Physics III

Geant4 Tutorial: version 10.0.p01

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Physics III – Low Energy Processes

Geant4 includes processes at low energy scales to ensure "complete" coverage of interactions with materials:

- Particle decays
- Optical photon interactions

Support for solid-state (crystal) interactions are in development

- Phonon propagation
- Electron/hole propagation
- Crystal channeling

Particle Decays

- Decay can happen in-flight or at rest
  - Derived from G4VRestDiscreteProcess

- Applies to all unstable, long-lived particles
  - Not used for radioisotopes (G4RadioactiveDecay)

- Different from other physical processes
  - mean free path for most processes: $\lambda = N \rho \sigma / A$
  - for decay in flight: $\lambda = \gamma \beta c \tau$
  - for decay at rest: "λ" $= \tau$

- Same process used for all eligible particles
  - retrieves branching ratios and decay modes from decay table stored for each particle type

Particle Decay Models Available

Phase space

- 2-body: $\pi^0 \rightarrow \gamma\ \gamma$
- 3-body: $K^0_L \rightarrow \pi^0\ \pi^+\ \pi^-$
- many body

Dalitz

- $P0 \rightarrow \gamma\ l+\ l-$

Muon and tau decay

- V – A, no radiative corrections, mono-energetic neutrinos

Semi-leptonic K decay

- $K \rightarrow \pi\ l\ \nu$

Defining Decay Channels

Geant4 provides decay modes for long-lived particles

- user can re-define decay channels if necessary

But decay modes for short-lived (e.g. heavy flavor) particles not provided by Geant4

- user must "pre-assign" to particle:
  - proper lifetime
  - decay modes
  - decay products
- process can invoke decay handler from external generator
  - must use G4ExtDecayer interface

Take care the pre-assigned decays from generators do not overlap with those defined by Geant4 (e.g., K^0_S , τ)

Specialized Particle Decays

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G4DecayWithSpin

- produces Michel electron/positron spectrum with 1st order radiative corrections
- initial muon spin is required
- propagates spin in magnetic field (precession) over remainder of muon lifetime

G4UnknownDecay

- only for not yet discovered particles (Higgs, SUSY, etc.)
- discrete process – only in-flight decays allowed
- pre-assigned decay channels must be supplied by user or generator

Optical Processes

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Propagation of optical photons and their interaction with materials is treated separately from regular electromagnetic processes. Why?

- Wavelengths are much larger than atomic spacing
- Treated (partially) as waves; no smooth transition to gammas
- Energy/momentum not generally conserved in G4 optics

Optical photons produced directly by three processes

- `G4Cerenkov`
- `G4Scintillation`
- `G4TransitionRadiation`

Optical Photon Transport

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- Rayleigh scattering
- Refraction and reflection at boundaries
- Bulk absorption
- Wavelength shifting

Geant4 keeps track of polarization

- but not overall phase, so no interference

Optical properties attached to G4Material (by user code)

- reflectivity, transmission efficiency, dielectric constants, surface properties, including binned wavelength/energy dependences

Photon spectrum attached to G4Material (by user code)

- scintillation yield, time structure (fast, slow components)

Optical Boundary Processes

G4OpBoundaryProcess

- refraction
- reflection

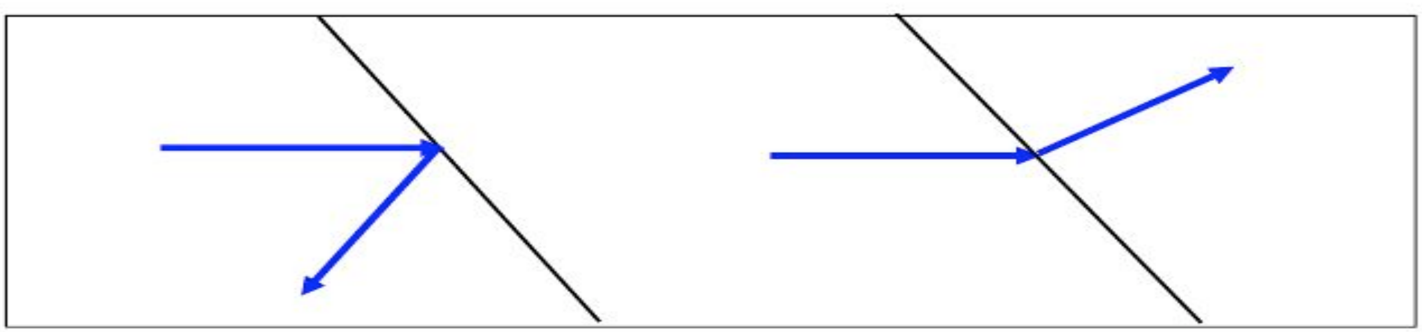
User must supply surface properties using G4OpticalSurfaceModel

Boundary properties

- dielectric-dielectric
- dielectric-metal
- dielectric-black material

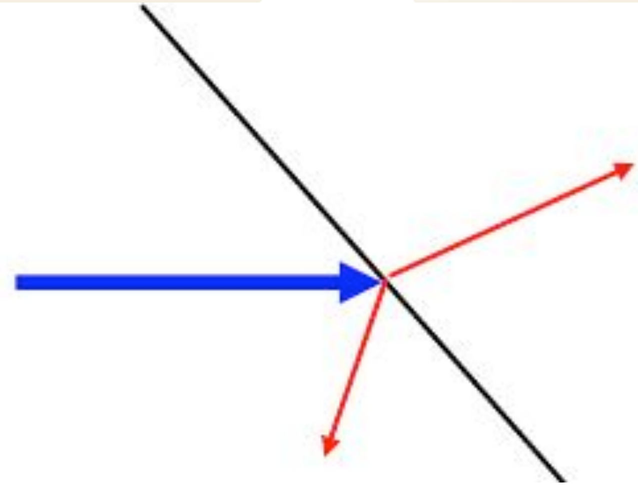
Surface properties

- polished
- ground
- front- or back-painted, …

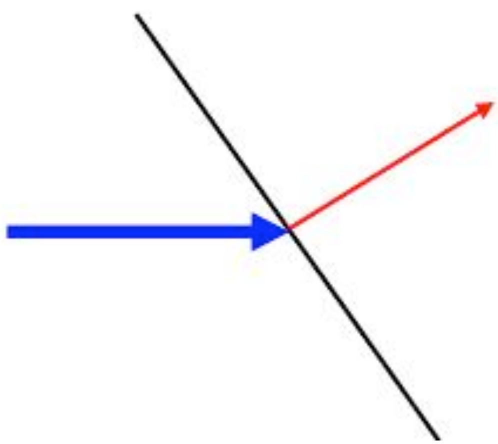


Reflection or Refraction?

Geant4 events reflect “particle-like” behaviour – no “splitting” of tracks



Each event has either a reflected or refracted photon, chosen randomly from user-input efficiencies



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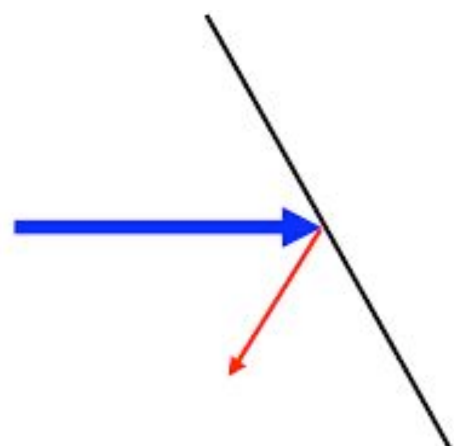


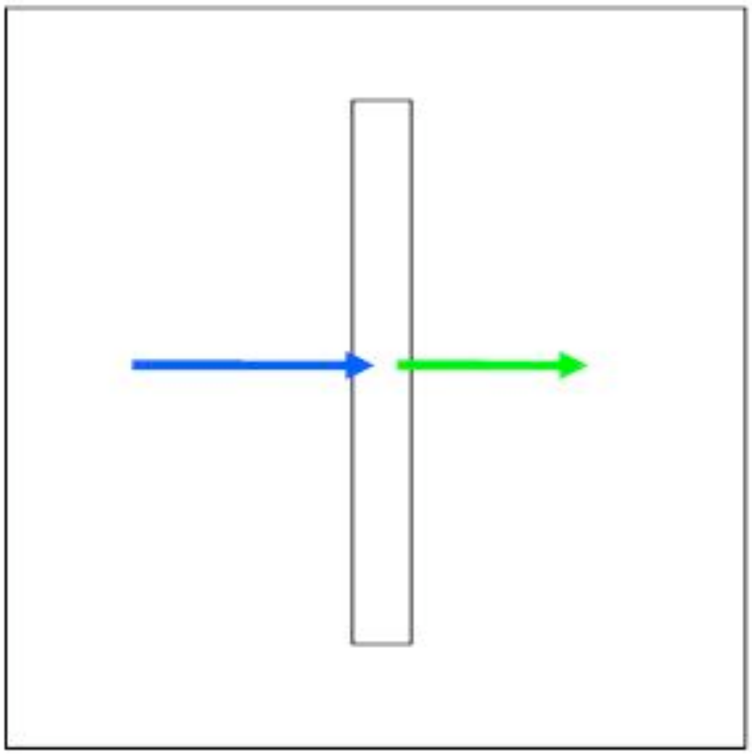
Optical Processes: Wavelength Shifting

Handled by G4OpWLS

- initial photon is killed, one with new wavelength is created
- builds its own physics table for mean free path

User must supply:

- absorption length as function of photon energy
- emission spectra parameters as function of energy
- time delay between absorption and re-emission



Optical Bulk Processes

`G4OpAbsorption`

- uses photon attenuation length from material properties to get mean free path
- photon is simply killed after a selected path length

`G4OpRayleigh`

- elastic scattering including polarization of initial and final photons
- builds its own physics table (for mean free path) using G4MaterialTable
- may only be used for optical photons (a different process provided for gammas)

Solid-State Physics Developments

A small group of Geant4 collaborators has been developing tools to support some solid-state physics processes

- Phonon propagation and scattering
- Electron/hole production and drift
- Crystal channelling of charged particles

A common feature for these processes is the need to define a "lattice structure" (numerical parameters) for a volume.

These tools are not ready for release yet; this presentation is meant to be informational and perhaps inspirational.

Lattices

Geant4 treats materials as uniform, amorphous collections of atoms. Steps may be of any length, in any direction, and some atom will be at the destination for interaction.

We have introduced `G4LatticeLogical` as a container to carry around parameters and lookup tables for use with the phonon handling processes.

There is a singleton `G4LatticeManager` which keeps track of lattices, and how they're associated with materials and volumes.

Phonons in Geant4

See `examples/extended/exoticphysics/phonons`

The processes developed so far support acoustic phonons, which are relevant for low-temperature (tens of mK) detectors.

Three polarization states are recognized

- Longitudinal (`G4PhononLong`)
- Transverse “slow speed” (`G4PhononTransFast`)
- Transverse “fast speed” (`G4PhononTransSlow`)

Currently no production process. Use `G4ParticleGun` to insert a phonon, which then propagates through volume.

Phonon Propagation

Phonons are assigned a wave vector $\vec{k}$ for their phase velocity.

- Group (propagation) velocity $\vec{v}_g$ is different due to the lattice anisotropies.
- `G4LatticeLogical` has a lookup table to convert between the two.

Phonon Interactions

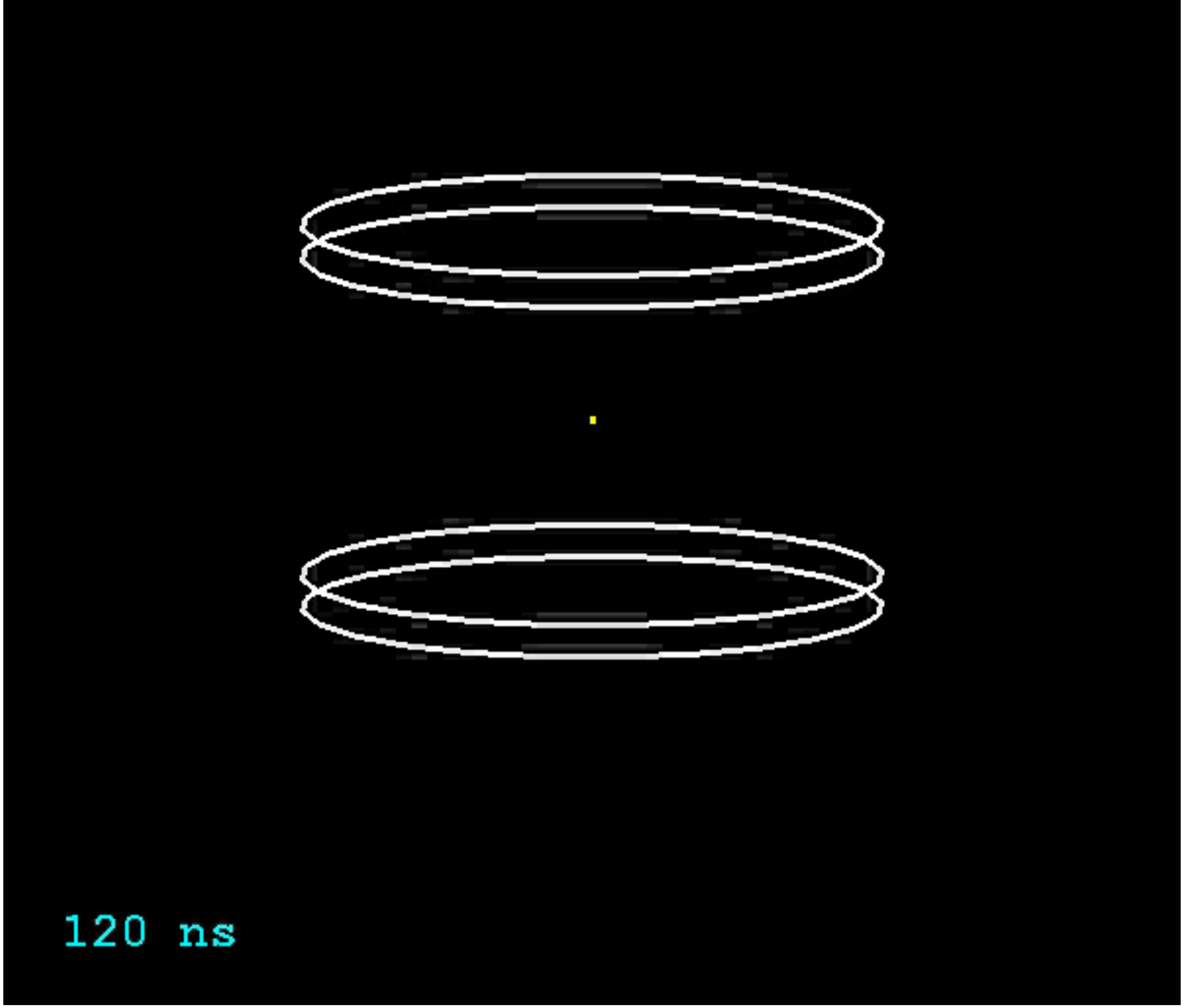
Three phonon processes are currently written, though may not be fully functional.

`G4PhononScattering` Treats scattering of phonons off of isotopic impurities or lattice defects, changing direction and randomizing the polarization state (mode mixing)

`G4PhononDownconversion` Longitudinal phonons split in two, either L ➔ L' T or L ➔ T T

`G4PhononReflection` Should handle reflection of phonons of volume boundaries; currently just kills.

Single Phonon Propagation



Phonon Caustics In Germanium

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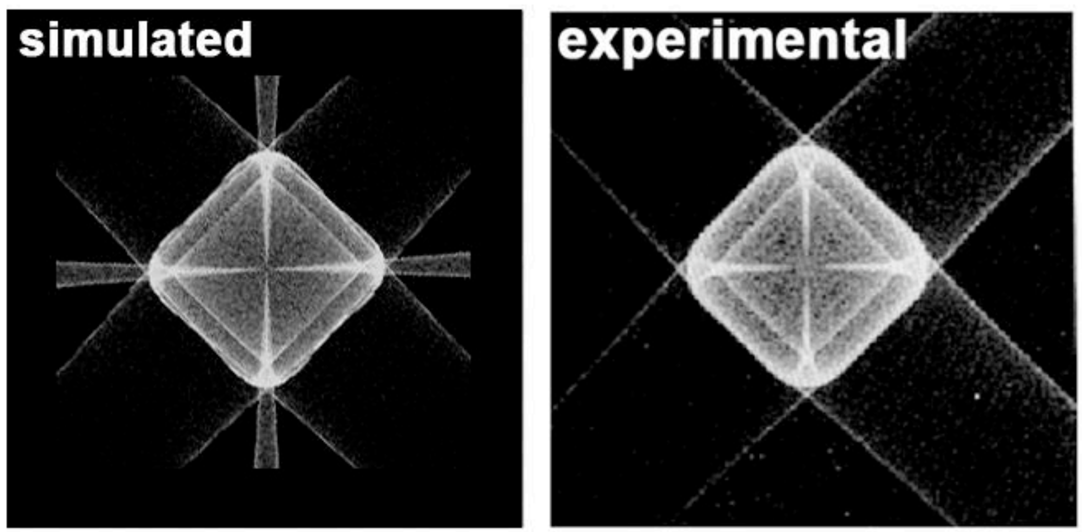
Generate phonons at the center of one face of a germanium crystal, and measuring the distribution of phonons on the opposite face. Focusing produces a pattern of *caustics*.



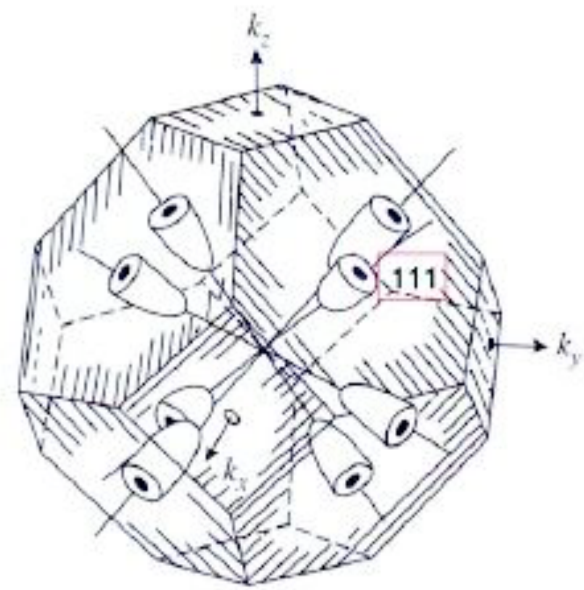
Caustics in Ge collected by `phonons` example

Caustics in Ge observed by Northrop and Wolfe PRL 19, 1424 (1979)

Electron/hole Transport

Energy-momentum relation (band structure) in Ge is highly anisotropic

- Eight equivalent minima (right)
- Electron develops a mass tensor
- Mass tensor diagonalizes in coordinate system aligned with symmetry axis
- Two components, $m_{||}$ and $m_{\perp}$, remain



L valleys of Ge

Electrons travel along, scatter between valleys (minima)

Holes drift along electric field lines

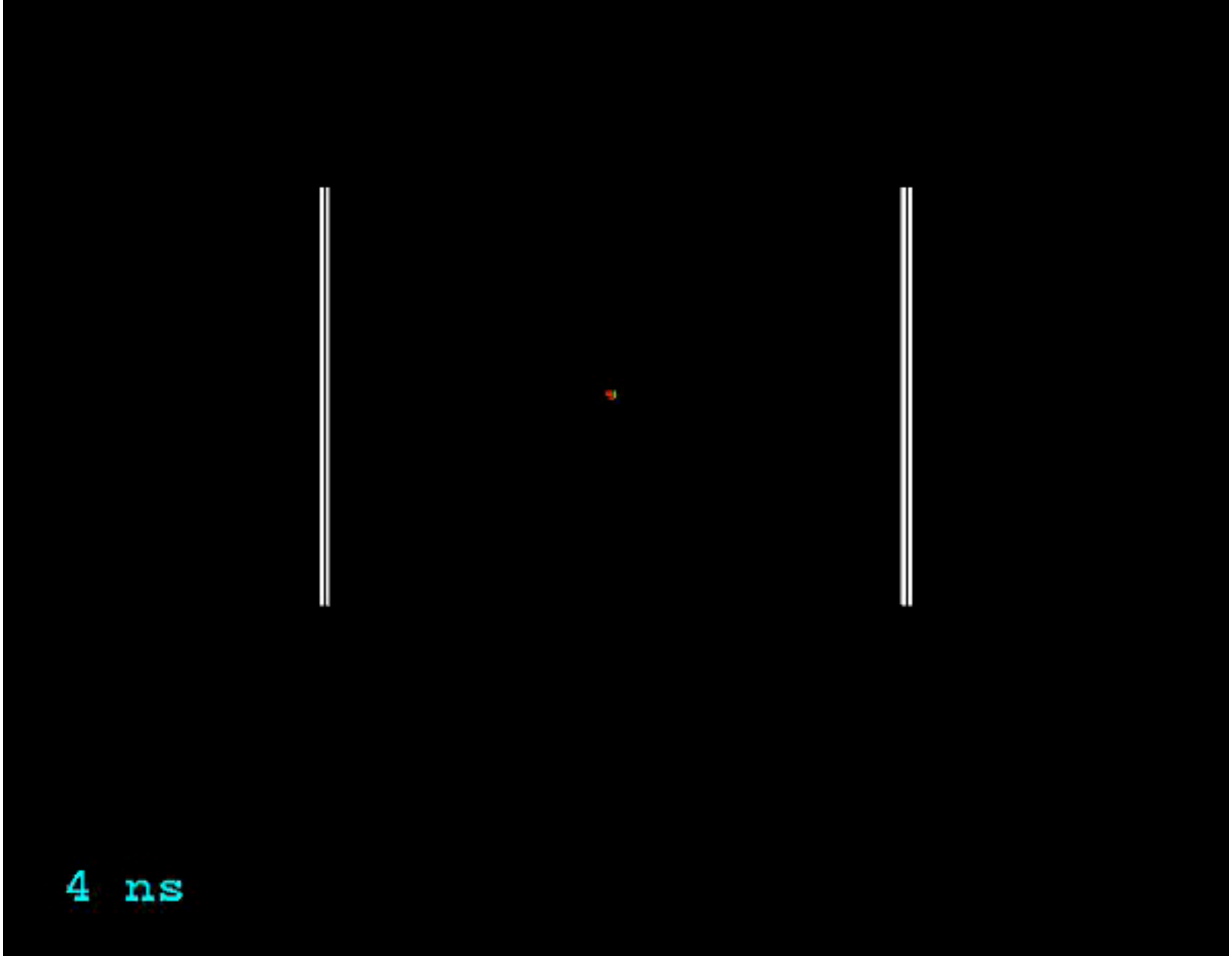
Luke Phonon Production

Charged particles (including holes) drifting through crystal can generate low-energy phonons along their trajectories.

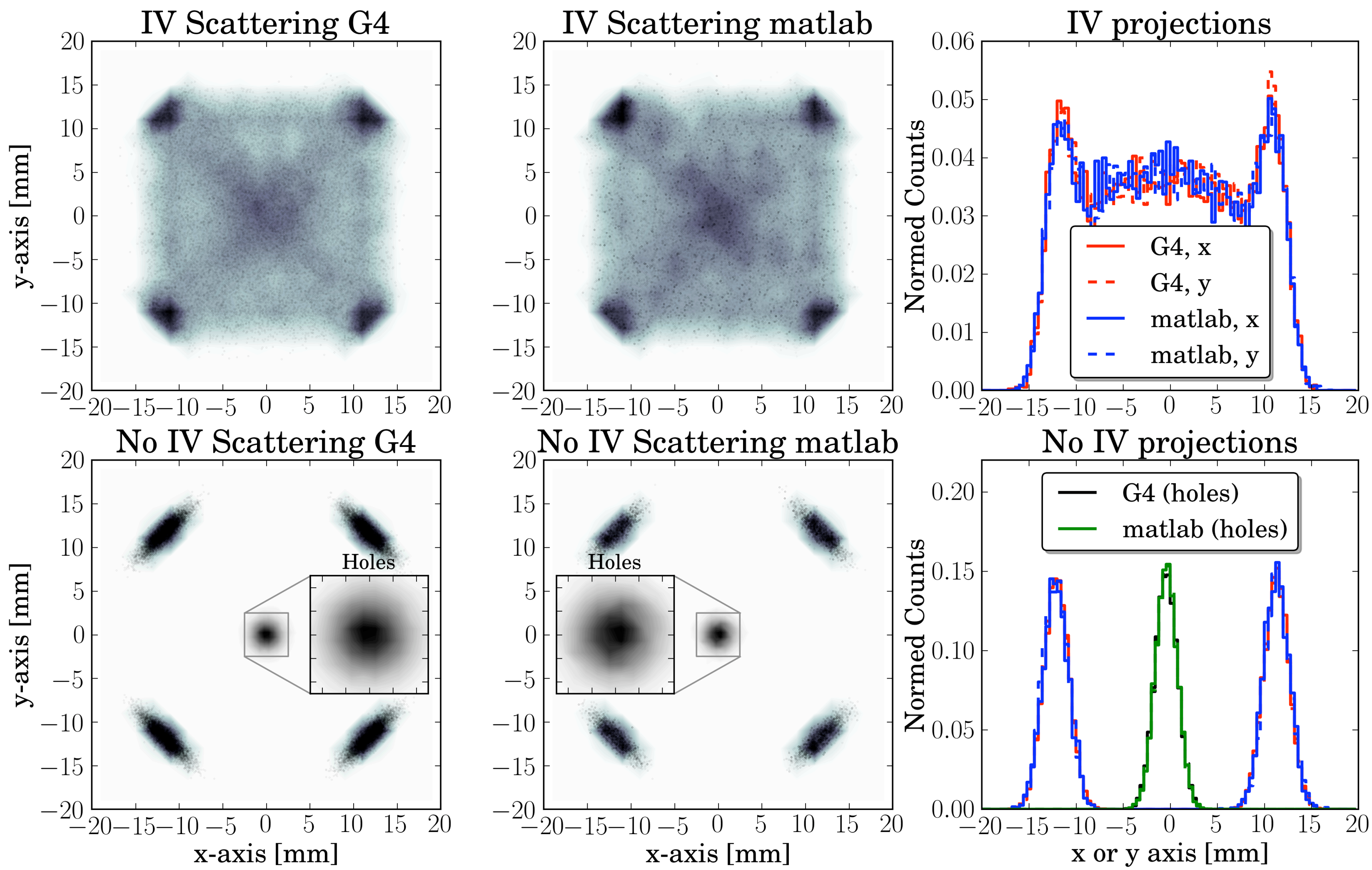
“Non-ionizing energy loss” can be calculated and stored by a few standard processes.

Code in development produces phonons which propagate as described previously.

Electron/Hole Transport



Intervalley Scattering



Comparison of G4 and Matlab simulations of CDMS crystals, R. Agnese, UFL

Crystal Collimation or Channeling

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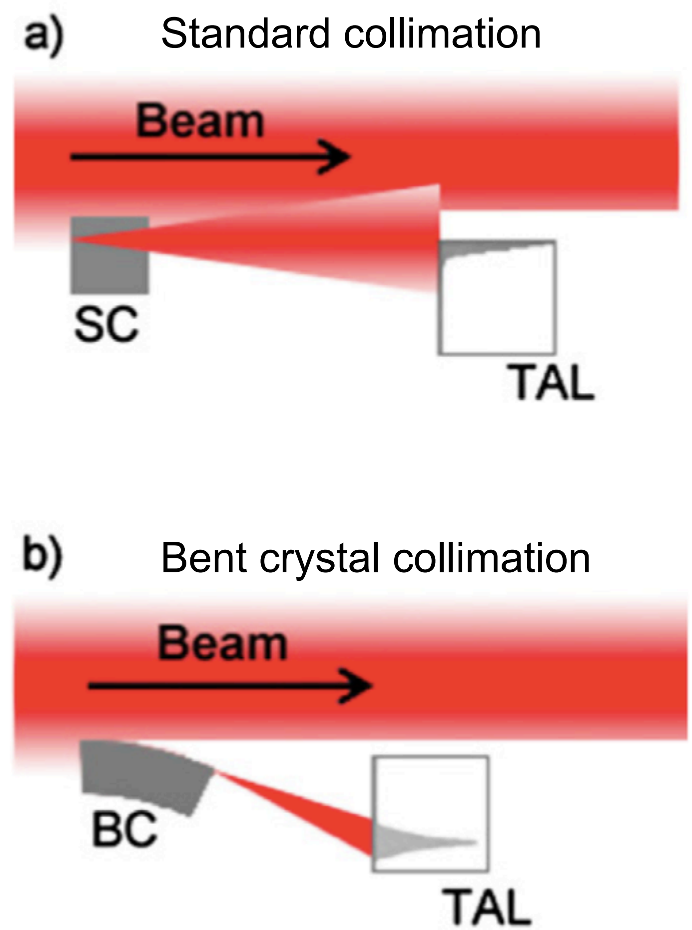
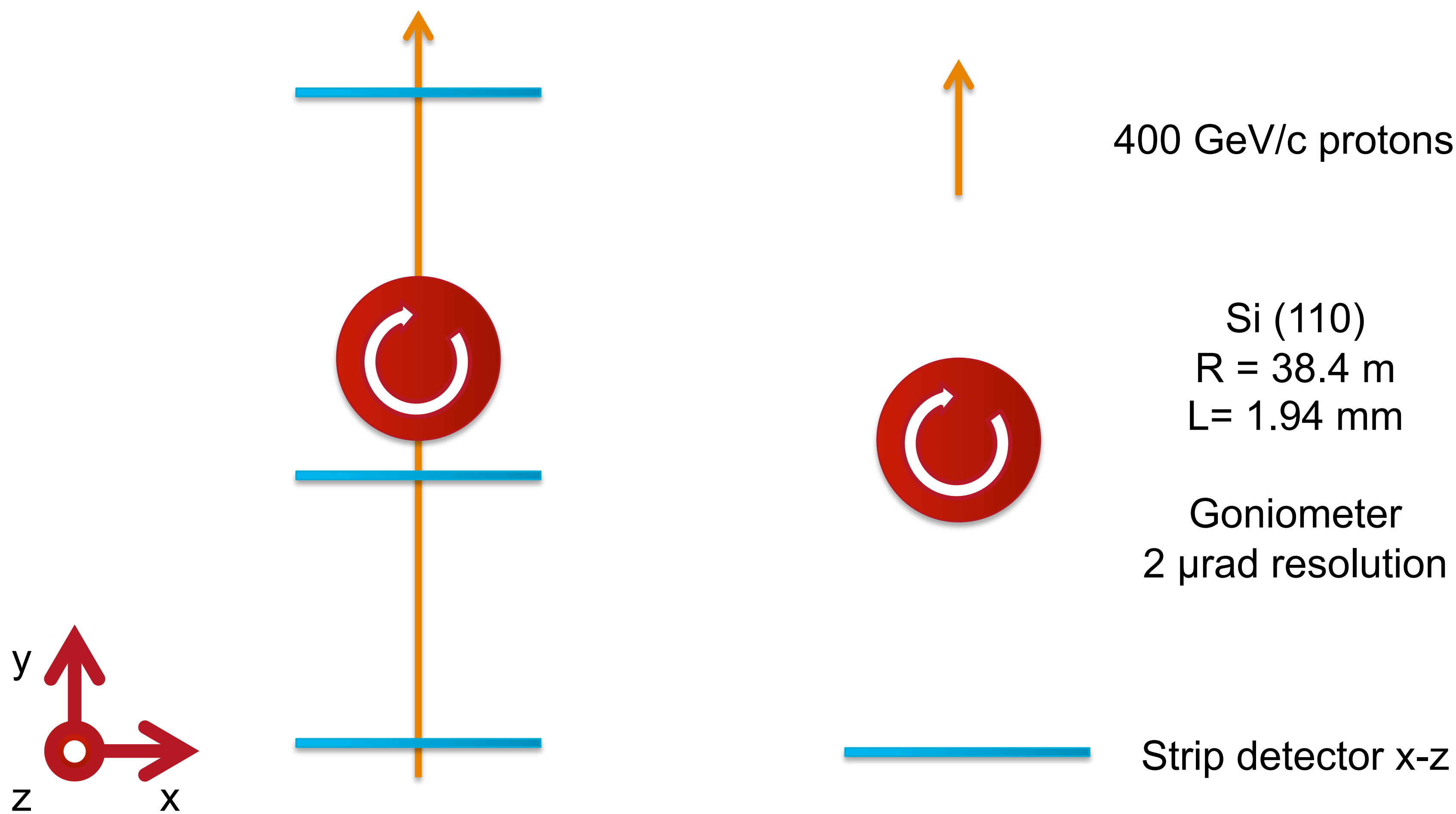
Developed by Enrico Bagli, U. Ferrara

- Crystal can be used as a primary collimator to deflect particles of the halo toward a secondary collimator.
- Main advantage is the possibility to deflect the beam out and reduce the beam losses.



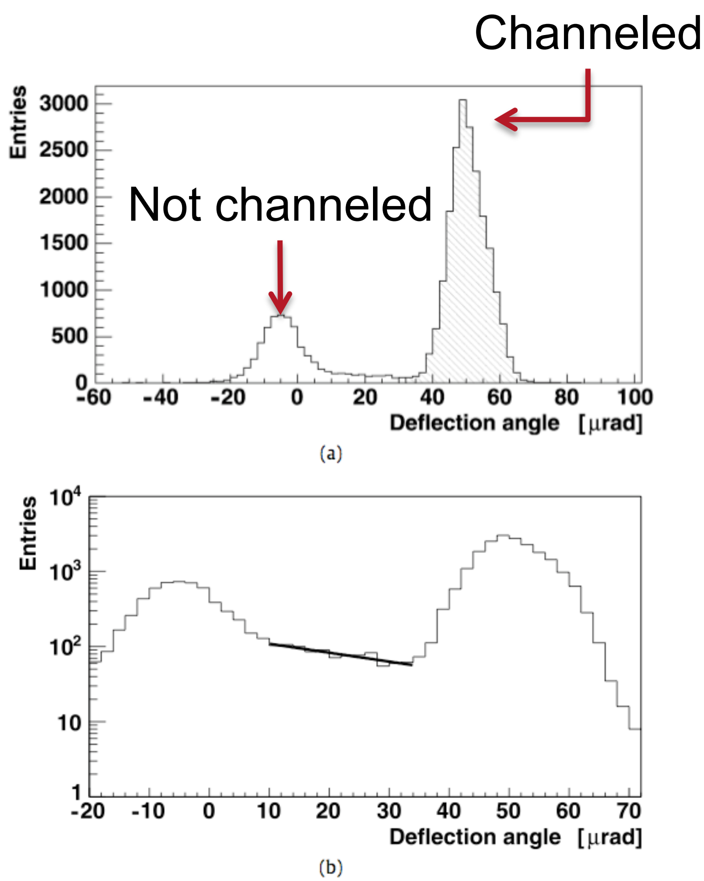
400 GeV/c proton beam on Si

W. Scandale et al., Phys. Lett. B 680 (2009) 129



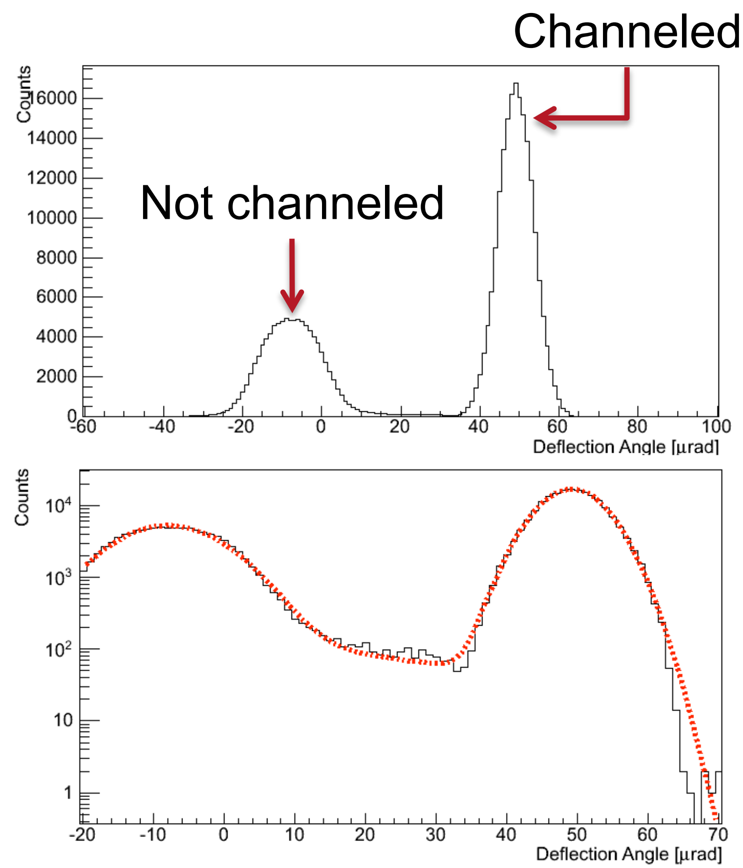
Nuclear Dechannelling Length

W. Scandale et al., Phys. Lett. B 680 (2009) 129



L_n = (1.53 ± 0.35 ± 0.20) mm

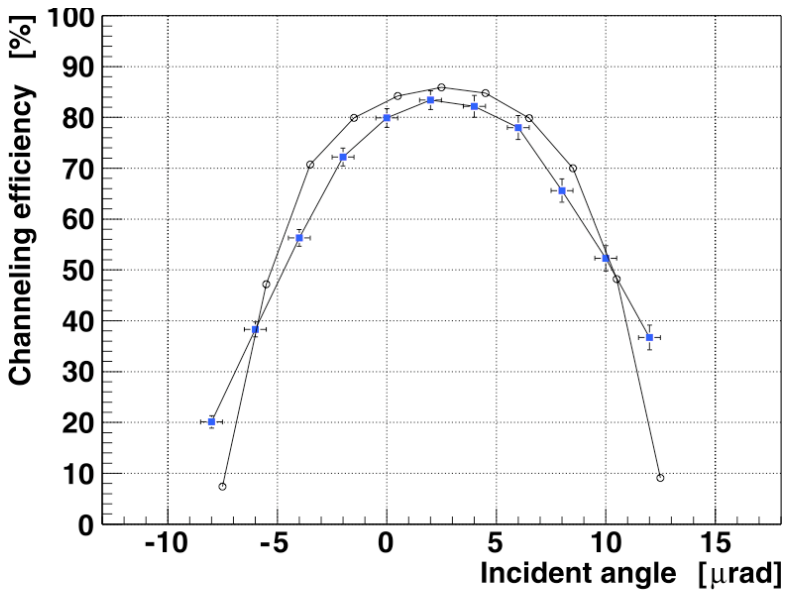
Geant4 Channeling



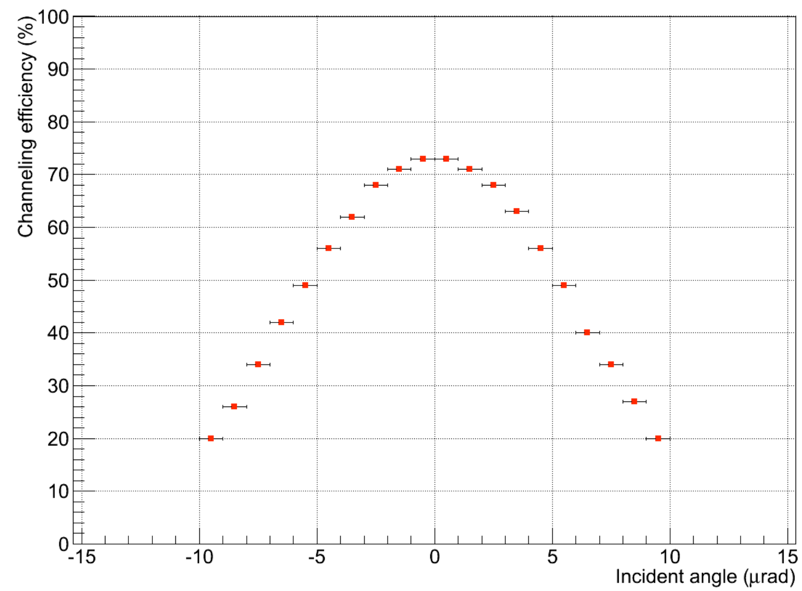
L_n = (1.31 ± 0.05) mm

Channeling Efficiency vs. Angle

W. Scandale et al., Phys. Lett. B 680 (2009) 129



Geant4 Channeling



- Experimental measurements (a)
- UA9 collaboration simulations (a)
- Geant4 Simulations (b)