Istituto Nazionale di Fisica Nucleare

European Commission

www.kisti.re.kr

Korea Institute of Science and Technology Information

Trillion

Crystal channelling and radiation emission

Dr. Alexei Sytov

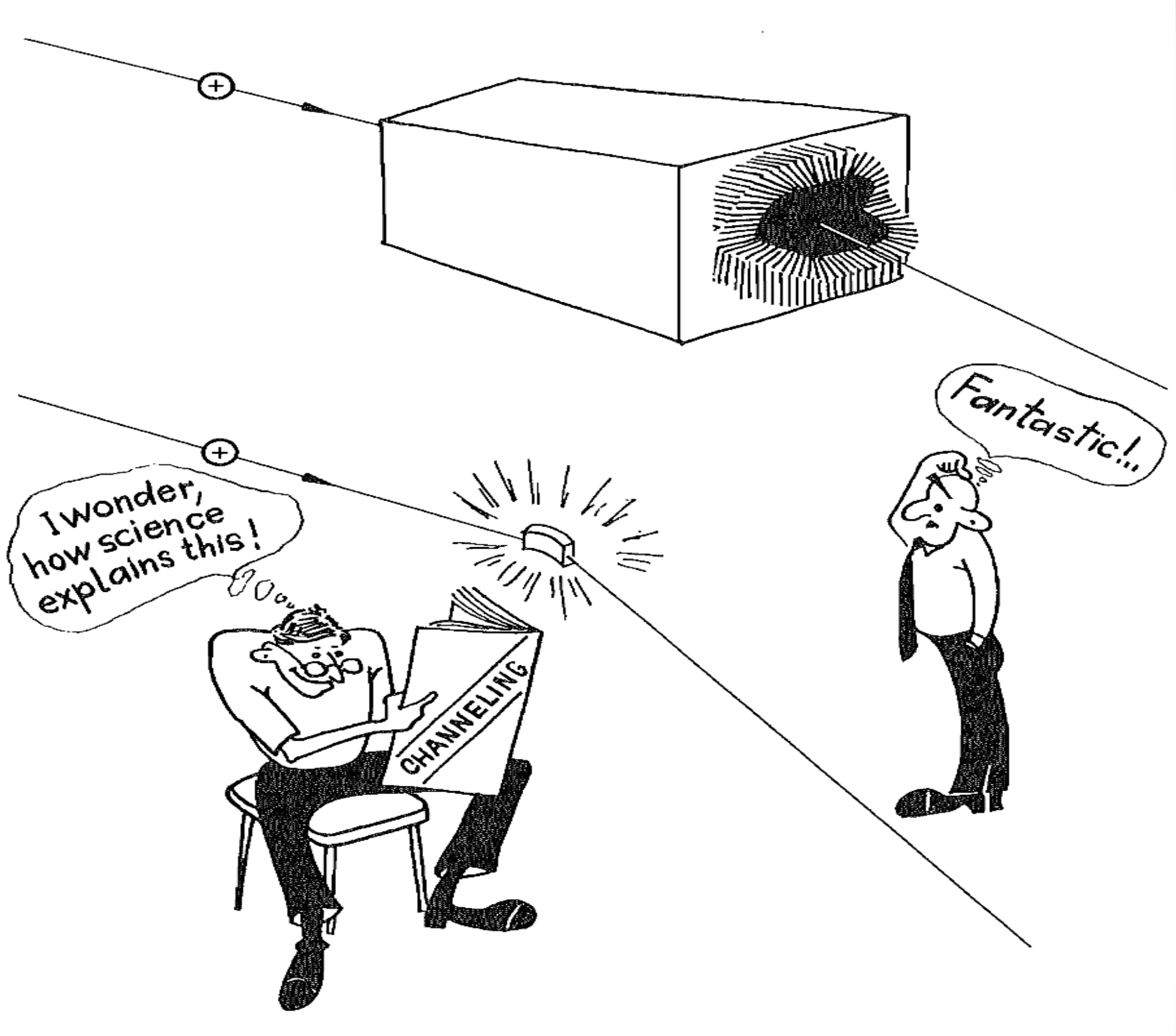
NanoAc 2022

Valencia, 23/11/22

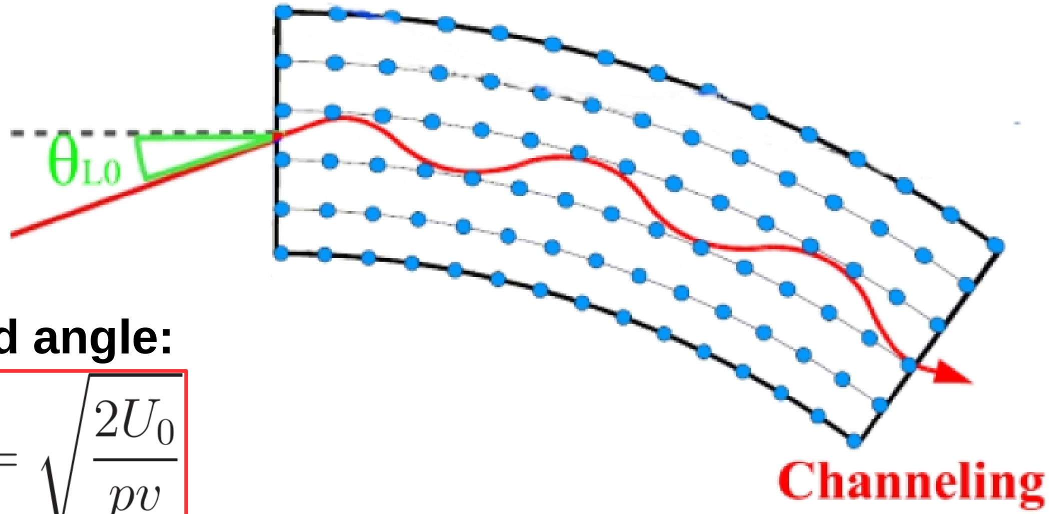
Outline

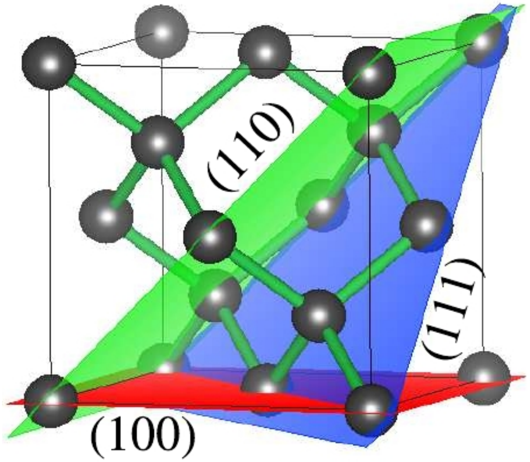
- **The world of channeling effect**
  - Channeling, Radiation and pair production
  - Electromagnetic shower acceleration
  - INFN Ferrara Group
  - High Performance Computing: Project **MIRACLE**
- **TRILLION - Marie Curie Individual Global Fellowships project**
  - The idea of the project
  - Applications
- **TRILLION**: implementation of the new physics into Geant4
  - Main conception: **FastSim** interface
  - What has been done by now?

The world of the channeling effect



Channeling effect*





Lindhard angle:

$$\theta < \theta_L = \sqrt{\frac{2U_0}{pv}}$$

Channeling* **is the effect of the penetration of charged particles through a monocrystal quasi parallel to its atomic axes or planes.** In dependence on the crystal alignment along either planes or atomic strings channeling can be divided into

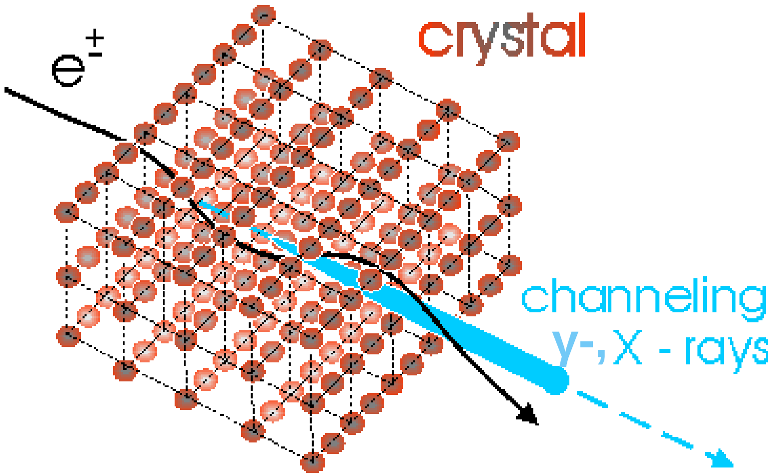
- ***Planar*** **channeling**
- ***Axial*** **channeling**

Planar/Axial field $10^9/10^{11}$ V/cm

*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

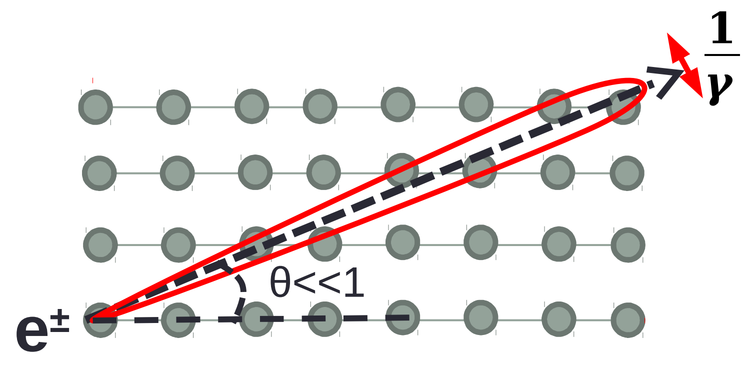
Coherent effects in a crystal

Channeling radiation*

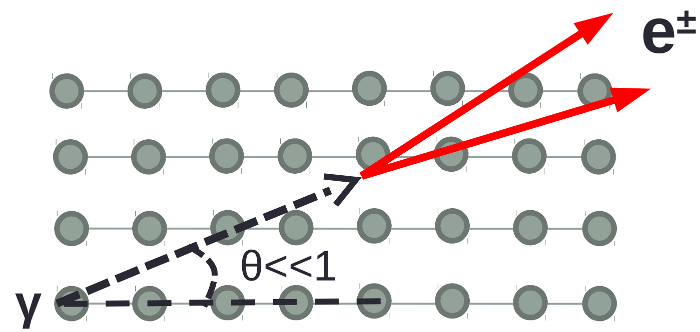


Coherent effects preserve
up to few mrad of particle
direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

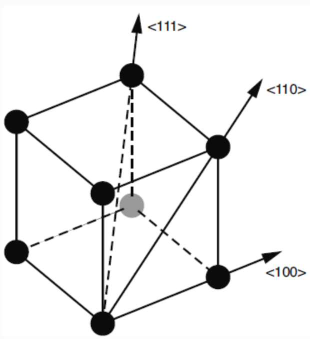


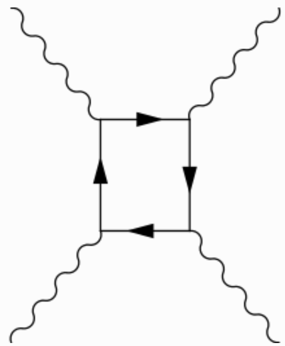
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)**
****B. Ferretti, Nuovo Cimento 7, 118 (1950).**
****M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).**
***** H. Überall, Phys. Rev. 103, 1055 (1956).**

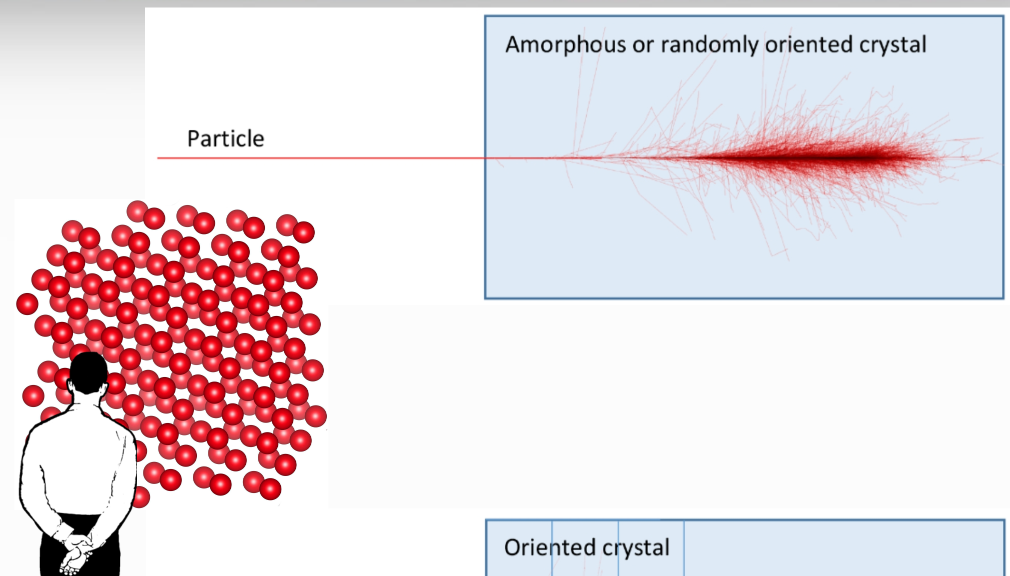
Electromagnetic shower acceleration

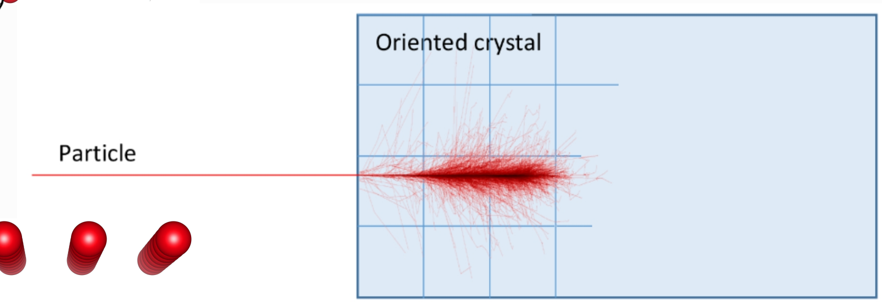
Axial field 10^{11} V/cm

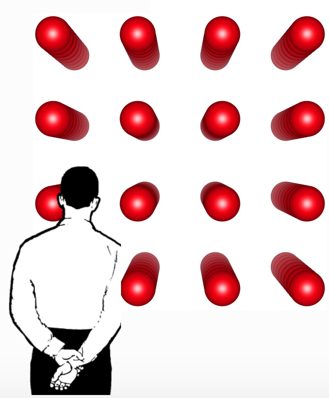
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**











The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced*.

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

INFN Ferrara team and collaborators on Crystal Channeling

Prof. Vincenzo Guidi

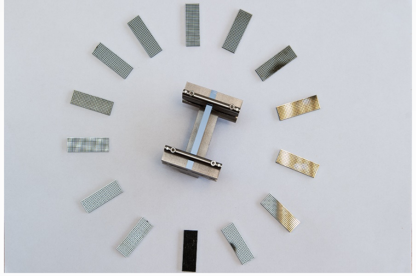
Dr. Laura Bandiera

INFN and University of Ferrara
INFN Legnaro Lab and University of Padua
INFN of Milan Bicocca and Insubria University
INFN and University of Milan
INFN and Sapienza University of Rome
INFN Frascati Lab

Main external collaborations
CERN, MAMI, DESY, MBN Center,
ESRF, Kharkiv, INP Minsk, IJCL Orsay

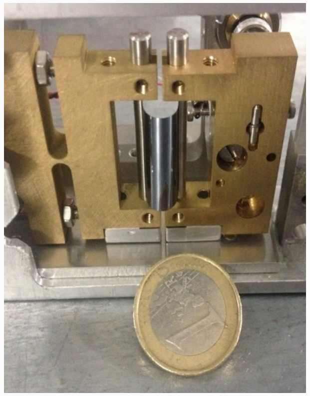
INFN Ferrara expertise

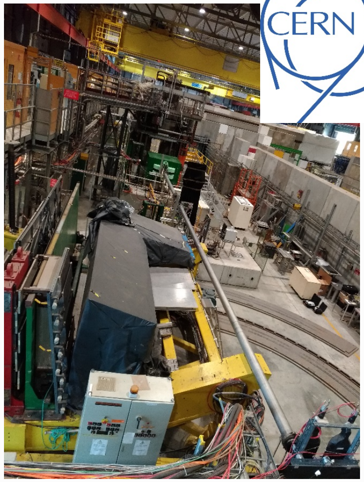
- **Combination of high-energy, accelerator and solid state physics**
  - Development of innovative ideas and research activities
  - Design of setups for channeling experiments
  - Crystals manufacturing and characterization
  - Data analysis
  - Simulations of channeling in crystals



$e^{\pm}$ @6 GeV DESY (Hamburg, Germany)

e^{-} @ subGeV MAMI (Mainz, Germany)





p, $e^{\pm}$, $\pi^{\pm}$ @ (20-400) GeV CERN (Geneve, Switzerland)

Channeling experiments at INFN

Istituto Nazionale di Fisica Nucleare

Involved in Channeling activities for about 20 years

CERN
- Collimation & beam steering
- Innovative radiation sources
- Pair production studies
- Innovative detectors

MAMI – Mainzer Mikrotron
- Beam steering
- Innovative radiation sources

DESY
- Innovative radiation sources
- Innovative detectors
- Beam extraction

SLAC
- Innovative radiation sources
- Beam steering

European Research Council – Established by the European Commission
- ERC-CoG CRYSBEAM (LHC beam extraction)
- ERC-CoG SELDOM (Studies of MDM and EDM of charmed baryons)
- MCA-IRSES CUTE (crystalline undulators)
- MSCA-RISE PEARL (crystalline undulators)
- MSCA-RISE N-LIGHT (crystalline radiation sources)
- INFRAIA AIDAInnova (crystal calorimeters)

Our project MIRACLE, no. HP10BIW7VR
Cineca ISCRA Class B National Italian project

MIRACLE

Medical physIcs and RAdiation in Crystals simuLation with gEant4

Main goal: to supply **Italian Geant4 community** and their international collaborators by CINECA HPC resources necessary to accomplish **MC_INFN** and **TRILLION** projects.

25/10/2021 - 25/10/2022

Marconi 100: 0.992 Mh for 1 year

Galileo 100: 2.4 Mh for 1 year

Italian organizations involved

- INFN Sezione di Catania
- INFN Sezione di Ferrara
- INFN Laboratori Nazionali del Sud
- INFN Napoli
- INFN Roma1
- Istituto Superiore di Sanità
- University of Messina
- University of Napoli

Foreign organizations involved

- ELI-Beamlines, Institute of Physics, (FZU), Czech Academy of Sciences
- Institute for Nuclear Problems, Belarusian State University
- University of Surrey

PI A. Sytov

Extended until 25/01/2023

INFN
Istituto Nazionale di Fisica Nucleare

European Commission

KiSTi
www.kisti.re.kr
Korea Institute of Science and Technology Information

Trillion

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

DESY.

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.

GEANT4
A SIMULATION TOOLKIT

Group:

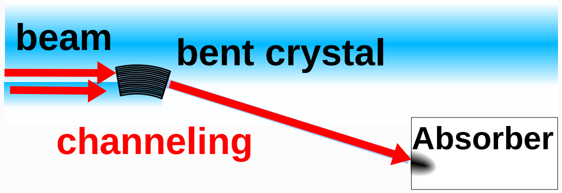
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

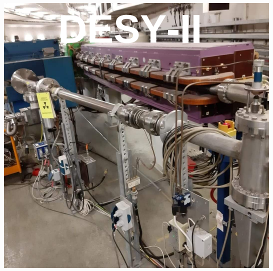
Location:

- 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)

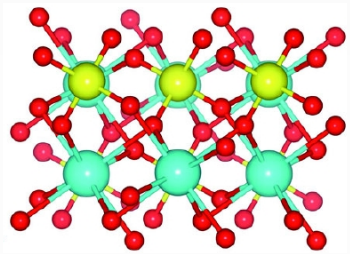
Applications*

Crystal-based collimation or beam extraction from an accelerator

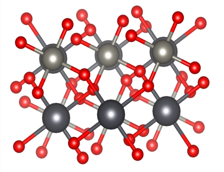




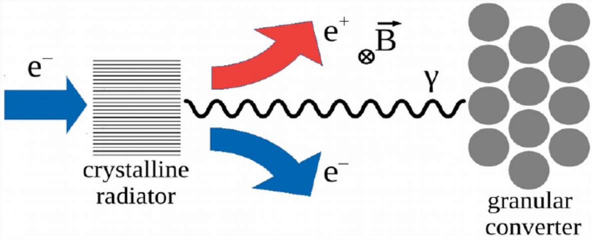
Ultrashort crystalline calorimeter

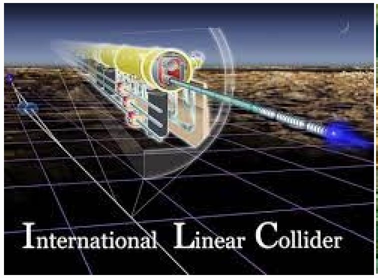


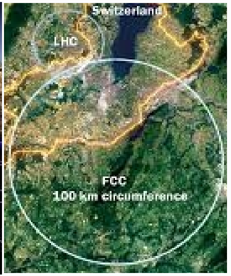
Oriented crystals



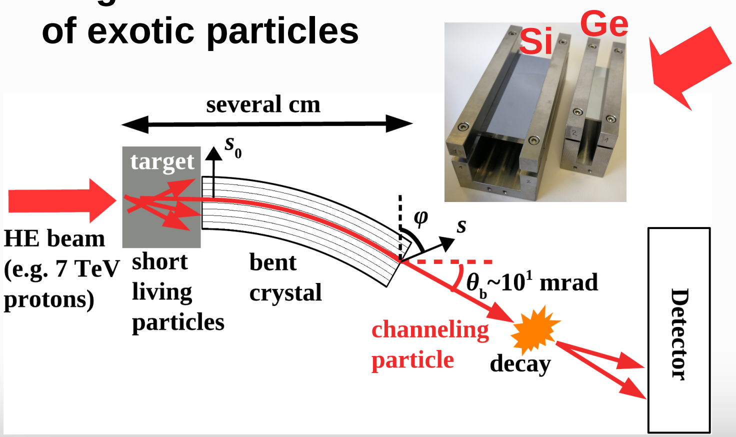
Positron source for future e+/e- and muon colliders



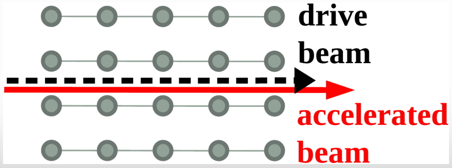




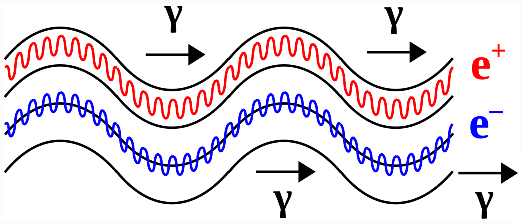
Measurement of dipole magnetic and electric moments of exotic particles

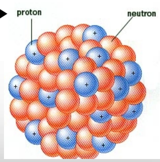


Plasma acceleration

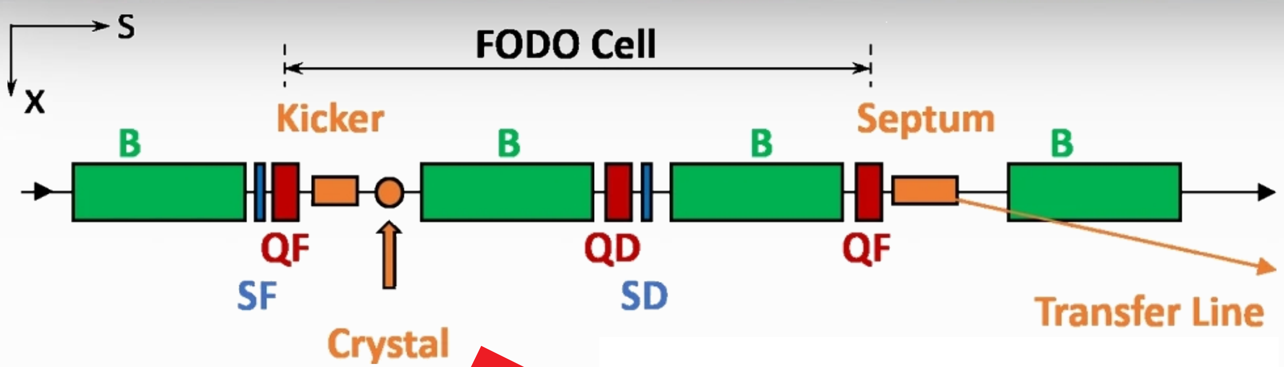


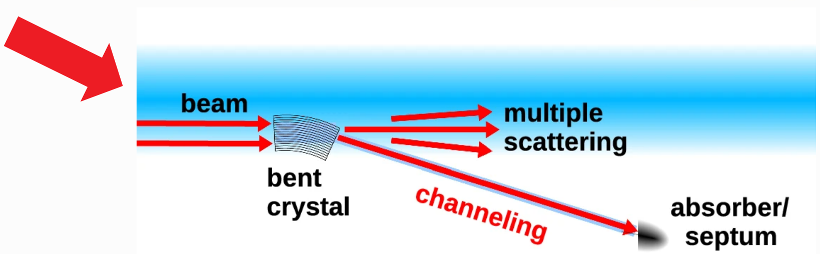
X and γ-ray source for nuclear and medical physics

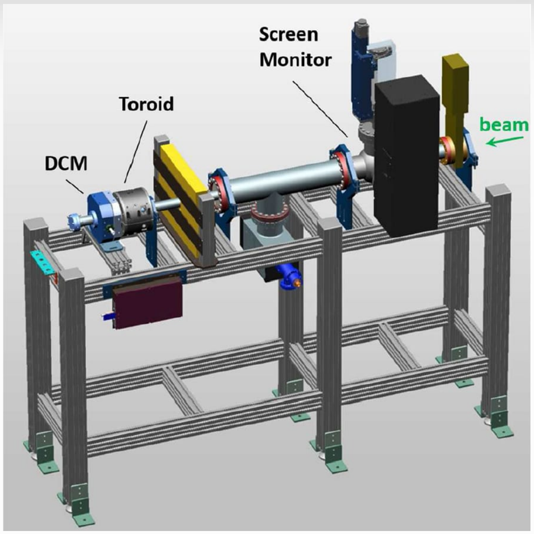




Crystal-based extraction: possible setup at DESY-II







6 GeV electrons

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:

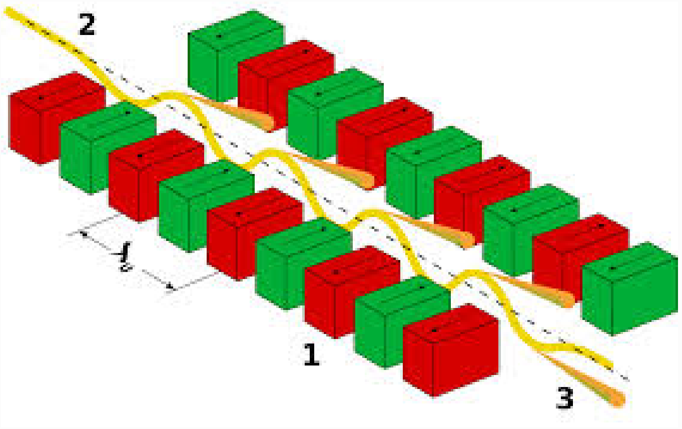
- DESY-II and any e-/e+ synchrotron or a **synchrotron light source**

Have been already applied at:

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

Channeling radiation in a bent crystal: Crystalline undulator

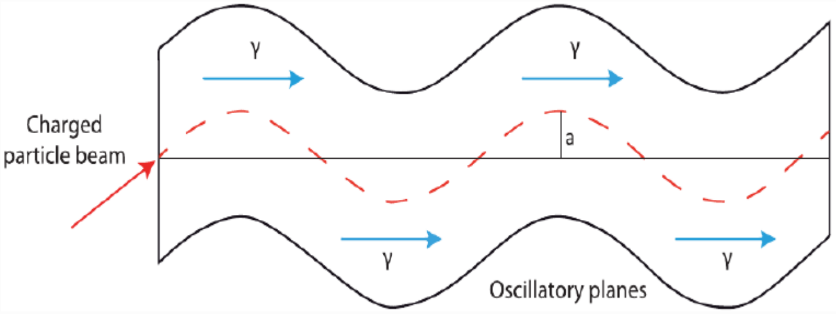
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



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



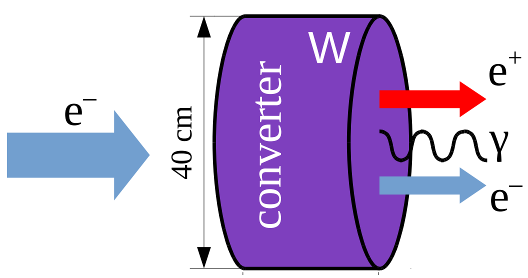
Crystalline X and gamma-ray source **can be applied** in:

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

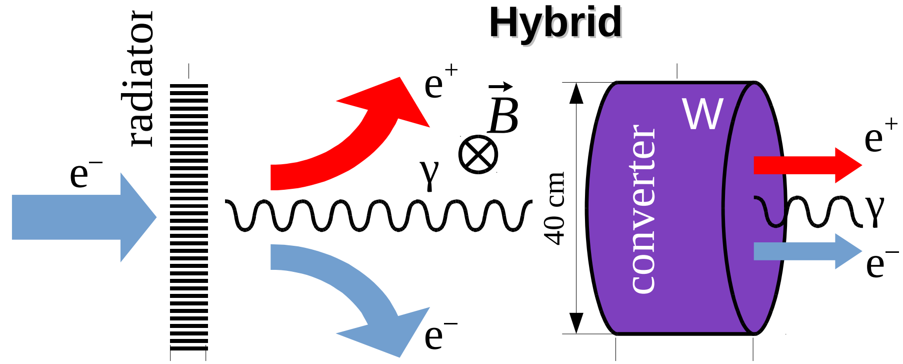
EU project MSCA RISE N-LIGHT G. A. 872196
Coordinator MBN RESEARCH CENTER (Germany)

Crystal-based hybrid positron source*

Conventional



Hybrid



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

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

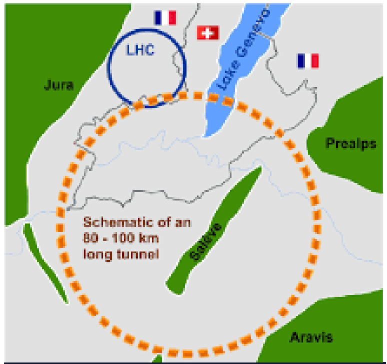
- Channeling radiation/coherent bremsstrahlung
- Coherent pair production

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**

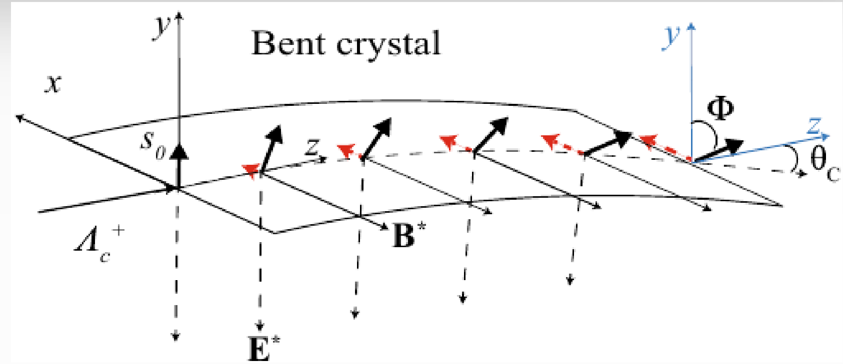


Simulation model can be also applied for **ultrashort crystalline calorimeter**

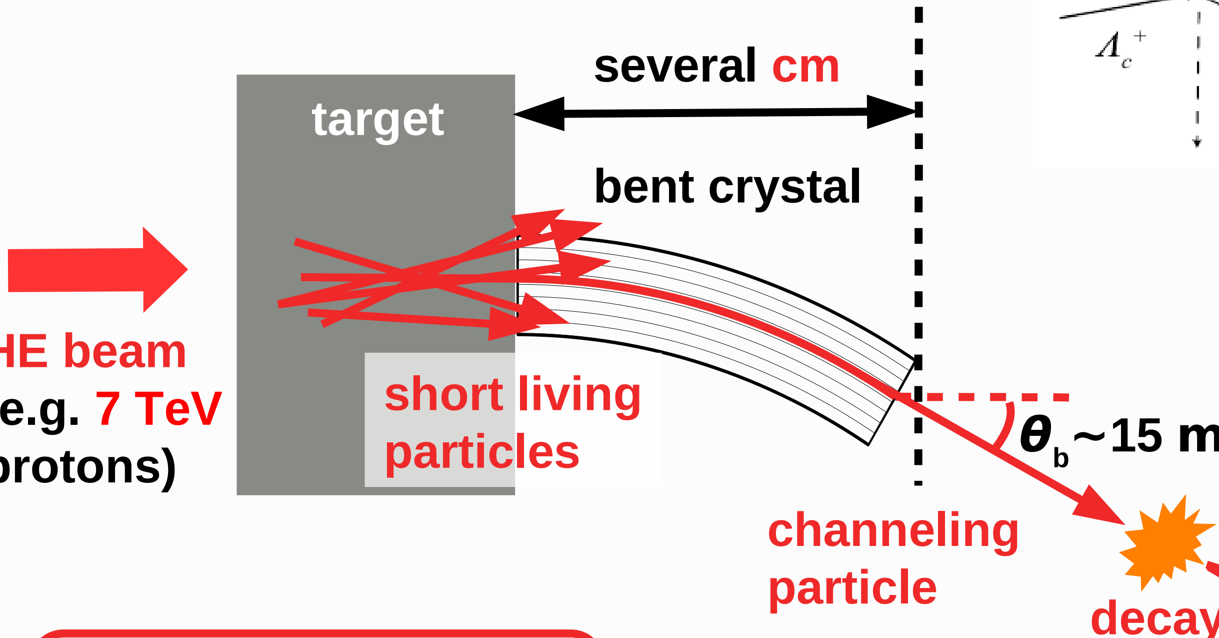
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

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: $1\text{-}10\ \mathrm{TeV/m}$

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

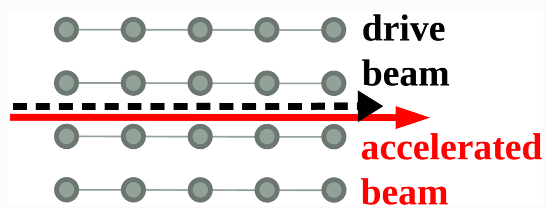
Channeling makes **crystal** almost **transparent** both to accelerated and to drive beam

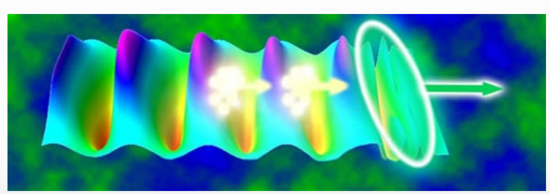
Possible drive beam:

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

Possible accelerated beam:

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





Compact muon collider?

R. Ariniello et al., arXiv: 2203.07459

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

Progress of channeling physics implementation into Geant4

GEANT4

A SIMULATION TOOLKIT

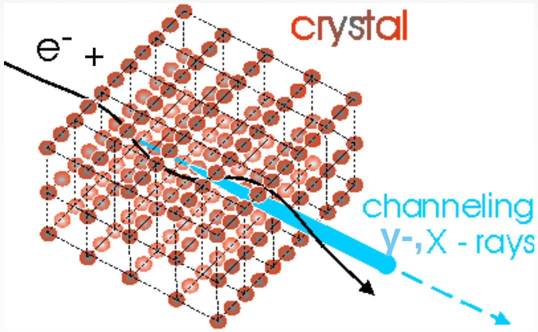
Geant4 is a toolkit for the simulation of the **passage** of particles **through matter**. Its areas of application include **high energy**, **nuclear** and **accelerator physics**, as well as studies in **medical** and **space science**.

Baseline simulation code: CRYSTALRAD

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential



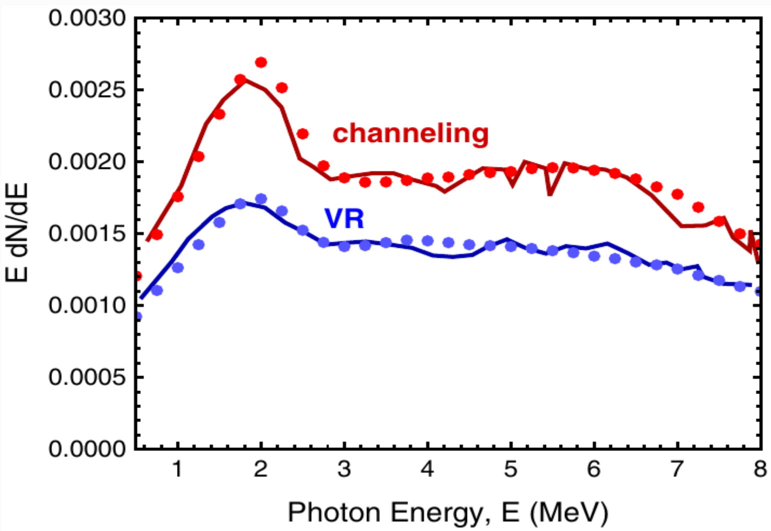
Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Nuclear scattering**
- **Ionization energy losses**
- **Crystal geometry**

Baier-Katkov formula:
integration is made over the classical trajectory

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

CRYSTALRAD *vs* experiment



Advantages:

- High calculation speed
- **MPI** parallelization for high performance computing

A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Solution: Geant4 FastSim interface

A. Sytov thanks **Prof. Vladimir Ivanchenko** (**CERN**) for this solution and the group of **Prof. Pablo Cirrone** (**INFN LNS**), in particular **Dr. Luciano Pandola** as well as **Prof. Kihyeon Cho** and **Dr. Kyungho Kim** (**KISTI**), **Prof. Susanna Guatelli** and **Prof. Anatoly Rosenfeld** (**University of Wollongong**) for fruitful discussions!

FastSim model:

- **Physics list independent**
- Declared in the **DetectorConstruction** (just **few lines of code**)
- Is activated **only** in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** at the step of FastSim model and then resumes them

```
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)
{
```

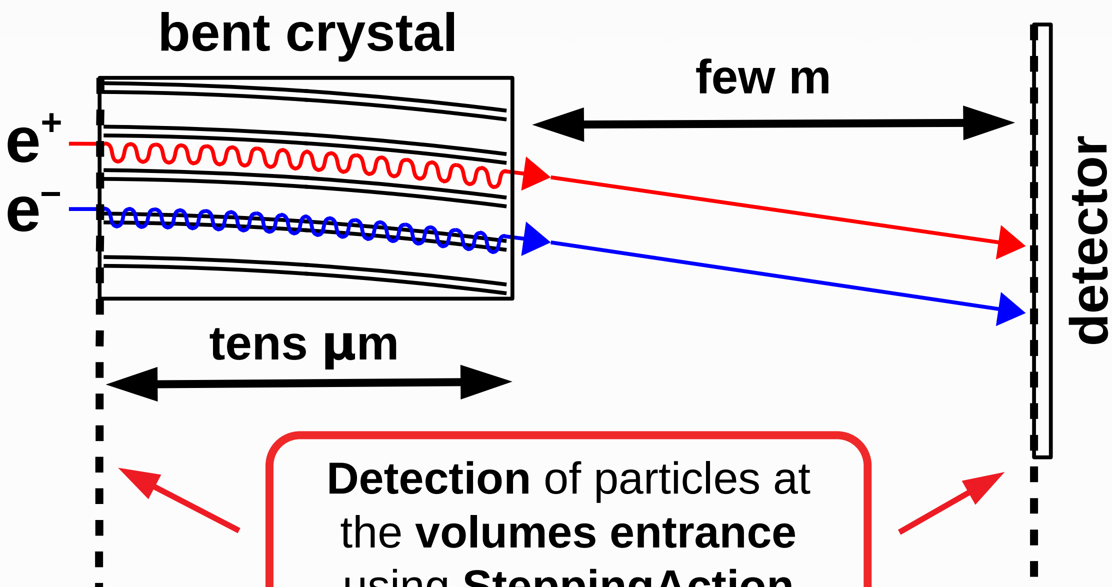
Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

First Geant4 channeling example for electrons/positrons

- **Inspired by** our experiments* of **855 MeV electron** beam deflection by an ultrashort **bent crystal** at **Mainz Mikrotron MAMI**



Beam setup in **run.mac** using **GPS** commands; all the **geometry** in **DetectorConstruction**

Multithreading works! Checked at the supercomputer **NURION@KISTI** (Korea)

Detection of particles at the **volumes entrance** using **SteppingAction**

Output both in **root** (only primary particles) and in **textfile** (all the particles) format

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

A. Sytov et al. Eur. Phys. J. C 77, 901 (2017)

First simulations with Geant4 channeling model: beam deflection by a bent crystal

Korea Institute of Science and Technology Information

www.kisti.re.kr

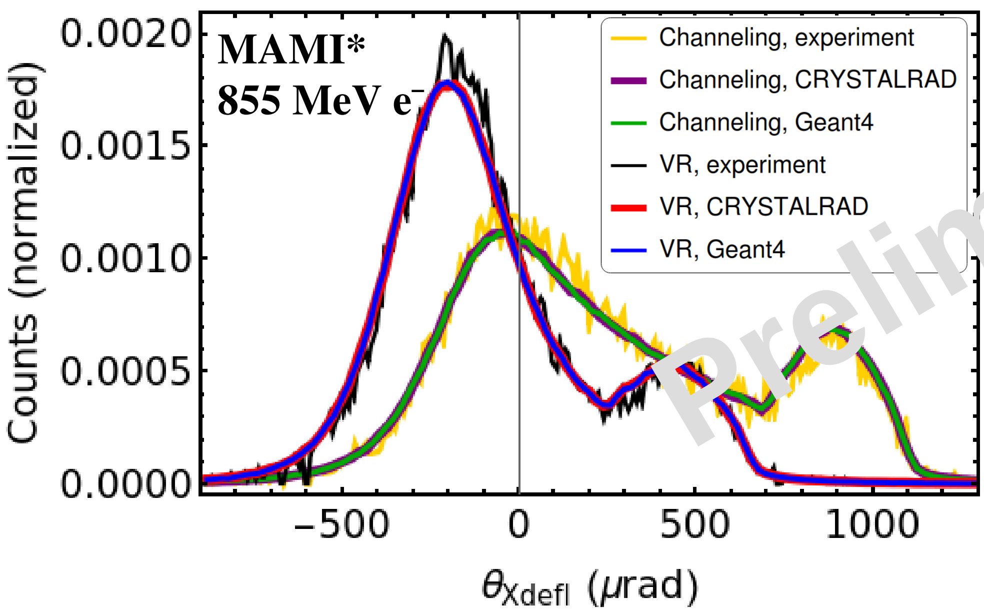
Istituto Nazionale di Fisica Nucleare

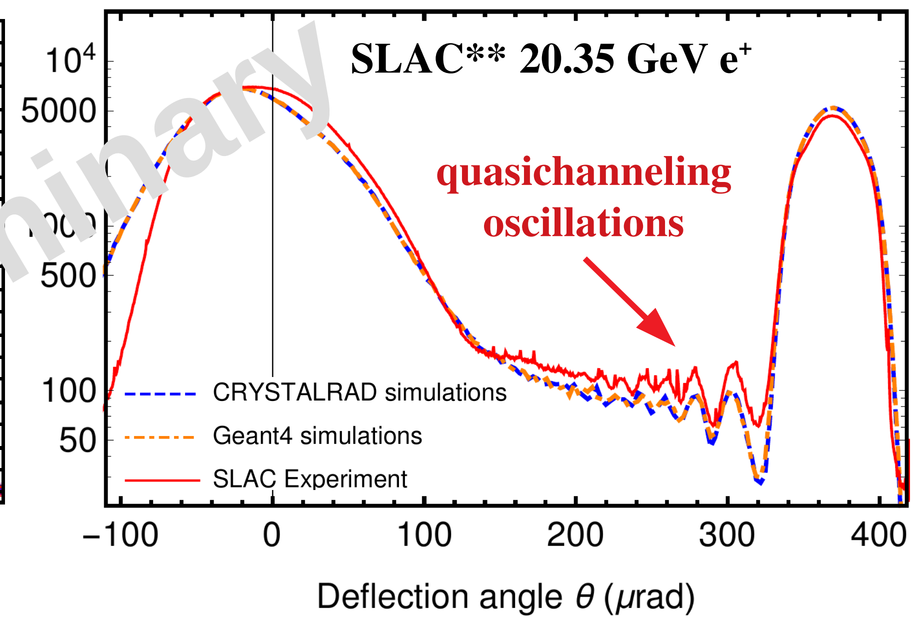
European Commission

Trillion

GEANT4 A SIMULATION TOOLKIT

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)

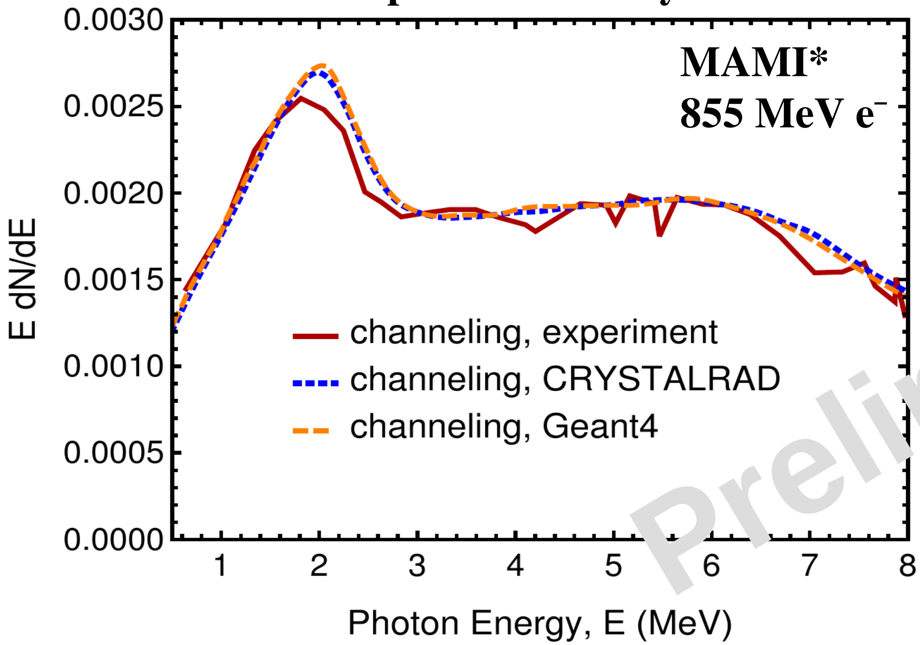
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

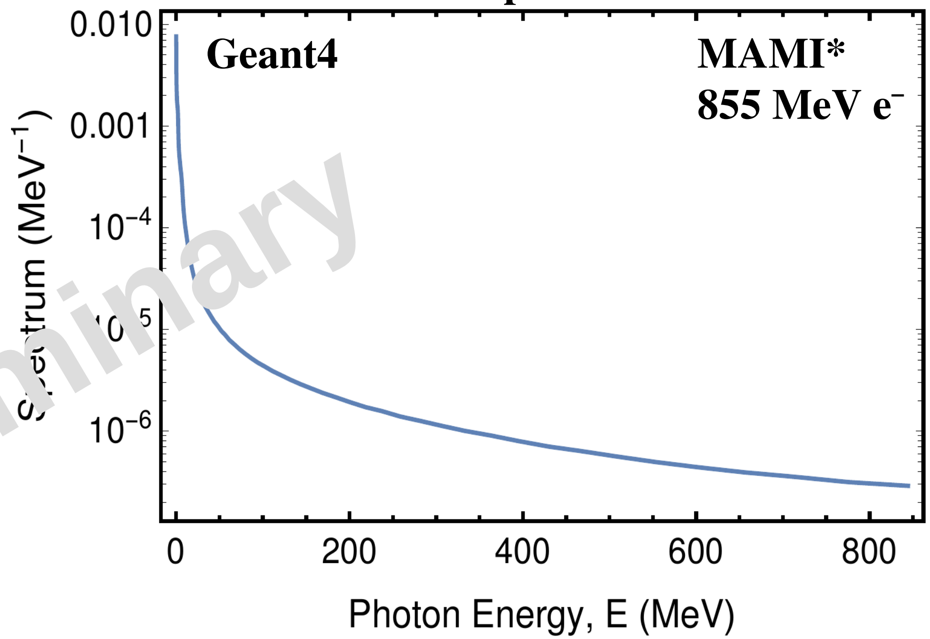
- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** (e.g. in **SteppingAction**)
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations

Spectral intensity



Full spectrum



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

How to use the Geant4 channeling model in your example?

- **Add to DetectorConstruction::Construct()**

```
//crystal volume
G4Box* crystalSolid = new G4Box("Crystal",CrystalSizeX/2,CrystalSizeY/2,CrystalSizeZ/2.);
G4LogicalVolume* crystalLogic = new G4LogicalVolume(crystalSolid,Silicon,"Crystal");
CrystalN1 = new G4PVPlacement(xRot,posCrystal,crystalLogic,"Crystal",logicWorld,false,0);
//crystal region (necessary for the FastSim model)
fRegion = new G4Region("Crystal");
fRegion->AddRootLogicalVolume(crystalLogic);
```

Volume declaration (completely standard)

G4Region declaration

- **Add to DetectorConstruction::ConstructSDandField()**

```
void DetectorConstruction::ConstructSDandField()
{
    // --------------- fast simulation ----------------------------
    //extract the region of the crystal from the store
    G4RegionStore* regionStore = G4RegionStore::GetInstance();
    G4Region* RegionCh = regionStore->GetRegion("Crystal");

    //create the channeling model for this region
    ChannelingFastSimModel* ChannelingModel = new ChannelingFastSimModel("ChannelingModel",RegionCh);
    //set the type of crystal planes
    G4String lattice = "(111)";
    //activate the channeling model
    ChannelingModel->Input(CrystalN1,lattice);
    //setting bending angle of the crystal planes (default is 0)
    BendingAngle = 0.905*mrad;
    ChannelingModel->GetCrystalData()->SetBendingAngle(BendingAngle);

    //activate radiation model (do it only when you want to take into account
    //radiation production in an oriented crystal; it takes a lot of computational power)
    ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim model declaration

Physical volume

Model activation

Additional options

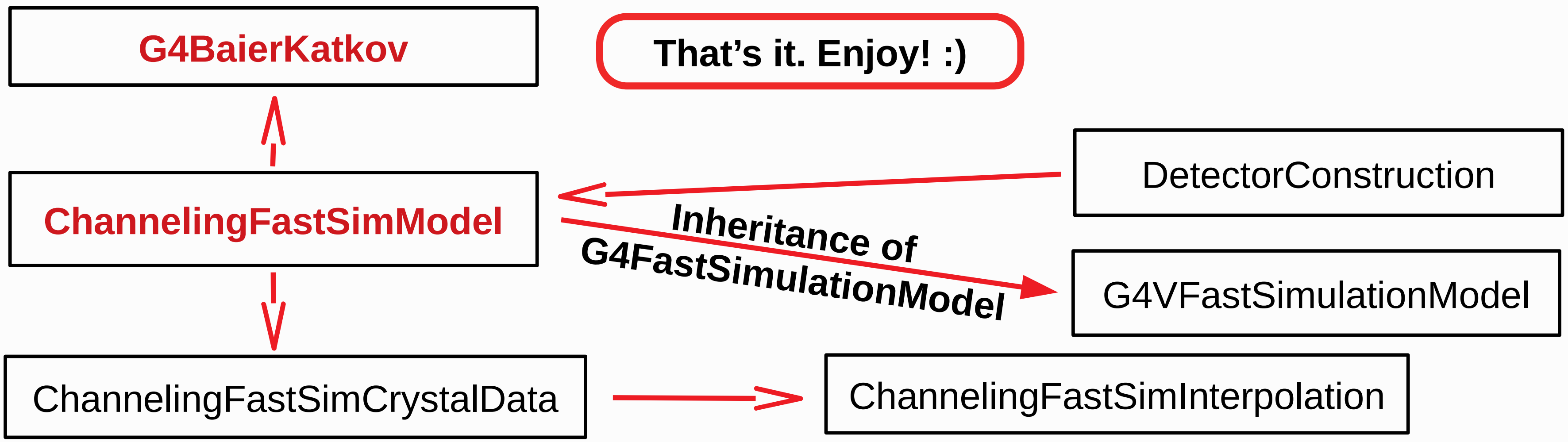
Radiation model activation

How to use the Geant4 channeling model in your example?

- **Add to main:**

Register FastSimulationPhysics

```
G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics();
fastSimulationPhysics->BeVerbose();
// -- activation of fast simulation for particles having fast simulation models
// -- attached in the mass geometry:
fastSimulationPhysics->ActivateFastSimulation("e-");
fastSimulationPhysics->ActivateFastSimulation("e+");
// -- Attach the fast simulation physics constructor to the physics list:
physicsList->RegisterPhysics( fastSimulationPhysics );
```



Physics list independent

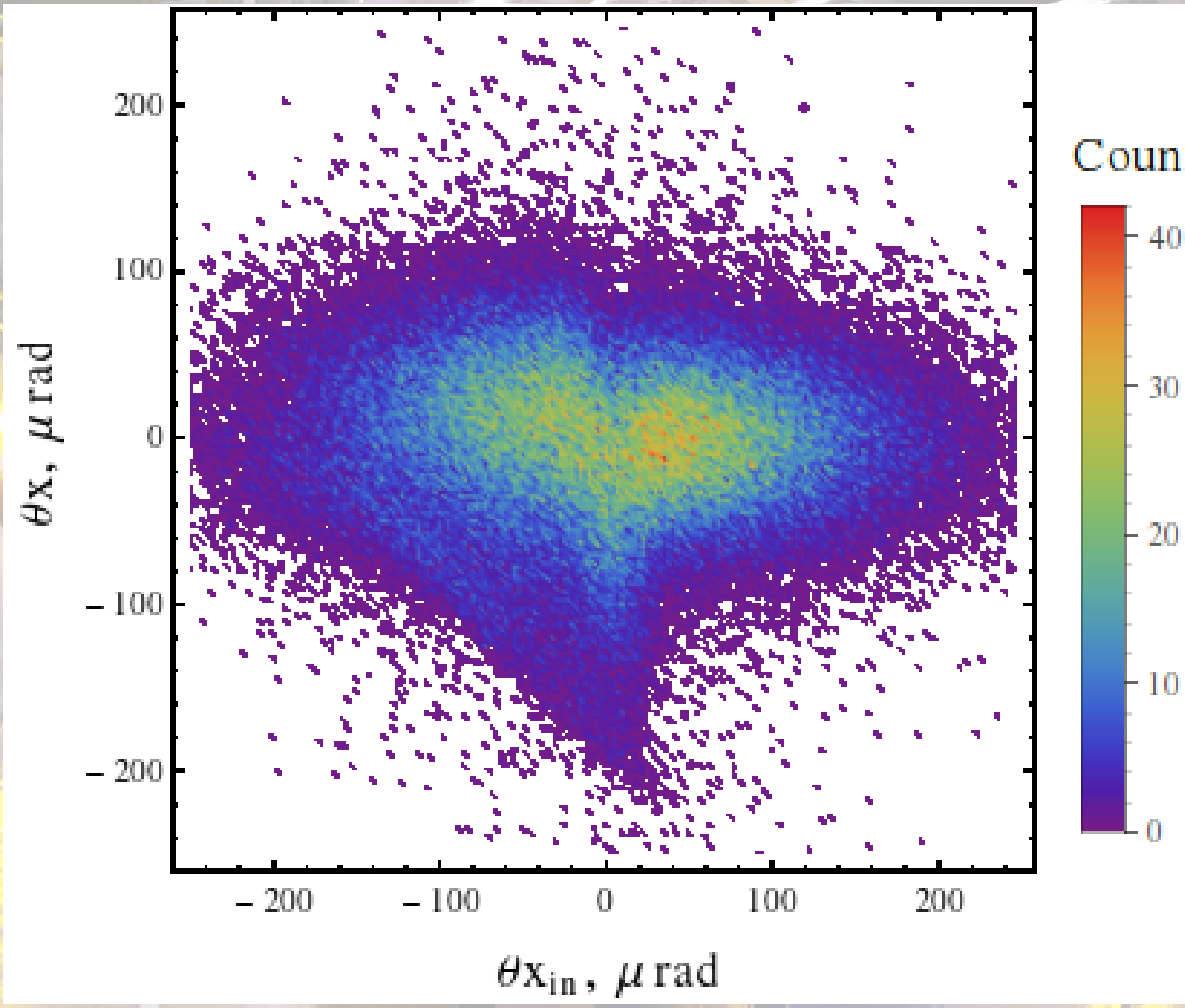
Conclusions

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

- 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 are ultrashort crystalline **calorimeter**, exotic particles **MDM** and **EDM measurement**, and **plasma wakefield acceleration**.

- Supercomputing project **MIRACLE** supplies **Geant4 developers** in Italy and their foreign collaborators with supercomputing resources.



Thank you for attention!