IONIZATION ENERGY LOSS OF HIGH-ENERGY NEGATIVELY CHARGED PARTICLES CHANNELED IN SILICON CRYSTALS

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S.V. Trofymenko , I.V. Kyryllin, *Eur. Phys. J. C*, 80 (2020) 689

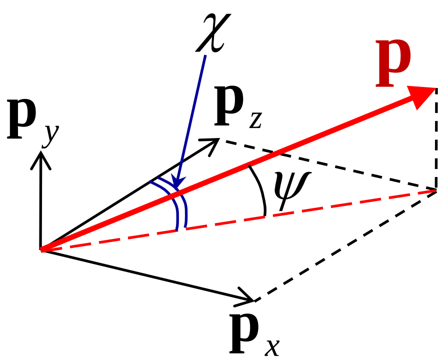
S.V. Trofymenko, I.V. Kyryllin, O.P. Shchus, *East Eur. J. Phys.* (2021), *submitted*

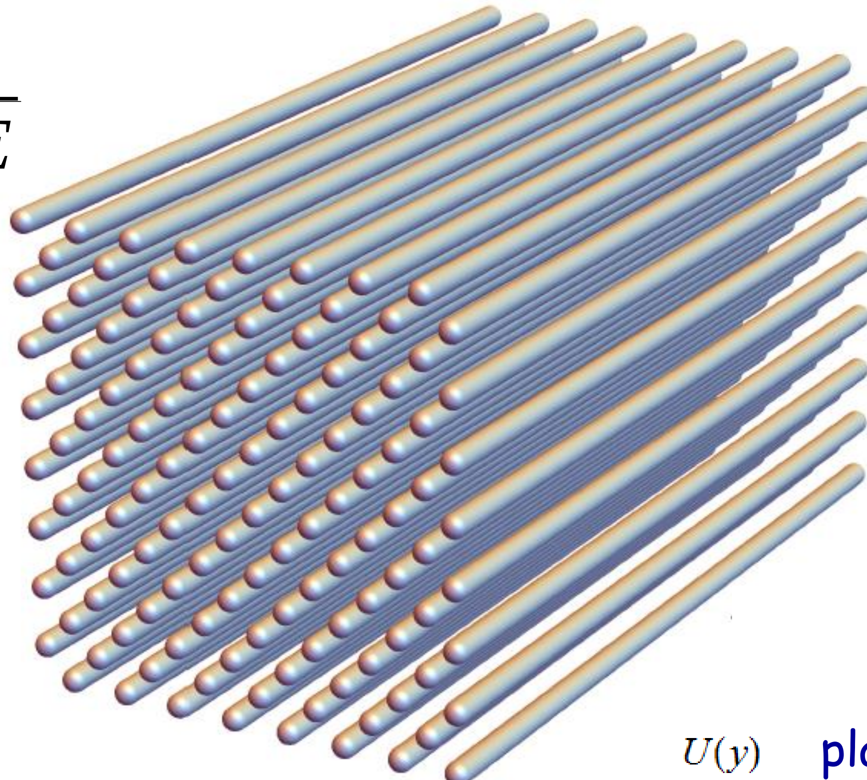
French-Ukrainian workshop on the instrumentation developments for HEP, October 27-29, 2021, IJCLab, Orsay, France

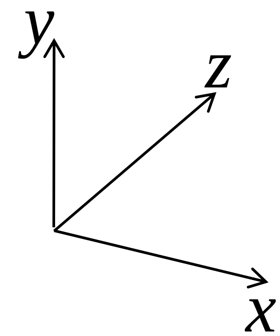
PLANAR CHANNELING OF PARTICLES IN CRYSTALS

$$\chi \gg \psi_c$$

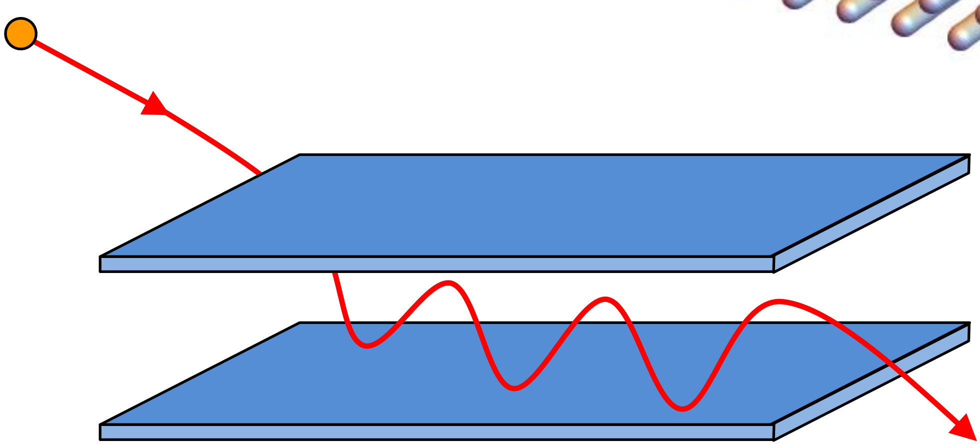
$$\psi < \psi_c = \sqrt{2U_0 / E}$$



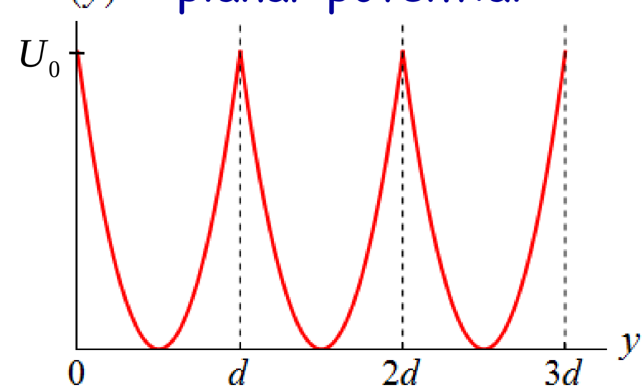




d – distance between planes

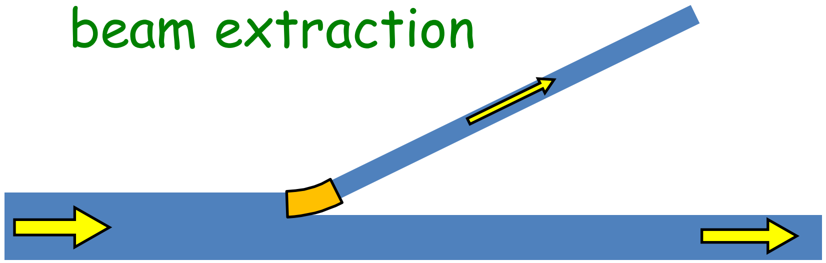


planar potential:

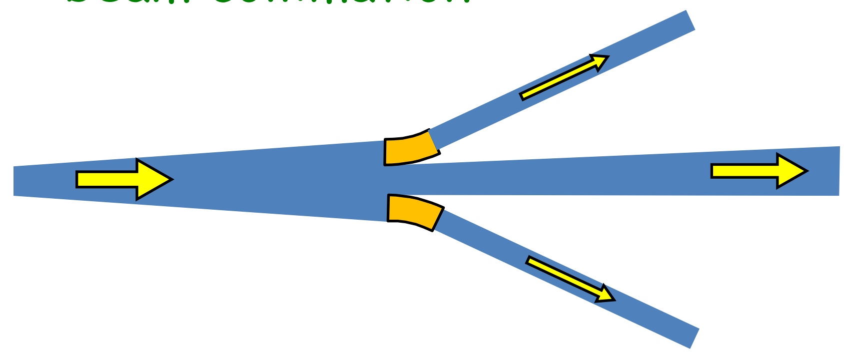


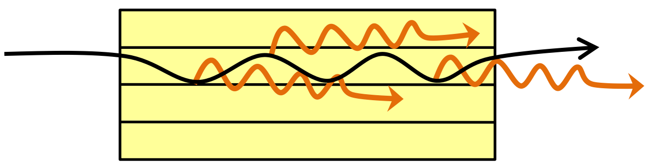
SIGNIFICANCE OF CHANNELING

beam extraction



beam collimation

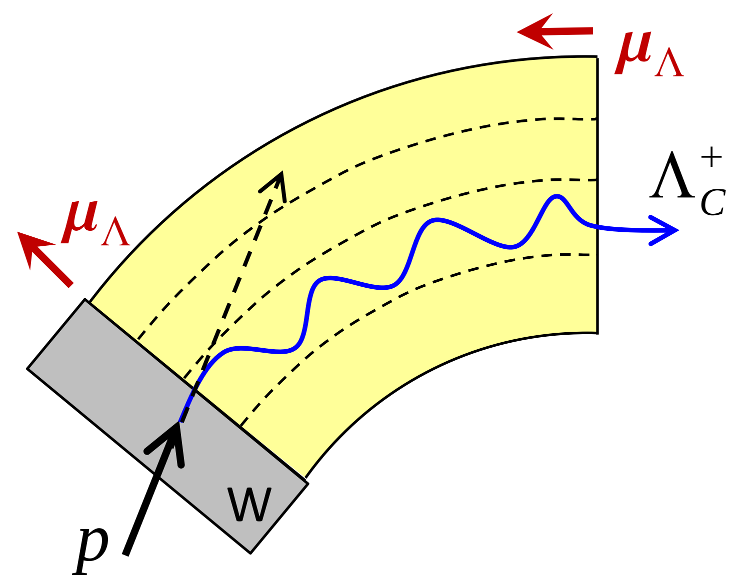




source of multi-MeV photons

short-living particles magnetic moment measurement (details in the talk by A. Fomin)

analogue to 10^4 Tesla magnetic fields



DECHANNELING LENGTH

$l_d = \xi E$ – length at which $1/e \approx 0.37$ of particles still remains channeled

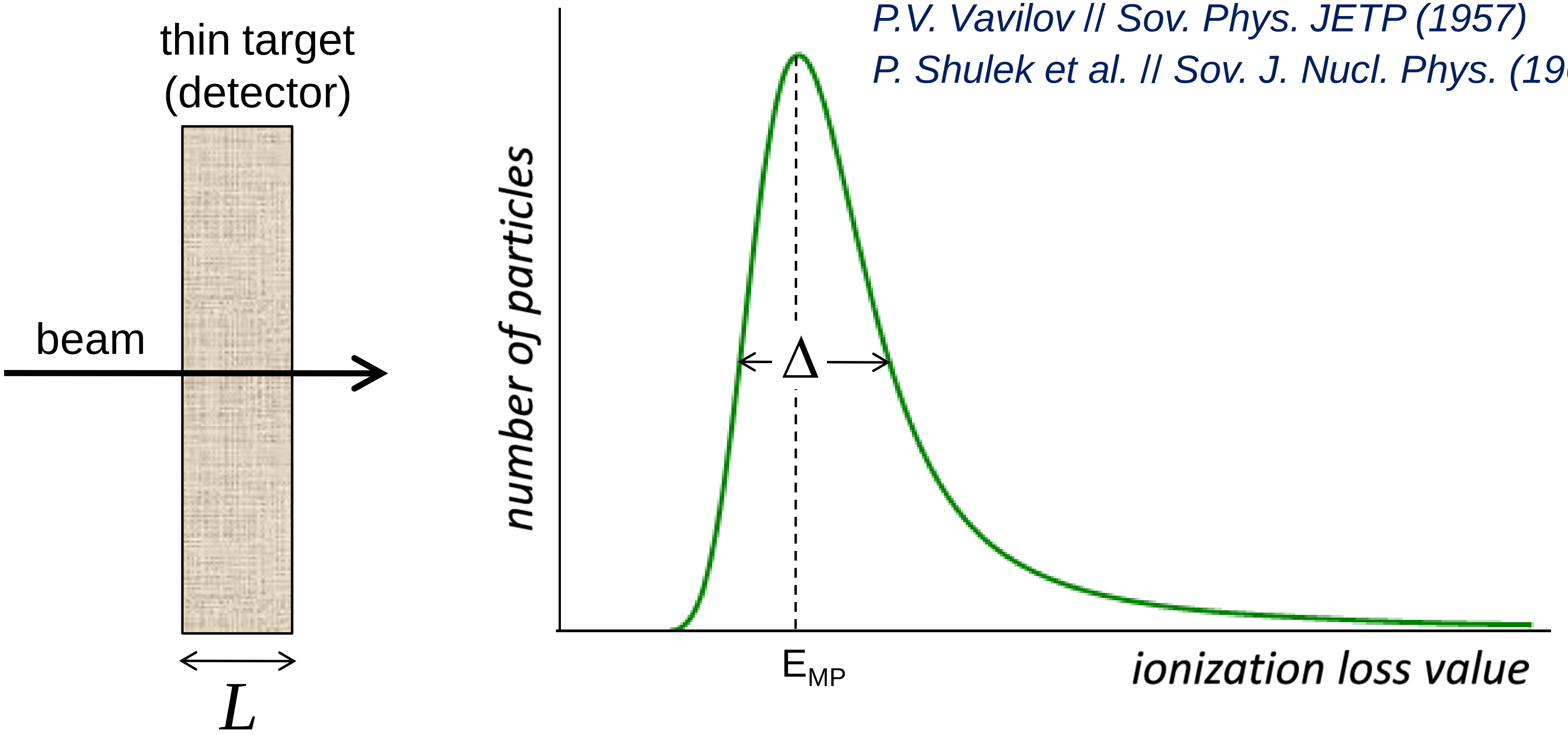
Plane	Particles	E(GeV)	ξ (μm/GeV)	Refs.
(110)	e^-		**17.8**	[1]
(110)	e^-	0.855	**21.1**	[2]
(110)	e^-	0.855	**48.0**	[3]
(110)	e^-	0.855	**9.7**	[4]
(110)	e^-	1.2	**24.2**	[5]
(110)	π^-	150	**6.2**	[6]
(111)	e^-		**23.6**	[1]
(111)	e^-	0.855	**23.7**	[7]
(111)	e^-	0.855	**15.9**	[4]
(111)	e^-	3.35-14	**15.3**	[8]
(111)	e^-	0.5-100	**27**	[9]
(111)	e^-	50	**6.6**	[10]

1. V. Baier et al., Electromagnetic Processes at High Energies in Oriented Single Crystals, 1998
2. H. Backe et al., NIMB, 2008
3. W. Lauth et al., Int. J. Mod. Phys. A, 2010
4. A. Kostyuk et al., J. Phys. B,2011
5. V.I. Vit'ko, G.D. Kovalenko, JETP, 1988
6. W. Scandale et al., Phys. Lett. B, 2013
7. A. Mazzolari et al., Phys. Rev. Lett., 2014
8. T.N. Wistisen et al., Phys. Rev. Accel. Beams 2016
9. M. Tabrizi et al., Phys. Rev. Lett., 2007
10. V.M. Biryukov, arXiv:0712.3904, 2007

Large uncertainty in the value of ξ

LANDAU DISTRIBUTION (SPECTRUM) FOR PARTICLE IONIZATION LOSS VALUES IN THIN TARGET

L.D. Landau // J. Phys. USSR (1944)
P.V. Vavilov // Sov. Phys. JETP (1957)
P. Shulek et al. // Sov. J. Nucl. Phys. (1967)



$$E_{MP} < \langle E \rangle \qquad E_{MP} \sim L \ln L \qquad \Delta \sim L$$

PREVIOUS STUDIES OF IONIZATION LOSS OF CHANNELED PARTICLES

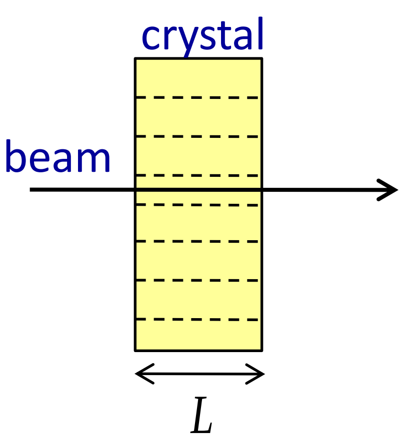
O. Fich et al., Phys. Rev. Lett., 1976

H. Esbensen et al., Nucl. Phys. B, 1977

H. Esbensen et al., Phys. Rev. B, 1978

S. Pape Møller et al., Phys. Rev. A, 2001

Most part of studies is for **positive particles** under condition $l_d >> L \longrightarrow$ shift of the maximum towards lower energies



from *H. Esbensen et al., Phys. Rev. B, 1978*

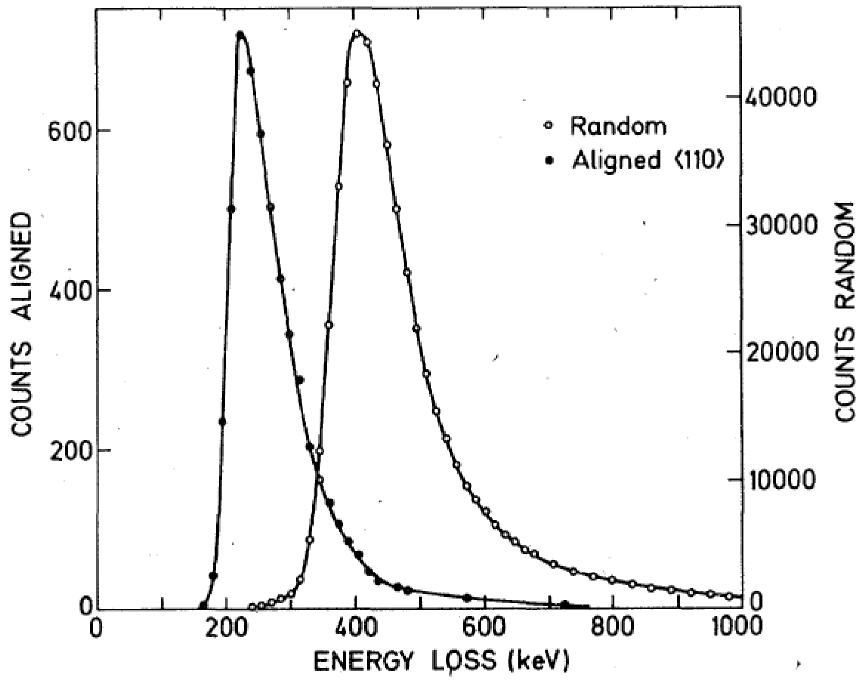
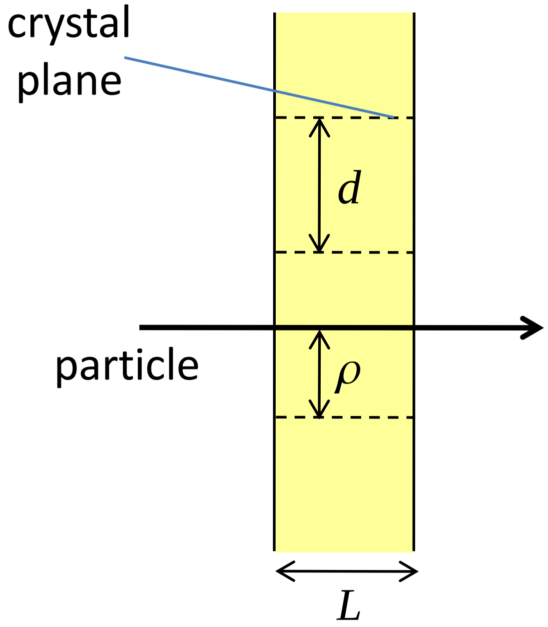


FIG. 6. Energy-loss spectra for 15-GeV/c protons incident on a 0.74-mm Ge single crystal. The dots correspond to particles channeled along a ⟨110⟩ axis, and the circles correspond to particles incident in a "random" direction.

Several studies for **negative particles** under condition $l_d << L \longrightarrow$ almost no effect

POSSIBILITY OF l_d DETERMINATION VIA MEASUREMENT OF IONIZATION LOSS SPECTRA



In the case when $l_d \sim L$ ionization loss spectrum for a single particle:

$$f_1(E,\rho) = l_d^{-1}(\rho)\int_0^L dx e^{-x/l_d(\rho)} \times$$

$$\times \int_0^E f_{\mathrm{ch}}(x,\varepsilon,\rho)\, f_{\mathrm{overbar}}(L-x, E-\varepsilon)\, d\varepsilon$$

Ionization loss spectrum for the whole beam:

$$l_d = \langle l_d(\rho) \rangle$$

$$f_{\mathrm{beam}}(E) = d^{-1}\int_0^d f_1(E,\rho)\, d\rho$$

Under the condition $l_d \sim L$ ionization loss spectrum is sensitive to the value of l_d

SIMULATION METHOD

Collision probability on the interval dx:

$$dP = n_{\text{eff}} \sigma dx$$

Effective electron density (distinction between close and distant collisions):

$$n_{\text{eff}} = (1-\alpha)n + \alpha n(\mathbf{r})$$

Energy loss probability on dx:

$$\rho(\mathcal{E}) = \sigma^{-1}(d\sigma / d\mathcal{E})$$

Particle trajectory from the numerical solution of:

$$\frac{d^2 x}{dt^2} = -\frac{v}{p}\frac{\partial U(x)}{\partial x}$$

and additional simulation of incoherent scattering

$n(\mathbf{r})$ – local electron density

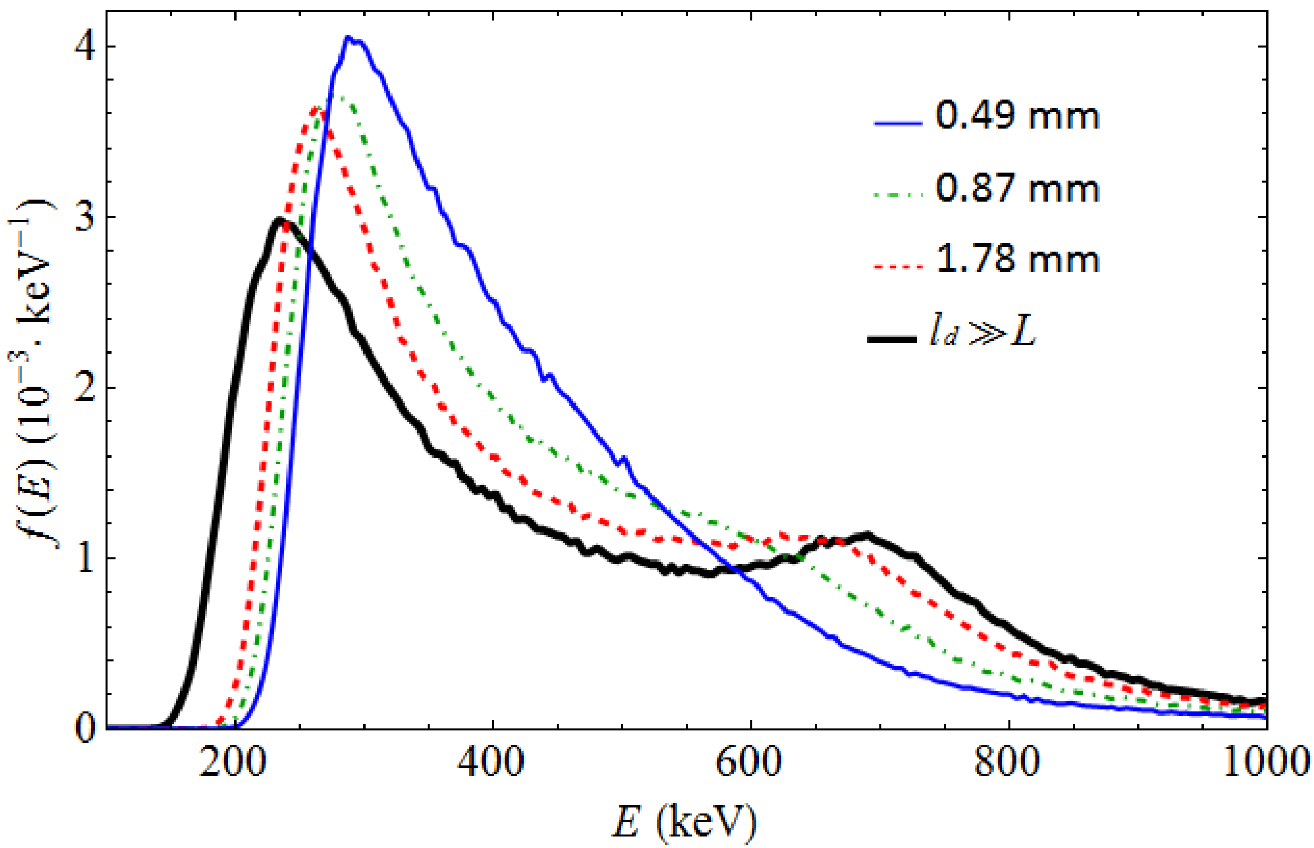
n – macroscopic average electron density

at high energies $\alpha \longrightarrow 1/2$

Energy loss cross section (*J.F. Bak et al., Nucl. Phys. B, 1987*):

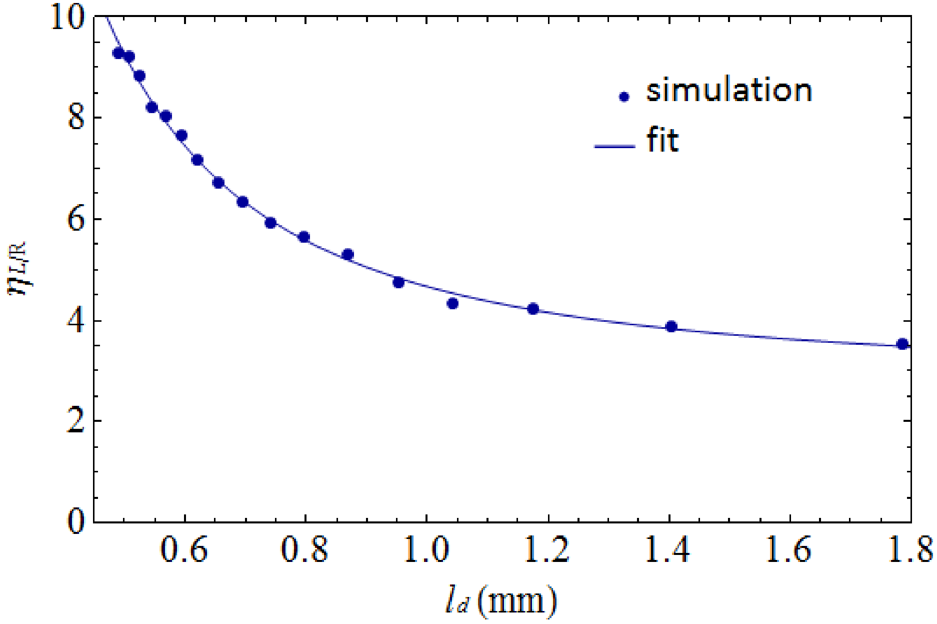
$$\frac{d\sigma(\mathcal{E})}{d\mathcal{E}} = \frac{2\pi e^4}{mc^2}\sum_i \frac{f_i}{\mathcal{E}}\left\{\ln\frac{2mc^2\mathcal{E}}{(\hbar\omega_p)^2}\delta(\mathcal{E}-E_i) \ + \ \mathcal{E}^{-1}H(\mathcal{E}-E_i)\right\}$$

DEPENDENCE OF THE SPECTRUM ON DECHANNELING LENGTH

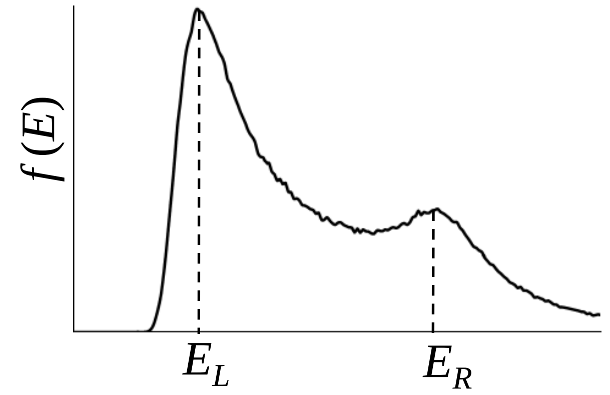


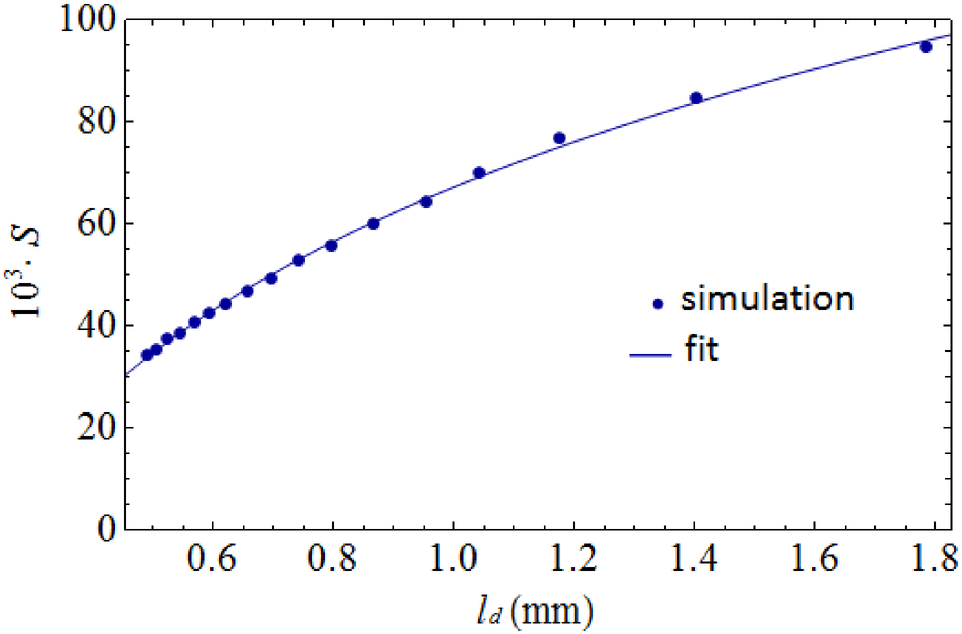
Ionization loss spectra of 150 GeV π^- mesons (available at SPS CERN) in 1 mm silicon target for different values of l_d (specified in the legend). The particles incident along (110) plane

DEPENDENCE OF THE SPECTRUM PARAMETERS ON THE DECHANNELING LENGTH

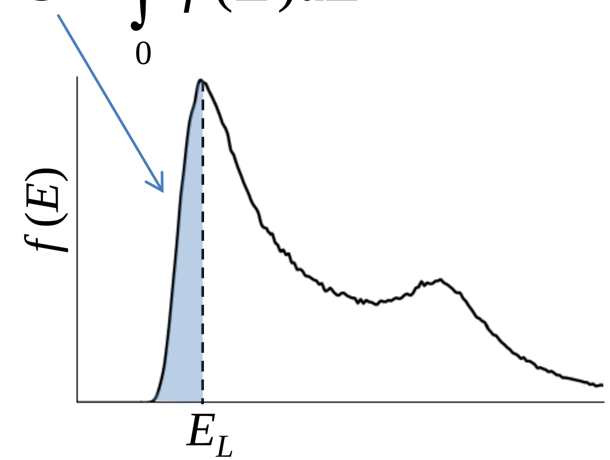


$$\eta_{L/R} = f(E_L) / f(E_R)$$

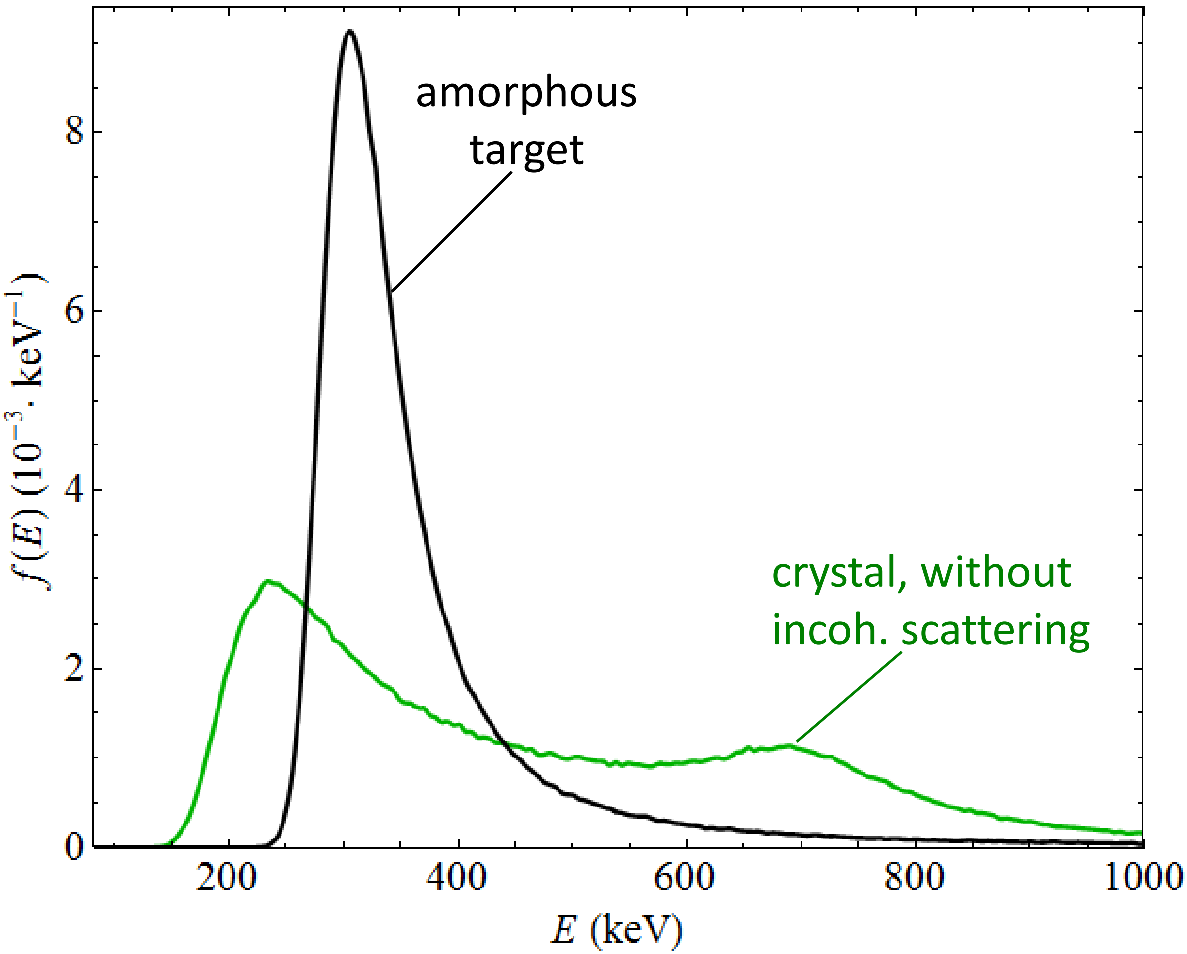




$$S = \int_0^{E_L} f(E) dE$$



PECULIAR FEATURES OF THE IONIZATION LOSS SPECTRUM OF NEGATIVE CHANNELED PARTICLES

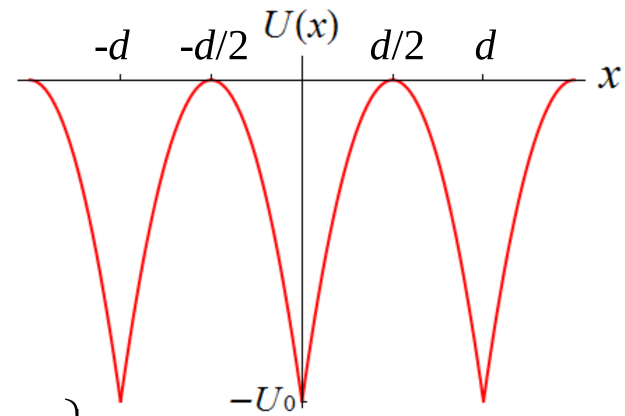


Distribution of ionization energy loss of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal (solid line) and during motion in an amorphous target (dashed line).

ANALYSIS OF NEGATIVE CHANNELED PARTICLES MOTION

$$U(x) = -U_0\left[\left(2\frac{x}{d}-1\right)^2 H(x) + \left(2\frac{x}{d}+1\right)^2 H(-x)\right]$$

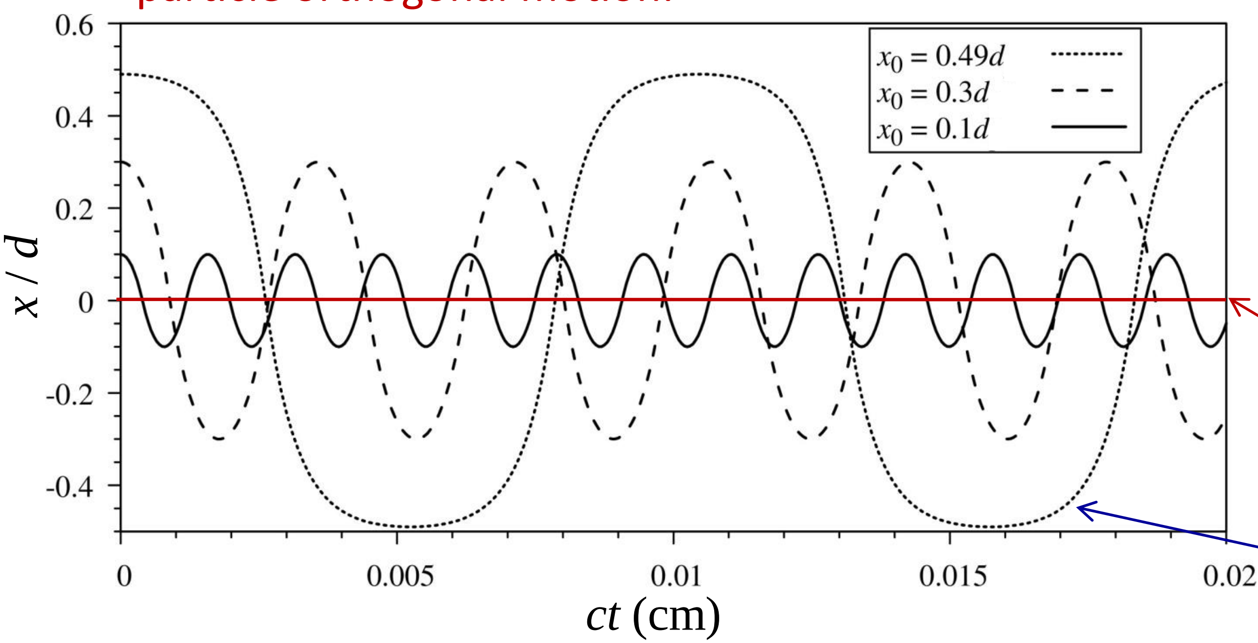
(110) planar potential:



$$\frac{d^2x}{dt^2} = -\frac{v}{p}\frac{\partial U(x)}{\partial x}$$

$$x(t) = d/2 + (x_0 - d/2)\,\mathrm{ch}\left\{\frac{2c}{d}\sqrt{\frac{2U_0}{pv}}\left[t - 2t_1 \mathrm{R}(t/2t_1)\right]\right\}\mathrm{sgn}\left[\cos(\pi t/2t_1)\right]$$

particle orthogonal motion:



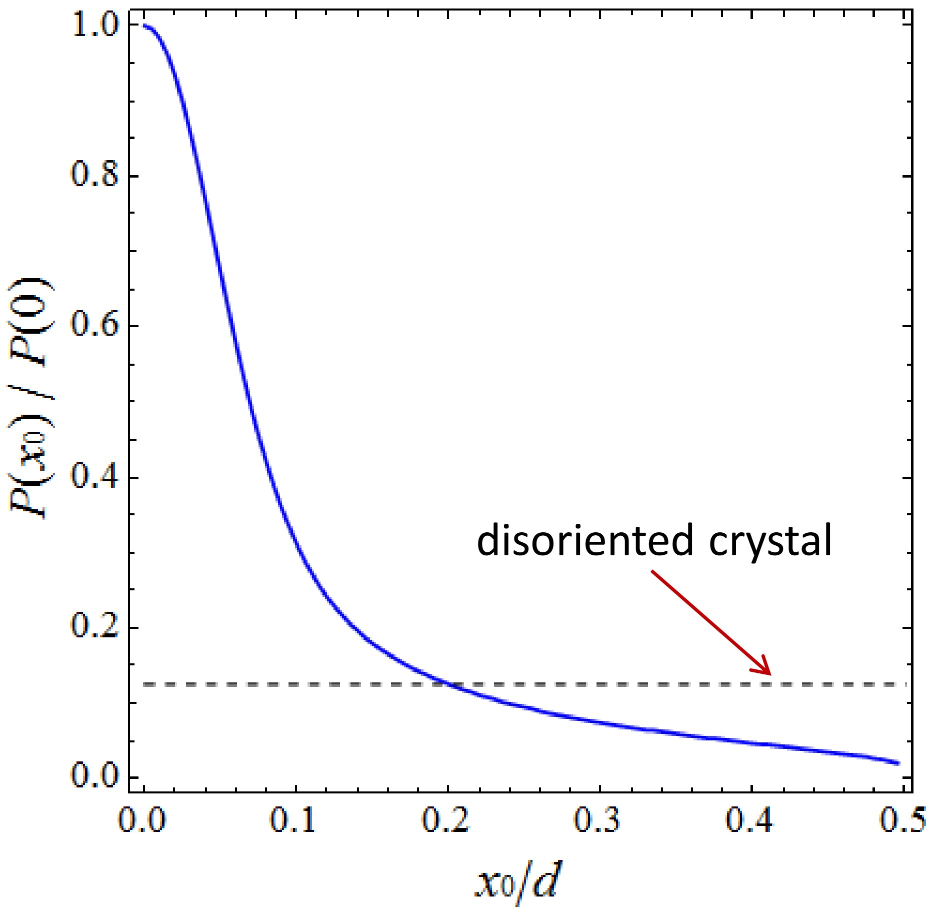
$$t_1 = \frac{1}{A}\,\mathrm{arch}\left(\frac{1}{1-2x_0/d}\right)$$

x_0 – impact parameter

crystalline plane

'hanging' mode of motion

PROBABILITY OF CLOSE COLLISIONS FOR CHANNELED NEGATIVE PARTICLES



Dependence of probability of close collisions of 150 GeV/*c* π^- mesons with atoms on the impact parameter (solid line)

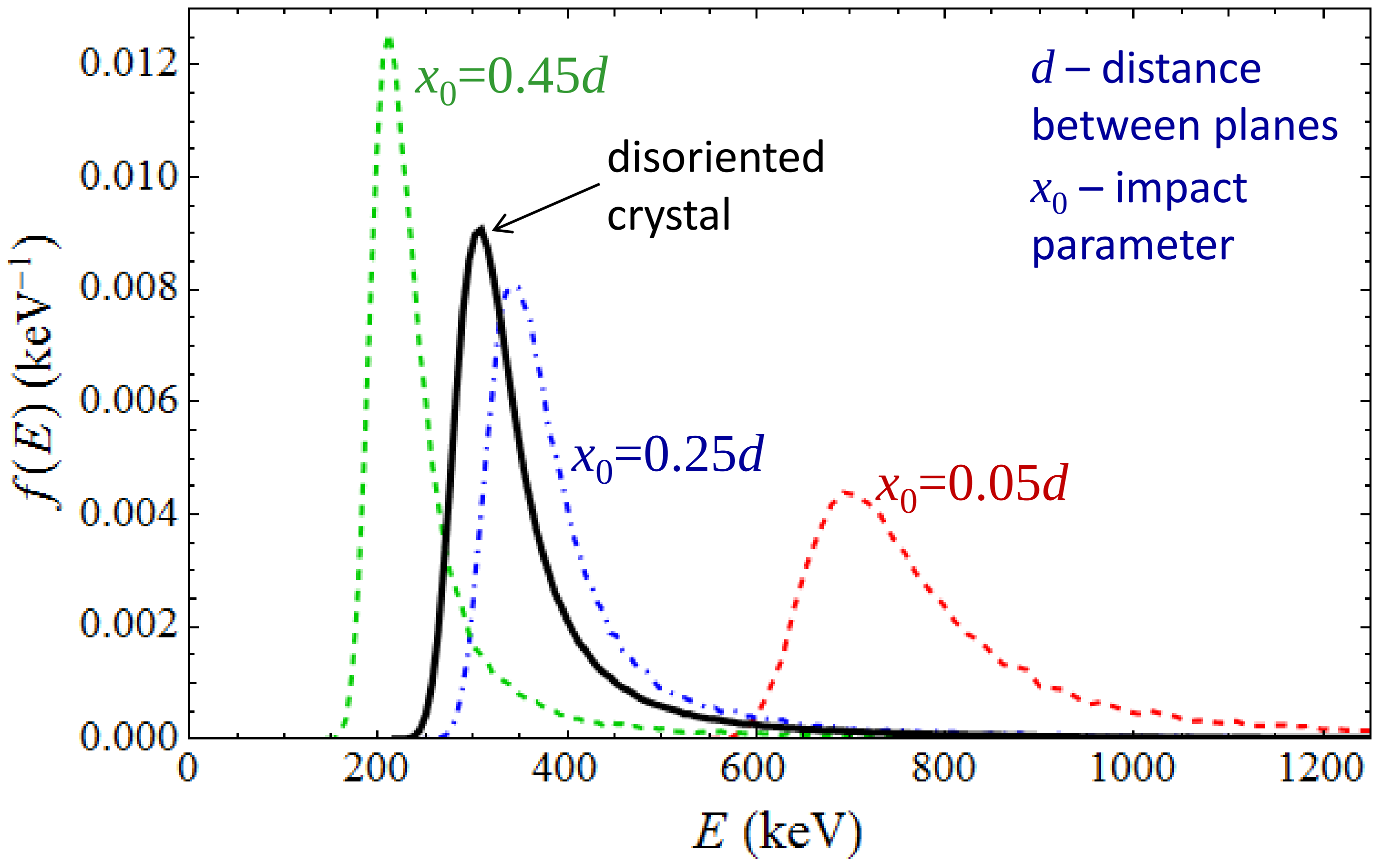
$$\frac{P(x_0)}{P(0)} = L^{-1}\int_0^T \exp\left(-\frac{x^2(t)}{2r_T^2}\right) v(t)dt$$

d – distance between planes

x_0 – impact parameter

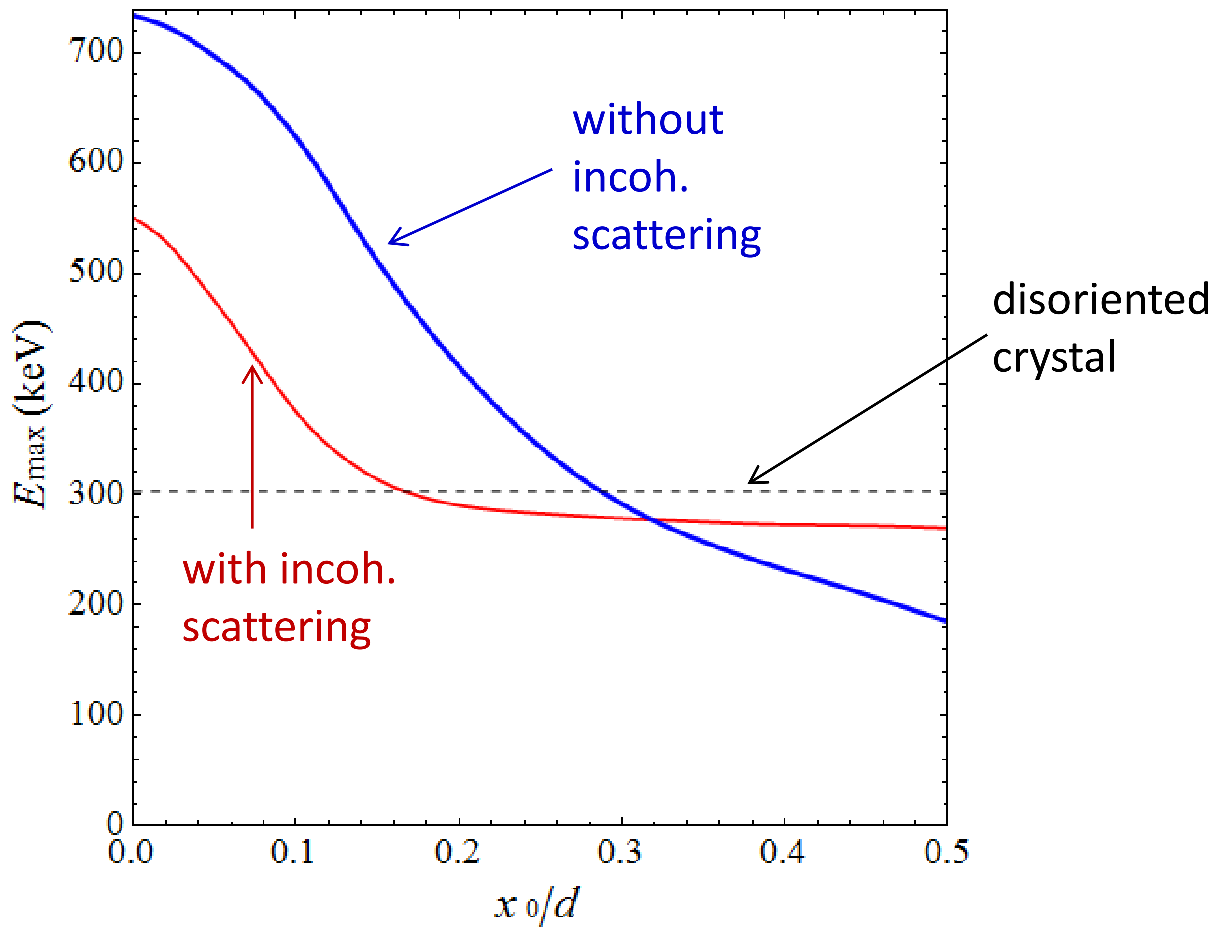
For a disoriented crystal: $\bar{P}_{\text{dis}} = \frac{2}{\sqrt{\pi}\xi}\text{erf}(\xi)$, where $\xi = d/\left(2\sqrt{2}r_T\right)$

IONIZATION LOSS SPECTRA FOR DIFFERENT IMPACT PARAMETERS



Ionization loss spectra of 150 GeV/*c* π^- mesons during planar channeling in the field of (110) planes of Si crystal for different values of the impact parameter

DEPENDENCE OF THE MOST PROBABLE IONIZATION LOSS ON THE IMPACT PARAMETER



The impact parameter dependence of the most probable ionization energy loss of 150 GeV/c π^- mesons during planar channeling in the field of (110) planes of Si crystal

CONCLUSIONS

- For $L \sim l_d$ the shape of the ionization loss spectrum is sensitive to the value of l_d
- A method of experimental determination of the dechanneling length, based on the measurement of the ionization loss spectrum, is proposed
- Most probable value of the ionization loss of negative particles considerably varies with the impact parameter with respect to the atomic plane
- Negatively charged channeled particles with large impact parameters can move in the 'hanging' mode having considerably suppressed probability of close collisions with the crystal atoms
- For a large group of incident particles, the most probable ionization energy loss during planar channeling in a crystal is lower than in an amorphous target, which explains the existence of the second (low energy) maximum of the spectrum

Test for an amorphous target: