Istituto Nazionale di Fisica Nucleare

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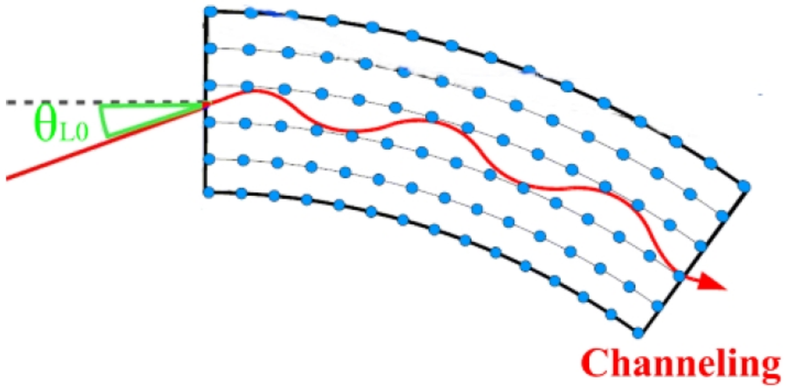
Project TRILLION: Implementation of steering and radiation effects in oriented crystals and their applications into Geant4

Dr. Alexei Sytov

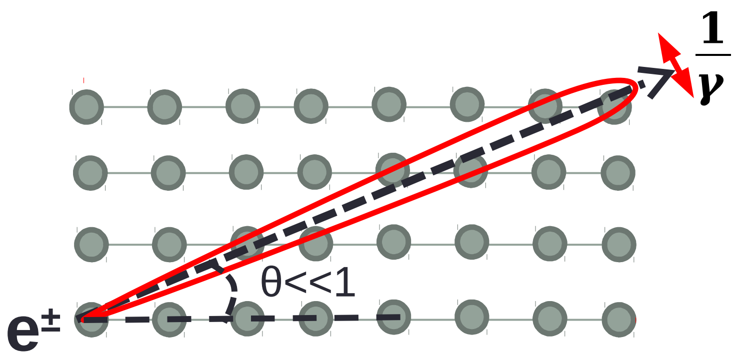
KPS 70th Anniversary and 2022 Fall Meeting
Busan, 2022/10/19

Coherent effects in a crystal

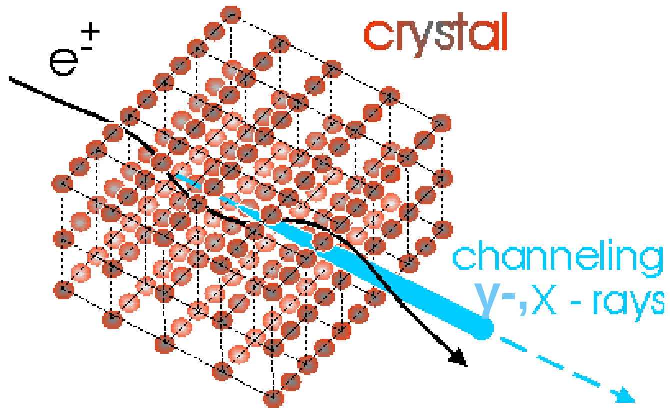
Channeling*



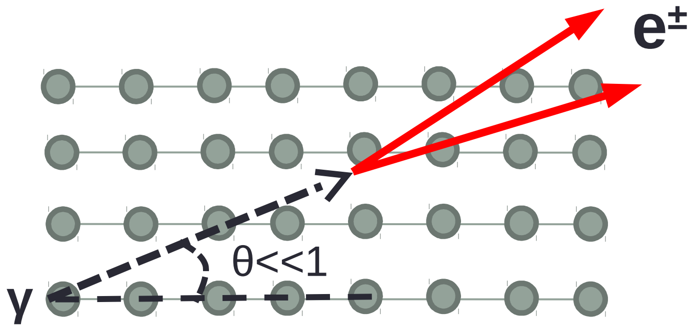
Coherent bremsstrahlung***



Channeling radiation**



Coherent pair production****



*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
**** H. Überall, Phys. Rev. 103, 1055 (1956).

Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2024, Project TRILLION GA n. 101032975

Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples to bring them to a large scientific and industrial community and under a free Geant4 license.

Group:

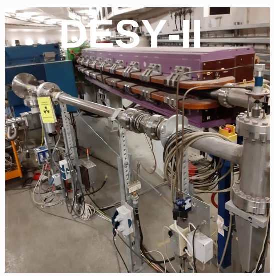
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

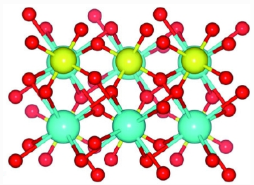
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Applications*

Crystal-based collimation or beam extraction from an accelerator

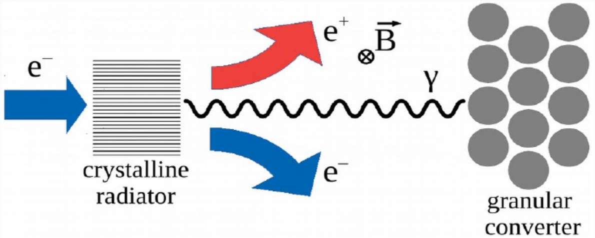


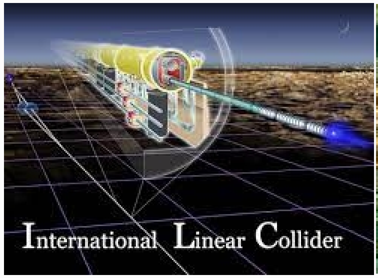
Ultrashort crystalline calorimeter

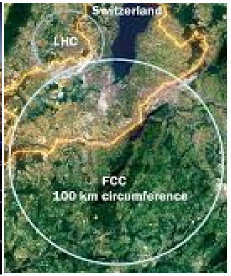


Gamma-ray Space Telescope

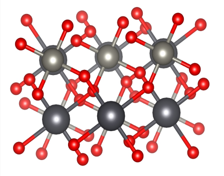
Positron source for future e+/e- and muon colliders



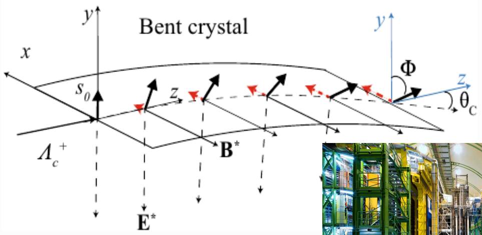




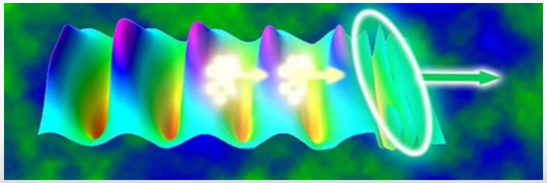
Oriented crystals



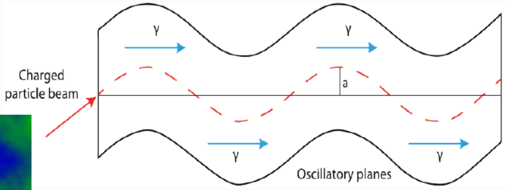
Measurement of dipole magnetic and electric moments of exotic particles

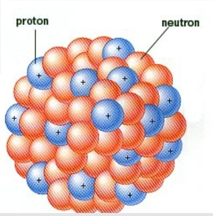


Plasma acceleration



X and y-ray source for nuclear and medical physics





The first step of TRILLION: Geant4 simulations of beam deflection by a bent crystal

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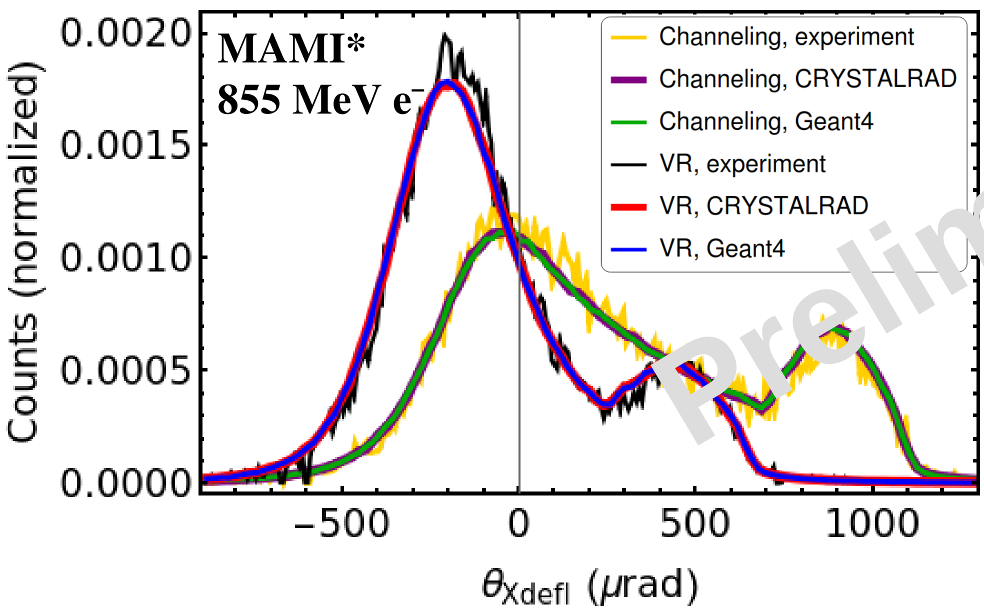
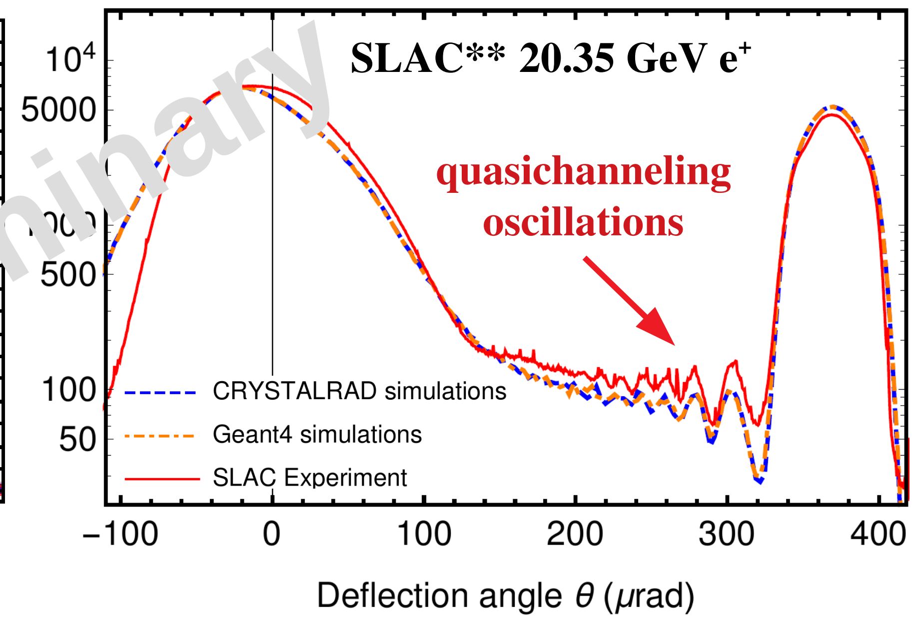
Geant simulations vs experiment and CRYSTALRAD simulations

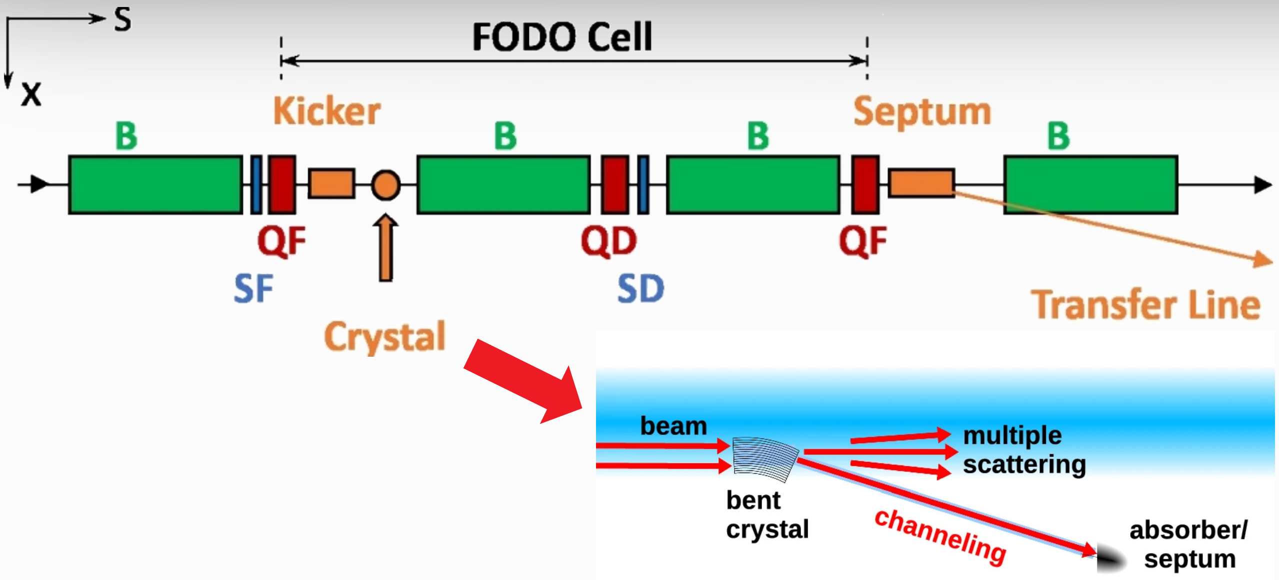


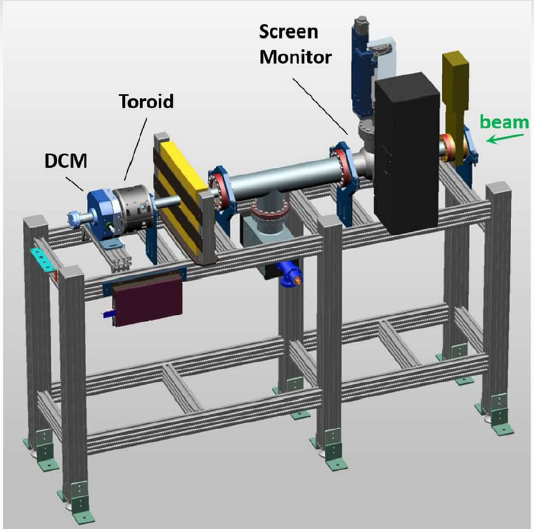


*A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)

**T. N. Wistisen, …, and A. Sytov. Phys. Rev. Lett. 119, 024801 (2017)

Crystal-based extraction: possible setup at DESY-II





Crystal-based beam extraction: applied only for protons,
never applied for electrons

Advantages:

- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- Few GeV electron beam, **typical for electron synchrotrons** existing in the world.

Can be applied at:

- DESY-II and any e-/e+ synchrotron or a **synchrotron light source**

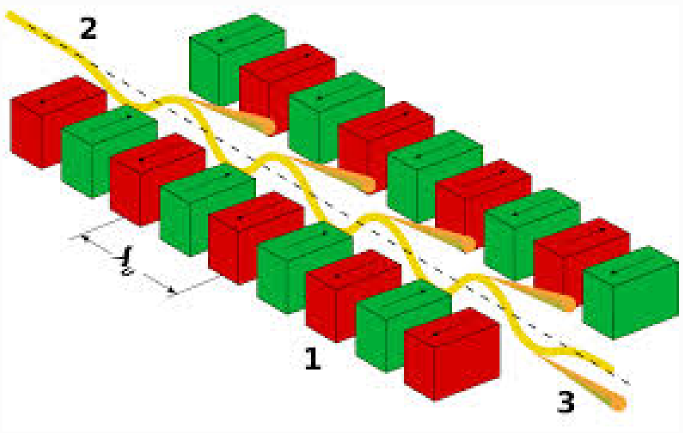
Have been already applied at:

- **LHC, Tevatron, SPS, RHIC, U-70**

A. Sytov et al., Eur. Phys. J. C 82, 197 (2022)

Channeling radiation in a bent crystal: Crystalline undulator

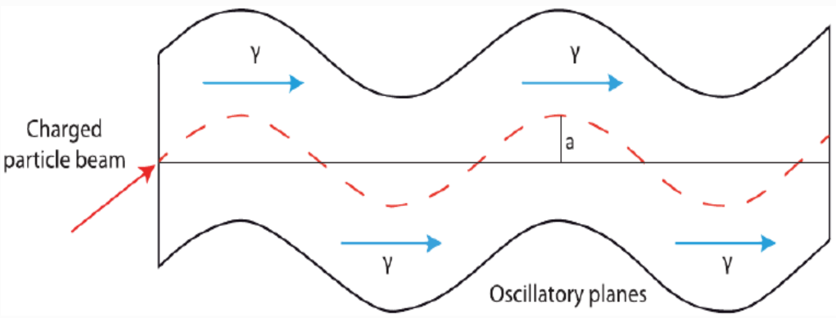
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



Advantage:

- Intense X- and gamma-rays produced in a crystal, in a compact piece of material

Innovative scheme: Crystalline undulator-> Hard X-rays and gamma rays $\lambda_u <$ mm

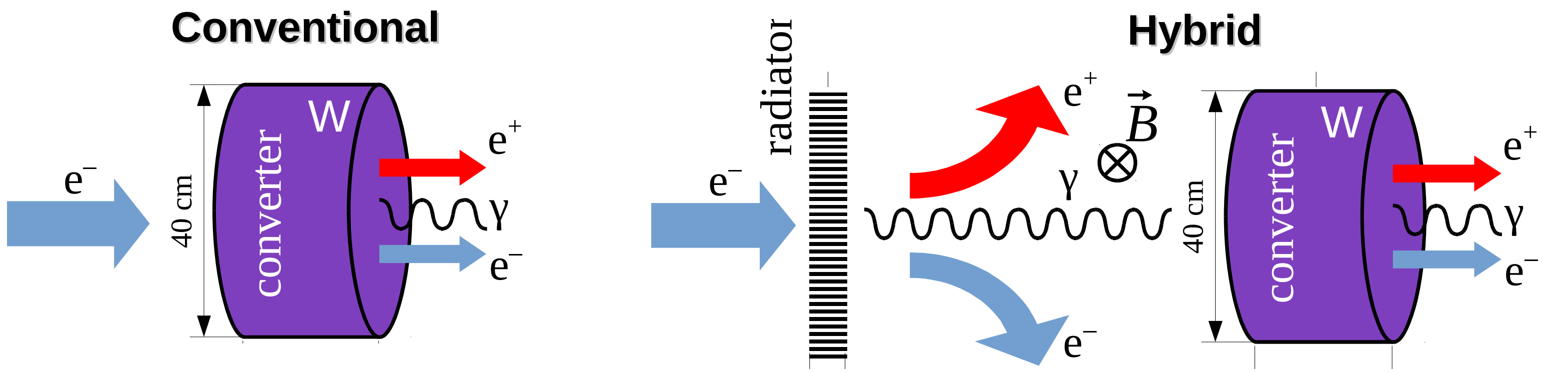


Crystalline X and gamma-ray source **can be applied** in:

- **Nuclear physics**
- **Medical physics**

EU project MSCA RISE N-LIGHT G. A. 872196
Coordinator MBN RESEARCH CENTER (Germany)

Crystal-based hybrid positron source*



Coherent effects in a crystal **accelerate electromagnetic shower** development

Coherent effects of e.m. shower in a crystal:

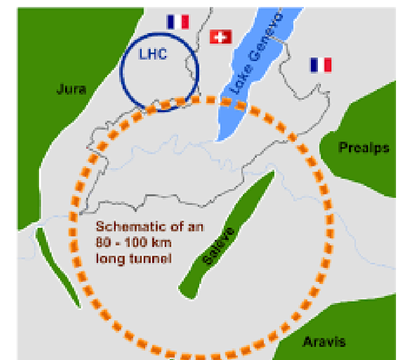
- Channeling radiation/coherent bremsstrahlung
- Coherent pair production

Advantages of the hybrid positron source:

- **Higher** positron yield
- Considerably lower peak deposited energy inside the target => **higher beam intensities**, **longer target lifetime**

Hybrid positron source can be applied at:

- **FCC-ee**
- **ILC**
- **Muon collider**

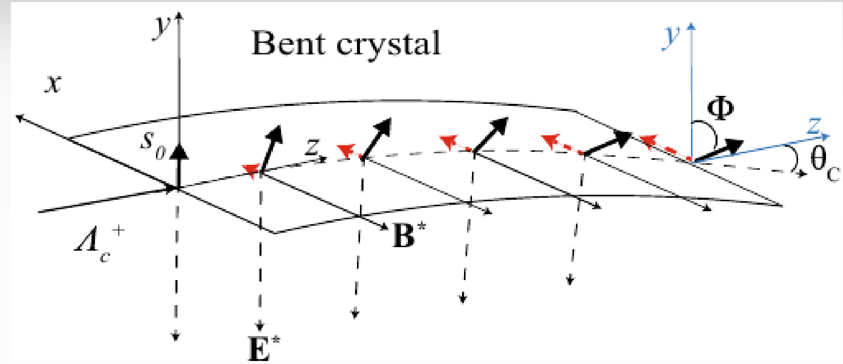


Simulation model can be also applied for **ultrashort crystalline calorimeter**

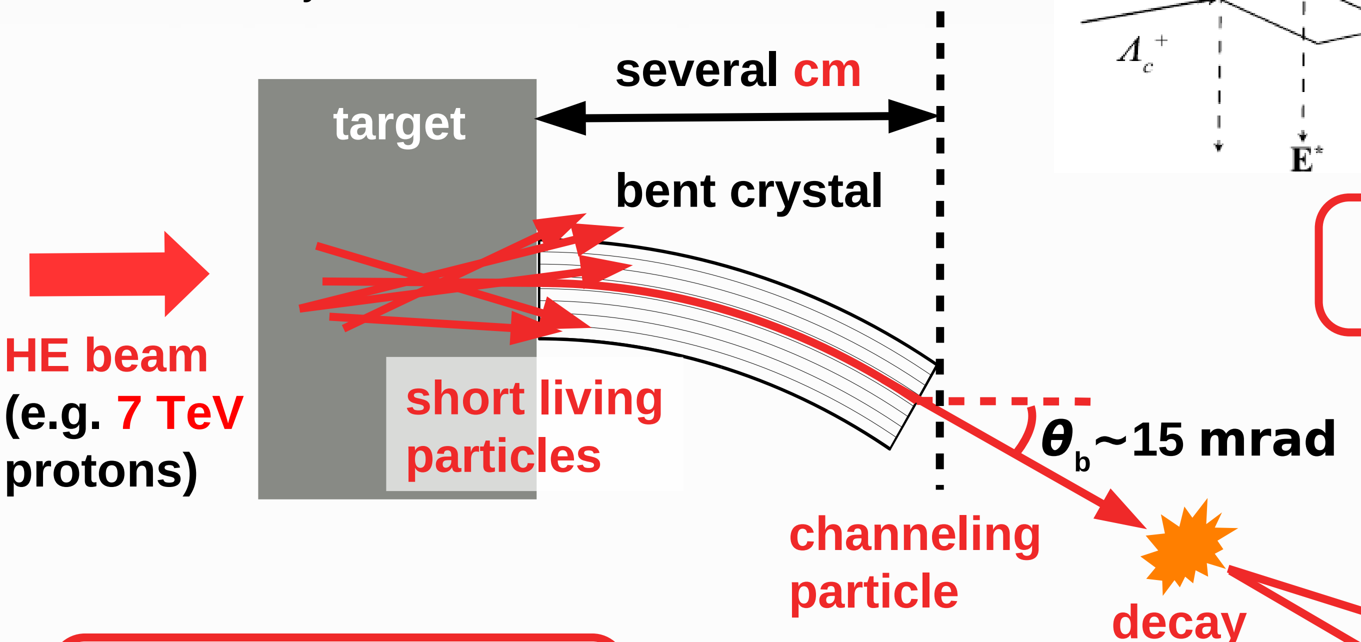
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

What we want:

- To measure **MDM** and **EDM** of exotic baryons



Experimental proof at Tevatron for Σ^+ **



Detector (e.g. LHCb)

polarization measurement

Crystal thickness must be **comparable** with the **life distance** of the particle

Possible particles: Λ_c^+, Ξ_c^+, ..., τ

* V. G. Baryshevskii, Pis'ma Zh. Tekh. Fiz. 5, 182 (1979)

**D. Chen et al. (E761 Collaboration) Phys. Rev. Lett. 69, 23 (1992)

Plasma wake-field acceleration in oriented crystals*

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Acceleration gradient: 1-10 TeV/m

Considerably **higher electron density** in a **solid state** than in a gaseous plasma

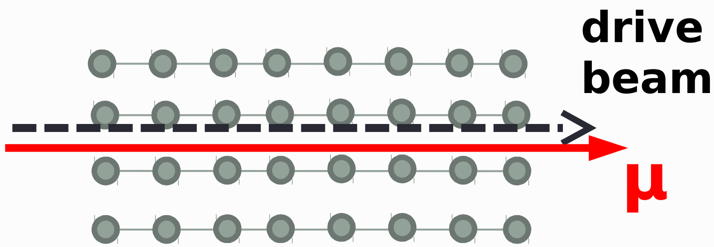
Channeling makes **crystal** almost **transparent** both to accelerated and to drive beam

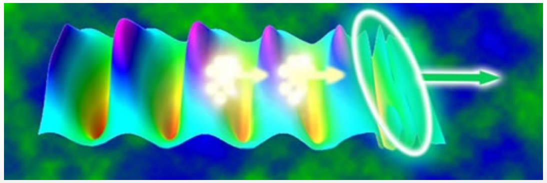
Possible drive beam:

- **X-rays**
- **electrons**
- **heavy high-Z beams**

Possible accelerated beam:

- **muons**
- **e+/e-**
- **protons**





Compact muon collider?

* R. Ariniello, …, and T. Tajima, Snowmass'2021 AF6: Advanced Acceleration Concepts, arXiv: 2203.07459

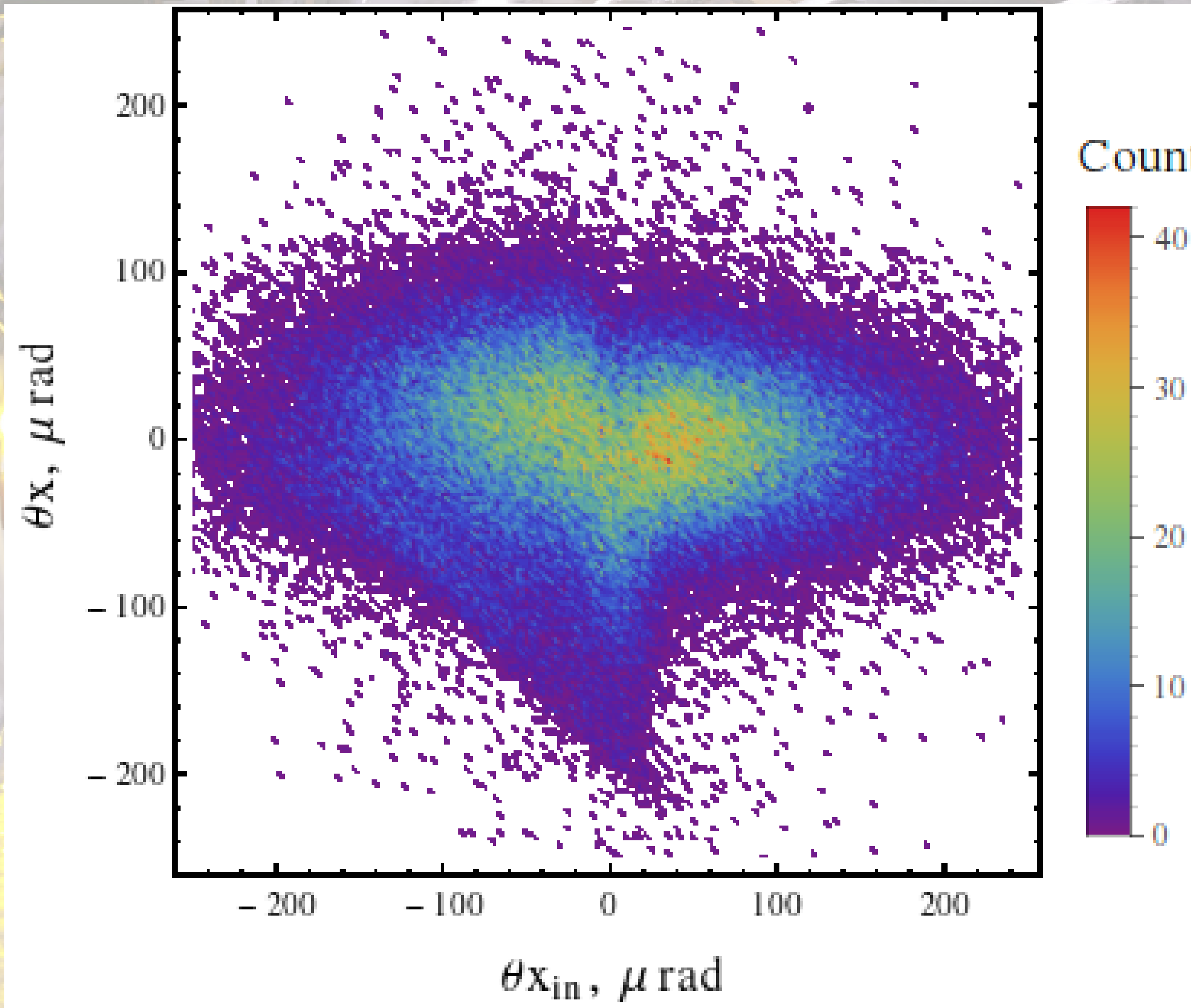
T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

Conclusions

- The goal of **TRILLION** is to implement **electromagnetic processes in oriented crystals** into **Geant4** which will bring most of possible applications of a crystal to a large scientific and industrial community.

- The Geant4 examples that will be developed can be **applied** in **nuclear** and **medical physics** (radiation source), at e-/e+ colliders – **ILC**, **FCC-ee** and **muon collider** (positron source) and at all **e-/e+ synchrotrons** existing in the world (crystal-based beam extraction).

- Additional applications can be applied in **detector physics** (crystalline ultrashort calorimeter), **particle physics** (magnetic and electric dipole measurement) and **innovative accelerator physics** (plasma acceleration).



Thank you for attention!

Solution: Geant4 FastSim interface

A. Sytov thanks **Prof. Vladimir Ivanchenko** (CERN) for this solution and the group of **Prof. P. Cirrone** (INFN LNS), in particular **Dr. L. Pandola** for fruitful discussions!

FastSim model:

- **Physics list** independent
- Declared in the **DetectorConstruction**
- Is activated only in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** until the exit from the model and then resumes them

Baseline simulation code: CRYSTALRAD*

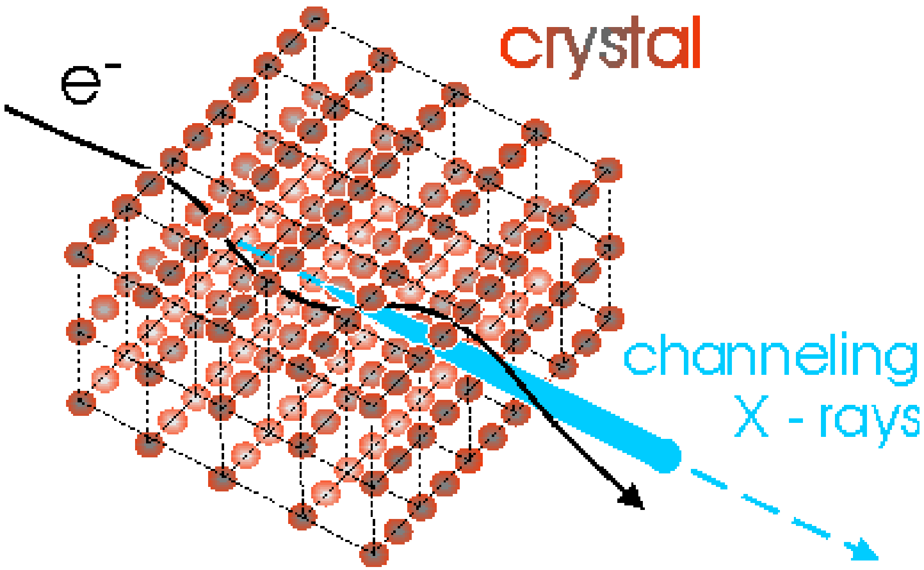
```
G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4Proton::ProtonDefinition()||
    &particleType == G4AntiProton::AntiProtonDefinition()||
    &particleType == G4Electron::ElectronDefinition() ||
    &particleType == G4Positron::PositronDefinition();// ||
    //&particleType == G4Gamma::GammaDefinition();
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
{
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

void TestModel::DoIt(const G4FastTrack& fastTrack,
                     G4FastStep& fastStep)
{
```

Insert particles for which the model is applicable

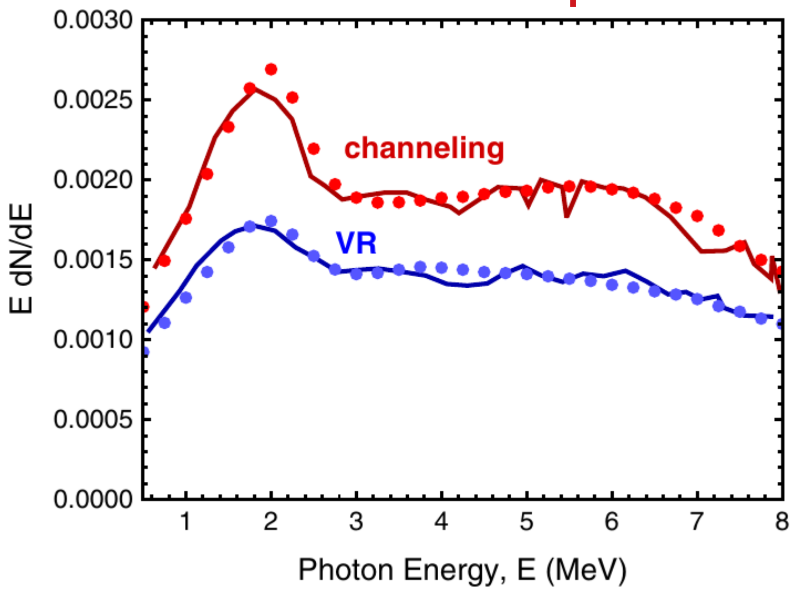
Insert the condition to enter the model

Insert what the model does

Baier-Katkov algorithm from CRYSTALRAD



CRYSTALRAD *vs* experiment



Baier-Katkov formula:

integration is made over the classical trajectory

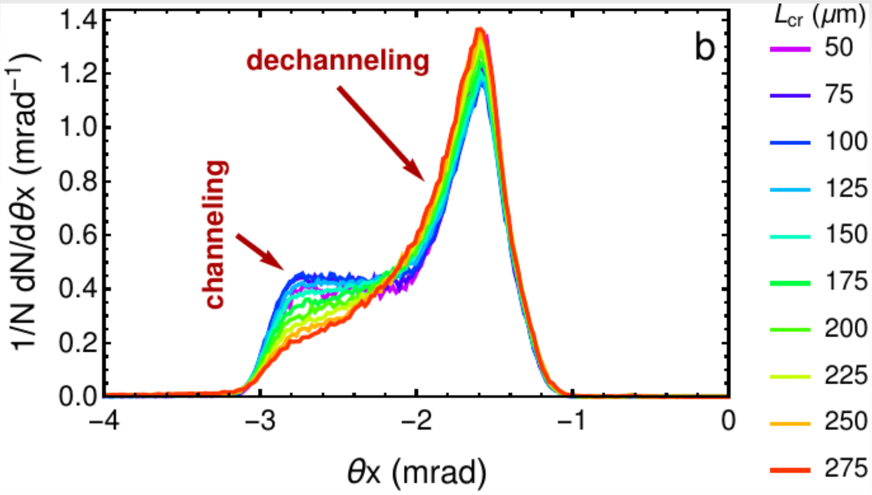
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

The **Baier-Katkov** method permits to simulate the emitted radiation in crystals in a wide energy range, from **sub-GeV** to **hundreds** of **GeV**.

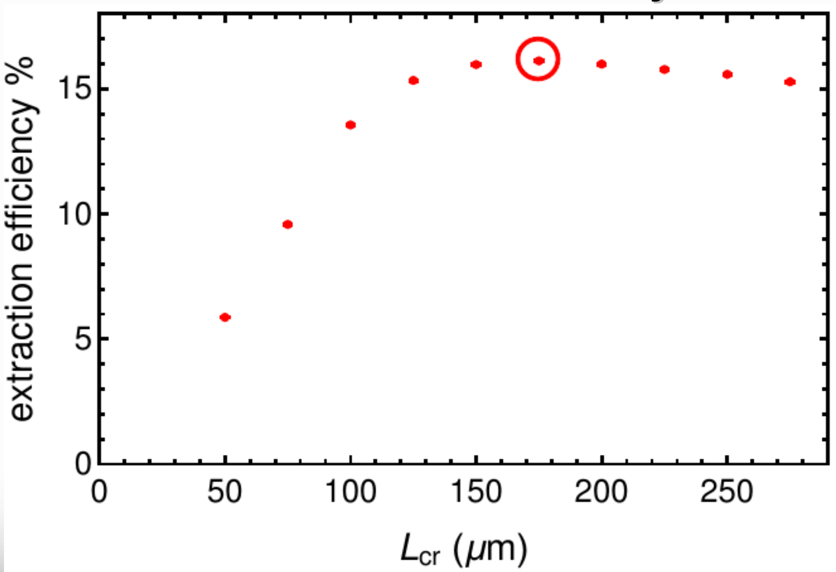
***L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)**
****V.N. Baier, V.M. Katkov, V.M. Strakhovenko World Scientific, Singapore (1998)**
*****V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903**
******A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)**

Crystal-based extraction: CRYSTALRAD simulation results

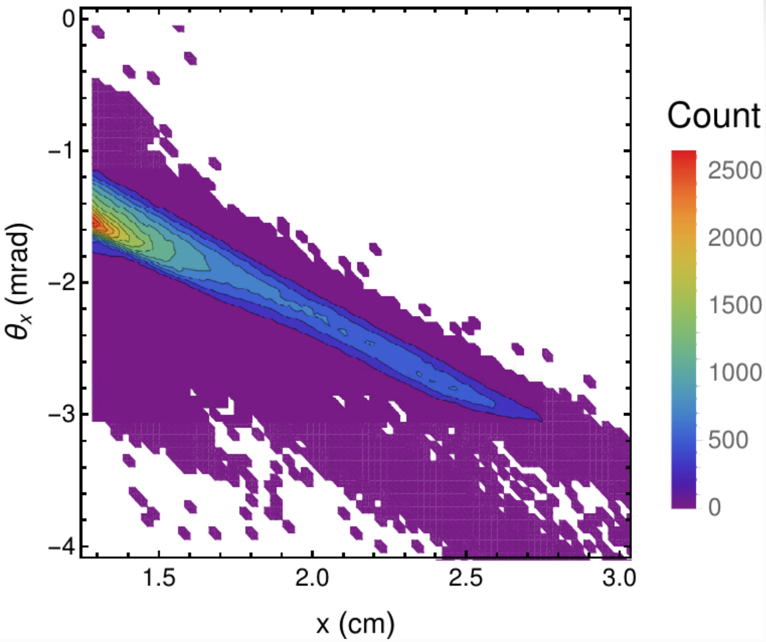
Angular divergence of extracted beam



Extraction efficiency



Phase space of extracted beam



Crystal parameters:

- **Si (111)**
- bending angle **1.75 mrad**
- Crystal length **0.175 mm**
- Crystal transverse thickness **1 cm**

Maximal extraction efficiency:
16.1 %