Frontier Detectors for Frontier Physics

14th Pisa meeting on advanced detectors

La Biodola • Isola d'Elba • Italy
27 May - 2 June, 2018

High-energy e^-/e^+ spectrometer via coherent interaction in a bent crystal

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INFN Istituto Nazionale di Fisica Nucleare

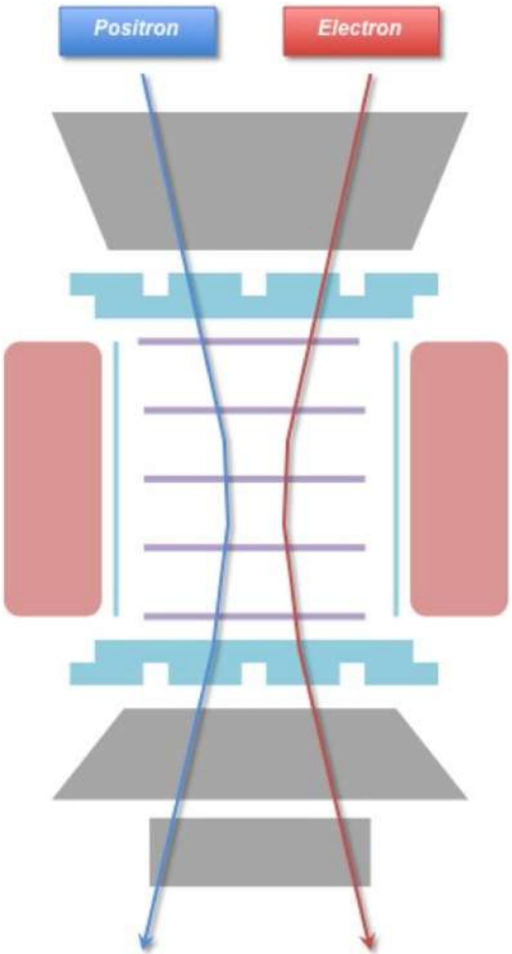
CRYS BEAM

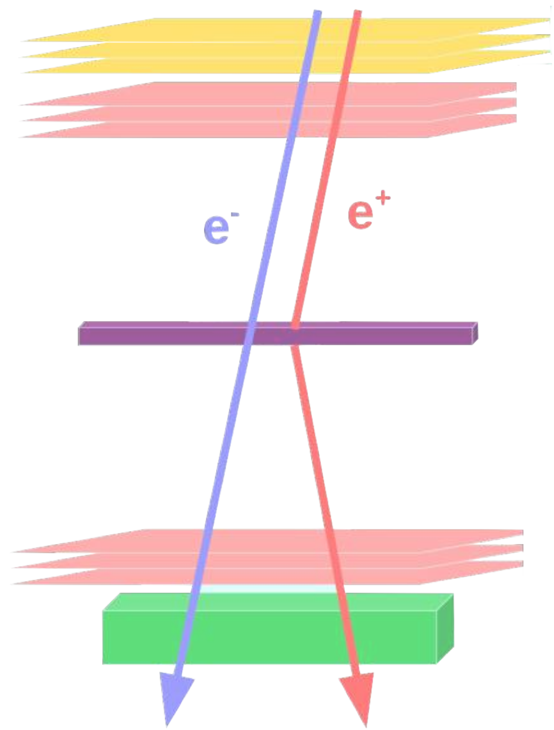
erc

ETH

Is it possible to measure the e^+/e^- ratio with a 1 cm bent crystal?

1 m

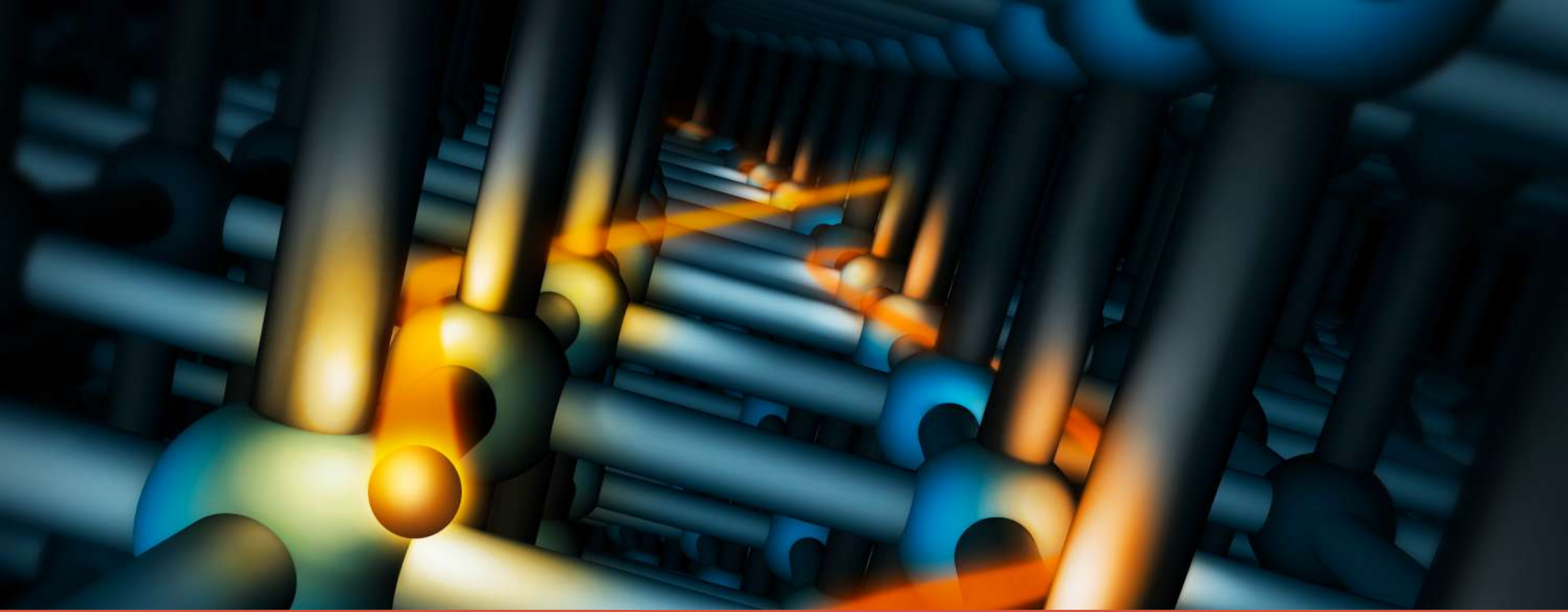




0.01 m

Outline

- Channeling:
  - Channeling
  - De-channeling
  - Channeling in bent crystals
- The idea
  - Basic scheme
  - Positron to electron ratio measurement
- Experimental Data
  - CERN SPS-H4 line
- Conclusions
  - Spin precession & Enhanced bremsstrahlung
  - Conclusions



CHANNELING

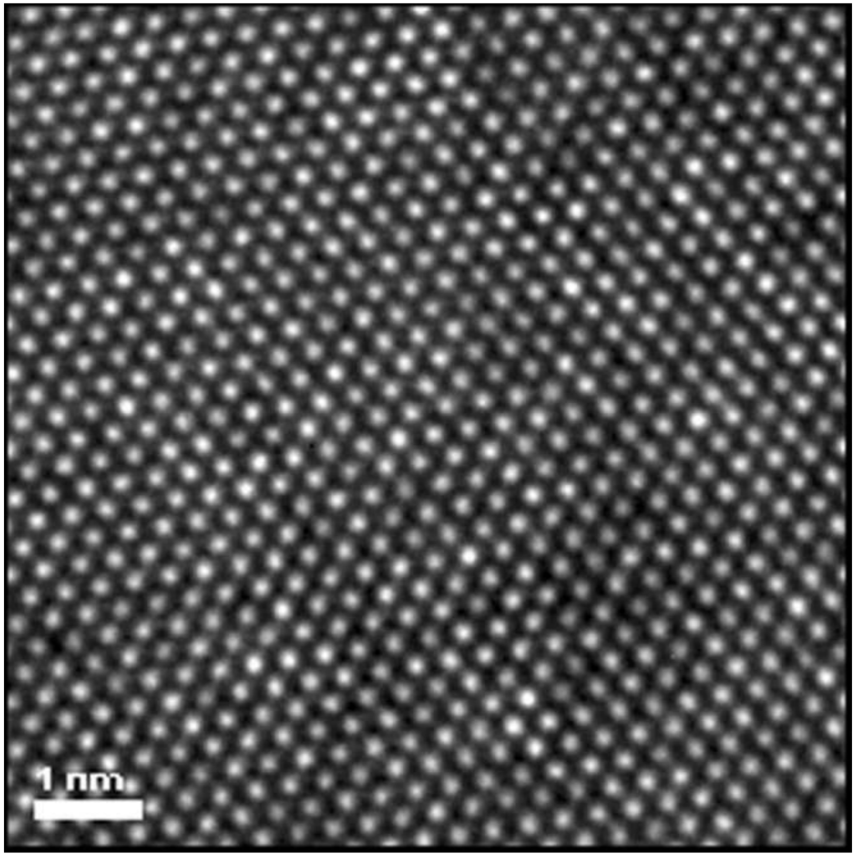
Entrapment of charged particles by the ordered pattern of crystalline atoms

Channeling
The Idea
Experimental data
Conclusions

Channeling

- A crystal is a microscopically ordered pattern of atoms.

HRTEM image of a silicon (Si) [110] crystallographic zone axis.

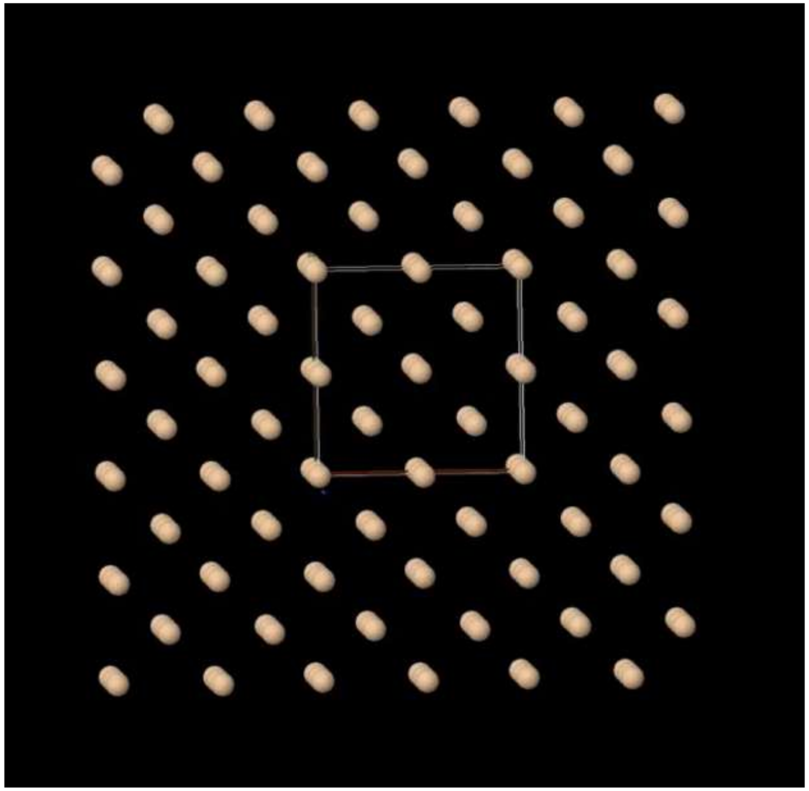


Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396

Channeling

- A crystal is a microscopically ordered pattern of atoms.
- The periodic arrangement of atoms generates a series of crystal planes.

Rotating Si crystal structure



Jmol: an open-source Java viewer for chemical structures in 3D. http://www.jmol.org/

Channeling

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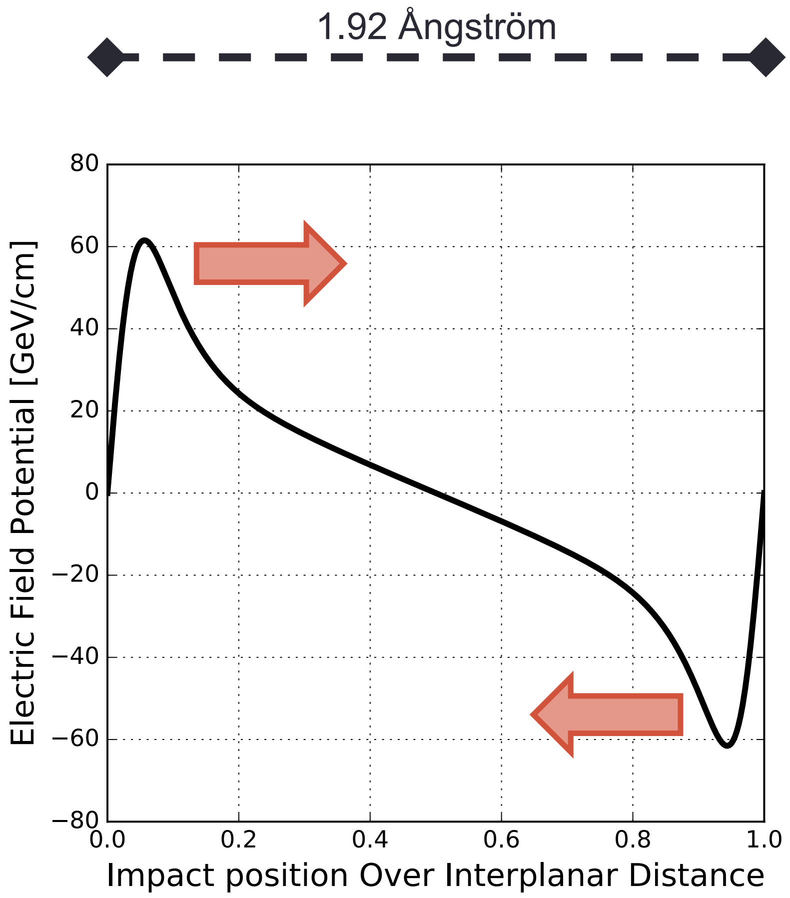
- The periodic arrangement of atoms generates a series of crystal planes.
- The ordered charges of the planes generates a strong electromagnetic field.

Inter-planar electric field for Si (110)



ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)

Channeling

- A crystal is a microscopically ordered pattern of atoms.
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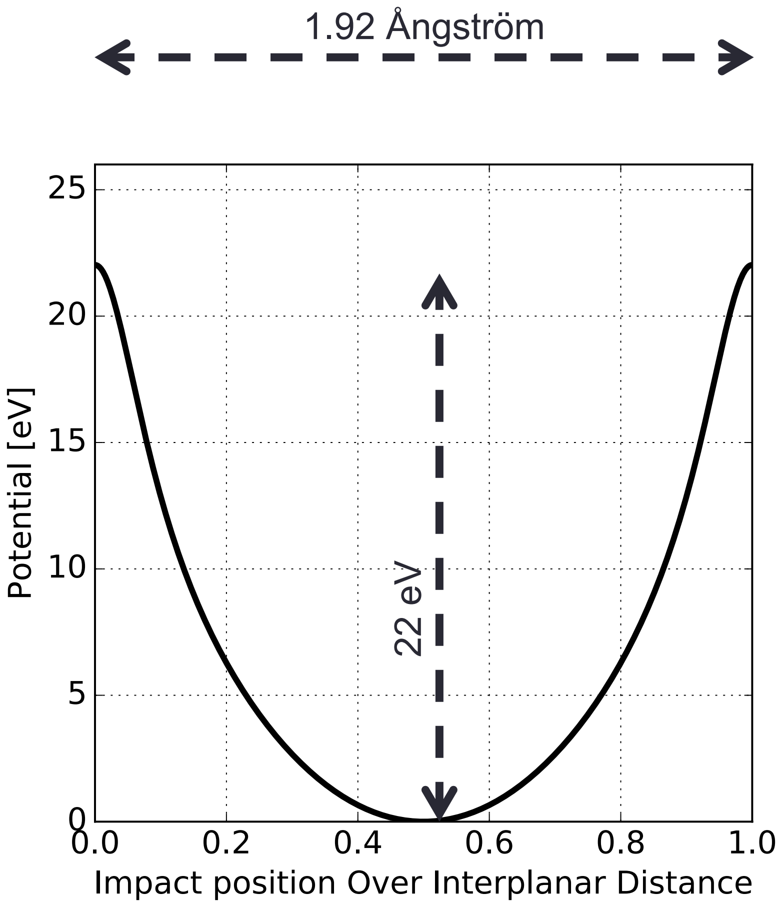
- The e.m. field generates a potential well able to constrain charged particles.

Inter-planar potential for Si (110)



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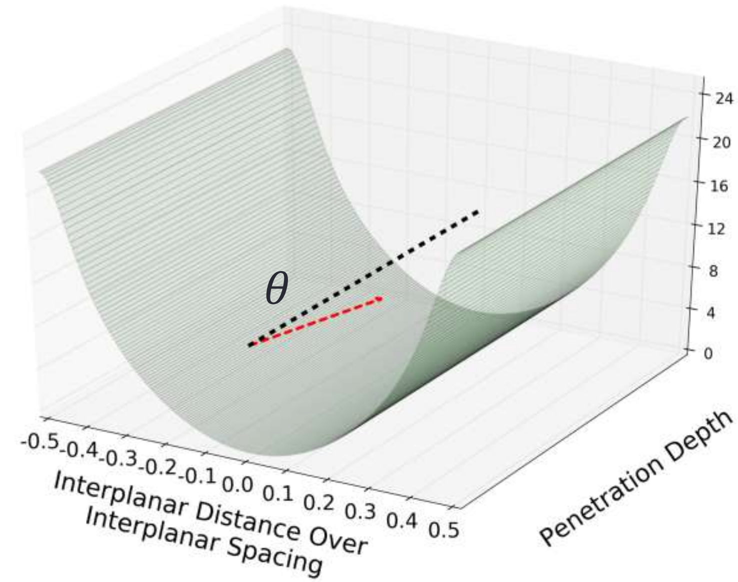

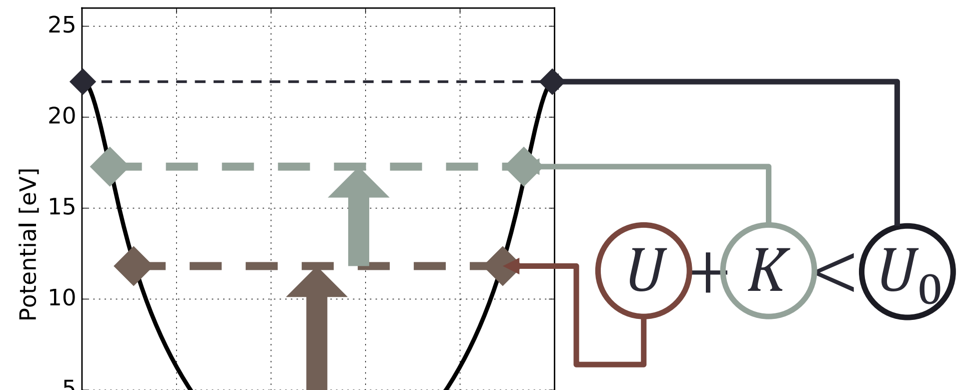

$$K = \frac{1}{2} p \beta \theta^2$$

Channeling

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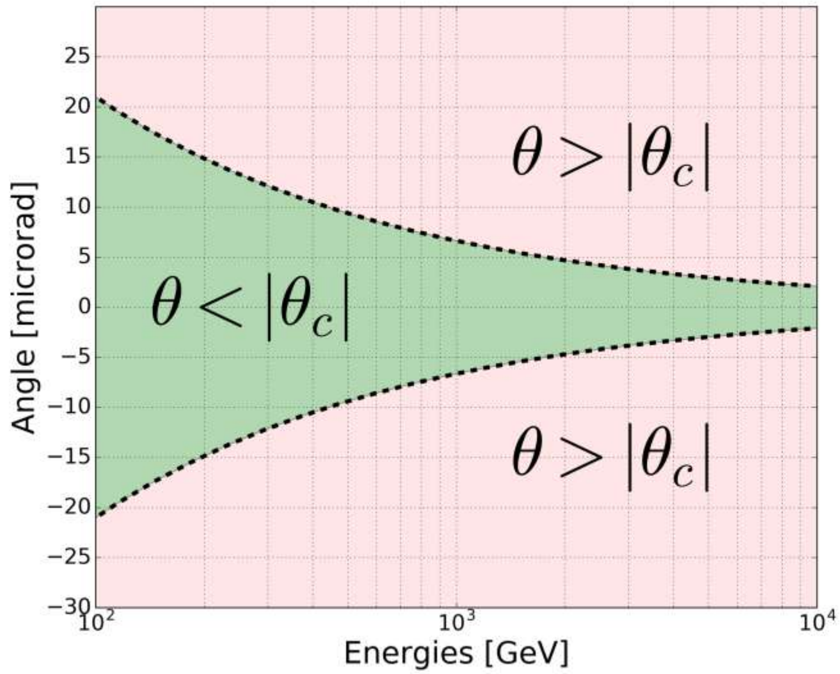
- Channeling occurs when the angle between the particle trajectory and the crystallographic plane is lower than the channeling critical angle, i.e. when the potential energy is lower than the potential well barrier.
- The channeling critical angle is proportional to the square root of the well depth of the inter-planar potential divided by the particle energy. Therefore, channeling is a directional process, especially for high-energy particles.



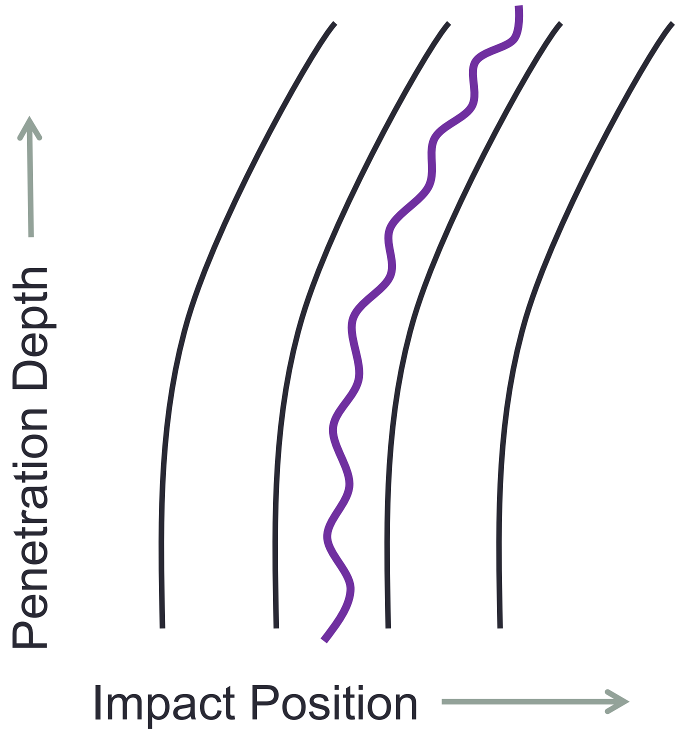
$$|\theta| < \theta_c = \sqrt{\frac{2U_0}{p\beta}}$$

J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14

Channeling in bent crystals

- In 1976 E. N. Tsyganov asks himself an interesting question.

"What will happen with the trajectory of the channeled particles if we bend the crystal? Up to some critical value of the bending radius a particle trajectory will repeat the shape of a bent crystal."



E. Tsyganov, *"Some aspects of the mechanism of a charge particle penetration through a monocrystal."* Tech. rep., Fermilab (1976) Preprint TM-682

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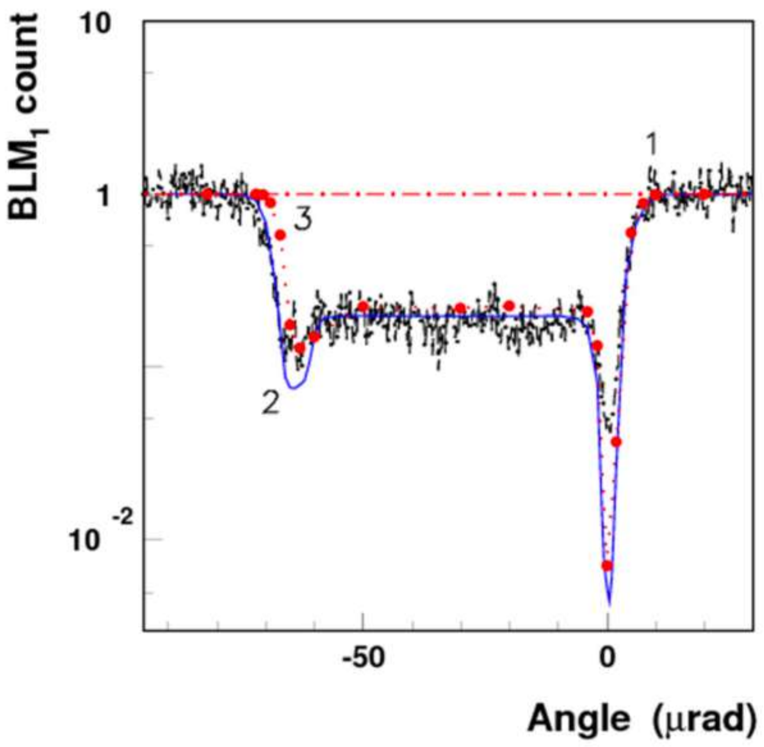

W. Scandale et al., *"Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC"* Physics Letters B 758 (2016), 129

Channeling in bent crystals

- In 1976 E. N. Tsyganov asks himself an interesting question.
- Channeling in bent crystals was observed from 195 MeV/c e- (MAMI) to 6.5 TeV/c proton (LHC).
- Curvature affects particle motion causing a centrifugal force, lowering the potential well barrier.

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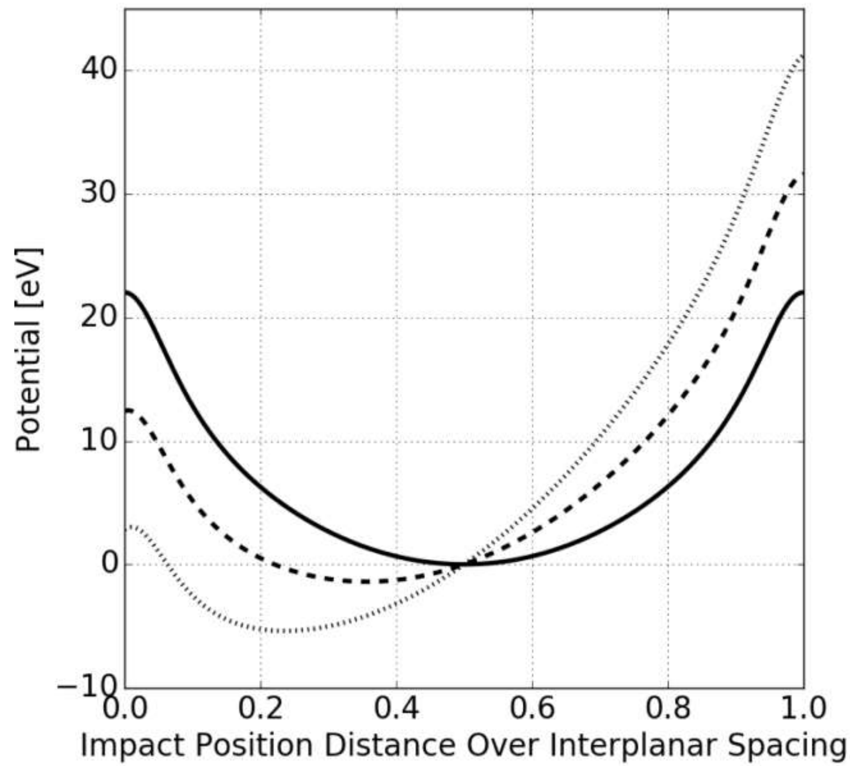
Inter-planar potential for Si (110)



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

Channeling in bent crystals

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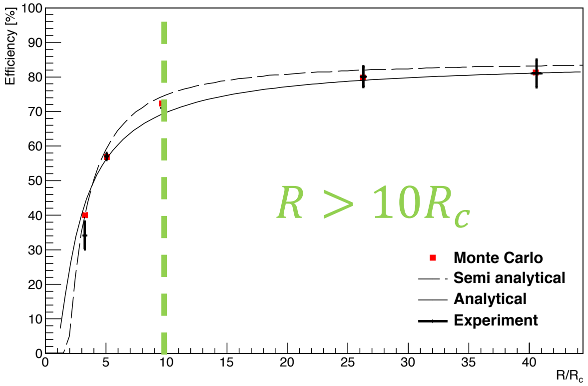
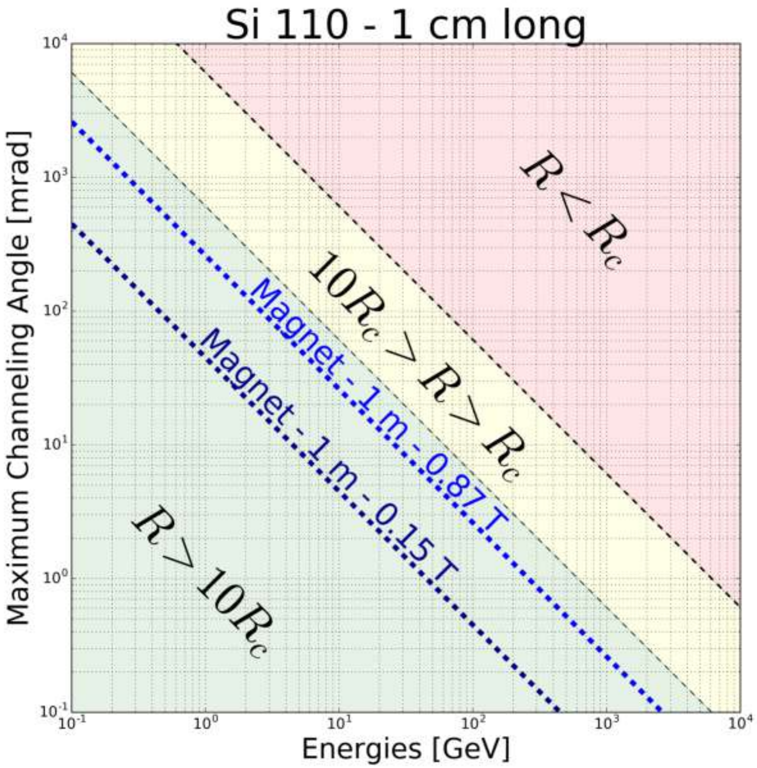
- Channeling in bent crystals was observed from 195 MeV/c e⁻ (MAMI) to 6.5 TeV/c proton (LHC).
- Curvature affects particle motion causing a centrifugal force, lowering the potential well barrier.
- The maximum achievable bending angle is determined by the critical radius, proportional to the particle momentum-velocity. At $10R_c$ the efficiency is almost the maximum achievable.



E. Bagli et al., Eur. Phys J. C, 74 (2014), 2740



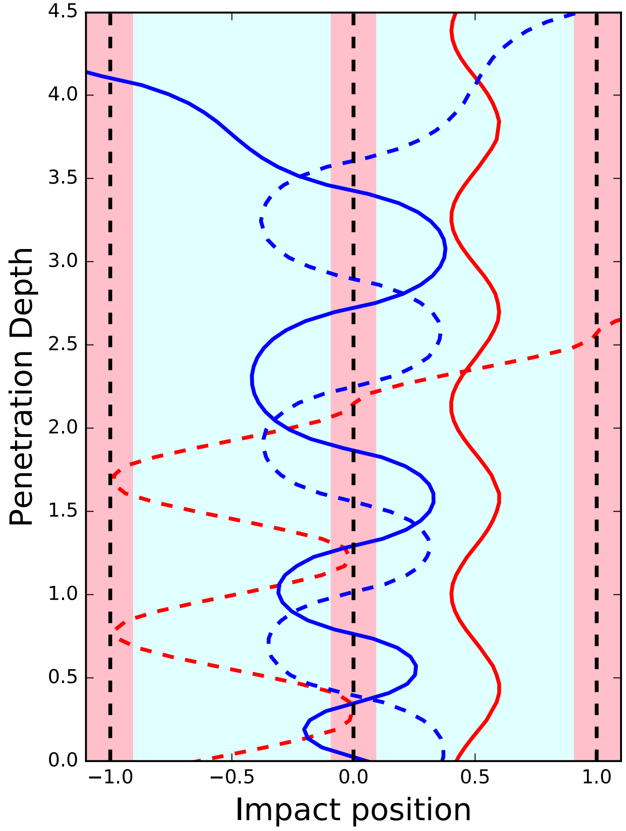
$$R_c = \frac{p\beta}{U'_{max}}$$

E. Tsyganov, Tech. rep., Fermilab (1976) Preprint TM-682

Dechanneling

- A particle that leaves the channeling state undergoes the *“dechanneling”* process.

Positrons and Electrons trajectories under channeling in a Si (110)



E. Bagli, V. Guidi, A. Howard, Astroparticle Physics 97 (2018) 27

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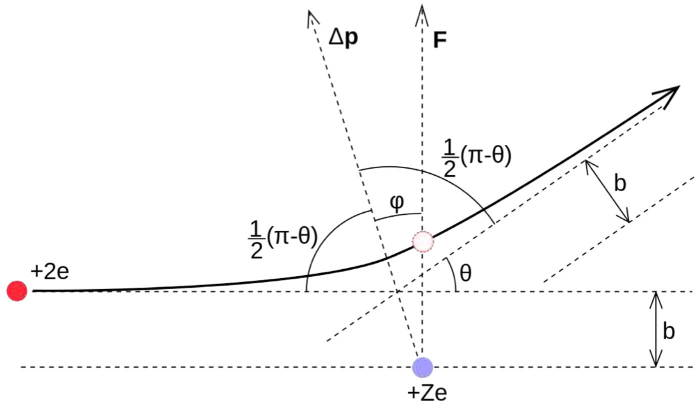

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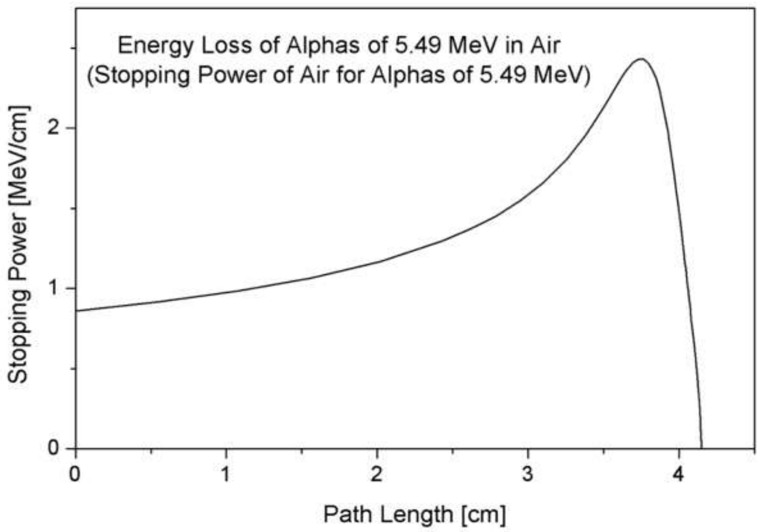

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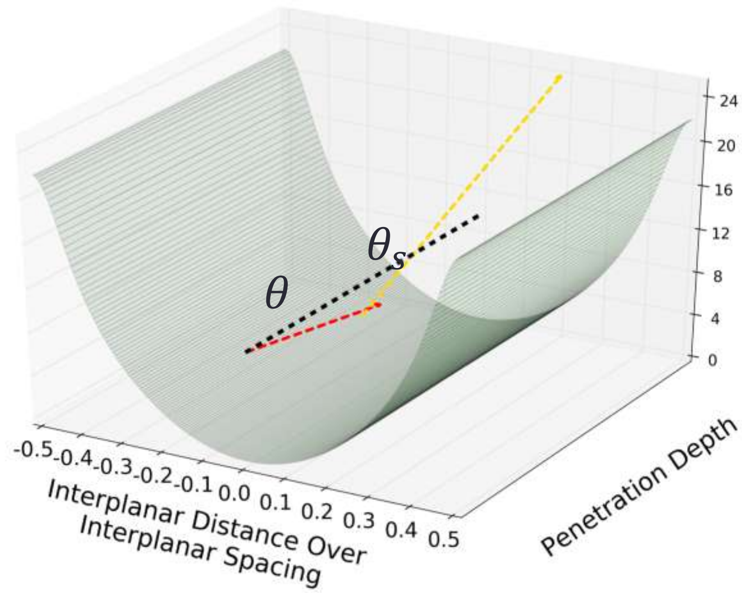

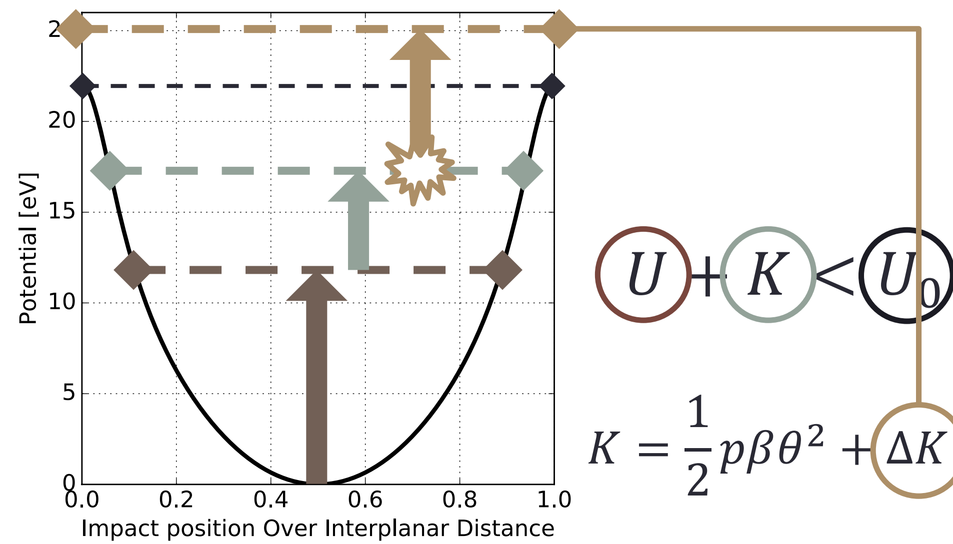

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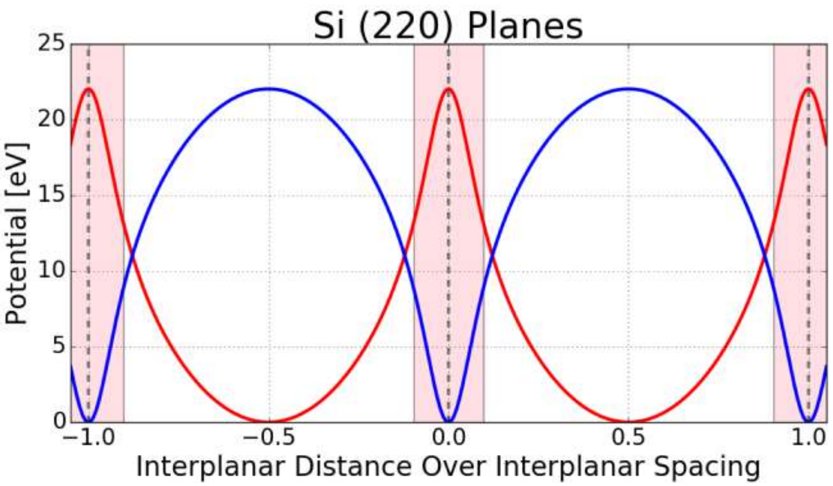
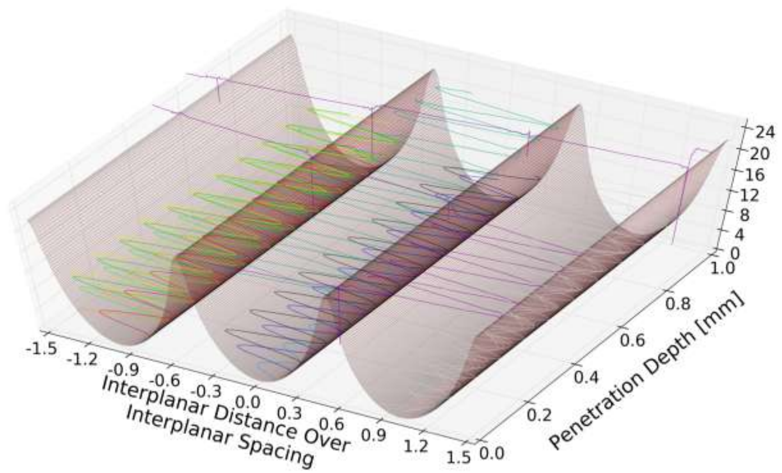
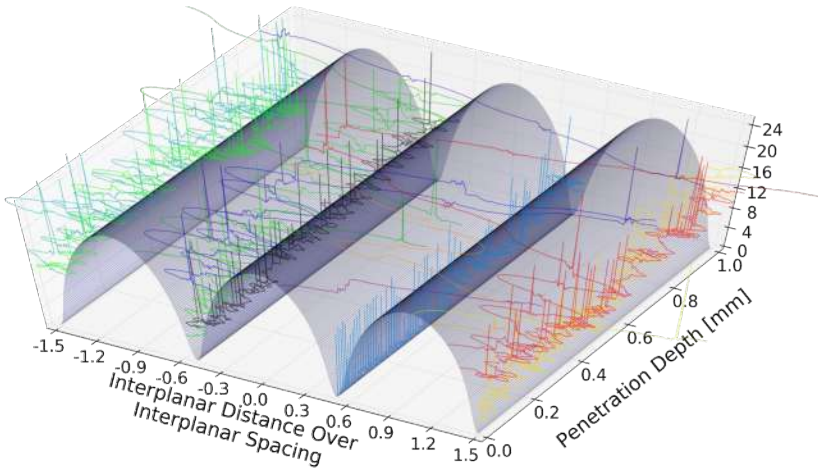
- Channeling depends on particle charge sign:







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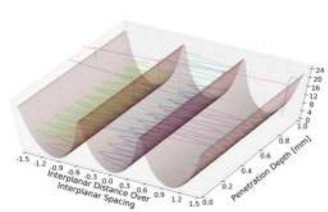
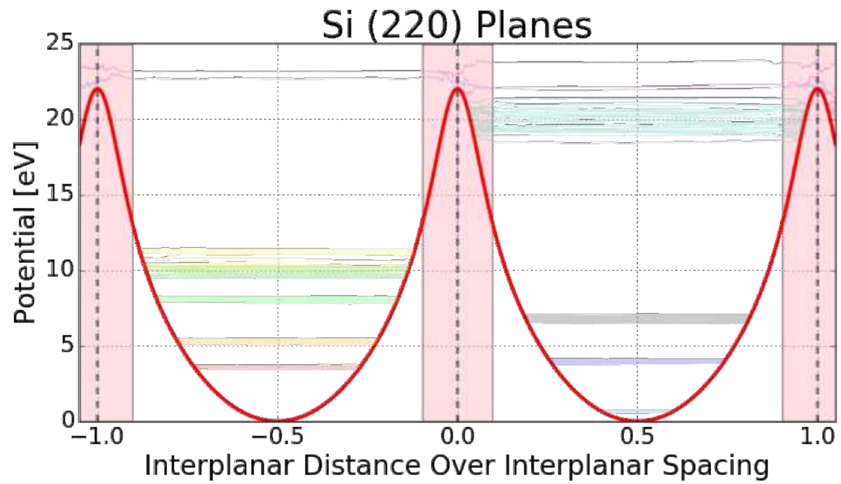
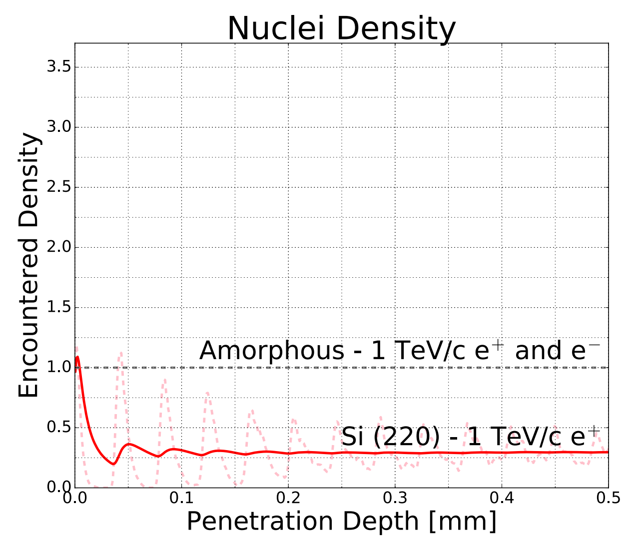
- Channeling depends on particle charge sign:
  - A positively charged particle that oscillates ***between*** two planes **rarely** interacts with the atomic nuclei.







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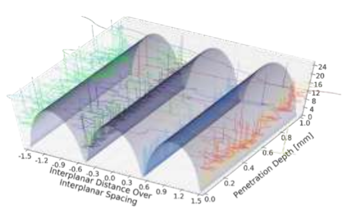
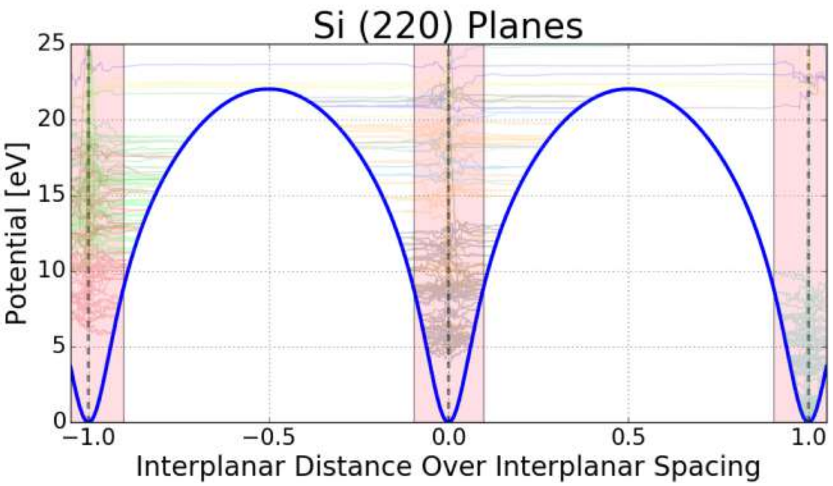
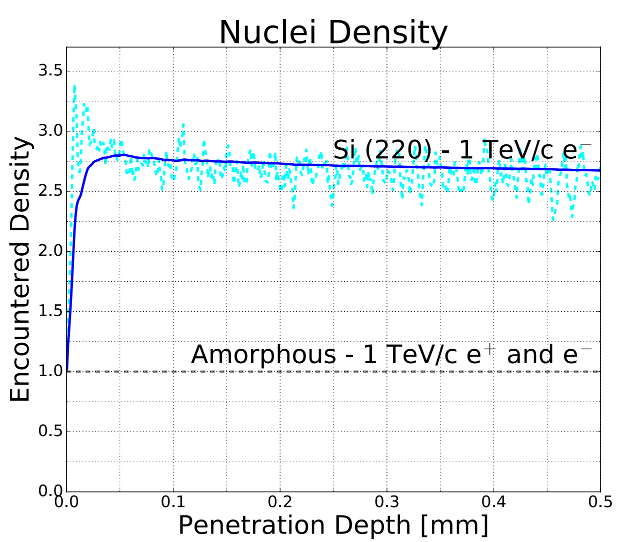
  - A negatively charged particle that oscillates ***over*** two planes **frequently** interacts with the atomic nuclei.







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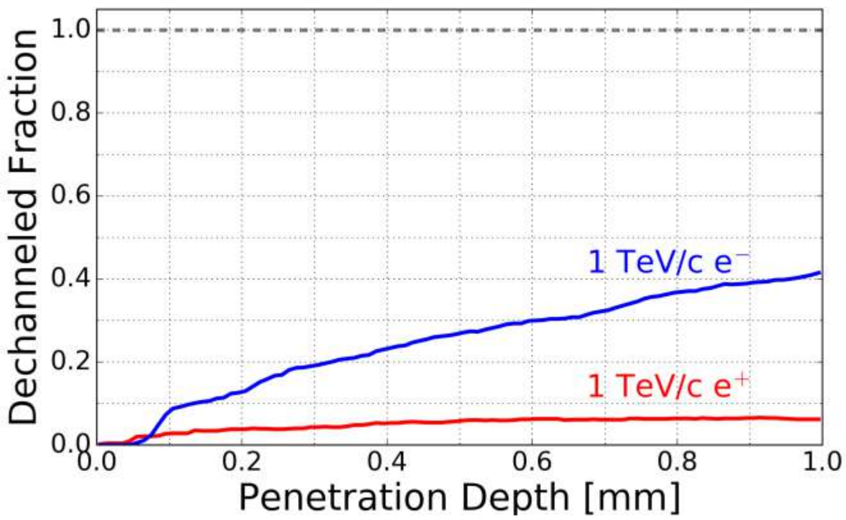
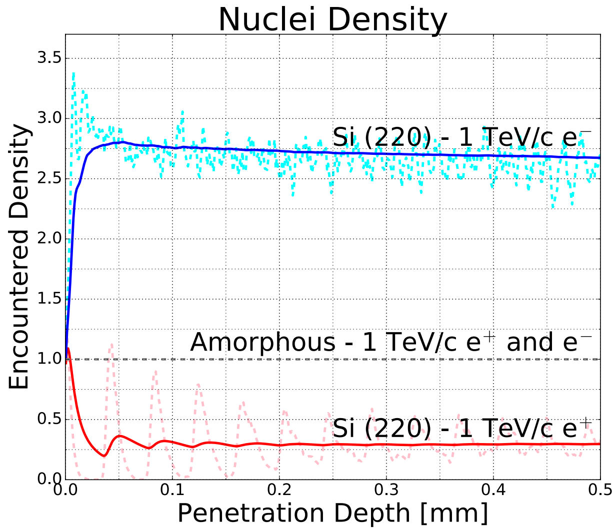
- ***Electrons dechannel more frequently than Positrons***



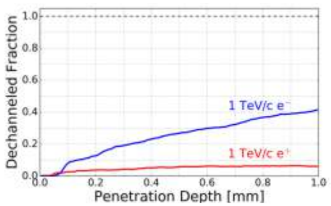


THE IDEA

Channeling
Conclusions
The Idea
Experimental data

Basic scheme

Different dechanneling rate for positive and negative particles



E. Bagli, V. Guidi, A. Howard, *"High-energy e⁻/e⁺ spectrometer via coherent interaction in a bent crystal "*, Astroparticle Physics 97 (2018) 27

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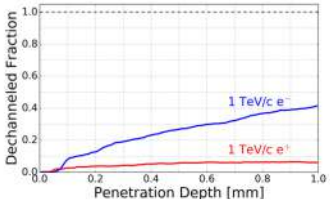

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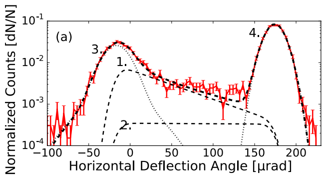
Deflection of charged particles under channeling in bent crystals



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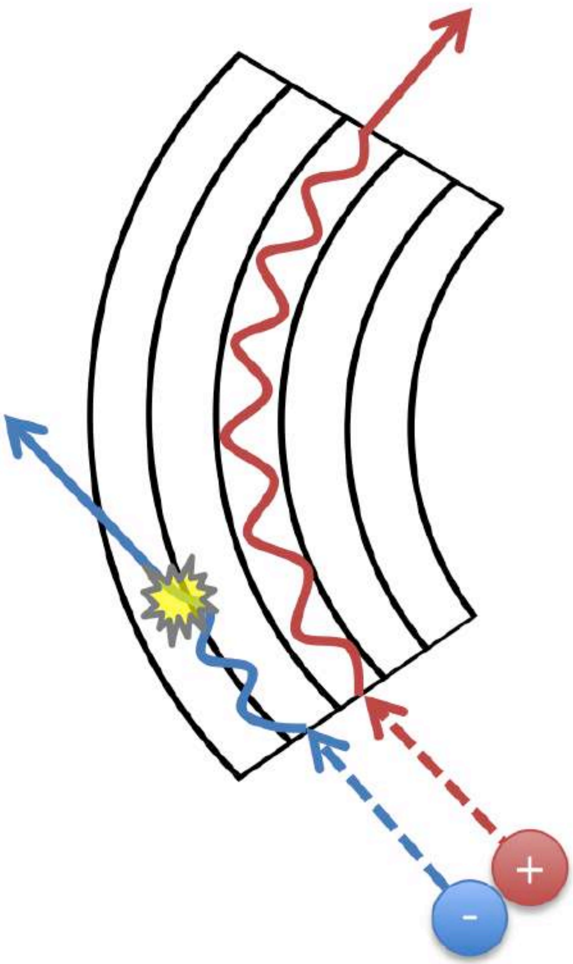

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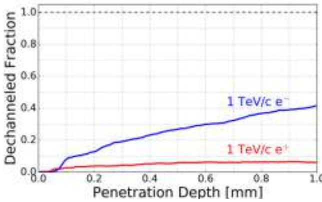

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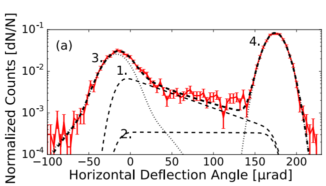
Deflection of charged particles under channeling in bent crystals



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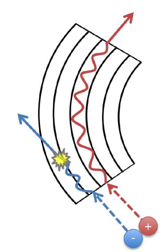
Positron to electron ratio measurement via channeling



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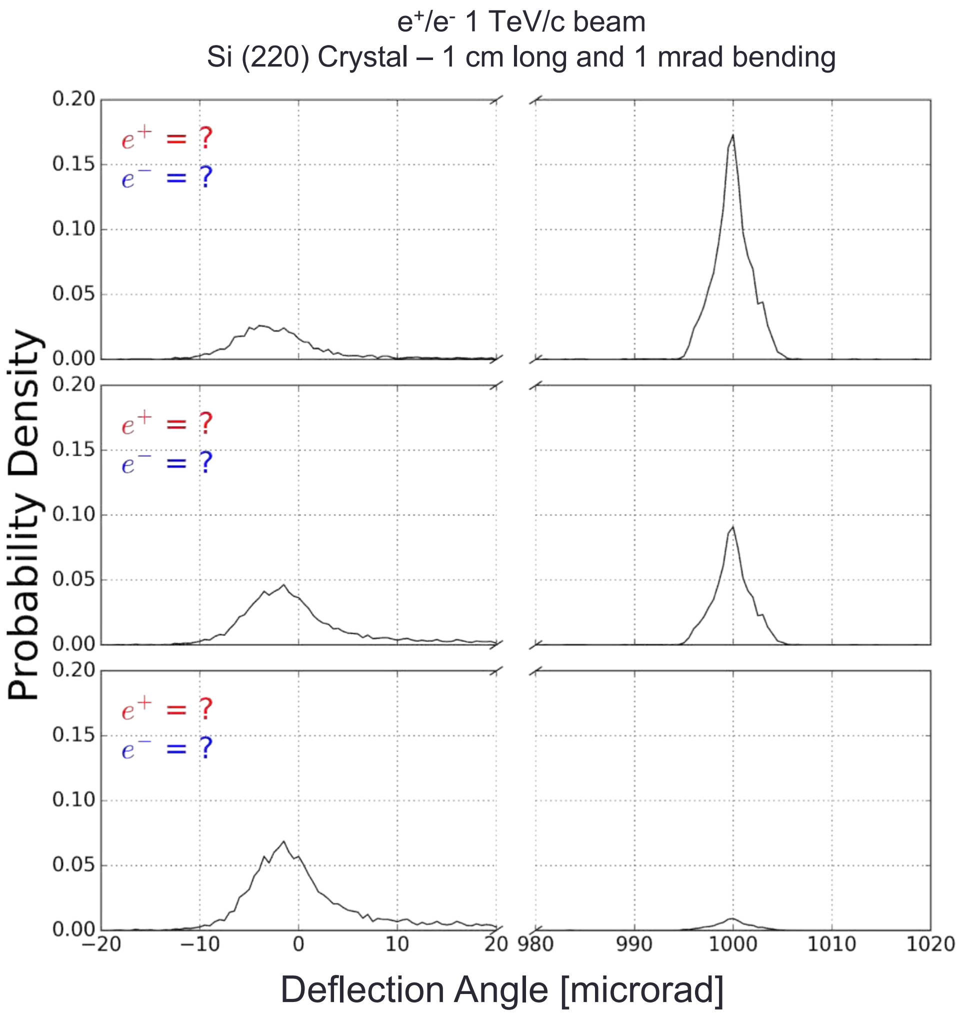
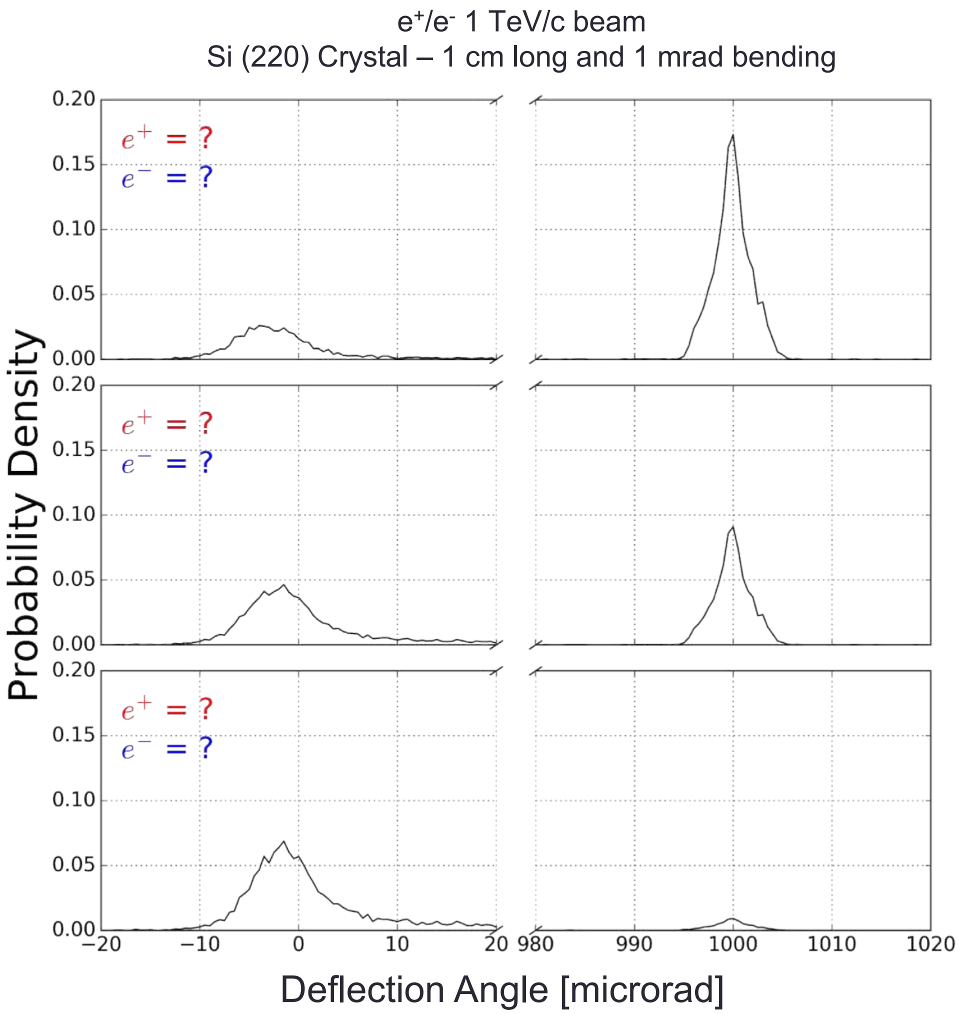
Positron to electron ratio measurement



- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.

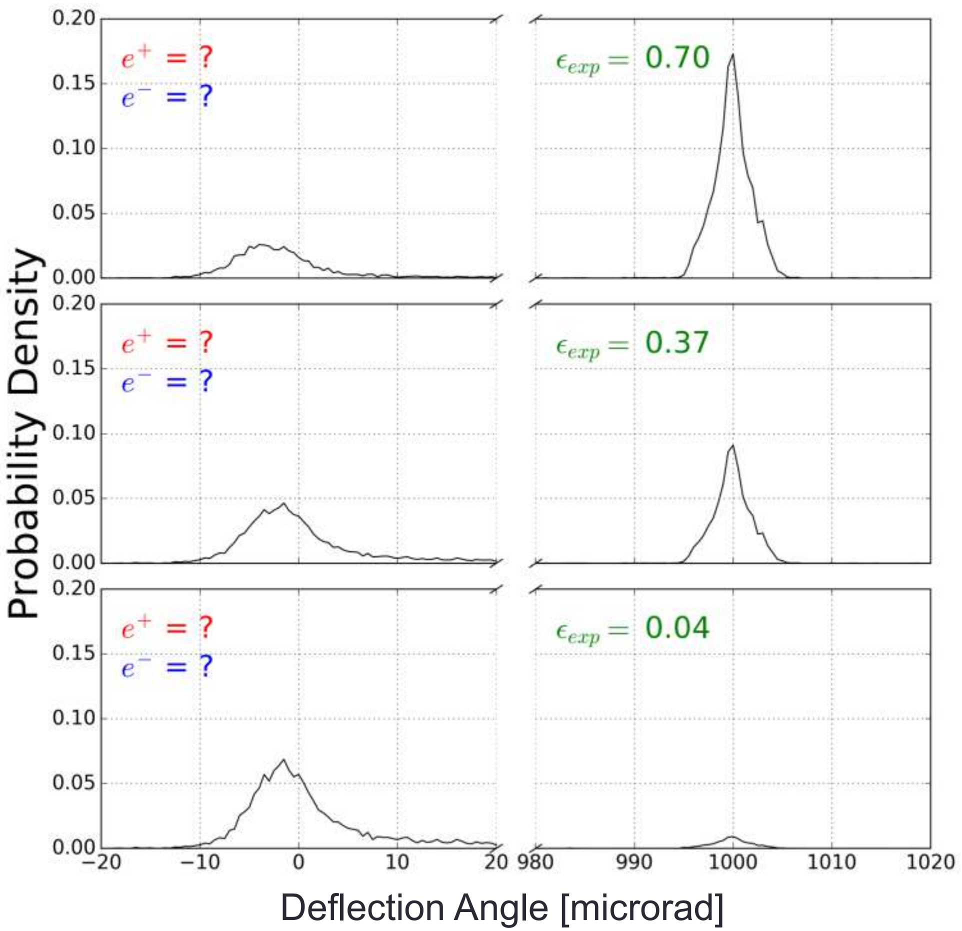
Positron to electron ratio measurement



- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.
- Two ingredients are needed:

Positron to electron ratio measurement

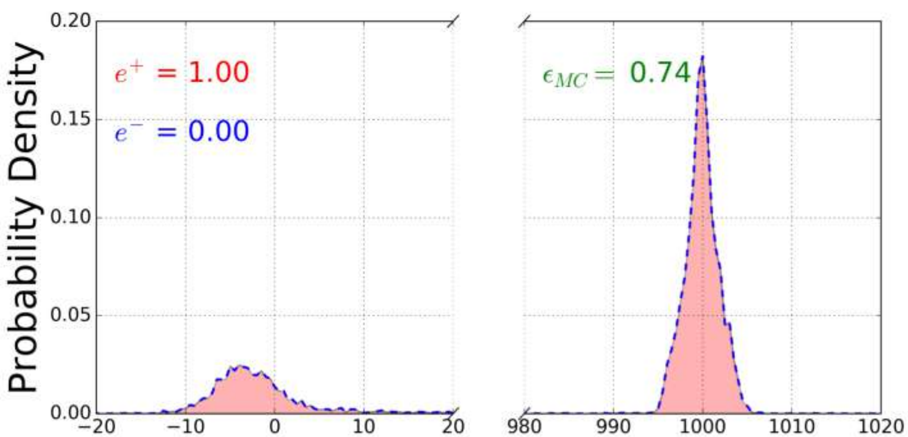
e^+/e^- 1 TeV/c beam
Si (220) Crystal – 1 cm long and 1 mrad bending



- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.
- Two ingredients are needed:
  - Experimental deflection distribution

Positron to electron ratio measurement

e^+/e^- 1 TeV/c beam
Si (220) Crystal – 1 cm long and 1 mrad bending



Deflection Angle [microrad]

- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.

- Two ingredients are needed:
  - Experimental deflection distribution
  - Monte Carlo

Positron to electron ratio measurement

e^+/e^- 1 TeV/c beam
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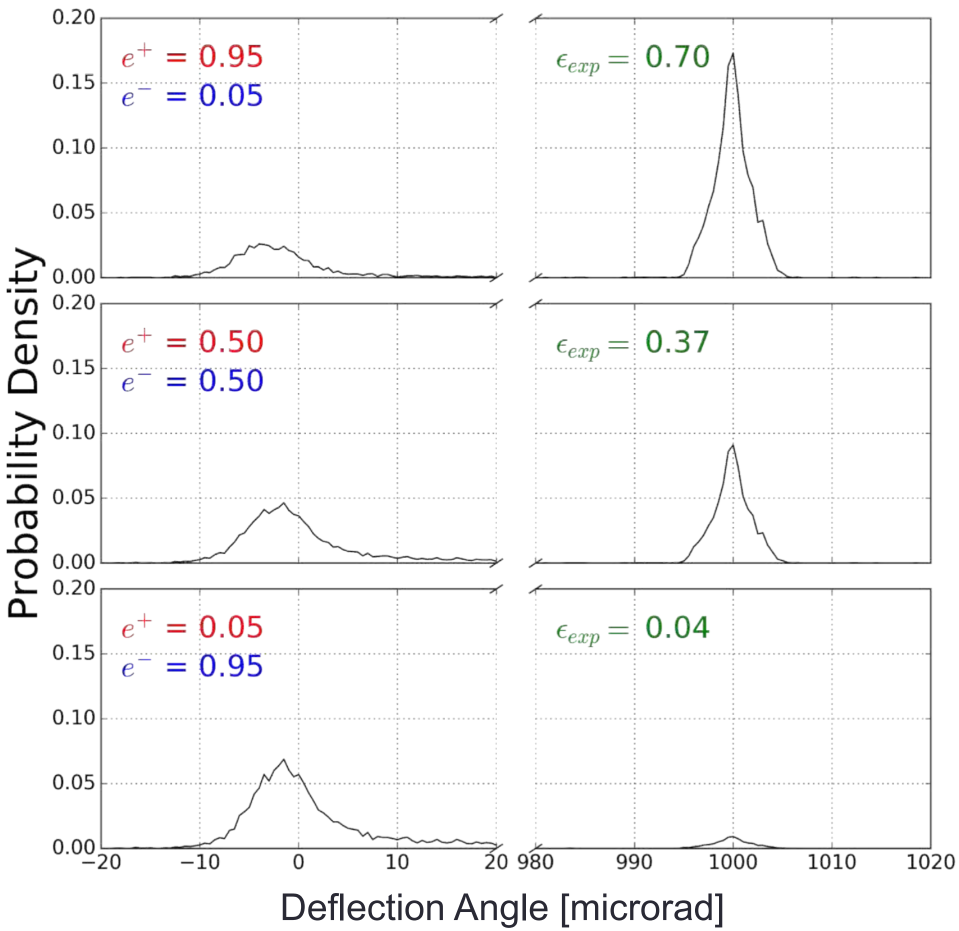
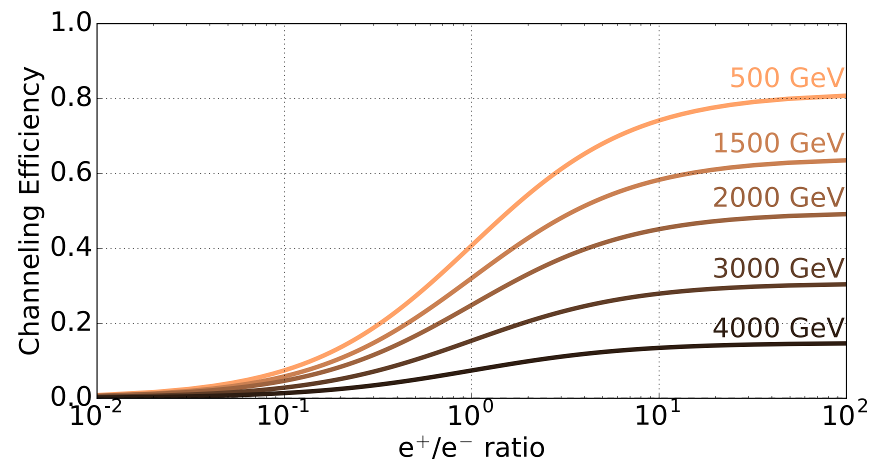


- By analysing a beam deflection distribution after the interaction with a bent crystal it is possible to determine the ratio between positrons and electrons.
- Two ingredients are needed:
  - Experimental deflection distribution
  - Monte Carlo
- As a result, it is possible to determine the ratio of positrons over electrons with channeling.



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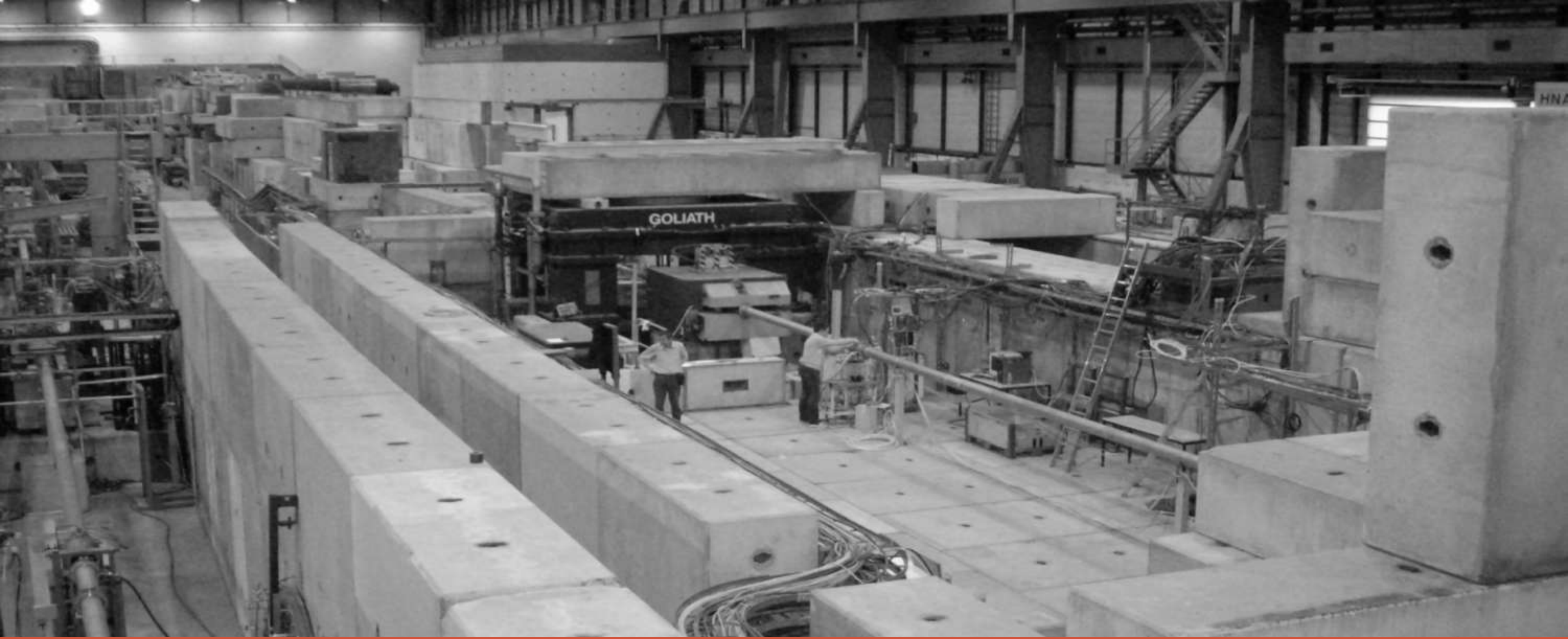
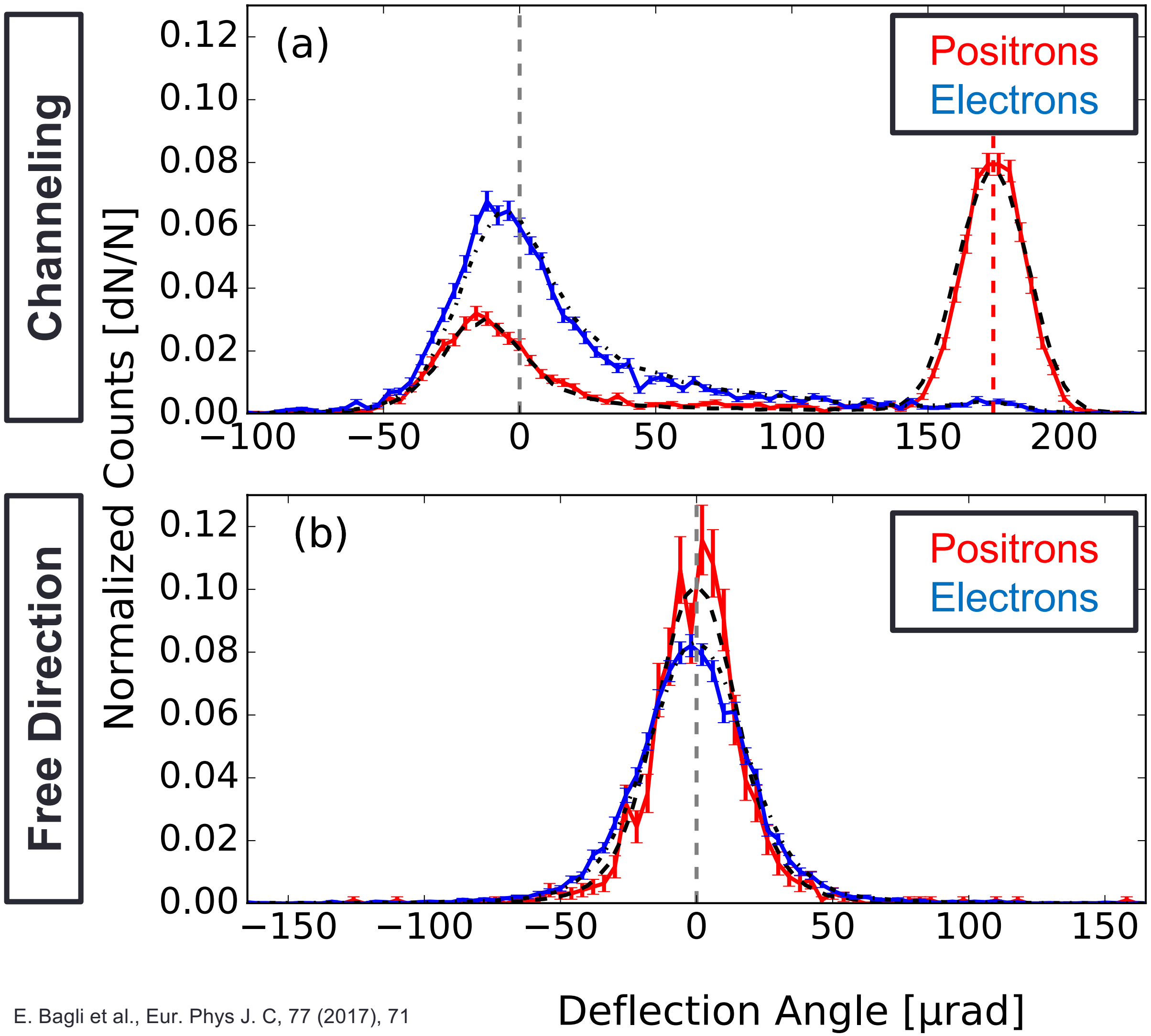


EXPERIMENTAL DATA

Test beam at the CERN SPS-H4 line

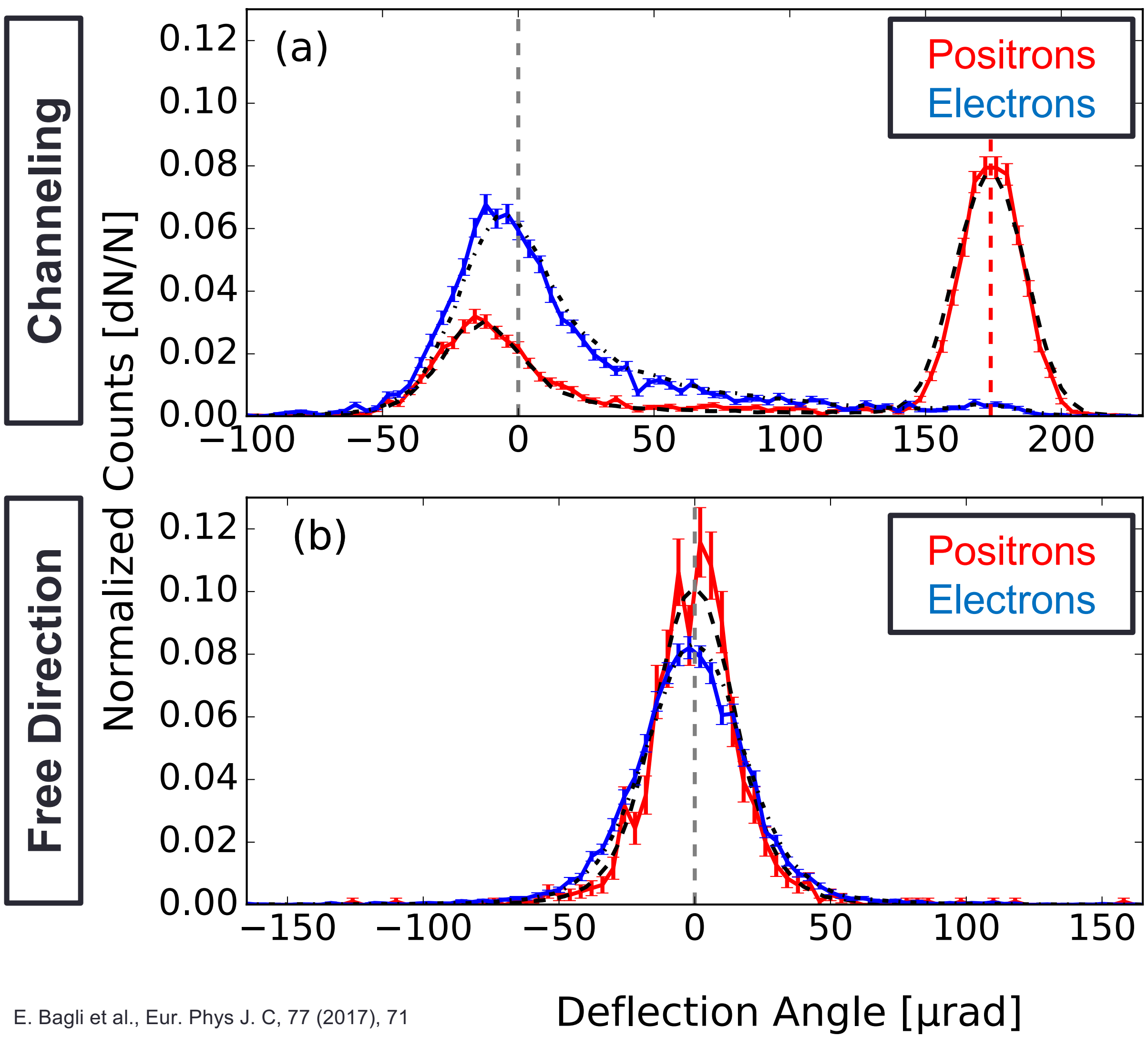
Channeling
Conclusions
The Idea
Experimental data

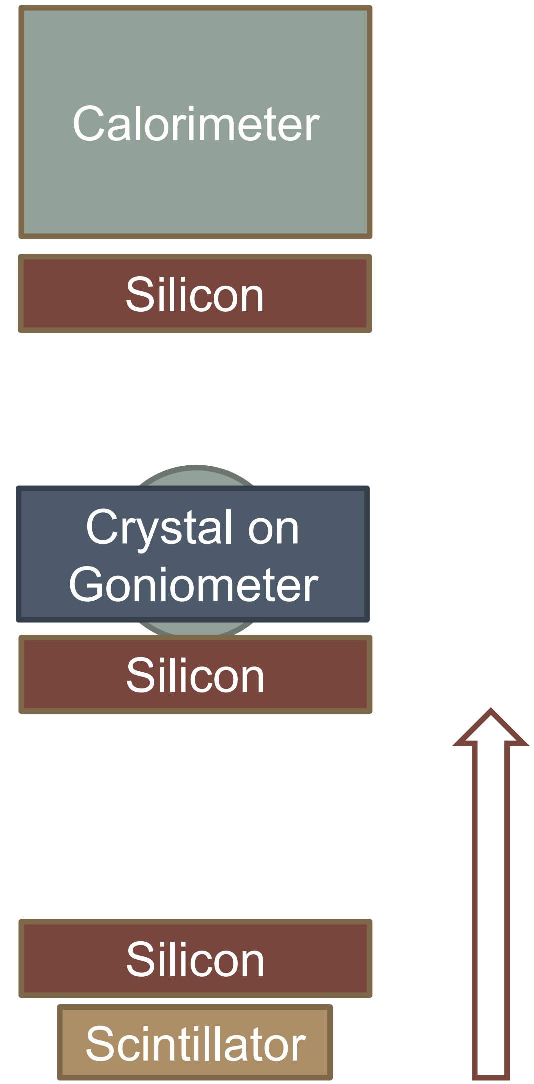
CERN SPS-H4 line



E. Bagli et al., Eur. Phys J. C, 77 (2017), 71

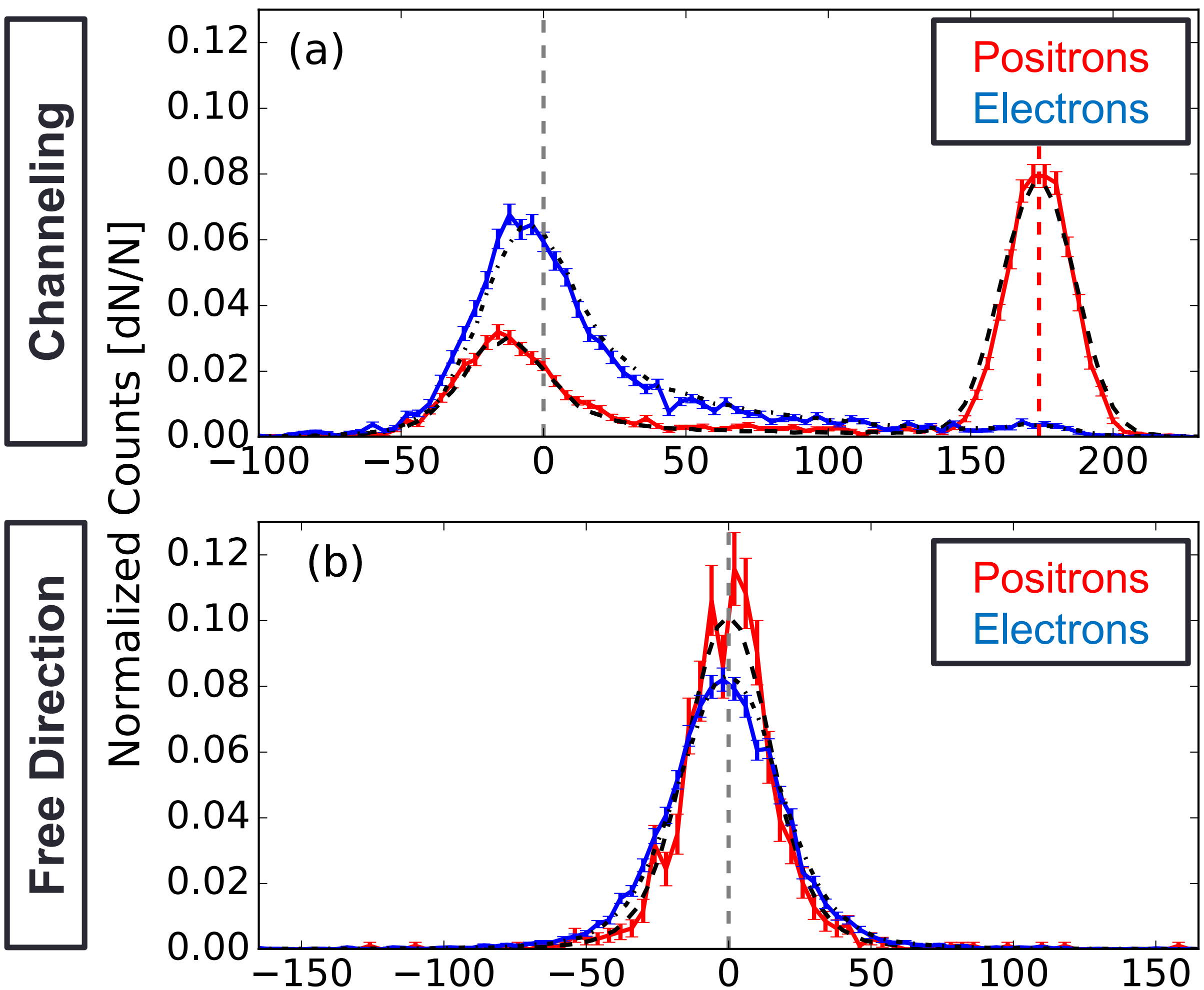
CERN SPS-H4 line



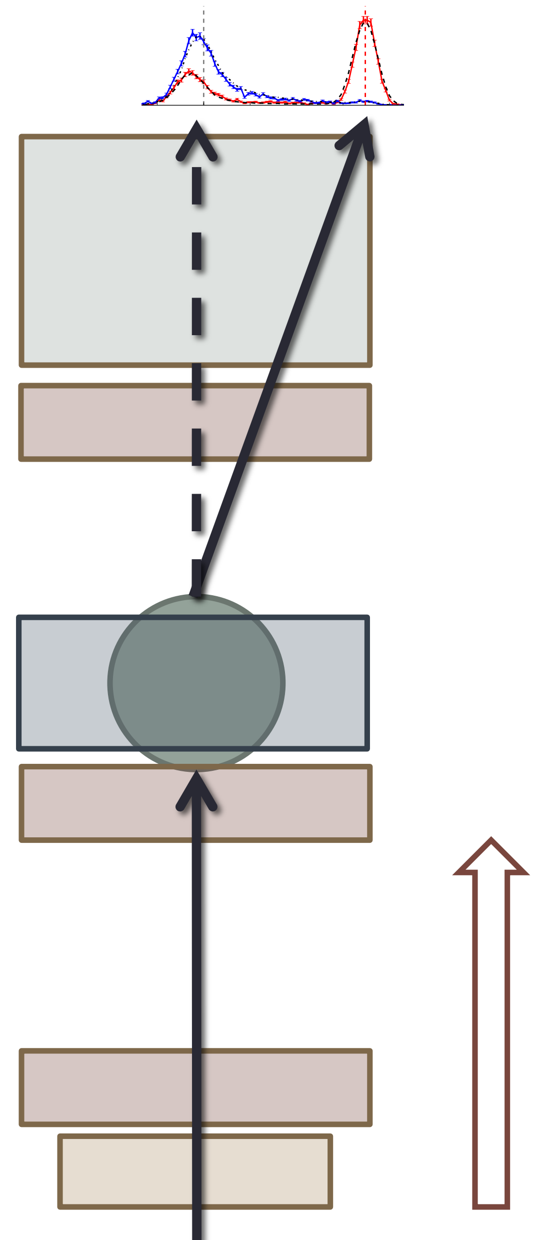


E. Bagli et al., Eur. Phys J. C, 77 (2017), 71

CERN SPS-H4 line

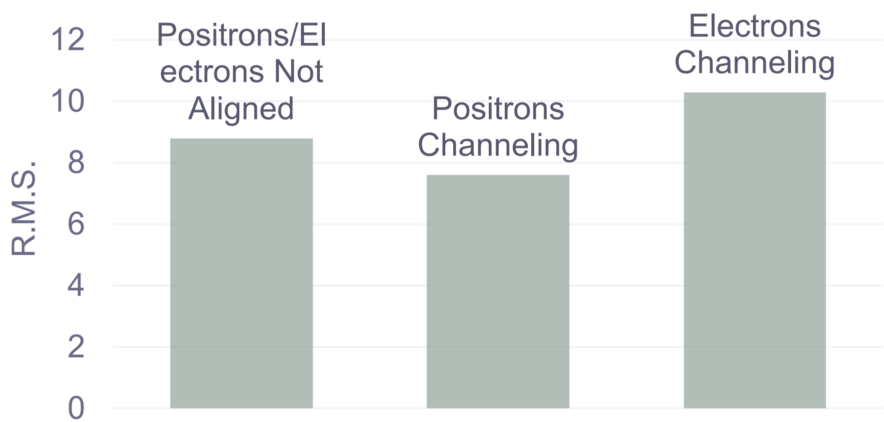


Deflection Angle [μrad]



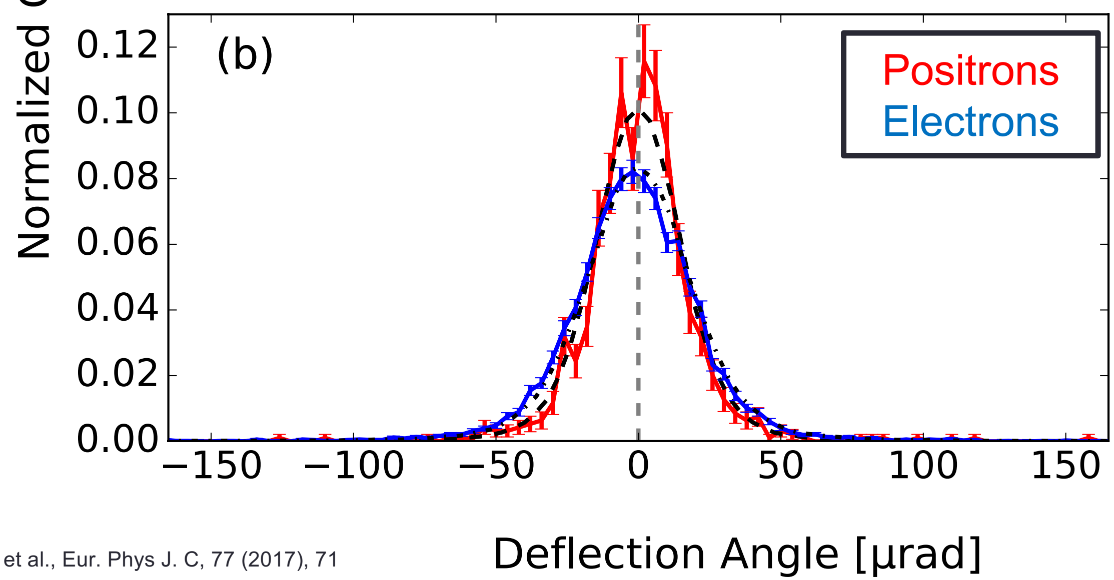
E. Bagli et al., Eur. Phys J. C, 77 (2017), 71

CERN SPS-H4 line



Particle	Condition	r.m.s. (μrad)
e^+/e^-	Not Aligned	8.8± 0.1
e^+	Channeling	7.6 ± 0.4
e^-	Channeling	10.3 ± 0.2

Free Direction

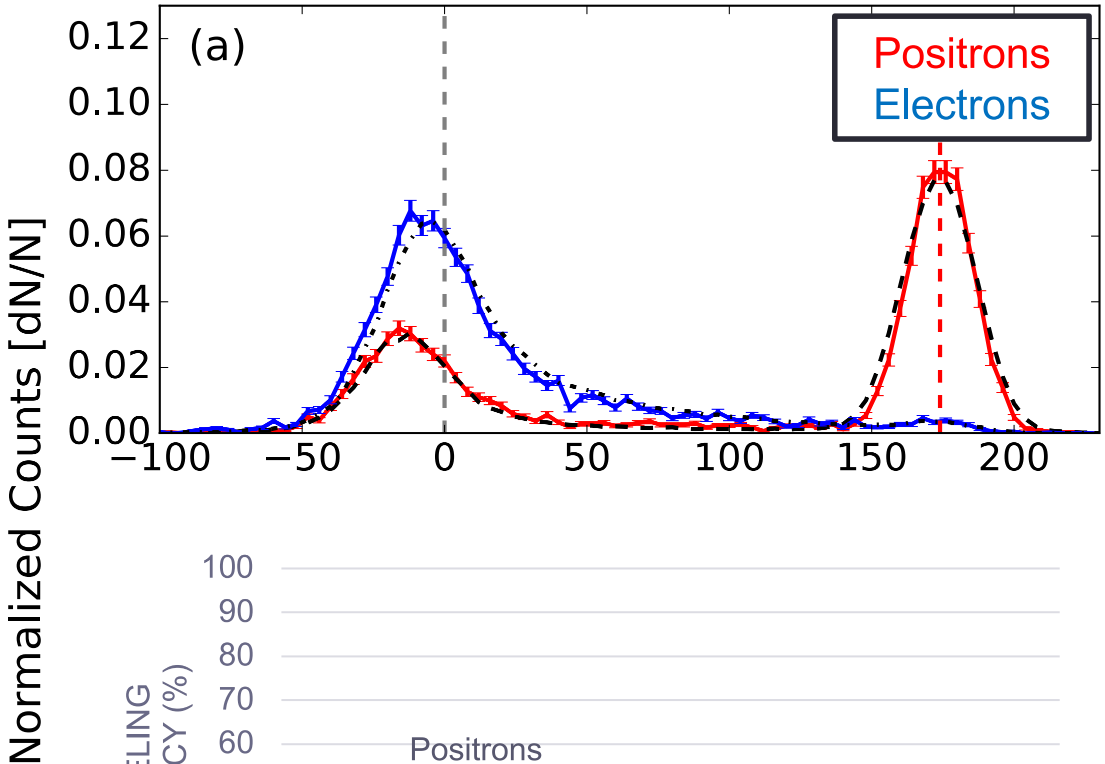


Electrons interact more frequently than positrons with nuclei, leading to an increase in the r.m.s. of the deflection distribution in the free direction.

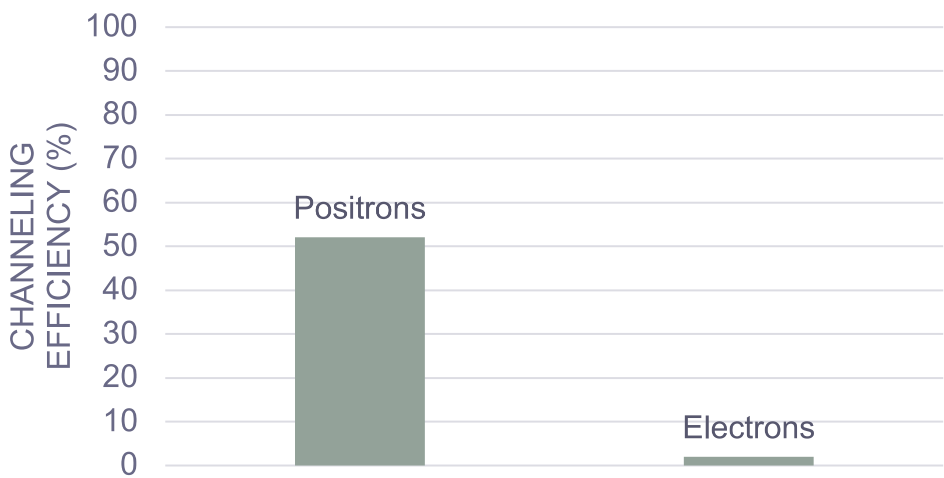
E. Bagli et al., Eur. Phys J. C, 77 (2017), 71

CERN SPS-H4 line

Channeling

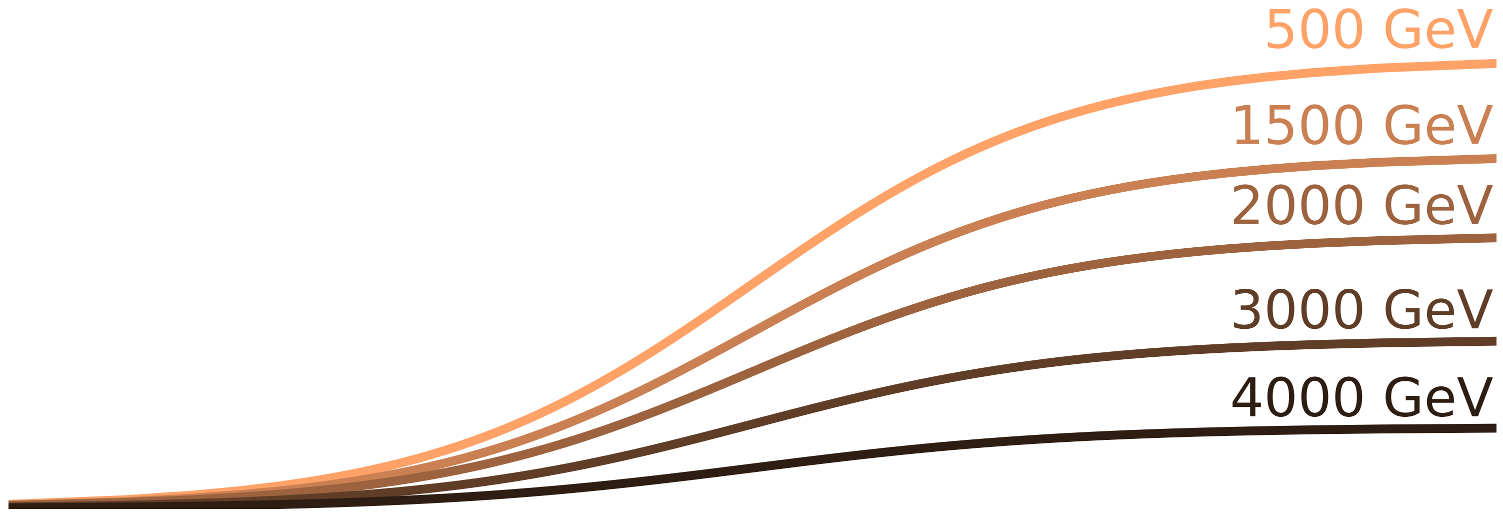


The channeling efficiency is by far greater for positrons rather than for electrons.



Particle	Channeling Efficiency (%)
e^+	54 ± 2
e^-	2 ± 2

E. Bagli et al., Eur. Phys J. C, 77 (2017), 71



CONCLUSIONS

And other usages of coherent effects

Channeling
The Idea
Experimental data
Conclusions

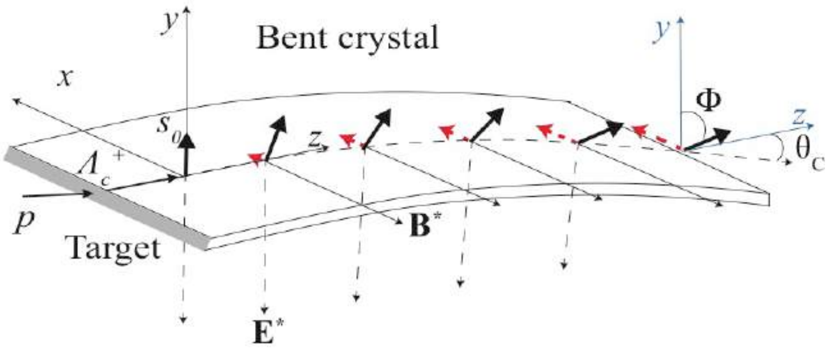
Spin precession

- The spin precession of a charged particle is induced by the interaction of its electromagnetic dipole moments, e.g. MDM and EDM, with external electromagnetic fields.

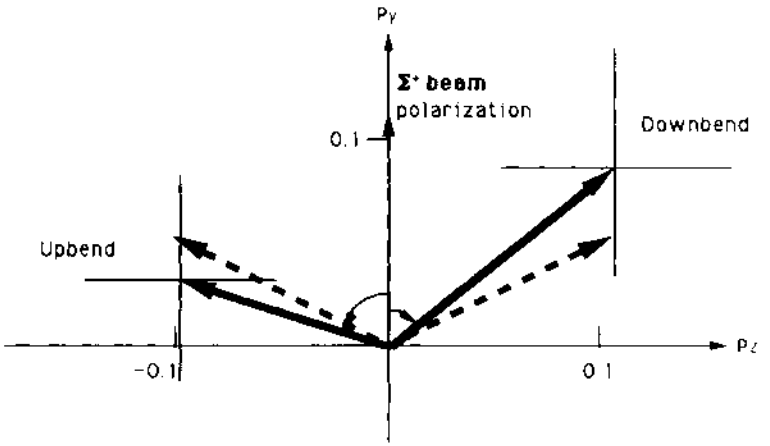
- The intense electric field between the crystal planes, $\boldsymbol{E}$, which deflects charged particles, transforms into a strong electromagnetic field $\boldsymbol{E}^* \approx \gamma \boldsymbol{E}$, $\boldsymbol{B}^* \approx -\gamma \boldsymbol{\beta} \times \boldsymbol{E}/c$ in the instantaneous rest frame of the particle and induces spin precession. In the limit of large boost, the spin precession induced by the MDM is:

$$\phi = \frac{g-2}{2} \gamma \theta_c$$

- Thanks to the extremely large magnitude of the electric field, the spin rotation angle in the crystal of several centimetres in length can reach several radians.



E. Bagli et al., Eur. Phys J. C, 77 (2017), 828



D. Chen et al., Phys. Rev. Letters 69 (1992), 3286

- V. G. Baryshevsky, Pis'ma. Zh. Tekh. Fiz. 5 (1979), 182
- V.L. Lyuboshits, Sov. J. Nucl. Phys. 31(1980), 509
- V. G. Baryshevsky, arXiv:1504.06702v1 (2015)
- F. J. Botella et al., Eur. Phys. J. C 77 (2017), 181

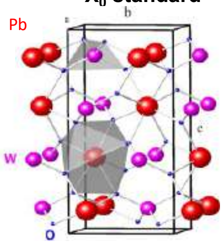
Compact Calorimeters with Oriented Crystals

Presenter: **Laura Bandiera**, INFN Sezione di Ferrara - bandiera@fe.infn.it -

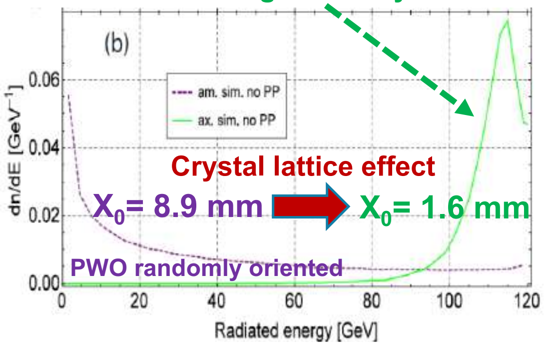
Motivation

The radiation length in an oriented crystal is strongly reduced !!

$PbWO_4$ scintillator crystal
X_0 standard = 8.9 mm



PWO X_0 reduction for electrons aligned to crystal axes



Possible Application Potentialities

- **FIXED-TARGET EXPERIMENT**: **forward e.m. calorimeters/preshower with reduced volume.**
- **BEAM DUMP**: compact active beam dump with an **increase of sensitivity to dark photons**.
- **SATELLITE BORNE GAMMA-RAY TELESCOPE**: Containing e.m. showers for energies > 10 GeV in a smaller volume. **Cost reduction, increase of sensitivity and energy resolution!**

L. Bandiera et al, ArXiv: 1803.10005

Is it possible to measure the e^+/e^- ratio with a 1 cm bent crystal?

1. Particles impinging on a bent crystal with a radius greater than the critical radius and an incoming angle lower than the critical angle undergo the channeling effect, which was used to **deflect particles from GeVs up to TeVs energies**.

2. The deflection efficiency is not constant and varies with the particle charge: for **negative particles** is **strongly limited**, while **positive particles** have **optimal deflection efficiency** at high-energy.

Due to the beam-splitting capability, channeling can be used to **measure the positron to electron ratio** of a fraction of particles in astrophysics experiments that do not involve the use of a magnet. In fact, a bent crystal, e.g. Si or Ge, for deflection via channeling would be a **non-cryogenic passive device**, i.e., with no energy consumption.

THANK YOU FOR THE ATTENTION

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