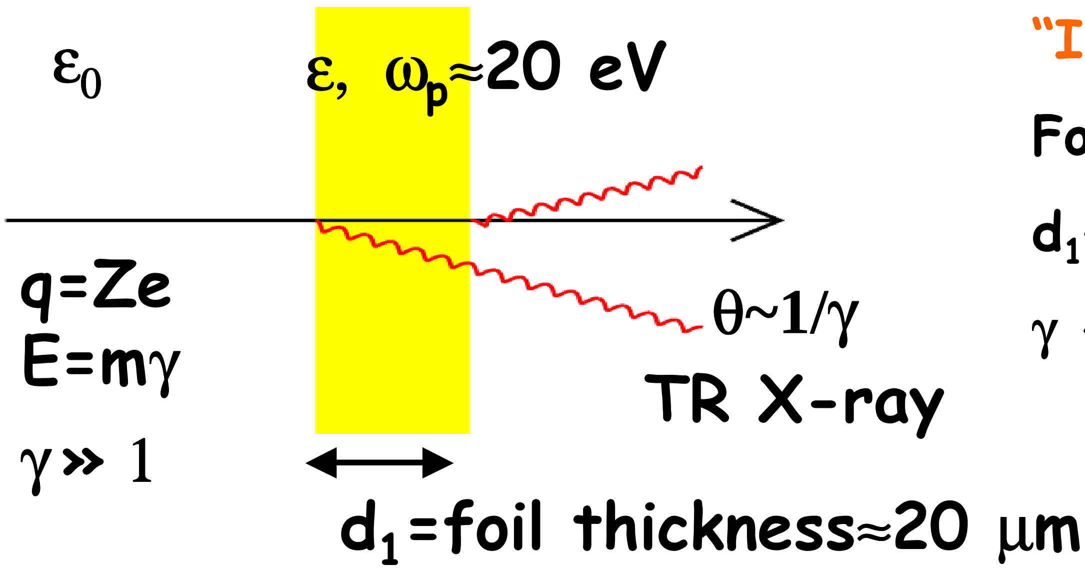
$\gamma \gg 1$

No Backward TR

Total TR energy $\approx 1/3\ \alpha\ Z^2\ \omega_p\ \gamma$

Number of X-rays/interface $\sim \alpha\ Z^2$

TR from a single foil



"Interference" effects:

Formation zone (z)

$d_1 \ll z \Rightarrow$ yield = 0

$\gamma < \gamma_{th} \Rightarrow$ yield = 0

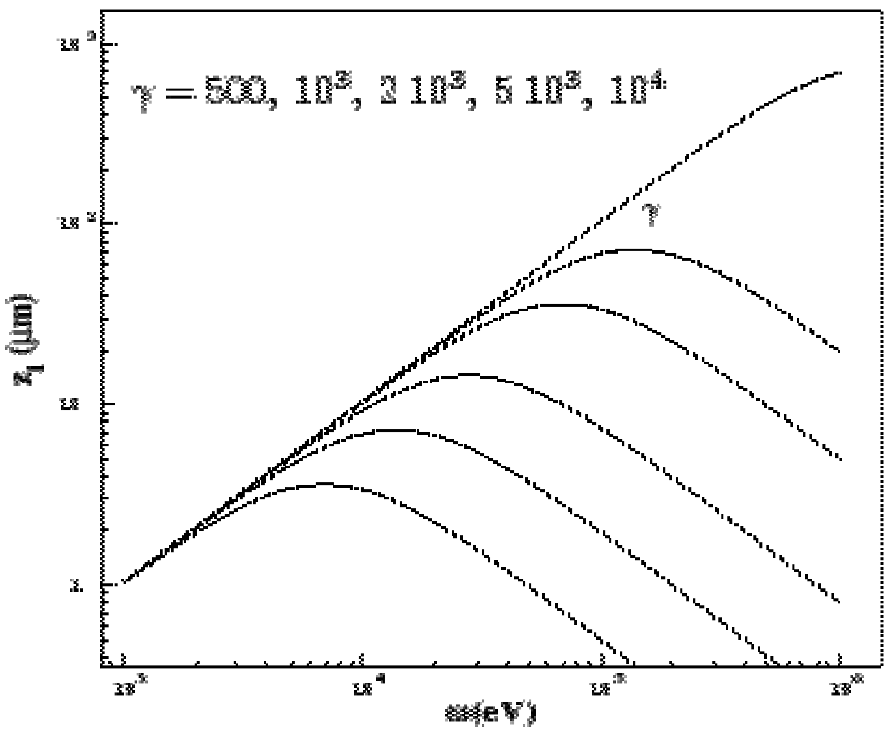
$\gamma_{th} = 2.5\, d_1(\mu m)\, \omega_p(eV) \sim 1000$

$\langle E_X \rangle \approx 0.3\, \omega_p\, \gamma_{th} \sim 10$ keV

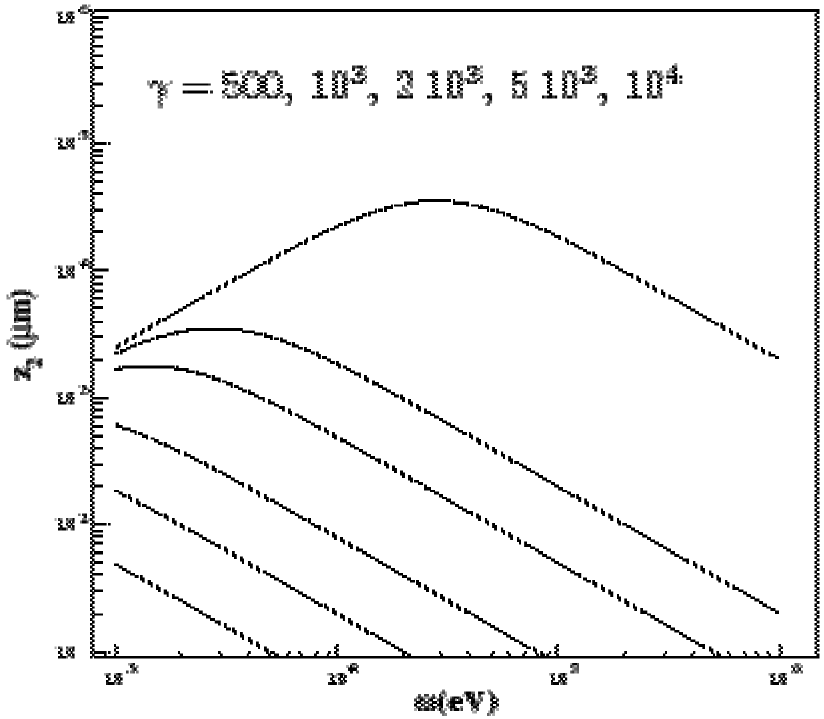
Number of X-rays $\approx \alpha Z^2$

Formation zone

$$Z = \frac{2}{\omega(1/\gamma^2 + (\omega_p/\omega)^2)}$$



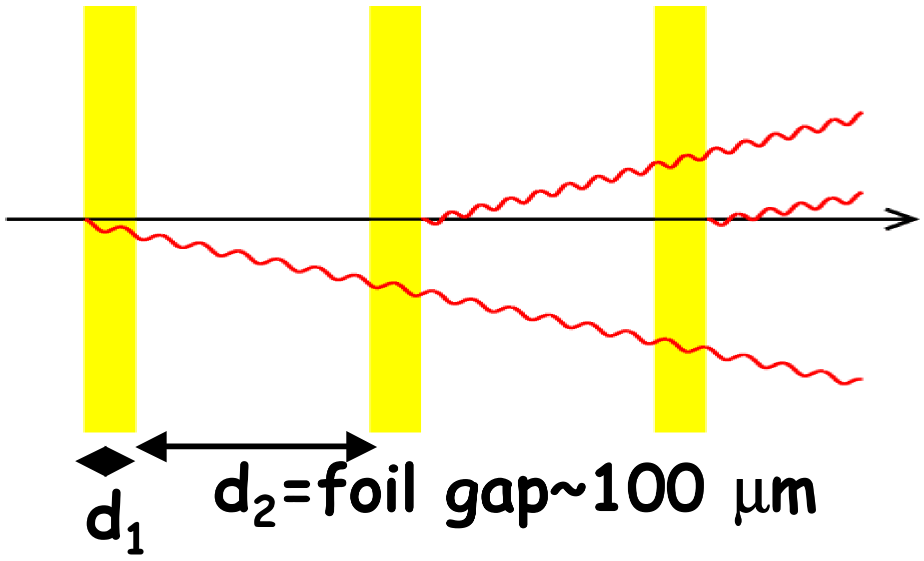
Polyethylene



Air

TR from a "multi-foil" radiator

N_{foil} = Number of foils ~100 up to ~ 1000



Interference effects:

gap formation zone

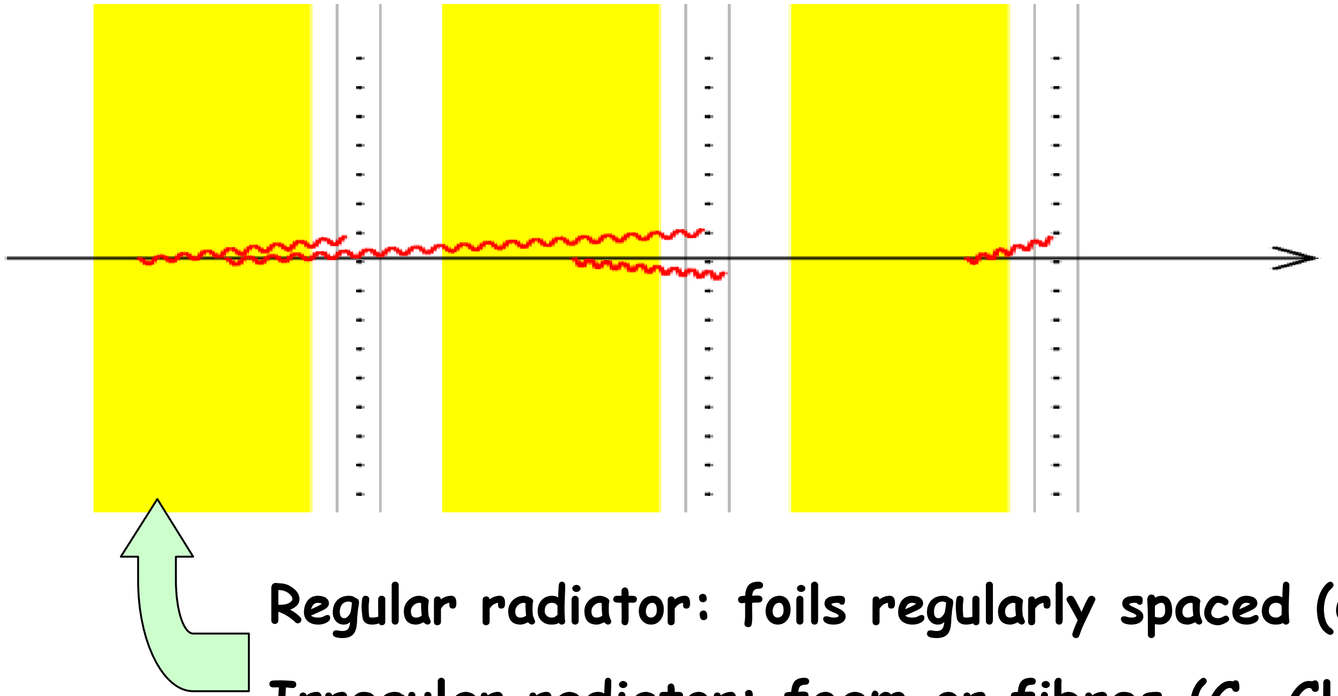
Saturation $\gamma > \gamma_{sat}$

$\gamma_{sat} \sim \gamma_{th} (d_2/d_1)^{\frac{1}{2}} \sim 10^4$ up to $\sim 10^5$

Number of X-rays $\sim \alpha Z^2 N_{foil} \sim Z^2$

Transition Radiator Detector (TRD)

X-ray detectors: MWPCs, Drift chambers,Straw tubes (Xe-CO_2)

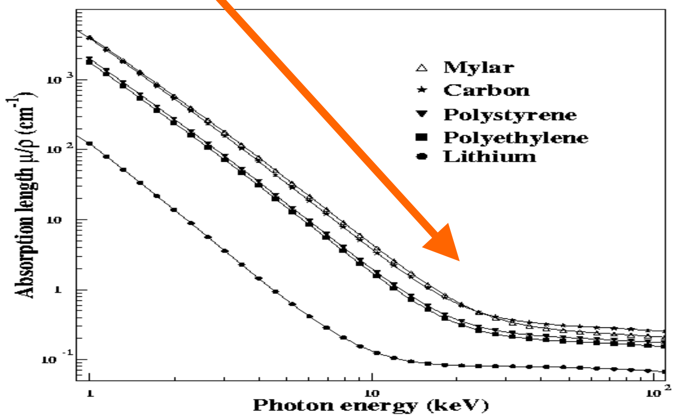


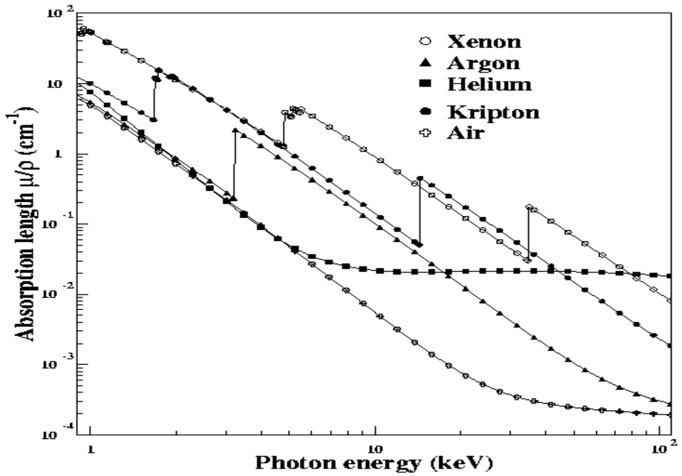
Regular radiator: foils regularly spaced (CH_2,Mylar)

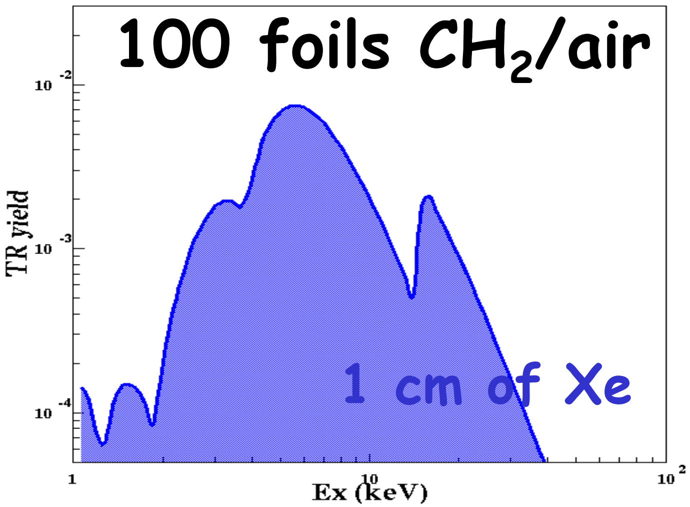
Irregular radiator: foam or fibres (C, CH_2)

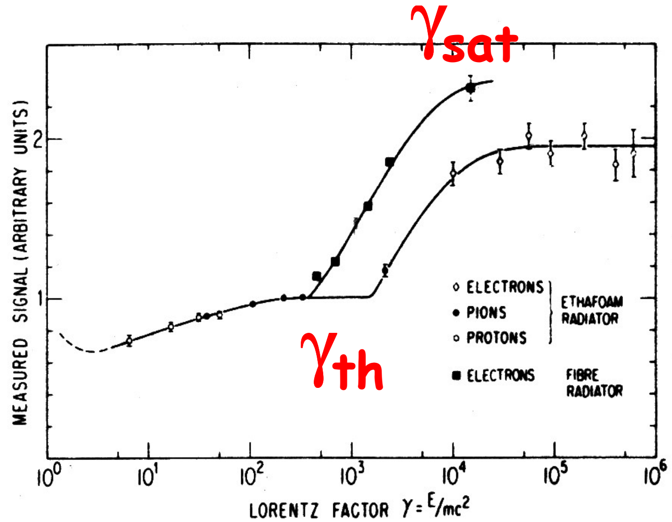
TR energy yield

Compton edge





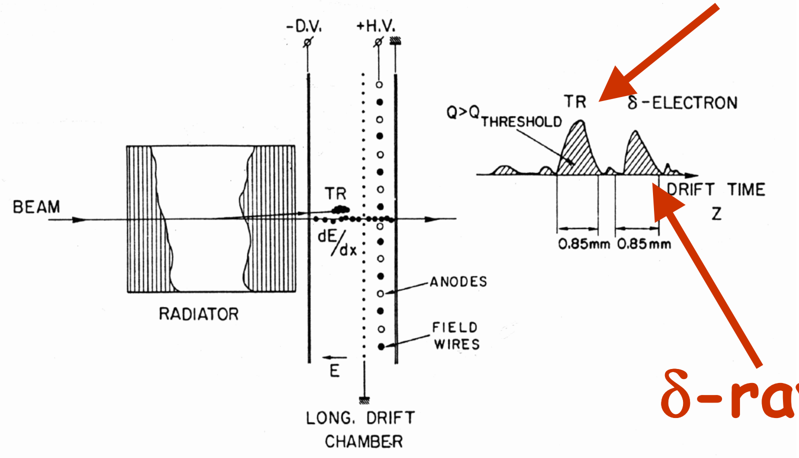




TRD Signal processing

Background:
incident particle
ionization loss

TR X-ray



δ-ray

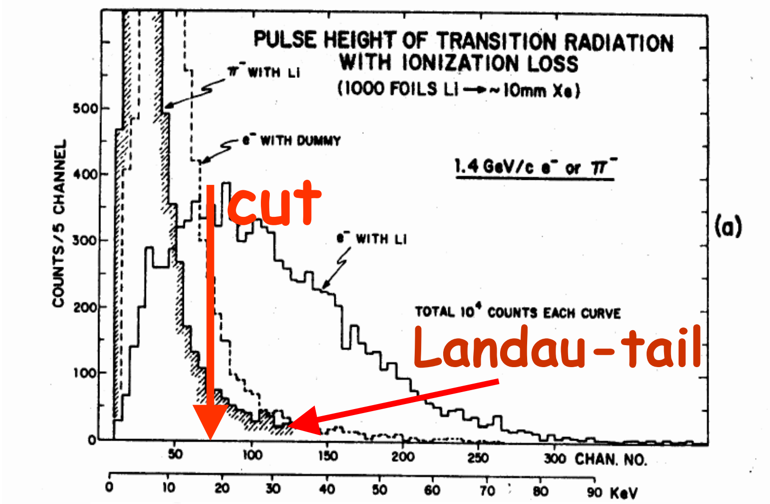
Q-method: charge analysis

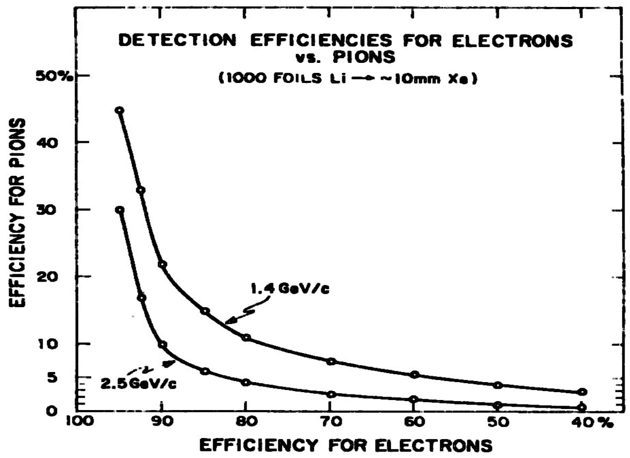
N-method: cluster-counting

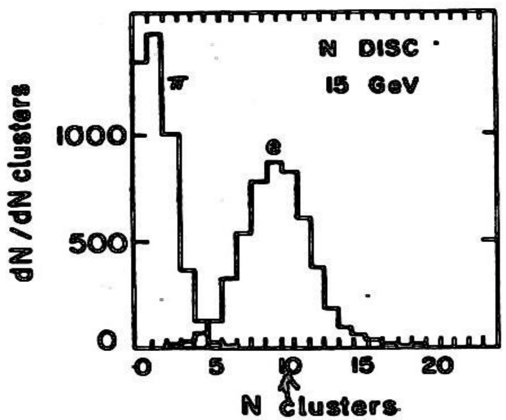
Electronics and detector geometry

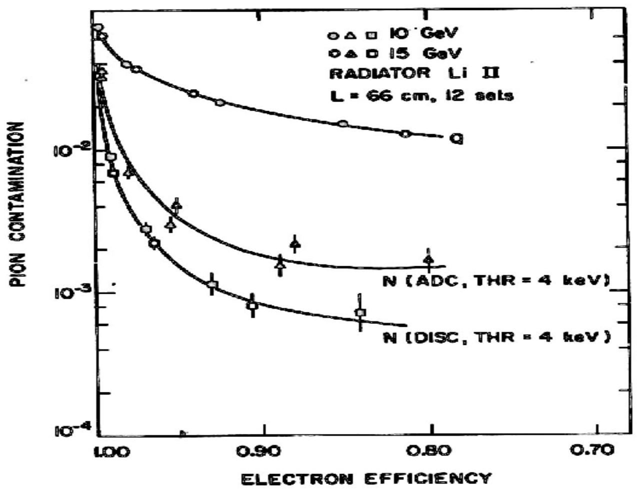
Off-line: likelihood or truncated mean (Q) methods

Q-method vs N-method







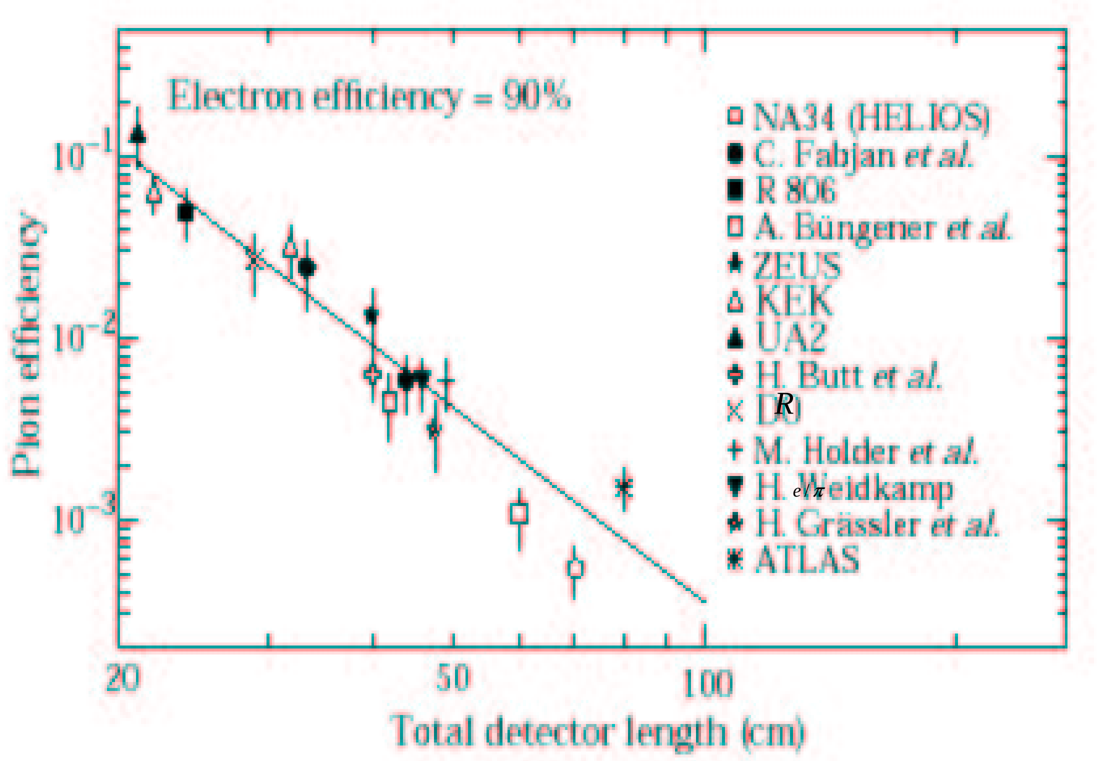


Rejection

Power

$R_{\pi/e} = \varepsilon_{\pi}/\varepsilon_{e}(90\%)$

TRD performance vs length



Rejection Power

$R_{\pi/e} = \varepsilon_\pi / \varepsilon_e(90\%)$

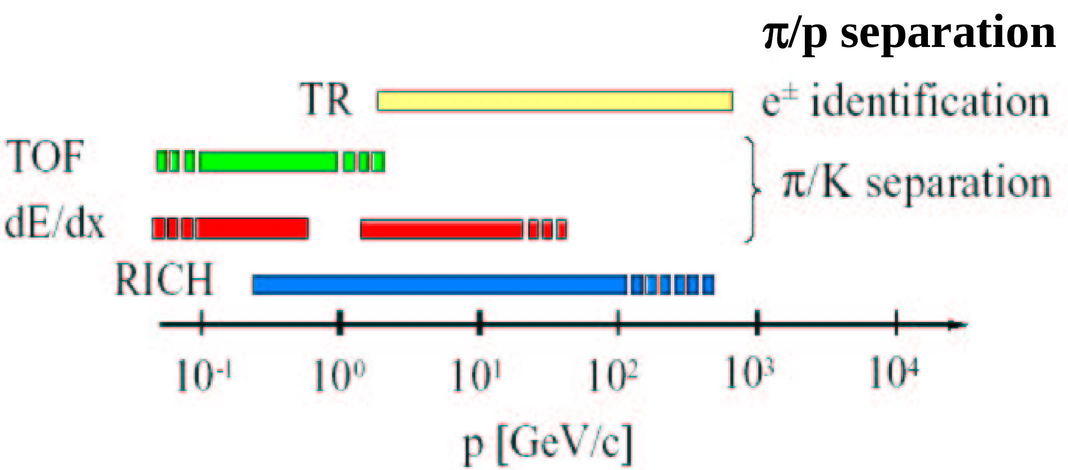
one order of magnitude in Rejection Power is gained when the TRD length is increased by ~ 20 cm

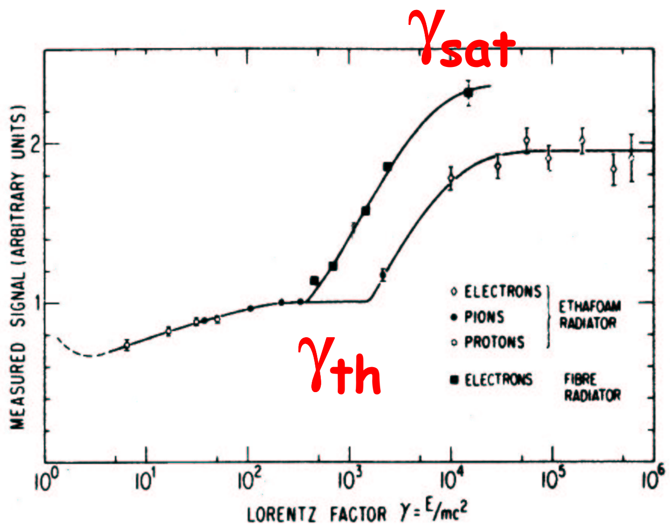
TRD applications

Particle ID: is based on the threshold properties of the TR

Energy measurement: if the mass is known, the energy can be evaluated only in the limited range between γ_{th} and γ_{sat}, and above γ_{sat} (below γ_{th}) it is possible only to set a lower (higher) limit

Charge measurement: charge identification of high energy nuclei in particle astrophysics





"TRDs for the 3rd millennium"

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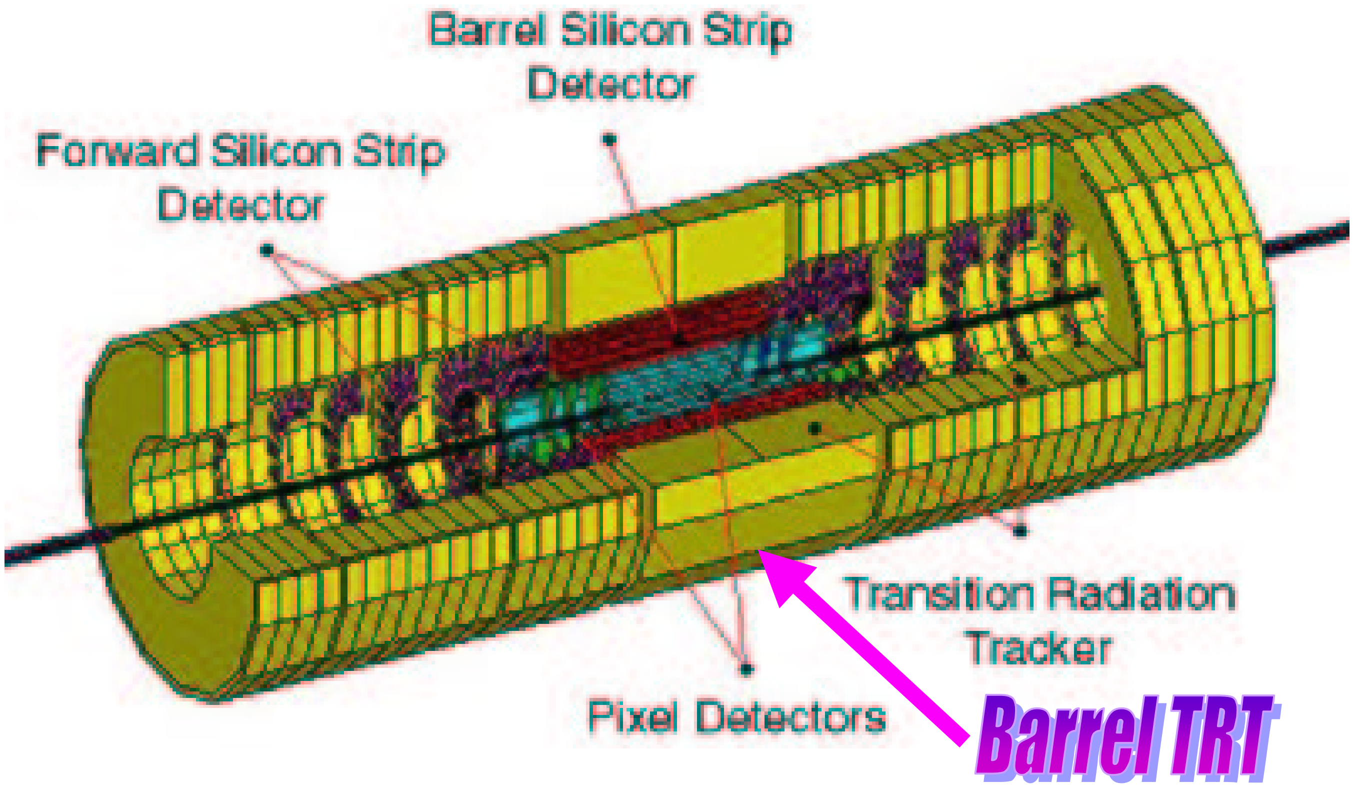
Last generation TRDs for new accelerators

- ATLAS @ LHC: $\varepsilon_\pi \sim 10^{-3}$-$10^{-2}$ @ $\varepsilon_e \sim 90\%$

- ALICE @ LHC: $\varepsilon_\pi \sim 10^{-3}$ @ $\varepsilon_e \sim 90\%$

- PHENIX @ RHIC: $\varepsilon_\pi \sim 10^{-3}$ @ $\varepsilon_e \sim 90\%$



TRT Design Parameters

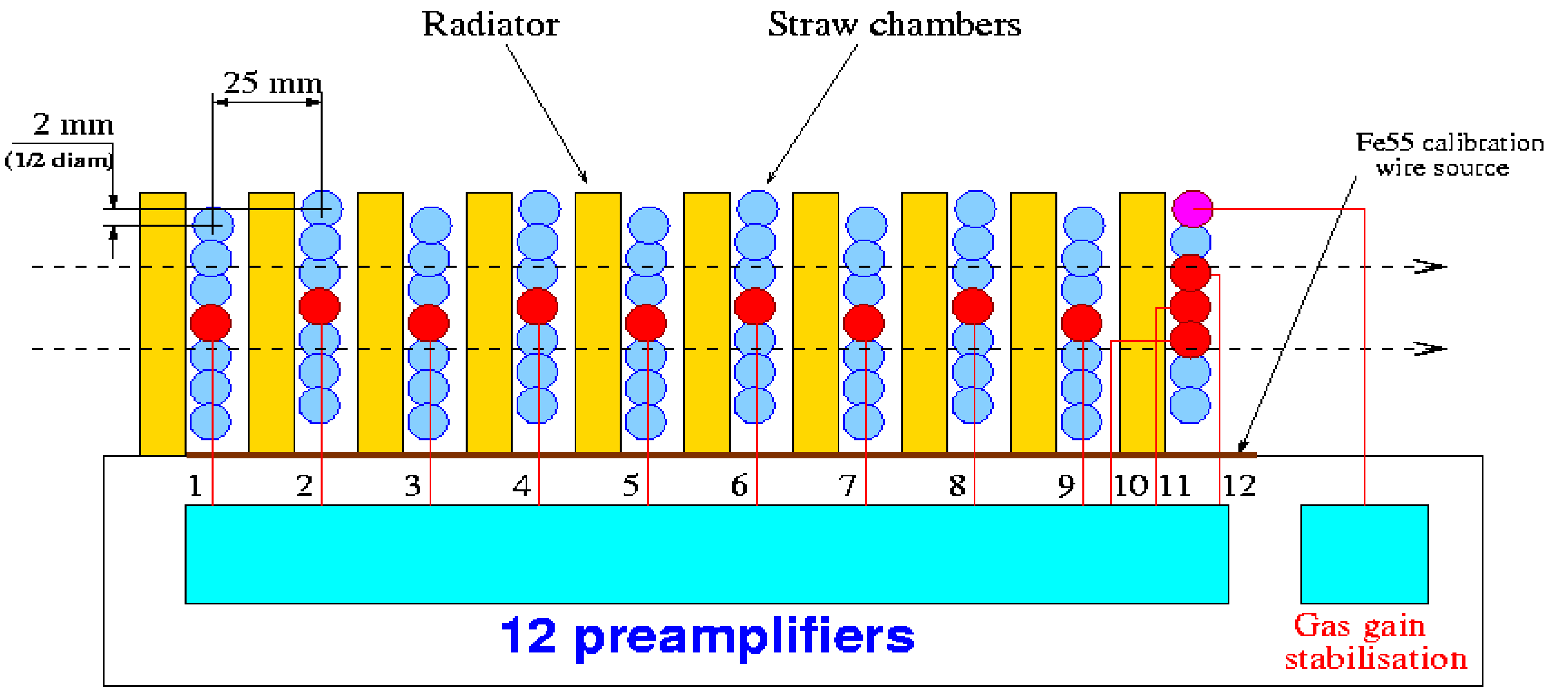
- **Straw based tracking chamber with TR capability for electron identification.**
- **Straws run in parallel to beam line.**
- **Active gas is $Xe/CO_2/O_2$ (70/27/3) operated at ~$2x10^4$ gas gain; drift time ~ 40ns (fast!)**
- **Counting rate ~ 6-18 MHz at LHC design luminosity 10^{34} $cm^{-2}s^{-1}$**

Chiho Wang
Duke University

TRD 2003
4-7 September 2003, Bari, Italy

Radiator prototype

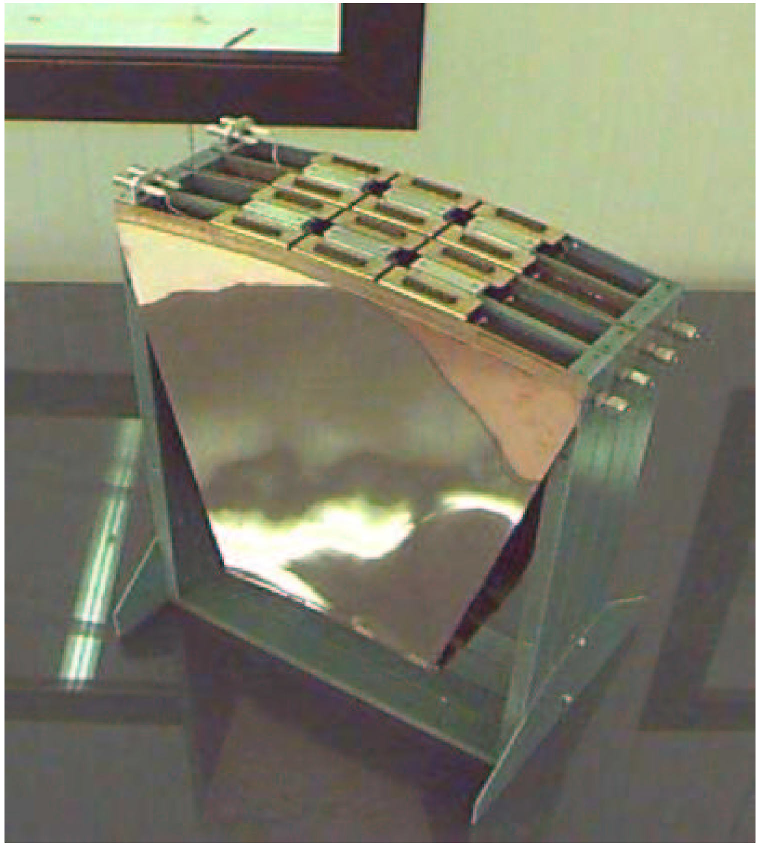
TRT prototype for radiator and dE/dx studies



Goals: precise measurement of *dE/dx* and TR spectra; different radiators performance study; comparison with MC predictions.

(V.Tikhomirov. ATLAS TRT test beam results. 4 September 2003, Bari, Italy.)

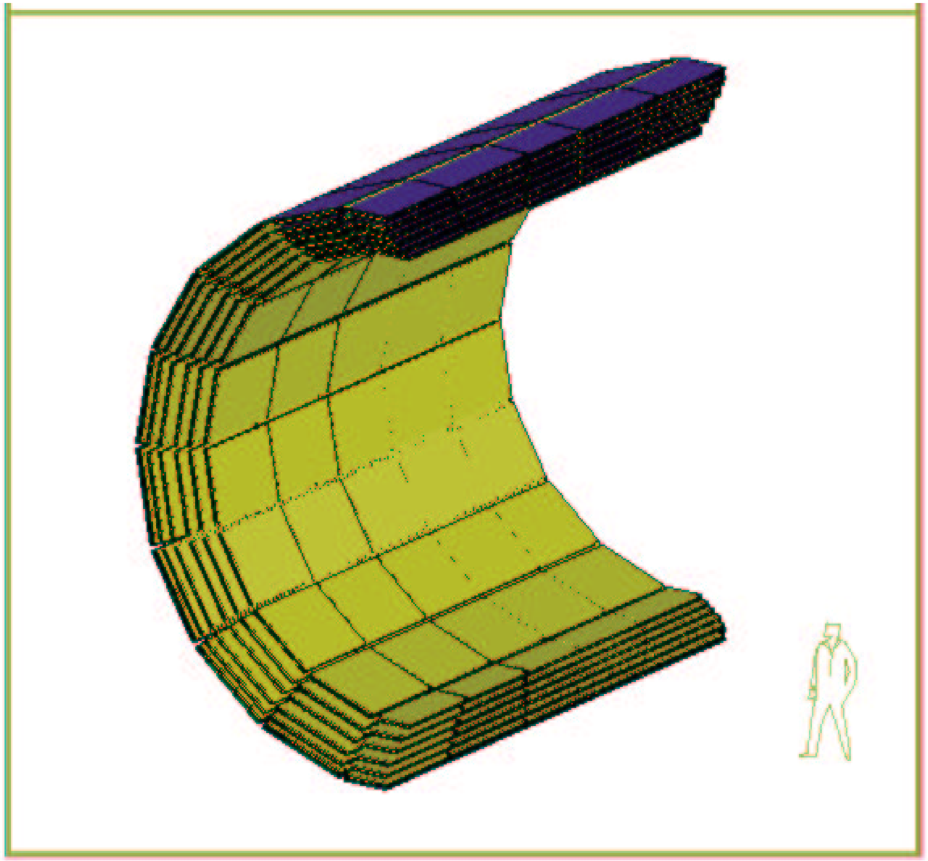
Sector prototype

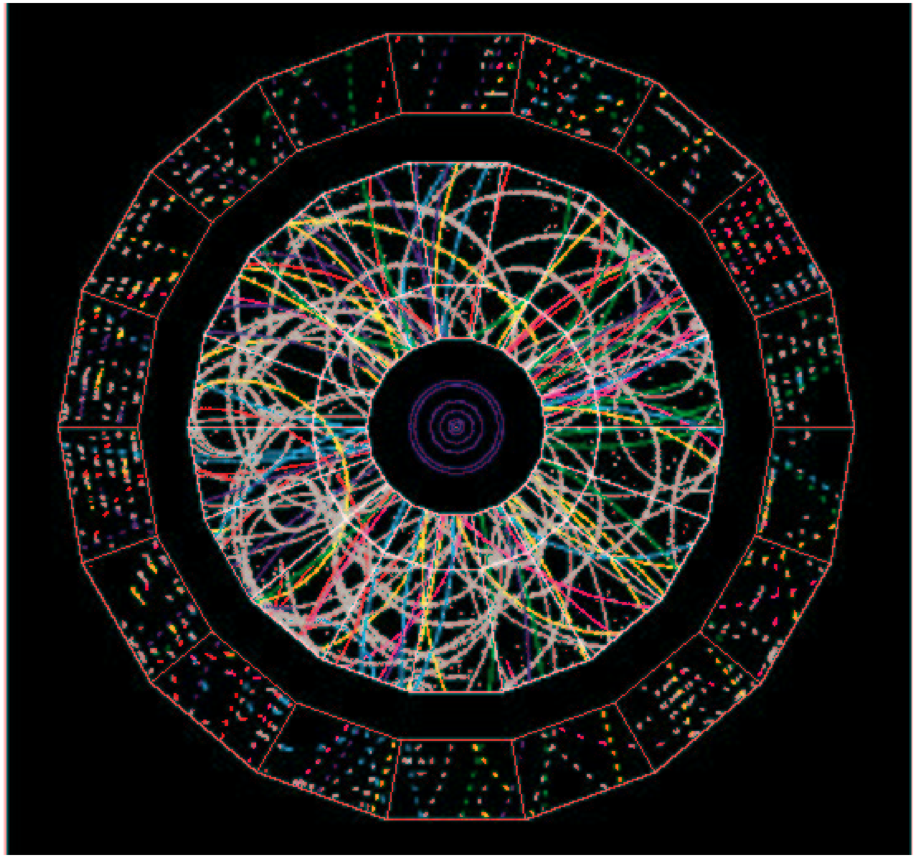


- Sector of ATLAS TRT end cap
- 384 straws, 16 layers on beam direction
- 4 mm straw diameter
- Regular radiator: 15 μm polyethylene foils with 200 μm spacing
- 70% Xe + 20% CF_4 + 10% CO_2 gas mixture (70% Xe + 27% CO_2 + 3%O_2 since 2002)
- 2.5 $\cdot 10^4$ nominal gas gain
- LHC type electronics

(V.Tikhomirov. ATLAS TRT test beam results. 4 September 2003, Bari, Italy.)

ALICE TRD @ LHC

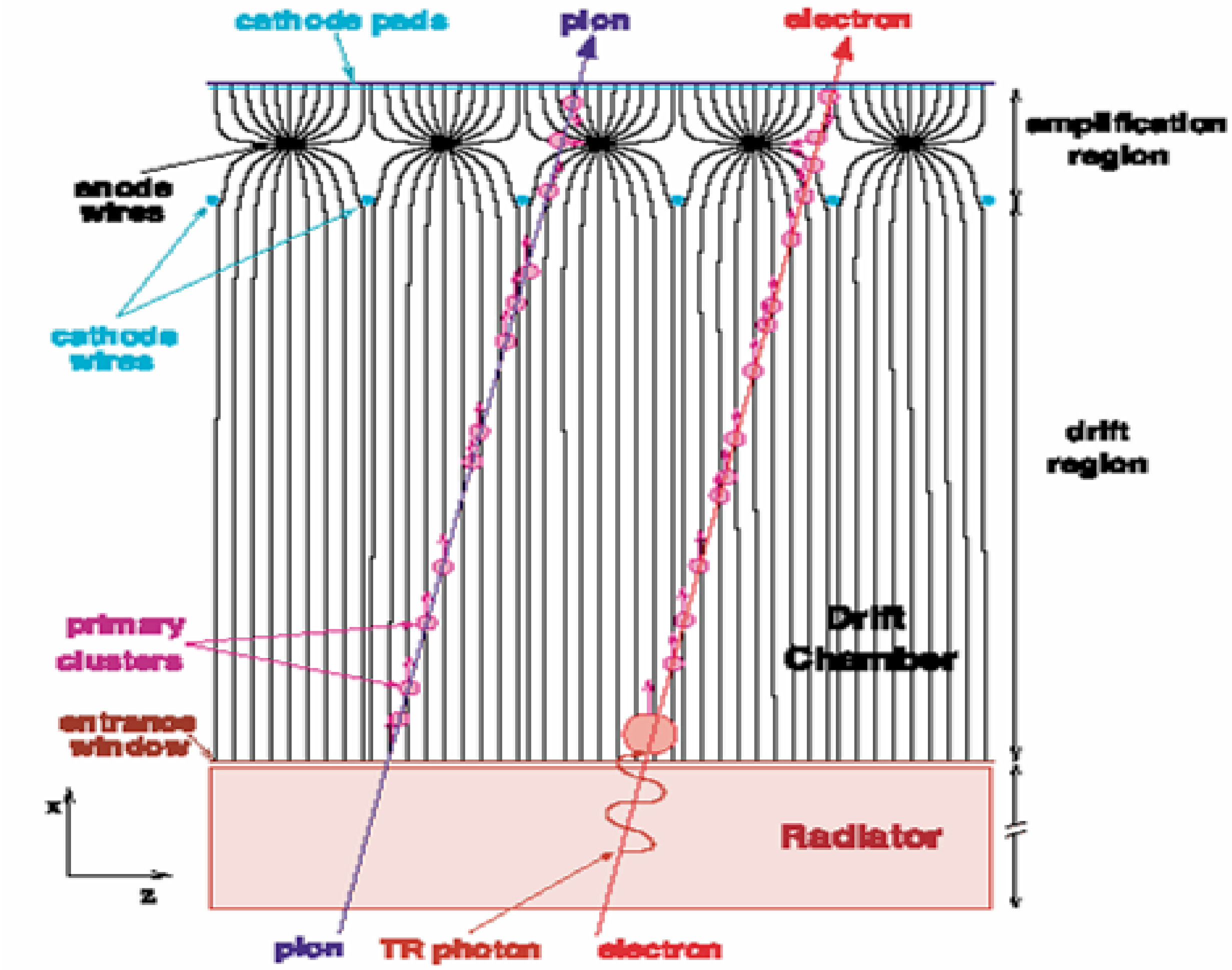




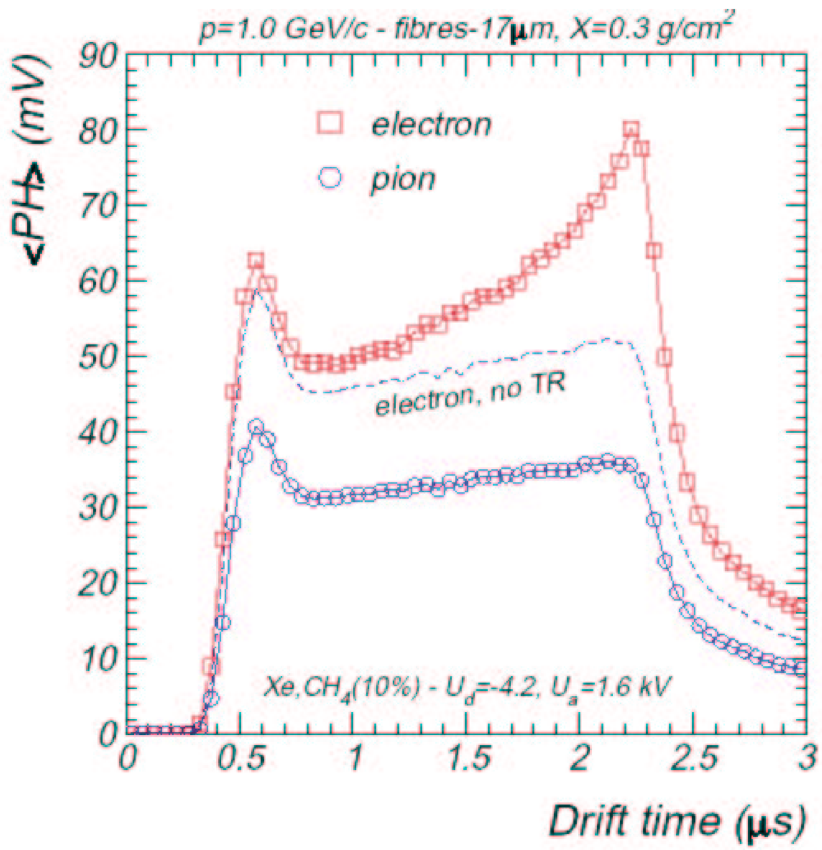
Carbon-polypropylene fibers/TEC (Xe-CO_2) with pad read-out,
e/π identification, tracking and triggering

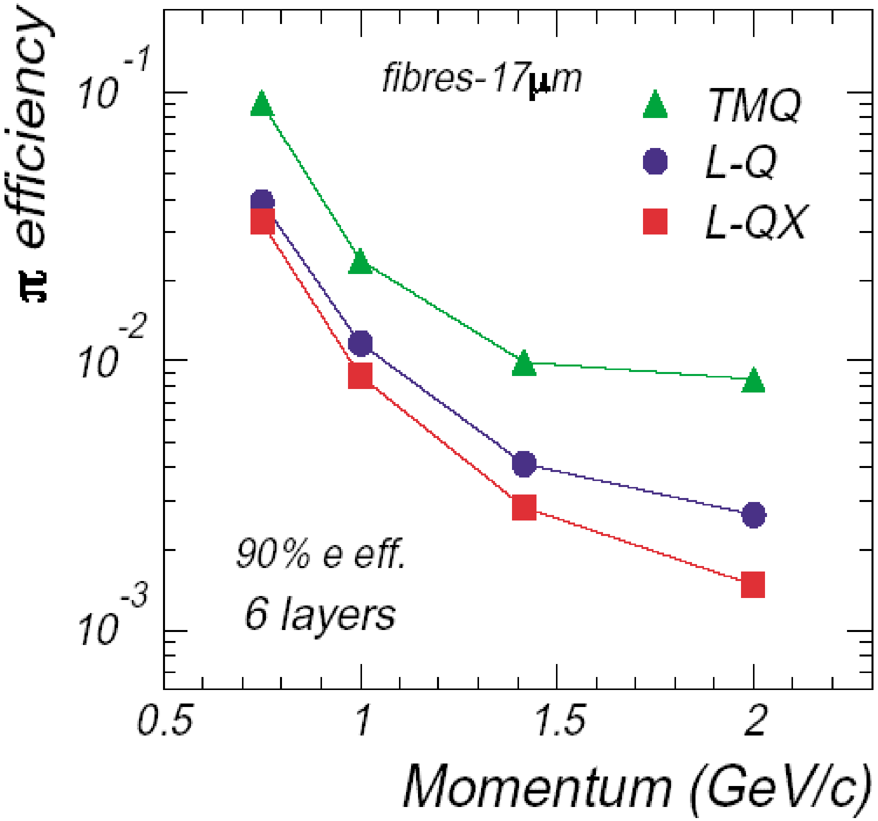
$\varepsilon_{\pi} \sim 10^{-3}$ @ $\varepsilon_{e} \sim 90\%$

ALICE TRD Chamber



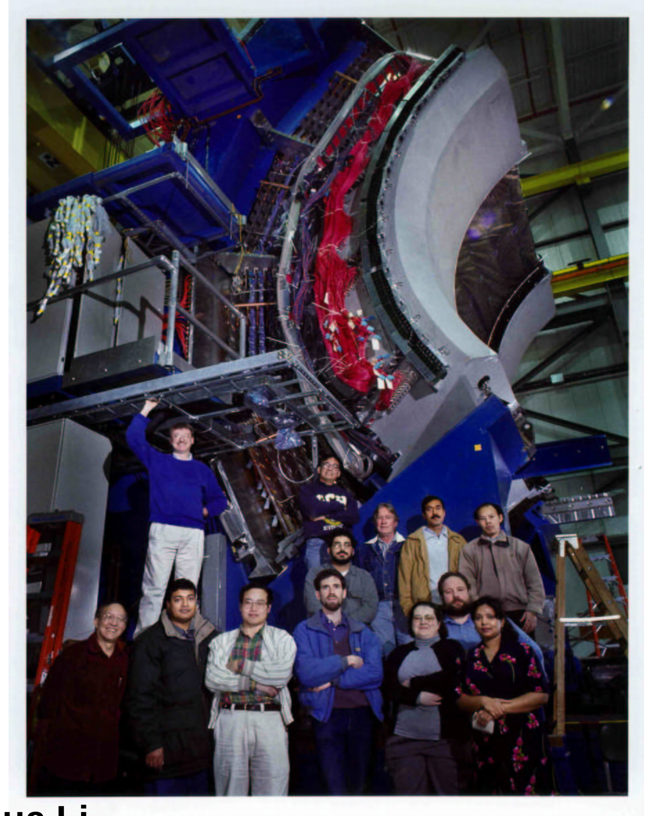
ALICE TRD performance





PHENIX Time Expansion Chamber TRD

- 24 chambers arranged in 4, 6-chamber sectors, each 3.7m × 2.0m × 0.1m containing 2700 wires
- polypropylene fibers/TEC (Xe-C_4H_{10}), e/π identification, tracking and momentum reconstruction using dE/dx



Xinhua Li
Univ. of California, Riverside, CA 92521, USA

TRDs for Cosmic Rays

- CRN (1985): polyolefin fibers/MWPC (Xe-He-CO_2), primary cosmic ray energy measurement (Space Shuttle)
- WIZARD-TS93 (1993): C-fibres/MWPC (Xe-CO_2), e/hadron identification (balloon flight), $\varepsilon_\pi \sim 10^{-3}$ @ $\varepsilon_e \sim 90\%$
- HEAT (1994): fibers/MWPC (Xe-CO_2), e/hadron identification (balloon flight), $\varepsilon_\pi \sim 10^{-3}$ @ $\varepsilon_e \sim 90\%$
- MACRO (1994-2000): CH_2 foam/square proportional tubes (Ar-CO_2), underground μ–energy measurement (LNGS)
- PAMELA (2004): C-fibers/straw tubes (Xe-CO_2), e/hadron identification (satellite mission), $\varepsilon_\pi \sim 10^{-2}$ @ $\varepsilon_e \sim 90\%$
- AMS2 (2006): Fiber/straw tubes (Xe-CO_2), e/hadron identification (Space Station) $\varepsilon_\pi \sim 10^{-3}$-$10^{-2}$ @ $\varepsilon_e \sim 90\%$

Hadron Colliders beyond LHC

Two main routes past LHC:

increase luminosity	increase energy:
SLHC	VLHC
$L=10^{35}\ cm^{-2}s^{-1}$	Phase I: $L=10^{34}cm^{-2}s^{-1}$, $\sqrt{s}$ = 40 TeV
$\sqrt{s}$ = 14 TeV	Phase II: $L=5\text{-}2\times10^{34}cm^{-2}s^{-1}$, $\sqrt{s}$ = 125-200 TeV

ELOISATRON: $L=10^{36}cm^{-2}s^{-1}$, $\sqrt{s}$ = 200-1000 TeV

Plans to reach far-energy frontier beyond the LHC require a significant, continued world-wide R&D effort, based on realistic studies of experimental conditions and ability to detect and reconstruct event characteristics in full. Fast particle (**leptons**) identification detectors (TRDs?) are needed !

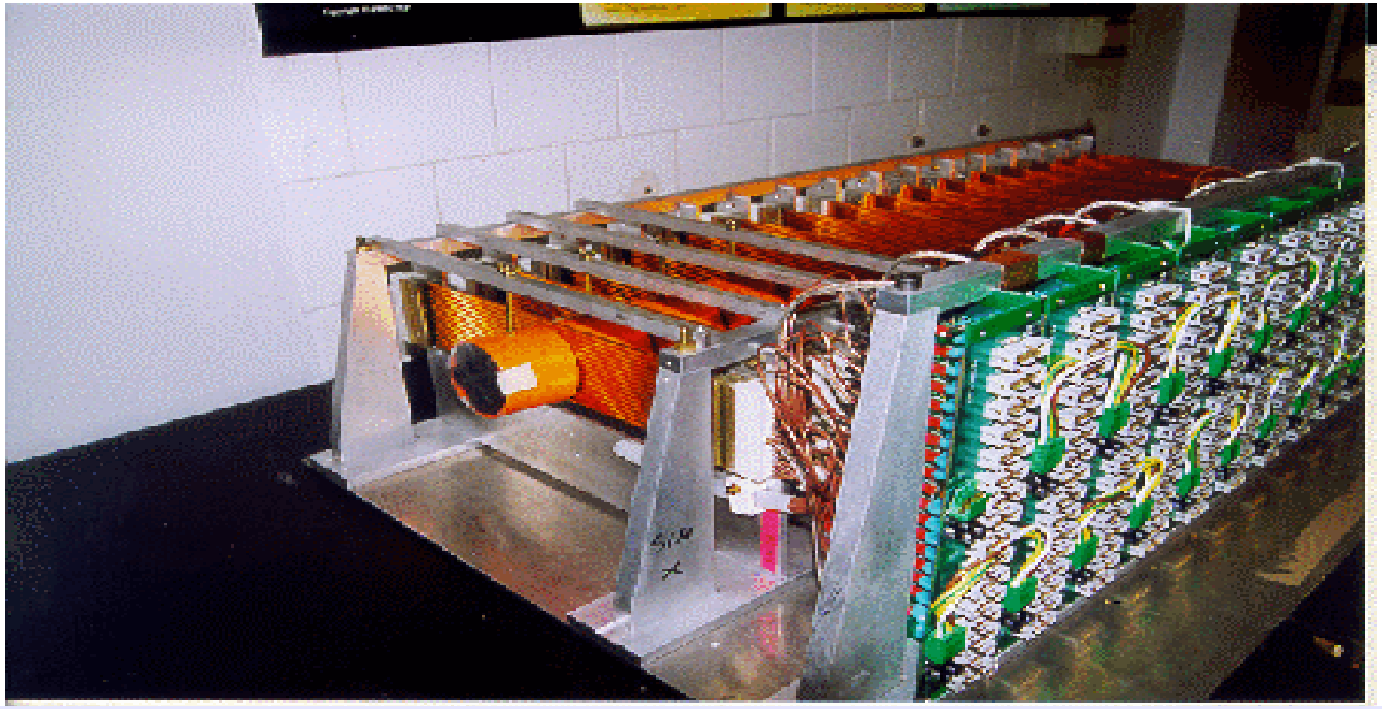
Some R&Ds for fast TRDs: TRDs to tag high energy hadron beam (as trigger or veto)

- E769 (1991)-E791: pions/kaons/protons beam at 250 GeV/c-500 GeV/c (2 MHz rate),
- 24 modules radiator (polypropylene foils)/double-gap MWPCs (Xe-CO_2),
- drift time ~ 120 ns (not yet so fast…),
- protons contamination of 2% @ 87% pions efficiency

Fast TRD to tag high energy hadron beam (as trigger or veto)

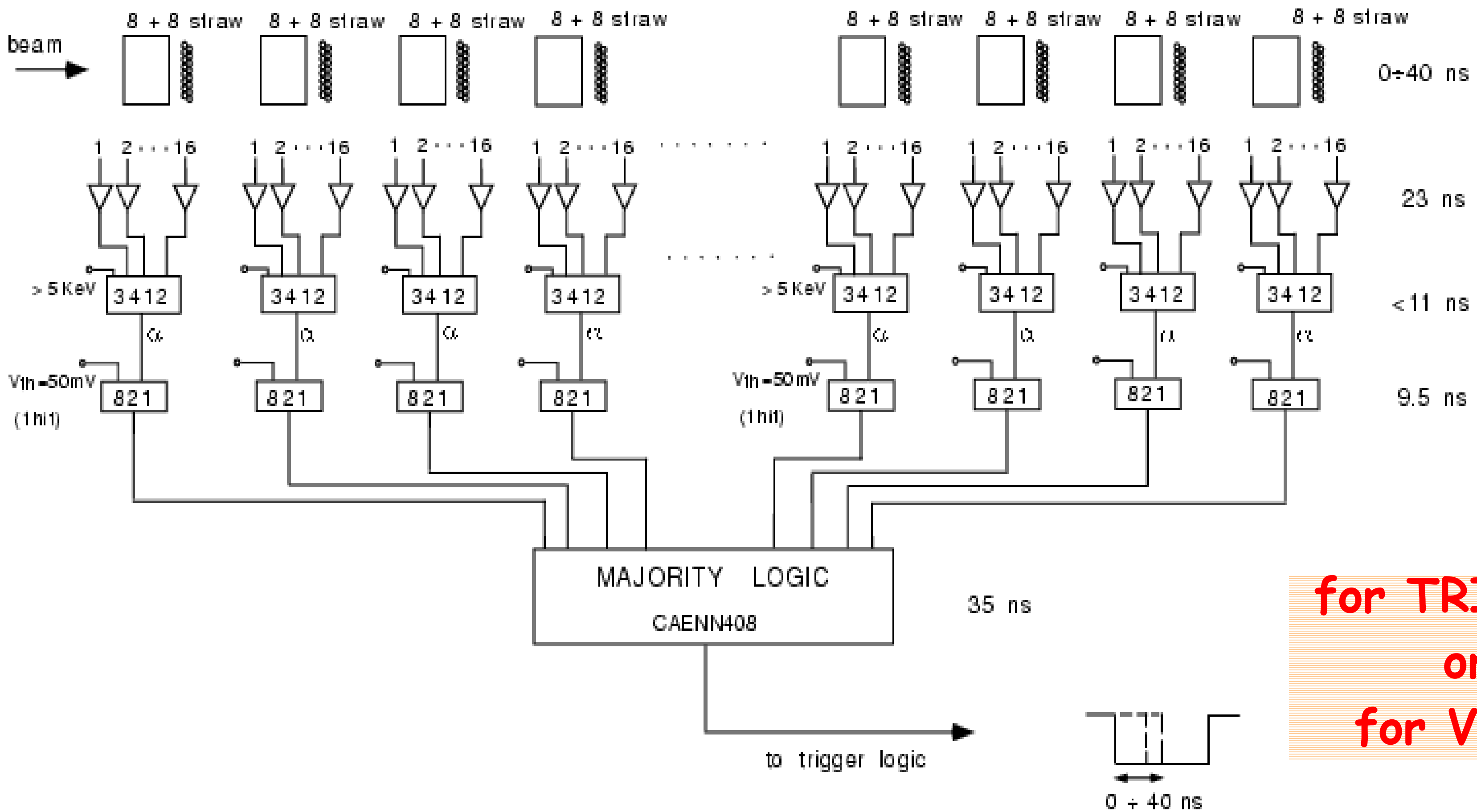
- TRD for SPS-beam proposed for NA57 experiment (1999)
- pions/kaons/protons beam ~ 200 GeV/c (4 MHz rate),
- 16 modules radiator (C-fibers)/double straw tubes layer (Xe-CO2),
- short drift time ~ 40 ns !
- protons (pions) contamination: 2-3 % @ 90% pions (protons) efficiency

Fast-TRD for a SPS-beam: detector view (P.Spinelli et al., 1999)



Radiator: 5 cm thick, made of short carbon fibers of 7 μm diameter
X-ray detector: kapton (30 μm thick) straw tubes, 4 mm diameter
Gas: Xe-CO_2 (70%-30%) @ 1 bar pressure

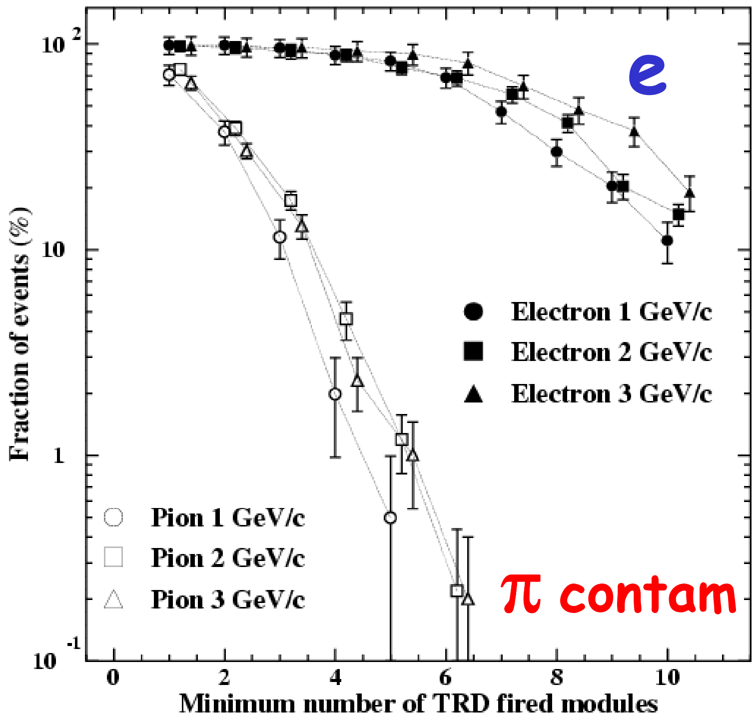
Fast-TRD for a SPS-beam: trigger layout



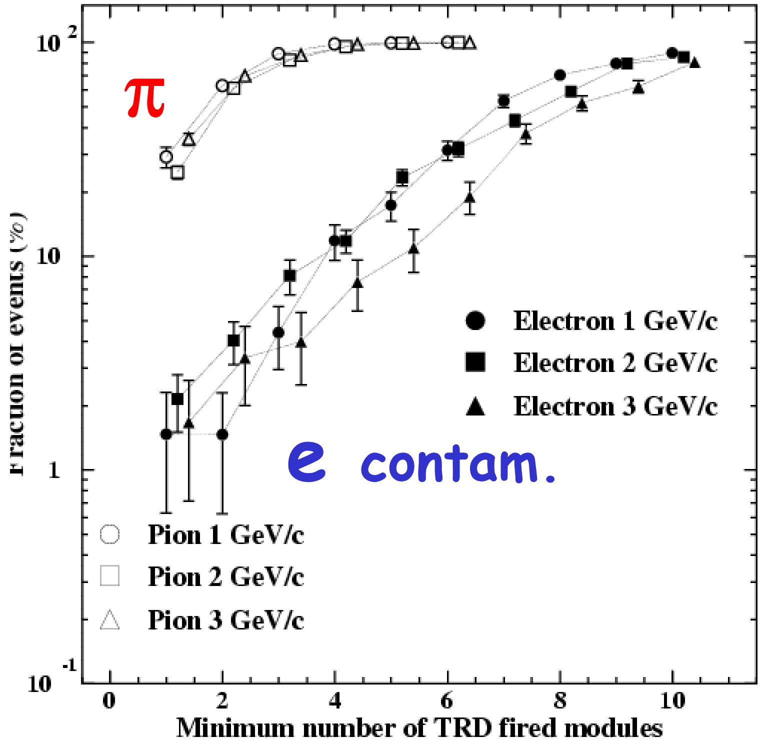
for TRIGGER
or
for VETO

Fast-TRD: e/π beam

Min.n° modules as **trigger**



Min.n° modules as **veto**



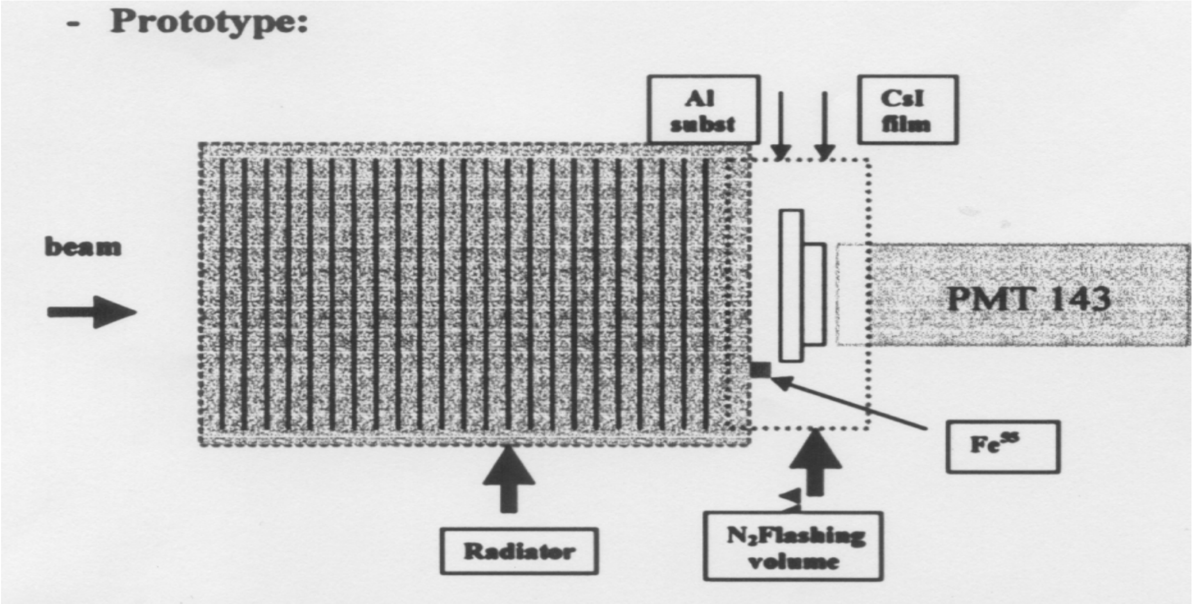
e/π ~ GeV/c ➡ π/p ~ 100 GeV/c up to 1 TeV/c

Limitations of TRD electron/hadron rejection power

- Hadron interactions (mainly in the radiator material) →short TRDs !
- Energetic δ-electrons on the hadron track→gaseous chambers indicated…
- dE/dx relativistic rise for hadrons in gaseous detectors @ a few 100 GeV/c

Novel applications: TRD based on thin films of heavy inorganic scintillators

V. Sosnovtev et al, TRD 2003 Workshop, Bari

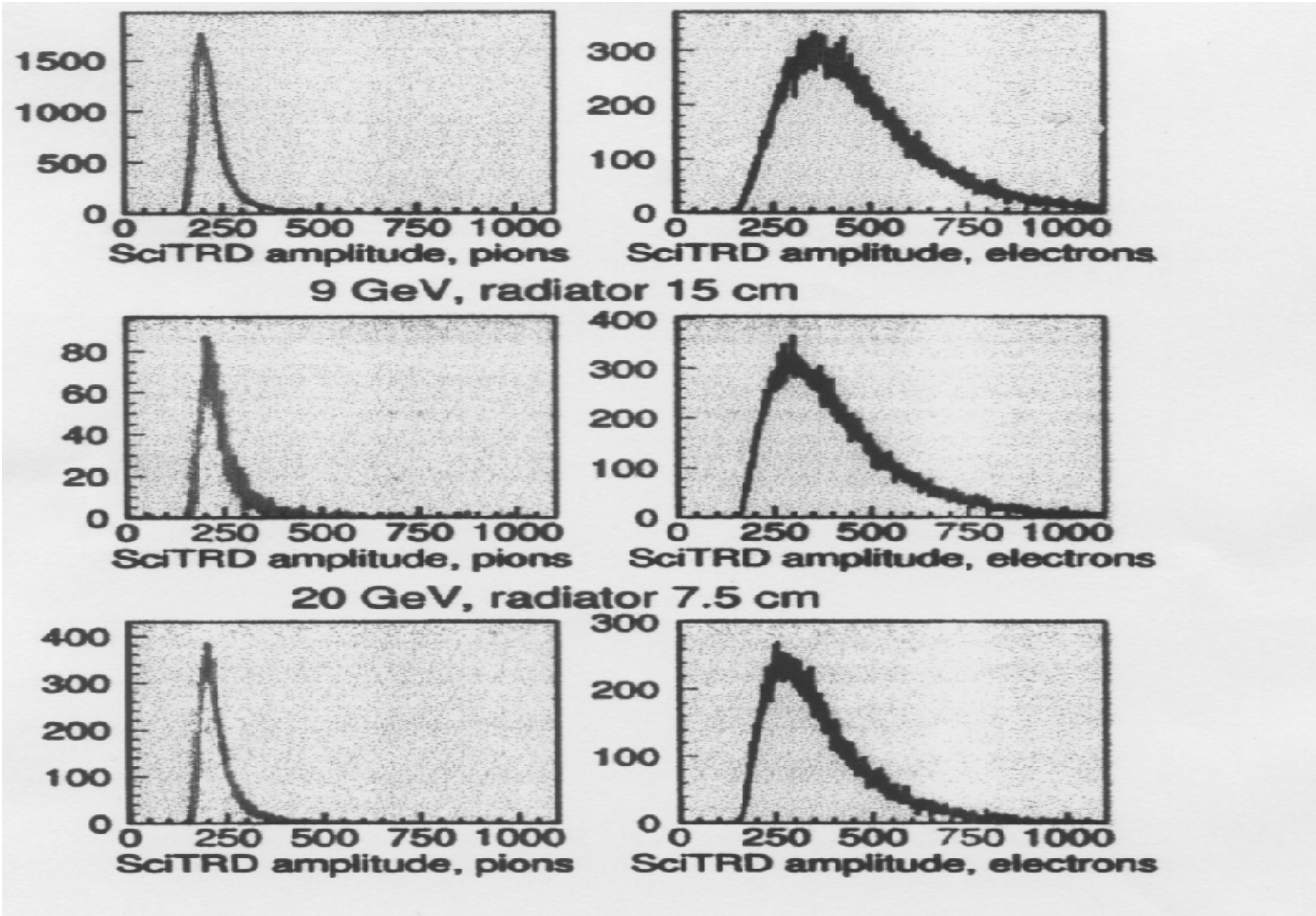


CsI 37μ thickness, decay time = 630 ns

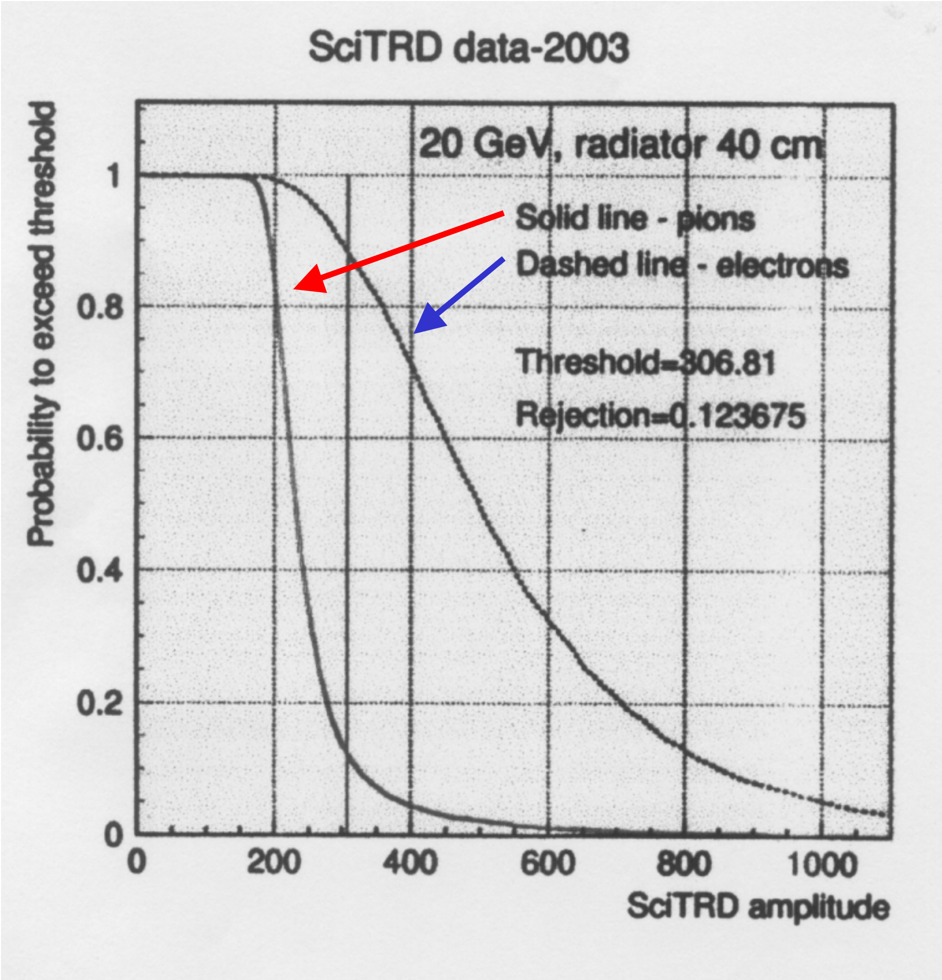
next R&D: Lu_2S_3:Ce, decay time =32ns! (very fast…)

PM → Silicon *multi-microcounter* PM (Dolgoshein talk)

Landau and TR energy distributions

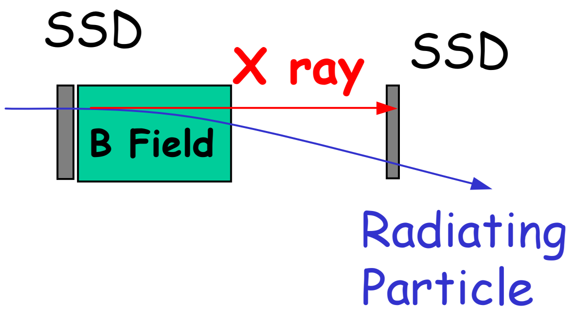


Rejection power



Novel applications : Silicon Strip TRD
(P.Spinelli et al., TRD 2003 workshop,Bari)

Silicon microstrip detectors track the radiating particle in a magnetic field and detect the TR X rays apart from the particle

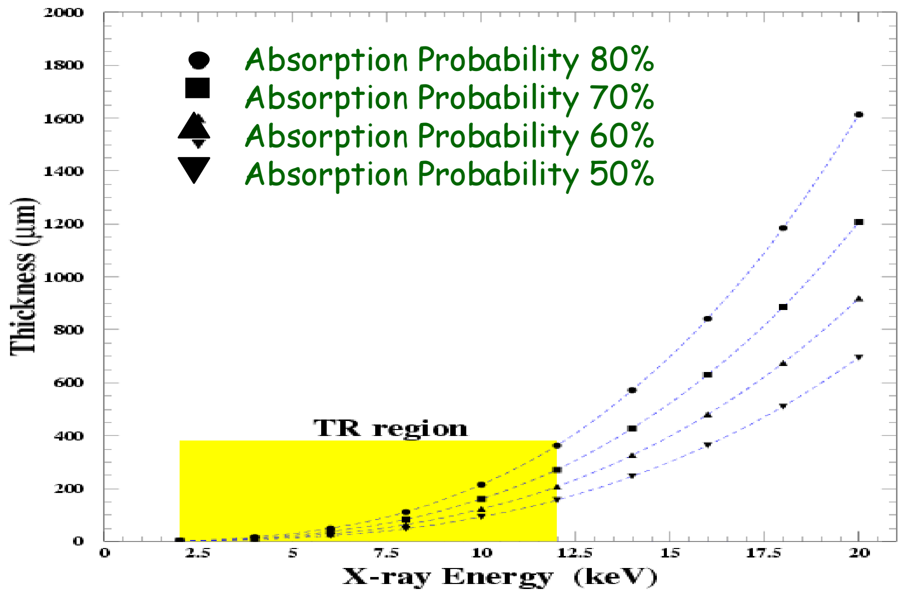


$$\frac{dE}{dx}_{Si} \approx 100keV \longleftrightarrow E_{TR} \approx 10keV$$

Typical 300-400μm thickness

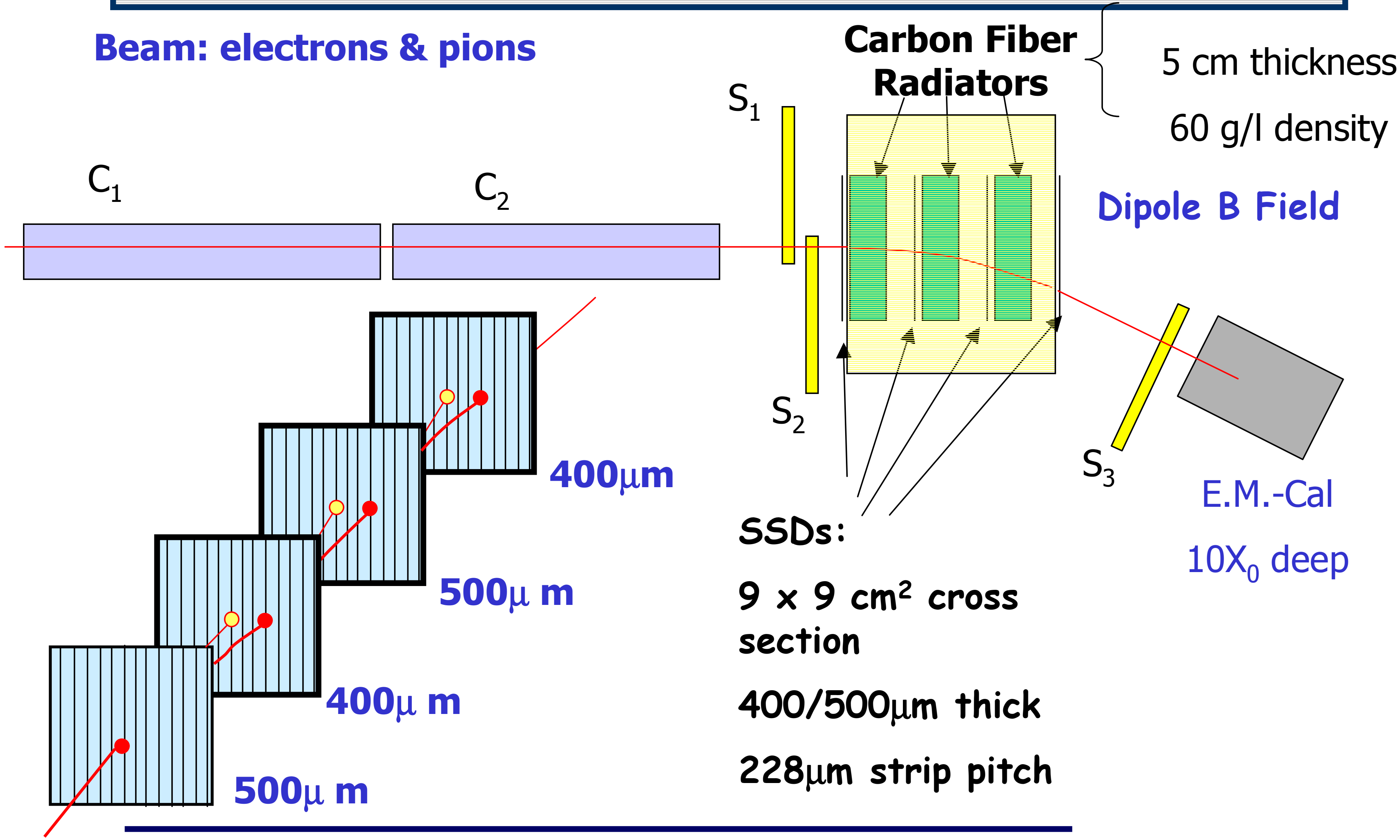
⇓

B Field ~ 1T



Beam Test 2003: The set-up

Beam: electrons & pions



SSDs:

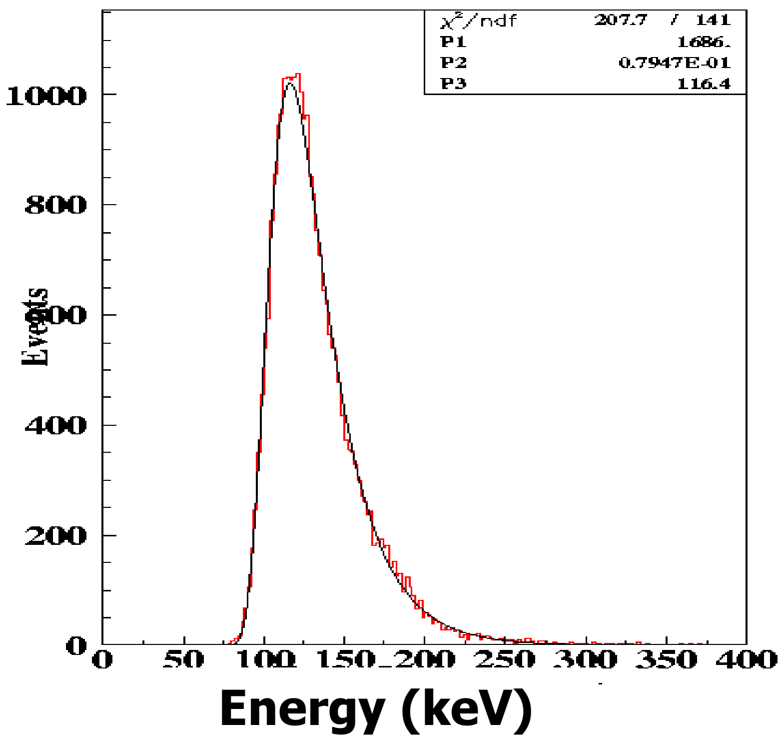
9 x 9 cm² cross section

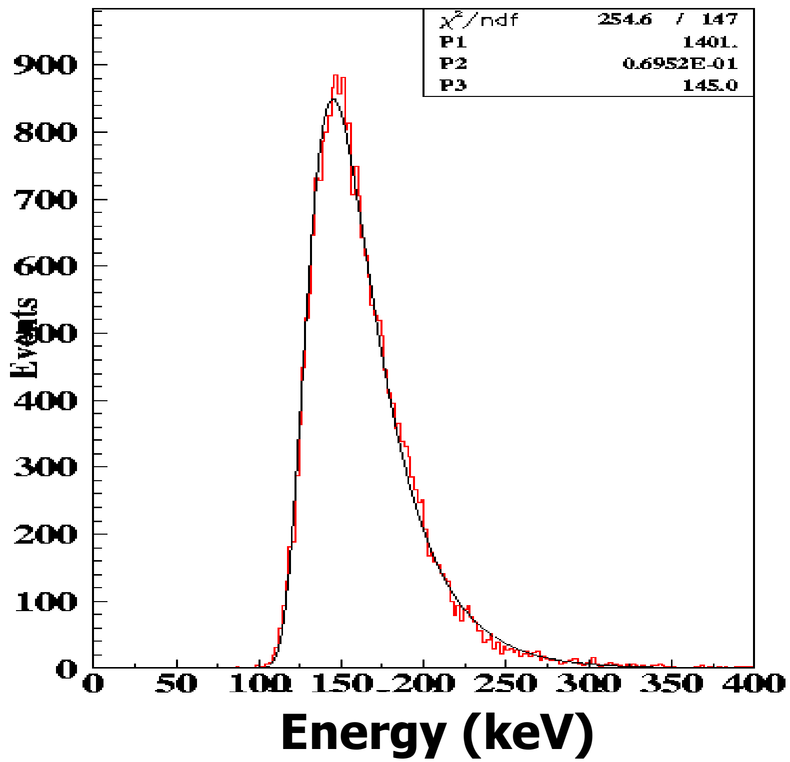
400/500μm thick

228μm strip pitch

SSD Calibration

The ADC channel distribution is fitted with a Landau distrib.: the most probable value has been set to 111 keV for pions at 3GeV/c in 400 μm (Bichsel PDG 2002)

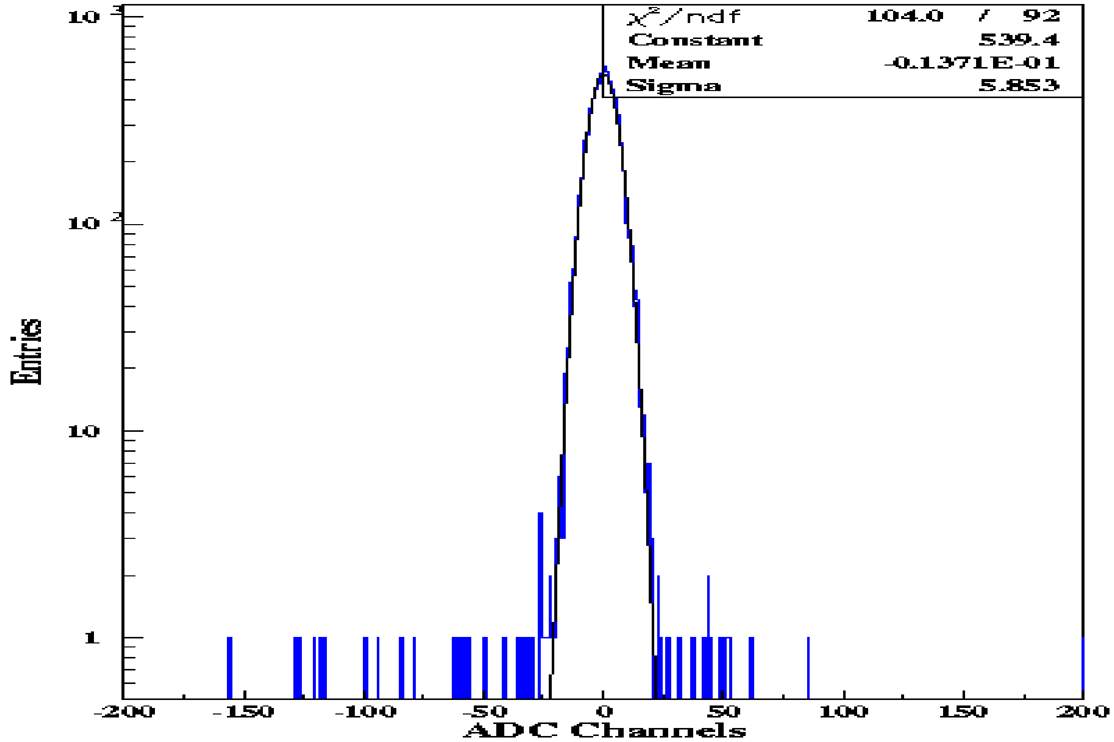




Electrons @ 3 GeV/c: 116 keV for 400 μm (Mod 1)

145 keV for 500 μm (Mod 2)

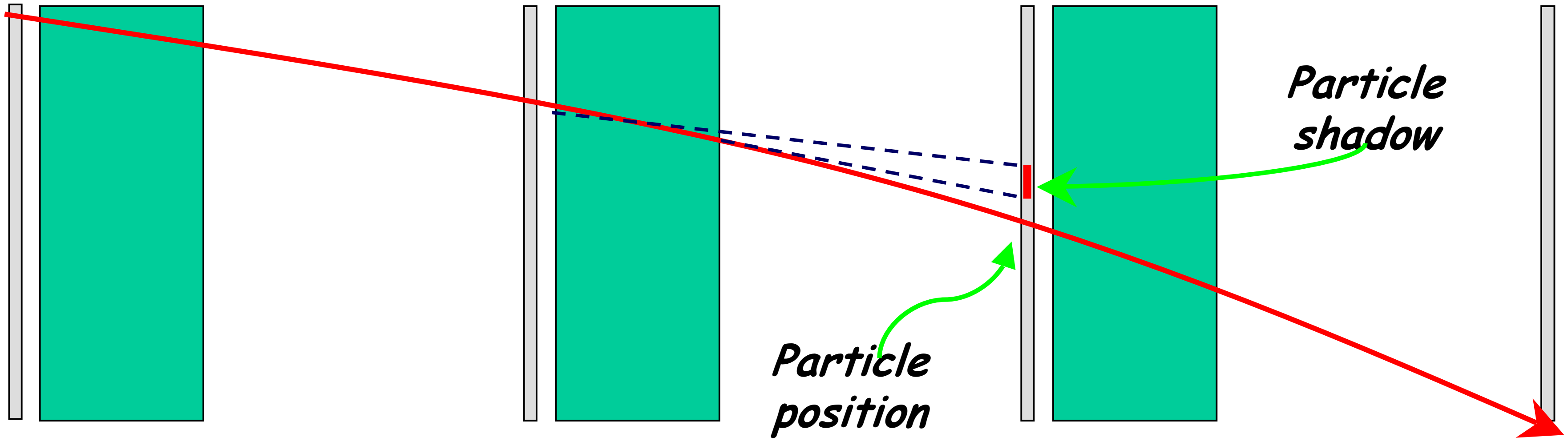
SSD Noise



σ=5.8 chs $\Rightarrow$ 1.3 keV

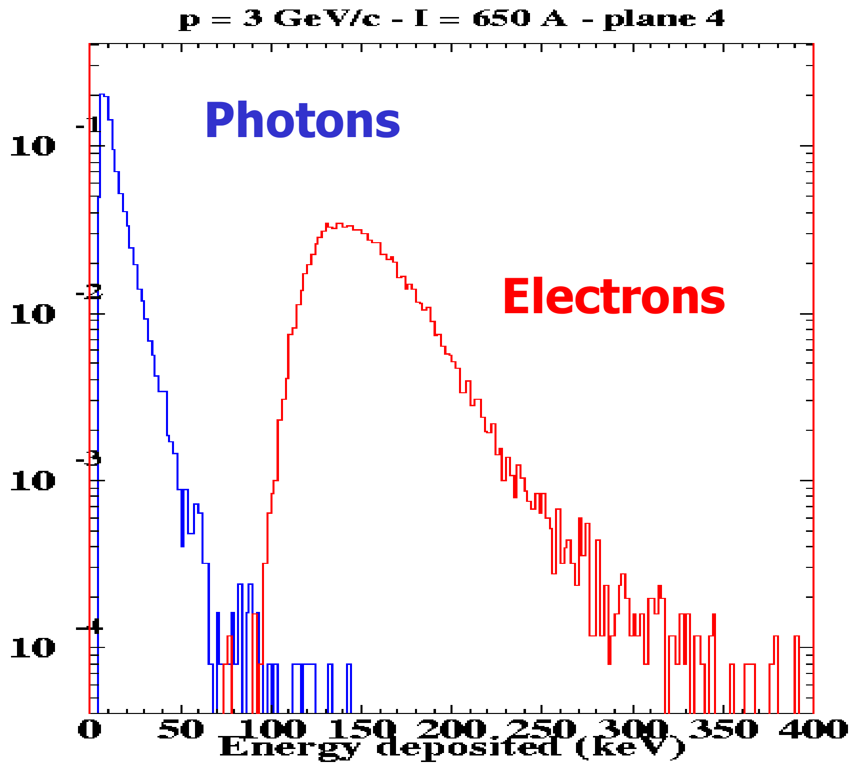
TR photons' search >3σ ~ 4 keV

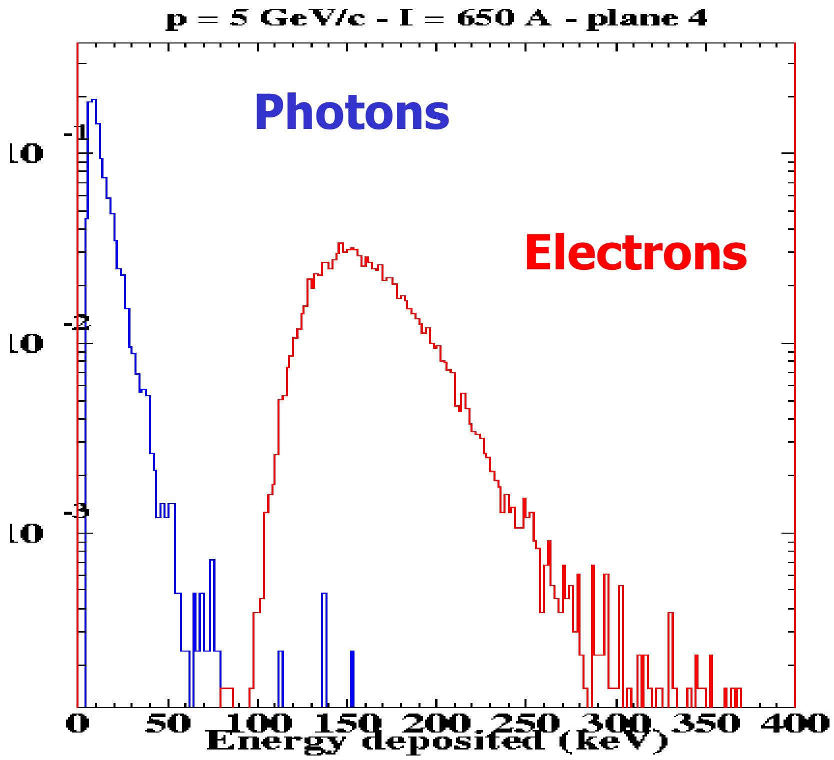
The X-ray search algorithm



- ✓ The particle trajectory in the bending plane is approximated by an arc of a circle
- ✓ The tangents to the trajectory are drawn from the points at the beginning and at the end of each radiator
- ✓ TR X-ray search is performed in the region of the particle shadow
- ✓ X-ray clusters must have at least one strip with S/N > 3σ (4 keV); adjacent strips with S/N > 1σ are also included in the cluster

Energy Spectra





$\langle E_\gamma \rangle$ = 12.8 keV @ 3GeV/c

$\langle E_\gamma \rangle$ = 14.2 keV @ 5GeV/c

The two spectra are obtained in two separate SSD regions

Si-TRD test beam performance

Si-TRD electron tagging:

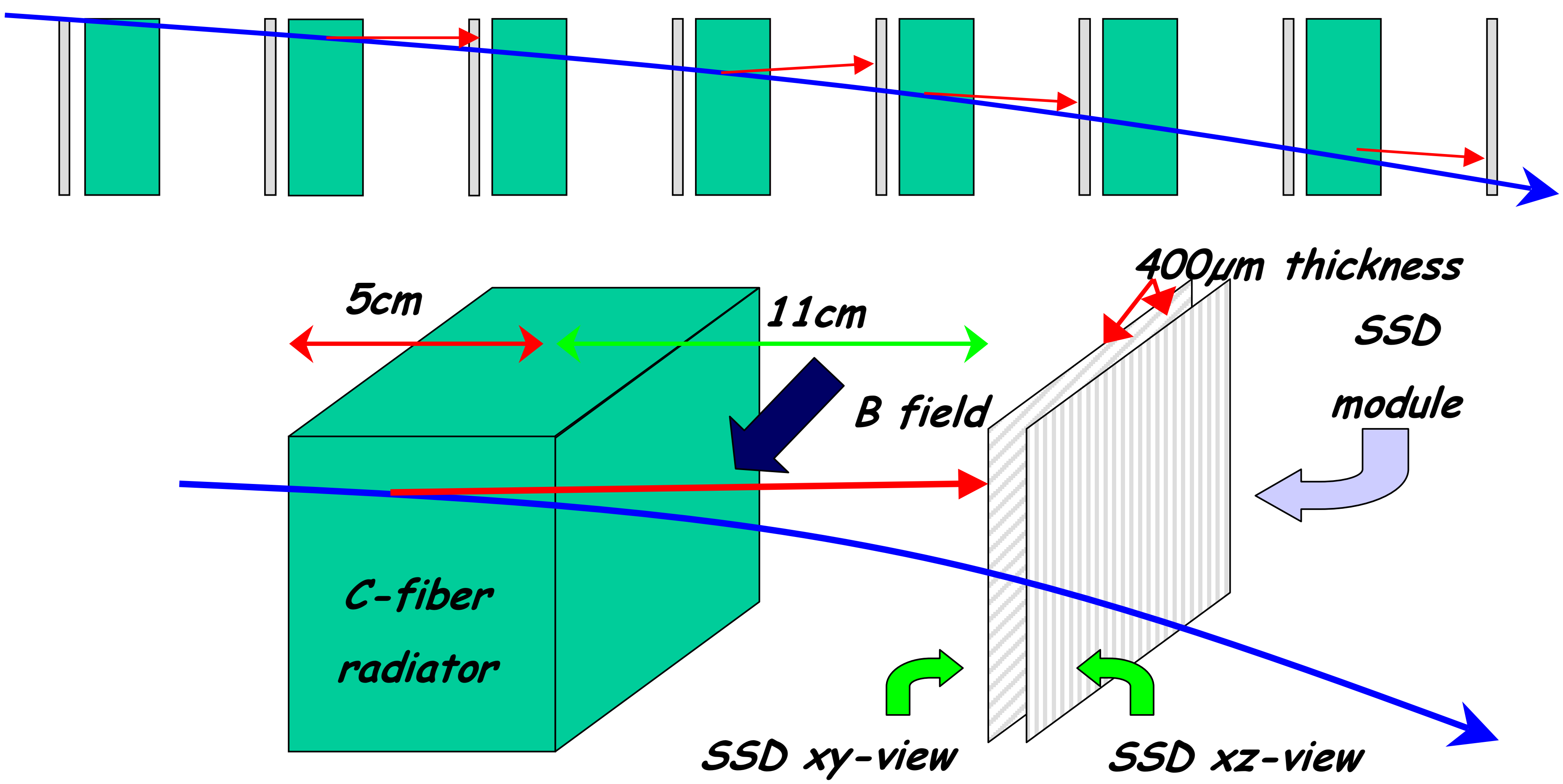
At least one TR photon (in the shadow region)

	3 GeV/c 1T	3 GeV/c 0.5T	5 GeV/c 1T	5 GeV/c 0.5T
e efficiency	80%	60%	55%	30%
π contamination	1.3%	1.3%	1.5%	1.5%
Rejection power	1.6%	2.1%	2.5%	4%

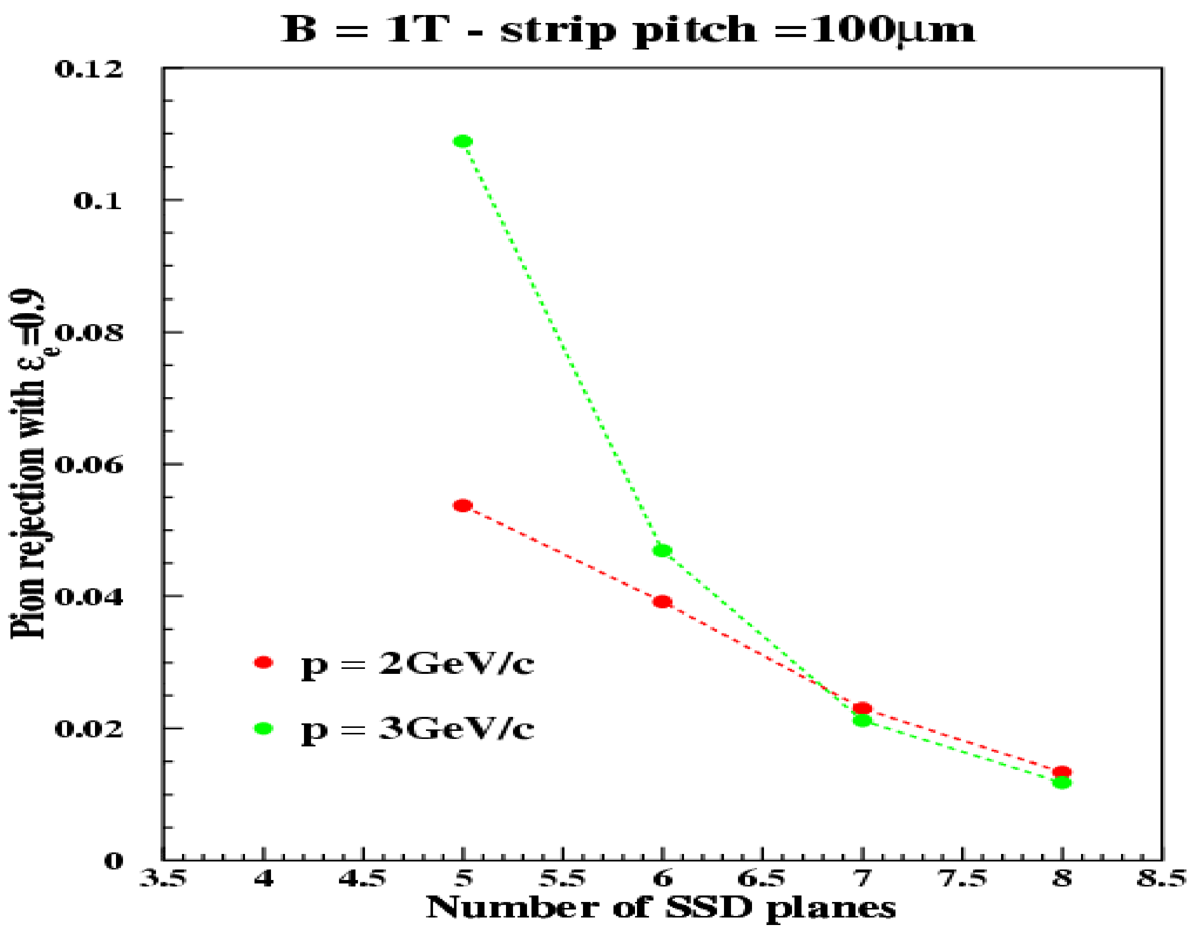
Time response ~ μs , depending on the electronics, (fair…)

But no gas is needed, and it can be used as spectrometer

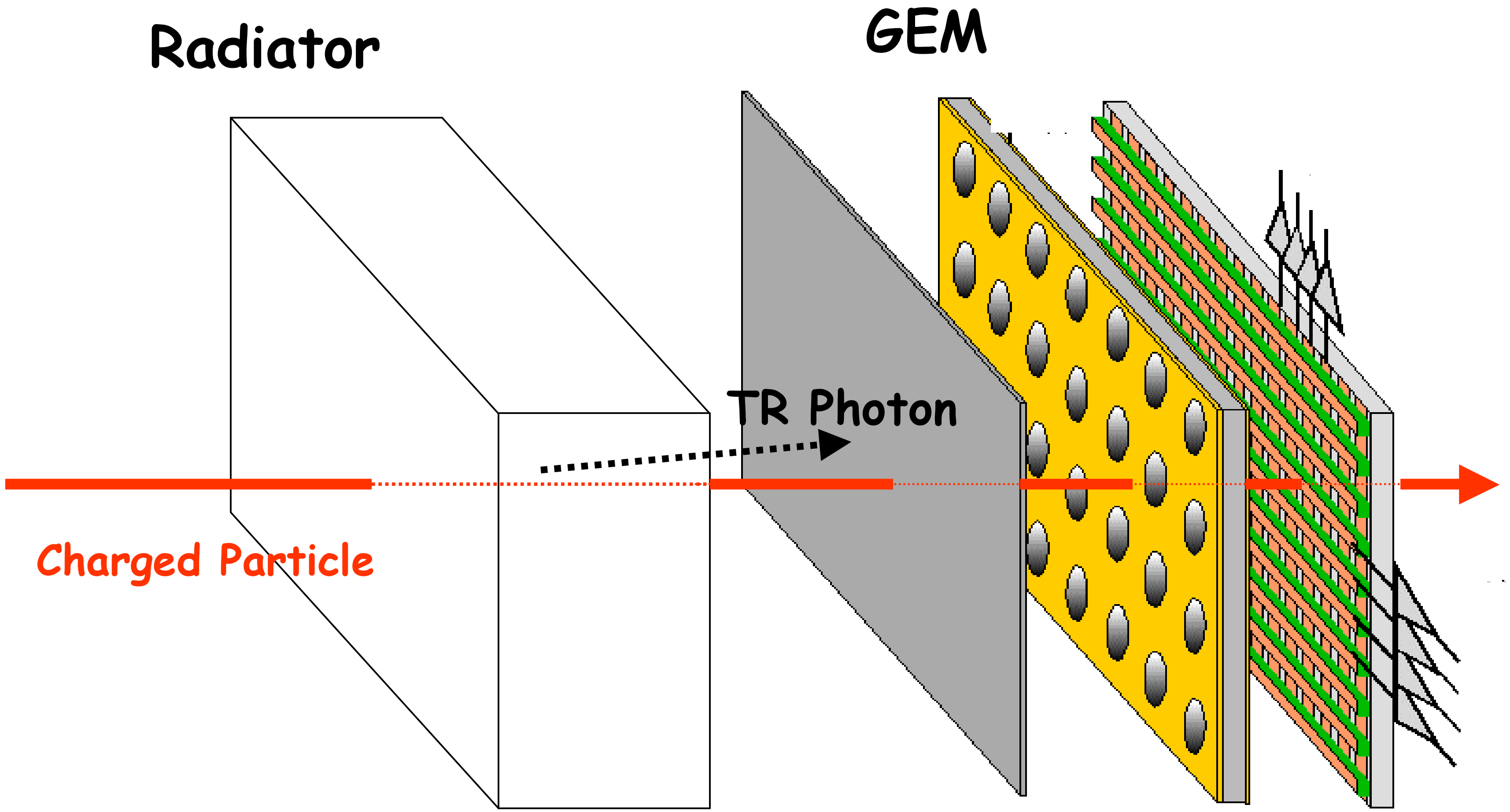
Multi-layer SI-TRD



Multi-layer Si-TRD rejection



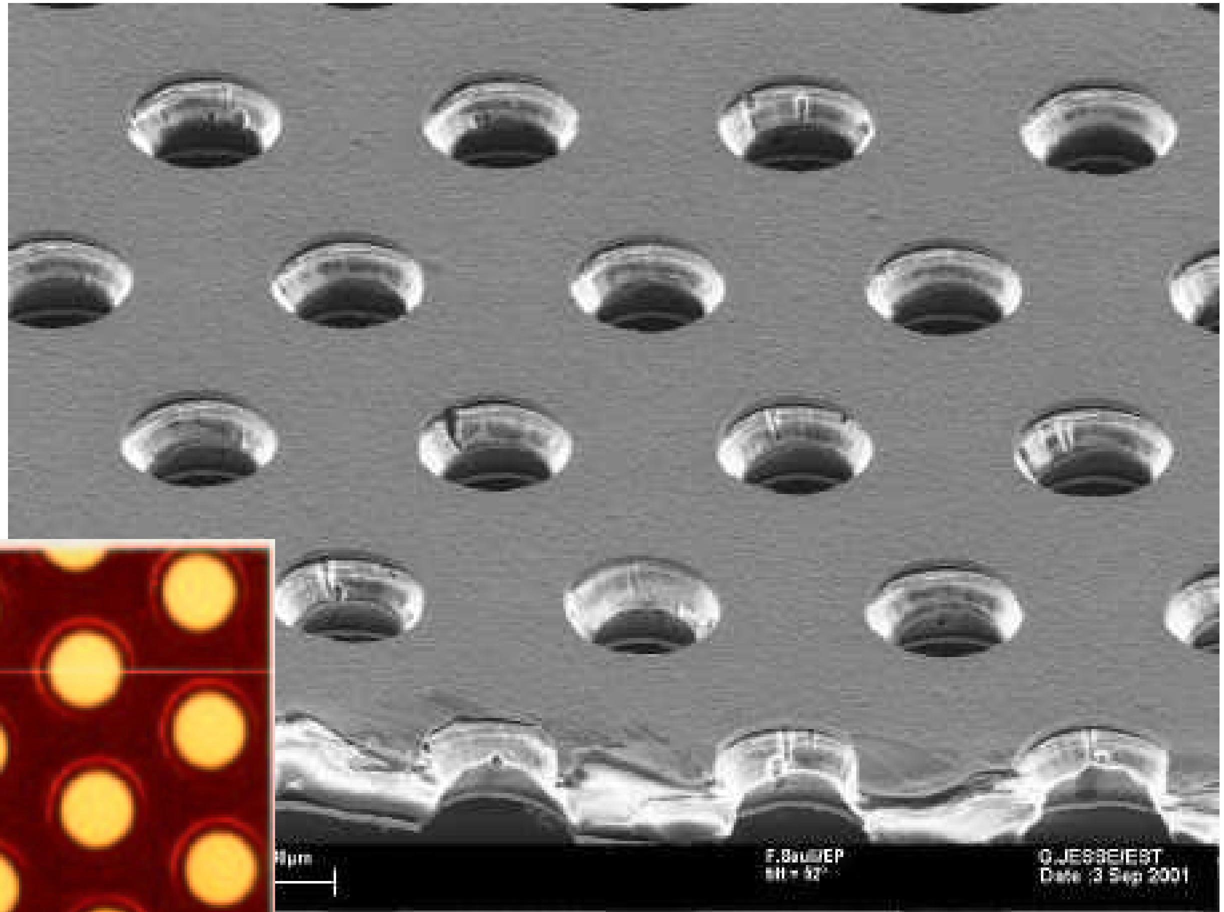
Next Future possible R&D for TRDs

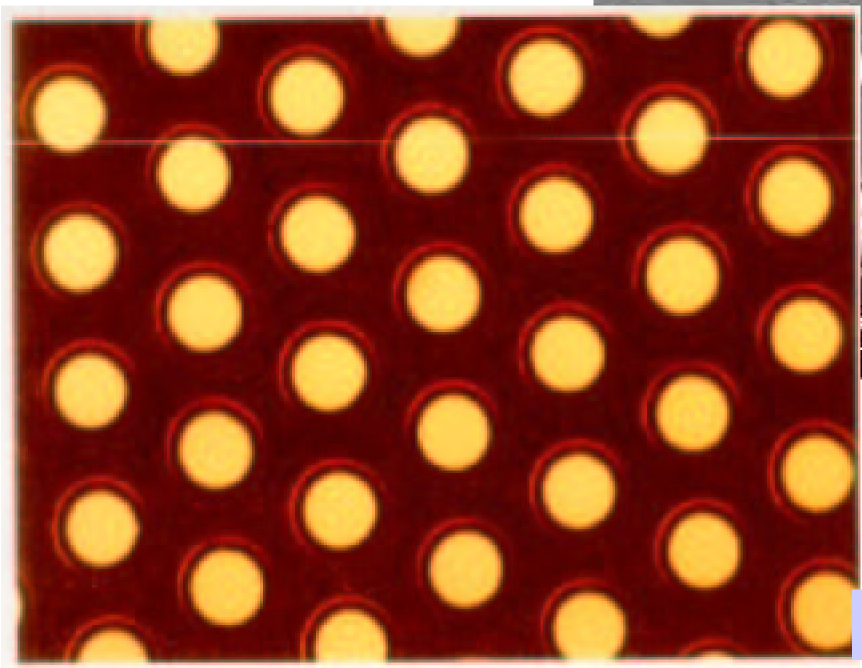


Signal time width ~ 10 ns ! (ultra fast!)

GEM (= Gas Electron Multiplier)

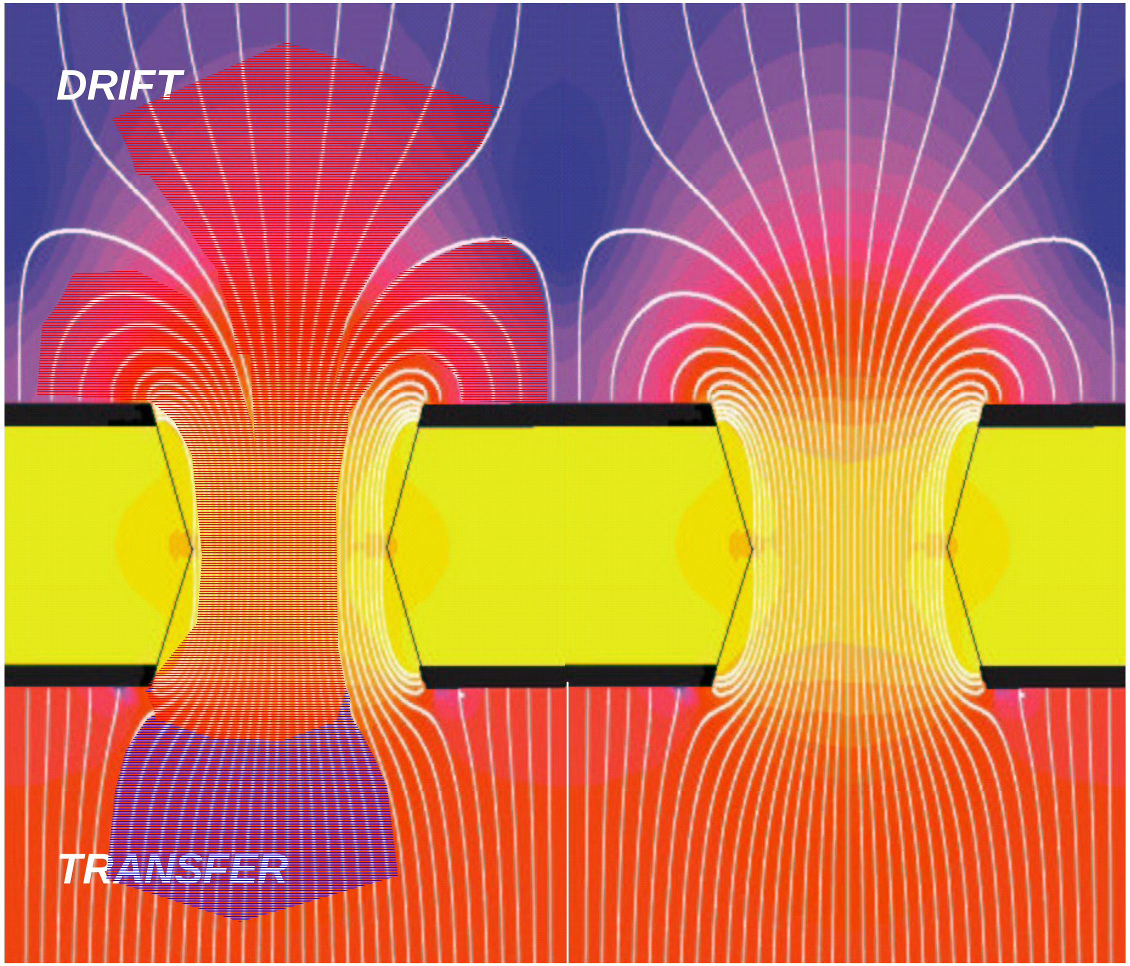
Thin metal-coated polymer foil chemically pierced by a high density of holes (technology developed at CERN)



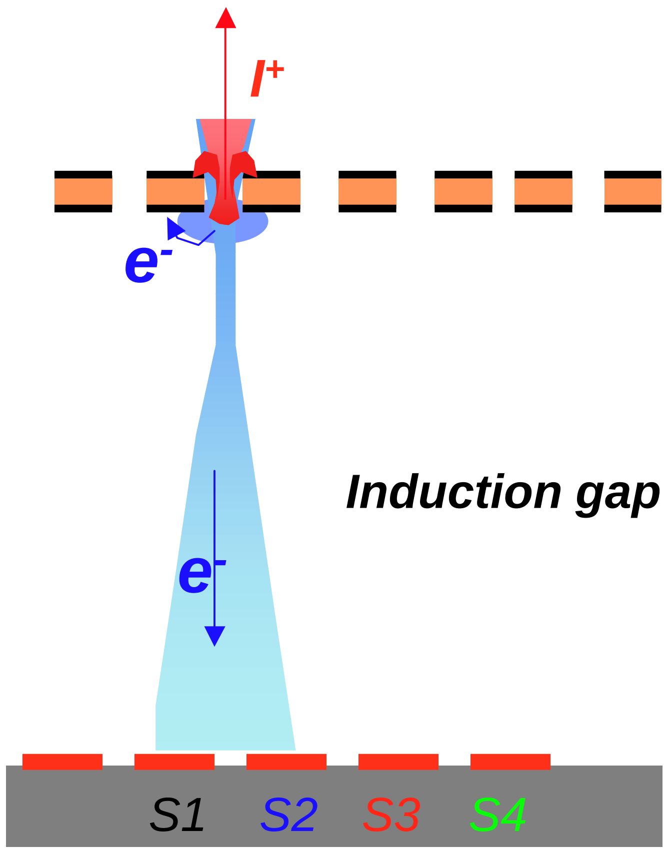


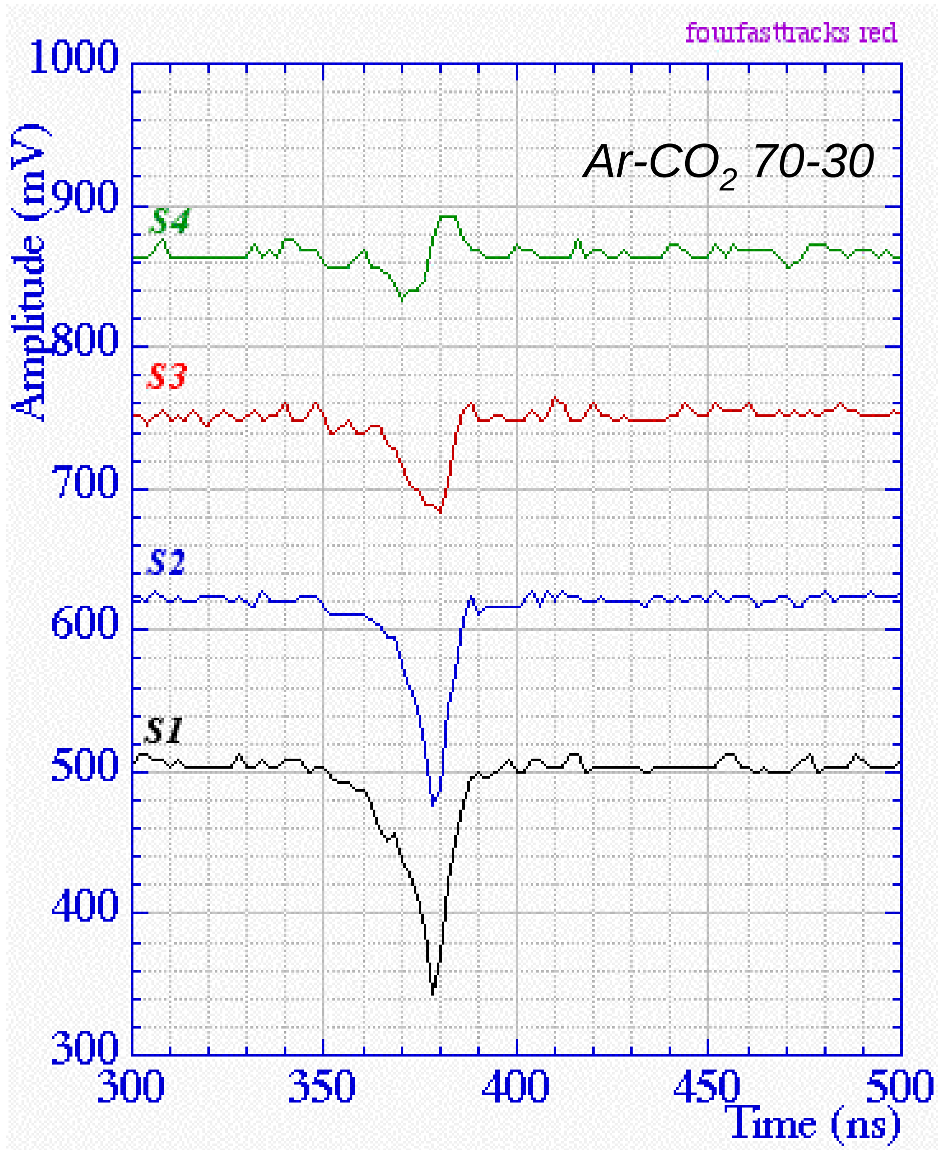
Typical geometry:
5 µm Cu on 50 µm Kapton
70 µm holes at 140 mm pitch

F. Sauli, Nucl. Instrum. Methods A386(1997)531


DRIFT
TRANSFER

GEM signal formation





Fast electron signal only

No positive ion tail → **very good multi-track time resolution**

Conclusions

- TRDs are well suited for high energy particle (lepton) identification ($\rightarrow$TeV region)
- TRDs can also be used for the measurement of known mass particles
- TRDs can be used as first level trigger fast devices on high energy beam lines
- R&D results on novel TRDs are promising for PID for next generation of "super colliders"