
# State of the art on crystal-assisted manipulation of high-energy particle beams

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*University of Ferrara and INFN - Italy*

*NA62 collaboration meeting*
*Ferrara, September 01, 2014*

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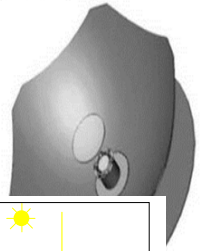
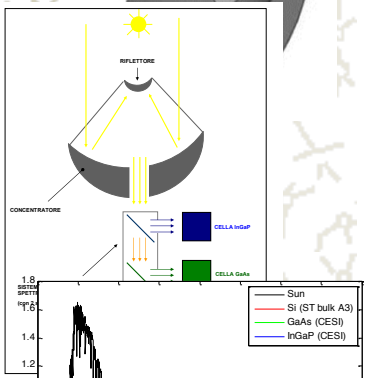
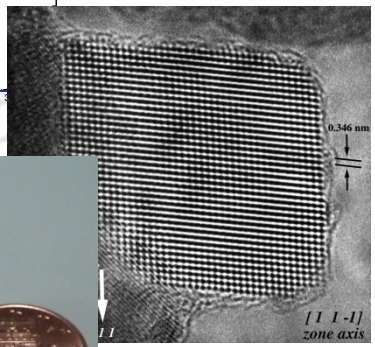
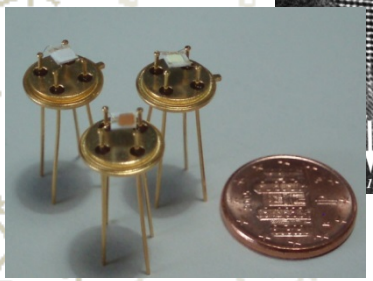
# Research activities

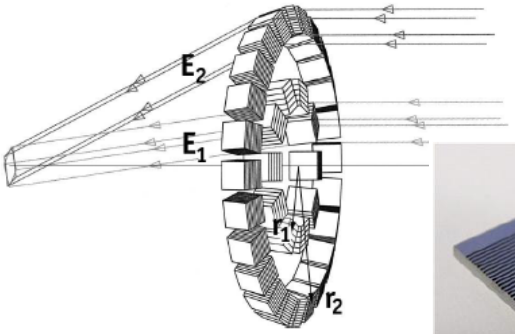
- Concentrated photovoltaics
- Microfabrication of Si (crystals for channeling exp.)
- Hard x-ray optics
- Sensing via chemoresistive metal oxides

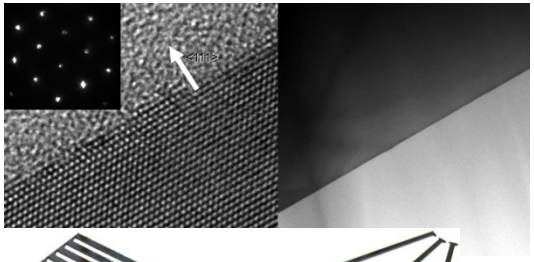


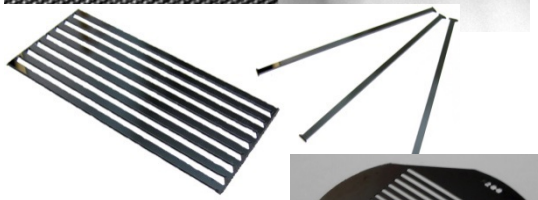


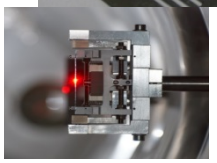



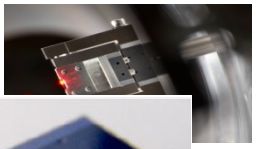



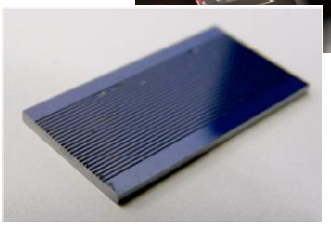










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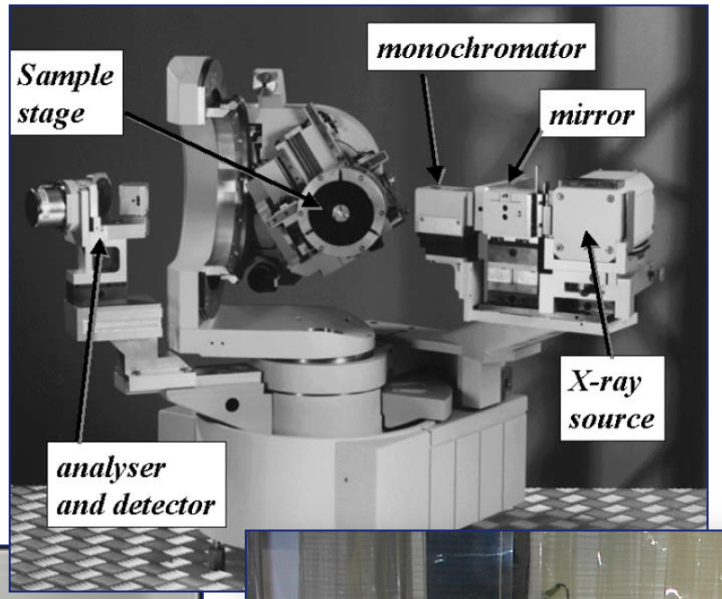
# Clean-room facilities




# Outlook

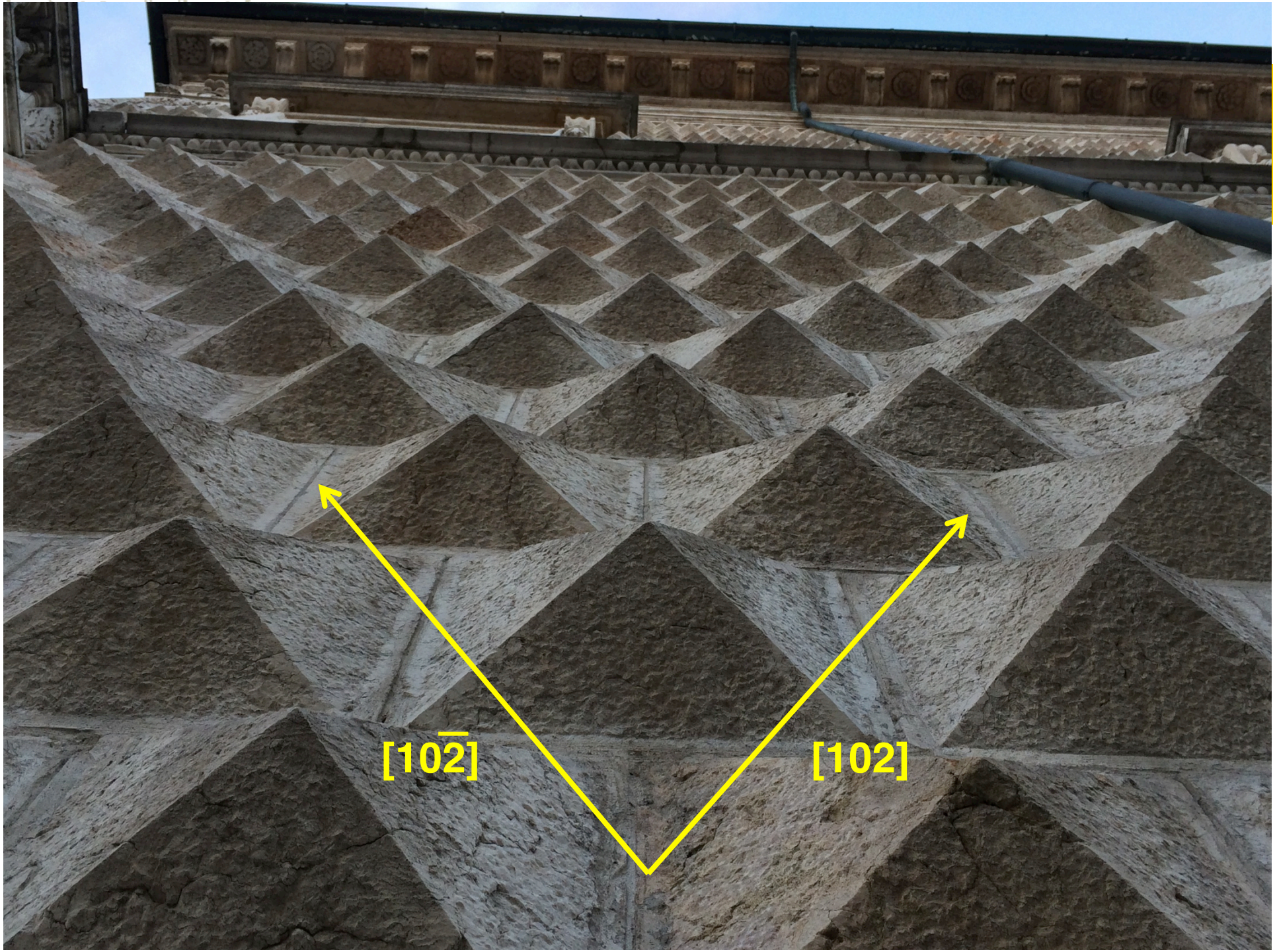
- Overview on channeling and other coherent interactions of charged particle with bent crystals;
- Experiments with positive particles at CERN
- Experiments with negative particles at CERN, SLAC and MAMI;
- Innovative schemes (e.g. beam collimation) and new perspectives for manipulation of particle trajectories

# What is crystal channeling?

The Palace of Diamonds – Ferrara

Designed by Biagio Rossetti

Built in 1493 - 1503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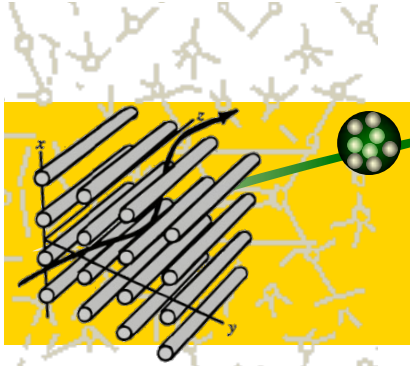
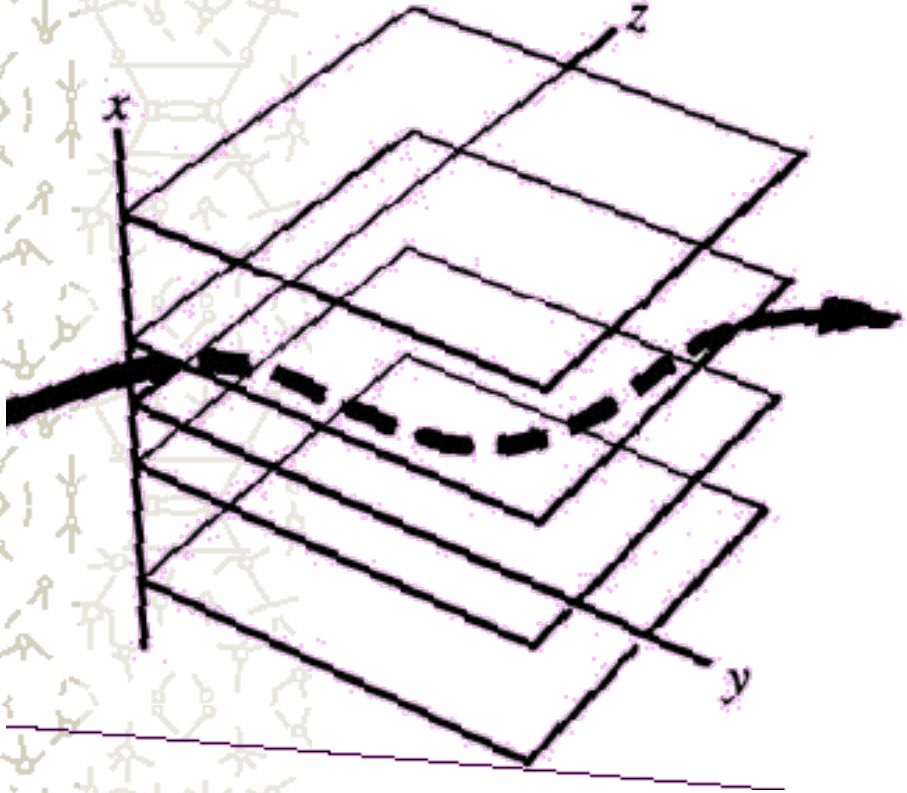
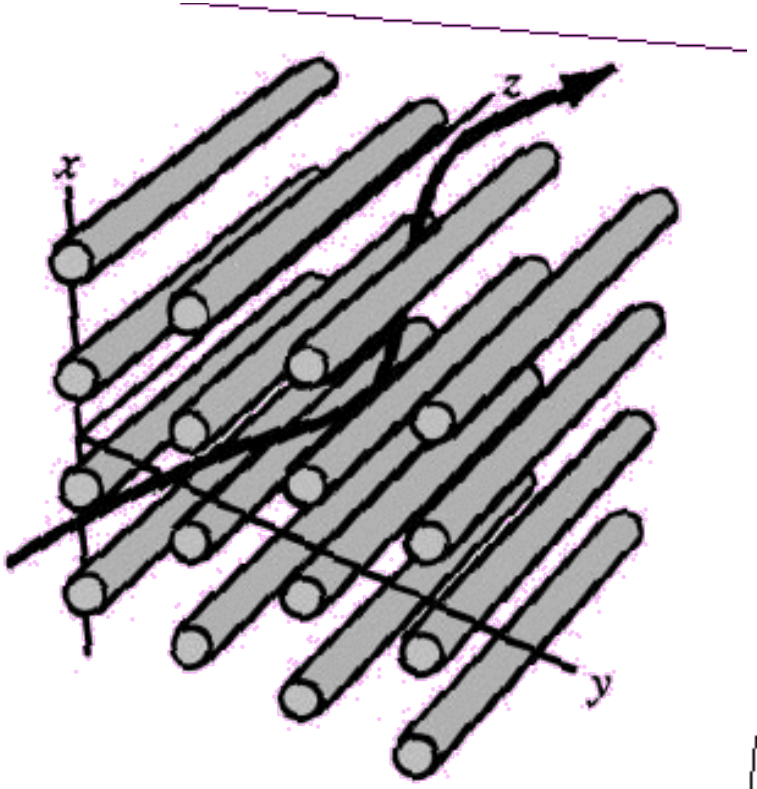


# What is crystal channeling?

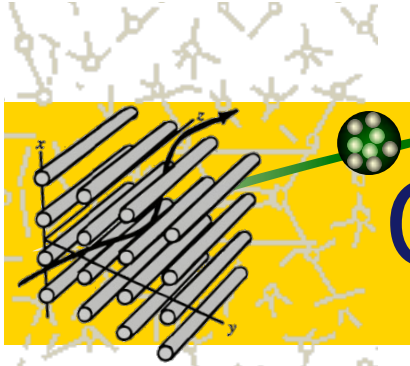
**Channeling** is the confinement of charged particles travelling through a crystal, by atomic planes or axes. **LINDHARD (1964)**



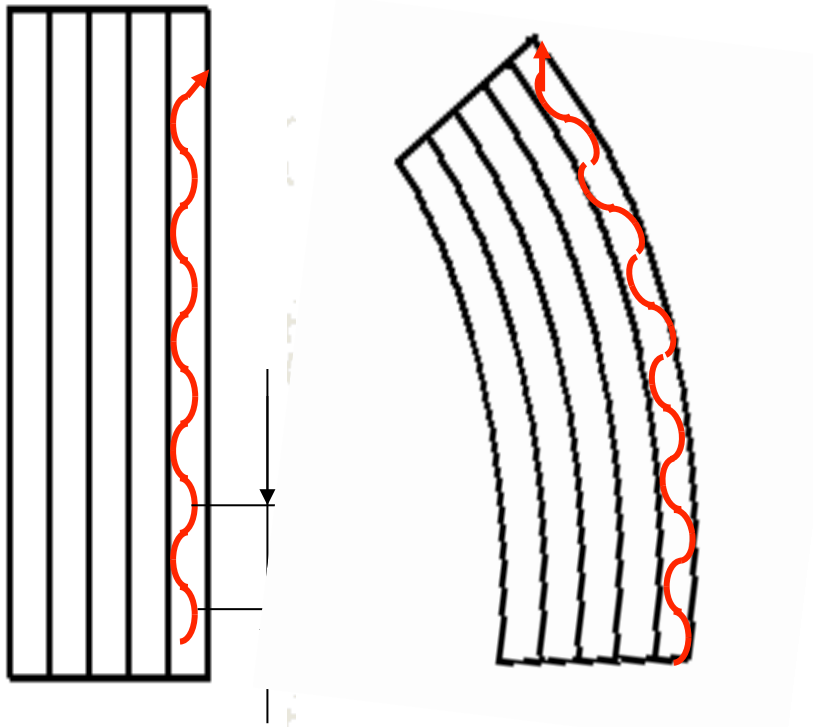




**Channeling** occurs as the trajectory of particles forms an angle lower than the **critical angle**

$$\theta_{max} = \sqrt{\frac{2U}{E}}$$



# Channeling in a bent crystal

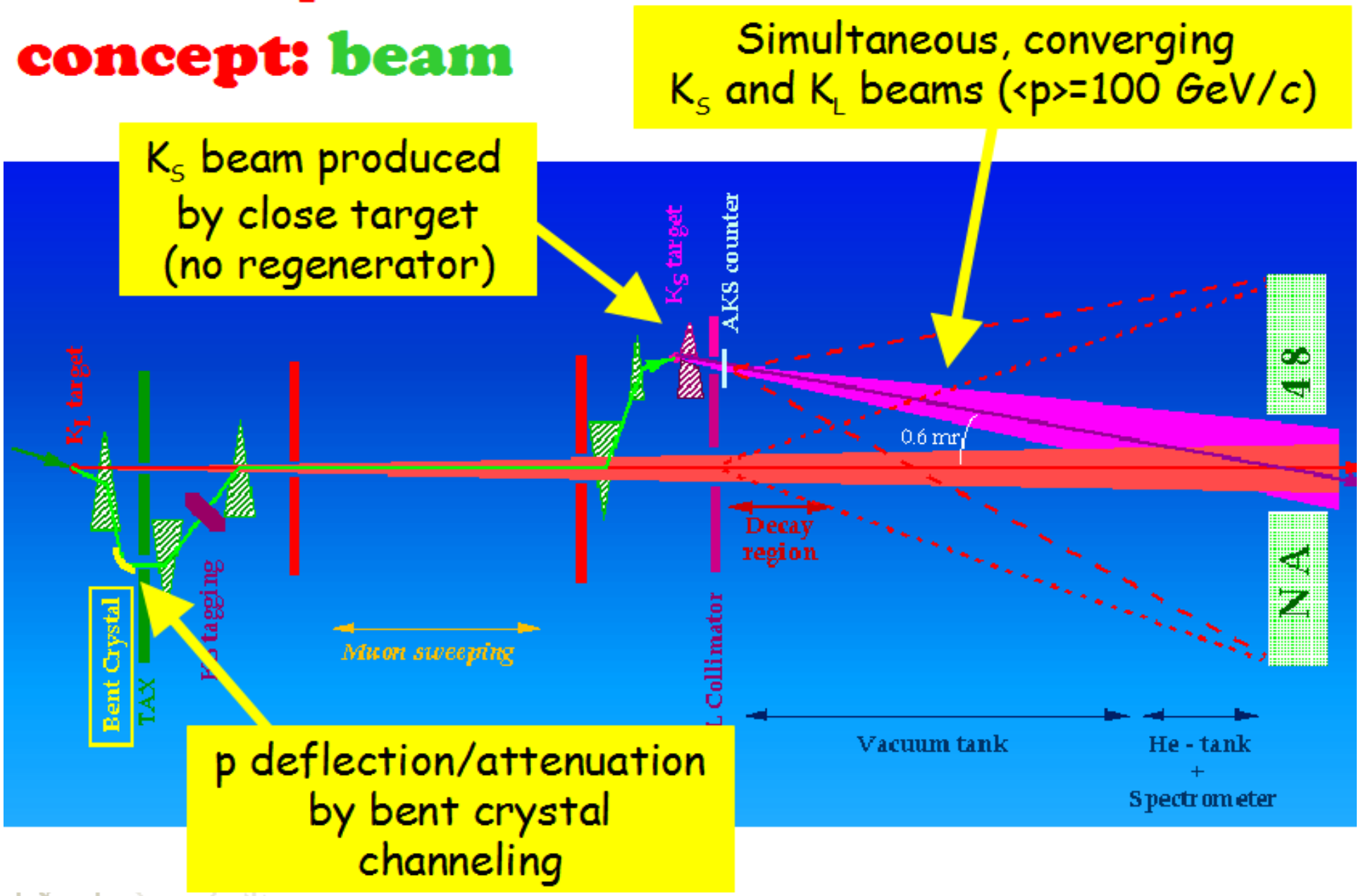


A channeled particle deviates from its initial direction by an angle equal to the bending angle of the crystal.

Bent crystals can be used for manipulation of particle trajectories in an accelerator

**Tsyganov (1976)**

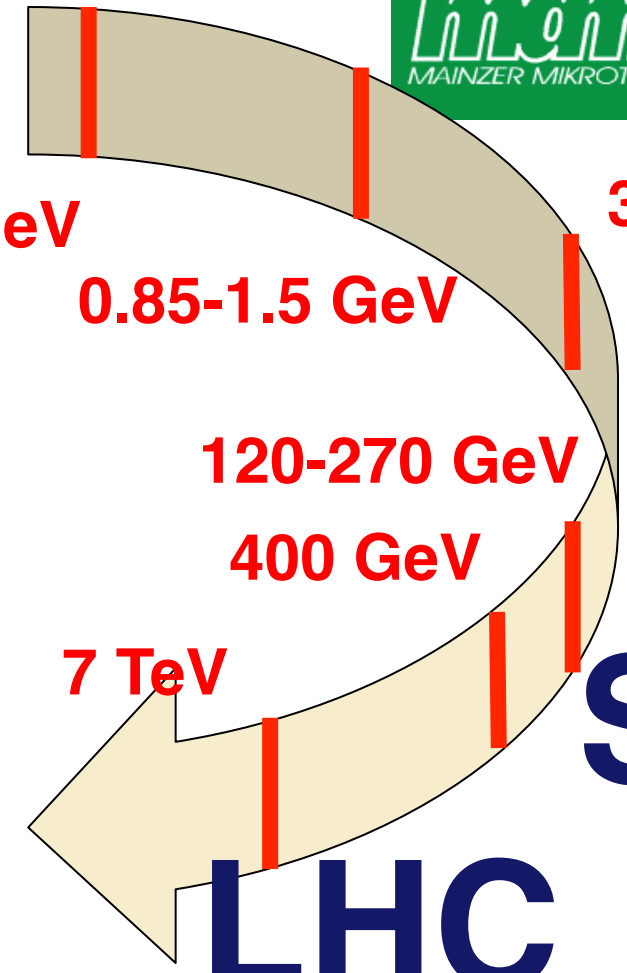
# The NA48 concept: beam



# Labs for channeling experiments

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

MAMI
MAINZER MIKROTRON




SLAC

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CERN

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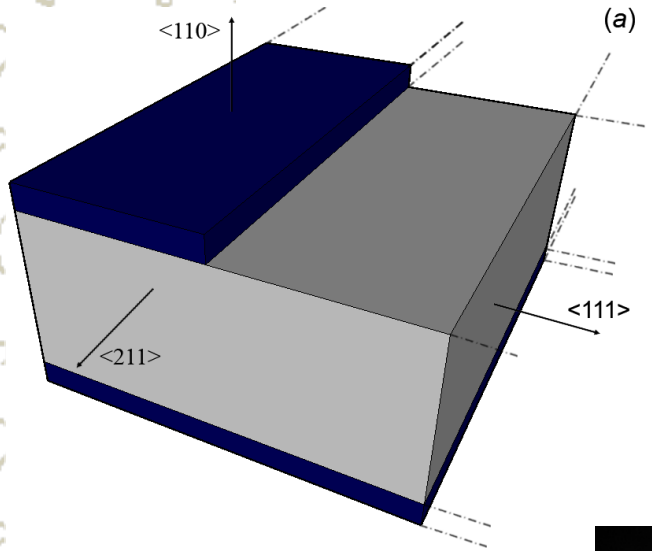
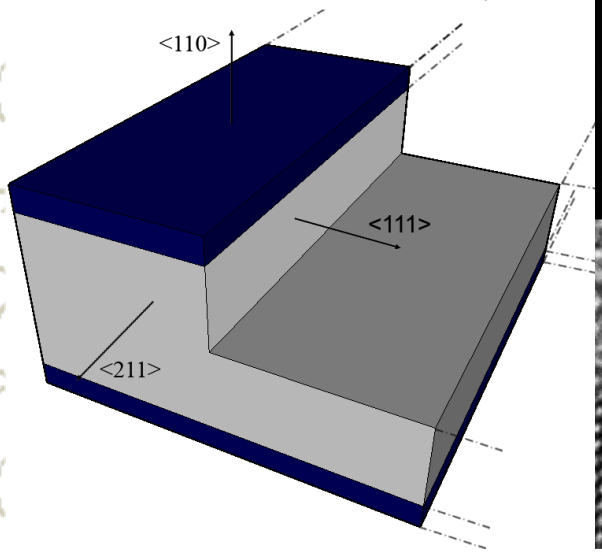
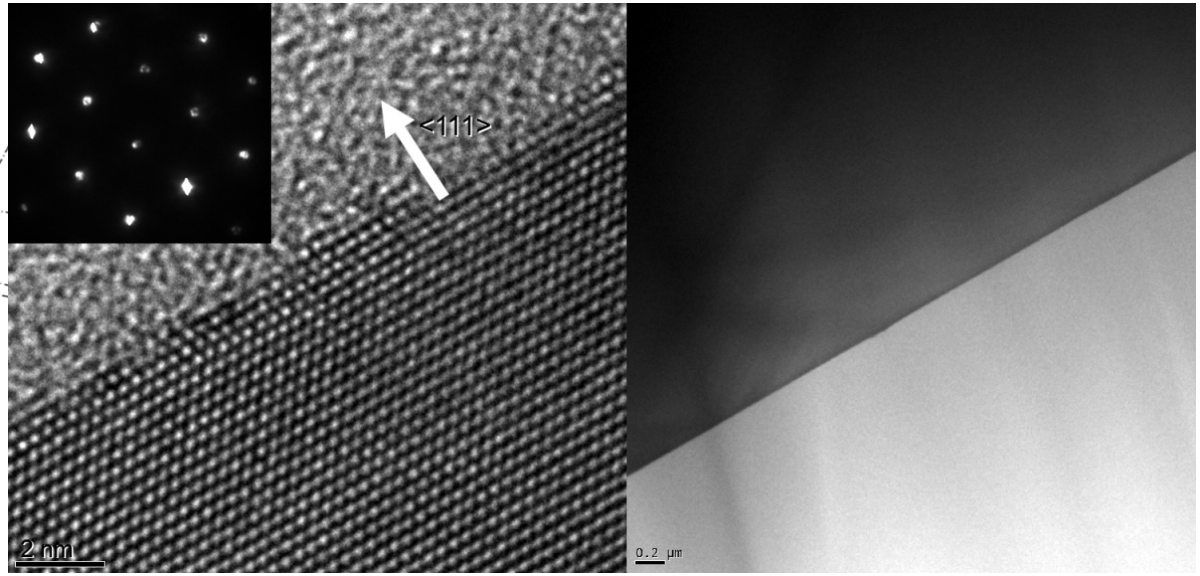
# Anisotropic etching




Anisotropic etching is a feasible way to tailor crystals to the wanted size without introducing new imperfections.



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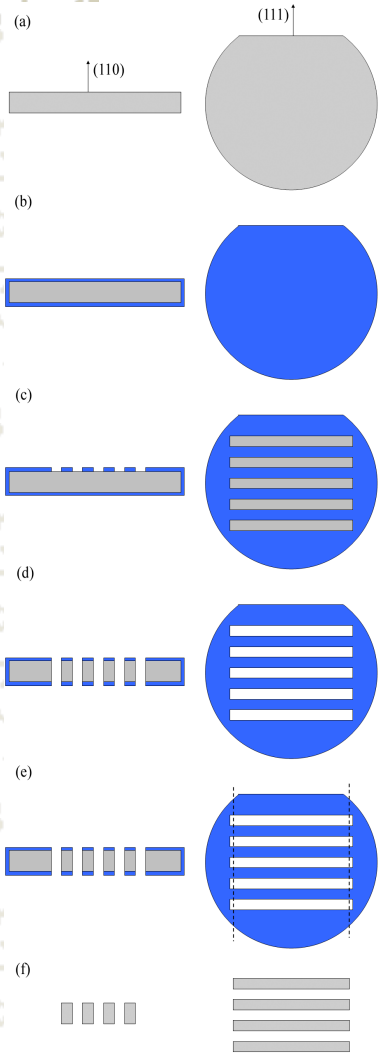
# Micromachining




a) Starting material: (110) silicon wafer

b) LPCVD deposition of silicon nitride thin layer

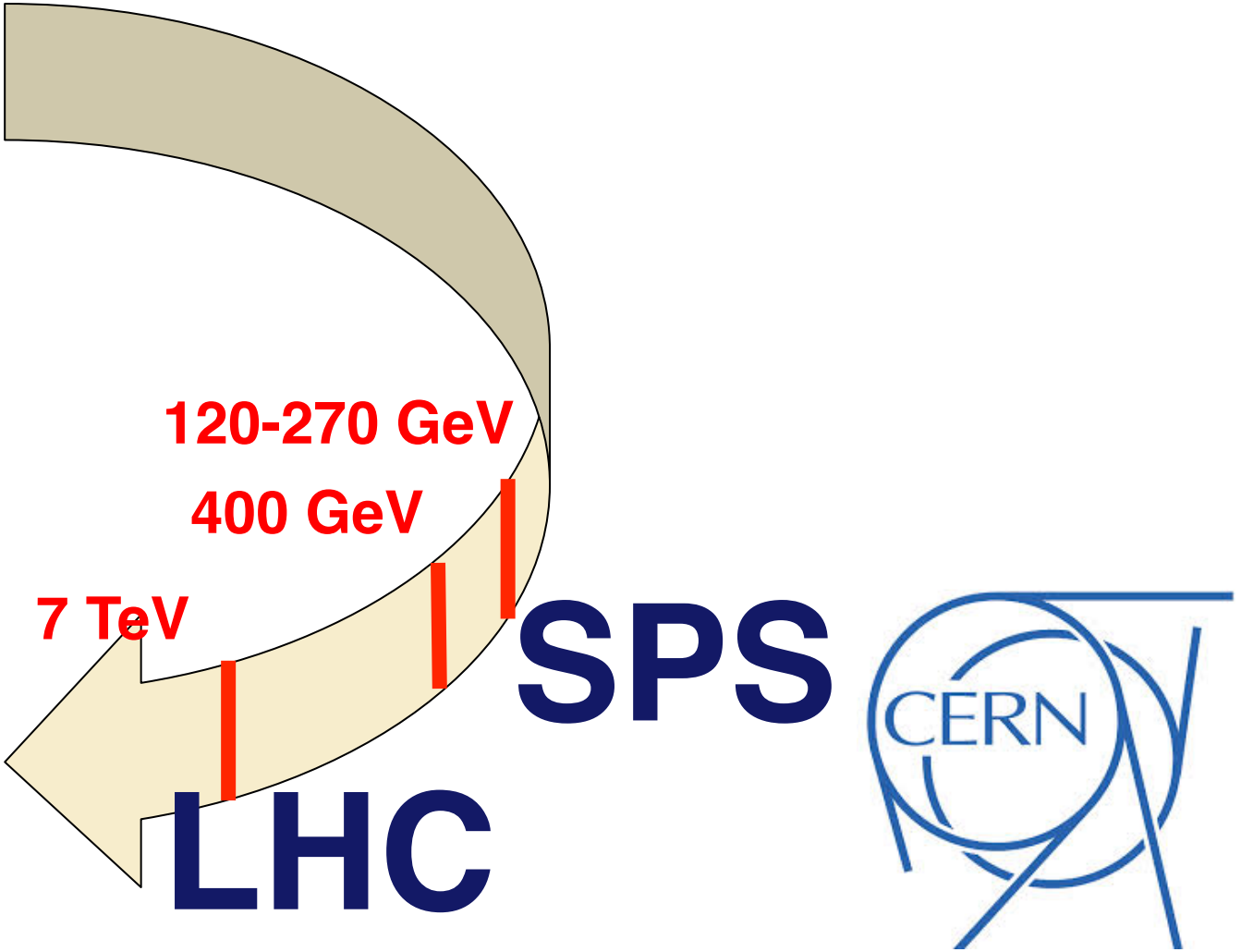
c) Silicon nitride patterning (photolithography)

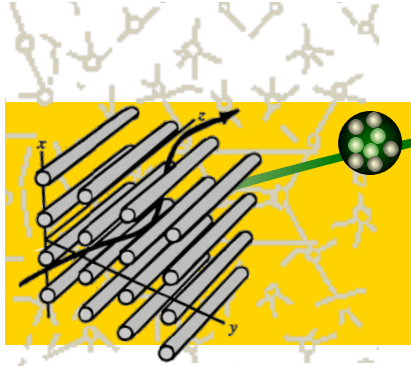
d) Etching of Si in KOH solution, silicon nitride acts as masking layer

e) Silicon strips release

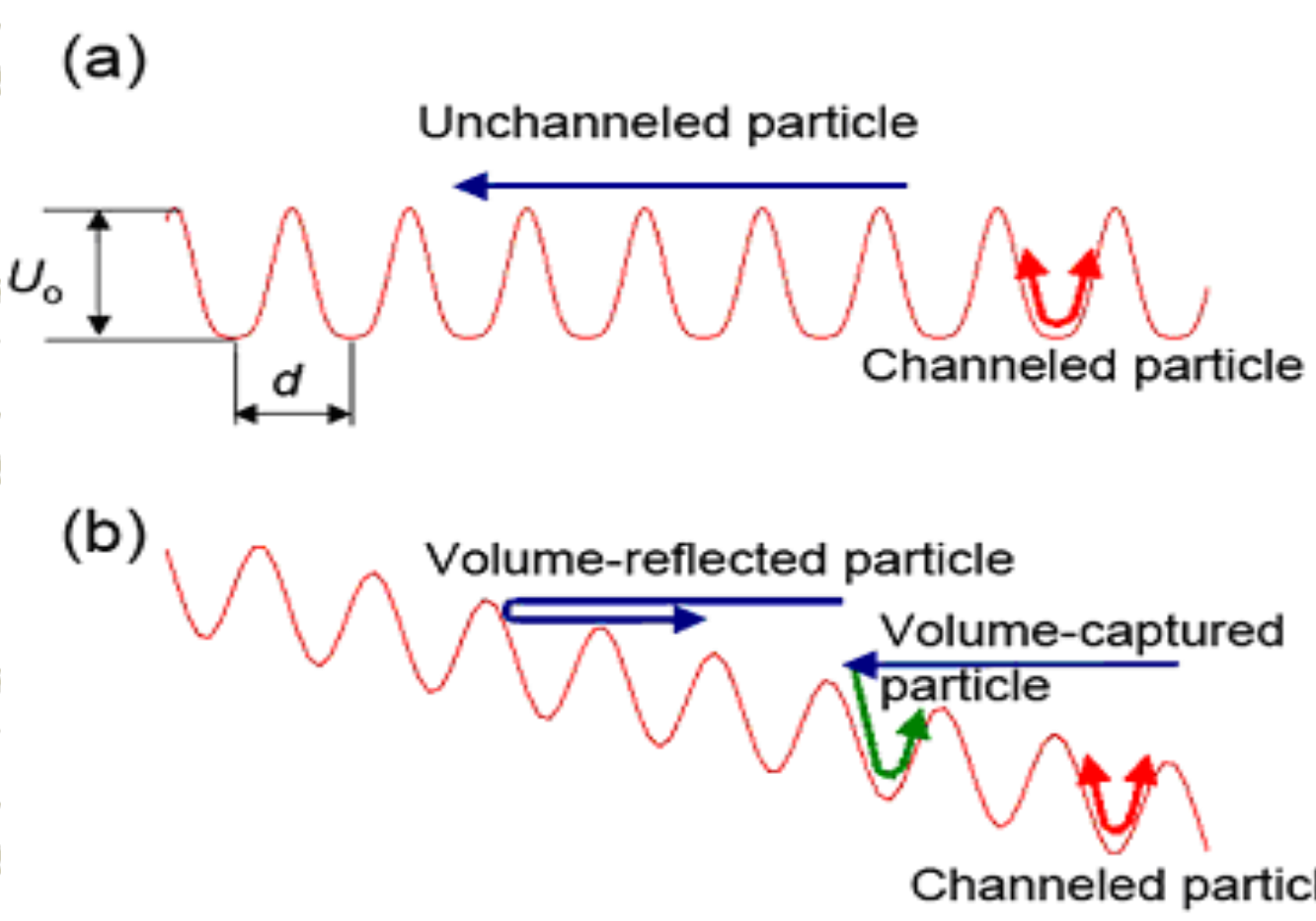
f) Removal of silicon nitride

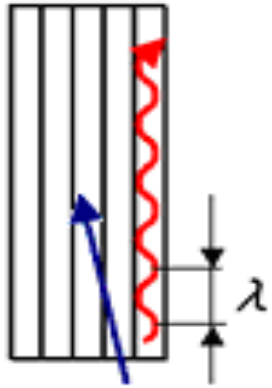
# Experiments with high-energy protons at CERN-SPS

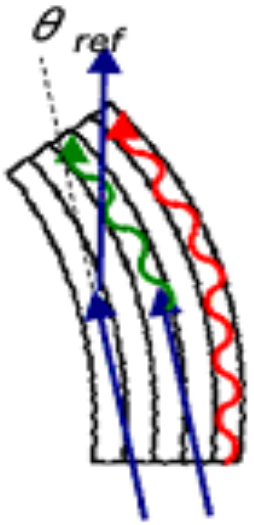




# Volume reflection as a new coherent effect

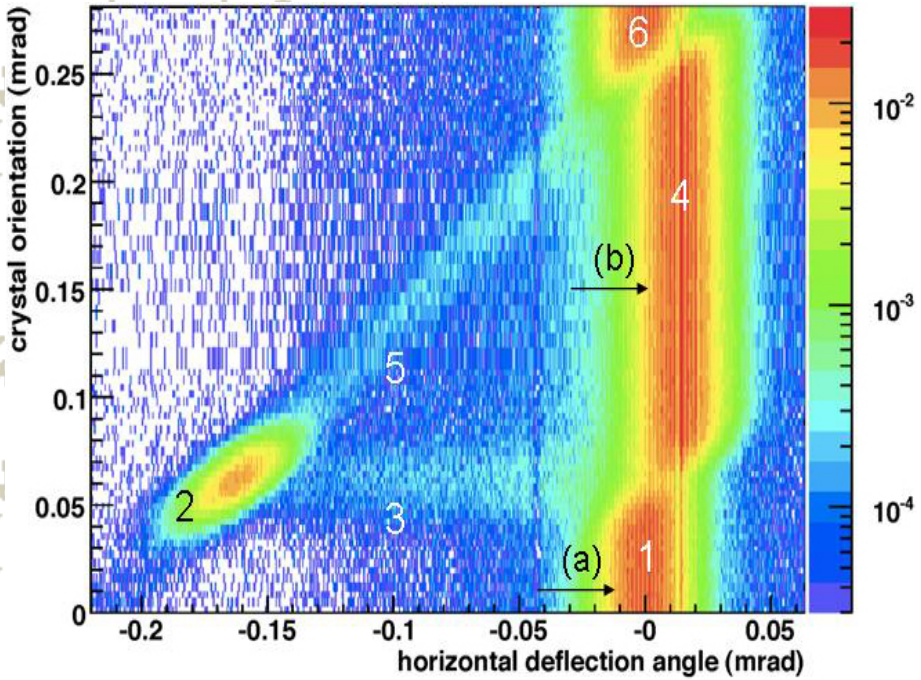



**Volume reflection: Taratin and Vorobiov (1988)**

# North Area Experiments (H8-H4)
# 400 GeV/c protons




1. Unperturbed beam
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture
6. Unperturbed beam

## Channeling [1]

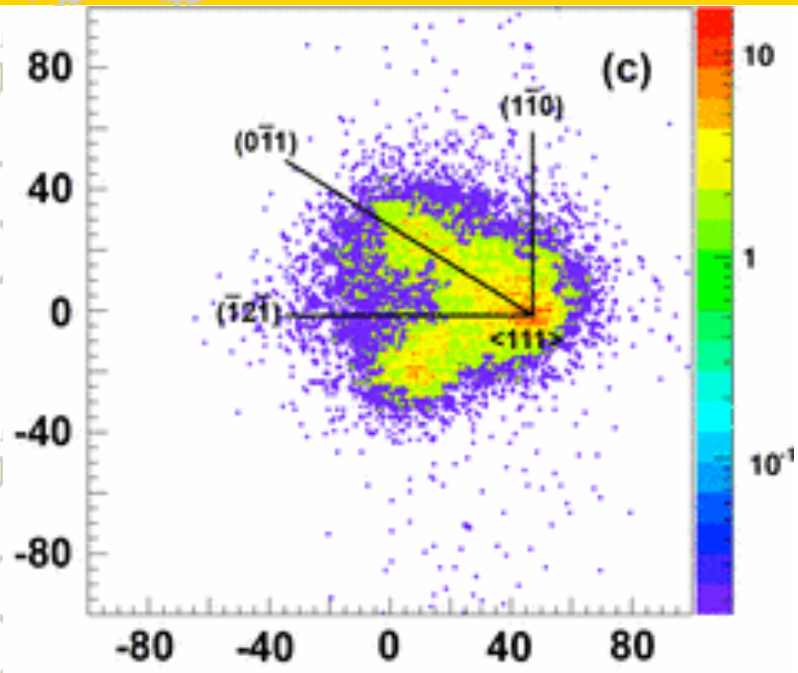
- ✓ Deflection angle: full bending angle
- ✓ Efficiency: > 60%
- ✓ Low angular acceptance

## Volume reflection [2]

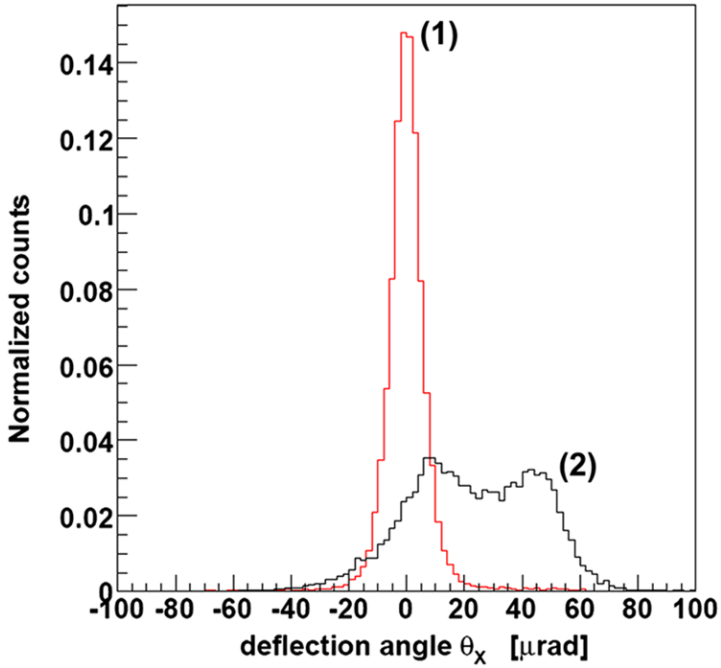
- ✓ Small deflection angle: 13.5 $\mu$rad ~ critical angle
- ✓ Efficiency: > 97%
- ✓ High angular acceptance


[1] W. Scandale et al., Phys. Rev. ST Accel. Beams 11 (2008) 063501
[2] W. Scandale et al., Phys. Rev. Lett. 98 (2007) 154801

# Axial case: 400 GeV/c protons




Angular distribution for
400 GeV/c protons deflected at a perfect alignment with
the {111} axis of a bent Si crystal [1]



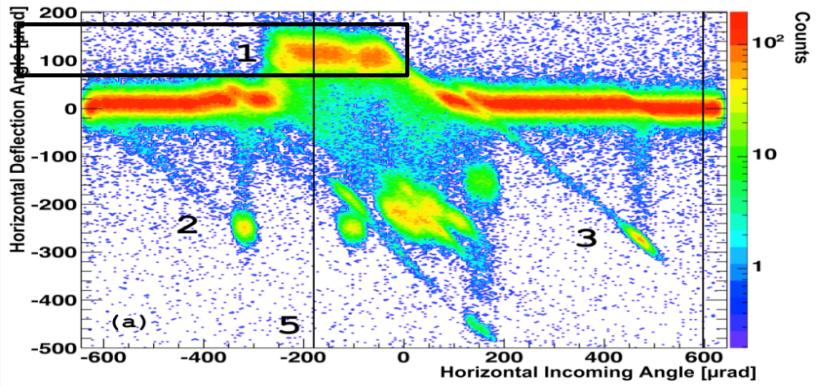

(1) Horizontal projection of the unperturbed beam profile and (2) of the distribution in axial channeling [1]

**Deflection efficiency > 90%**

[1] W. Scandale et al., Phys. Rev. Lett. 101 (2008) 164801

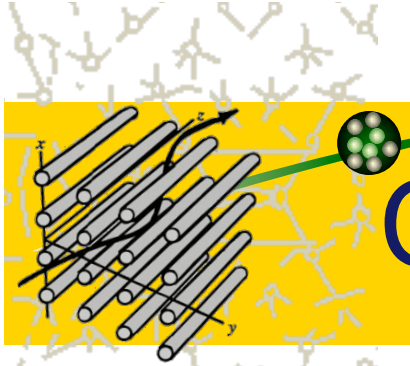
# Multi-volume reflection

**A series of aligned crystals provide increase of deflection angle with respect to an individual VR.**

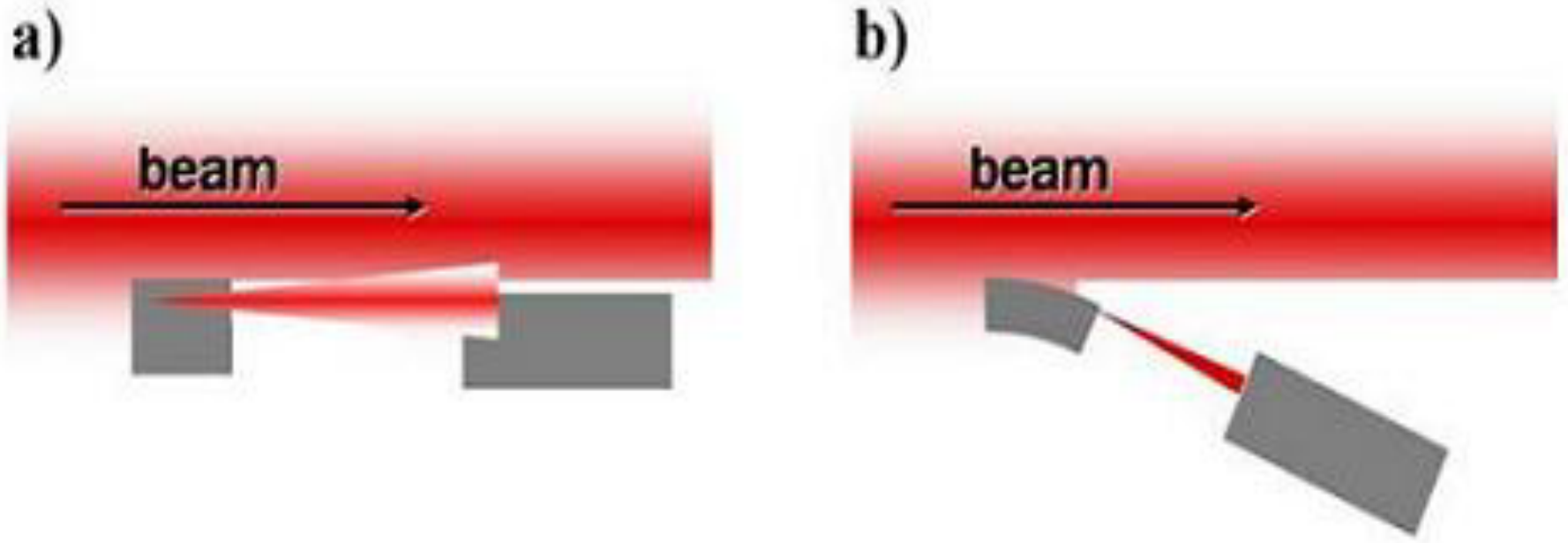

**400 GeV/c protons are deflected of about 100 µrad with a multistrip crystal. To obtain the same result with a bending magnet ~ 1000 Tesla is needed;**

[1] E. Bagli et al., Journal of Instrumentation 7 (04), P04002



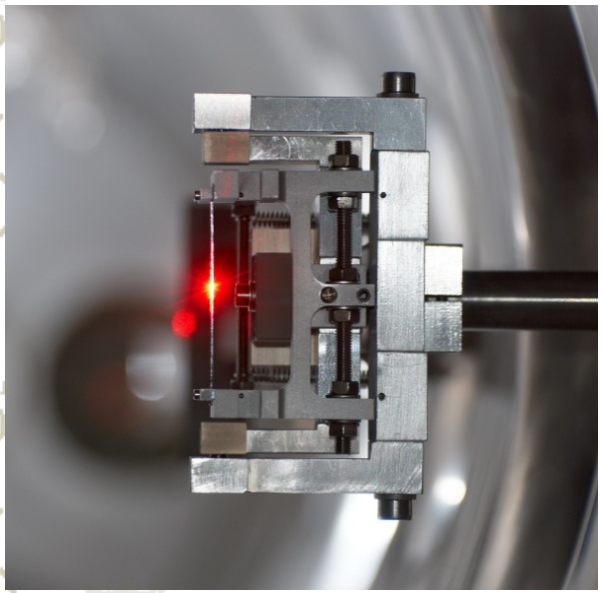
# Crystal assisted collimation

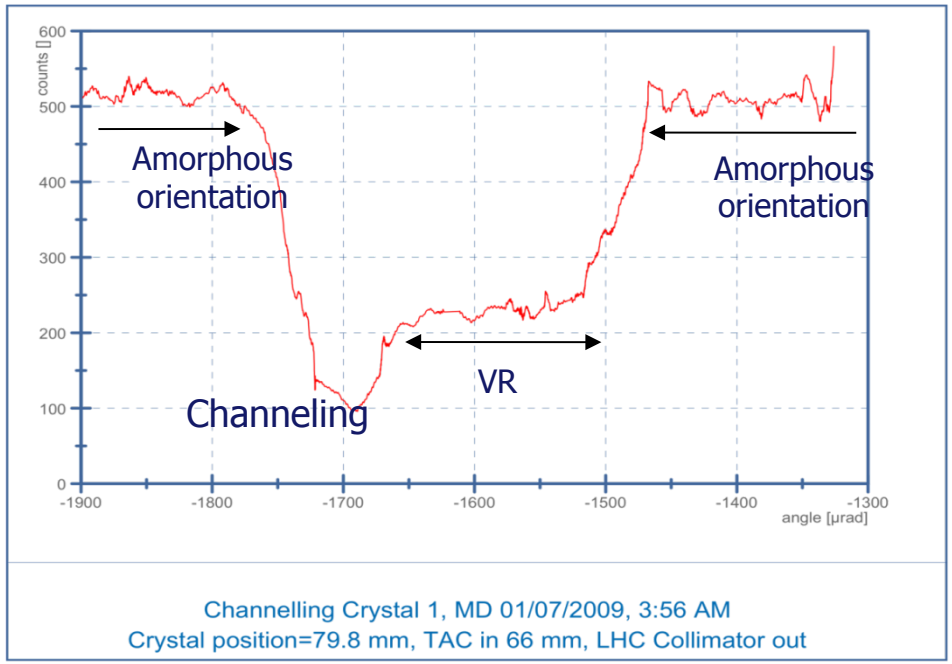
**A "smart target" which kicks all particles in only one direction**




**a) multi-stage collimation system:** an amorphous material spread the primary halo so that it can be intercepted by a secondary collimator**.**
**b) crystal-assisted collimation:** a curved crystal deviates the halo directly to the primary absorber.

# The UA9 experiment at CERN: Crystal-based collimation

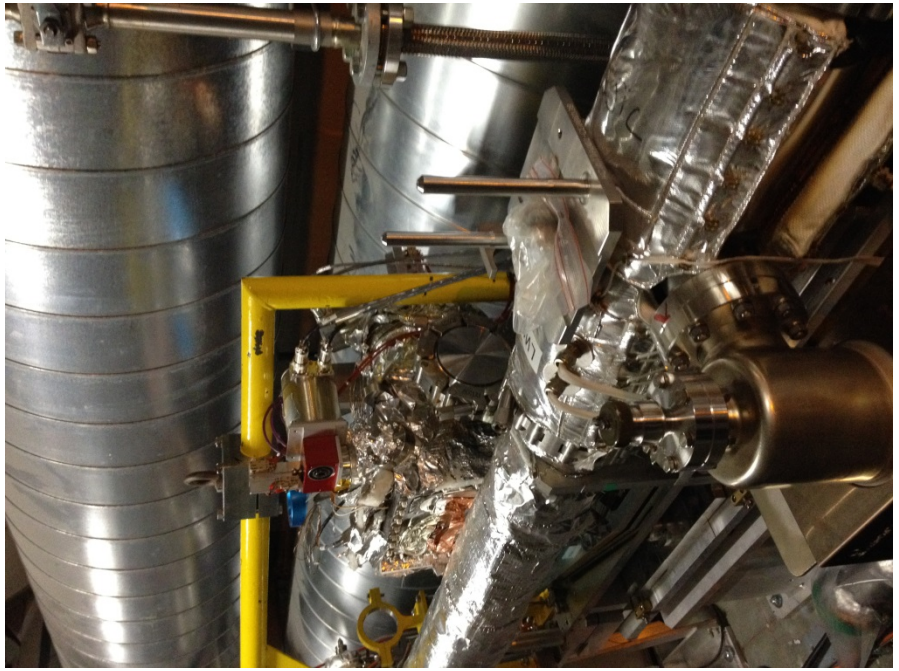





The halo loss rate due to nuclear inelastic interactions of 120 GeV/c protons in the aligned crystal was up to five times smaller than for its amorphous orientation.

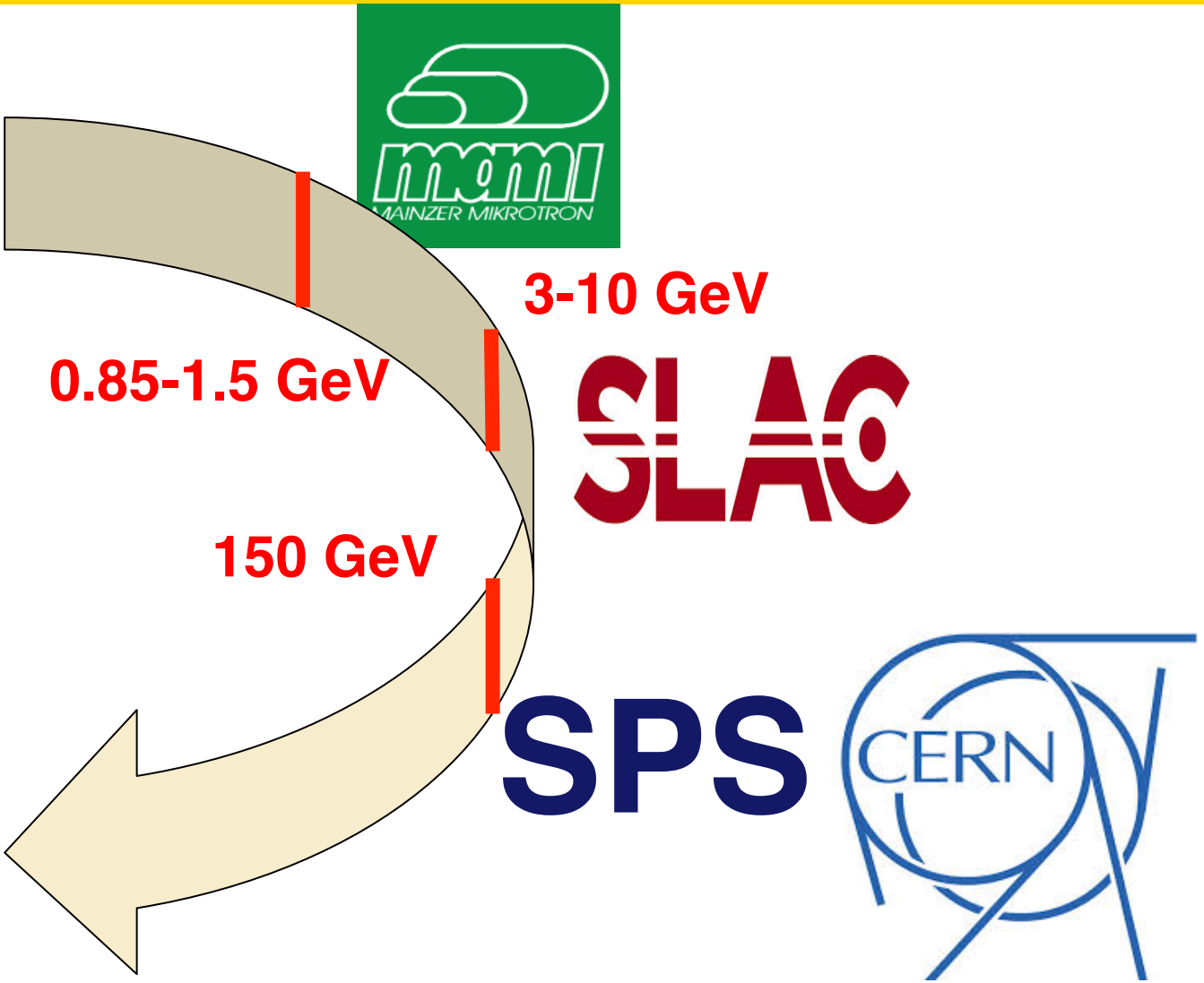
**[1] W. Scandale et al. PLB 692 (2010) 78**

# LHC crystal-based collimation



2 bent Si crystals were mounted on LHC on February 2014 to be tested as primary collimators in planar channeling orientation

# Experiments with negative particles

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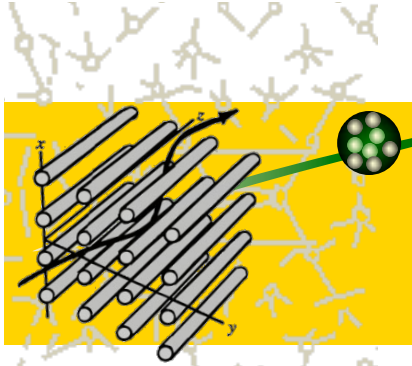
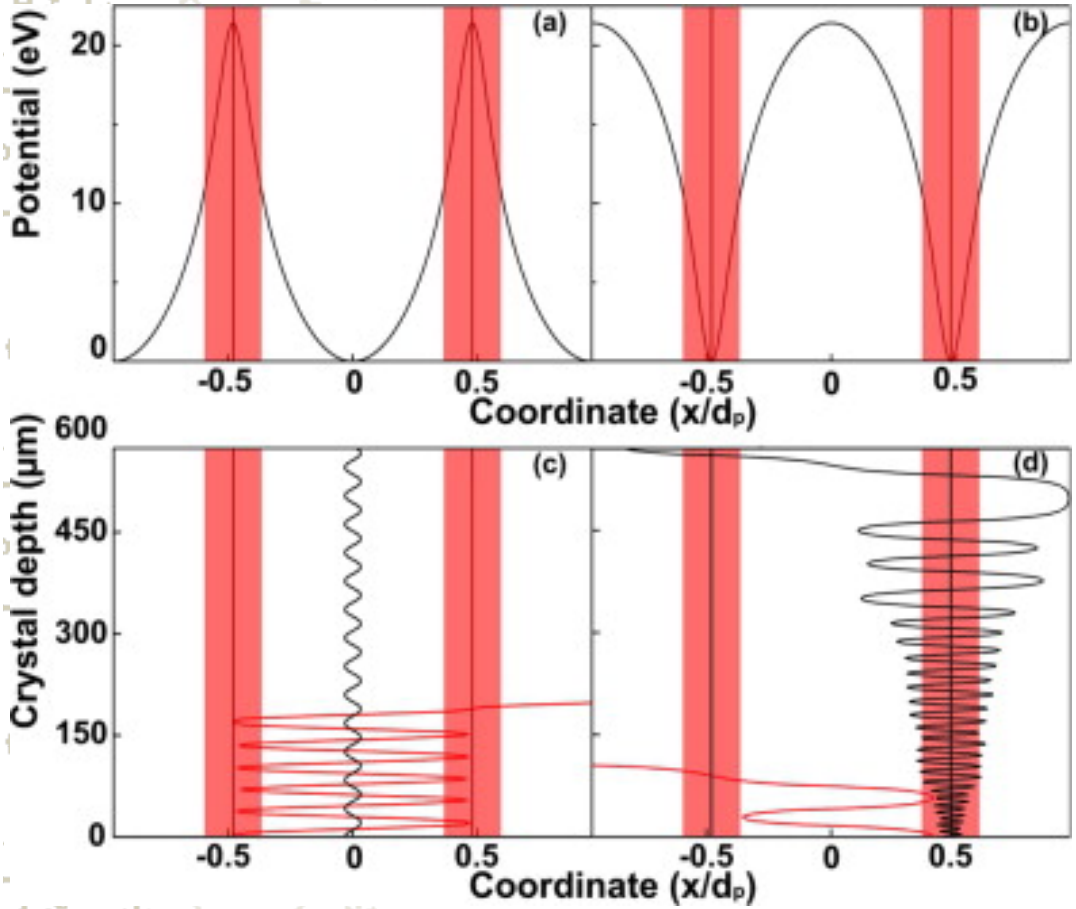


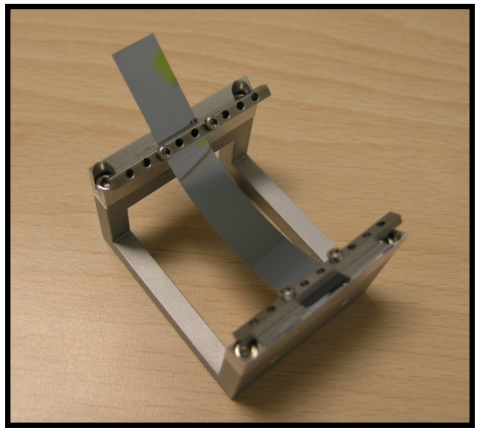
# Dechanneling of positive and negative particles

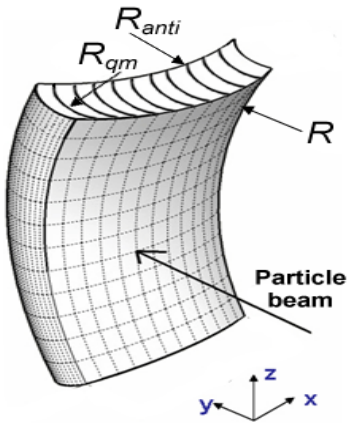
## Positive vs negative




**Channeled negative particles are dechanneled faster than positive ones due to higher probability to suffer nucler incoherent scattering;**

**Ultra thin bent crystals are required for efficient deflection of negative particles**

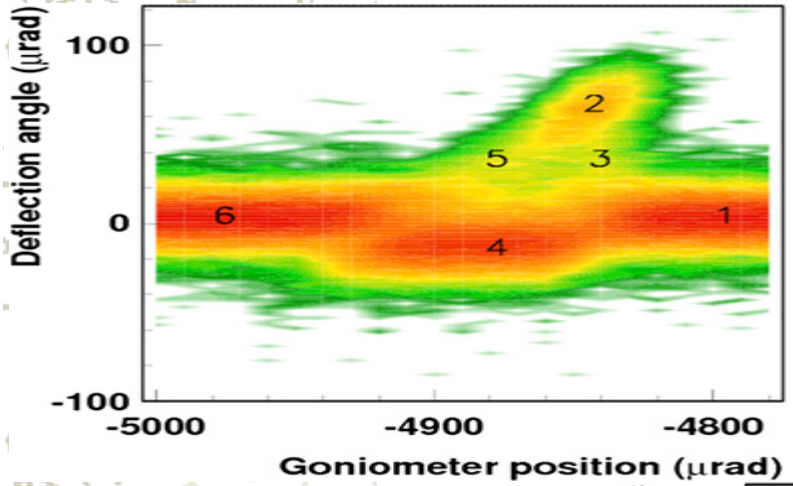





**Quasi-mosaic crystals [1]**

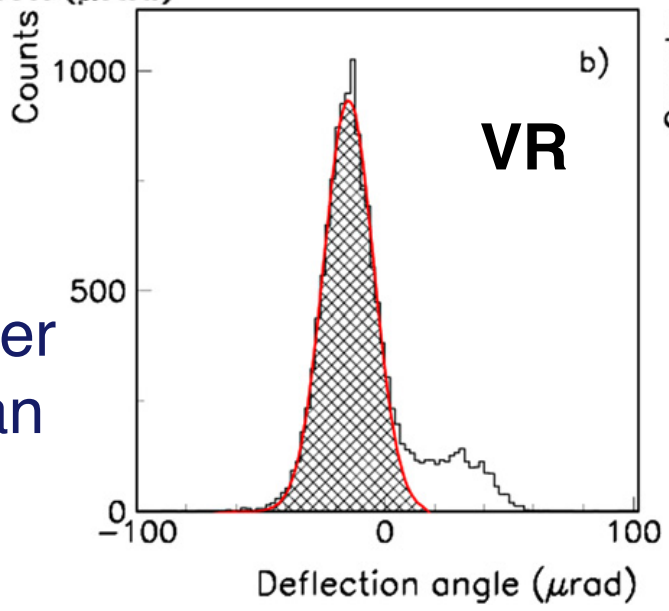
[1] V. Guidi et al., J. Phys. D: Appl. Phys. 42 (2009) 182005

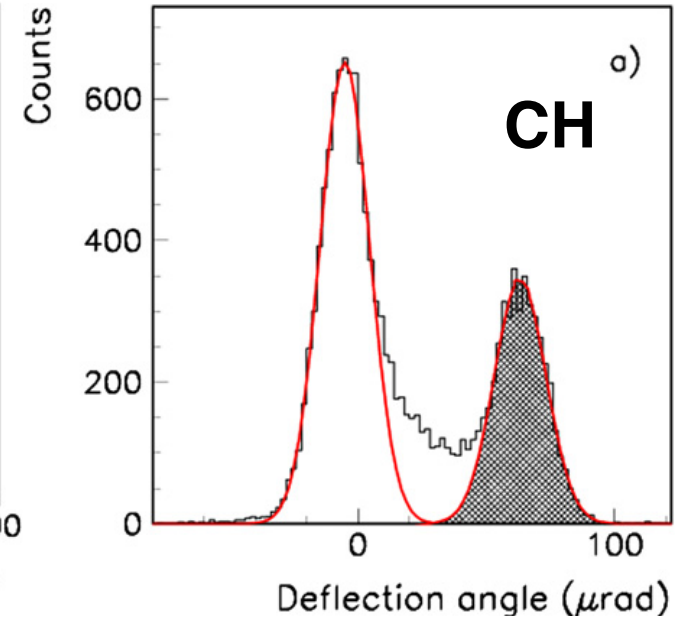
# Planar channeling of 150 GeV/c negative pions



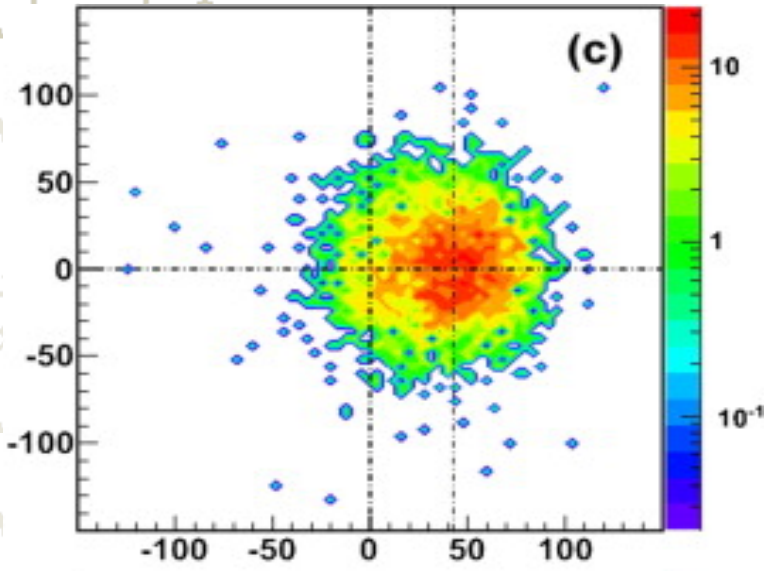

Negative particles have a similar behavior compared to positive ones under coherent interaction with crystal planes

VR has an higher efficiency and a larger angular acceptance but lower deflection angle than for channeling

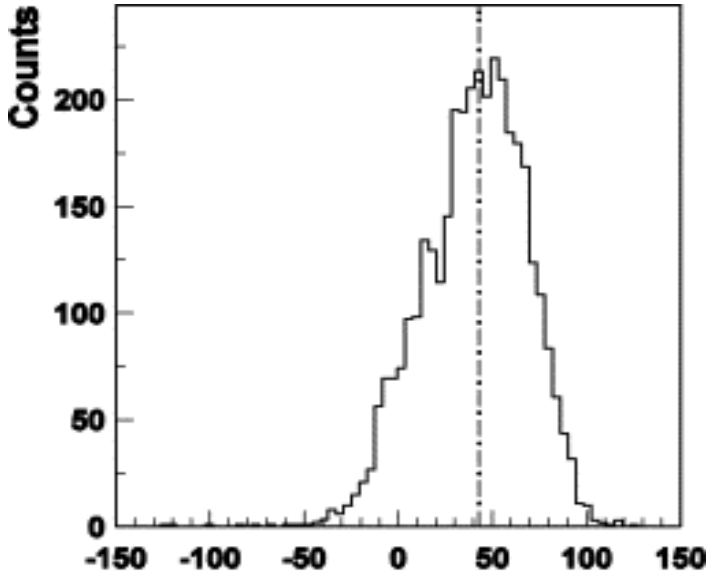


# Axial channeling of 150 GeV/c negative pions




Angular distribution at a perfect alignment with the {111} axis of a bent Si crystal [1]




Horizontal projection of the distribution in axial channeling [1]

**The deflection occurs mainly due to doughnut scattering of above-barrier particles by the atomic strings of the crystal**

**Deflection efficiency > 90% as for positive particles!!**

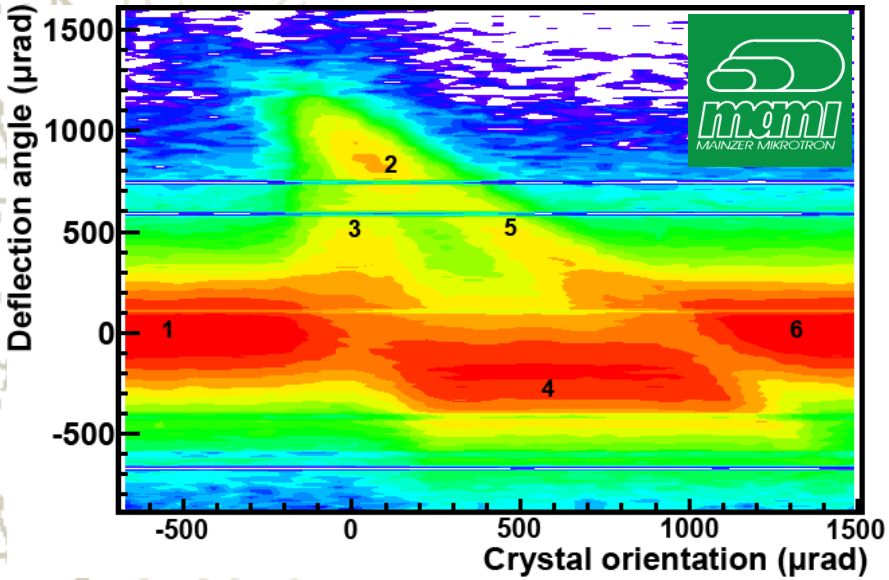
**Positive and negative particles show a similar dynamics in axial channeling**

[1] W. Scandale et al., Physics Letters B 680 (2009) 301–304

# Lower energy experiments

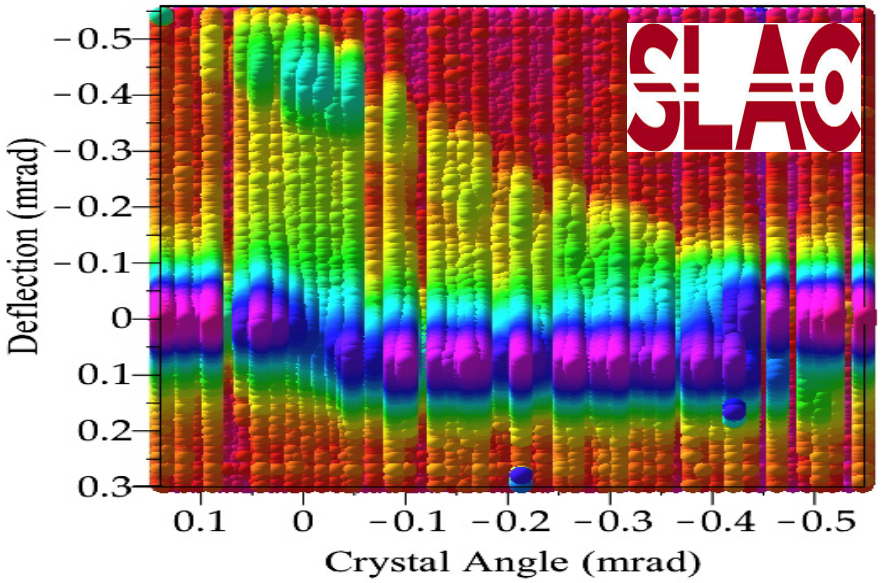
**The technology for bent crystal fabrication was pushed to its extreme limit, starting from the ~ mm bent crystals for CERN (150 GeV) to arrive at the 30/60 $\mu$m bent crystals used in MAMI (0.855GeV) and SLAC (3-10 GeV).**

## 0.855 GeV $e^-$

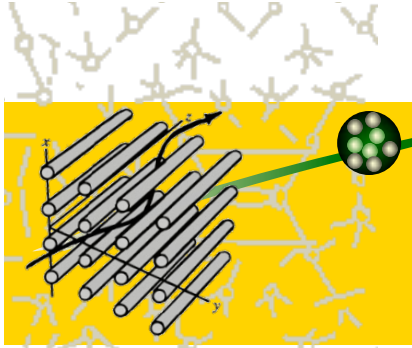



A. Mazzolari et al.,
Phys. Rev. Lett. 74 (2014) 2740

## 6.3 GeV $e^-$

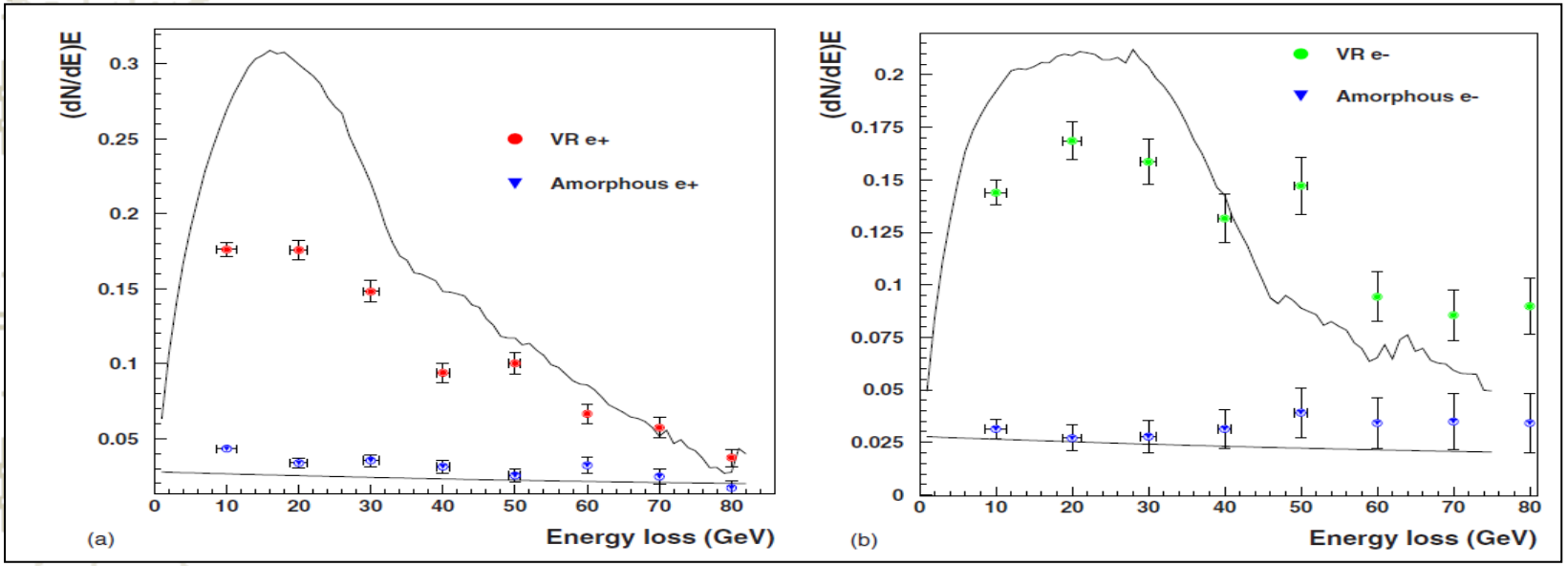



Experiment T-513 (Uli Wienands)
very preliminary



# Generation of e.m. radiation in crystals

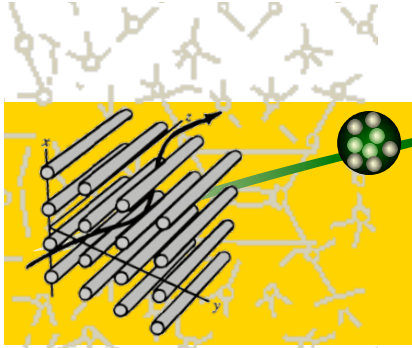
**More intense spectra of electromagnetic radiation compared to the amorphous case** (i.e. Bremsstrahlung)




**VR [1] and MVROC [2] radiation are similar for electrons and positrons**
**And has a high efficiency (> 95%) and a large angular acceptance**

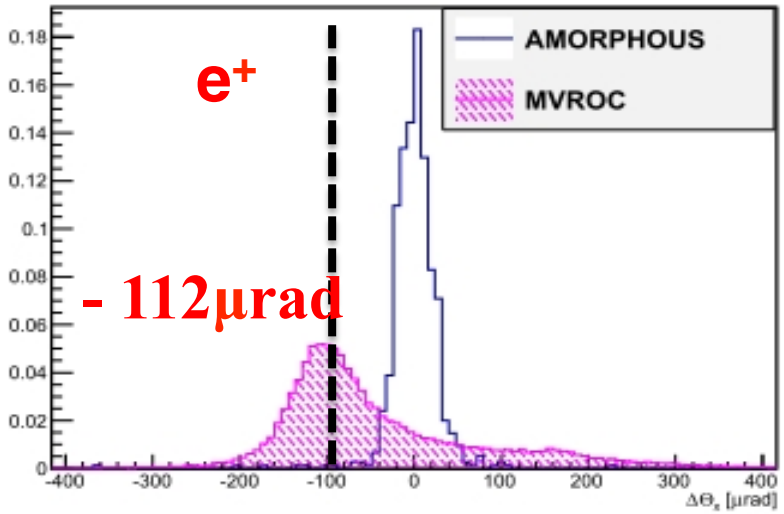
➡ **Possible applications in collimation for future ILC [2,3]**


[1] W. Scandale et al., Physical Review A 79 (2009) 012903
[2] L. Bandiera et al., Physical review letters 111 (2013) 255502
[3] A. Seryi, Nucl. Instrum. and Meth. A 623 (2010) 23

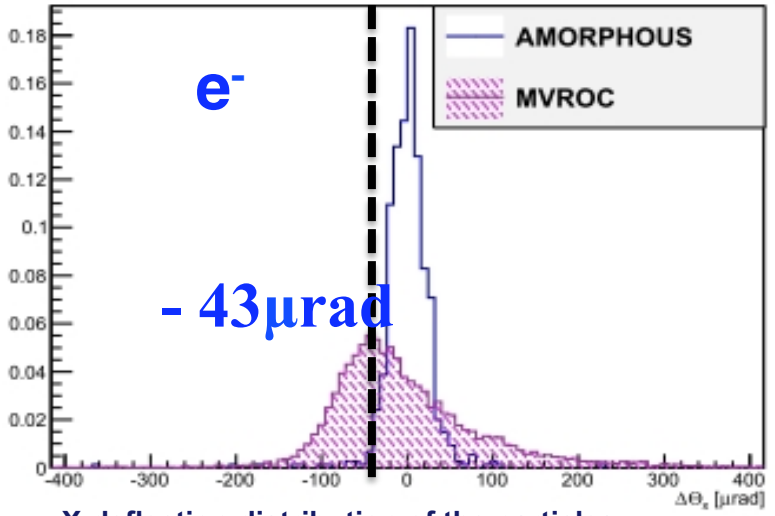


# Possible schemes for discrimination of negative and positive particles

## Deflection of particle via Volume Reflection (VR) or Multiple Volume Reflection (MVROC) depends on particle charge




X-deflection distribution of the particles




X-deflection distribution of the particles

## Possible applications for the discrimination of particles/antiparticles

# Summary

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- Coherent interactions in bent crystals can be used for efficient steering of particle beams.
- It works over a very broad energy range and particle charge provided that the crystals are properly designed and manufactured.
- Results of experiments performed at CERN, SLAC and MAMI regarding both dynamics and radiation emission in bent crystal.



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*Thank you for your attention*

The disquieting muses
Giorgio de Chirico 1918

Sensor and Semiconductor Laboratory