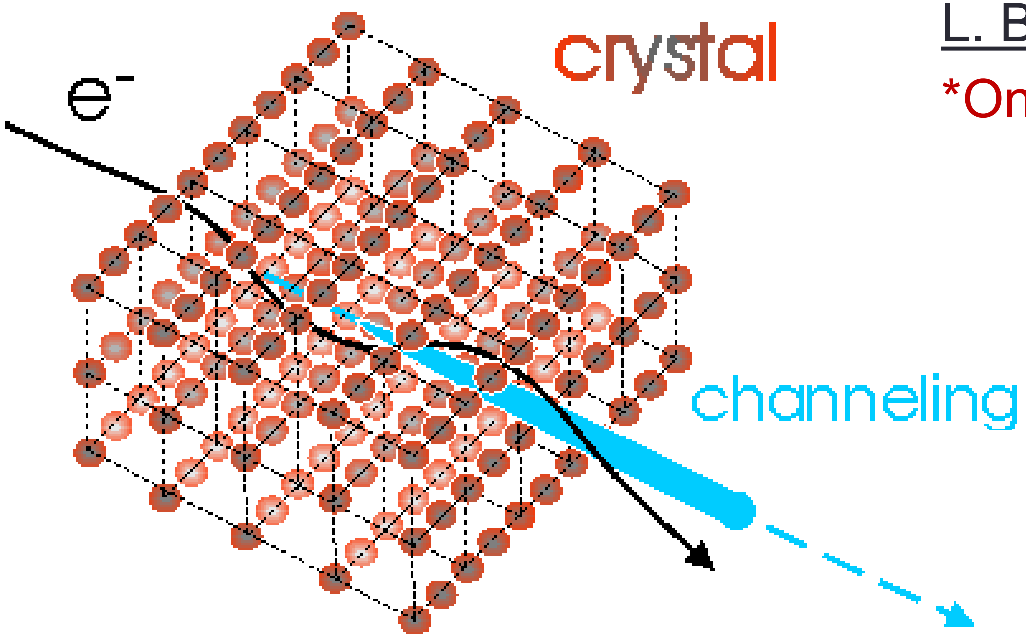
Channeling radiation for Muon Collider

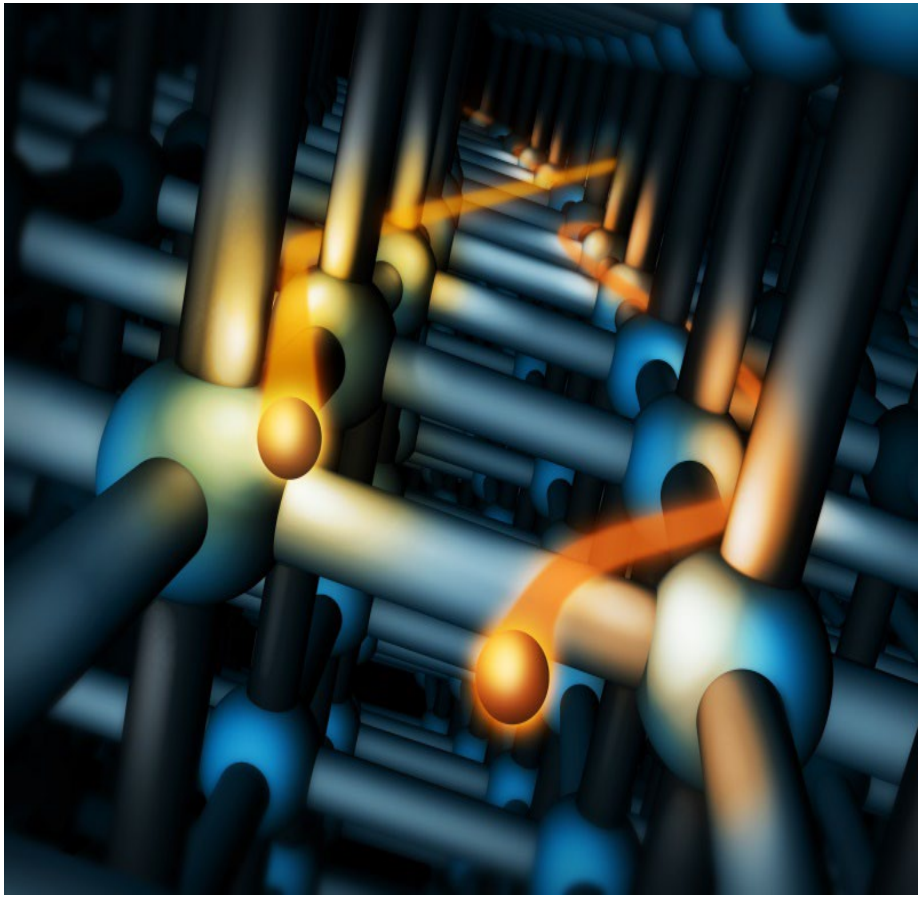


L. Bandiera*, V. Tikhomirov
*On behalf of the INFN ELIOT team

Muon Collider Meeting
CERN, 02/04/2020

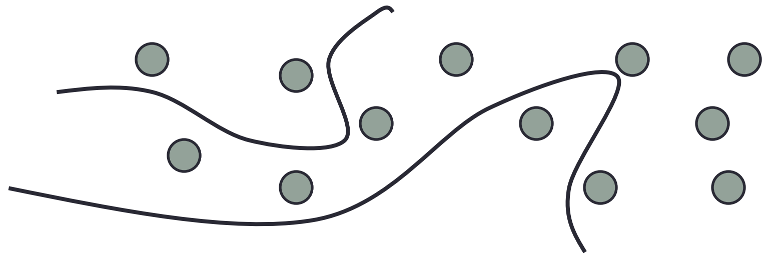
Outlook

- Introduction on Channeling Radiation;
- Possible application for muon collider:
  - Realistic Monte Carlo based on Baier Katkov quasiclassical operator method;
  - Feasibility tests.
- Conclusions.



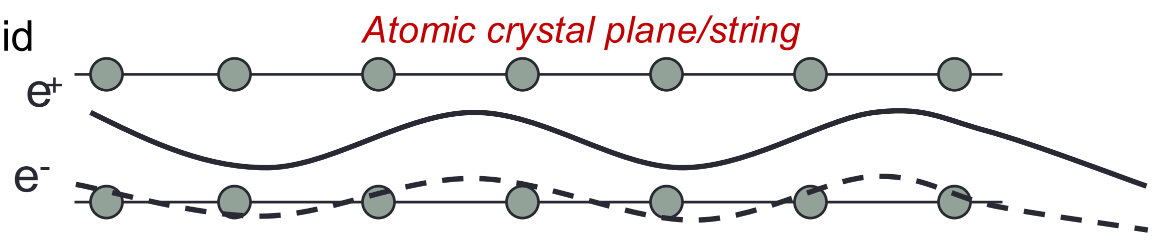
Channeling

Amorphous or randomly oriented crystalline solid



Oriented crystalline solid
(Si, C, Ge, W…)

channeling



Positively-charged particles <u>are repulsed from the nuclei of the axis (plane)</u> and hence can be captured inside the interaxial (interplanar) potential wells.

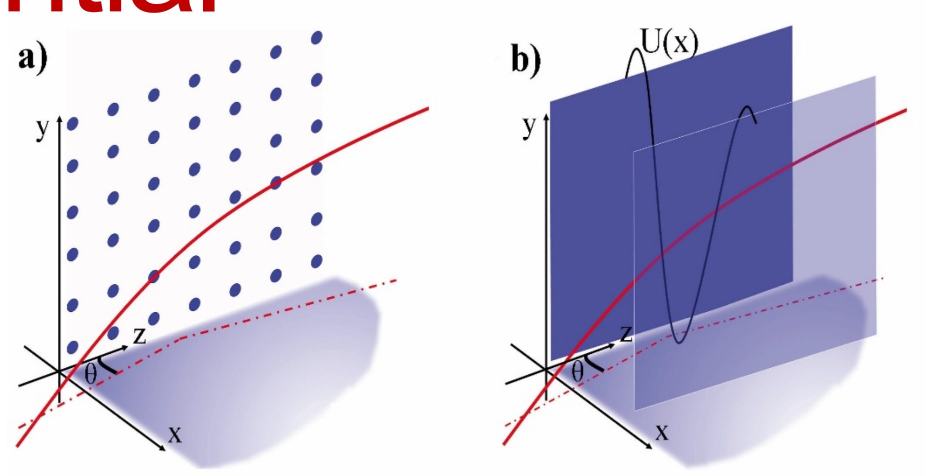
Negatively-charged particles <u>are attracted towards the positively-charged nuclei of the axis (plane)</u>, thus oscillate around the atomic axes (or planes).

Channeling and Continuous Potential

$$U_{pl}(x) = N d_p \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} V(x, y, z)\, dy\, dz$$

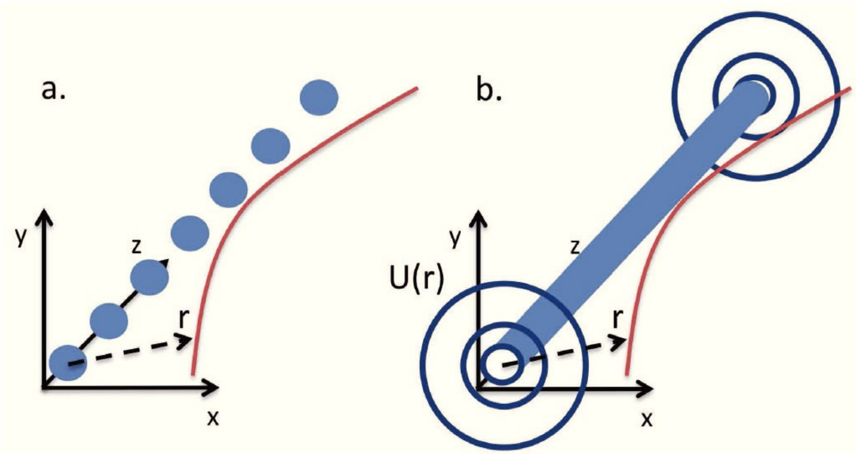
$$V_{TF}(r) = \frac{Z_i Z e^2}{r} \Phi\left(\frac{r}{a_{TF}}\right)$$

is the particle-atom screened Coulomb potential

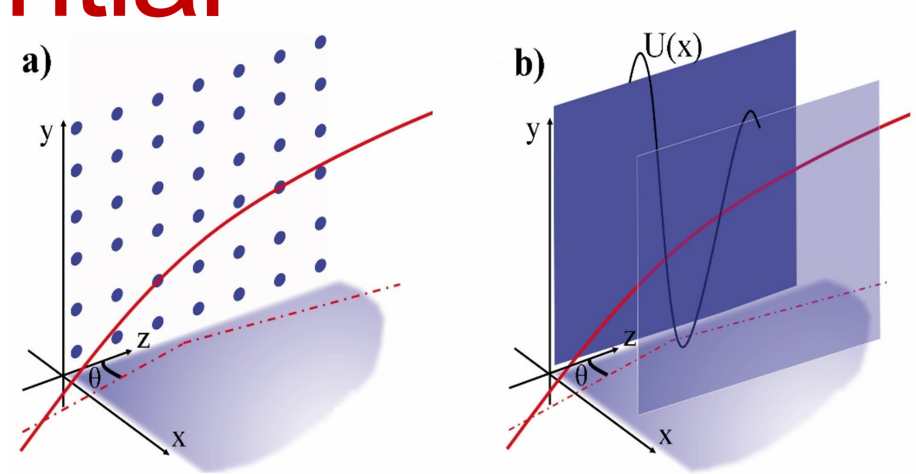


Planar Channeling

Channeling and Continuous Potential



Axial Channeling



Planar Channeling

Channeling occurs as the trajectory of particles forms an angle lower than the critical angle:

$$\theta_c = \sqrt{\frac{2U_0}{pv}}$$

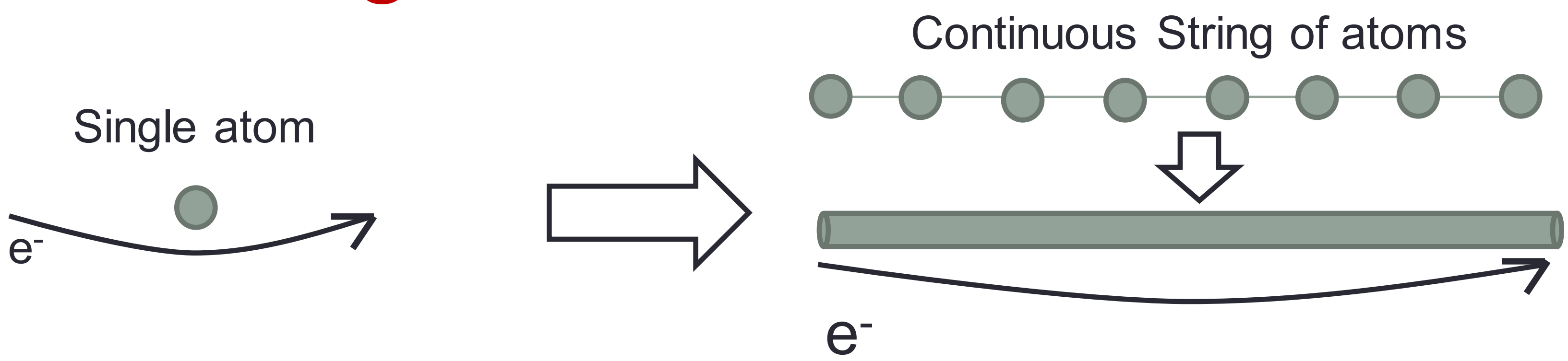
max of U(x)

momentum velocity

For e^- @1 GeV in W crystal:
Plane (110): $U_0 \approx$ 140 eV; $\theta_C \approx$ 0.5 mrad
Axis <111>: $U_0 \approx$ 1 keV; $\theta_C \approx$ 1.5 mrad

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

Channeling radiation



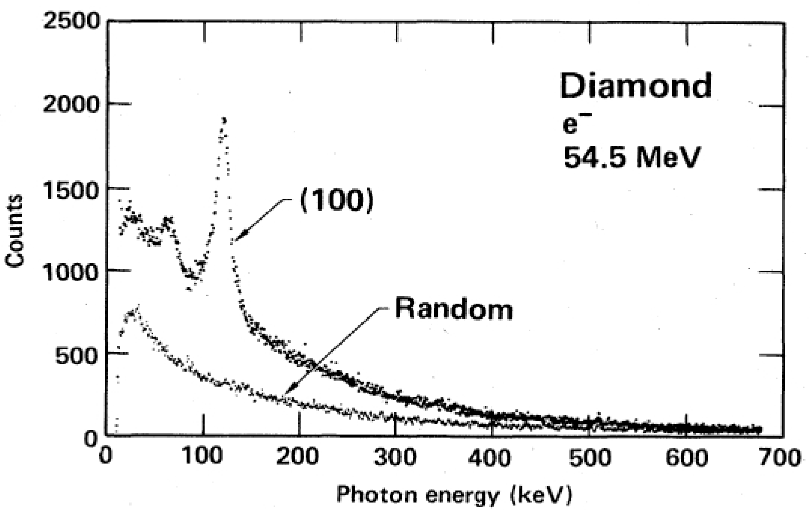
Polarized & forward emission – analogous to undulator

Radiation frequency in the forward direction:

Lorentz + Doppler effect

$$\omega \approx 2\gamma^2\omega_0 = \frac{4}{d_p}\sqrt{\frac{2U_0}{m}}\gamma^{3/2}$$

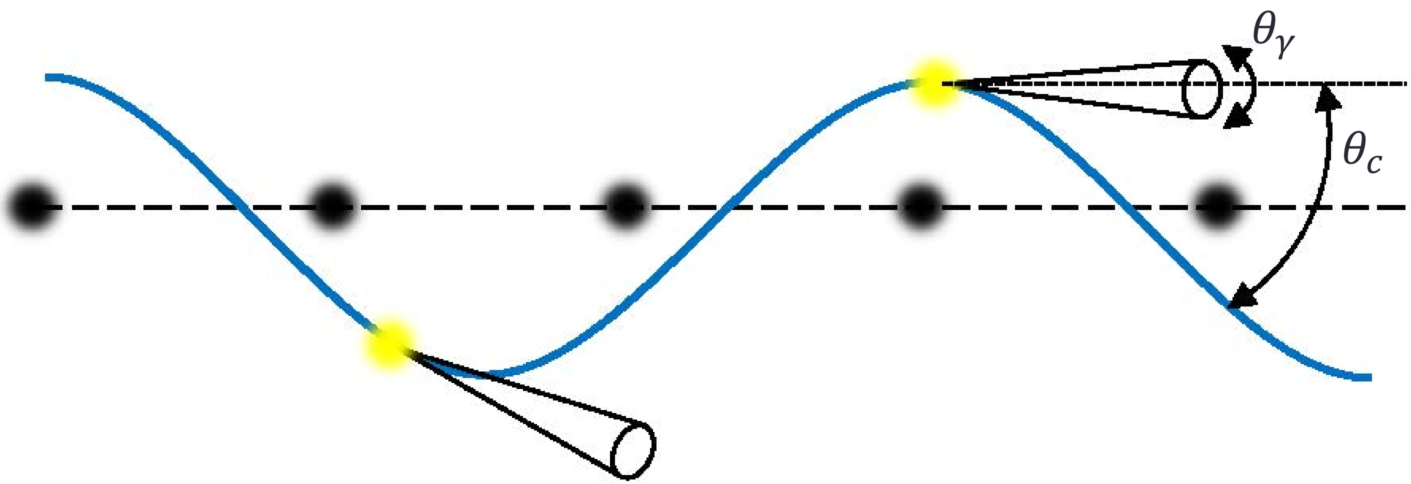
$\omega_0 = 2\pi/\lambda$ – frequency of motion



M. Kumakhov, Physics Letters A 57, 17 (1976).

Synchrotron-like channeling radiation in crystals

At energies ≥ GeV (depending on the atomic number Z)



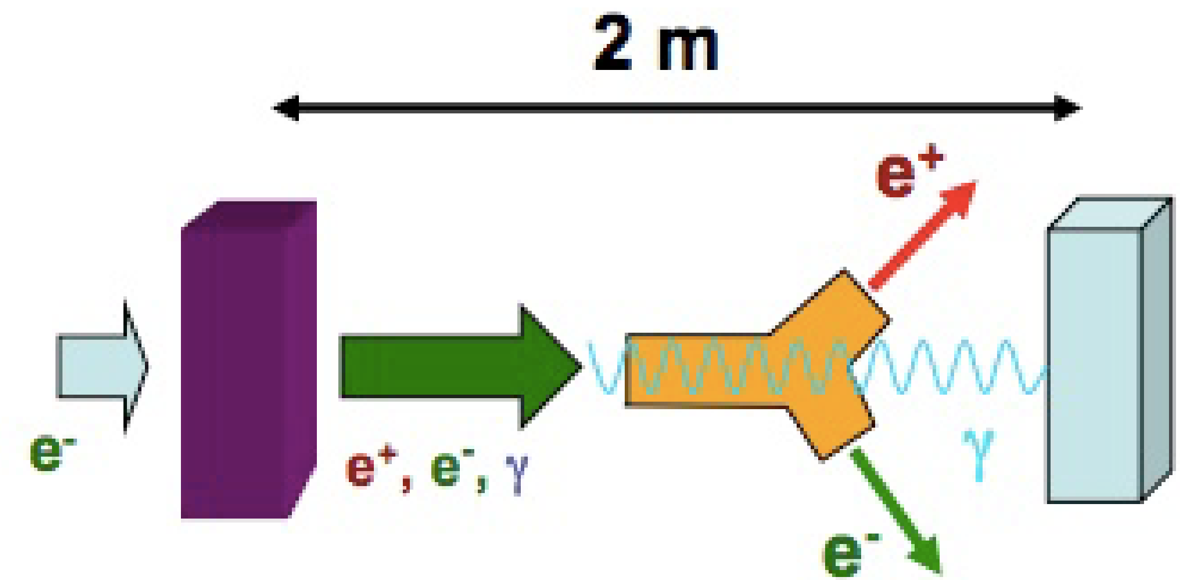
Radiation emission angle: $\theta_\gamma = 1/\gamma$

Synchrotron radiation regime: $\theta_\gamma \ll \theta_c$

Intense emission of radiation, continuous spectrum, large emission of soft photons!

Possible application of Channeling Radiation for muon collider

Hybrid crystal based positron source for LEMMA



Thin crystal radiator (thickness< X_0)
(to limit the heating)

Amorphus converter target

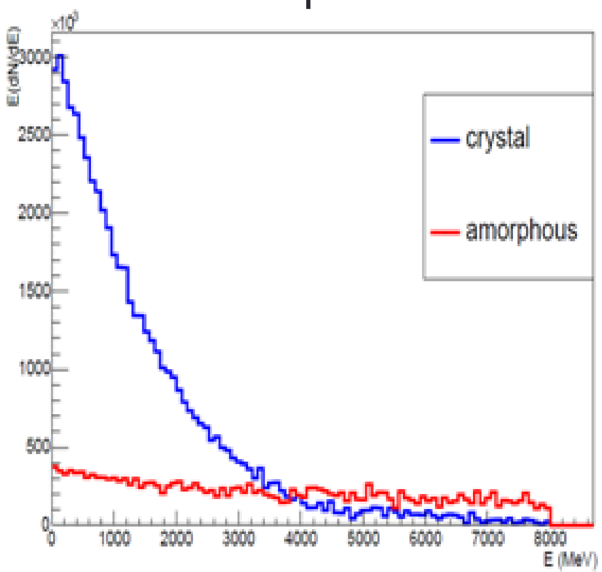
Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868
see I. Chaikovska talk

Recent test at KEK in Japan with a W crystal NIMB 402 (2017) 58

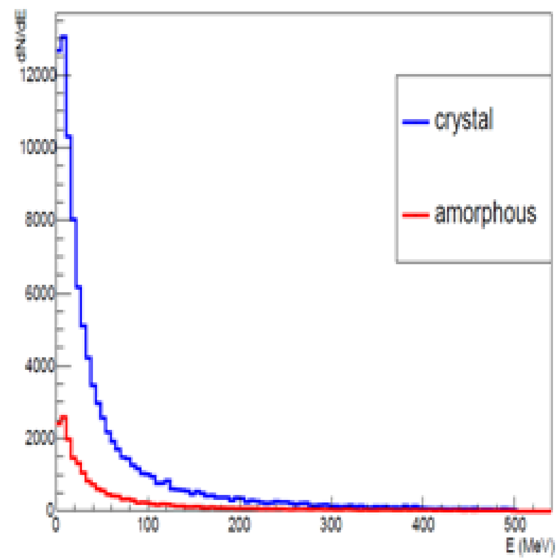
Crystal based positron source

- **Main advantages**
  - **Enhancement of photon generation in crystals in channeling conditions ➔ enhancement of pair production in the converter target**
  - **High rate of soft photons ➔ creation of soft positrons easily captured in matching systems.**

Photon spectrum



Positron spectrum



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- **Open questions:**
  - **Define the best e-beam and target parameters**
  - **Crystal radiator quality**
  - **Target resistance**

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We can contribute to these tasks!

Crystal based positron source for LEMMA

- **Main advantages**
  - Enhancement of photon generation in crystals in channeling conditions ➔ enhancement of pair production in the converter target
  - High rate of soft photons ➔ creation of soft positrons easily captured in matching systems.

- **Open questions:**
  - Define the best e-beam and target parameters ➔ realistic Monte Carlo simulations & feasibility tests
  - Crystal radiator quality ➔ purchase crystalline materials (tipically W that provides the strongest axial potential and thereby strongest radiation enhancement) from different producers and perform crystallographic characterization (*see A. Mazzolari talk*)
  - Converter target resistance

An algorithm for computation of radiation emission in oriented crystals

Based on the Baier Katkov general method for calculation of radiation generated by e± in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2+E'^2\right)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)} \qquad (1)$$

where the integration is made over the classical trajectory.

The generality of the Baier-Katkov operator method permits to simulate the electromagnetic radiation emitted by e± in very different cases, e. g., straight, bent and periodically bent crystals, crystalline defects and for different beam energy range, from sub-GeV to TeV.

Baier-Katkov quasiclassical operator method (1967-1968)

General method for calculation of radiation generated by $e^{\pm}$ in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

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where the integration is made over the classical trajectory.

Why classical trajectory?

2 types of quantum effects :

- the quantization of particle motion $\sim\hbar\omega_0/E$
  In crystals: nearly negligible for electron/positron energy >10-100 MeV
- the quantum recoil of the particle when it radiates a photon with energy $\hbar\omega\sim E$
  NOT negligible for electron/positron energy >10 GeV (depending on atomic number Z)

An algorithm for radiation in crystals

Integration of the BK formula

SMALL ANGLE APPROXIMATION: Since the angle between particle trajectories and crystal planes or axes is small and at ultrarelativistic energies the radiation angle $1/\gamma$ is much smaller than unity the particle velocity **v** and photon momentum **k** can be represented in the form :

$$\mathbf{v}(t) \simeq \mathbf{v}_\perp(t) + \mathbf{e}_z\left[1 - 1/2\gamma^2 - v_\perp^2(t)/2\right],$$
$$\mathbf{k} = \mathbf{n}\omega \simeq \mathbf{e}_\perp\omega\theta + \mathbf{e}_z\omega\left(1 - \theta^2/2\right),$$

where the angle $\theta \ll 1$ represents the radiation angle. The formula (1) can be rewritten as:

$$\frac{dE}{d^3k} \sim \frac{\alpha}{8\pi^2}\frac{\varepsilon^2 + \varepsilon'^2}{\varepsilon'^2}\omega^2 C, \qquad (2)$$

where $$C = |\, \boldsymbol{I}_\perp \,|^2 + \gamma^{-2}\frac{\omega^2}{\varepsilon^2 + \varepsilon'^2}\,|\, J \,|^2 \qquad (3)$$

V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903]

L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015).

An algorithm for radiation in crystals

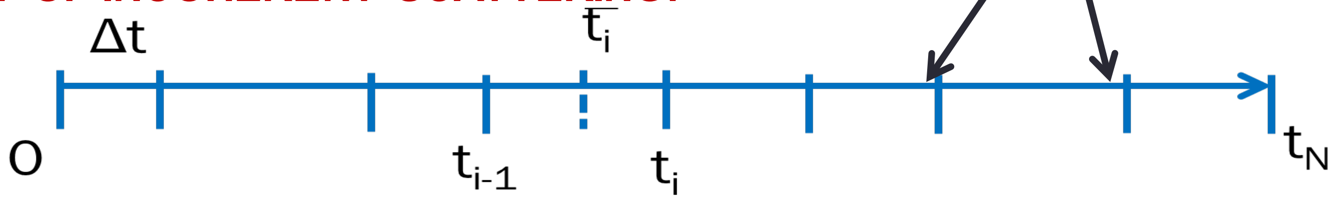
Integration of the BK formula

SMALL ANGLE APPROXIMATION: the integrals of eq. (1) can be represented as follows:

$$\begin{matrix} J \\ \boldsymbol{I}_\perp \end{matrix} = \int_{-\infty}^{+\infty} dt \begin{matrix} 1 \\ (\boldsymbol{v}_\perp - \boldsymbol{\theta}) \end{matrix} e^{-i\phi(t)} \qquad (4)$$

being $\phi(t) = \frac{\omega'}{2} \int_{-\infty}^{t} dt' [\gamma^{-2} + (\boldsymbol{v}_\perp(t') - \boldsymbol{\vartheta})^2]$ and $\omega' = \omega\varepsilon/\varepsilon'$.

ACCOUNT OF INCOHERENT SCATTERING:

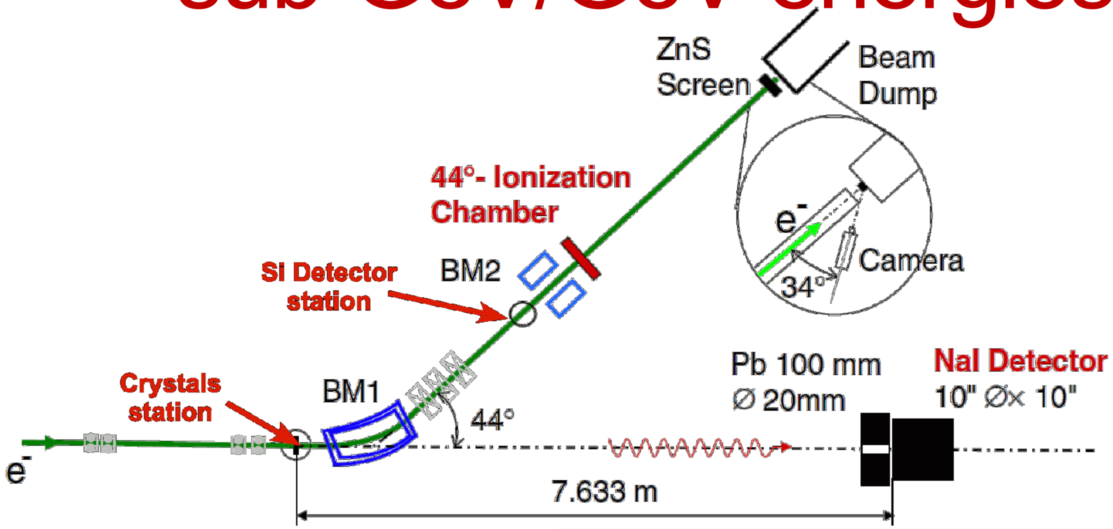


The **particle trajectory is then divided in N small steps**, within which the particle trajectory is calculated through the integration of equation of motion in the continuous potential. **At the end of each step the scattering by nuclei and electrons is sampled** and the transverse velocity for the i-step becomes $\mathbf{v}_{\perp,\mathbf{i}} \to \mathbf{v}_{\perp,\mathbf{i}} + \theta_{\mathbf{s},\mathbf{i}}$

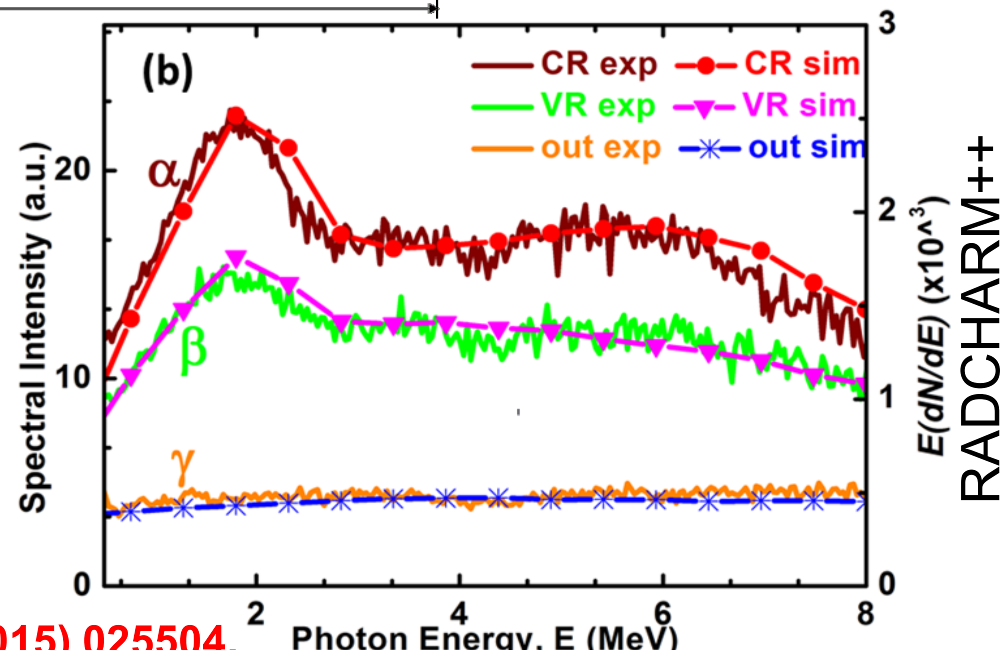
The integration over θ leads to the radiation spectral intensity, ωdN/dω.

[1] L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res. B 355, 44 (2015).
[2] V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903]
[3] A. I. Sytov, V. V. Tikhomirov, and L. Bandiera, Phys. Rev. Accel. Beams 22, 064601 (2019).

Comparison with past experiments: sub-GeV/GeV energies

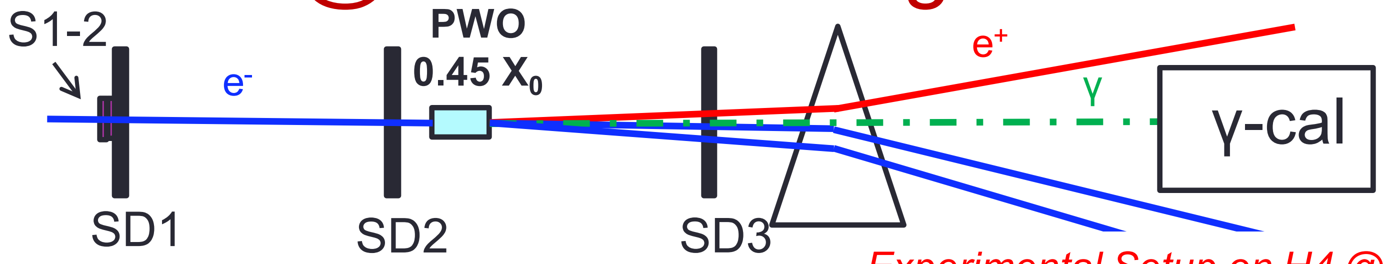


Comparison with experiment performed at the Mainzer Mikrotron with 0.855 GeV electrons interacting with a 30.5 μm bent Si crystal along the (111) planes

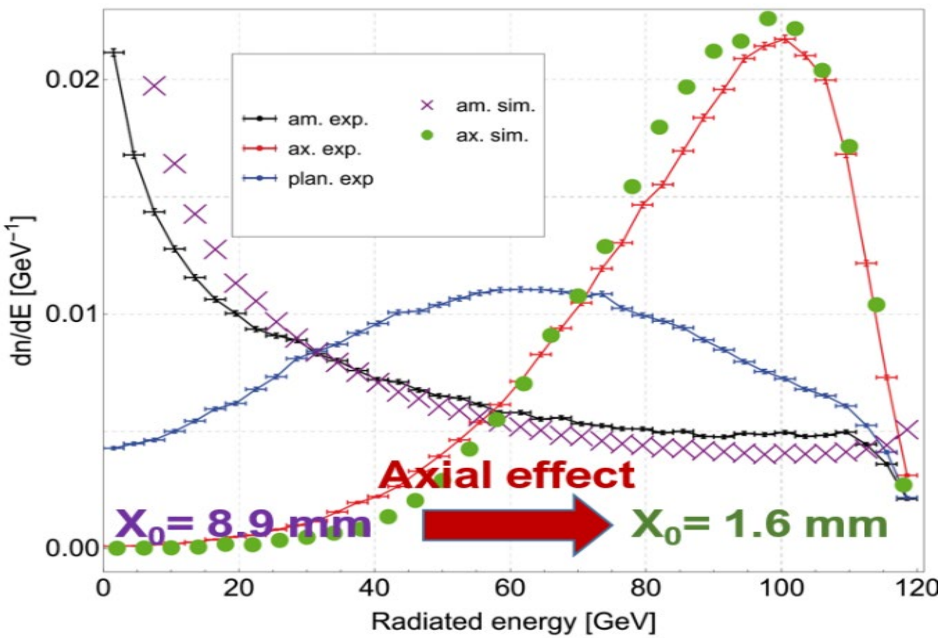


L. Bandiera et al., Phys. Rev. Lett. 115 (2015) 025504.

Comparison with past experiments @ 120 GeV energies



Experimental Setup on H4 @CERN SPS



Strong radiation enhancement in an axially oriented high-Z **scintillator crystal** (PWO, *which is the material of the CMS ECAL*) in comparison to the random orientation.

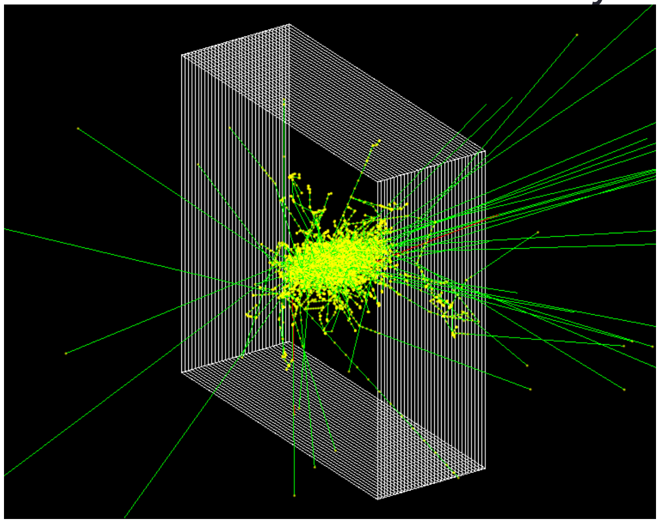
Possible application for compact forward e.m. calorimeters

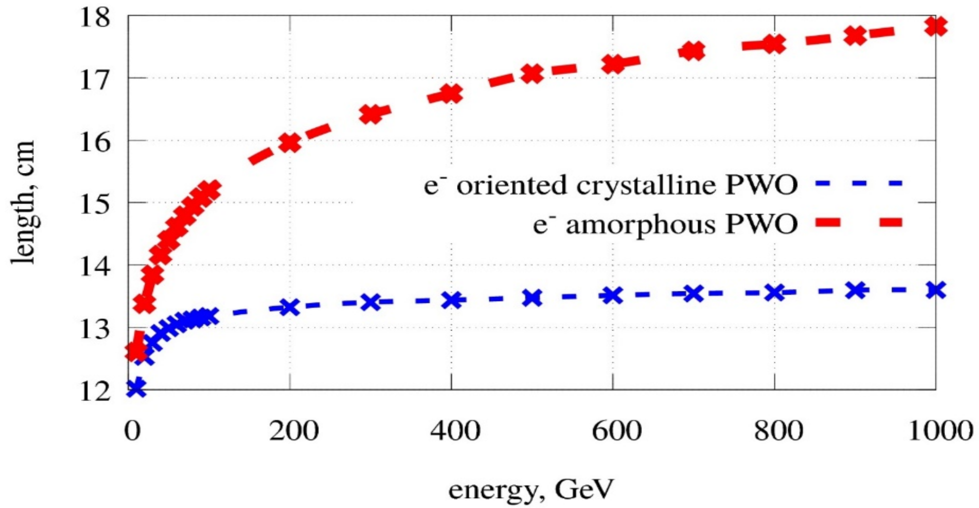
L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

First step for implementation of the Baier-Katkov algorithm in Geant4

The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full BK Monte Carlo.

Example for an electromagnetic crystal calorimter made of axially oriented PWO crystals (as for CMS ECAL)





Electromagnetic shower vs. beam energy, for primary electrons. Since the crystalline strong field effect increases with beam energy with a consequent X_0 decreasing, the shower length is almost constant with energy.

L. Bandiera, V.V.Haurylavets, V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) p.124-126

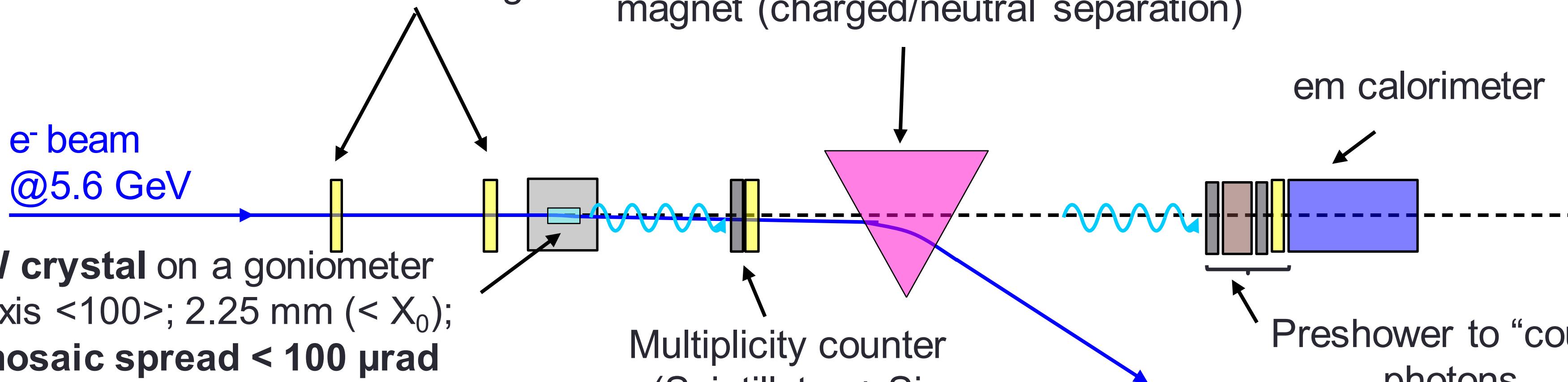
Tests on beam

The ELIOT team has a long experience in carring out experiments on Channeling Radiation in different laboratories worldwide (CERN SPS&PS, SLAC, MAMI, DESY..), providing all the necessary equipment for future tests:

- Setup: detectors, DAQ etc..;
- High-precision goniometer for crystal orientation with the beam;
- Crystals and their characterization (*see A. Mazzolari talk*);
- Simulation and data analysis.

Tests on beam

To check our Monte Carlo simulation for positron source we carried out a test beam @DESY TB



The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168 (AIDA-2020).

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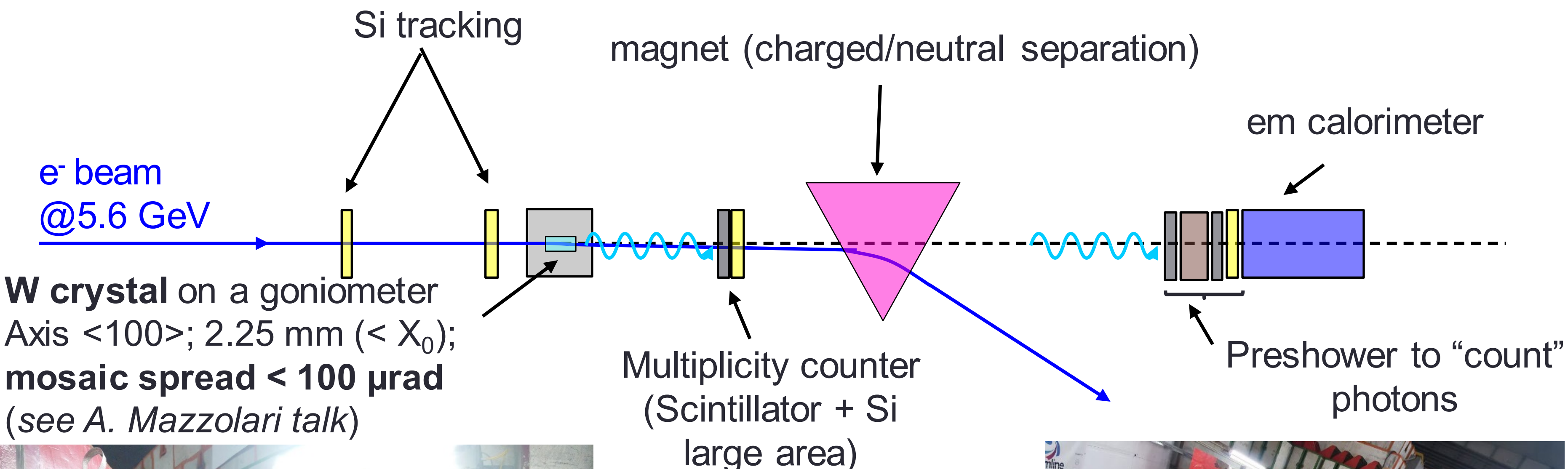

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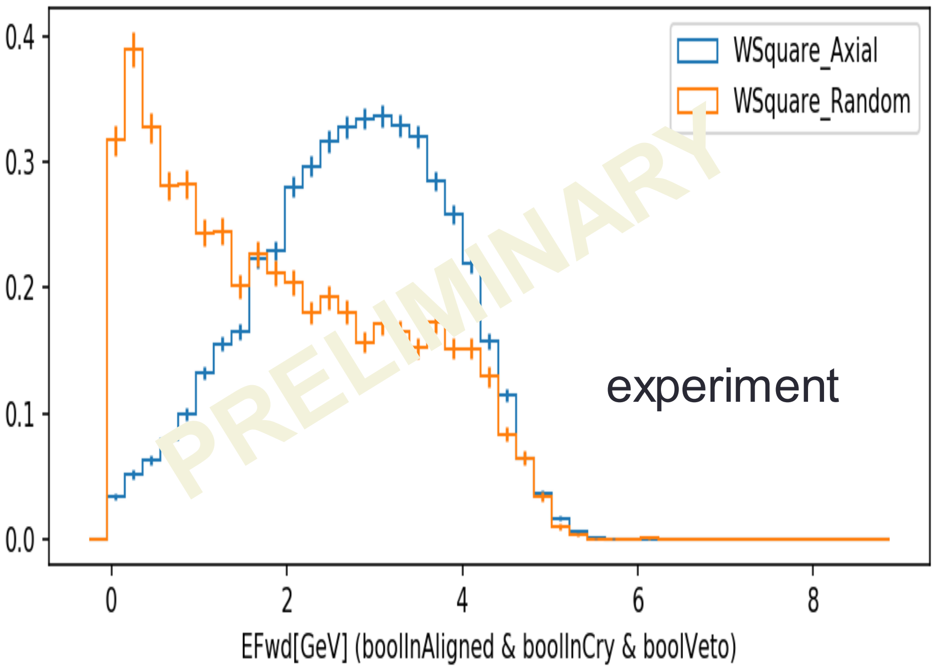
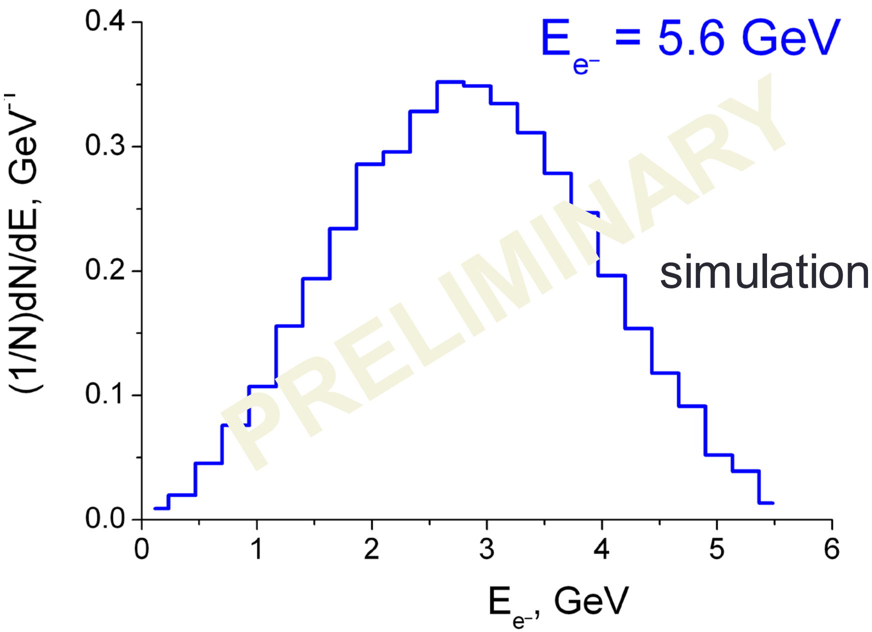
Radiative energy loss in axial channeling collected at the calorimeter



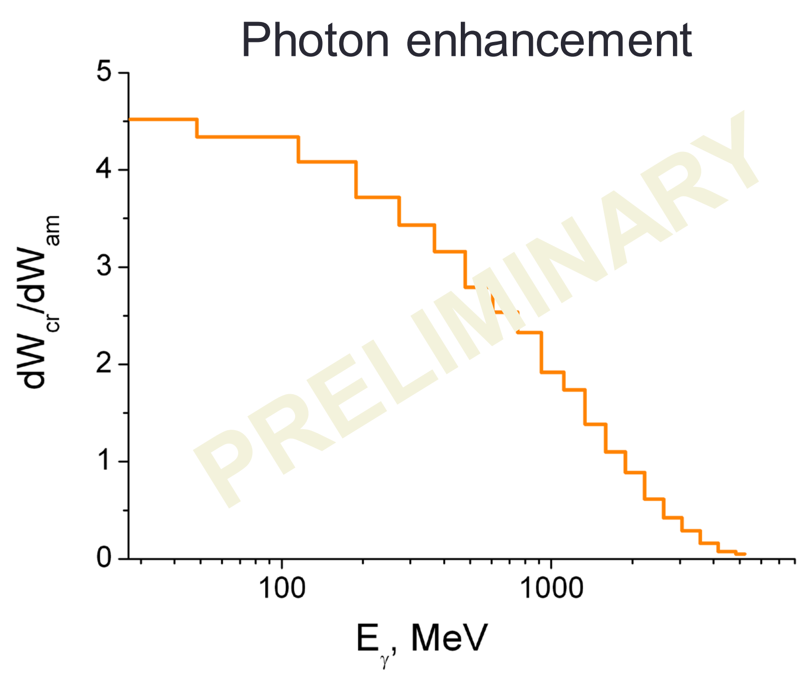


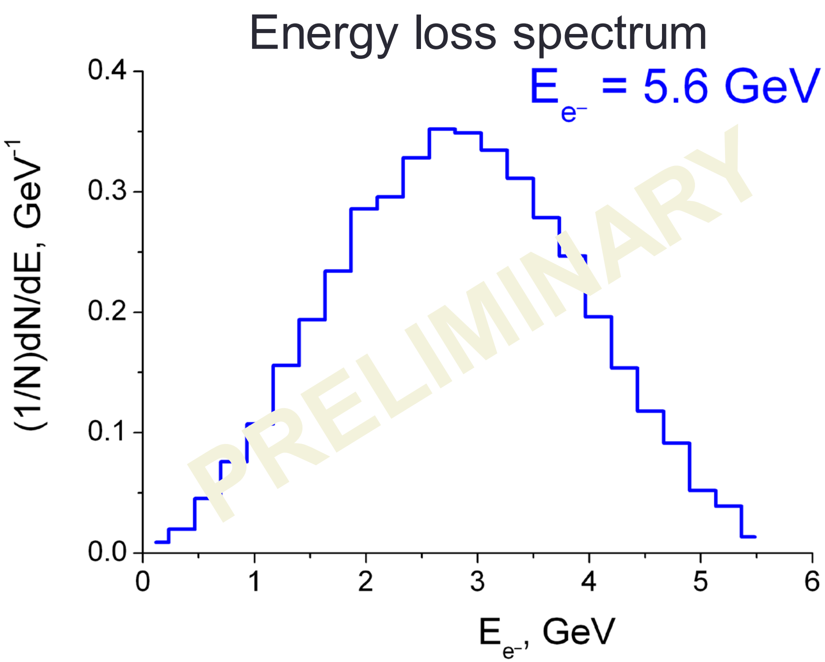
The setup can be modified for future tests @PS/SPS at CERN or @DESY in collaboration with the I. Chaikovska team to measure also the positron yield as already done at KEK and SPS in the past.

MC simulation

To check our Monte Carlo simulation for positron source we carried out a test beam @DESY TB

Simulated Photon and Energy loss spectra

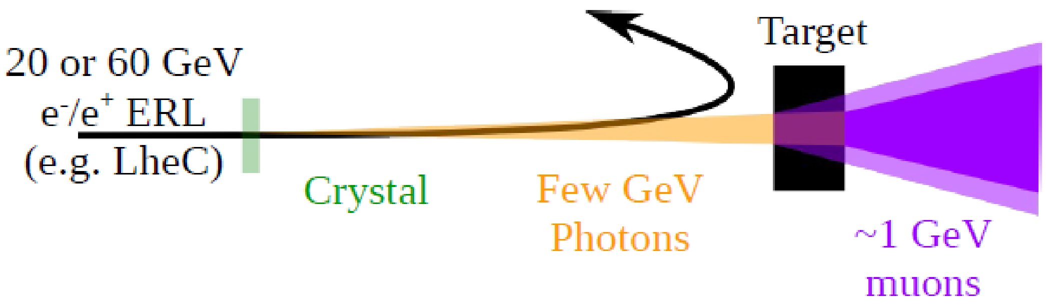


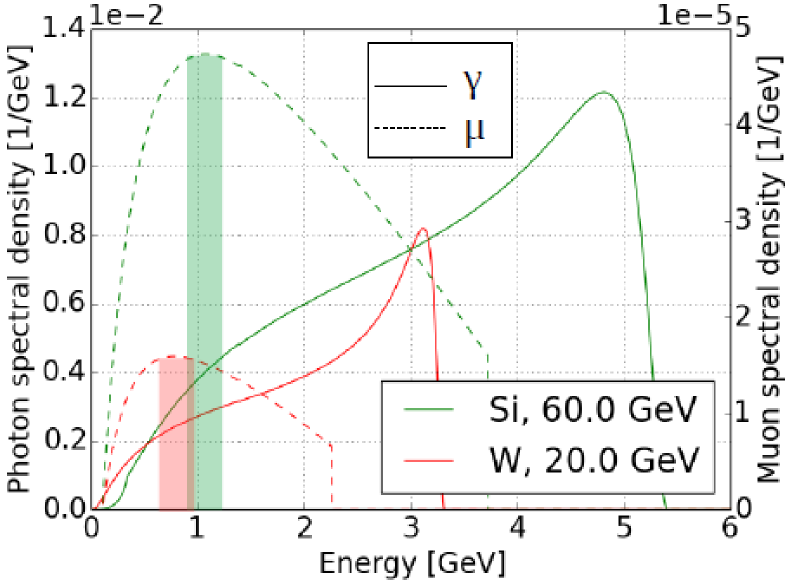


The soft part of radiation spectrum is essential for positron production and needs to be thoroughly measured

Muon pair production based on channeling radiation

Another possible application of Channeling Radiation for Muon Collider





- First estimates suggest that muon rates in the order of 10^{12}/s within a bandwidth of ±10% can be achieved which is compatible with collider application
  - The emittance is dominated by the target length and may likely be optimised (Here with a 5 cm tungsten target ε_n=0.3 mm)
  - The dechannelling model seem optimistic for electrons due to an underestimation of multiple scattering on the nuclei
    - → Possibly favors the usage of positrons rather than electrons
    - → Requires detailed modeling of the dechanneling process
- Achieving the required longitudinal structure needs to be worked out (ERL design with large bunch charge, bunch trains with an accumulator ring, …)

Courtesy of Xavier Buffat

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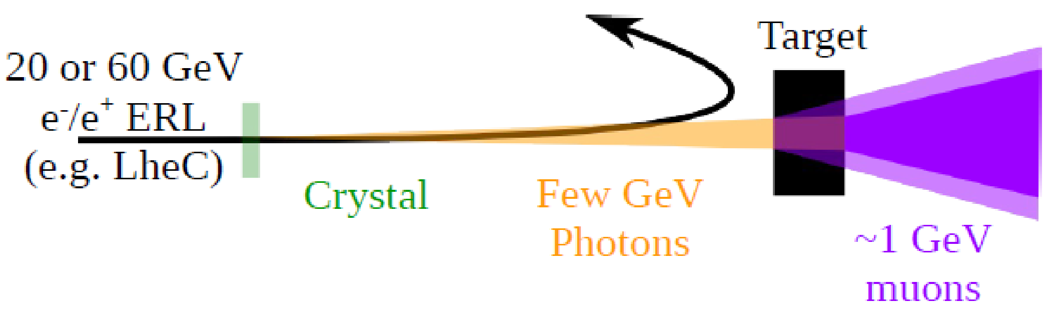

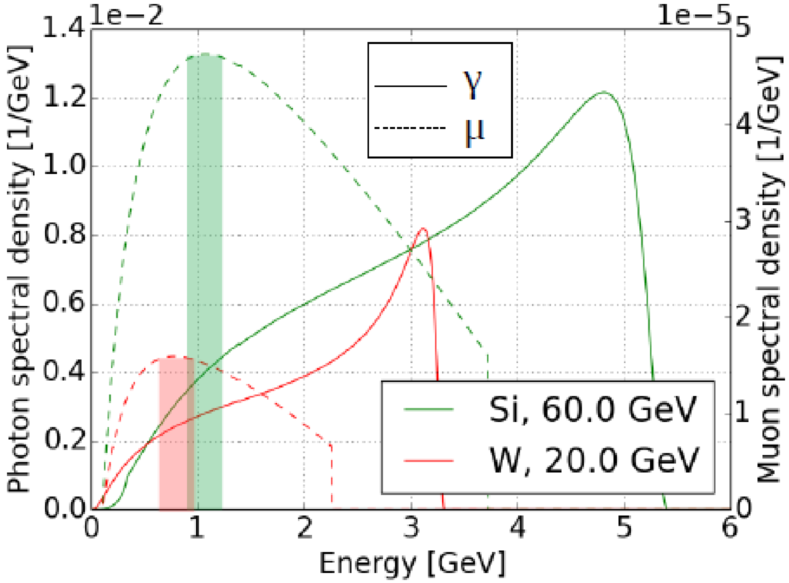

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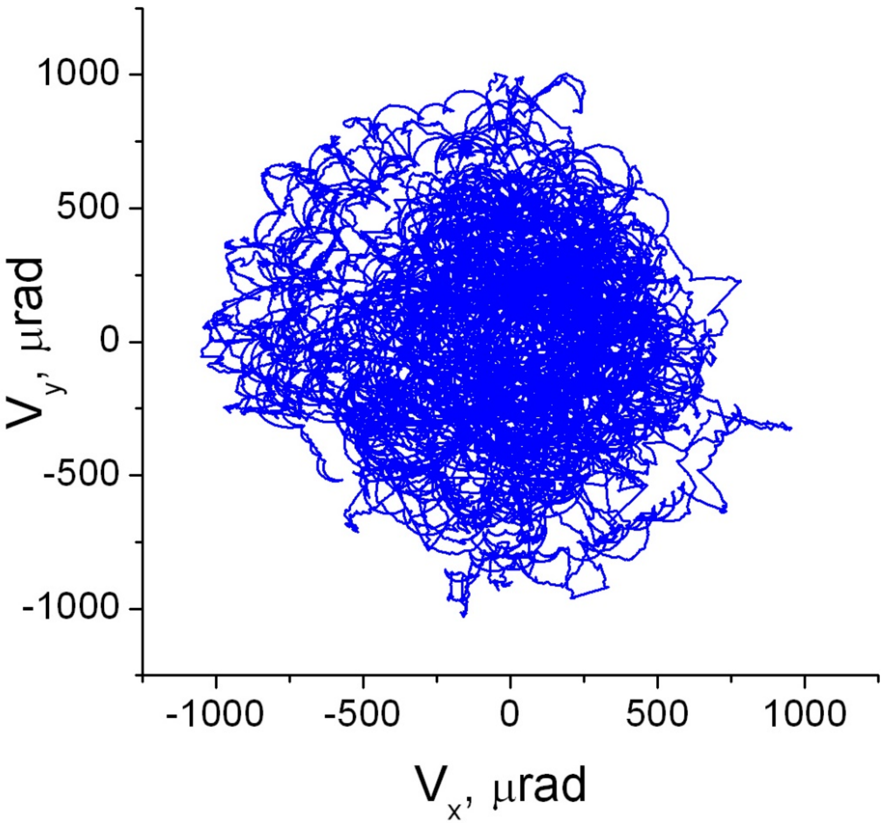
Courtesy of Xavier Buffat

Summary and future perspectives

- An algorithm to compute the radiation emitted by relativistic $e^{\pm}$ in crystals based on the Baier-Katkov method has been presented;
- Comparison with past experiments at different energies from sub-GeV to hundreds-GeV show a very good agreement.
- An experimental test on Channeling Radiation emitted by 5.6 GeV electrons in an axially oriented W crystal was conducted at DESY in December 2019 as a benchmark for the exploitation of our Simulation model to the design of a crysal based positron source.
- **New experiments with short crystals and good angular resolution in the energy range of interest for the hybrid positron source are needed to validate the used model and as feasibility tests.**
- **The developed MC can be exploited in a dedicated design for the LEMMA positron source.. And also for other possible applications for muon collider, e.g., muon pair production from gammas, crystalline targets, etc..**

THANK YOU FOR THE ATTENTION!

Positron source first dedicated simulations with the BK algorithm



Example of electron trajectories

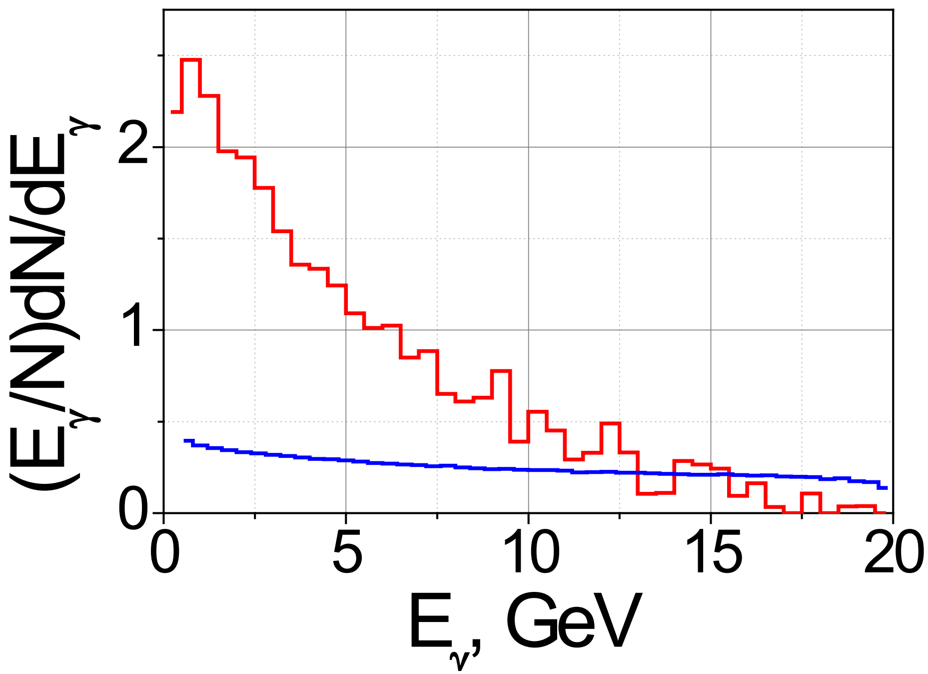
Simulation parameters:

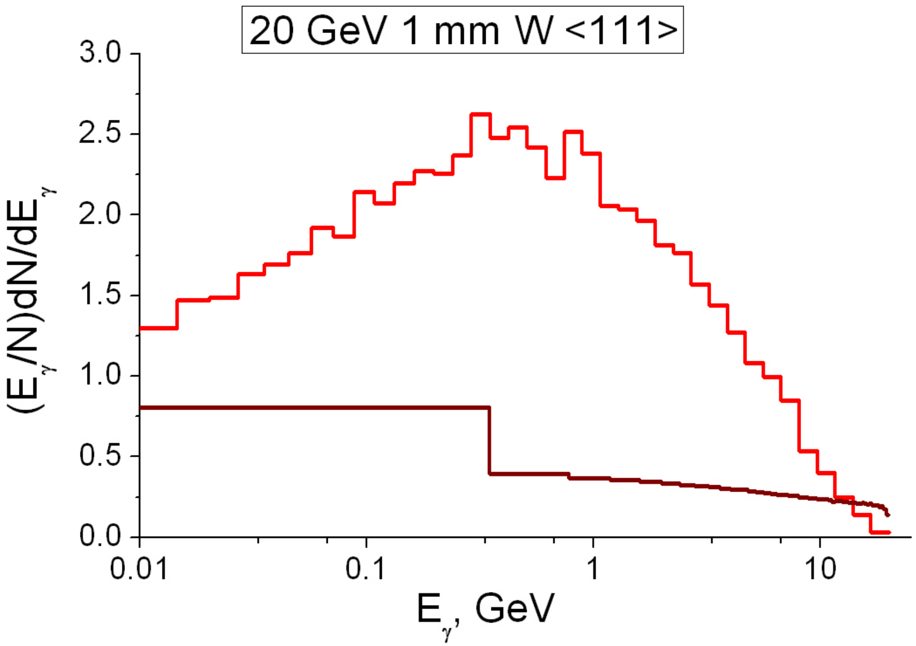
- **e^- beam of 20 GeV** (as one of the possibility for FCC-ee)
- **W crystal aligned with the <111> axis** due to the strong axial potential (1 keV)

Strong radiation enhancement

- **Crystal thickness 1 mm** to be shorter than 1 radiation lenght -> avoid photo conversion inside the radiation and consequent target heating

Simulation of radiation enhachement





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