Silicon radiation damage at the LHC experiments

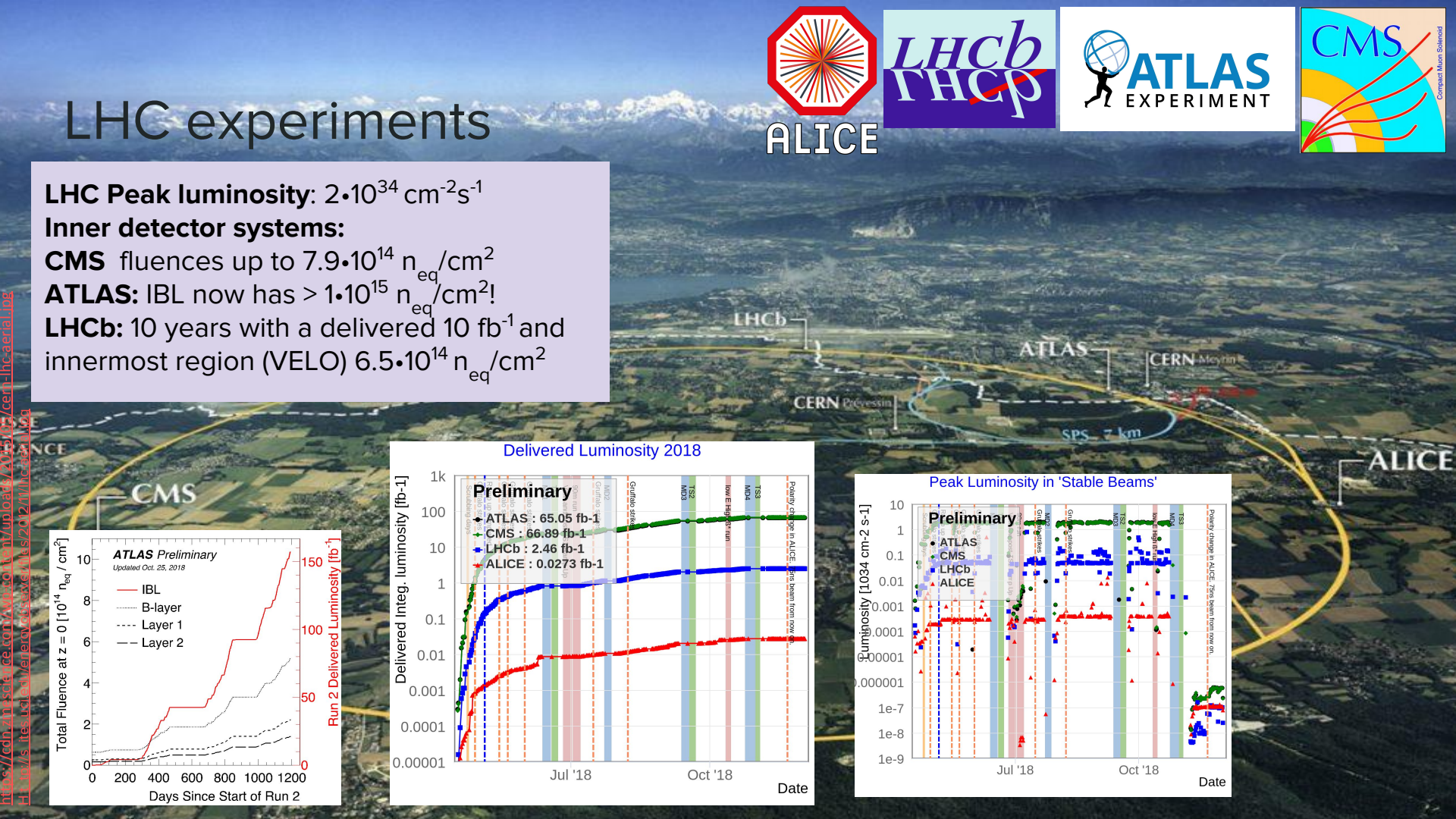
A brief overview

Many thanks to Ben Nachman and Marco Bomben
jory.sonneveld@cern.ch

Photo courtesy of Erik Butz

LHC experiments

LHC Peak luminosity: $2 \cdot 10^{34}$ cm^{-2}s^{-1}
Inner detector systems:
CMS fluences up to $7.9 \cdot 10^{14}$ n_{eq}/cm^2
ATLAS: IBL now has > $1 \cdot 10^{15}$ n_{eq}/cm^2!
LHCb: 10 years with a delivered 10 fb^{-1} and innermost region (VELO) $6.5 \cdot 10^{14}$ n_{eq}/cm^2



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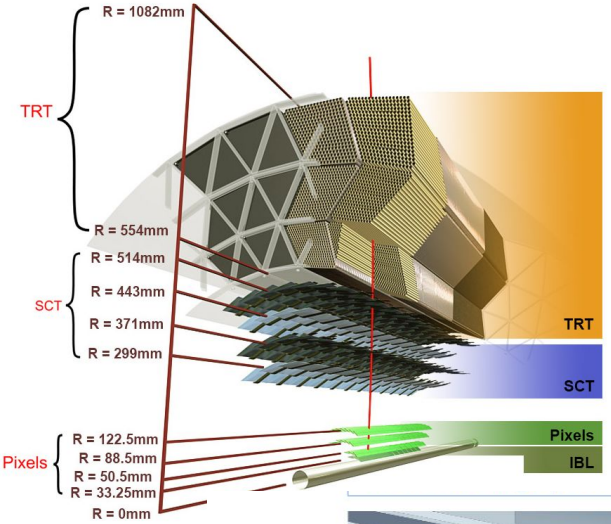
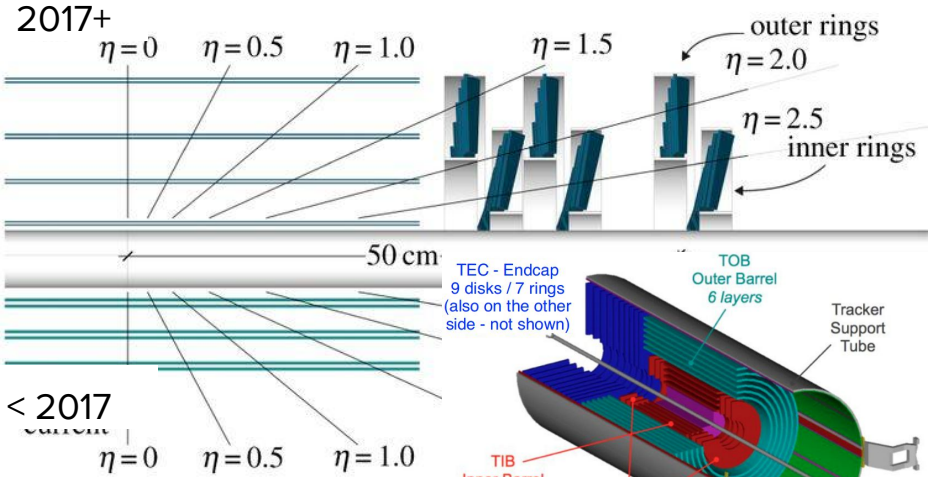
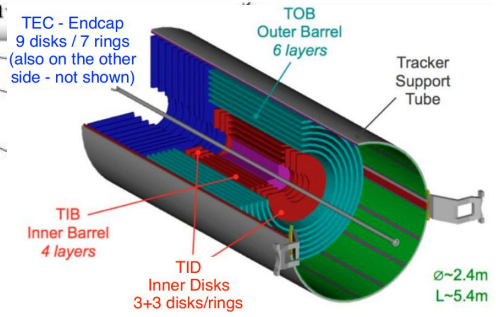


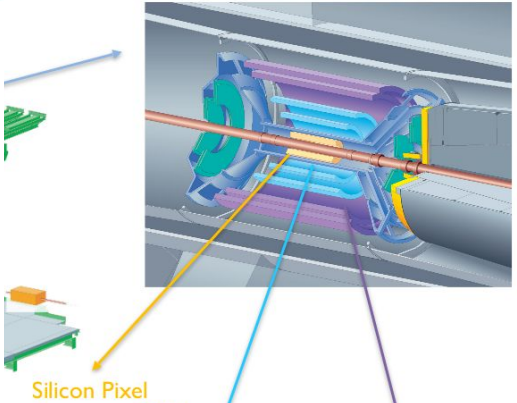
ATLAS: 3.325 cm from beam line

LHC Run 2: inner detector systems December 2018

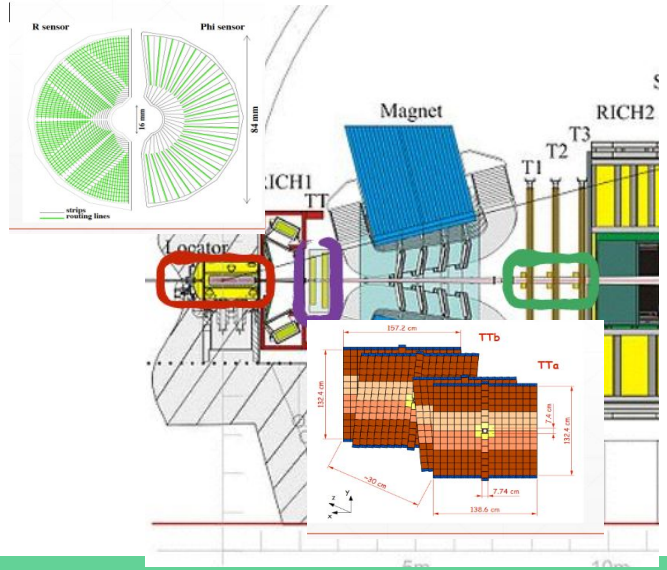


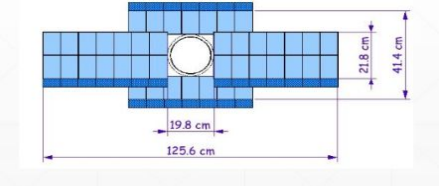


CMS: 2.9 cm from beam line



ALICE: 3.3 cm from beam line

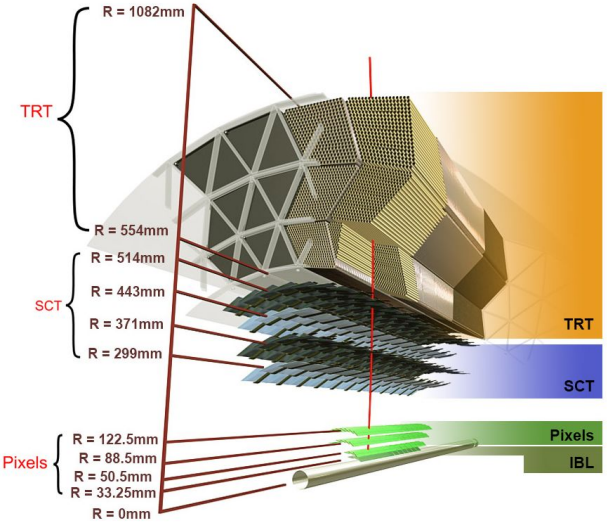




LHCb: 0.7 cm from beam line

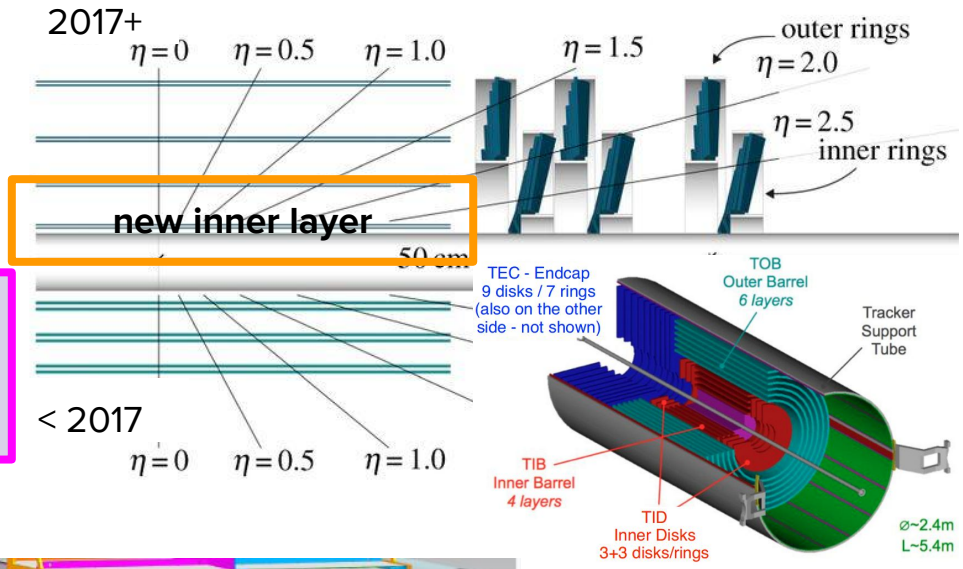
Inner tracker upgrade in LS2

Velo upgrade in LS2

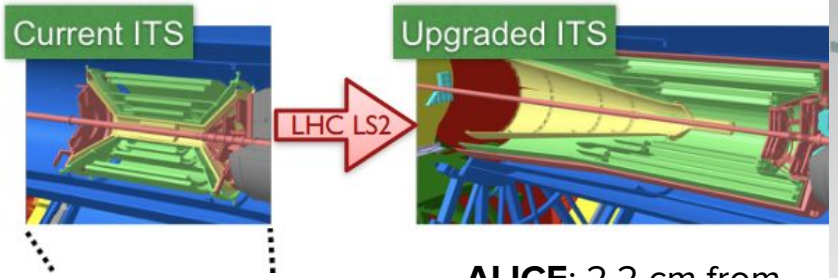


ATLAS: 3.325cm from beam line

LHC Run 2: inner detector systems early 2021

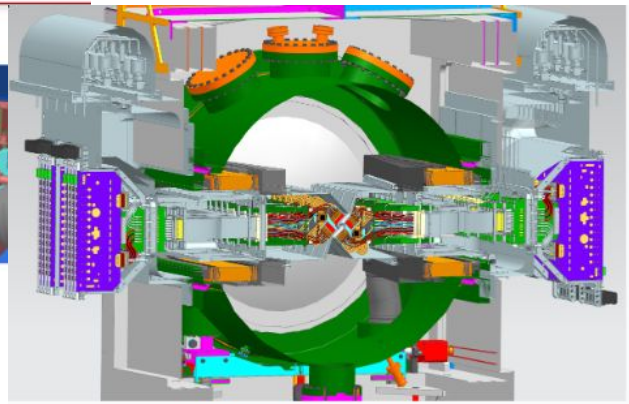


CMS: 2.9 cm from beam line



ALICE: 2.2 cm from beam line, monolithic active pixel sensors 33 µm x 33 µm

Inner tracker upgrade in LS2

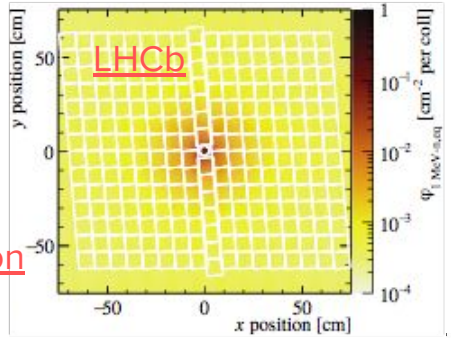


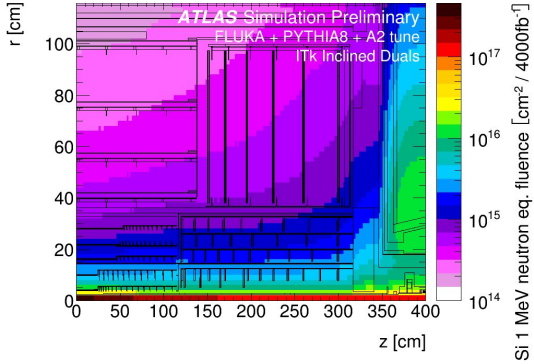
LHCb: 0.51 cm from beam line, pixel sensors 55 µm x 55 µm in VELO

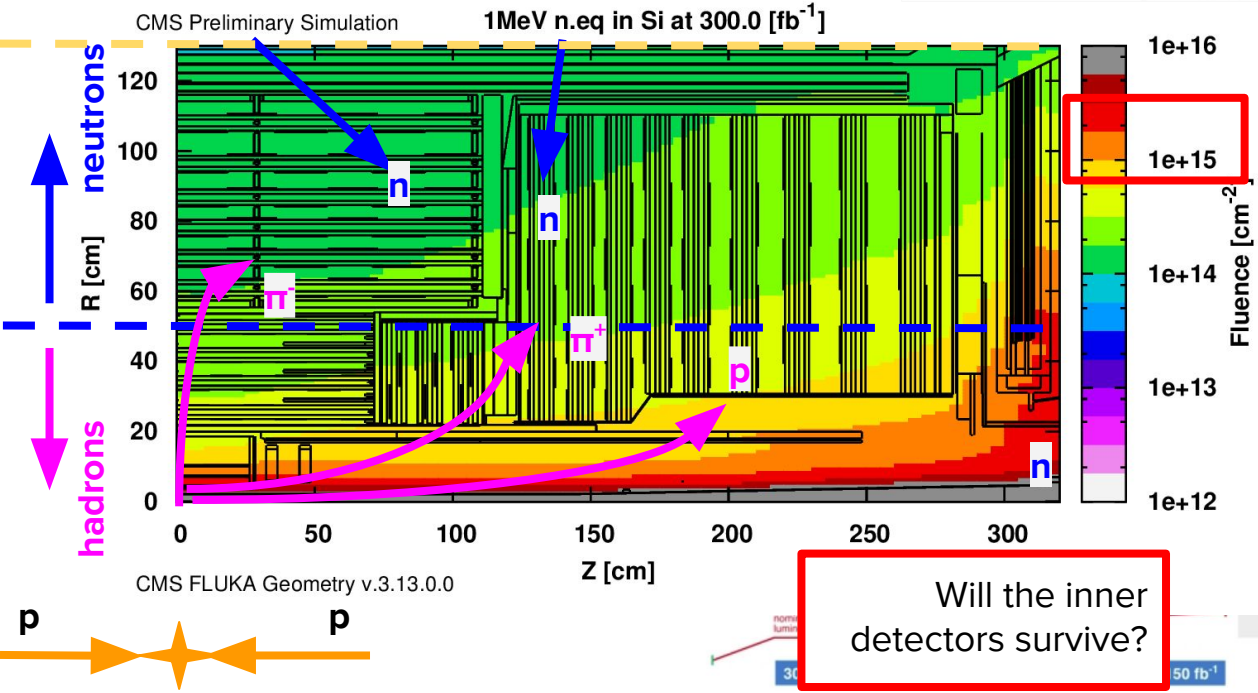
VELO and trackers upgrade in LS2

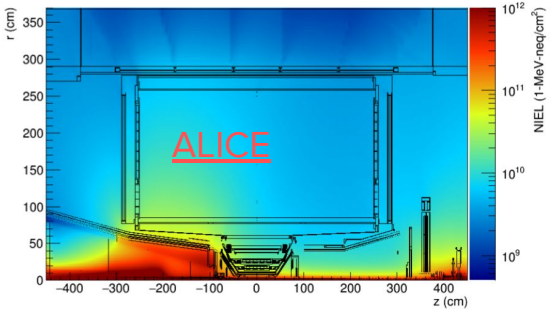
High particle rates

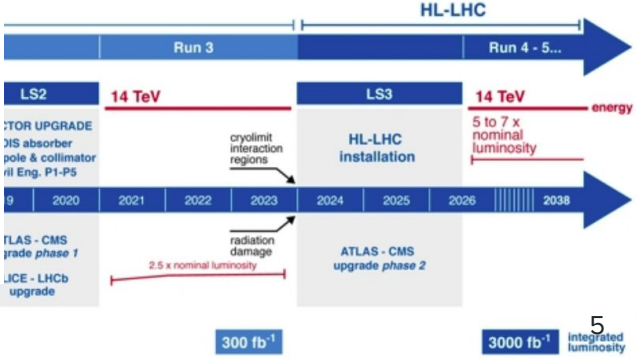
See radiation background monitoring and simulation session











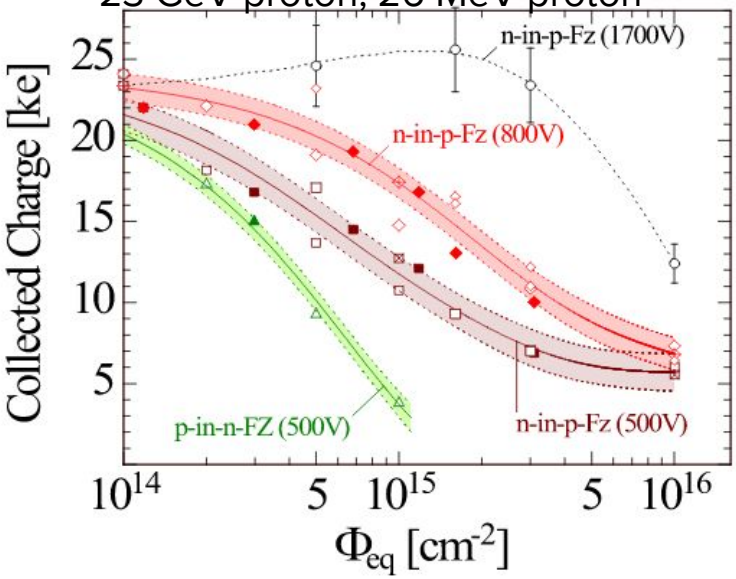
Will the inner detectors survive?

Effects from radiation damage

Effects from radiation damage can be challenging in operation of detectors as well as for physics:

- Increasing leakage currents
- Charge accumulation in silicon oxide layers
- Single event upsets, in readout only → see electronics session
- Decreasing signal-to-noise ratios
- Changing depletion voltages
- Radiation induced activation of components

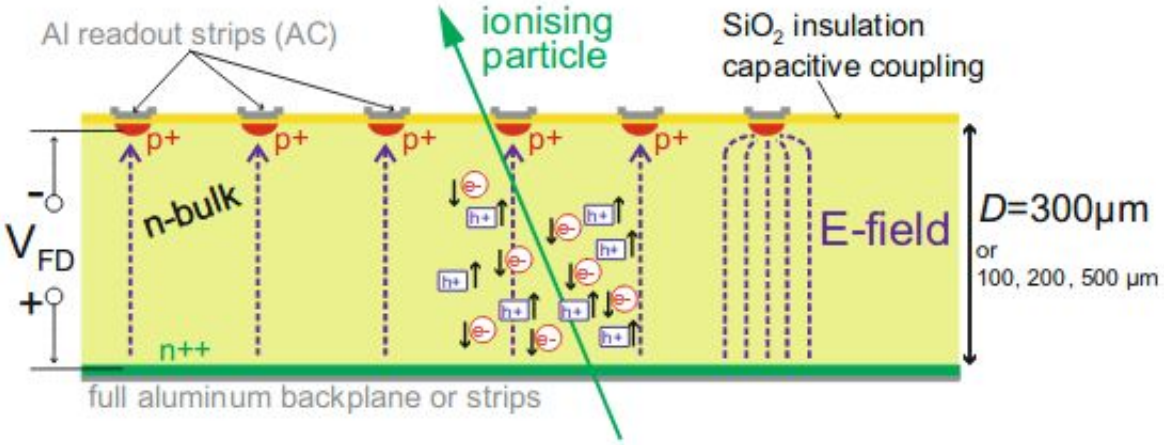
23 GeV proton, 26 MeV proton



From Michael Moll

Ideal signal detection with silicon sensors

- A minimum ionizing particle (MIP) traveling through a fully depleted region (V_{FD}) creates electron hole pairs
- The charges drift to opposite directions under the electric field
- Within nanoseconds, charges are collected at the readout

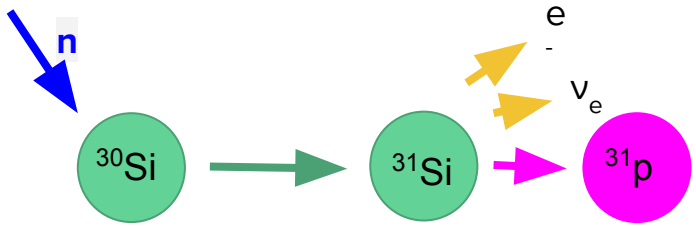


p-in-n silicon sensor

From Frank Hartmann

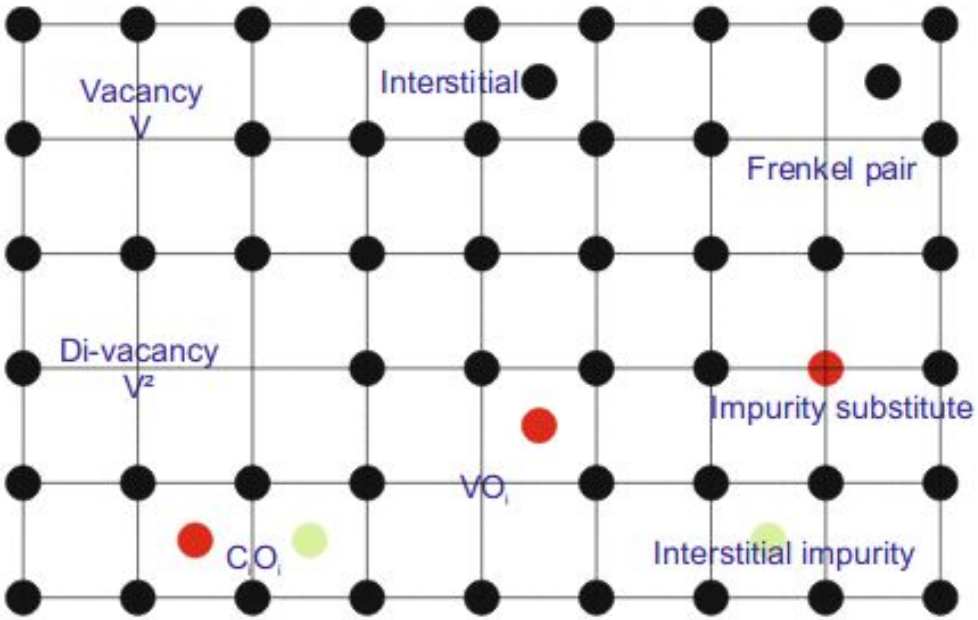
Microsocopic defects

- **Bulk damage**: non-ionizing energy loss (NIEL), e.g.:

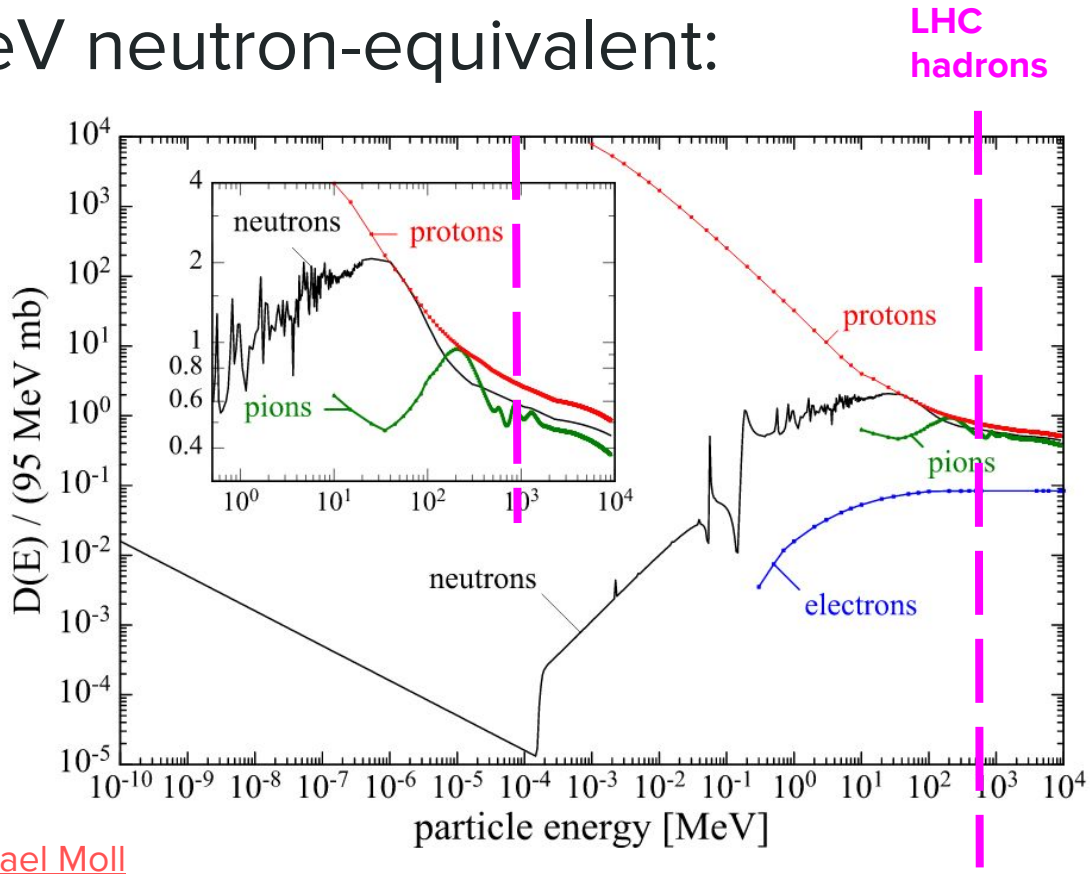


  - Frenkel pair: vacancy + interstitial

- **Surface damage**, or ionizing energy loss: not considered for silicon but important in silicon oxide



1 MeV neutron-equivalent:



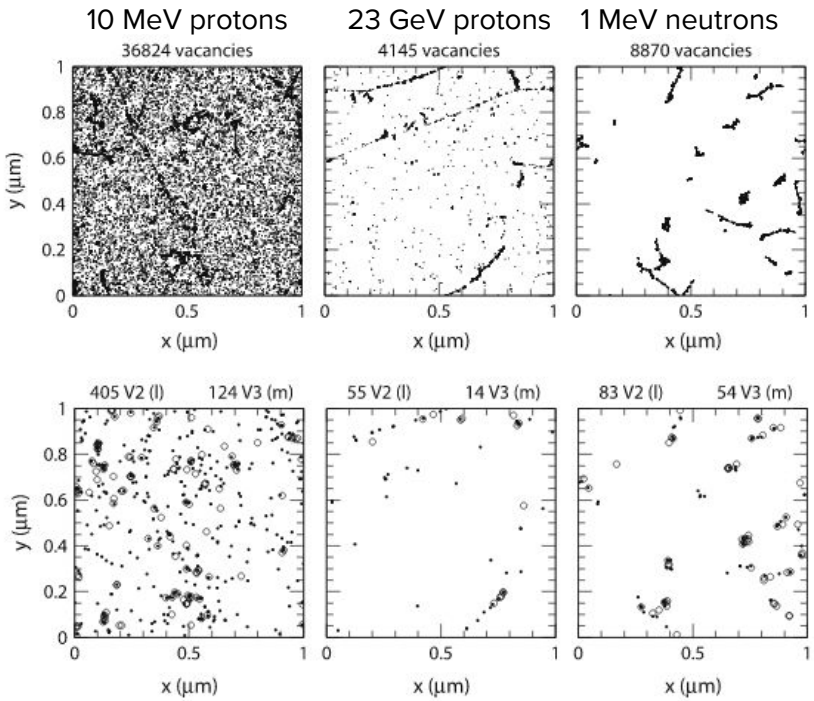
Michael Moll

D(E): displacement damage function in

- 1 MeV neutron-equivalent, or
- NIEL cross section MeV mb
- Reference: 1 MeV neutron-equivalent at 95MeV mb

Radiation damage

Annealing: recombination



time

Effects from radiation damage:

- Leakage current increase
- Space charge distribution: bulk doping in undamaged sensors but contribution from defects after irradiation → change in operational voltage
  Material dependent (oxygen-content) and particle-type-dependent
- Trapping → decreased charge collection efficiency

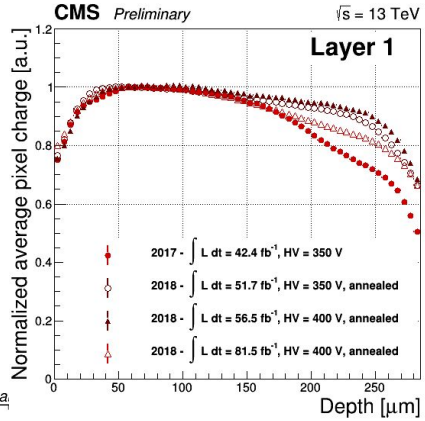
From Michael Moll

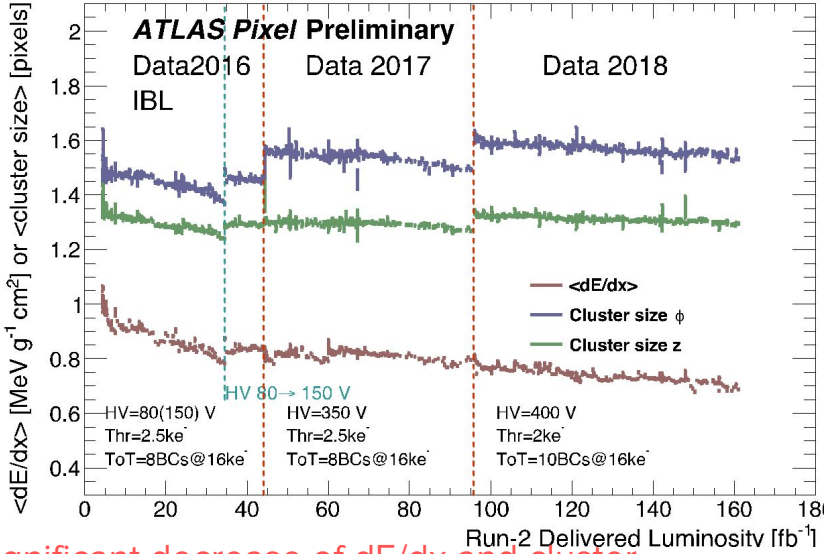
https://rd.springer.com/book/10.1007/978-3-319-64436-3

Impact on data

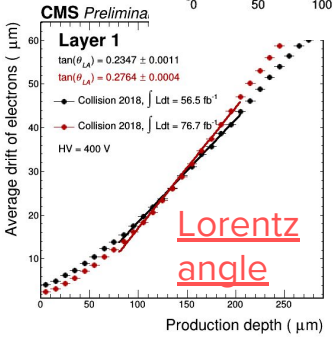
Modeling radiation damage is important for performance (➜ operational voltage) but also for physics: see afternoon session

Average pixel charge

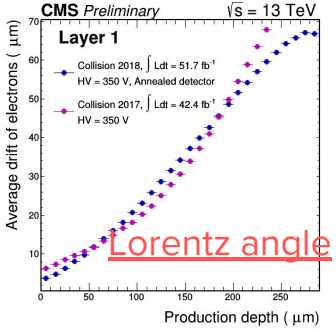




Significant decrease of dE/dx and cluster size for IBL

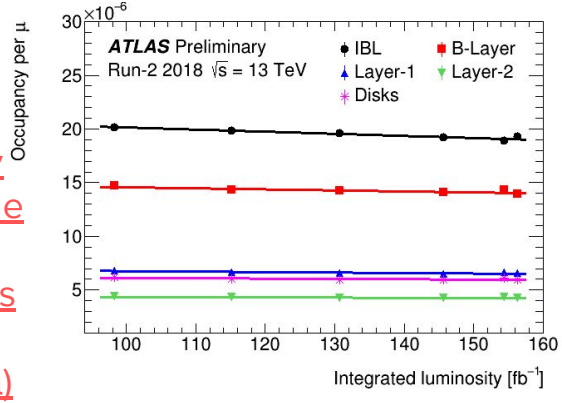


Lorentz angle



Lorentz angle

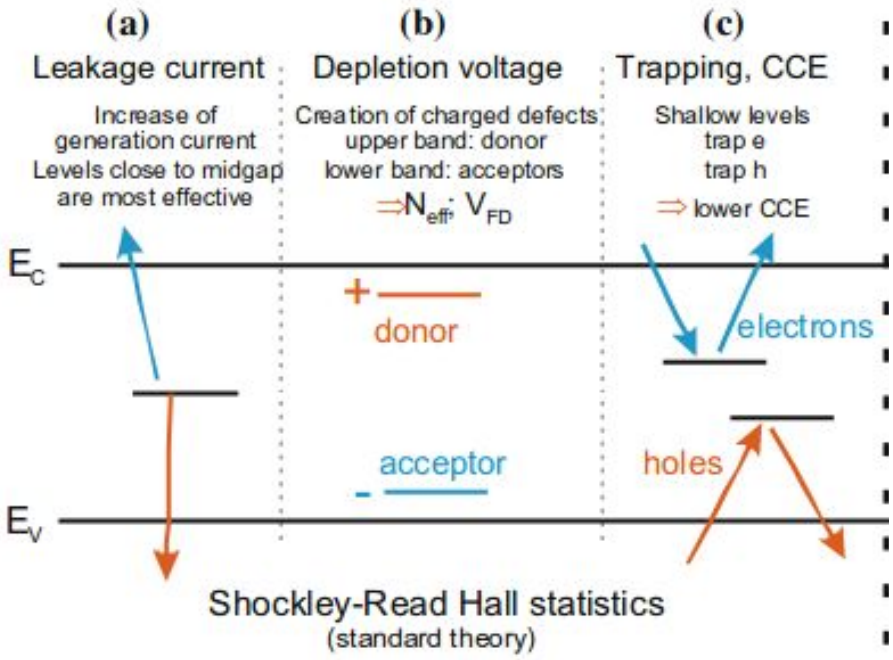
Pixel occupancy per average number of interactions per bunch crossing (μ)



Modeling radiation damage

Modeling of radiation damage is very important for data quality

- Hamburg model can serve to model leakage currents and depletion voltages
- To model **signal**: need to include defect parameters from trapping in Poisson and transport equations like in technology computer-aided design (TCAD).

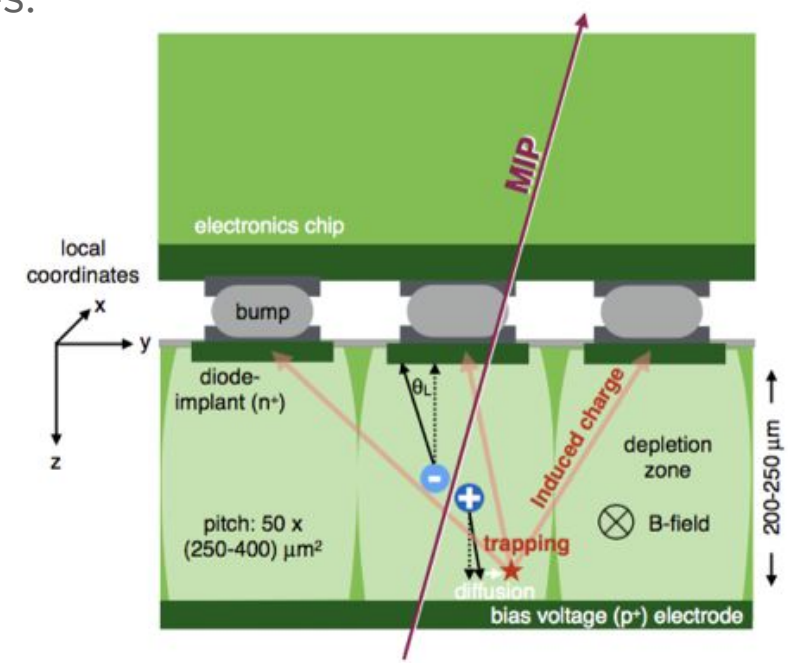


From Michael Moll

Not so ideal signal detection: radiation damage

Charges induced by an incident particle are collected with reduced efficiency as a result of radiation damage that causes:

- **Deformation** of the electric field
- **Trapping** induces screening of charge
- Diffusion or annealing deflects the path: **Annealing**
- Magnetic field, which changes with operational bias voltage and changing electric field, deflects the path: **Lorentz angle**



From Ben Nachman

Modeling radiation damage: the depletion voltage Hamburg model

Assumptions:

$$V_{\text{dep.}} = |N_{\text{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

- Little trapping
- No double junction
- 1 MeV neutron equivalence

$$\Delta N_{\text{eff}}(t) = N_{\text{beneficial a.}}(t) + N_{\text{stable damage}} + N_{\text{reverse a.}}(t)$$

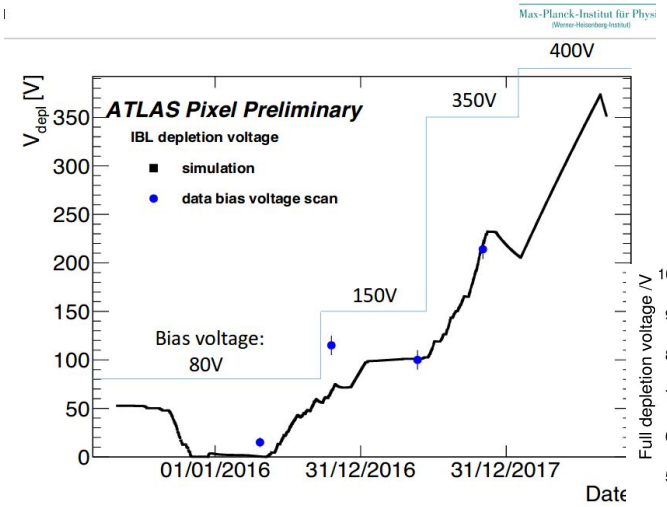
Input:

$$dN_A^{\text{stable}}/dt \propto \Phi(t)$$

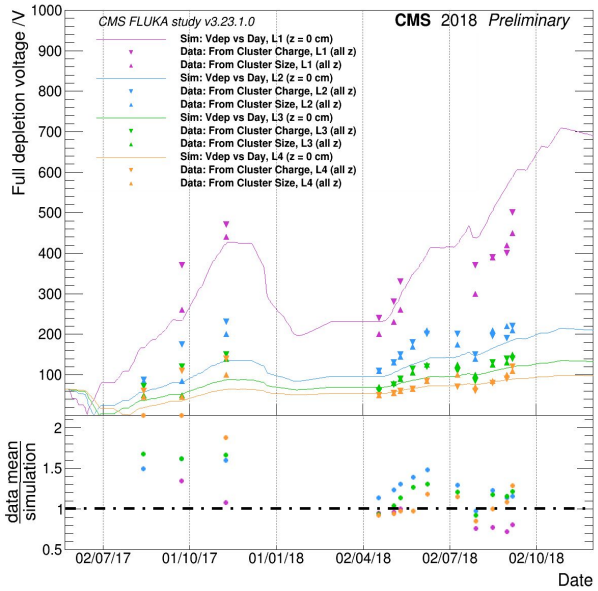
- Fluence
- Temperature over time (in order to include annealing effects)
- Sensor thickness d, sensor material

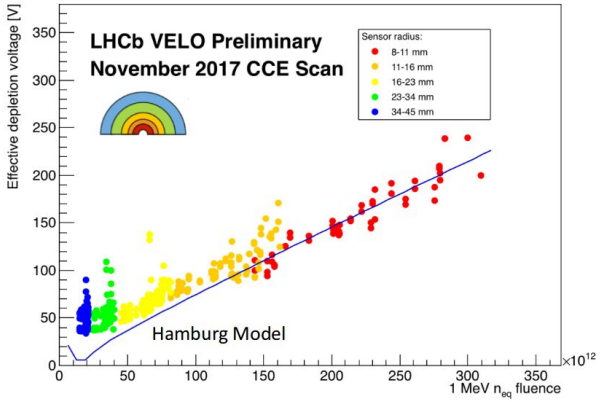
Output: effective space charge N_{eff} ➔ depletion voltage V_{dep}

Depletion voltage measurements vs prediction



Difficult to fit all data points -- up to where is the Hamburg model valid?

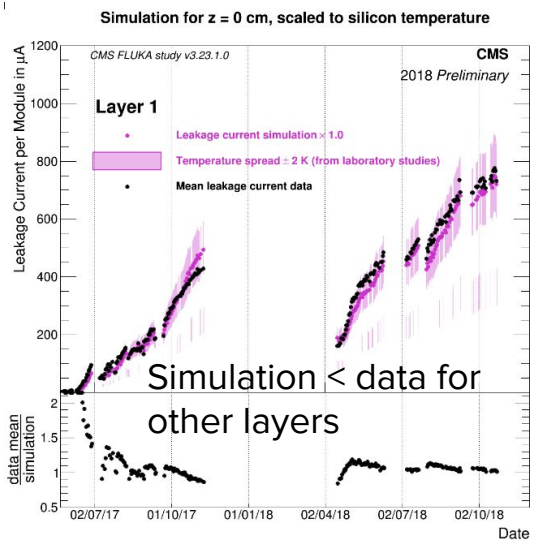


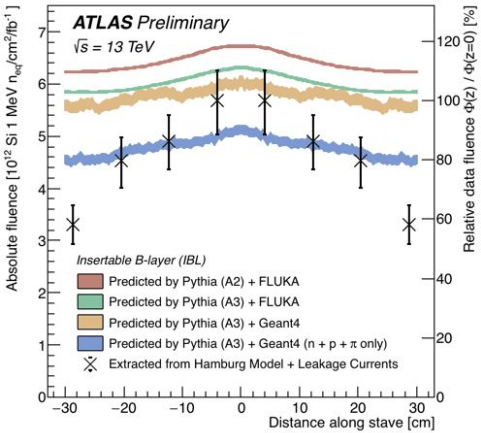


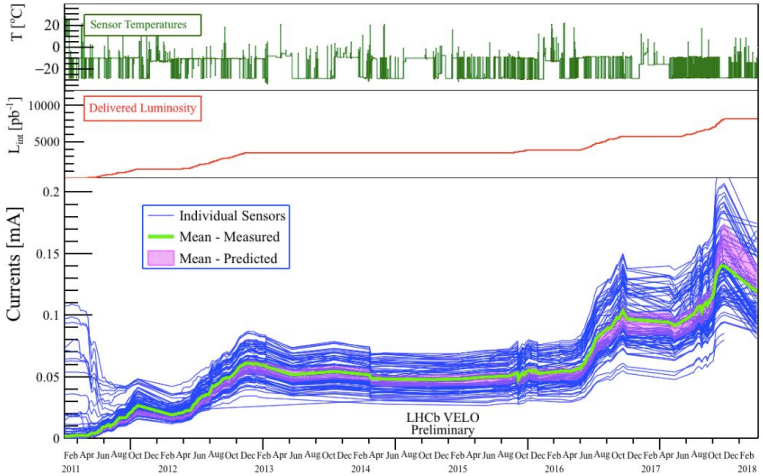
Slides by Beyer 2018

Slides by Barter 2018

Leakage current measurements vs prediction







ATLAS radiation damage results

From Vinícius Franco Lima

See talk by Finn Feindt

$I(T) \propto T^2 \exp(-E_{eff}/2k_BT)$

$E_{eff} = 1.214 \pm 0.014$ eV

➜ 8-10% reduction of leakage current for 1 °C between 0 °C and -20 °C

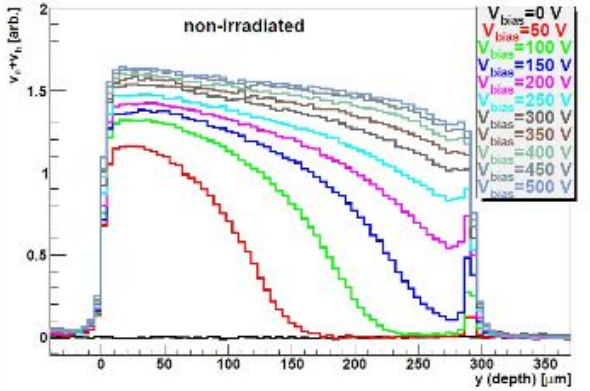
Chilingarov

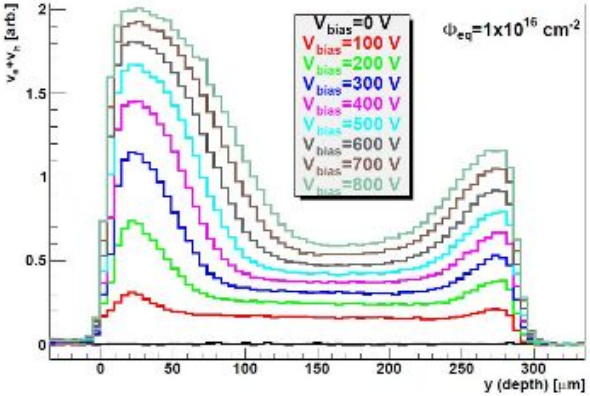
ATLAS sees a z-dependence.
Does CMS see this, too? ➜ see talk by Finn Feindt

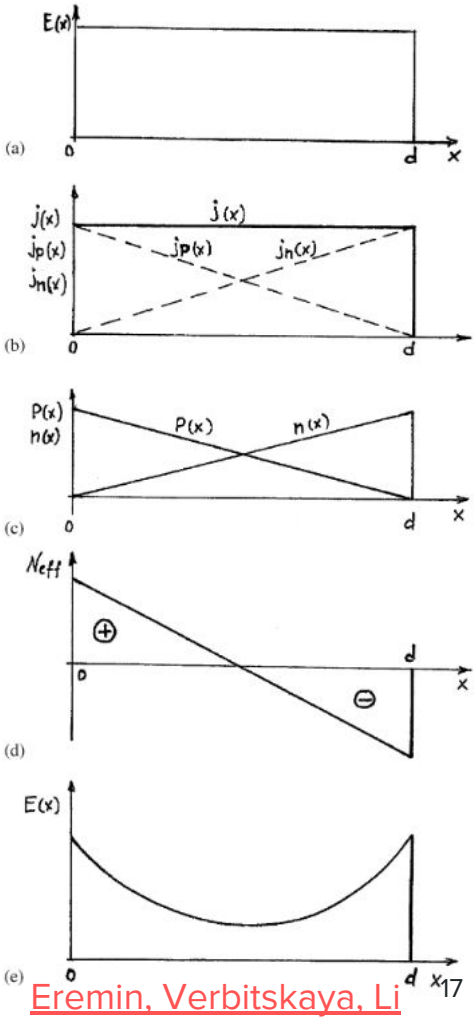
Assumption: no double junction

Homogeneous electric field in Hamburg model holds only for non-irradiated silicon: a double junction forms in irradiated silicon.

Pictured:
p-type microstrip detector made from float zone silicon: 5 kΩcm, 300µm, and V_{dep} = 180 V







Kramberger, Cindro, Mandić, Mikuž, Milovanović, Zavrtanik

Eremin, Verbitskaya, Li

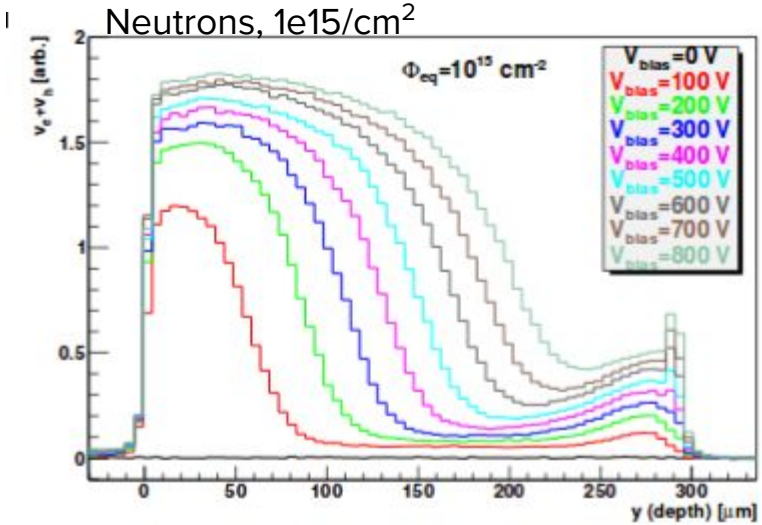
Kramberger, Cindro, Mandíc, Mikuž, Milovanović, Zavrtanik 2014

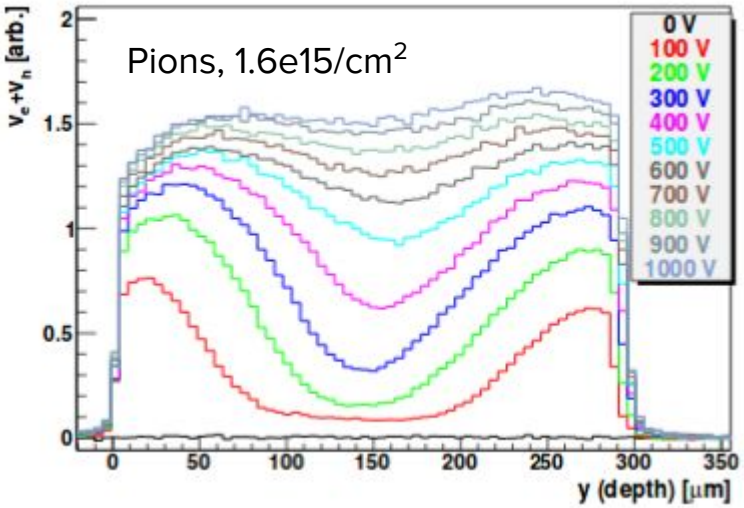
Assumption: neutron-equivalent

We always talk of ‘neutron-equivalent’: is this really applicable?

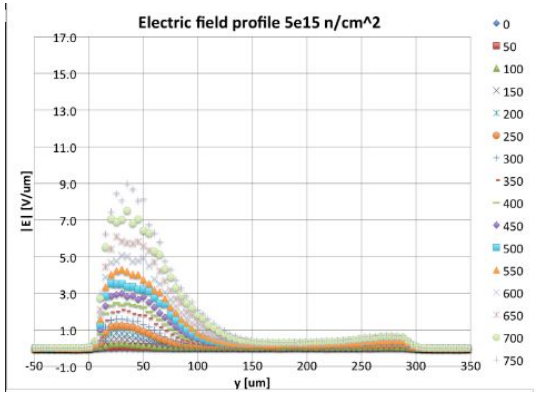
Most non-ionizing energy loss in inner tracking systems from pions.

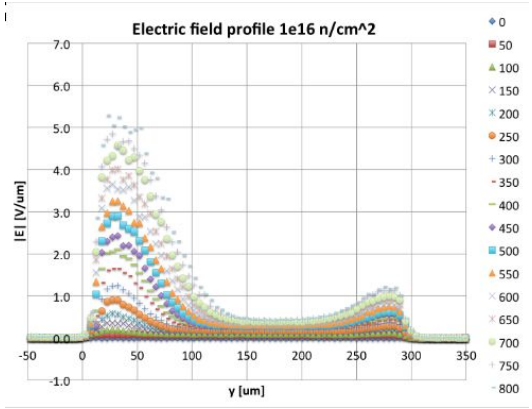
In outer and forward tracking systems, most bulk damage comes from neutrons.



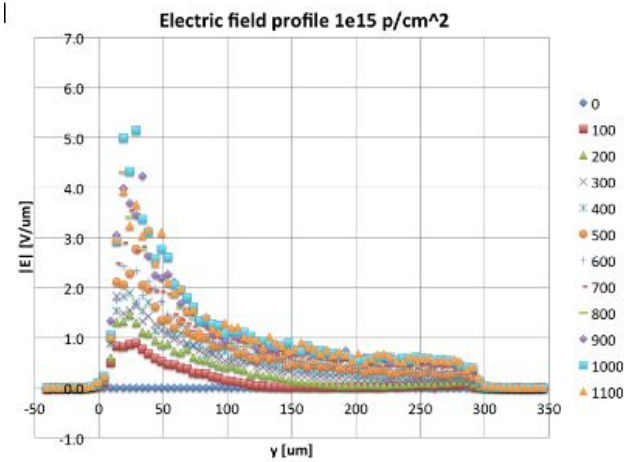


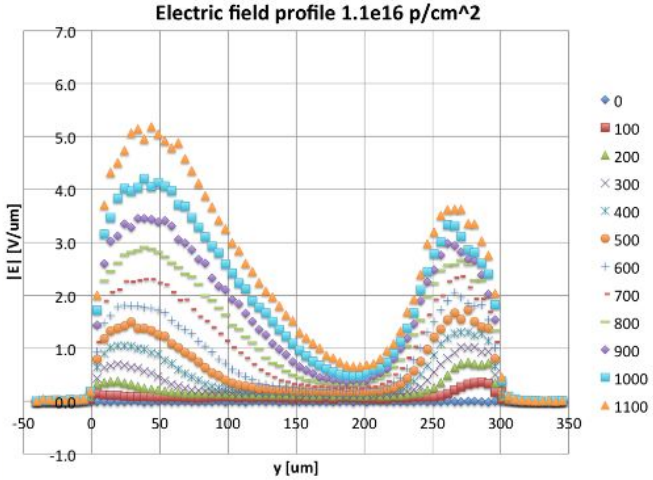
Protons vs neutrons





- Smaller peak fields for neutrons
- Less pronounced double junction for neutrons
- Protons have flatter field at junction (less peaked)





From Marko Mikuž

Beyond the Hamburg model: simulation for data

Different ways of simulating bulk defects like trapping and altered electric fields, as well as annealing and Lorentz angles

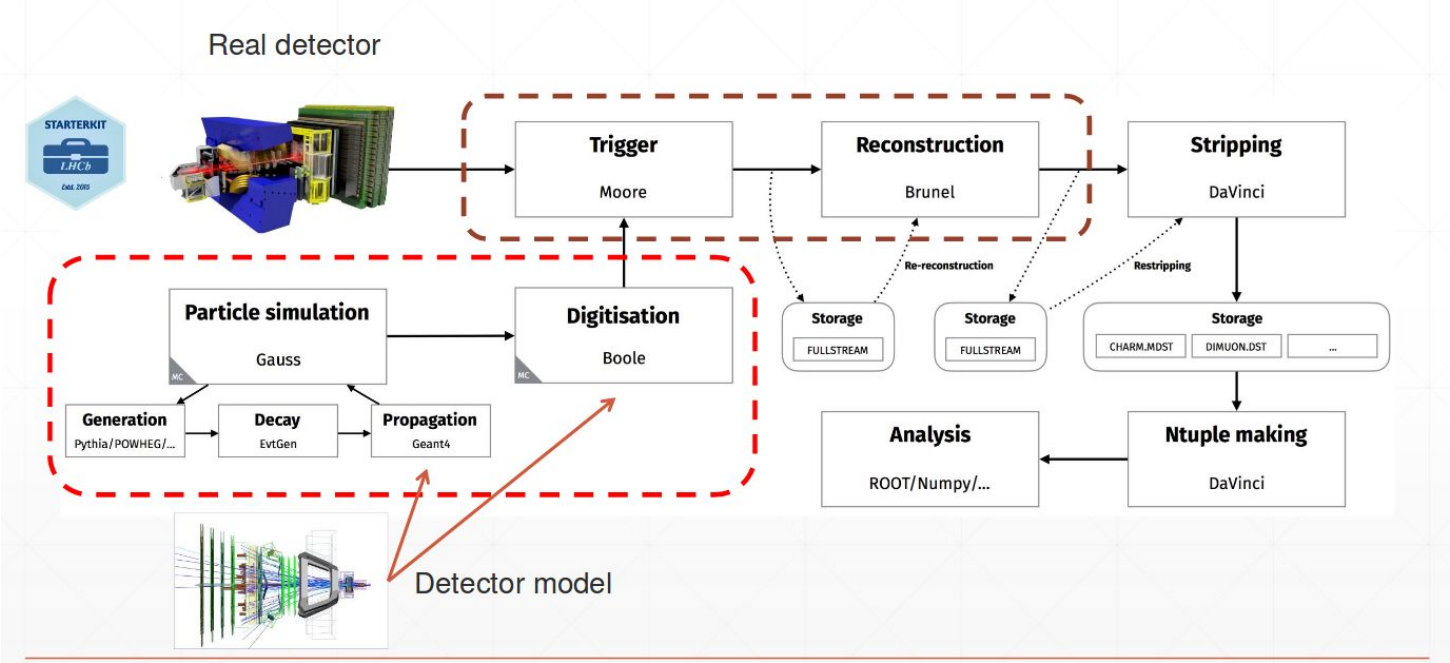
	ATLAS	CMS	LHCb
Energy Deposition	Bichsel Model + G4 (δ-rays)	Pixelav (applied as correction to G4)	Geant4
Energy spreading	from Bichsel + chunking	from Bichsel + chunking	Uniform (space) + uniform/Gauss (E)
E-field/ Lorentz angle	TCAD (Chiochia et al.)	TCAD (tuned to data)	N/A
Diffusion	Einstein	Einstein	tuned
Noise	capacitive coupling + noise	readout noise	capacitive coupling + noise
Radiation damage	**trapping + charge induction**	**trapping + charge induction**	**charge & 'diffusion' corrections**

See afternoon session

From Ben Nachman

Simulation of radiation effects in LHCb

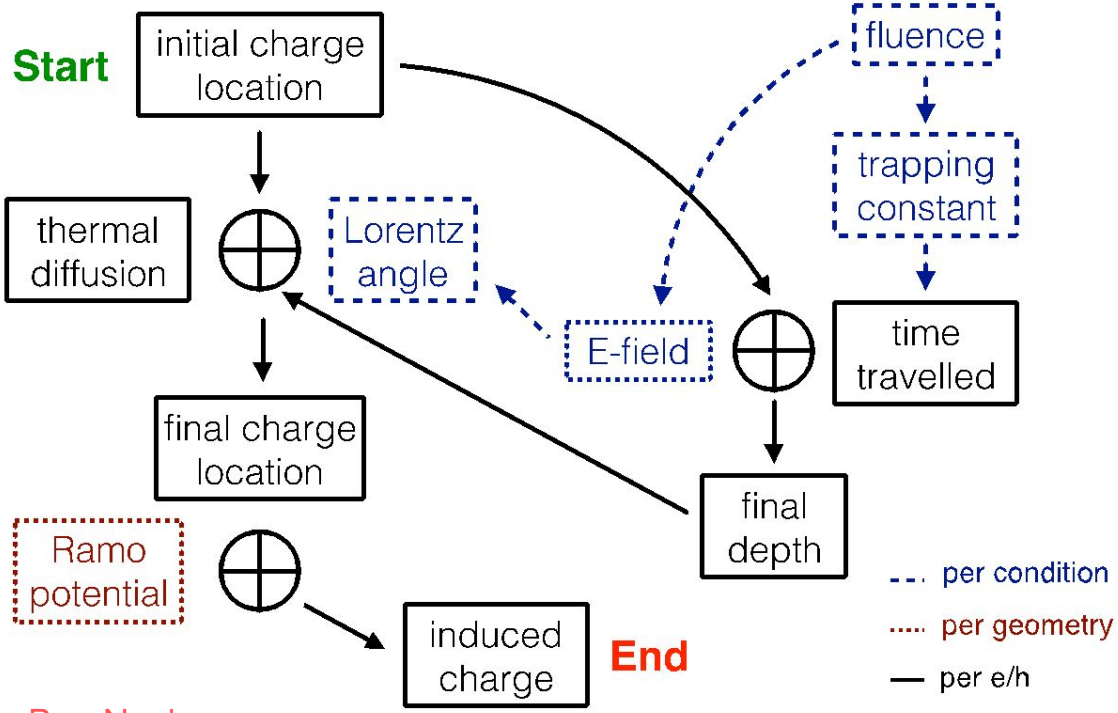
Charge is reduced and “diffusion length” increased to match data.



From Tomasz Szumlak

The ATLAS digitizer for simulation of radiation

- Double peak electric field
- Fluence from FLUKA + pythia

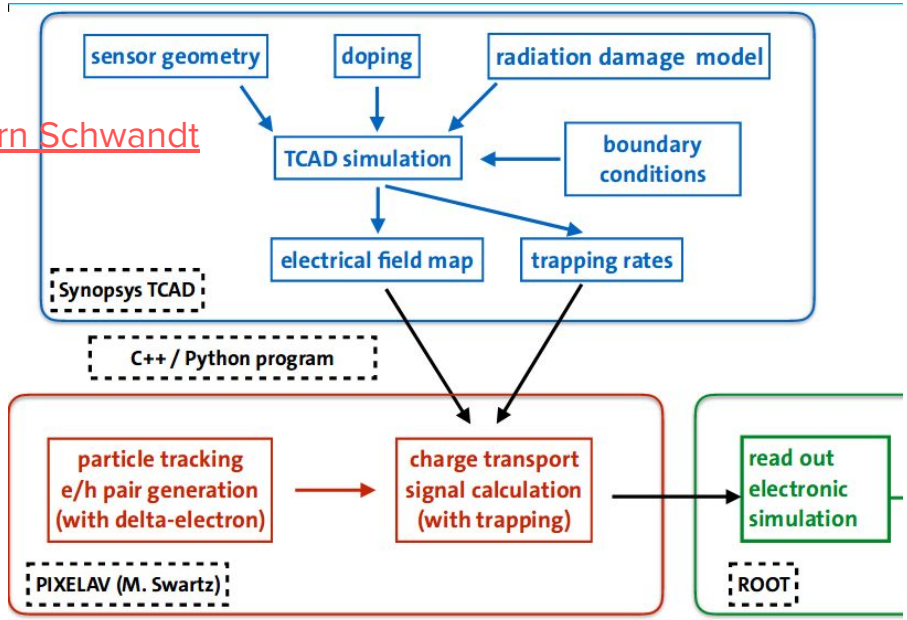


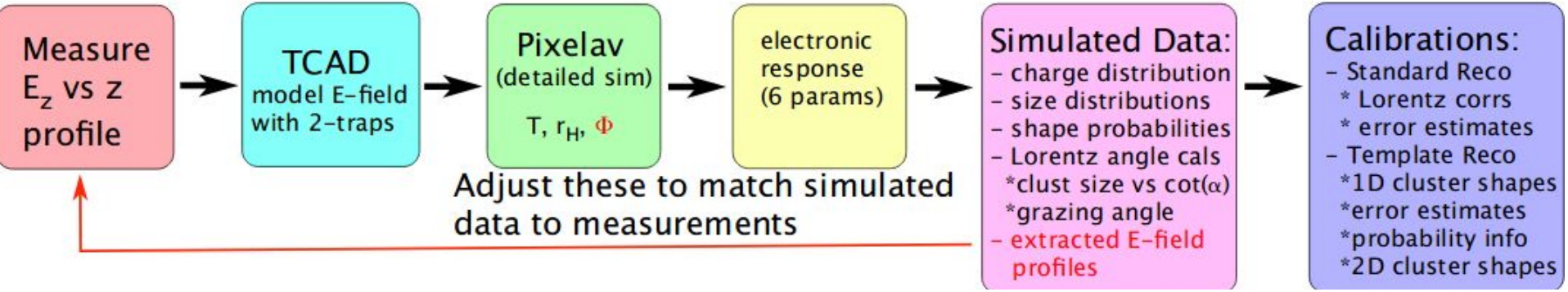
From Ben Nachman

CMS simulation

- Works up to 1.2e15n_{eq}/cm^2: good for predictions in run 3
- Perform detailed independent simulation and apply correction factors;
- Cluster reweighting to reflect fluctuations

From Jörn Schwandt



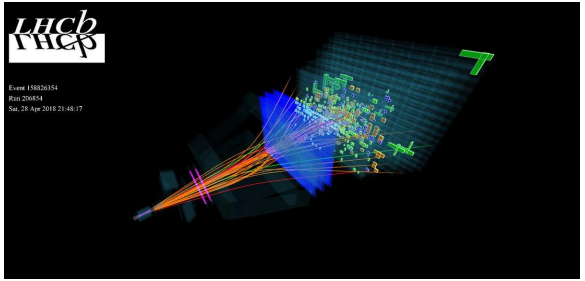


From Morris Swartz

Summary

Effects from radiation damage can be challenging in operations and for physics:

- Increasing leakage currents
- Charge accumulation in silicon oxide layers
- Single event upsets
- Decreasing signal-to-noise ratios
- Changing depletion voltages
- Radiation induced activation of components



Modeling these effects is important, but can be challenging:

- Do we need a nontrivial space charge distribution in the Hamburg model?
- Temperature modeling and dependence
- How do leakage currents depend on r and z?