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New Possibilities to Facilitate Collimation of Both Positively and Negatively Charged Particle Beams by Crystals

"Channeling 2008" *October 28, 2008 Erice Italy*

Outline

Introduction

Channeling probability increase at high energies by the ***crystal cut***

Multiple ***volume reflection by crystal axes*** in a single crystal

Conclusions

The LHC upgrade need

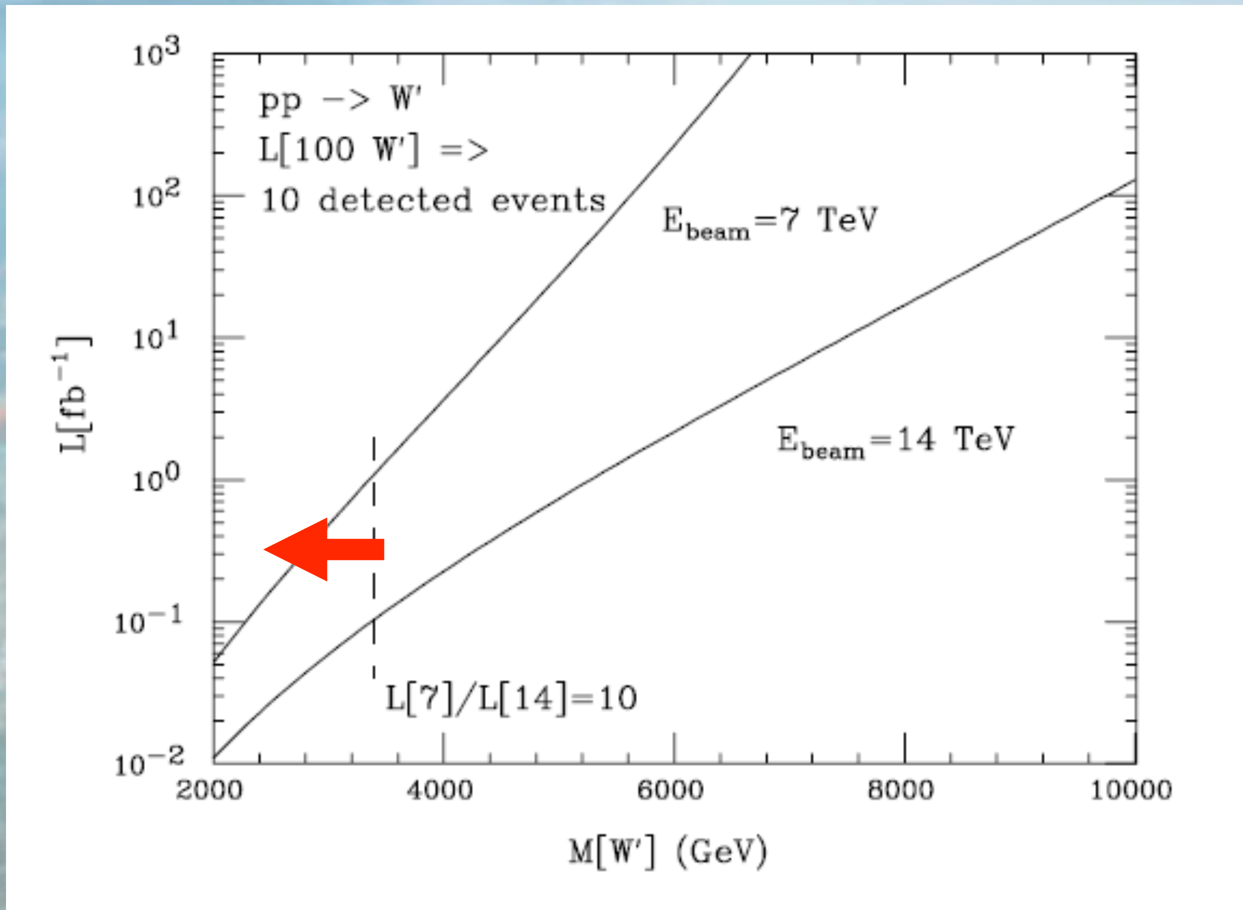
Fifteen years of planning and R&D, followed by over 10 years of construction, should be followed by a comparable period of the LHC exploitation.

Luminosity upgrade: $L = 10^{34}\,cm^{-2}s^{-1} \times 10$

Energy upgrade: $\varepsilon = 7\,TeV \times 2$

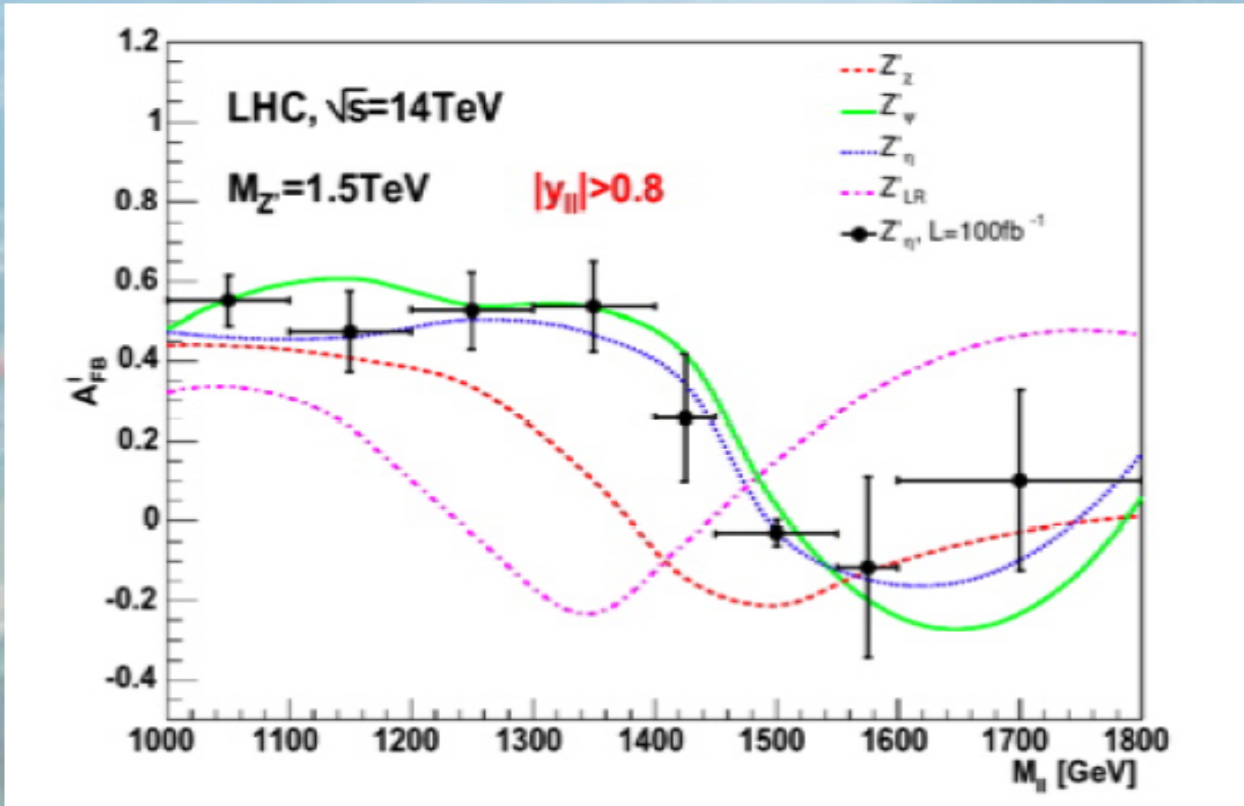
What is better?

Luminosity upgrade in more efficient at M < 3.5 TeV

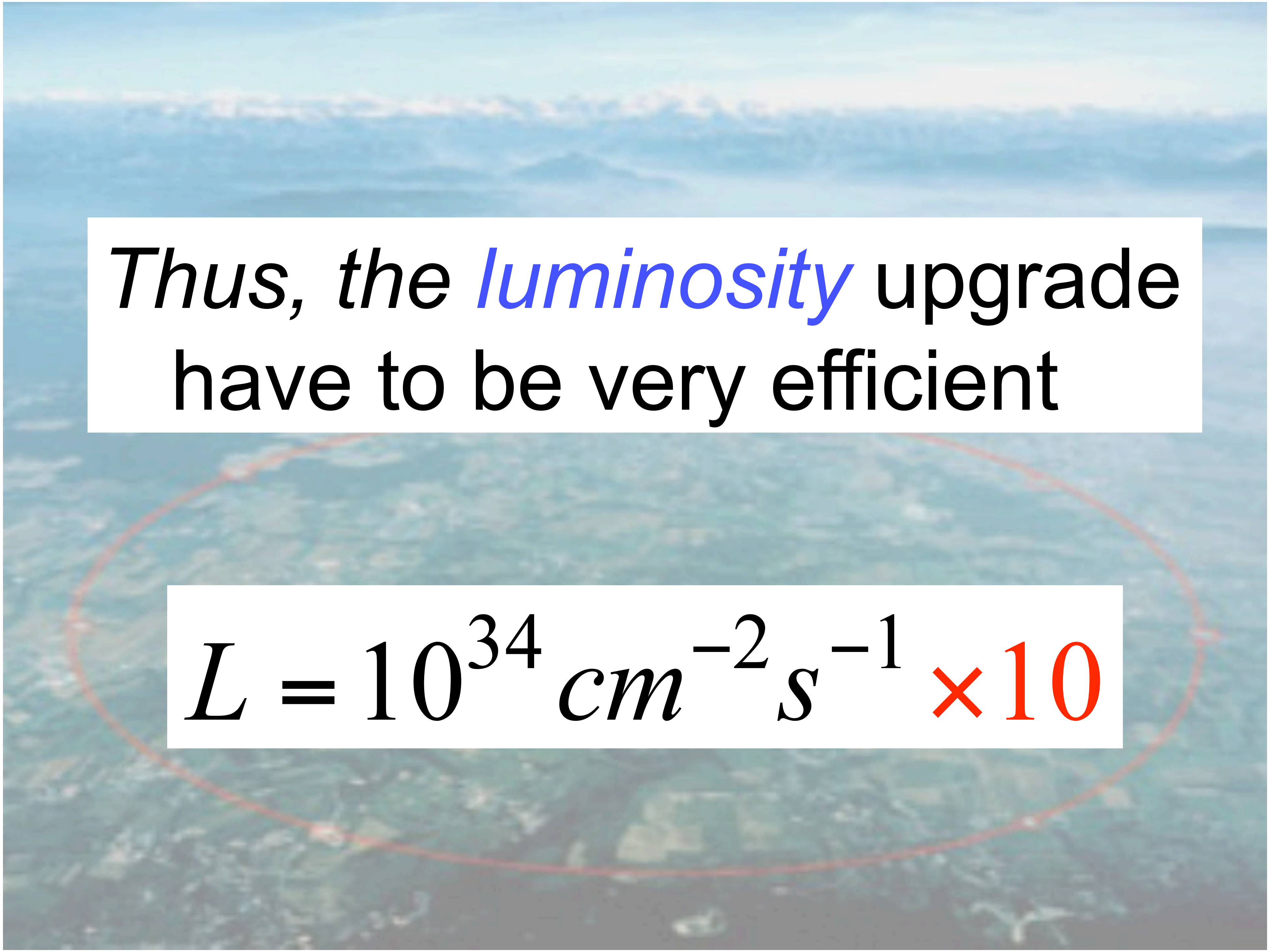


Integrated luminosity required to produce 100 W' events in pp collisions at $\sqrt{S} = 14$ and 28 TeV.

Statistics is too low for a clear separation among possible models at integrated luminosity of 100fb^{-1}



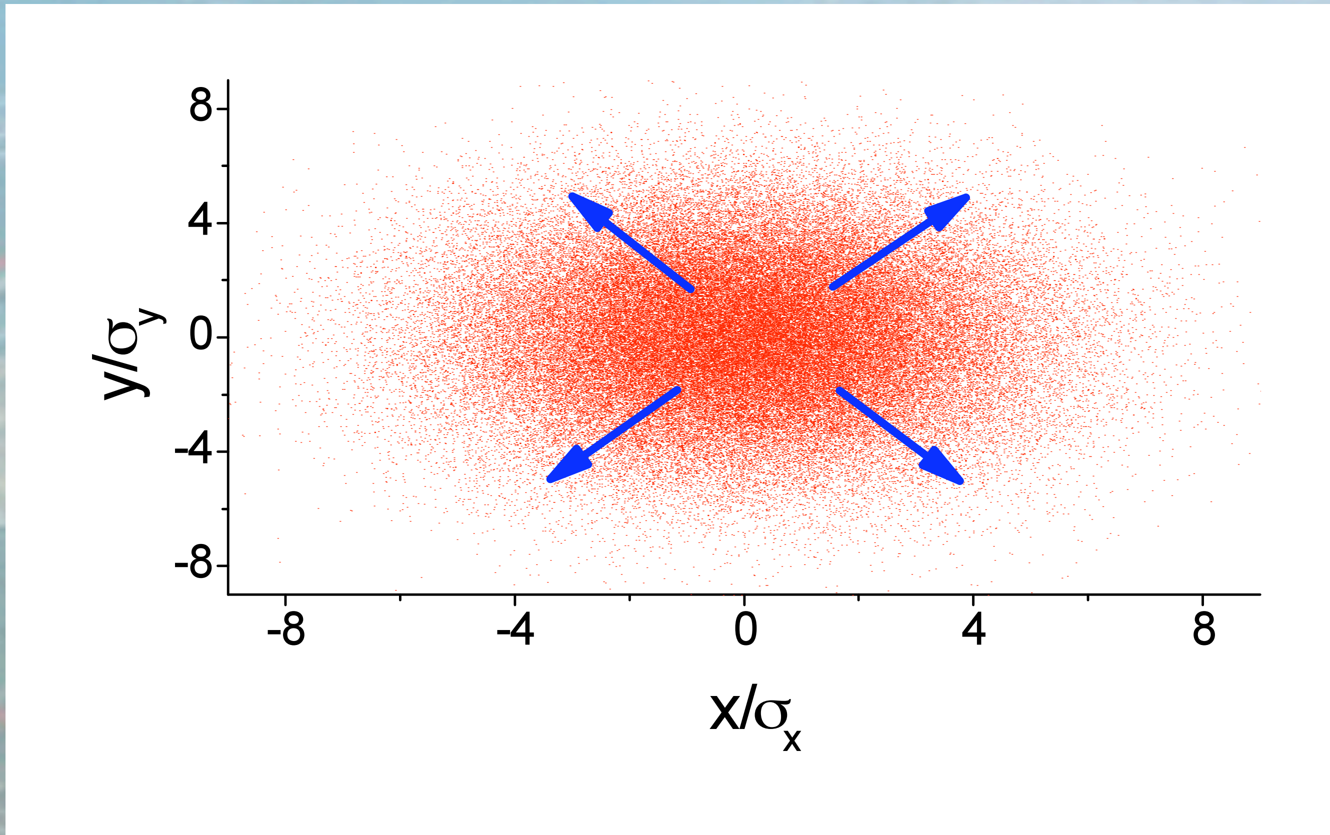
Average leptonic forward-backward asymmetry, as a function of the dimuon invariant mass, for various Z' models.



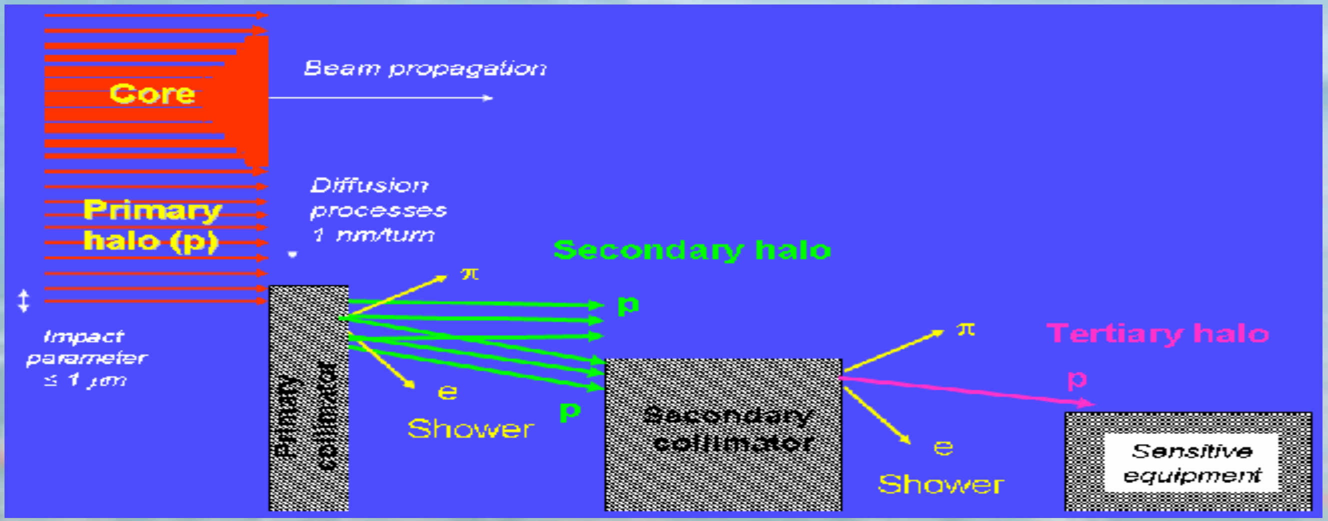
Thus, the luminosity upgrade have to be very efficient

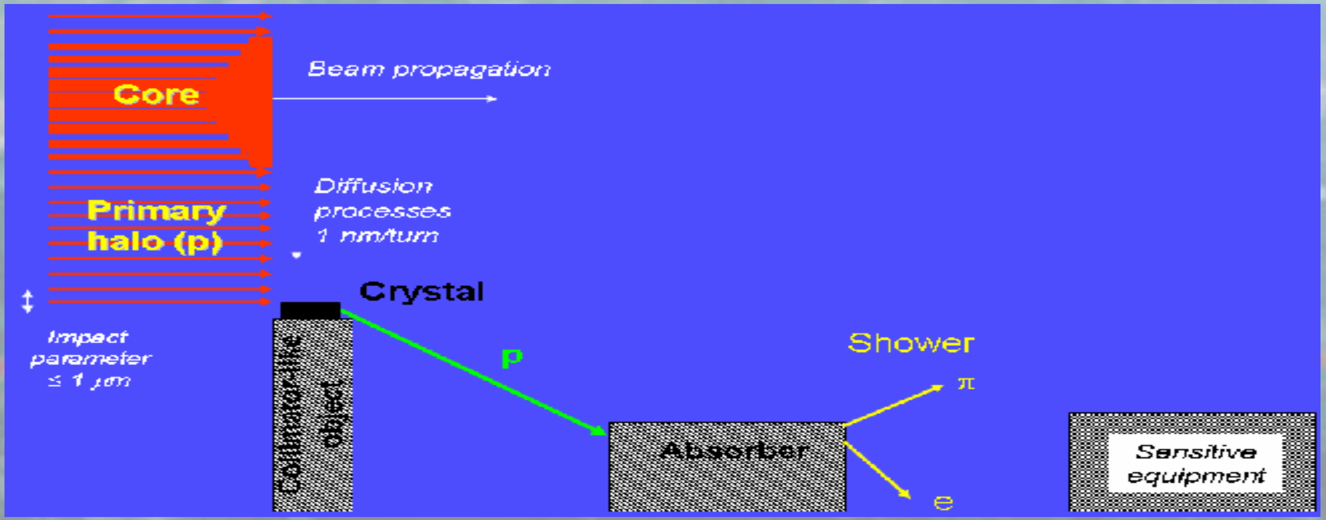
$$L = 10^{34}\,cm^{-2}s^{-1} \times 10$$

However luminosity increase will intensify the beam **halo** formation

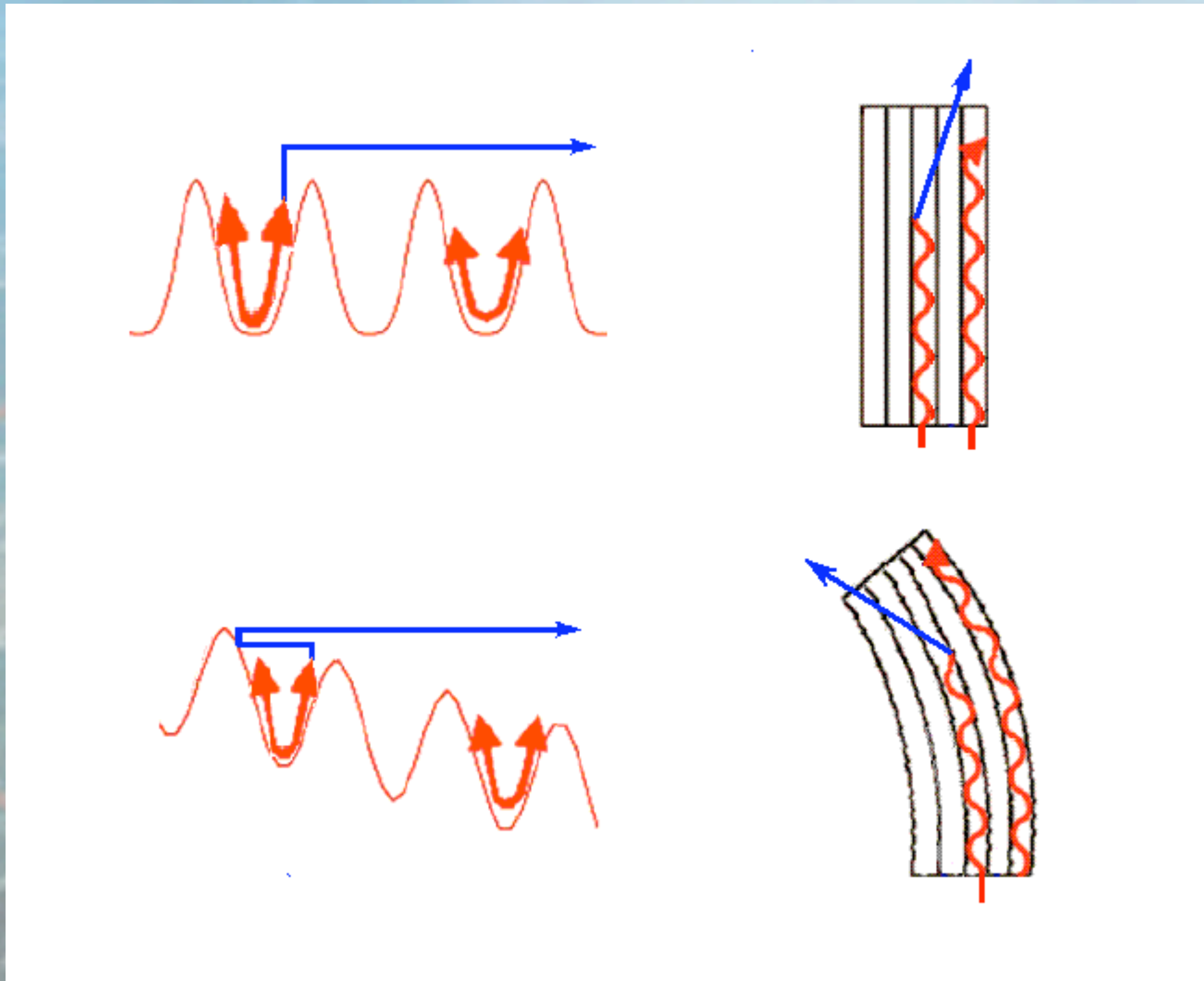


Crystals improve collimation efficiency

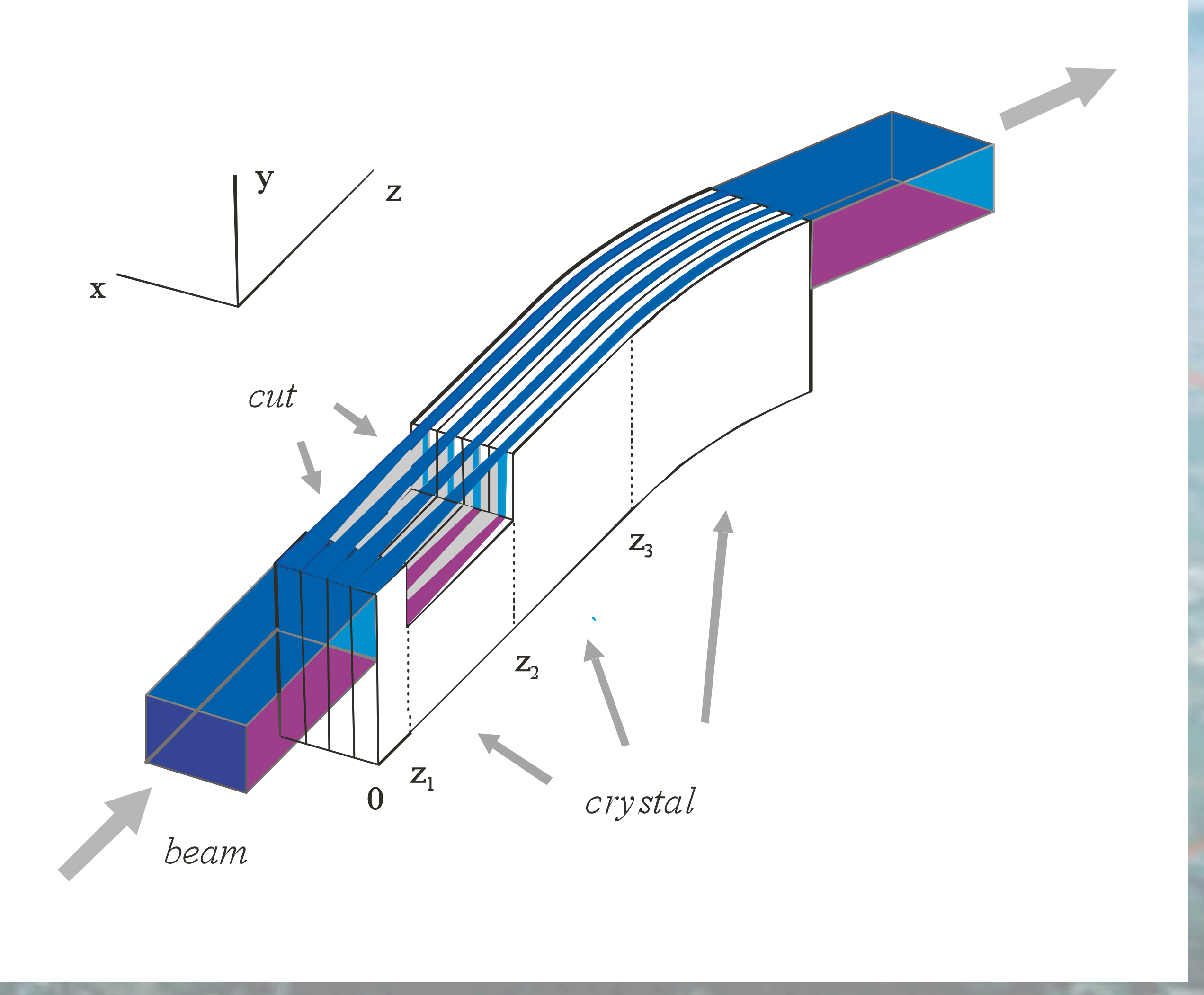




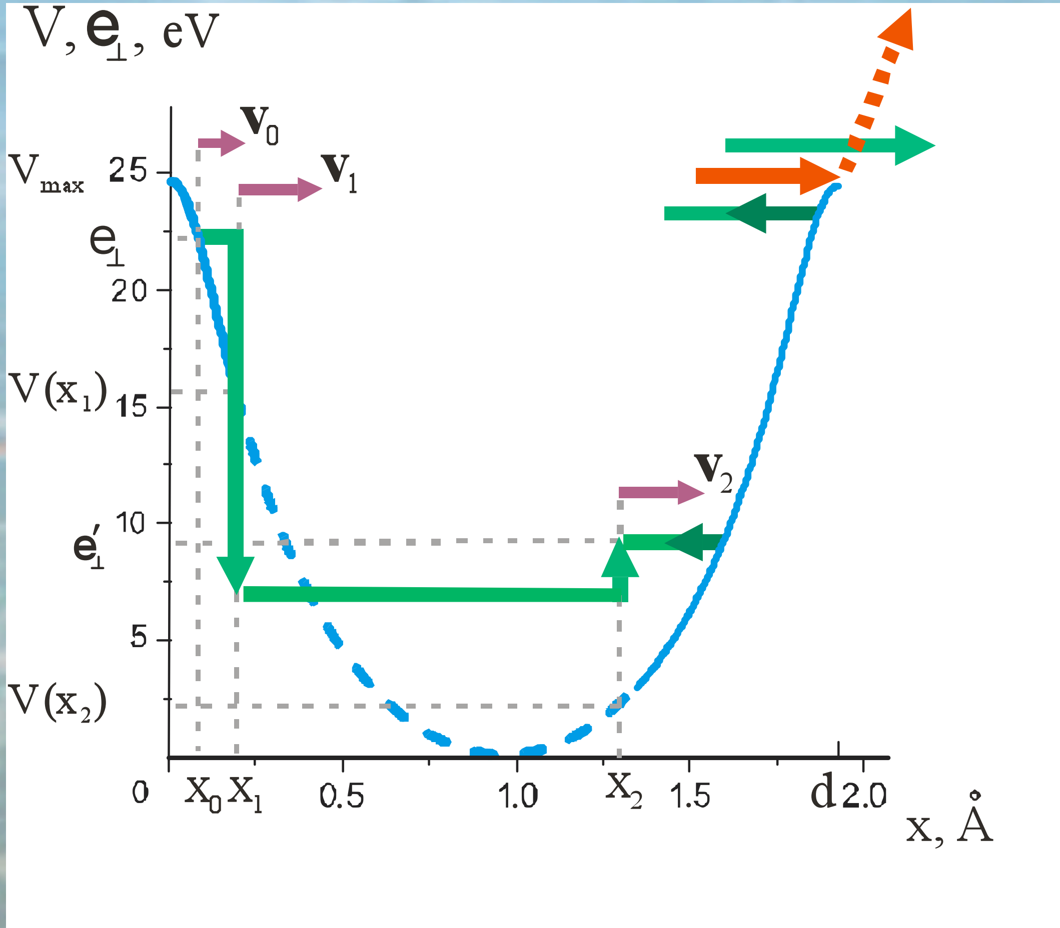
At least 15% of particles ***dechannel***
due to incoherent scattering



The capture probability can be increased **by a plane cut** V.V.*Tikhomirov, JINST, 2(2007)P08006*

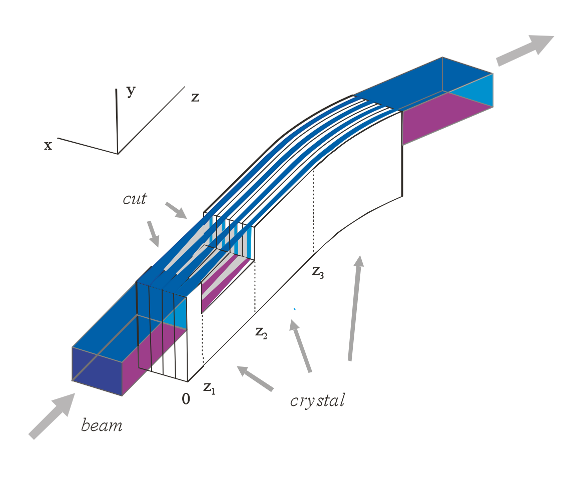


Transverse energy reduction *by the cut - 1*

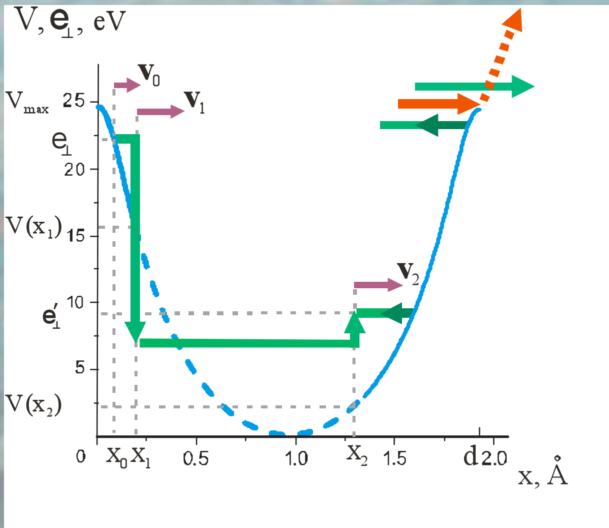


The cut diminishes the potential energy V(x) conserving the transverse kinetic energy

Particle motion in the cut region $0 < z < z_2$



$$V(x)=\frac{k}{2}\left(x-\frac{d}{2}\right)^2,\quad z=\upsilon_{\|}\cdot t,\quad \omega=\sqrt{\frac{k}{\varepsilon}}.$$



$z=0$

$x_0 \equiv x(0)=d/2+a_0$

$\upsilon_0 \equiv \upsilon_x(0)$

$$\varepsilon_{\perp 0}=\varepsilon\frac{\upsilon_0^2}{2}+V(x_0)=\varepsilon\frac{\upsilon_0^2}{2}+k\frac{a_0^2}{2}$$

$z=z_1$

$x_1 \equiv x(t_1)=d/2+a_0\cdot cos(\omega t_1)+\upsilon_0\cdot sin(\omega t_1)$

$\upsilon_1 \equiv \upsilon_x(t_1)=-a_0\omega\cdot sin(\omega t_1)+\upsilon_0\omega\cdot cos(\omega t_1)$

$$\varepsilon_{\perp 1}=\varepsilon\frac{\upsilon_1^2}{2}+V(x_1)\Rightarrow\varepsilon\frac{\upsilon_1^2}{2}+0$$

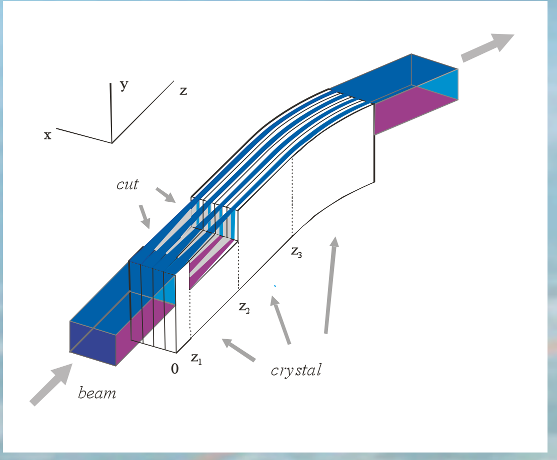
$z=z_2$

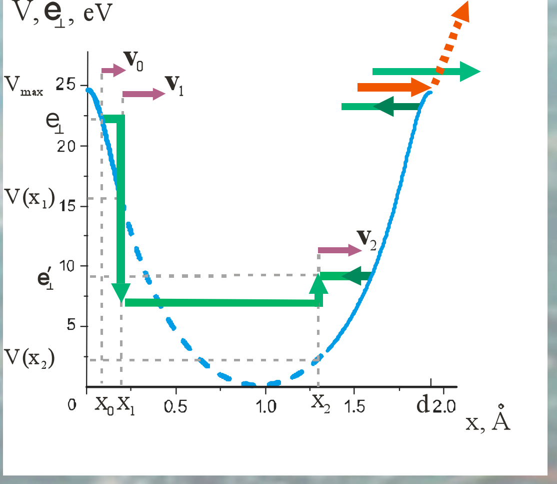
$x_2 \equiv x(t_2)=x_1+\upsilon_1\cdot(t_2-t_1)$

$\upsilon_2 \equiv \upsilon_x(t_2)=\upsilon_1$

$$\varepsilon_{\perp 2}=\varepsilon\frac{\upsilon_1^2}{2}+V(x_2)\le\frac{1}{2}\varepsilon_{\perp 0}$$

To the optimization of the cut coordinates $z_{1,2}$





$$\varepsilon_{\perp 2} = \varepsilon\frac{\upsilon_1^2}{2} + V(x_2) \equiv A\upsilon_0^2 + B\upsilon_0 a_0 + Ca_0^2$$

$$= \frac{\varepsilon}{2}\left\{1 + \omega(t_2 - t_1)\left[2cos(\omega t_1)sin(\omega t_1) + \omega(t_2 - t_1)cos^2(\omega t_1)\right]\right\}\upsilon_0^2$$

$$+ \sqrt{k\varepsilon}\cdot\omega(t_2 - t_1)\left\{\left[cos^2(\omega t_1) - sin^2(\omega t_1)\right] - \omega(t_2 - t_1)cos(\omega t_1)sin(\omega t_1)\right\}\upsilon_0 a_0$$

$$+ \frac{k}{2}\left\{1 - \omega(t_2 - t_1)\left[2cos(\omega t_1)sin(\omega t_1) - \omega(t_2 - t_1)sin^2(\omega t_1)\right]\right\}a_0^2$$

$$B = 0 \quad \Rightarrow$$

$$z_2 = z_1 + 2\cdot ctg(2\omega t_1)\upsilon_{\|}/\omega$$

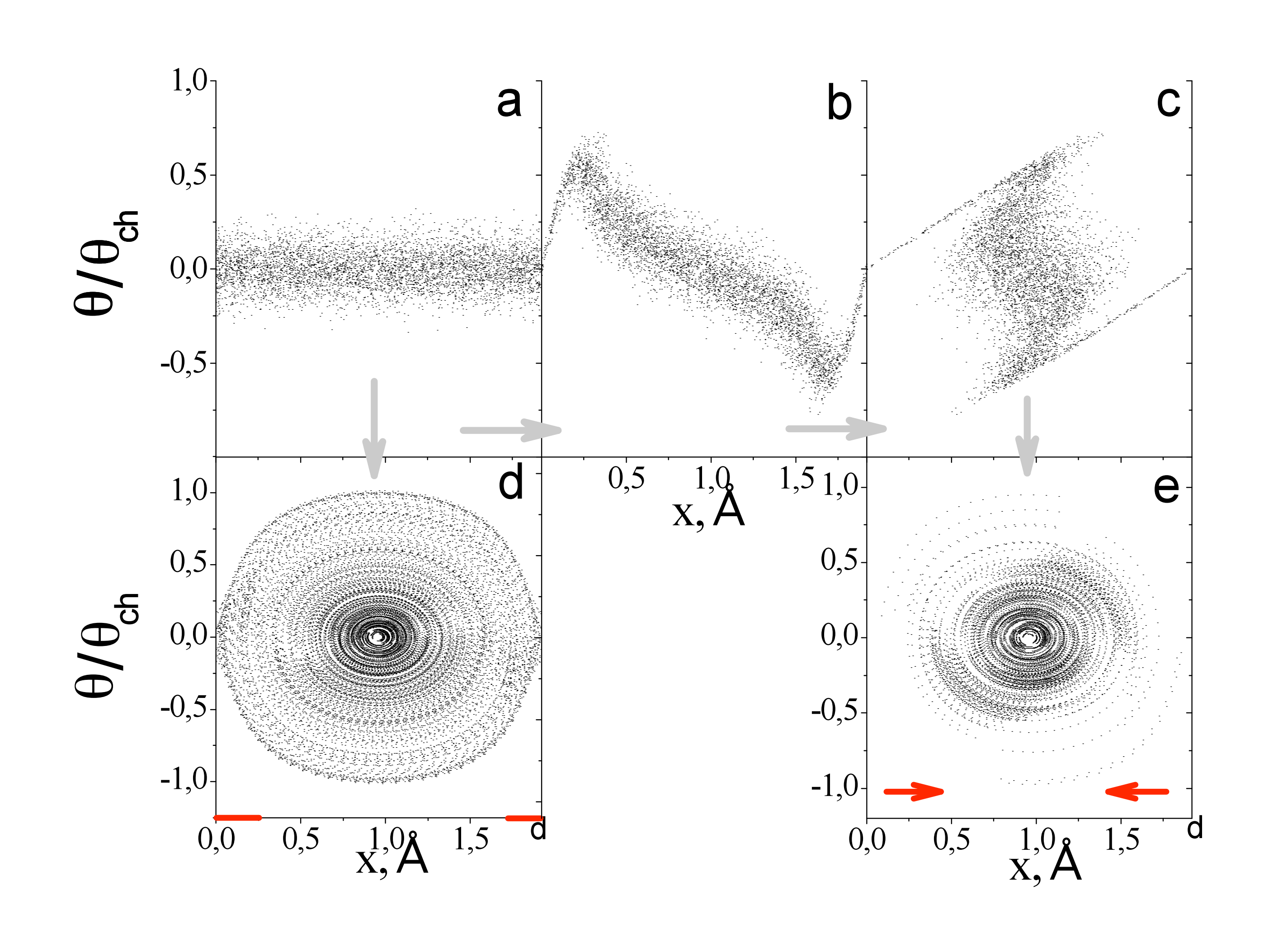
$$\varepsilon_{\perp 2} = \varepsilon\frac{\upsilon_0^2}{2}ctg^2(\omega t_1) + k\frac{a_0^2}{2}tg^2(\omega t_1) \quad \sim \quad \frac{a}{y} + b\cdot y \quad \Rightarrow$$

$$z_1 = \frac{\upsilon_{\|}}{\omega}arctan\sqrt{\frac{\vartheta_0}{\theta(a_0)}}, \quad \theta(a_0) \equiv \frac{\sqrt{2V(a_0)/\varepsilon}}{\upsilon_{\|}/c}, \quad V(a_0) = \frac{1}{2}ka_0^2.$$

$$\left(\varepsilon_{\perp 2}\right)_{min} = 2\frac{\vartheta_0}{\theta(a_0)}V(a_0) \quad \Rightarrow \quad \vartheta_0 < \frac{1}{4}\sqrt{2V(a_0)/\varepsilon}$$

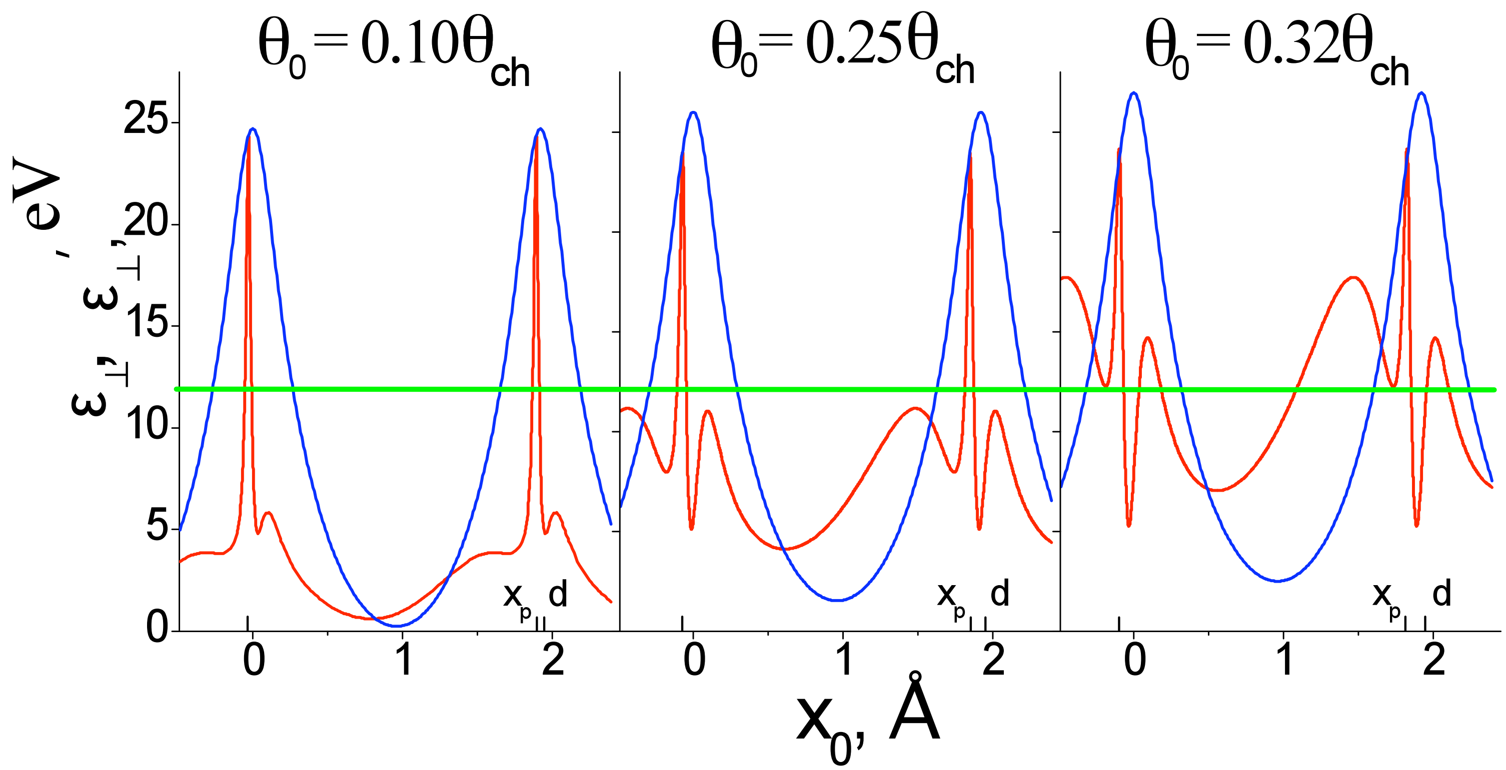
$$z_2/z_1 = 4.235 \quad at \quad \vartheta_0 = 0.25\sqrt{2V(a_0)/\varepsilon}$$

Phase space transformation by the cut



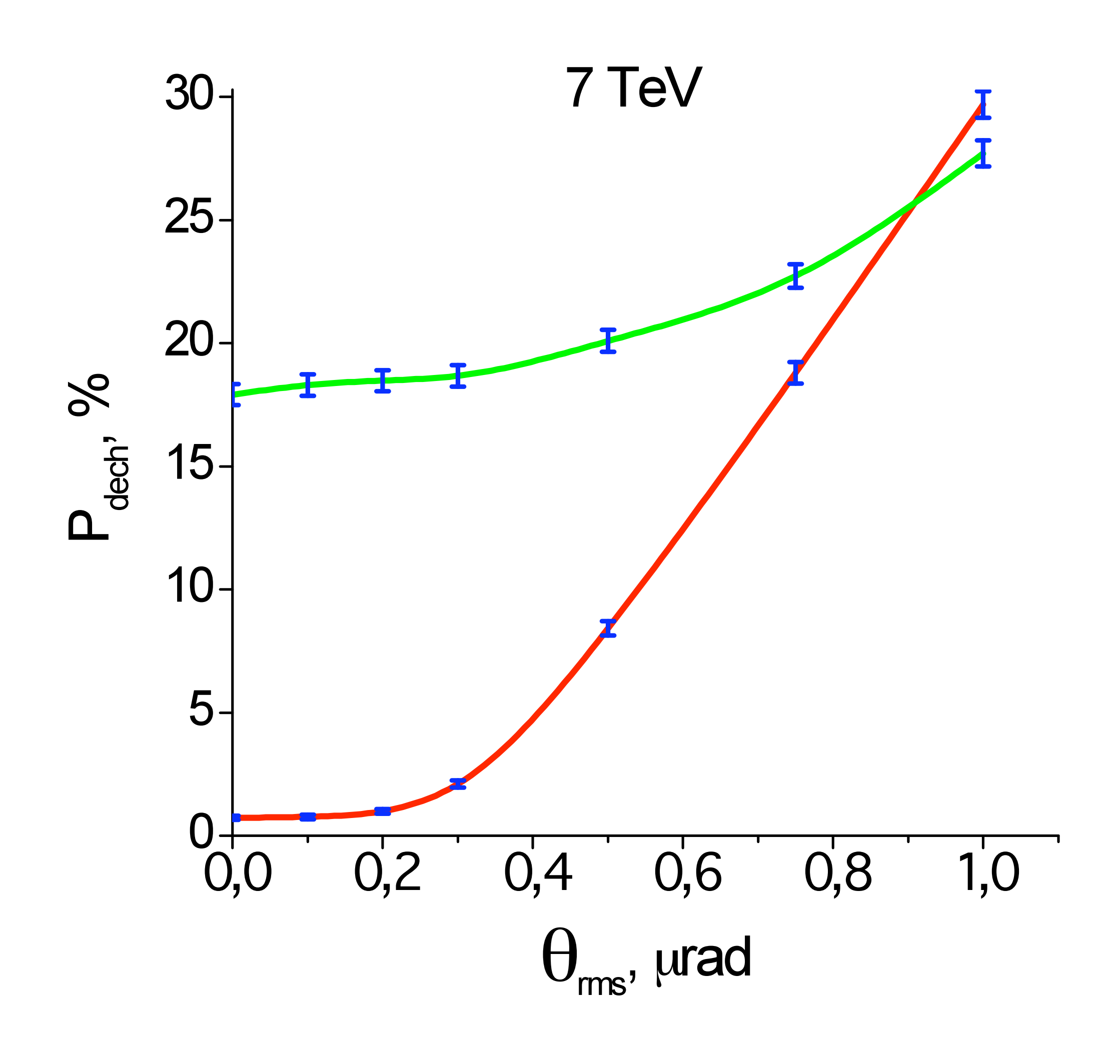
Protons are removed from the high nuclear density regions

Transverse energy reduction *by the cut* - 2



Only 1-2% of protons avoid transverse energy reduction by the cut

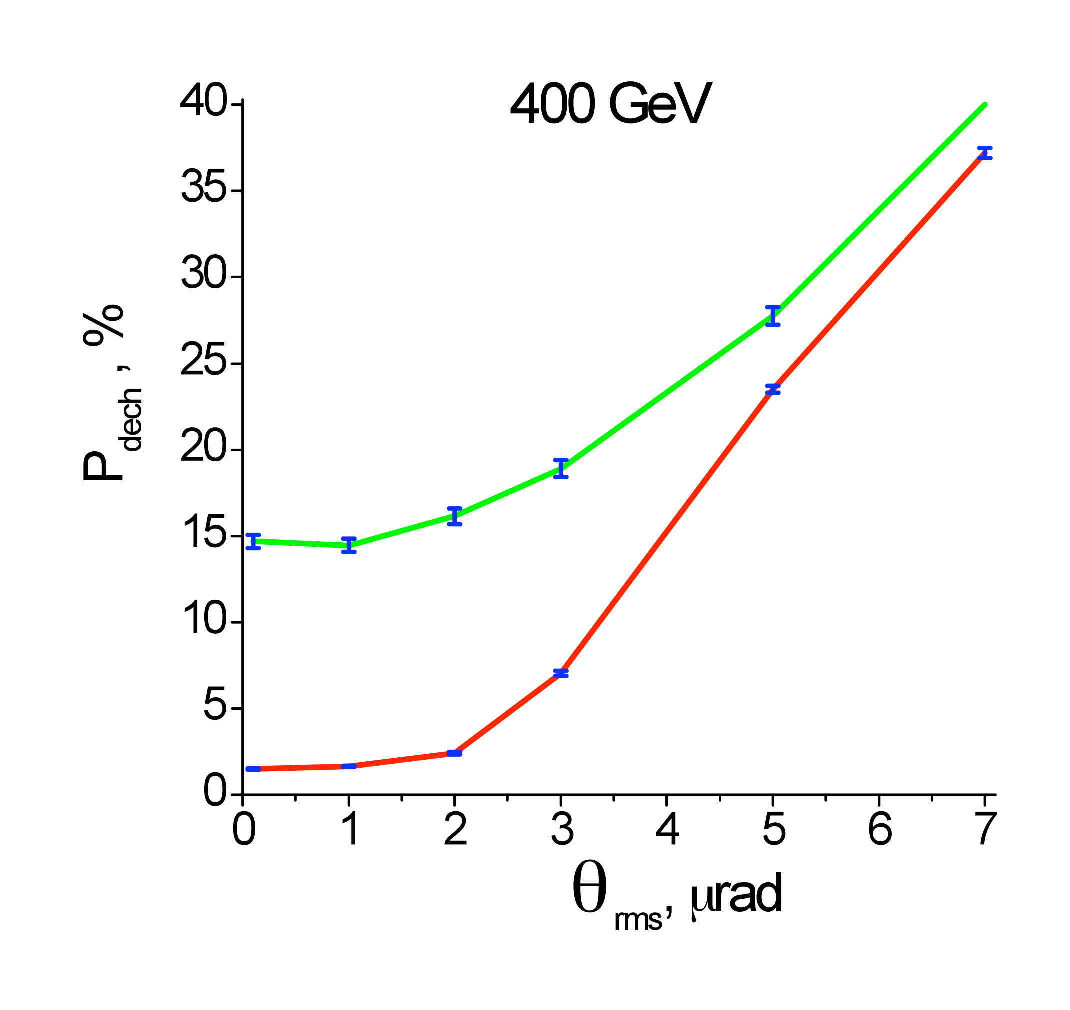
Dechanneling suppression by the cut at 7 TeV



$$z_1 = 17\,\mu m,$$
$$z_2 = 71\,\mu m,$$
$$z_3 = 1\ cm,$$
$$R_b = 100\,m$$

The cut decreases the dechanneling probability from 18 to 1-2%

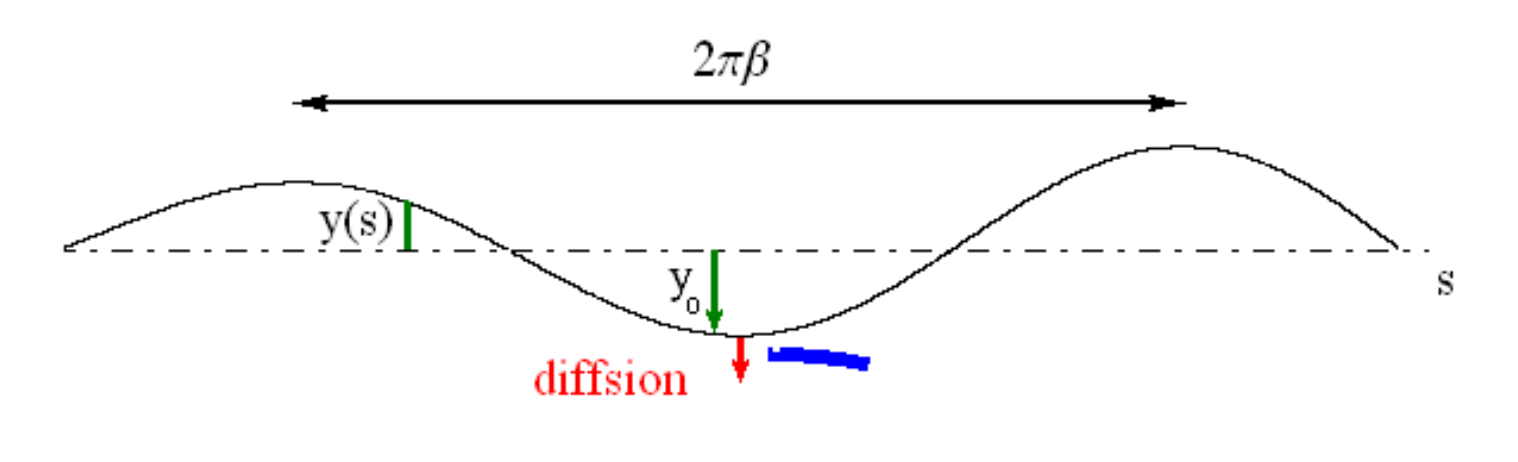
Dechanneling suppression by the cut at 400 GeV



$$z_1 = 4\,\mu m,$$
$$z_2 = 14\,\mu m,$$
$$z_3 = 1\ mm,$$
$$R_b = 10\,m$$

The cut decreases the dechanneling probability from 15 to 1%

"β-theory"

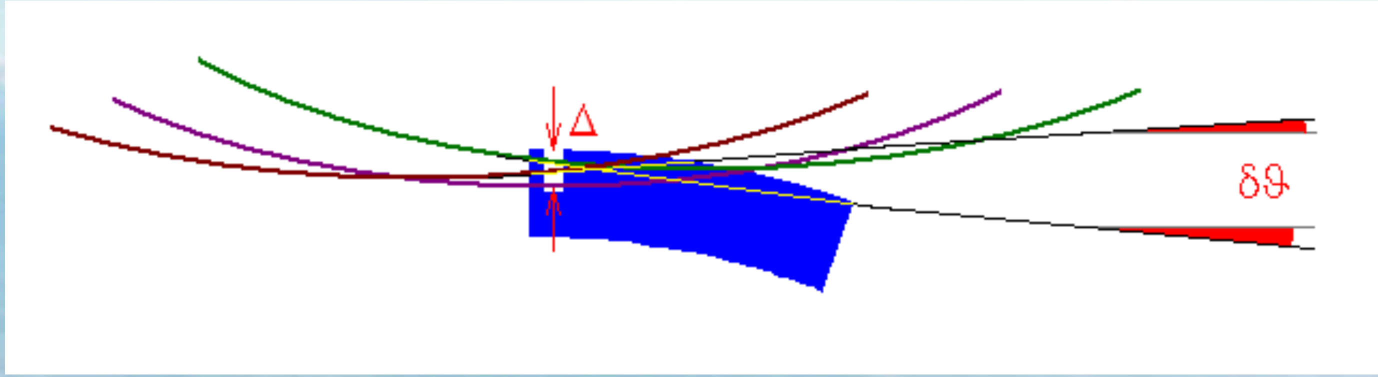


$$y(s) = a\sqrt{\beta(s)}\cos\psi(s) \;-\; \textit{transverse coordinate} \;,$$

$$s \;-\; \textit{longitudinal coordinate}\,,$$

$$\beta(s) - \beta - \textit{function},$$

$$\psi(s) = \int_{s_0}^{s} \frac{ds}{\beta(s)} \approx \frac{s - s_0}{\beta(s_0)} - \textit{betatron phase}\,.$$



$$y(s) \approx y_0\left[1+\frac{\beta'(s-s_0)}{2\beta}-\frac{(s-s_0)^2}{2\beta^2}\right] = y_{\max} - \frac{y_0}{2\beta^2}\left(s-s_0-\frac{1}{2}\beta'\beta\right)^2,$$

$$y_{\max} = y_0\left(1+\frac{1}{8}\beta'^2\right) = y_{cr}+\Delta, \quad y_0 \approx a\sqrt{\beta(s_0)} \approx k\sigma = k\sqrt{\varepsilon\beta}, \qquad \varepsilon - \text{emittance}, \quad k \approx 6$$

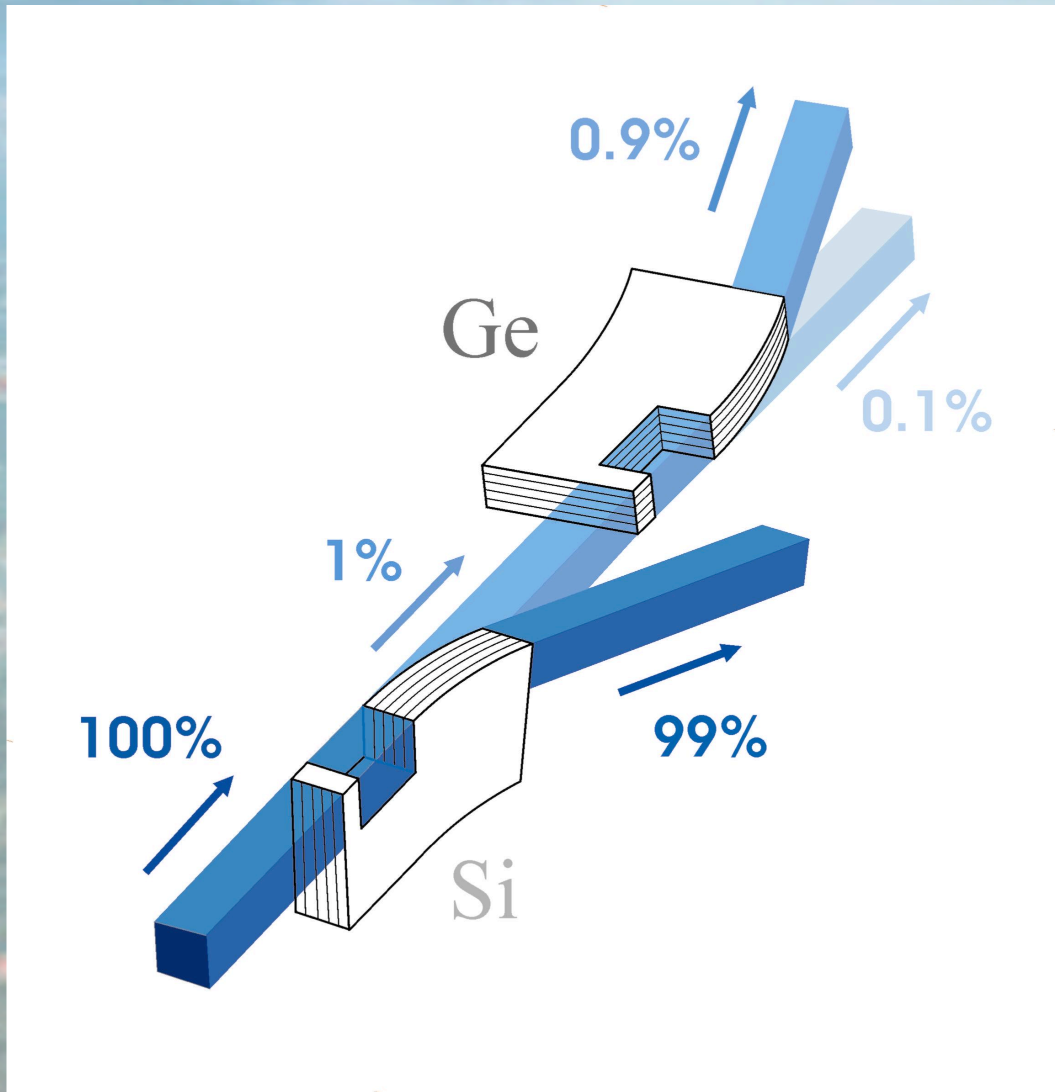
$$y(s) > y_{cr} \quad \text{if} \quad \frac{y_0}{2\beta^2}\left(s-s_0-\frac{1}{2}\beta'\beta\right)^2 < \Delta, \quad \text{or} \quad \left|s-s_0-\frac{1}{2}\beta'\beta\right| < \sqrt{\frac{2\Delta}{y_0}}\beta << \beta$$

$$\delta\vartheta \equiv y'(s) = -\frac{y_0}{\beta^2}\left(s-s_0-\frac{1}{2}\beta'\beta\right),$$

$$|\delta\vartheta| \le \delta\vartheta_{\max} \approx \frac{\sqrt{2y_0\Delta}}{\beta} \approx 0.2\mu rad, \quad \sqrt{<\delta\vartheta^2>} \approx 0.1\mu rad,$$

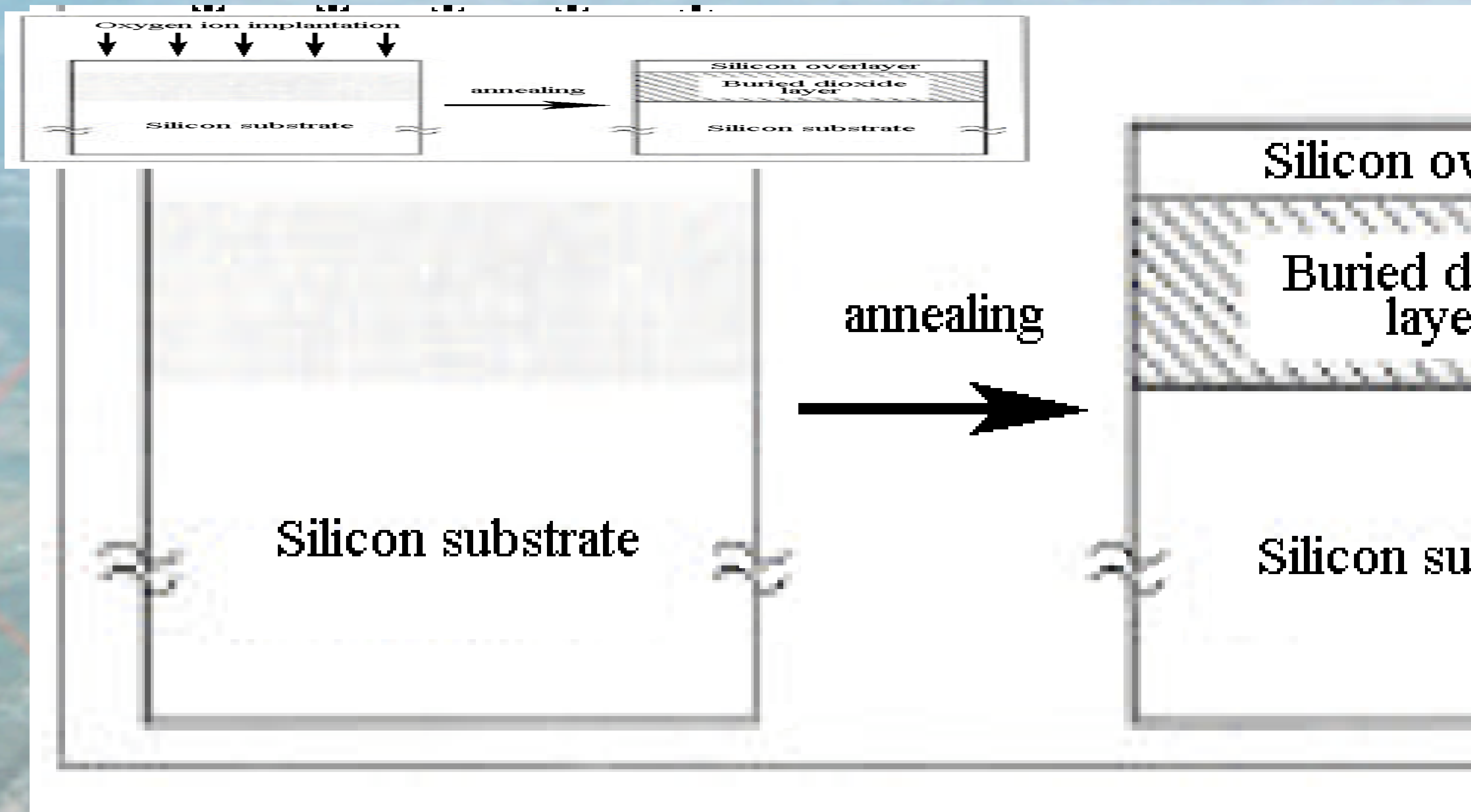
for $\Delta = 1\mu m, \quad \beta = 350m, \quad y_{cr} = 2.5\,mm$

A pair of crystals with cuts bent in orthogonal planes allows to deflect **99.9%** of protons

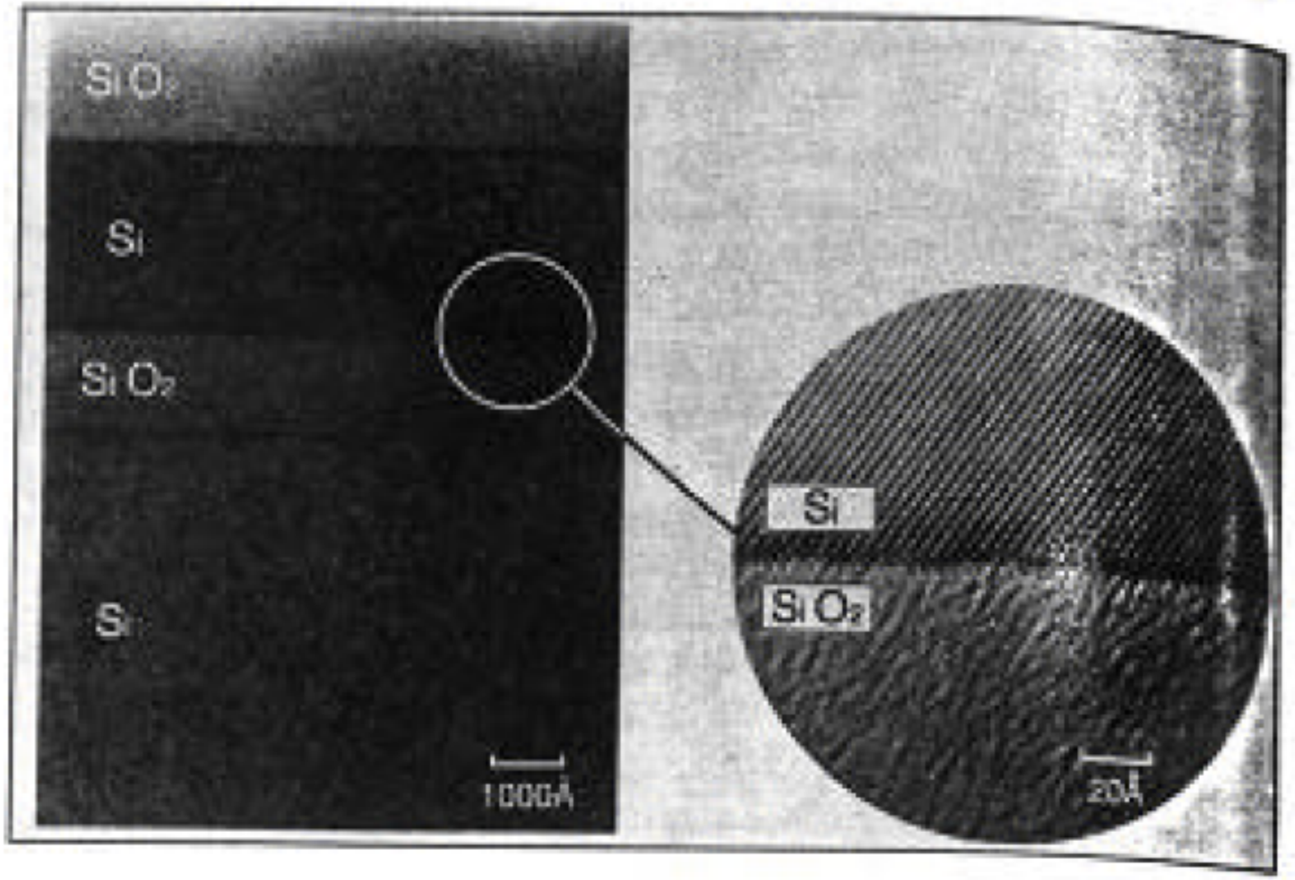


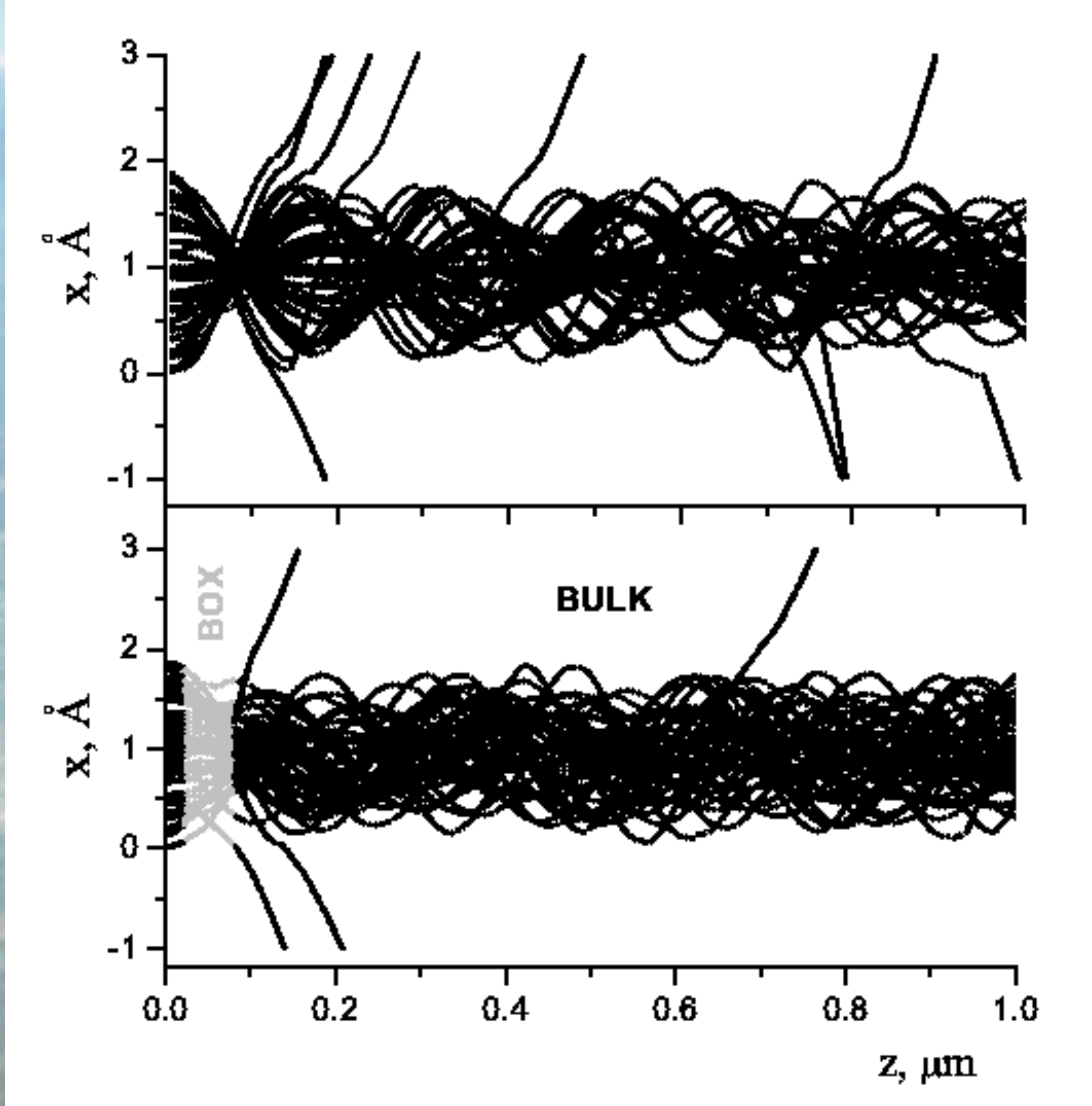
SIMOX technology

BOX layer can be used instead of *very thin* **cut**



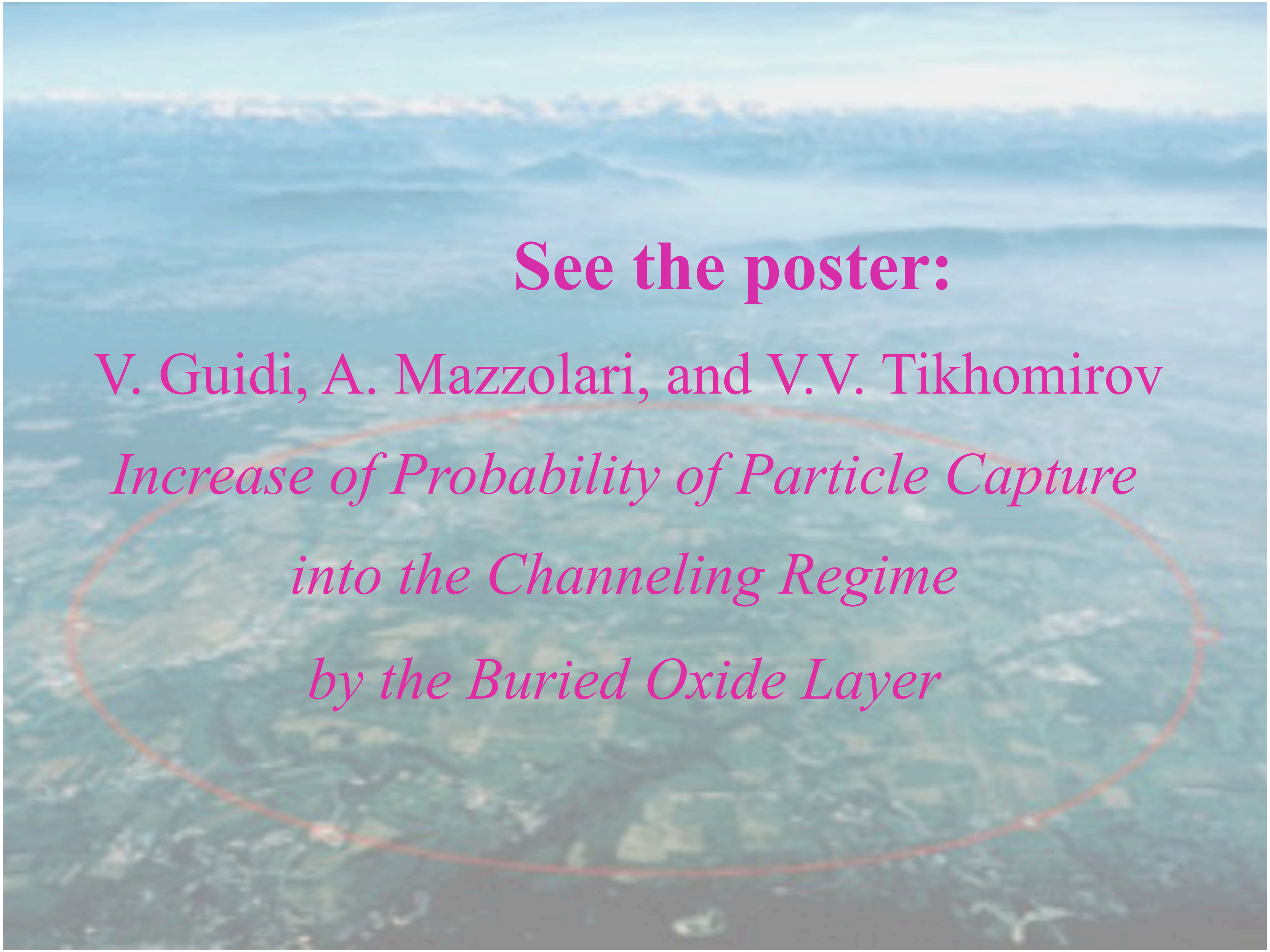
High resolution image of SIMOX wafer





BOX layer "focuses" protons like a ***cut*** diminishing their transverse energy

$z_1 = 20\,nm,$
$z_2 = 80\,nm,$
$z_3 = 1\,\mu m,$
$E_p = 7\,MeV$


See the poster:
V. Guidi, A. Mazzolari, and V.V. Tikhomirov
Increase of Probability of Particle Capture
into the Channeling Regime
by the Buried Oxide Layer

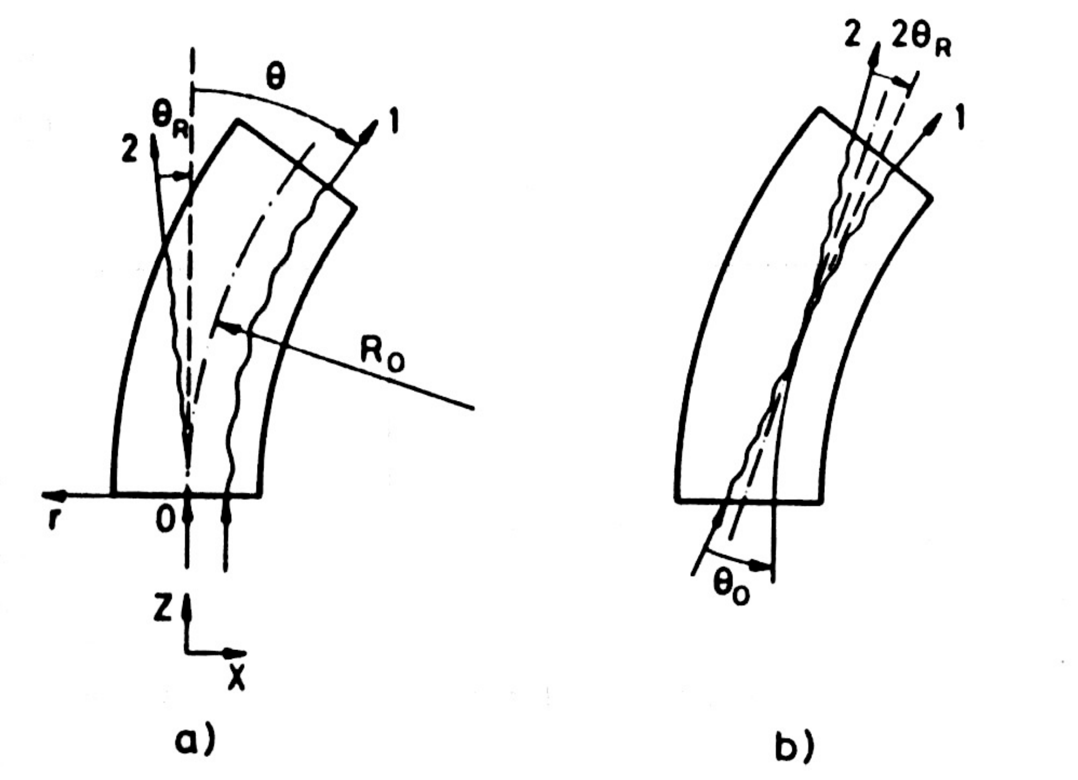
The *__cut__* allows to increase the proton (nuclei) deflection efficiency and to decrease the accompanying proton absorption by 1-2 orders of magnitude

Volume Reflection prediction

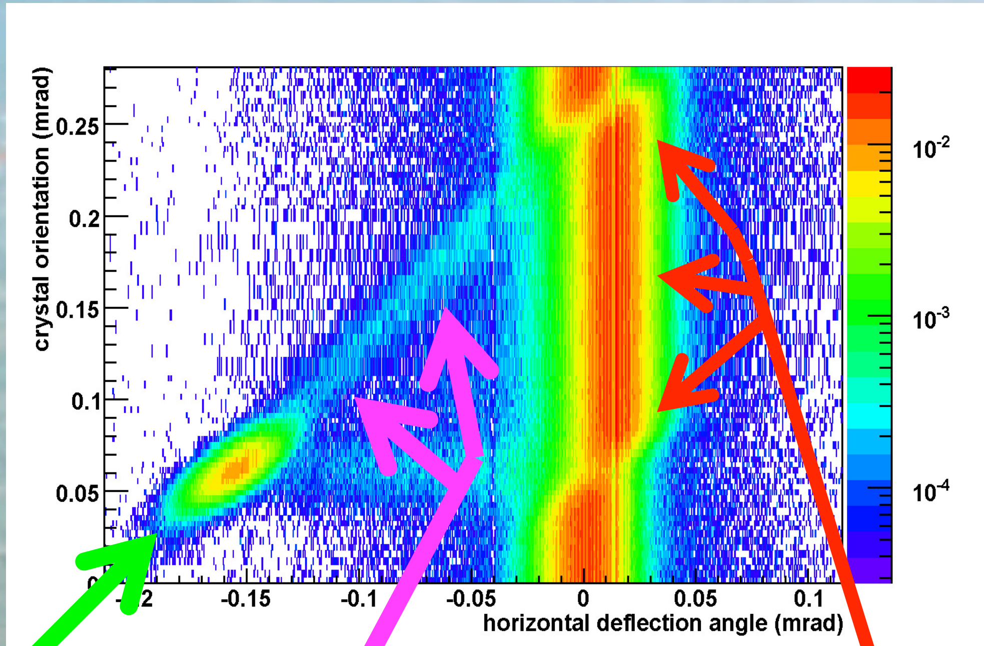
A.M.Taratin and S.A.Vorobiev, Phys. Lett. A119 (1987) 425

and

A.M.Taratin and S.A.Vorobiev, NIM B26 (1987) 512



Volume reflection CERN H8-RD22 experiment Sept 2006



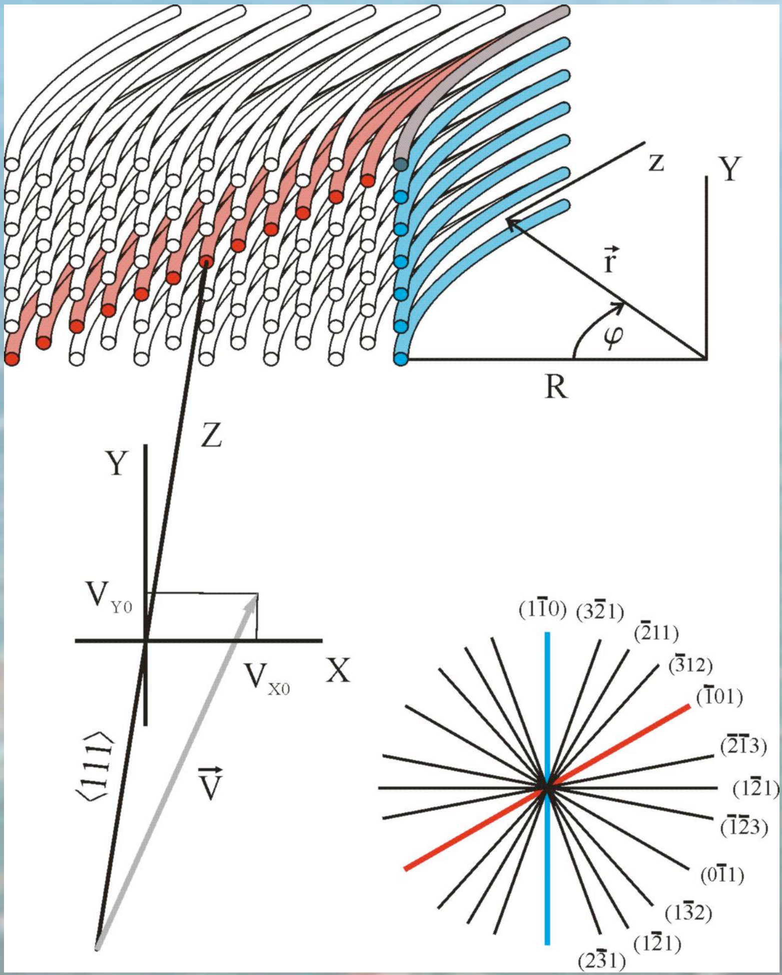
channeling

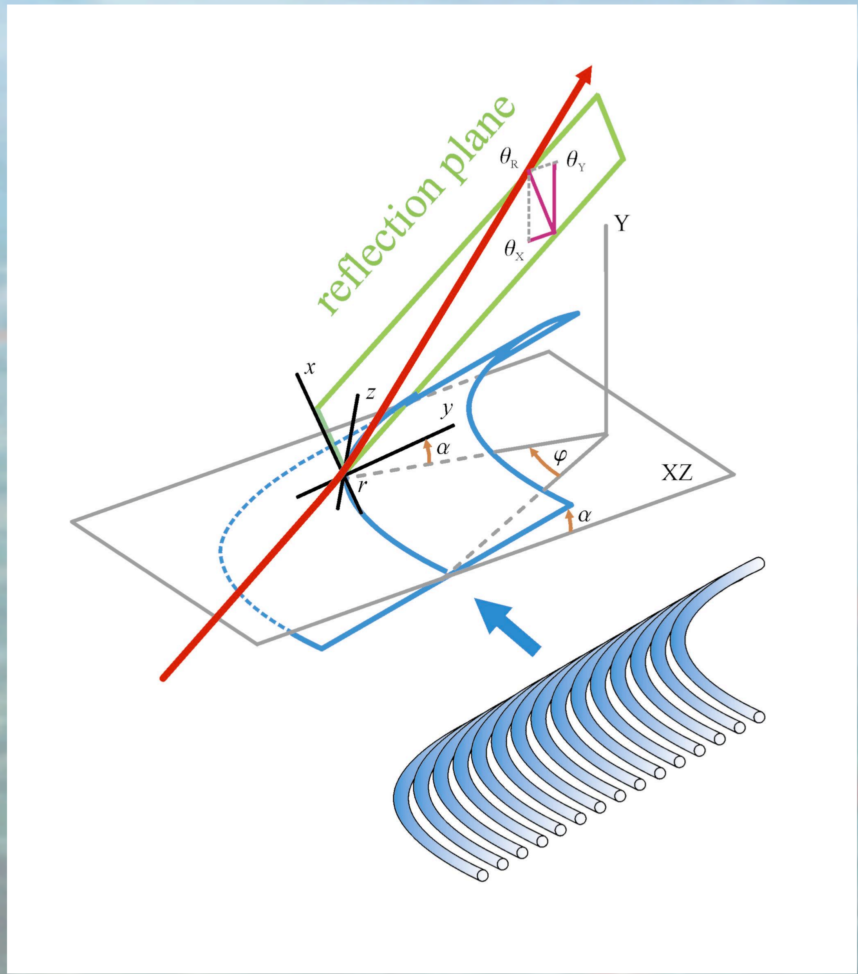
Volume capture

Volume reflection

Volume reflection by crystal ***axes***

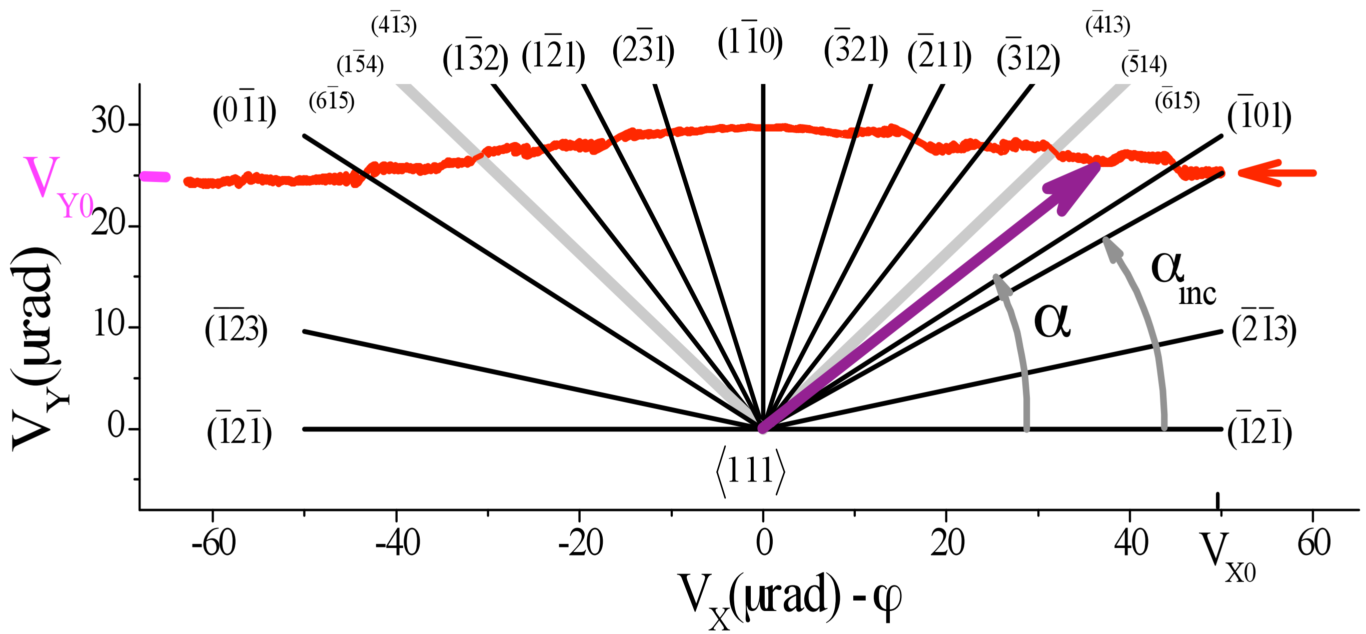
V.V. Tikhomirov, PLB 655(2007)217



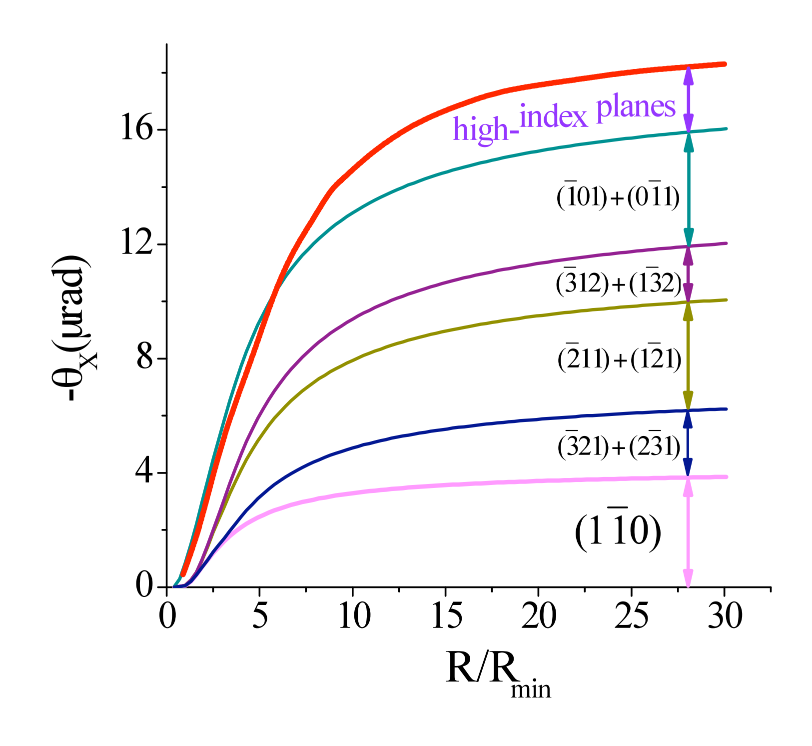


Axes form ***many*** inclined reflecting planes

Protons are reflected from ***many*** crystal plane sets of ***one*** crystal



Reflection from many crystal planes increase VR angle ***4 times – 1*** (LHC case)



$$\upsilon_x(x) = \sqrt{\frac{2}{\varepsilon}\left(\varepsilon_{\perp x} - V(x) + \frac{p\upsilon_{\|}}{R}x\cdot \sin\alpha\right)}\cdot c$$

$$\varepsilon_{\perp x} - V(x_{turn}) + \frac{p\upsilon_{\|}}{R}x_{turn}\cdot \sin\alpha = 0$$

$$\tilde{\upsilon}_x = \sqrt{\frac{2}{\varepsilon}\left(\varepsilon_{\perp x} - V(x_{turn}) + \frac{p\upsilon_{\|}}{R}x_{turn}\cdot \sin\alpha\right)}\cdot c$$

$$\upsilon_y(x) = \sqrt{\frac{2}{\varepsilon}\left(\varepsilon_{\perp x} - \frac{p\upsilon_{\|}}{R}y\cdot \cos\alpha\right)}\cdot c$$

$$\theta_X = \theta_R(R/\sin\alpha)\cdot \sin\alpha$$

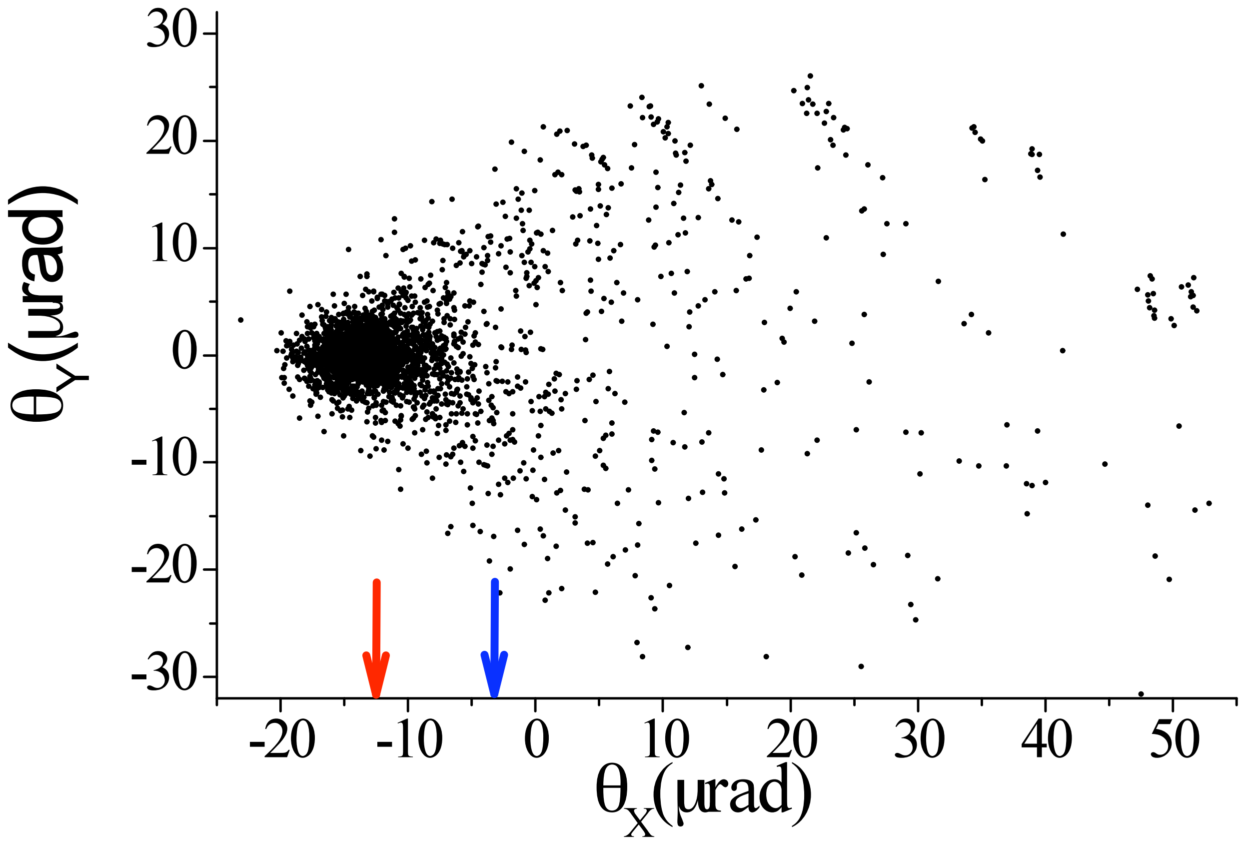
$$\theta_Y = \theta_R(R/\sin\alpha)\cdot \cos\alpha$$

$$\theta_R(R/\sin\alpha) = \frac{2\upsilon_{\|}}{R/\sin\alpha}\int_{x_{turn}}^{\infty}\left(\frac{1}{\tilde{\upsilon}_x} - \frac{1}{\upsilon_x(x)}\right)dx$$

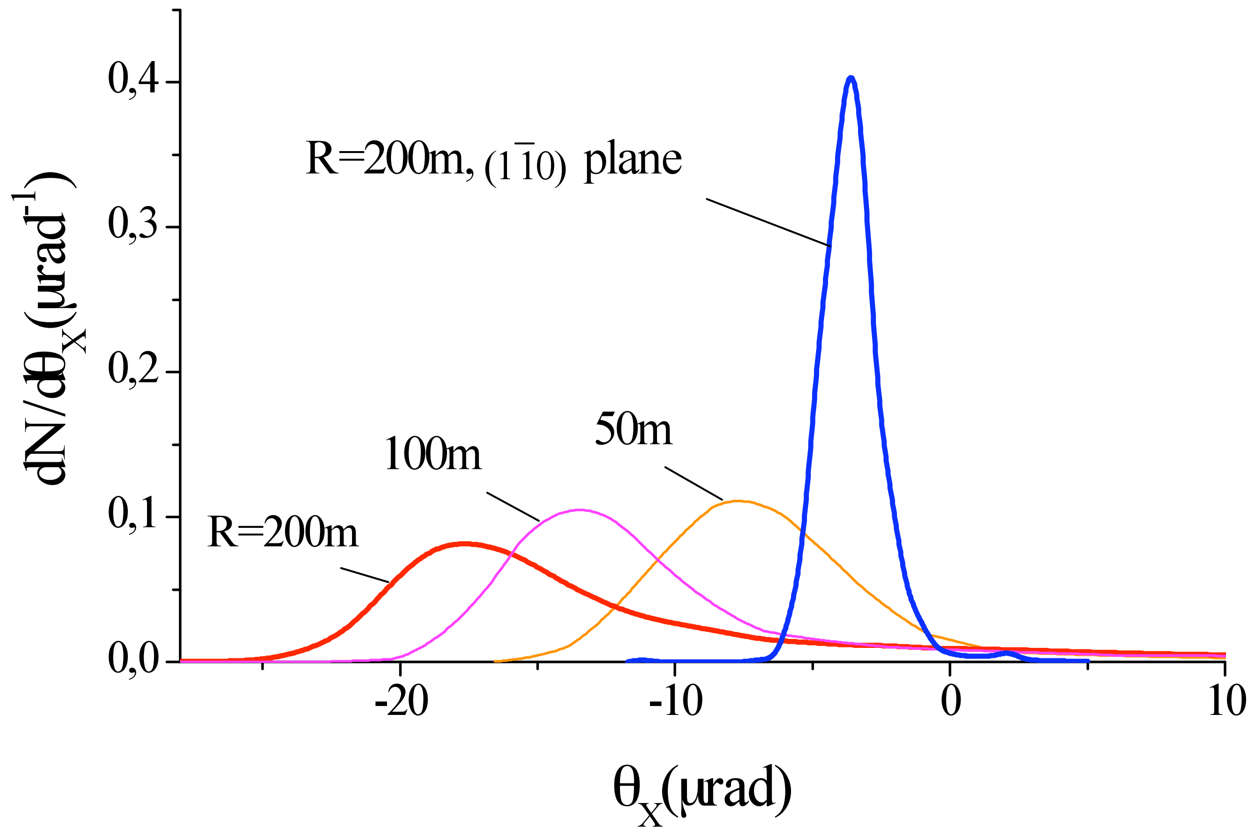
V.V. Tikhomirov, PLB 655(2007)217

The approach of V.A. Maisheev, Phys. Rev. ST Accel. Beams 10:084701,2007 was used.

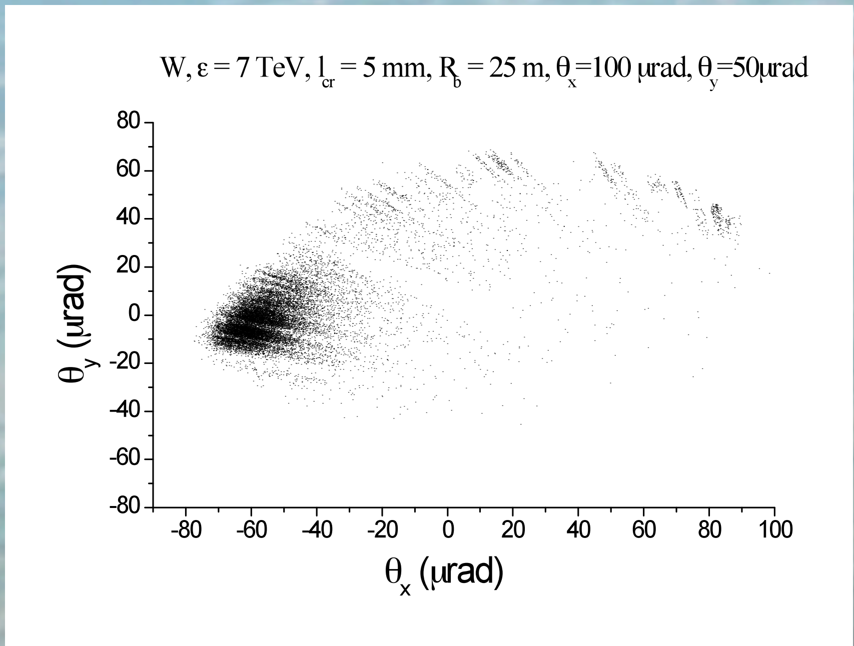
Direct simulations of distribution of multiple reflected protons (LHC case)

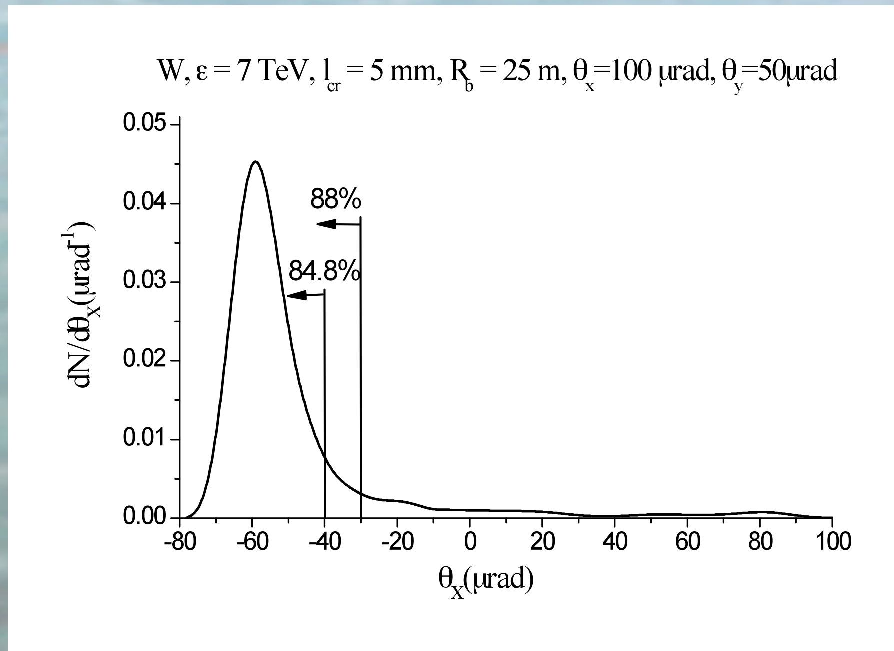


Reflection from many crystal planes increase VR angle *4 times* – *2* (LHC case)

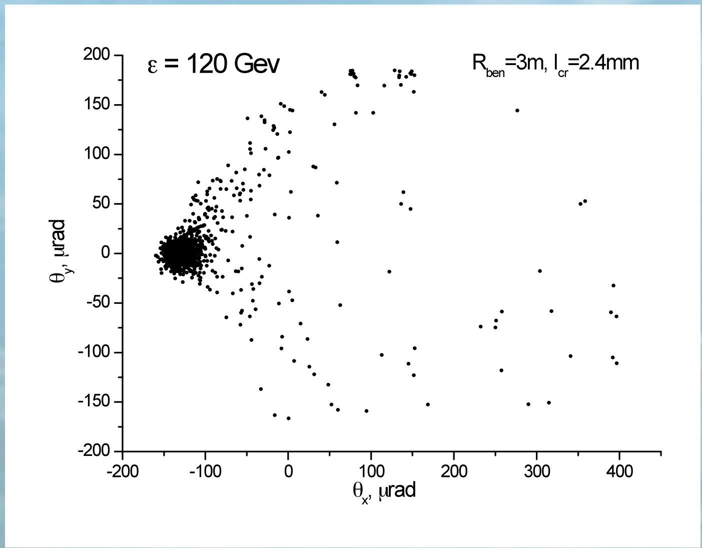


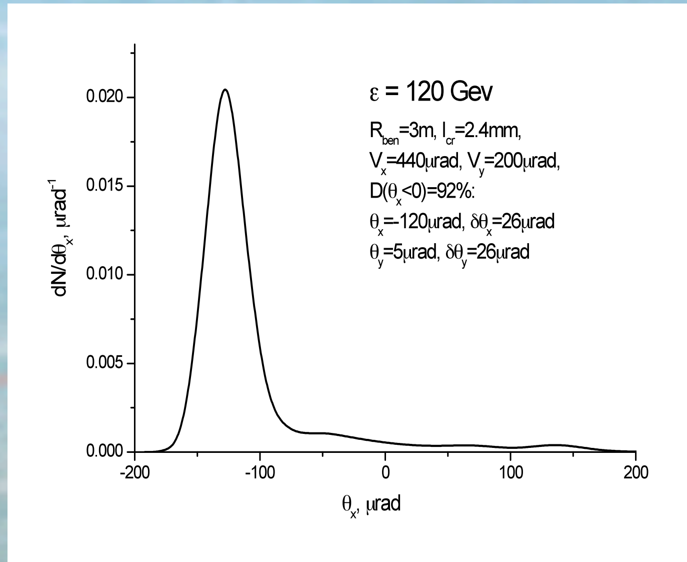
Reflection from many planes in single **W** crystal allows to reach a big one-pass deflection efficiency

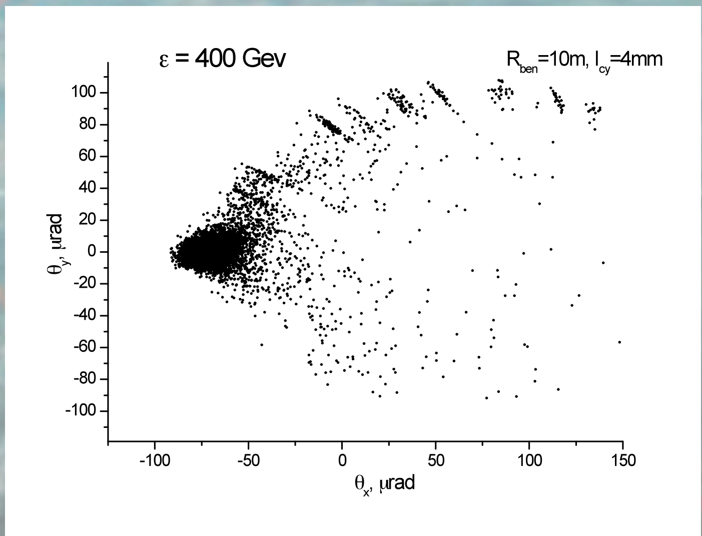


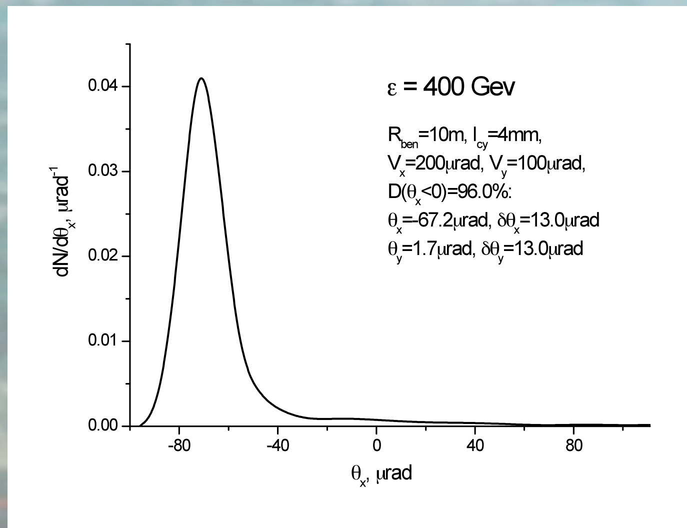


To the observations at the SPS

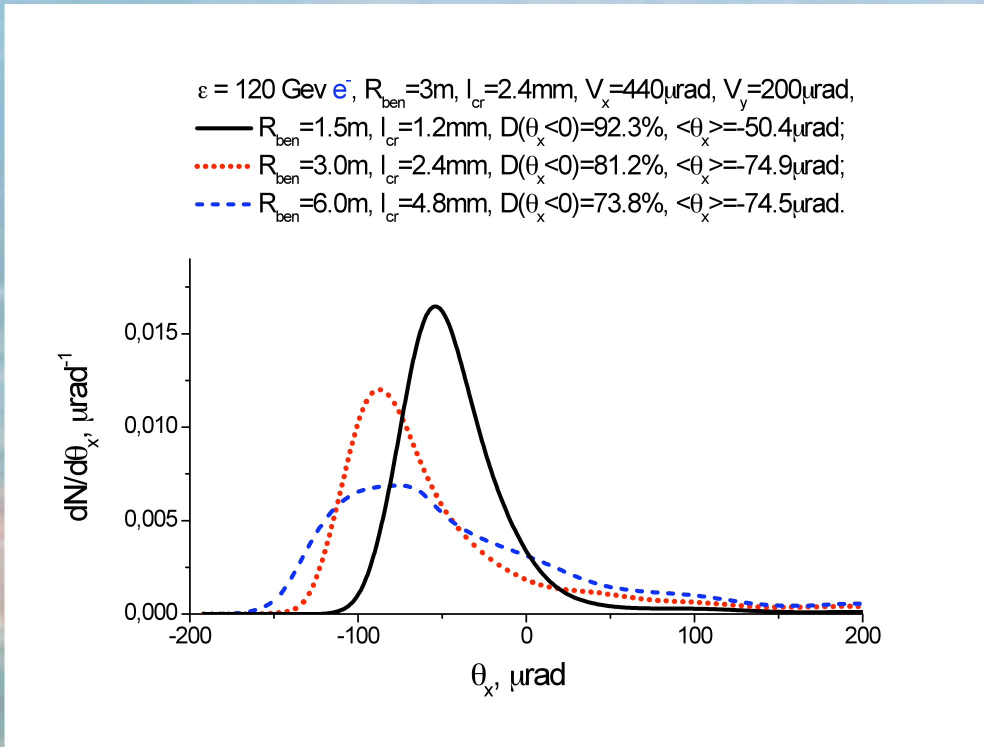


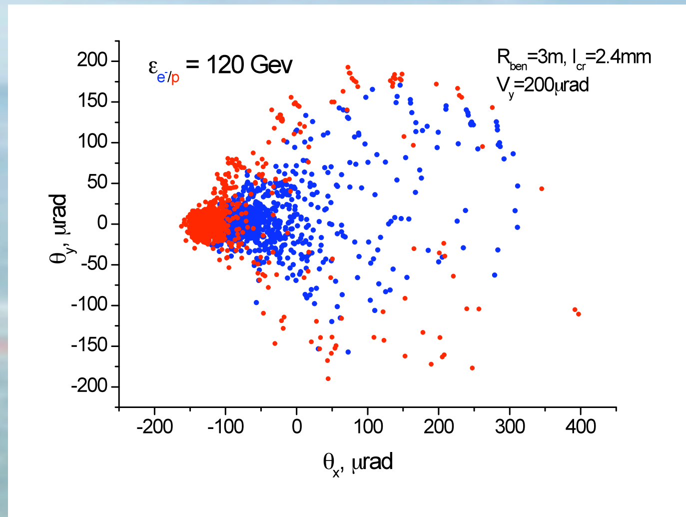


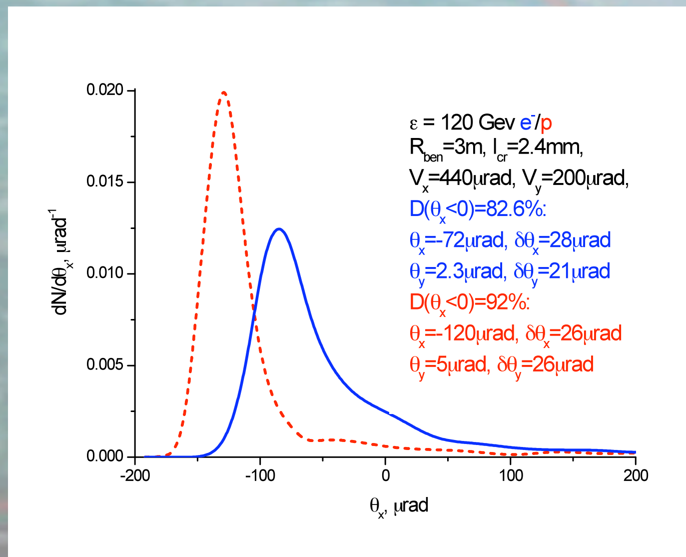




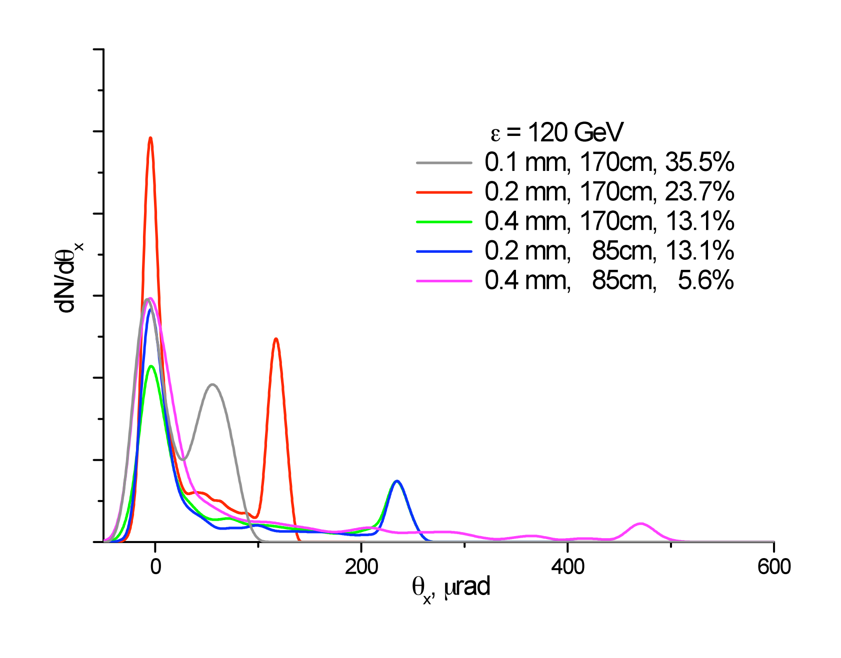
Volume reflection of *negative* particles

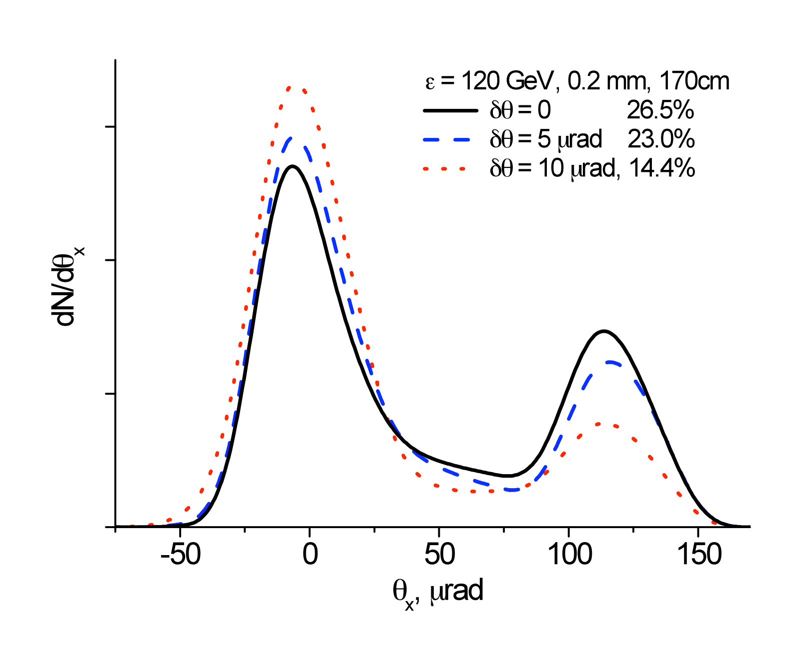


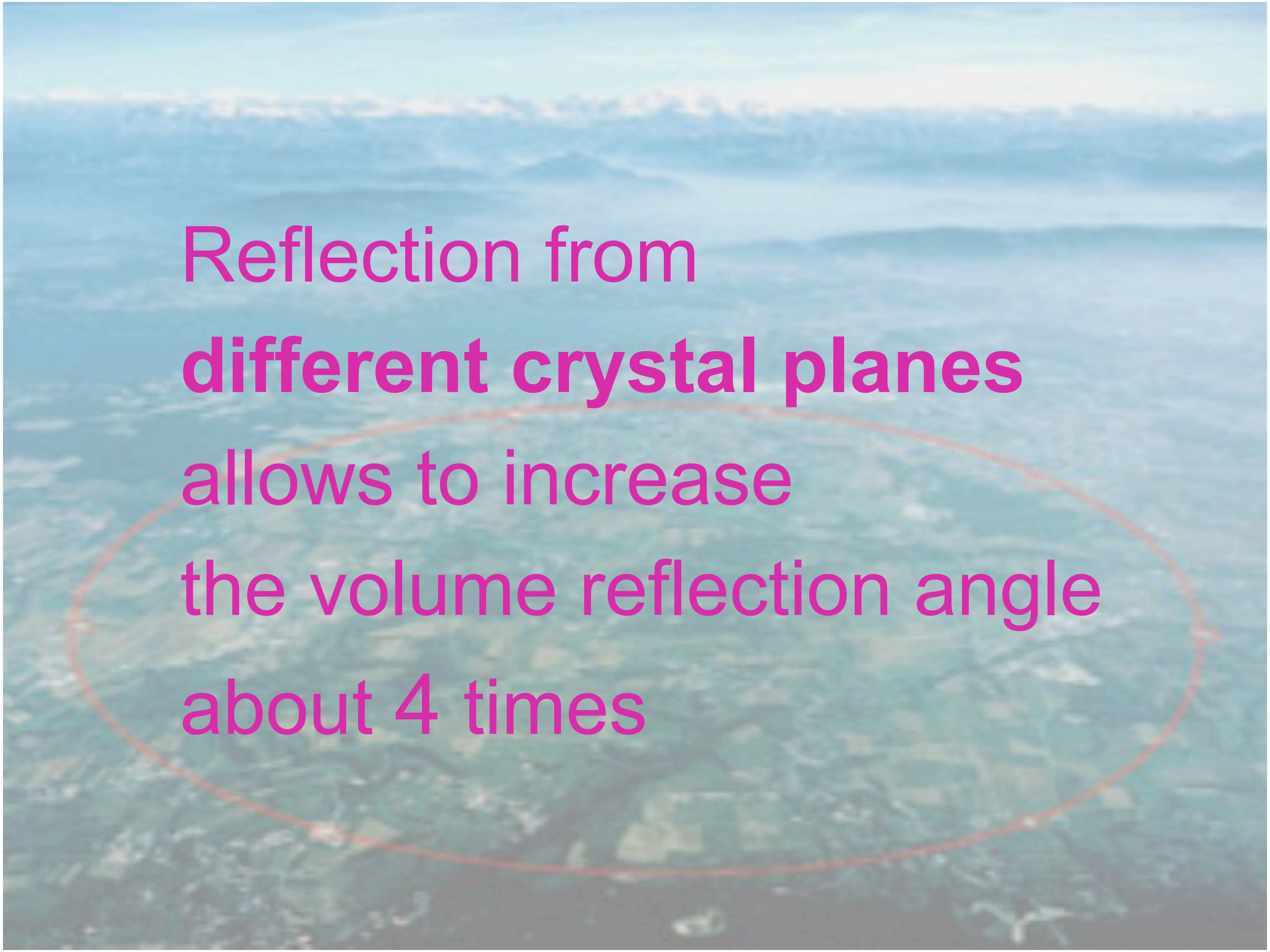




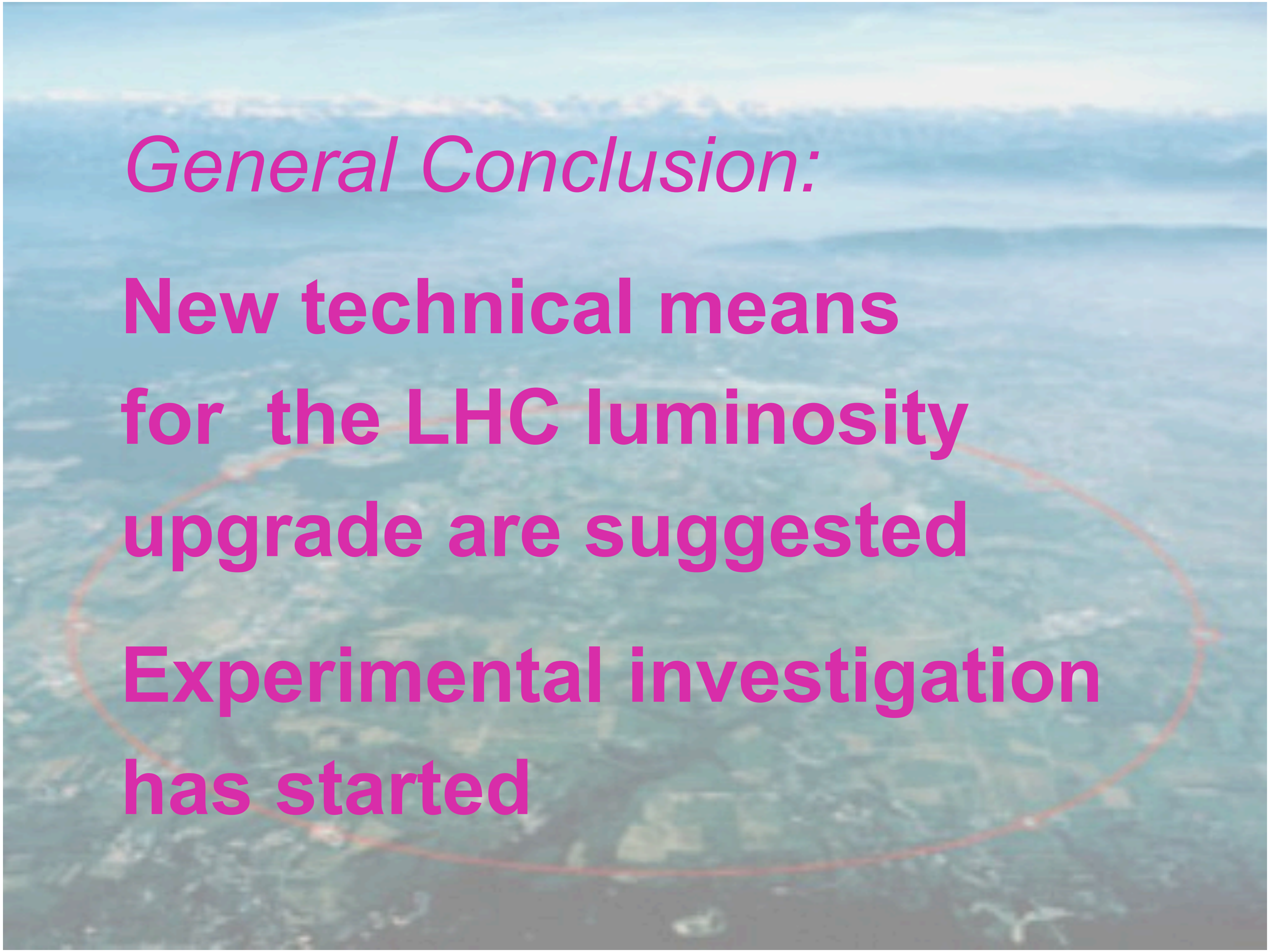
Planar channeling of negative particles in bent crystals







Reflection from
different crystal planes
allows to increase
the volume reflection angle
about 4 times



General Conclusion:

New technical means for the LHC luminosity upgrade are suggested

Experimental investigation has started

Thank you for attention!