# G4ChannelingFastSimModel and G4BaierKatkov model for the FCC-ee crystal-based positron source

A. Sytov, F. Alharthi, L. Bandiera, N. Canale, I. Chaikovska, R. Chehab, K. Cho, G.A.P. Cirrone, S. Guatelli, V. Haurylavets, S. Hwang, V. Ivanchenko, L. Pandola, G. Paternò, V. Mytrochenko, R. Negrello, A. Rosenfeld, V. Tikhomirov, Y. Wang

sytov@fe.infn.it

Channeling 2024, Riccione, 09/09/24

# Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2025, 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:**

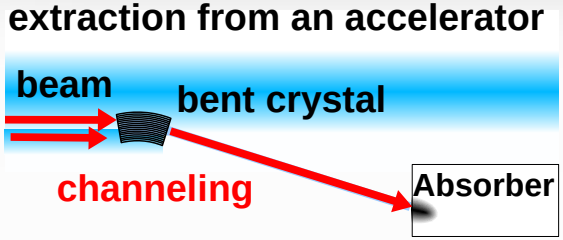
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

**Location:**

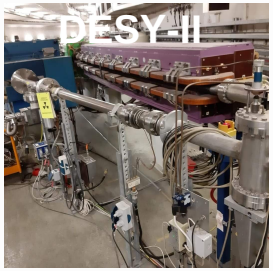
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

# Applications*

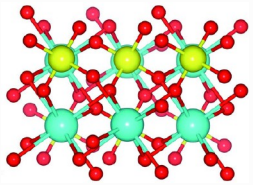
**Crystal-based collimation or beam extraction from an accelerator**





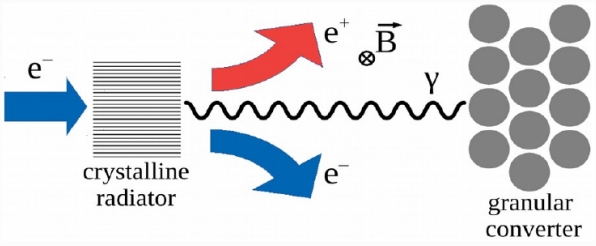


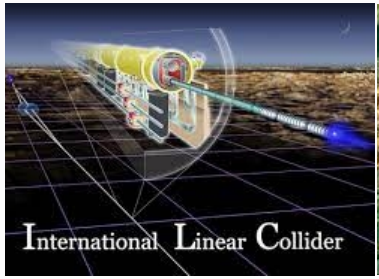

**Ultrashort crystalline calorimeter**



**Gamma-ray Space Telescope**

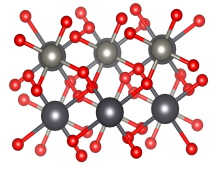
**Positron source for future e+/e- and muon colliders**



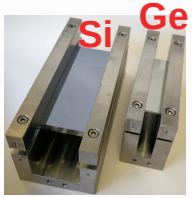





**Oriented crystals**



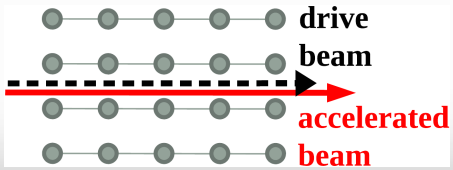
**Measurement of dipole magnetic and electric moments of exotic particles**



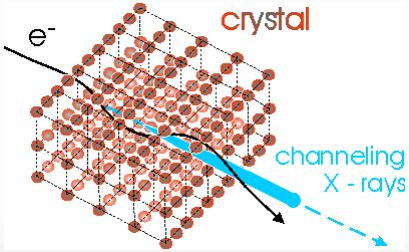


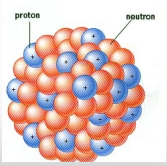


**Plasma acceleration**




**X and γ-ray source for nuclear and medical physics**




*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

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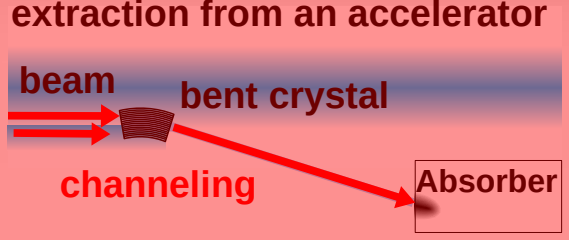


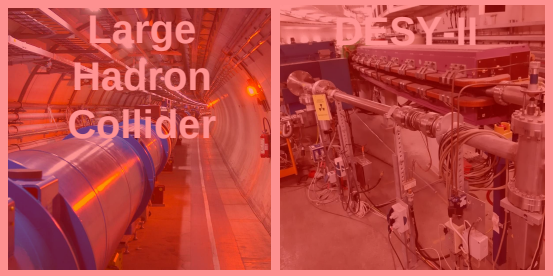


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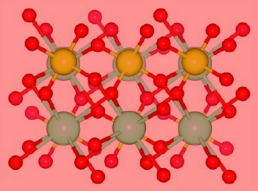

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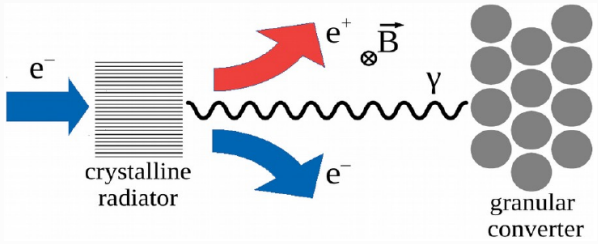
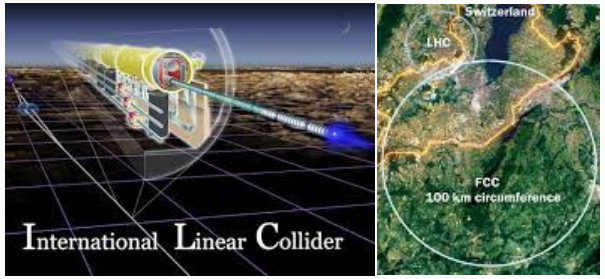
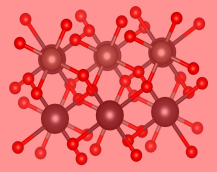



**Oriented crystals**



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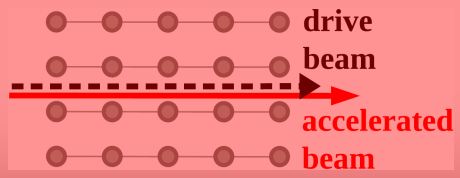


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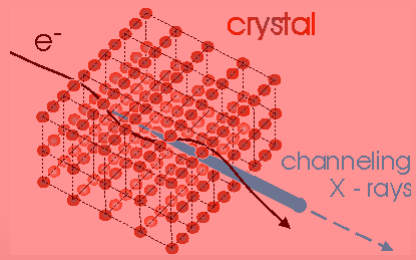
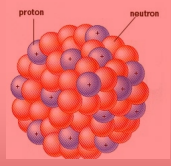
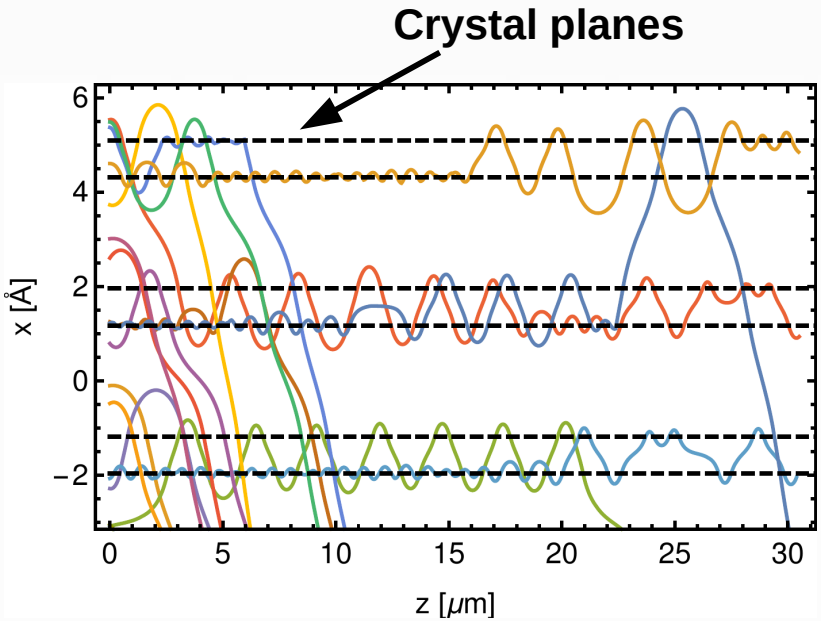



*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

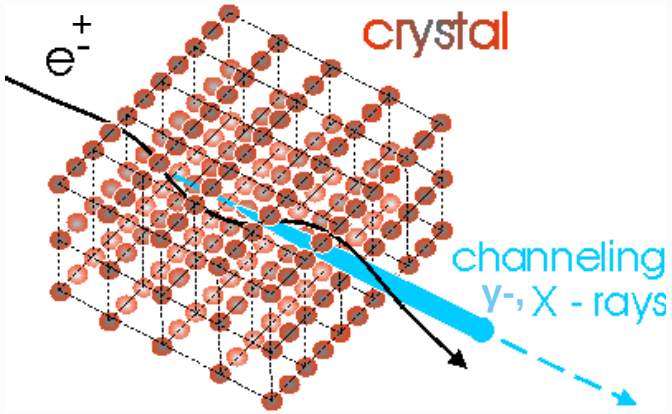
# Baseline channeling simulation technique: CRYSTALRAD Monte Carlo simulation code

**Main conception** – simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single **scattering simulation** at every step




**channeling***

**New 2024: ionization losses in channeling**




**Baier-Katkov formula:**

integration is made over the classical trajectory

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


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. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)

A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

# Current status

**In Geant4 since geant4-11.2.0 !**

**geant4-v11.2.0/source/parameterisations/channeling/**

**Please use it!**

**https://geant4.web.cern.ch/download**

**Don't hesitate to contact me in the case of any problems/issues/suggestions**

**sytov@fe.infn.it**

**Geant4 Physics Reference Manual:**

**https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/solidstate/channeling/channeling_fastsim.html**

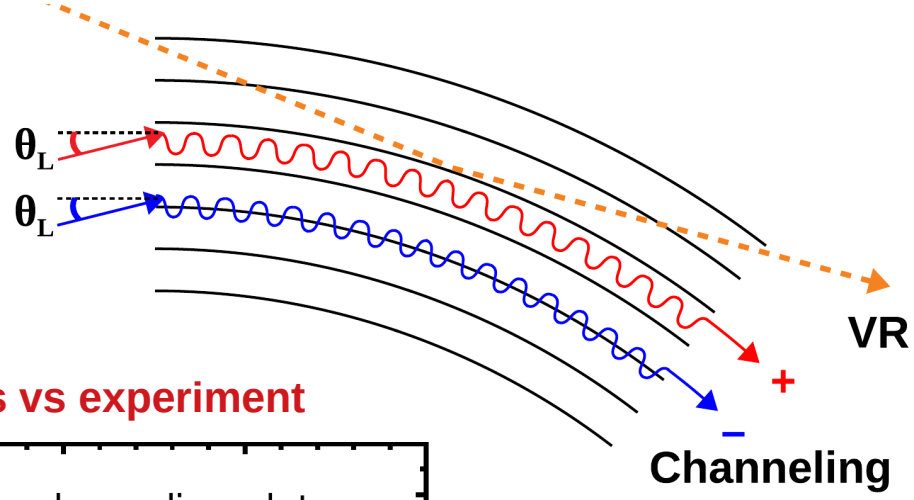
**Please cite our papers if you use our model:**

1. **A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)**
2. **A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)**

# Geant4 channeling model validation: beam deflection by a bent crystal

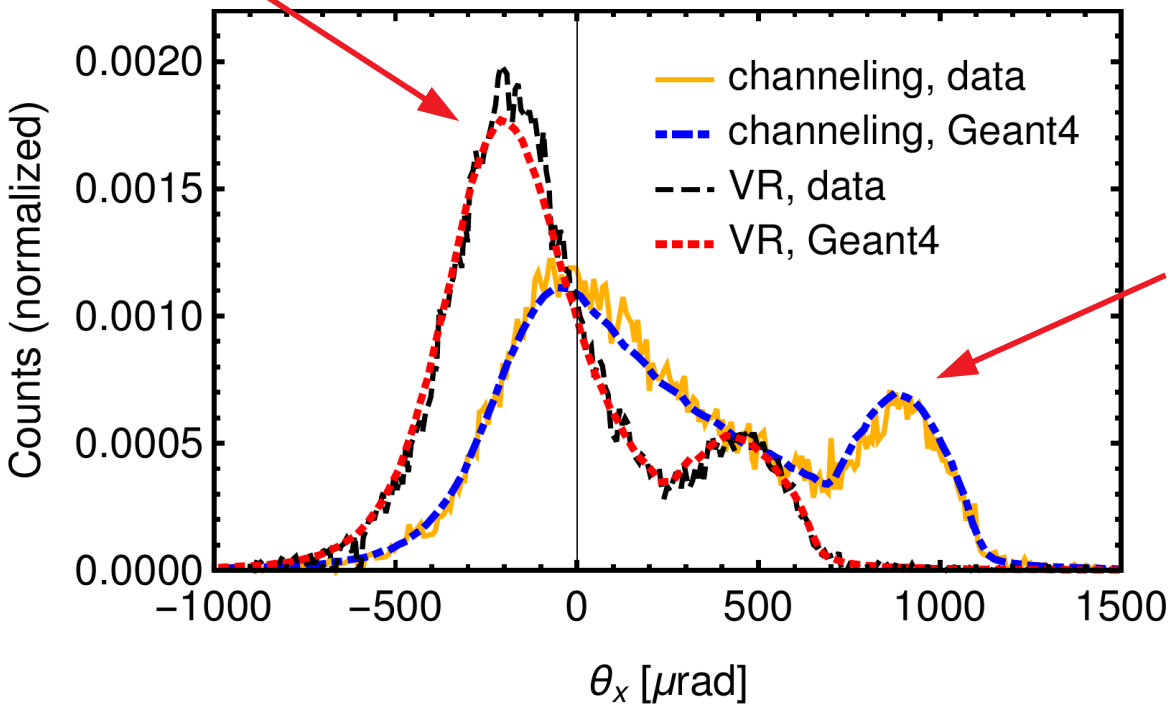
**855 MeV electrons**

**15 µm thick bent crystal**




**volume reflection (VR)**

**Geant simulations vs experiment**

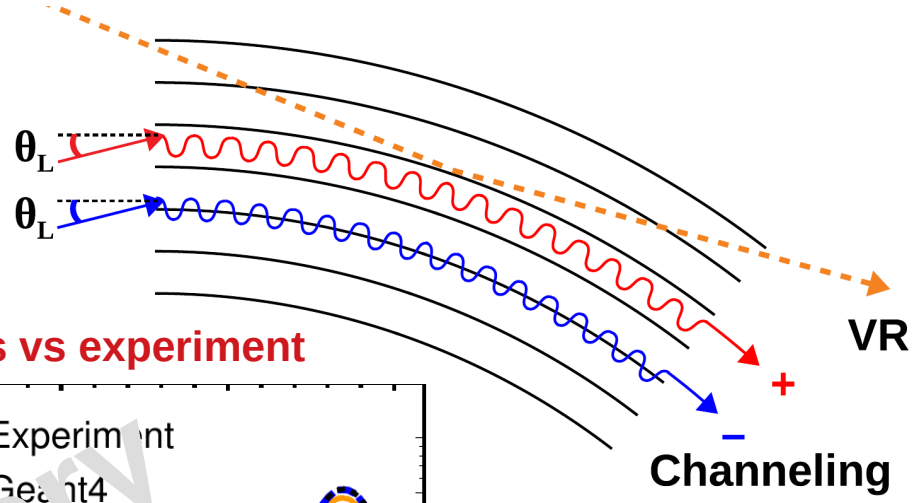



**channeling**

# More Geant4 channeling model validation: quasichanneling oscillations* at SLAC FACET Facility

**20.35 GeV positrons**

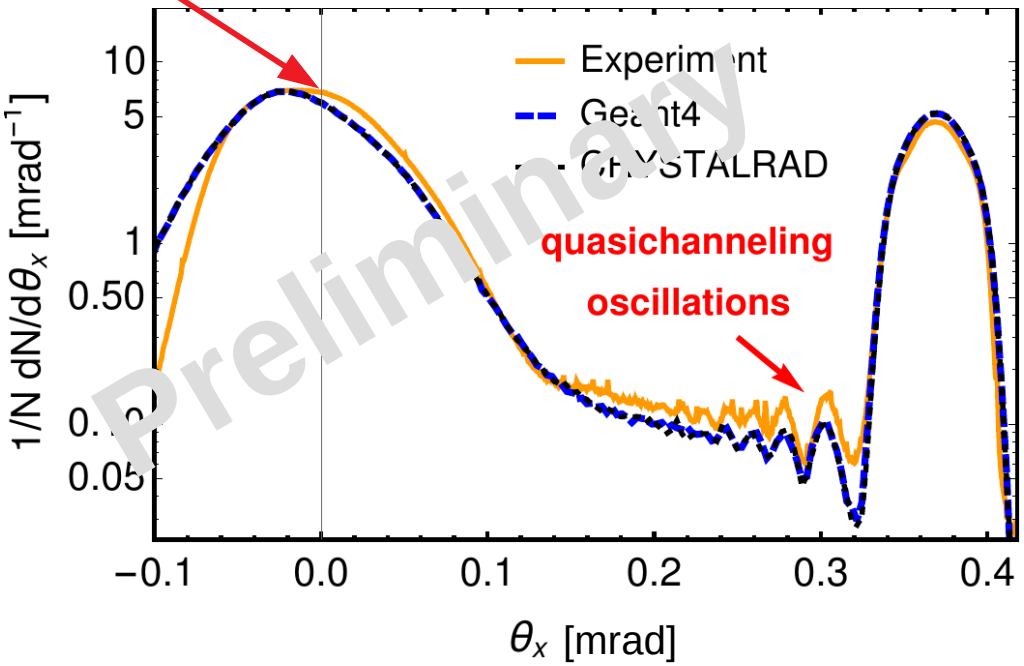
**60 µm thick bent crystal**




**volume reflection (VR)**

**channeling**

**Geant simulations vs experiment**






**To be submitted for publication soon**

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

# Recent experiment
# Channeling of 530 MeV positrons in a bent crystal

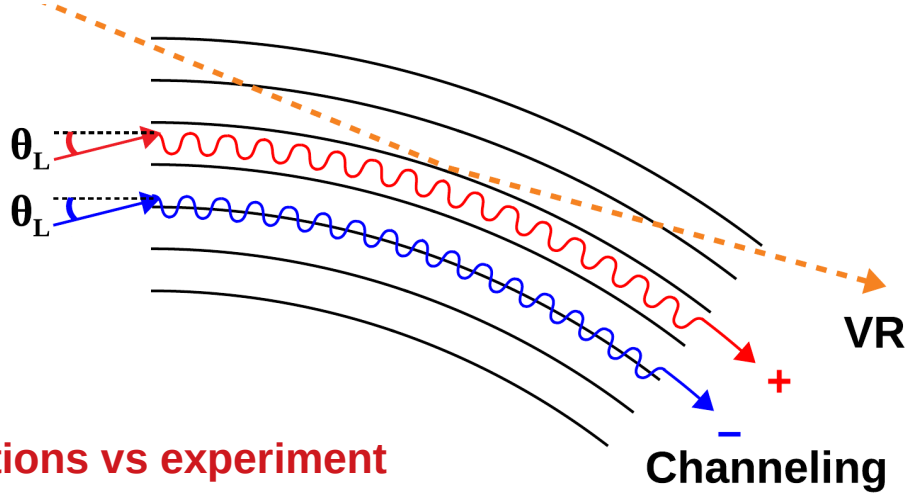

**Tomorrow talk of Riccardo Negrello**
**Don’t miss!**

# Recent experiment
# Channeling of 530 MeV positrons in a bent crystal

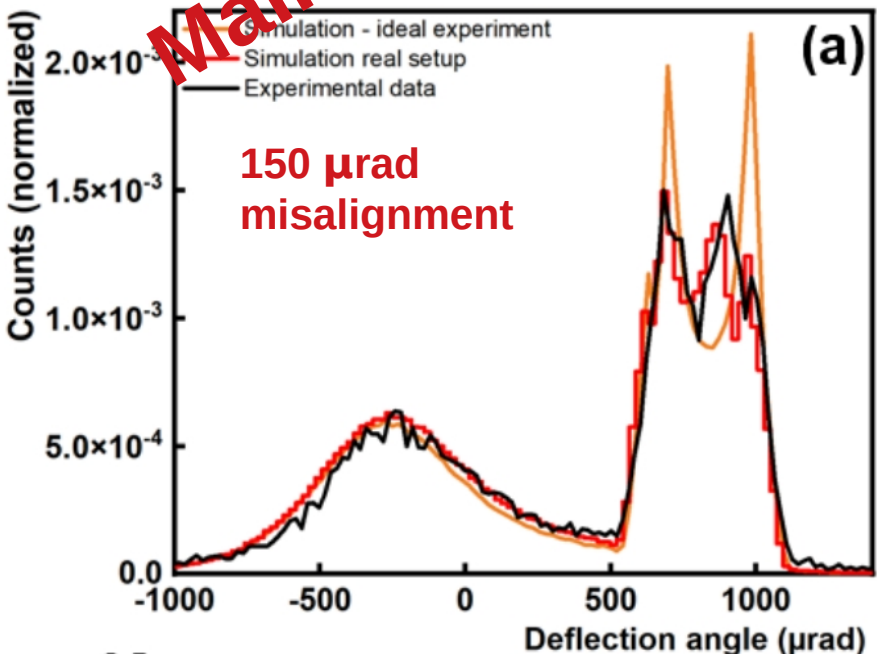
**530 MeV positrons**

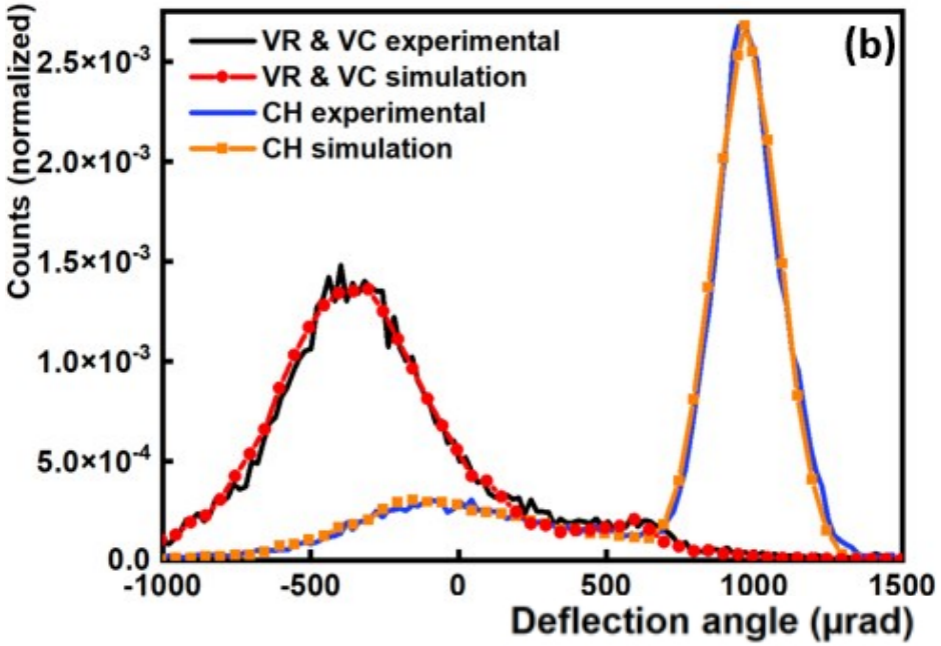
**30 µm thick bent crystal**

**New experiment Mainz Mikrotron 2024**




**Geant4 simulations vs experiment**

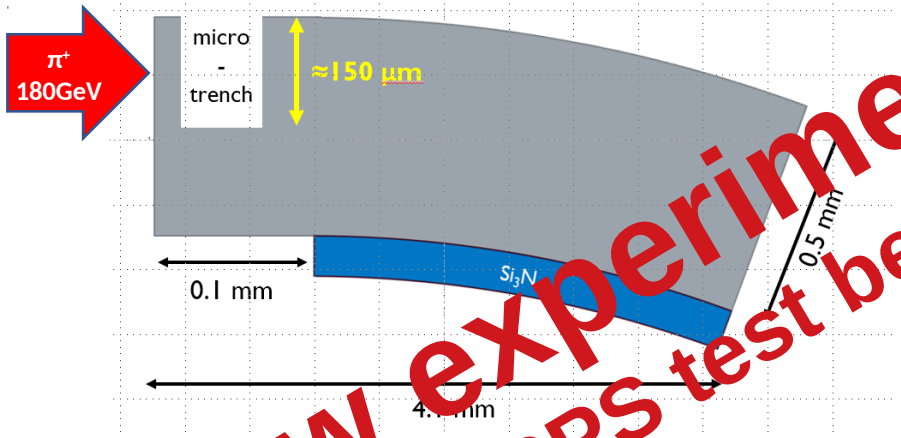


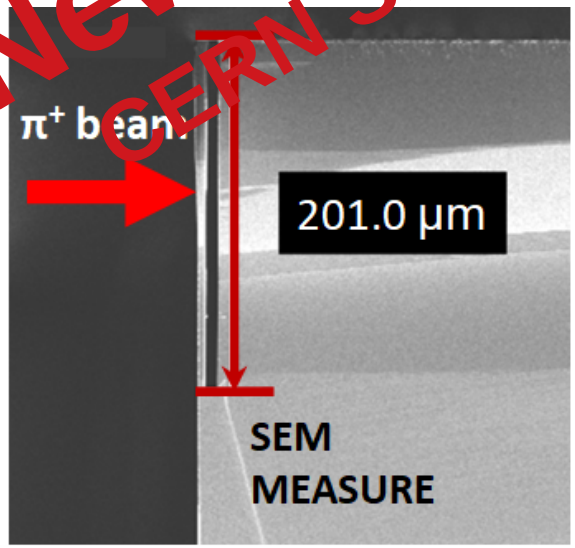
# Geant4 simulations of the experiment GALORE (2023): Crystalline cut to drastically increase the channeling efficiency


**Wednesday talk of Marco Romagnoni**
**Don’t miss!**

# Geant4 simulations of the experiment GALORE (2023): Crystalline cut to drastically increase the channeling efficiency



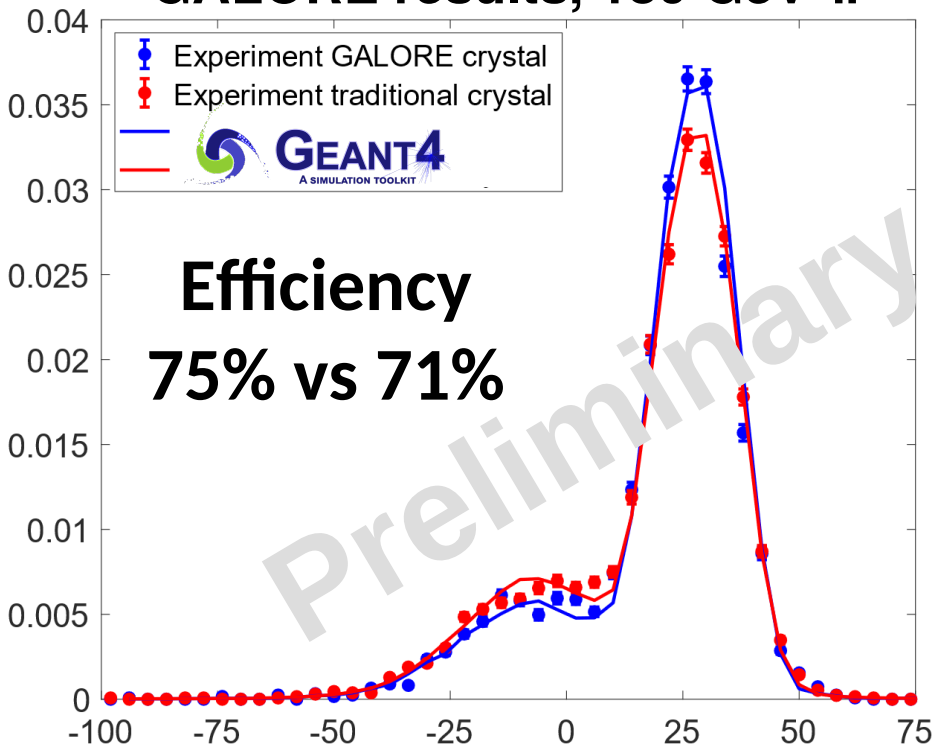

New experiment
CERN SPS test beam




**Geant4 simulations vs experimental data**

**Courtesy of M. Romagnoni**

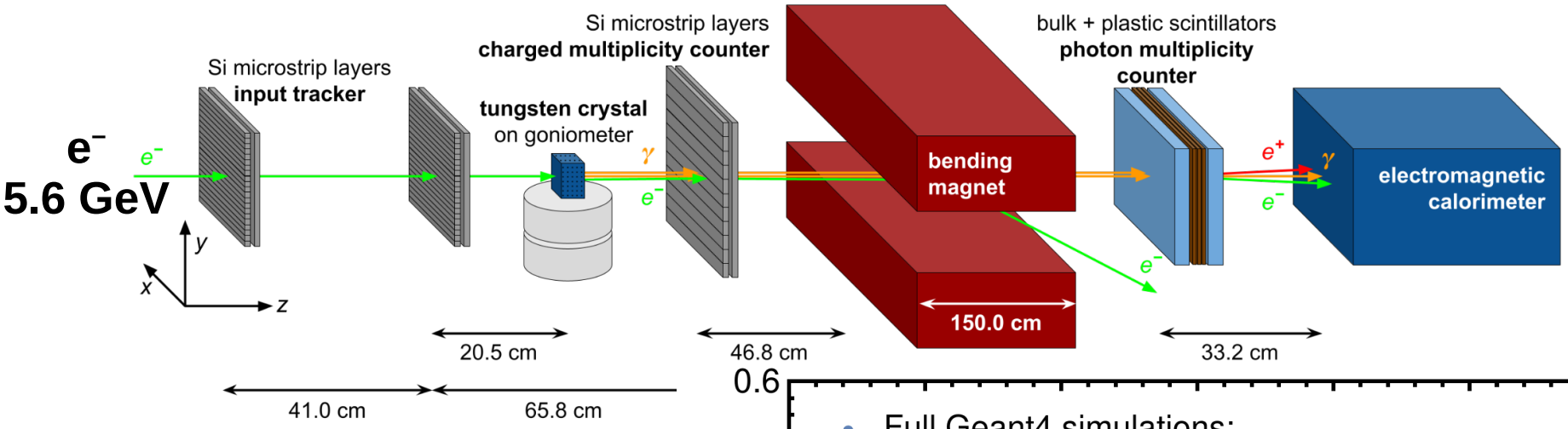
**GALORE results, 180 GeV π⁺**

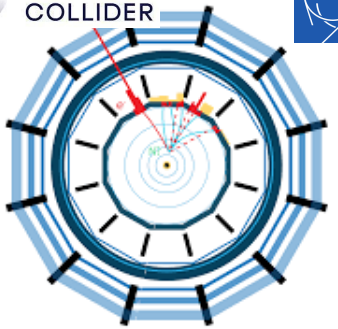


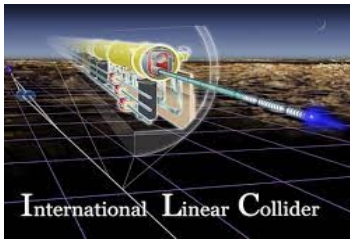

M. Romagnoni, ..., A. Sytov et al. Crystals 12 (9), 1263 (2022)
M. Romagnoni, ..., A. Sytov et al. Eur. Phys. J. D 76, 135 (2022).

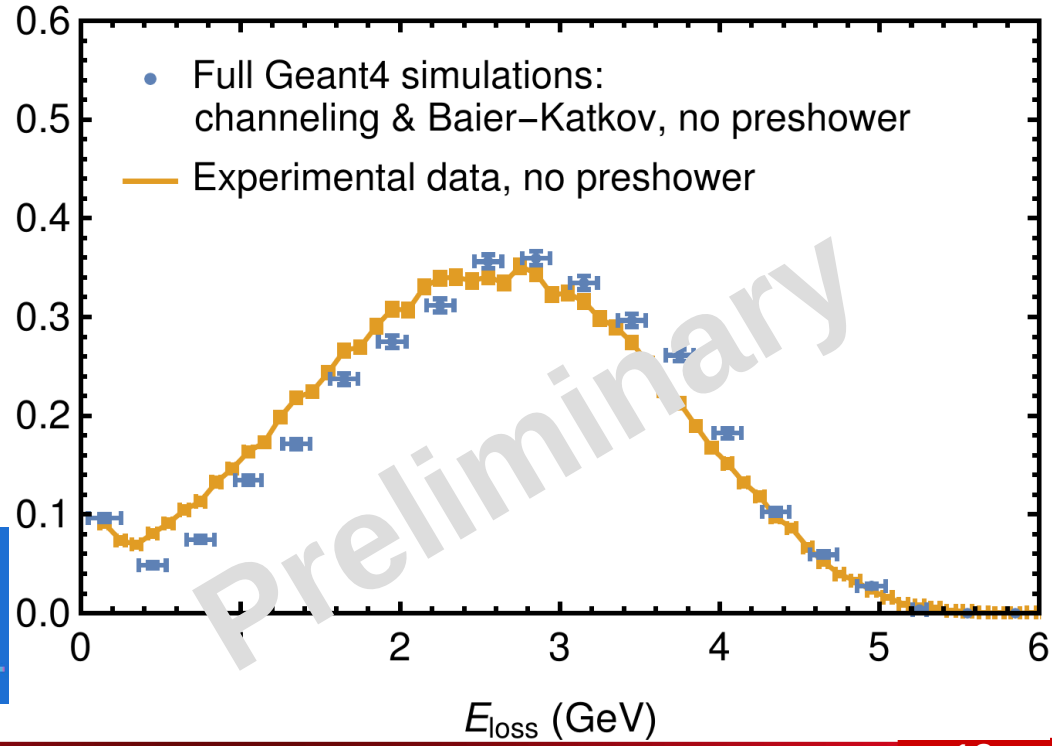
*V.V. Tikhomirov JINST 2 P08006 (2007)

# Full Geant4 simulations of the DESY experiment* for the FCC-ee positron source project





***Intense positron source Based On Oriented crySTals* - e+BOOST**
**(PI L. Bandiera)**
**PRIN2022-2022Y87K7X**
**Financed by Italian Ministry of University and Research - PRIN project**



*L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

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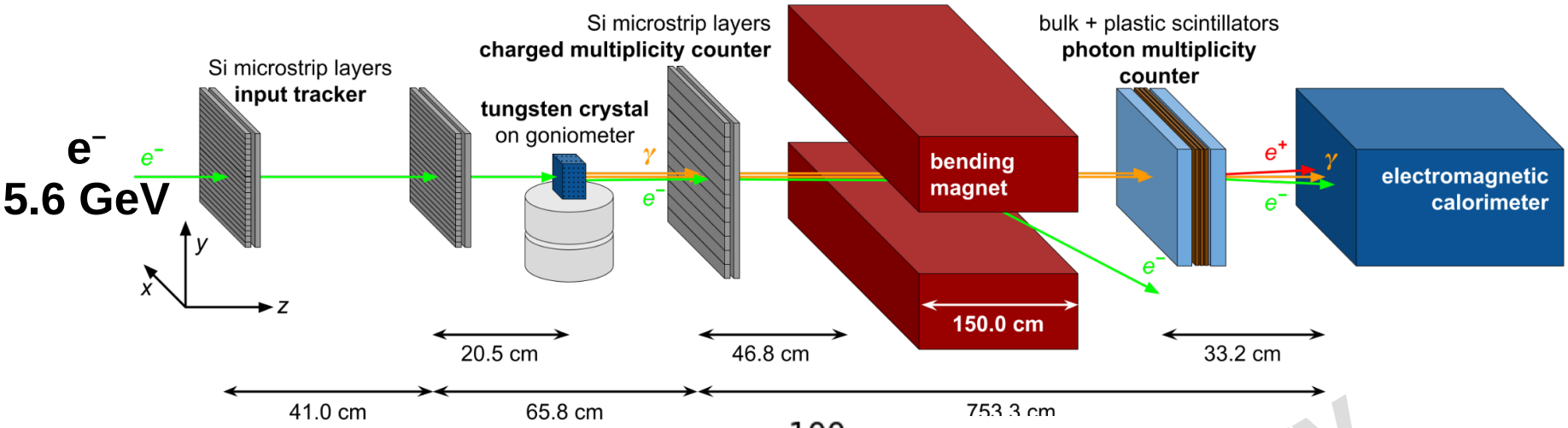


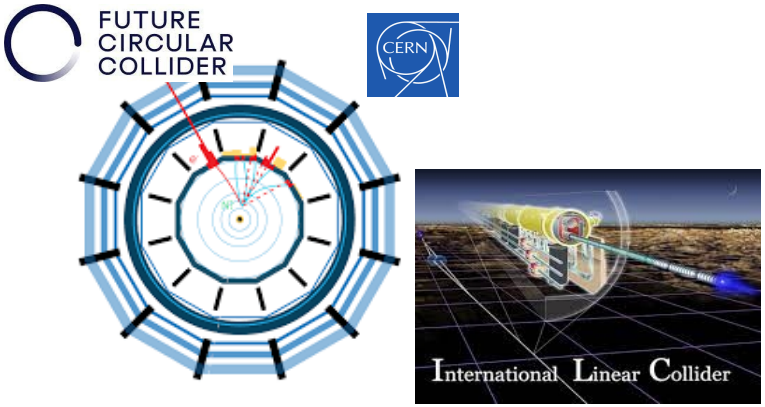


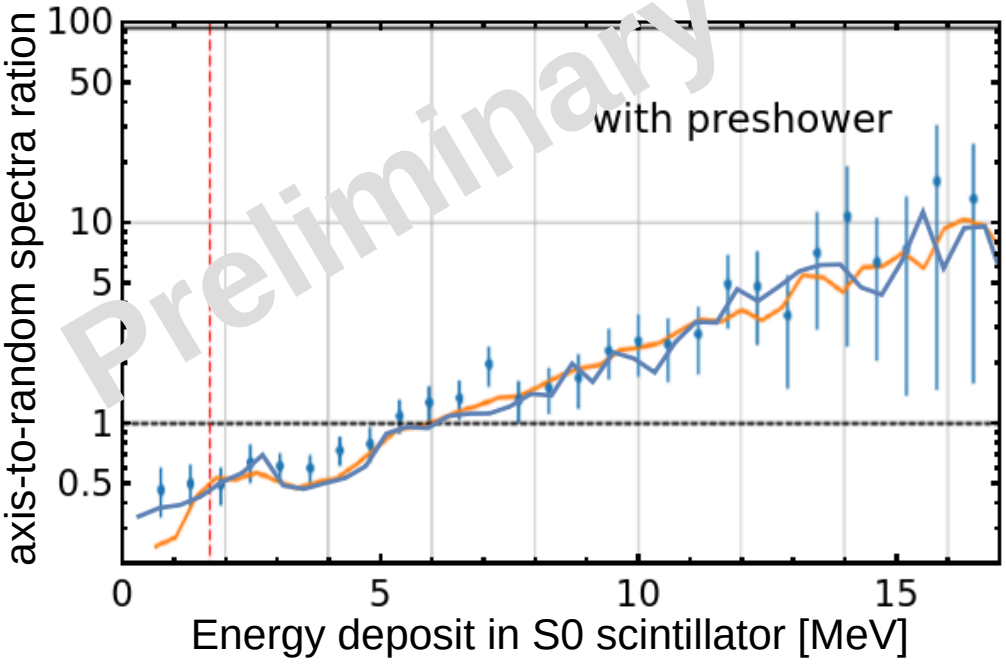


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**PRIN2022-2022Y87K7X**
**Financed by Italian Ministry of University and Research - PRIN project**

Ministero dell'Università e della Ricerca
Bando PRIN 2022
UNIVERSITÀ RICERCA

*L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

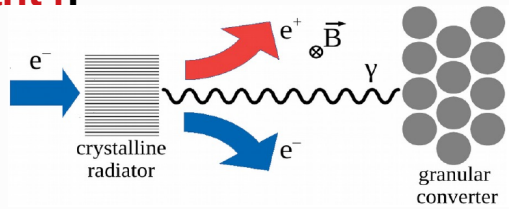
# Approximate list of examples to include in Geant4 in 2024

**Examples:**

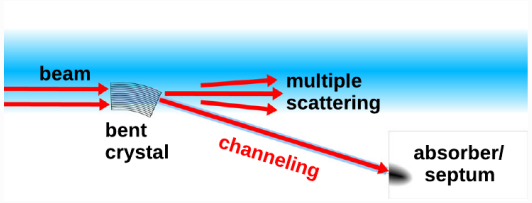
- Very **easy example** to demonstrate basic commands to include the channeling model in DetectorConstruction (no input/simple output) — **Submitted**
- **Complex example** including both channeling and radiation model, input with macro commands, root output and full spectrum of options — **To submit**
- **Pair production model** and dedicated example of electromagnetic shower in a scintillator crystal — **Almost ready**

**Specific applications to implement into Geant4:**

- **Crystal-based hybrid positron source for FCC-ee** — **To submit**




- **Crystalline deflector to extract a charged particle beam from an accelerator** (electron synchrotron, hadron collider) using **BDSim** code. — **Works! Don't miss my tomorrow presentation!**



# Acknowledgments

**Marie Sklodowska-Curie Action Global Individual Fellowships TRILLION** (G.A. 101032975) is in synergy with the following projects I would like to acknowledge:

- **GEANT4INFN** project (INFN Geant4 group);
- **INFN OREO, PRIN E+BOOST, INFN GALORE, RD-MUCOL, RD-FCC,**
- **H2020-MSCA-RISE N-LIGHT** (G.A. 872196) and **EIC-PATHFINDER-OPEN TECHNO-CLS** (G.A. 101046458) projects.
- We acknowledge the **CINECA** award under the **ISCRA** initiative, for the availability of high-performance computing resources and support.
- This work is also supported by the Korean National Supercomputing Center with supercomputing resources including technical support (**KSC-2022-CHA-0003**).

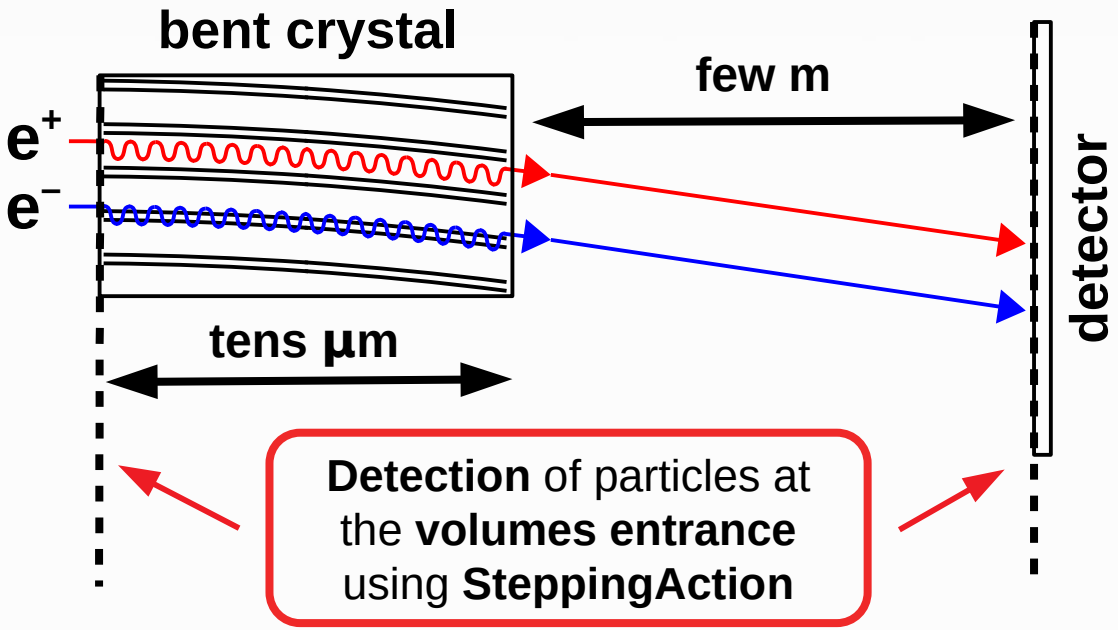
I also thank the **Geant4 collaboration** members, in particular:

**Prof. Vladimir Ivanchenko** (**CERN**), **Prof. Pablo Cirrone and Dr. Luciano Pandola** (**INFN LNS**), **Prof. Kihyeon Cho, Prof. Soonwook Hwang** and **Dr. Kyungho Kim** (**KISTI**), **Prof. Susanna Guatelli** and **Prof. Anatoly Rosenfeld** (**University of Wollongong**), **Dr. Gianfranco Paternò (INFN Ferrara) as well as Prof. Makoto Asai (Jlab) and Prof. Marc Verderi (IN2P3/LLR)** for fruitful collaboration and discussions!


감사합니다 !

# 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**




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

**Multithreading** works!
Checked at the supercomputer
**Galileo100@CINECA** (Italy)
**NURION@KISTI** (Korea)

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

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

# Main concept of full ab-inition G4BaierKatkov

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1v_2-1)+\omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$$

Monte Carlo integration by photon **3 components of momentum**

$\vec{k}$

**Radiation probability** calculated **per photon**

Monte Carlo integration by photon **energy** and **angles**

$\omega$, $\theta x$, $\theta y$

$\vec{k}_i \Rightarrow P_i$

If radiation happens, **select a photon** from using ***Pi*** as their **weight** and generate it

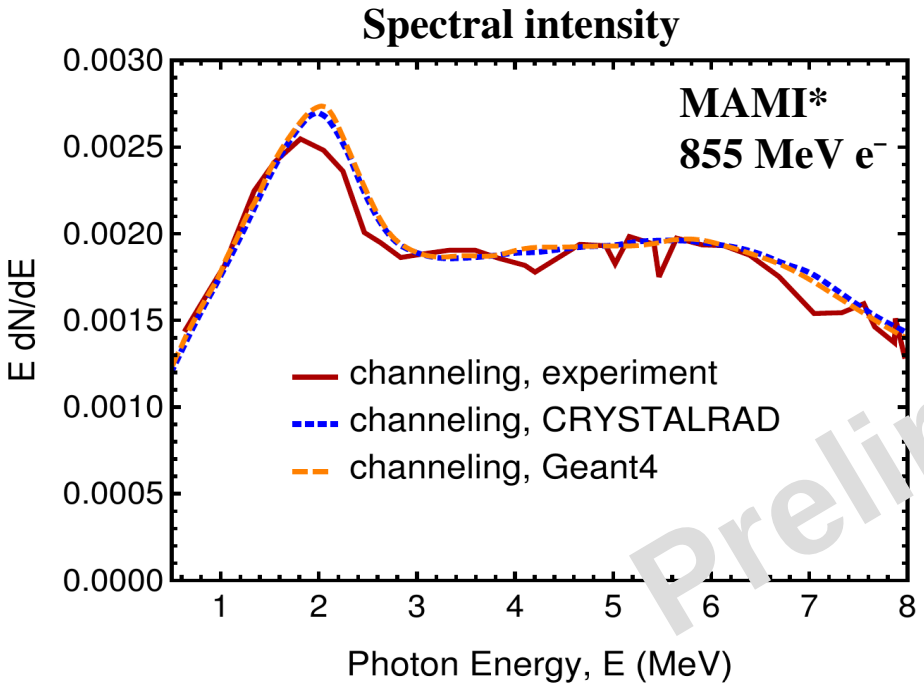
Photon **energy** and **angular distribution** naturally comes **from Baier-Katkov**

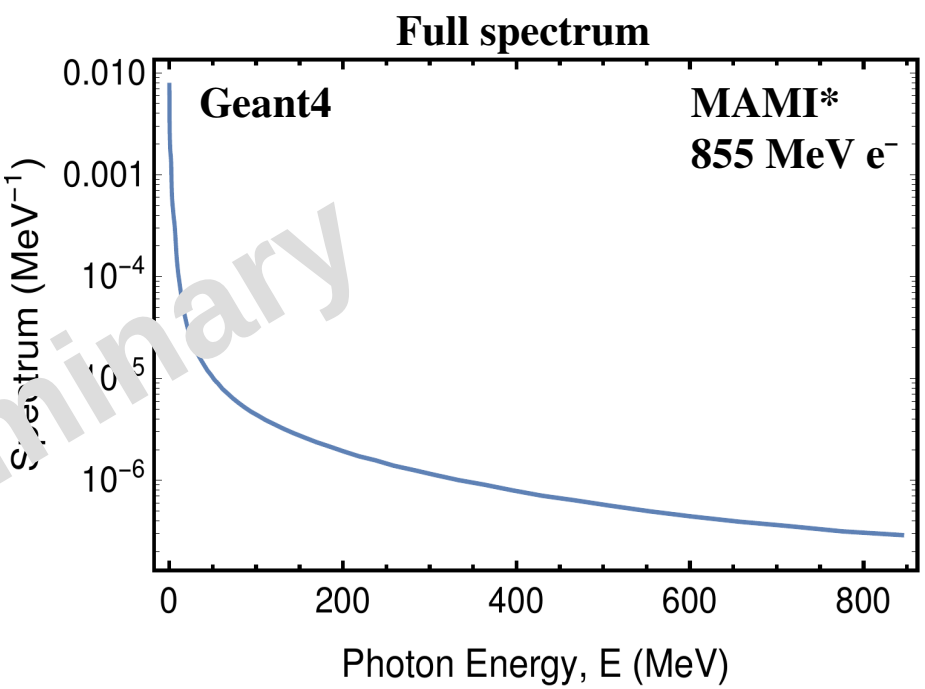
# First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

**G4BaierKatkov:**

- **Physics list independent**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

**Geant simulations vs experiment and CRYSTALRAD simulations**



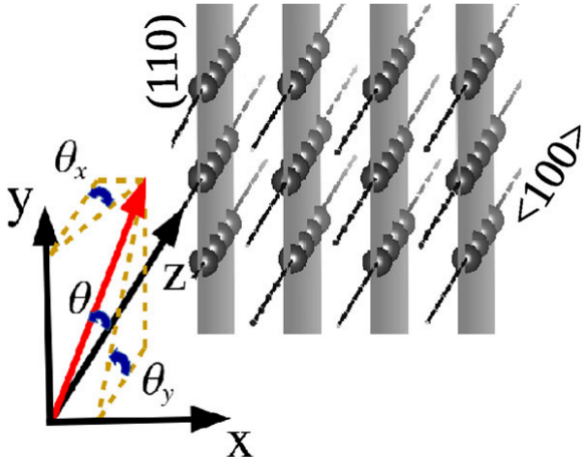

Preliminary

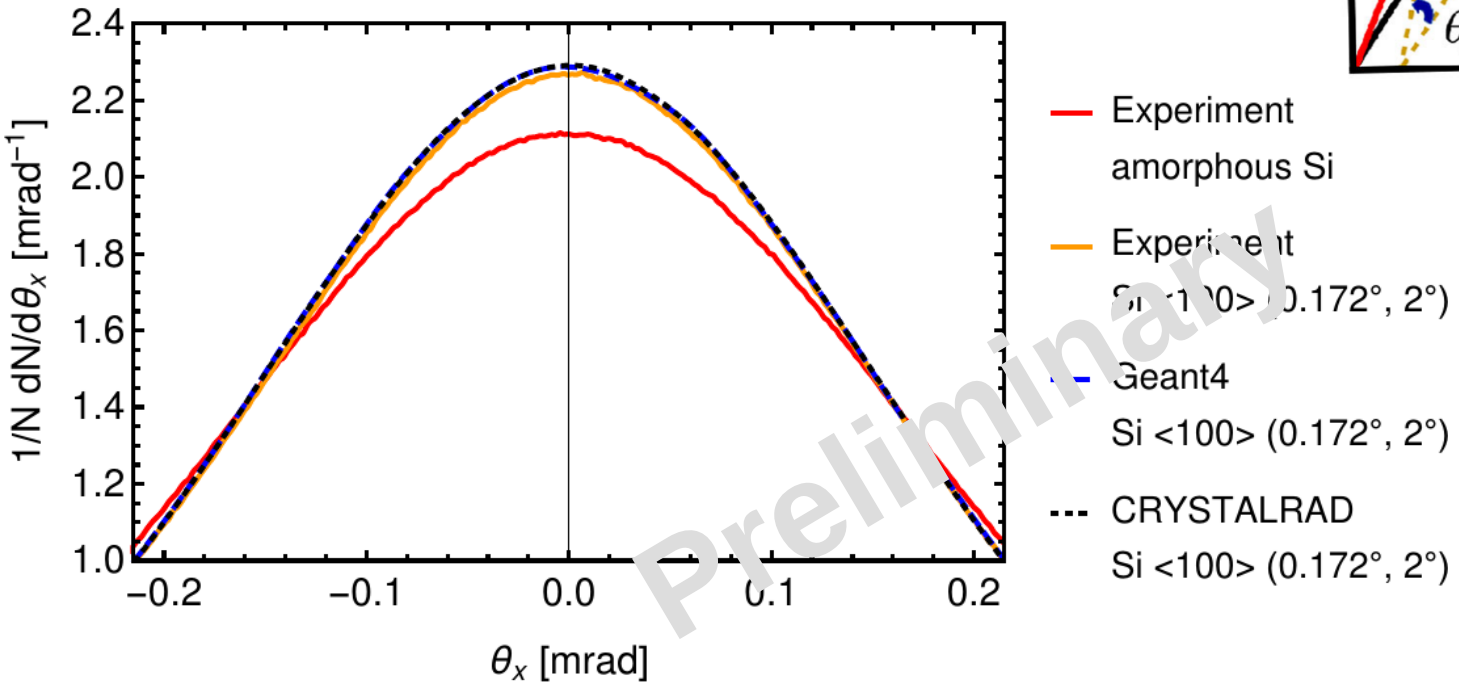
**To be submitted for publication soon**

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

# 2D Geant4 channeling model validation: coherent scattering suppression effect*

**Multiple scattering in crystal and multiple scattering in amorphous material are different!**




Preliminary

**To be submitted for publication soon**

*A. Mazzolari, A. Sytov et al. Eur. Phys. J. C 80, 63 (2020)

# Why the implementation of channeling and Baier-Katkov models into Geant4 is so challenging?

**Challenges of trajectory simulation**

- **Complicated geometry** of crystal planes/axes especially in a bent crystal;
- **Complicated spacial structure** of cristalline **electric fields** and **atomic density** depending on the material and alignment;
- Different types of **scattering dependent** on the charge particle **positions** vs crystal planes/axes;
- **Incompatibility** of channeling with **Geant4 standard physics lists**: especially with **multiple coulomb scattering** and **bremsstrahlung** process: impossible to modify **continuous-discrete Geant4** processes during execution.

**Challenges of Baier-Katkov**

- Need for **recording trajectory** in order to simulate the spectrum;
- Multidimensional integral => **low simulation speed**;
- Hard gamma radiation => need to **return** the particle **back to the radiation point**, which is **not allowed in Geant4** in a simple way.

# Old channeling model in Geant4

**Currently implemented***
**Channeling physics:**

- Only trajectories (**no radiation**)
- Only for hadrons
- Changing cross-sections using **Geant4 Biasing**

**To do:**

- To resolve the **problems** with modification of **continuous discrete processes**
- To add channeling of **e+/e-**
- To add channeling **radiation**
- To add coherent **pair production**

**Problem** with modification of the **electromagnetic physics list**:
class G4ChannelingOptrChangeCrossSection

```
93
94      switch (type) {
95          case fNotDefined:
96              fProcessToDensity[processName] = fDensityRatioNone;
97              break;
98          case fTransportation:
99              fProcessToDensity[processName] = fDensityRatioNone;
100             break;
101         case fElectromagnetic:
102             if(subType == fCoulombScattering ||
103                subType == fMultipleScattering){
104                fProcessToDensity[processName] = fCancelProcess;
105             }
106             if(subType == fIonisation ||
107                subType == fBremsstrahlung){
108                fProcessToDensity[processName] = fCancelProcess;
109             }
110             if(subType == fPairProdByCharged ||
111                subType == fAnnihilation ||
112                subType == fAnnihilationToMuMu ||
113                subType == fAnnihilationToHadrons){
```

It is not possible to turn off/to modify **continuous discrete processes** (multiple scattering, ionization losses) in this way but only **discrete processes**

**Crucial for e+/e-**
though not so important for high energy protons

*E. Bagli Eur. Phys. J. C 74, 2996 (2014)

# How to implement an external code into Geant4? Geant4 FastSim interface, solution to most of challenges

**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

```
71  G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
72  {
73    return
74      &particleType == G4Proton::ProtonDefinition()||
75      &particleType == G4AntiProton::AntiProtonDefinition()||
76      &particleType == G4Electron::ElectronDefinition() ||
77      &particleType == G4Positron::PositronDefinition();// ||
78      //&particleType == G4Gamma::GammaDefinition();
79  }
80
81  //....oooOOOOOooo........oooOOOOOooo........oooOOOOOooo........oooOOOOOooo......
82
83  G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
84  {
102 }
103
104 //....oooOOOOOooo........oooOOOOOooo........oooOOOOOooo........oooOOOOOooo......
105
106 void TestModel::DoIt(const G4FastTrack& fastTrack,
107                      G4FastStep& fastStep)
108 {
```

Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

# Manufacturing and characterization of bent silicon crystals @INFN Ferrara