A. Sytov
On behalf of INFN Ferrara
INFN Sezione di Ferrara, Dipartimento di Fisica e Scienze della Terra, Università di Ferrara

CHANNELING MODEL IN GEANT4

MC-INFN/GEANT4 meeting, June 12, 2020

Tasks for 2020

Milestones 2020:

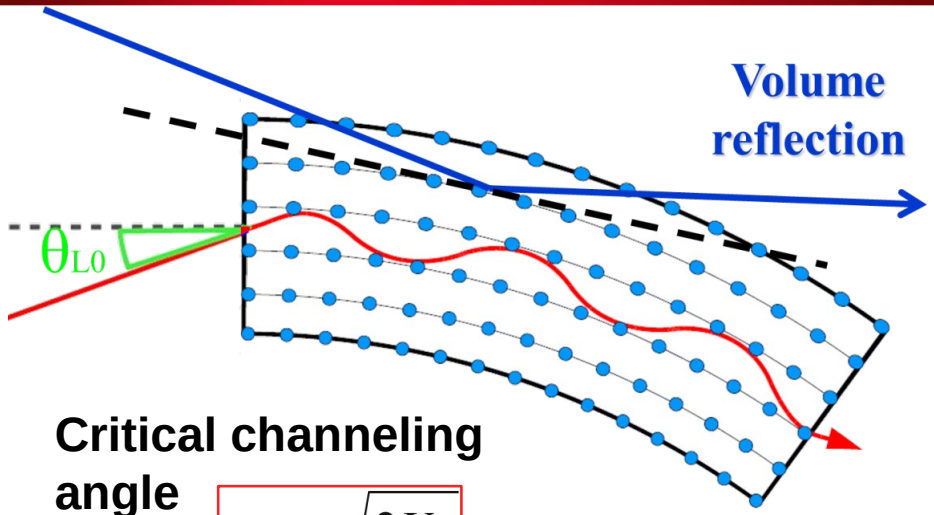
- **Comparison** between **Geant4** simulations and **experimental** data as well as simulations by the **CRYSTALRAD** simulation code.

- Proposal of **Geant4 channeling model improvements**.

In particular:

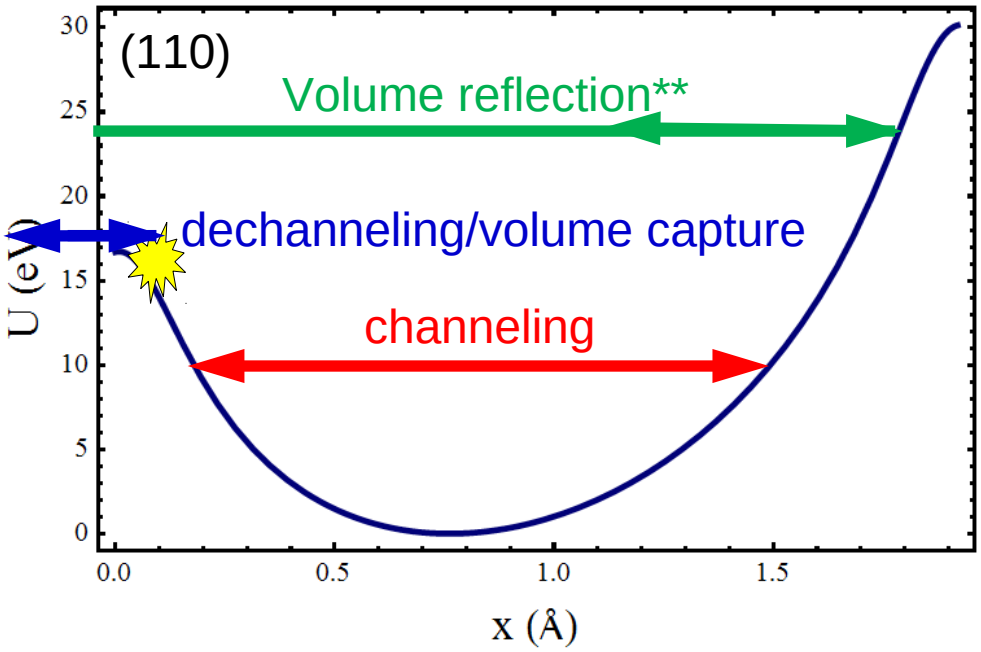
- **To verify** the model of **channeling** effect of **Geant4** through the existing **experimental data** in the experiments, carried out with the participation of the group of Ferrara, namely for 855 MeV electrons at the **Mainzer Mikrotron MAMI** as well as for 20.35 GeV electrons and positrons at the **SLAC FACET facility**.
- **Geant4** will be **compared** with the simulation results by means of the **CRYSTALRAD** simulation code already validated through the experiments mentioned above.
- In particular, the presence and the **peak positions** of **quasichanneling oscillations** will be **verified** in the simulations by Geant4 for both electrons and positrons.

Channeling and volume reflection in a bent crystal*



Critical channeling angle

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



Pecularities of channeling simulations:

- Very **small steps ~ nm-μm**
- The next step depends on the previous one
- **Multiple scattering** makes the trajectory stochastic
- **Strong single scattering** may be crucial

No channeling cross-section,
Channeling effect is complicated

Standard **Coulomb scattering** models **may be invalid** at small steps

***E.N. Tsyganov, Fermilab TM-682 (1976)**

****A.M. Taratin, S.A. Vorobiev, NIM B 26, 512 (1987)**

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**

New: unification of the **CRYSTAL*** code developed by **A. Sytov** and the **RADCHARM++**** code developed by **L. Bandiera** into the **CRYSTALRAD***** code to simulate the radiation spectra by **Baier-Katkov** formula

Advantages:

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

What have we been granted by (2016-2020)?

- **FERMI: 200 kh**
- **GALILEO: 500 kh**
- **MARCONI: 900 kh**

***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)**

Validation of simulations and articles published

Experimental validation of our simulation model for protons, electrons and positrons

A. Mazzolari, A. Sytov et al. **Eur. Phys. J. C** 80, 63 (2020)
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. **Phys. Rev. Acc. and Beams** 22, 064601 (2019)
T. N. Wistisen, …, and A. Sytov. **Phys. Rev. Lett.** 119, 024801 (2017)
A. I. Sytov et al. **Eur. Phys. J. C** 77, 901 (2017)
A.I. Sytov, V.V. Tikhomirov. **NIM B** 355 (2015) 383–386.
L. Bandiera et al. **Phys. Rev. Lett.** 115, 025504 (2015)
A. Mazzolari et al. **Phys. Rev. Lett.** 112, 135503 (2014)
V. Guidi, L. Bandiera and V. Tikhomirov, **Phys. Rev. A** 86, 042903 (2012)
L. Bandiera et al. **Phys. Rev. Lett.** 111, 255502 (2013)
V. Guidi, A. Mazzolari and V. Tikhomirov, **J. of Appl. Phys.** 107, 114908 (2010)

Experiments for which we do simulations

- INFN ELIOT
- SELDOM, Horizon 2020 n. 771642
- PEARL Project, H2020-MSCA-RISE-2015 call, n. 690991

Dedicated supercomputer time on Galileo: project BRAVI, Cineca ISCRA Class C, no. HP10C4LCQ9

```
*****************************************************************************
* Welcome to GALILEO /                                                      *
*            GALILEO @ CINECA - NeXtScale cluster - CentOS 7.4!             *
*                                                                           *
* 1022 compute nodes with:                                                  *
*      - 2*18-core Intel Xeon E5-2697 v4 (Broadwell) at 2.30 GHz            *
*      - 128 GB RAM                                                         *
*   60 compute nodes equipped with 1 nVidia K80 GPUs                        *
```

140 kh for 9 month

One scope of the project is simulations using **channeling model introduced into Geant4**

INFN Section of Ferrara

- Prof. Vincenzo Guidi
- Dr. Laura Bandiera
- Dr. Andrea Mazzolari
- Mattia Soldani

Project collaborators

Institute for Nuclear Problems, Belarusian State University, Minsk, Belarus

- Prof. Victor Tikhomirov
- Viktar Haurylavets
- Alesia Leukovich

What's new in Geant4 G4Channeling

New models:
Active only at near channeling conditions (small angles w.r.t. the crystal planes)

- Multiple and single **Coulomb scattering*** on screened atomic potential
- **Single Coulomb scattering on electrons**
- **Ionization energy losses in channeling**

```
void ClAtScattering(G4double &tx, G4double
void ClElScattering(G4double &tx,G4double &
void IonizationLosses(G4double &Ez0,G4doubl
```

```
455 void G4ChannelingS::ClAtScattering(G4double &tx,G4double &ty,G4dou
456 {
457         G4double ksi=0.1;
458
459 //      calculation of the teta2-minimal possible angle of a sing
460         G4double E1=k2*dZEFN; //for high speed of a program
461 //      (real formula is (4*pi*N0*wpl(x)*dz*zz1*zz2*alpha*hdc/ez)
462         G4double teta122=tetamax12/(ksi*tetamax12/E1+1.); // teta
463         G4double teta22;
464         G4double t;
465 //      if the angle of a single scattering is less teta1 - minim
```

The **Coulomb scattering model** in the **CRYSTALRAD** simulation code has been experimentally validated at the Mainzer Mikrotron **MAMI***

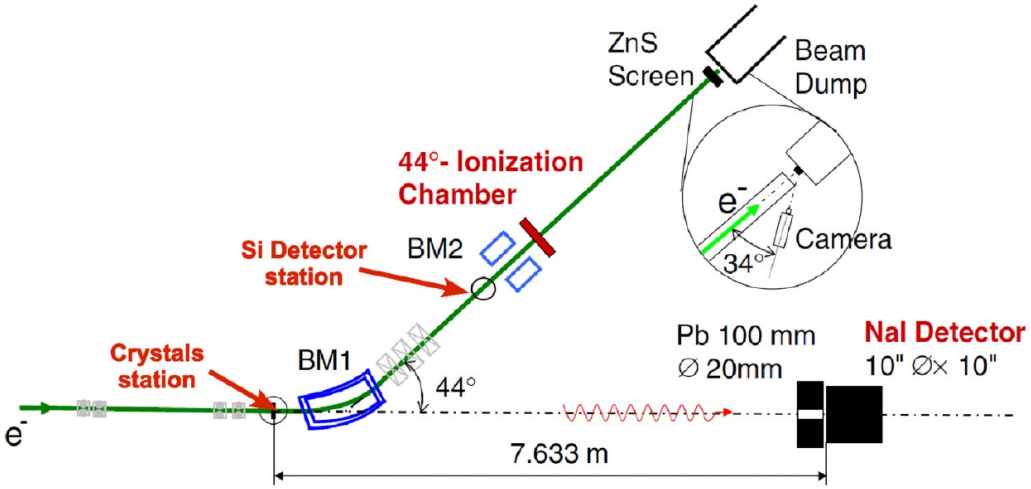
Revised Class **G4ChannelingOptrChangeCrossSection (G4VBiasingOperation): turning off** when channeling simulation is active of:

- **Coulomb scattering** processes
- **Ionization energy losses**

The verification of both **Physics Lists** and modification of the cross sections in **G4ChannelingOptrChangeCrossSection** is **in progress**

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

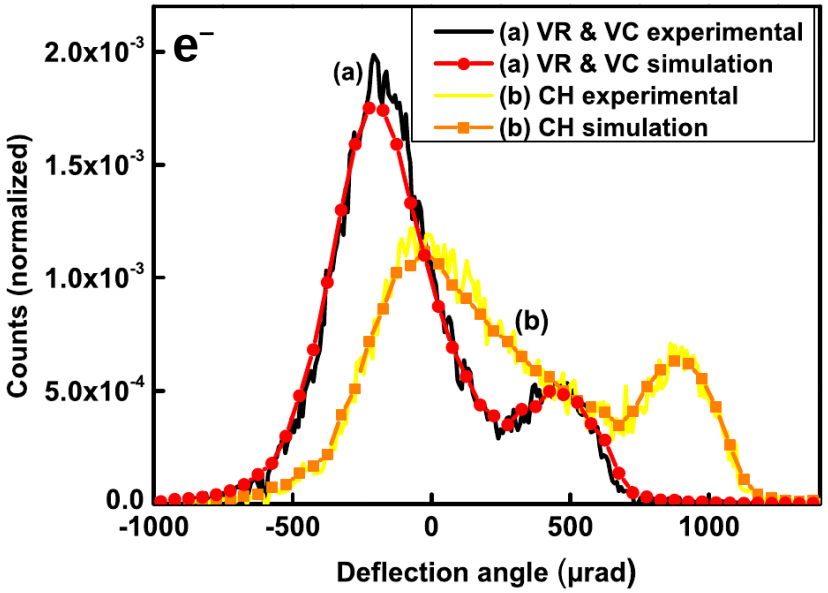
Preliminary results: Geant4 simulation of channeling of 855 MeV electrons at Mainzer Mikrotron MAMI



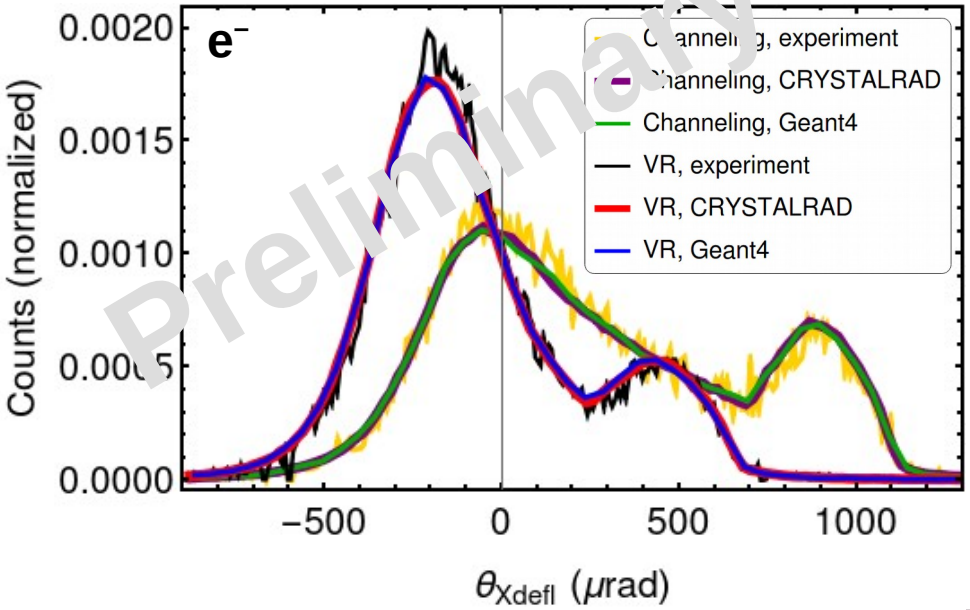
Simulation parameters

- Silicon crystal **30.5 µm** thick
- Planes: **(111)**
- Electron beam **855 MeV**
- Beam divergence **30 µrad**

Results published in 2014*



Geant simulations vs experiment and CRYSTALRAD simulations



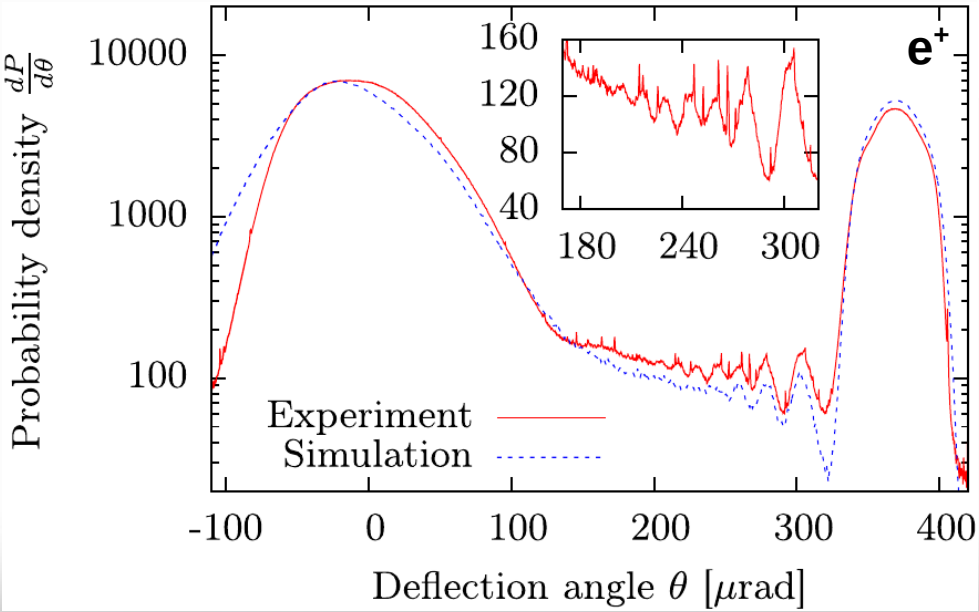
A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)

Preliminary results: Geant4 simulation of the effect of quasichanneling oscillations observed at SLAC FACET for 20.35 GeV e^+/e^-

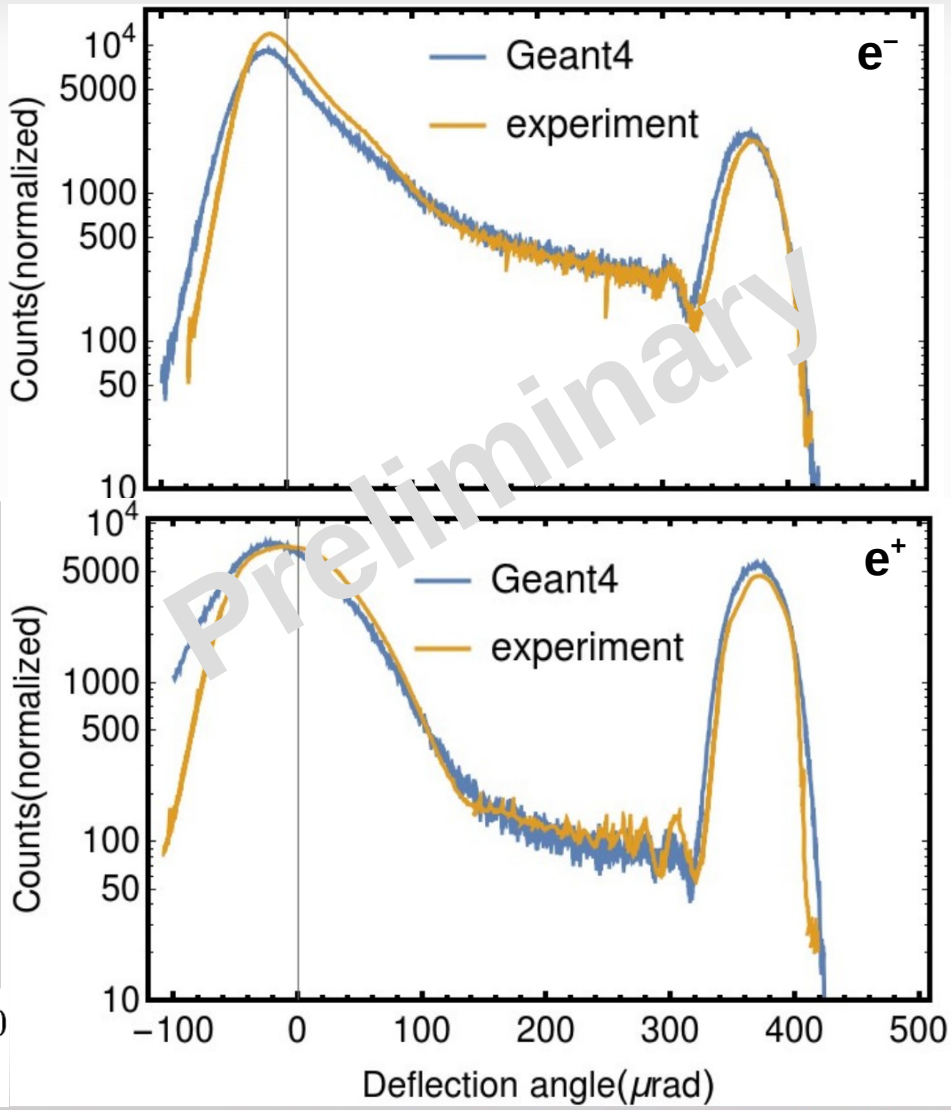
Quasichanneling oscillations in the deflection angle distributions, the effect **predicted by A. Sytov***

***A.I. Sytov et al. Eur. Phys. J. C 76, 77 (2016)**

CRYSTAL simulations *vs* experiment published in 2017*



Geant simulations *vs* experiment



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

Preliminary conclusions for 2020

Milestones 2020:

- **Comparison** between **Geant4** simulations and **experimental** data as well as simulations by the **CRYSTALRAD** simulation code.

- Proposal of **Geant4 channeling model improvements**.

Preliminarily done

In particular:

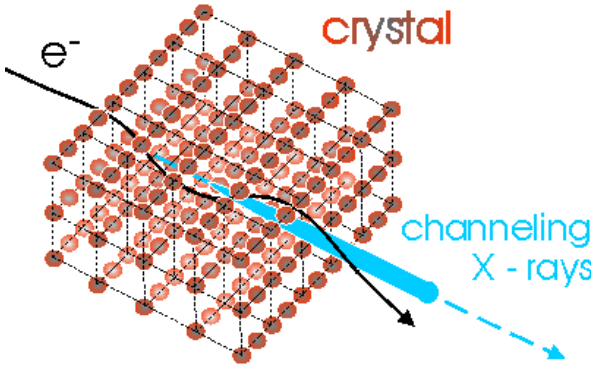
- The model of **Coulomb scattering** and **ionization energy losses** under the channeling conditions has been introduced into the class **G4Channeling**.
- The class **G4ChannelingOptrChangeCrossSection** has been revised.
- **Geant4** simulations have been **compared** with published **experimental data** and **CRYSTALRAD** simulations for channeling and volume reflection of 855 MeV electrons at Mainzer Mikrotron **MAMI**.
- **Geant4** simulations have been **compared** with published results for **experiment** and **CRYSTALRAD** simulations of the observation of **quasichanneling oscillations** at **SLAC FACET**.

Future task: introduction Baier-Katkov algorithm from CRYSTALRAD into Geant4 to simulate channeling radiation

The electromagnetic radiated energy is evaluated with **the Baier-Katkov formula** **

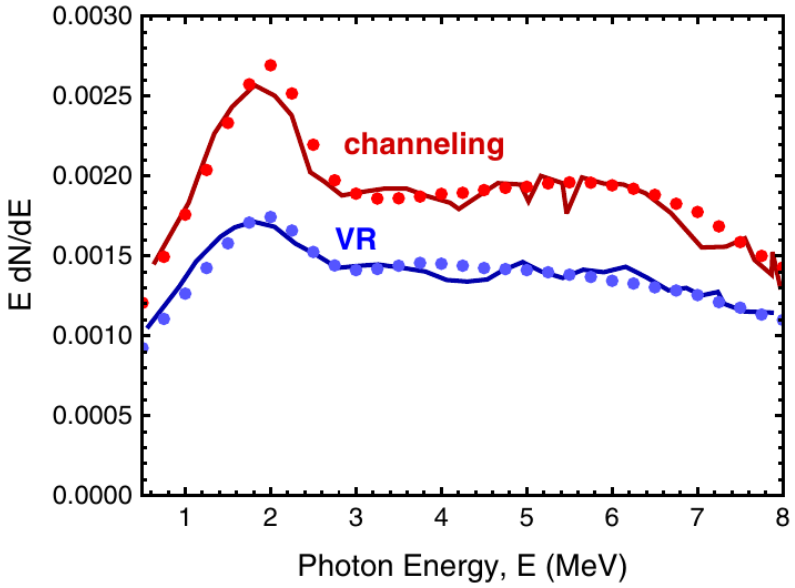
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1v_2-1)+\omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)} \qquad (1)$$

where the integration is made over the classical trajectory.



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

CRYSTALRAD *vs* experiment



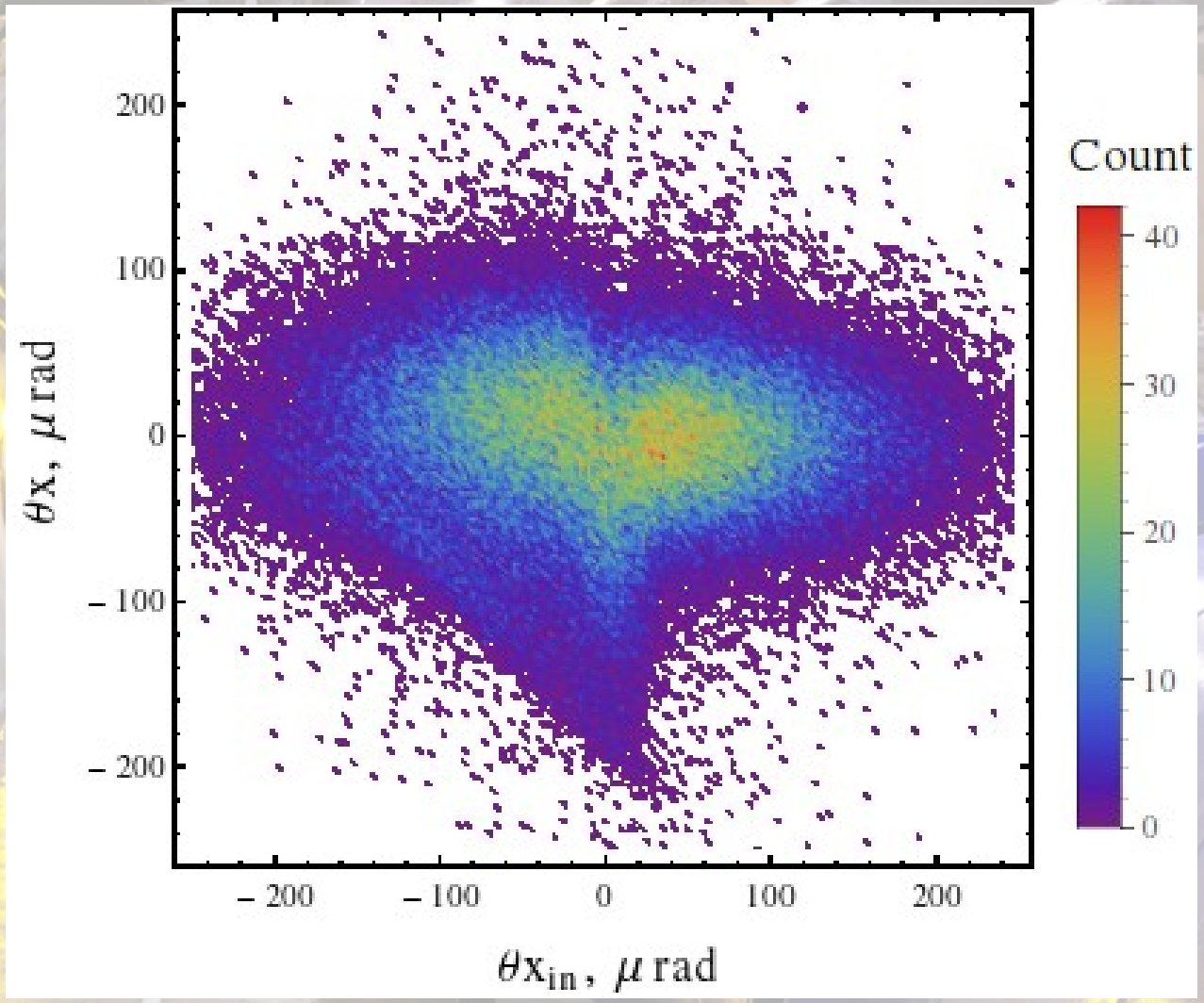
***L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)**
****V.N. Baier, V.M. Katkov, V.M. Strakhovenko World Scientific, Singapore (1998)**
*****V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903**
******A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB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

Tasks for 2021

Milestones 2021:

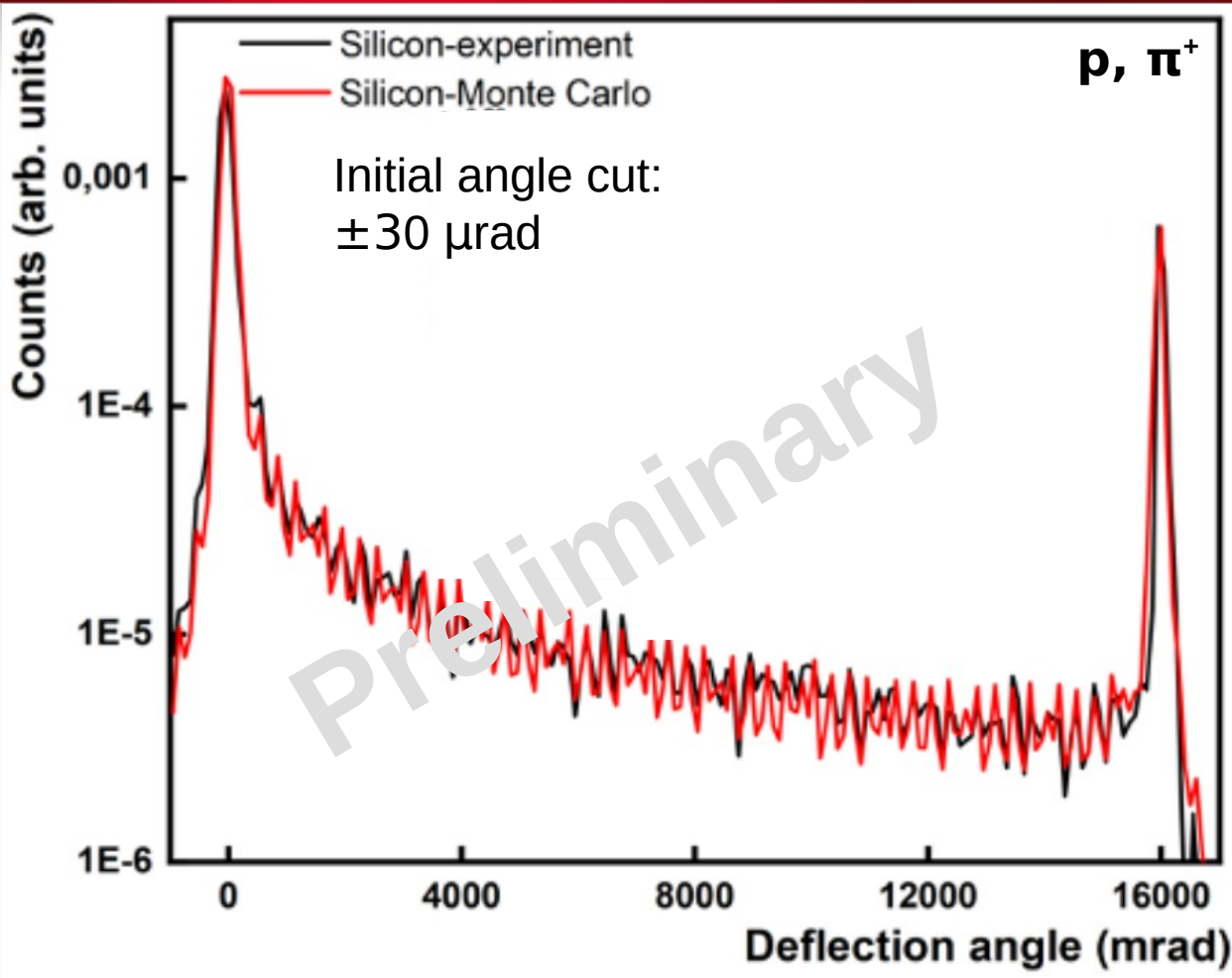
- Inclusion of the **Baier-Katkov method** for computation of radiation in oriented crystals into Geant4 and comparison with **experimental data**.

- Geant4 **channeling** and **channeling radiation model improvements**.



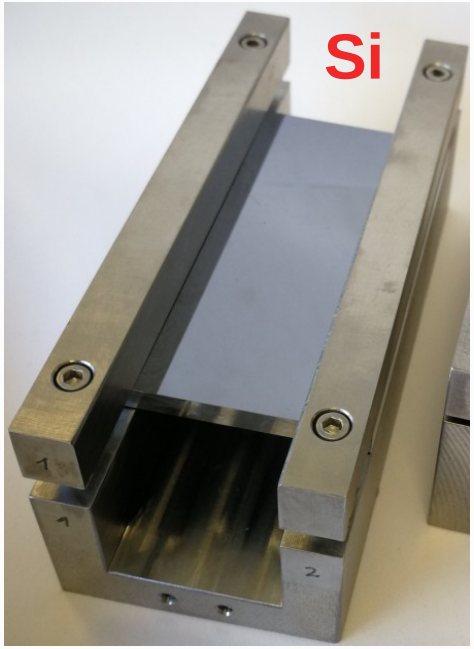
Thank you for attention!

Geant4 simulation of SELDOM experiment at CERN SPS H8 on 180 GeV protons and pions channeling in 8 cm long Si bent crystal



Si

- length: **8 cm**
- bending angle: **16 mrad**
- planes: **(111)**



Simulation of complete setup
Not only the crystal