EXPERIMENTAL INVESTIGATION ON STEERING OF ULTRARELATIVISTIC PARTICLE BEAMS THROUGH AXIALLY ORIENTED BENT CRYSTALS

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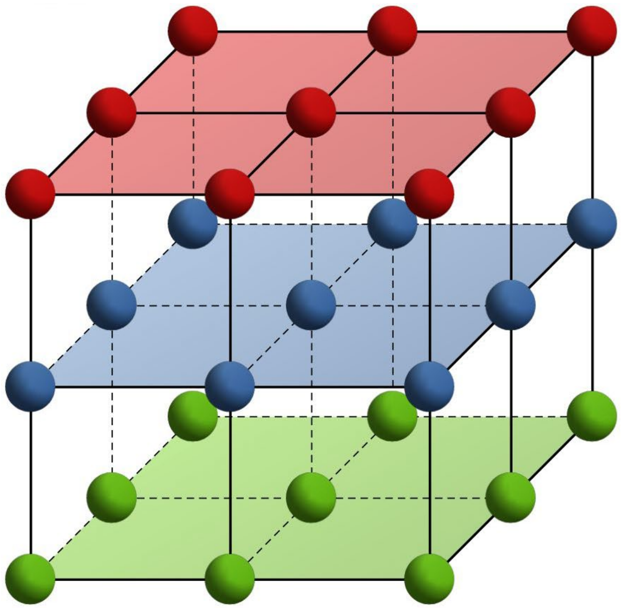
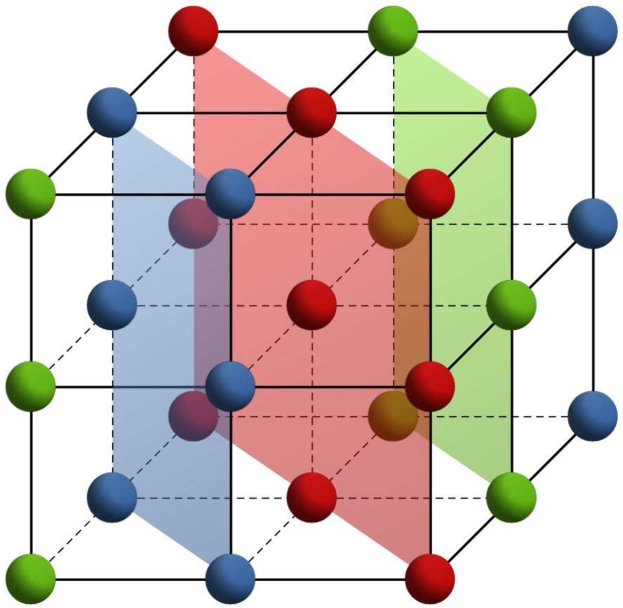
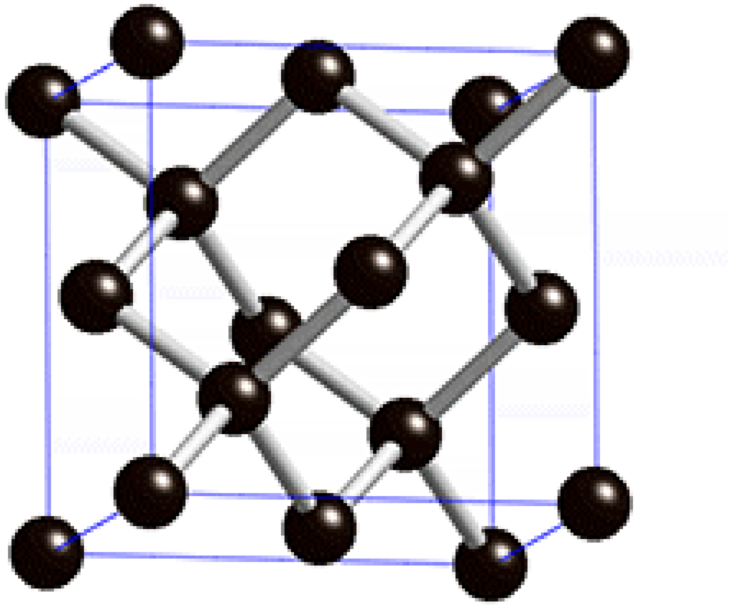
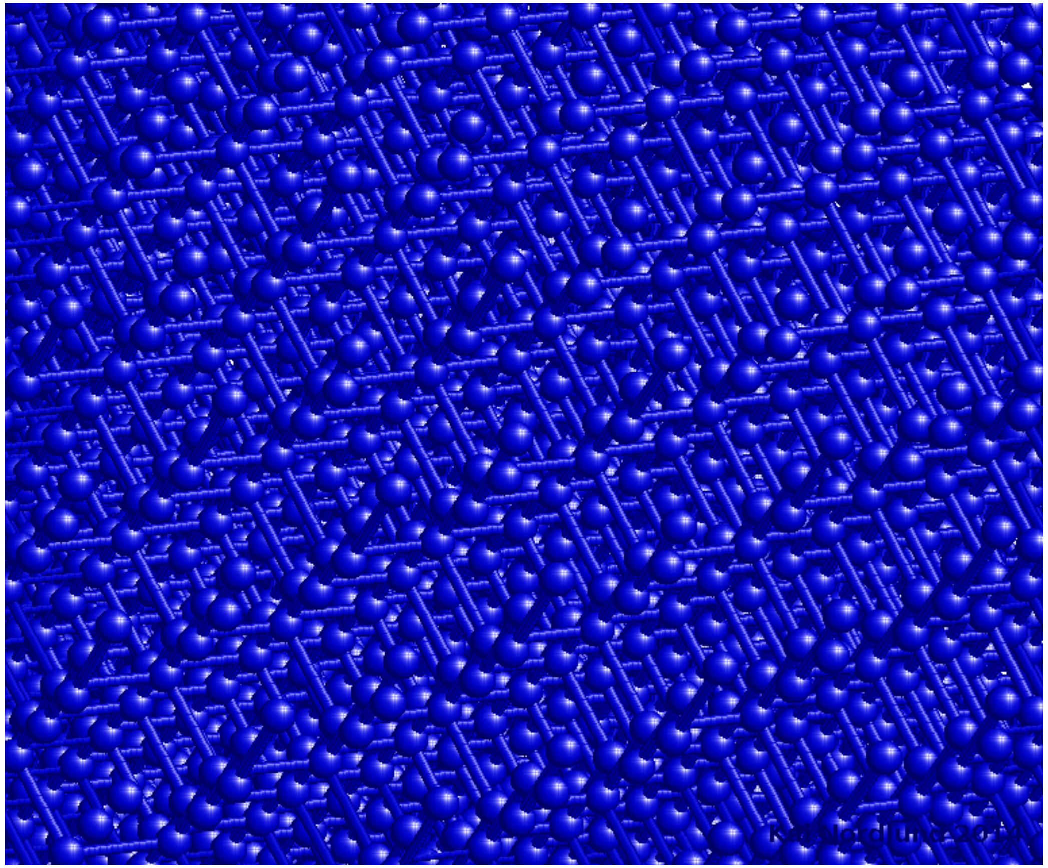
The crystal lattice

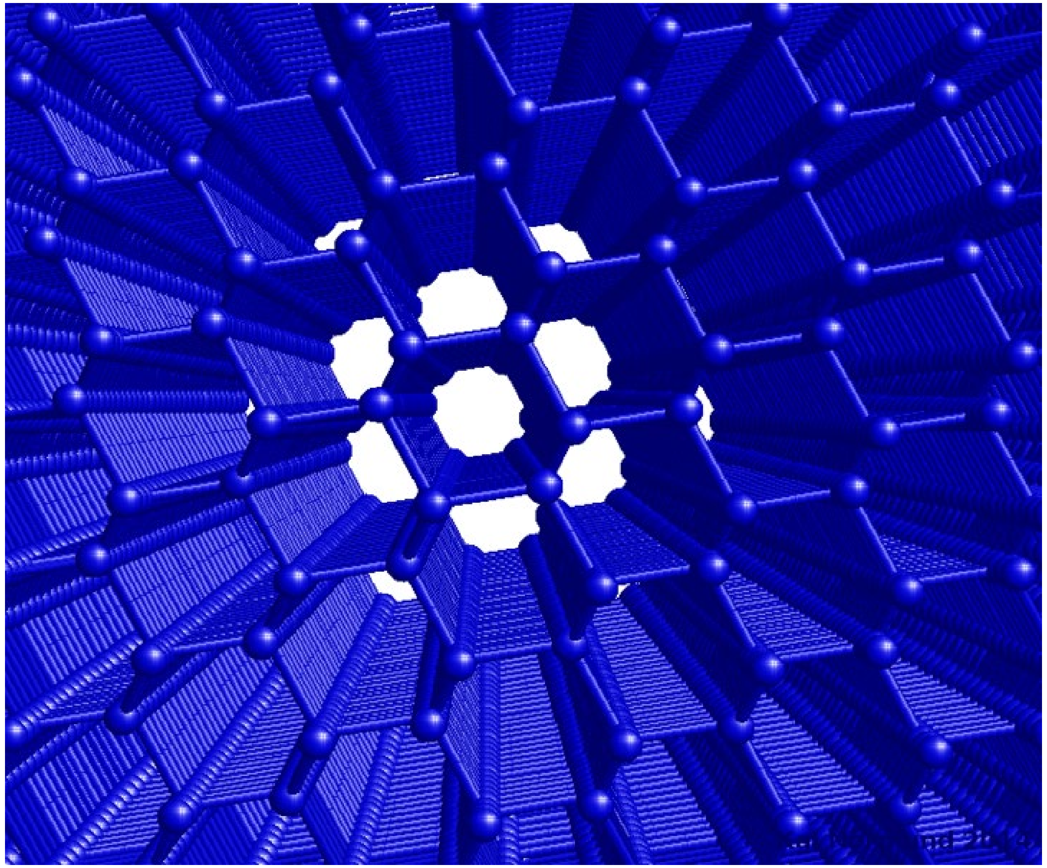




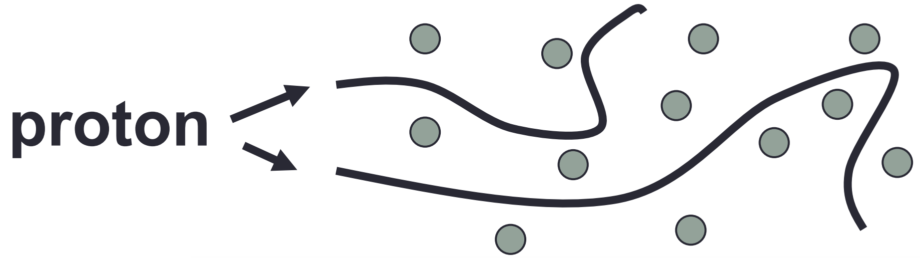


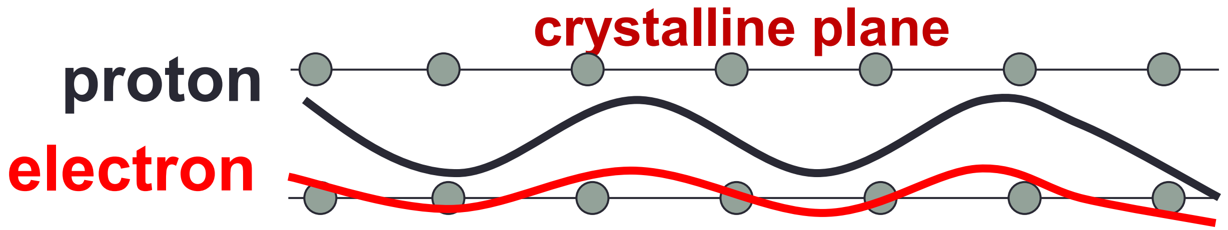
A strong electrostatic potential

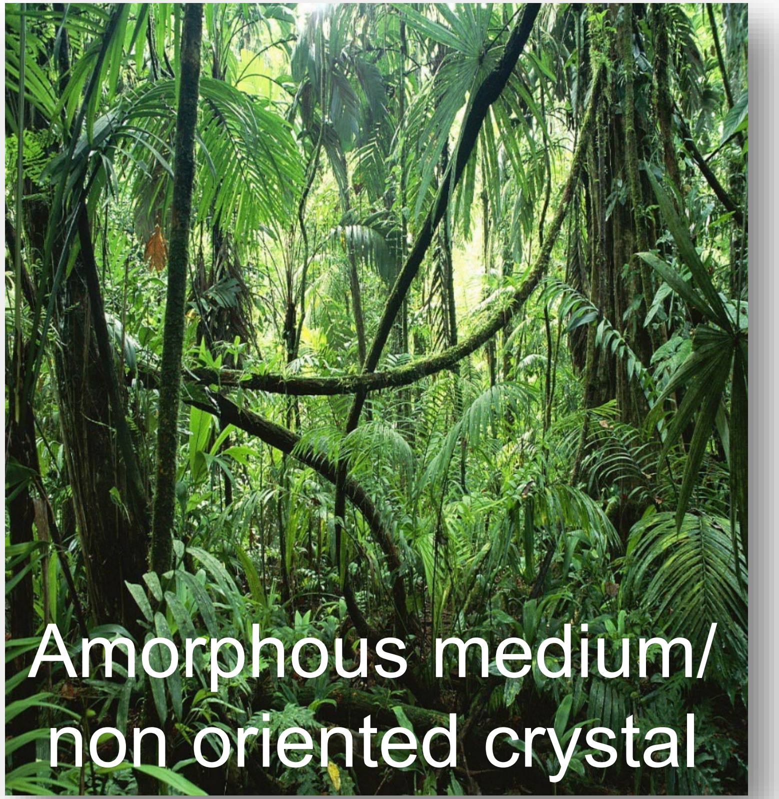




Channeling: trapping of charged particles







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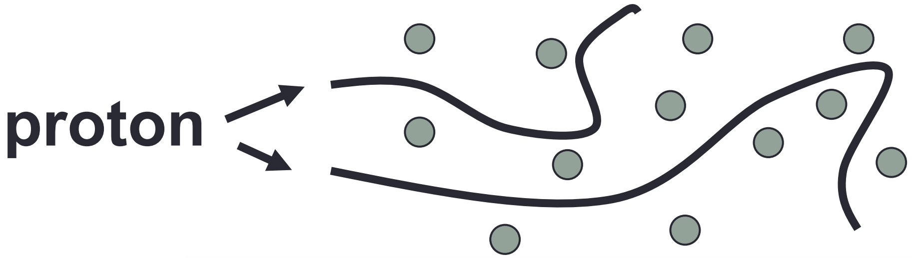
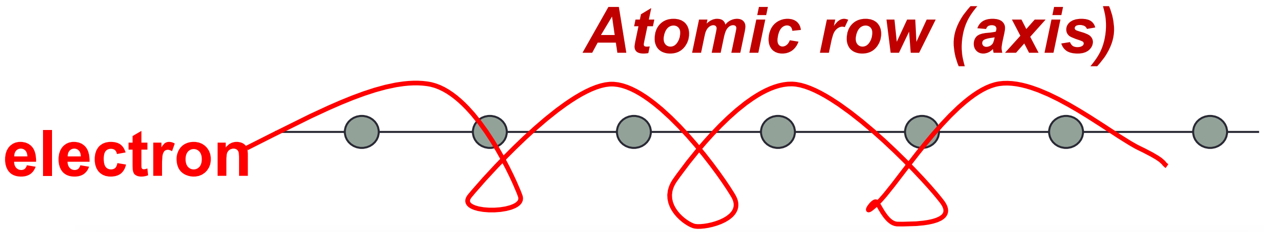
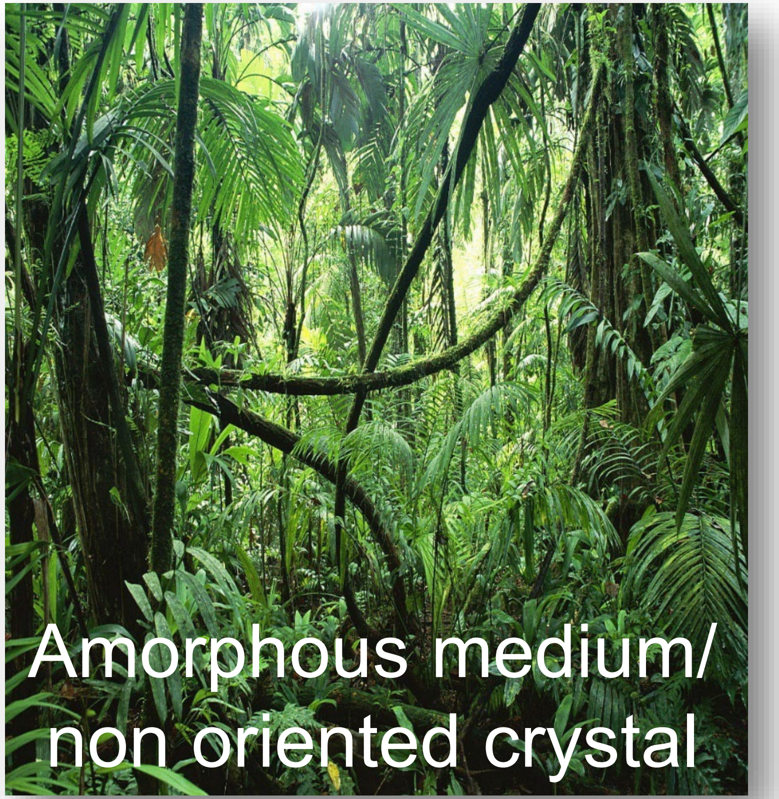
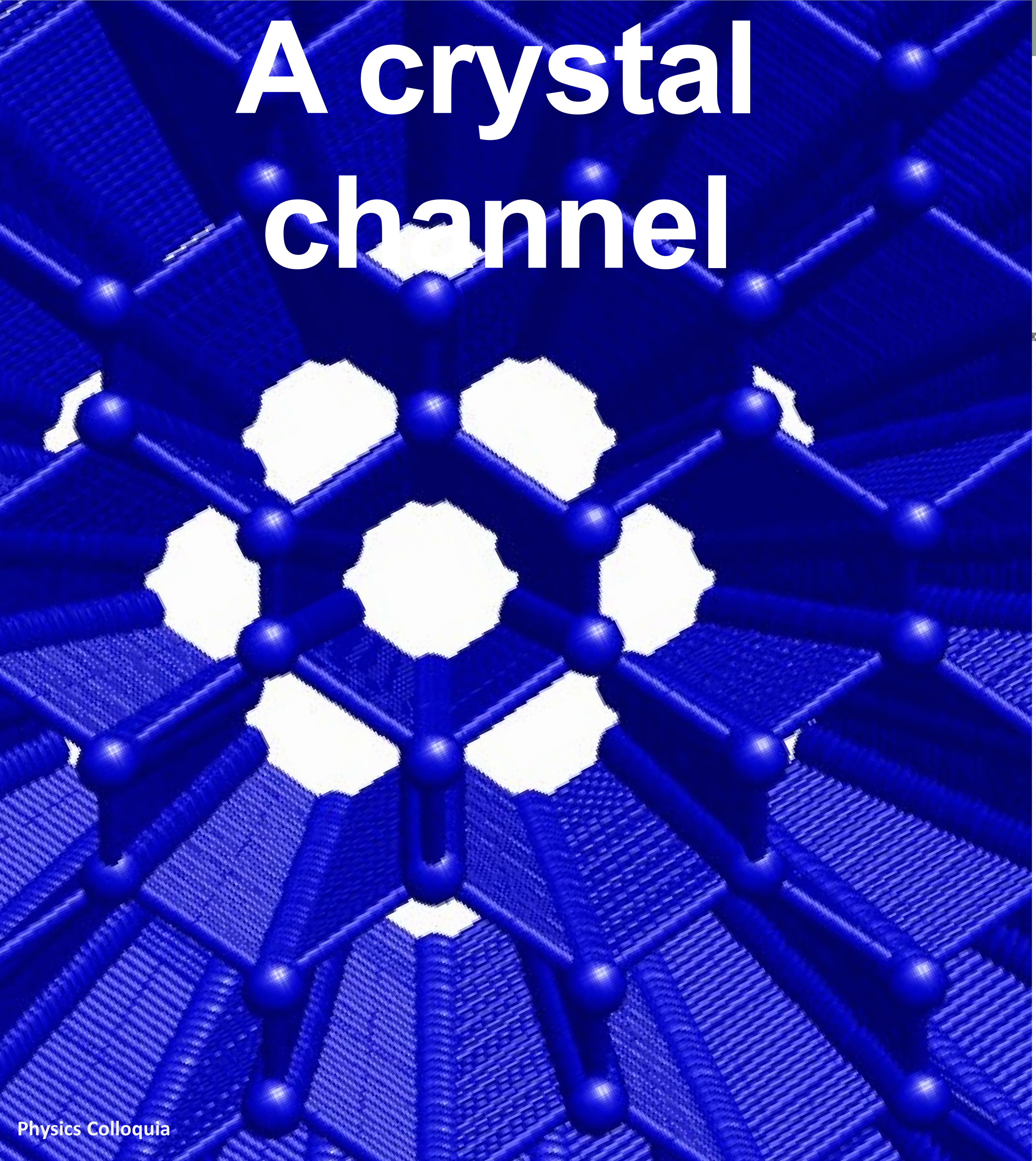
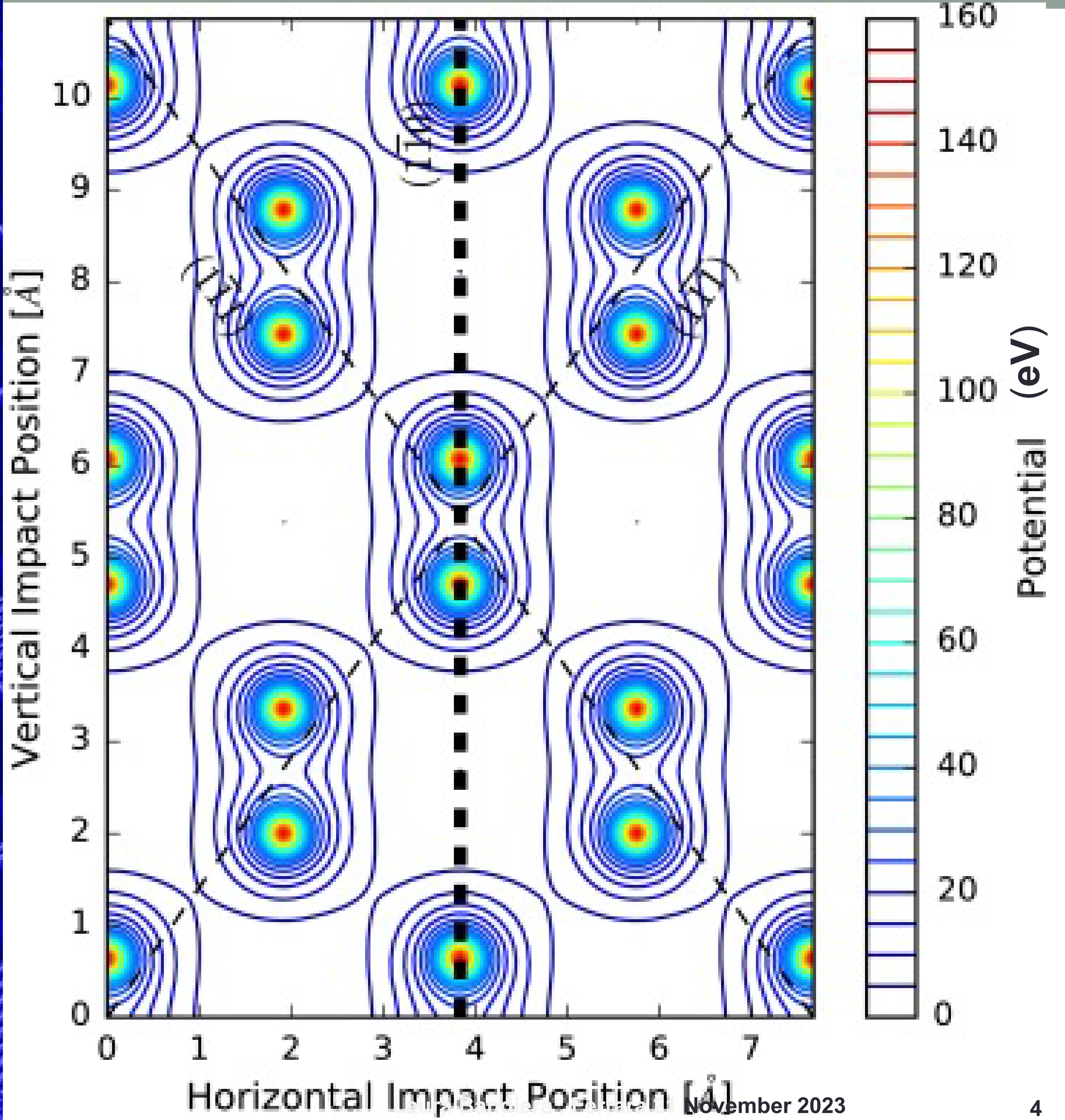




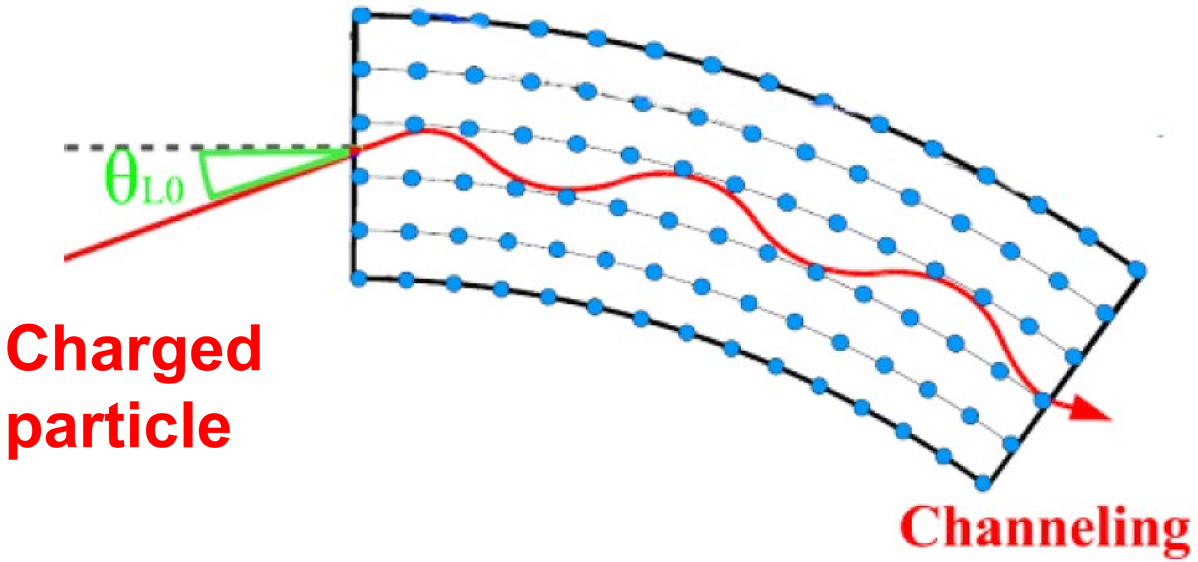


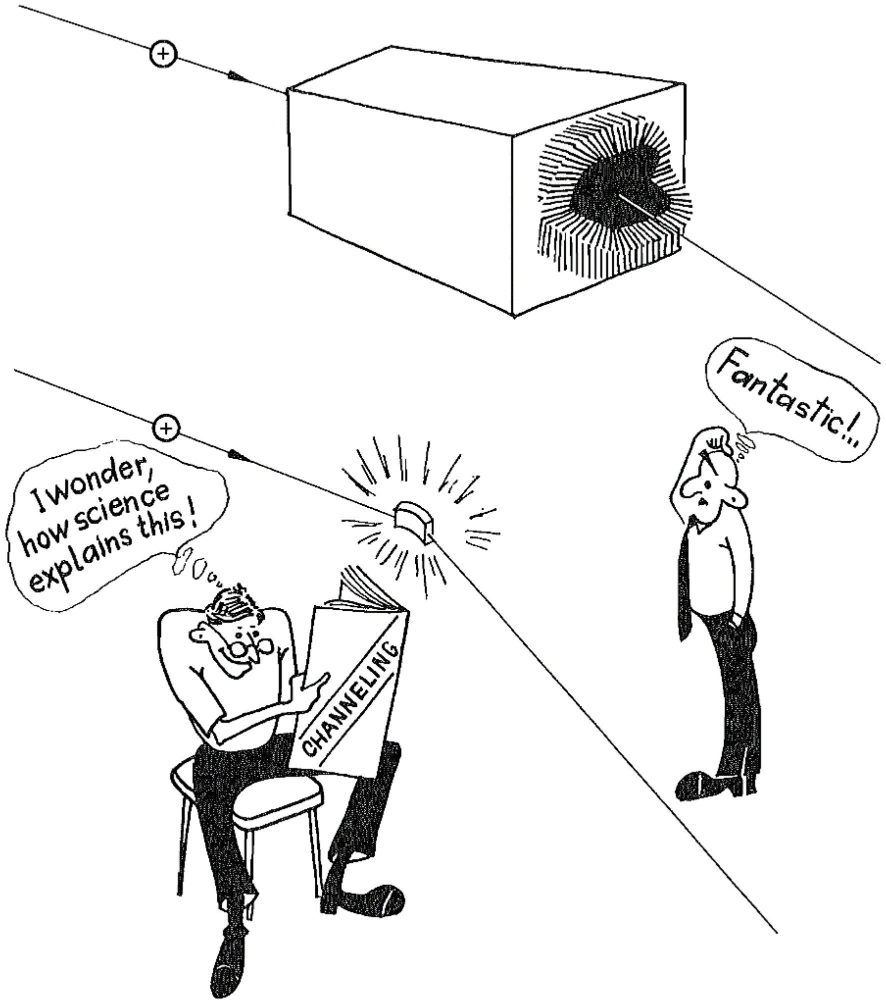
A crystal channel





Bending a crystal:
A way to steer a particle beam





E. Tsyganov, 1976

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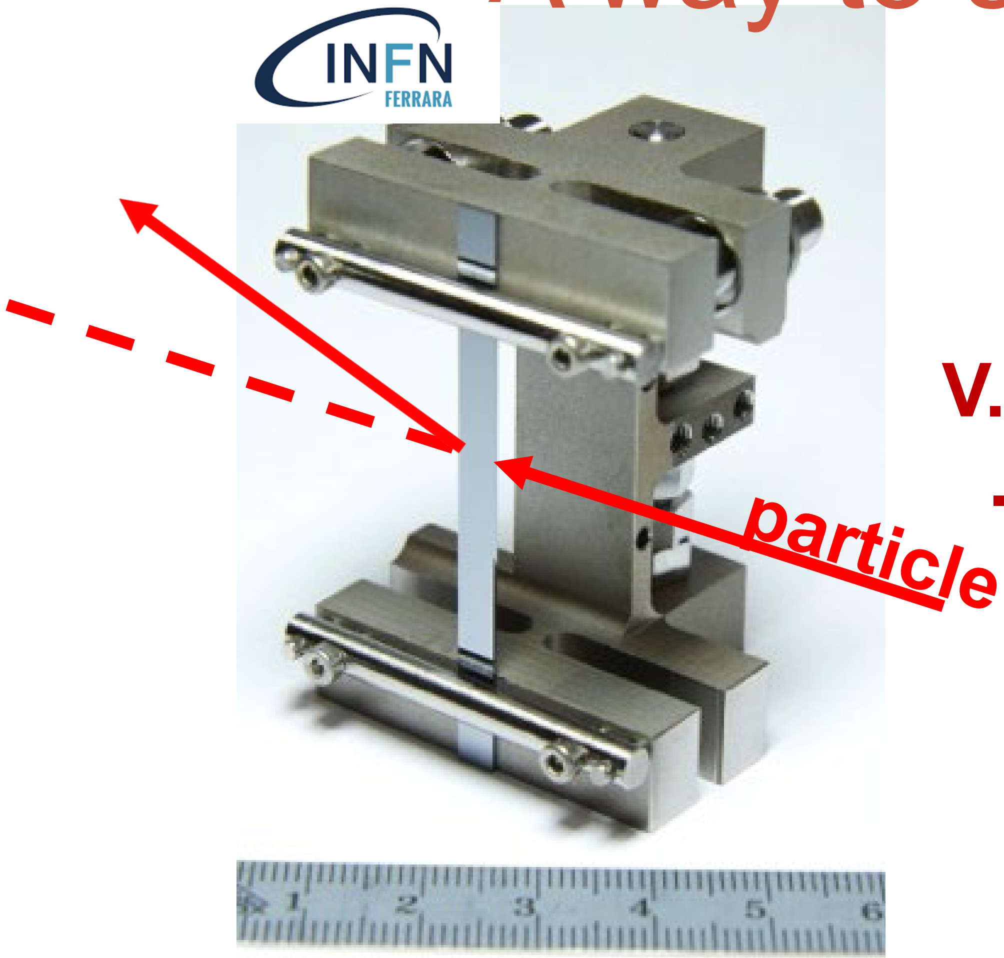


Bent Si crystal – 4 mm long
Installed in the LHC collimation system

V.S

8.3 Tesla supermagnet – 15 m long

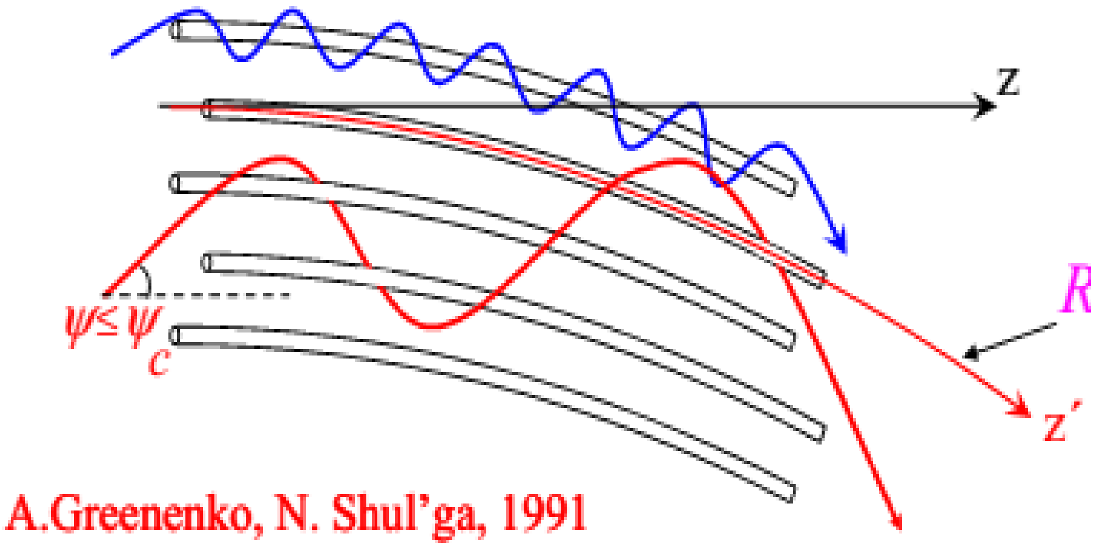
Deflection of 50 μrad at 6.5 TeV is equivalent to a 300 T dipole magnet bending!

Axial Channeling in a Bent Crystal

- Stochastic Deflection proposed by A.A. Greenenko and N.F. Shul'ga in 1991 [Pis'ma Zh. Eksp. Teor. Fiz. 54 (1991) 520]

- Experimentally observed by H8-RD22/UA9 collaboration at CERN in 2008 for protons and in 2009 for π^{-}-mesons

In case of axial alignment, most of the particles are deflected through multiple scattering by atomic strings (**Stochastic Deflection**) rather than by axial channeling (or **hyperchanneling**)



Stochastic deflection mechanism

Over-barrier

Greenenko-Shul'ga condition: $$\alpha < \alpha_{st} = \frac{2R\psi_c^2}{l_0}$$

α_{st} is the maximum angle achievable through SD;

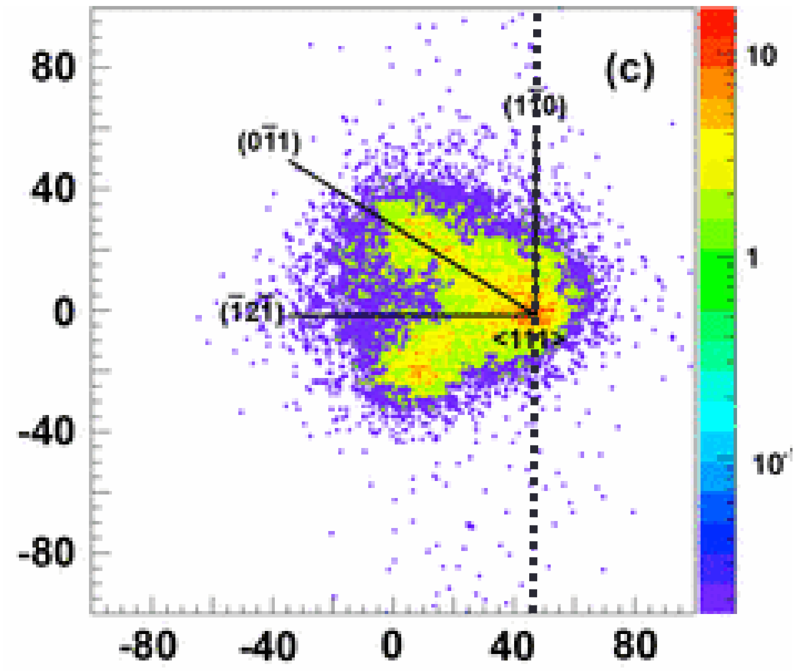
α is the crystal bending angle;

R is crystal curvature radius;

ψ_c is the critical angle of axial channeling;

l_0 is the mean free path of the particle between successive collisions with strings of atoms in a crystal.

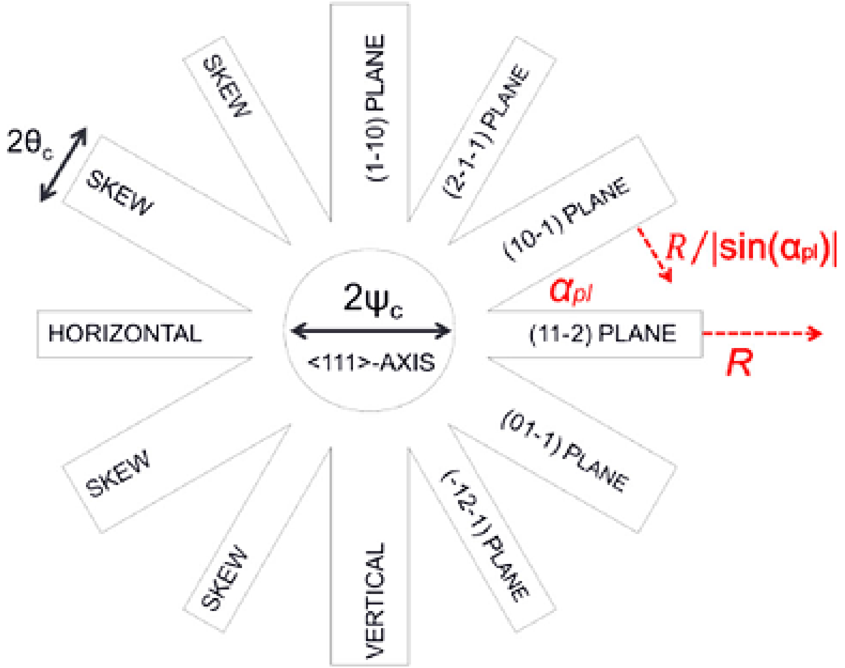
First result with high-energy positively charged particles



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

Deflection efficiency > 90%

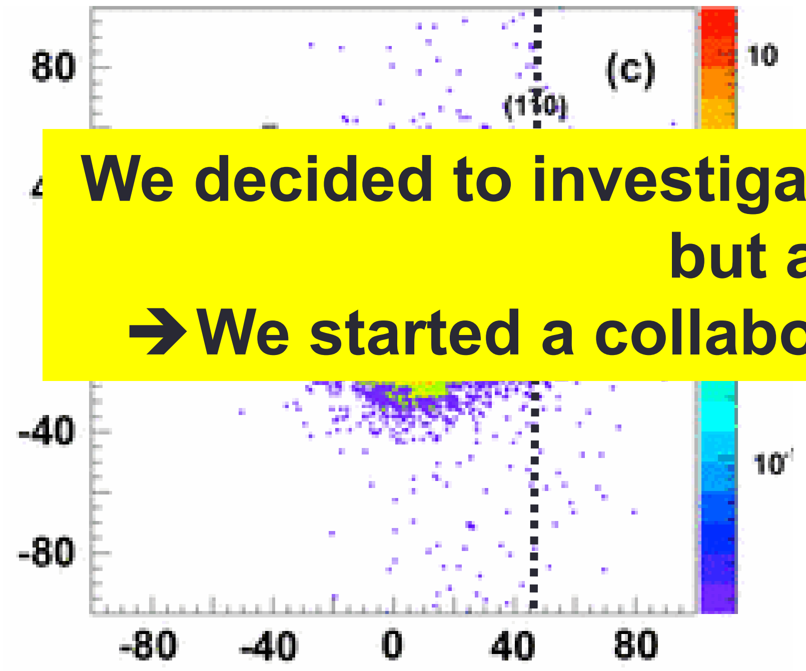
*W. Scandale et al., Phys. Rev. Lett. 101 (2008) 164801

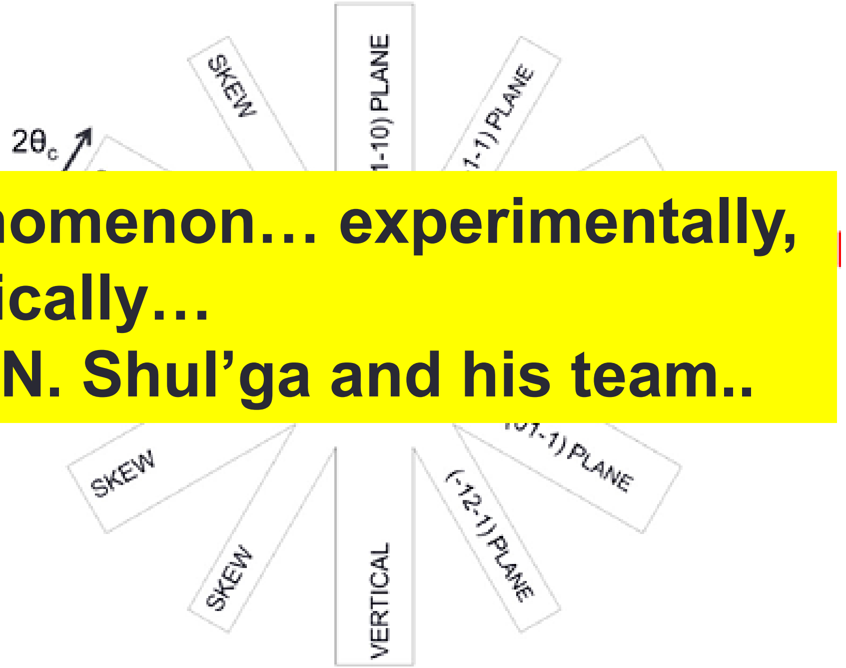


Crystal parameters:
(110) *Bent Planes*
<111> *Bent Axes* ($\psi_c \approx 21$ *μrad*)
Length L = 2 mm
Radius R = 40 m

FOR POSITIVE PARTICLES: Relaxation of axial-to-planar channeling in skew planes!

First result with high-energy positively charged particles





We decided to investigate this phenomenon… experimentally, but also theoretically…
➔We started a collaboration with N. Shul'ga and his team..

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FOR POSITIVE PARTICLES: Relaxation of axial-to-planar channeling in skew planes!

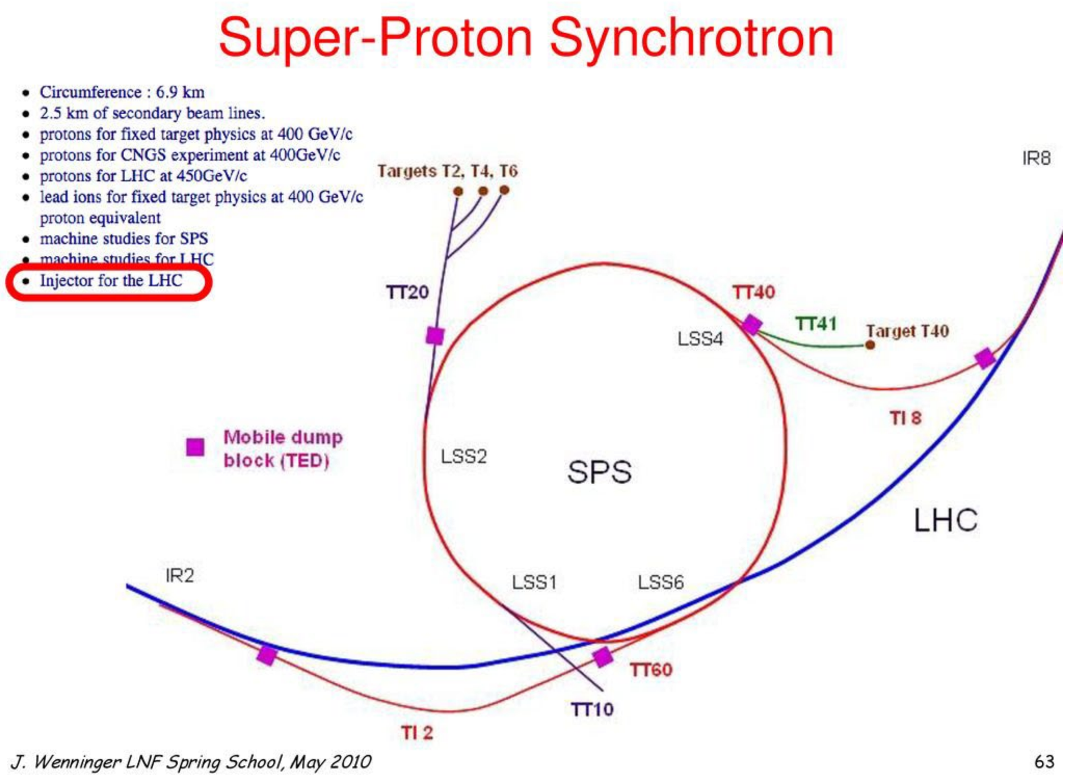
INFN Ferrara &UNIFE – KIPT Collaboration during the years

- 2011 – V. Guidi (UNIFE) visited KIPT
- 2012 – N. Shul'ga visited UNIFE as *Copernicus Visiting Scientist* for eminent scientist
- 2013 I was a guest at the KIPT *Akhiezer Institute for Theoretical Physics* for a month during my PhD

- During the years S. Fomin, A.Shchagin, V. Truten and I. Kyryllin (several times) visited INFN Ferrara and UNIFE
- …The collaboration with the KIPT group, also including S. Shul'ga, S. Trofymenko, and M. Bondarenko, is ongoing

My visit to Kharkiv in October-November 2013

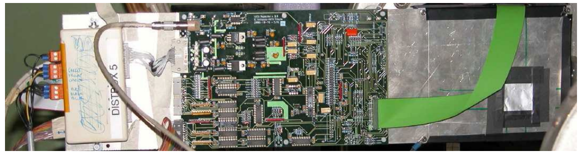
Experiment at CERN Super Proton Synchrotron extracted lines

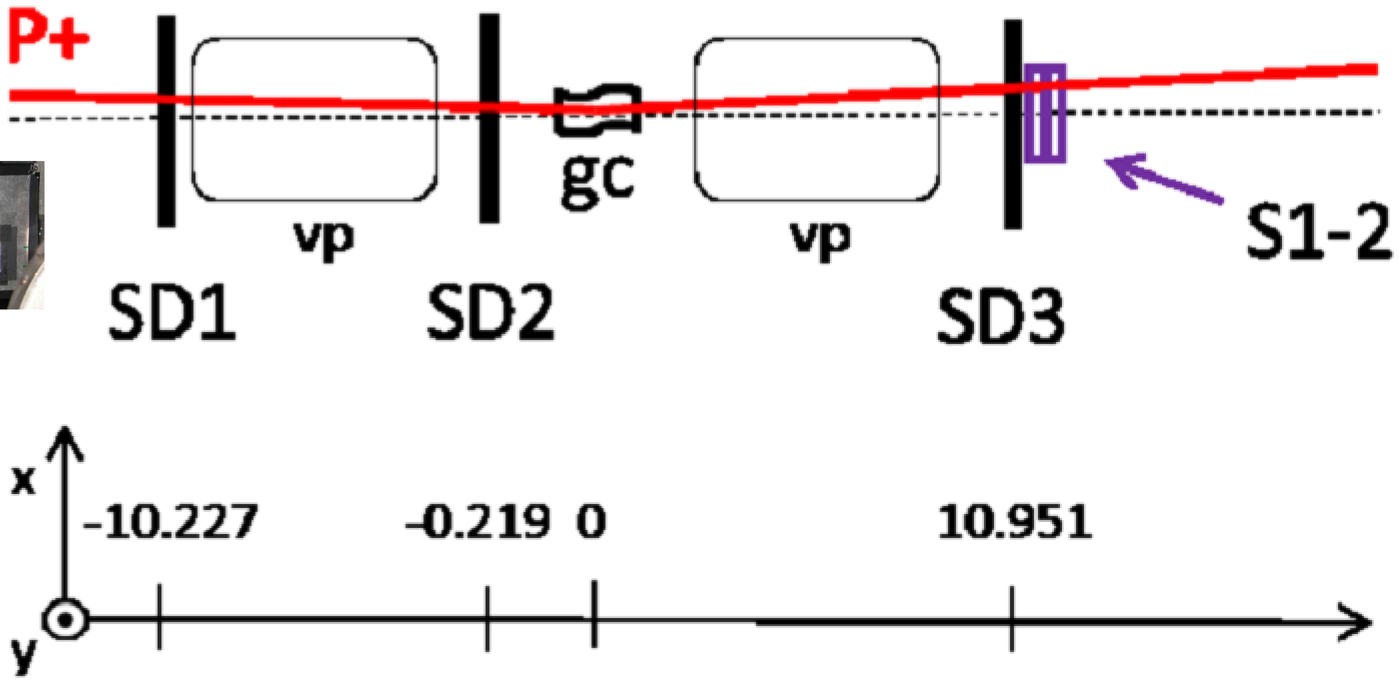


On the extracted beamline from the Super Proton Synchrotron, “clean” beams of p, e $^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$ are available **->** ideal facility for the studies with bent crystals at high-energy (10-400 GeV).

Experiment at H8 line of CERN SPS: 400 GeV/c protons

Double sided silicon detectors SDi (300μm thick) [5-μm spatial resolution]



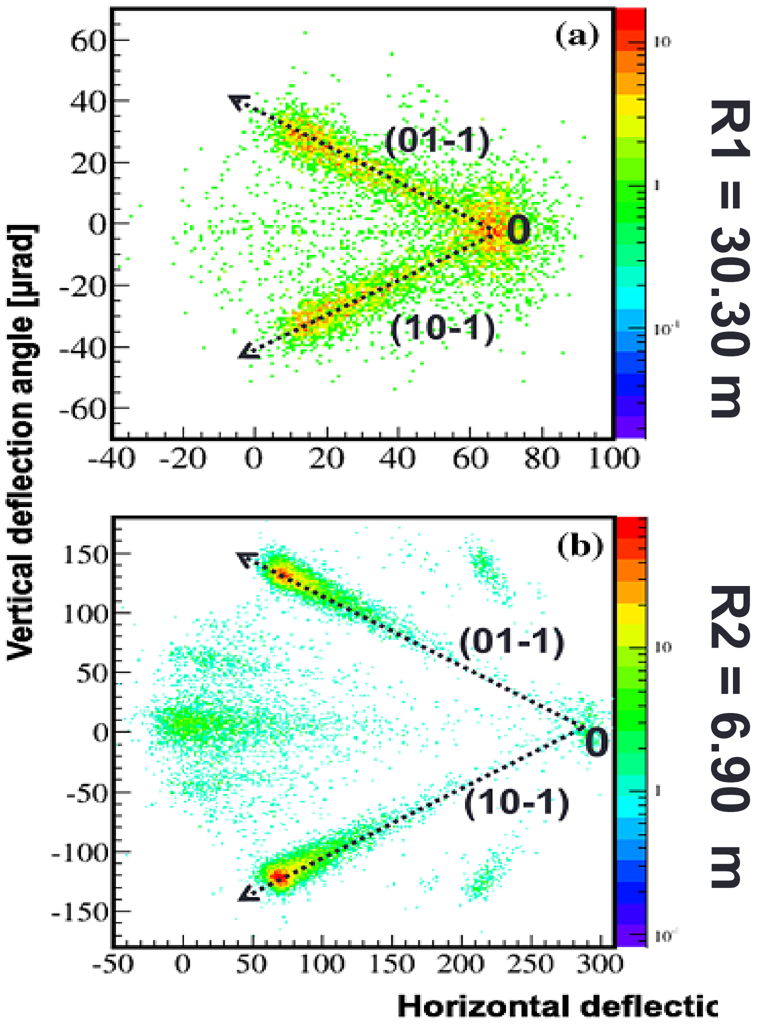


Crystal is mounted on an high-precision goniometer (~1 μrad resolution).

Two bent crystals were mounted on a high-precision goniometer with the possibility to be aligned in either horizontal or vertical direction:

R_1 = 30.30 m and R_2 = 6.90 m

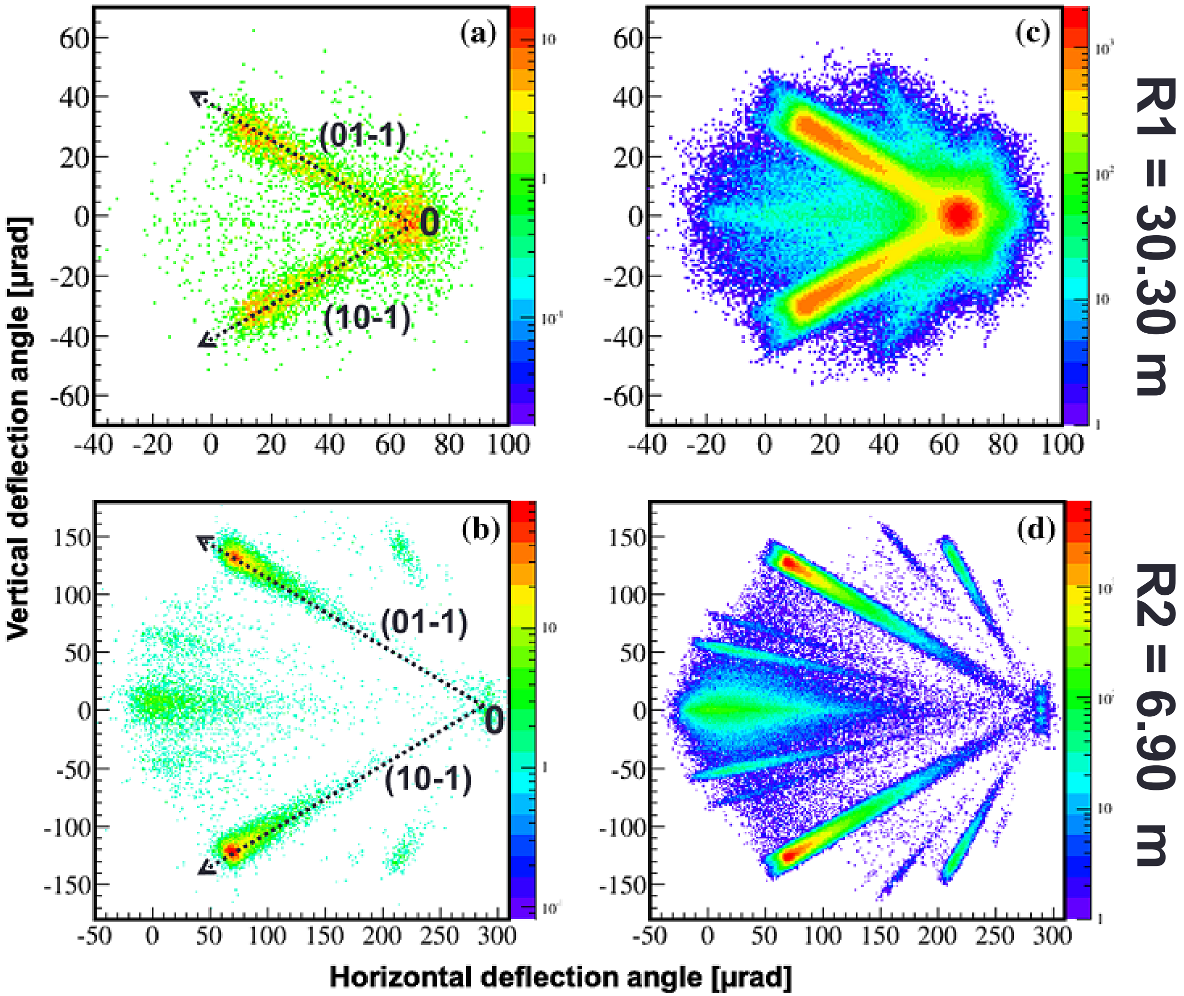
Experimental results - 400 GeV/c protons



- **Incidence angle** $\sqrt{\theta_{X,in}{}^2 + \theta_{Y,in}{}^2} \leq 5\ \mu rad$
- **Total steering:** 98% of the beam is deflected with an horizontal angle > 0
- **(a)** About 30% of the beam deflected at the nominal bending angle α_1 (axial alignment); other protons relaxed in skew (110) planes.
- **(b)** >80% in the (110) skew planes and splitted at the crystal exit by 250 μrad. **Lack of dechanneling from skew planes, since protons are captured in a skew planar channel without approaching close to atomic strings**

L. Bandiera, A. Mazzolari, …. I. V. Kirillin, N. F. Shul'ga,…et al. Eur. Phys. J. C 76 (2016) 80

Comparison with simulation



The code* solves the equation of motion in the field of the continuum potential through numerical integration and also accounts for the contribution of incoherent scattering with atomic nuclei and electrons.

Theoretical interpretation and Monte Carlo simulation developed by I. Kyryllin and N. F. Shul'ga

***NF Shul'ga, IV Kirillin, and VI Truten. Phys. Lett. B, 702(1):100–104, 2011.**

L. Bandiera, A. Mazzolari, …. I. V. Kirillin, N. F. Shul'ga,…et al. Eur. Phys. J. C 76 (2016) 80

Relaxation Length

- **It is clear that the escape velocity from SD to skew planes increases while R decreases;**
- **Exponential form between the two peaks in the distributions.**

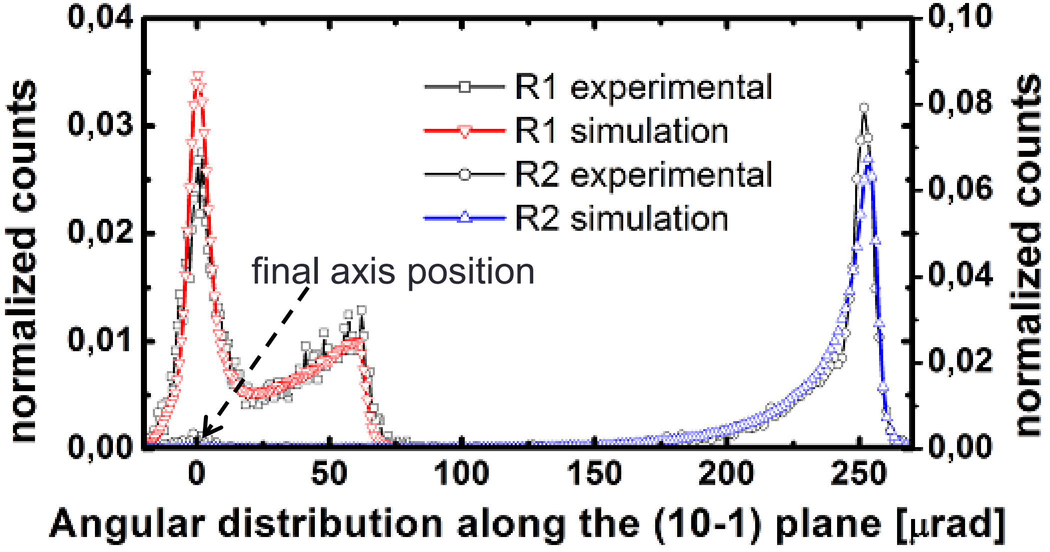
By assuming that the rate of particle escaping from stochastic deflection is proportional to the number of particles that are in this regime, *N*:

$$N(l) = N_0 e^{-Cl} = N_0 e^{-l/l_R}$$

Therefore, the number of particles captured under channeling regime in all the skew planes

$$N_{pl}(l) = N_0 \left(1 - e^{-l/l_R}\right)$$

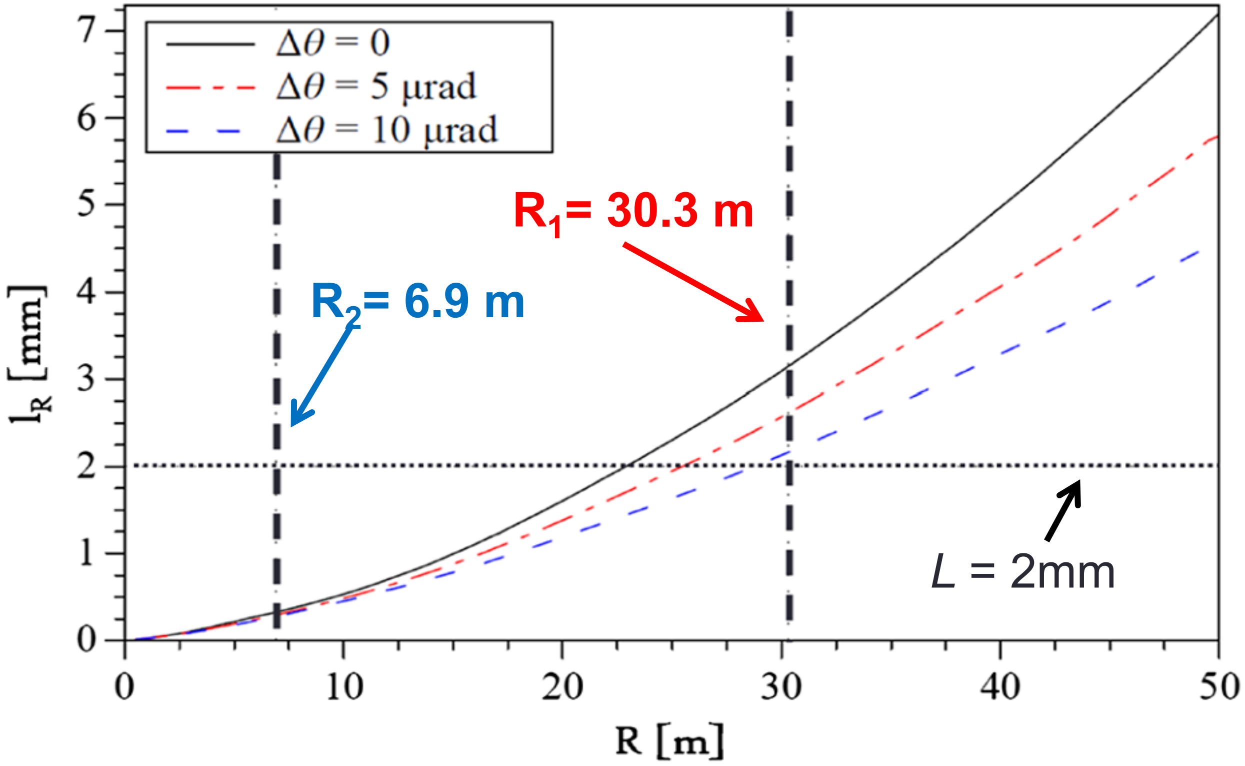
(10-1) plane deflection-distribution



The relaxation length l_R determines the maximum crystal length for efficient steering of particles at the full bending angle α = L/R.

L. Bandiera, A. Mazzolari, …. I. V. Kirillin, N. F. Shul'ga,…et al. Eur. Phys. J. C 76 (2016) 80

Relaxation Length vs R for positive particles



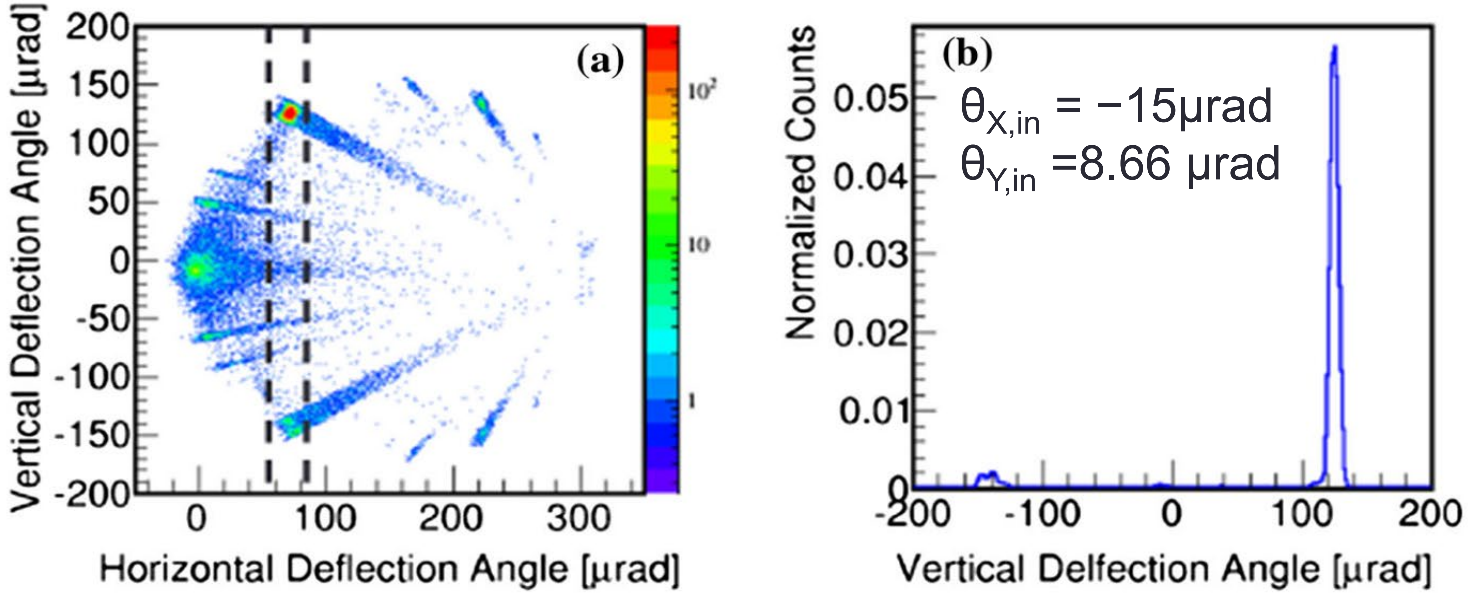
Condition A If L ≤ l_R -> efficient beam deflection as for the crystal with R_1= 30.3 m;
Condition B If L ≫ l_R and L ≪ $l_{Dechannling}$ -> beam splitting in the strongest skew planes as for the crystal with R_2= 6.9 m.

L. Bandiera, A. Mazzolari, …. I. V. Kirillin, N. F. Shul'ga,…et al. Eur. Phys. J. C 76 (2016) 80

Possible Applications

Case A: $L \leq l_R$ - the crystal behaves as a **total beam steerer** that can be exploited for beam manipulation, e.g. for **collimation/extraction**;

Case B: $L \gg l_R$ and $L \ll l_D$, the crystal behaves as a **beam splitter**, which be exploited to set up an extracted beam layout on two experimental channels (with adjustable beam intensity) in just one extraction point.



L. Bandiera, I. Kirillin, ….. et al. Nucl. Instrum. Meth. B 402 (2017) 296-29

First investigation on steering of **120 GeV/c electrons and positrions** through an axially oriented bent crystal

The Greenenko-Shul’ga conditions

$$\alpha < \alpha_{st}$$

for positive particles standard condition

$$\alpha_{st} = \frac{2R\psi_c^2}{l_0}$$

First investigation on steering of ultrarelativistic **electrons and positrions** through an axially oriented bent crystal

The Greenenko-Shul'ga conditions

$$\alpha < \alpha_{st}$$

for positive particles standard condition

$$\alpha_{st} = \frac{2R\psi_c^2}{l_0}$$

for negative particles modified condition

$$\alpha_{st} = \frac{L_{st}}{R} = \frac{\psi_m^2}{l/R + \xi R}$$

ψm= 1.5ψc;

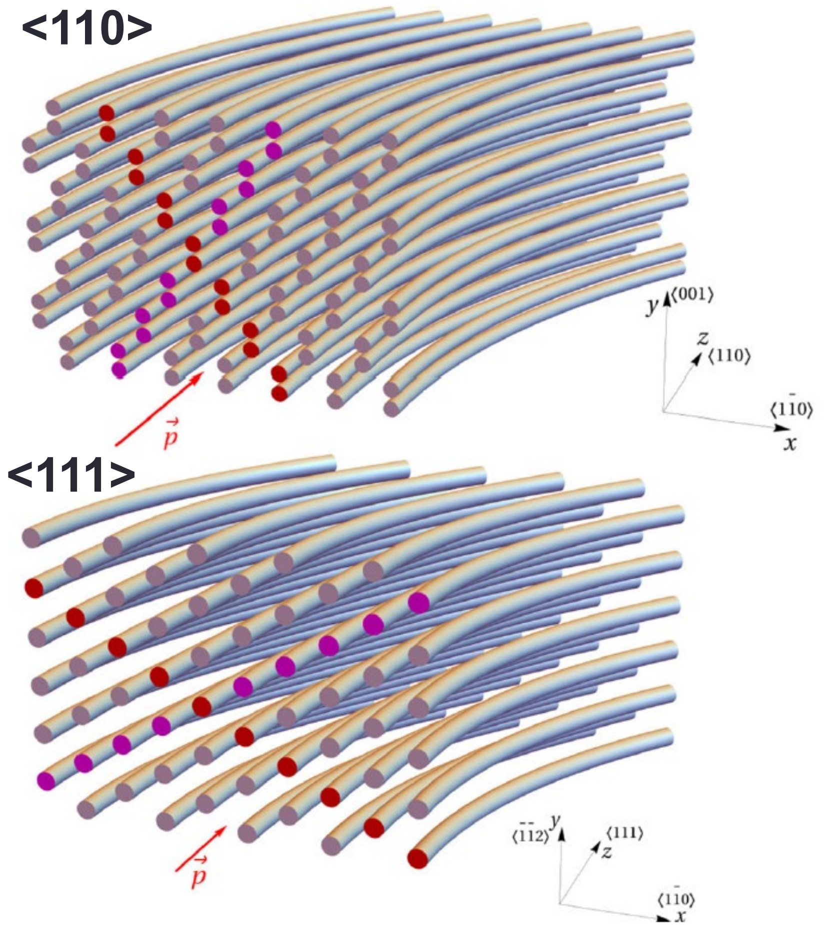
l is **the mean length of the path** that the particle crosses **during scattering on one atomic string;**

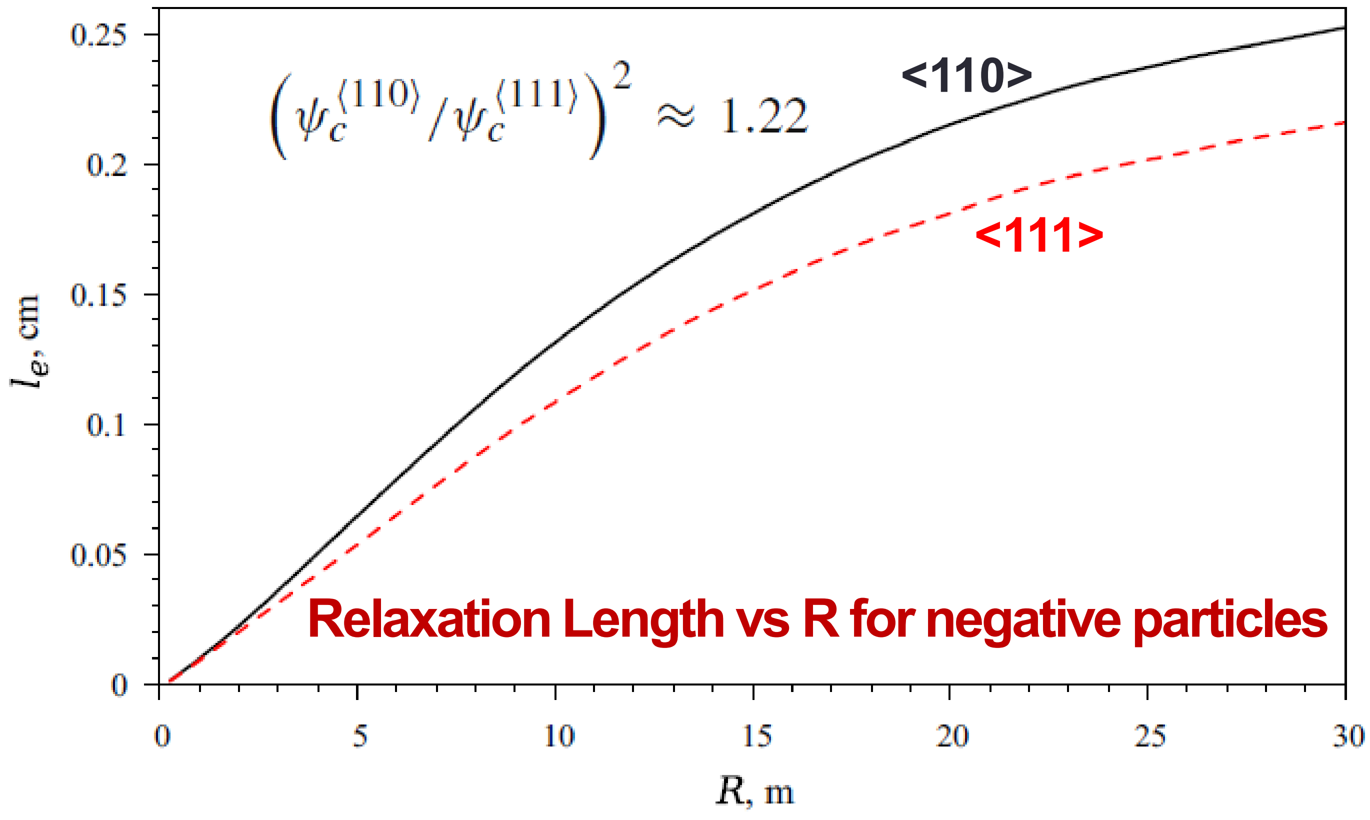
ξ is a constant of proportionality between the mean square angle of **incoherent multiple scattering** on atomic thermal vibrations, electronic subsystem atoms, etc., and the thickness of the crystal.

L. Bandiera, I. V. Kyryllin,... N. F. Shul'ga,.. et al. Eur. Phys. J. C 81 (2021) 238

Theoretical interpretation and Monte Carlo simulation developed by I. Kyryllin and N. Shul'ga from KIPT

Deflection efficiency vs axis choice and curvature Radius





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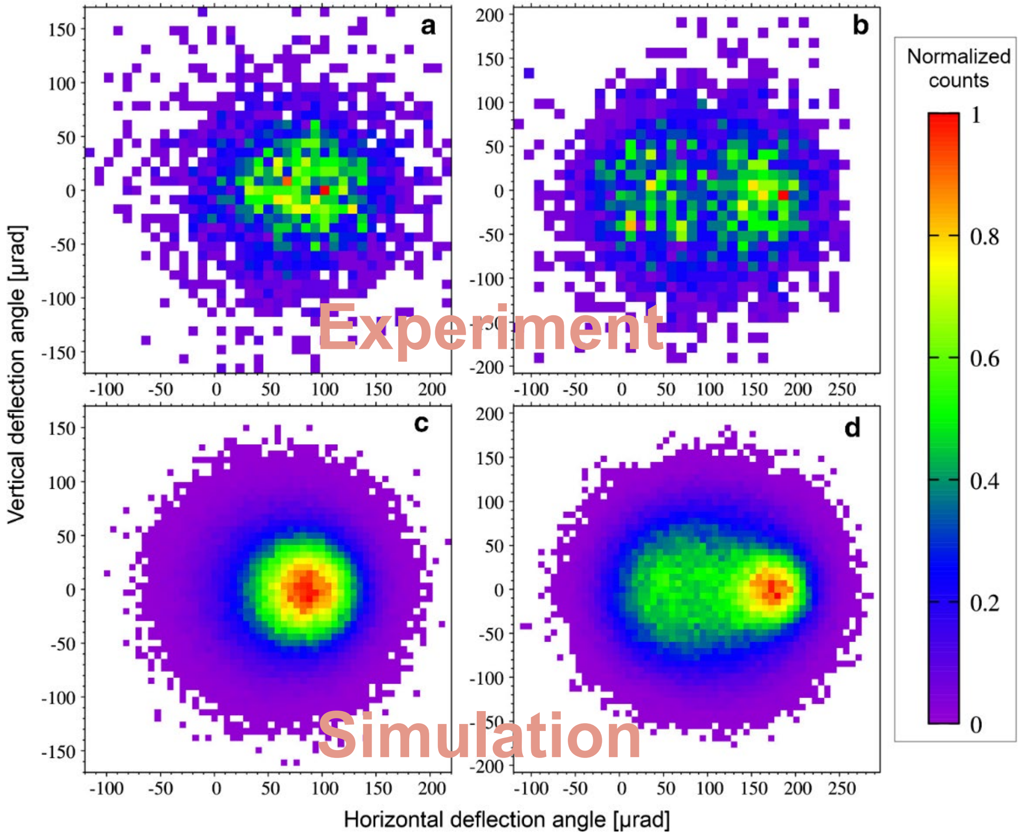
SPS
H4 line

Positive vs. Negative Axial Deflection: 120 GeV e±

Electrons

<110> axis, R= 22m <111> axis, R= 11m



Positrons

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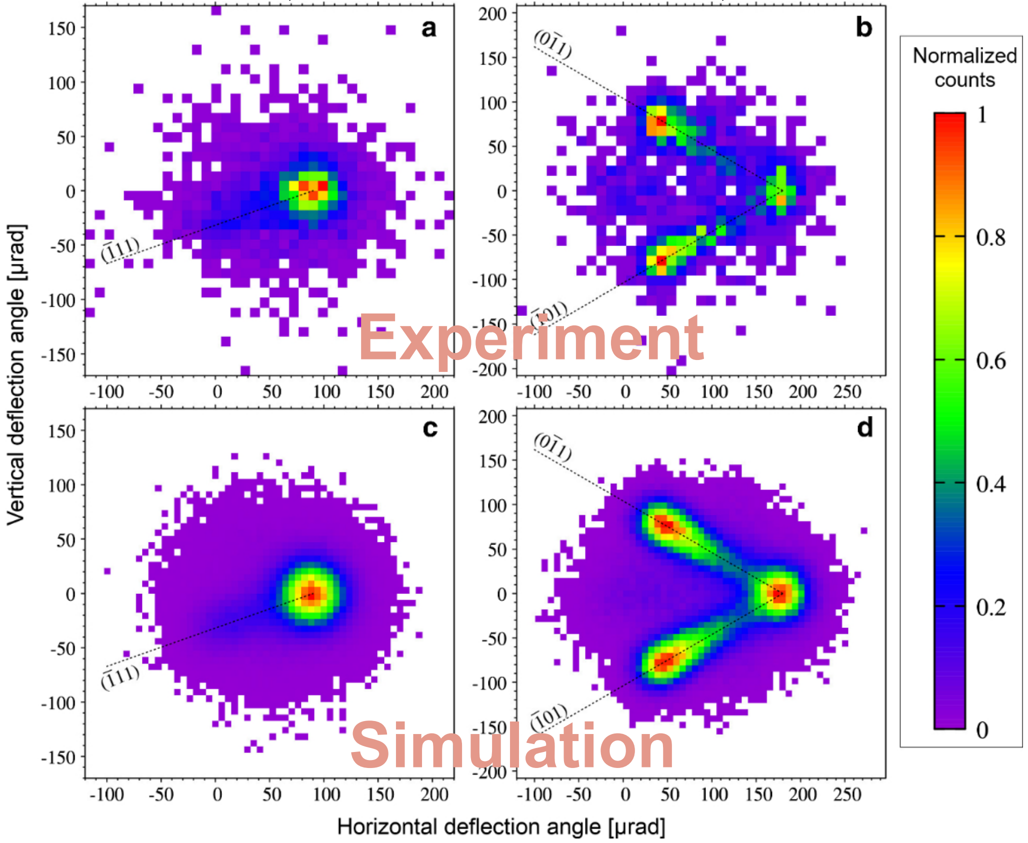

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Deflection of more than 90% of the electron beam. APPLICATION: Since planar deflection could be highly inefficient to steer TeV negative beams, axial deflection could be really a good option.

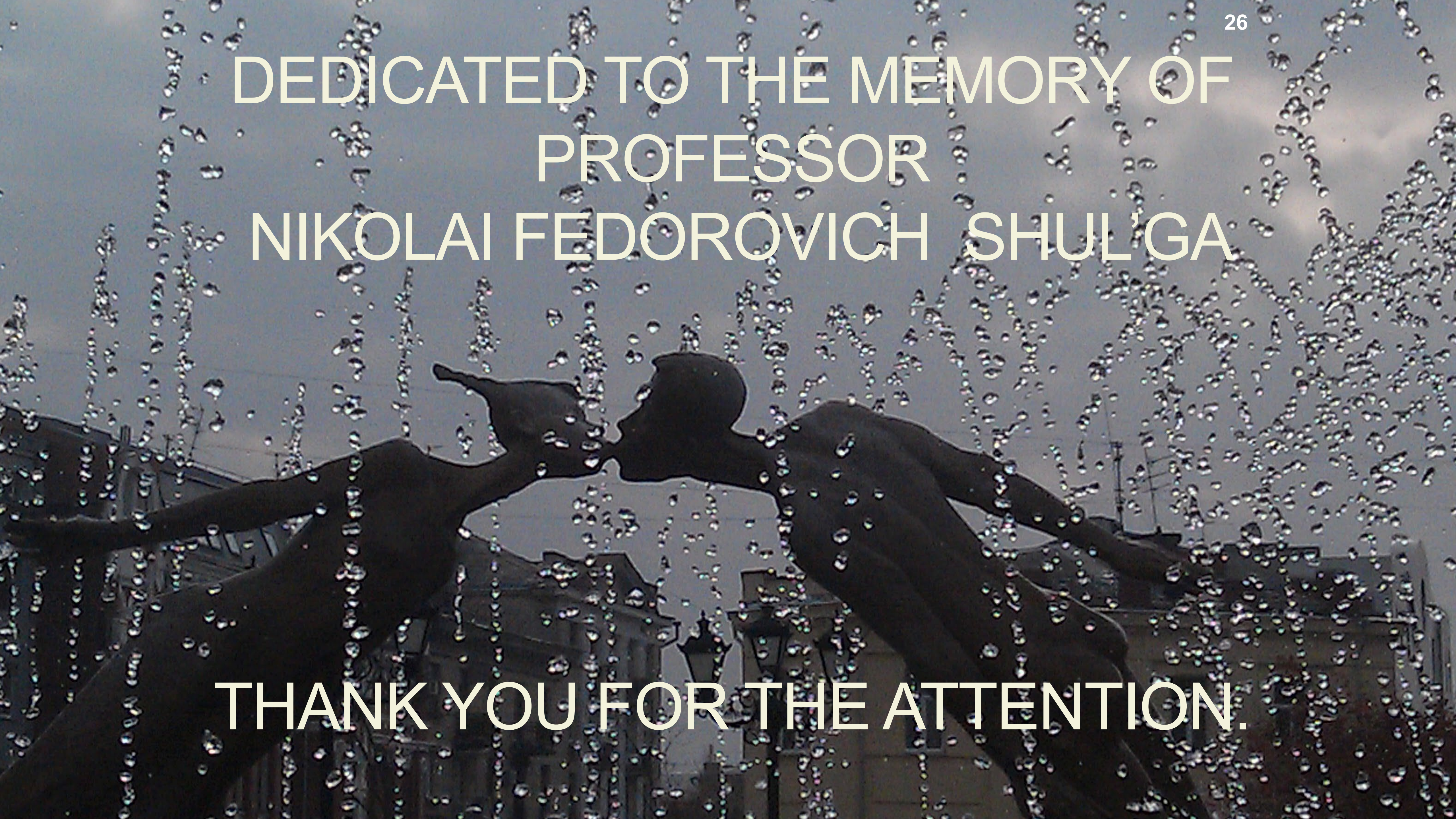
Conclusion and future perspectives

- An investigation on the mechanism of relaxation of axially confined 400 GeV/c protons to planar channeling and the first investigation of stochastic deflection for electrons and positrons in a bent crystal was carried out at the extracted lines from CERN Super Proton Synchrotron;

- The experimental results were compared to computer simulations, showing a good agreement;

- The necessary conditions for the exploitation of axial confinement or its relaxation for particle beam manipulation in high-energy accelerators, e.g. for beam steering or splitting, have been identified.

- In particular, stochastic deflection has proven to be more versatile than planar channeling, allowing for the efficient **steering of negative particles** as well. This approach should be investigated further **for potential use in the collimation of future e+/e- Colliders and for the Muon Collider.**


DEDICATED TO THE MEMORY OF
PROFESSOR
NIKOLAI FEDOROVICH SHUL'GA
THANK YOU FOR THE ATTENTION.