Simulations of Silicon Radiation Detectors for HEP Experiments

Benjamin Nachman

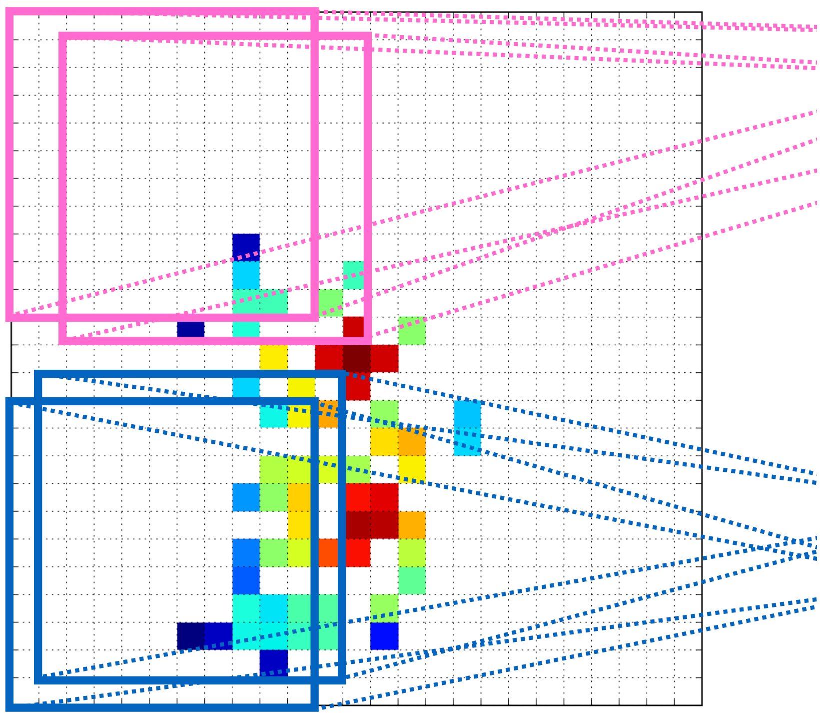
Lawrence Berkeley National Laboratory

bpnachman.com

bpnachman@lbl.gov

@bpnachman

bnachman



Berkeley Lab

Snowmass IF3

July 19, 2022

Simulations of Silicon Radiation Detectors for High Energy Physics Experiments

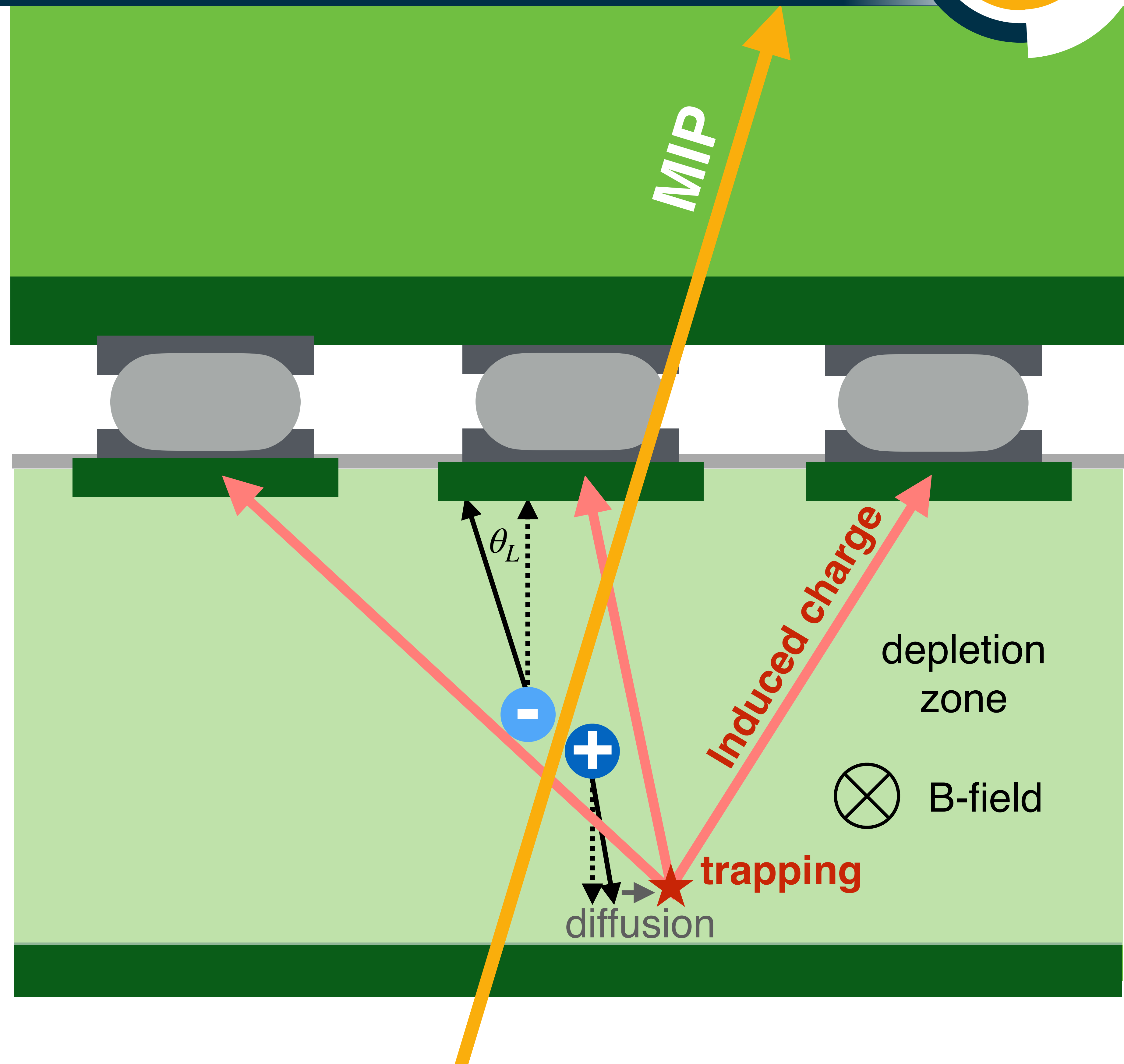
B. Nachman (ed.),[1] T. Peltola (ed.),[2] P. Asenov,[6,7] M. Bomben,[8] R. Lipton,[5] F. Moscatelli,[6,7] E. A. Narayanan,[9] F. R. Palomo,[3] D. Passeri,[6,11] S. Seidel,[9] X. Shi,[12] J. Sonneveld[4]

[1] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2] *Department of Physics and Astronomy, Texas Tech University, Lubbock, TX 79409, USA*
[3] *Electronic Engineering Dept., School of Engineering, University of Sevilla, 41092 Spain*
[4] *Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands*
[5] *Fermilab, P.O. Box 500, Batavia Il USA*
[6] *INFN Sezione di Perugia, Perugia, Italy*
[7] *Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*
[8] *Université de Paris & Laboratoire Astroparticule et Cosmologie, Paris, France*
[9] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA*
[11] *Engineering Department, University of Perugia, Perugia, Italy*
[12] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

E-mail: bpnachman@lbl.gov, timo.peltola@ttu.edu

Abstract: Silicon radiation detectors are an integral component of current and planned collider experiments in high energy physics. Simulations of these detectors are essential for deciding operational configurations, for performing precise data analysis, and for developing future detectors. In this white paper, we briefly review the existing tools and discuss challenges for the future that will require research and development to be able to cope with the foreseen extreme radiation environments of the High Luminosity runs of the Large Hadron Collider and future hadron colliders like FCC-hh and SPPC.

Overview



MIP
θ_L
Induced charge
depletion zone
B-field
trapping
diffusion

Overview

Pythia+

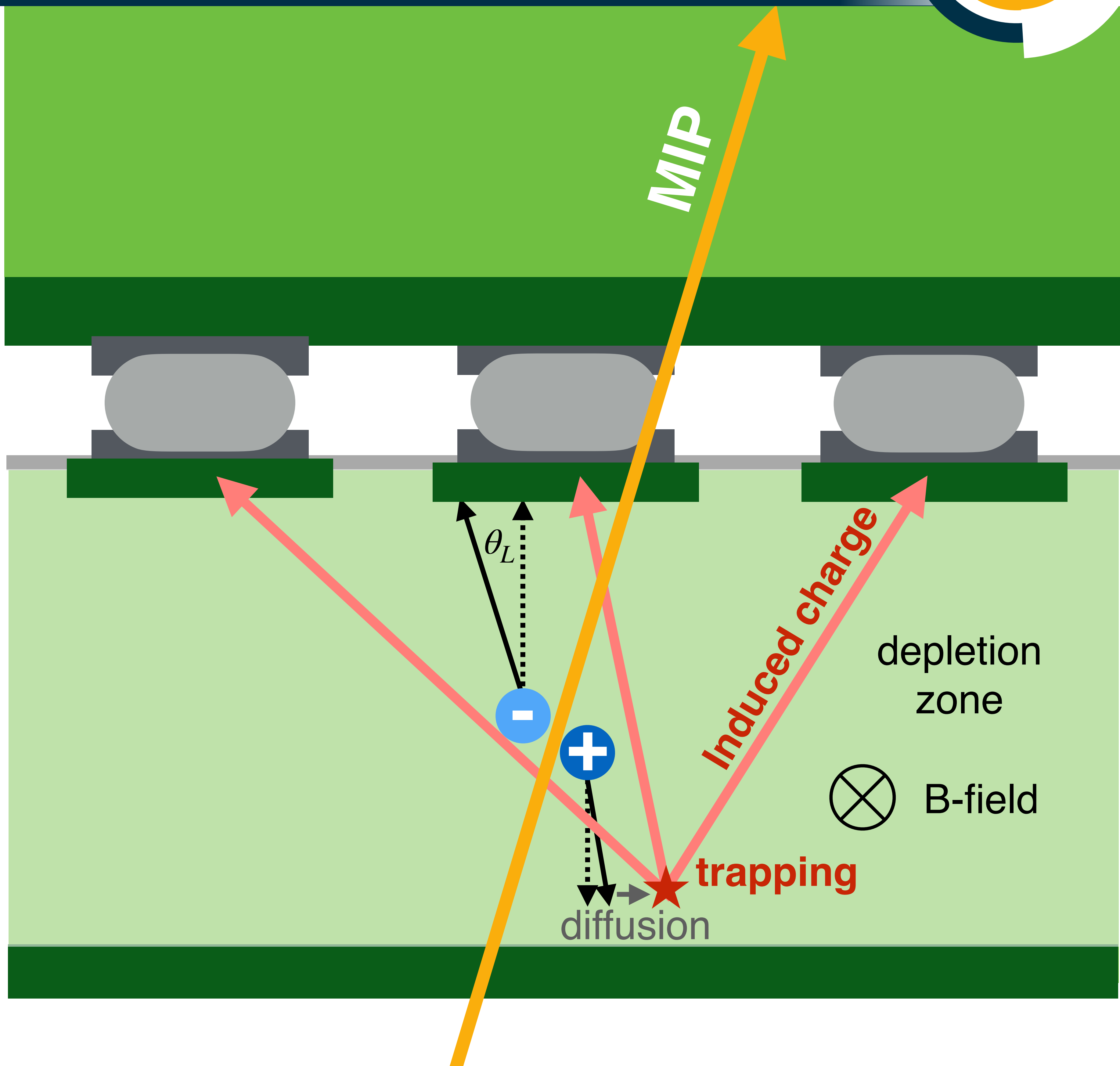
Geant4/FLUKA for fluence

TCAD for E-field

Hamburg Model for annealing

Modified drift-diffusion

Detector-specific + generic (e.g. Allpix[2])



Overview

Pythia+
Geant4/FLUKA for fluence

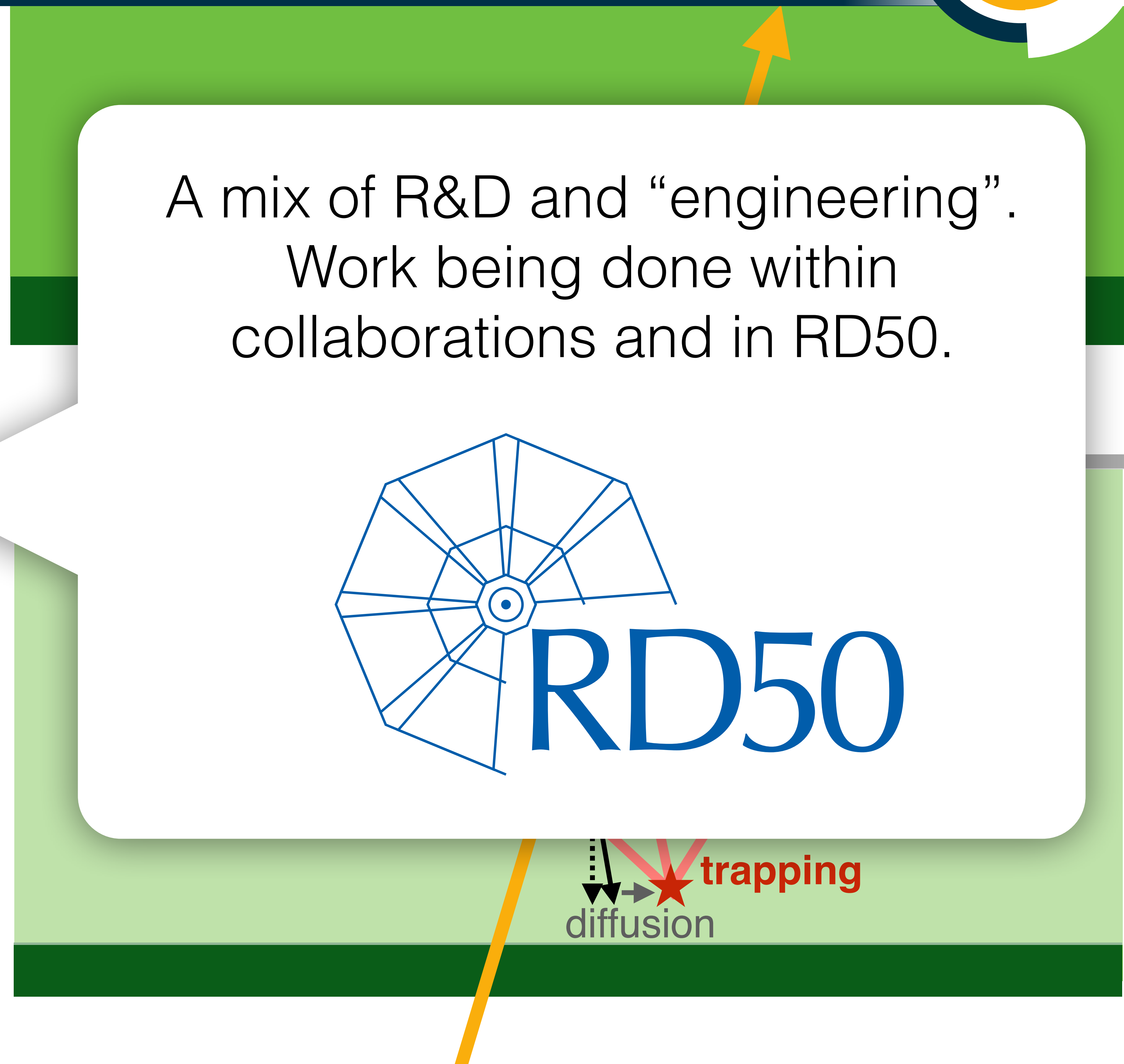
TCAD for E-field

Hamburg Model for annealing

Modified drift-diffusion

Detector-specific + generic (e.g. Allpix²)

A mix of R&D and "engineering". Work being done within collaborations and in RD50.



BNL, Brown, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse

neering”.
ithin
RD50.

E-field

Hamburg Model for annealing

Modified drift-diffusion

Detector-specific + generic (e.g. Allpix^2)

Flux Simulation

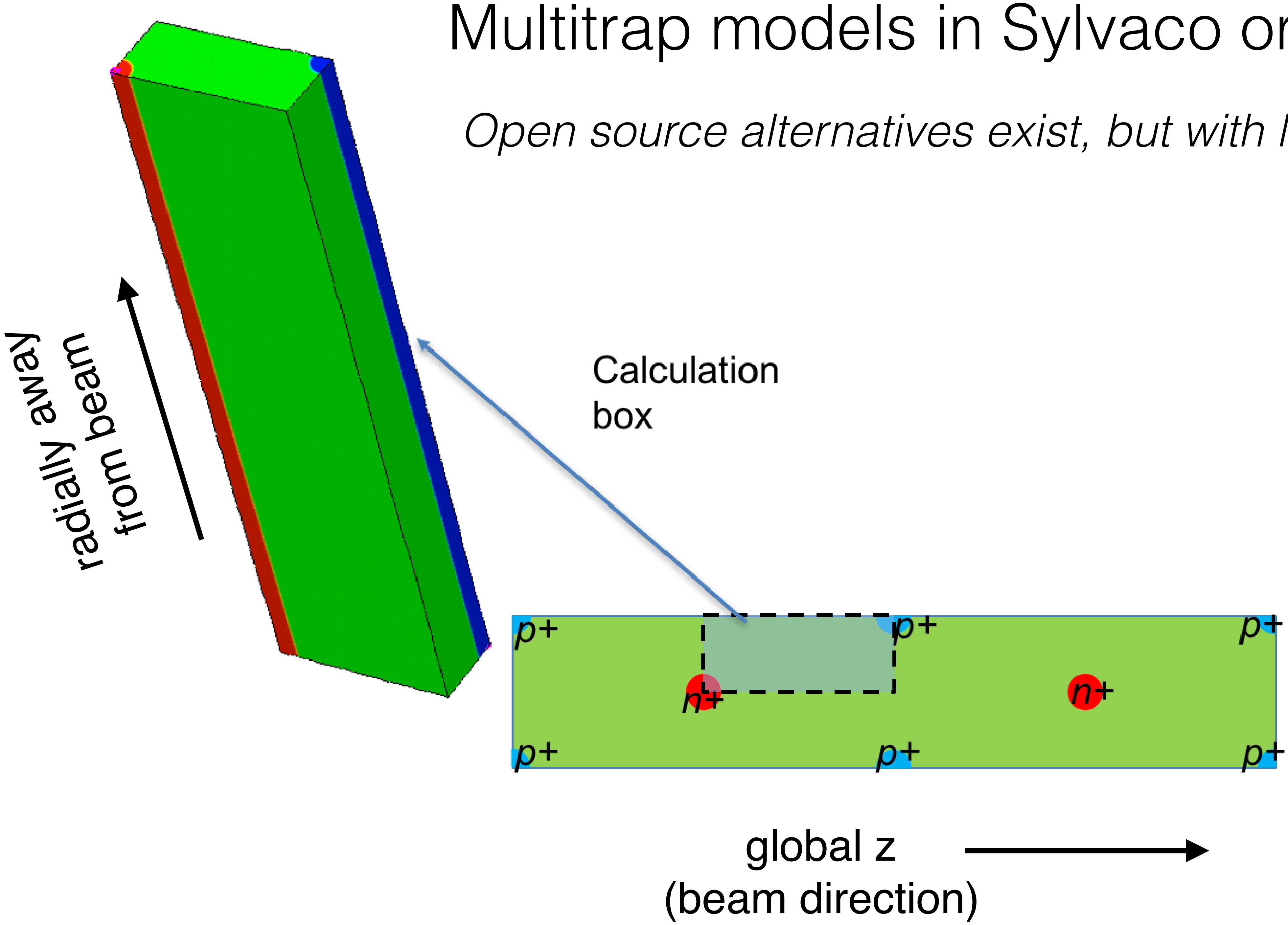
Physics modeling	Particle multiplicity, energy, composition	**Caution:** *Tuned to data, but still significant uncertainty (PDFs, MEs, frag., etc.)*
	↓ *Pythia*	
Transport model	Geometry and Particle transport	
	↓ *FLUKA or Geant4*	**Caution:**
Damage factors	Non-ionizing damage	*Largely unknown due in part to the availability of monochromatic beams and uncertainty in converting to 1 MeV n_{eq}*
	↓ *RD50 damage factors*	(more on this later)
	Predicted Φ	

(this is only for NIEL, but similar story for SEUs and ionizing energy loss)

Device Properties (no annealing)

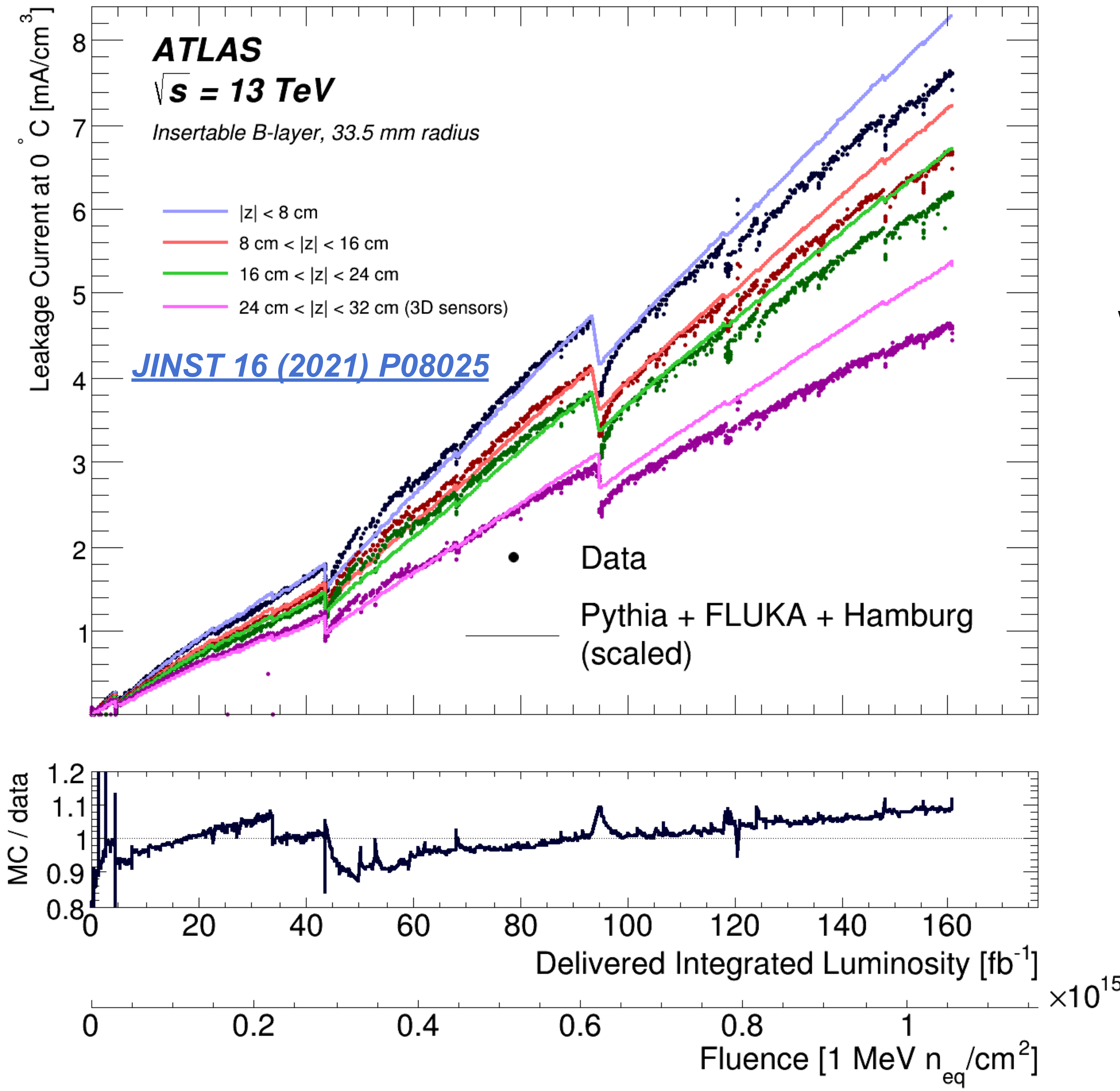
Multitrap models in Sylvaco or Synopsis

Open source alternatives exist, but with less precision



[JINST 16 (2021) P08025](#)

Device Properties (with annealing)



Simplified model with multi-trap states (no relation to the previous page) - different models for leakage current and depletion voltage

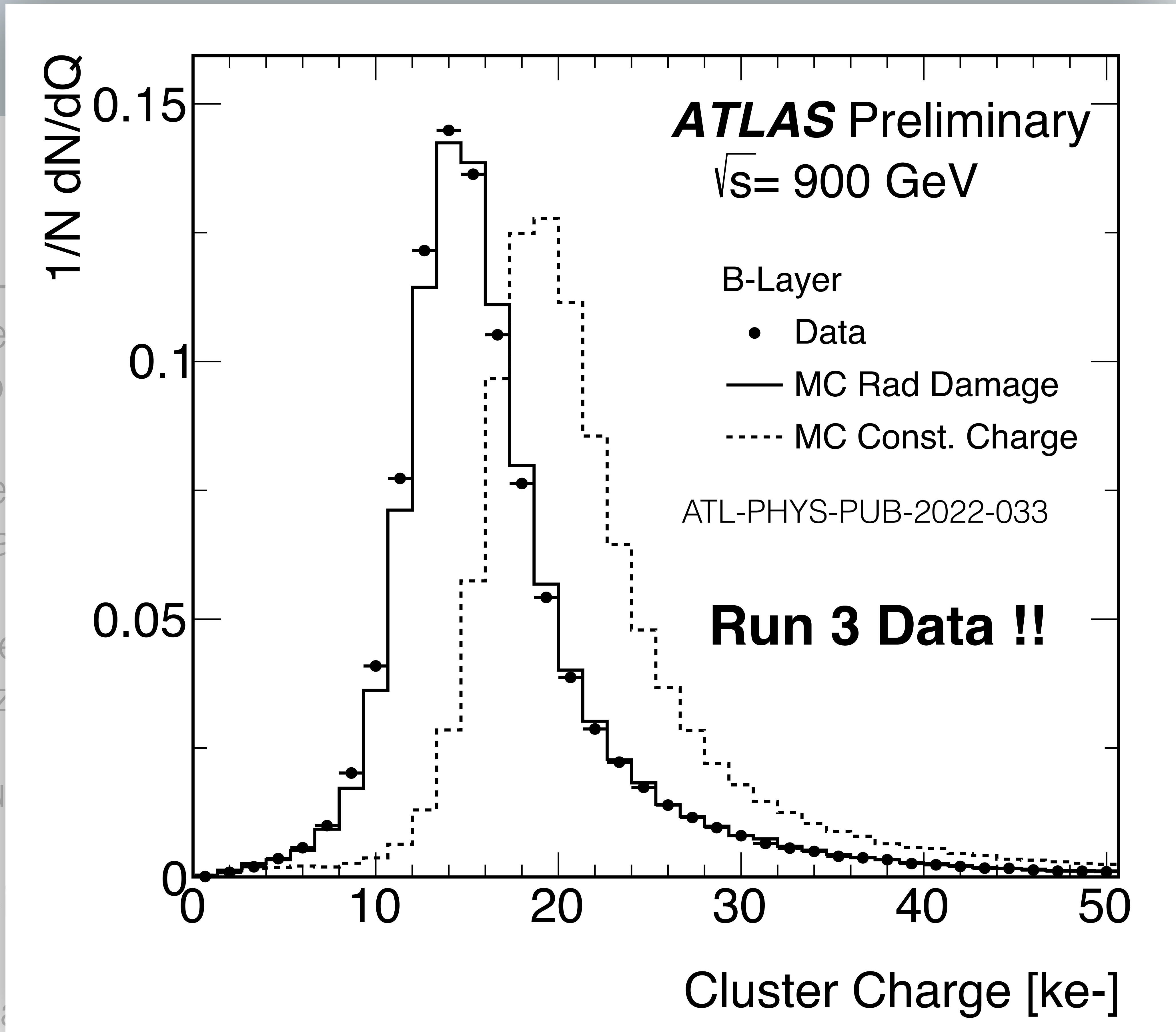
Full Detector Systems

	ATLAS EXPERIMENT	CMS	LHCb
Energy Deposition	Bichsel Model + G4 (δ-rays)	Geant4	Geant4
Energy spreading	from Bichsel + chunking	from Geant4	Uniform (space) + uniform/Gauss (E)
E-field/ Lorentz angle	uniform	uniform	N/A
Diffusion	Einstein	Einstein	tuned
Noise	capacitive coupling + noise	not discussed	capacitive coupling + noise
Radiation damage	**none**	**none**	**none**

Full Detector Systems + Rad Damage

	ATLAS EXPERIMENT	CMS	LHCb
Energy Deposition	Bichsel Model + G4 (δ-rays)	Pixelav (applied as correction to G4)	Geant4
Energy spreading	from Bichsel + chunking	from Bichsel + chunking	Uniform (space) + uniform/Gauss (E)
E-field/ Lorentz angle	TCAD (Chiochia et al.)	TCAD (tuned to data)	N/A
Diffusion	Einstein	Einstein	tuned
Noise	capacitive coupling + noise	not discussed	capacitive coupling + noise
Radiation damage	**trapping + charge induction**	**trapping + charge induction**	**charge & 'diffusion' corrections**

Full



Ene
Depo

nt4

Ene
sprea

(space) +
Gauss (E)

E-fie
Lorentz

/A

Diffu

ned

No

citive
g + noise

Radi
damage | **charge induction** | **charge induction** | **'diffusion' corrections**

Challenges and Needs

- Proprietary Software (TCAD)
- Computational requirements for TCAD
- TCAD Uncertainties?
- TCAD + Annealing?
- Damage Model Uncertainty?
- New Effects / Devices for future colliders?

Executive Summary

There are currently a variety of tools available for simulating the properties of silicon sensors before and after irradiation. These tools include finite element methods for device properties, dedicated annealing models, and testbeam/full detector system models. No one model can describe all of the necessary physics. Most of these models are either fully or partially developed by HEP scientists and while there are many open-source tools, the most precise device property simulations rely on expensive, proprietary software.

The development of these simulations happens inside existing experimental collaborations and within the RD50 Collaboration at CERN. RD50 is essential for model research and development and provides an important forum for inter-collaboration exchange.

While existing approaches are able to describe many aspects of signal formation in silicon devices, even after irradiation and annealing, there is significant research and development (R&D) required to improve the accuracy and precision of these models and to be able to handle new devices (e.g. for timing) and the extreme fluences of future colliders. The US particle physics community can play a key role in this R&D program, but it will require resources for training, software, testbeam, and personnel.

For example, there is a great need for (1) a unified microscopic model of sensor charge collection, radiation damage, and annealing (no model can currently do all three), (2) radiation damage models (for leakage current, depletion voltage, charge collection) with uncertainties (and a database of such models), and (3) a measurement program to determine damage factors and uncertainties for particle types and energies relevant for current and future colliders.

Executive Summary

There are currently a variety of tools available for simulating the properties of silicon sensors before and after irradiation. These tools include finite element methods for device properties, dedicated annealing models, and testbeam/full detector system models. No one model can describe all of the necessary physics. Most of these models are either fully or partially developed by HEP scientists and while there are many open-source tools, the most precise device property simulations rely on expensive, proprietary software.

The development of these simulations happens inside existing experimental collaborations and within the RD50 Collaboration at CERN. RD50 is essential for model research and development and provides an important forum for inter-collaboration exchange.

While existing approaches are able to describe many aspects of signal formation in silicon devices, even after irradiation and annealing, there is significant research and development (R&D) required to improve the accuracy and precision of these models and to be able to handle new devices (e.g. for timing) and the extreme fluences of future colliders. The US particle physics community can play a key role in this R&D program, but it will require resources for training, software, testbeam, and personnel.

For example, there is a great need for (1) a unified microscopic model of sensor charge collection, radiation damage, and annealing (no model can currently do all three), (2) radiation damage models (for leakage current, depletion voltage, charge collection) with uncertainties (and a database of such models), and (3) a measurement program to determine damage factors and uncertainties for particle types and energies relevant for current and future colliders.

There are currently a variety of tools available for simulating the properties of silicon sensors before and after irradiation. These tools include finite element methods for device properties, dedicated annealing models, and testbeam/full detector system models. No one model can describe all of the necessary physics. Most of these models are either fully or partially developed by HEP scientists and while there are many open-source tools, the most precise device property simulations rely on expensive, proprietary software.

The development of these simulations happens inside existing experimental collaborations and within the RD50 Collaboration at CERN. RD50 is essential for model research and development and provides an important forum for inter-collaboration exchange.

While existing approaches are able to describe many aspects of signal formation in silicon devices, even after irradiation and annealing, there is significant research and development (R&D) required to improve the accuracy and precision of these models and to be able to handle new devices (e.g. for timing) and the extreme fluences of future colliders. The US particle physics community can play a key role in this R&D program, but it will require resources for training, software, testbeam, and personnel.

For example, there is a great need for (1) a unified microscopic model of sensor charge collection, radiation damage, and annealing (no model can currently do all three), (2) radiation damage models (for leakage current, depletion voltage, charge collection) with uncertainties (and a database of such models), and (3) a measurement program to determine damage factors and uncertainties for particle types and energies relevant for current and future colliders.

Backup