Measurement of deflection efficiency and nuclear de-channeling length using short bent silicon crystals

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Outlook

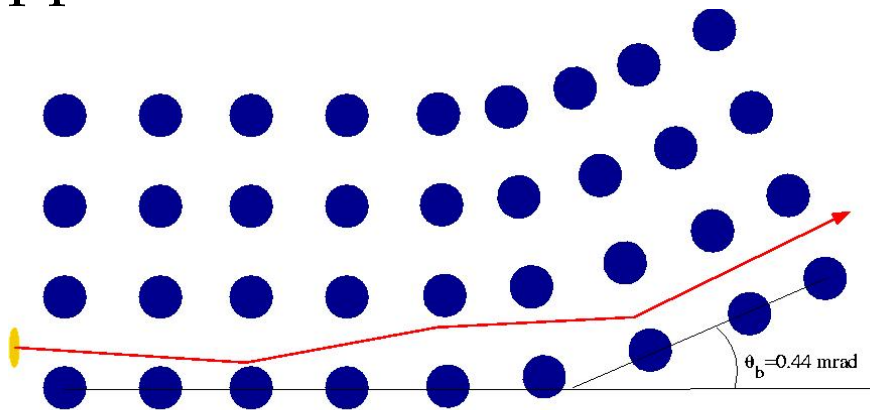
- Channeling phenomena
  - Brief overview
- H8-RD22 experiment at the CERN SPS
  - Experimental layout and tracking detectors
  - Proton beam
  - Goniometric system
  - Silicon crystals
  - 2007 data taking and analysis
  - Results on deflection efficiency and nuclear de-channeling length
- Conclusive remarks

Channeling phenomena

Channeling in crystals (1)

- Charged particles entering a crystal nearly parallel to a planar (axial) direction will be trapped and oscillate in potential wells
- Critical angle (θ_C)
  - Angular acceptance for channeling
  - $\theta_C \sim 10$ μrad for 400 GeV/c protons on Si

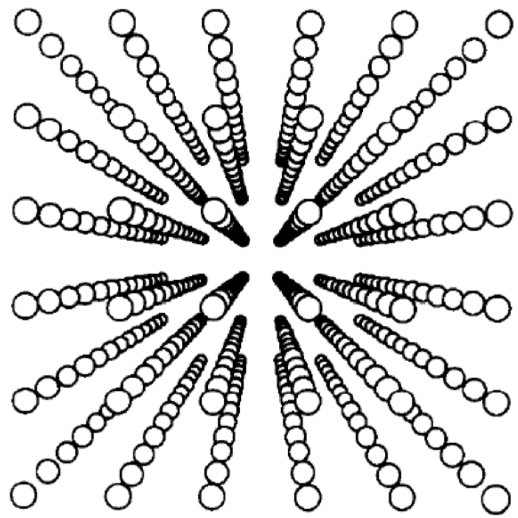
$$\theta_C = \sqrt{\frac{2U_0}{pv}}$$



- De-channeling: due to multiple scattering, transverse energy increases with penetration depth → channeled particles may become transferred to the "random" beam
  - for well-channeled particles, de-channeling process is an exponential depletion of the number of channeled particles → de-channeling length
- A bent crystal can be used to steer particles through channeling (up to a critical curvature)

Channeling in crystals (2)

- Axial channeling
  - incident particle aligned to crystallographic axis (complicated field from atomic strings)
  - critical angle is ~3 times higher than in planar case (de-channeling length is larger)
  - requires low beam divergence and good alignment in both planes

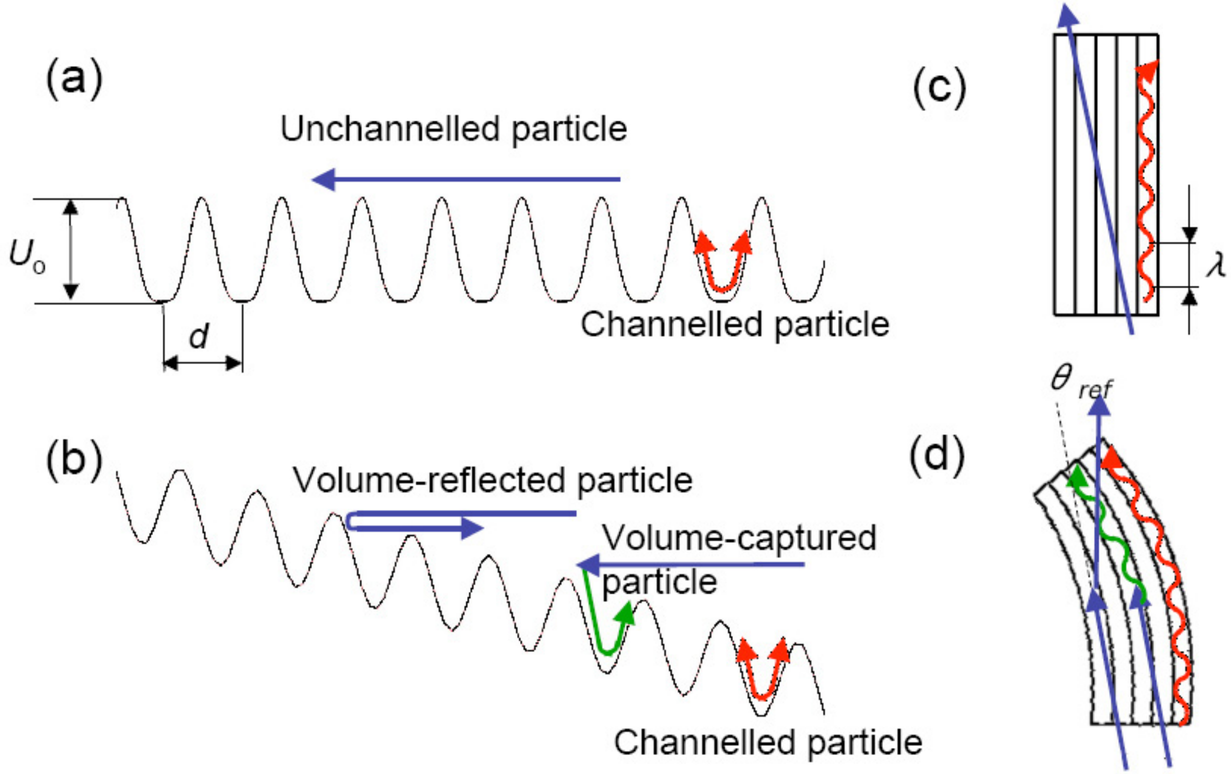


- Negative particles
  - focused around atomic planes (strings) → larger multiple scattering → de-channeling length shorter than for positive particles (10 times or even more)
- Applications to HEP
  - Beam bending, extraction, splitting, attenuation
  - Measurement of magnetic moment for short-lived particles
  - Halo cleaning in hadronic machines (LHC, Tevatron)
  - Diffractive physics (TOTEM experiment)

Volume Reflection effect

Possible processes:

- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection

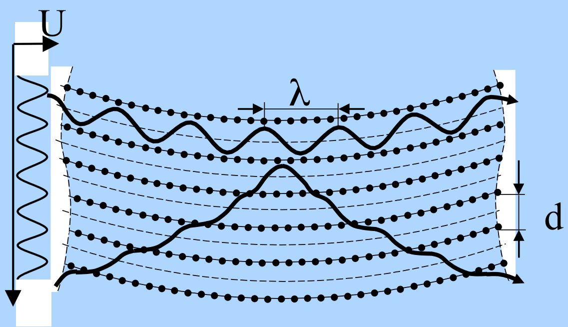


Volume reflection

Prediction in 1985-'87 by

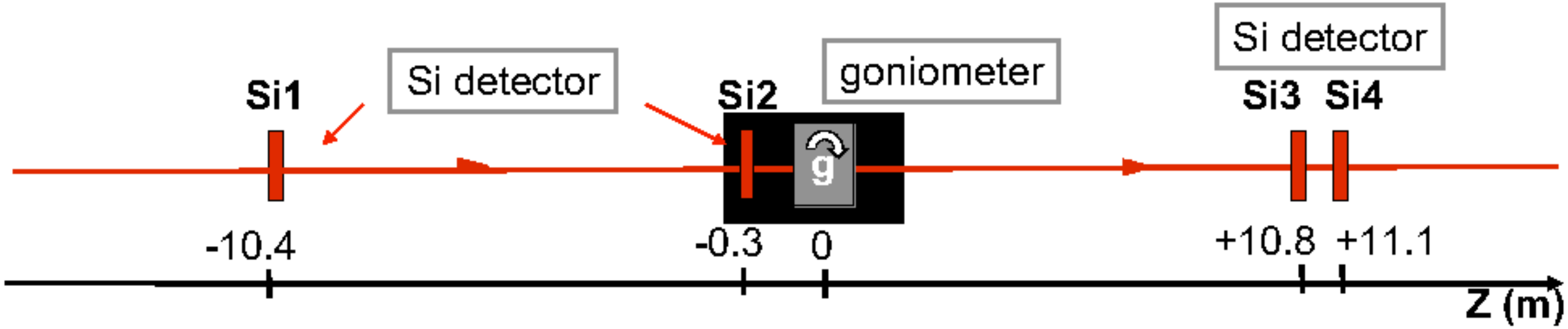
A.M.Taratin and S.A.Vorobiev,

First observation 2006 (IHEP - PNPI - CERN)

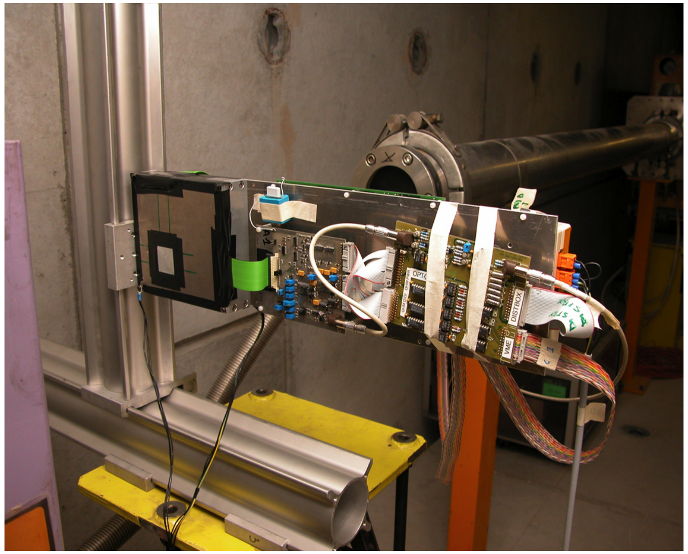


H8-RD22 Experiment at the CERN SPS

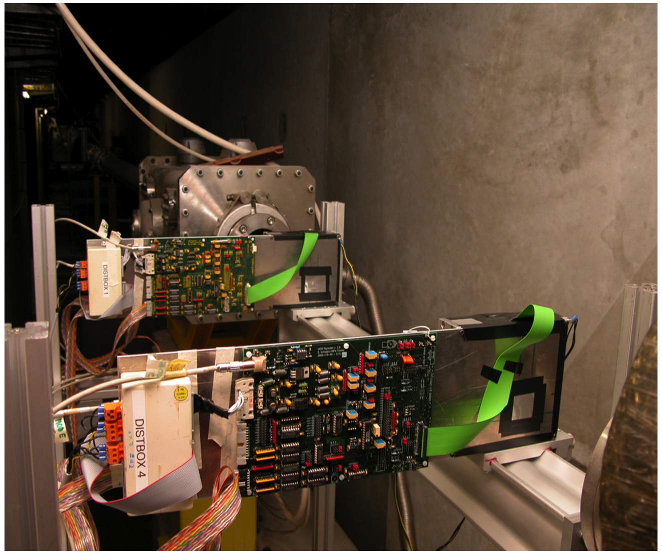
H8-RD22 layout (May 2007 run)



- double-sided silicon microstrip detectors (INFN Trieste)
- 50 μm read-out pitch, **~5 μm** spatial resolution

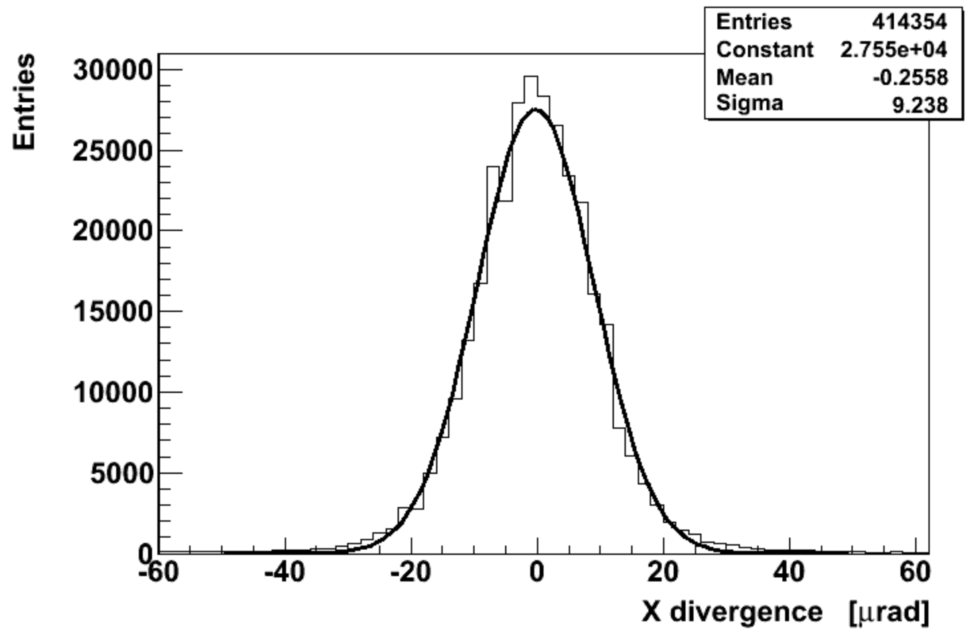


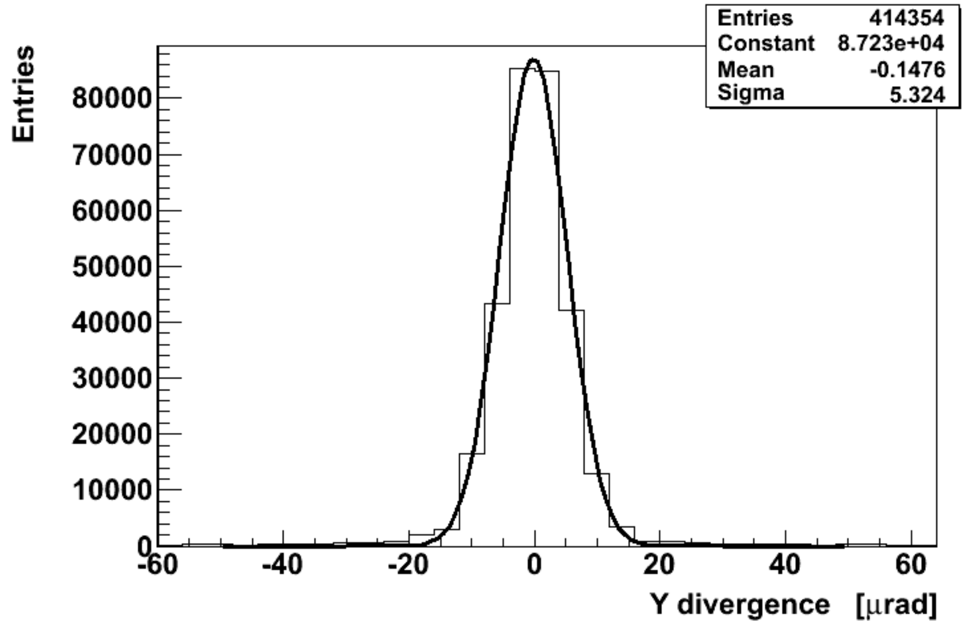
- 1.92×1.92 cm^2 active surface
- 2.1 kHz DAQ rate (zero suppression)



Proton beam

- 2 weeks beam time in May-June 2007
- CERN SPS H8 beamline
- primary 400 GeV/c proton beam
- typical beam intensity on T4 target: **~20 × 10^{11} ppp**
- the experiment required reduced rates **~10^5-10^6 ppp**



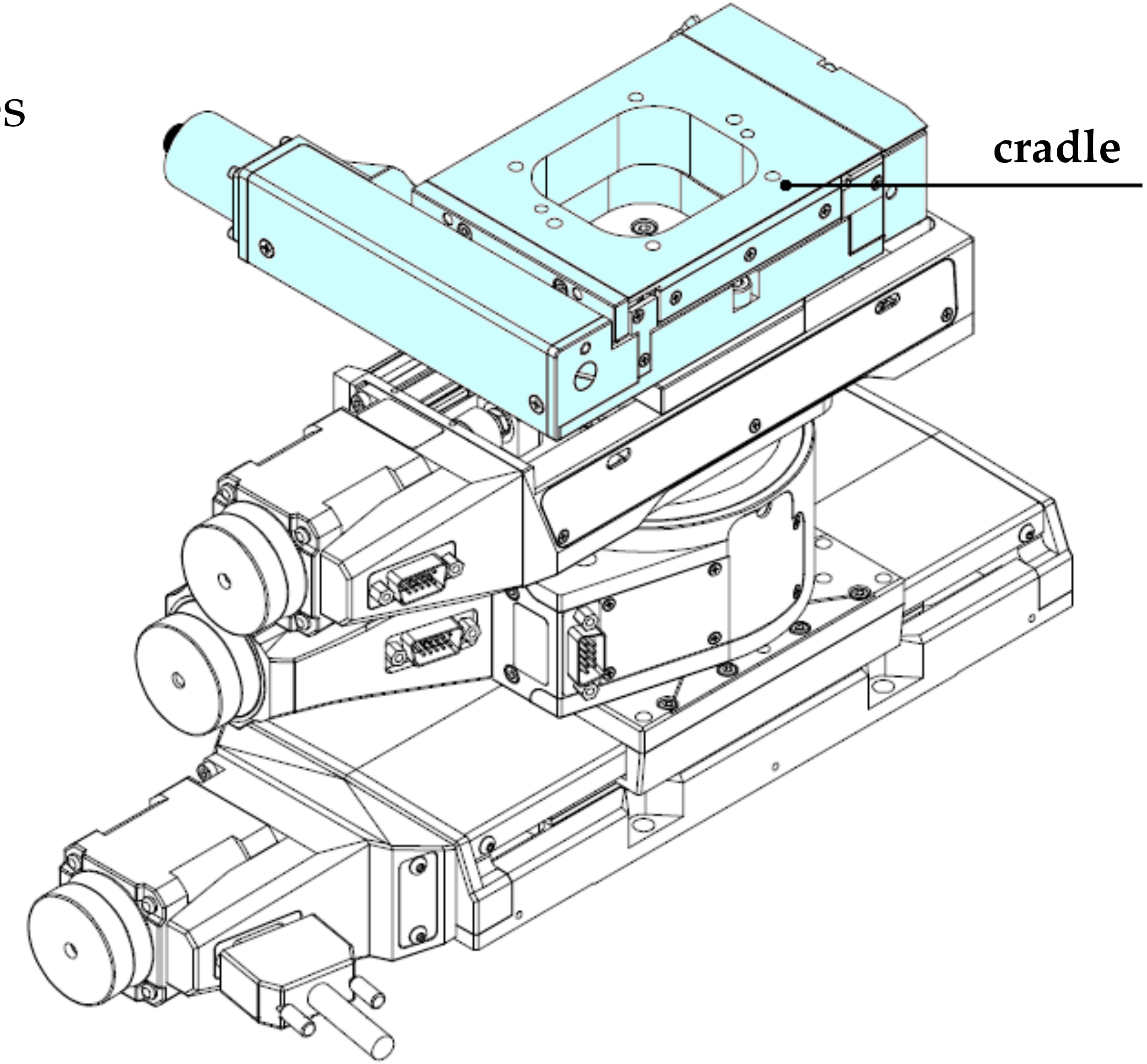


Measurement results

- **~9 μrad** divergence in X – the bending direction – and **~5 μrad** in Y (gaussian fit sigma)
- **~2 mm** beam spot size at crystal location

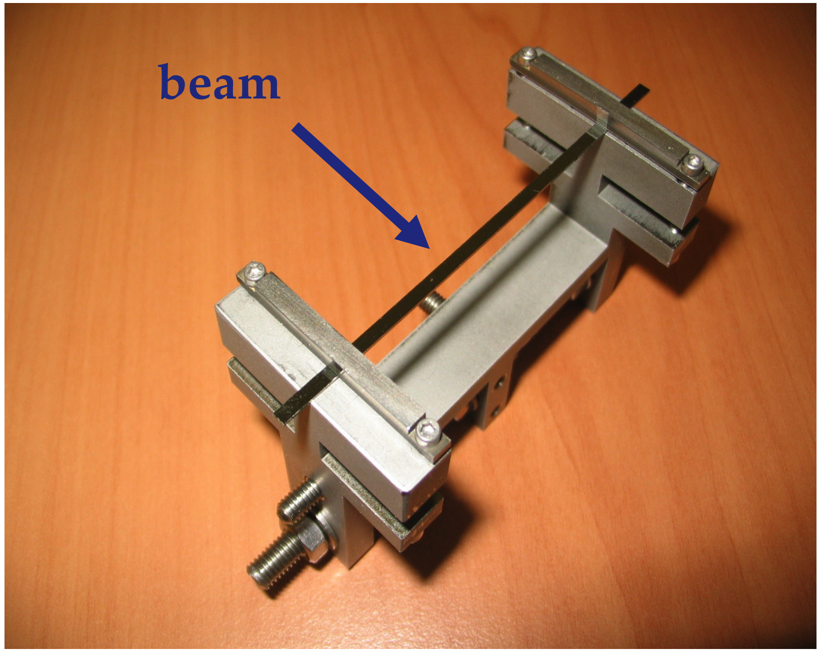
High precision goniometer

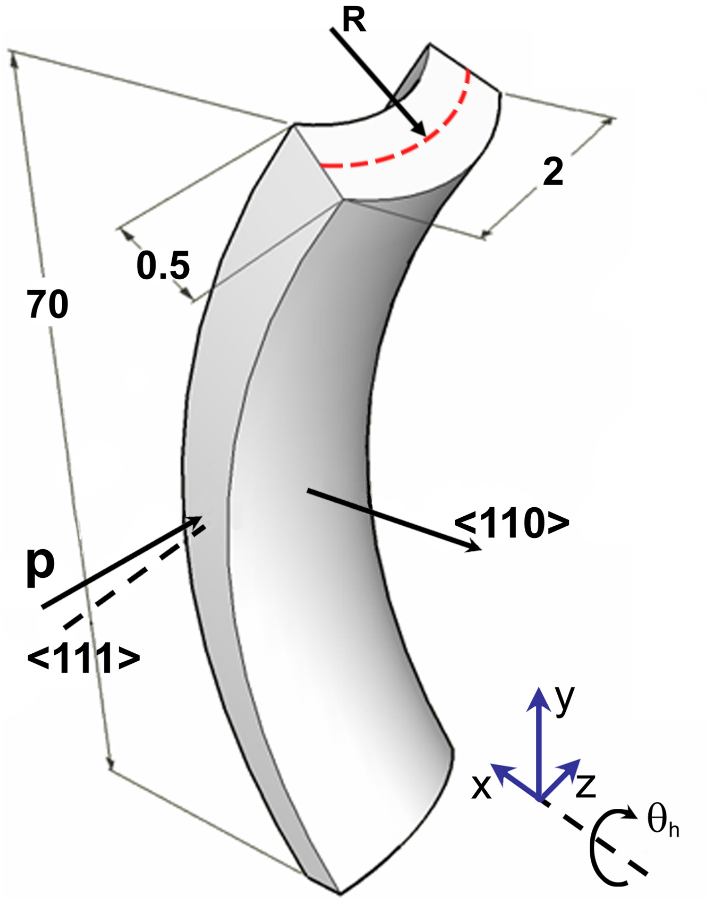
- two translational stages
  - 2 μm bidirectional repeatability
  - full range of 102 mm (upper stage) and 52 mm (lower stage)
- rotational stage
  - 360° rotation range
  - 1.5 μrad repeatability
- cradle stage
  - ±6.3° range
  - 1.5 μrad repeatability



Strip silicon crystals

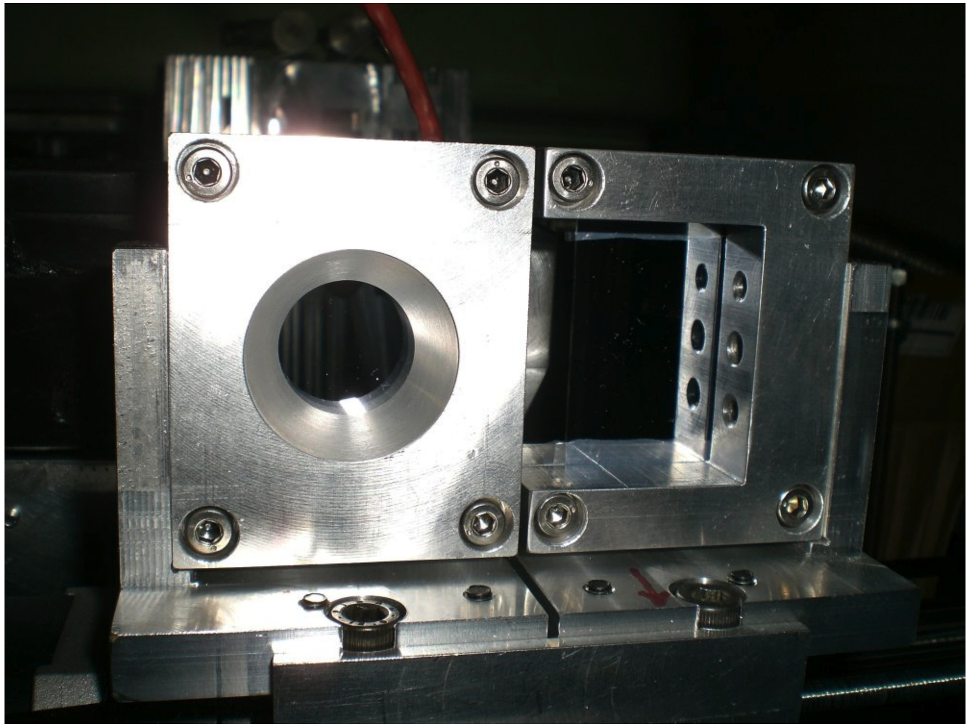
- Strip Crystals have been fabricated in the Sensors and Semiconductor Laboratory (Ferrara University)
- A primary curvature is imparted by mechanical external forces, which result in a secondary (anticlastic) curvature.





- **ST9** crystals size: $0.5 \times 70 \times 1.94\ mm^3$

Quasi-mosaic silicon crystals



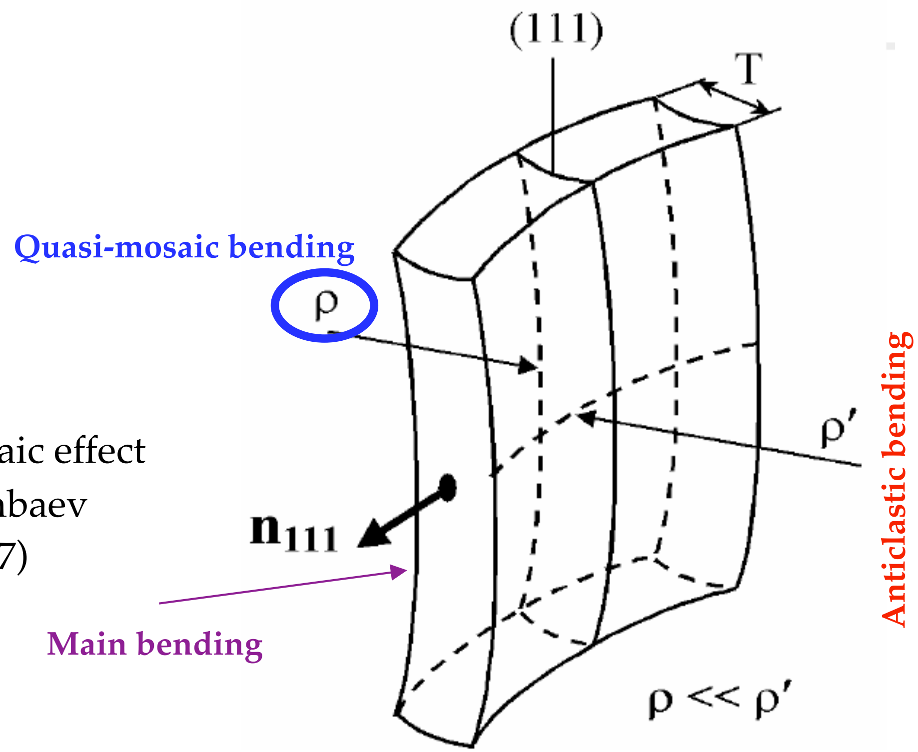
Quasi-Mosaic Crystals fabricated in PNPI (Gatchina, Russia)

- mechanical bending of the crystal induces bending of the atomic planes (initially flat and normal to large faces of plate) due to anisotropy
- ρ depends on the choice of crystallographic plane and on the angle of n_{111} respect to the crystal face

Crystal plate sizes:

~ 30 × 55 × 1 mm^3

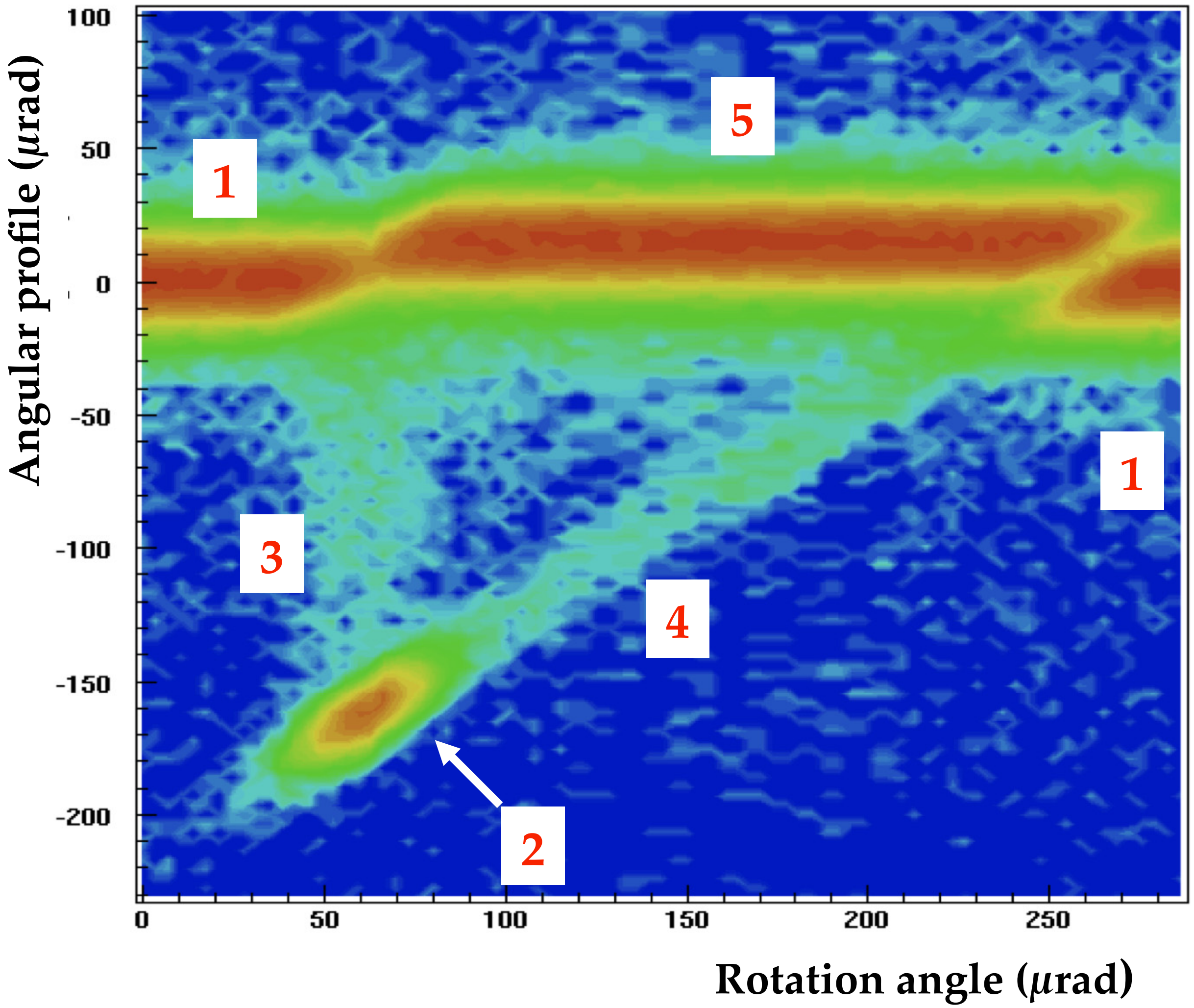
Quasi-Mosaic effect
O.I.Sumbaev
(1957)



Data taking

- Pre-alignment of the crystal w.r.t the beam line using optical methods (laser)
- Precise positioning of crystal on beam: use lateral translation stage until an enhancement of the multiple scattering is observed in downstream silicon detectors
- Fast angular scan of the crystal w.r.t the beam direction until channeling peak or volume reflection region are visible
- High statistics scan using smaller angular steps, in the range defined by the fast angular scan (at most a few $\times 10^4$ events written to disk per SPS pulse)
- Additional high statistics data acquisition may be done at fixed angular values

Angular beam profile

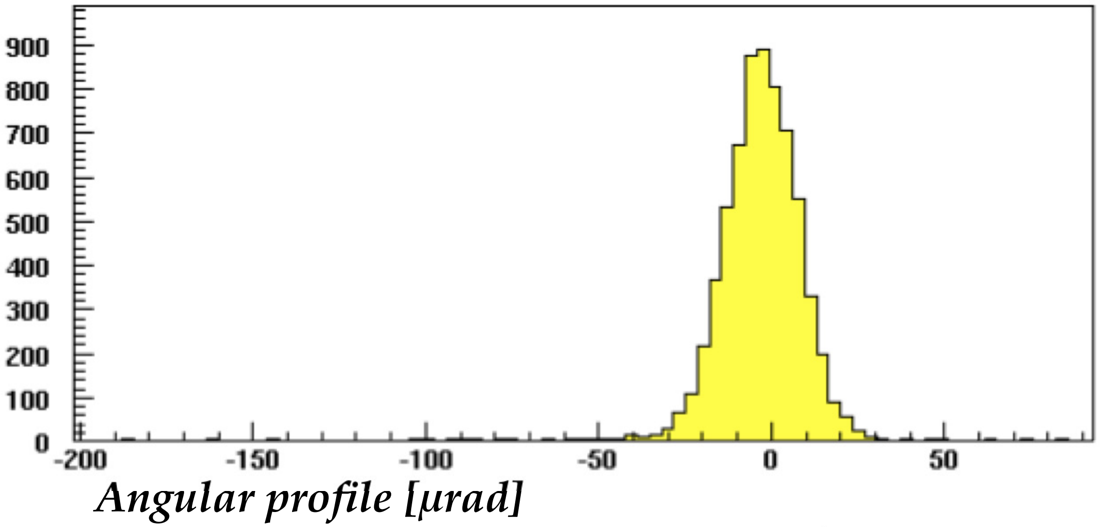


The **angular profile** is the change of beam direction induced by the crystal

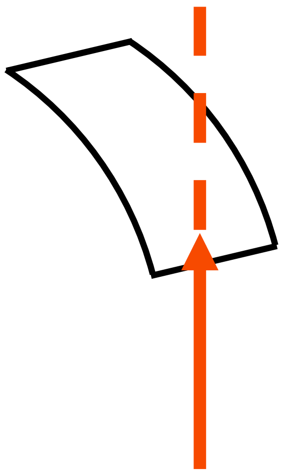
The **rotation angle** is angle of the crystal w.r.t. beam direction

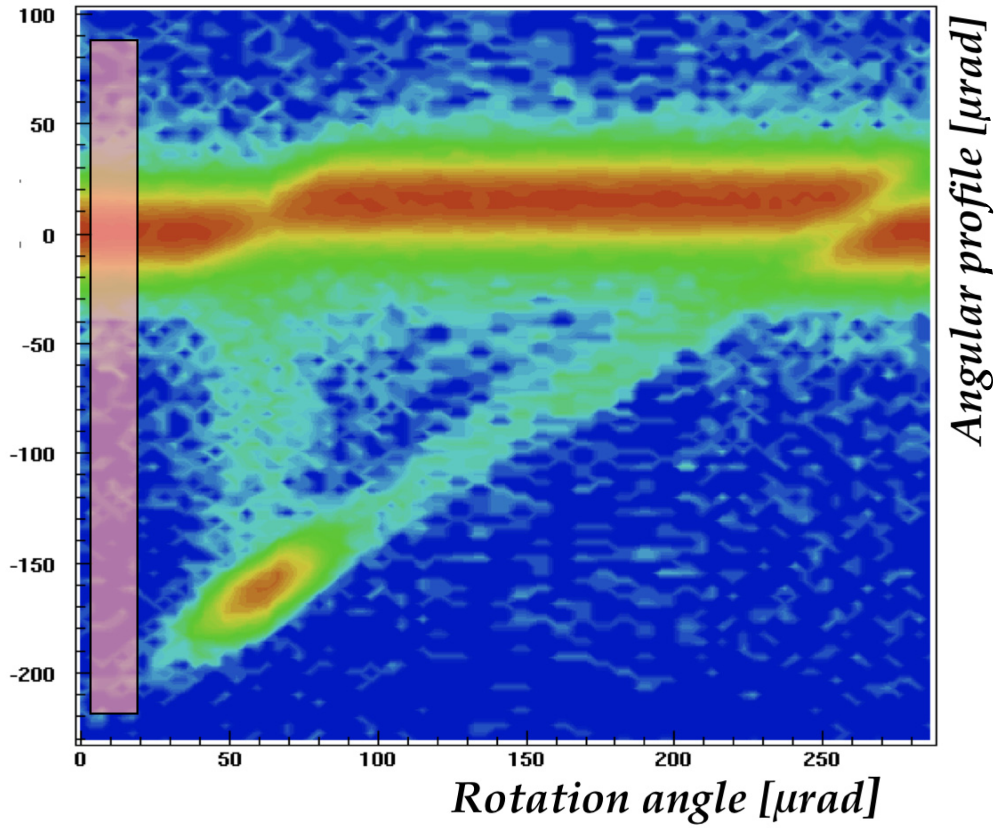
The **particle density** decreases from red to blue

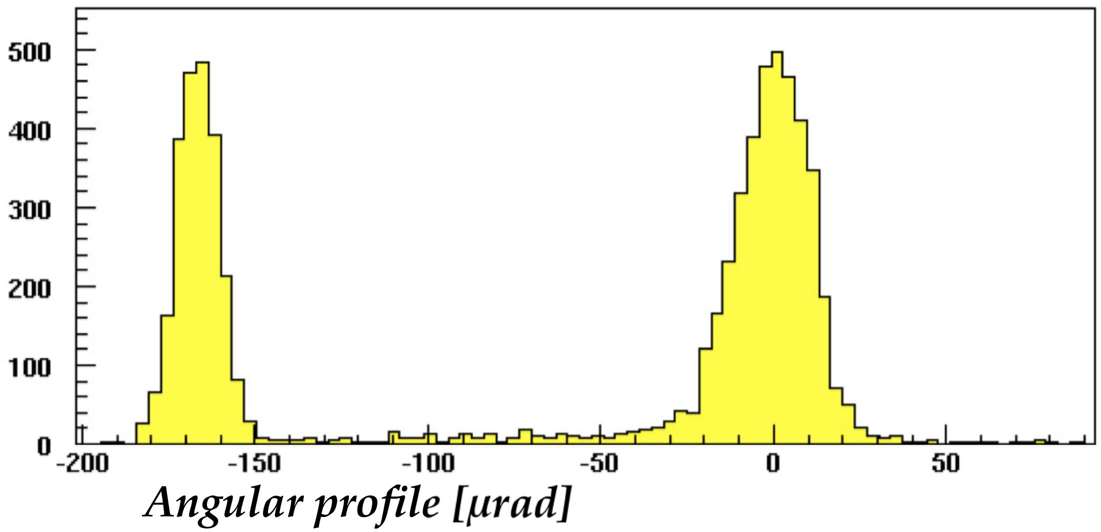
1 - "amorphous" orientation
2 - channeling
3 - de-channeling
4 - volume capture
5 - volume reflection


900
800
700
600
500
400
300
200
100
0
-200
-150
-100
-50
0
50
Angular profile [μrad]

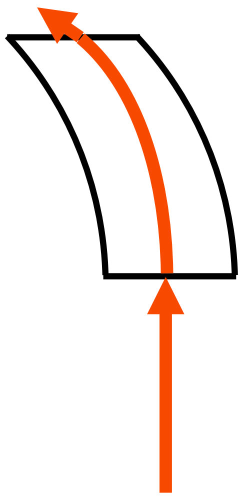
Amorphous

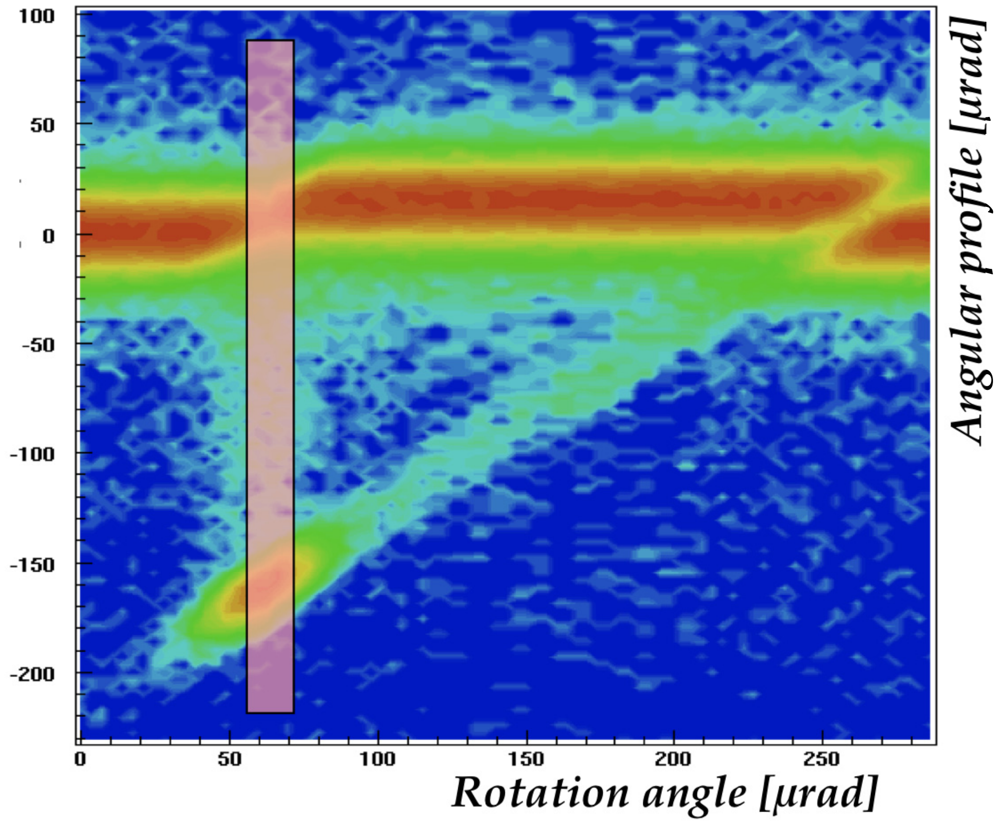



100
50
0
-50
-100
-150
-200
0
50
100
150
200
250
Rotation angle [μrad]
Angular profile [μrad]

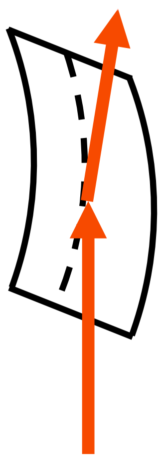

500
400
300
200
100
0
-200
-150
-100
-50
0
50
Angular profile [µrad]

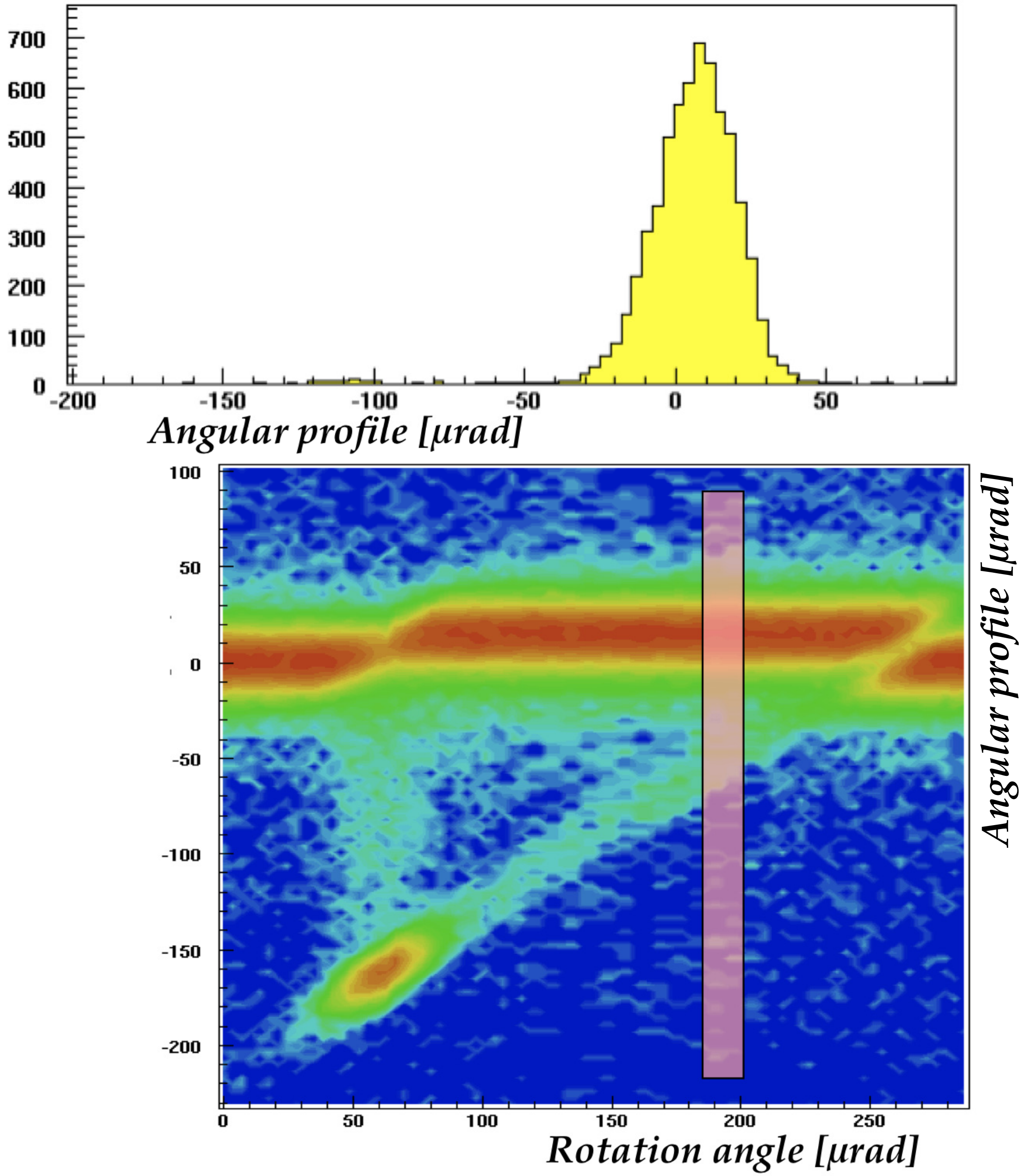
Channeling




100
50
0
-50
-100
-150
-200
0
50
100
150
200
250
Rotation angle [µrad]
Angular profile [µrad]

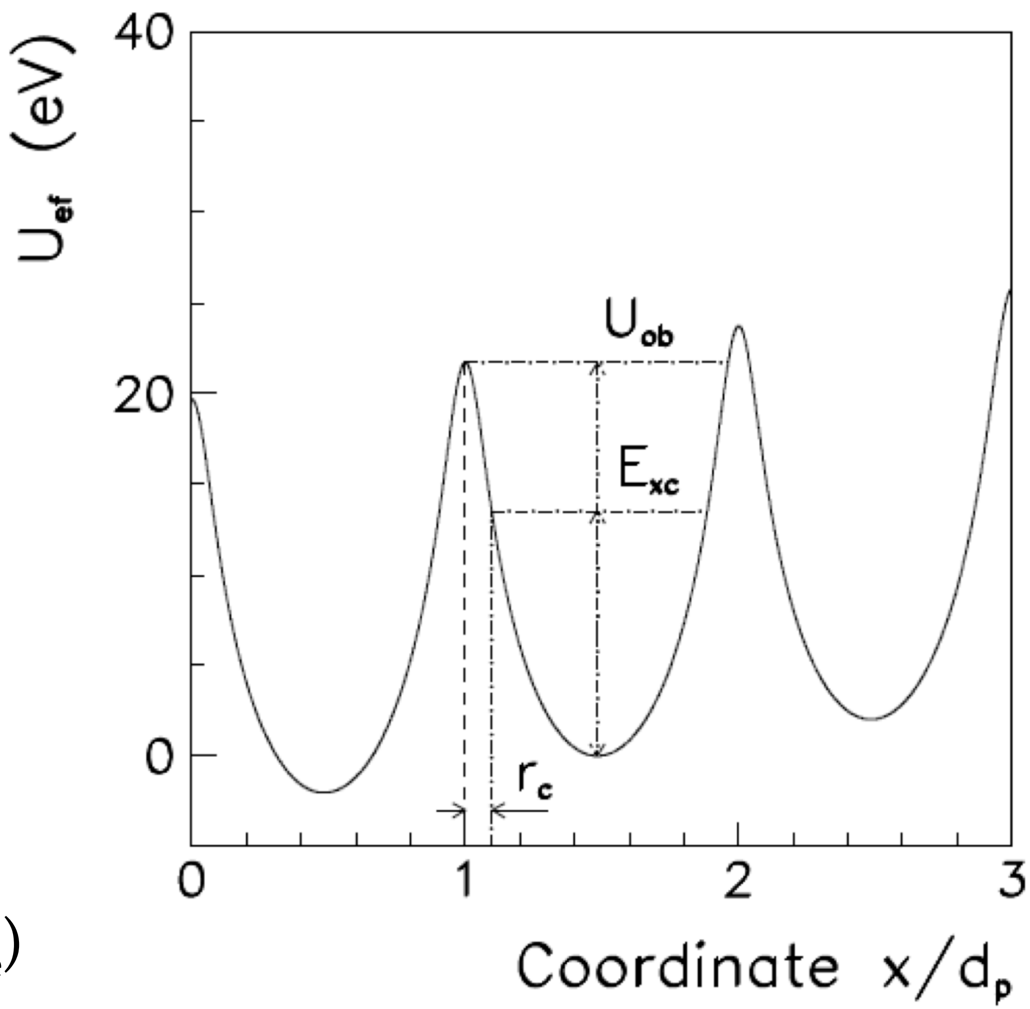
Volume Reflection





Deflection efficiency: Theory

- Effective planar potential, governing transverse particle motion
- full depth U_{ob} depends on crystal radius of curvature R
- if a particle's initial transverse energy $E_{x0} < U_{0b}$ → it is channeled (entry face)
- during passage through the crystal, particles may leave their bound states due to multiple coulomb scattering
  - on the nuclei (MSN)
  - on the electrons (MSE)
- nuclear (L_n) and electron (L_e) de-channeling lengths ($L_n \ll L_e$)

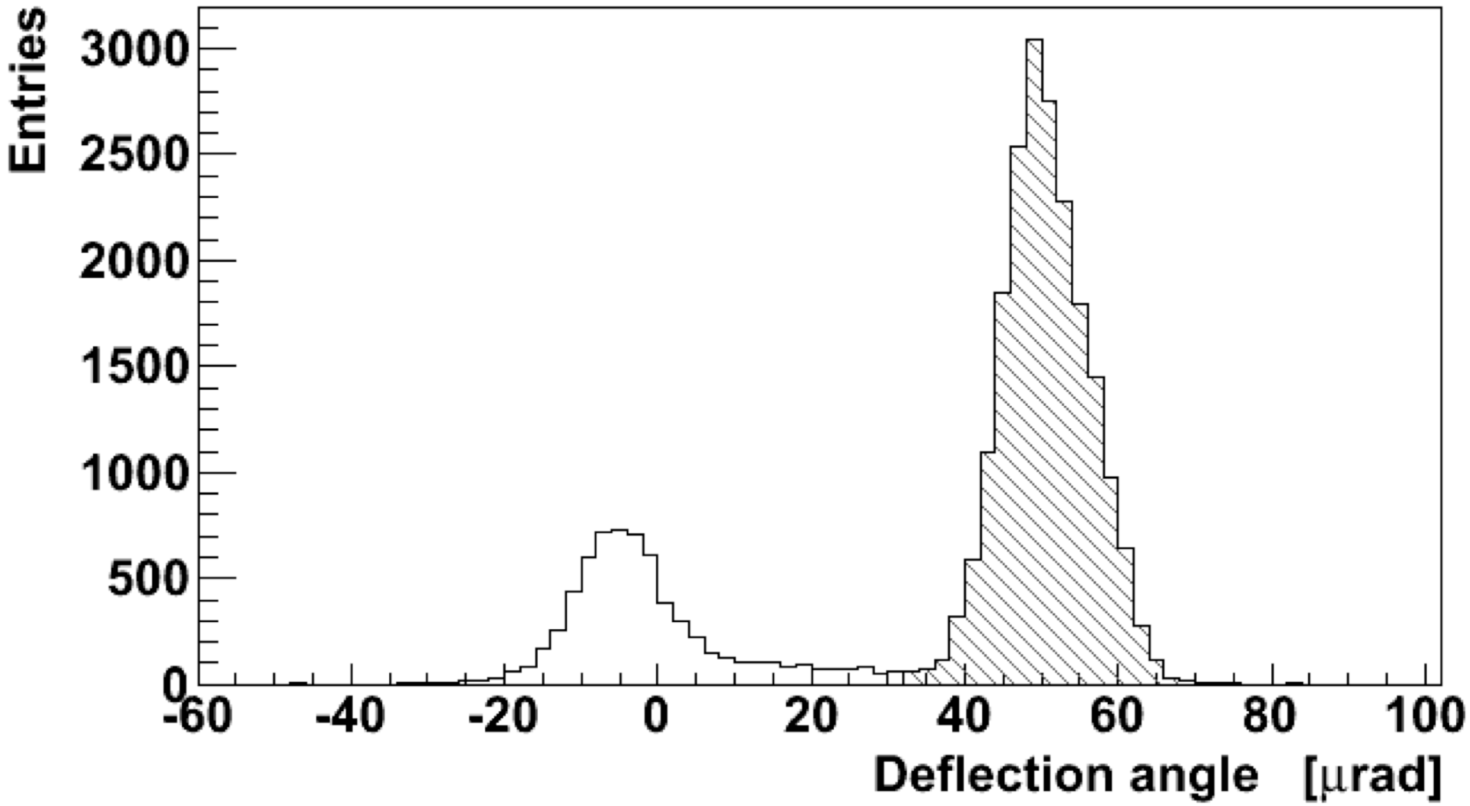


Deflection efficiency determination for ST9 crystal

- After offline detector alignment, particle deflection distributions are produced
- Only particles hitting the crystal surface are selected
- Particles with incoming angles – before the crystal – outside the (-5 μrad,+5 μrad) interval in both X and Y directions are discarded
- A gaussian fit to the channeling peak in the horizontal deflection distribution gives the deflection angle (θ_d) and its RMS deviation (σ_d)
- The fraction of particles deflected to angles greater than ($\theta_d - 3\sigma_d$) over the total determines the deflection efficiency P_d

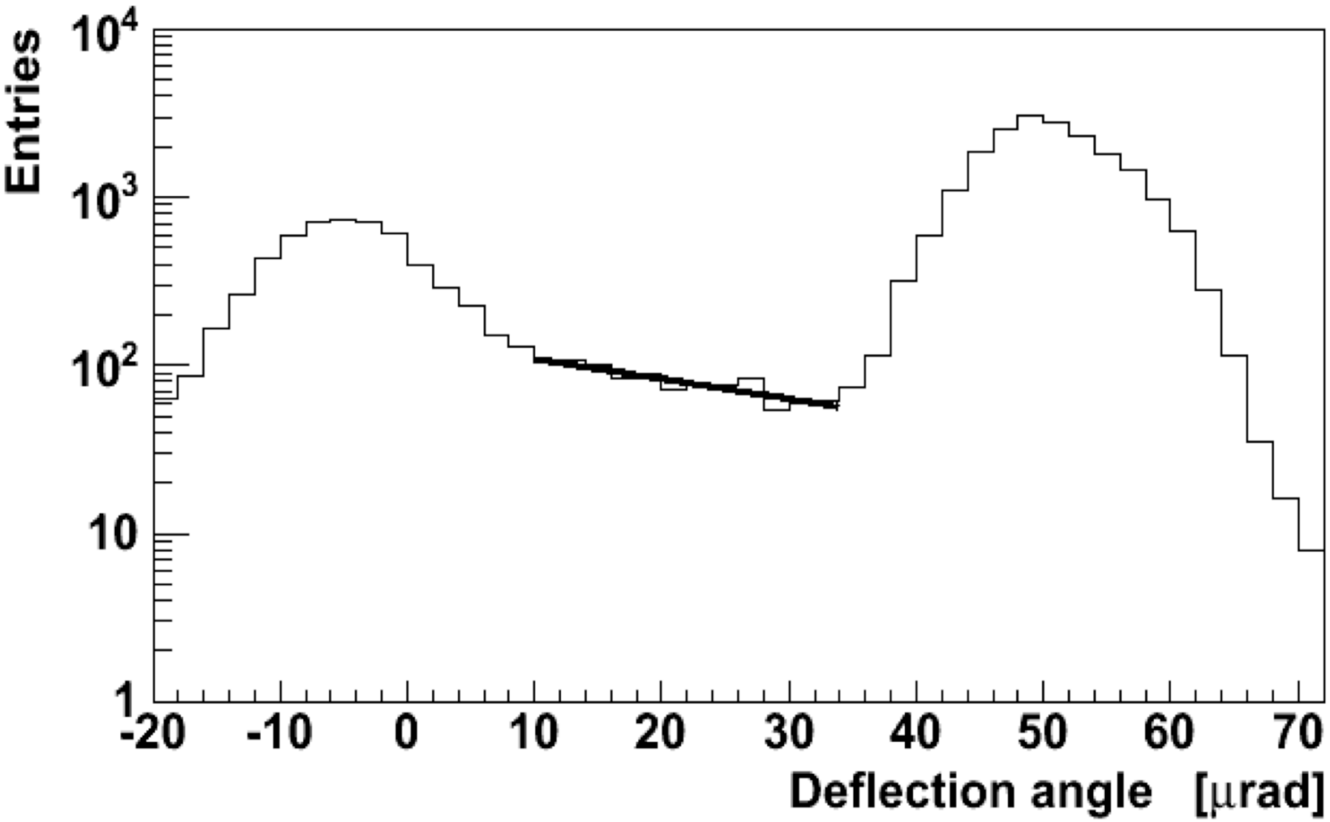
Deflection measurement

- a gaussian fit to the channeling peak gives:
  - deflection angle: $\theta_d = (50.5 \pm 0.1)$ μrad
  - RMS deviation: $\sigma_d = (5.67 \pm 0.04)$ μrad
- resulting deflection efficiency: **$P_d = (75.2 \pm 0.7_{stat} \pm 0.5_{syst})$ μrad**



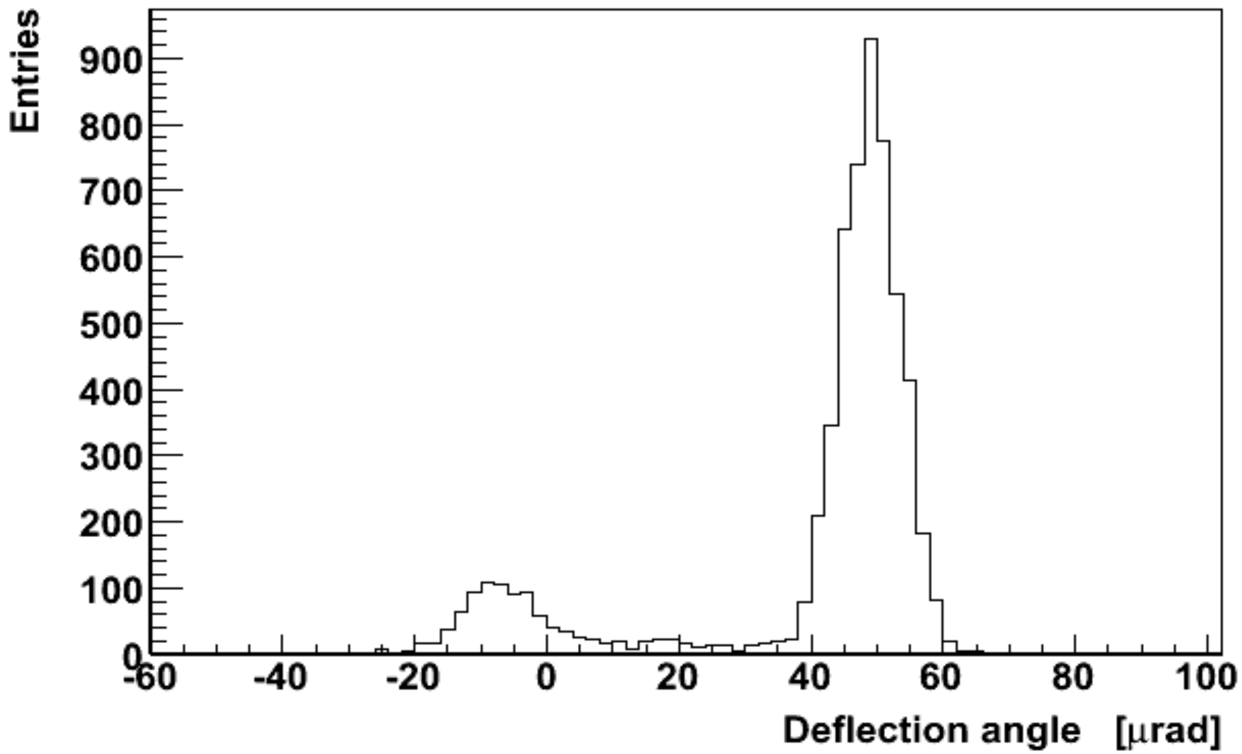
Nuclear de-channeling length

- the peak on the left side is due to particles which were not captured into channeling states at the crystal entrance
- particles between the two maxima are the de-channeled ones, which were lost due to MSN
- l=Rθ, where l is the crystal length traversed before de-channeling
- an exponential fit to the data gives: **$L_n = (1.53 \pm 0.35_{stat} \pm 0.20_{syst})$ mm**
- Good agreement with simulation (L_n = 1.5 mm)



Finer measurement

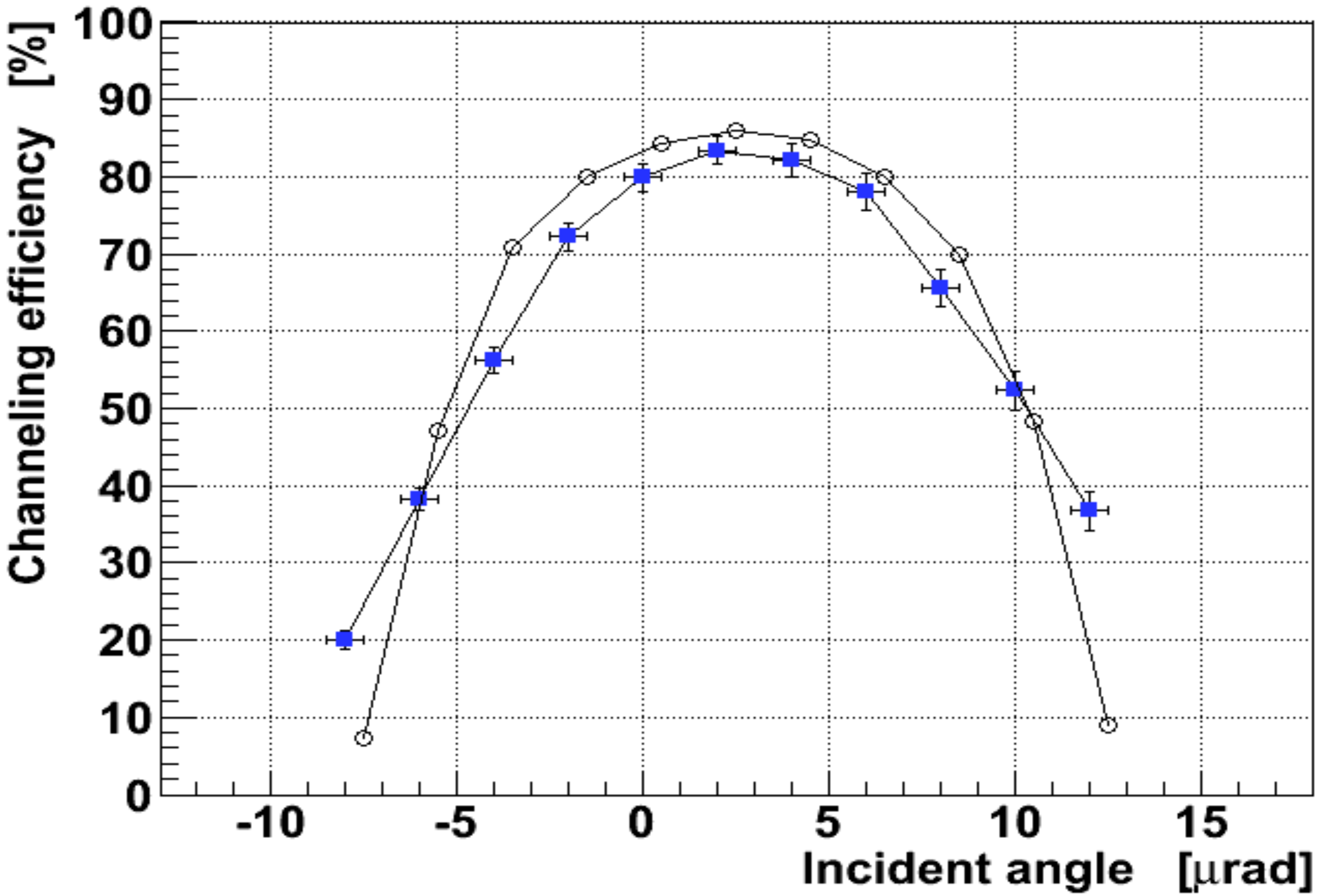
- Finer scan (without changing crystal orientation) performed offline by selecting different (and contiguous) angular windows, 2 μrad wide
- For each window, the deflection efficiency P_d is computed
- Maximum measured value **$P_d = (83.4 \pm 1.6_{stat} \pm 0.9_{syst})\%$**



- Simulations give a maximum $P_d = 86\%$ and a value of 95.5% for the capture efficiency. Thus, deflection inefficiency due to MSN is about 10% (fraction of de-channeled particles)

Deflection Efficiency Results

- Maximum value of P_d corresponds to the optimal choice of incoming particle direction



- DATA: blue squares
- Simulation: white circles

Measurement with QM crystal

- measurements have also been performed with a Quasi-mosaic crystal (QM2)
- length along the beam: 0.84 mm
- bent along (111) planes (bending radius R=11.2 m)
- only particles that hit a well defined area at the crystal entry face are selected
- deflection efficiency is measured varying divergence cut
- **~72%** maximum efficiency, measured in a 3 μrad wide incoming angular window
- the stronger bending w.r.t strip crystal decreases the channel potential depth (hence the lower efficiency)

Conclusive remarks

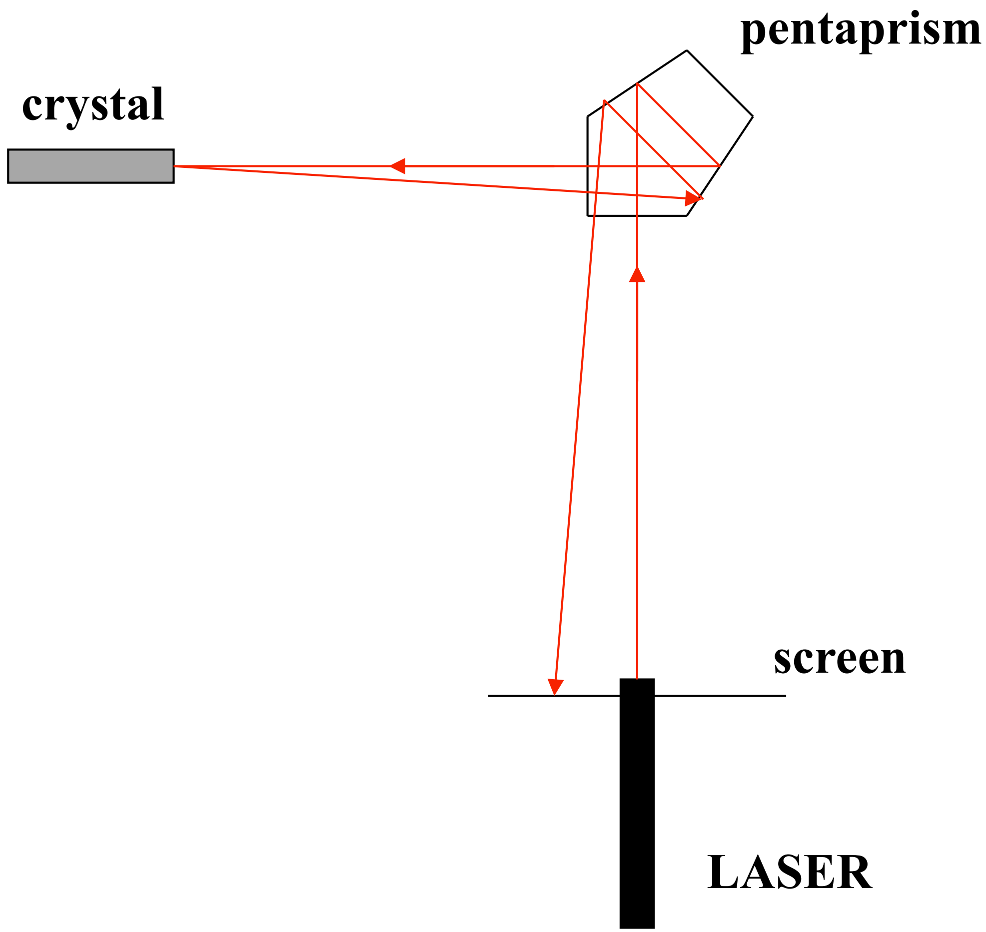
- Single-pass deflection efficiency larger than 80% has been measured using short silicon crystals
  - the measured value of 83.4%, measured with strip crystals, is close to the maximum value expected for parallel beams
  - such crystals are expected to be fully adequate for beam halo collimation in hadronic machines

- The fast de-channeling stage due to multiple coulomb scattering on the nuclei of the crystal atoms has been detected
  - nuclear de-channeling length was measured to be about 1.5 mm, in good agreement with simulations

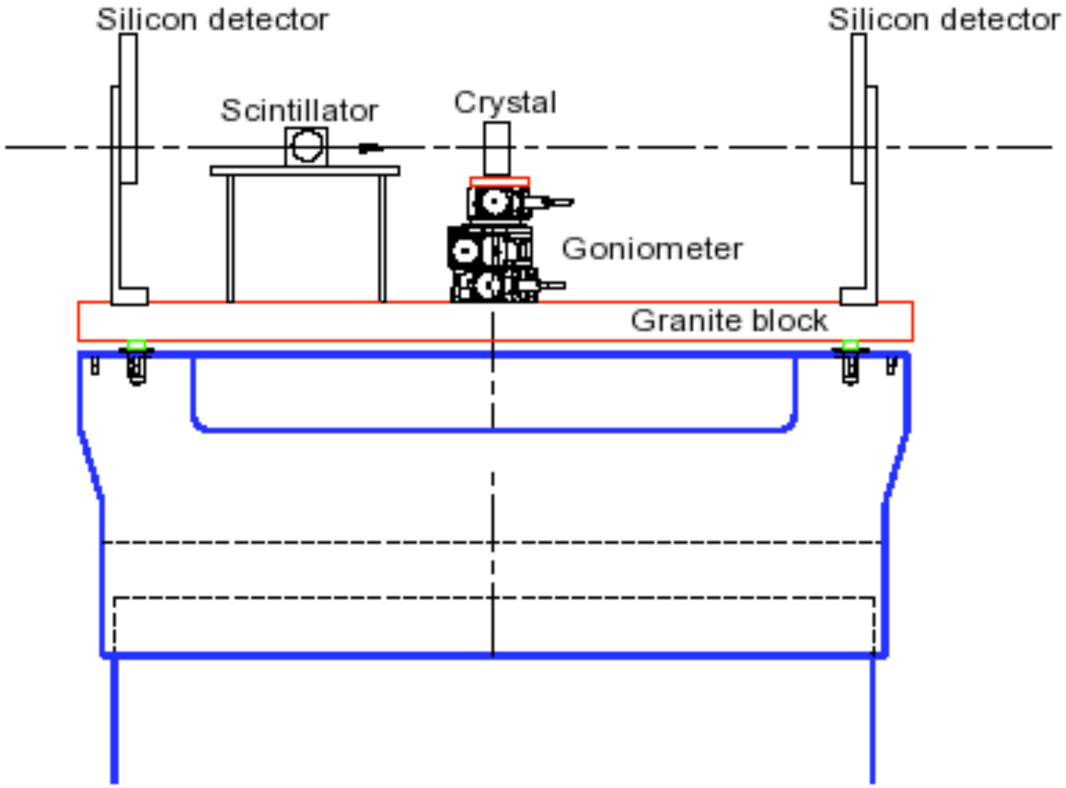
SPARES

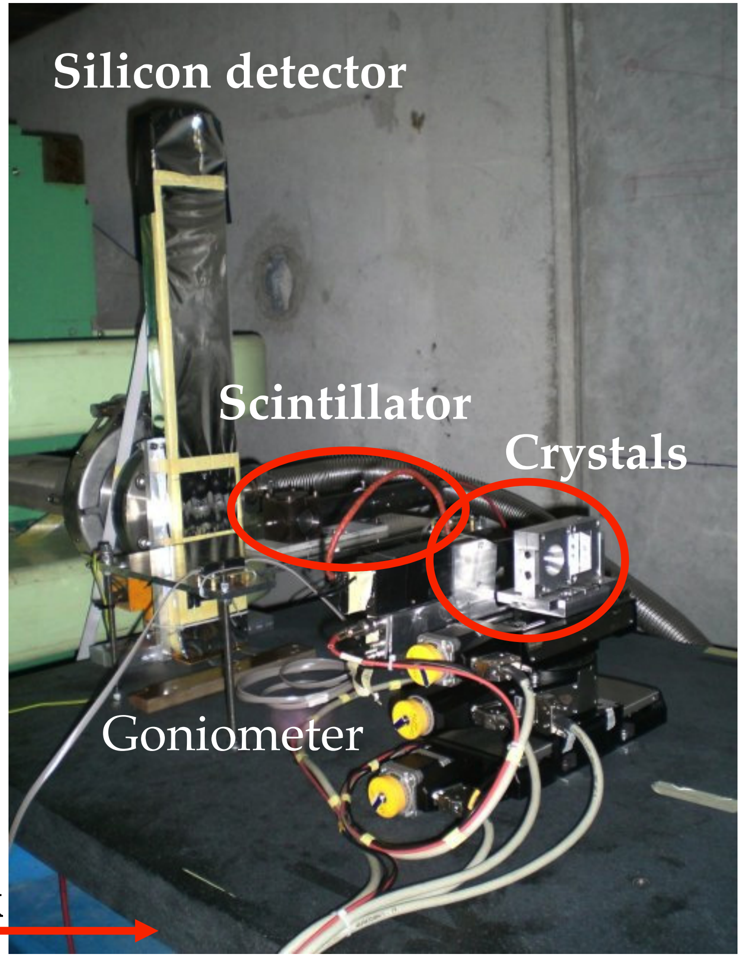
Laser pre-alignment

- laser beam, parallel to proton beamline
- measurement of laser beam deflection (1 mm precision)
- considering prism-crystal distance (~1 m) and prism-laser distance (~ 4 m), accuracy of crystal pre-alignment was about 0.1 mrad



Goniometer assembly





Granite Block