Dr. Alexei Sytov

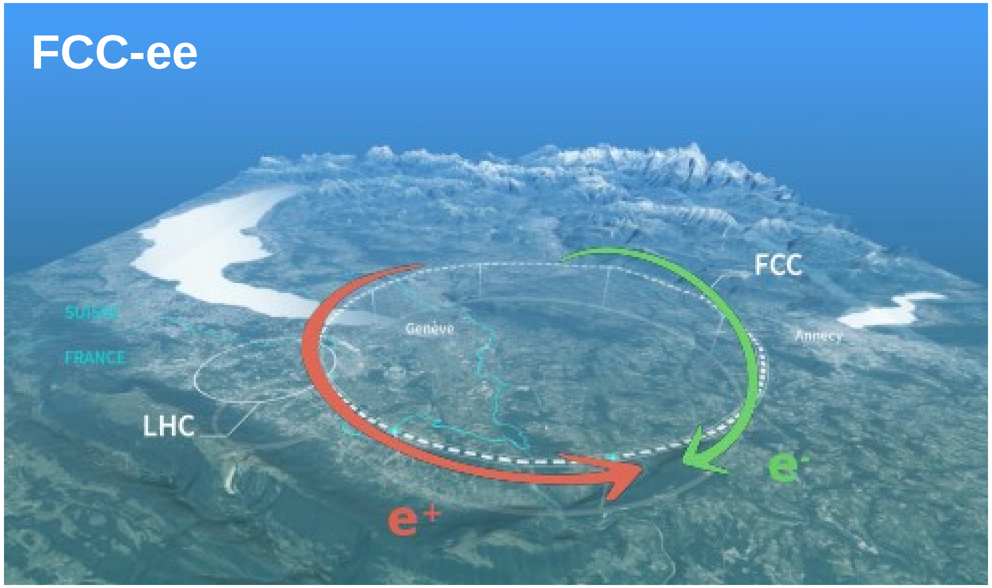
on behalf of

F. Alharthi, A. Bacci, L. Bandiera, D. Boccanfuso, I. Chaikovska , R. Chehab, S. Carsi, D. De Salvador,
V. Guidi, V. Haurylavets, O. Iorio, G. Lezzani, L. Malagutti, S. Mangiacavalli, P. Monti Guarnieri, A. Mazzolari,
V. Mytrochenko, R. Negrello, G. Paternò, M. Prest, M. Romagnoni, M. Rossetti Conti, A. Selmi, F. Sgarbossa,
M. Soldani, A. Sytov, V. Tikhomirov, E. Vallazza

A crystal-based positron source for FCC-ee

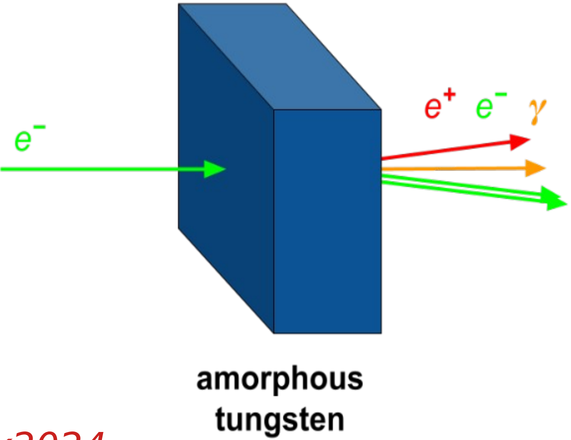
2nd FCC Italy & France Workshop
Venezia, 05/11/2024

Positron source for future lepton colliders



Operation Mode	Final Energy [GeV]	Beam Current [mA]
Z	45	1270
W	80	137
H	120	26.7
ttbar	182.5	4.9

Frank Zimmermann, FCCWeek2024



All the future **e+e- colliders** will need an **intense positron source**

Potential challenges:
Target overheating/melting;
Background of secondaries

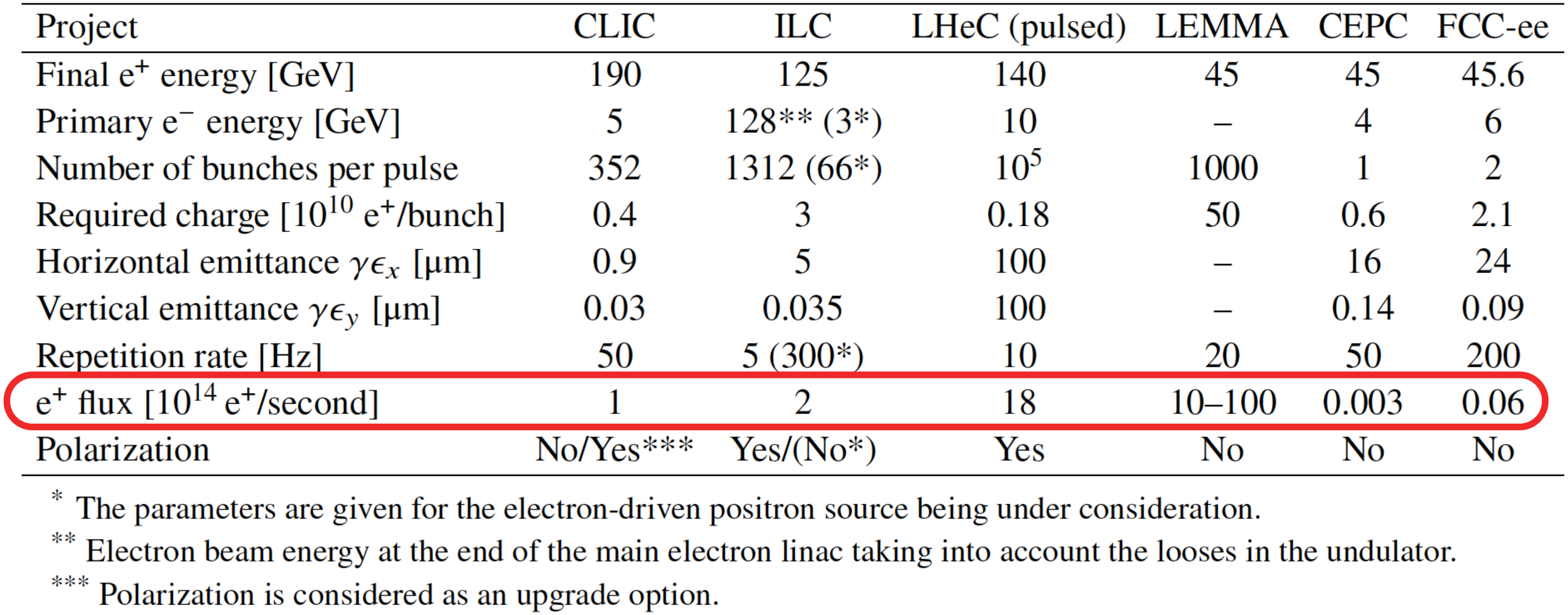
Peak Energy Deposition Density (**PEDD**) limit:
35 J/g for **W***

The main **challenge**:
to **increase positron yield**
and to **decrease PEDD**

***S. Maloy et al., SIc target analysis. LANL LA UR-01-1913 72 (2001)**

Future collider project challenge: positron flux

Demonstrated (**a world record** for existing accelerators): **e+ flux**:
~**6e12 e+/s** (SLC e+ source)



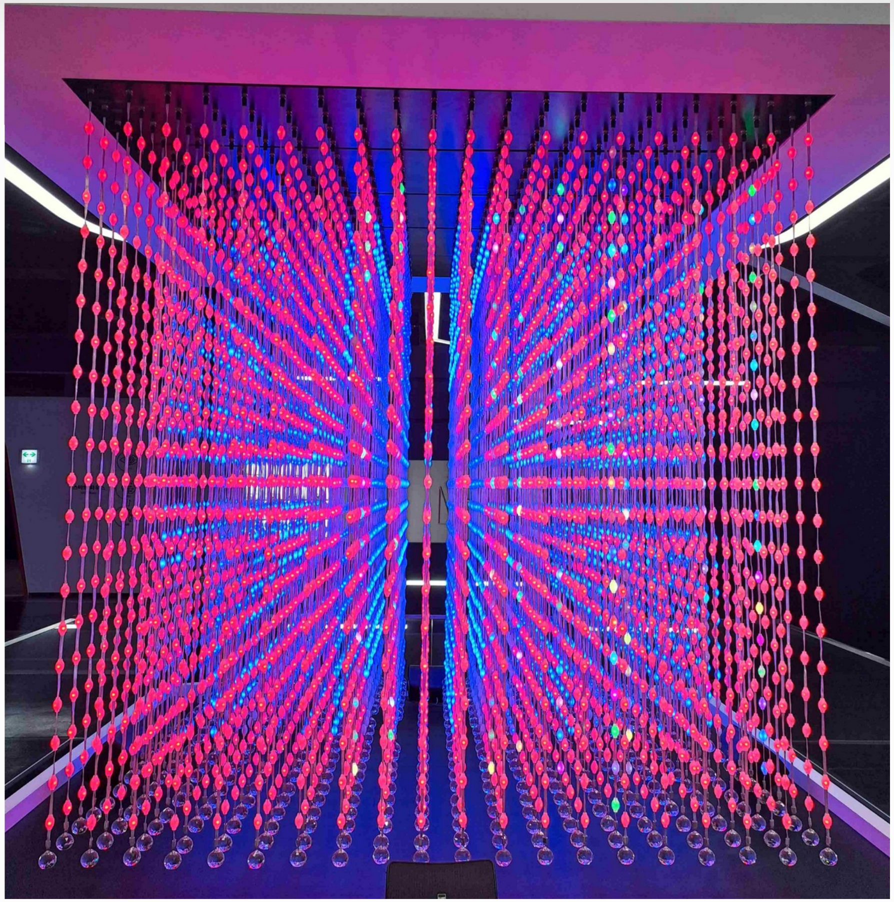
Project	CLIC	ILC	LHeC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	–	4	6
Number of bunches per pulse	352	1312 (66*)	10^5	1000	1	2
Required charge [10^{10} e^+/bunch]	0.4	3	0.18	50	0.6	2.1
Horizontal emittance $\gamma\epsilon_x$ [µm]	0.9	5	100	–	16	24
Vertical emittance $\gamma\epsilon_y$ [µm]	0.03	0.035	100	–	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	50	200
e^+ flux [10^{14} e^+/second]	1	2	18	10–100	0.003	0.06
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

* The parameters are given for the electron-driven positron source being under consideration.
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.
*** Polarization is considered as an upgrade option.

Strong need for a novel positron source

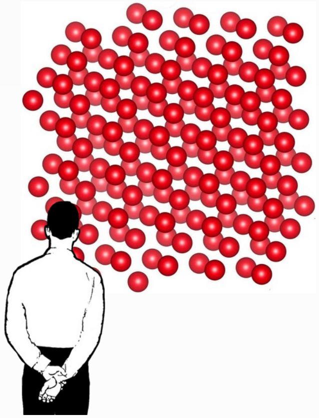
*** I. Chaikovska et al. JINST 17, P05015 (2022)**

How an oriented crystal looks like

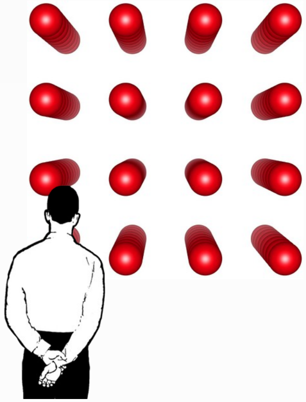


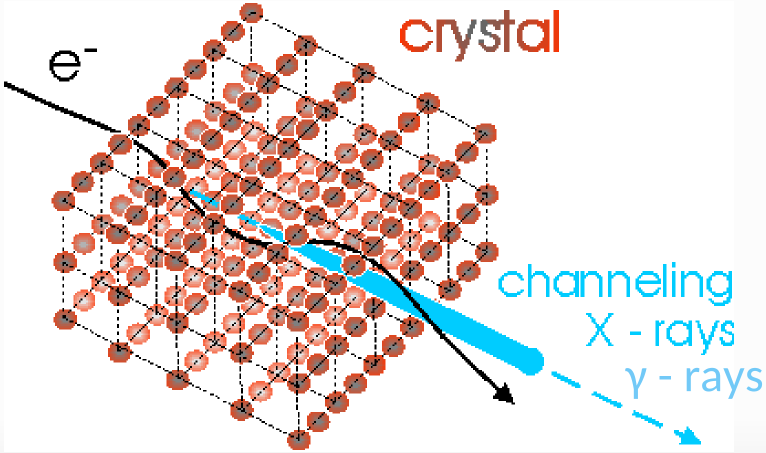
from National Science Museum, Daejeon, Korea

Non-oriented crystal



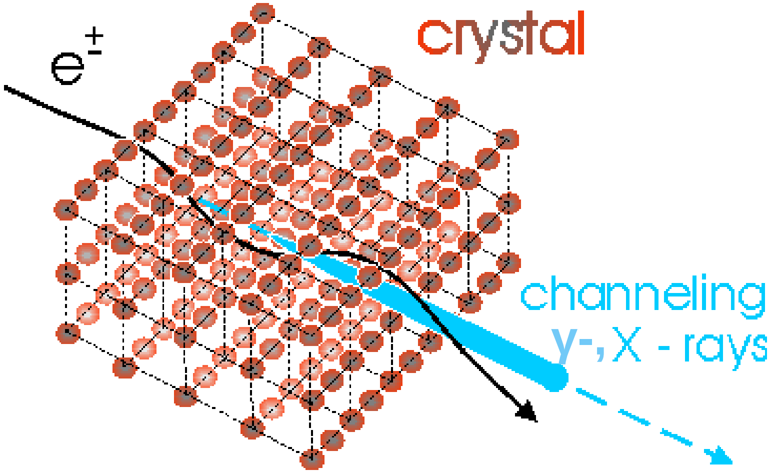
Oriented crystal





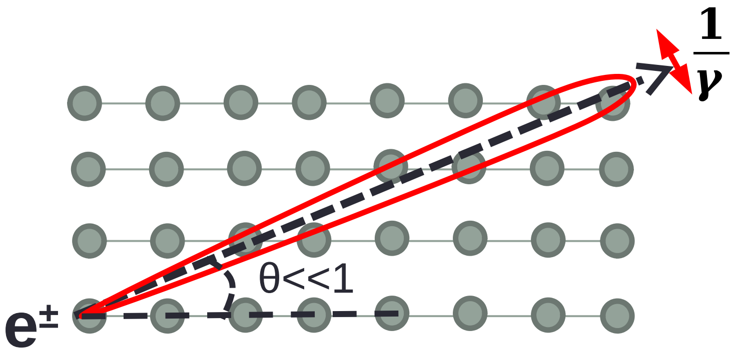
What about coherent effects in crystals?

Channeling radiation*

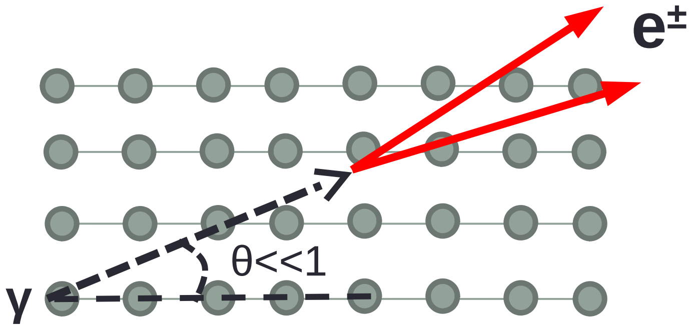


Coherent effects preserve
up to few mrad of particle
direction vs the crystal axis

Coherent bremsstrahlung**



Coherent pair production***

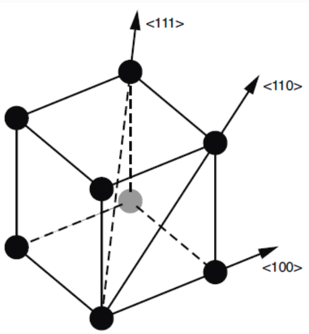


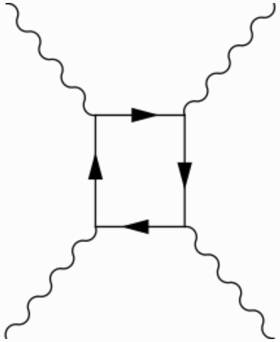
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)**
****B. Ferretti, Nuovo Cimento 7, 118 (1950).**
****M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).**
***** H. Überall, Phys. Rev. 103, 1055 (1956).**

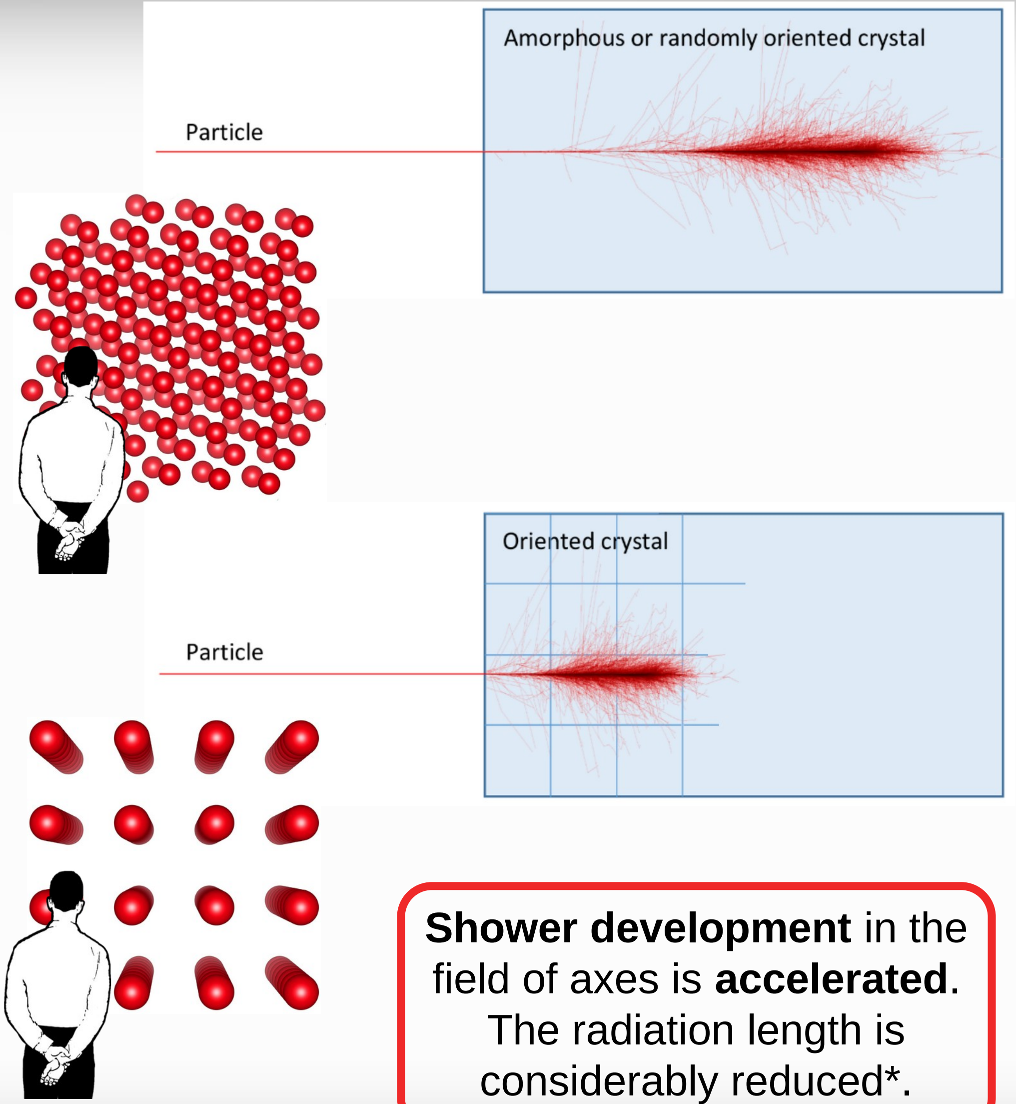
Electromagnetic shower acceleration

Axial field 10^{11} V/cm

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







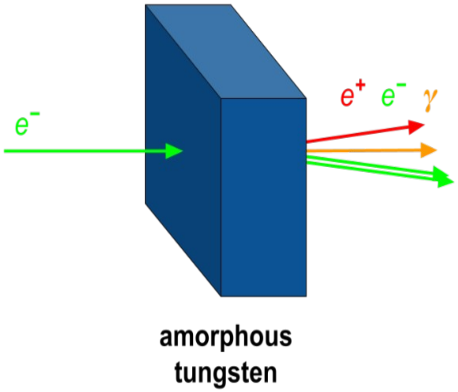
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

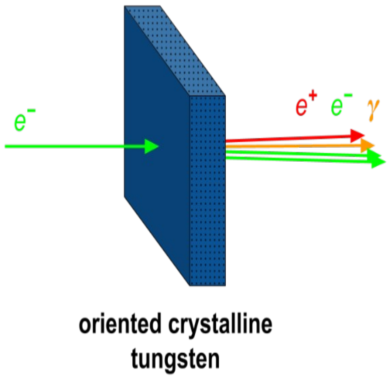
L. Bandiera et al., Phys. Rev. Lett. 121, 021603 (2018)

Different types of crystal-based positron source*

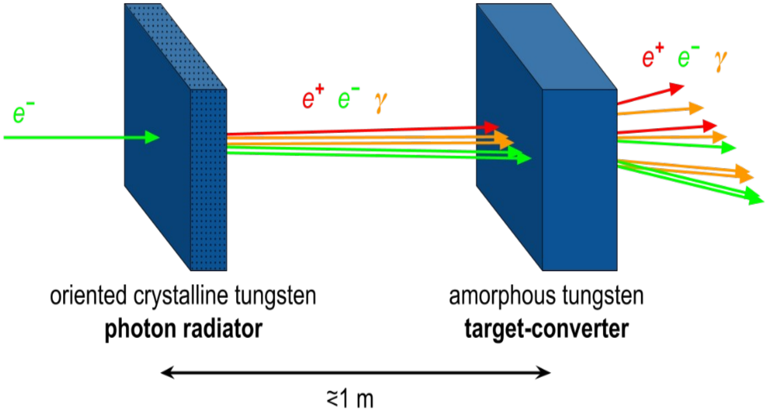
Conventional target



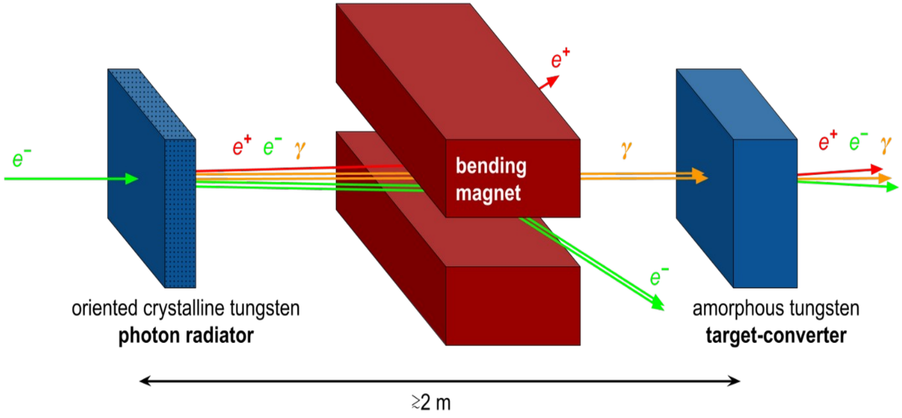
Crystal target



Hybrid scheme



Hybrid scheme with magnetic field



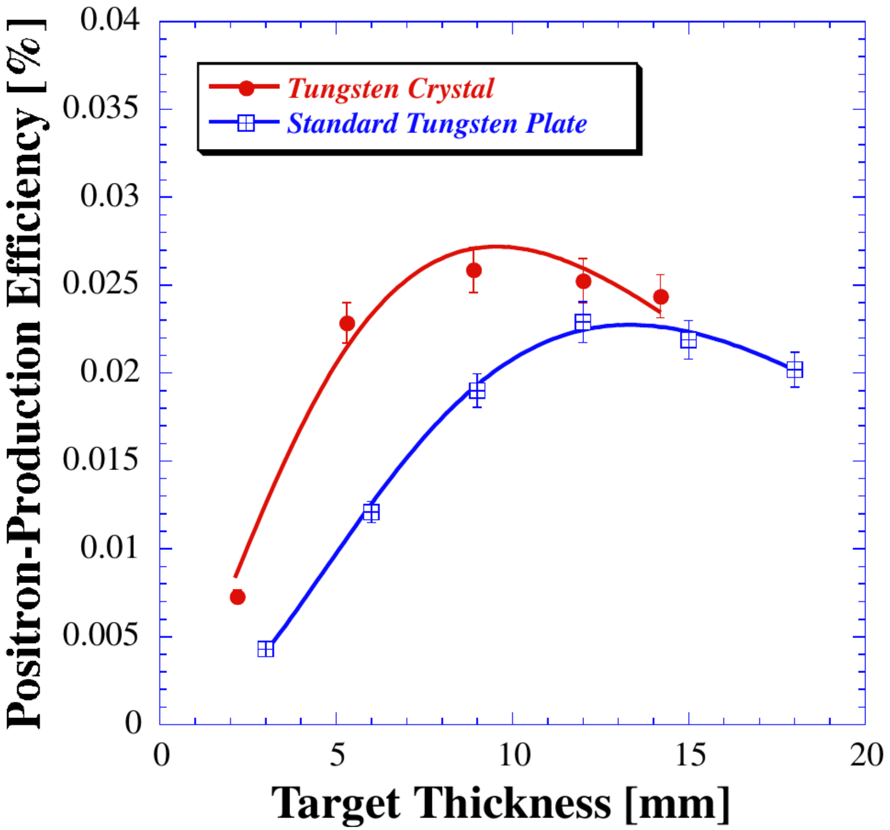
Hybrid positron source: two stages

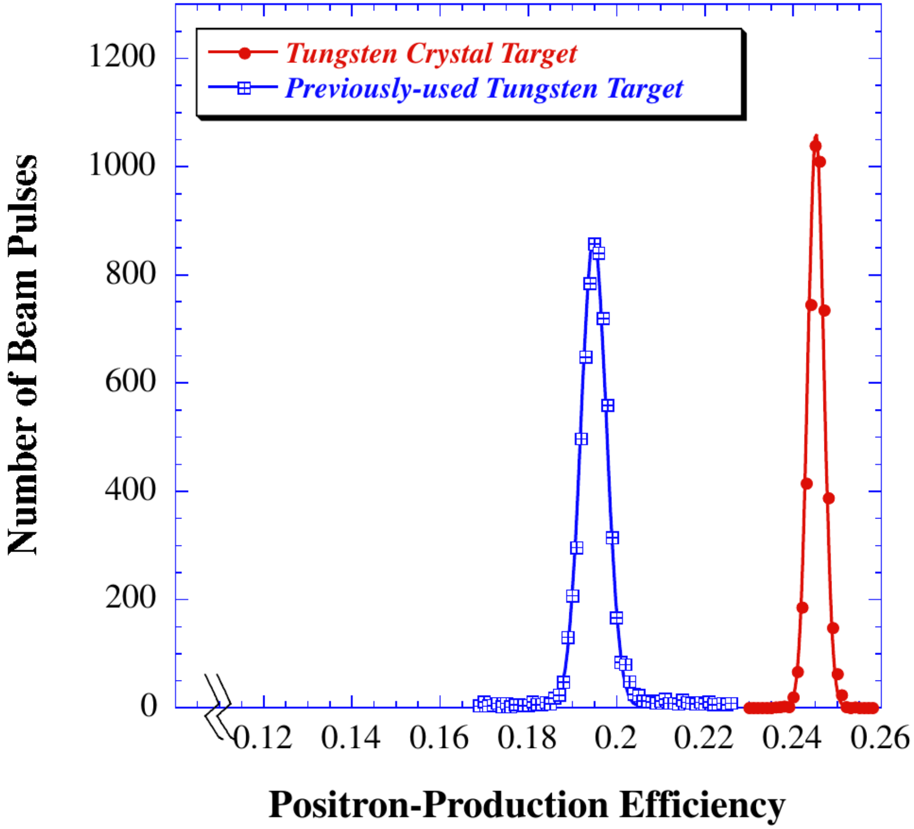
- **1. Radiation production** and **beam scattering** at the first target
- **2. pair production** in the second target
- Optional magnetic field between 2 targets to reduce PEDD at the second target

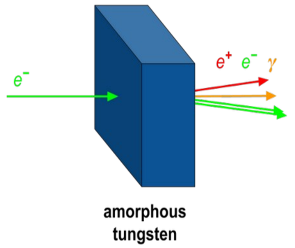
positron yield increase
PEDD reduction

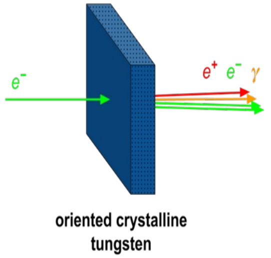
R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285

First application of a tungsten single-crystal positron source at the KEK B factory (2006)*









An **oriented W crystal**:
gives **rise** to the **positron yield** up to **25 %**
reduces heat load by **20 %**

These results were published in the following paper:

***T. Suwada et al. Phys. Rev. ST Acc. and Beams 10, 073501 (2007)**

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:

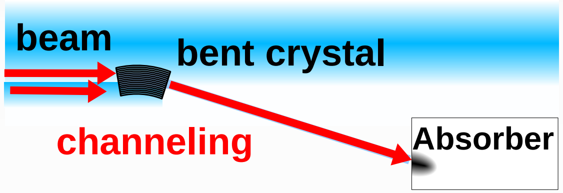
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

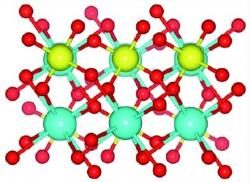
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Applications*

Crystal-based collimation or beam extraction from an accelerator

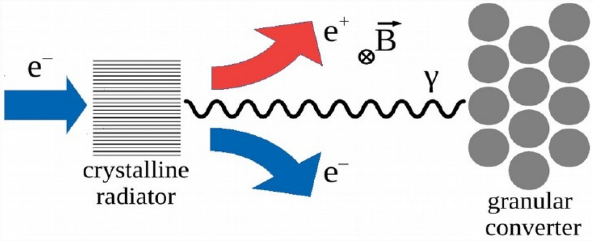


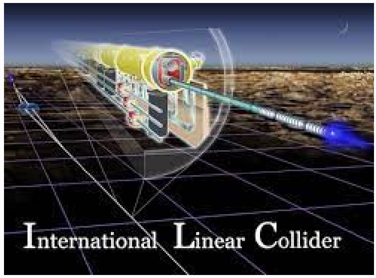
Ultrashort crystalline calorimeter

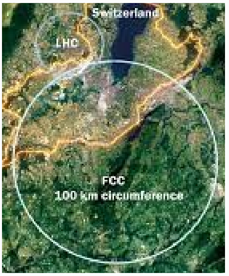


Gamma-ray Space Telescope

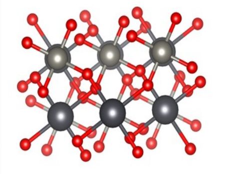
Positron source for future e+/e- and muon colliders



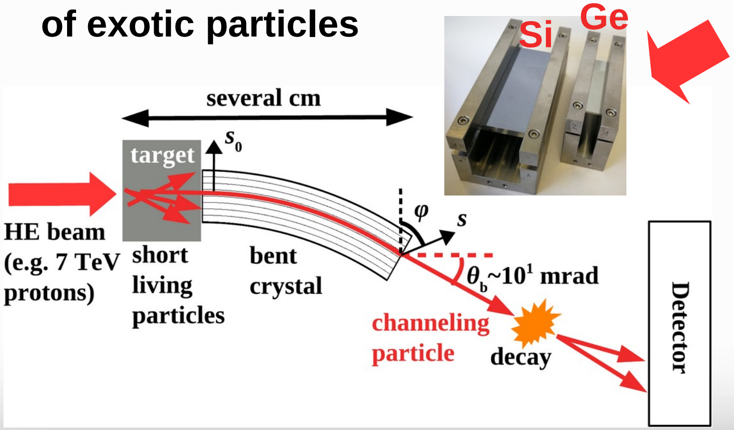




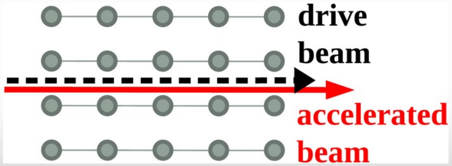
Oriented crystals



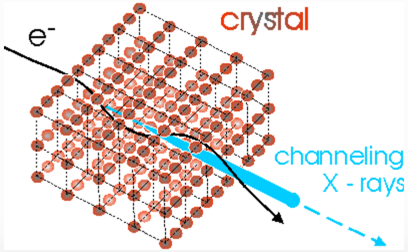
Measurement of dipole magnetic and electric moments of exotic particles

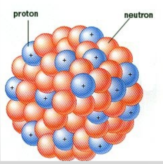


Plasma acceleration



X and γ-ray source for nuclear and medical physics

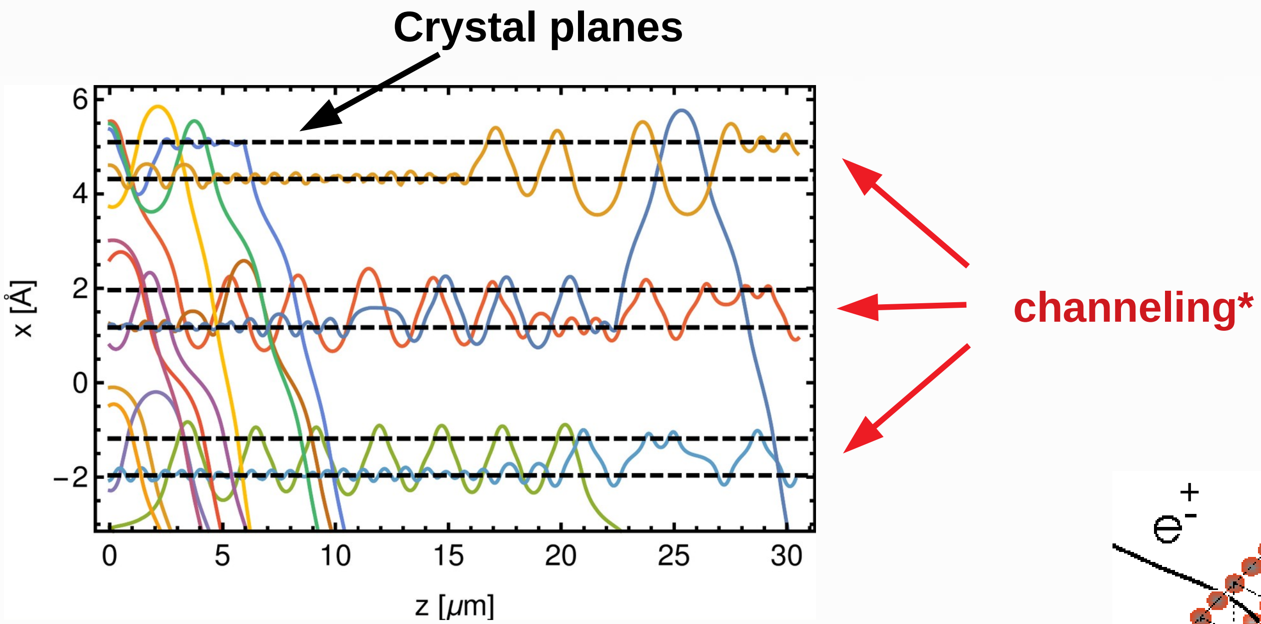




*A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)

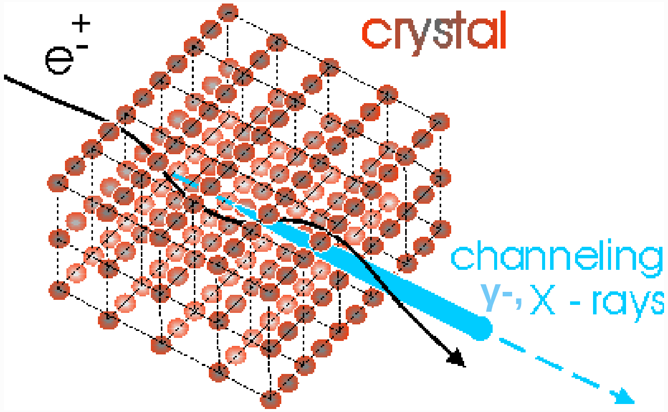
FULL Geant4 simulation model

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:

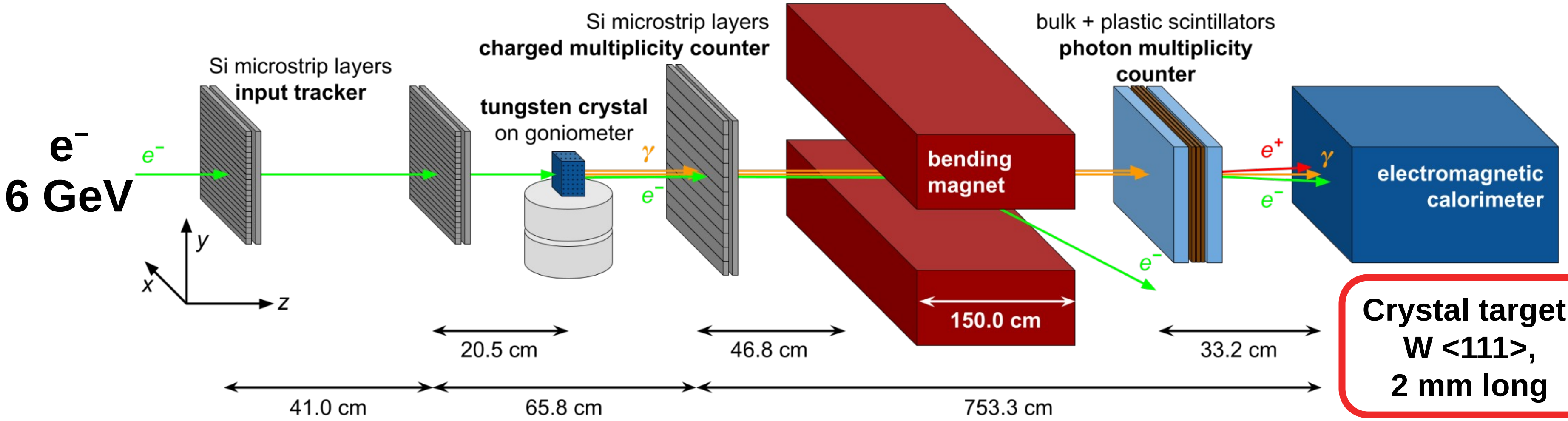
integration is made over the classical trajectory

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

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

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

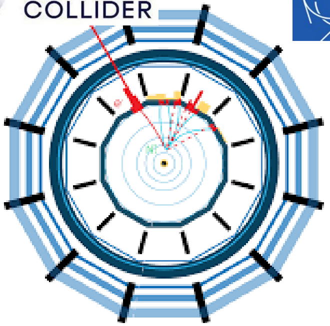
Full Geant4 simulations of the DESY and CERN PS experiment* for the FCC-ee positron source project

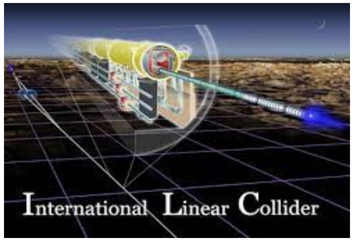


Crystal target:
W <111>,
2 mm long

FUTURE
CIRCULAR
COLLIDER

CERN

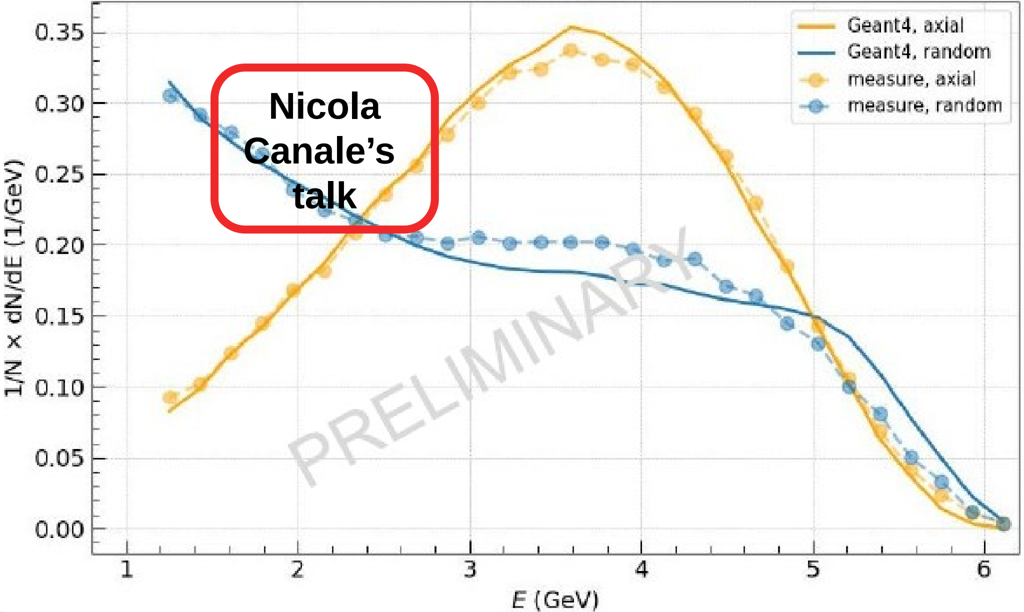




Intense positron source Based On Oriented crySTals - **e+BOOST**
(PI L. Bandiera)
PRIN2022-2022Y87K7X
Financed by Italian Ministry of University and Research - PRIN project

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

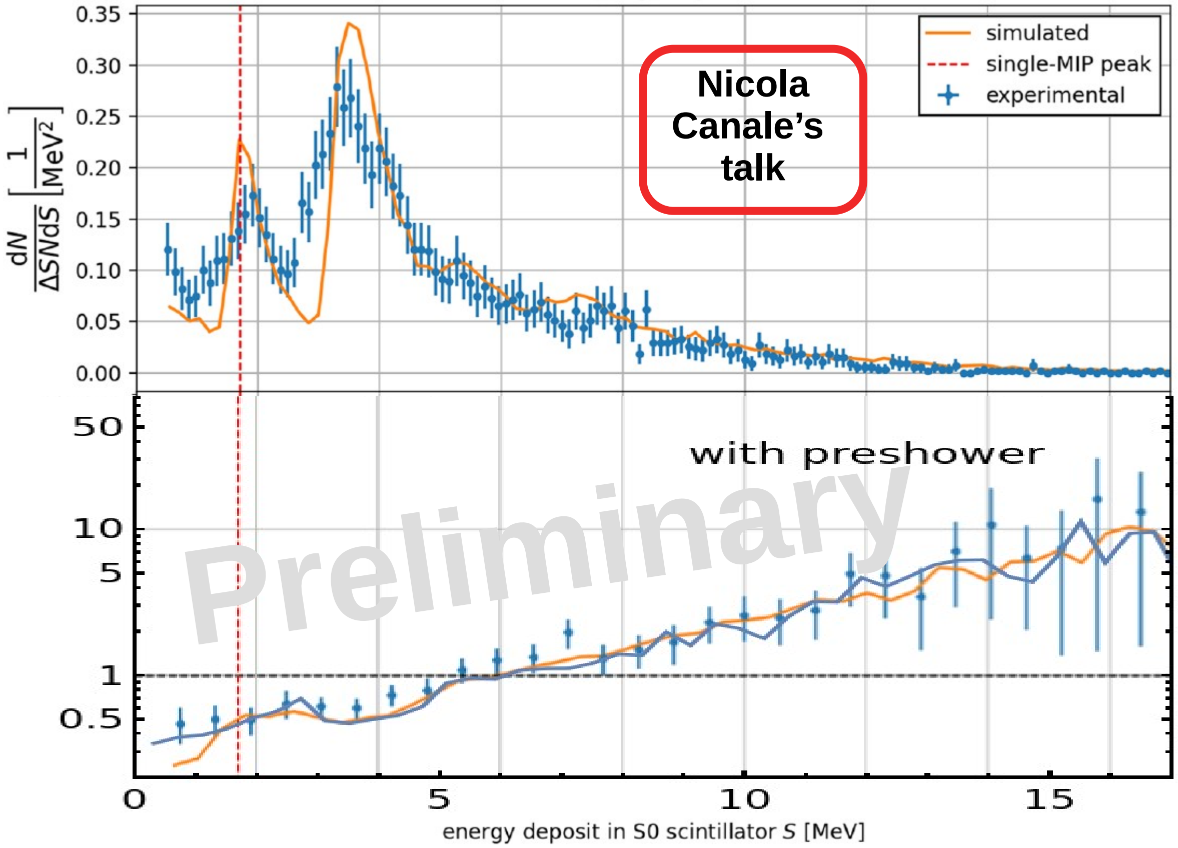
Radiative energy loss measured by the Ecal



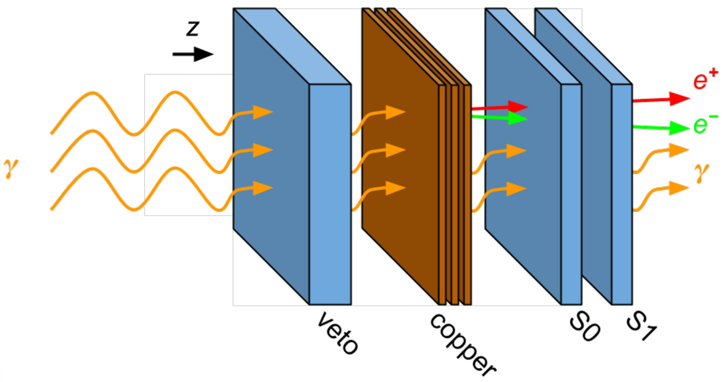
Nicola Canale's talk

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

Experimental results on photon emission enhancement



Nicola Canale’s talk



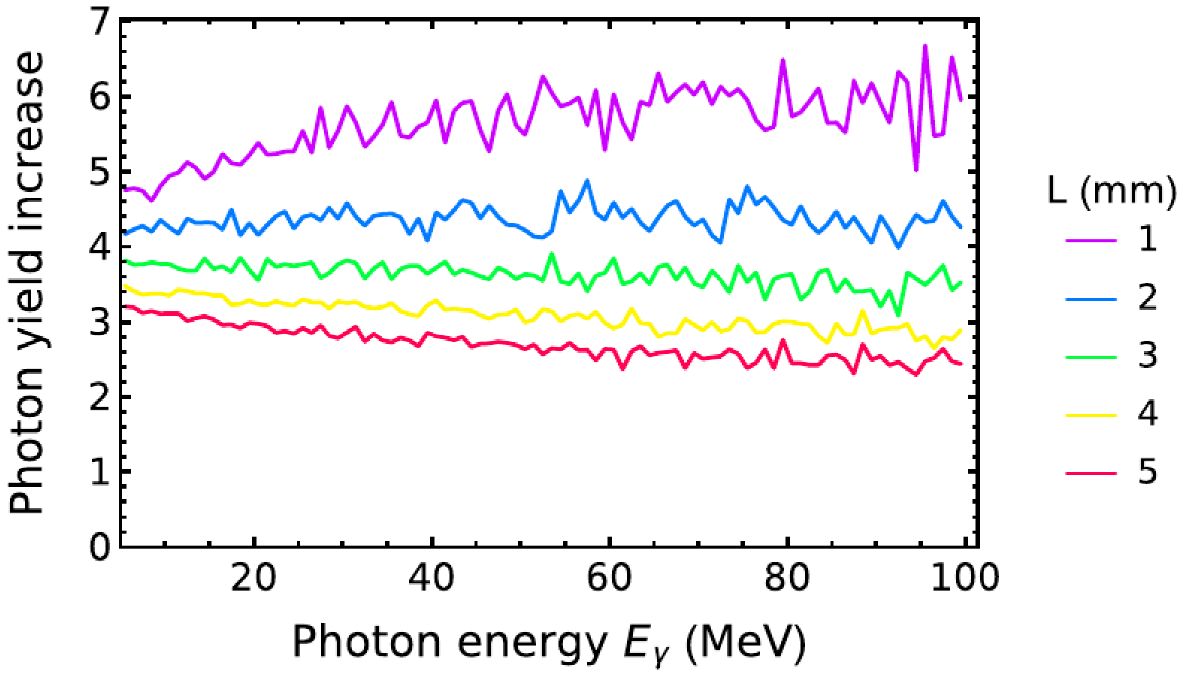
The **number of photons** produced in the crystal was **measured** by using a **preshower**

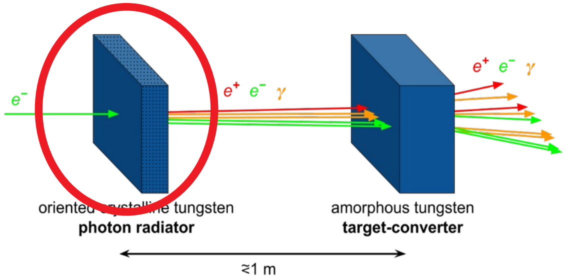
The experimental results show **photon multiplicity increase** for the **axial crystal alignment**

Agreement between **experiment** and **simulations** allows us to **use** our **simulation codes** for the **design** of a crystal-based positron source

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

Simulations of photon yield increase in a crystal vs random





Simulation input:

- e- energy: **6 GeV**
- angular divergence: **0.1 mrad**
- r.m.s. transverse beam size: **0.5 mm**
- **W, axes <111>**

Crystal thickness (mm) N_γ	1	2	3	4	5
$<$ 100 MeV, amorphous	1.1	2.6	4.6	7.4	10.9
$<$ 100 MeV, ⟨111⟩ axis	6.1	11.3	17.2	24.0	31.8
Full spectrum, amorphous	2.3	4.7	7.5	11.0	15.1
Full spectrum, ⟨111⟩ axis	11.0	17.6	24.0	31.0	38.8

Mainly **soft γ photons** will be **used** for **positron** production due to requirements of the capture system

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

More details in the talks of

Gianfranco Paternò

„New developments for FCC-ee with a single crystal-based positron source”

and

Nicola Canale

„New experimental tests on crystal radiators”

NEW developments in Geant4

Full Simulation Models:

- **G4ChannelingFastSimModel** – **channeling** model along with crystal structure and geometry classes.

In Geant4 since 2023

- **G4BaierKatkov** – model of **radiation** in an oriented crystal based on G4ChannelingFastSimModel

In Geant4 since 2023

- **G4CoherentPairProduction** – model of pair production in an oriented crystal

MERGED* in October 2024

Examples:

- **ch1** a very **easy example** to demonstrate basic commands to include both **channeling** and **radiation** model in DetectorConstruction (no input/ simple output)

MERGED* in September 2024

- **ch2** a **complex example** including both **channeling** and **radiation** model, crystalline undulator, input with macro commands, root output and full spectrum of options

MERGED* in September 2024

- **ch3** a very **easy example** to demonstrate basic commands to include **pair production** to simulate **electromagnetic shower** in an oriented crystal.

Submitted for MERGE*

- **Crystal-based positron source for FCC-ee**

Prepared (G. Paternò's talk)

***MERGED = included in the Geant4 main release, the end of 2024: geant4-v11.3.0**

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)

Conclusions

- **Positron sources** are a **key element** of past, present and future lepton colliders. Future projects require the development of the new types of positron sources to **reduce the Peak Energy Deposition Density, the background of secondary particles** and to **increase** the **positron yield** as well.

- The novel schemes of **crystal-based positron sources** have been tested **experimentally** at KEK, at CERN and DESY. The **simulation** codes have been **validated**.

- A preliminary version of a **FCC-ee crystal-based positron source** has been **simulated**. It provides a **reduction** of **PEDD** and **positron yield increase** as well.

- The crystal-based positron source will be implemented as a **Geant4 example** in the frame Marie Curie IF **TRILLION** project, GA n. 101032975.

Acknowledgements

We acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Call for tender No. 104 published on 02.02.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU – Project Title : "Intense positron source Based On Oriented crySTals - e+BOOST" 2022Y87K7X– CUP I53D23001510006

We also acknowledge the support of UE Commision through TRILLION (G.A. No 101032975).

e+BOOST
PRIN2022-
2022Y87K7X

Bando
PRIN 2022

Finanziato
dall'Unione europea
NextGenerationEU

Ministero
dell'Università
e della Ricerca

Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

European
Commission

EIC-PATHFINDER-OPEN
TECHNO-CLS
(GA 101046458)

Trillion
Marie Curie Global Fellowships,
Project TRILLION
GA n. 101032975

FUTURE
CIRCULAR
COLLIDER

PSI

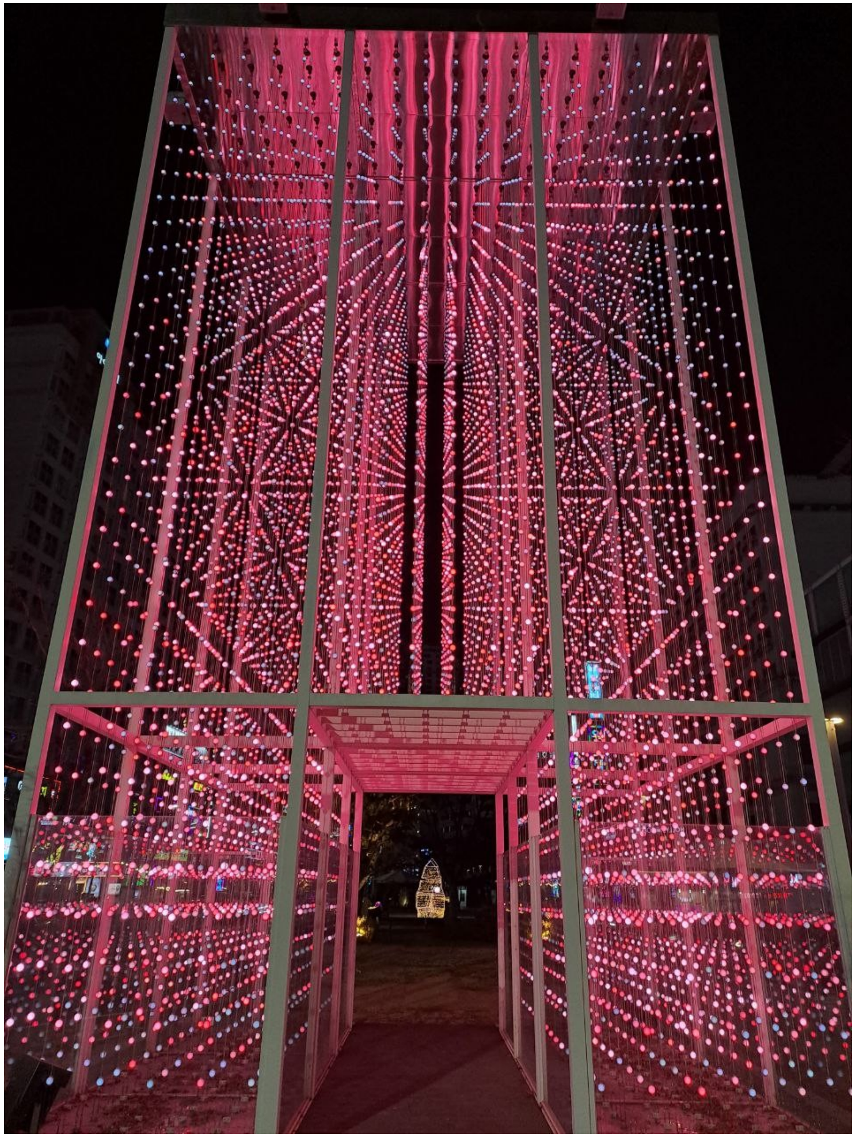
CHART

IJCLab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

anr
GA No ANR-21-
CE31-0007

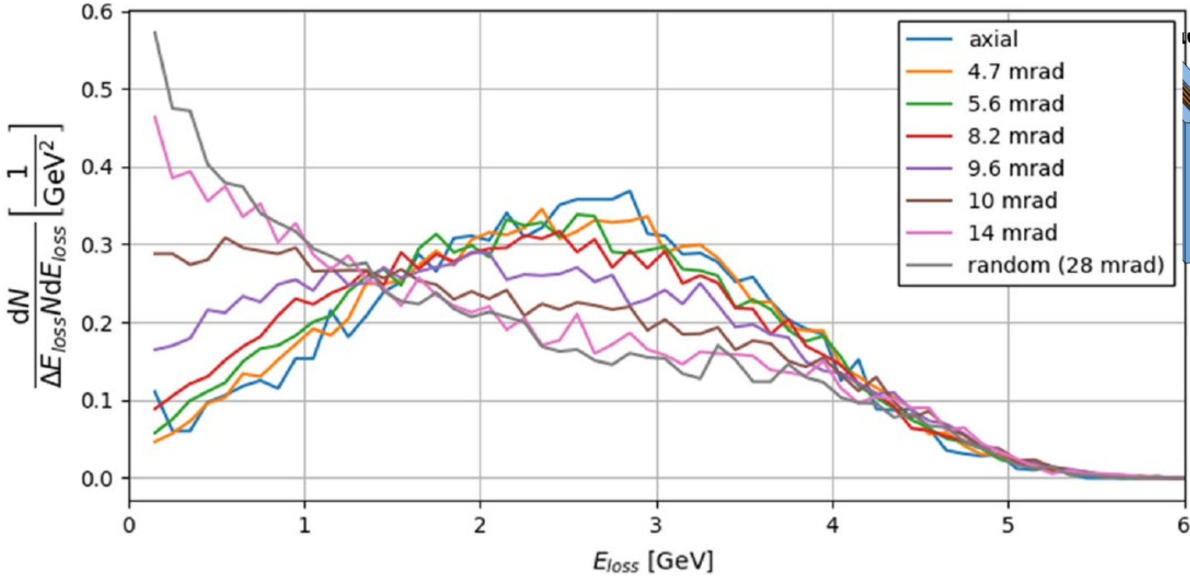
cnrs

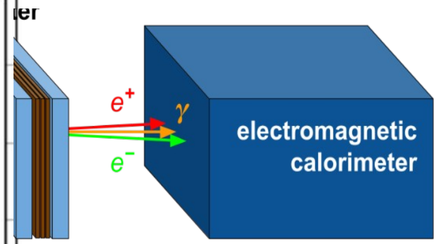
TECHNO-CLS

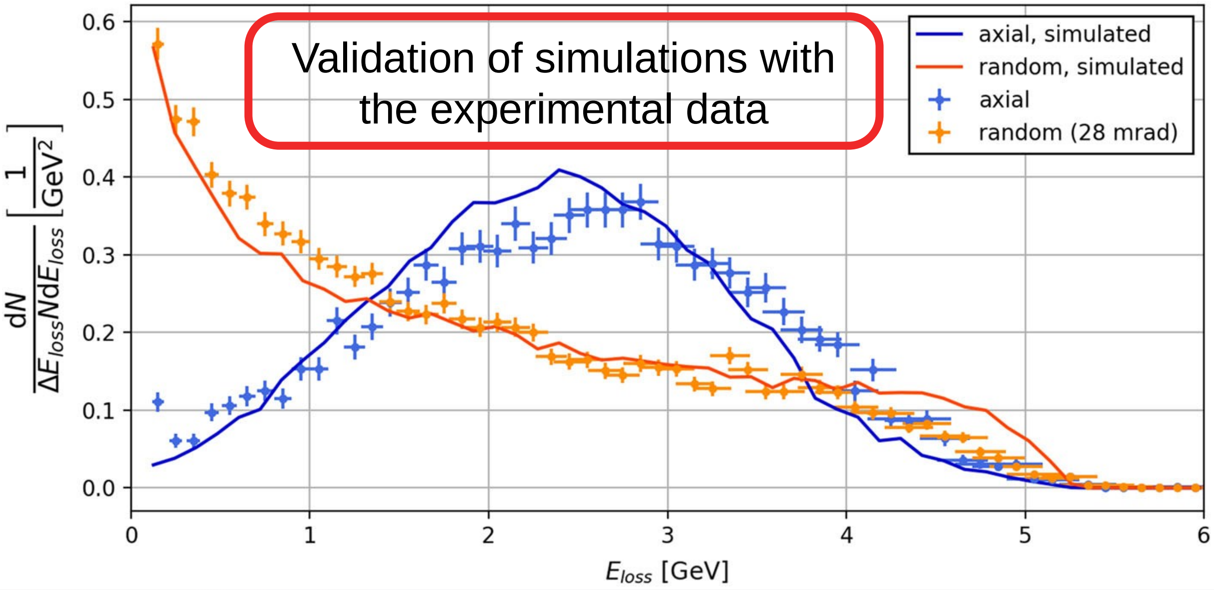


Thank you for attention!

Radiation energy loss measurement (from axial to random alignment)







Validation of simulations with the experimental data

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

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

```
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)
{
```

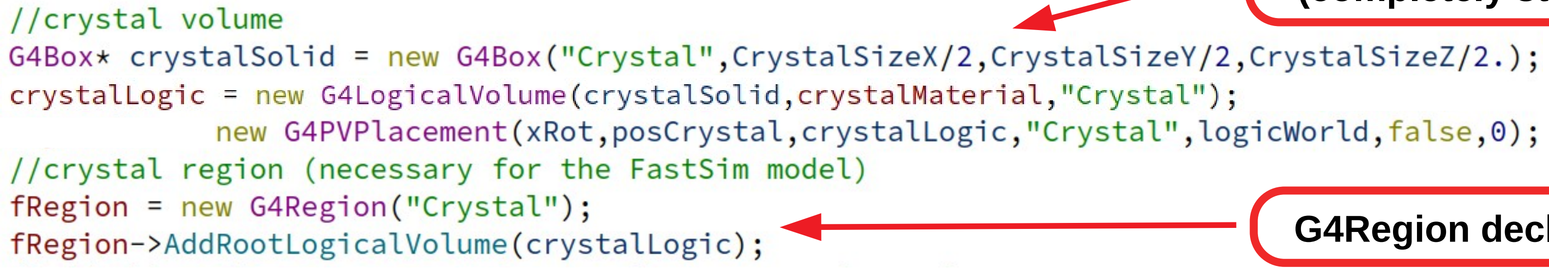
Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

How to use the Geant4 channeling model in your example?

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

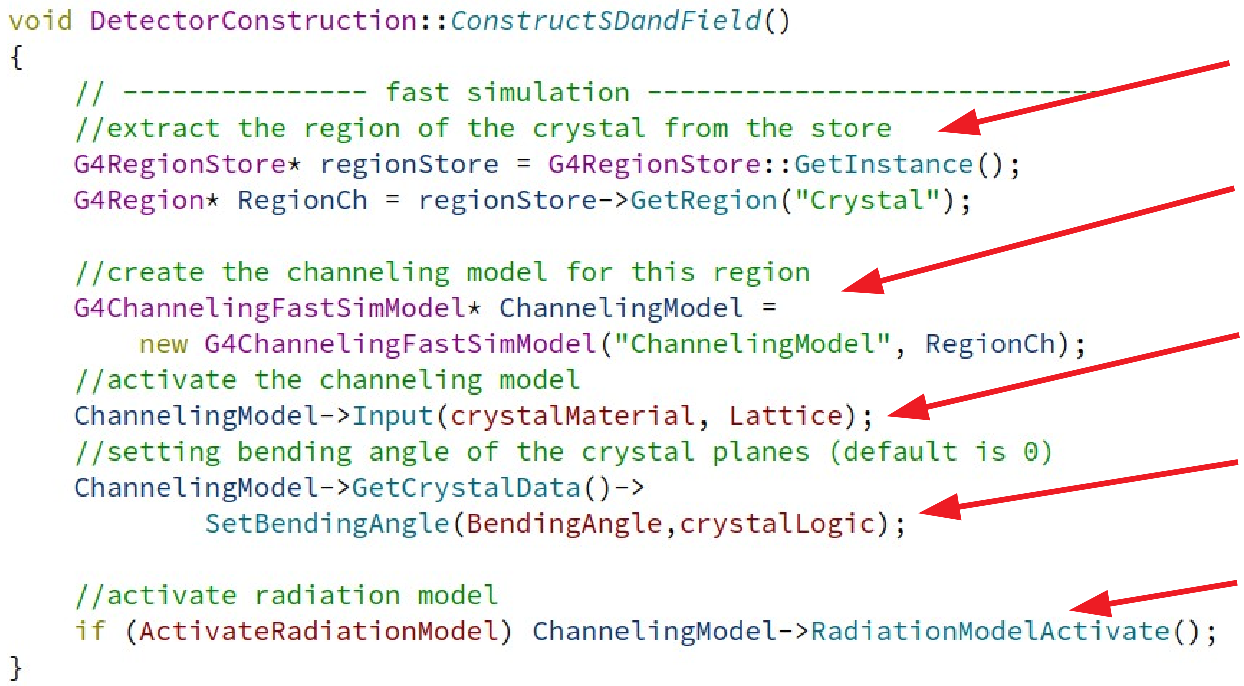


```
//crystal volume
G4Box* crystalSolid = new G4Box("Crystal",CrystalSizeX/2,CrystalSizeY/2,CrystalSizeZ/2.);
crystalLogic = new G4LogicalVolume(crystalSolid,crystalMaterial,"Crystal");
               new G4PVPlacement(xRot,posCrystal,crystalLogic,"Crystal",logicWorld,false,0);
//crystal region (necessary 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
    G4ChannelingFastSimModel* ChannelingModel =
        new G4ChannelingFastSimModel("ChannelingModel", RegionCh);
    //activate the channeling model
    ChannelingModel->Input(crystalMaterial, Lattice);
    //setting bending angle of the crystal planes (default is 0)
    ChannelingModel->GetCrystalData()->
            SetBendingAngle(BendingAngle,crystalLogic);

    //activate radiation model
    if (ActivateRadiationModel) ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim model declaration

Model activation and input

Optional

Radiation model activation

The model of Coulomb scattering

Coulomb scattering cross-section on atom following from screened Coulomb potential:

$$\frac{d\sigma_{cr}}{d\Omega} = \frac{d\sigma_{coh}}{d\Omega} + \frac{d\sigma_{inc}}{d\Omega} \qquad \frac{d\sigma_{inc}}{d\Omega} = N(1-D)\frac{d\sigma_{at}}{d\Omega}$$

Motion in averaged potential

Debye-Waller factor

Coulomb scattering process is divided into **multiple** and **single scattering**:

- **Multiple scattering *$\vartheta \leq \vartheta_2$***:

$$< \vartheta^2_{Cms} > = < n_N > \Delta z \int_0^{\vartheta_2}\int_0^{2\pi} \frac{d\sigma_C}{d\Omega}\left(1-\exp(-p^2\vartheta^2u_1^2)\right) d\varphi\vartheta^3 d\vartheta$$

Debye-Waller factor

- **Single scattering *$\vartheta > \vartheta_2$*** by **(1)** and taking into account the **Debye-Waller factor**.
- **Single scattering on electrons**, Rutherford cross-section:

$$\frac{d\sigma_{Ce}}{d\Omega} = 4\frac{z^2e^4}{p^2v^2}\frac{1}{\vartheta^4}$$

M. L. Ter-Mikaelian, High-energy electromagnetic processes in condensed media. Wiley. New York, 1972.

Main concept of full ab-inition G4BaierKatkov

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

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

$$\vec{k}$$

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

ω, θx, θy

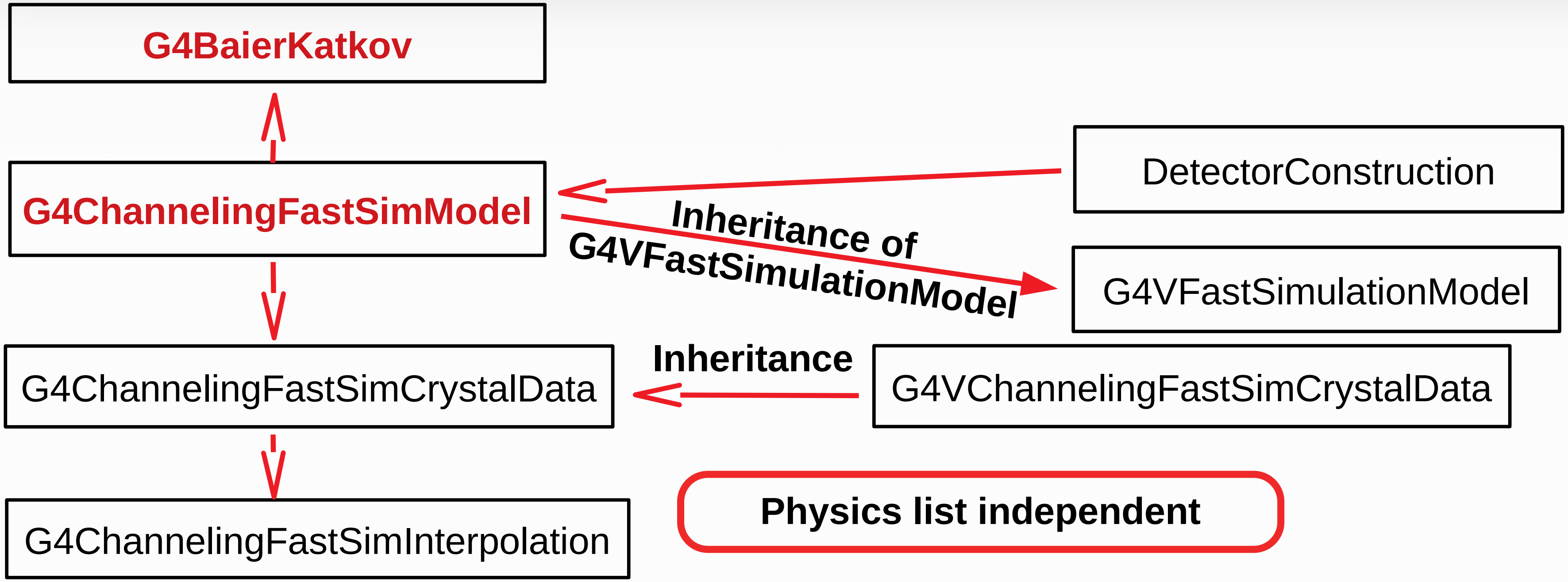
Radiation probability calculated **per photon**

$$\vec{k}_i \Rightarrow P_i$$

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**

Structure of classes



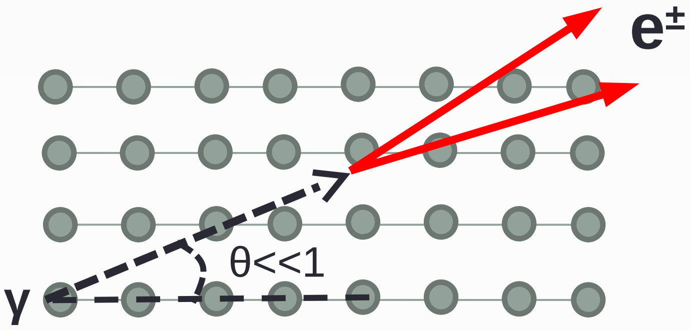
Physics list independent

Additional classes:

- **G4VChannelingFastSimCrystalData:** multiple and single Coulomb scattering, ionization losses
- **G4ChannelingFastSimCrystalData:** read crystal lattice data files from **G4CHANNELINGDATA**, logical volume to crystal plane/axis geometry transformation
- **G4ChannelingFastSimInterpolation:** crystal lattice data and 3D-spline interpolation functions

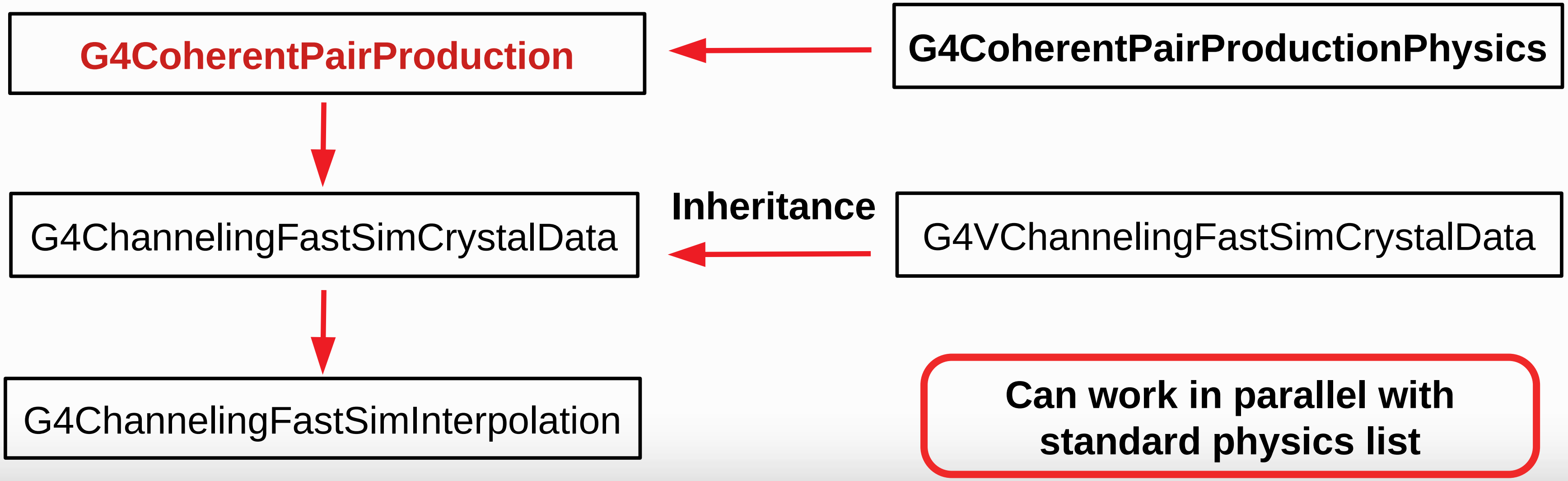
New 2024: Coherent pair production Geant4 process

Coherent pair production***



Key idea:

- Randomly **generate e± pairs**
- **Track e±** in the crystal
- Use **Baier-Katkov** formula to calculate the **probability of pair production**
- Randomly **select a pair according to this probability** and generate secondaries



G4CoherentPairProduction

G4CoherentPairProductionPhysics

G4ChannelingFastSimCrystalData

Inheritance

G4VChannelingFastSimCrystalData

G4ChannelingFastSimInterpolation

Can work in parallel with standard physics list

***** H. Überall, Phys. Rev. 103, 1055 (1956)**