Radiation Damage Monitoring in the Upgraded VELO Detector

Saliha Bashir

Supervisors: Agnieszka Obłąkowska-Mucha and Tomasz Szumlak

"2nd Symposium on New Trends in Nuclear and Medical Physics" 24-26 September, 2025

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Outline

- Radiation damage in silicon sensors
- Silicon tracking detectors
- LHCb spectrometer and upgraded VELO detector
- Macroscopic changes
- Prediction of Radiation Damage
- Limitations of FLUKA
- Particles produced in Pythia and Herwig
- Data-driven Calculations
- Radiation damage monitoring for LHCb VELO
- Conclusion

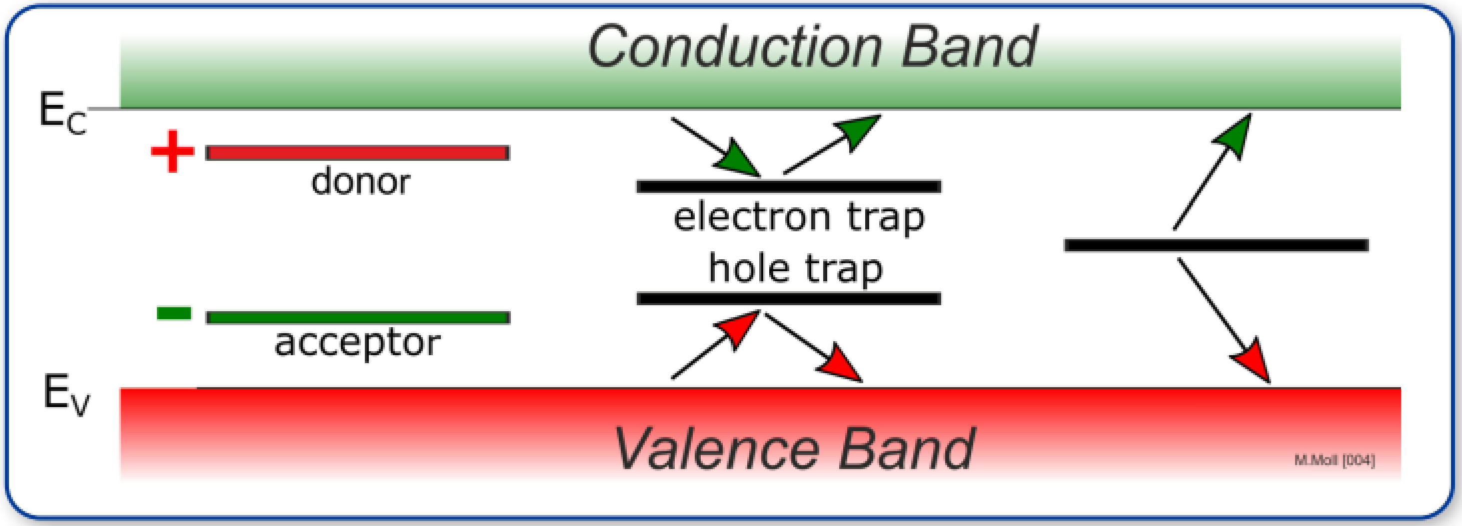
Impact of radiation on silicon sensors and silicon sensors at LHC

Prediction of damage using simulation tools

Data-driven calculations and monitoring of radiation damage in VELO

Radiation damage in silicon sensors

Radiation-induced changes in properties and structures of the silicon tracking detectors are observed as macroscopic effects caused by microscopic defects:



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper half, acceptors in lower half of the band gap

trapping (e and h)
⇒ CCE
shallow defects do not contribute at RT due to fast de-trapping

generation
⇒ leakage current
levels close to midgap most effective

SIMDET-Moll-2021

Constant monitoring of radiation influence on VELO sensors:

- Current-Voltage scans (IV)
- Current-Temperature scans (IT)
- Charge Collection Efficiency (CCE)

Radiation damage in silicon sensors

Radiation-induced changes in properties and structures of the silicon tracking detectors are observed as macroscopic effects caused by microscopic defects:

The microscopic defects accumulate over time and have a damaging impact on the sensor performance.

charged defects
$\Rightarrow N_{eff}$, V_{dep}
e.g. donors in upper half, acceptors in lower half of the band gap

trapping (e and h)
$\Rightarrow$ CCE
shallow defects do not contribute at RT due to fast de-trapping

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$\Rightarrow$ leakage current
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[SIMDET-Moll-2021]

Constant monitoring of radiation influence on VELO sensors:

- Current-Voltage scans (IV)
- Current-Temperature scats (IT)
- Charge Collection Efficiency (CCE)

NOW: DRD3

RD50

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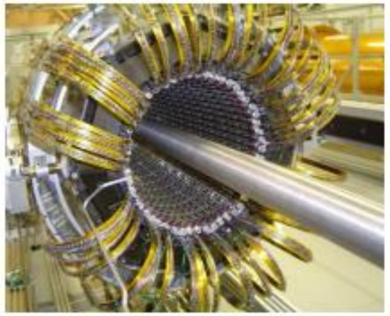
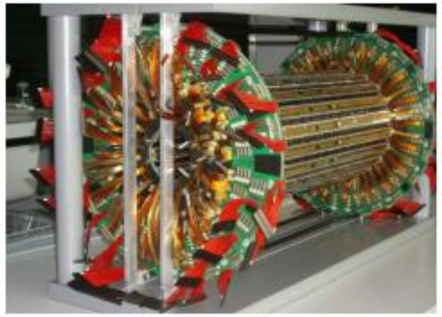
Silicon Tracking Detectors

Silicon tracking detectors are used in almost all HEP experiments:

Different sensor technologies, designs, operating conditions,….



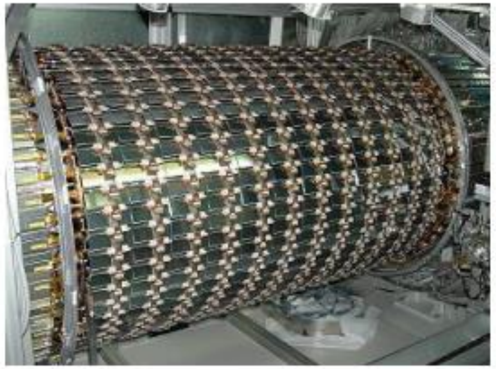
ATLAS Pixel Detector



CMS Pixel Detector

LHCb VELO (New Velo for Run3:2022)

ALICE ITS Barrel
New ITS for Run3:2022)



ATLAS SCT Barrel

CMS Strip Tracker IB

LHCb VELO (New Velo for Run3:2022)

ALICE ITS Outer Barrel
(Insertion Test 2021)

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NOW: DRD3

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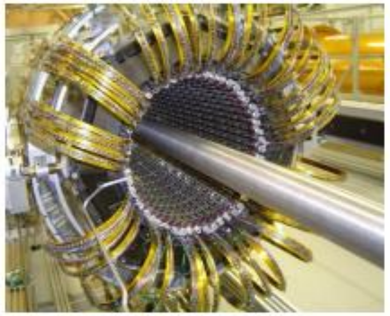

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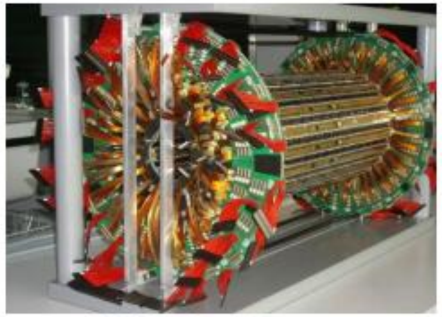

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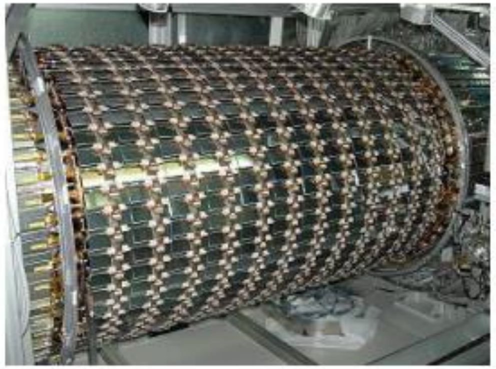

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ALICE ITS Outer Barrel
(Insertion Test 2021)

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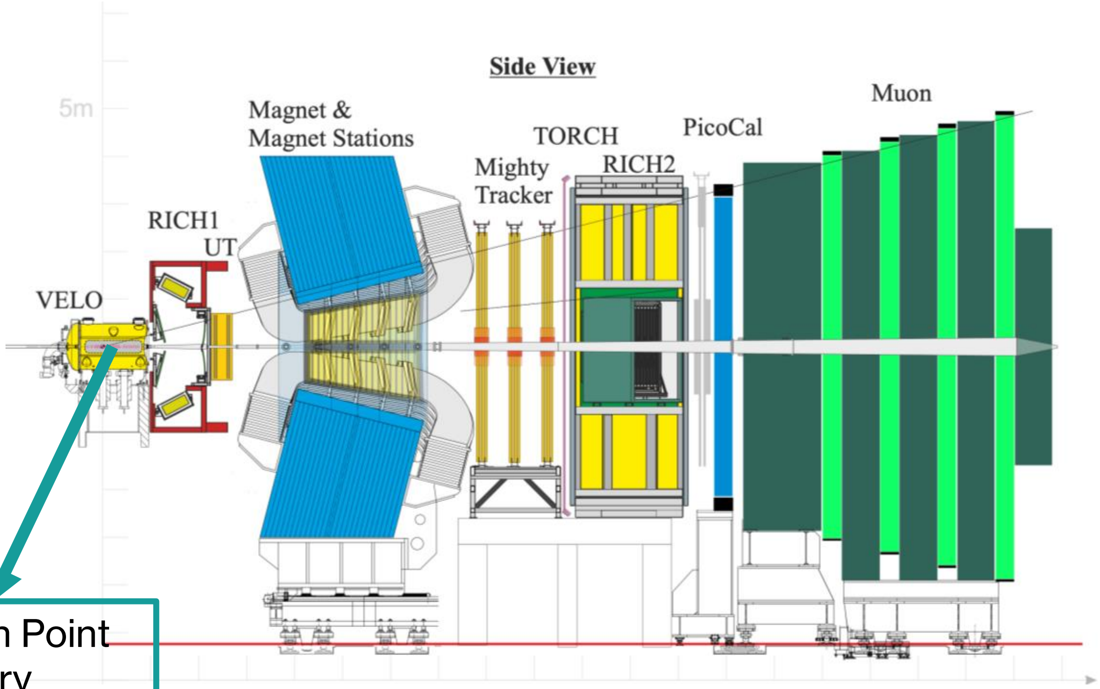
LHCb spectrometer

- LHCb is a single armed forward spectrometer, located at LHC
- Complementary kinematical coverage compared to CMS and ATLAS .



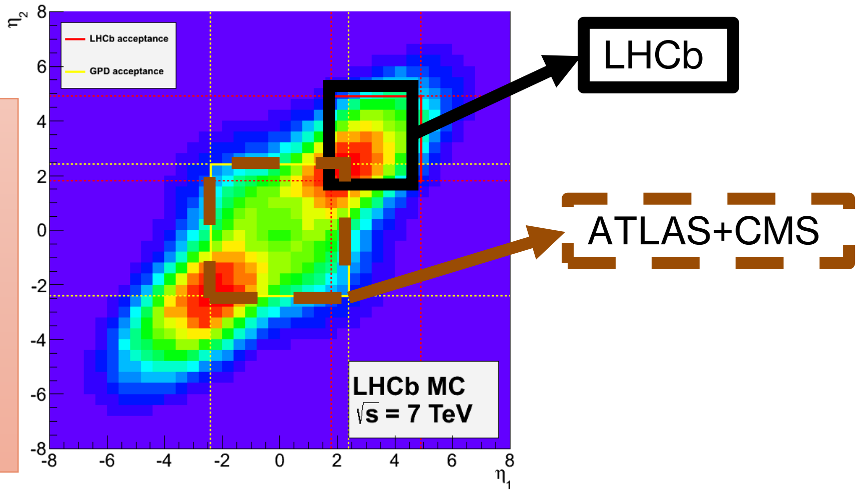
Interaction Point and Primary focus
Vertex **Lo**cator

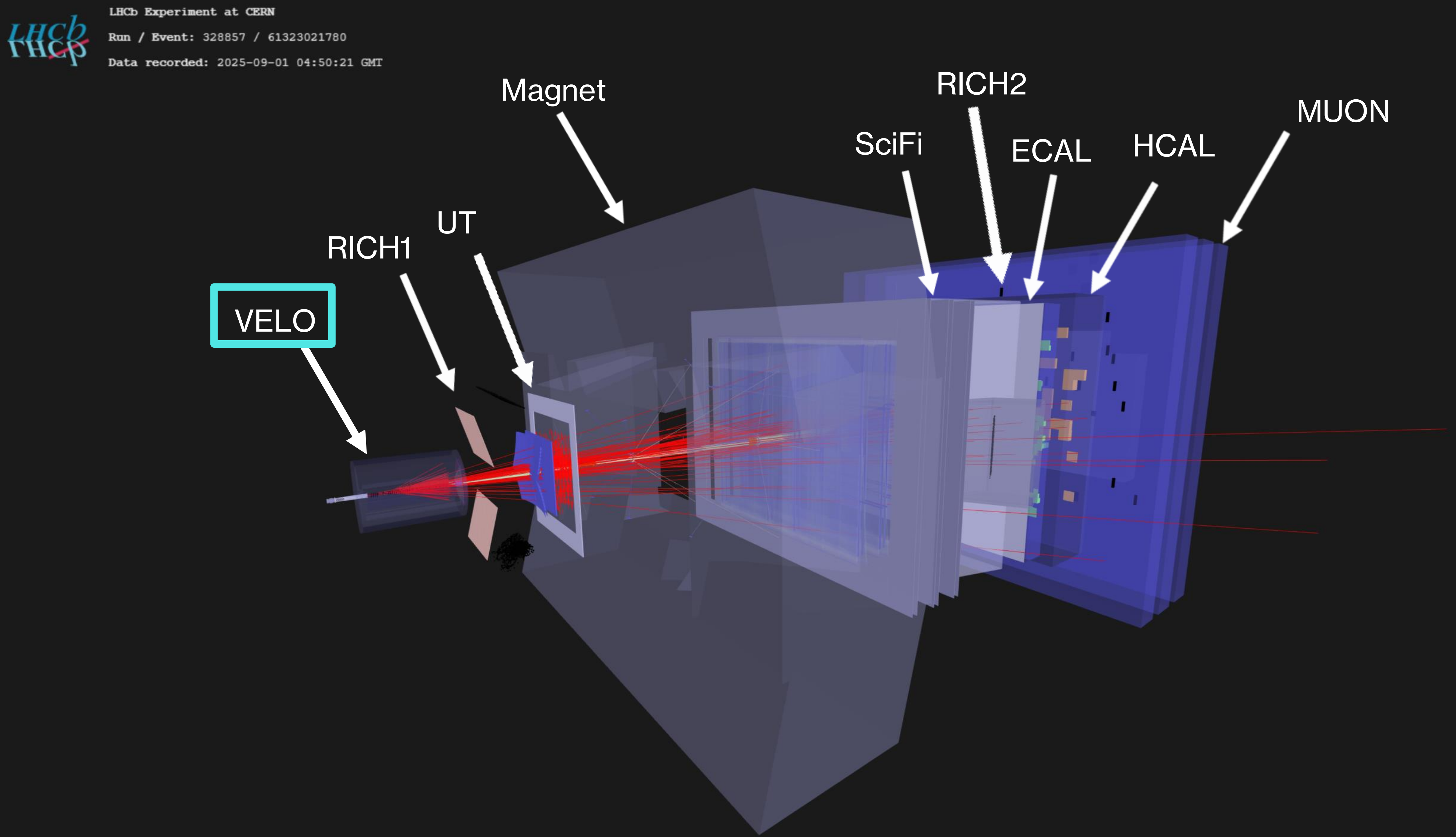
Physics program:

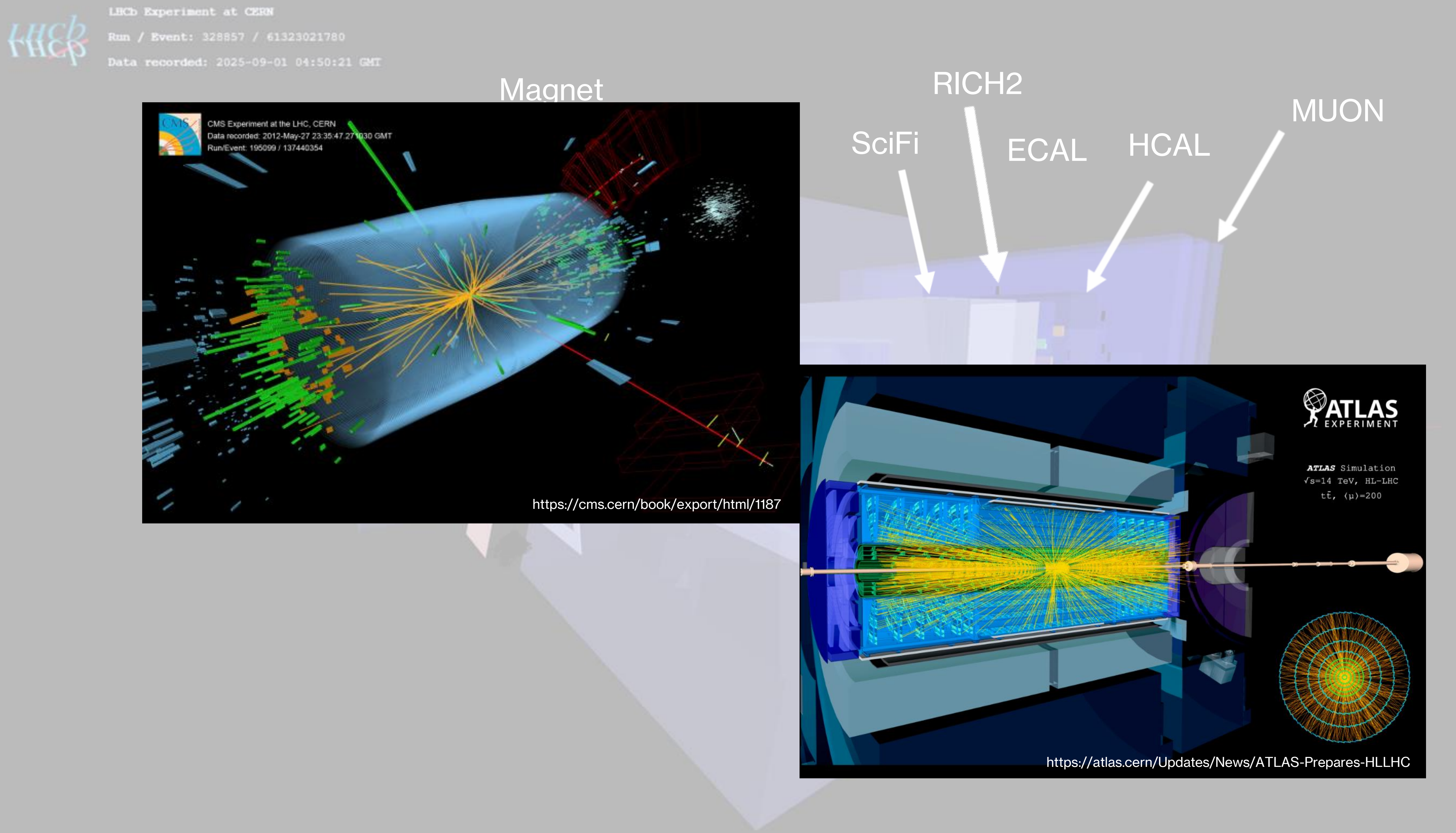
- CP Violation ,
- Rare B decays,
- B decays to charmonium and open charm,
- Charmless B decays,
- Semileptonic B decays,
- Charm physics,
- B hadron and quarkonia,
- QCD, electroweak, exotica …

Excellent performance:

- 3 fb^{-1} accumulated in Run 1
- 5.6 fb^{-1} in Run 2
- Excellent Vertex Resolution
- Precise tracking: $\delta p/p \sim 0.4 - 0.6\%$
- Hadronic identification 2-100 GeV/c



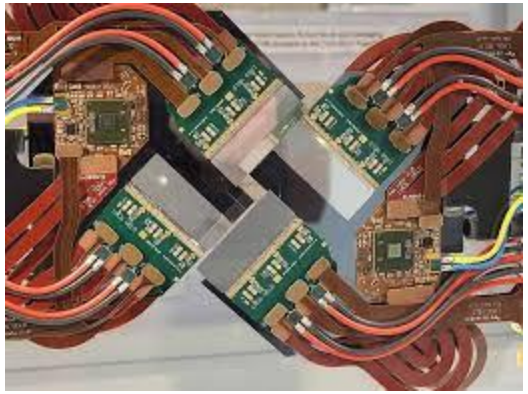

LHCb Experiment at CERN
Run / Event: 328857 / 61323021780
Data recorded: 2025-09-01 04:50:21 GMT
Magnet
RICH2
MUON
SciFi
ECAL
HCAL
UT
RICH1
VELO



https://cms.cern/book/export/html/1187

https://atlas.cern/Updates/News/ATLAS-Prepares-HLLHC

VErtex Locator (VELO) – Run 3-4



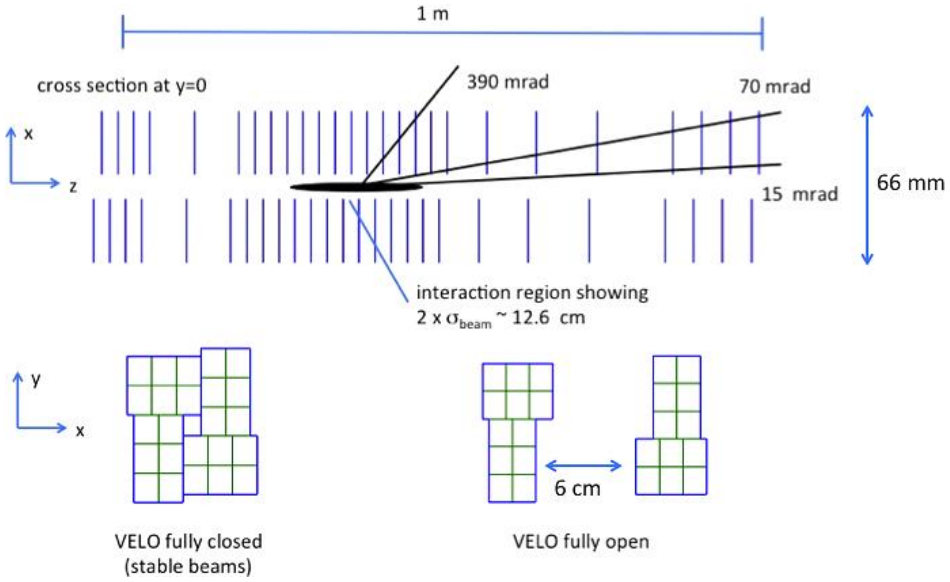
The Vertex Locator (VELO) is a silicon pixel tracking detector in the heart of the LHCb spectrometer.

Geometry

- Pixel size: **55 × 55 μm²** → much finer granularity having higher resolution.

Detector Geometry & Modules

- The detector is composed of 52 modules divided into two detector halves.
- operating at just a **5 mm radius** from the LHC beams.
- The new readout ASIC for the VELO, is capable of operating at the 40 MHz collision rate and can cope with up to 900 million hits/s/ASIC.



Leakage Current (Run 1-2)

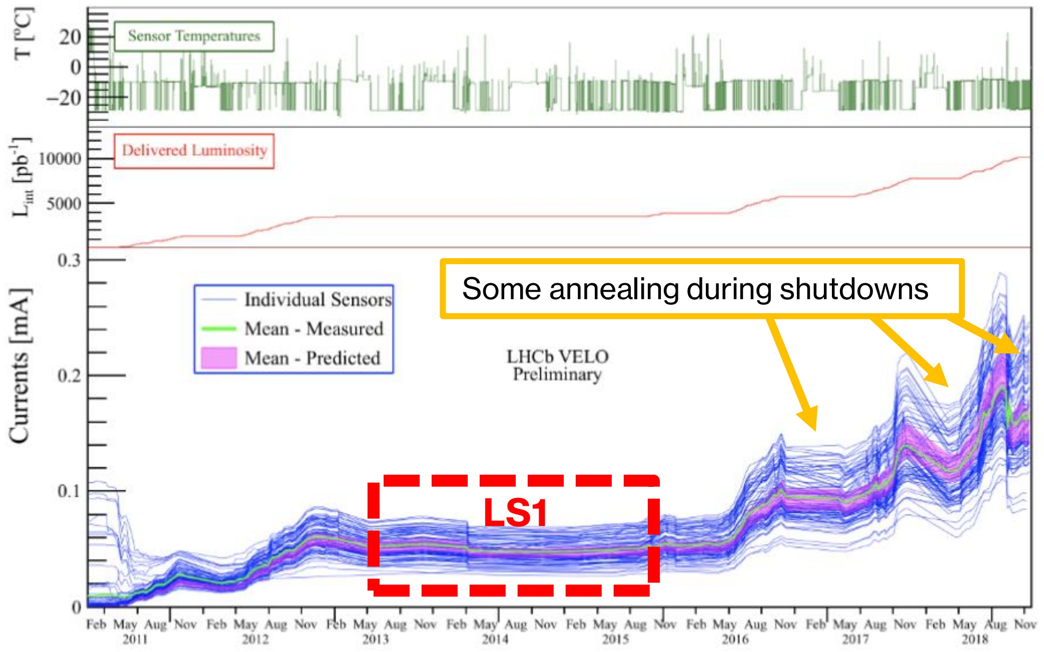
- The level of leakage current reveals the amount of radiation damage contained in a detector volume.
- The currents of the sensors are measured while operating at nominal conditions (**depletion voltage**, temperature).
- The increase in leakage current is proportional to the accumulated fluence (time, delivered luminosity):

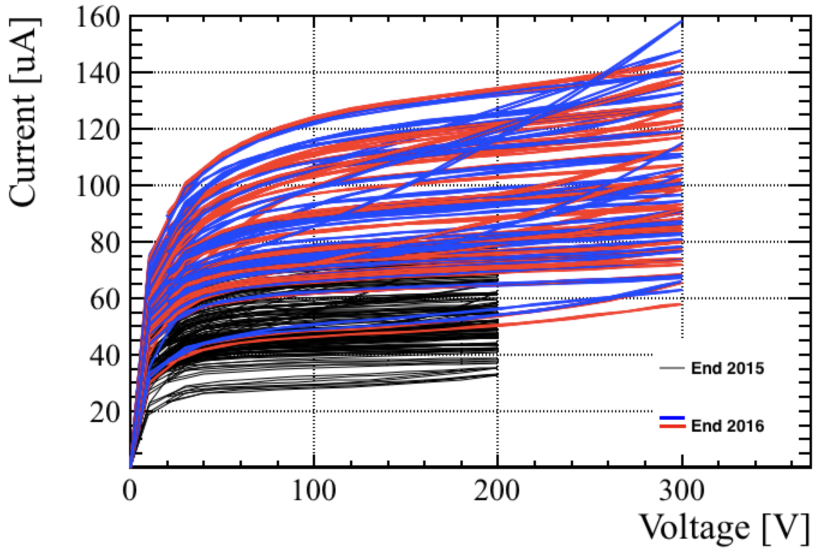
FYI

Current VS Voltage scans: Taken Weekly

$$\Delta I = \alpha V_{ol} \phi_{eq}$$

(α(T) – temperature-dependent constant)





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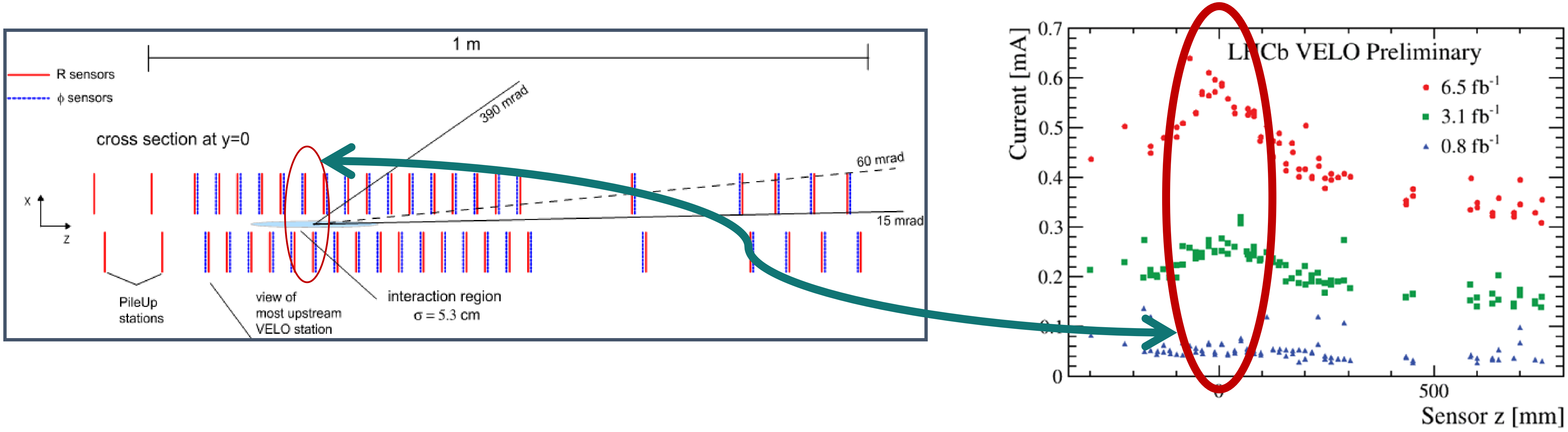
Leakage Current w.r.t. Sensor position (Run 1-2)



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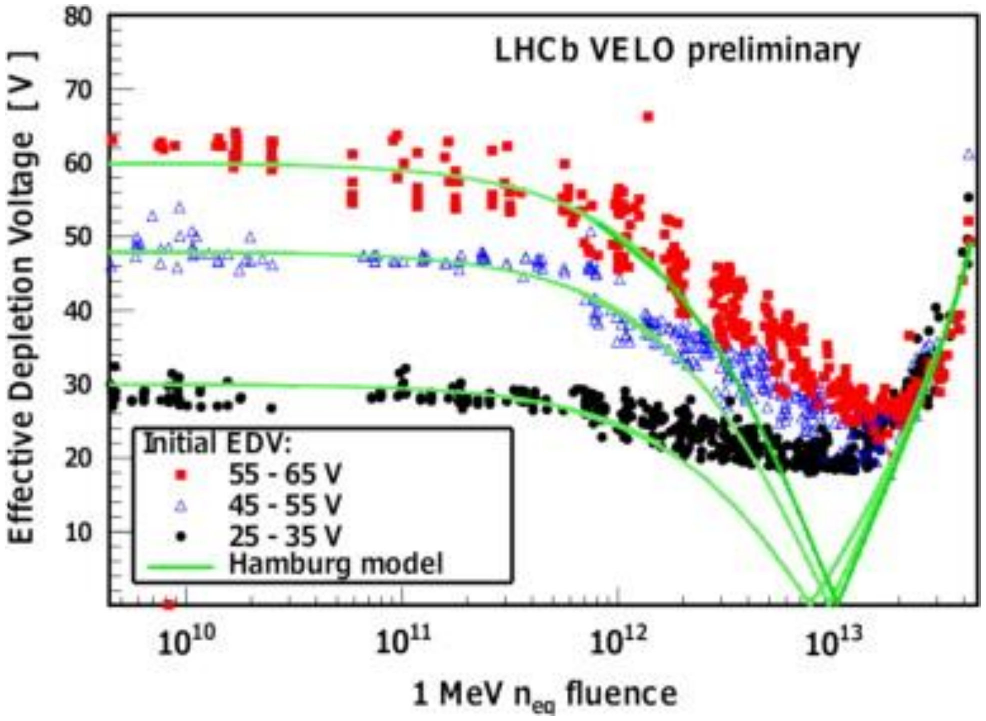
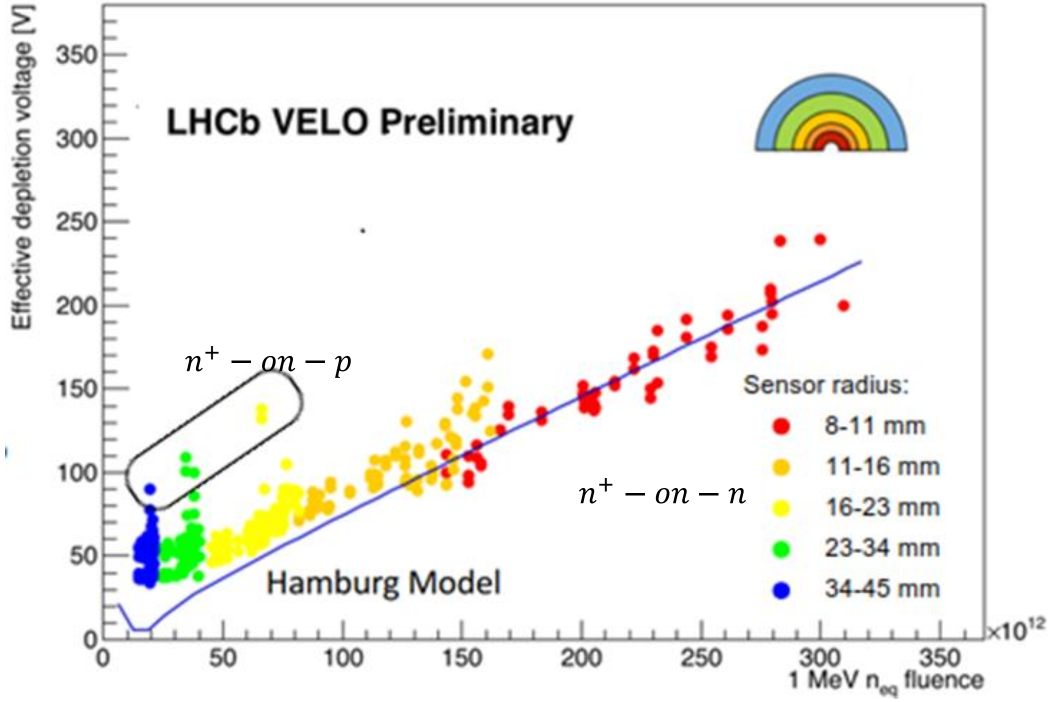
Effective Depletion Voltage (Run 1-2)

- Radiation damage can create defects that **act like dopants themselves**, effectively altering the net doping concentration.
- This can *change the type* of semiconductor (n-type to p-type, called type inversion).
- It alters how much voltage is needed to deplete the active region of the detector fully.
- As a consequence, a much higher bias voltage is required to reach full depletion.





2013 JINST 8 P08002

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How to predict the damage?

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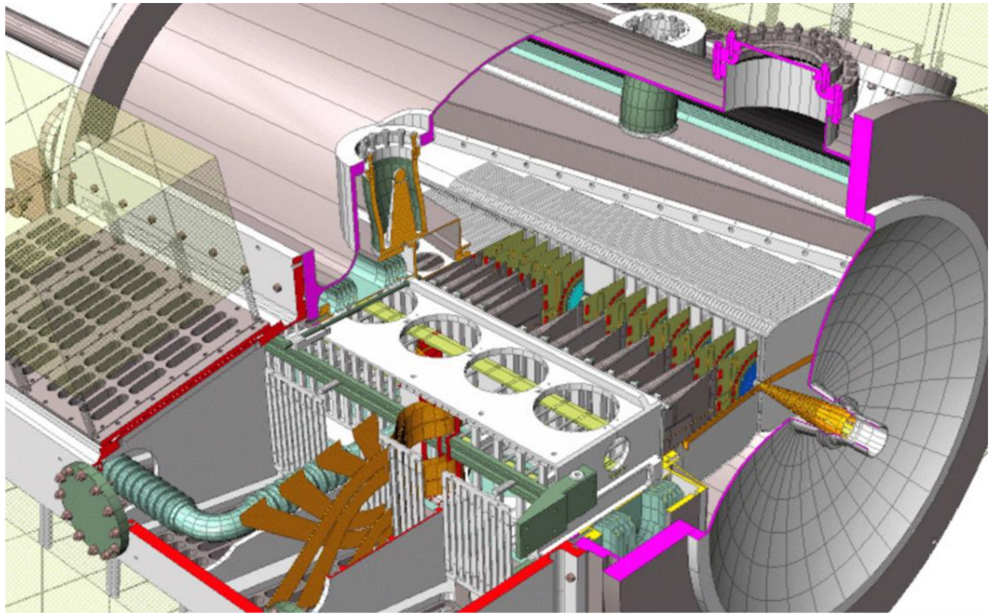
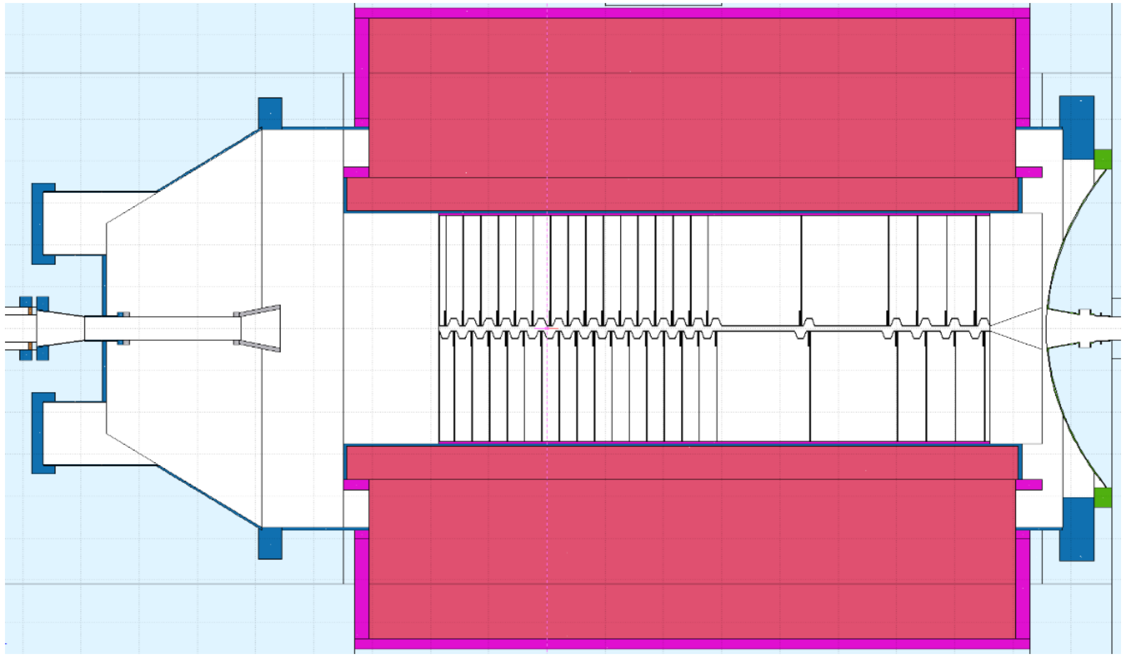
We should have:
- very detailed description of the detector and the experimental cavern,
- physics model for the generation of proton-proton collisions.

GEANT4 A SIMULATION TOOLKIT



https://geant4.web.cern.ch/

FLUKA

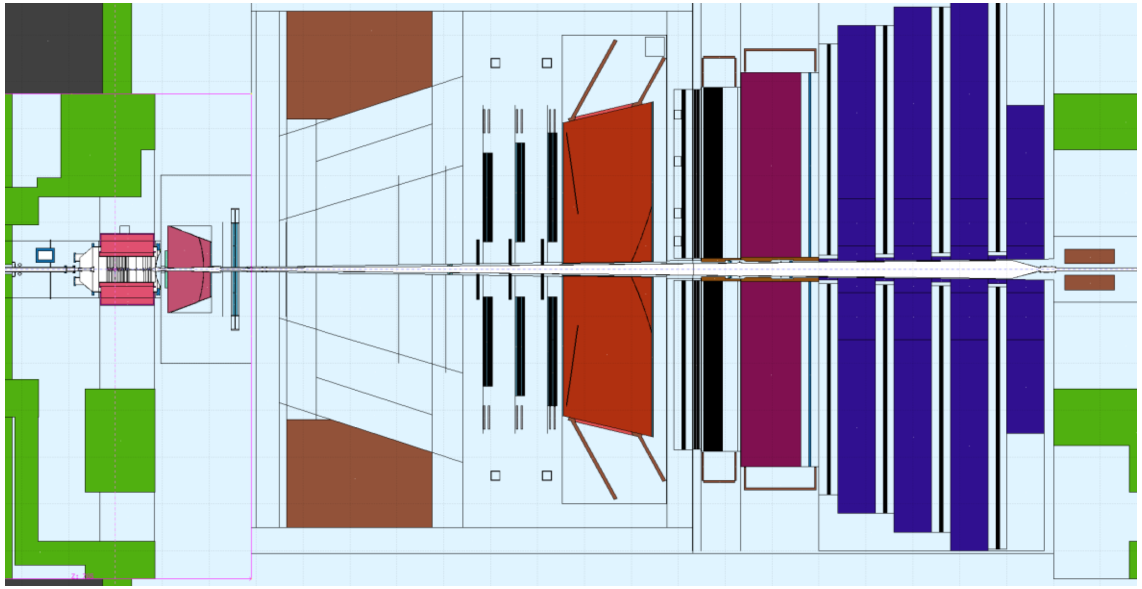


https://fluka.cern/

FLUKA simulaton of LHCb detector

- Monte-Carlo-based particle transport code.
- Version developed and maintained by CERN Written primarily in Fortran.
- Combinatorial Geometry (i.e., CSG).
- Very reliable radiation simulation, especially low-energy neutrons (down to 10^{-14} GeV)

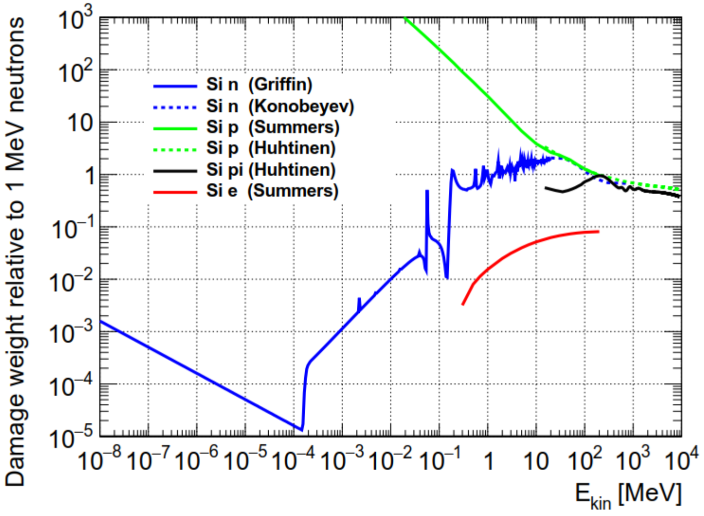
- Geometry description of the LHCb detector in Fluka – before Run 1-2, updated for Run 3-4.
- Plans for the Upgrade 2 (Run 5-6) – time-consuming (gdml to fluka ?).

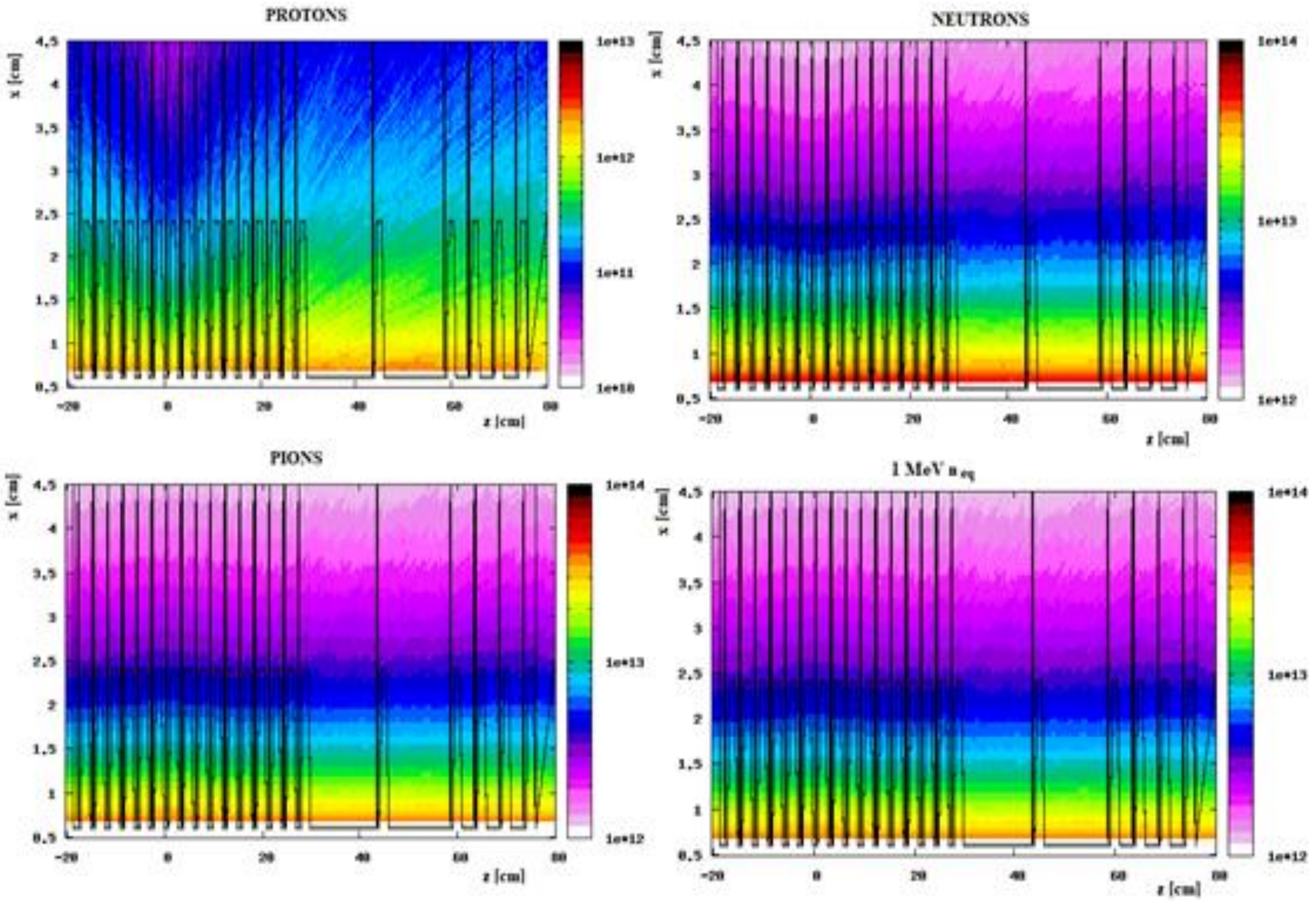


A.Mucha 14th Trento Workshop on Advanced Silicon Radiator Detectors 25-27 of February 2019

Simulation of particle radiation in LHCb

- In the LHC environment, the main source of particle radiation:
  - prompt production of particles (pions, protons, neutrons, kaons, electrons, muons, and photons),
  - production of secondary particles in interactions with the detectors and the decay of radionuclides.





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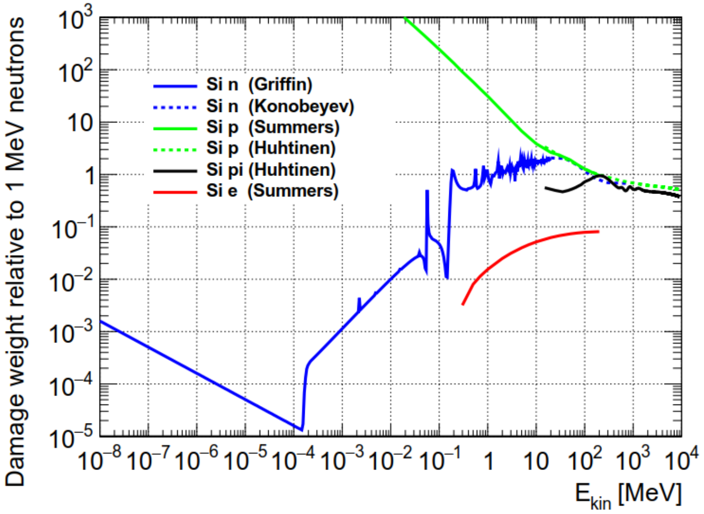

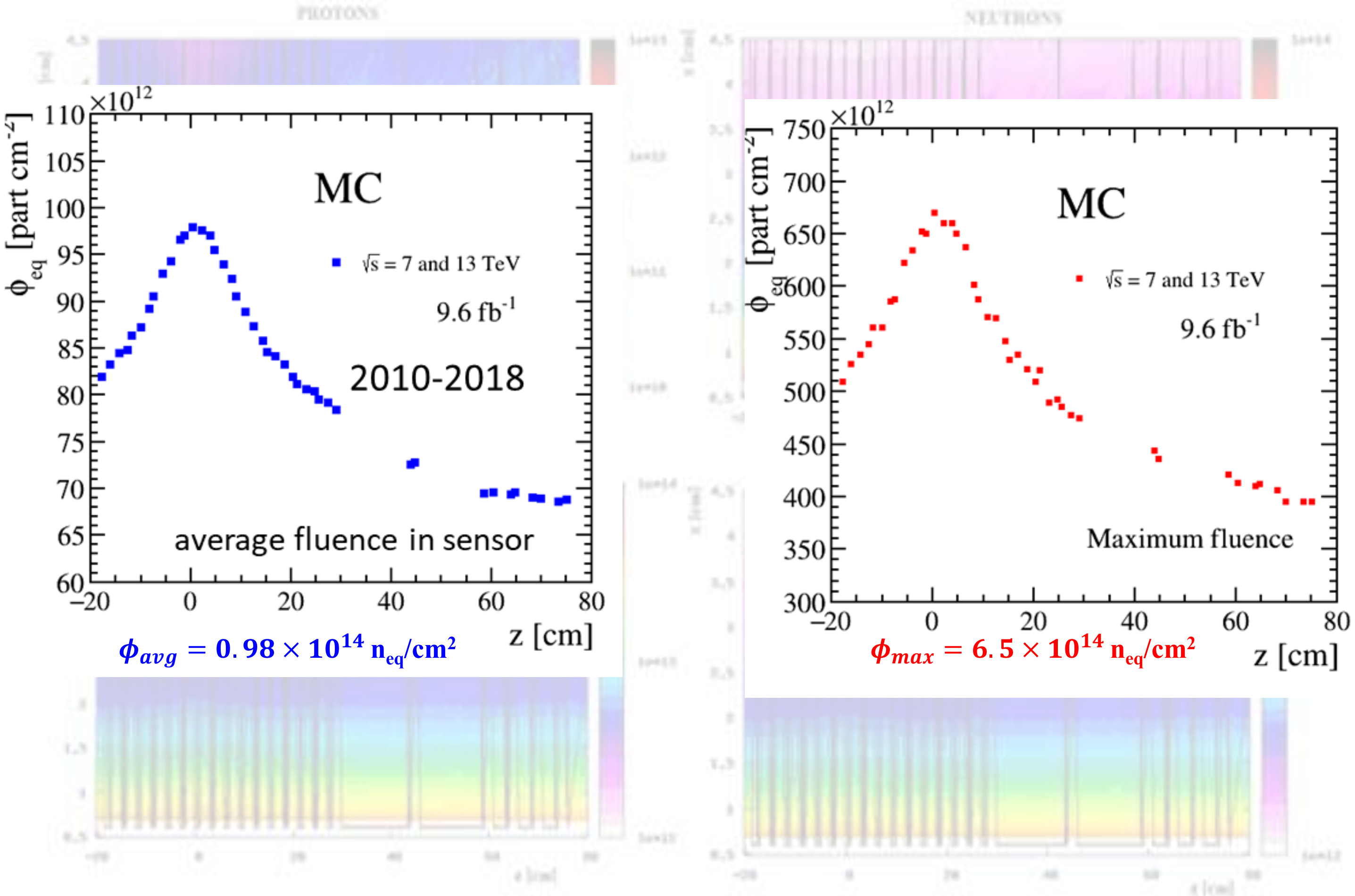

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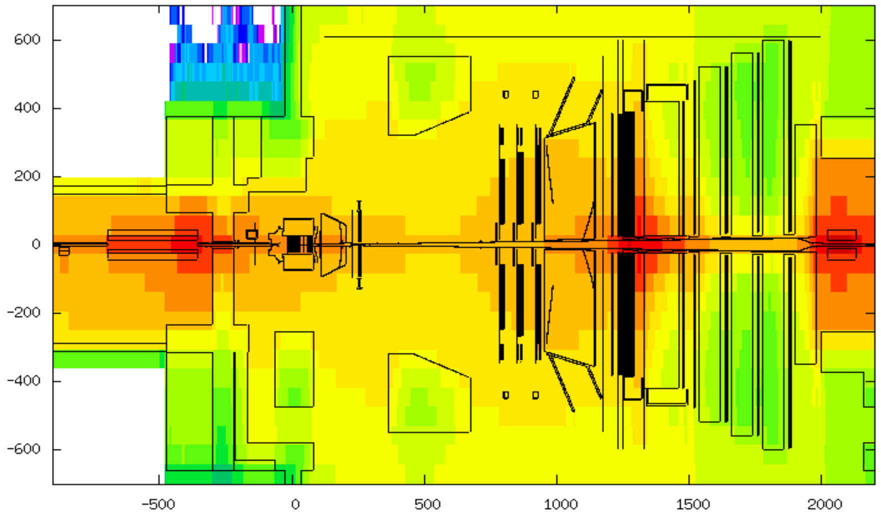
Neutron equivalent fluence in the LHCb spectrometer



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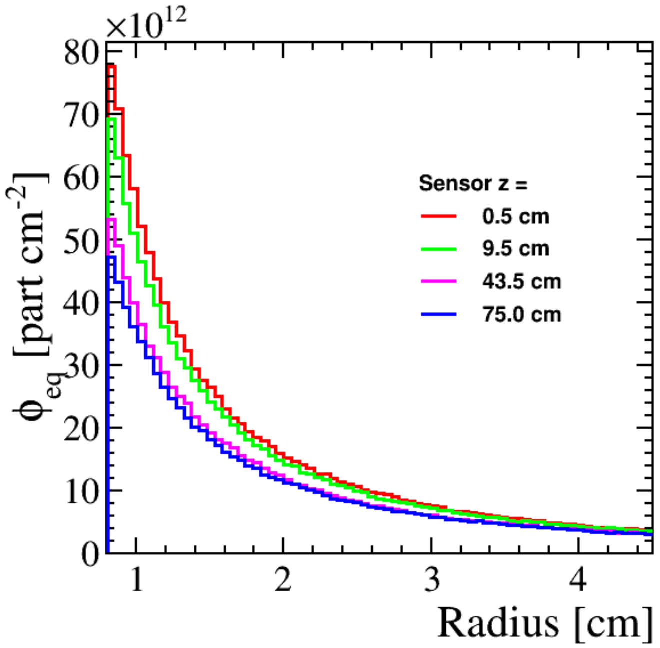

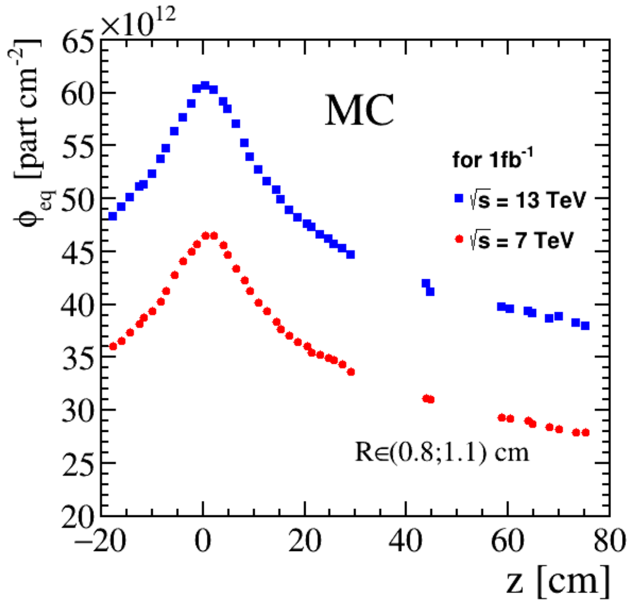

IEEE Trans. Nucl. Sci. 65 (2018) 1127-1132

- The leakage current is measured across the entire sensor.
- The fluence exhibits a strong dependence on the radius.
- The sensor tips may be significantly damaged (reason for annealing at the end of Run 2).
- Dependence of fluence on the center of mass energy.

Limitations in Fluence Measurement at LHCb

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We have dose monitoring, but fluence cannot be reliably measured with the installed sensors – simulations fill that gap

Passive dosimeters
- **good for integrated dose**, not particle fluence.

Active sensors
- **real-time dose**,
- limited neutron fluence only.

Particle fluence
- **cannot be measured directly.**

FLUKA simulations
- used to **estimate fluence** instead of direct measurement.

Dosimeters

Active Dosimeters

real-time, immediate readings of radiation exposure using electronic components

Passive Dosimeters

cumulative exposure over time by absorbing radiation and require laboratory analysis to determine the total dose received

Limitations of the usage FLUKA for LHC Run 5

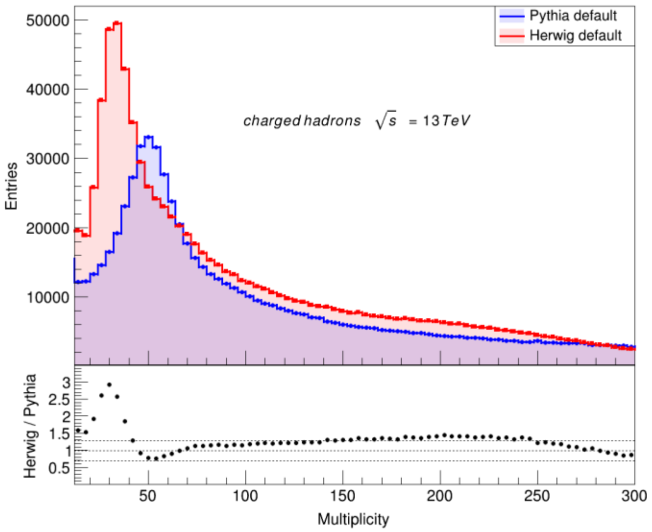
Geometry limitations (man-power and time)

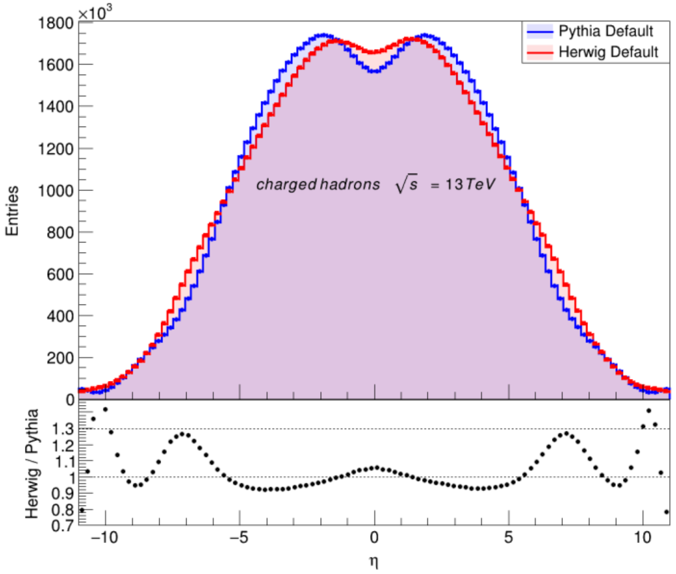
- Full detector and surrounding infrastructure geometry is missing, → impacts accuracy, especially for **backscattering studies**.
- For the upcoming upgrade, no complete geometry description is currently available.
- A conversion tool from **GDML to FLUKA input** was recently developed, but it is **not yet functional**.

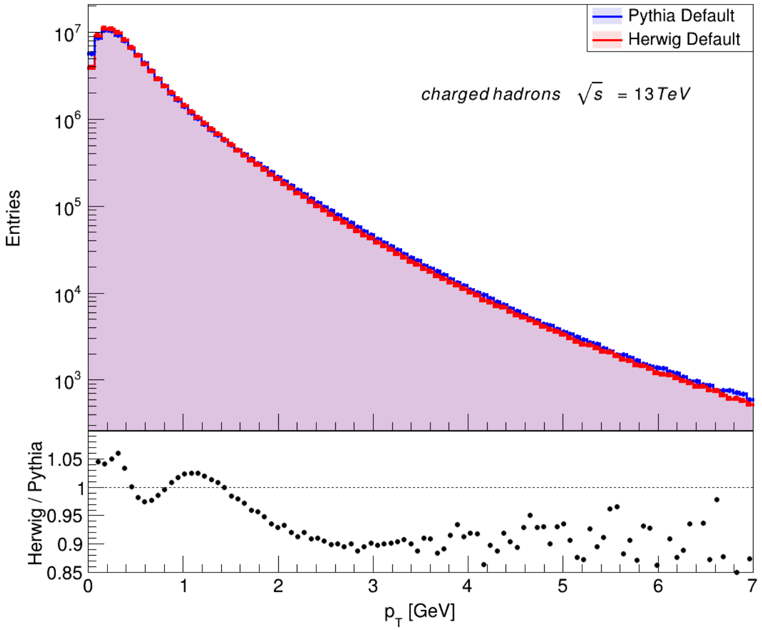
Embedded event generator issues

- Need to assess how different event generators influence simulation results.
- Plan: compare **particle production in pp interactions** across different generators.
- Focus on **Pythia vs. Herwig** differences in particle spectra and distributions.

Particles in Herwig and Pythia



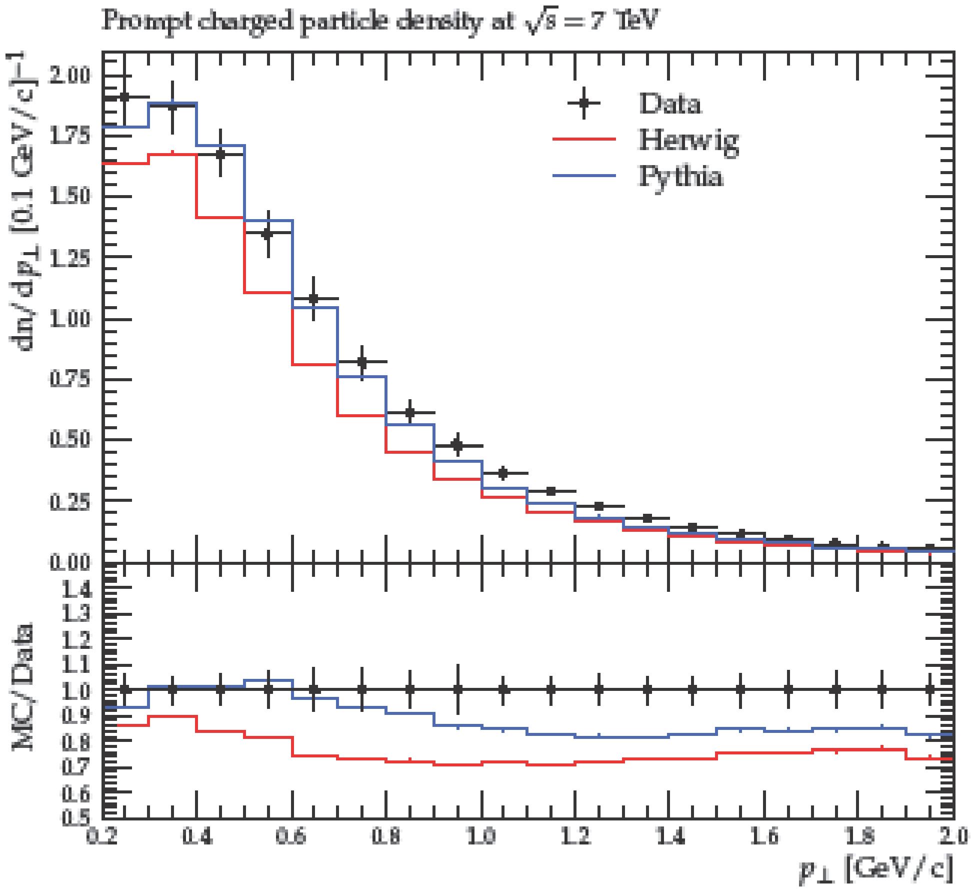




number of particles per one proton-proton interaction

N_{had}	**Pythia**	**Herwig**
Pions	77.5%	80.9%
Protons	11.98%	8.5%
Kaons	10.47%	10.55%
Charged	**92.55**	**92.81**

Comparison of generators with LHCb data



- Discrepancies occur at low momentum and in the very forward region.
- Both generators show a slight variation in the absolute number of hadrons.
- When compared with LHCb data, Pythia is more in agreement with the data.

Data-driven Particle flux analysis

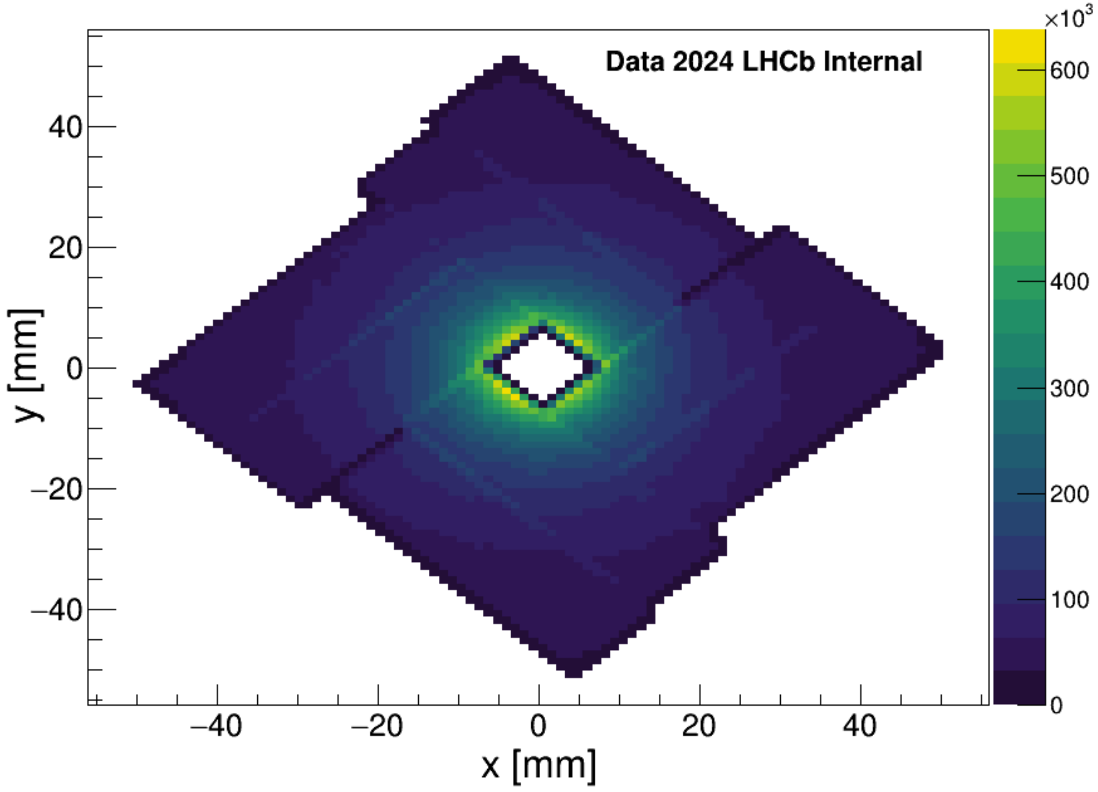
Objective
- Perform data-driven calculations of particle interactions

Requirements
- Particle flux with PID
- Kinetic energy of each particle
- Including neutrons

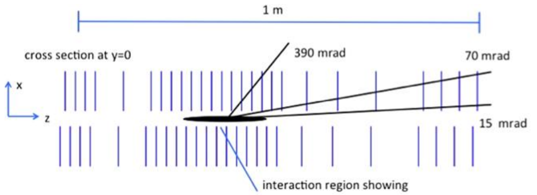
Calculate n_{eq}
- At the surface of silicon sensor

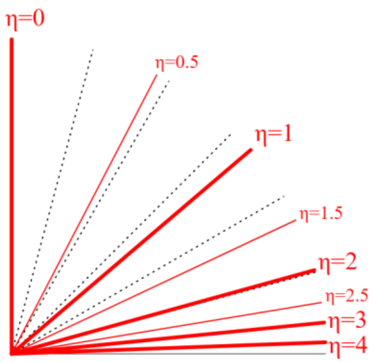
Limitations
- Track reconstruction alone is insufficient

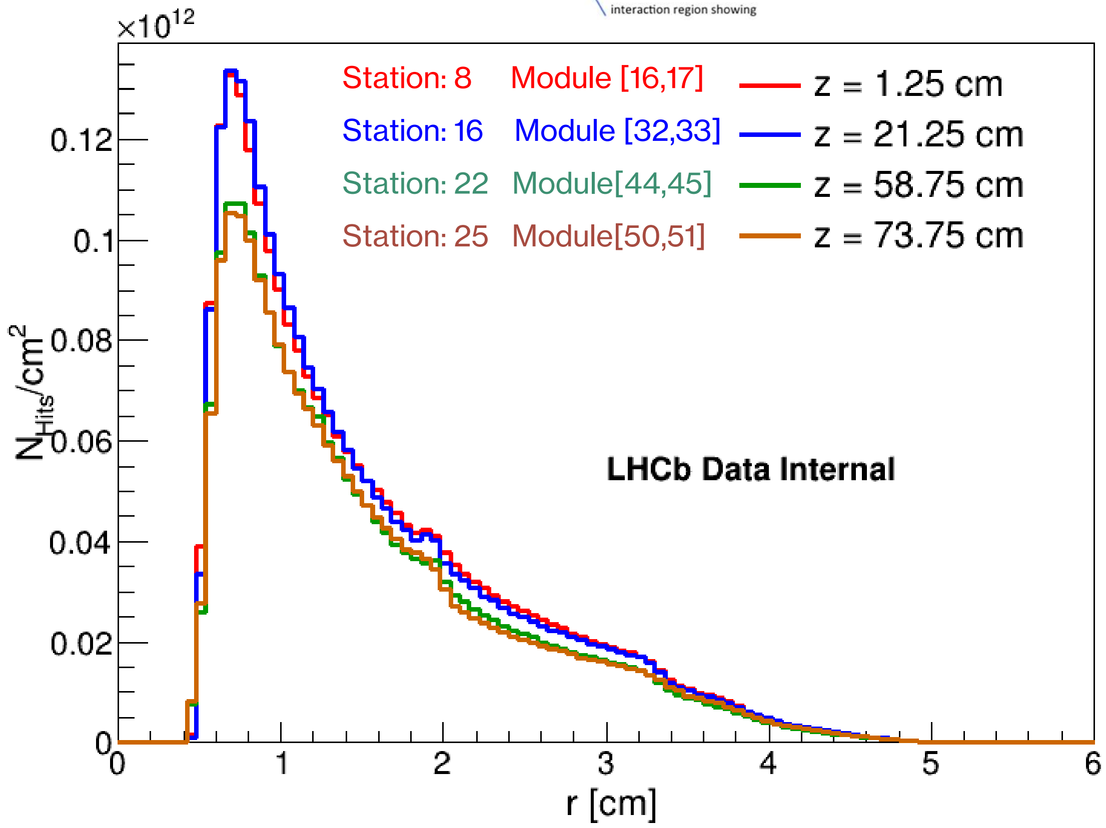
Approach
- Use a method based on VELO hits

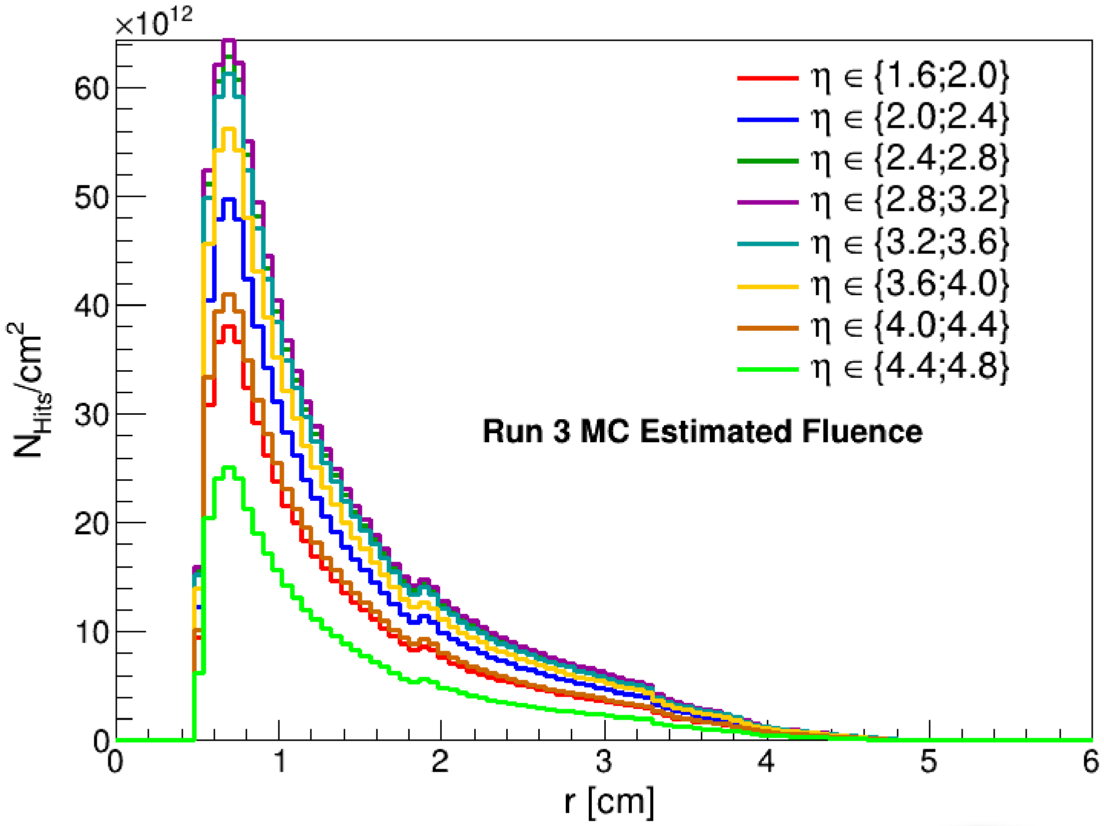


Radial Hit density for Data and MC









Ongoing Study..!!!

Conclusion

- The **upgraded VELO detector faces significant challenges from radiation damage** in its silicon sensors.
- Macroscopic effects, such as **leakage current, depletion voltage**, will be affected as fluence increases.
- To anticipate these effects, reliable radiation **prediction methods** are essential.
- While simulations with tools like **FLUKA** are powerful, they suffer from limitations. This makes purely simulation-based predictions uncertain.
- Direct fluence measurements are not feasible, which highlights the importance of complementary, data-driven approaches.
- By extracting detailed flux information, including particle identification and energy spectra, we can move beyond track reconstruction and apply hit-based methods to estimate radiation impact more accurately.
- Ultimately, combining simulations with carefully designed data-driven strategies will be crucial for understanding and predicting radiation damage in the upgraded VELO.
- This integrated approach will help ensure stable long-term operation of the detector, safeguarding its physics performance within the LHCb experiment.

Thank you...!!

Any Questions?

Back-up

Solid State Detectors – Why Silicon?

- **Some characteristics of Silicon crystals**
  - Small band gap E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/μm (average)
  - High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
  - Very pure < 1ppm impurities and < 0.1ppb electrical active impurities
  - Rigidity of silicon allows thin self supporting structures
  - Detector production by microelectronic techniques

    ⇒ well known industrial technology, relatively low price, small structures easily possible

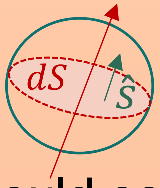
- **Alternative semiconductors**
  - **Diamond**
  - Gallium arsenide (GaAs)
  - Gallium nitride (GaN)
  - **Silicon Carbide (SiC)**
  - Germanium (Ge)

	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.52	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Fluence definitions

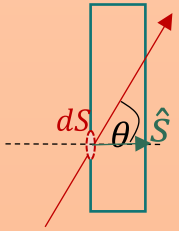
1. Fluence – number of particles dN traversing the sphere of cross section dS:

$$\phi = \frac{dN}{dS}$$



When counting particles hitting the VELO sensors one should consider $cos\theta$:

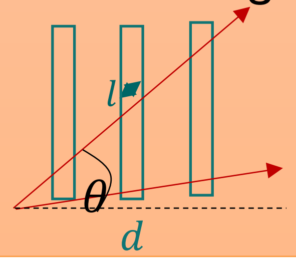
$$\phi = \frac{dN}{dS_{\parallel}} = \frac{dN}{dS\ \ cos\theta}$$



That makes the particles crossing at large angle the most dangerous.

2. We can take the track length - fluence is then defined as the track length density:

$$\phi = \frac{\sum l}{V} = \frac{\sum d/cos\theta}{V}$$



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  - **cannot be measured directly**.
- **FLUKA simulations**
  - used to **estimate fluence** instead of direct measurement.

Sensor	**Type**
Alanine / TLD / RPL	**Passive**
PiN diodes	**Passive / Active**
BPW diodes	**Passive**
MCP	**Passive**
UHTR	**Passive**
REM box	**Active**