INFN FERRARA

Istituto Nazionale di Fisica Nucleare

EXPERIMENTAL INVESTIGATION OF STOCHASTIC DEFLECTION OF ULTRARELATIVISTIC PARTICLE BEAMS IN BENT CRYSTALS

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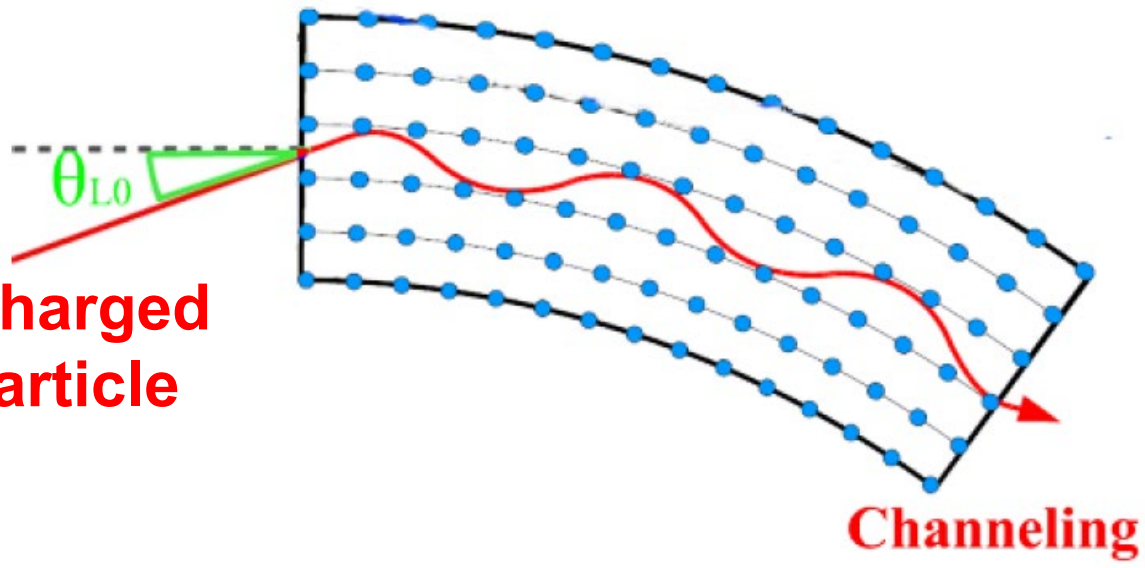
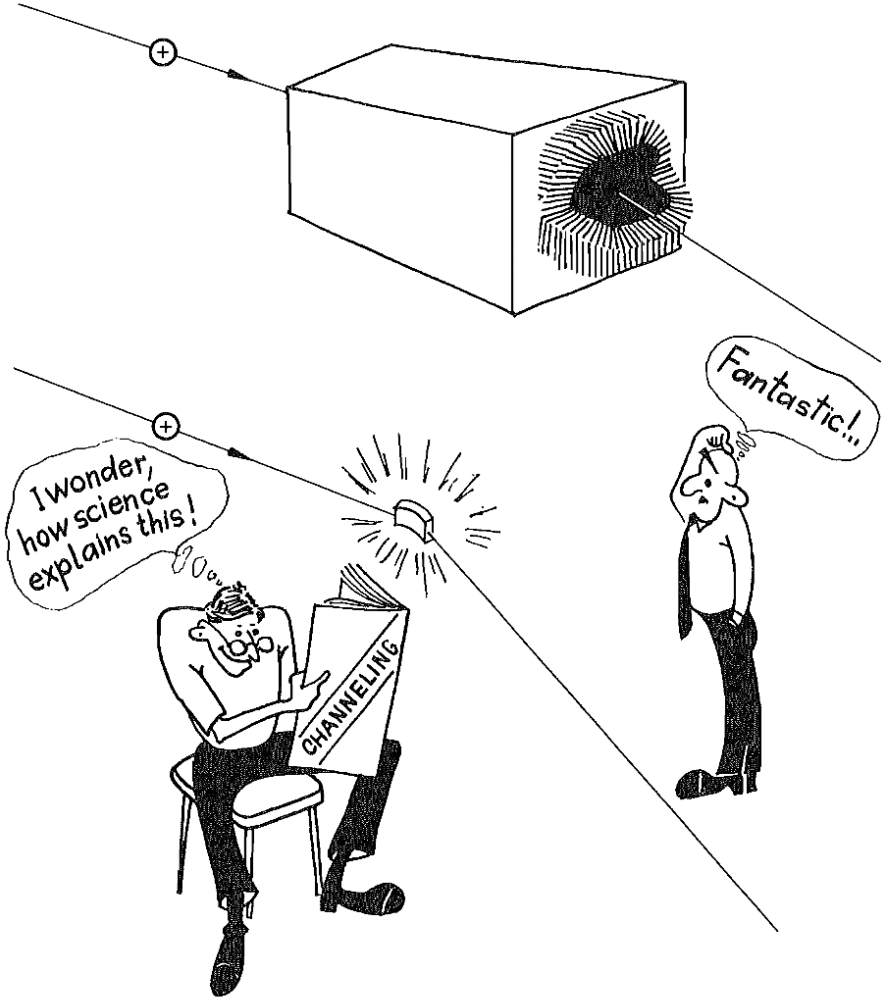
Bending a crystal:
A way to steer a particle beam



E. Tsyganov, 1976

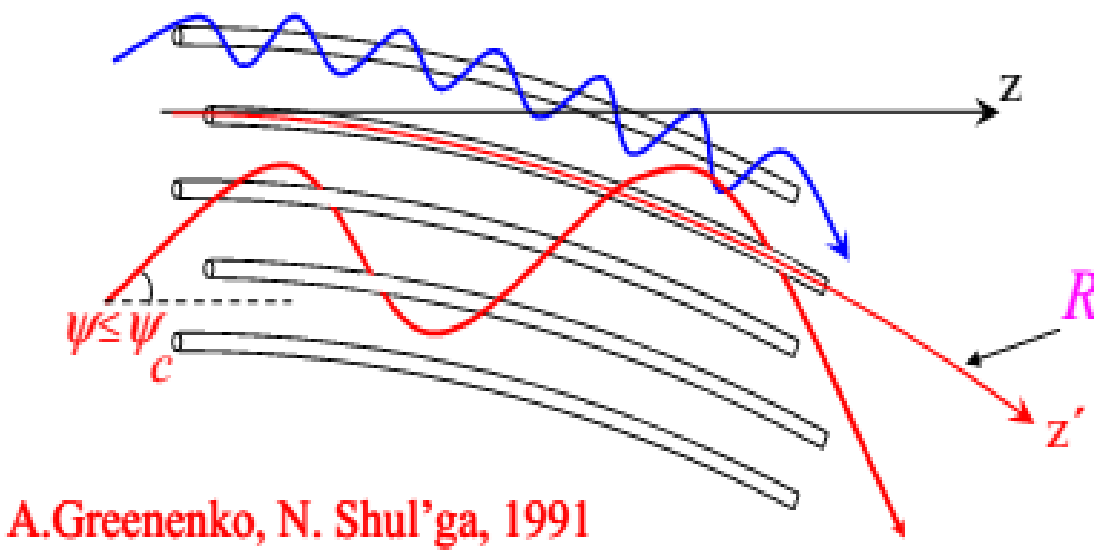


Axial Channeling

- 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;

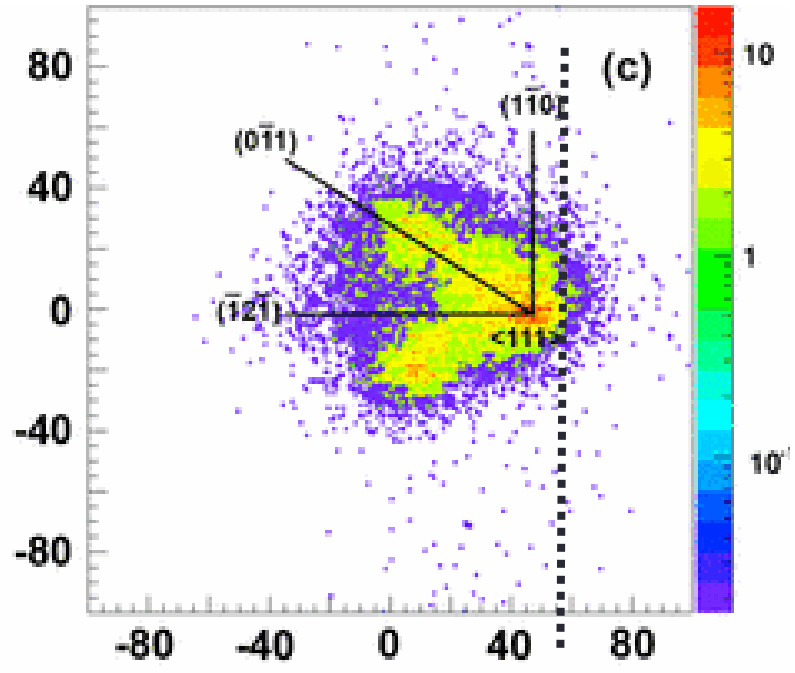
α is the crystal bending angle;

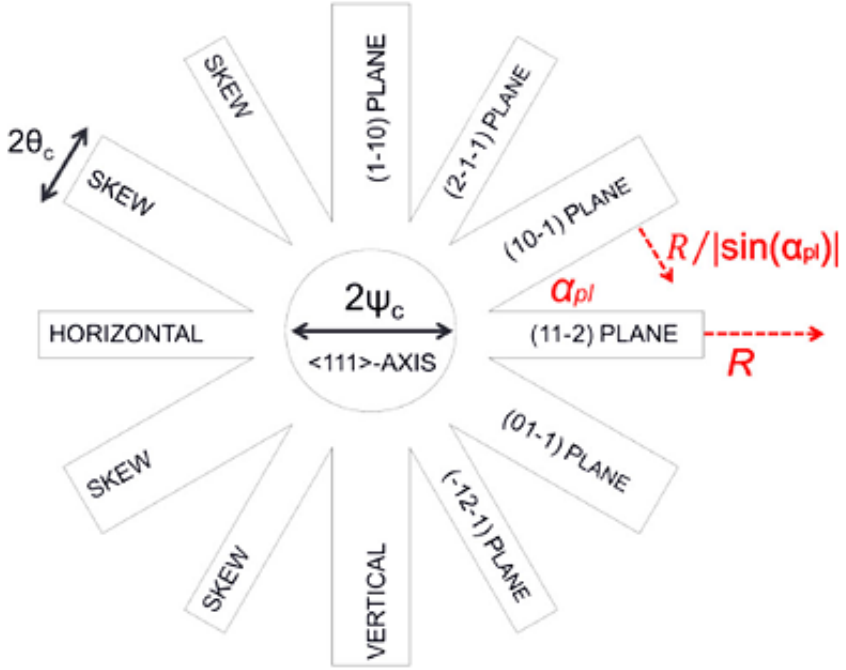
R is crystal curvature radius;

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***

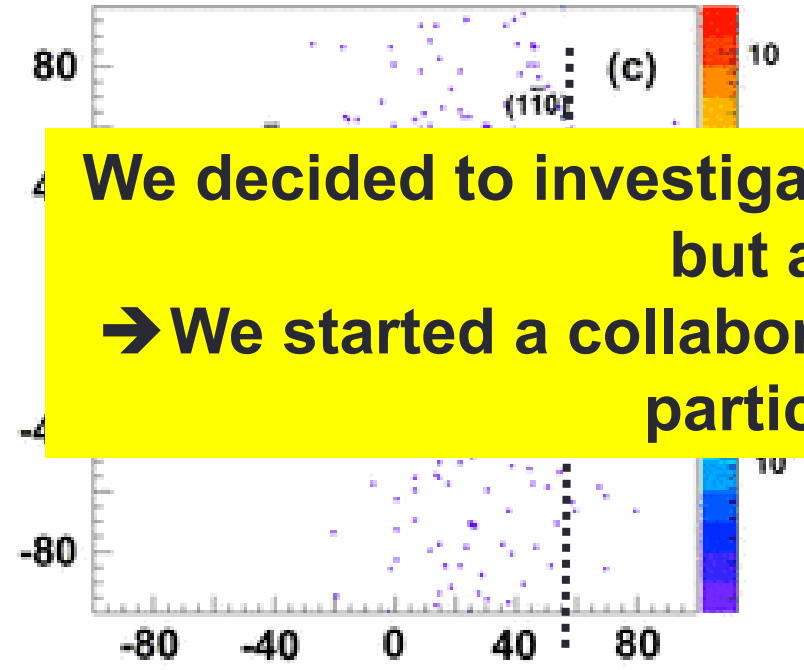
Deflection efficiency > 90%

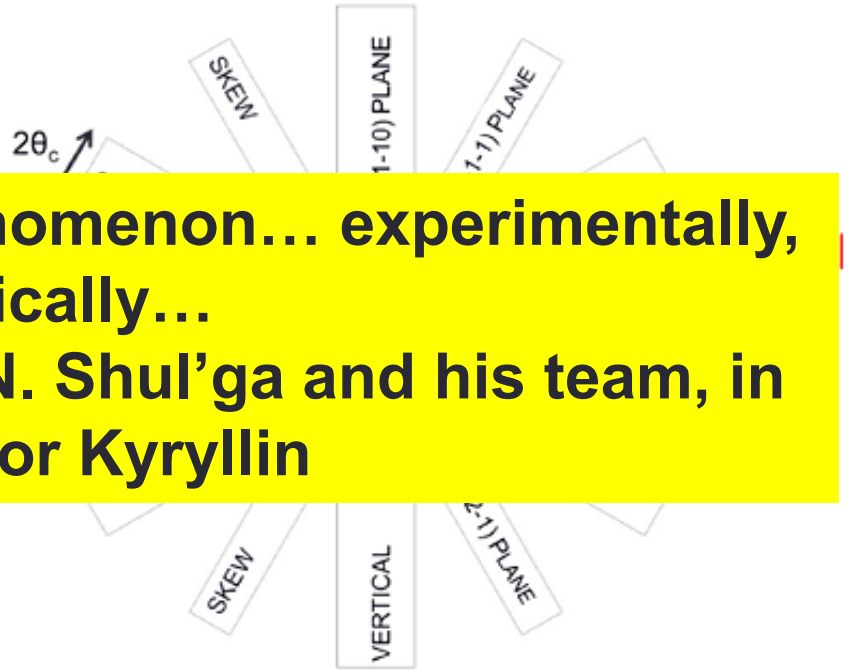
*W. Scandale et al., Phys. Rev. Lett. 101 (2008) 164801

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, in particular with Igor Kyryllin

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

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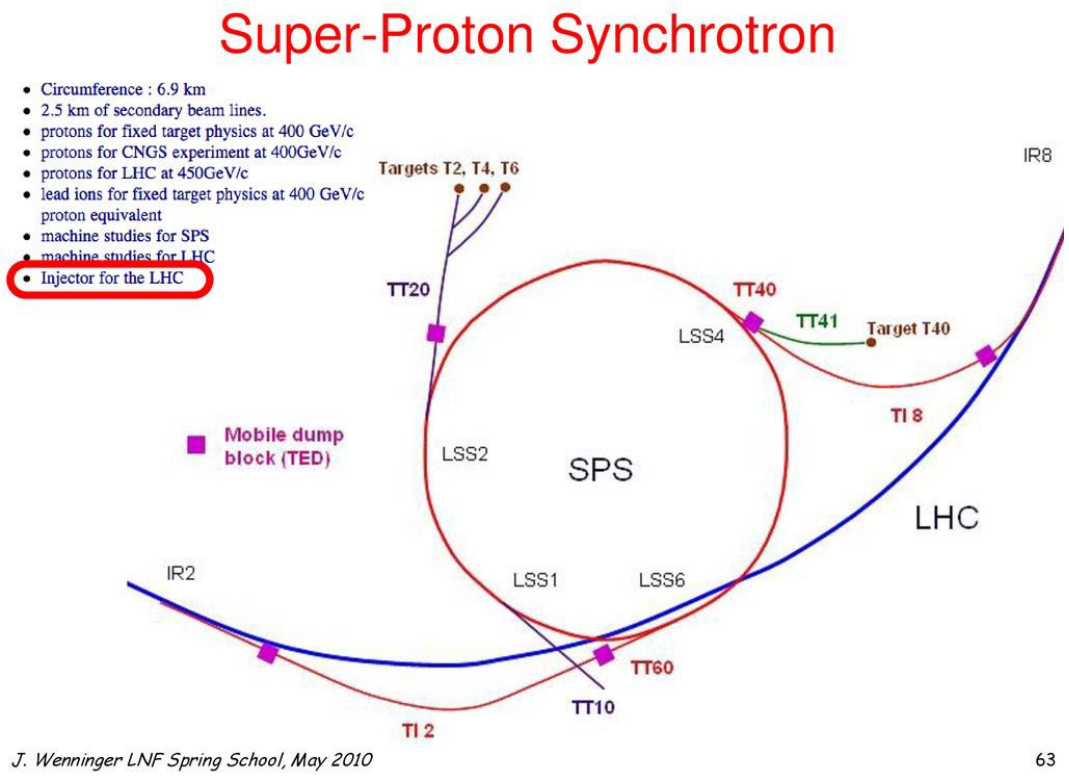
FOR POSITIVE PARTICLES: Relaxation of axial-to-planar channeling in skew planes!

INFN Ferrara &UNIFE – KIPT Collaboration during the years

- 2011 – V. Guidi (UNIFE) visited KIPT
- 2012 – Mykola F. Shulga was guest at UNIFE as Copernicus Visiting Scientist for eminent scientist
- 2013 I was guest for a month at the KIPT *Akhiezer Institute for Theoretical Physics* as visiting PhD student

- During the years S. Fomin, A.Shchagin, V. Truten and I. Kyryllin (several times) visited INFN Ferrara and UNIFE
- And the collaboration still continue with all the KIPT group, including S. Shul'ga, S. Trofymenko and M. Bondarenko

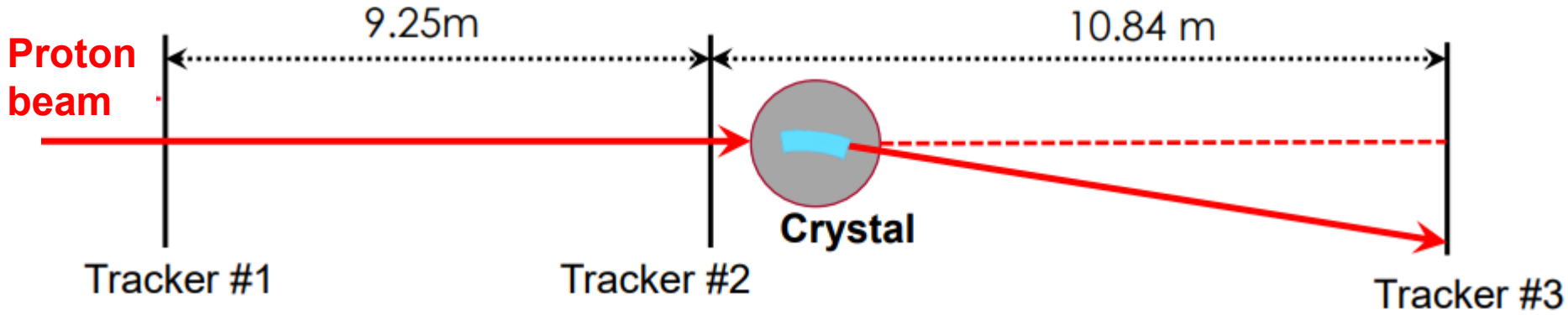
Experiment at CERN Super Proton Synchrotron extracted lines

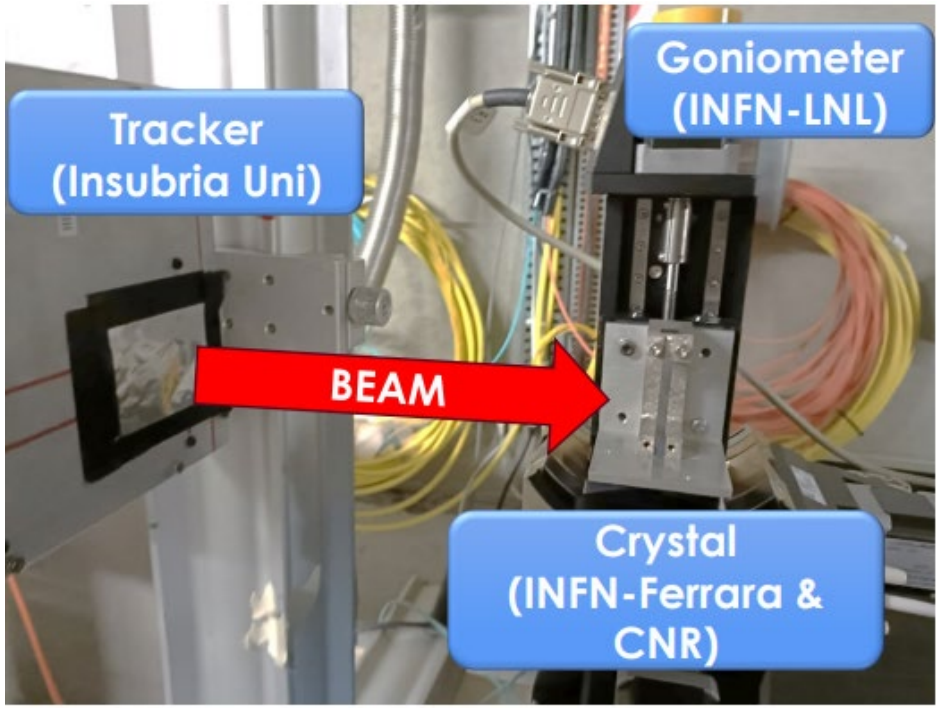


On the extracted beamline from the Super Proton Synchrotron, “clean” beams of p, e ±, μ± and π± are available **->** ideal facility for the studies with bent crystals at high-energy (10-400 GeV).

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

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



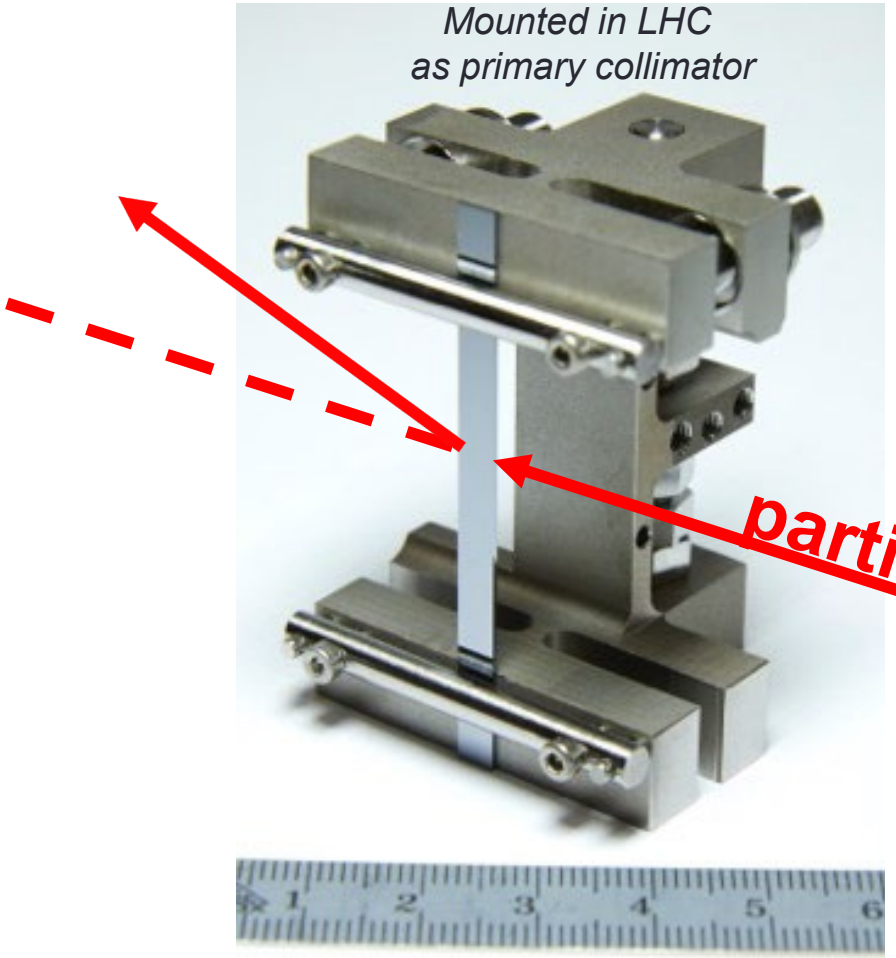


Two bent crystals were mounted on a high-precision goniometer with the possibility to be aligned in either horizontal or vertical direction:

R_1 = 30.30 m and R_2 = 6.90 m

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

Bent crystals realized @ INFN FERRARA



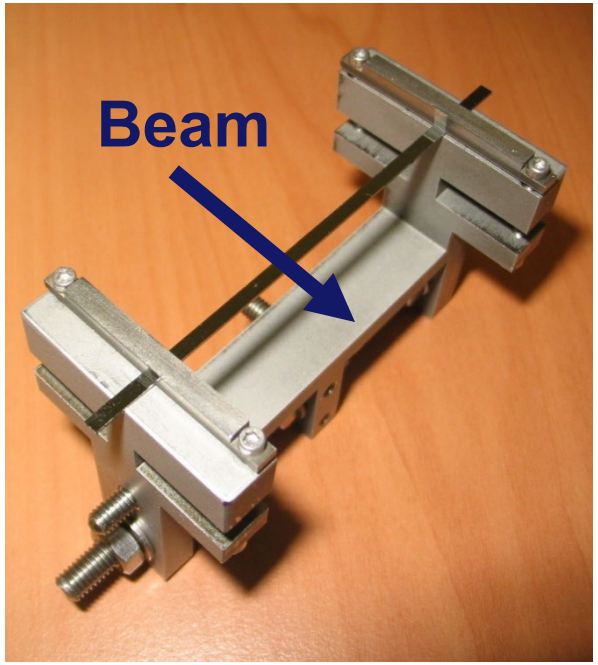
V.S.

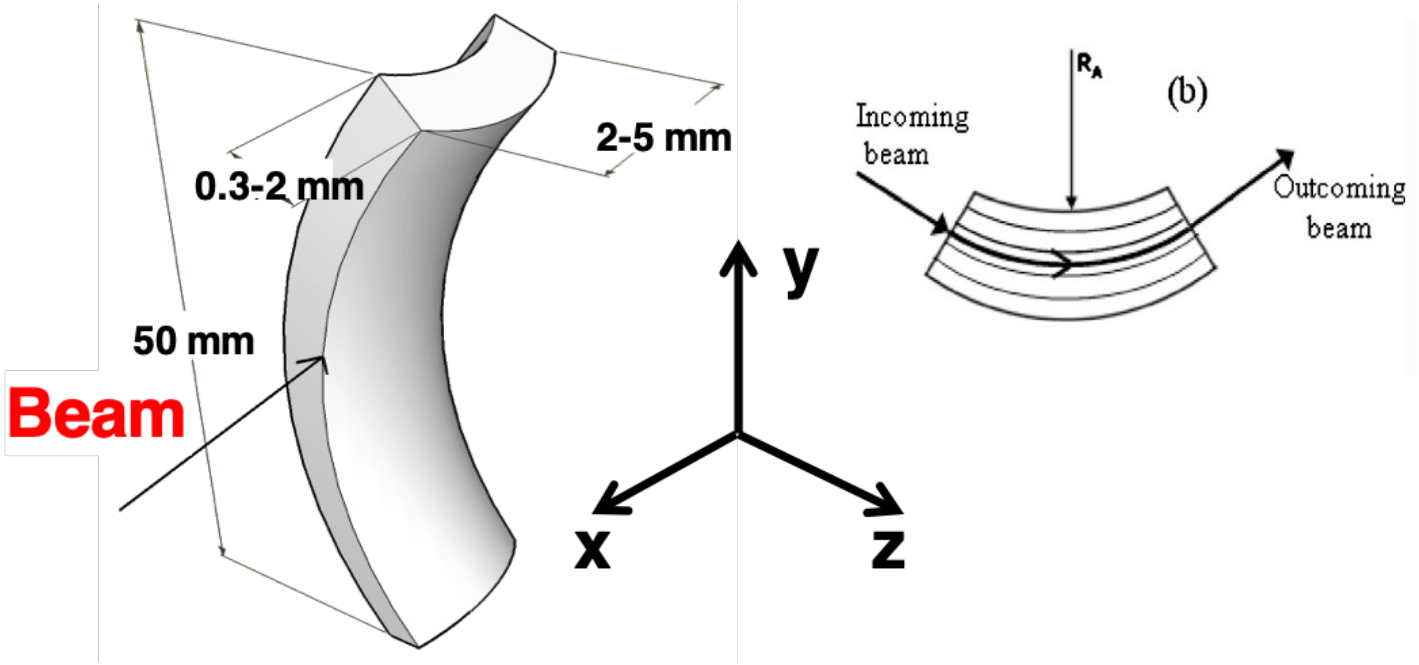
Bent Si crystal – 4 mm long

8.3 Tesla supermagnet – 15 m long

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

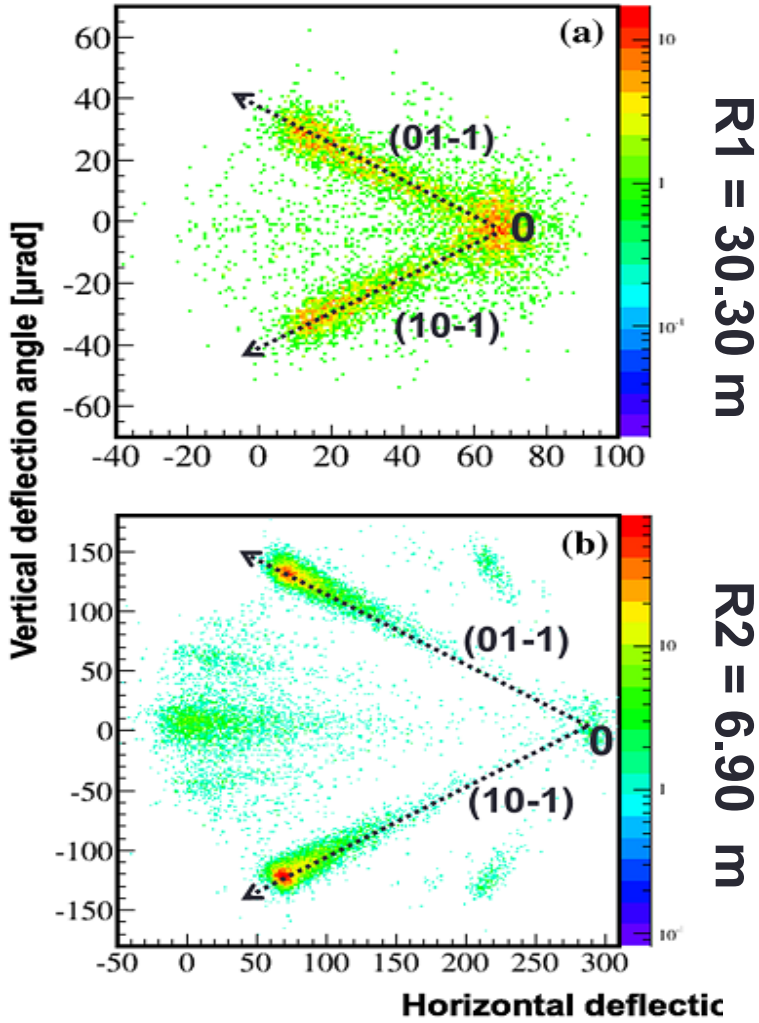
Bent crystals realized @





Bent Si crystal – 2 mm long

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** -> NO nuclear dechanneling. And NO electronic dechanneling since the crystal is << electronic dechanneling length (20 cm).

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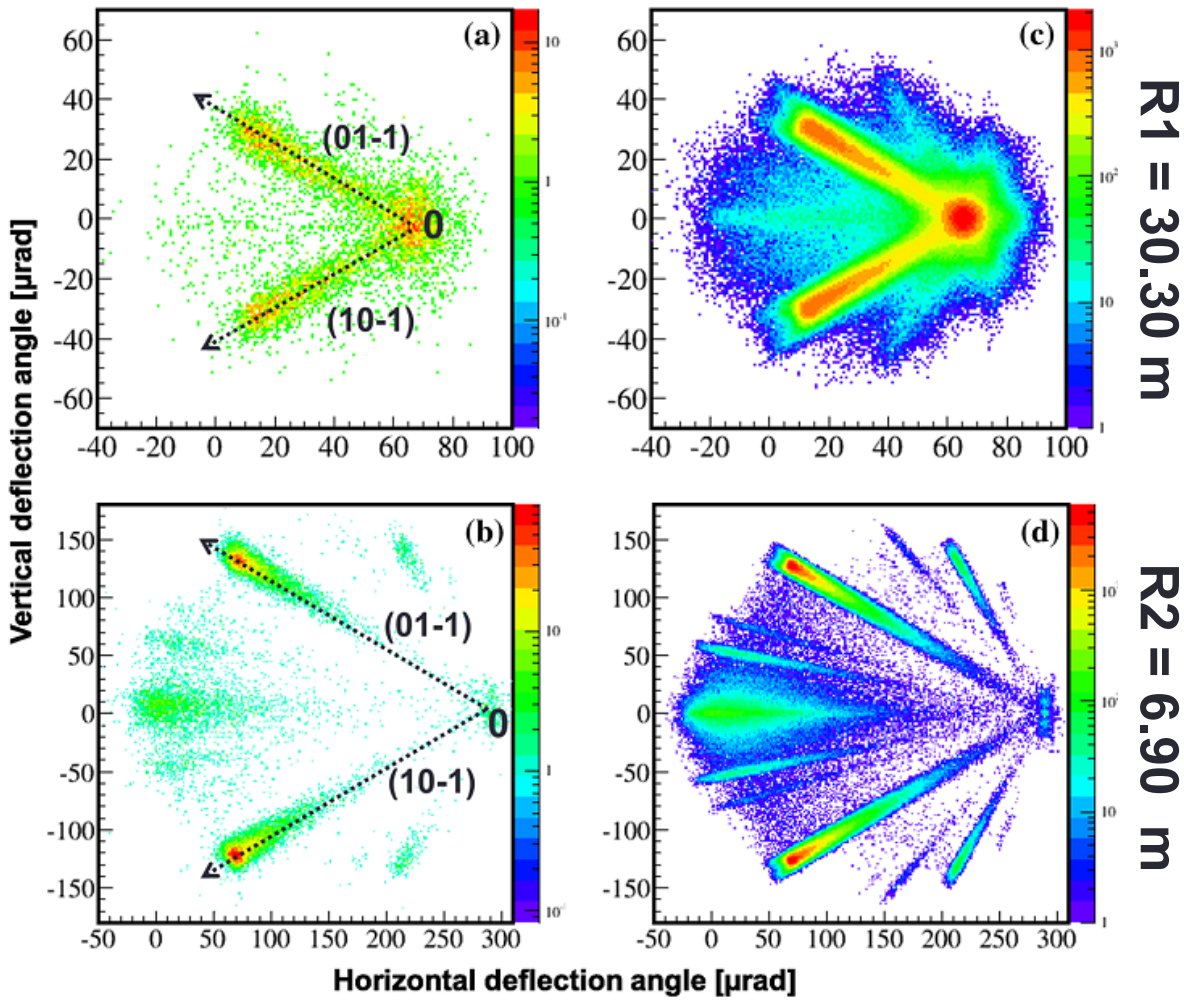
Comparison with simulation



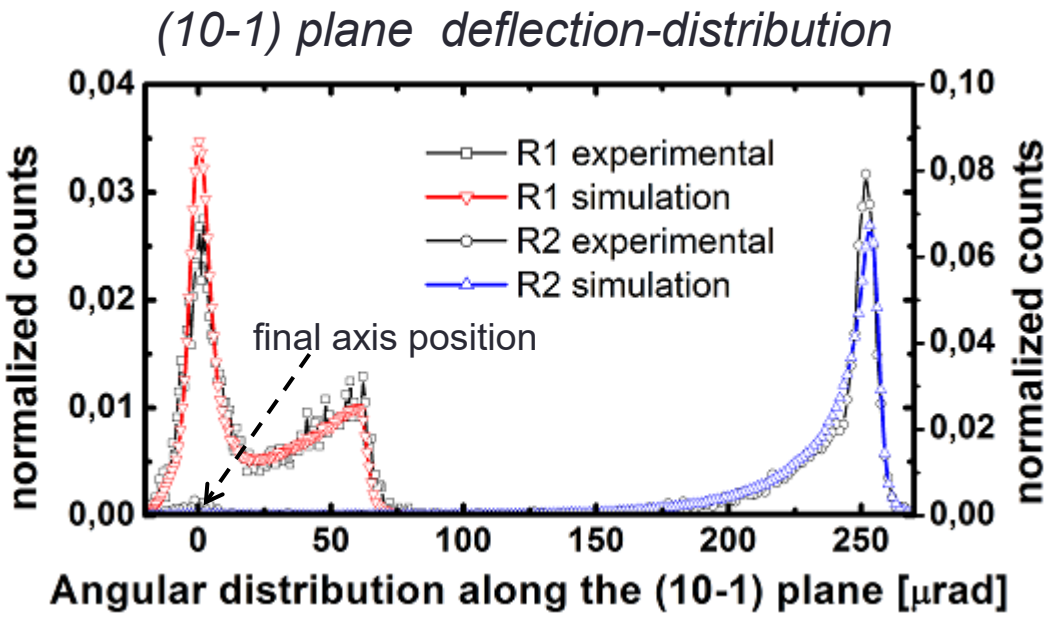
The code* solves the equation of motion in the field of continuum potential through numerical integration and also takes into account the contribution of incoherent scattering with atomic nuclei and electrons.

Theoretical interpretation and Monte Carlo simulation developed by I. Kyryllyn and N. Shulg'a from KIPT

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

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*:

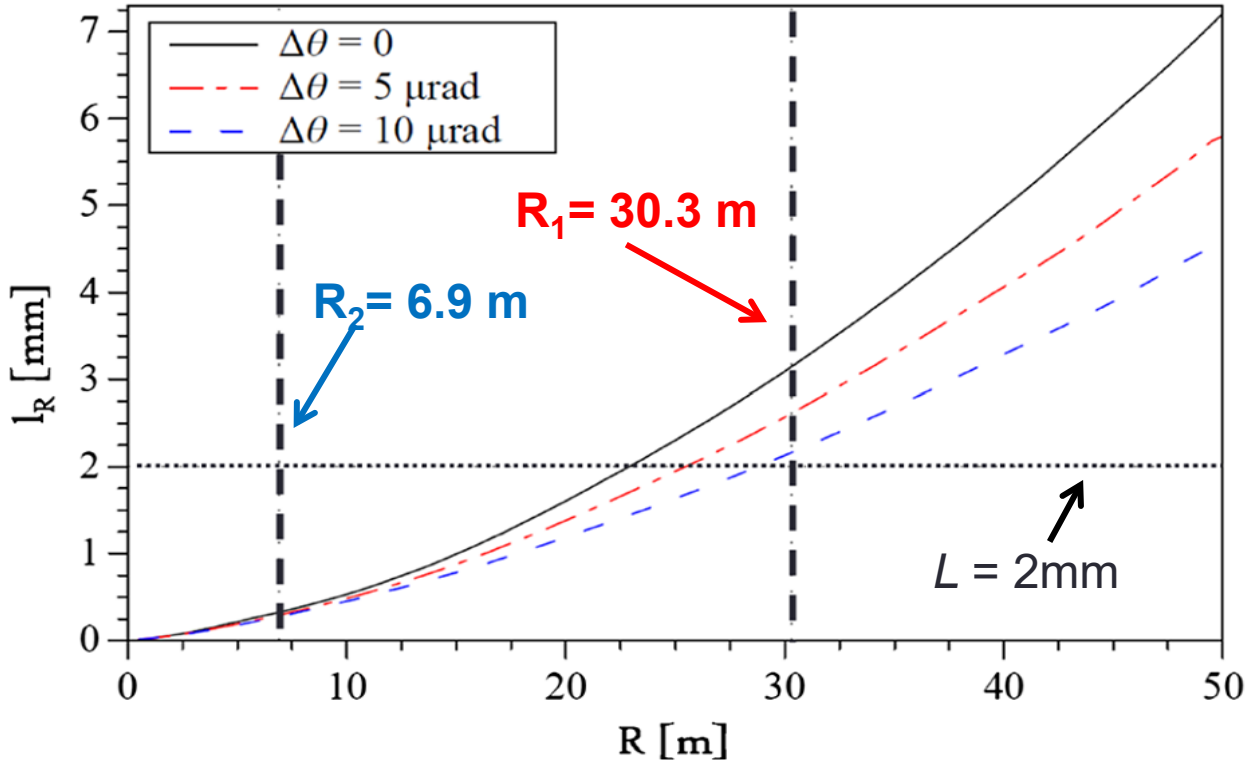
$$N(l) = N_0 e^{-Cl} = N_0 e^{-l/l_R}$$

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

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

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

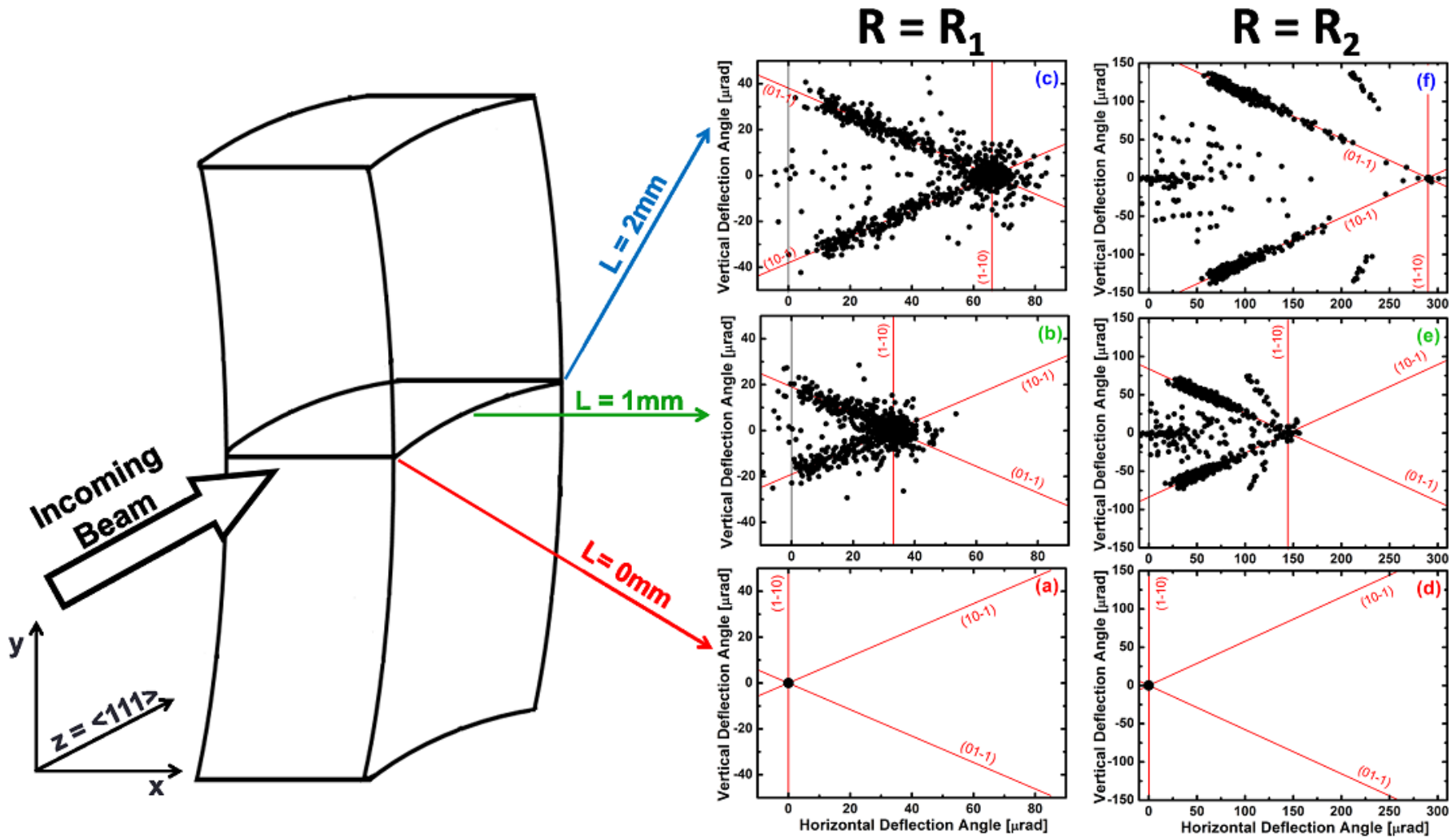
Relaxation Length vs R for positive particles



Condition A If $L \leq l_R$ -> efficient beam deflection through SD as for the crystal with R_1= 30.3 m;

Condition B If $L \gg l_R$ and $L \ll l_D$ -> beam splitting in the strongest skew planes as for the crystal with R_2= 6.9 m.

Evolution of the beam distribution vs. crystal length



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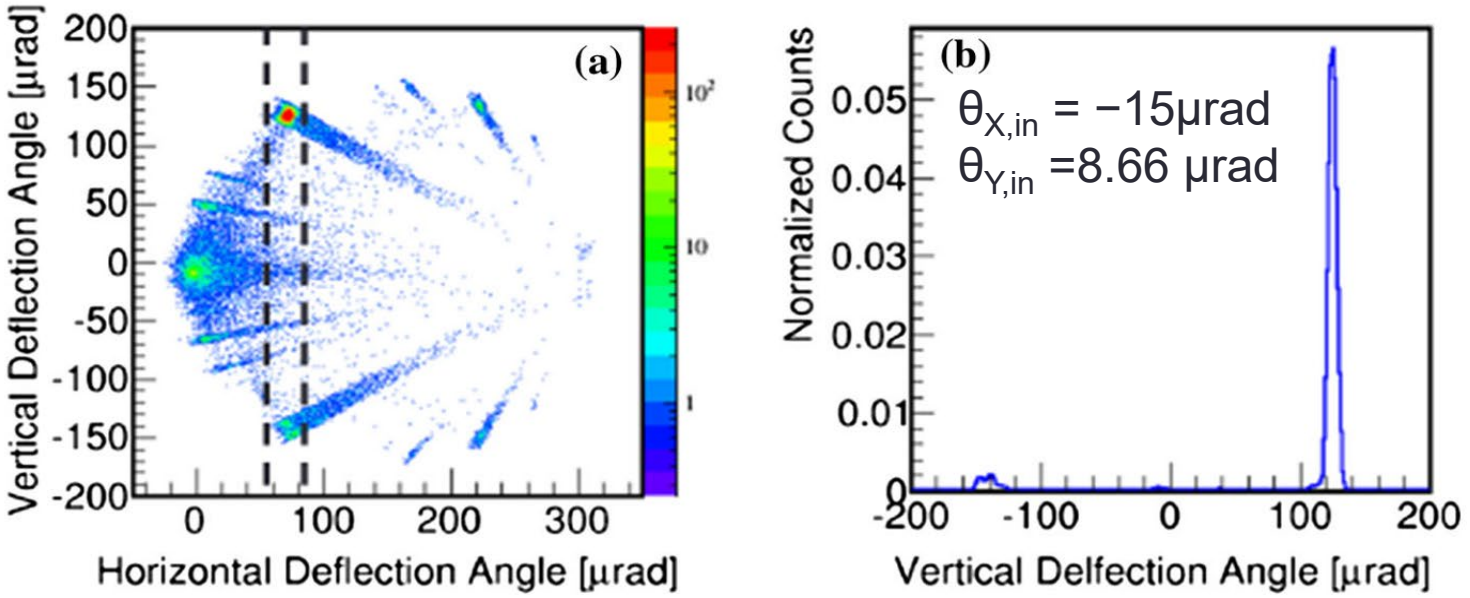
Possible Applications

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.



Bandiera, L., Kyryllin, I, … Shul'ga N.F… *et al.* , *NIM B 402*, 1–6.

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

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

$\psi_m = 1.5\psi_c$ is the maximum value of the angle ψ for which particles take part in the stochastic deflection;

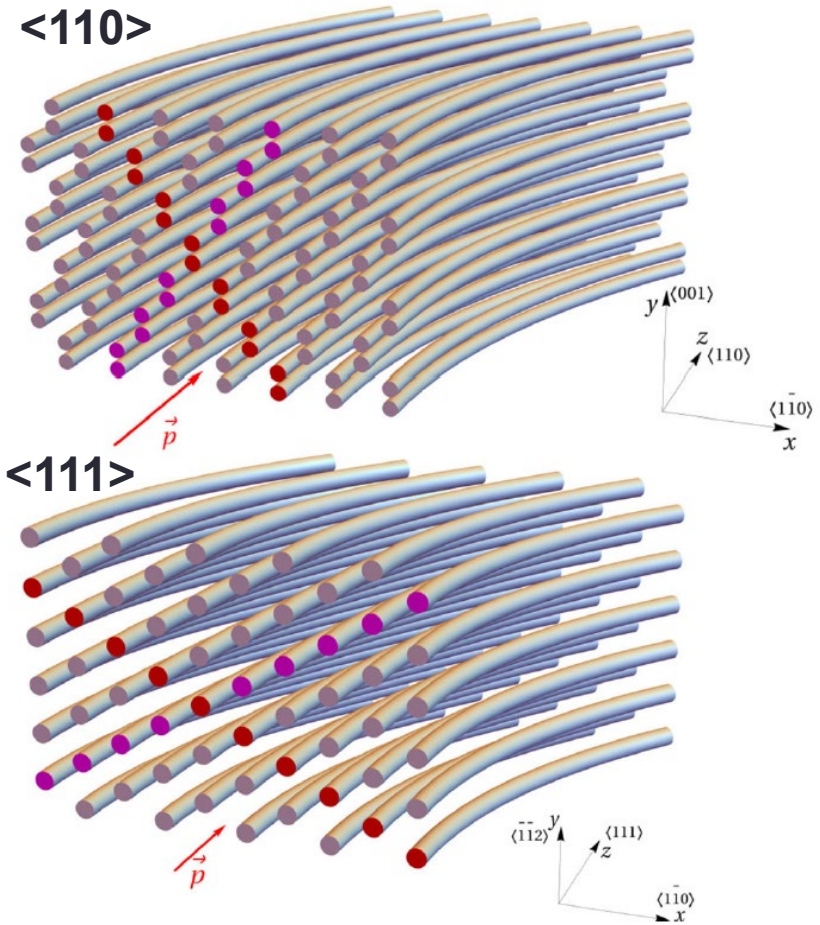
l is the mean length of the path that the particle crosses during scattering on one atomic string in the direction that is parallel to this atomic string;

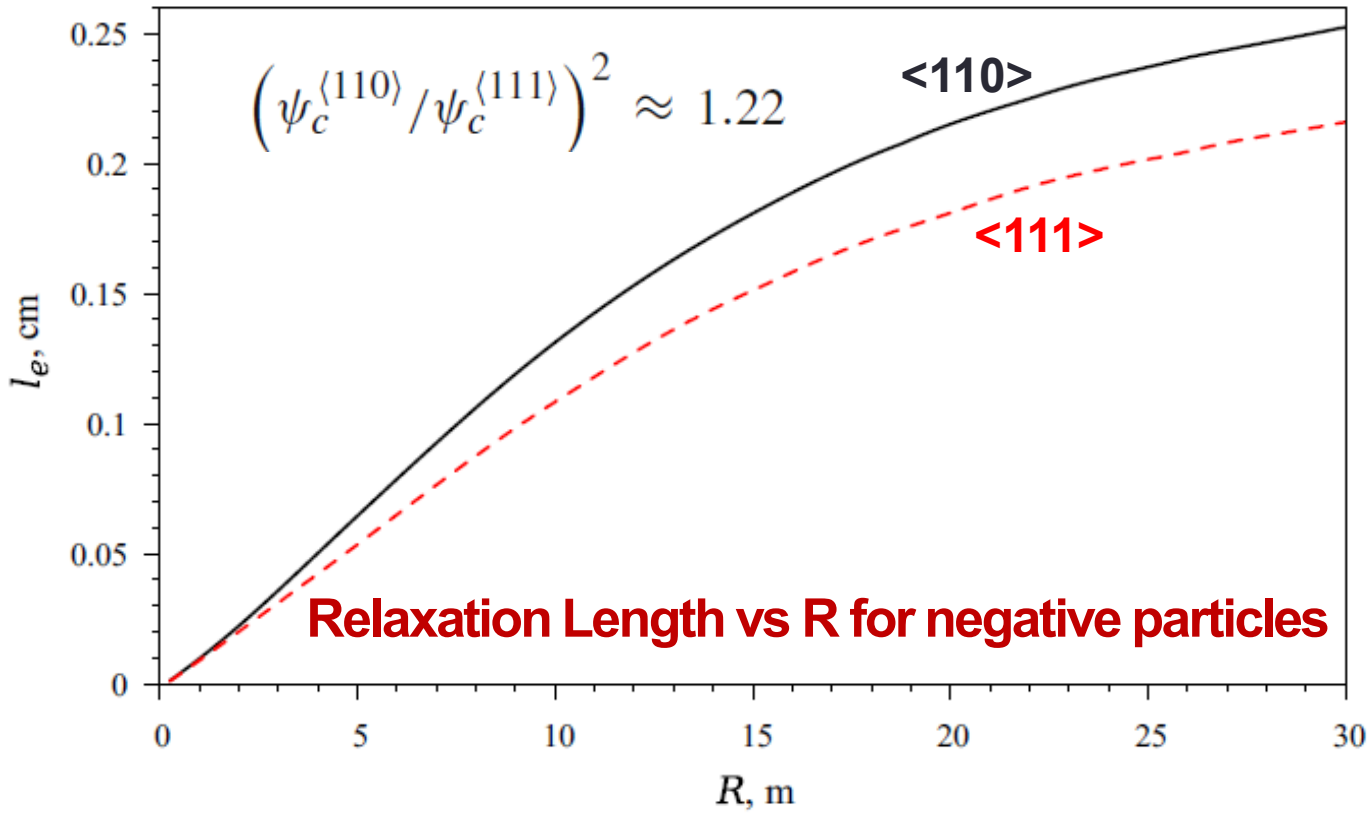
ξ is a constant of proportionality between the mean square angle of **incoherent multiple scattering** on atomic thermal vibrations, electronic subsystem atoms, etc., and the thickness of the crystal..

I. V. Kirillin, N. F. Shul'ga, L. Bandiera, V. Guidi, A. Mazzolari Eur. Phys. J. C (2017) 77:117

Theoretical interpretation and Monte Carlo simulation developed by I. Kyryllyn and N. Shulg'a from KIPT

Deflection efficiency vs axis choice and curvature Radius

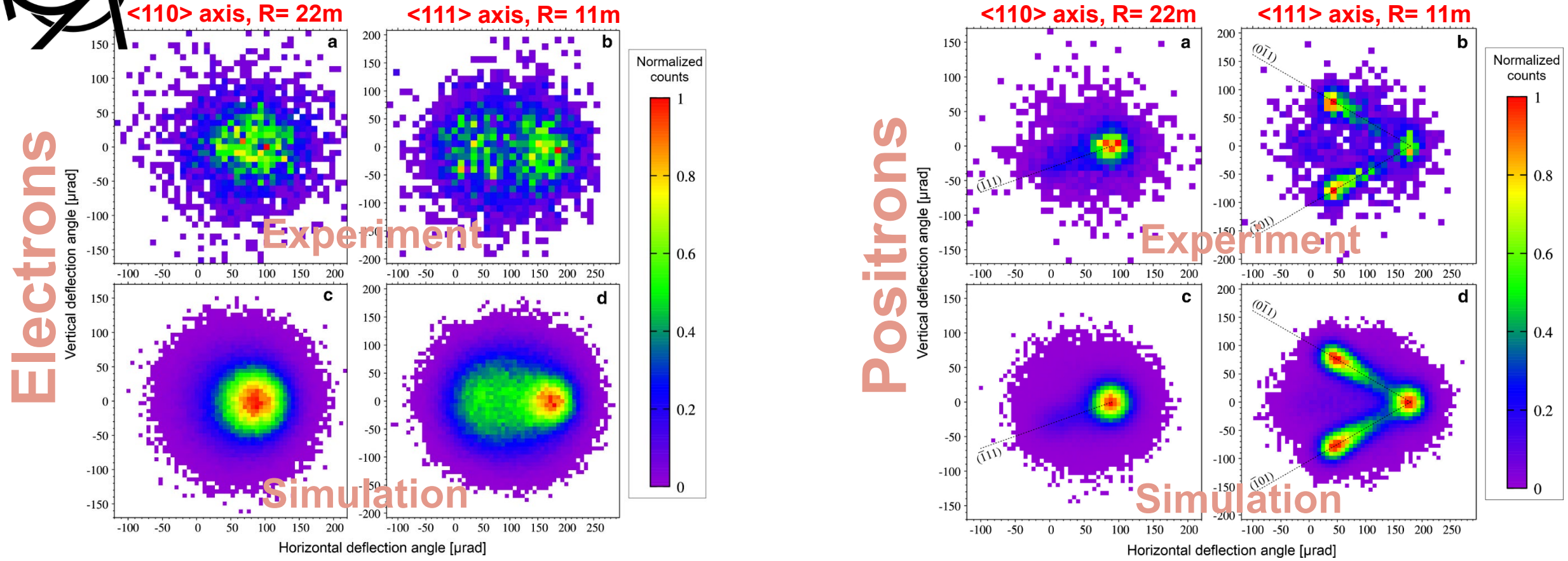




L. Bandiera, I. V. Kyryllin,... N. F. Shul'ga,.. et al. Eur. Phys. J. C 81 (2021) 238

Theoretical interpretation and Monte Carlo simulation developed by I. Kyryllyn and N. Shulg'a from KIPT

Positive vs. Negative Axial Deflection: 120 GeV e±



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

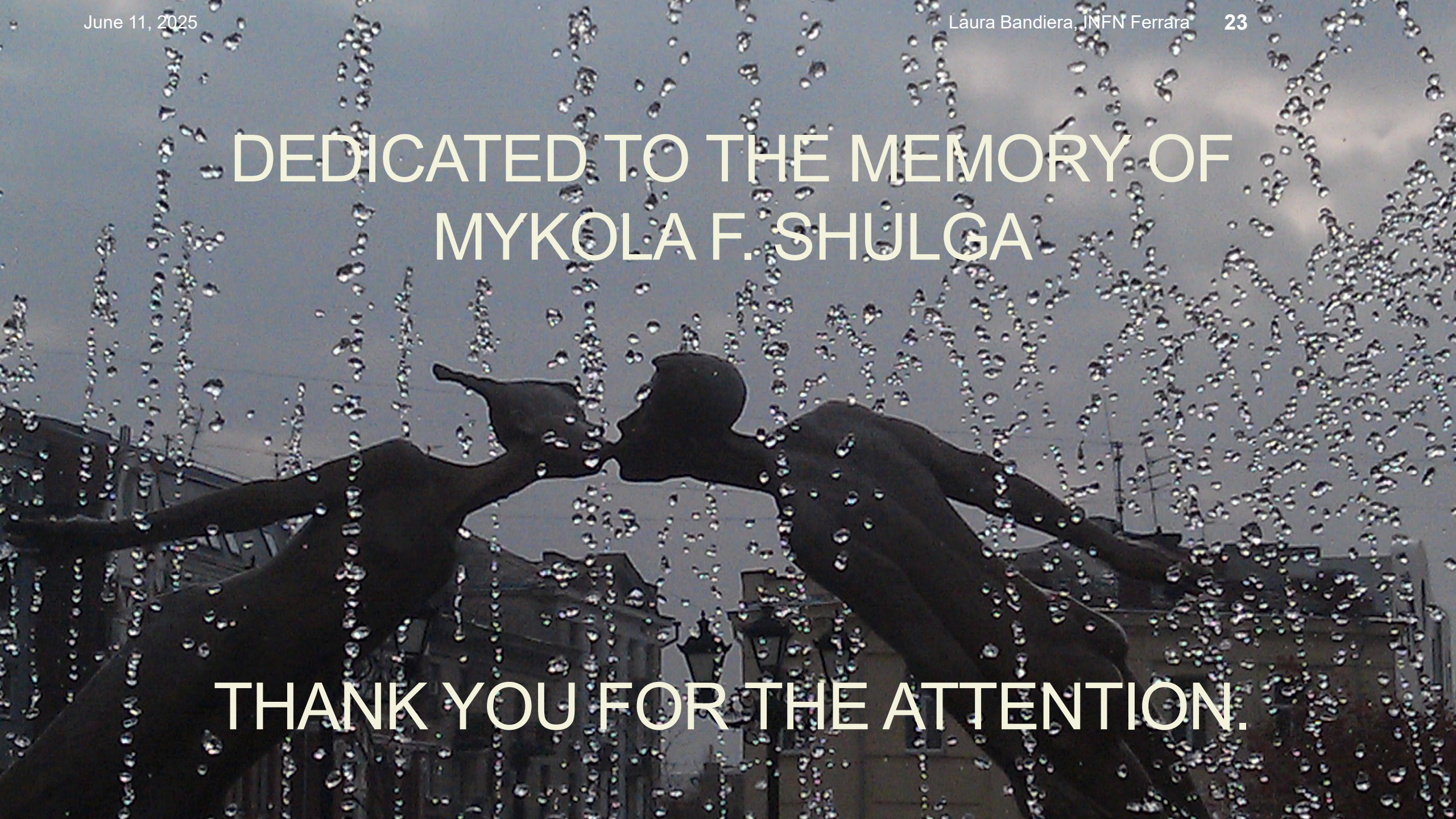
Deflection of more than 90% of the electron beam.
APPLICATION: beam steering of high-energy negative particles

Conclusions

- An investigation on the mechanism of relaxation of axially confined 400 GeV/c protons to planar channeling in a bent crystal was carried out at the extracted line H8 from CERN Super Proton Synchrotron;
- The first investigation of stochastic deflection for electrons and positrons was carried out at the extracted line H4 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.

Last but not least… my first meeting with Mykola F. Shulga

Channeling 2012 in Alghero



DEDICATED TO THE MEMORY OF MYKOLA F. SHULGA

THANK YOU FOR THE ATTENTION.