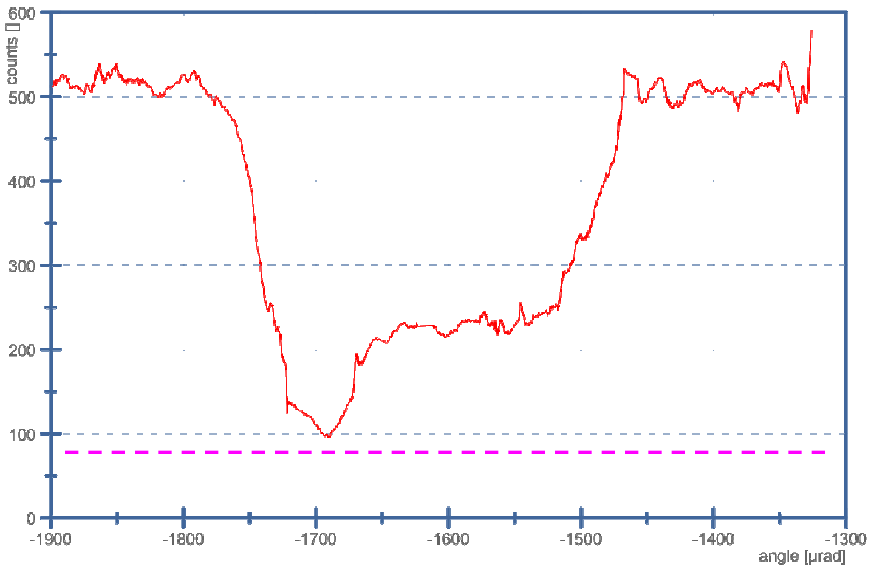
Probability of nuclear interactions of protons in a bent silicon crystal

It is well known that probability of close collisions with atoms is suppressed for channeled positive particles

Inelastic interactions with atomic nuclei should be also suppressed

How much?



Our measurements of beam losses in the SPS show the decrease in 5 times for channeling orientation

However, there are contributions from multiple passages

Is there some background when the crystal is far?

Probability of nuclear interactions – atomic density

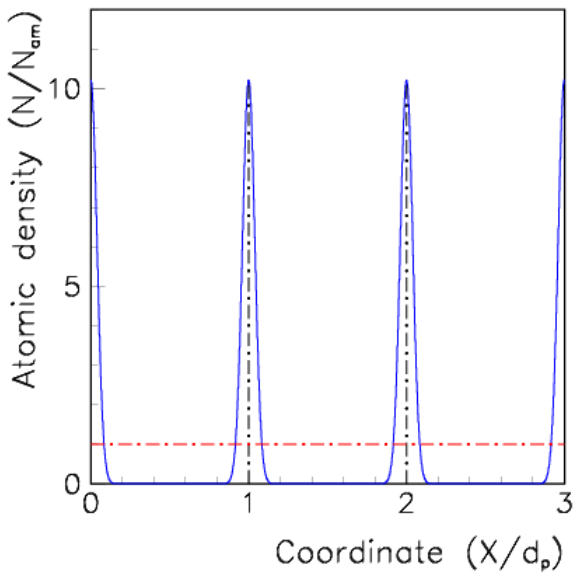
For a substance with atomic density N and length L – $P_{in}=\sigma_{in}NL$

For interaction of 400 GeV/c protons with Si nuclei in Glauber approach σ_{in} = 0.506 b

Atomic density in Si – $N=0.05\times10^{-24}$ cm^{-3} with L = 2 mm $\rightarrow$ P_{in}=0.506%

Thermal vibration of atoms around the plane position

gives the atomic distribution $N(x) \sim \exp(-x^2/(2u_1^2))$, u_1=0.075Å



There are no atoms in the middle of channel

At the plane position – $N(0)=10\ N_{am}$

Interactions occur near the planes

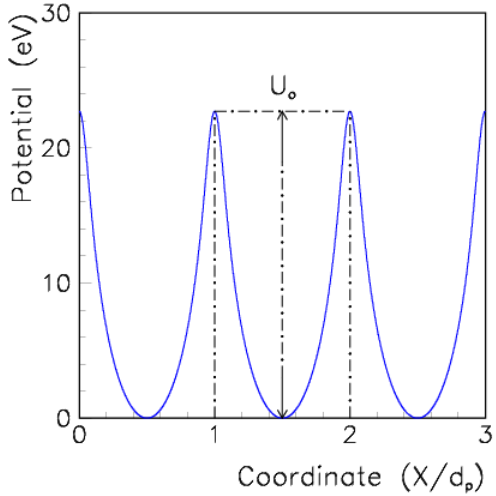
"nuclear corridor" width $6u_1 < 0.25\ d_p$

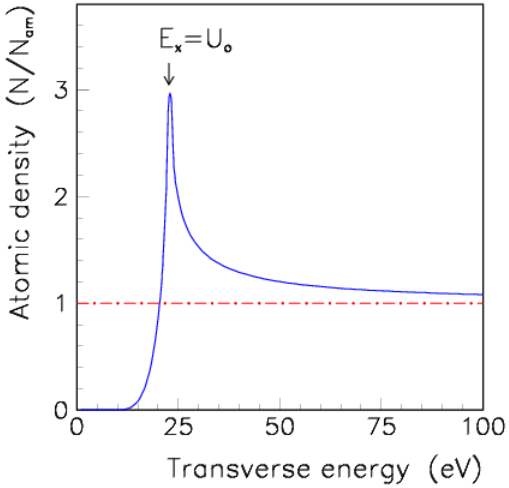
(110) Si channel width d_p=1.92 Å

Atomic density along trajectories – channeling and volume reflection

Potential averaged along the planes governs particle trajectories

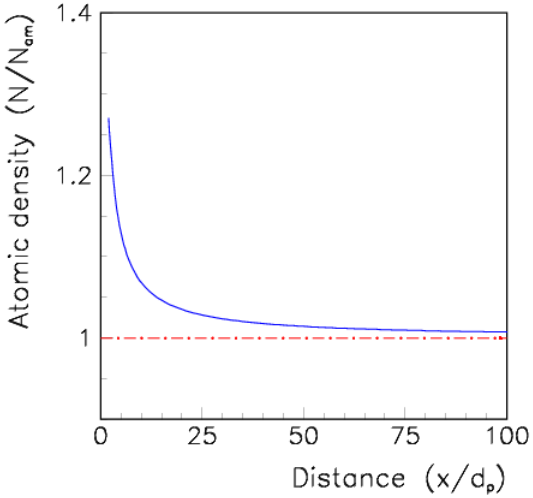
Averaged density is larger than N_{am} when transverse energy E_x is close to U_o for channeled particles with large amplitudes and for above-barrier particles



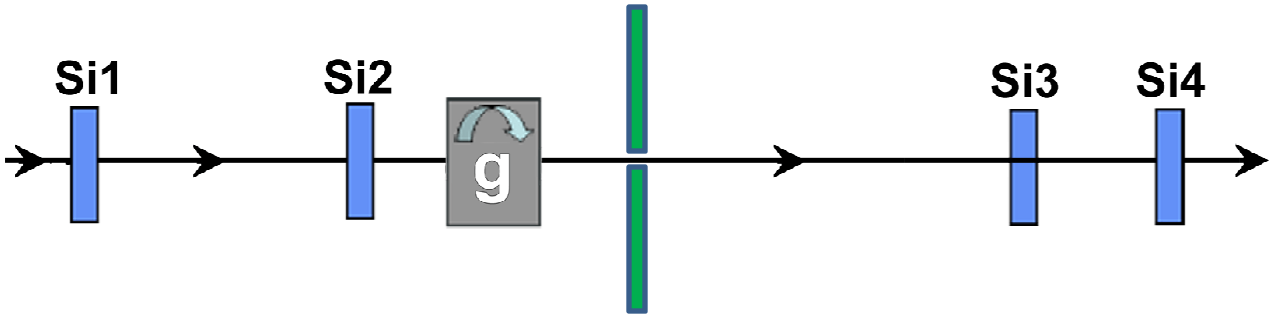


At VR in bent crystals near tangency point averaged density $N > N_{am}$ (27%)

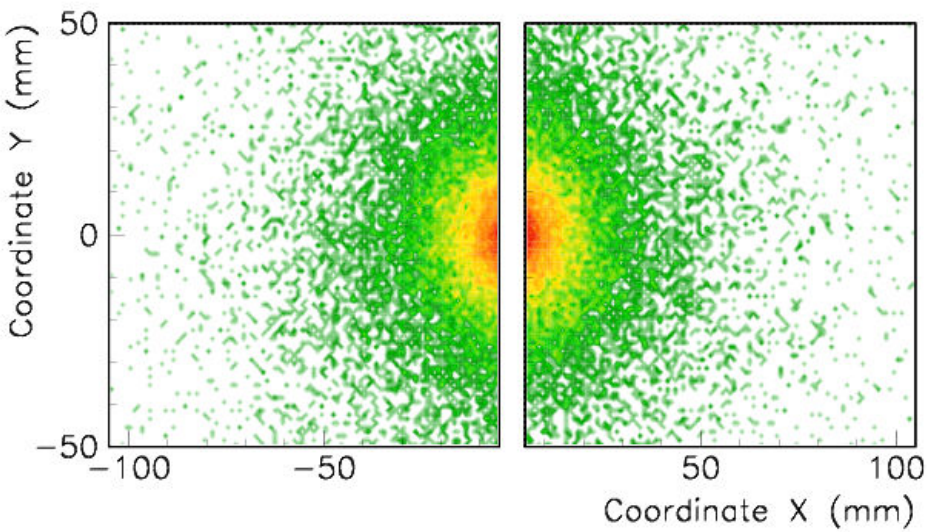
Averaged along L=2 mm – $N=1.02\ N_{am}$



Experiment with 400 GeV/c protons at H8 of the SPS



Two 10×10 cm^2 scintillation detectors – 60 cm behind the crystal



Distributions of secondary particles generated in inelastic interactions according to FRITIOF model

Part of coincidences – F_{12}=0.655

Beam fraction deflected by the bent crystal

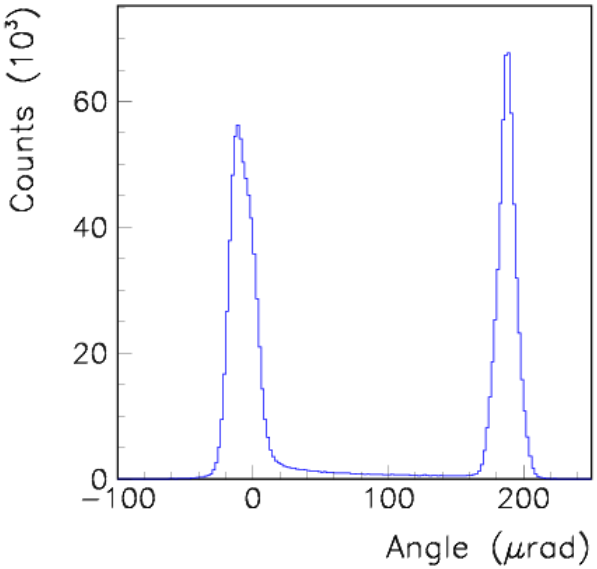
Incident beam divergence – σ_x=13.4 μrad

Critical channeling angle for 400 GeV/c protons in (110) Si – θ_c=10 μrad

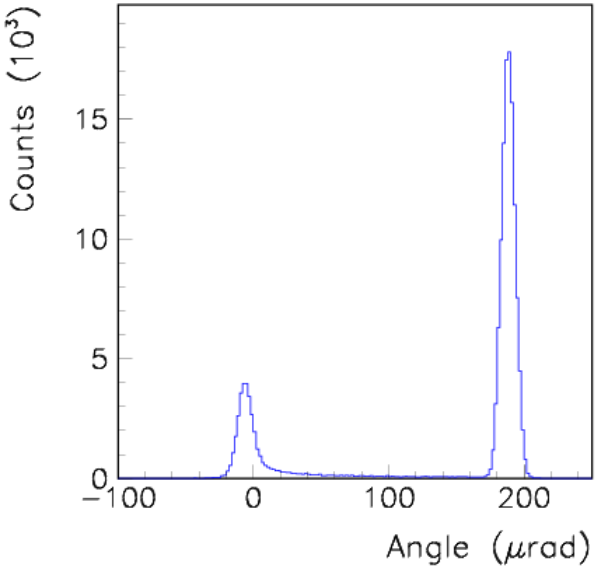
Particles with large incident angles can be avoided → angular cut

Cutting angle θ_{cut} – half size of the incident beam cone

θ_{cut}=20 μrad



θ_{cut}=1.5 μrad



Deflected fraction P_d

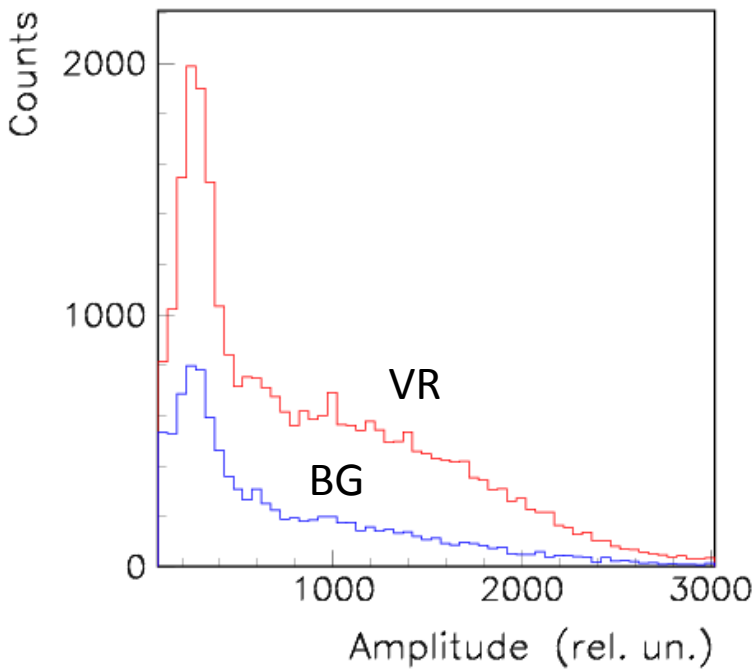
P_d=44.6%

P_d=72.5%

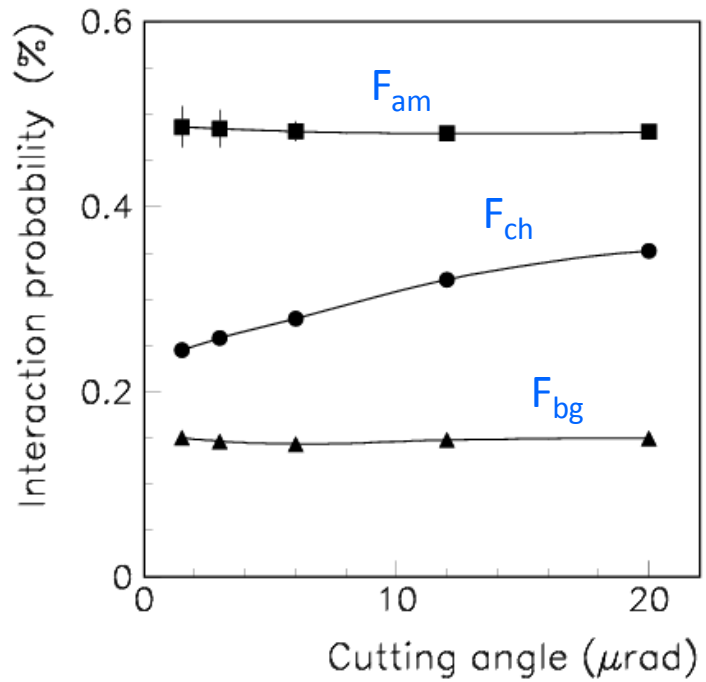
Scintillation detector amplitudes – inelastic events

Selected amplitude threshold A_b cuts the intrinsic detector background
Inelastic events occur also upstream the crystal – background spectrum (blue)

Amplitude spectra



Interaction frequency



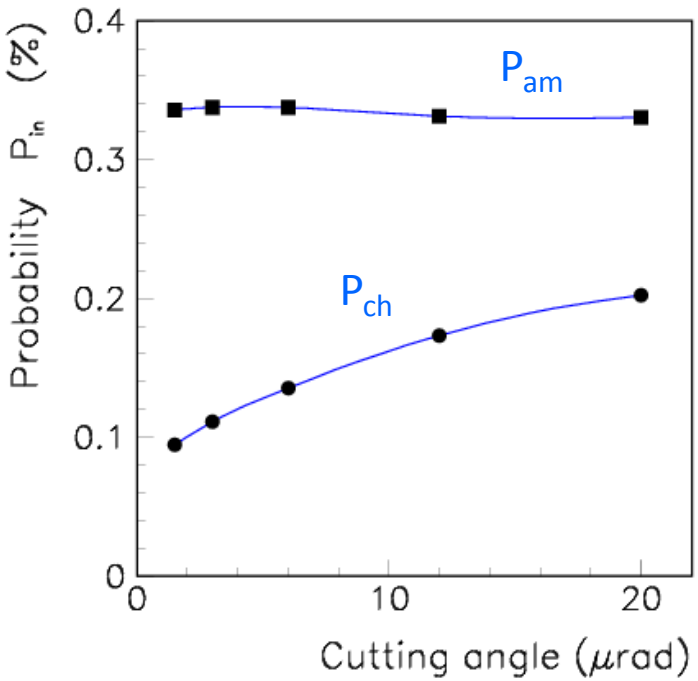
Interaction frequency – $F_{in}=N(A>A_b)/N_o$, $N(A>A_b)$ – number of coincidence in S_1 and S_2
N_o – incident particle number for given angular cut (triggers)

Nuclear interaction probability for amorphous and aligned crystal

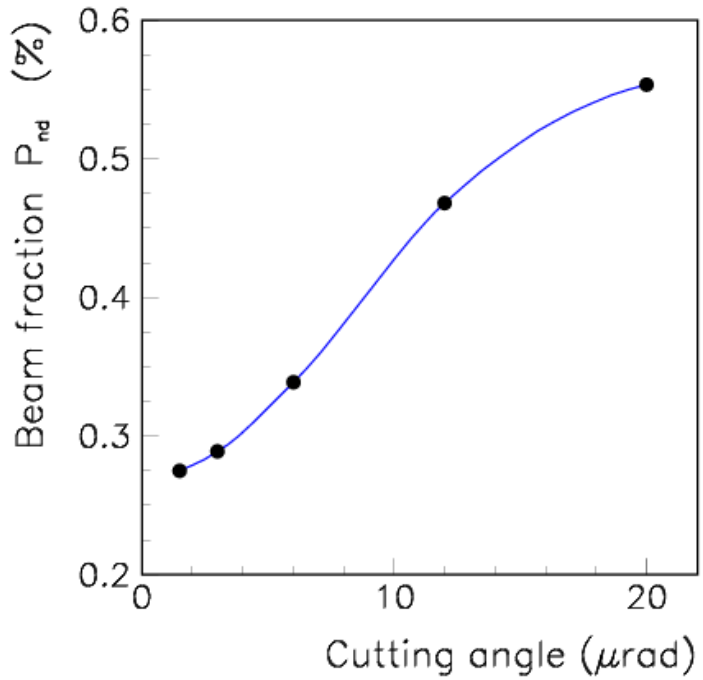
Interaction probability – $P_{in}=F_{in} - F_{in}(BG)$

For amorphous orientation $P_{am}=0.33\%$ → $P_{amc}=P_{am}/F_{12}=0.504\%$

Interaction probability



Non-deflected part



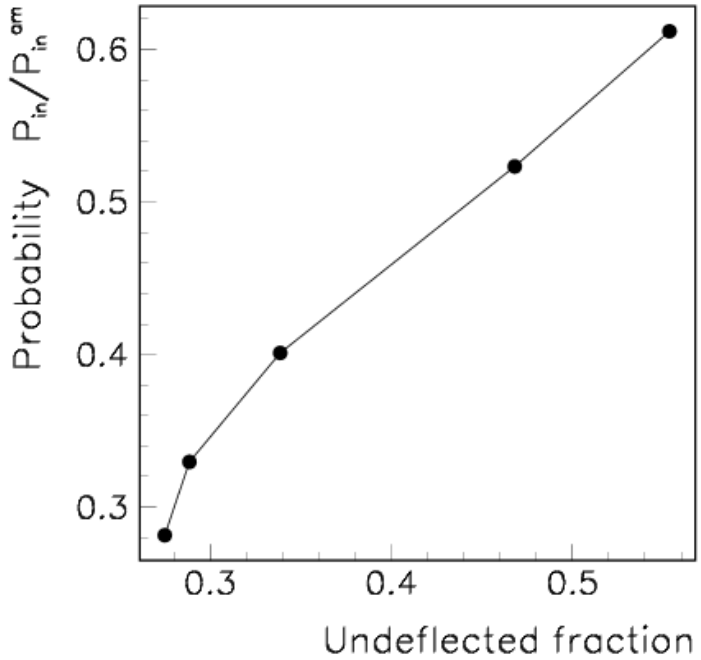
Non-deflected beam part P_{nd} increases when θ_{cut} increases

This increases the interaction probability

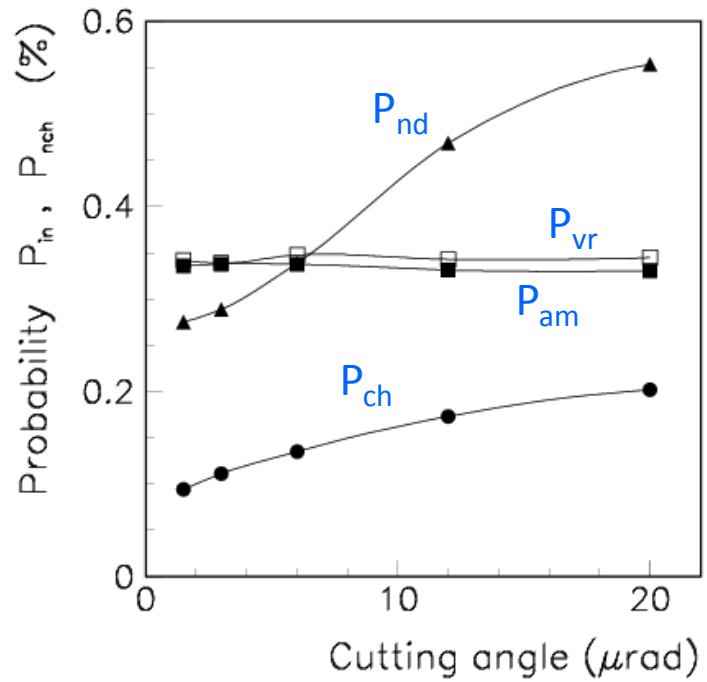
Interaction probability for channeling and volume reflection

For CH interaction probability decreases more than 3.5 times for min P_{nd} = 0.275

Probability ratio P_{ch}/P_{am}



VR case is shown



Interaction probability for volume reflection P_{vr} is larger by 2-4% that P_{am}

Conclusions

Goniometer instability and angular resolution of 3 μrad allowed to observe the deflection of protons with maximum efficiency P_d=72.5%

Inelastic interactions are produced by non-deflected beam part $P_{nd}=1-P_d$ and for maximum CH efficiency the inelastic probability was close to $P_{ch}=P_{nd}\times P_{am}=0.28P_{am}$

For parallel beam the deflection efficiency can be close to 85%
So, inelastic interaction probability in one passage should decrease about 5 times

Contribution of multiple passages of circulating particles at amorphous crystal orientations should increase this ratio

Considerable decrease of inelastic interaction yield in aligned crystal is additional advantage in compare with amorphous primary collimator