# Geant4 code for the optimization of Positron Sources based on oriented crystals

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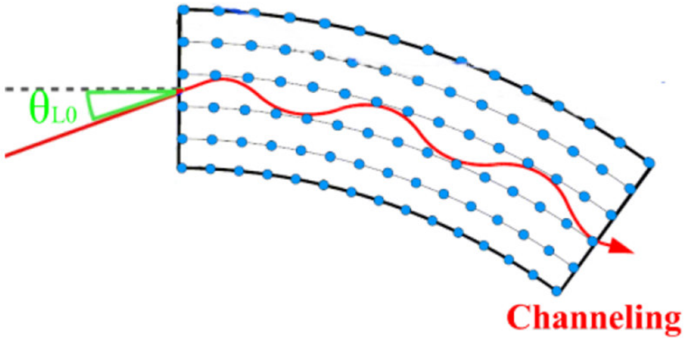
*e+BOOST meeting, Ferrara 11/01/2024*

# Coherent effects in a crystal

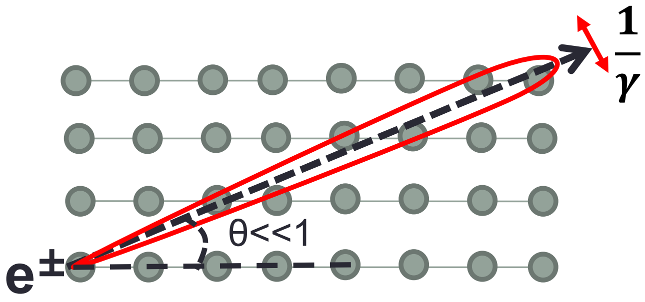
**Channeling***



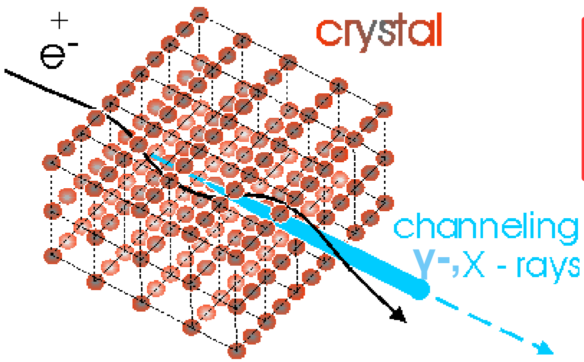

**Enegies:**
**MeV - TeV**

**Equivalent magnetic field: more than 100 T**

**Coherent bremsstrahlung*****

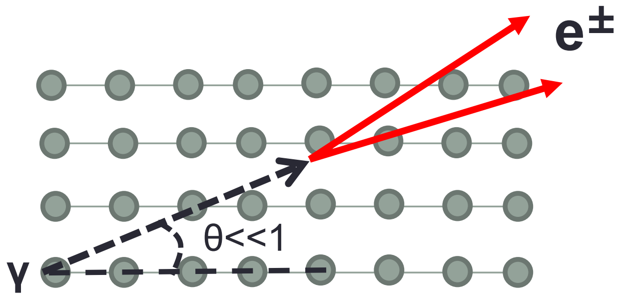



**Channeling radiation****




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

**Coherent pair production******

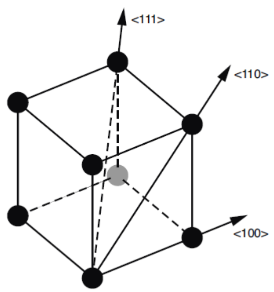


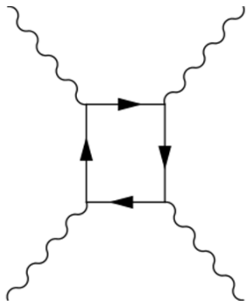

*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).

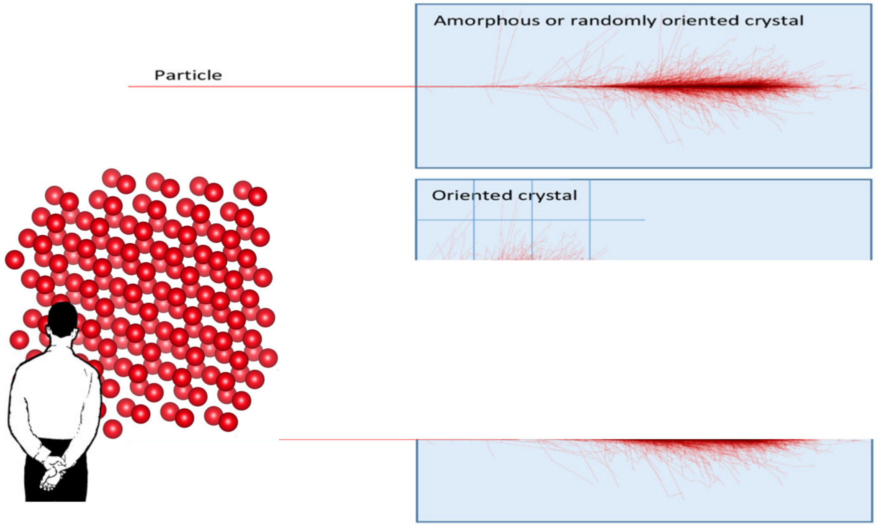
# Electromagnetic shower acceleration

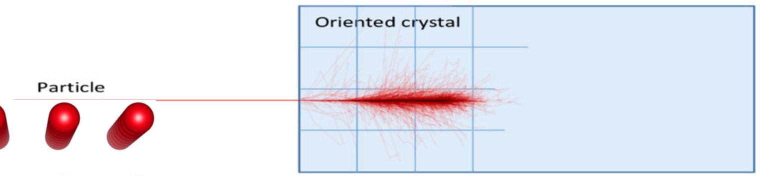
**Axial field $10^{11}$ V/cm**

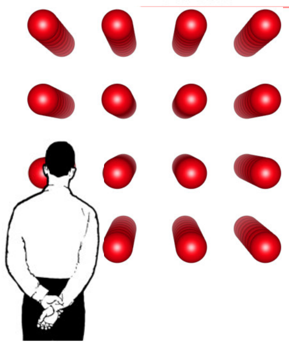
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**





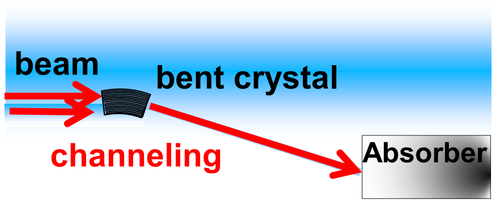



The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

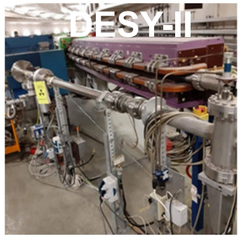
**Shower development** in the field of axes is **accelerated**. The radiation length is considerably reduced*.

# Some of the possible applications of oriented crystals

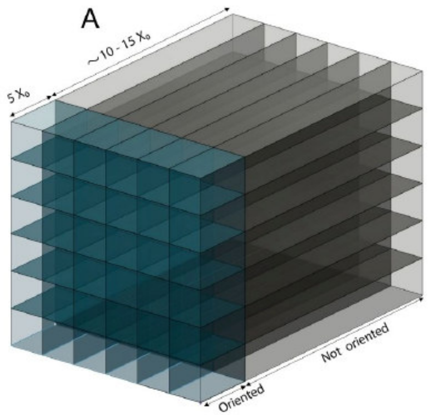
**Crystal-based collimation or beam extraction from an accelerator**



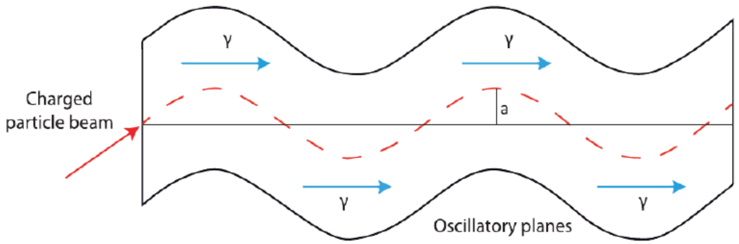




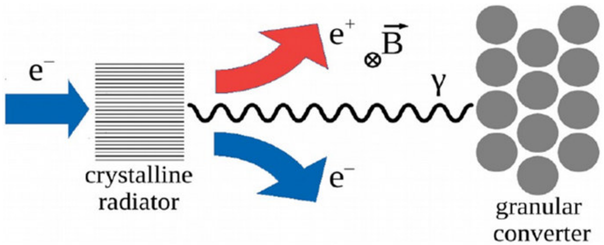

**Compact Oriented Calorimeter for Gamma-ray Space Telescopes**

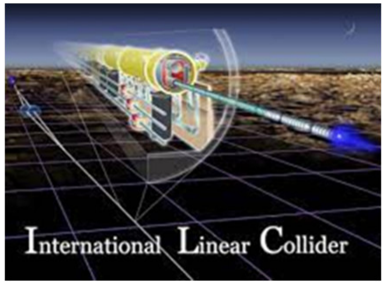


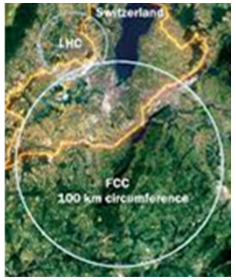

**Crystalline source of hard X-ray and gamma radiation, crystalline undulator (CU)**




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



# **MC Codes** available to our group to simulate coherent interactions of charged particles in oriented crystals

- In general purpose MC particle tracking codes, like Geant4, **matter is natively described as homogeneous, isotropic, amorphous.**
- **CRYSTAL**: code developed in Fortran by V. Tikhomirov. It is based on the Baier-Katkov quasi-classical method and can consider many effects, but each time must by manually adapted to the specific case...
- **CRYSTALRAD**: code developed in C++ by A. Sytov (it includes RADCHARM routine developed by L. Bandiera for radiation, also based on Baier-Katkov method).
- **Crystal support introduced in Geant4** by E. Bagli (former colleague) since Geant4 10.3. It allows the user to define a crystal from the unit cell → ab-initio approach, but includes only particle deflection, not radiation nor strong field effects…
- **Now**, we use **two different approaches** to simulate in **Geant4** respectively:
  1) **Particle deflection and radiation** → it makes use of a **Fast Simulation** model to stop the standard tracking inside selected volumes and run a code, ***G4ChannelingFastSimModel*** (included in Geant4 11.2), which is similar to CRYSTALRAD (A. Sytov).
  2) **Electromagnetic shower boost due to strong field effects** → through **bremsstrahlung and pair-production cross sections modification**, as a function of energy and angle w.r.t. desired axis, according to the results obtained through CRYSTAL code (which is based on the Baier-Katkov quasi-classical method). Mainly developed by V. Haurylavets.
- At the moment, we have not yet implemented a full simulation including coherent pair-production (not required for positron source simulation).

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

- **In the DetectorConstruction:**

```
//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**

```
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**

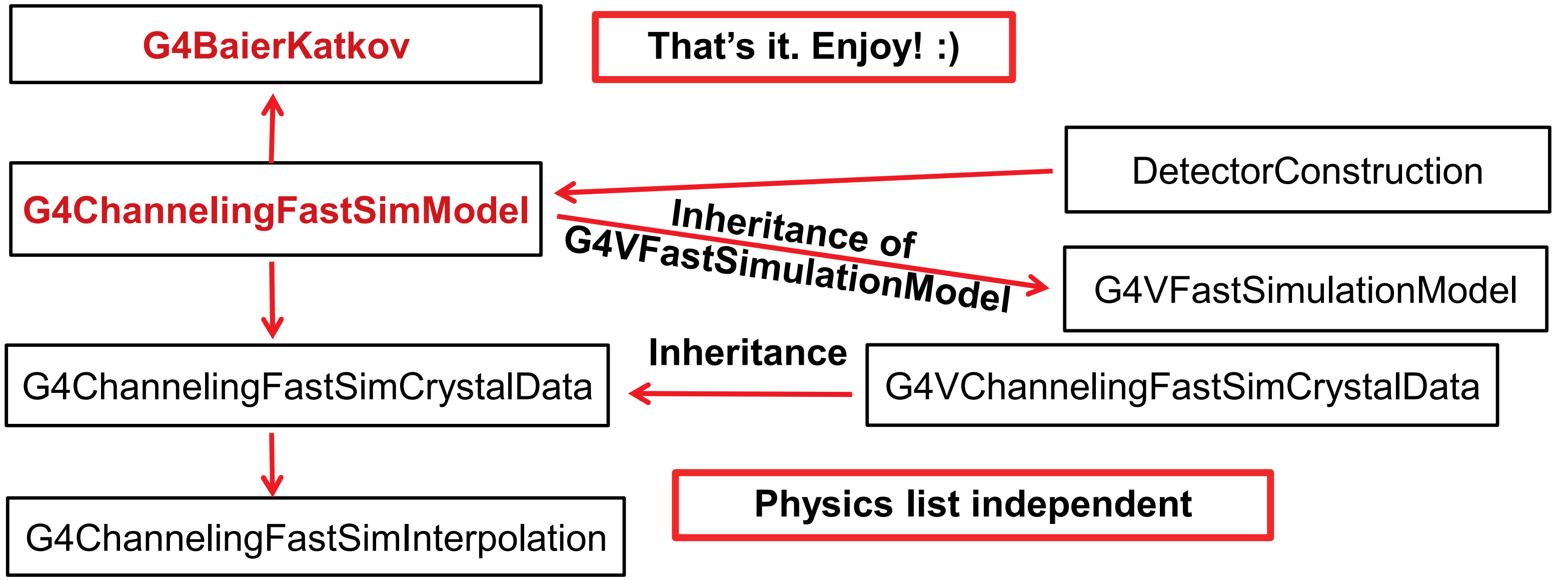
**Radiation model activation**

# How to use the Geant4 channeling model in your example?

- **Add to main (or in a PhysicsList):**

**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 );
```



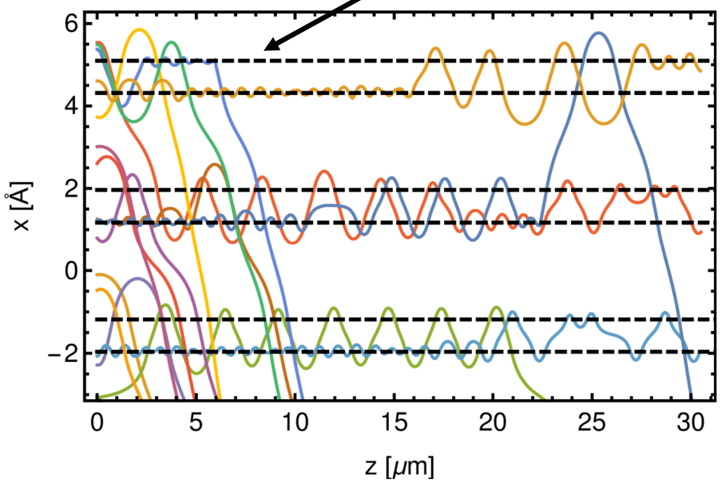
# Channeling simulation technique: **G4ChannelingFastSimModel**

- **Channeling** model using FastSim interface (trajectories): **READY**
- **Radiation** model (Baier-Katkov method) → **TESTING NOW**
- **Radiation** and **positron source Geant4 examples** **FOR SOME MATERIALS**

**A. Sytov and G. Paternò @INFN Ferrara**

This model, together with **multiple and single Coulomb scattering** on nuclei and electrons and standard or pre-calculated (through BK) **pair-production** CS, allows us to simulate the **Radiator** Crystal for positron sources

**Trajectories:**



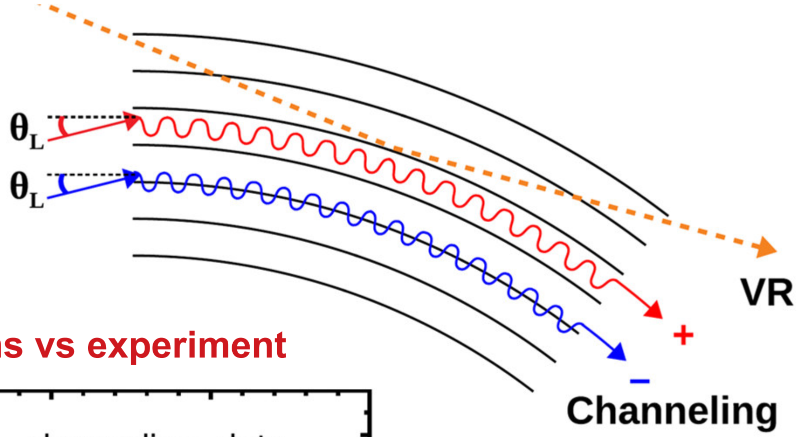

**Baier-Katkov formula:** $\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$

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. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)
*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

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

**855 MeV electrons**

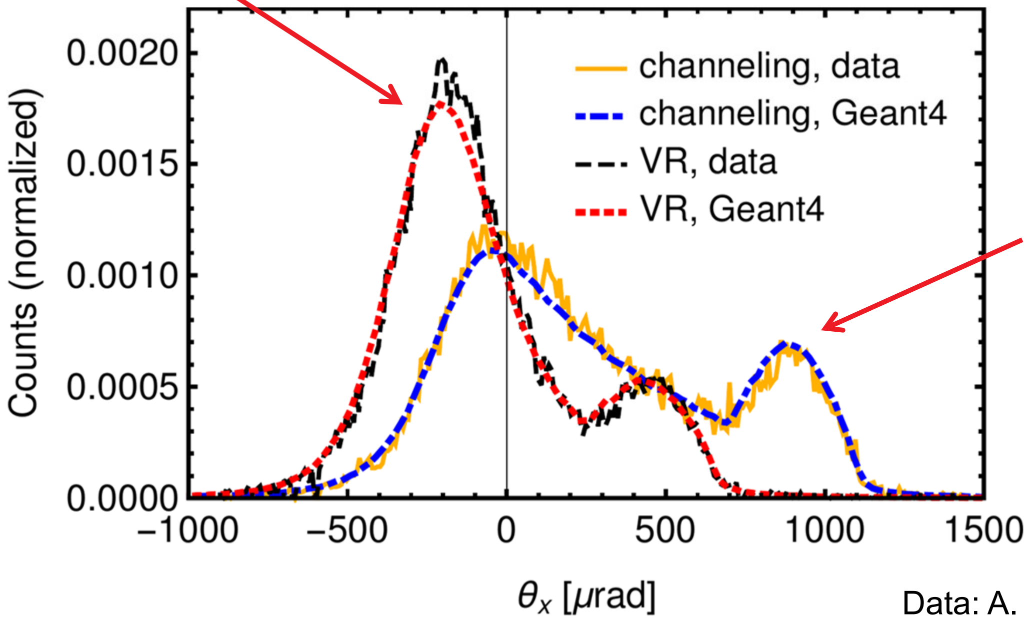
**15 μm thick bent crystal**




**volume reflection (VR)**

**Geant4 simulations vs experiment**

**channeling**



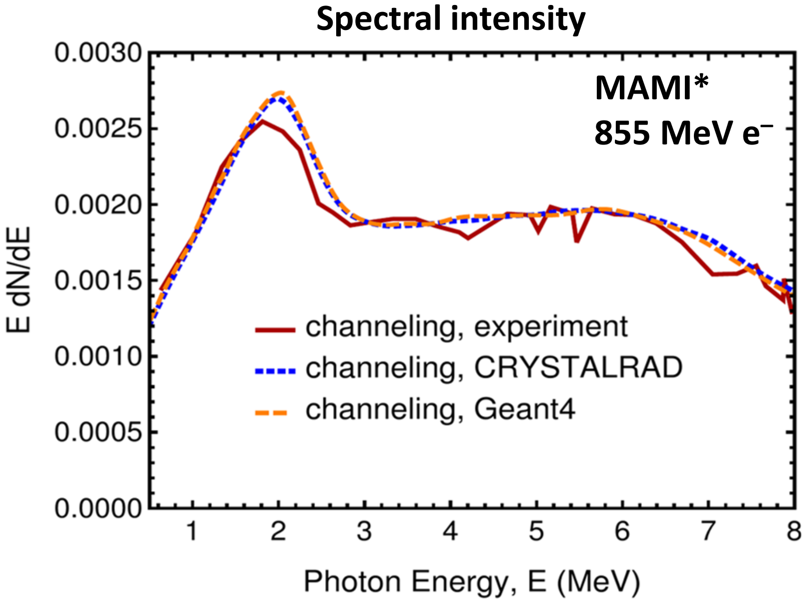

Data: A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)

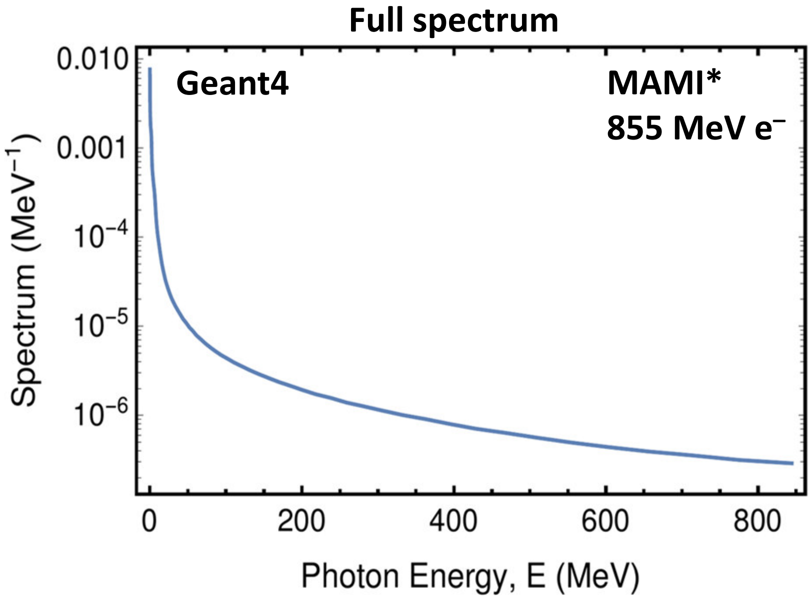
# First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI

**G4BaierKatkov**:

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

**Geant4 simulations vs experiment and CRYSTALRAD simulations**




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

# Current **Geant4 applications** useful to simulate coherent interactions of charged particles in oriented crystals

- **FastSimChannelingRad**: it allows us to test *G4ChannelingFastSimModel* for different crystalline materials and orientations.

- **OCalo4Sat**: it can be used to simulate electromagnetic calorimeters composed of oriented crystals. It can take advantage both of *G4ChannelingFastSimModel* model and EM shower boost based on cross-section modification.

- **PositronSource**: it can be used for the optimization of a Positron Source based on oriented crystals. It is based on the *G4ChannelingFastSimModel* model.

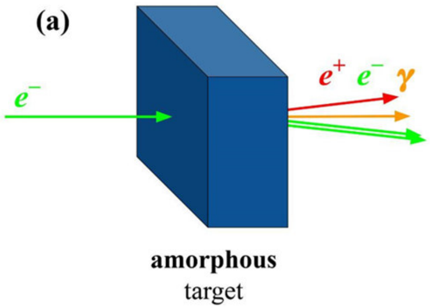
- **TestBeamOC**: it is conceived to simulate the experiments with oriented crystals we carry out at different facilities. It is currently under development, but specific versions implemented by M. Soldani and P. Monti-Guarnieri and based on previous coherent models are available.

*These applications are continuously developed by me within the framework of various projects, e.g.* ***Geant4infn****.*

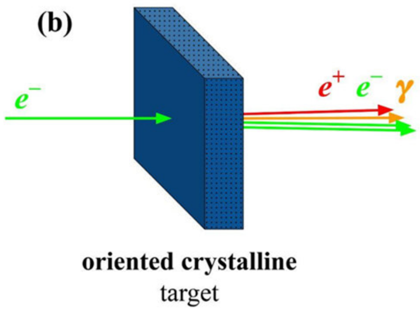
# Positron source for future lepton colliders

**UNPOLARIZED POSITRON SOURCES**

**1. Conventional**

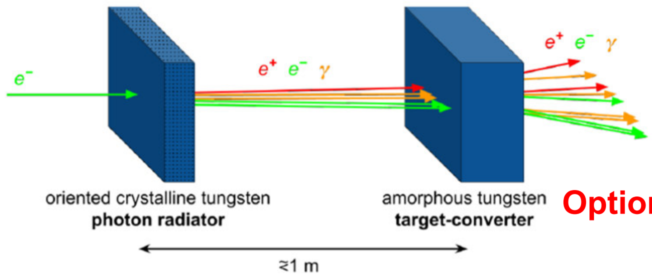



**2. e+ from channeling radiation**



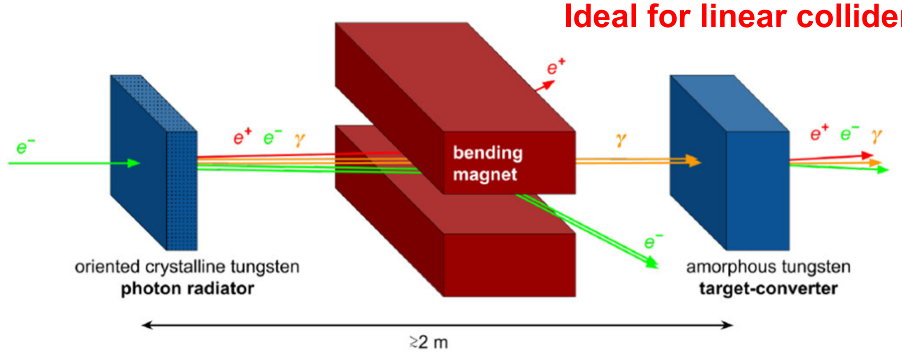

**Tests performed at CERN (WA 103) and at KEK**

**3. Hybrid crystal-based positron source**




**Option for FCCee**

**Ideal for linear colliders**

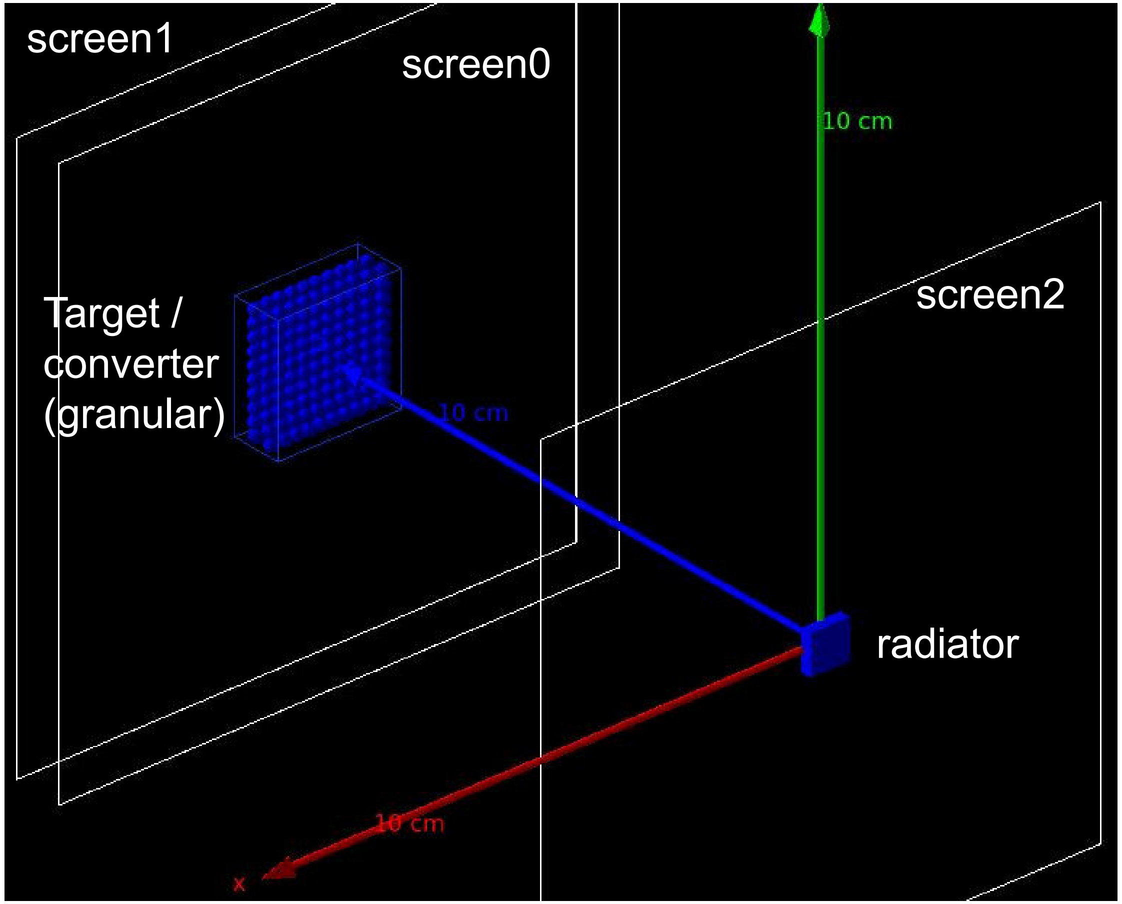


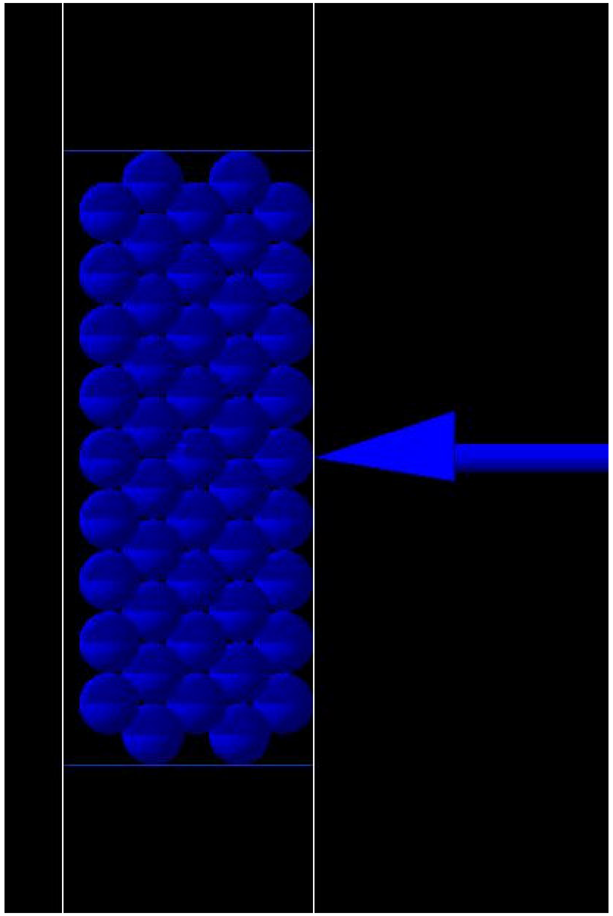

*Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868*

# **PositronSource** Geant4 application

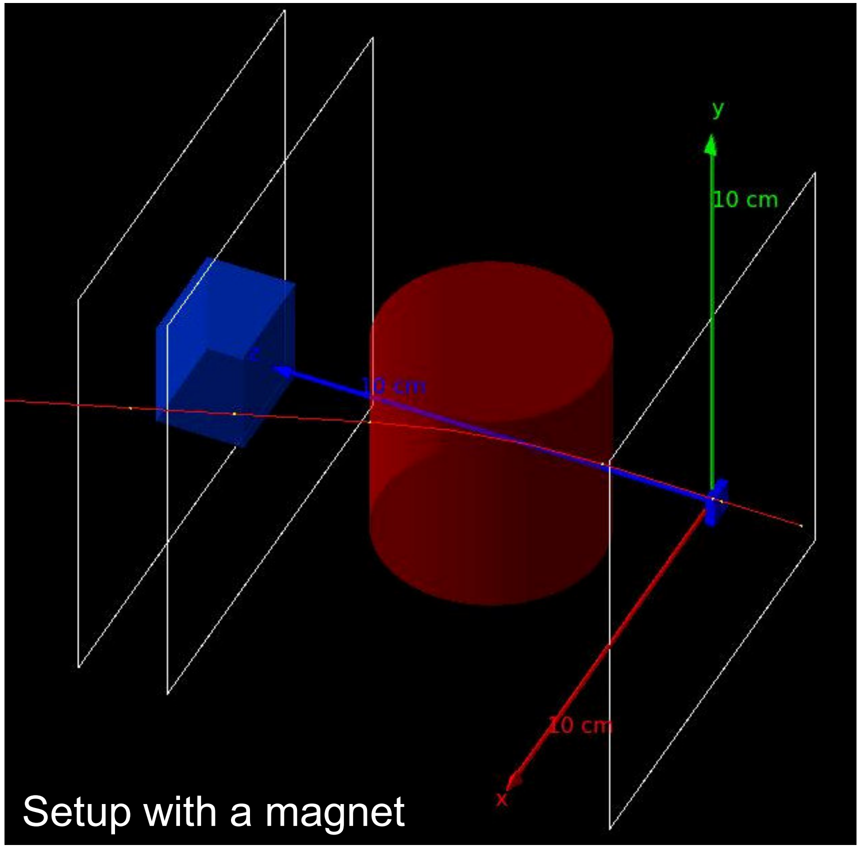
- It allow us to simulate a crystal-based Positron Source, according to the previous schemes, namely **conventional, oriented-crystal and hybrid positron sources**.
- The code relies on ***G4ChannelingFastSimModel*** to simulate coherent effects in crystals. Alternatively, the phase-space of particles obtained through CRYSTAL code can be imported and tracked into the considered setup.
- Apart from converter (which can be granular) and radiator crystals, a region with a **magnetic filed** or a **collimator** can be included in the setup.
- The **scoring** is made through 1-3 virtual scoring screens to store a **root ntuple**: (screenID,particle,x,y,px,py,pz,t,eventID) at the exit of the radiator and at entrance and exit of the converter. Also, the **energy deposited in the crystals per event** is recorded, as well as the **energy distribution (voxelized)** in the converter (or the radiator) in a text file.
- The application is fully compatible with **multi-threading**.
- A set of **custom commands** have been created; thus, the user does not need to re-compile the application to change a parameter. The entire setup can be controlled -> very useful for a systematic study.
- The code, as well as scripts and result files, can be found in this **Drive shared folder**: https://drive.google.com/drive/folders/11GblTtv1djklzjlSzMkdf7BgF415n6Bs?usp=drive_link

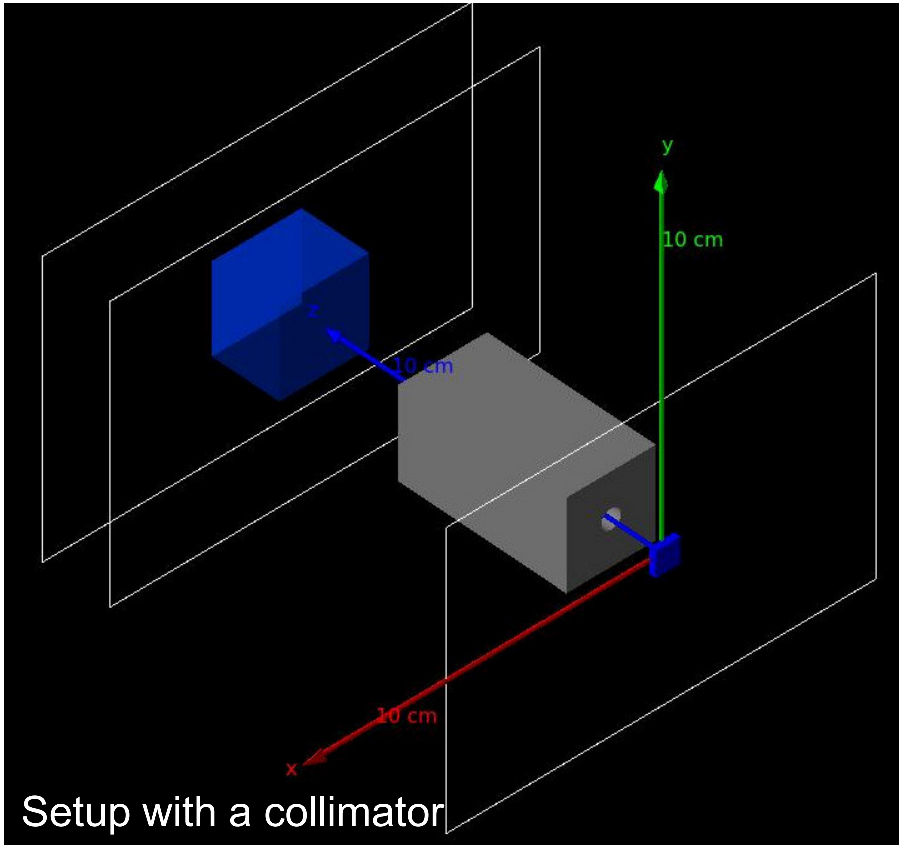
# **PositronSource** Geant4 application



# **PositronSource** Geant4 application



# **PositronSource** Geant4 application

```
#Positron Source type
#/det/isHybridSource false                  #defualt true

#Radiatior Crystal settings
/crystal/setCrystalMaterial W               #PWO, BGO, C, W, Ge, Si (default)
/crystal/setCrystalSize 7. 7. 2. mm
/crystal/setCrystalLattice <111>            #planes (e.g. (111)) or axes (e.g. <111>)
#/det/setRadiator true                       #default is false (if !isHybridSource -> automatically true)

#Converter Crystal settings
/det/setRadiatorConverterSepDistance 50. cm
/det/setConverterSize 199.75 199.75 11.6 mm #th=17.6mm->conventional, th=11.6mm->hybrid
#/det/setGranularConverter true              #default is false
#/det/setSphereRadius 1.1 mm

#other geometry settings
#/det/setMagneticField true                  #default is false
#/det/setMagneticFieldValue 5. tesla
#/det/setMagneticFieldRegionLength 20. cm

#/det/setCollimator true                     #default is false
#/det/setCollimatorAperture 5.5 mm
#/det/setCollimatorThickness 50. cm
#/det/setCollimatorSide 2.5 m
#/det/setRadiatorCollimatorSepDistance 5. cm

#/crystal/setVirtualDetectorSize 40. 40. 0.001 cm

#Voxelization settings
/det/setVoxelization true                   #activate the voxelization of the Converter Crystal (defualt false)
/det/setColumns 401                         #799
/det/setRows 401
/det/setSlices 24                           #36 for th=17.6mm, 24 for th=11.6mm
#/det/setAbsorberDxVoxel 1. mm
#/det/setAbsorberDyVoxel 1. mm
/det/setAbsorberDzVoxel 0.5 mm

/run/initialize
```

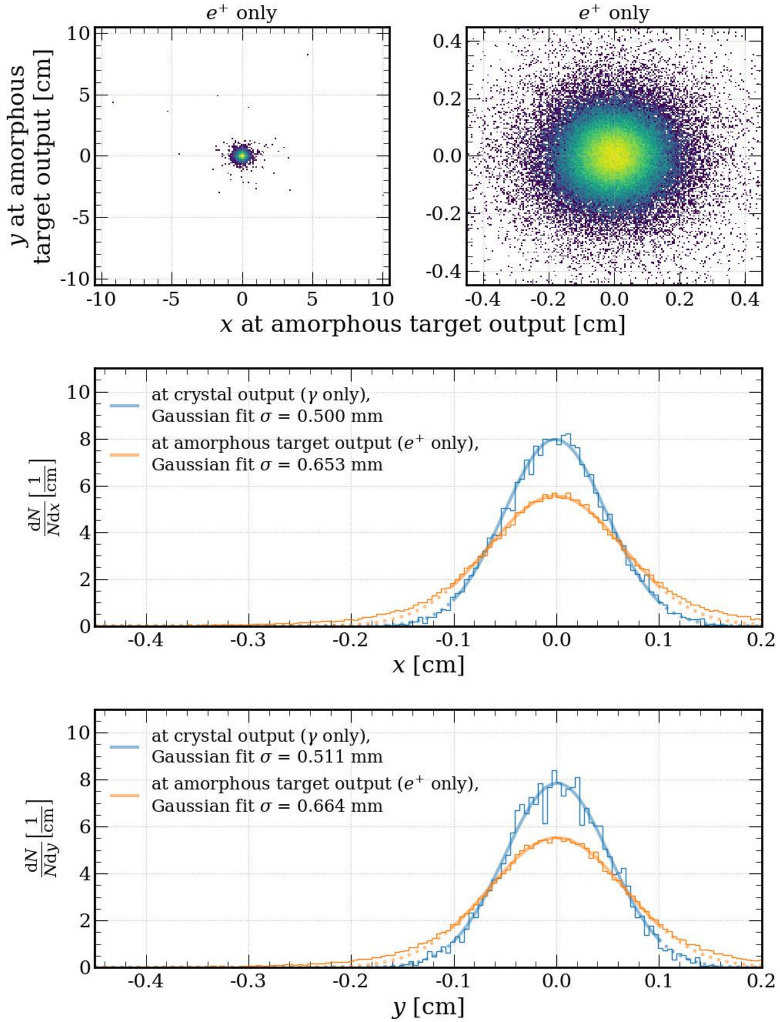
run.mac

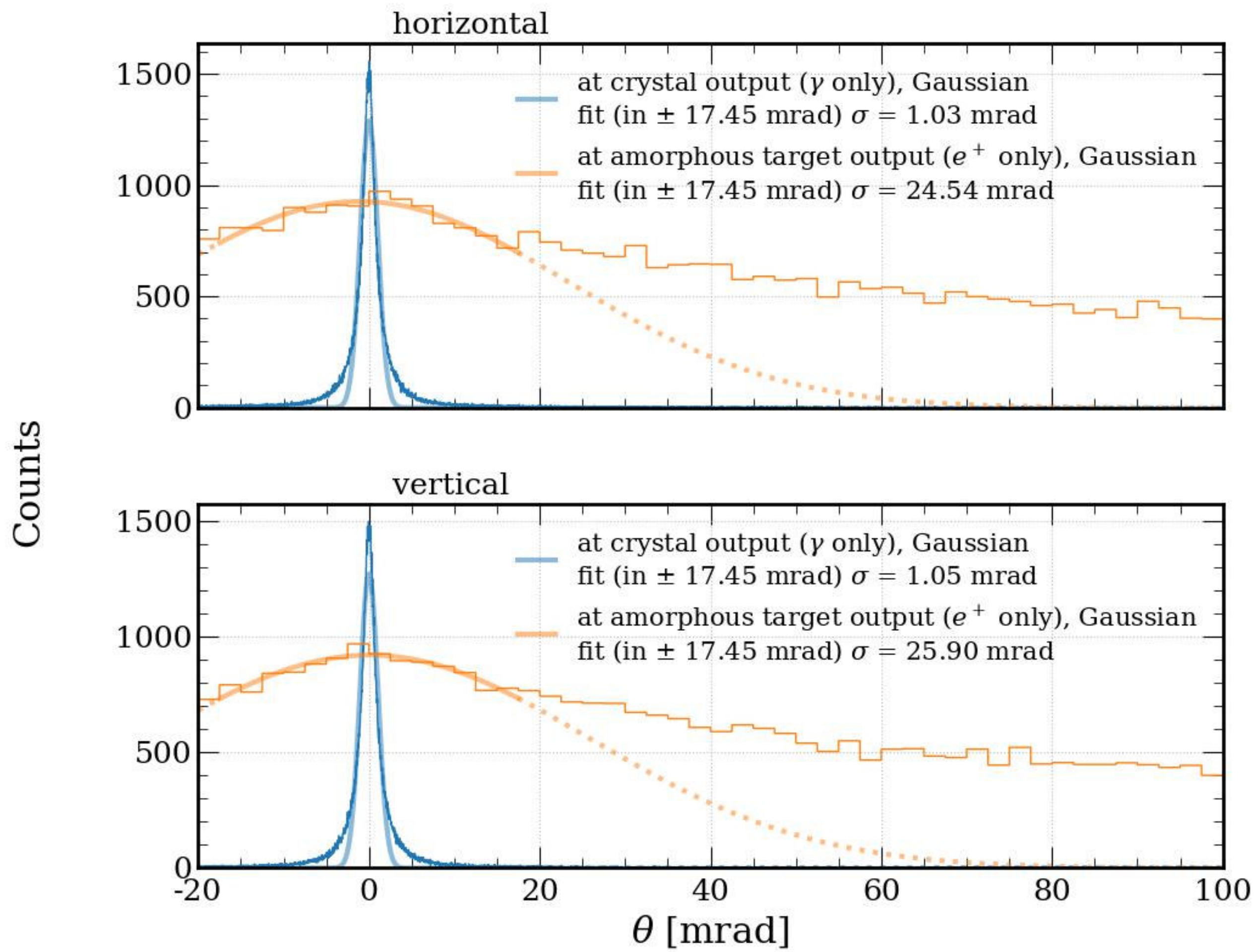
# **PositronSource** Geant4 application

```
/run/initialize

/control/verbose 0
/run/verbose 1                             #to see the Couples CutsVsRegion
/tracking/verbose 0
#/run/dumpCouples

/run/setfilenamesave output/output_6GeV_W2p0mm_readPS_D50cm.root

/gun/ReadFromFile true                     #defualt false
/gun/SetFileName input/W2.0mm_6GeV_all.dat  #put these lines after /run/initialize

#beam
/gps/particle e-
#coordinate distribution
/gps/pos/centre 0. 0. -5. cm
/gps/pos/type Beam
/gps/pos/sigma_x 0.5 mm
/gps/pos/sigma_y 0.5 mm
#angular distribution
/gps/ang/type beam2d
/gps/ang/rot1 1  0  0
/gps/ang/rot2 0 -1  0
/gps/ang/sigma_x 100.E-6 rad
/gps/ang/sigma_y 100.E-6 rad
#energy distribution
/gps/ene/mono 6. GeV

#/score/create/boxMesh boxMesh1
#/score/mesh/boxSize 99.875 99.875 5.8 mm   #semi-quantities (z=8.8 for th=17.6mm, 5.8 for th=11.6mm)
#/score/mesh/nBin 401 401 24                #799 799 36
#/score/mesh/translate/xyz 0. 0. 505.83 mm   #[505.83 if D=500 or 5.82 if D=0] CHECK ALWAYS! <------
#/score/quantity/energyDeposit Edep          #[MeV];
#/score/close
#/score/list

#statistics
/run/printProgress 100
/run/beamOn 236741                         #10000 #236741 #353796

#/score/dumpQuantityToFile boxMesh1 Edep output/Edep_6GeV_W2.0mm_readPS_D50cm.txt
```

run.mac

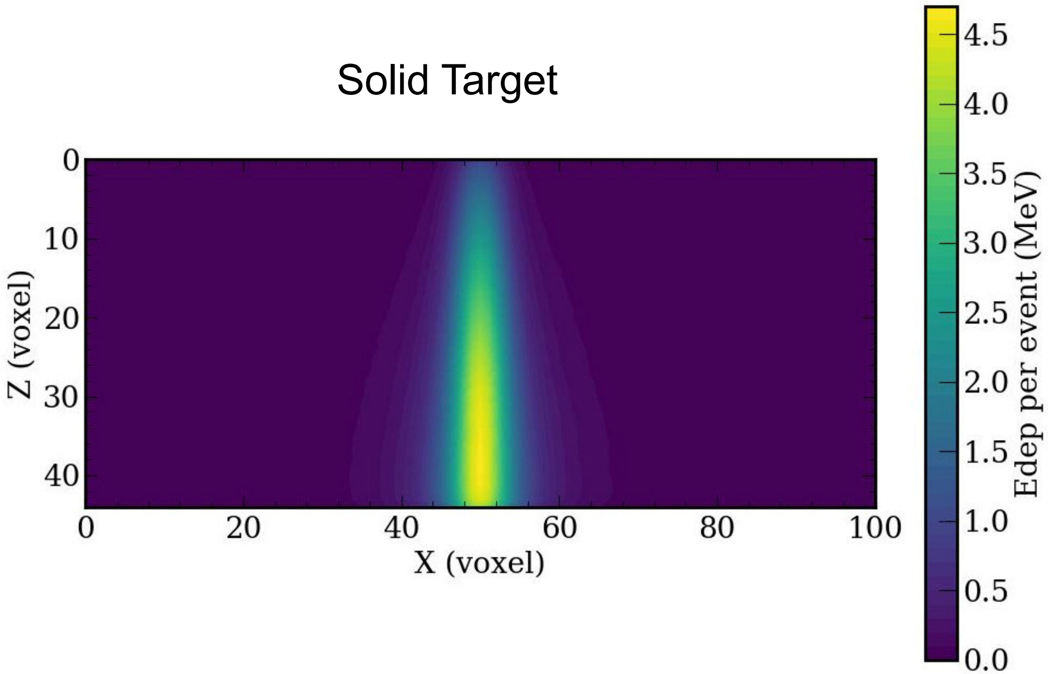
# **PositronSource** Geant4 application



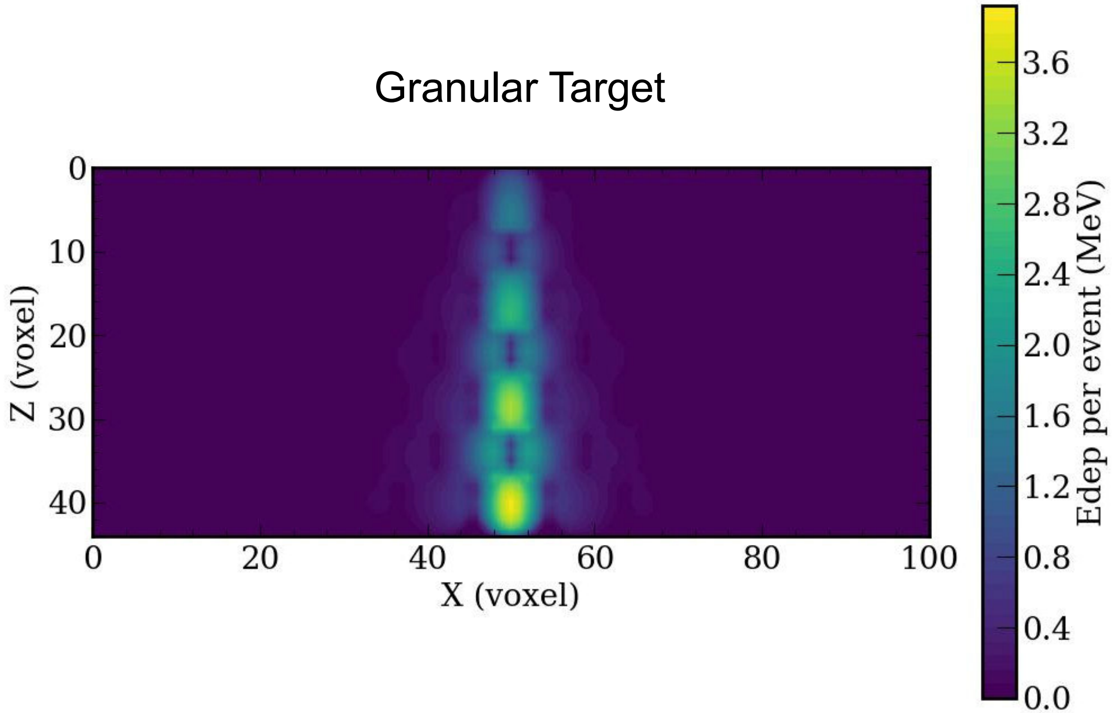



# **PositronSource** Geant4 application

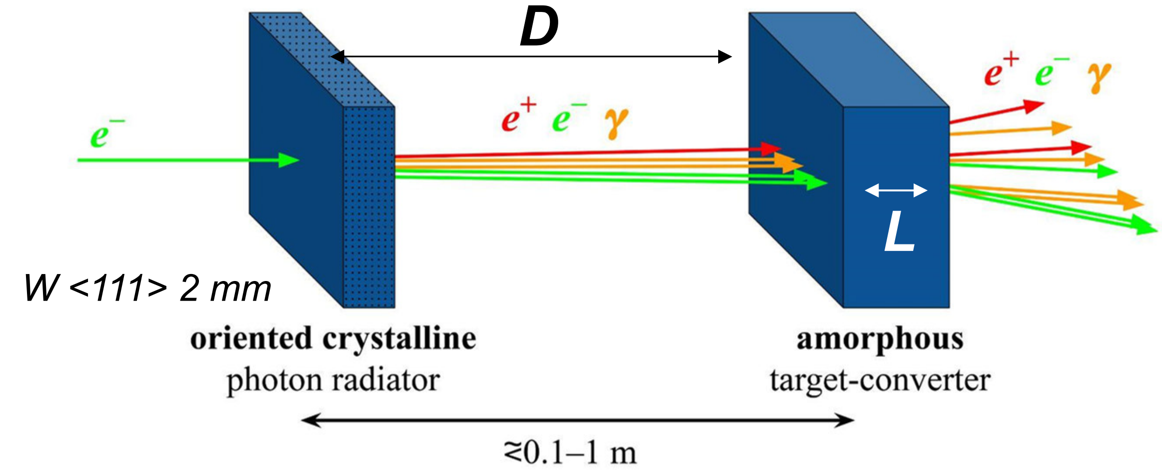
Solid Target



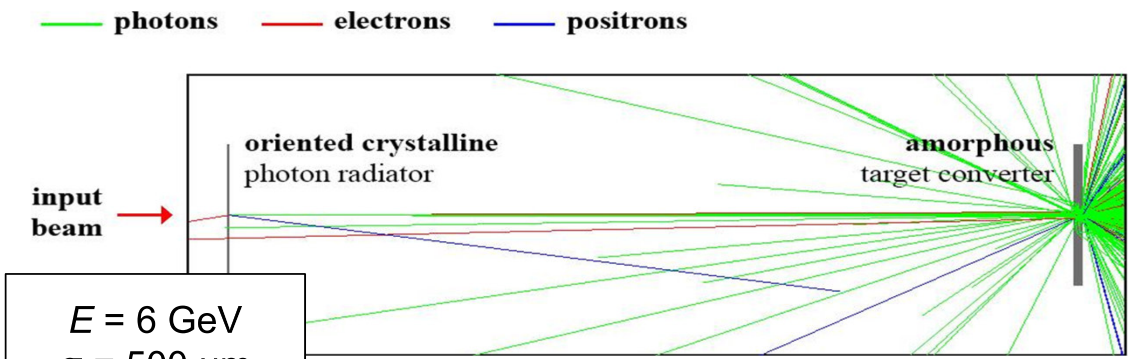

Granular Target



# Hybrid source optimization for FCC-ee




energy deposit and PEDD in amorphous converter can be reduced by tuning ***L*** (while keeping the radiator thickness fixed to maximise EM enhancement) and ***D***




$E$ = 6 GeV
σ = 500 μm
σ’ = 100 μrad

**Geant4** simulation of the downstream stage…

(***upstream stage already optimised with dedicated code and experimental data→ dedicated input files***)

L. Bandiera *et al.*, **EPJC 82**, 699 (2022)

Collabortion with IJCLab (leaber I. Chaikovska)

**The starting point**: results reported in **M. Soldani** et al, NIMA, 2024, https://doi.org/10.1016/j.nima.2023.168828

| Scheme | conv. | hybrid | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $L_{\text{crys}}$ [mm] | – | | | | 2 | | | |
| $D$ [m] | – | 0.6 | | 1 | | | 2 | |
| $L$ [mm] | 17.6 | | | | 11.6 | | | |
| (a = 5.5 mm) Collimator? | no | no | no | yes | no | no | yes | no |
| Magnet? | no | no | no | no | yes | no | no | yes |
| $E_{\text{dep}}$ [GeV/$e^-$] | 1.46 | 1.34 | 1.32 | 1.13 | 1.32 | 1.27 | 1.11 | 1.27 |
| PEDD [MeV/(mm$^3 \cdot e^-$)] | 38.3 | 12.8 | 8.4 | 8.2 | 8.4 | 4.1 | 3.8 | 3.9 |
| Out. $e^+/e^-$ | 13.7 | 15.1 | 15.1 | 13.6 | 15 | 14.9 | 13.7 | 14.9 |
| Out. $e^+$ beam size [mm] | 0.7 | 1 | 1.2 | 1.2 | 1.2 | 1.5 | 1.5 | 1.5 |
| Out. $e^+$ beam div. [mrad] | 25.9 | 27.4 | 26.8 | 27.7 | 28.9 | 29.2 | 25.6 | 27.1 |
| Out. $e^+$ mean energy [MeV] | 48.7 | 46.2 | 45.6 | 47.4 | 45.9 | 46.1 | 47.7 | 46.3 |
| Out. $n/e^-$ | 0.37 | 0.31 | 0.31 | 0.27 | 0.29 | 0.29 | 0.26 | 0.3 |
| Out. $\gamma/e^-$ | 299 | 310 | 308 | 270 | 307 | 301 | 268 | 301 |

conventional (amorphous)
collimator
magnet

We need to **improve the capture efficiency** of the dowstream stage (not reported here)

# Summarizing…

- We have different options to simulate coherent interactions of charged particles in oriented crystals.
- The simulation environment has now been fully developed and can be used for more sophisticated studies (e.g., capture simulations), in order to arrive to the <u>conceptual design for the hybrid scheme.</u> In parallel, other crystals can be simulated and checked. Eventually, <u>the performance will be compared to the conventional scheme.</u>