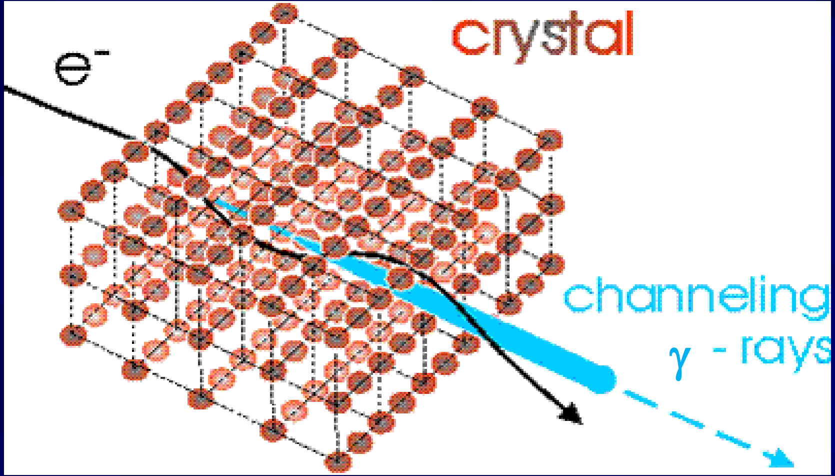

PARTICLE IDENTIFICATION BY MEANS OF CHANNELING RADIATION IN HIGHLY COLLIMATED BEAMS

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Channeling Radiation for PID

- **The Channeling Radiation effect could be used for PID to identify (reject) electrons/positrons from hadrons**
- **Application: particle identification in high energy unseparated beams where Cerenkov counters become unpractical and TRDs cannot perform full e/h discrimination**
  - small amounts of materials (in terms of X0) along the beam lines
  - highly collimated beams required

Cherenkov and transition radiation

- **Cherenkov radiation**: A charged particle radiates if its velocity is greater than the local phase velocity of light
- **Transition radiation**: A charged particle radiates if it crosses the boundary from one medium to another with different optical properties
- Both these processes imply small energy losses, but are used in high-energy physics detectors (PID, Particle Identification)

Cherenkov radiation

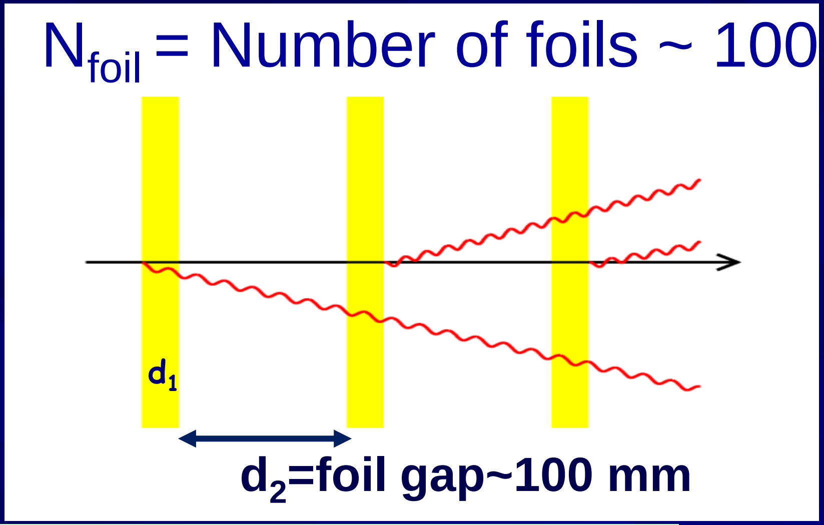
- The angle θ_c of Cherenkov radiation, relative to the particle direction, for a particle with velocity βc in a medium with index of refraction n is given by

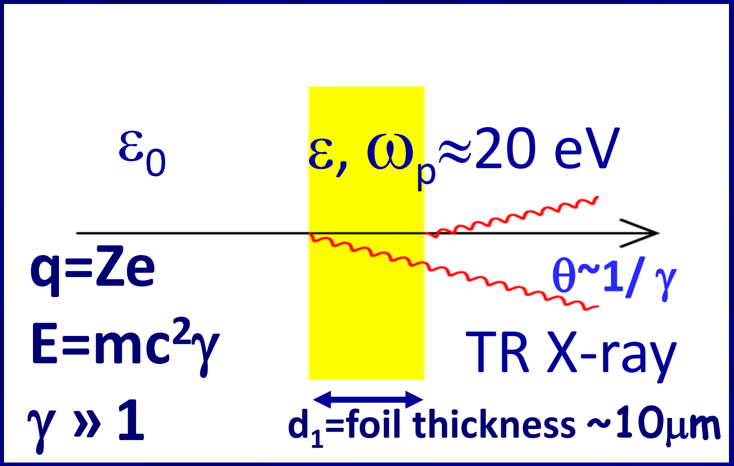
$$\begin{aligned} & \cos\theta_c = (1/n\beta) \\ \text{or} \quad & \tan\theta_c = \sqrt{\beta^2 n^2 - 1} \\ & \quad \approx \sqrt{2(1-1/n\beta)} \quad \text{for small } \theta_c, \textit{e.g.} \text{ in gases.} \end{aligned}$$

- The threshold velocity β_t is 1/n, and $\gamma_t = 1/(1-\beta_t^2)^{1/2}$.
- Therefore, $\beta_t\gamma_t = 1/(2\delta+\delta^2)^{1/2}$, where $\delta = n - 1$.
- **Threshold Cherenkov detectors**: in their simplest form, allow to make a yes/no decision based on whether the particle is above or below the Cherenkov threshold velocity.
- A straightforward enhancement of such detectors uses the number of observed photoelectrons (or a calibrated pulse height) to discriminate between species or to set probabilities for each particle species

Transition Radiation Detector

TRD is composed by multiple modules, each consisting of a radiator (multi-foils or foam) and a X-ray detector (gaseous detector).



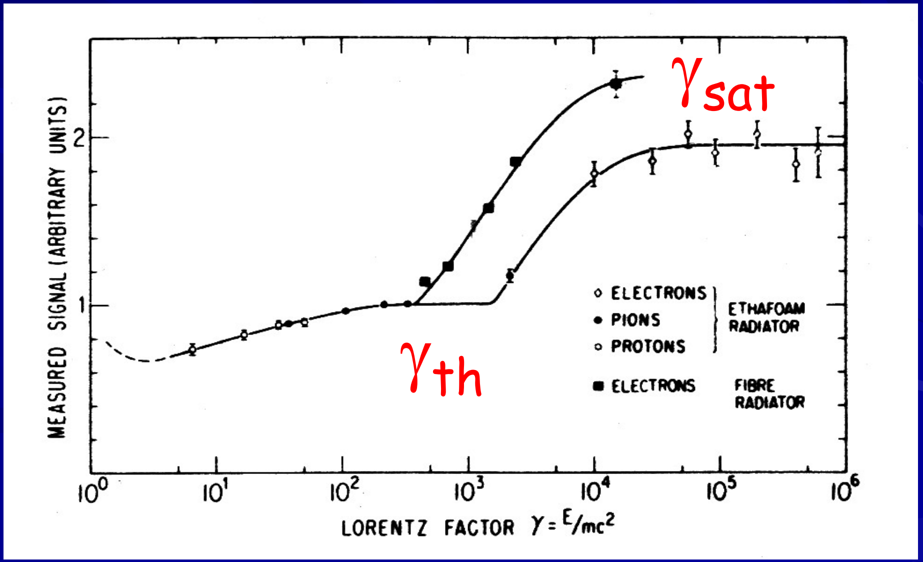


γ_{th} = 2.5 d_1(μm) ω_p(eV) ≈ 1000

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

$\gamma_{sat} \sim \gamma_{th}\, (d_2/d_1)^{1/2} \sim 10^4$

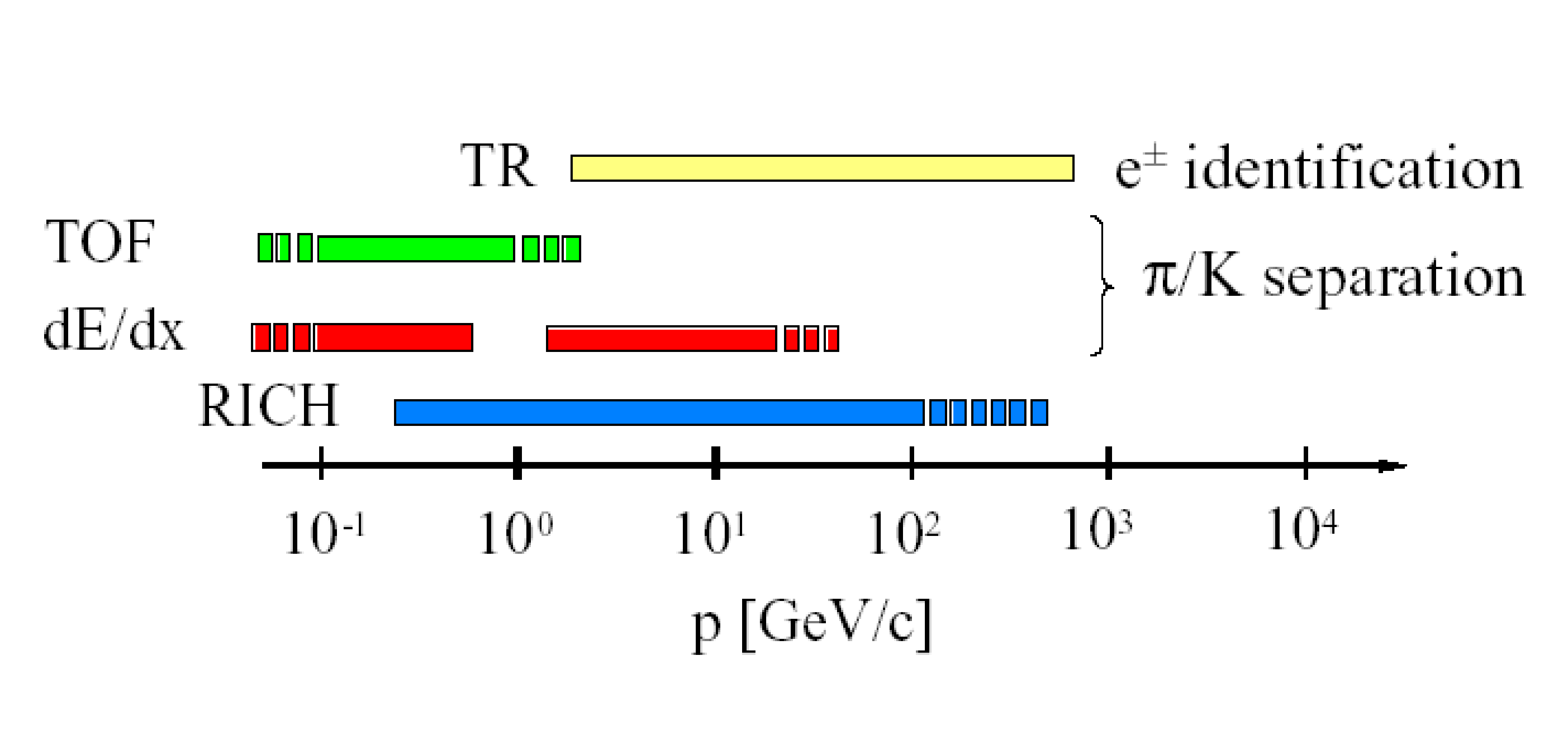
Number of X-rays ~ a $Z^2 N_{foil} \sim Z^2$



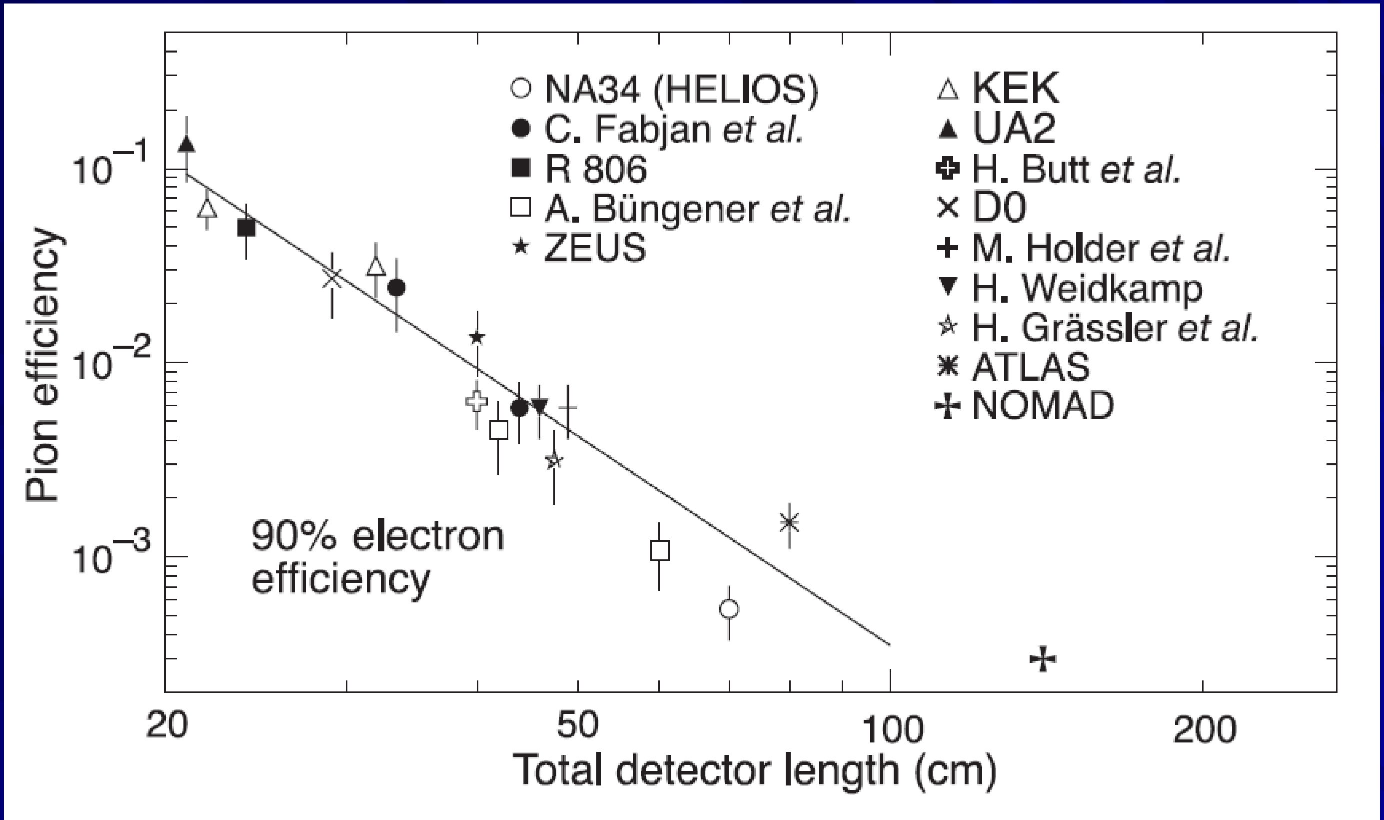
TRDs normally work as threshold devices, ensuring the best electron/pion separation in the momentum range ~ 1 GeV/*c* < *p* < ~150 GeV/*c*

PID techniques

- Particle ID: usually is based on the threshold properties of the radiation emitted (e.g. Cherenkov and transition radiation)



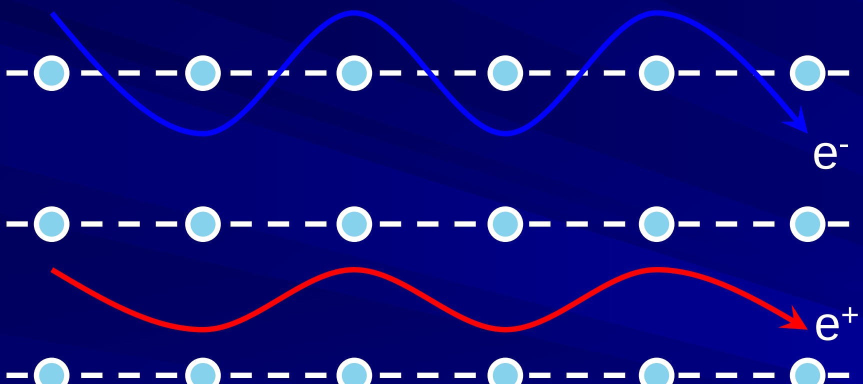
TRD performance vs length



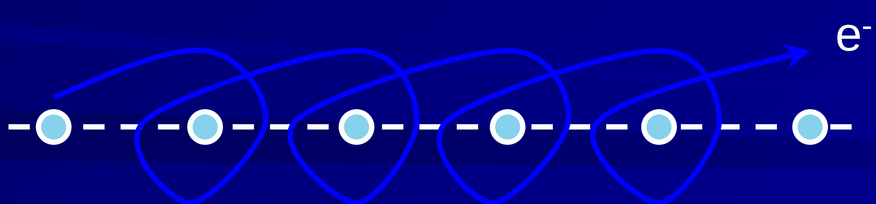
- A good particle ID performance requires a “long” TRD:
  - large amounts of materials along the beam line
    - typically, a 50cm long TRD corresponds to ~10%X_0
    - possibility of some EM showers initiating in the TRD

Channeling Radiation (ChR)

- **Channeling radiation is emitted when a charged particle crosses a crystal along a major crystal axis or plane**
  - **The charged particle is trapped in the potential wells due to the planes, resulting in a strong steering effect**



atomic crystal plane



atomic crystal axis

- **ChR is emitted if the incidence angle of the particle is smaller than a critical value ψ_{crit} (Lindhard angle) depending on the crystal and on the process (planar or axial channeling)**
- **Planar channeling: the particle is trapped between the crystal planes**
- **Axial channeling: the particle is channeled along a crystal axis**

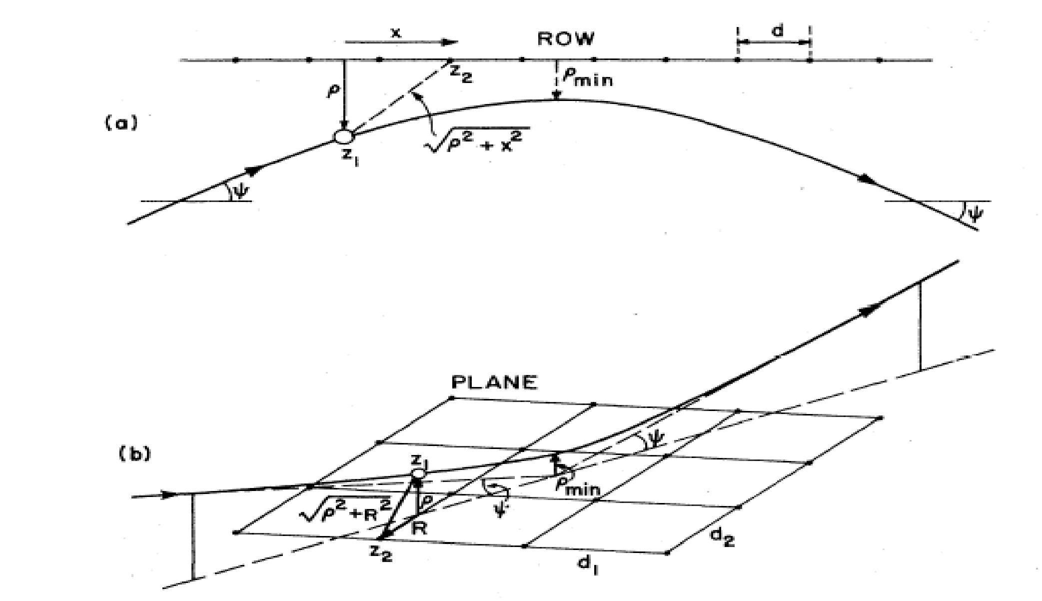
Features of the Channeling Radiation

- It strongly depends on the charge sign
- It depends not only on the particle velocity, but on its energy as well
- It exhibits characteristic frequencies (peaks) depending on the particle and on the crystal
- High degree of linear polarization for planar channeling
- In the hard X-ray and γ-ray ranges it exceeds other types of radiation approximately by two orders of magnitude in spectral intensity and by three orders in luminosity

  - Emitted energy: $\Delta E \propto \gamma^2$
  - Photon energy: $\omega \propto \gamma^{3/2}$
  - Photon emission angle: $\theta \sim 1/\gamma$

Critical angle

$$\psi_{crit}(\mathrm{deg}) = \begin{cases} 0.307\sqrt{Z_1 Z_2/dE} & \text{axial} \\ 0.545\sqrt{nZ_1 Z_2 a/E} & \text{planar} \end{cases}$$



E is the energy (MeV)

d is the atomic distance (Å) in a row

n is the atomic density in the planes (atoms/(Å)^2), $n=Nd_p/d^3$

N = atoms per unit cell

d_p = interplanar distance

a = screening length (Å)

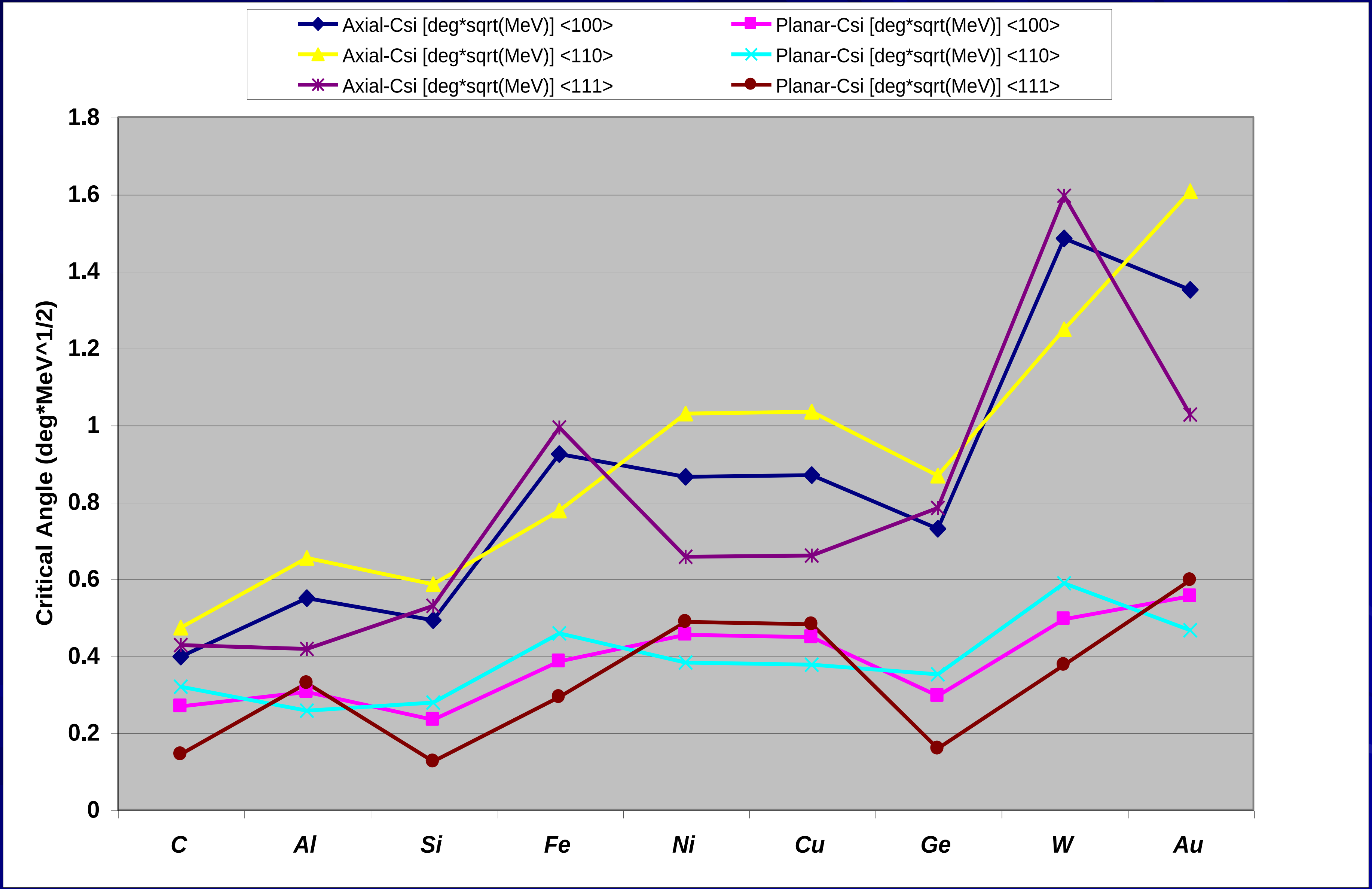
$$a(\mathrm{\AA}) = \begin{cases} 0.4685\, Z_2^{-1/3} & \text{incident ion full ionized} \\ 0.4685\left(\sqrt{Z_1}+\sqrt{Z_2}\right)^{-2/3} & \text{incident ion not full ionized} \end{cases}$$

TABLE II. Values by which the lattice constant must be multiplied to compute the interatomic spacings d in axial directions and the interplanar spacings d_p for planar directions in the simplest (monatomic) cubic structures.

Structure	Atoms per unit cell	Axis ⟨100⟩	Axis ⟨110⟩	Axis ⟨111⟩	Plane (100)	Plane (110)	Plane (111)
fcc	4	1	$1/\sqrt{2}$	$\sqrt{3}$	1/2	$1/2\sqrt{2}$	$1/\sqrt{3}$
bcc	2	1	$\sqrt{2}$	$\sqrt{3}/2$	1/2	$1/\sqrt{2}$	$1/2\sqrt{3}$
fcc (diamond)	8	1	$1/\sqrt{2}$	$\sqrt{3}/4, 3\sqrt{3}/4$	1/4	$1/2\sqrt{2}$	$1/4\sqrt{3}, \sqrt{3}/4$

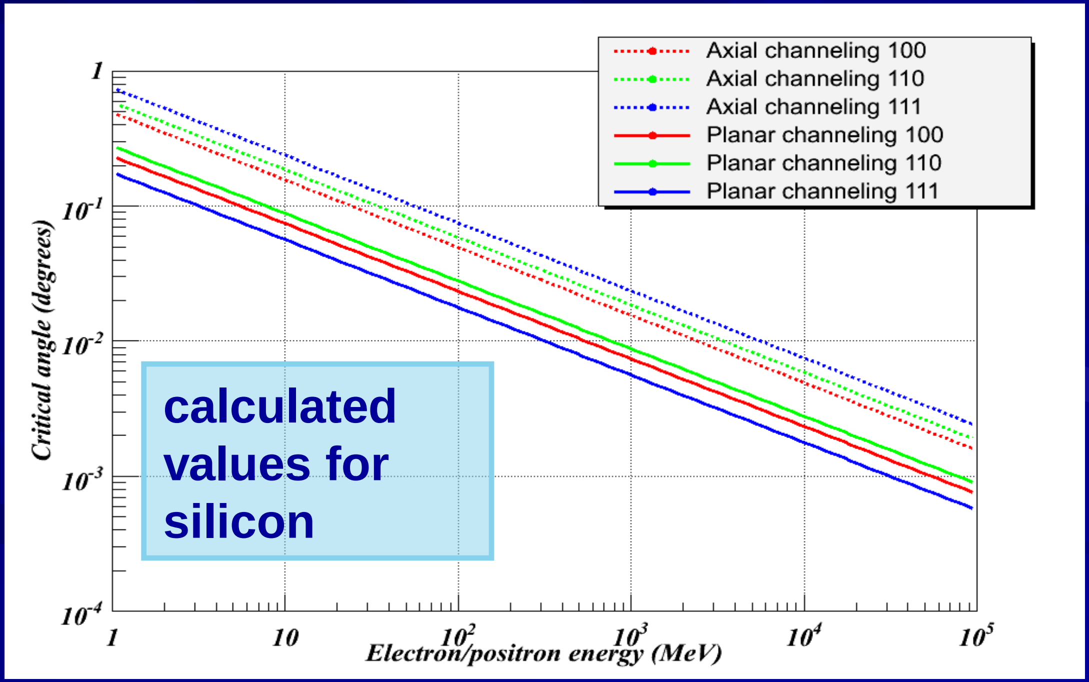
D.S. Gemmell, Rev. Mod. Phys. 46 (1974) 129

Critical angle

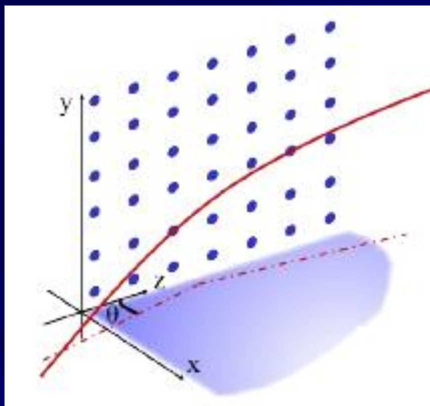


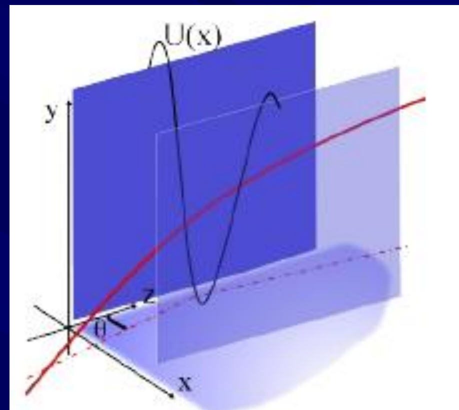
Critical angle in silicon

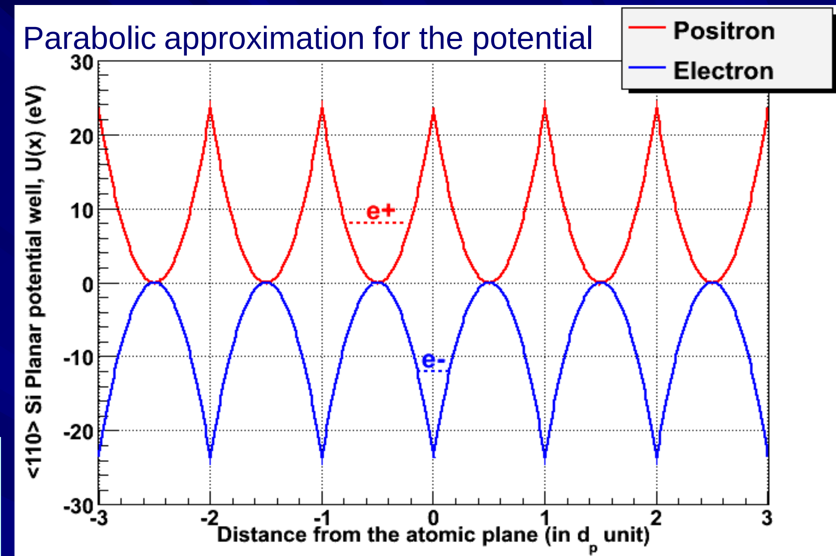
- The critical angle for axial channeling is larger than the one for planar channeling
  - ...but planar channeling effect is easier to achieve
- The critical angle decreases with increasing energy
  - higher beam energy requires better collimation



Energy spectra for <110> planar in silicon

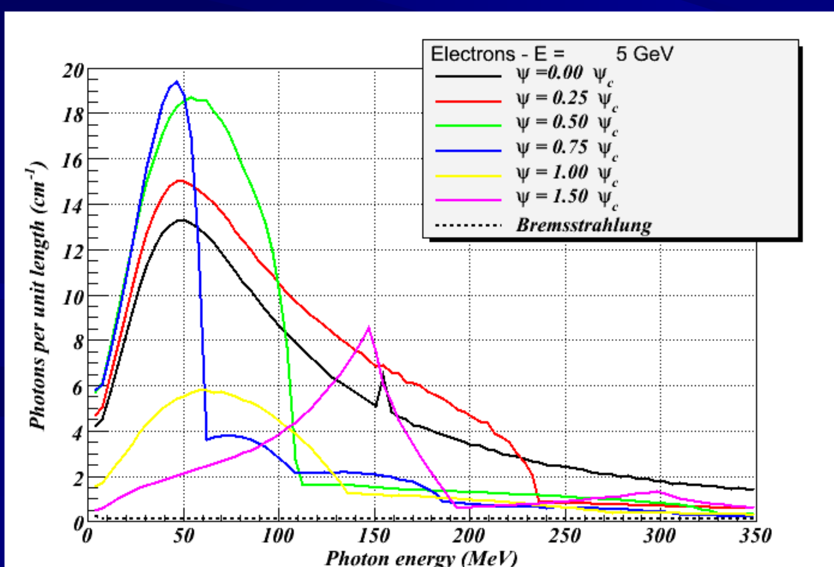


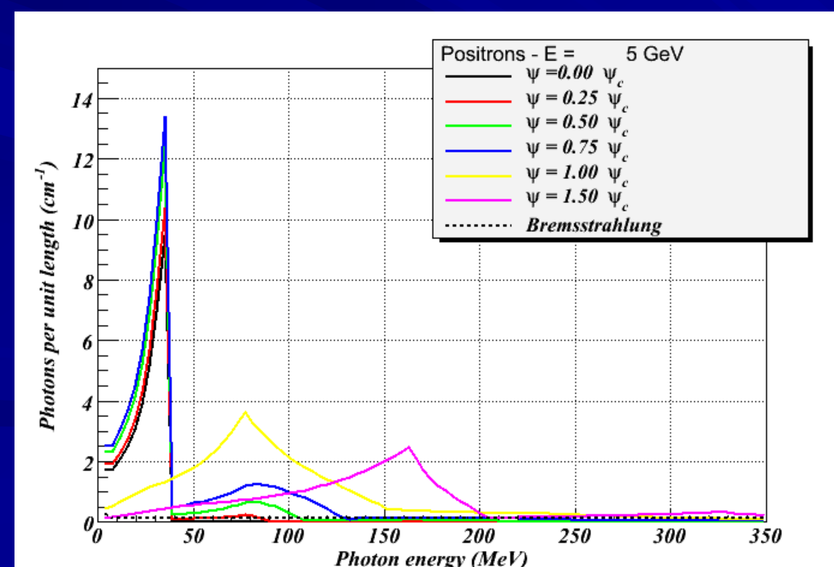




$$U(x) \propto U_m \left(\frac{2}{d_p} x \right)^2$$

$$U_m(eV) = \frac{90.5 N Z_1 Z_2 a}{d^2}$$



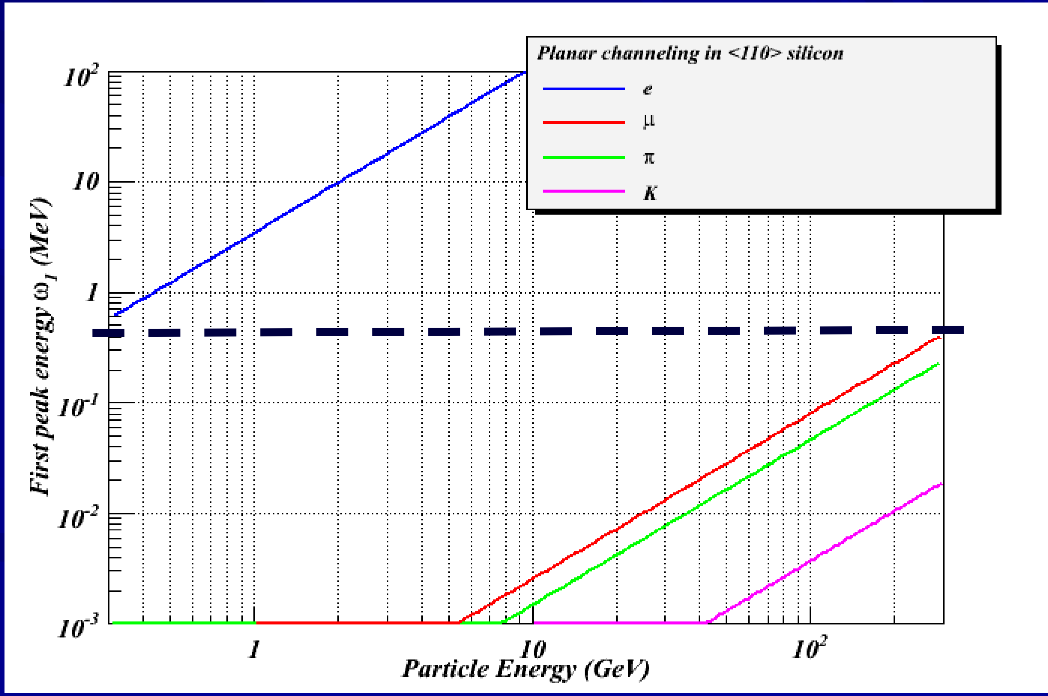


Characteristic frequencies

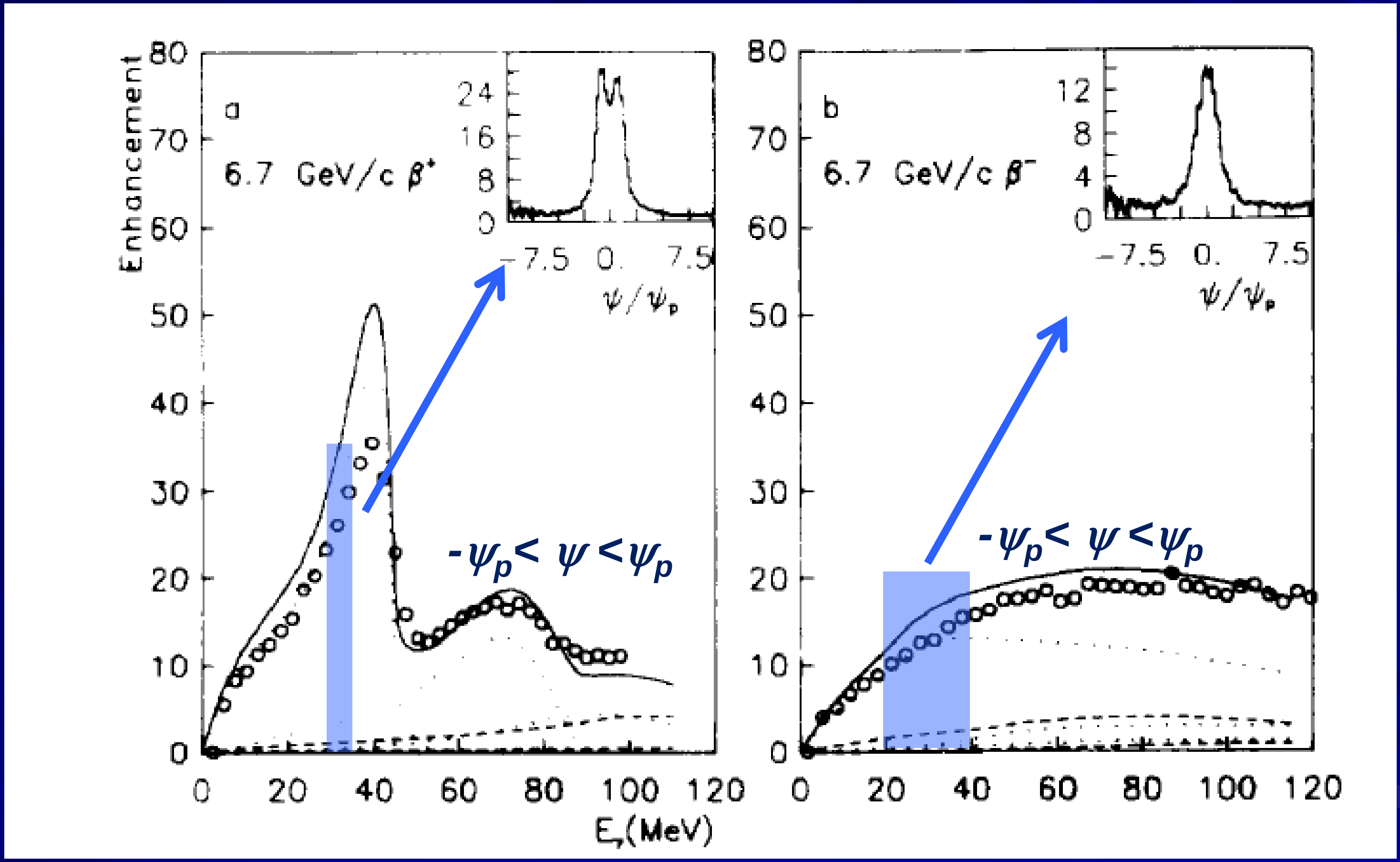
- Intensity spectra show peaks at the frequencies $\omega_k = 2k\gamma^2\Omega$ (k=1,2,3...) where γ is the Lorentz factor of the incident particle

$$\Omega(\mathrm{MeV}) \approx 2\frac{2\cdot 10^{-3}}{d_p(A)}\sqrt{\frac{2U_m}{E}} \Rightarrow \omega_1(\mathrm{MeV}) \approx 4\left(\frac{E}{m}\right)^2 \frac{2\cdot 10^{-3}}{d_p(A)}\sqrt{\frac{2U_m}{E}}$$

- For energies up to a few hundreds of GeV, channeling photons produced by heavy particles are mainly in the energy region below 1MeV
- Channeling photons produced by electrons (positrons) have energies in the range 1-100MeV up to 10GeV beam energy



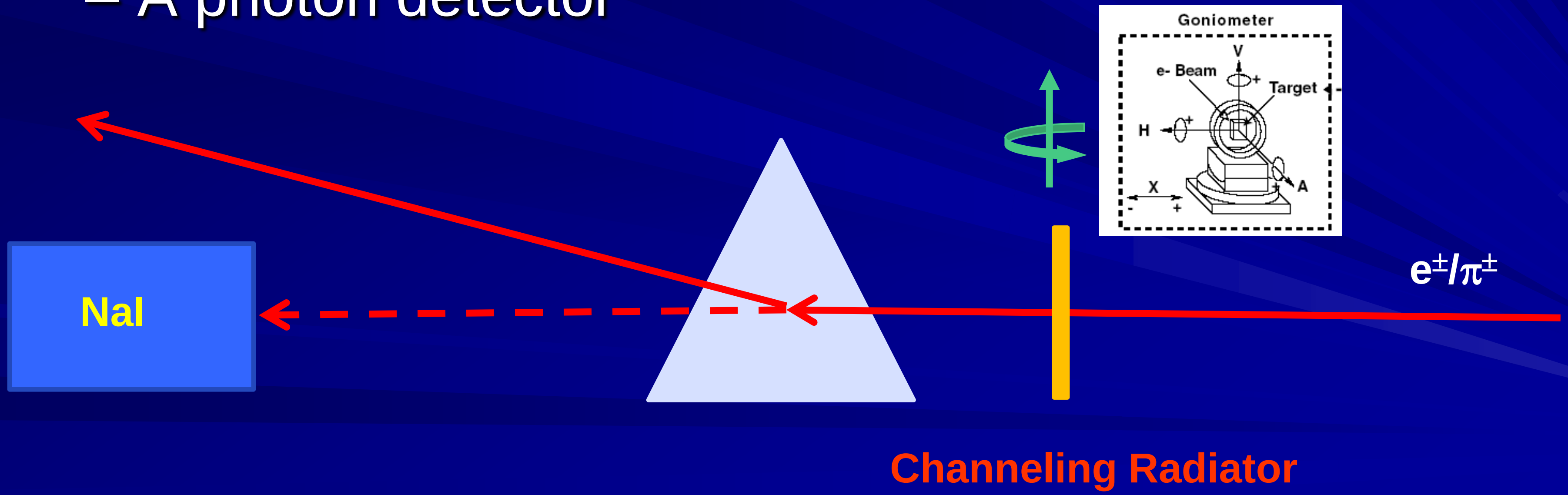
Channeling radiation spectra (J. Bak et al., Nucl. Phy. B254 (1985) 491)



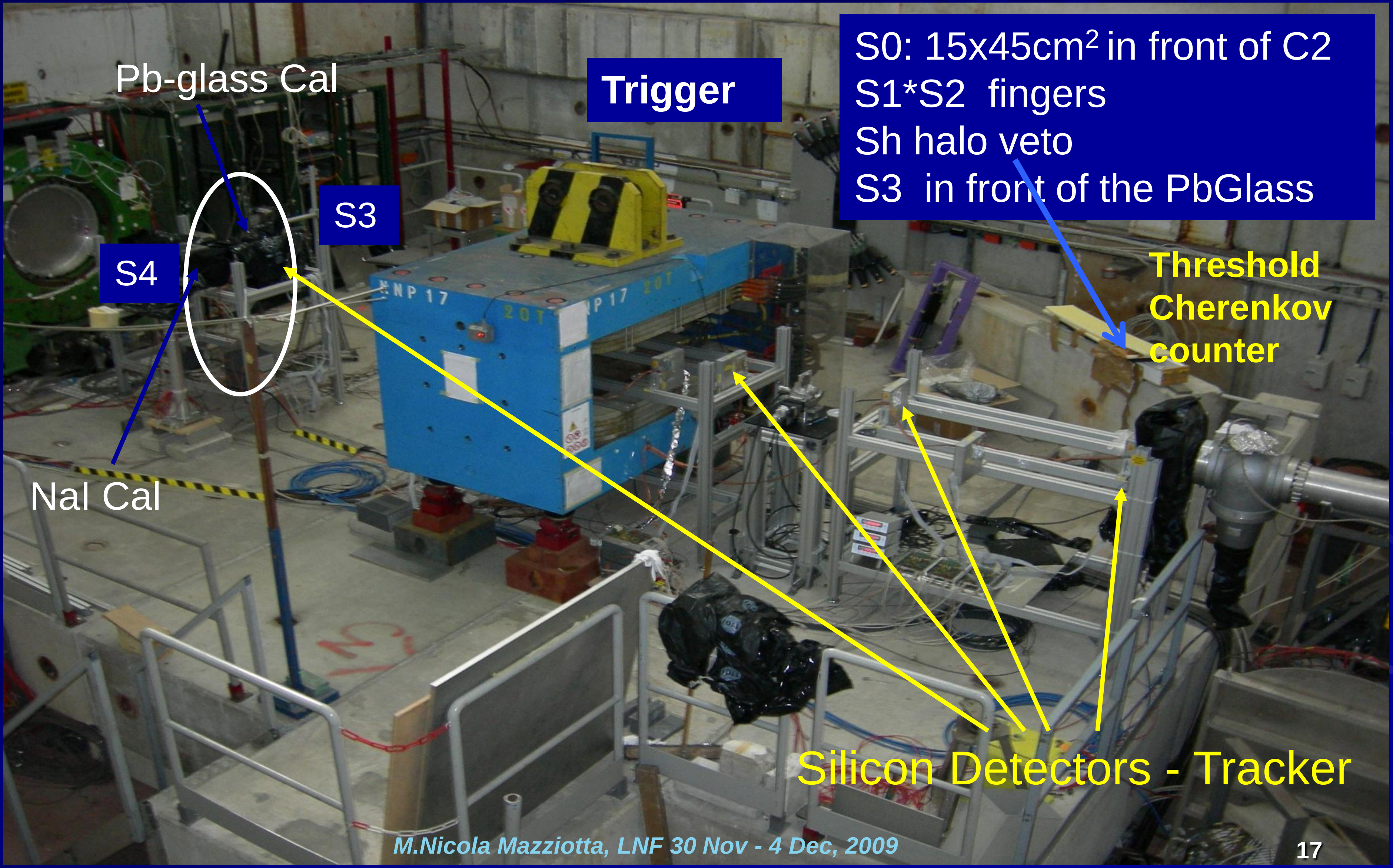
Photon energy spectra (the enhancement is evaluated with respect to the random case) for <110> planar channeling radiation from 6.7 GeV/c positrons and electrons traversing a 0.105 mm thick silicon crystal with incidence angles in (-ψ_p, ψ_p).

How to check the idea

- A beam test is needed
  - A particle beam with different charged particles (i.e. electrons and pions)
  - An oriented crystal to produce channeling photons
  - A magnet to separate the radiation from charged particle
  - A photon detector



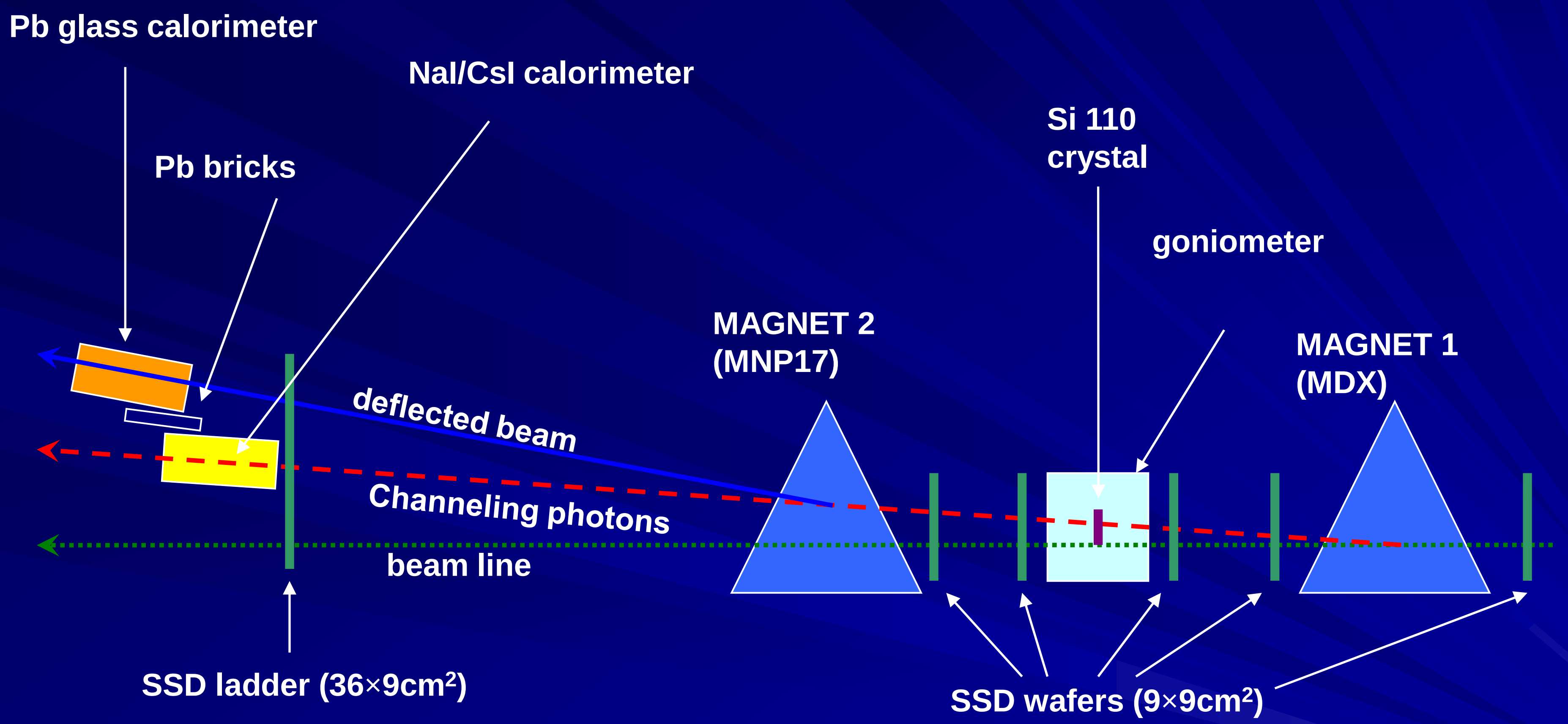
Beam test 2006@CERN PS-T9 line: experimental setup



Beam test set-up

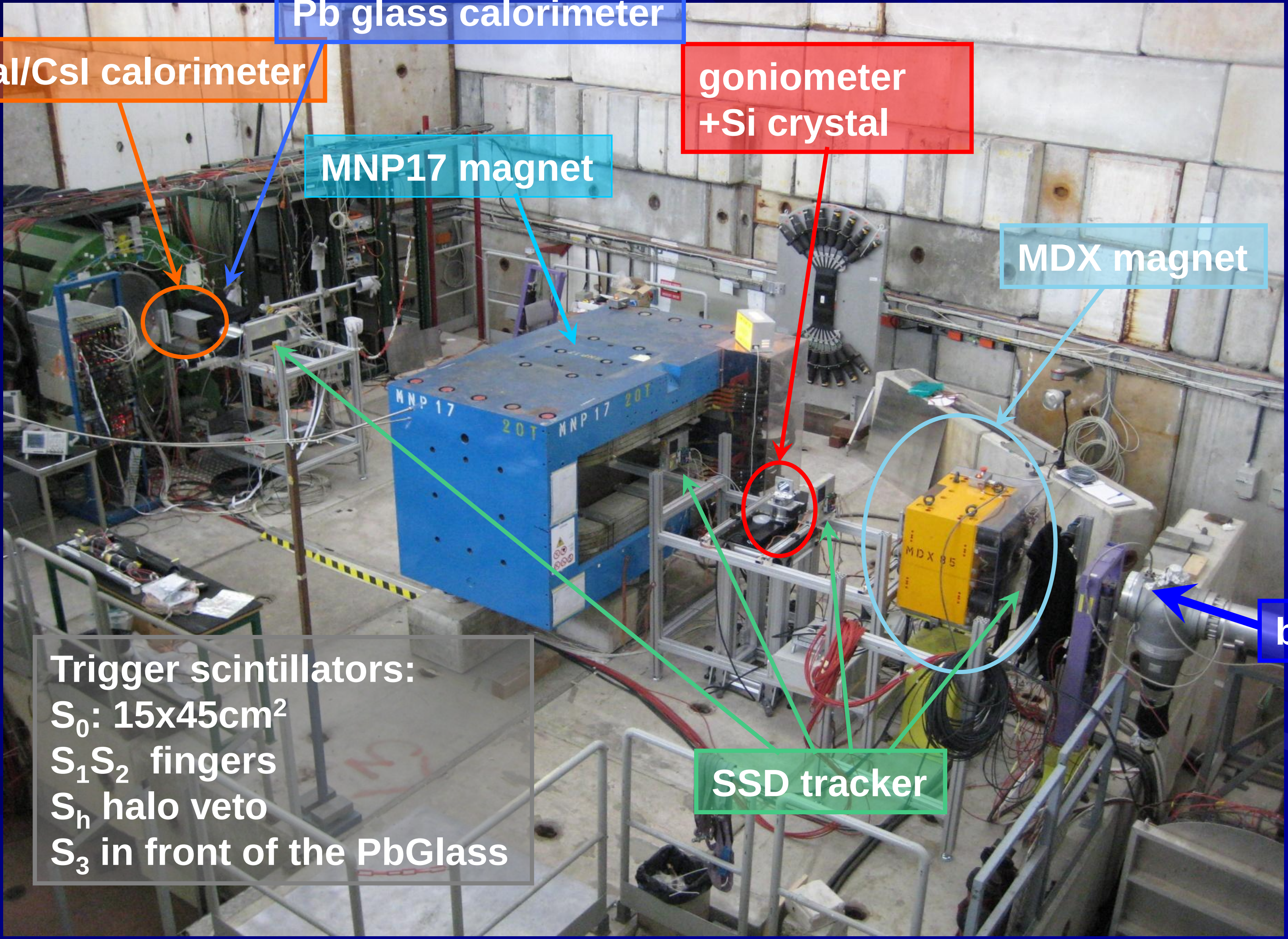
- S0: beam intensity monitor
- S1 and S2: select a small beam spot
- Sh: halo VETO (plastic scintillator with 24 mm hole in the center)
- S3: to select particles entering the Pb-glass calorimeter
- S4: located in front of CsI/NaI CAL and used as trigger (B OFF) or as Veto (B ON)
- SSDs: particle tracking and beam properties studies
  - 6 chambers horizontal and vertical views of single side silicon strip detectors of 384 strips and 228 micron pitch
  - 1 chamber 384 strips vertical view and 4x384 strips in the bending view.
- NaI/CsI CAL: detect channeling photons
- PbGlass: tag electrons/pions in conjunction with upstream Cherenkov counters
- Too much material along the beam line!
  - Additional upstream material is also because of instrumentations to monitor the beam optics along the line
  - Beam contamination due to bremsstrahlung radiation

Beam test at CERN-PS T9 line (2007)

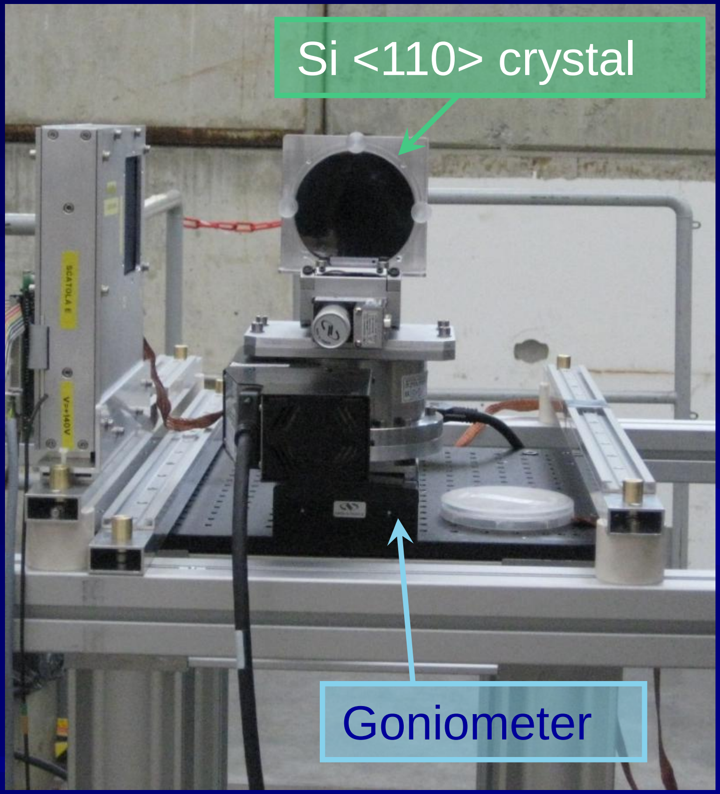


- A set of plastic scintillators were used to provide the trigger
- Two gas Cerenkov counters disposed along the beam line were used together with the Pb-glass calorimeter for particle identification
- The SSDs could be easily removed from the beam line

Beam test 2007: experimental set-up



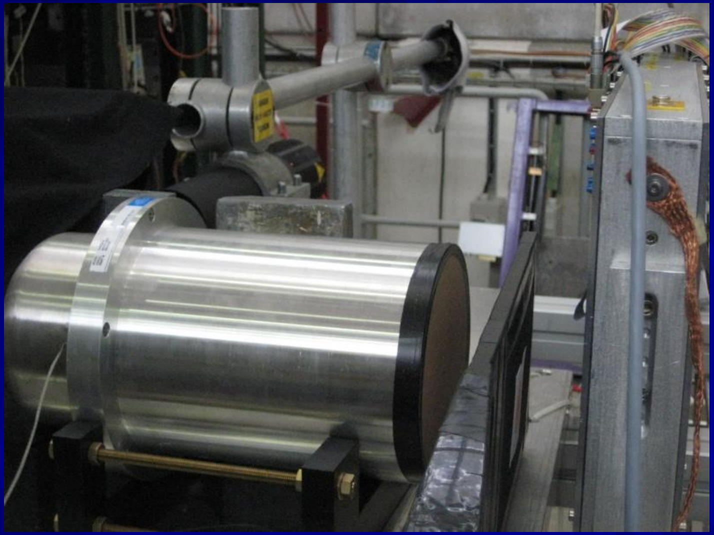
The crystal and the goniometer



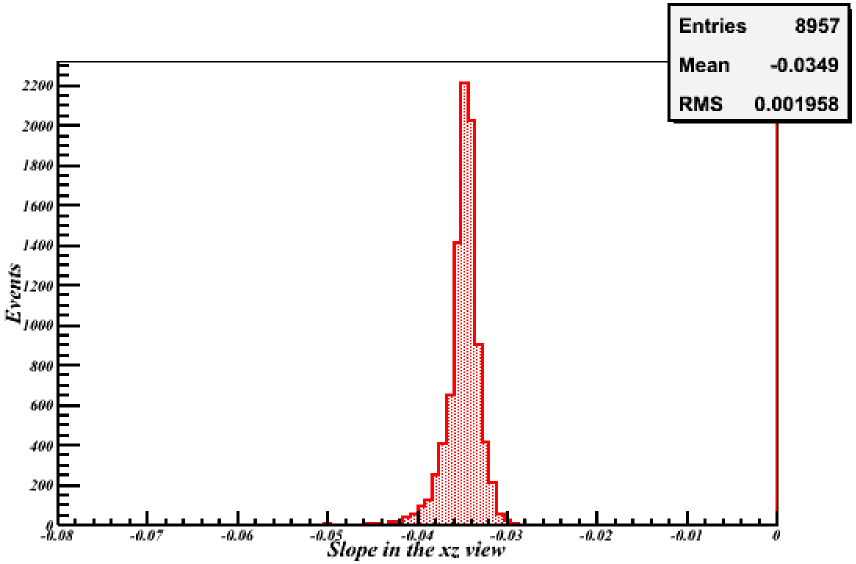
- Si <110> oriented crystal
  - thickness = 500µm (0.5%X_0)
  - miscut angle = 0.1°
- 3-axis goniometer + linear stage (Newport)
  - 0.001° angle precision
  - The linear stage allows to remove the Si crystal from the beam
  - custom control software

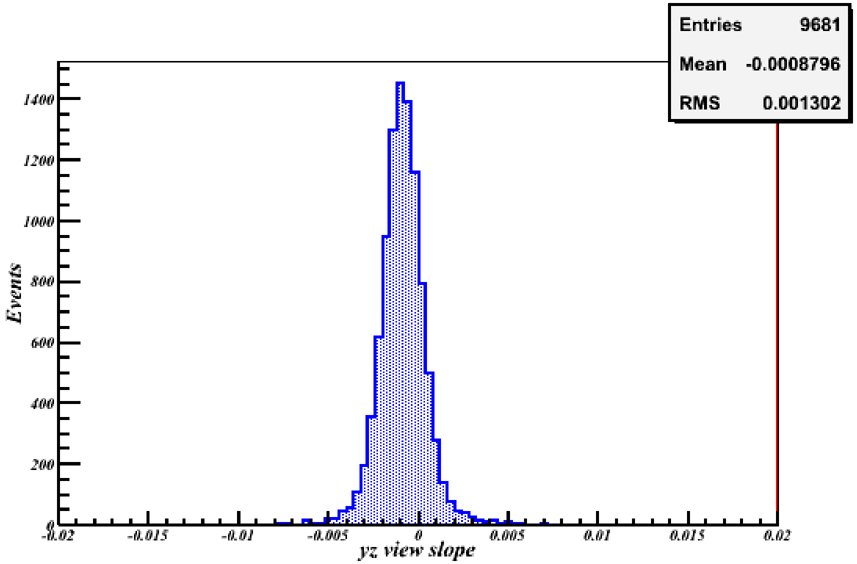
The E.M. calorimeters

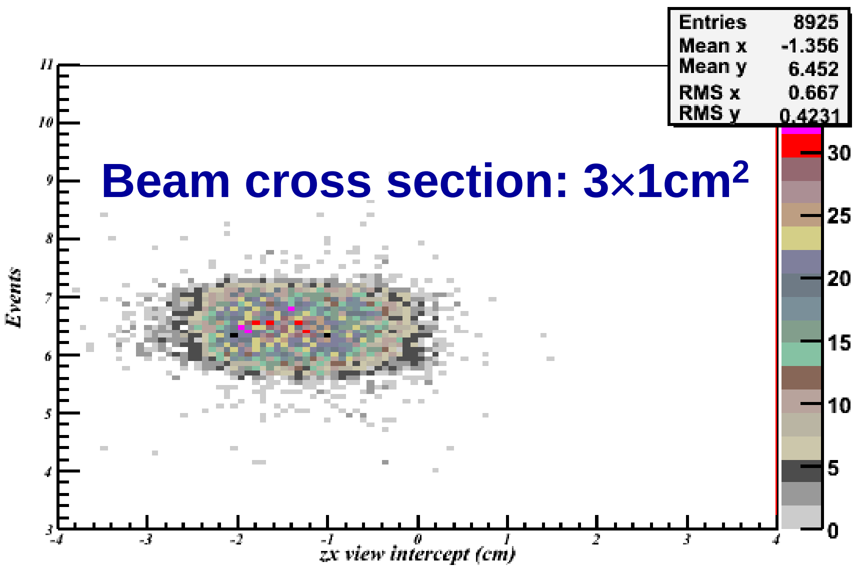
- NaI calorimeter:
  - single NaI crystal, 6'' diameter, 8'' length
  - the crystal is readout by a 5'' diameter XP3550 PMT
- CsI segmented calorimeter:
  - 7 layers (4 horizontal + 3 vertical view), each composed by 3 CsI bars, $3\times3\text{cm}^2$ cross section, 12cm length
  - 21cm total length
  - The bars are readout at both ends by two PIN PDs ($18\times18\text{mm}^2$ and $10\times10\text{mm}^2$)
- The calorimeters have been calibrated with an electron beam with energies up to 500MeV at INFN-Frascati BTF facility



Study of the beam divergence at PS-T9





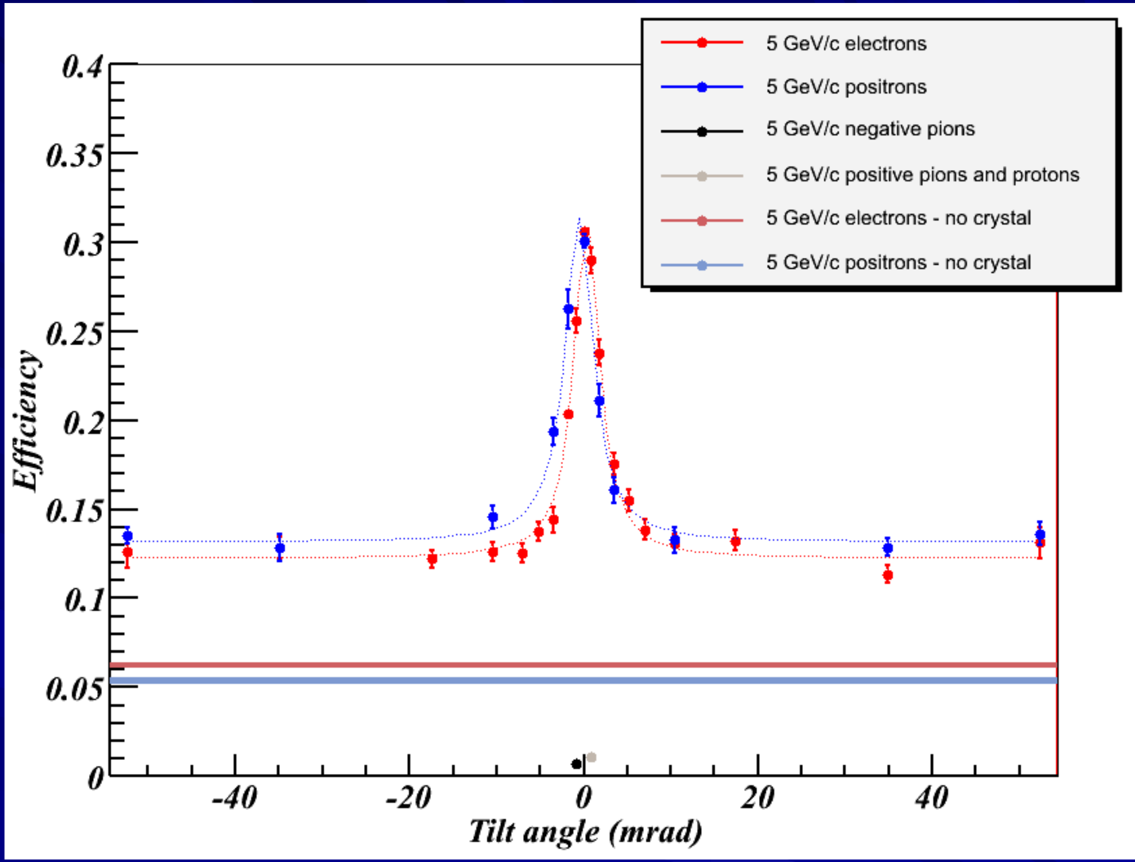


Beam cross section: 3×1cm^2

- **Study performed with 5 GeV/c electrons and pions**
- **Beam divergence:**
  - **2 mrad in the bending plane**
  - **1.3 mrad in the not-bending plane**
- **Electron critical angle is about 0.15 mrad (i.e. 0.1 beam divergence)**
  - **Low efficiency is expected**

Photons Vs Si <110> tilt angle

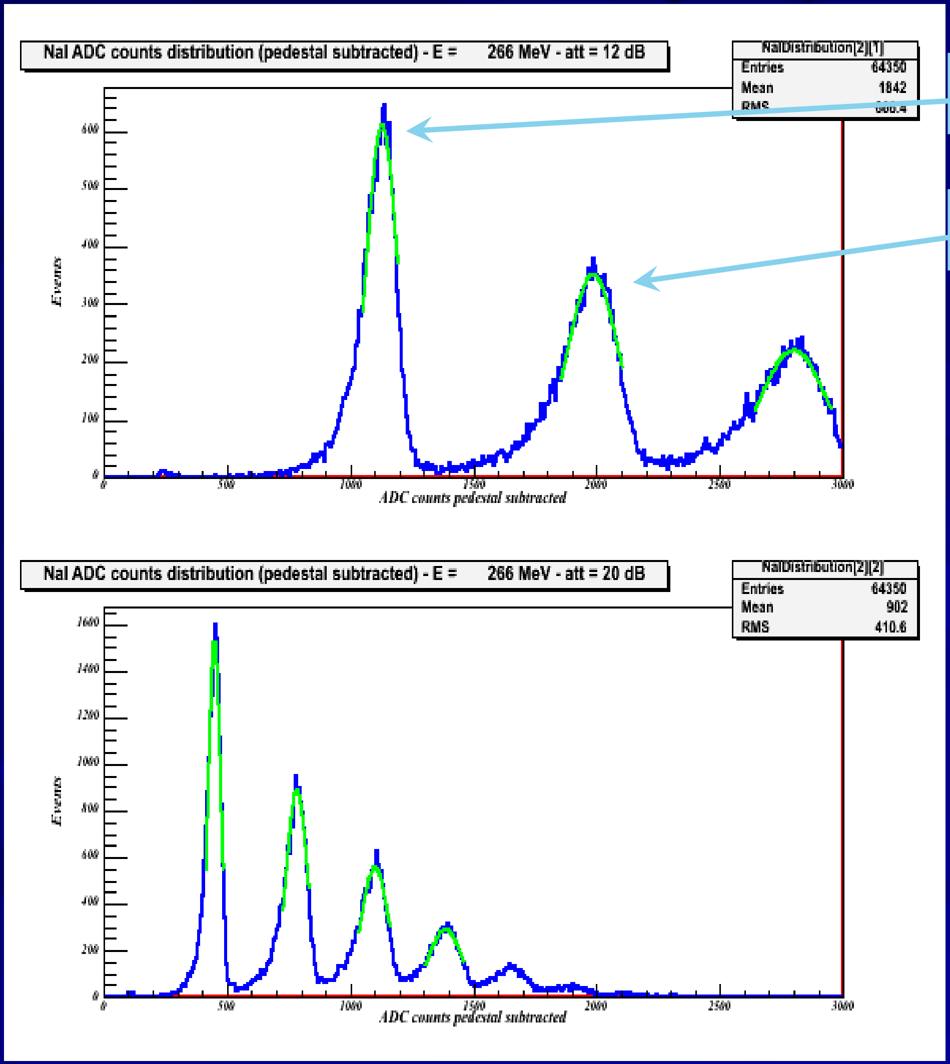
- SSDs removed from the beam line
- No selection on incoming and outcoming particle direction
- measurement performed with the NaI calorimeter
- efficiency = fraction of events with charge > ped+3σ in the NaI calorimeter
- energy threshold: 3σ≈1.0MeV



- An efficiency peak is found for both electrons and positrons with SNR≈4
- The FWHM of the peak is about 4 mrad (i.e. the beam divergence)
- Pion background → photon detection efficiency ≈ 0.01

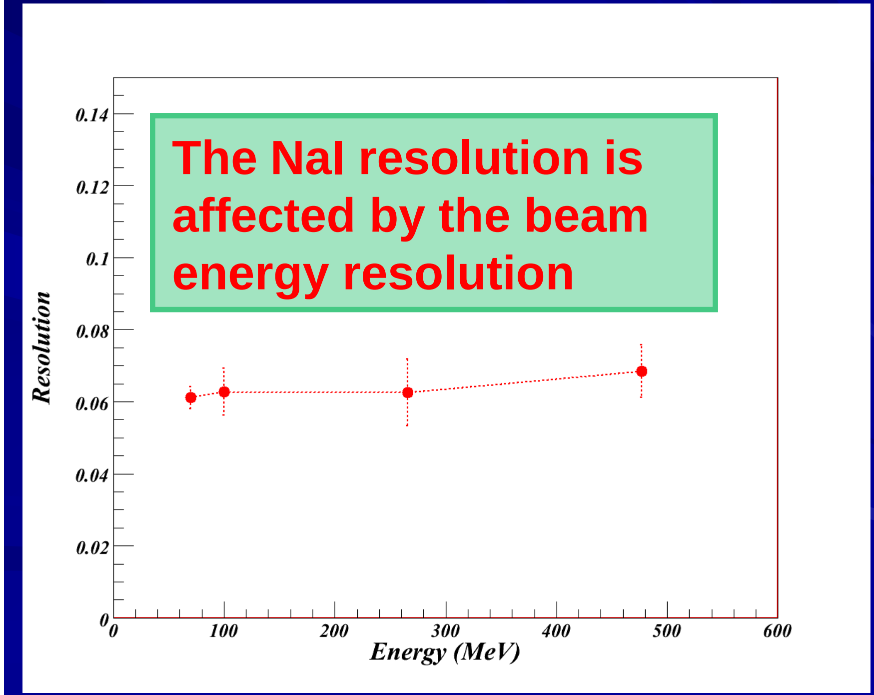
Calorimeter energy response

- The calorimeters were calibrated at the BTF facility in Frascati with an electron beam with energies up to 500MeV

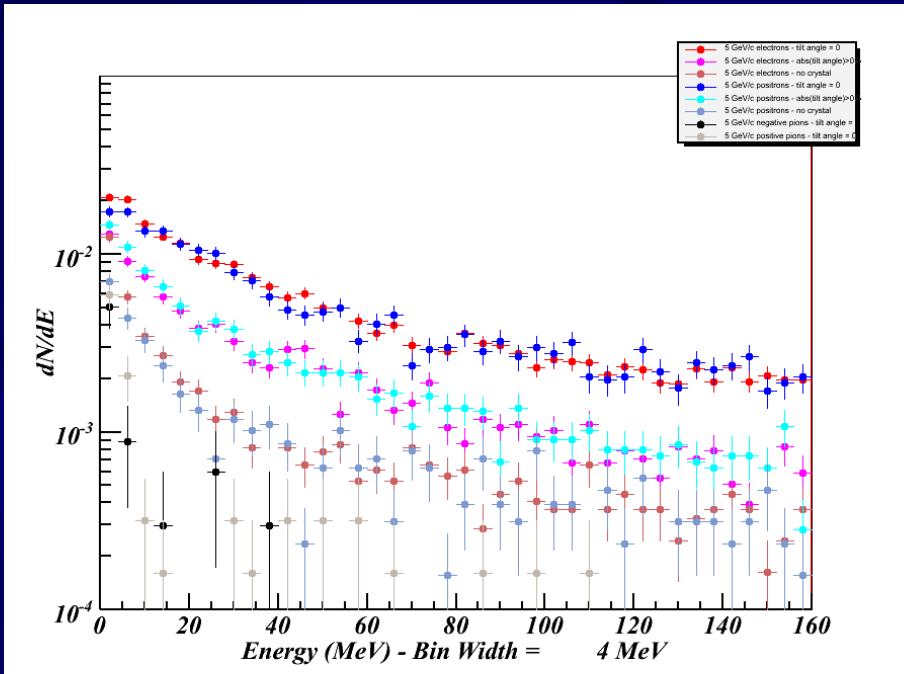


single electron peak

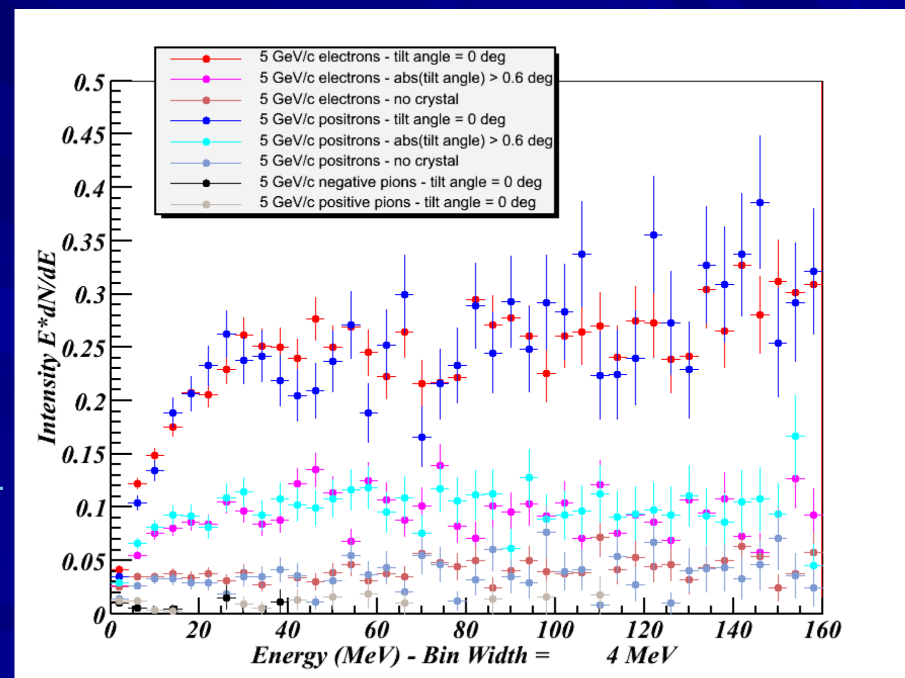
double electron peak



Energy and intensity spectra



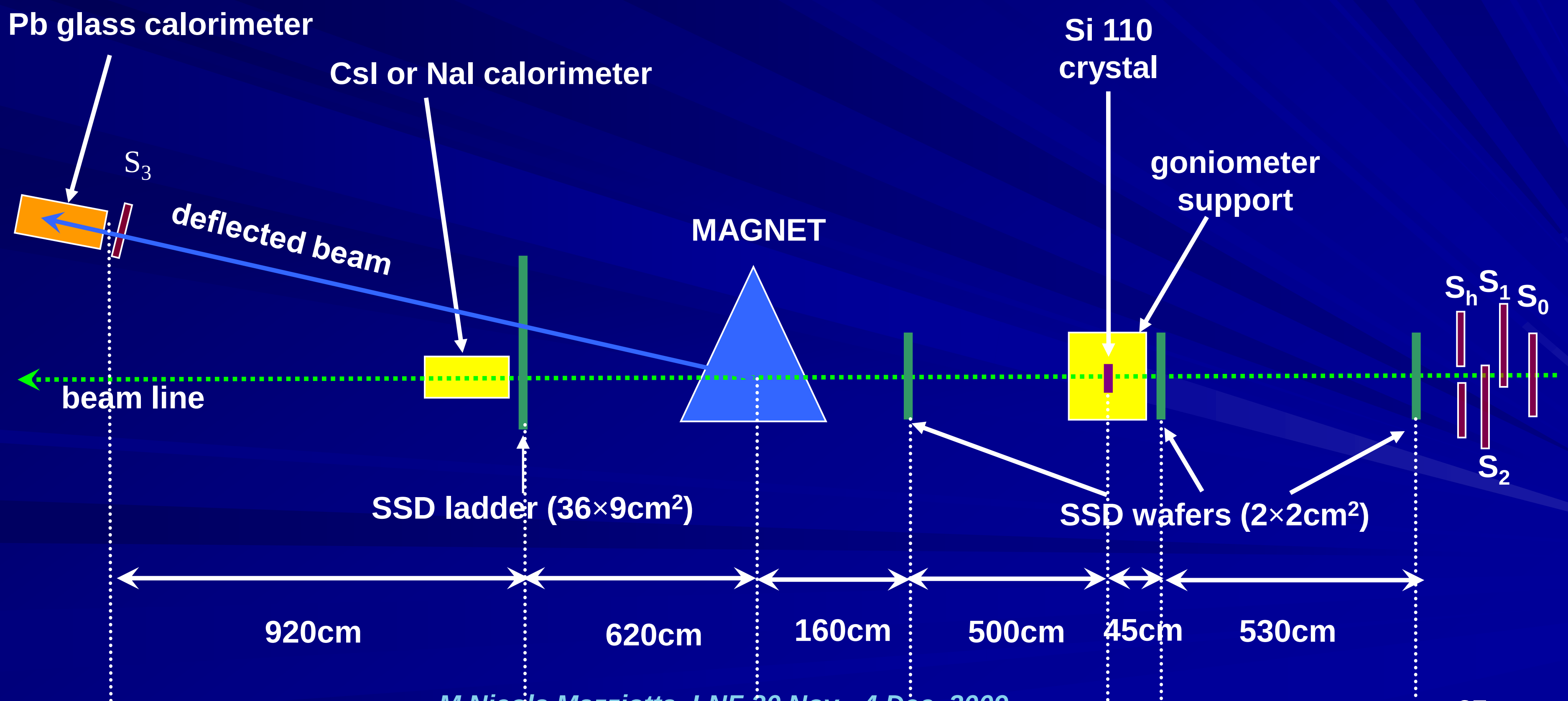
Energy spectra measured with the NaI calorimeter



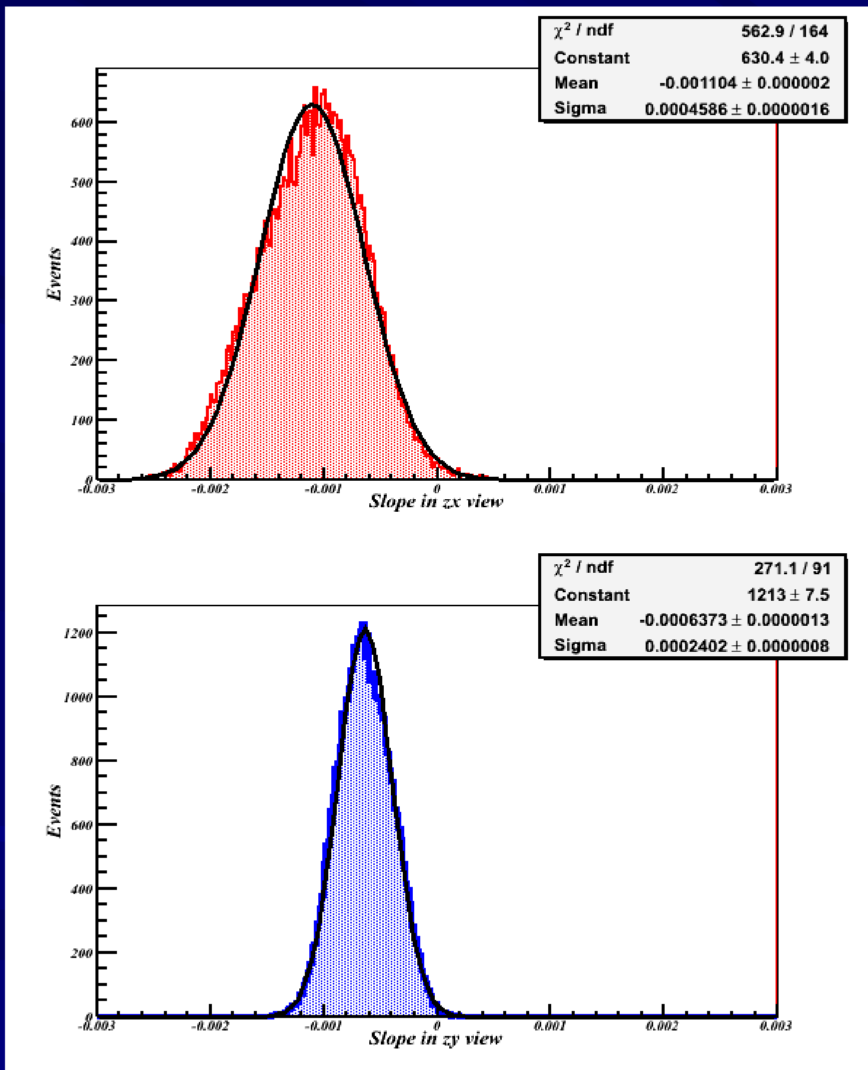
- **Photon intensity spectra at channeling angle exhibit a peak at 30 MeV, consistent with the expected value of ω_1**
- **Intensity spectra at angles far from the channeling peak are almost flat**
- **A flat background of ≈0.03 photons/beam particle is observed**

Beam test at CERN-SPS H4 line (2008)

- A single magnet has been used in the set-up
  - Large background expected due to the beam interaction with upstream materials
- The H4 line provides clean beams (electron/positron/hadron)
  - A Pb-glass calorimeter has been used to improve the electron/hadron identification



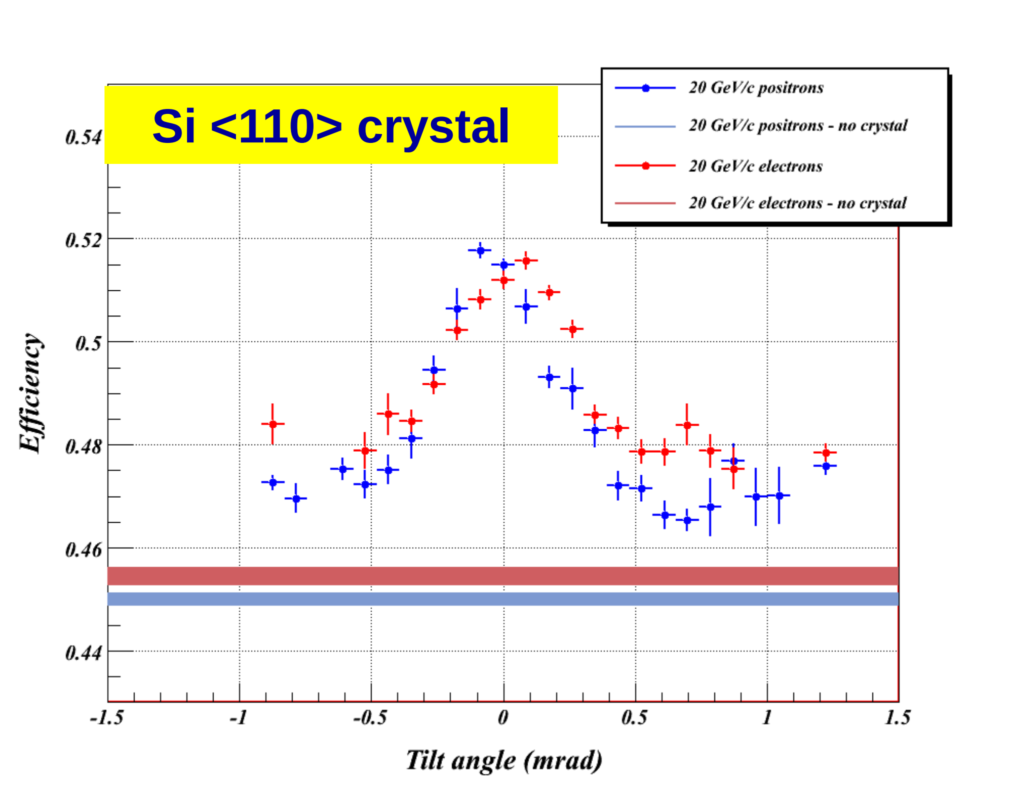
Study of the beam divergence at SPS-H4



- **Study performed at 20 GeV/c**
- **Beam divergence:**
  - **0.46 mrad in the bending plane**
  - **0.24 mrad in the perpendicular plane**
- **Electron critical angle is about 0.06 mrad (i.e. 0.1 beam divergence)**
  - **Low efficiency is excepted**

Photon Efficiency vs tilt angle at 20 GeV

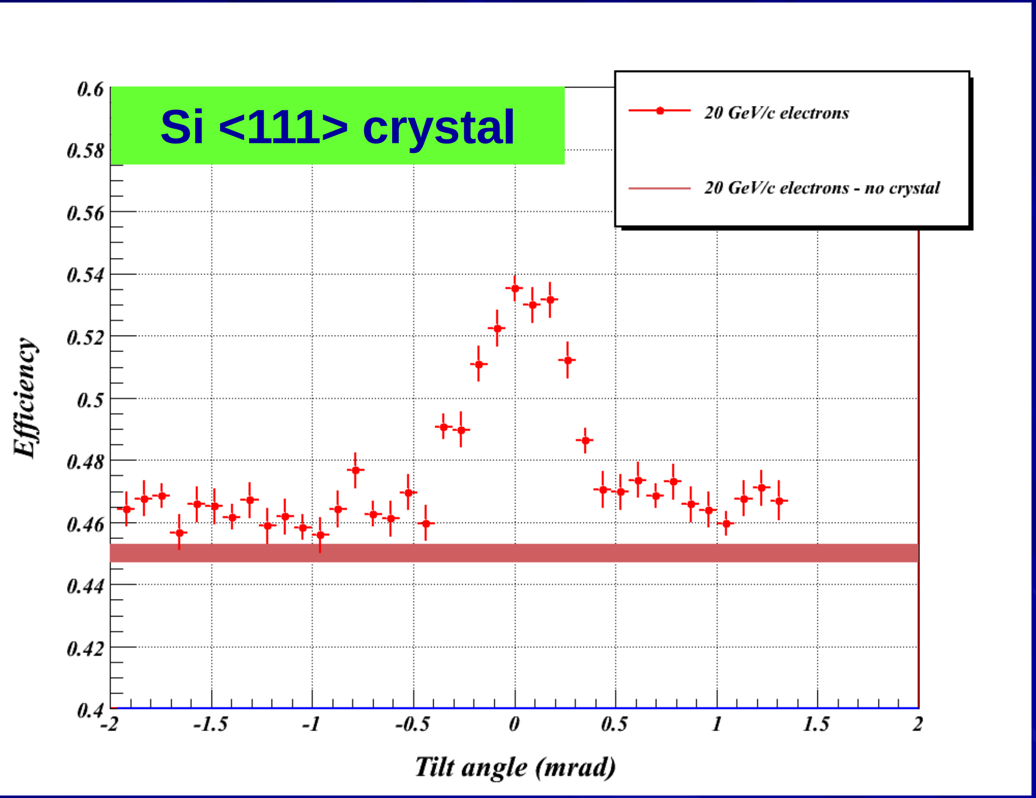
- SSDs removed from the beam line
- No selection on incoming and outcoming particle direction
- measurement performed with the NaI calorimeter
- efficiency = fraction of events with charge > ped+3σ in the NaI calorimeter
- energy threshold: 3$\sigma \approx$1.0MeV



- An efficiency peak is found for both electrons and positrons with SNR≈4
- The FWHM of the peak is about 0.5mrad (i.e. the beam divergence)
- Pion background → photon detection efficiency < 10^{-3}

Photon Efficiency vs tilt angle at 20 GeV

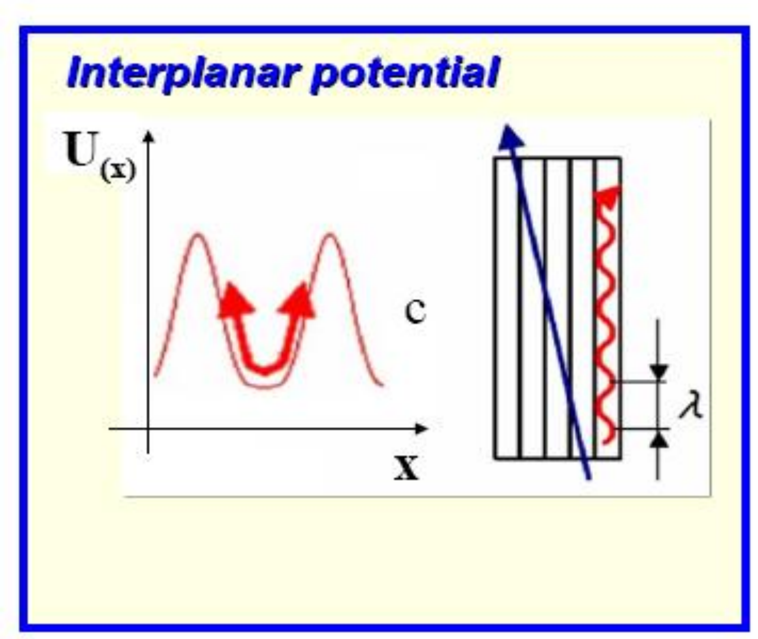
- SSDs removed from the beam line
- No selection on incoming and outcoming particle direction
- measurement performed with the NaI calorimeter
- efficiency = fraction of events with charge > ped+3σ in the NaI calorimeter
- energy threshold: 3σ≈1.0MeV

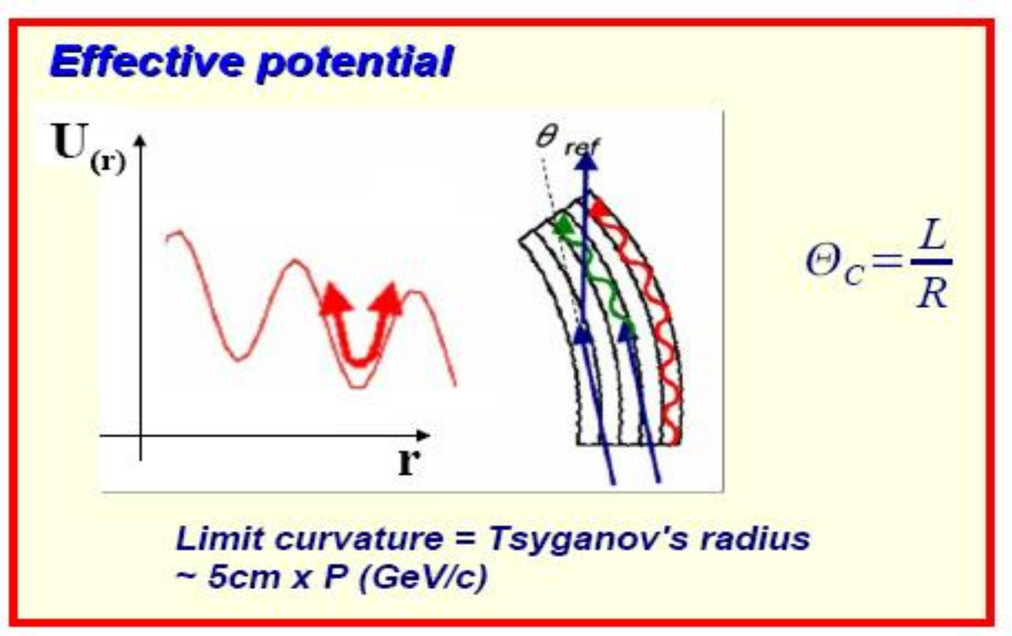


- An efficiency peak is found for electrons with SNR≈4
- The FWHM of the peak is about 0.5mrad (i.e. the beam divergence)
- Pion background → photon detection efficiency < 10^{-3}

Channeling in bent crystals

- *E. N. Tsyganov (1976): channeling in bent crystals*
  - *CRYSTALS can be used to deviate particles*
  - *First experimental evidence: FNAL 1979*

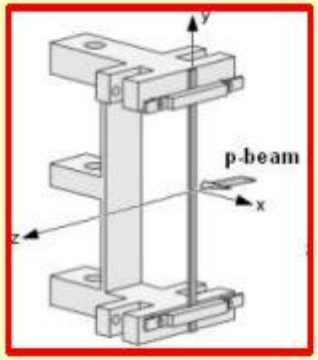


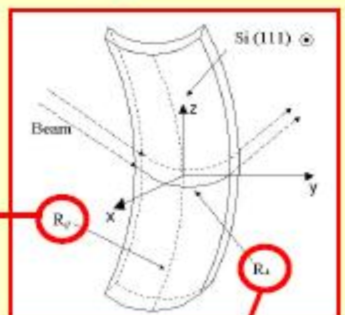


Credits: Michela Prest et al.
http://insulab.dfm.uninsubria.it/images/download_files/public/presentations/seminar_geneve.pdf

Silicon Bent Crystals layout

STRIP CRYSTALS



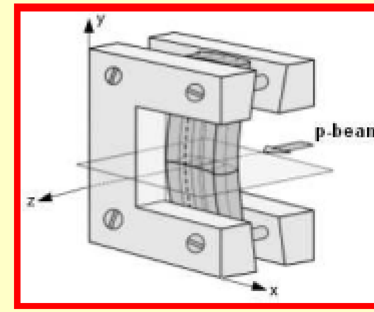


primary curvature

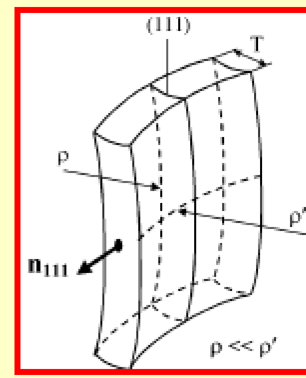
secondary curvature generated by the anticlastic forces

INFN Ferrara and IHEP

QUASIMOSAIC CRYSTALS



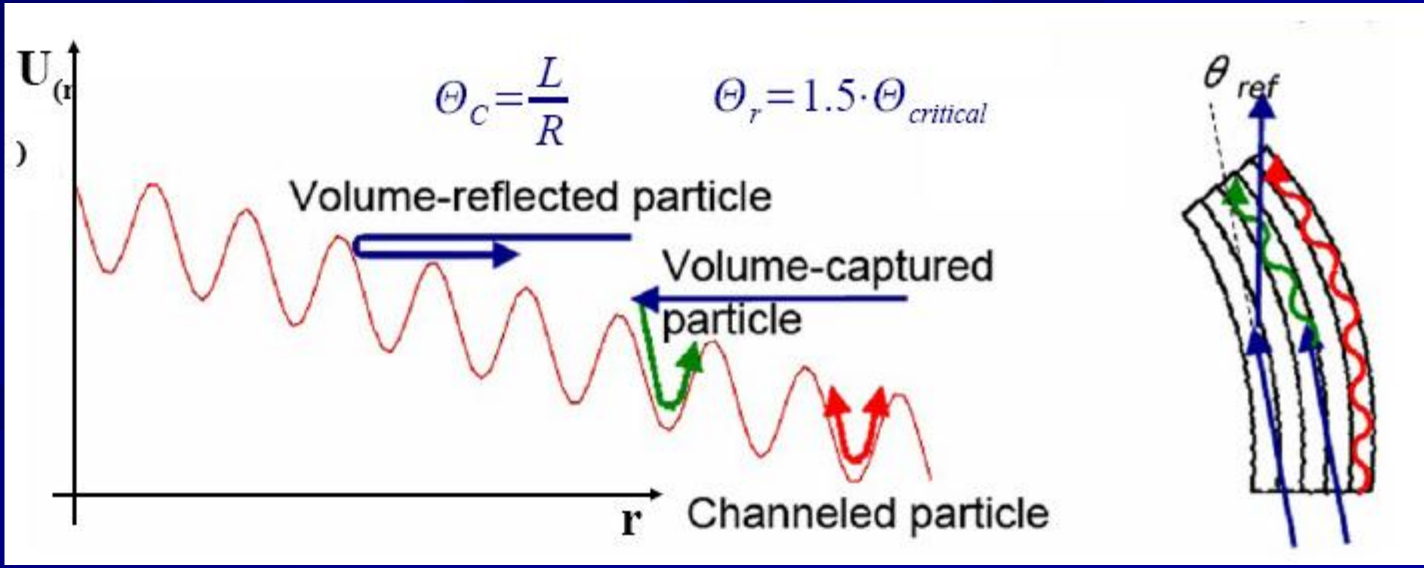
- The (111) crystalline planes are normal to the large face and parallel to the edges
- The crystal is bent in the yz plane → ρ = principal curvature
- The anticlastic forces produce the secondary curvature (ρ') in xz (quasimosaic curvature)



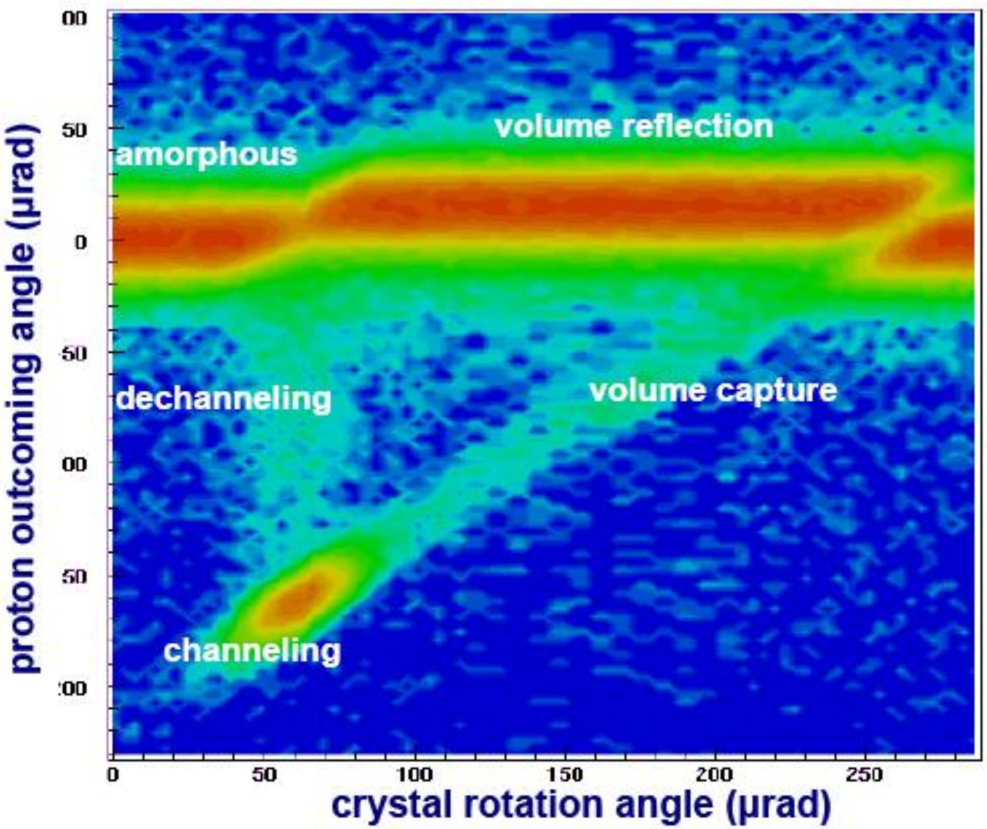
PNPI

Volume Reflection Effect

- New phenomena: an initially misaligned particle becomes tangent with a channel
  - volume capture if the particle enters in channeling losing energy
  - volume reflection if the effective potential reflects it
    - High efficiency



First observation @400GeV/c: CERN (2006)



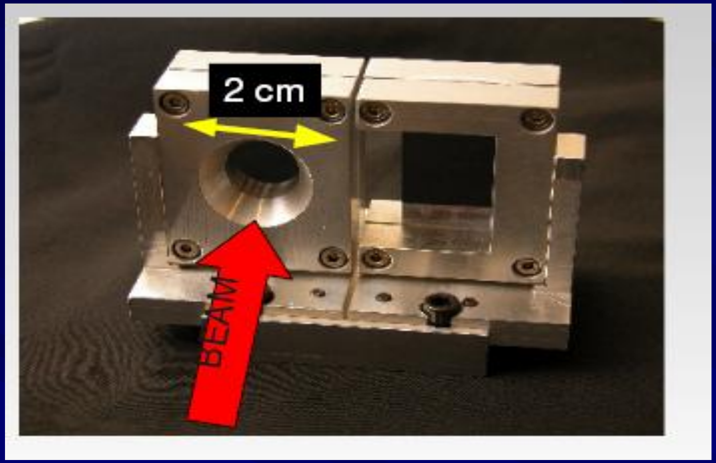
Single strip crystal

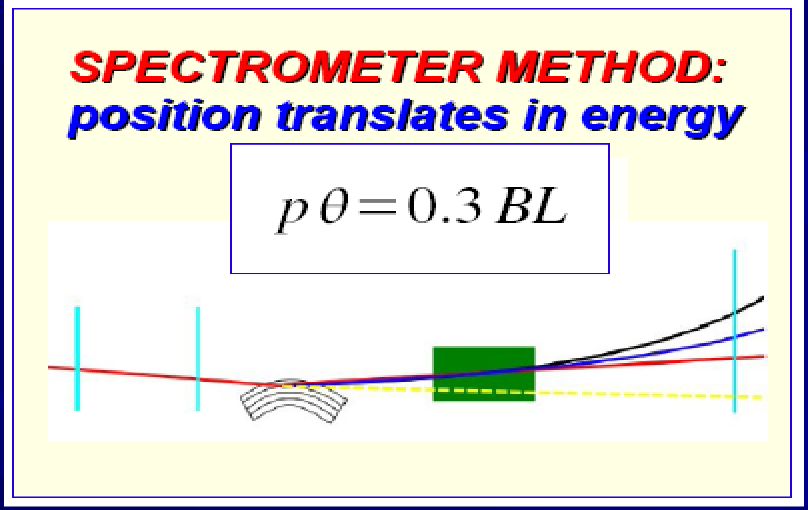
- *First measurement* of the volume reflection effect with a proton beam of 400 GeV/c

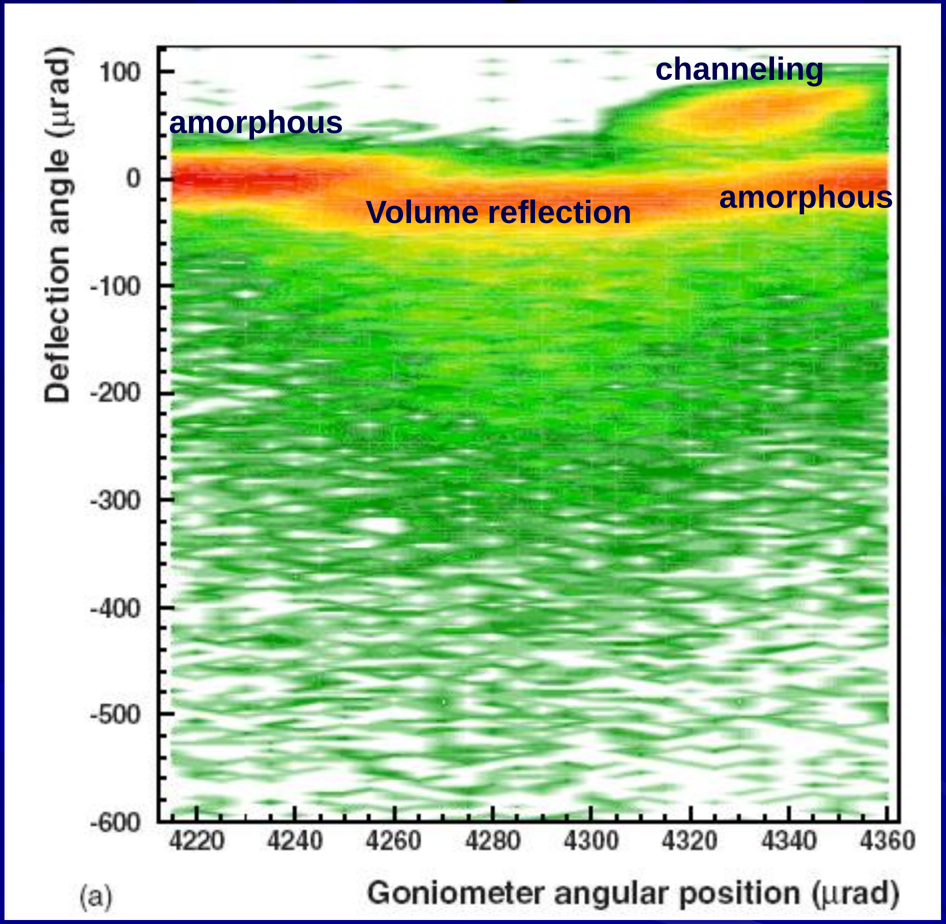
EFFICIENCY	VALUE
VOLUME REFLECTION	$98.2 \pm 0.1\%$
CHANNELING	$51.2 \pm 0.7\%$
VOLUME CAPTURE	$1.3 \pm 0.1\%$
DECHANNELING	$5.0 \pm 0.4\%$

W. Scandale et al. PRL 98, 154801 (2007)

Radiation emitted in a bent crystal



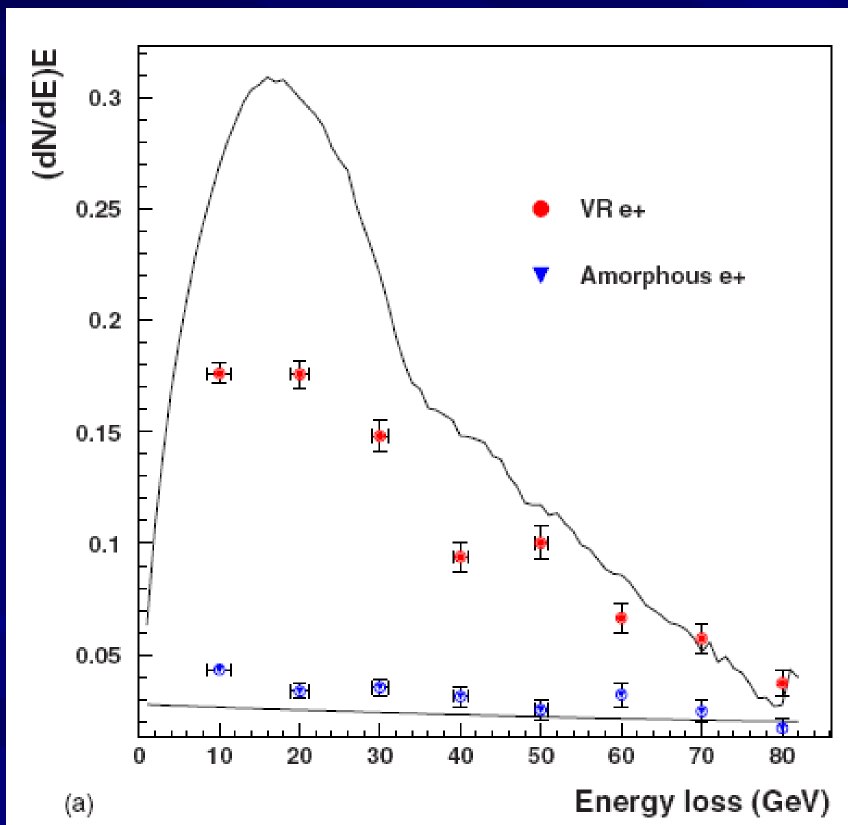




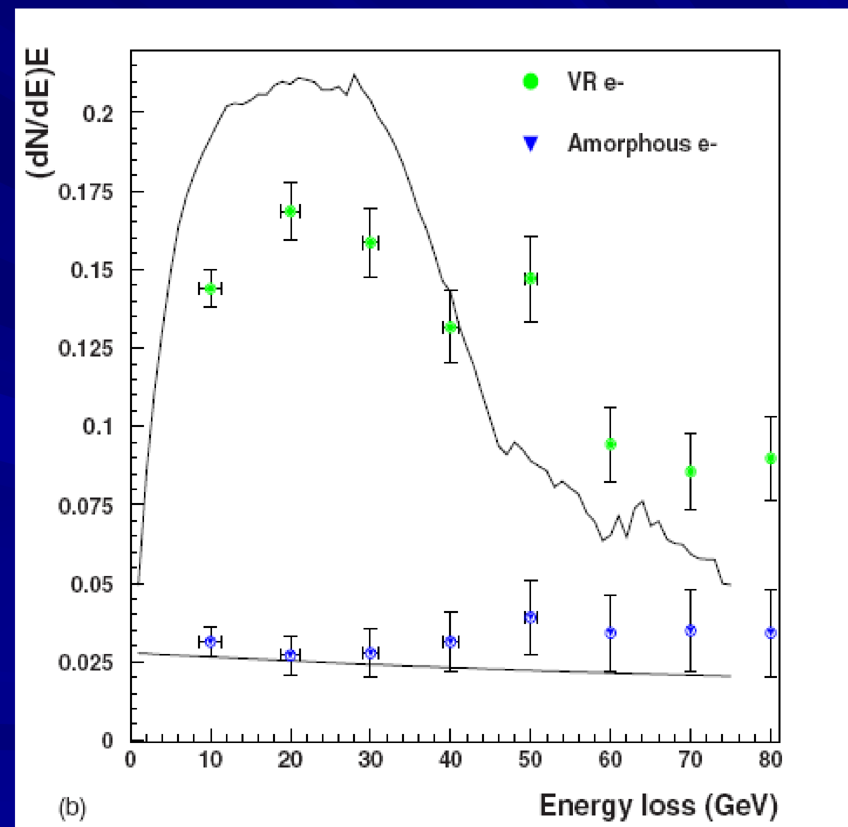
Electron/positron at 180 GeV/c CERN SPS-H4 (D. Bolognini et al., PHYSICAL REVIEW A 79, 012903 2009)

Radiation emitted in Volume reflection

Positrons



Electrons



Conclusions

- A measurement has been performed of the channeling radiation emitted by electrons and positrons crossing a 500μm thick (0.5%X_0) <110> and <111> silicon crystals
  - the channeling peak has been found, even though the beam divergence was ~10 times larger than the expected channeling angle
    - a SNR~4 has been observed at the channeling peak
  - no significant differences found between e^+/e^-
    - Probably due to the large beam divergence
- No radiation has been found from pions
  - Some signals have been measured due to pedestal fluctuations
- Bent crystals could be used to increase the efficiency looking into the volume reflection