Crystal routine studies

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Outline

- CRYSTAL-channeling simulation code
  - Introduction
  - Algorithm
  - Specific details
- Single passage simulation
  - Comparison of the results with SixTrack crystal module simulations
  - Observation of interesting effects for the LHC
  - Considering of the miscut angle problem for the LHC
- New effects for the LHC collimation
  - A technique to improve crystal channeling efficiency of charged particles (crystal cut)
  - Multiple volume reflection in one bent crystal (MVROC)
  - Combination of MVROC and channeling

My mission at CERN: CRYSTAL-channeling* simulation code

- To compare CRYSTAL-channeling simulation results with CRYAPR modeling.
- To check the proper consideration of all possible effects by both of these codes, to look for new interesting effects.
- To understand, if some our ideas can be useful for the LHC collimation.

CRYAPR**

- Statistical treatment of various interactions between protons and crystal, optimized for multi-turn tracking in an accelerator.

CRYSTAL-channeling*

- Routine for the tracking proton trajectories in crystal by solving equation of motions with interplanar field potential***:

$$pv\frac{d^2x}{dz^2}+U'(x)+\frac{pv}{R}=0$$

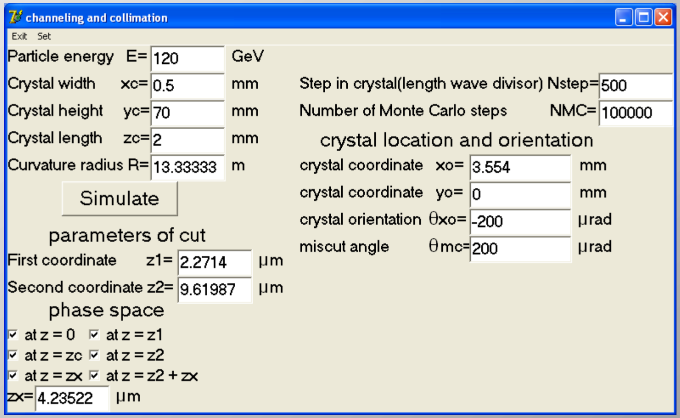
*Designed by V. Tikhomirov, A. Sytov.

**I.Yazynin, 4th Crystal Channeling Workshop 2009, CERN, March 24-27, 2009;
V. Previtali, These de Doctorat. Lausanne, 2010;
D. Mirarchi, S. Redaelli, W. Scandale, V. Previtali, MOPWO035, IPAC2013.

***V.M.Biryukov, Y.A.Chesnokov, V.I.Kotov,
Crystal channeling and its application at high energy accelerators, Springer, 1997.

Creation and evolution of CRYSTAL-channeling

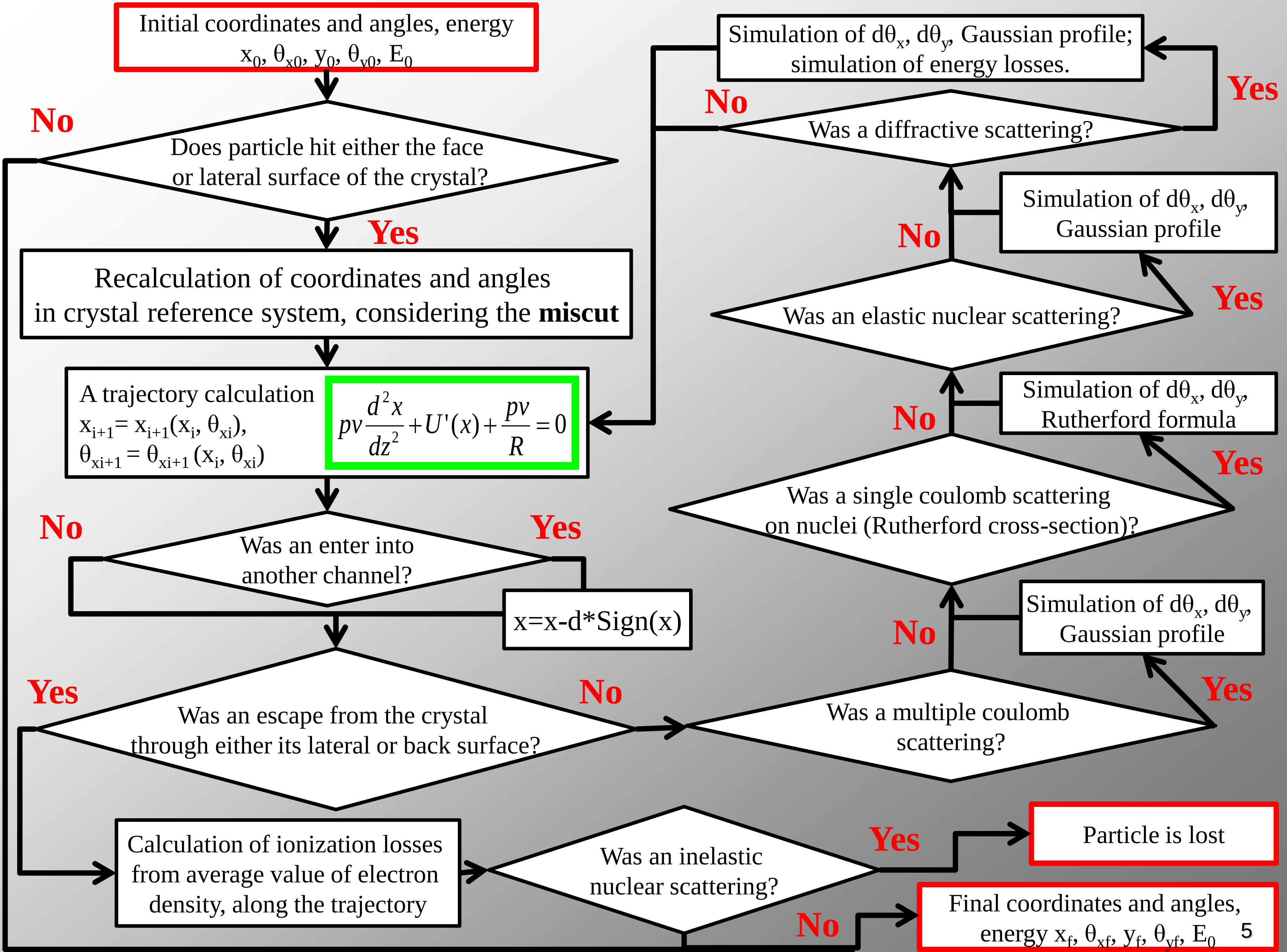
Main conception: Victor Tikhomirov codes.



Spring 2011 – first version on Delphi
Summer 2011 – first attempts of simulation (UA9 experiment, miscut angle influence)

Summer 2012 (Fermilab summer student internship PARTI) – rewriting the code on Fortran language and its considerable modification, combining of it with STRUCT*, first attempts of simulation of experiment at the Recycler Ring**
Autumn 2012 – winter 2013 – Simulation of experiment at the Recycler Ring**, comparison of the results with Yazynin code***
Spring 2013 – MPI modification for parallel simulations

*I. Baishev, A. Drozhdin, N. Mokhov, X. Yang, 'STRUCT Program User's Reference Manual', SSCL–MAN–0034 (1994), http://www-ap.fnal.gov/users/drozhdin/.
**V.Shiltsev, Novel Slow Extraction Scheme for Proton Accelerators Using Si Bent Crystal, Proc. IAAA IPAC12, New Orleans, USA, 2012.
***I.Yazynin, 4th Crystal Channeling Workshop 2009, CERN, March 24-27, 2009.


Initial coordinates and angles, energy
x0, θx0, y0, θy0, E0
Does particle hit either the face
or lateral surface of the crystal?
No
Yes
Recalculation of coordinates and angles
in crystal reference system, considering the **miscut**
A trajectory calculation
xi+1= xi+1(xi, θxi),
θxi+1 = θxi+1 (xi, θxi)
$pv\frac{d^2x}{dz^2}+U'(x)+\frac{pv}{R}=0$
Was an enter into
another channel?
No
Yes
x=x-d*Sign(x)
Was an escape from the crystal
through either its lateral or back surface?
Yes
No
Calculation of ionization losses
from average value of electron
density, along the trajectory
Was an inelastic
nuclear scattering?
Yes
Particle is lost
No
Final coordinates and angles,
energy xf, θxf, yf, θyf, E0
Was a multiple coulomb
scattering?
Yes
Simulation of dθx, dθy,
Gaussian profile
No
Was a single coulomb scattering
on nuclei (Rutherford cross-section)?
Yes
Simulation of dθx, dθy,
Rutherford formula
No
Was an elastic nuclear scattering?
Yes
Simulation of dθx, dθy,
Gaussian profile
No
Was a diffractive scattering?
Yes
Simulation of dθx, dθy, Gaussian profile;
simulation of energy losses.
No

Specific features

Spline interpolation of:

- Interplanar potential
- Interplanar electric field
- Density of nuclei
- Density of electrons

$$\Delta x_i = x_i - x;$$

$$S(x) = a_i + \Delta x_i (b_i + \Delta x_i (c_i + d_i \Delta x_i))$$

Advantages:

- At least 10 mathematical operations necessary for function calculation
- Reading spline coefficients from input file makes an algorithm universal for any potential type
- 1000 interpolation nodes is more than enough for accuracy of 10^{-7} – 10^{-8}.

Step changing:

Channeling step:

$$dz_0 = \lambda / N_{steps} = \pi d_{pl} \sqrt{\frac{pv}{2U_0}} / N_{steps}$$

Usually N_{steps}=350.

Amorphous step:

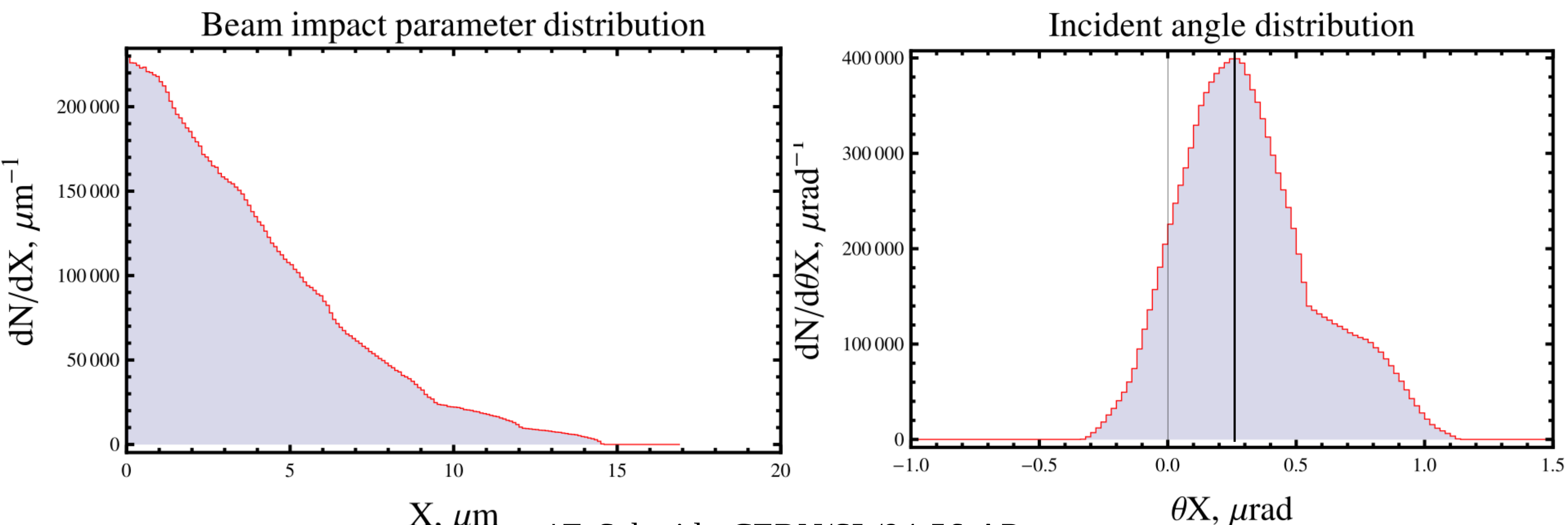
$$dz = \frac{5\theta_L}{\pi\sqrt{2}} dz_0 / \theta_x = 1{,}12\, dz_0 / \theta_x$$

Starting from: $\theta_x = \frac{5}{\pi\sqrt{2}} \theta_L$

Simulations input

- **Crystal parameters**: crystal length l_{cr}=**3**, 4, 5 mm; bending angle θ_b=**40**, 50, 60 μrad; θ_{cr}=0, –25, –35, –100, 100 μrad for l_{cr}=**3** mm, θ_b=**40** μrad; l_{cr}=4 mm, θ_b=50 μrad and θ_{cr}=0 μrad for remaining combinations of length and bending angle.
- Ideal crystal without amorphous layer, miscut, crystal torsion, imperfections, …
- Input beam distrubution at the crystal entrance was calculated for the LHC case with SixTrack* for **7 TeV** energy.
- Only output distribution from crystal was considered (single passage effects).

A similar setup was used for comparison between the SixTrack module and Taratin's code.

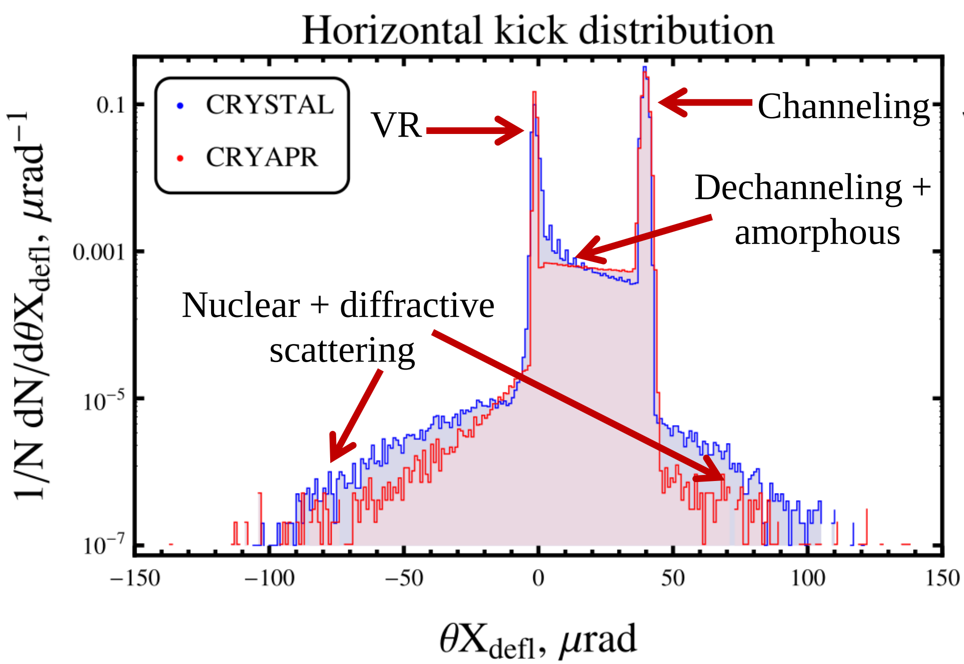


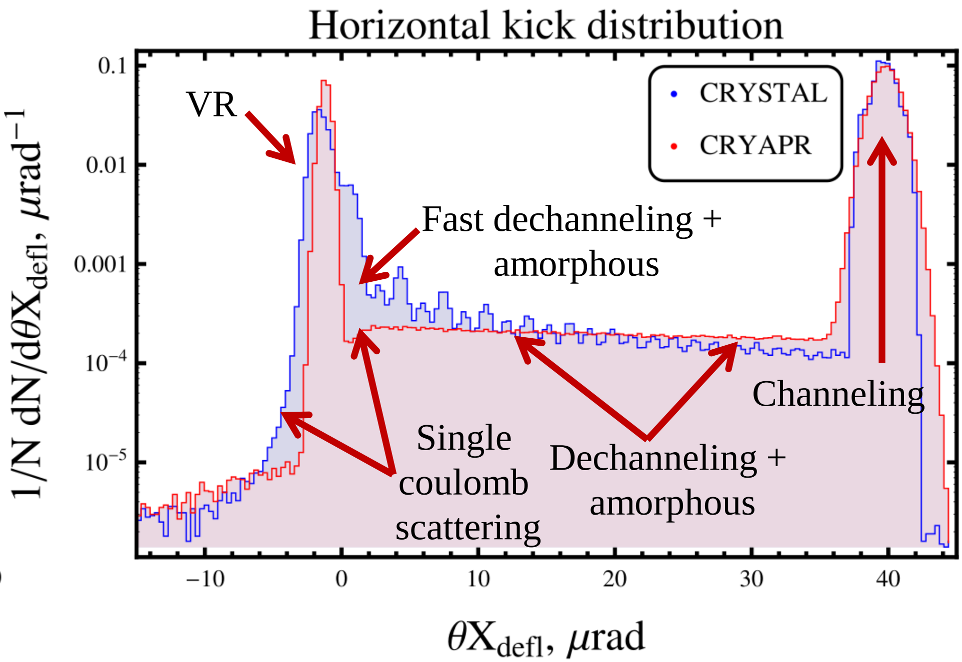
*F. Schmidt, CERN/SL/94-56-AP.

G. Robert-Demolaize, R. Assmann, S. Redaelli, F. Schmidt, FPAT081, PAC2005.

D. Mirarchi, S. Redaelli, W. Scandale, V. Previtali, MOPWO035, IPAC2013.

Horizontal kick distribution, channeling orientation

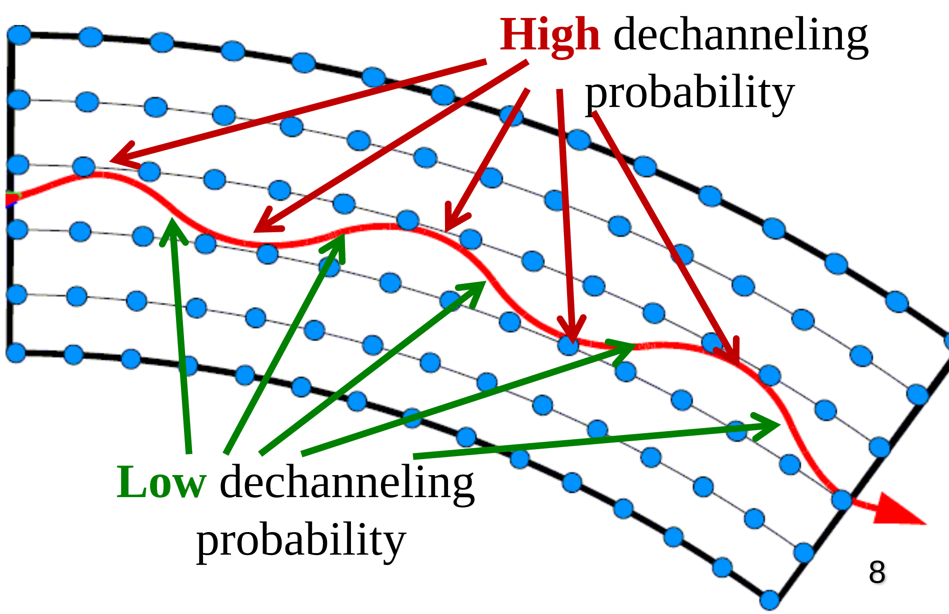




High dechanneling probability is achieved at maxima of channeling oscillations, **low** dechanneling probability at minima of them.

At **7 TeV** very few number of oscillations: 4 per mm + low angular divergence of the incident beam => high correlation between phase of different particles => *"dechanneling peaks"*.

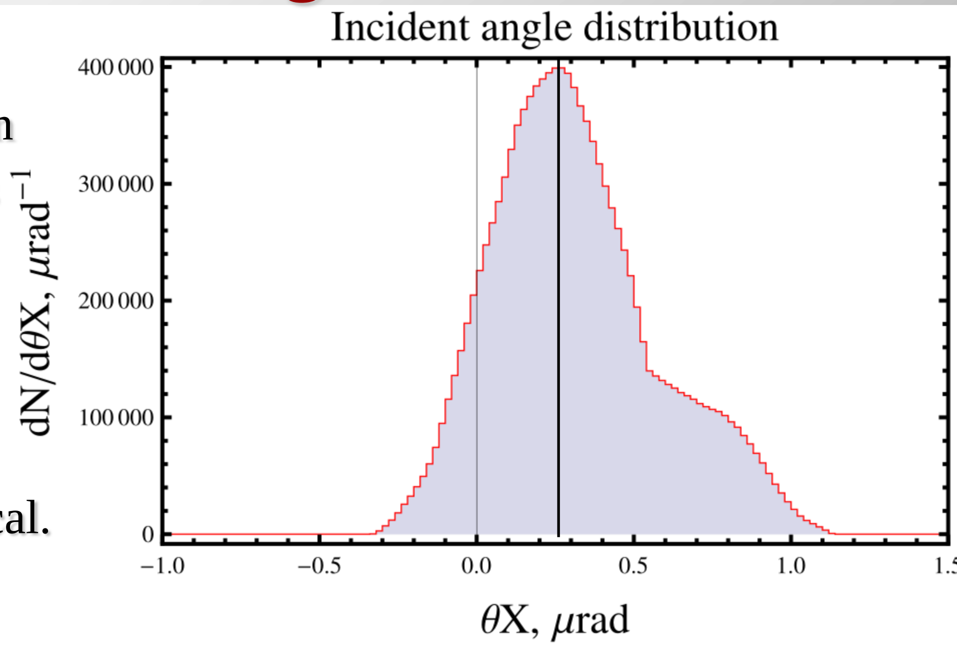
About 1.3 % of particles dechannel at the first mm of crystal (4 oscillations). It may be important for collimation.



Dechanneling peaks and initial angular distribution*

Peculiarities of the LHC case:

- Very high energy => very few oscillations in crystal => good correlation between trajectories
- Rather large impact parameter => initial angular distribution is asymmetric and shifted from ideal angle value for left crystal point.
- Bending radius is rather small=> interplanar potential is considerably asymmetrical.

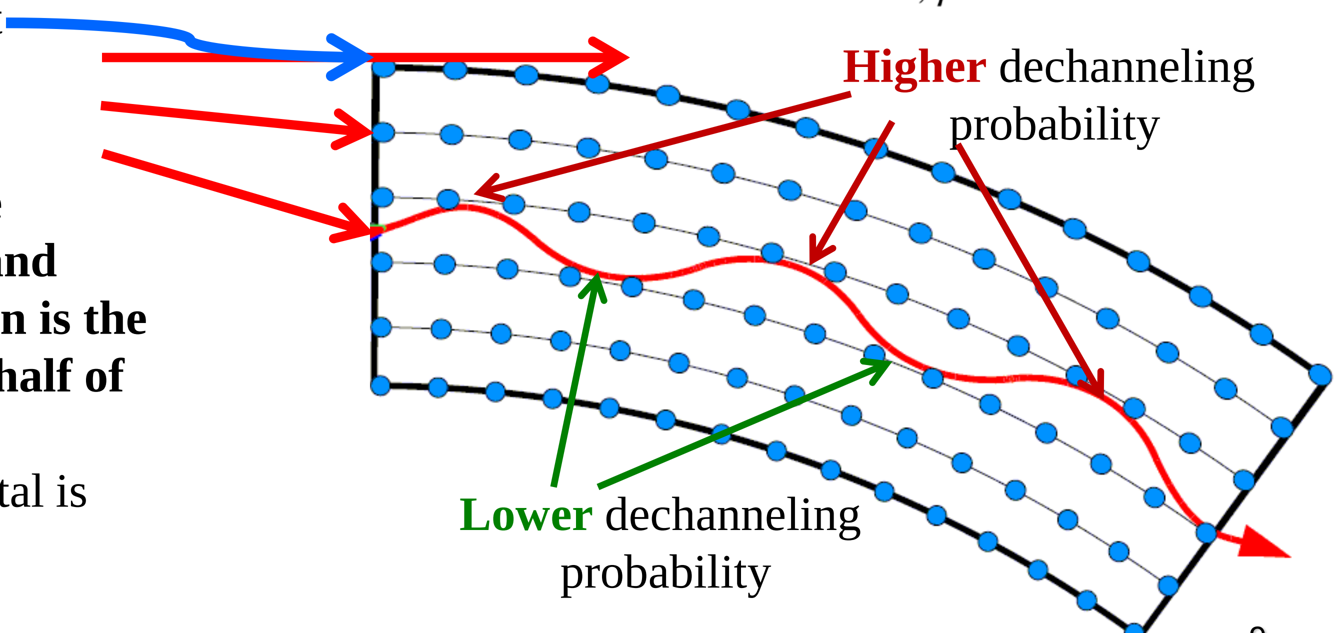


Optimal orientation for left point of the crystal is

$$\theta_{\text{tilt}} = -\alpha * \sqrt{\epsilon/\beta}$$

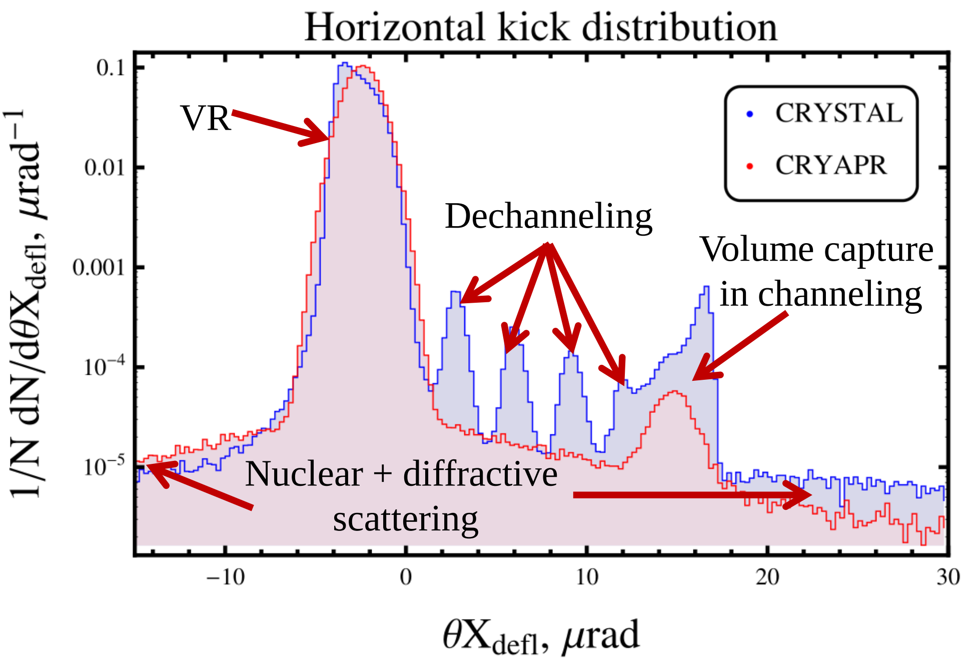
Asymmetry of both plane potential in bent crystal and initial angular distribution is the reason of less height of a half of "dechanneling peaks".

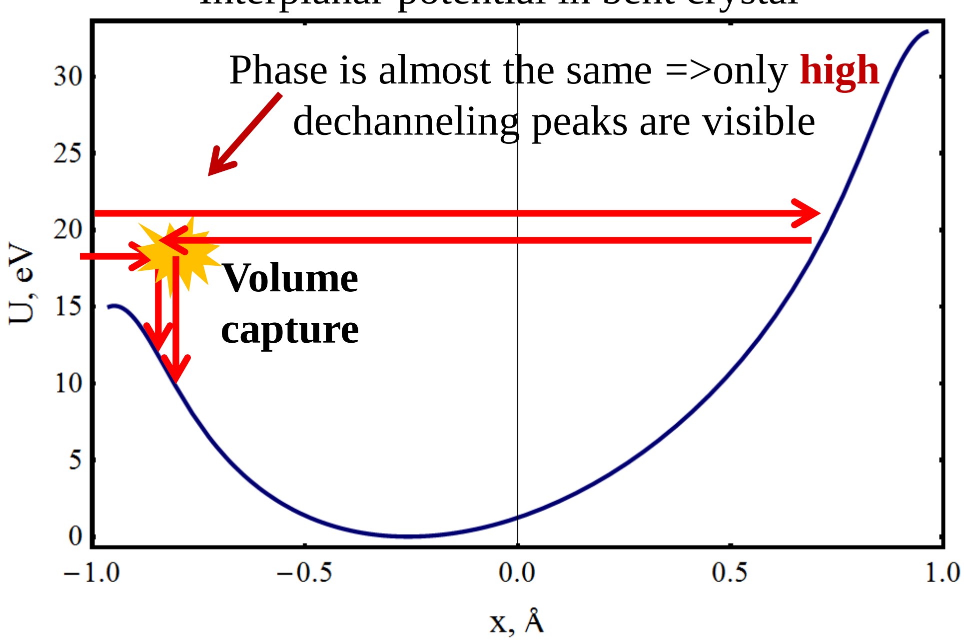
Ideal alignment of the crystal is important for collimation.



*Calculated with SixTrack,
D. Mirarchi, S. Redaelli, W. Scandale, V. Previtali, Layouts for crystal collimation tests at the LHC, IPAC2013.

Volume capture, VR orientation: –25μrad





Volume capture:

CRYAPR: **0.05%**.

CRYSTAL-channeling: **0.3%** + ~0.3% (dechanneled) ≈0.6%.

By Biryukov approximation formula*:

$$\eta_{VC} = \frac{\pi}{2}\frac{R\theta_c}{L_{De}}$$

R=75m, L_{De}≈3m,

θ_c=2.1μrad (bent)=>$\boldsymbol{\eta_{VC}}$**=0.008%.**

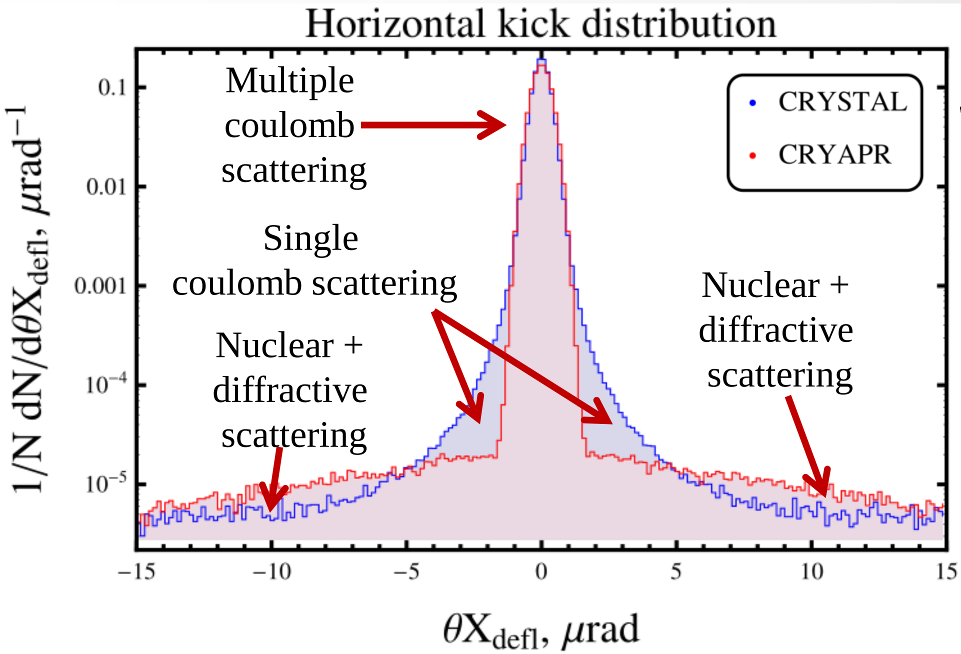
But for 7 TeV $L_{Dn} \sim l_{cr}$ and $L_{De} >> l_{cr}$.

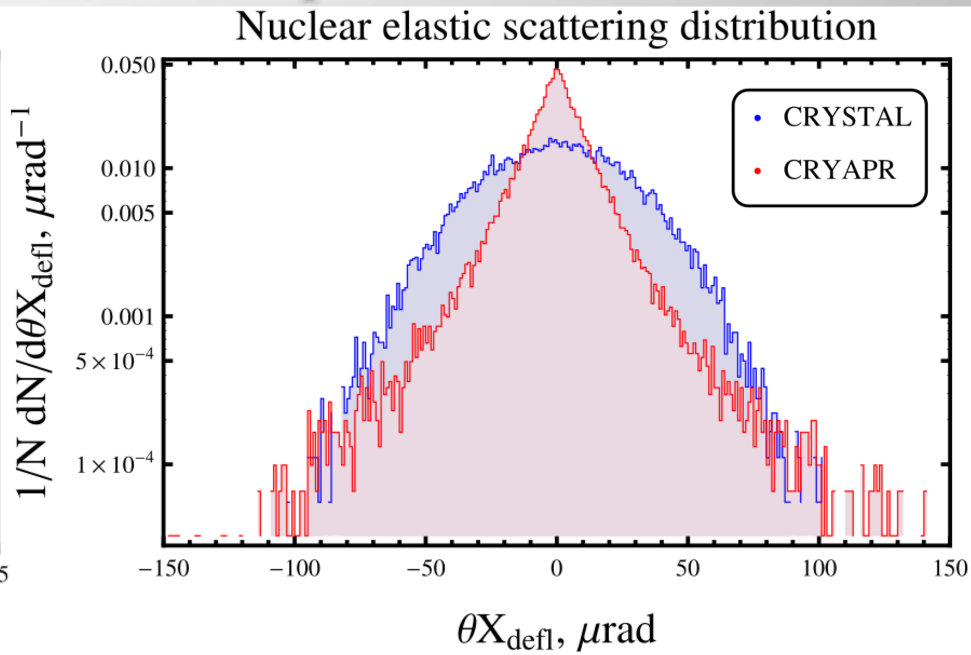
So, the main mechanism for both the volume capture and dechanneling at 7 TeV is scattering by nuclei but not by electrons. So, L_{Dn}~2.6cm and:

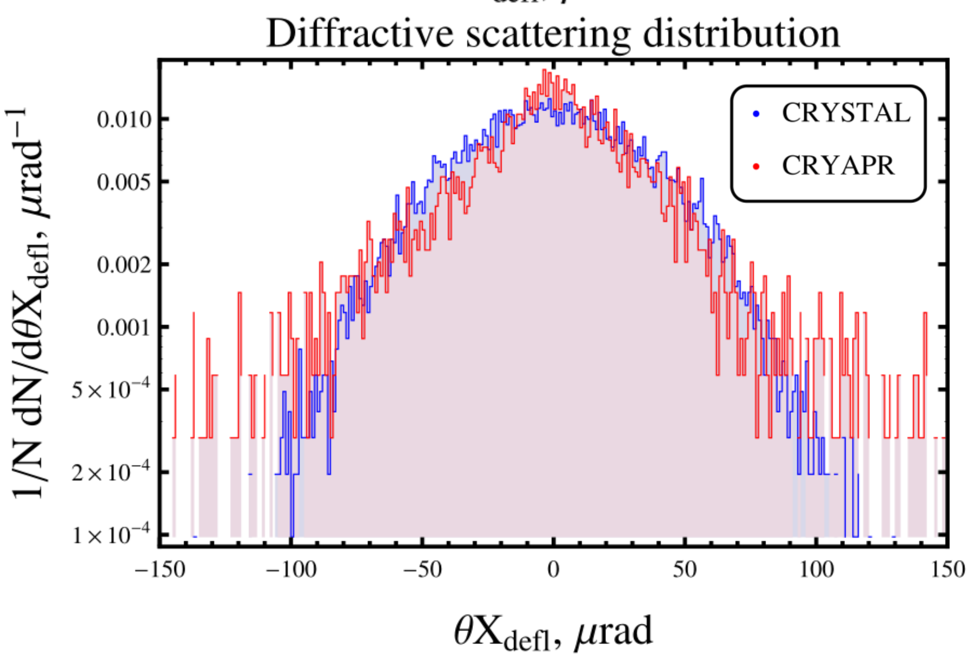
$$\eta_{VC} = \frac{\pi}{2}\frac{R\theta_c}{L_{Dn}} \approx 0.9\%.$$

*V.M.Biryukov, Y.A.Chesnokov, V.I.Kotov, Crystal channeling and its application at high energy accelerators, Springer, 1997.

Horizontal kick distribution, amorphous orientation



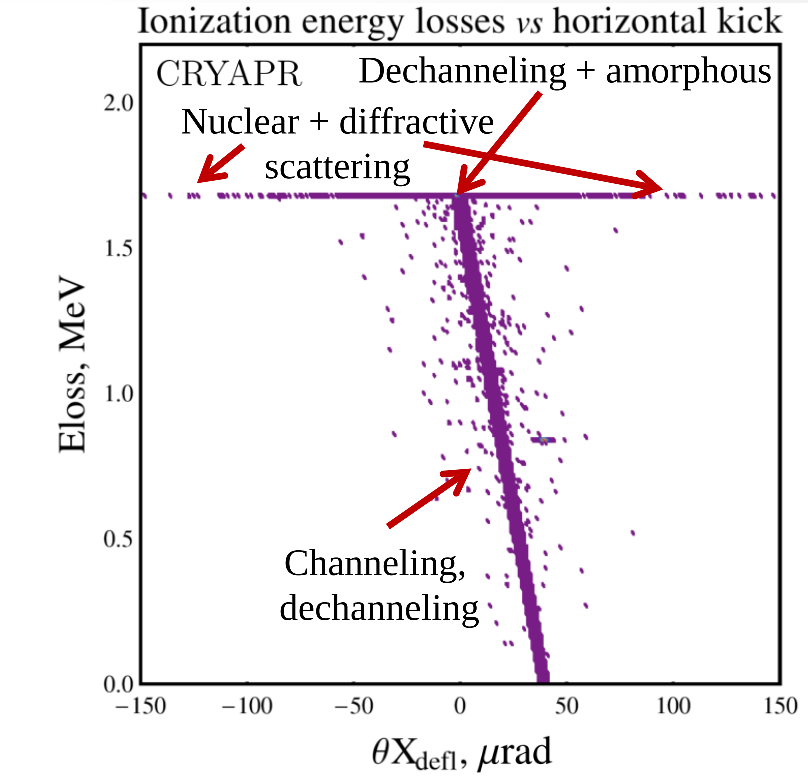


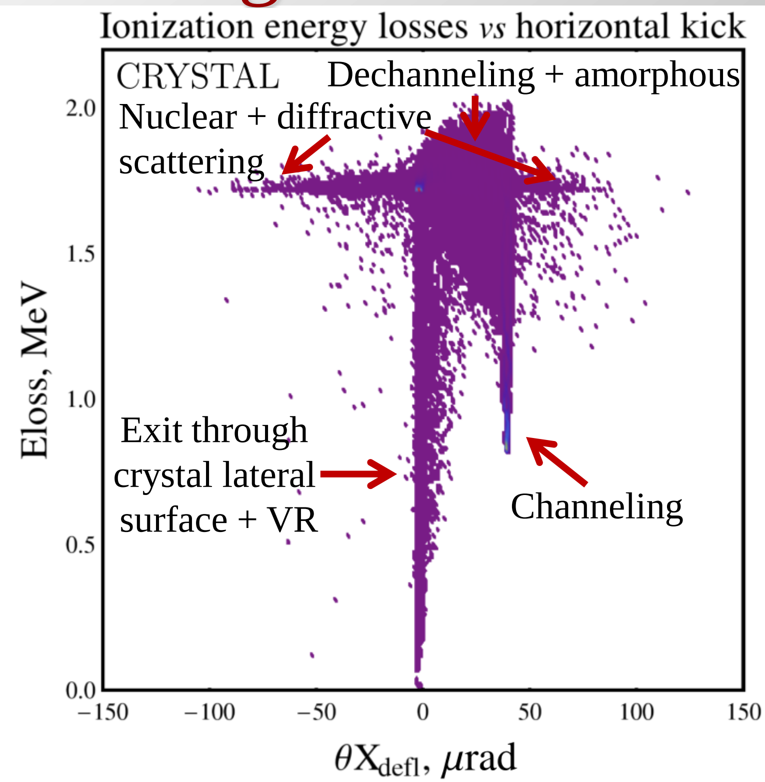


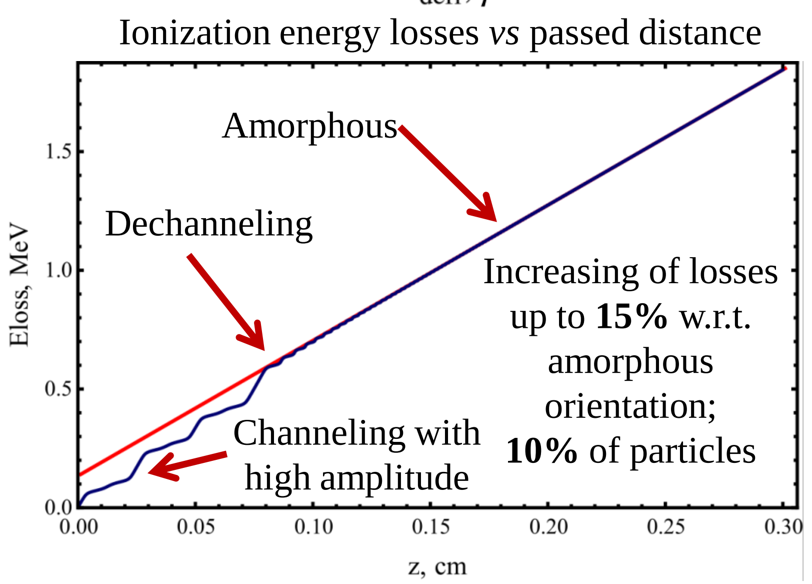
About 0.7% of particles are scattered by single coulomb scattering. It may be important for collimation.

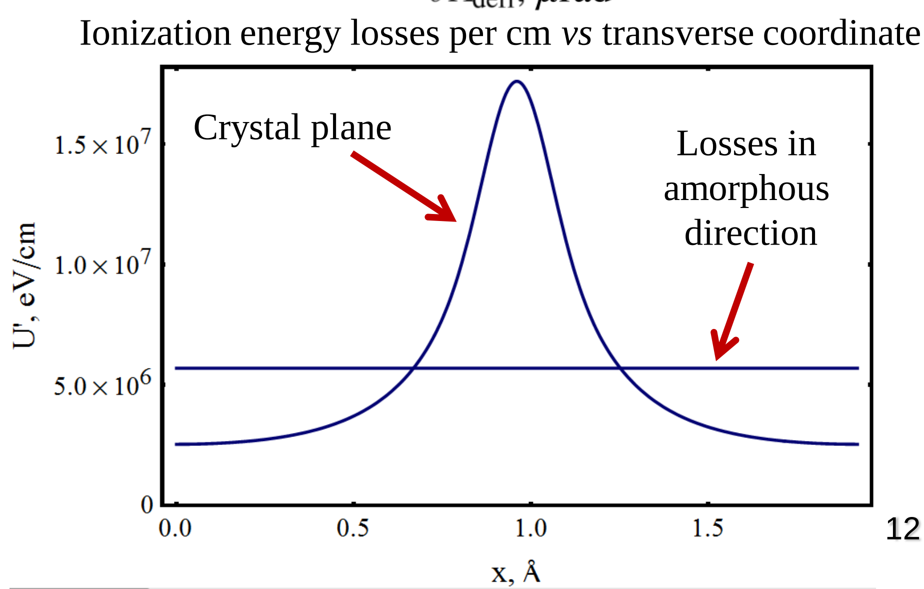
About 0.3% of particles will be scattered by either elastic or diffractive nuclear scattering. A correct model for such events can be also essential.

Ionization losses, channeling orientation

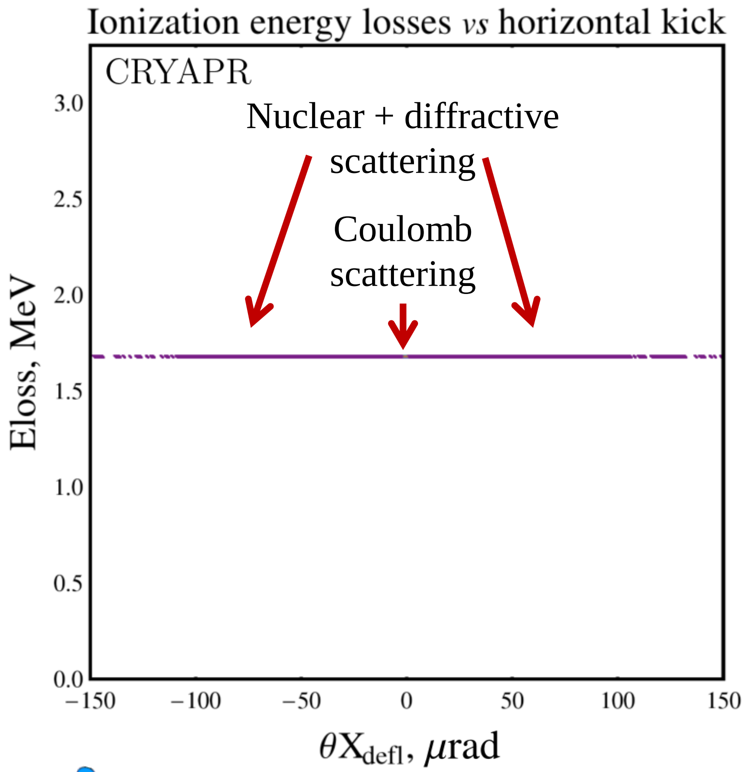


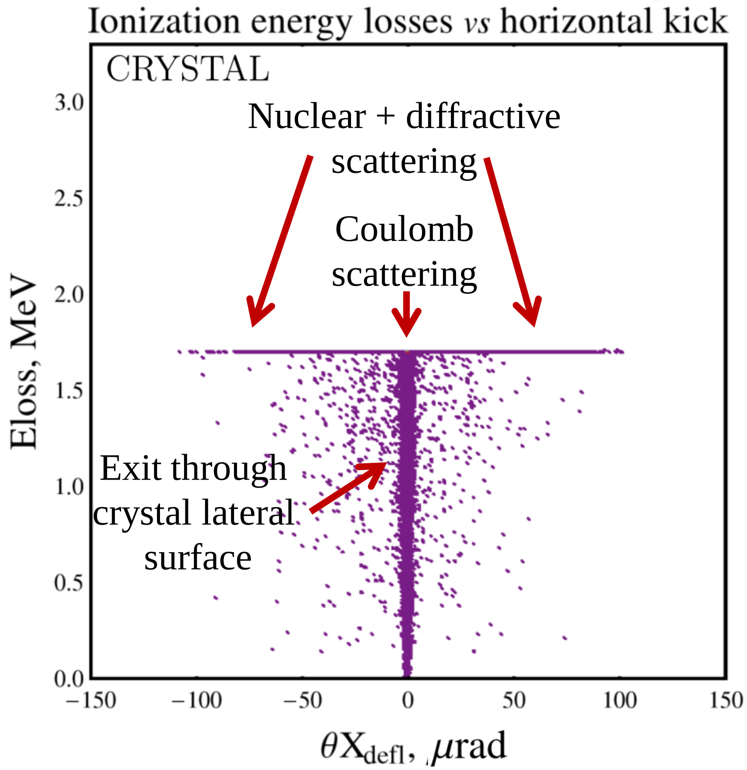


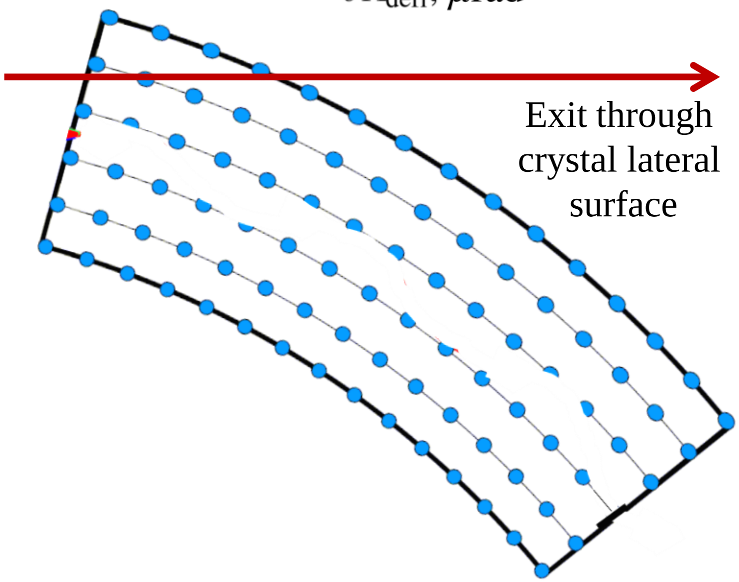




Ionization losses, amorphous orientation: 100μrad



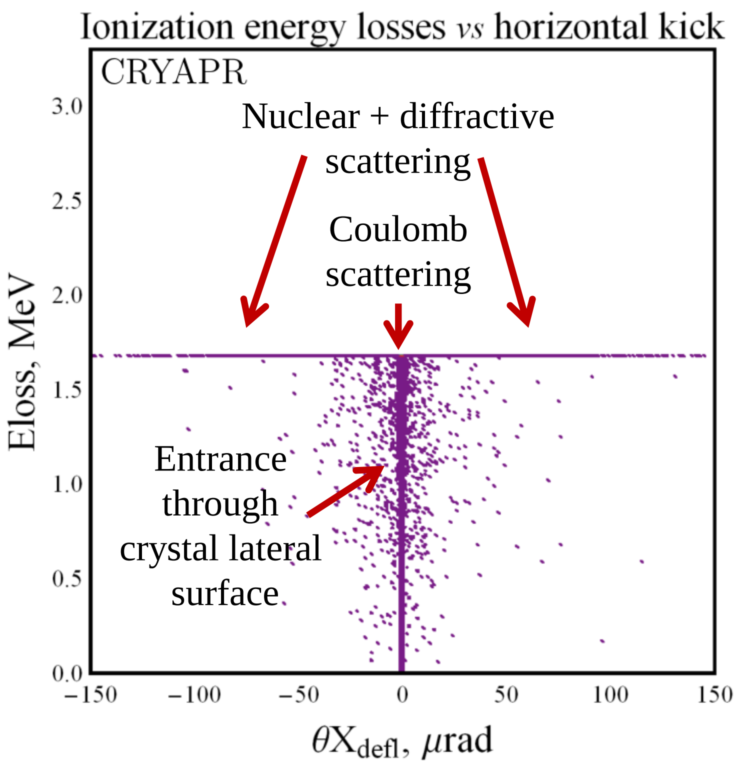


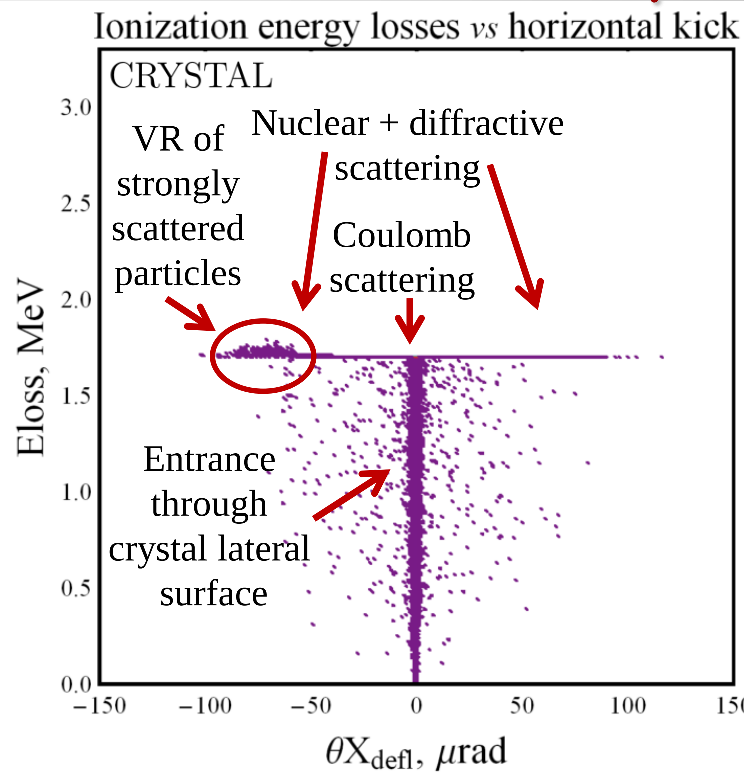


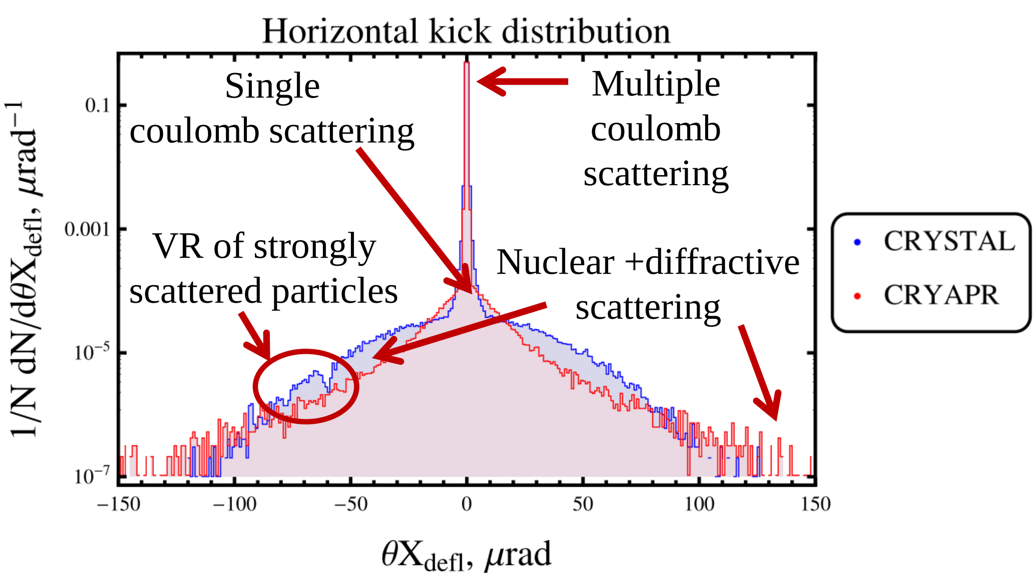
About 7% of particles will escape the crystal through its lateral surface at amorphous orientation.
It may be important for collimation.

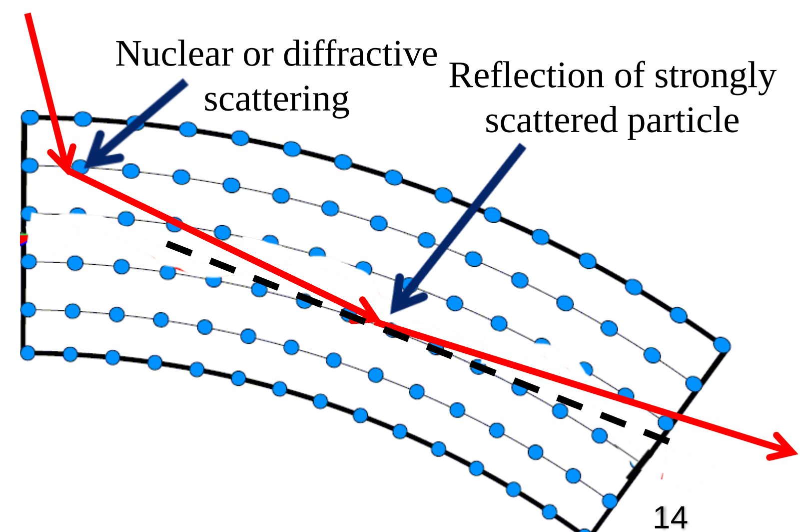
Ionization losses for LHC proton beam are not important, but for heavy ion beam they are important: dEloss~20-50GeV/cm for 574TeV ions.

Ionization losses, amorphous orientation: –100μrad

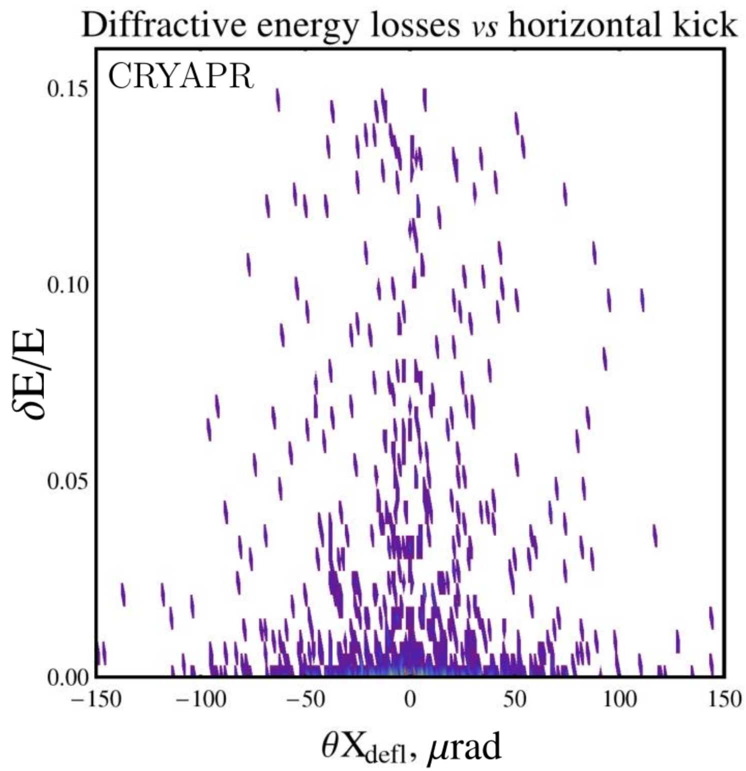


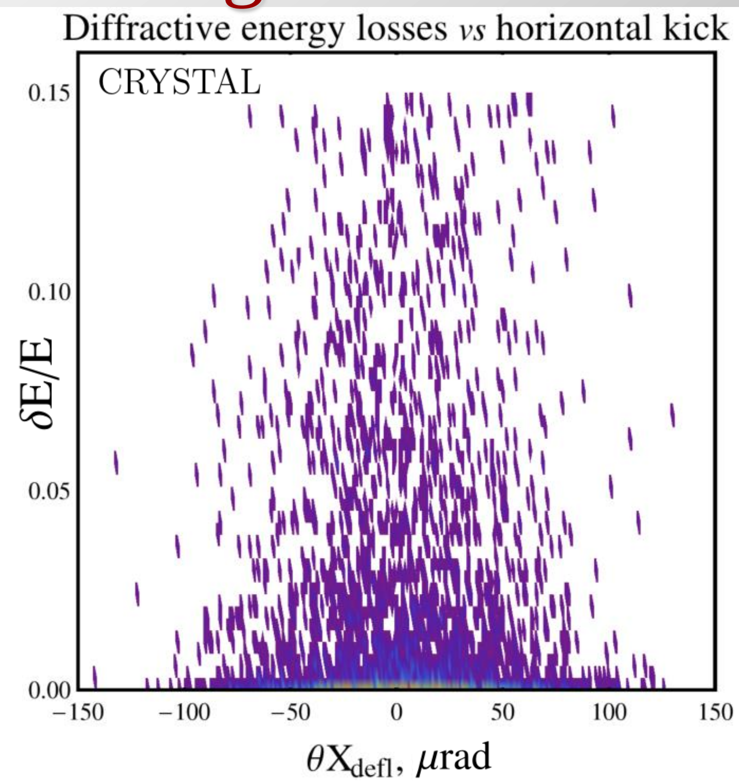


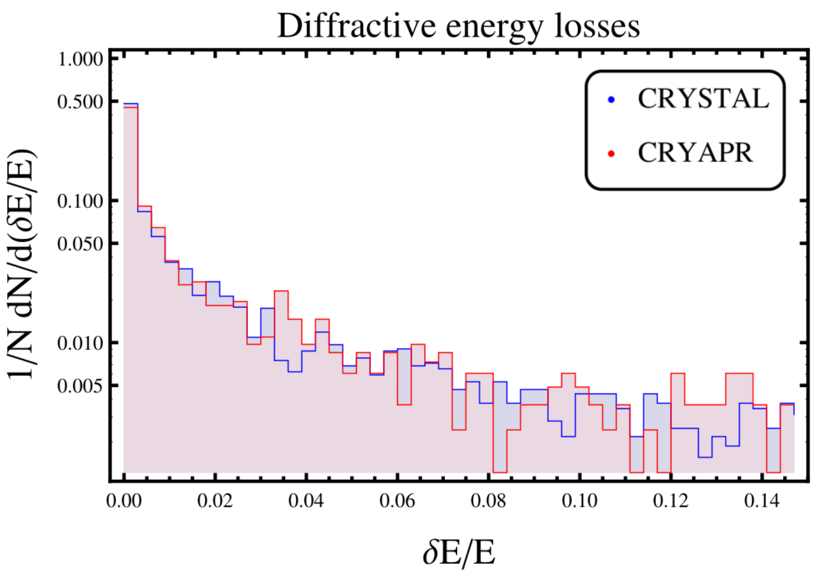




Diffractive losses, channeling orientation





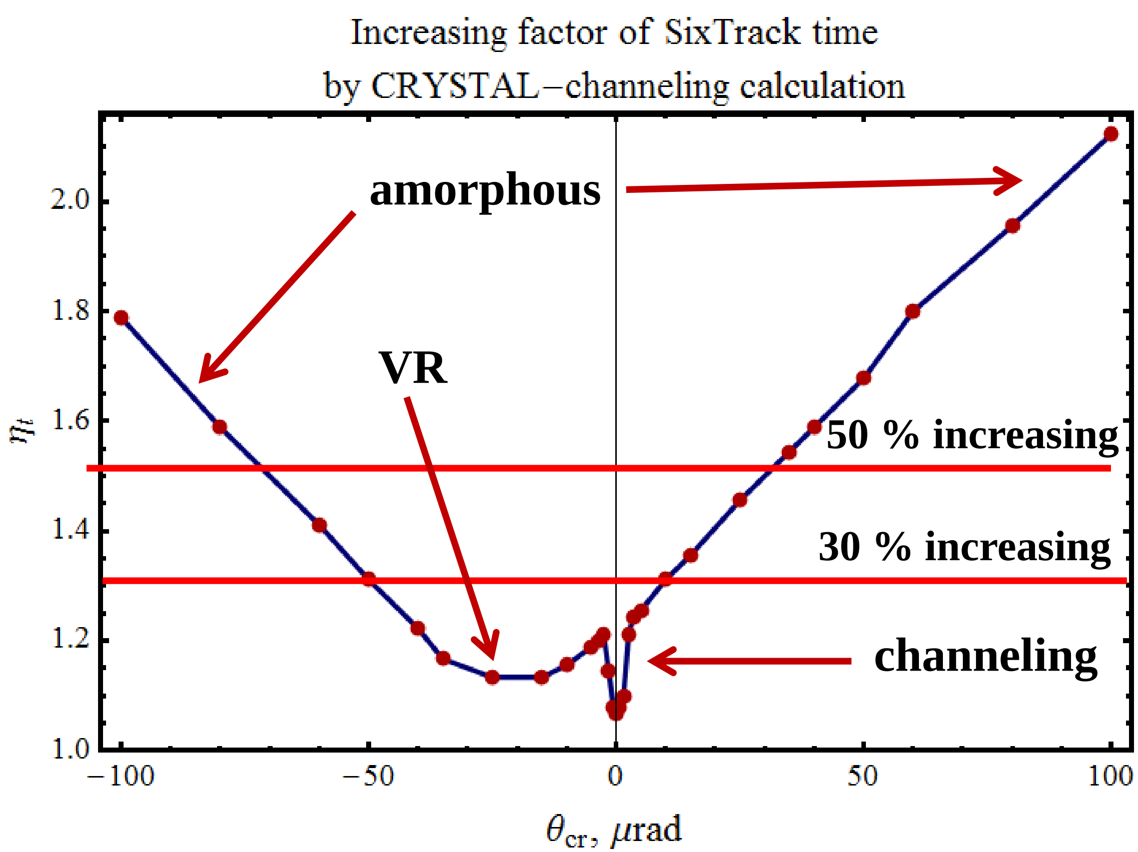


Difference is explained simply by different statistics caused by different models of elastic nuclear scattering.

About 0.3% of particles will be scattered by either elastic or diffractive nuclear scattering. Energy deposition is enough for considerable changing the trajectory in accelerator. A correct model for such events is important.

Percentage of different effects and calculation time analysis

θ_{cr}[μrad]> l[mm], θb[μrad]	0 (channeling)			-25 (VR)			100 (amorphous)		
		CRYAPR	CRYSTAL		CRYAPR	CRYSTAL		CRYAPR	CRYSTAL
3, 40	CH	75.64±0.04%	76.85±0.04%	CH	0.0492±0.0019%	0.313±0.005%	CH	0	0
	DC	2.351±0.013%	2.256±0.01%	DC	0.0008±0.0003%	$3*10^{-5}\pm5*10^{-5}$%	DC	0	0
	VR	21.78±0.04%	15.93±0.03%	VR	98.962±0.009%	88.12±0.03%	VR	0	0
	NES	0.074±0.003%	0.0543±0.0019%	NES	0.313±0.005%	0.194±0.004%	NES	0.313±0.005%	0.180±0.004%
	DIFF	0.0085±0.0008%	0.0321±0.0015%	DIFF	0.0352±0.0016%	0.112±0.003%	DIFF	0.0353±0.0016%	0.102±0.003%
	ABS	0.148±0.004%	0.191±0.004%	ABS	0.640±0.007%	0.688±0.007%	ABS	0.638±0.007%	0.636±0.007%
	CS	$1*10^{-5}\pm3*10^{-5}$%	4.687±0.018%	CS	0	10.57±0.03%	CS	99.013±0.008%	99.082±0.008%



For about 10 millions of particles the average time of calculation of SixTrack at lxplus was 5 h.

The calculation time by CRYSTAL-channeling strongly depends on crystal orientation.
Calculation was performed by i7 processor, 4 cores, 2.3 GHz.

For estimation it was put that calculation at lxplus is 3 times faster.

THE MISCUT ANGLE INFLUENCE ON THE FUTURE LHC CRYSTAL BASED COLLIMATION SYSTEM

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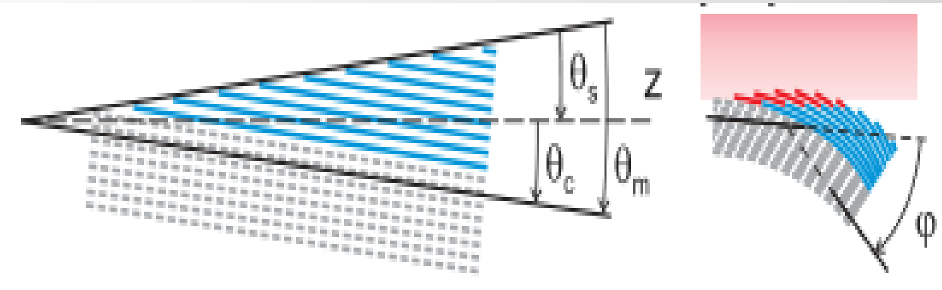
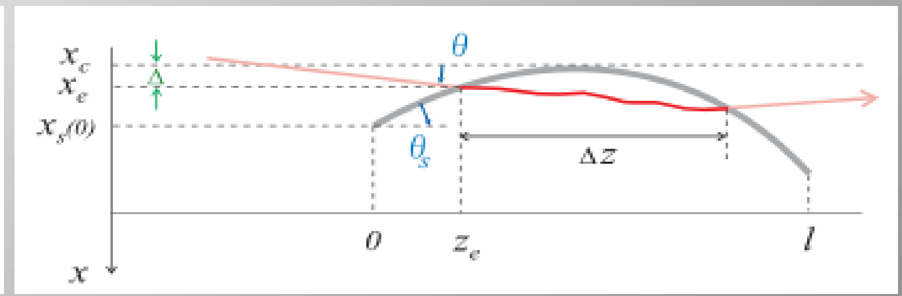
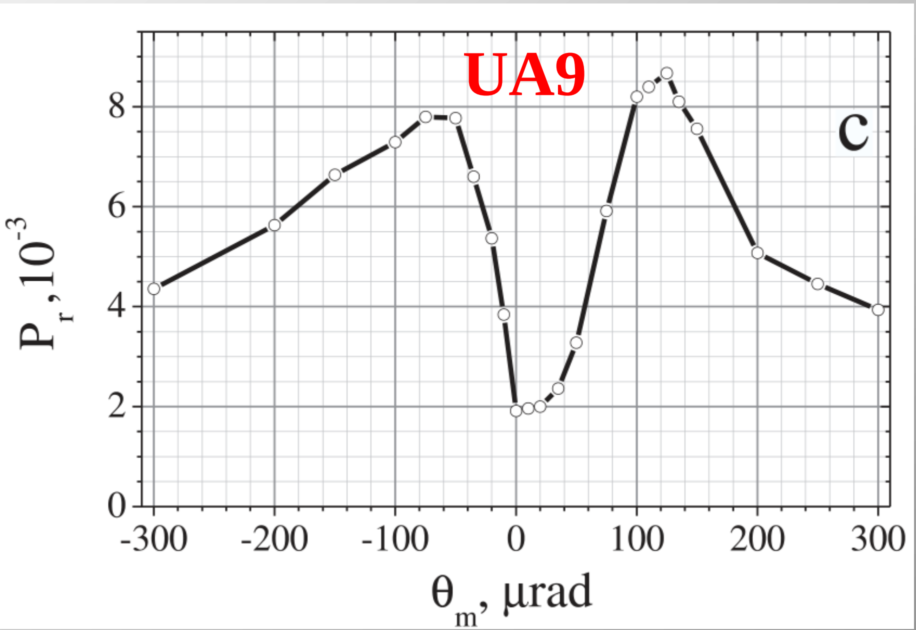
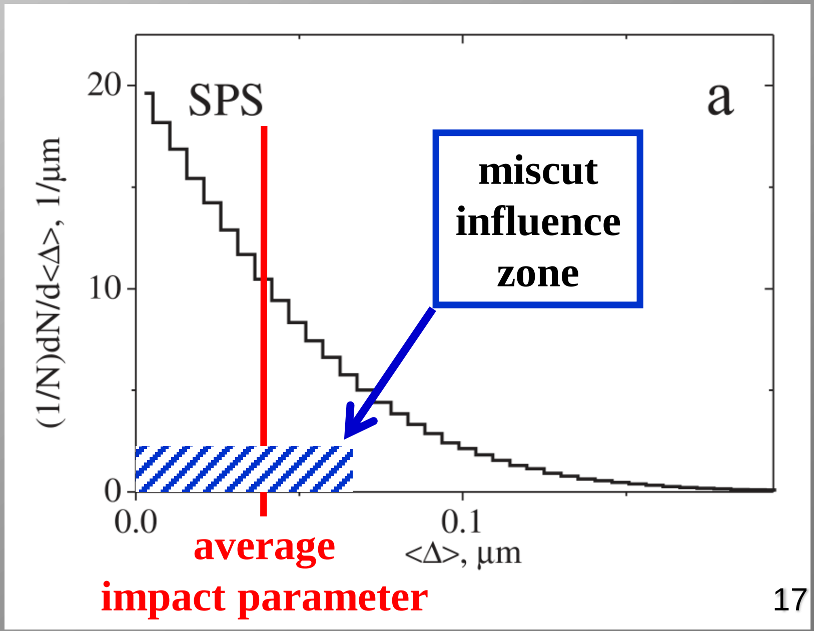
Series: Nuclear Physics Investigations (57), p. 88-92.

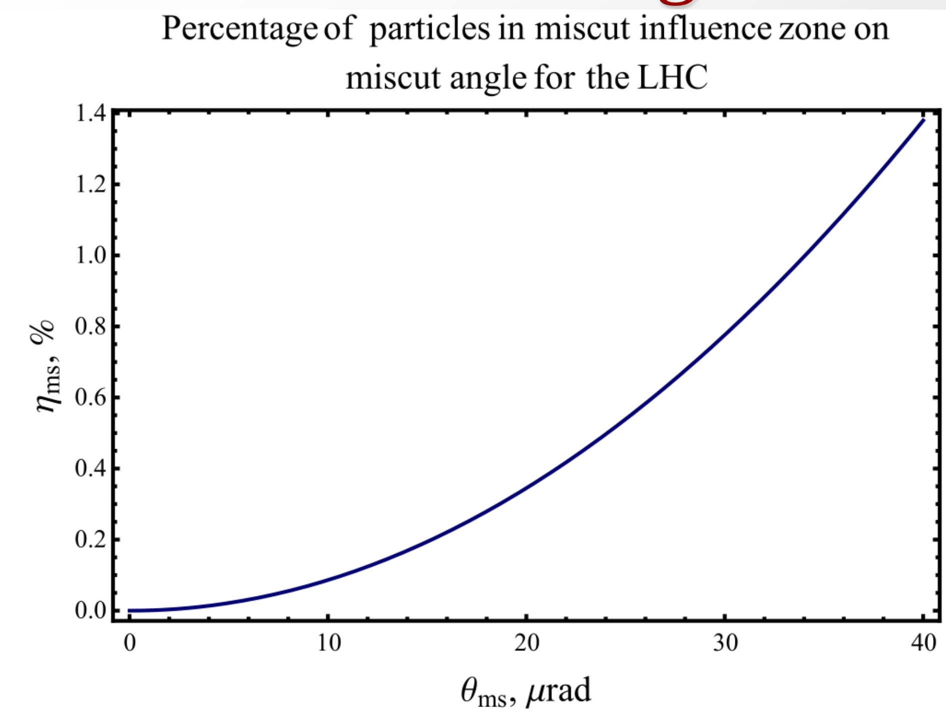








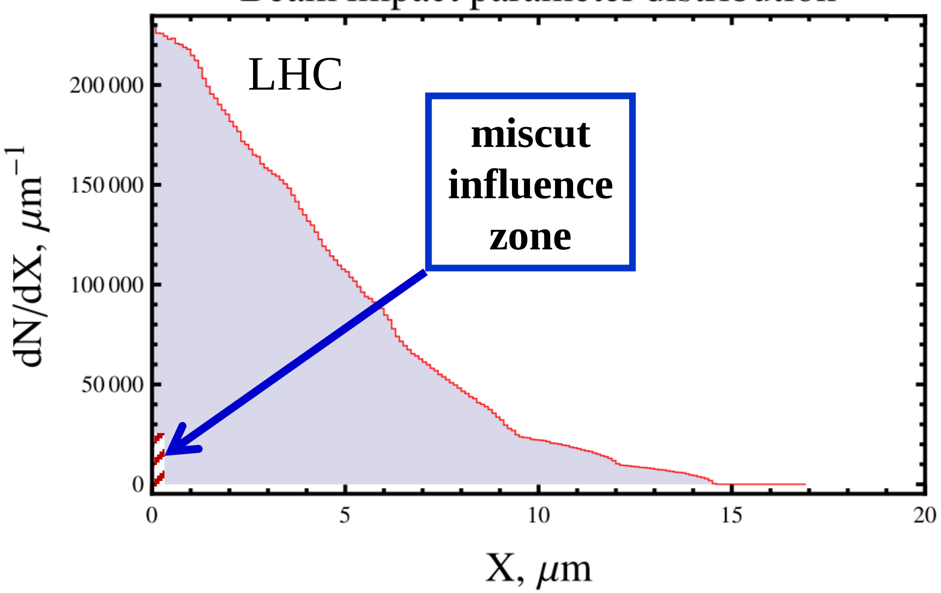
Miscut angle influence for the LHC

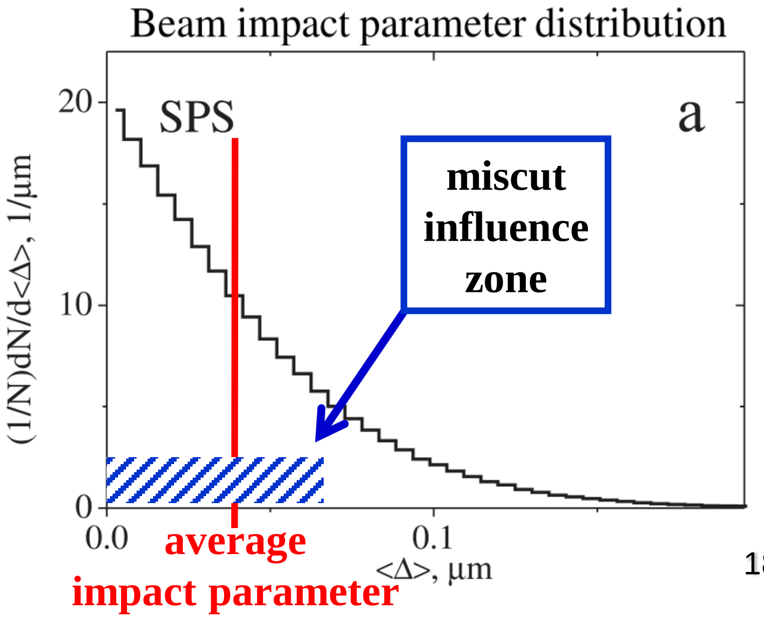


LHC miscut influence zone:

- 1.4% of particles for θ_{ms}=40μrad
- 0.78% of particles for θ_{ms}=30μrad
- 0.35% of particles for θ_{ms}=20μrad
- 0.086% of particles for θ_{ms}=10μrad

Depending on its value miscut angle may be important for collimation

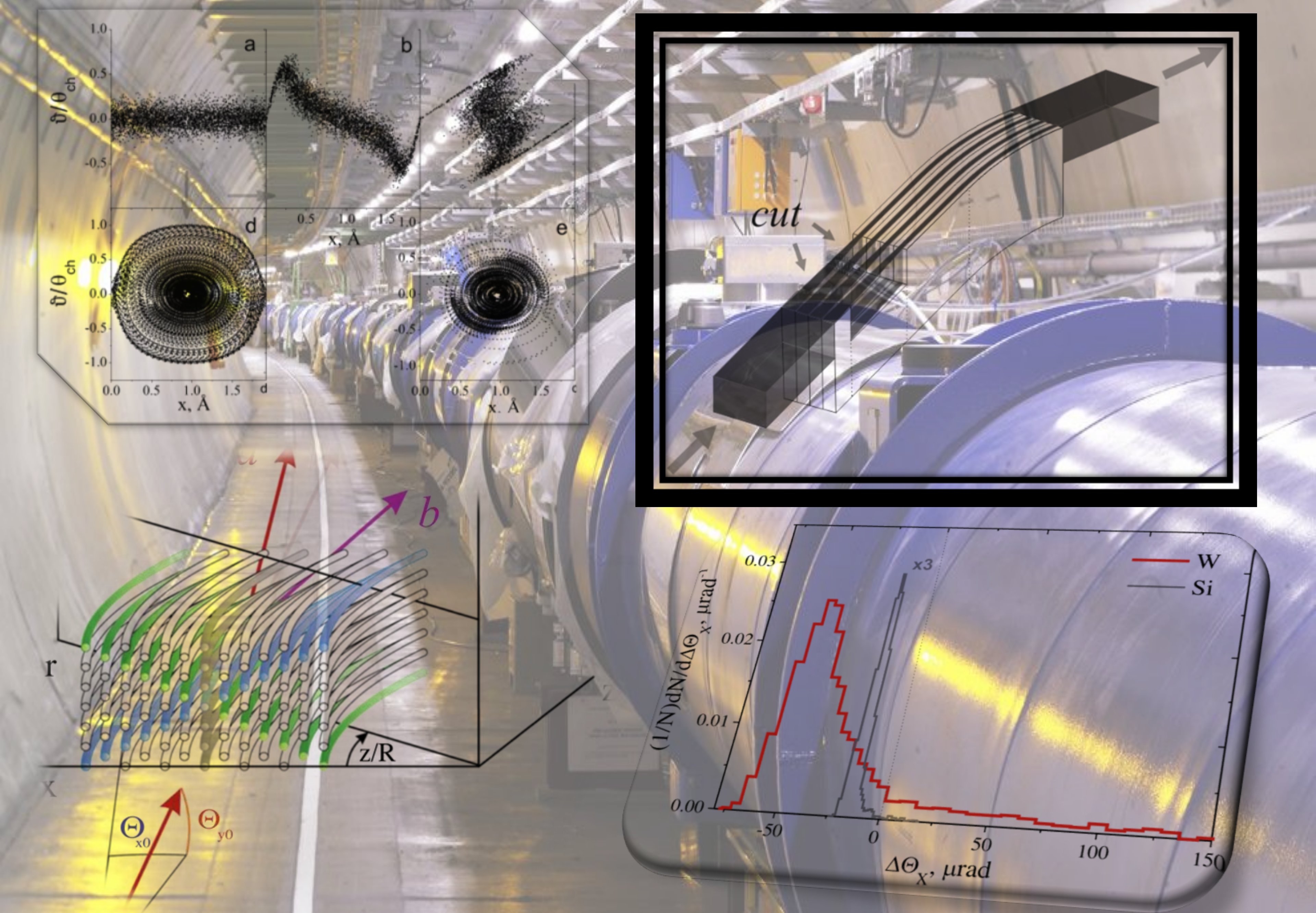




Overview of important effects for collimation

- **Channeling** profile: may be important only for a large negative miscut.
- **Volume reflection** profile is important for any crystal orientation.
- **Single coulomb scattering** at large angle (more than 1μrad) occurs with 0.25% and 0.7% of particles for channeling and amorphous orientation correspondingly. So, it may be important for any crystal orientation.
- **Fast dechanneling** occurs with about 1.3% of particles for channeling orientation. So, it may be also important.
- **Nuclear elastic, diffractive and inelastic scattering and diffractive energy losses** are essential for crystal collimation. So, the correct model for such effects is very important.
- **Ionization energy loss** map reflects almost all effects occurring in crystal. It may be important for heavy ions.
- **Escape of particles through the lateral surface of the crystal** involves about 0.25%, 2% and 7% for channeling, VR and amorphous orientation correspondingly. It is very important for collimation.
- **Miscut angle** can be important for the same reason as the previous effect for values θ_{ms}>10-20 μrad.

New effects for the collimation at the LHC



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A technique to improve crystal channeling efficiency of charged particles

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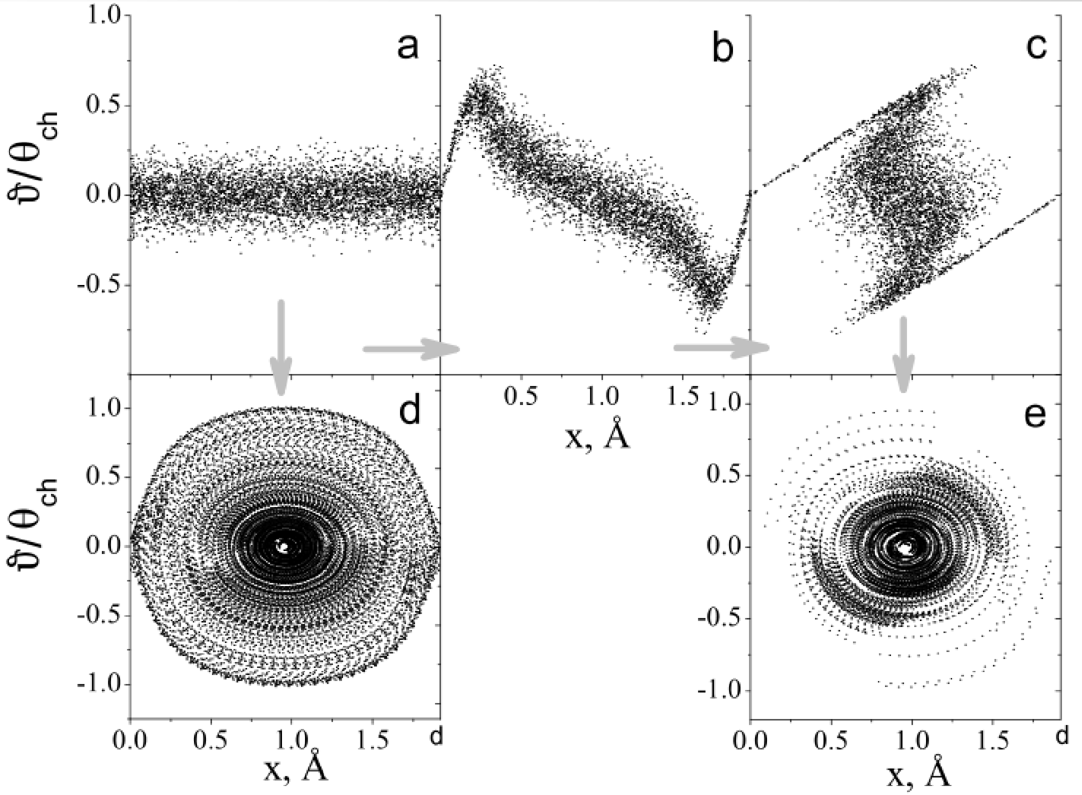
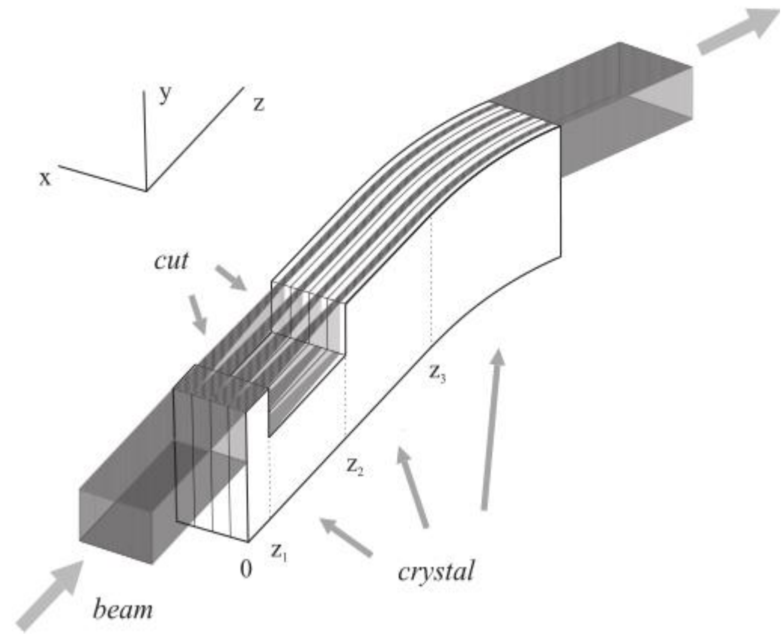
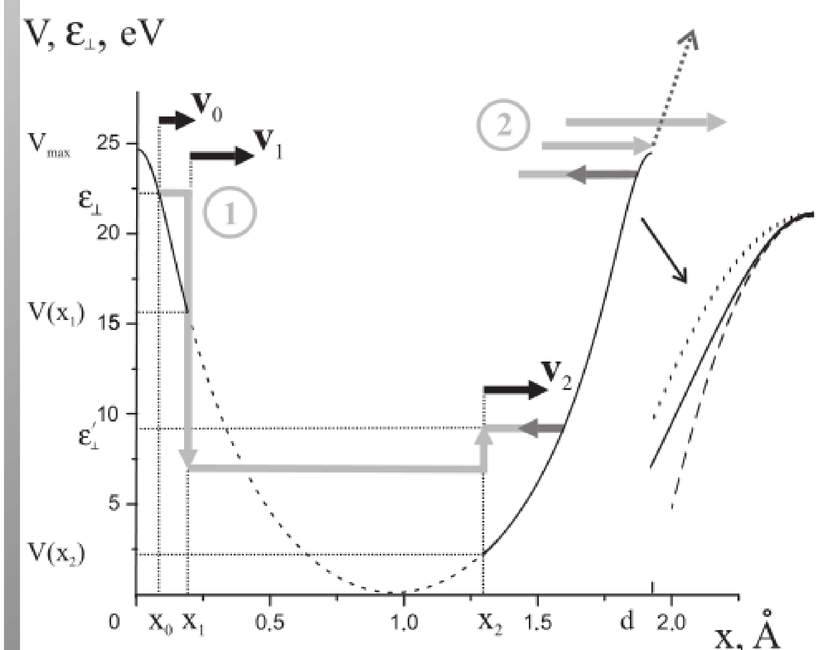


Proton "phase space" a) at $z = 0$, b) at $z = z_1$, c) at $z = z_2$ and e) at $z = z_2+\pi\nu_{\parallel}/2\omega$ in the cut presence and d) at $z = z_1+\pi\nu_{\parallel}/\omega$ in the absence of the latter





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A technique to improve crystal channeling efficiency of charged particles

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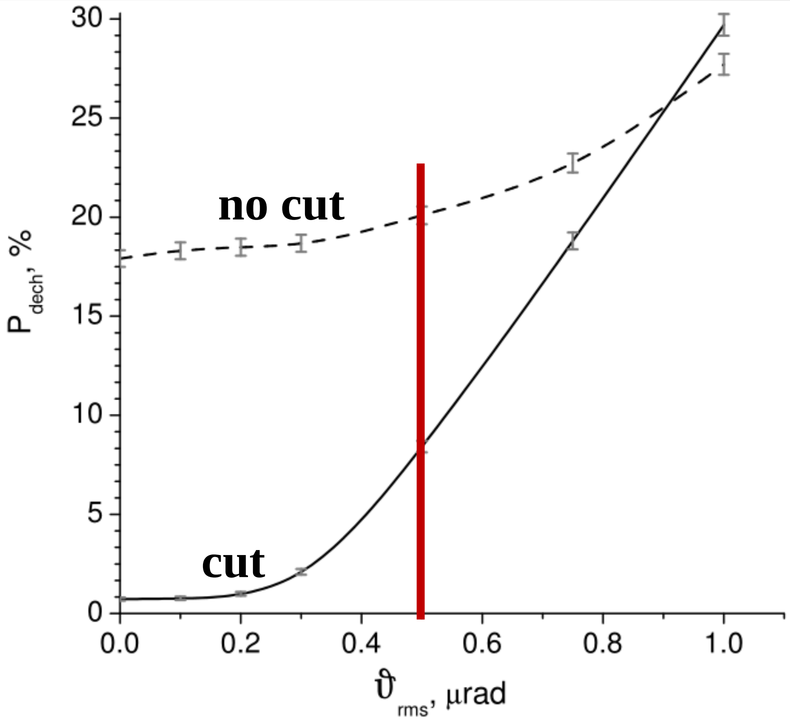
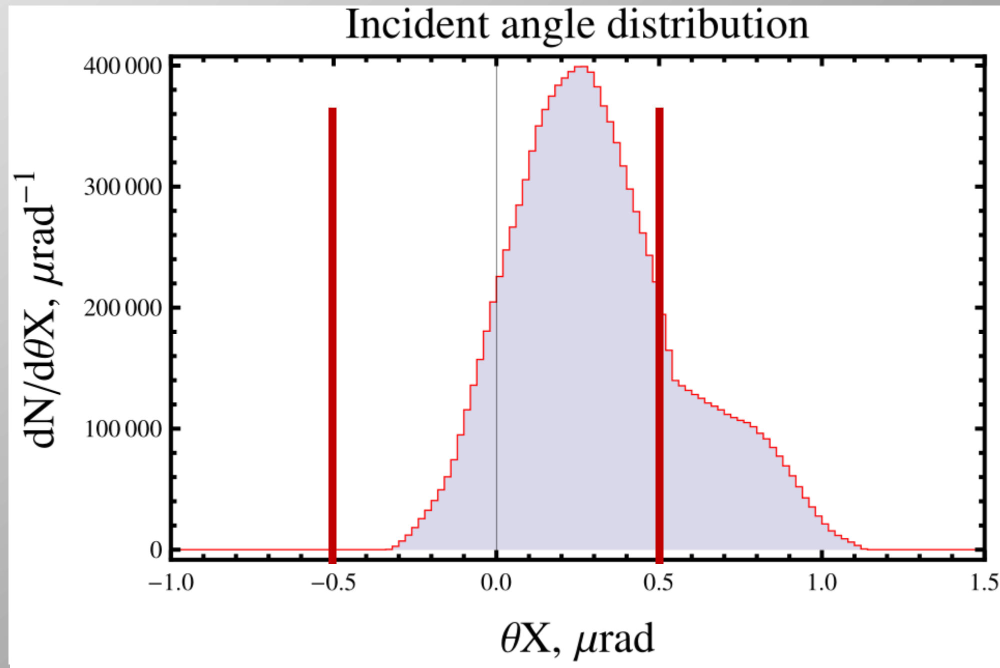
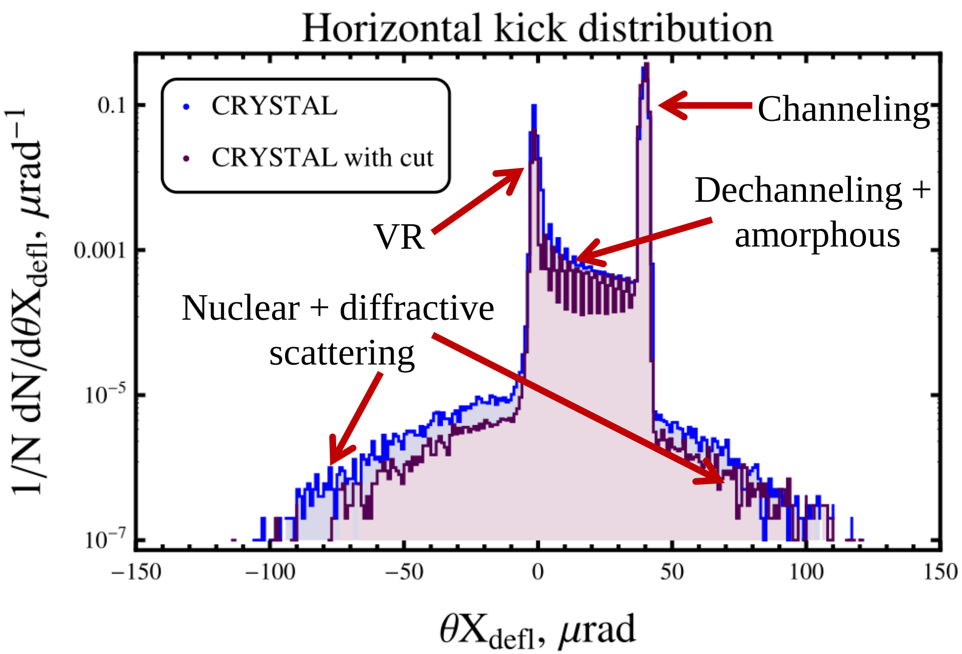


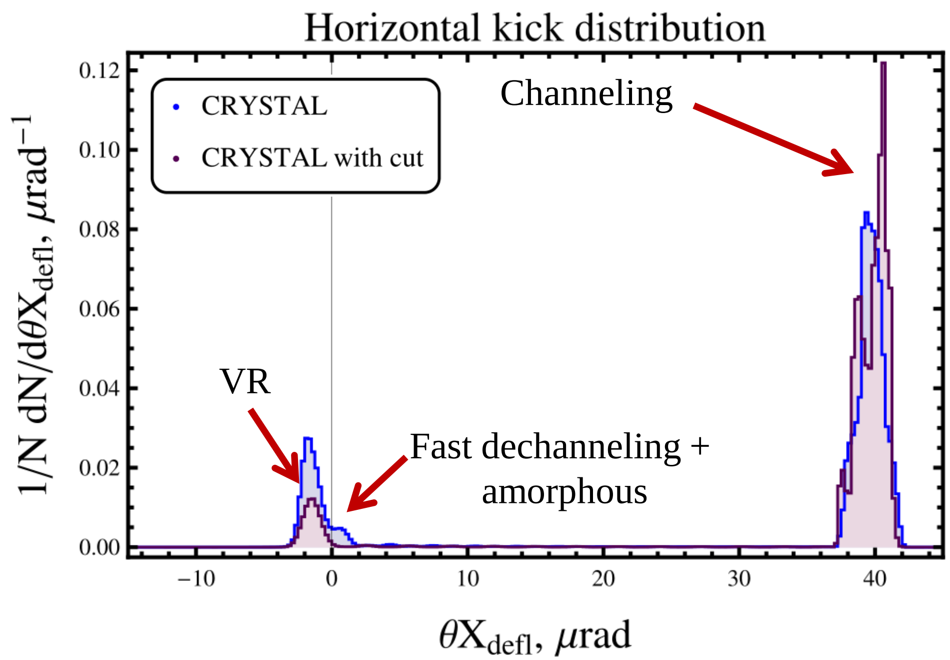
Dependence of the **7TeV** proton dechanneling probability in a 1 cm bent Si crystal on the r.m.s. incidence angle



Angular divergence of the beam is small enough for application of this technique.

A technique to improve crystal channeling efficiency for the LHC!





θb[μrad]-> l[mm] |	40		
		CRYSTAL	CRYSTAL-cut
3	CH	76.85±0.04%	90.25±0.03%
	DC	2.256±0.01%	1.504±0.010%
	VR	15.93±0.03%	7.73±0.03%
	NES	0.0543±0.0019%	0.0273±0.0014%
	DIFF	0.0321±0.0015%	0.0163±0.0010%
	ABS	0.191±0.004%	0.096±0.003%
	CS	4.687±0.018%	0.374±0.005%
	Time	i7 (4 cores): 1:09	i7 (4 cores): 0:53

Channeling efficiency increases by **13.5**%! Nuclear interactions decrease in **2** times!

Cut parameters: z_1=**17μm**; cut thickness z_2-z_1 **54μm** for the LHC energy. Quite real!

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J. Phys. D: Appl. Phys. **42** (2009) 165301 (6pp) — doi:10.1088/0022-3727/42/16/165301

Increase in probability of ion capture into the planar channelling regime by a buried oxide layer

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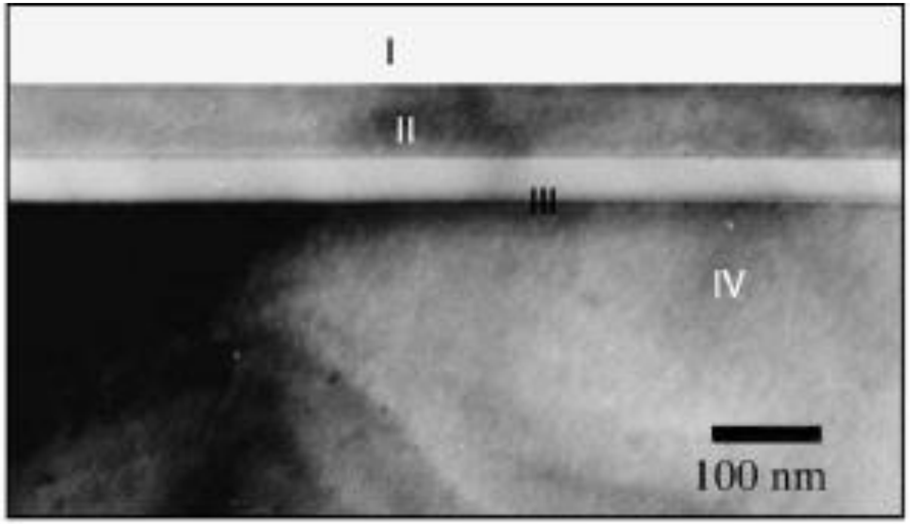
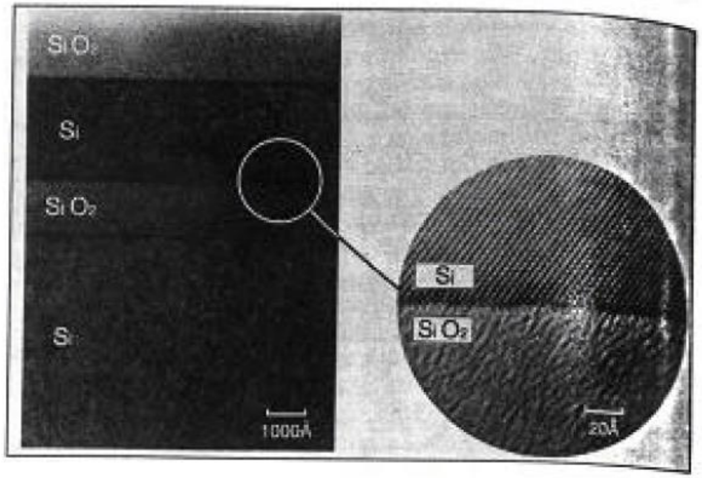
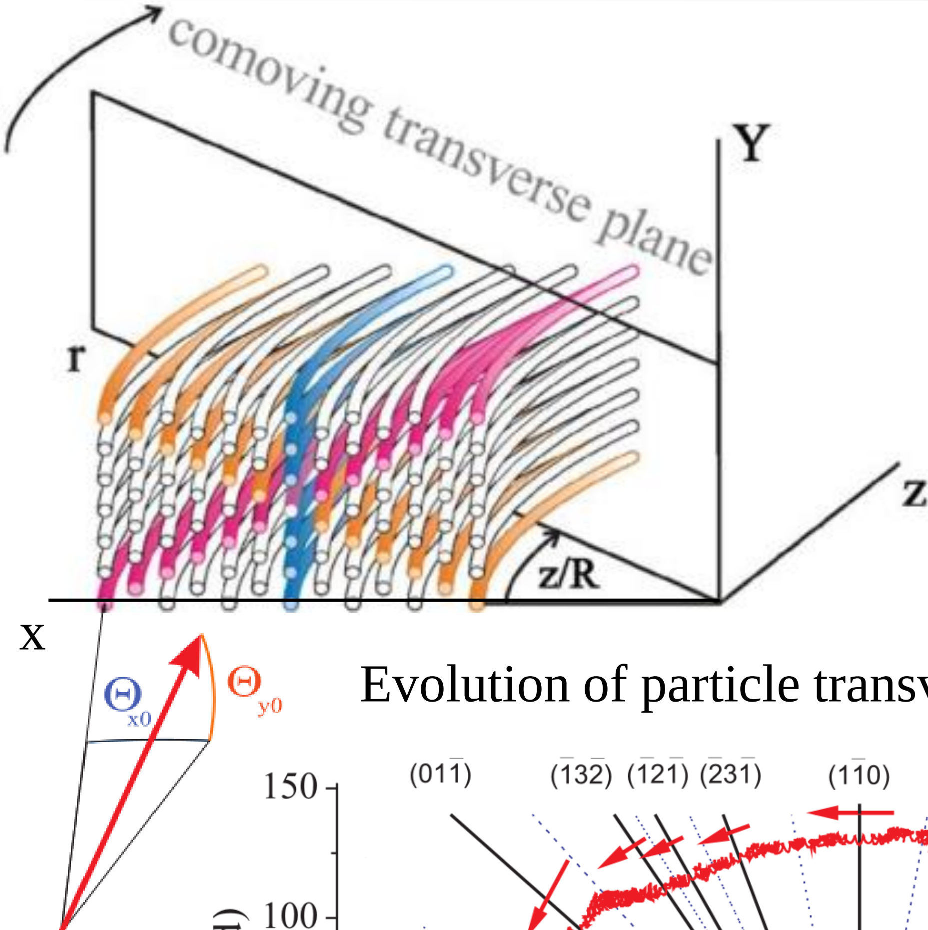
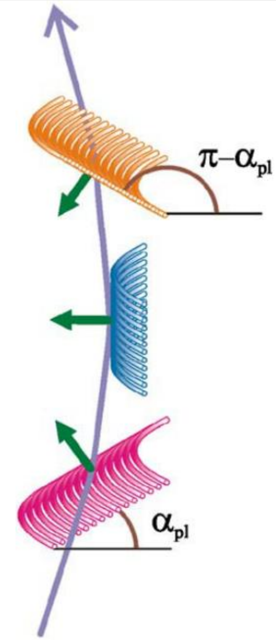
Cut parameters: the crystal layer before **17µm**; cut thickness **54µm** for the LHC energy. Quite real! Much simpler to make an amorphous layer instead of the cut.





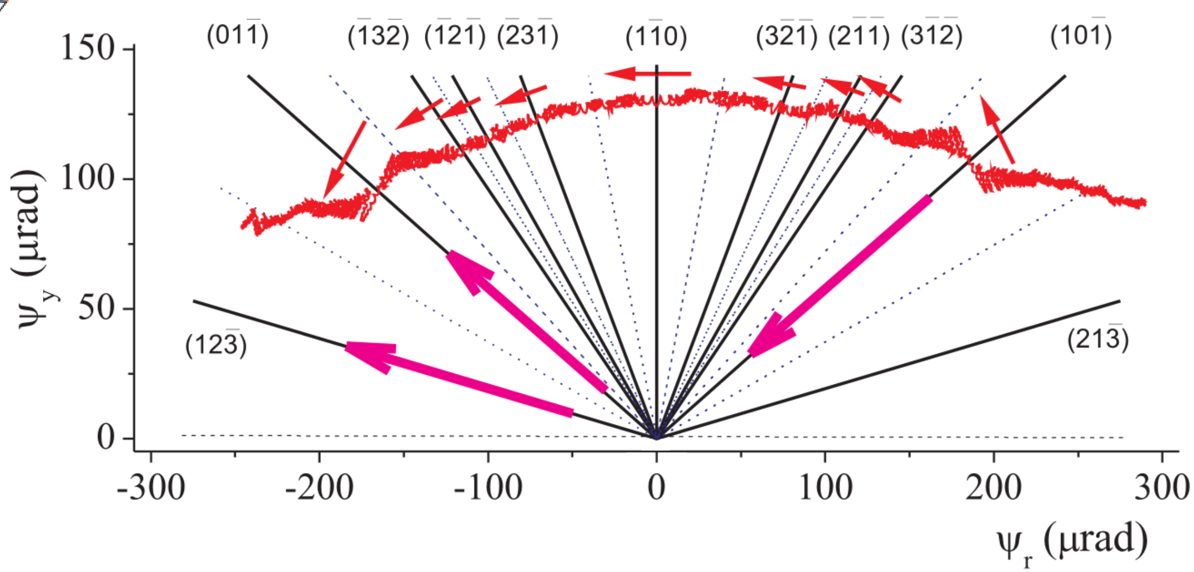
Multiple Volume Reflection in one bent crystal (MVROC)*





Axes form
many inclined
reflecting planes

Evolution of particle transverse velocity in the ry plane**



*V. Tikhomirov, PLB 655 (2007) 217;
V. Guidi, A. Mazzolari and V. Tikhomirov, JAP 107 (2010) 114908
**V.V. Tikhomirov, A.I. Sytov, NIM B 309 (2013) 109–114.

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Original Russian Text © A.G. Afonin, V.T. Baranov, M.K. Bulgakov, I.S. Voinov, V.N. Gorlov, I.V. Ivanova, D.M. Krylov, A.N. Lun'kov, V.A. Maisheev, S.F. Reshetnikov, D.A. Savin, E.A. Syshchikov, V.I. Terekhov, Yu.A. Chesnokov, P.N. Chirkov, I.A. Yazynin, 2011, published in Pis'ma v Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, 2011, Vol. 93, No. 4, pp. 205–208.

Collimation of the Circulating Beam in the U-70 Synchrotron by Means of the Reflection of Particles in Crystals with Axial Orientation

A. G. Afonin, V. T. Baranov, M. K. Bulgakov, I. S. Voinov, V. N. Gorlov, I. V. Ivanova, D. M. Krylov, A. N. Lun'kov, V. A. Maisheev, S. F. Reshetnikov, D. A. Savin, E. A. Syshchikov, V. I. Terekhov, Yu. A. Chesnokov, P. N. Chirkov, and I. A. Yazynin

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Observation of multiple volume reflection by different planes in one bent silicon crystal for high-energy negative particles

W. SCANDALE[1], A. VOMIERO[2], E. BAGLI[3], S. BARICORDI[3], P. DALPIAZ[3], M. FIORINI[3], V. GUIDI[3], A. MAZZOLARI[3], D. VINCENZI[3], R. MILAN[4], G. DELLA MEA[5], E. VALLAZZA[6], A. G. AFONIN[7], YU. A. CHESNOKOV[7], V. A. MAISHEEV[7], I. A. YAZYNIN[7], A. D. KOVALENKO[8], A. M. TARATIN[8(a)], A. S. DENISOV[9], YU. A. GAVRIKOV[9], YU. M. IVANOV[9], L. P. LAPINA[9], L. G. MALYARENKO[9], V. V. SKOROBOGATOV[9], V. M. SUVOROV[9], S. A. VAVILOV[9], D. BOLOGNINI[10,11], S. HASAN[10,11], A. MATTERA[10,11], M. PREST[10,11] and V. V. TIKHOMIROV[12]

Physics Letters B 682 (2009) 274–277

First observation of multiple volume reflection by different planes in one bent silicon crystal for high-energy protons

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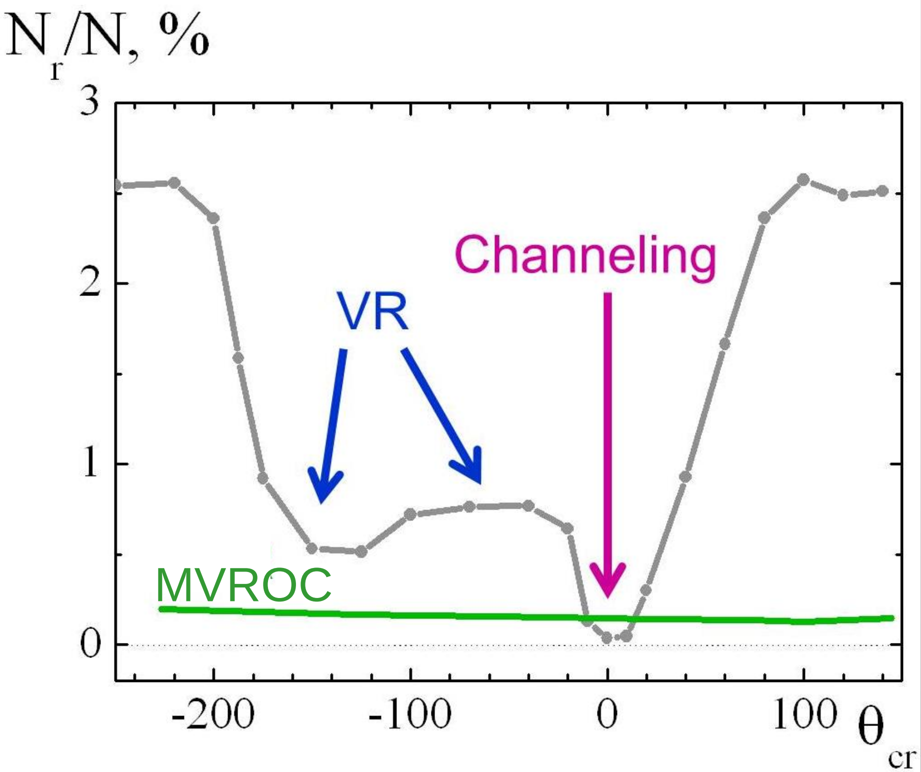
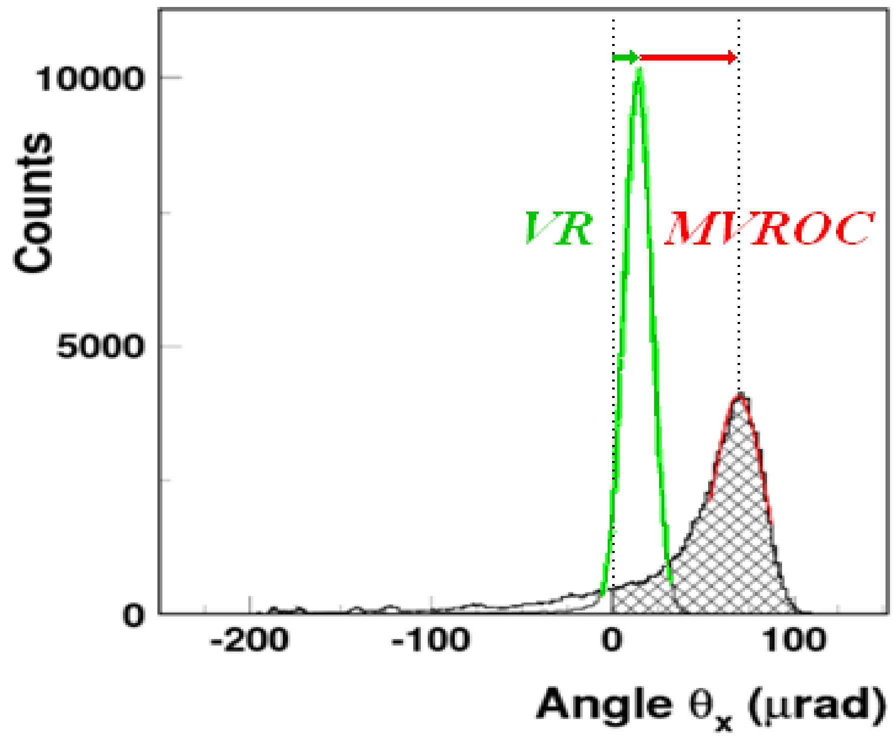
Applications of MVROC

MVROC for
the UA9 experiment



First MVROC observation

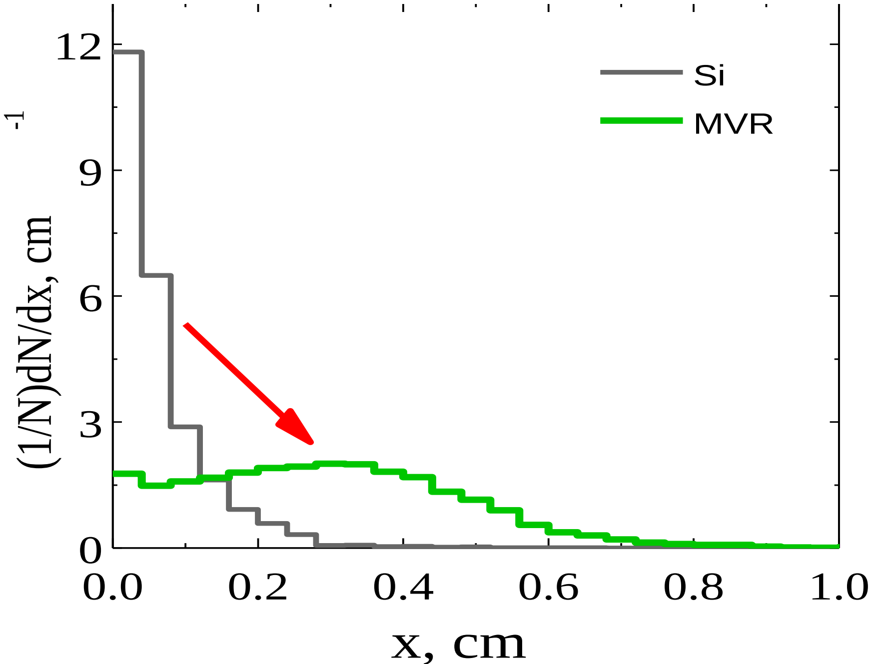
W. Scandale et al, PLB 682(2009)274



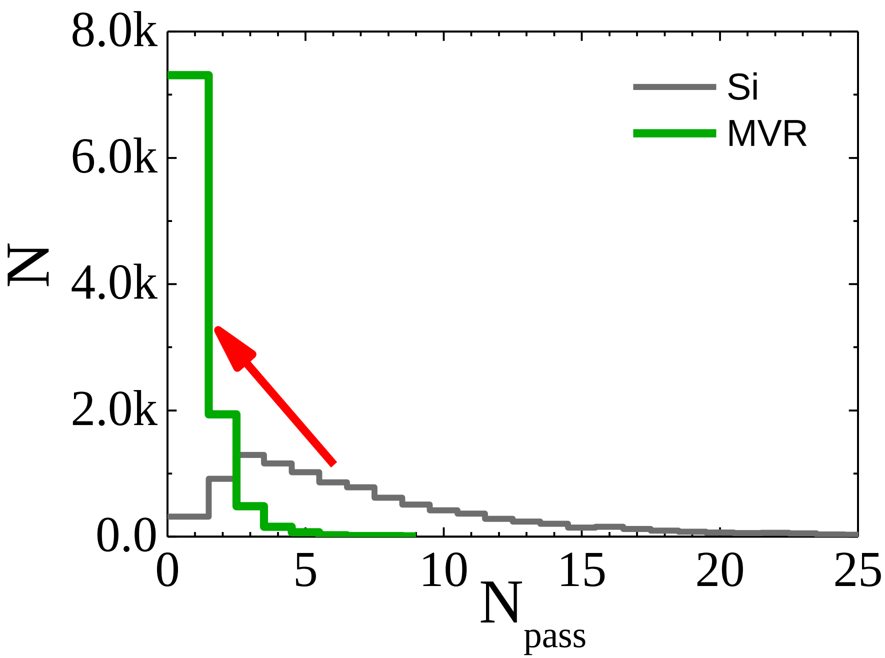
MVROC indeed increases reflection angle ***5 times***

Distributions of the impact parameter and number of the crystal transversals in usual Si crystal and crystal in MVR orientation

Impact parameter distribution



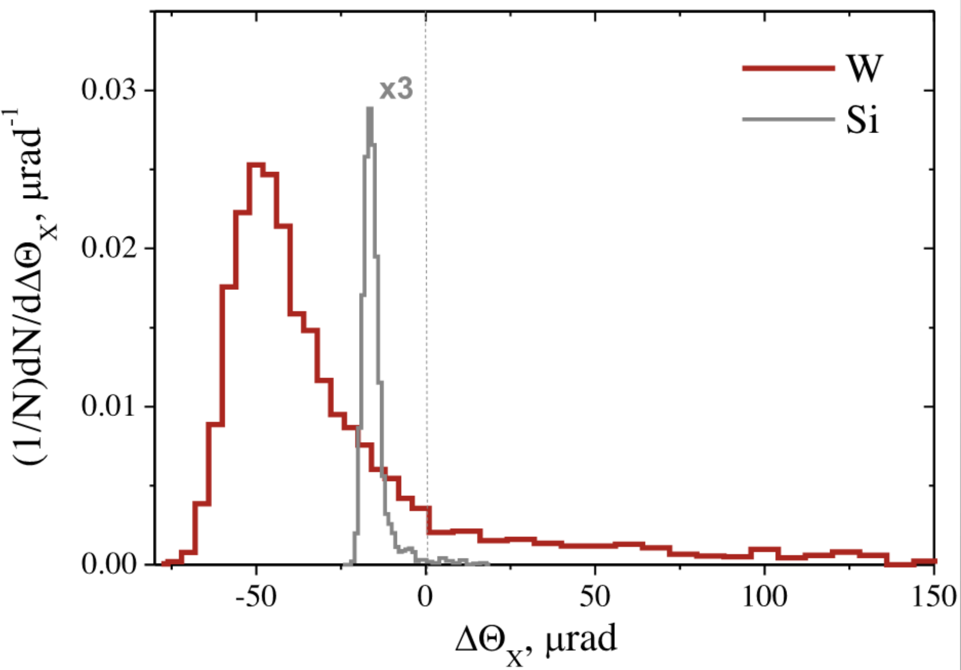
Crystal passages number distribution



MVR both increases the impact parameter and decreases the crystal transversals number at rough alignment

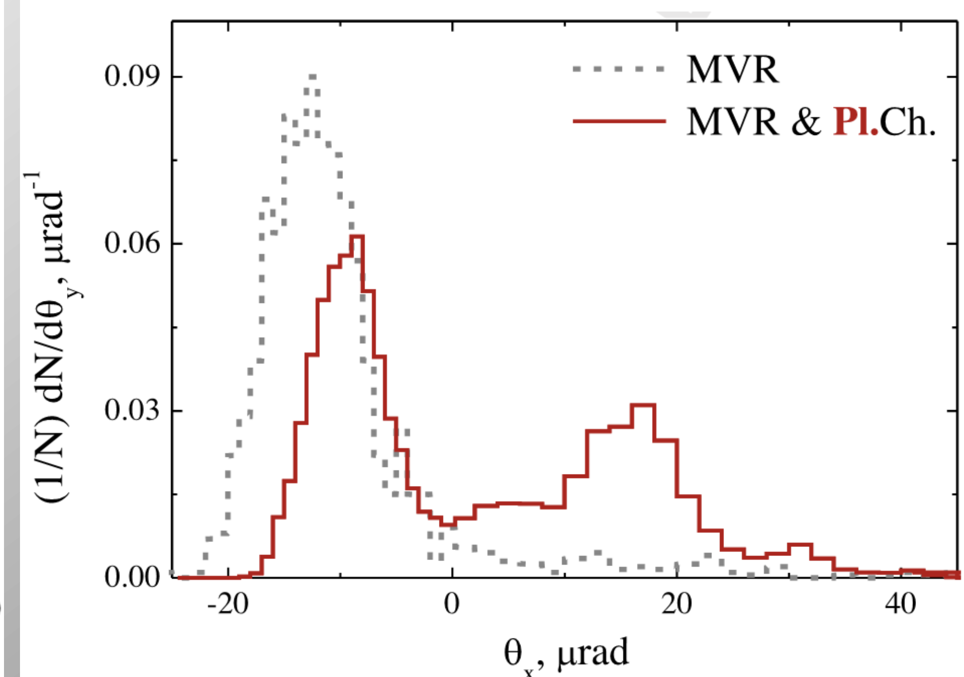
Modifications of MVROC*

Angular distributions of 7 TeV protons behind 5 mm **W** <111> (left peak) and **Si** <111> (right peak) crystals for MVROC deflection. $\delta\Theta_{X,Y} = 4$ µrad in both cases.



The MVROC in tungsten crystal could deflect a majority of halo particles onto secondary collimators at the **first passage** through the primary crystalline collimator.

Angular distributions of 7 TeV protons behind 5mm Si <111> crystal. Dashed line – for the unperturbed by channeling **MVROC** and solid line for **MVROC accompanied by planar channeling**. $\delta\Theta_{X,Y} = 4$ µrad in both cases .



Combined action of the MVROC and planar channeling increases the r.m.s. angle nearly **three-four** times.

*V.V. Tikhomirov, A.I. Sytov, NIM B 309 (2013) 109–114.

Conclusions

- Systematic comparison of CRYSTAL-channeling with different crystal routine was performed.
- I found some difference related to the physics treatment of the particles dynamics in the crystal:
  - dechanneling peaks well correlated with channeling oscillations;
  - channeling/VR profile;
  - volume capture;
  - single coulomb and nuclear elastic scattering;
  - correlation between horizontal kick and ionization losses;
  - simulation of escape through the crystal lateral surface.
- Crystal cut can considerably increase the channeling efficiency and decrease inelastic losses in crystal. Additionally it can be the first experimental test of this effect.
- MVROC in Tungsten crystal and combined action of MVROC and channeling are also nice effects for experimental test at the LHC.

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Thank you for attention!