Radiation effects in the LHC experiments: Impact on detector performance & operation

Benjamin Nachman

Lawrence Berkeley National Laboratory

Brown bag instrumentation seminar

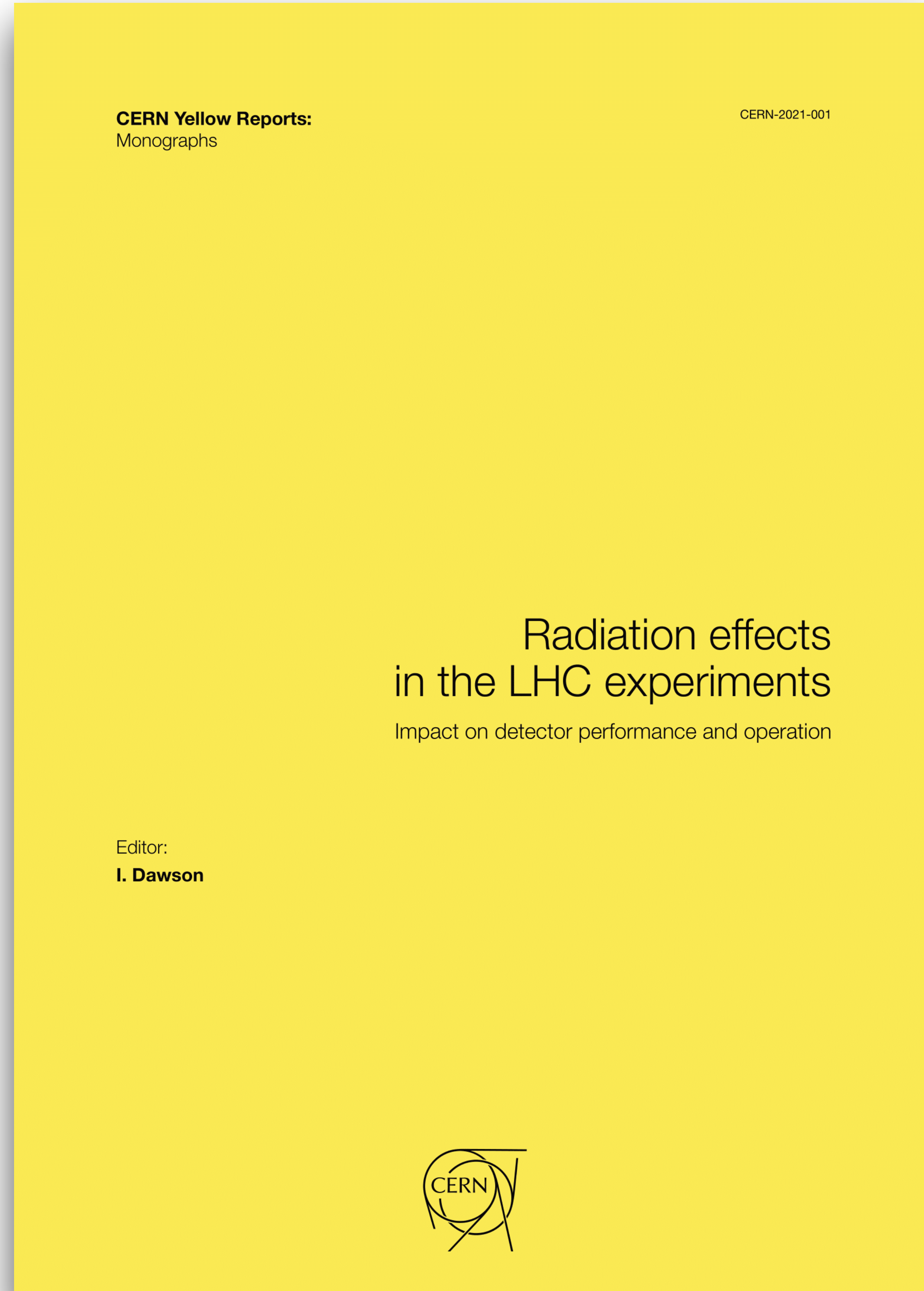
May 5, 2021

BERKELEY LAB

RD50

ATLAS EXPERIMENT

Overview


CERN Yellow Reports:
Monographs

CERN-2021-001

Radiation effects
in the LHC experiments
Impact on detector performance and operation

Editor:
I. Dawson

CERN

Radiation effects in the LHC experiments: Impact on detector performance and operation

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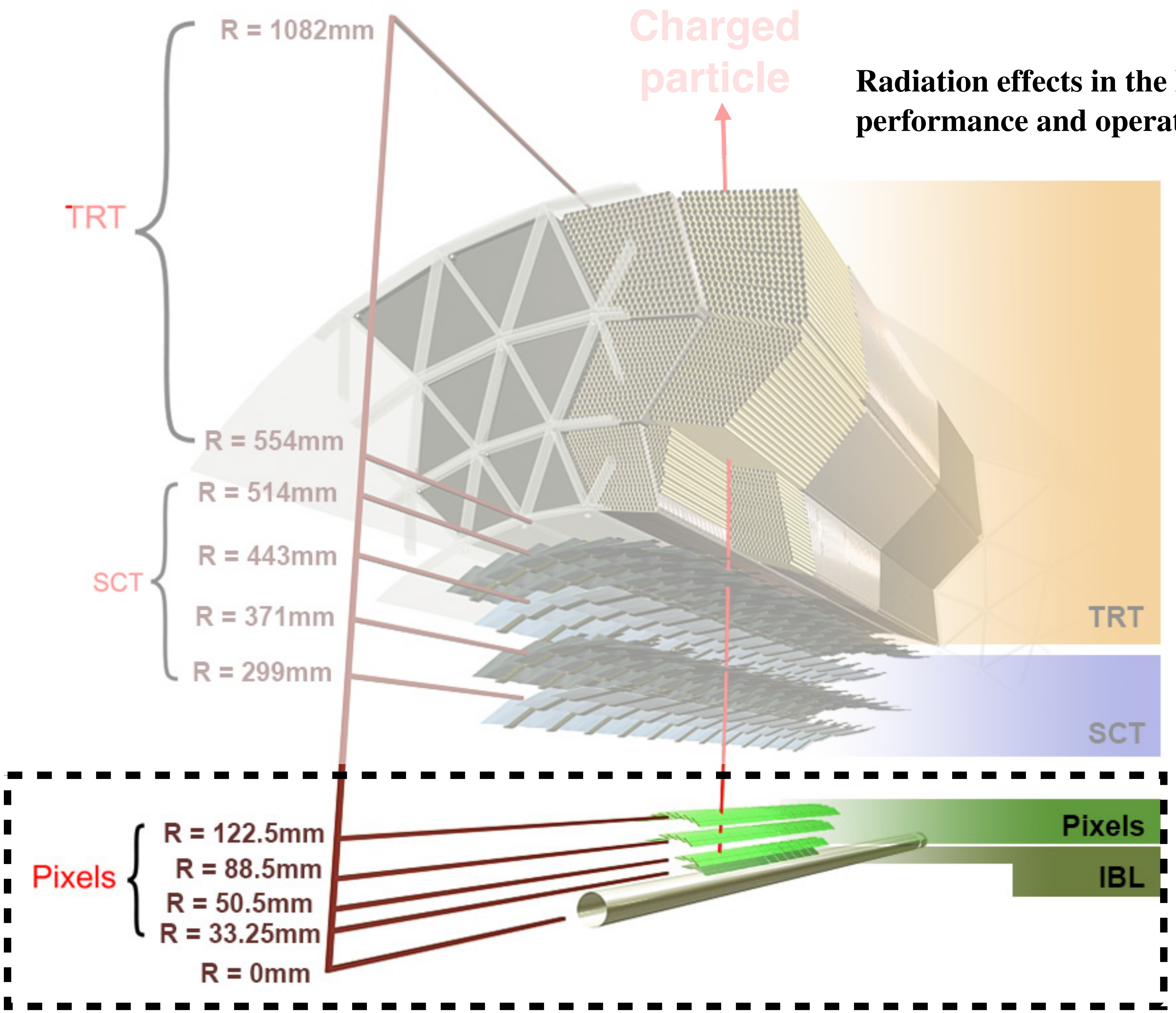
Section editors: M. Bindi, M. Bomben, E. Butz, P. Collins, A. de Cosa, I. Dawson, S. Mallows, M. Moll B. Nachman, J. Sonneveld

Abstract
This report documents the knowledge and experiences gained by the LHC experiments in running detector systems in radiation environments during 2010–2018, with a focus on the inner detector systems. During this time, the LHC machine has delivered a large fraction of the design luminosity to the experiments and the deleterious effects of radiation on detector operation are being observed and measured. It is timely to review the findings from across the experiments. Questions we aim to answer include: Are the detector systems operating and performing as expected? How reliable are the radiation damage models and predictions? How accurate are the Monte Carlo simulation codes? Have there been unexpected effects? What mitigation strategies have been developed? A major goal of this report is to provide a reference for future upgrades and for future collider studies, summarizing the experiences and challenges in designing complex detector systems for operation in harsh radiation environments.

Keywords
Radiation effects; LHC experiments; radiation environments; simulation; modelling; detectors; electronics.

https://doi.org/10.23731/CYRM-2021-001

Overview



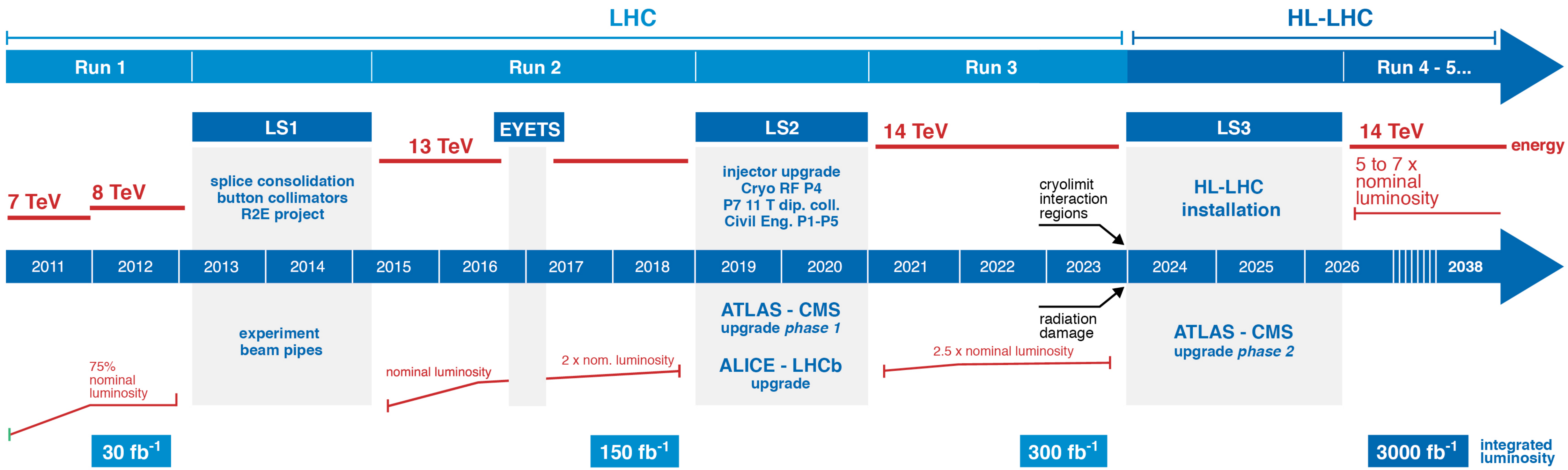
Radiation effects in the LHC experiments: Impact on detector performance and operation

mostly silicon detectors

(closest to the interaction point = most radiation damage)

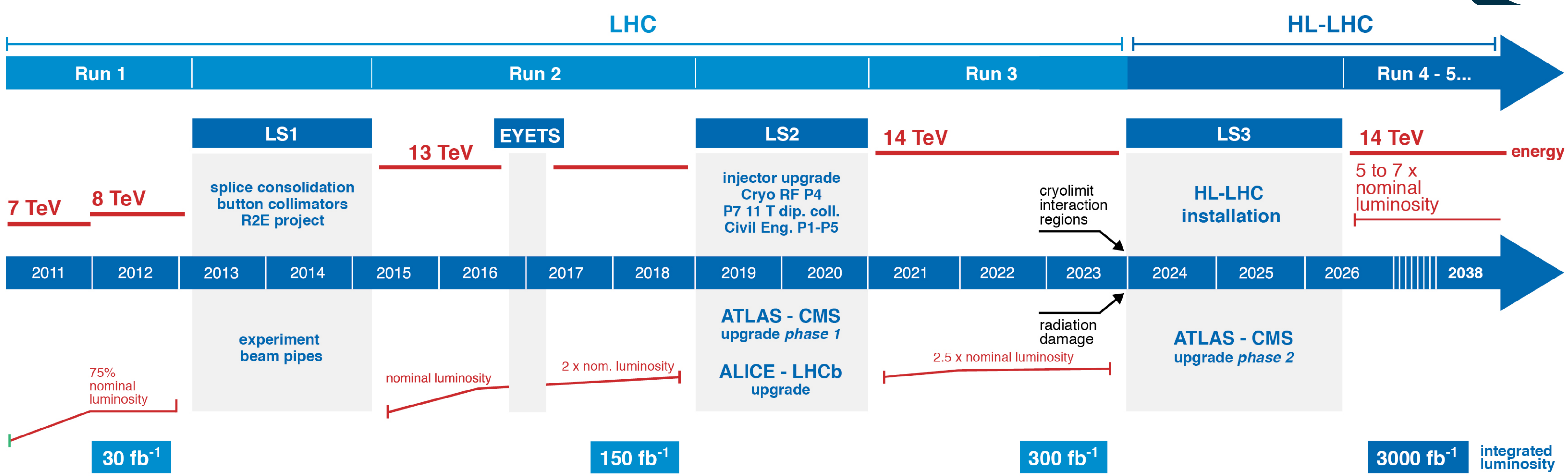
https://doi.org/10.23731/CYRM-2021-001

Why now?



LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
injector upgrade
Cryo RF P4
P7 11 T dip. coll.
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

Why now?



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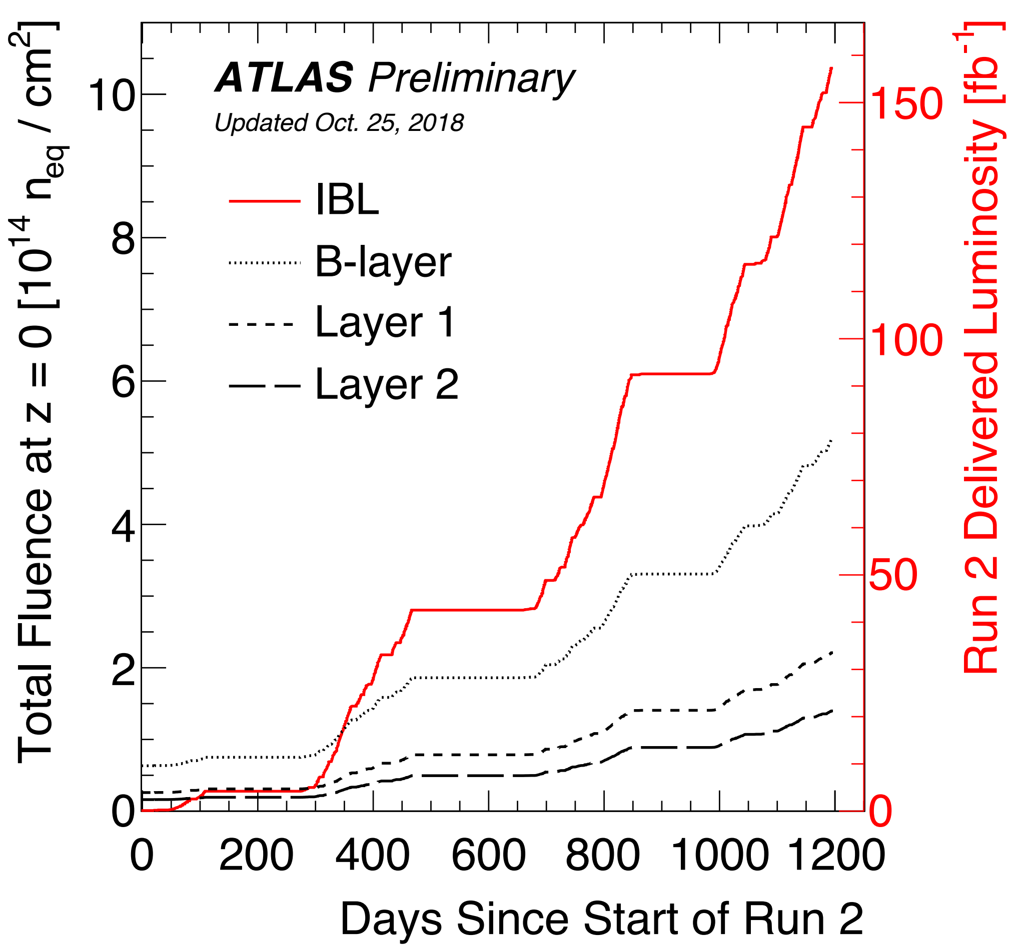
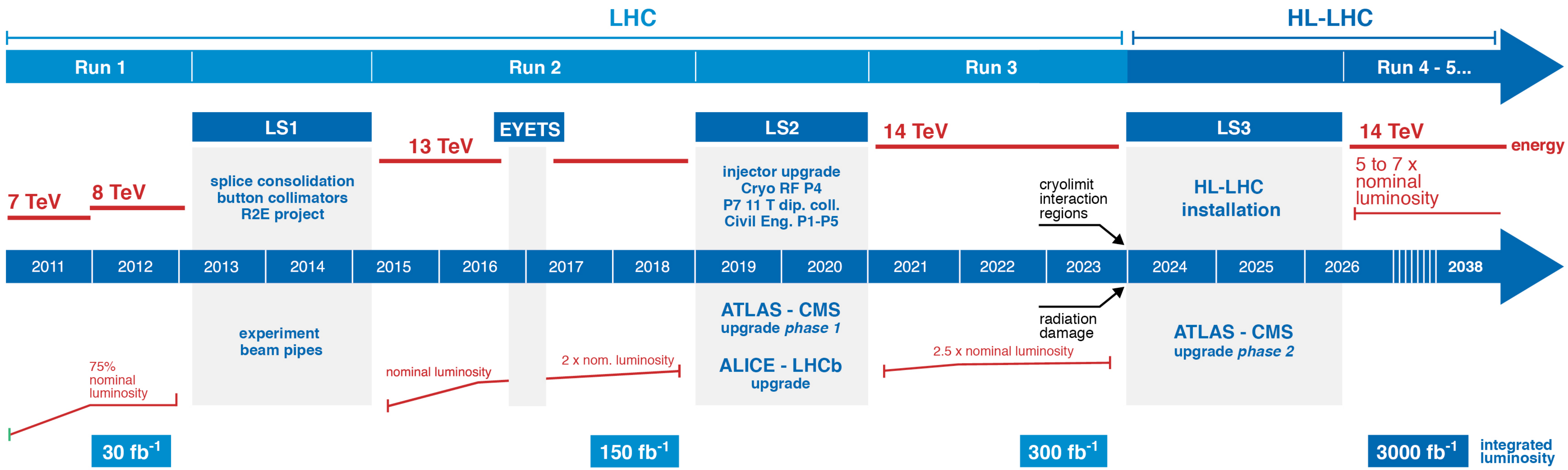
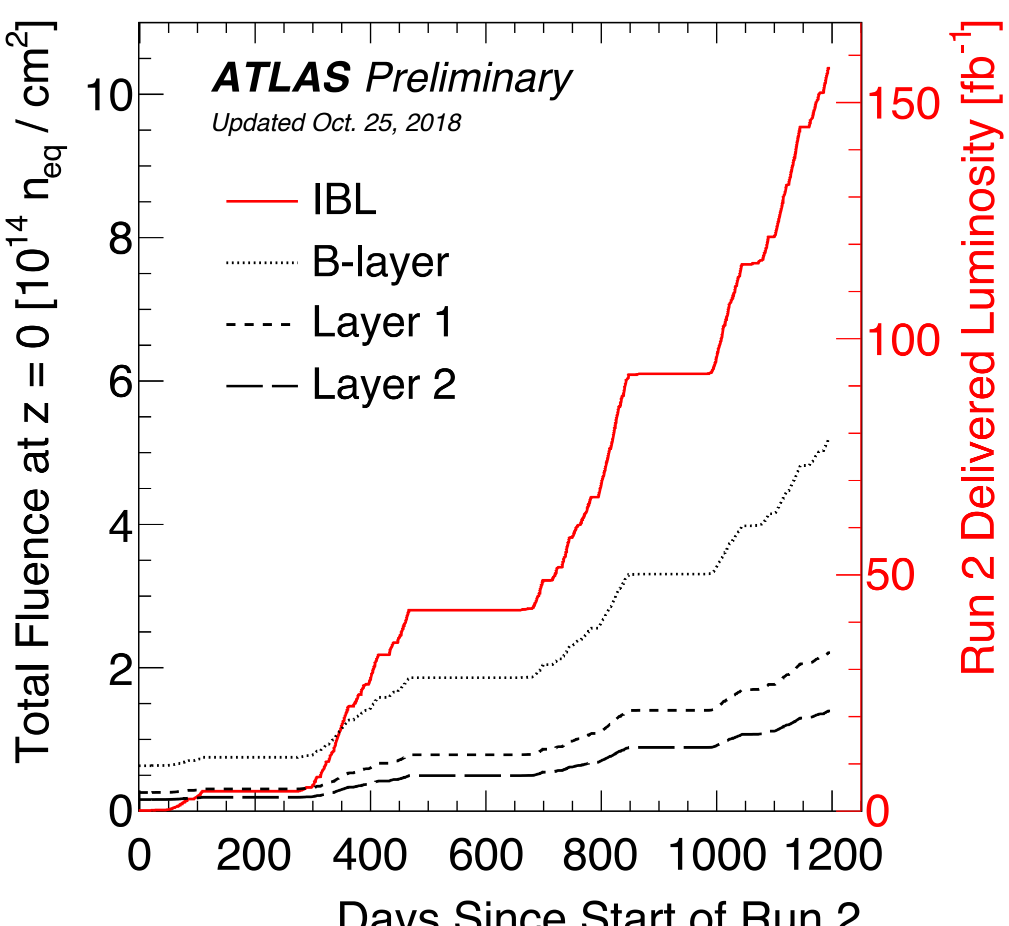


ATLAS Preliminary
Updated Oct. 25, 2018
IBL
B-layer
Layer 1
Layer 2
Total Fluence at z = 0 [10^14 n_eq / cm^2]
Run 2 Delivered Luminosity [fb^-1]
Days Since Start of Run 2
0
2
4
6
8
10
0
50
100
150
0
200
400
600
800
1000
1200

Why now?





We have now passed 10^{15} 1 MeV n_{eq}/cm^2 !

We have huge, irradiated detectors to inform Run 3 / HL-LHC / beyond

Why now?

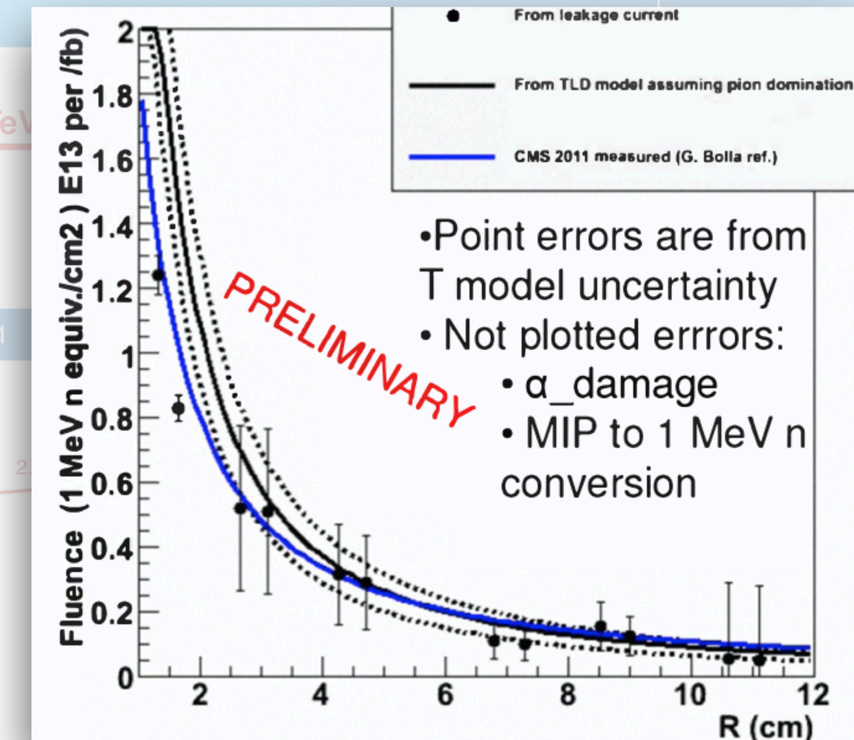
Context:

Tevatron: ~10^{14} n_{eq}/cm^2

HL-LHC: ~10^{16} n_{eq}/cm^2

Charge lifetime:
~ O(ns)/(10^{-16} cm^2 x fluence);
drift time in our sensor is O(ns)

CDF Collaboration, Run II



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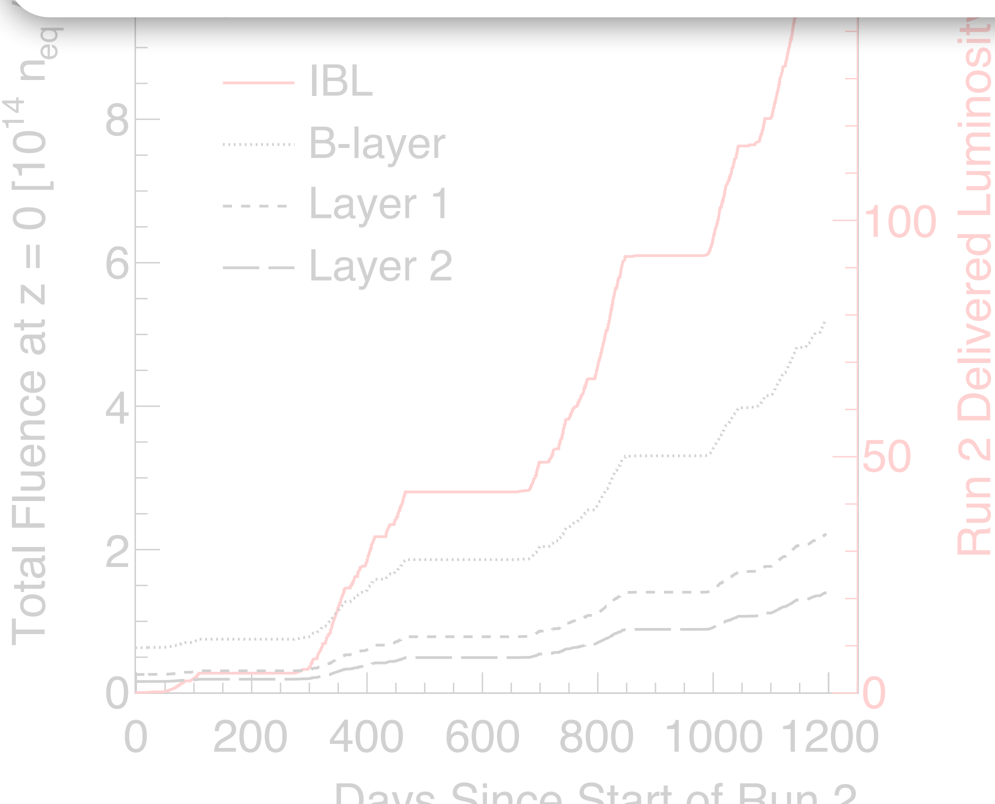

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Why now?

https://indico.cern.ch/event/769192/

Radiation effects in the LHC experiments and impact on operation and performance

11-12 February 2019
CERN
Europe/Zurich timezone

Search...

https://indico.cern.ch/event/695271/

Radiation effects at the LHC experiments and impact on operation and performance

23-24 April 2018
CERN
Europe/Zurich timezone

Search...

Session

LHC-experiment radiation damage workshop

20 Nov 2017, 09:00
6/2-024 - BE Auditorium Meyrin (CERN)

Conveners

LHC-experiment radiation damage workshop
Ben Nachman (Lawrence Berkeley National Lab. (US))

https://indico.cern.ch/event/663851/sessions/250141/#20171120

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2019 workshop packed agenda

Goal: bring together experts across the LHC experiments and share experiences of running complex detector systems in harsh radiation environments.

…How well are we modelling and monitoring radiation damage?
…Have there been unforeseen effects, if so how was the impact mitigated?
…What are the operational plans for LS2 to ensure performance success for Run 3?
…What lessons can be learned for the LHC upgrades and future tracking detector systems?

Session 1: Sensor Measurements

Silicon radiation damage at the LHC experiments	Jory Sonneveld	6-2-024 - BE Auditorium Meyrin, CERN	09:15 - 09:45
CMS pixel radiation damage measurements	Finn Feindt	6-2-024 - BE Auditorium Meyrin, CERN	09:45 - 10:05
Leakage current measurements with the ATLAS pixel detector	Aidan Grummer	6-2-024 - BE Auditorium Meyrin, CERN	10:05 - 10:25
CMS strip radiation damage measurements	Jean-Laurent Agram	6-2-024 - BE Auditorium Meyrin, CERN	10:25 - 10:45
Coffee break		6-2-024 - BE Auditorium Meyrin, CERN	10:45 - 11:10
Sensor measurements with the ATLAS SCT	Kazuya Mochizuki	6-2-024 - BE Auditorium Meyrin, CERN	11:10 - 11:30
Radiation effects in the LHCb VELO Run 1+2	Gediminas Sarpis	6-2-024 - BE Auditorium Meyrin, CERN	11:30 - 11:50
Recent results of the RD50 Collaboration	Marta Baselga	6-2-024 - BE Auditorium Meyrin, CERN	11:50 - 12:10
Discussion		6-2-024 - BE Auditorium Meyrin, CERN	12:10 - 12:30
Lunch break			

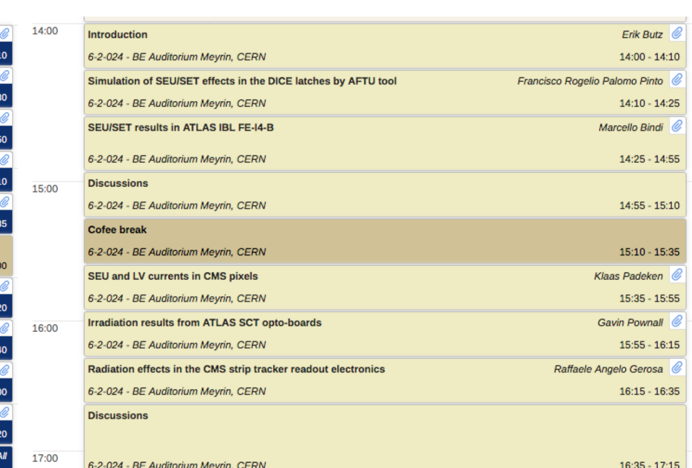
Session 2: Sensor Simulations

		6-2-024 - BE Auditorium Meyrin, CERN	12:30 - 14:00
Introduction		6-2-024 - BE Auditorium Meyrin, CERN	14:00 - 14:10
Overview	Mathieu Benoit	6-2-024 - BE Auditorium Meyrin, CERN	14:10 - 14:45
Silicon Pixel Sensor Simulation in the CMS Monte Carlo Framework	Cristina Ana Mantilla Suarez	6-2-024 - BE Auditorium Meyrin, CERN	14:45 - 15:05
Pixel Radiation Damage Measurements with ATLAS	Paolo Sabatini	6-2-024 - BE Auditorium Meyrin, CERN	15:05 - 15:25
Coffee Break		6-2-024 - BE Auditorium Meyrin, CERN	15:25 - 15:50
Lorentz angle measurements and simulations in ATLAS	Javier Llorente Merino	6-2-024 - BE Auditorium Meyrin, CERN	15:50 - 16:10
Status and Plans for ATLAS Radiation Damage Simulation	Alex Zeng Wang	6-2-024 - BE Auditorium Meyrin, CERN	16:10 - 16:30
Silicon Strip Sensor Simulation in the CMS Monte Carlo Framework	Eric Chabert	6-2-024 - BE Auditorium Meyrin, CERN	16:30 - 16:50
Discussion		6-2-024 - BE Auditorium Meyrin, CERN	16:50 - 17:15

Session 3: Radiation Simulation

Introduction	Ian Dawson	6-2-024 - BE Auditorium Meyrin, CERN	09:00 - 09:10
Radiation damage simulation and modelling in FLUKA	Vasilis Vlachoudis	6-2-024 - BE Auditorium Meyrin, CERN	09:10 - 09:30
Radiation background simulation capabilities of Geant4	Prof. Vladimir Ivantchenko	6-2-024 - BE Auditorium Meyrin, CERN	09:30 - 09:50
Event generators for simulating radiation backgrounds	Deepak Kar	6-2-024 - BE Auditorium Meyrin, CERN	09:50 - 10:10
On the uncertainties of silicon hardness factors	Mika Huhtinen	6-2-024 - BE Auditorium Meyrin, CERN	10:10 - 10:35
Coffee break		6-2-024 - BE Auditorium Meyrin, CERN	10:35 - 11:00
ATLAS simulations, predictions, comparison with data	Sven Menke	6-2-024 - BE Auditorium Meyrin, CERN	11:00 - 11:20
CMS simulations, predictions, comparison with data	Sophie Mallows	6-2-024 - BE Auditorium Meyrin, CERN	11:20 - 11:40
LHCb simulations, predictions, comparison with data	Agnieszka Mucha et al.	6-2-024 - BE Auditorium Meyrin, CERN	11:40 - 12:00
ALICE simulations, predictions, comparisons with data	Antonello Di Mauro	6-2-024 - BE Auditorium Meyrin, CERN	12:00 - 12:20
Discussion	All	6-2-024 - BE Auditorium Meyrin, CERN	12:20 - 12:35

Session 4: (Opto)Electronics

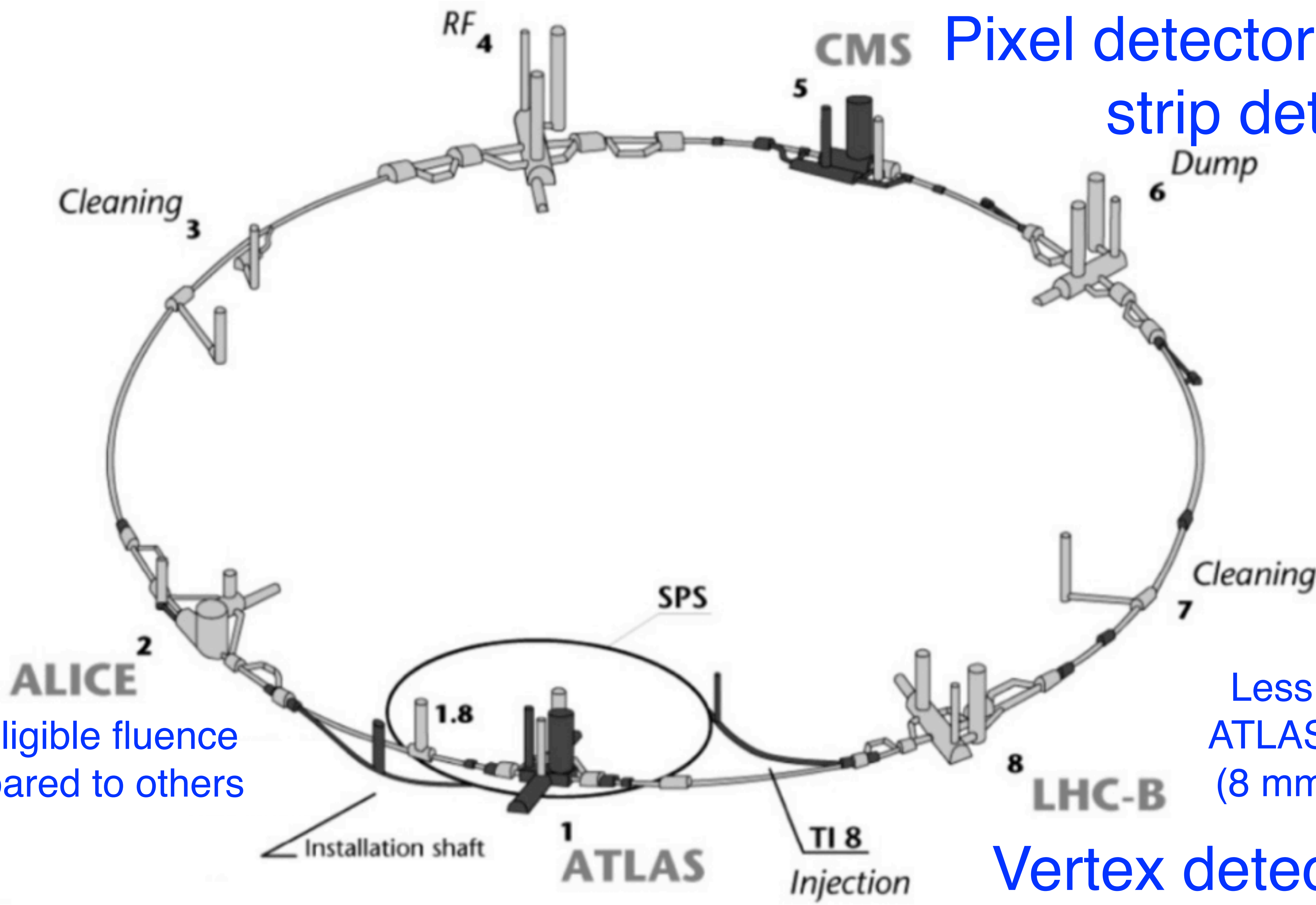


Introduction	Erik Butz	6-2-024 - BE Auditorium Meyrin, CERN	14:00 - 14:10
Simulation of SEU/SET effects in the DICE latches by AFTU tool	Francisco Rogelio Palomo Pinto	6-2-024 - BE Auditorium Meyrin, CERN	14:10 - 14:25
SEU/SET results in ATLAS IBL FE-I4-B	Marcello Bindi	6-2-024 - BE Auditorium Meyrin, CERN	14:25 - 14:55
Discussions		6-2-024 - BE Auditorium Meyrin, CERN	14:55 - 15:10
Cofee break		6-2-024 - BE Auditorium Meyrin, CERN	15:10 - 15:35
SEU and LV currents in CMS pixels	Klaas Padeken	6-2-024 - BE Auditorium Meyrin, CERN	15:35 - 15:55
Irradiation results from ATLAS SCT opto-boards	Gavin Pownall	6-2-024 - BE Auditorium Meyrin, CERN	15:55 - 16:15
Radiation effects in the CMS strip tracker readout electronics	Raffaele Angelo Gerosa	6-2-024 - BE Auditorium Meyrin, CERN	16:15 - 16:35
Discussions		6-2-024 - BE Auditorium Meyrin, CERN	16:35 - 17:15

Workshop webpage: https://indico.cern.ch/event/769192/

Across the LHC

Pixel detector (replaced 2016), strip detector



~negligible fluence compared to others

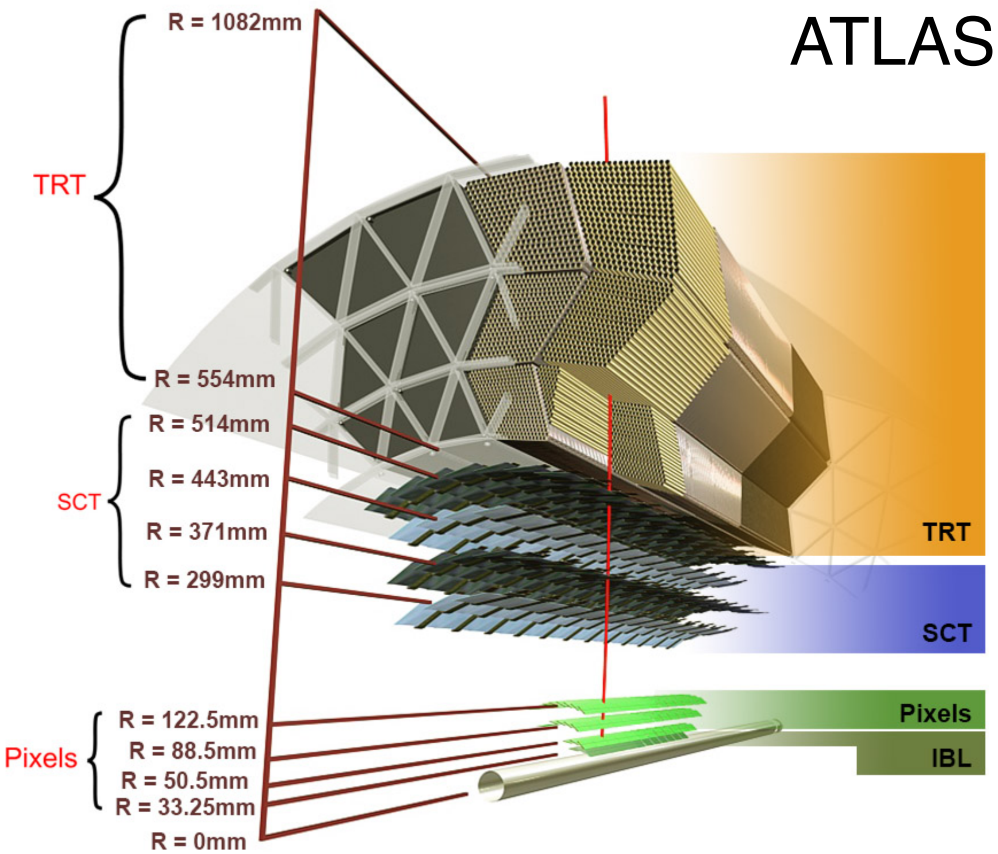
Less luminosity than ATLAS/CMS but closer (8 mm versus few cm)

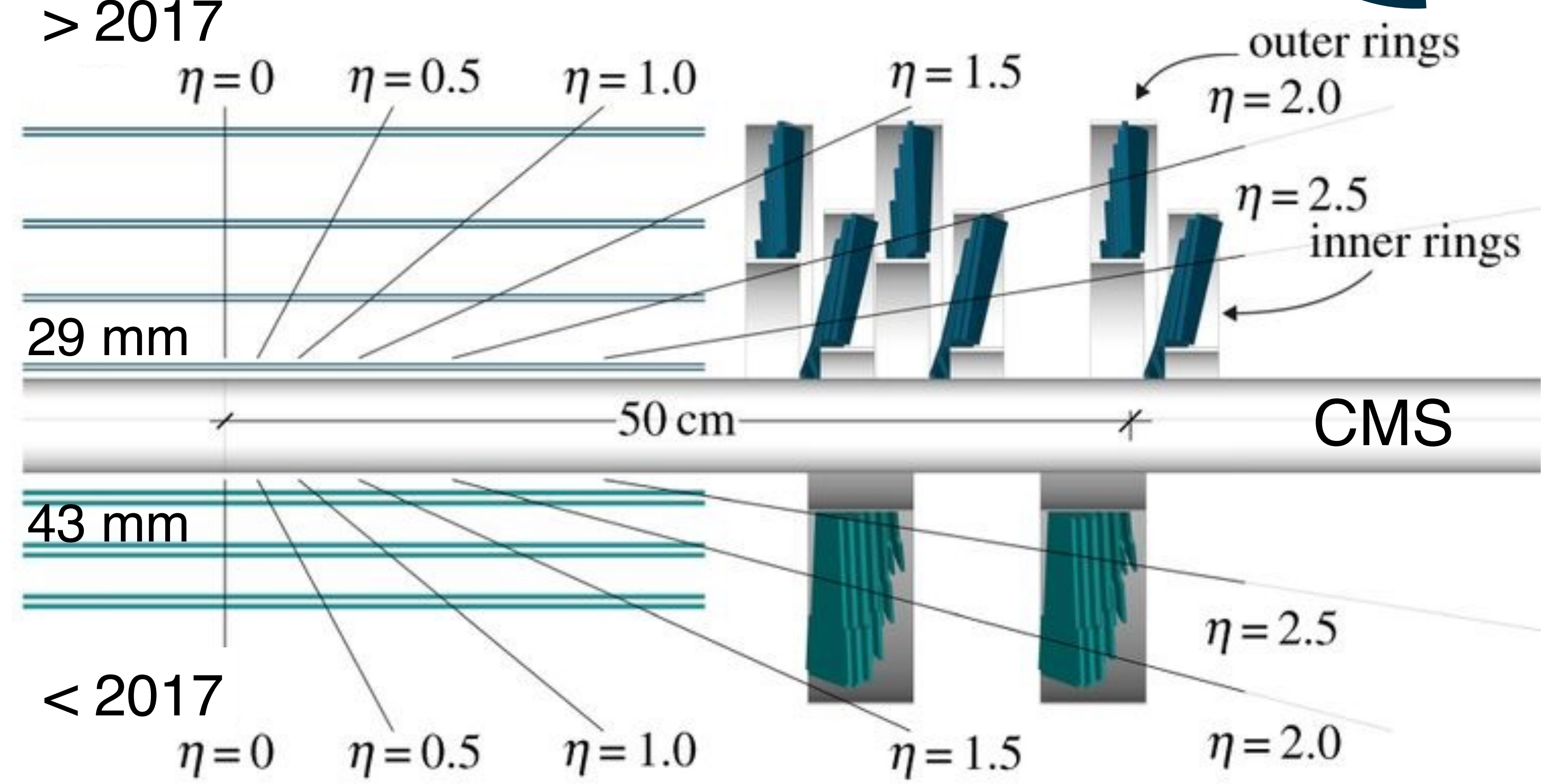
Vertex detector (VELO) strip detector (ST)

Pixel detectors (augmented in 2013), strip detector (SCT)

Across the LHC

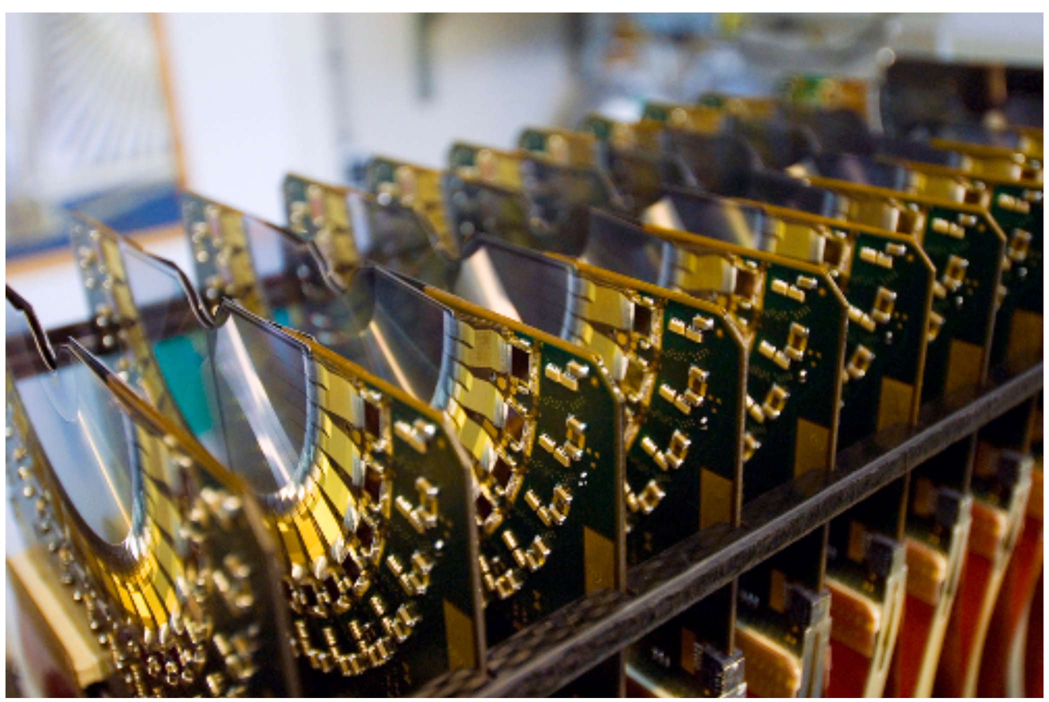
ATLAS

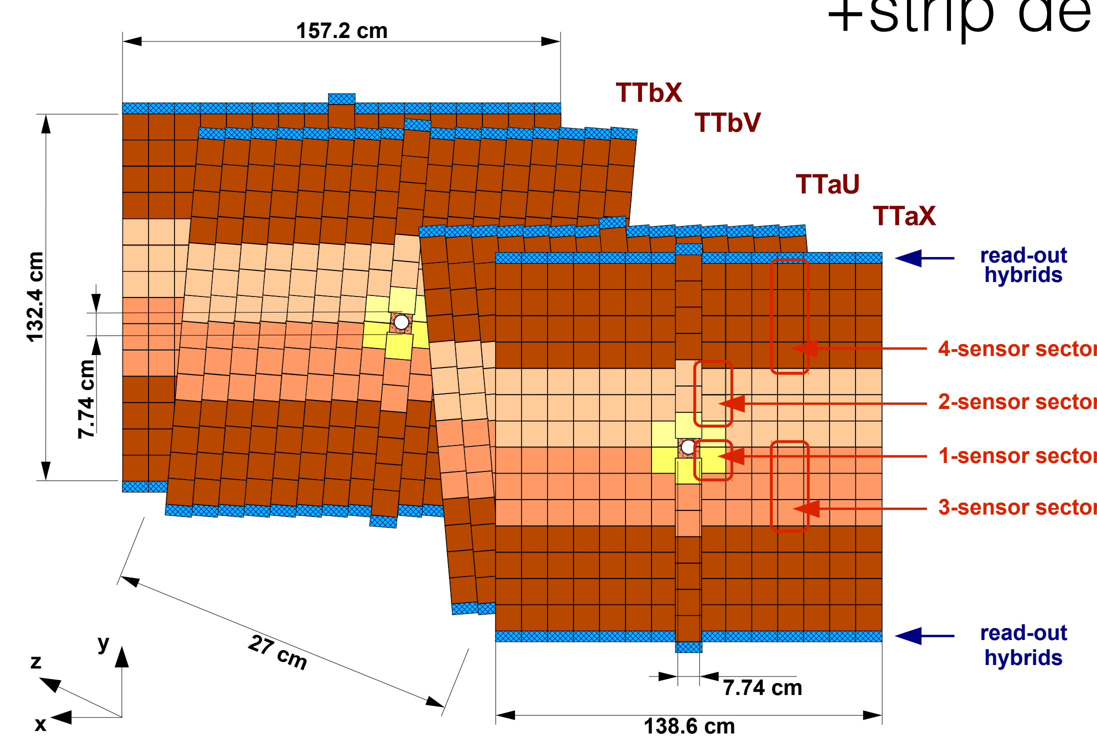




+strip detector

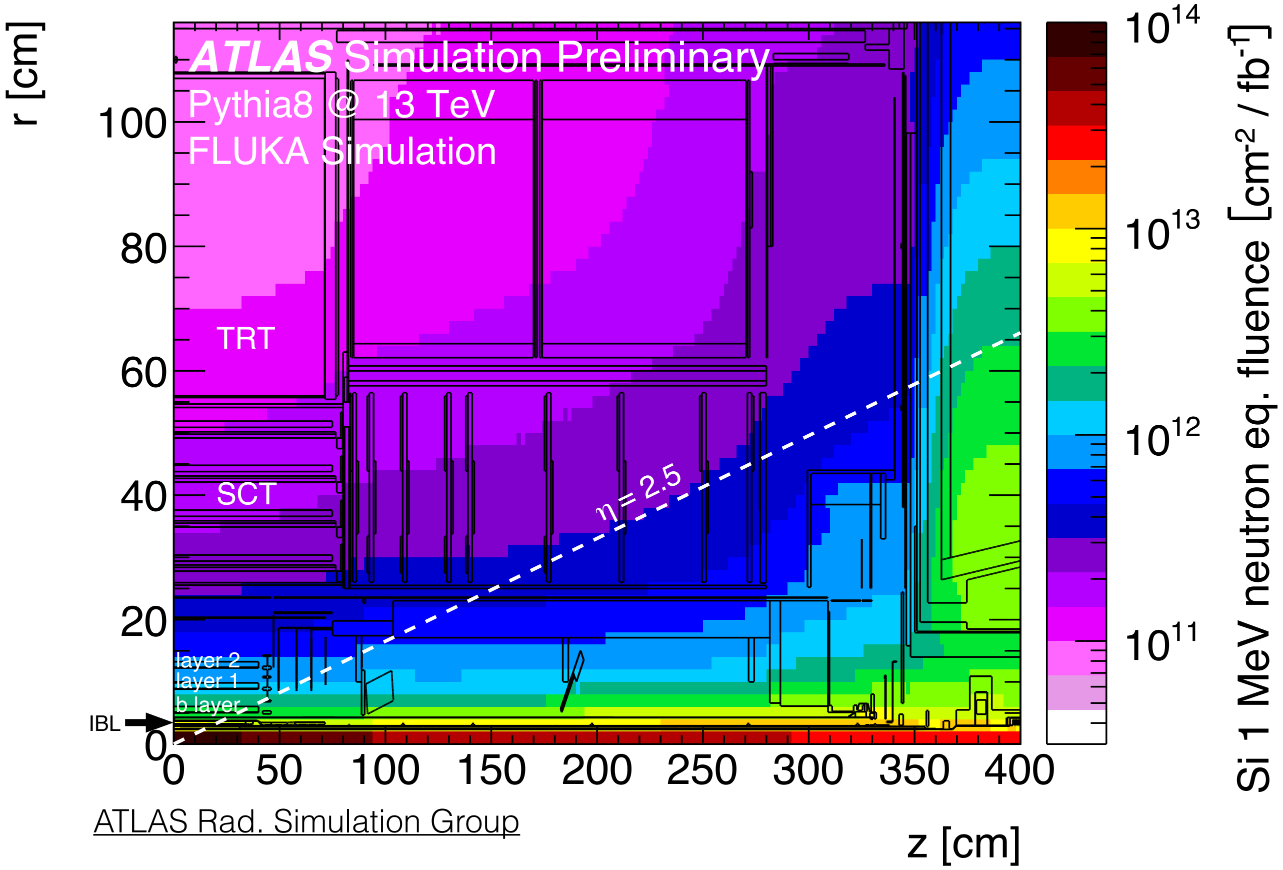
LHCb

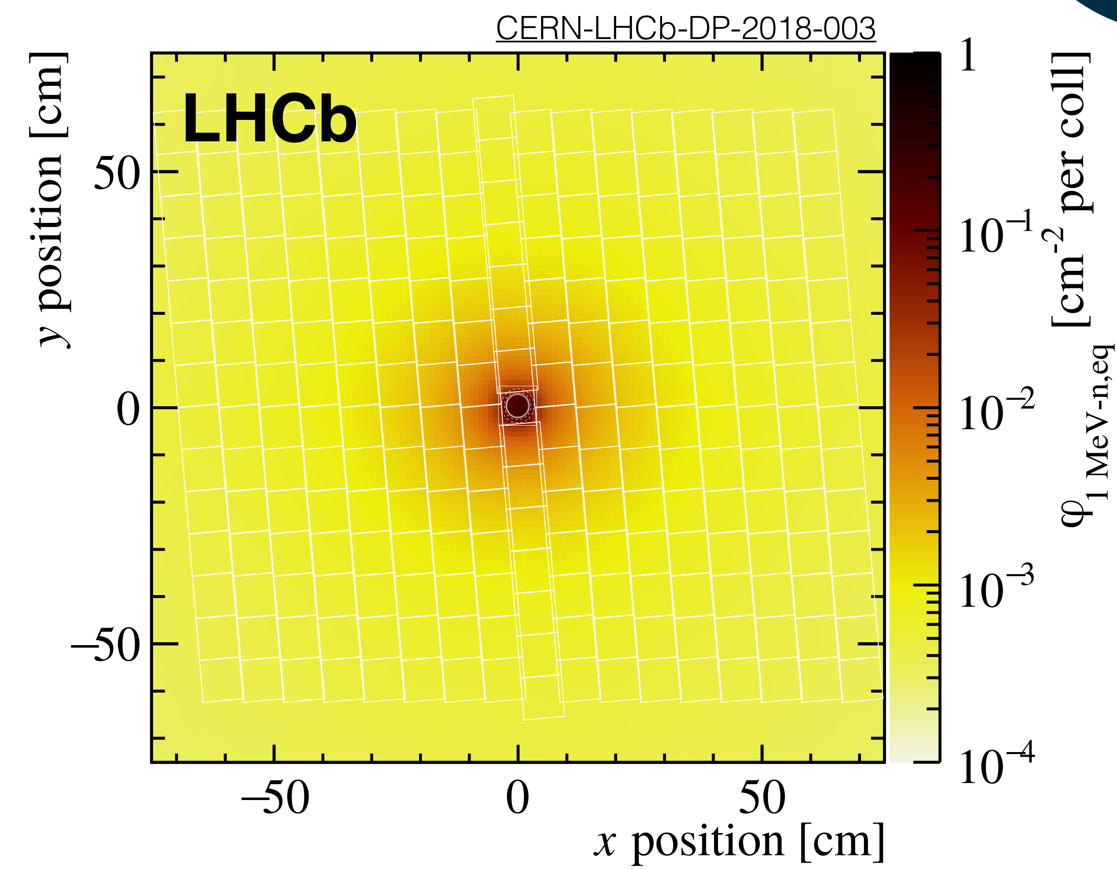


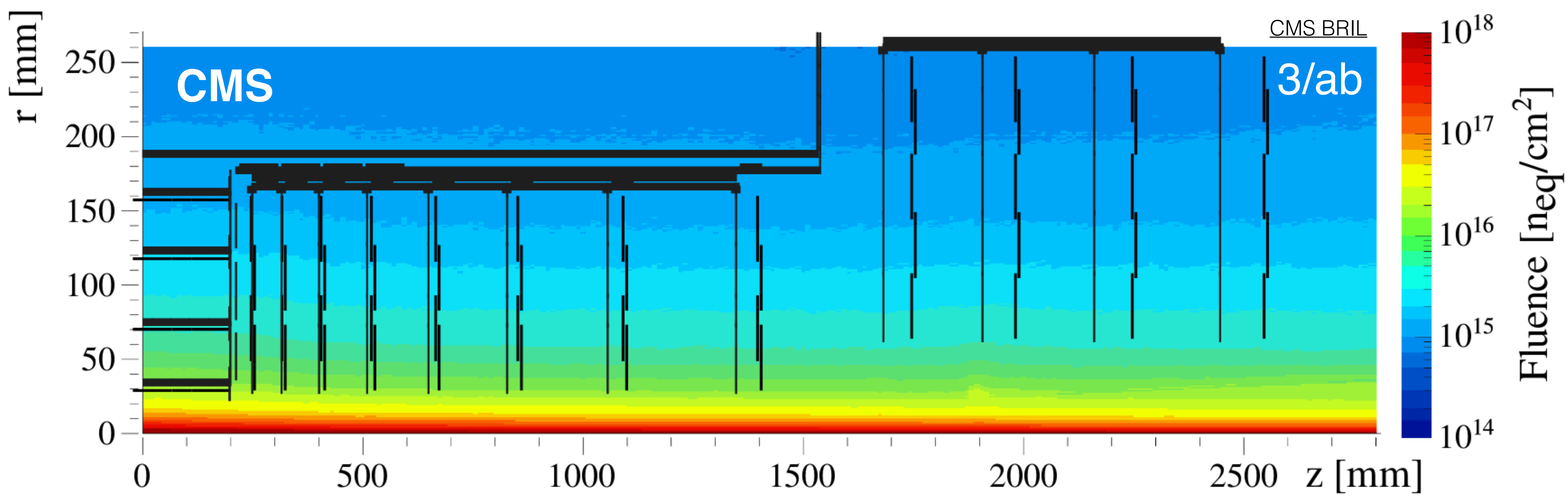


Not shown: ALICE tracking detector - more in a later slide

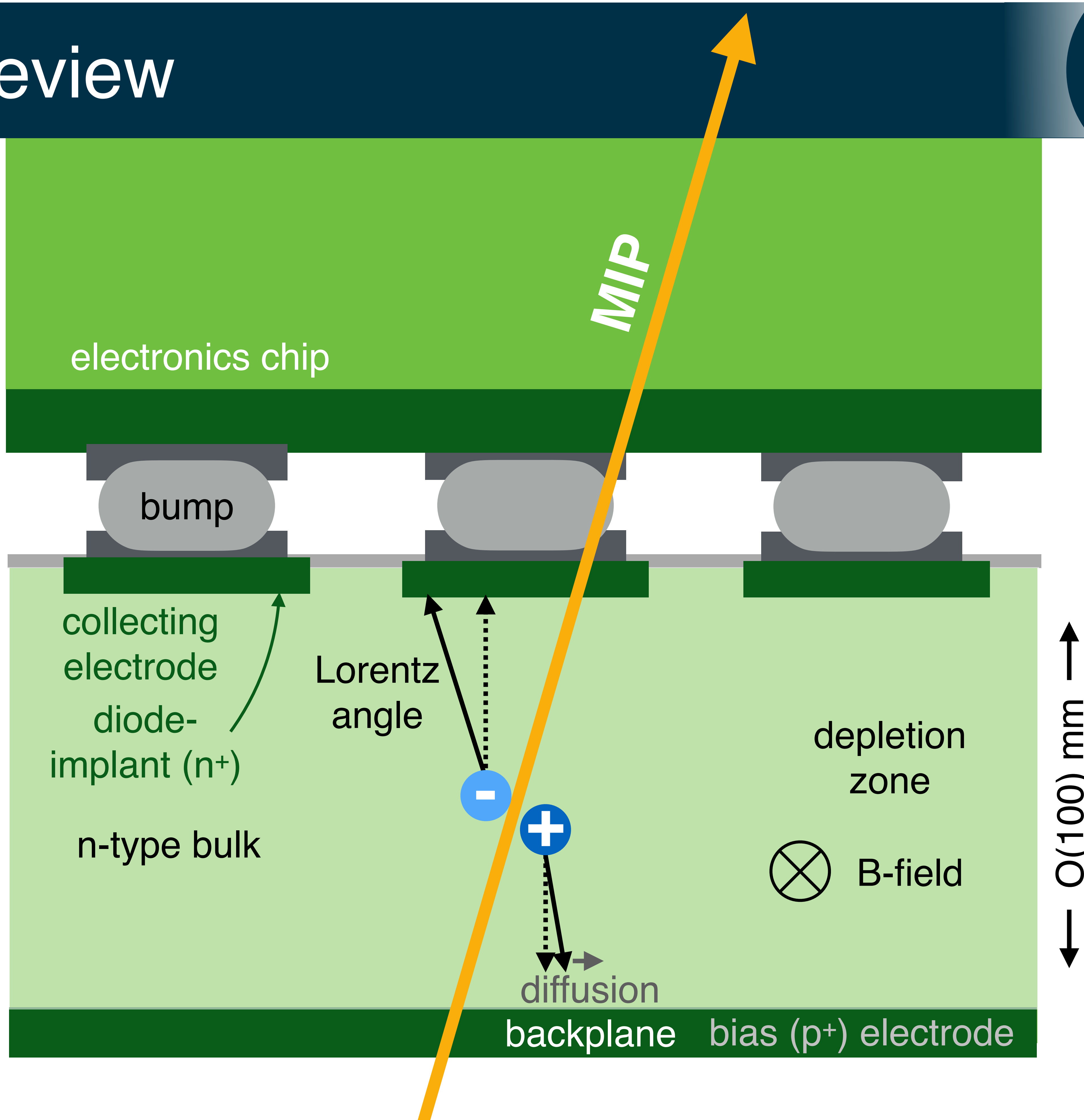
Across the LHC







Brief Review



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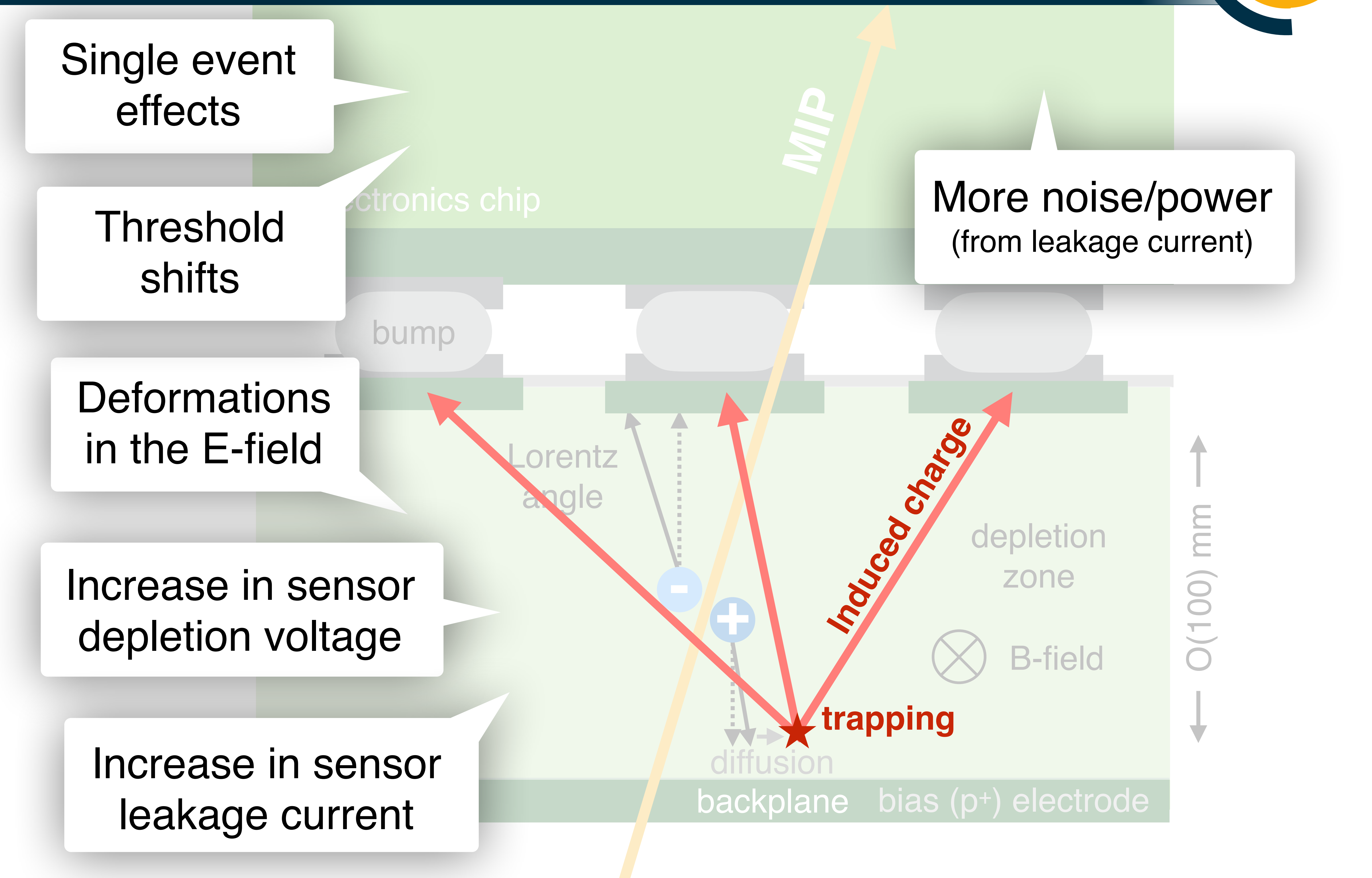


Brief Review

Single event effects

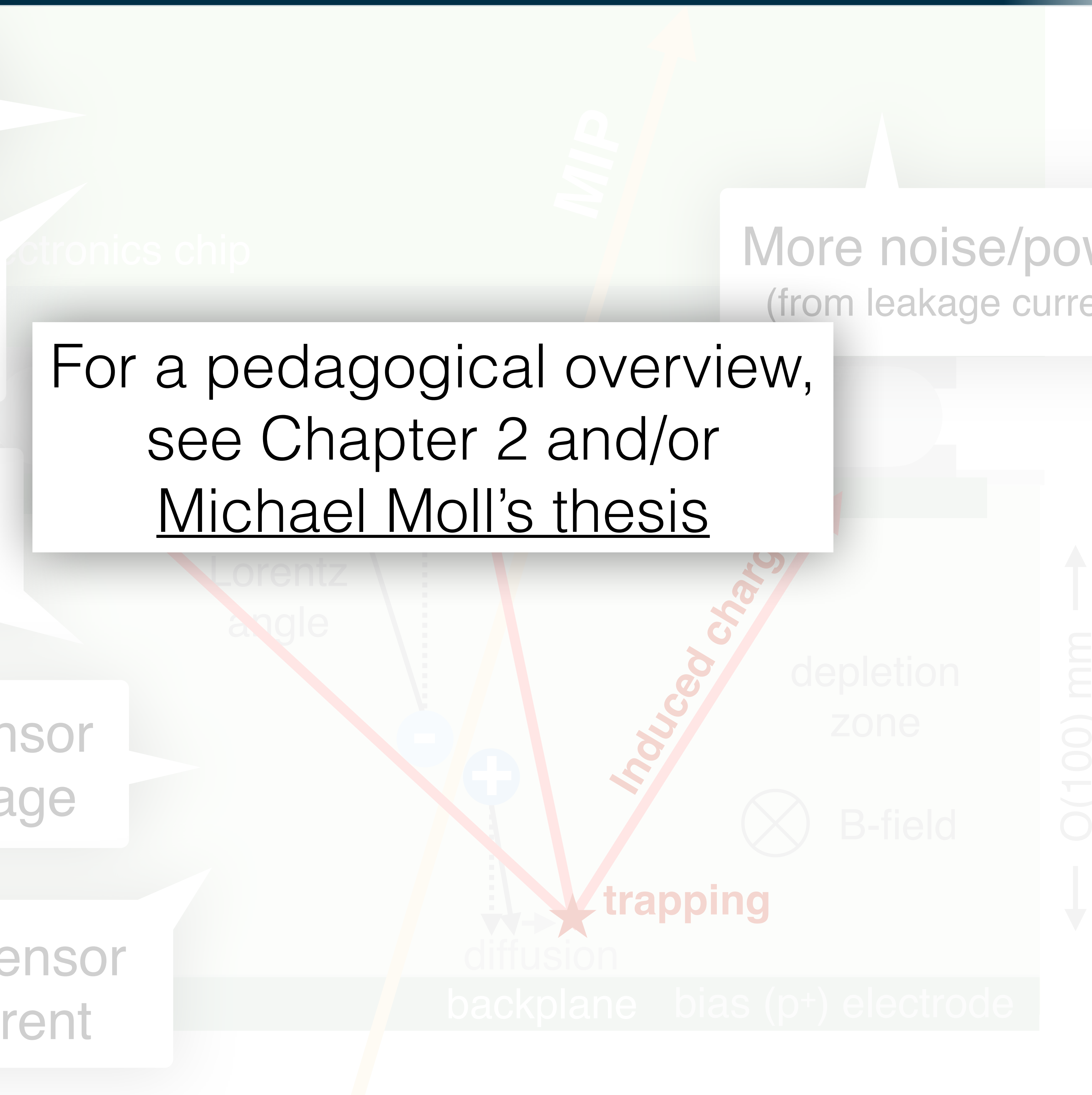
Threshold shifts

Deformations in the E-field

Increase in sensor depletion voltage

Increase in sensor leakage current

More noise/power
(from leakage current)



For a pedagogical overview, see Chapter 2 and/or Michael Moll's thesis

(1) Radiation Simulations

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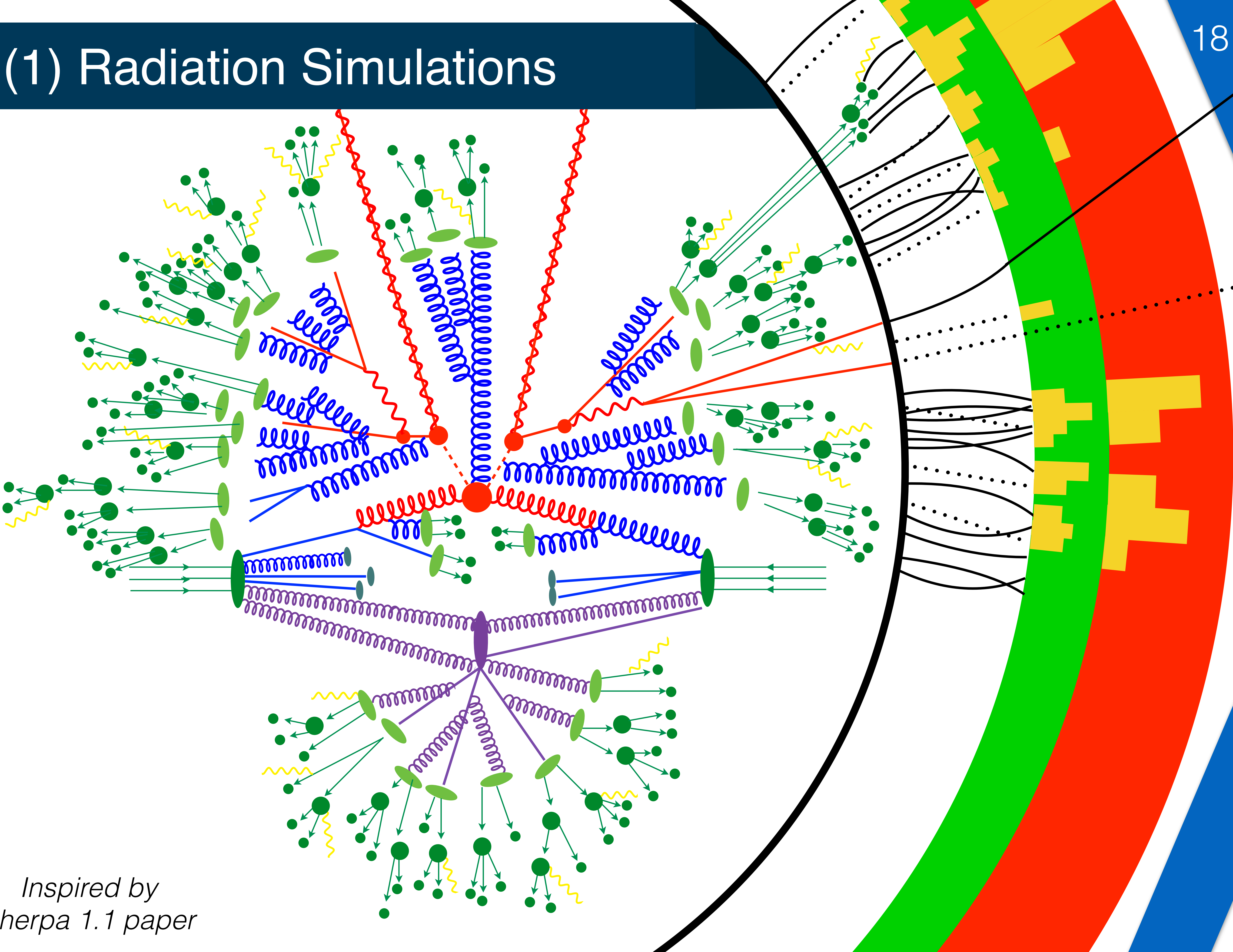


Inspired by Sherpa 1.1 paper

(1) Radiation Simulations

Minimum bias particle production

Pythia 8 and DPMJet III

↓

Particle Transport and Energy Loss

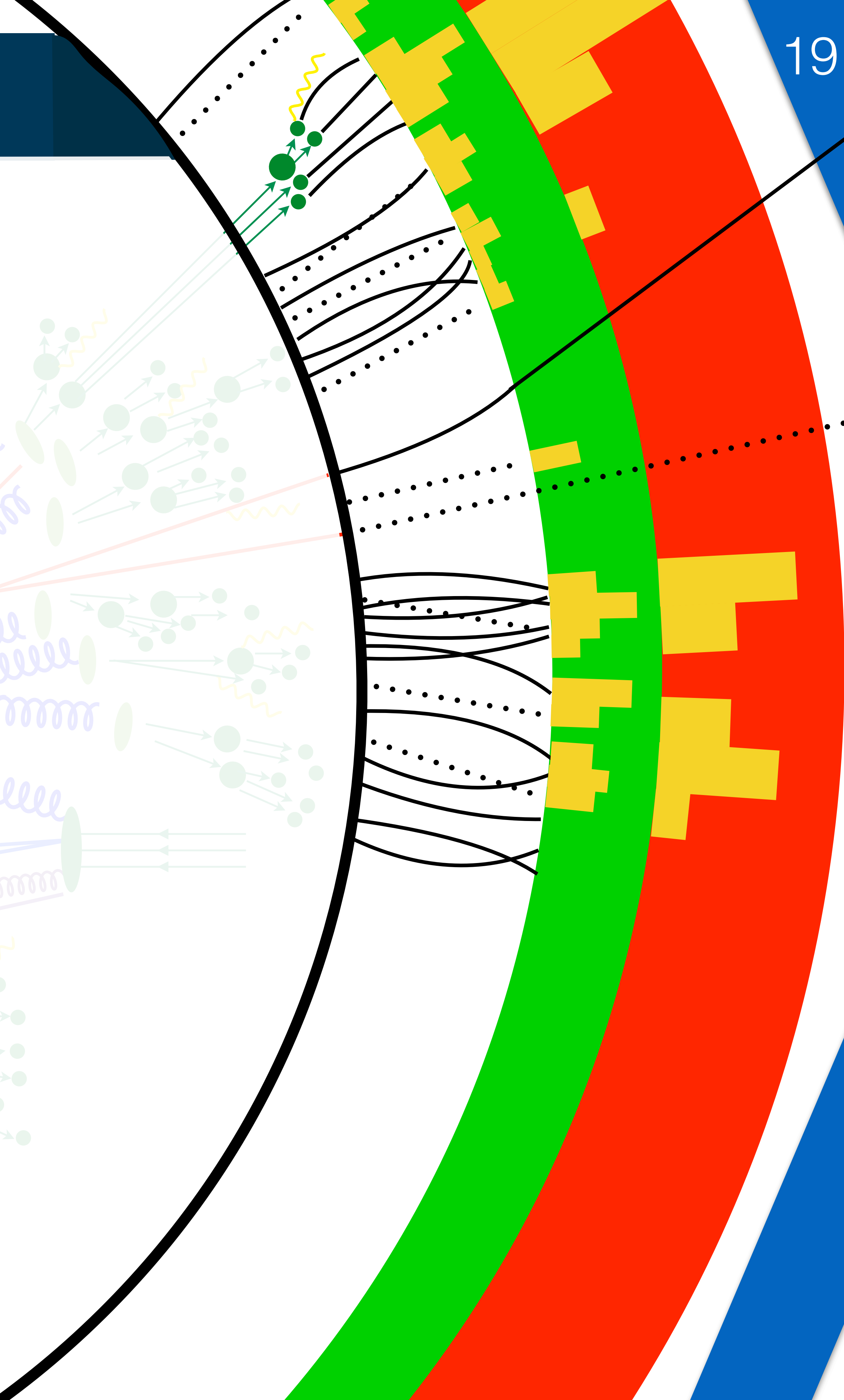
FLUKA and Geant 4

(and sometimes MARS and GCalor)

↓

Fluence / Dose / Flux of high energy hadrons

RD50 tables and FLUKA/Geant 4



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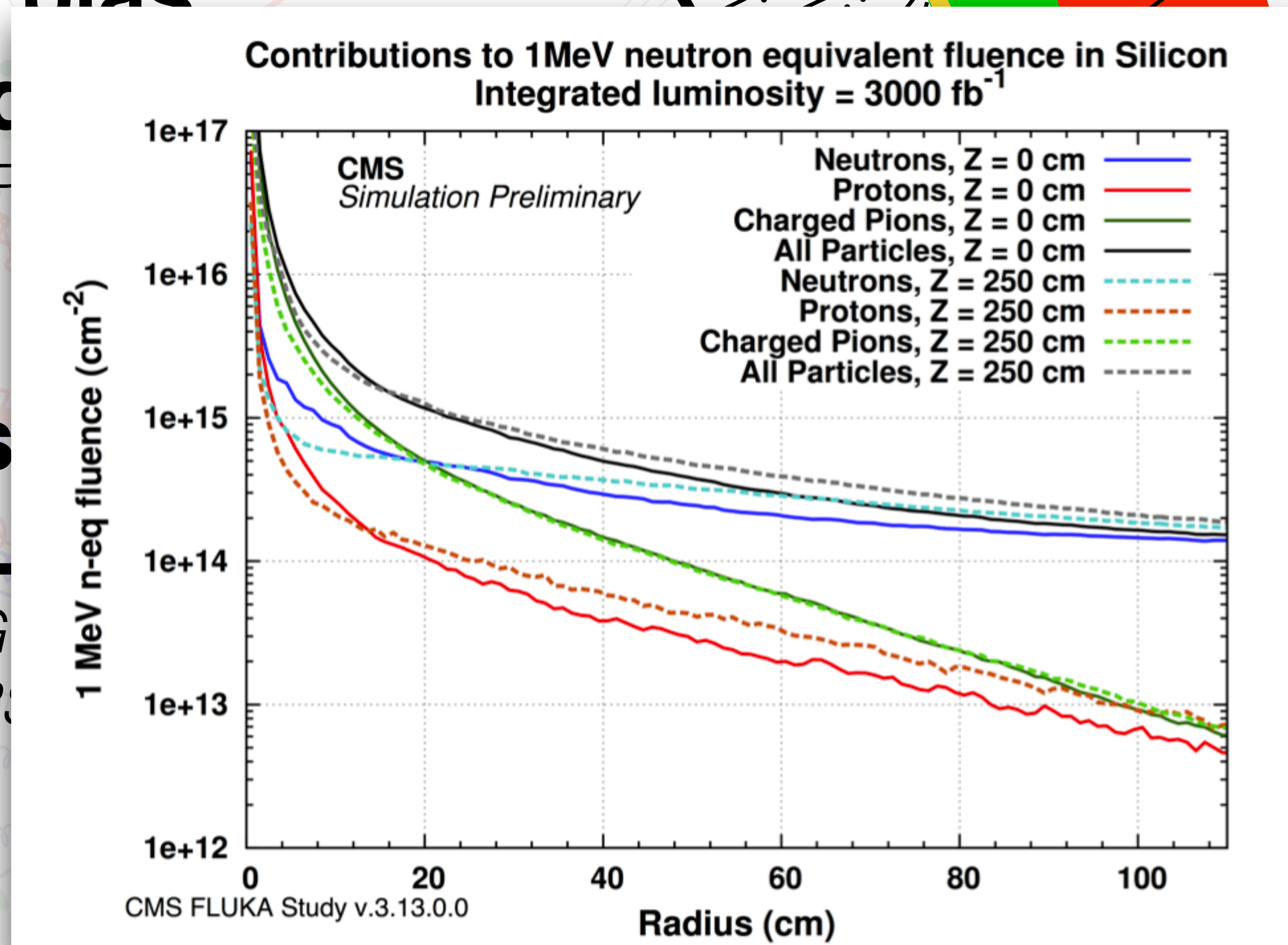

(2) Damage Measurements

(2) Damage Measurements

The most important quantity to measure is the fluence (ϕ).

Many sensor properties are proportional to ϕ

can use these for calibration and validation

Caution:

Annealing can affect in different ways!

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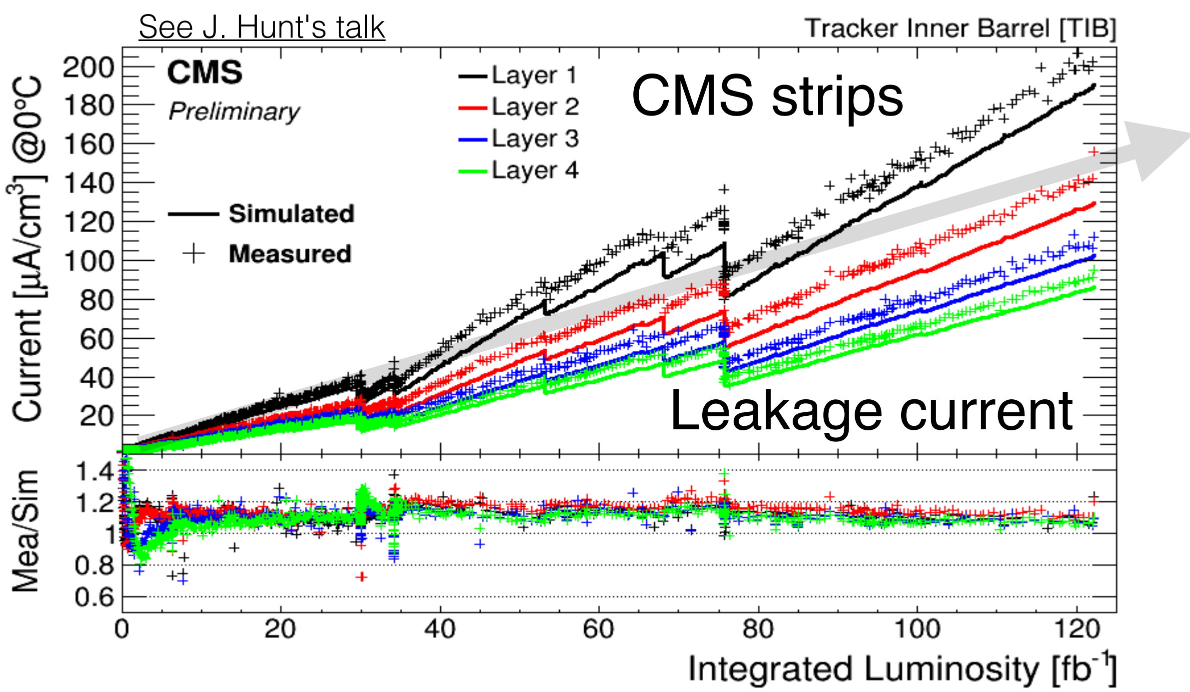

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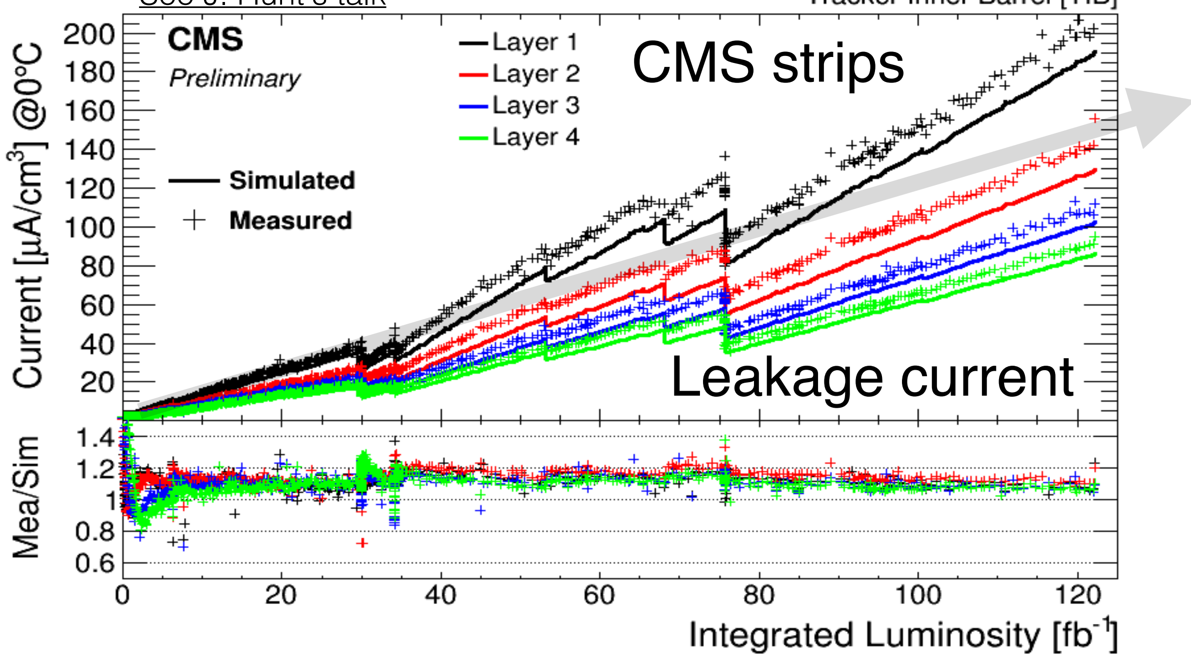
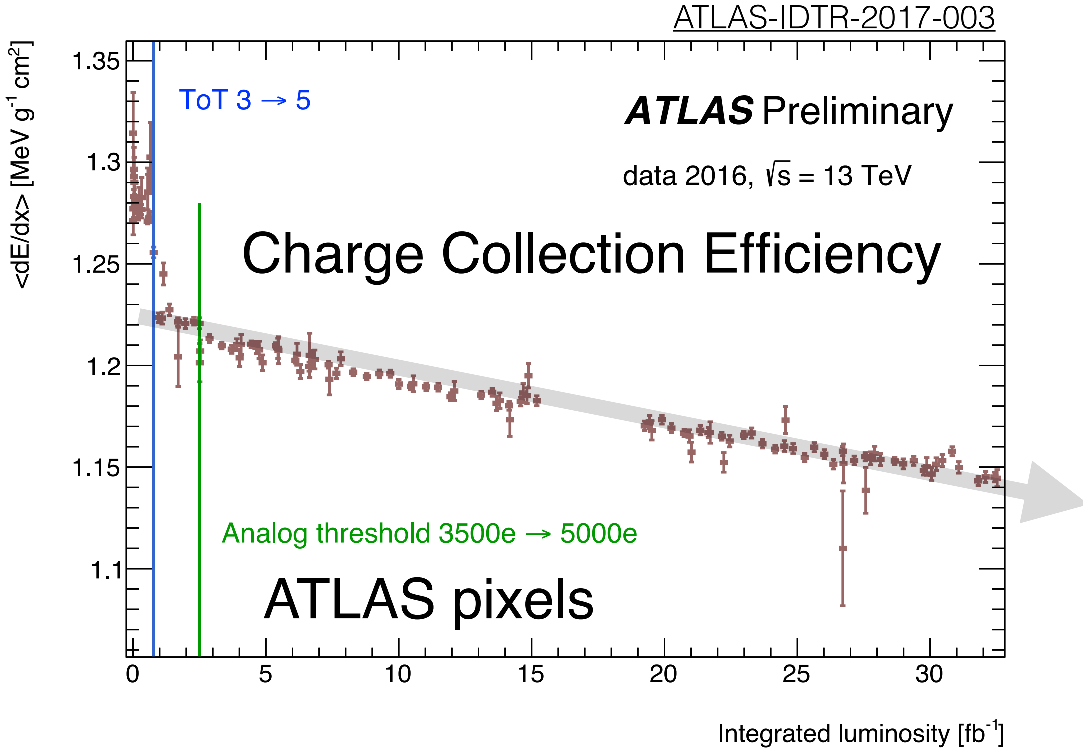
See J. Hunt's talk



ATLAS-IDTR-2017-003



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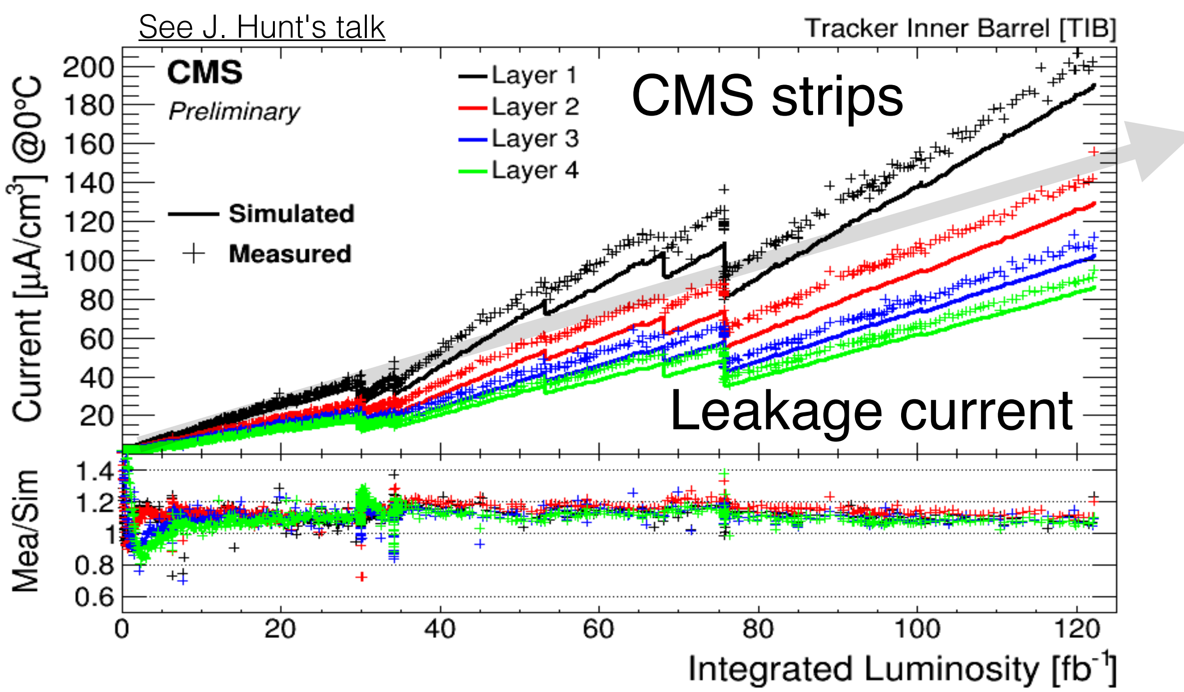

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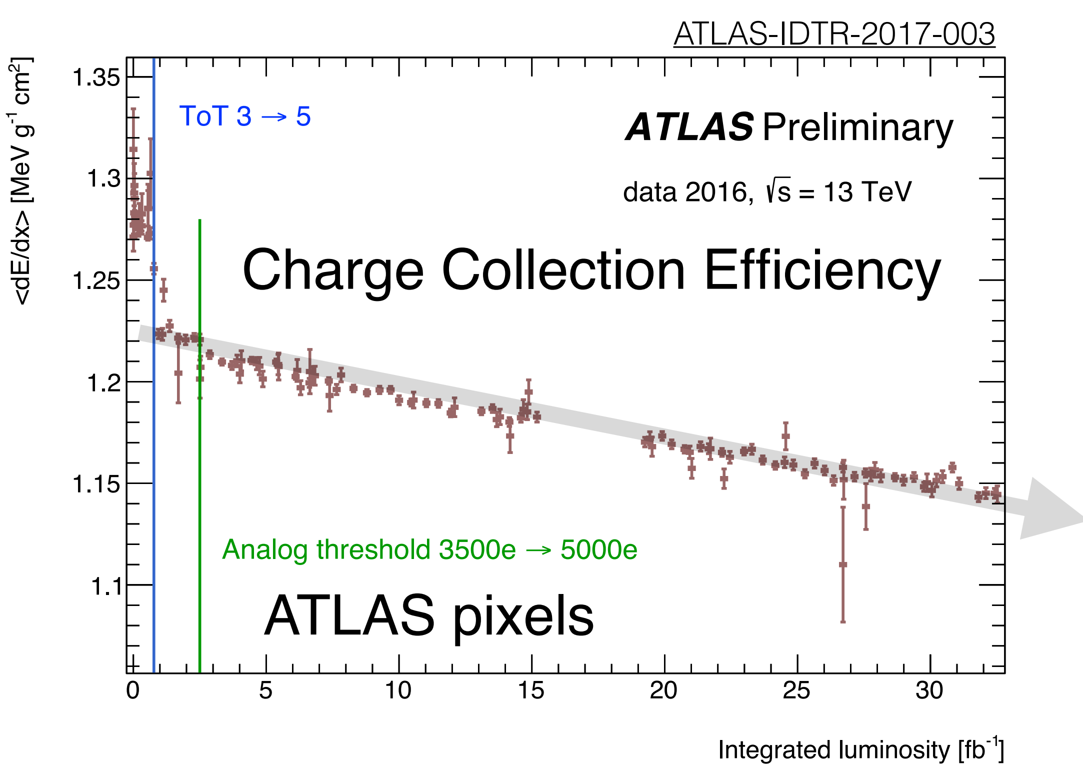

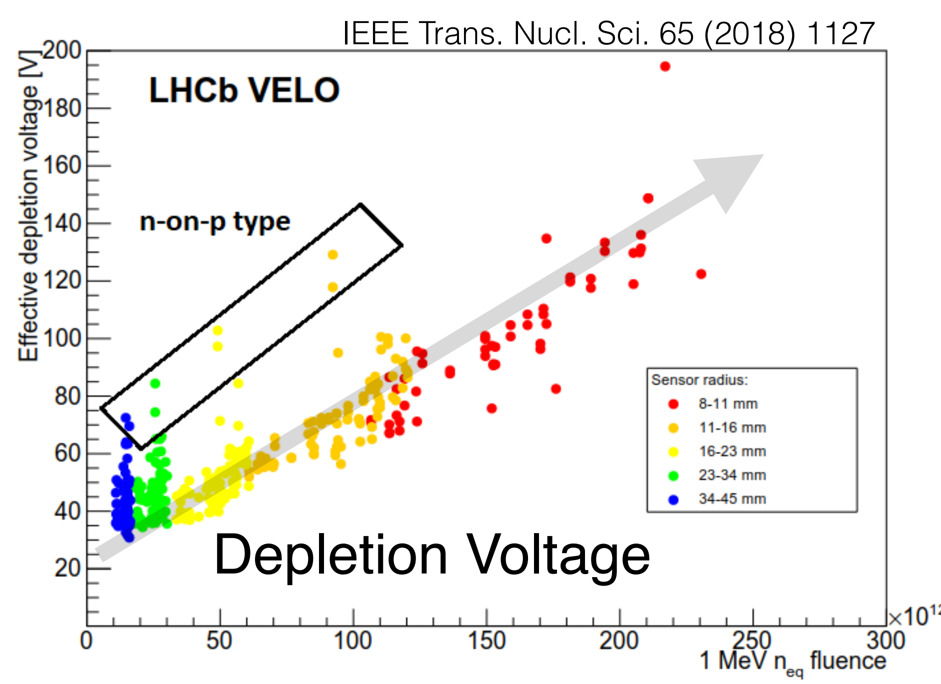

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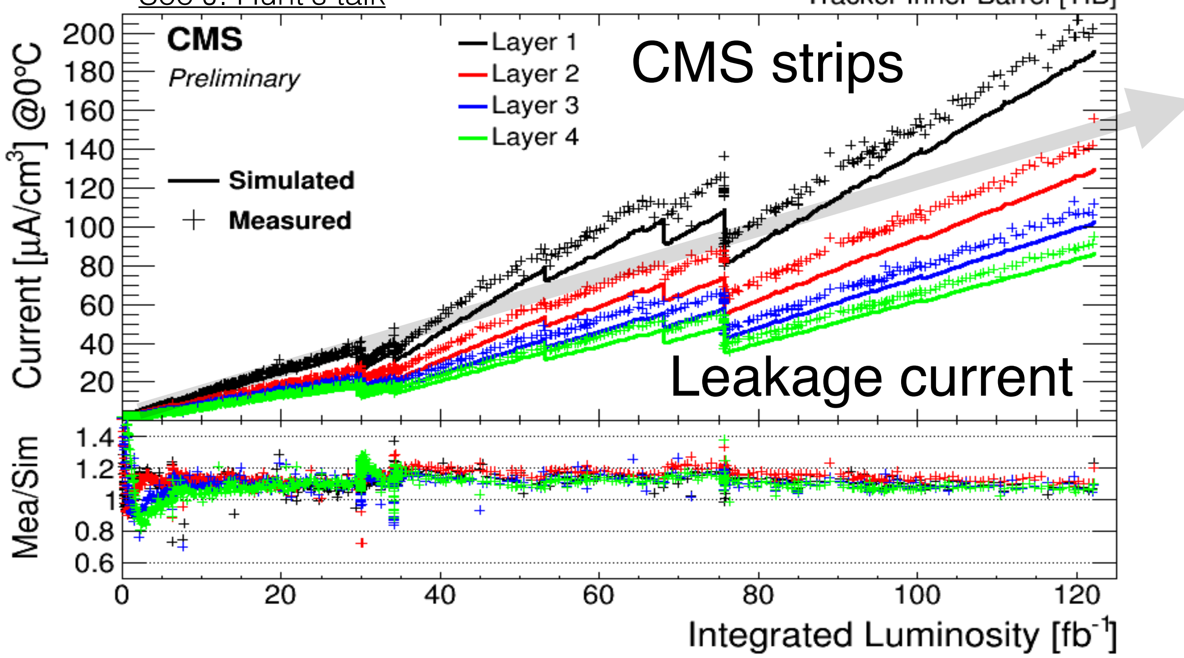

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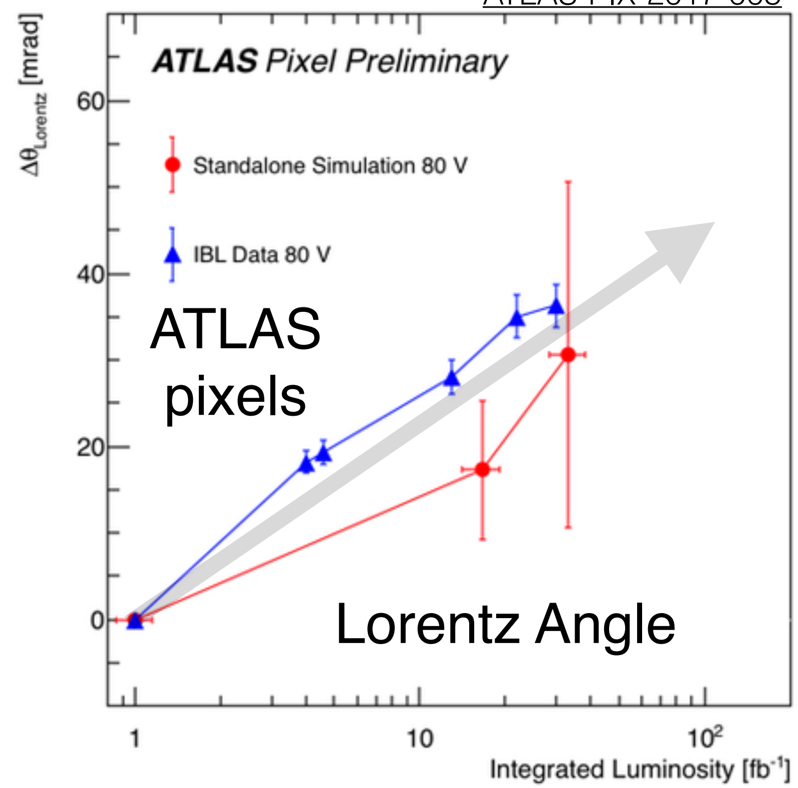

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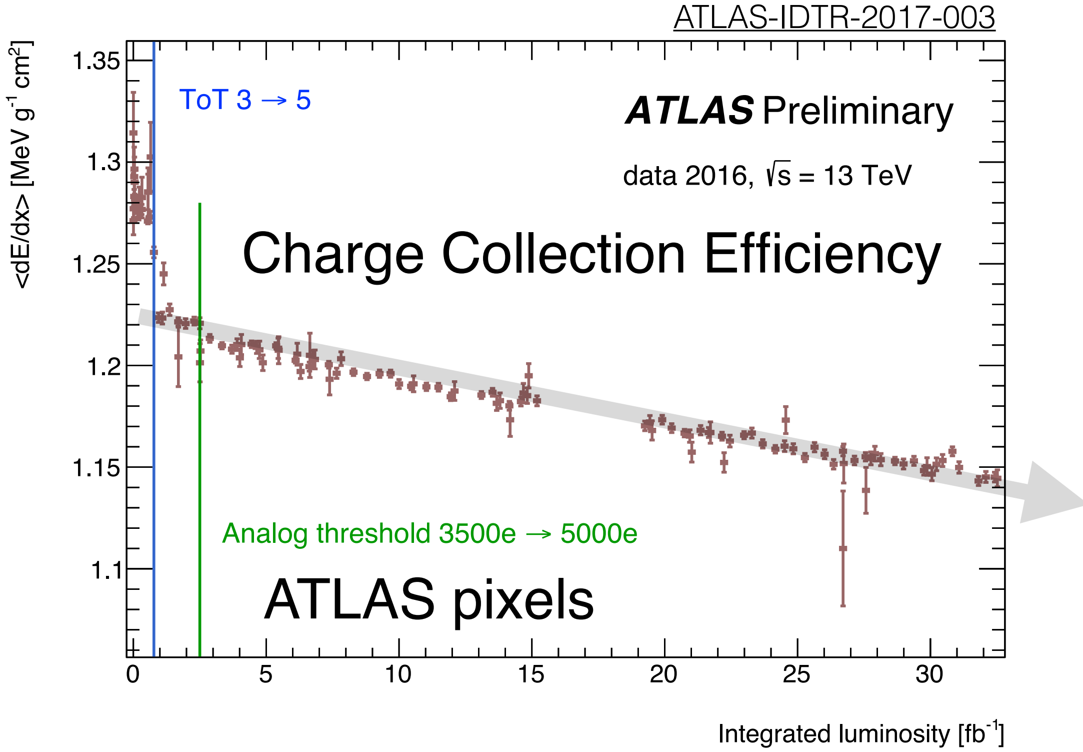
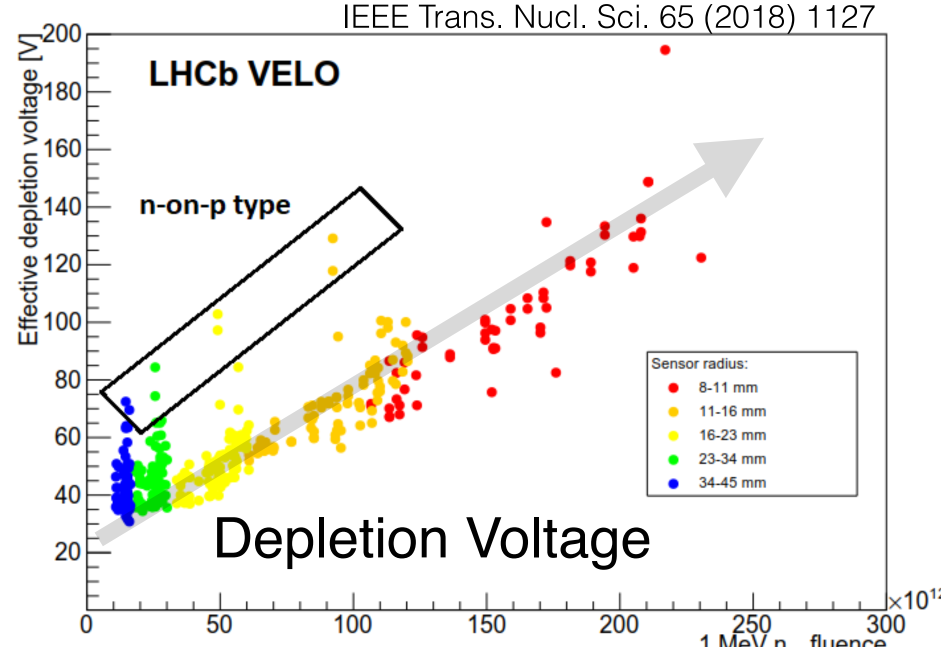


IEEE Trans. Nucl. Sci. 65 (2018) 1127



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Fluence Monitoring

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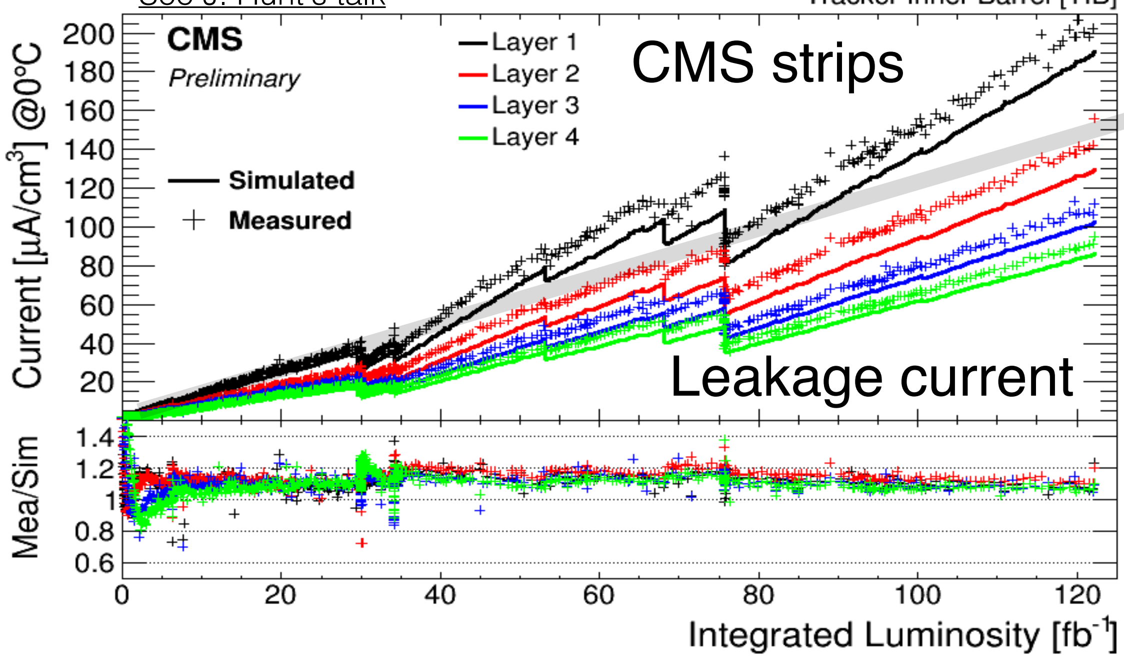


$$I_{\rm leak} = (\Phi / L_{\rm int}) \cdot V \cdot \sum_{t=t_0}^{T} L_{{\rm int},i} \cdot [\text{annealing}]$$

"Hamburg Model" or "Sheffield-Harper model"

Different approaches to time-dependence of annealing terms

Caution:

Models assume uniform space-charge and a small number of effective defect states.

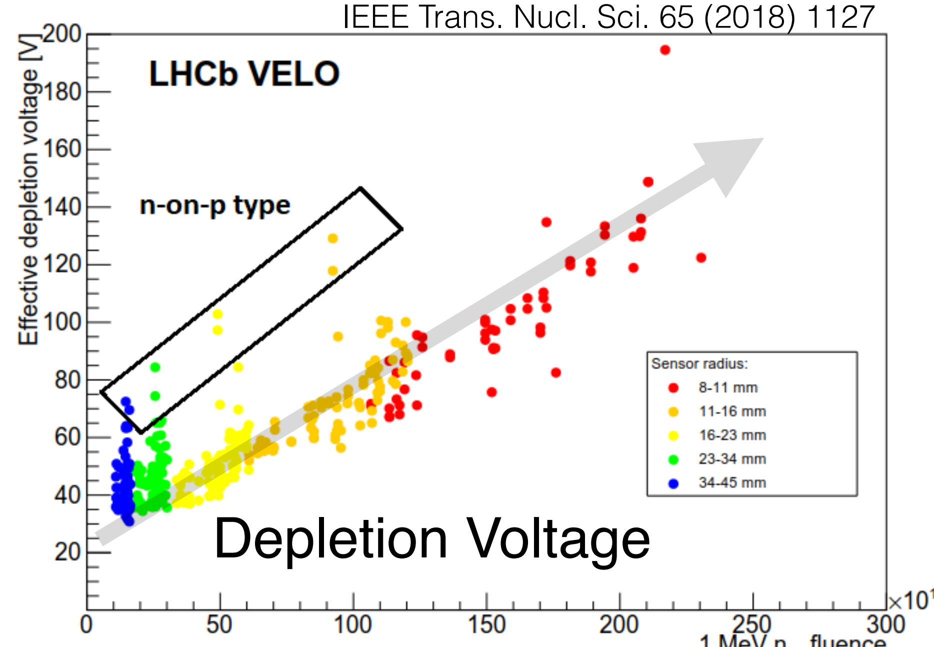
$$V_{\rm dep.} = |N_{\rm eff}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

$$N_{\rm eff}(t) = N_0(t) - N_A^{\rm stable}(t) + N^{\rm annealing}(t)$$

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

"Hamburg Model"

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



Comparing to Simulations

Radiation Simulation

Particle multiplicity, energy, composition

↓ *DPMJet or Pythia*

Geometry and Particle transport

↓ *FLUKA or Geant4*

Non-ionizing damage

↓ *RD50 damage factors*

Predicted ϕ

Comparing to Simulations

Radiation Simulation	Leakage Current
Particle multiplicity, energy, composition	Raw leakage current
↓ *DPMJet or Pythia*	↓
Geometry and Particle transport	Temperature correction
↓ *FLUKA or Geant4*	↓
Non-ionizing damage	Fit ϕ/L in Hamburg/ Sheffield-Harper model
↓ *RD50 damage factors*	↓
Predicted ϕ	Measured ϕ

Comparing to Simulations

Radiation Simulation	Leakage Current	Depletion Voltage
Particle multiplicity, energy, composition	Raw leakage current	Measure charge versus HV
↓ *DPMJet or Pythia*	↓	↓
Geometry and Particle transport	Temperature correction	Define $V_{dep.}$ = saturation point
↓ *FLUKA or Geant4*	↓	↓
Non-ionizing damage	Fit ϕ/L in Hamburg/ Sheffield-Harper model	Fit ϕ/L in Hamburg model
↓ *RD50 damage factors*	↓	↓
Predicted ϕ	Measured ϕ	Measured ϕ

Comparing to Simulations

Radiation Simulation

Particle multiplicity, energy, composition

↓ *DPMJet or Pythia*

Geometry and Particle transport

↓ *FLUKA or Geant4*

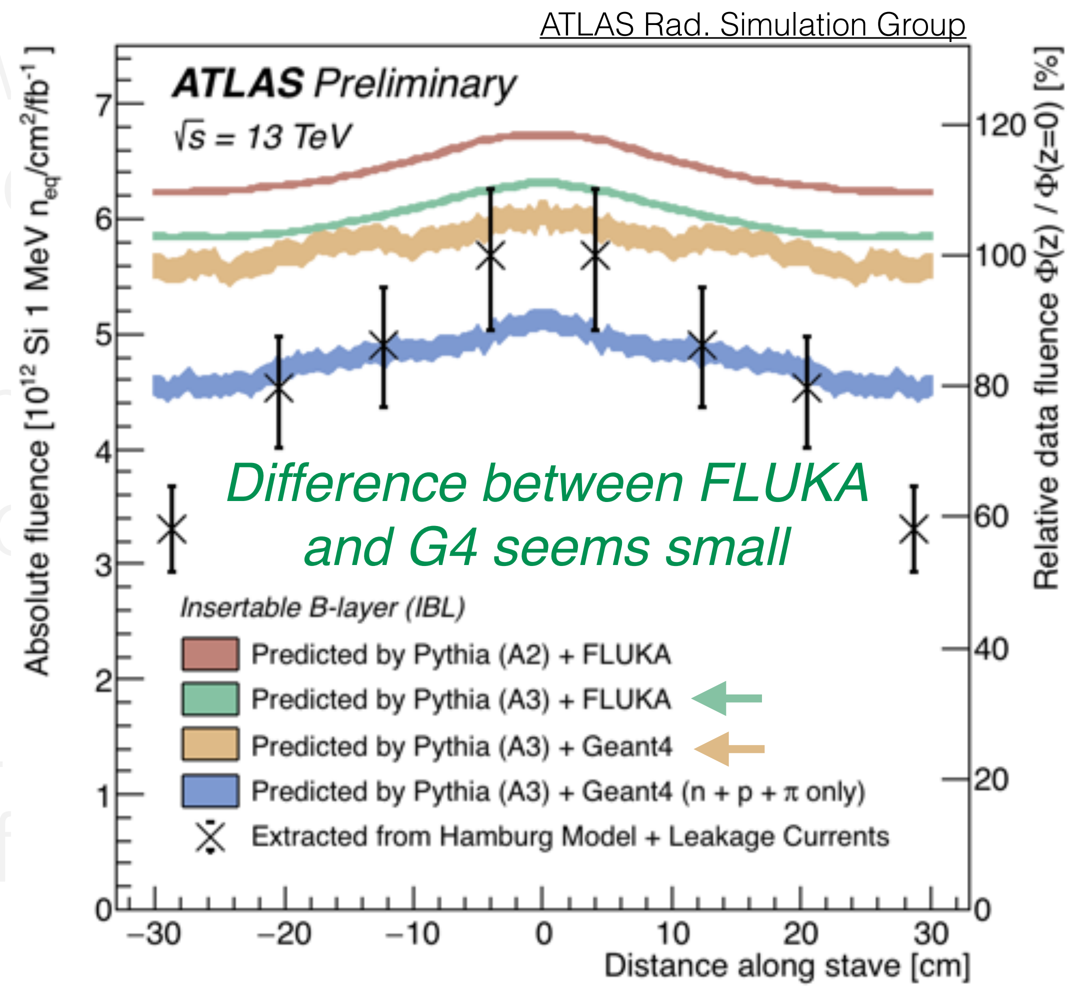
Non-ionizing damage

↓ *RD50 damage factors*

Predicted Φ

Caution:

Tuned to data, but still significant uncertainty (PDFs, MEs, frag., etc.)



Large (and largely unknown) uncertainties in many of these factors!

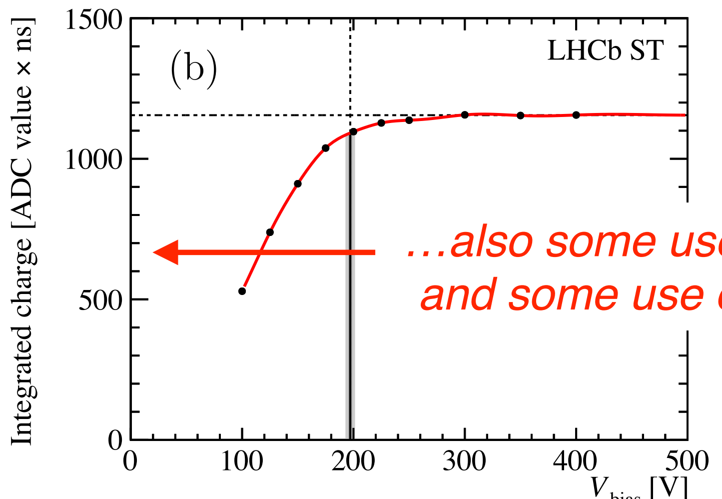
…due in part to the availability of monochromatic beams and uncertainty in converting to 1 MeV n_{eq}

Comparing to Simulations

Caution:

No community consensus on silicon activation energy (most common is 1.21 eV from A. Chilingarov)

The kink is not uniquely defined!



…also some use ADCs and some use charge

CERN-LHCb-DP-2018-003

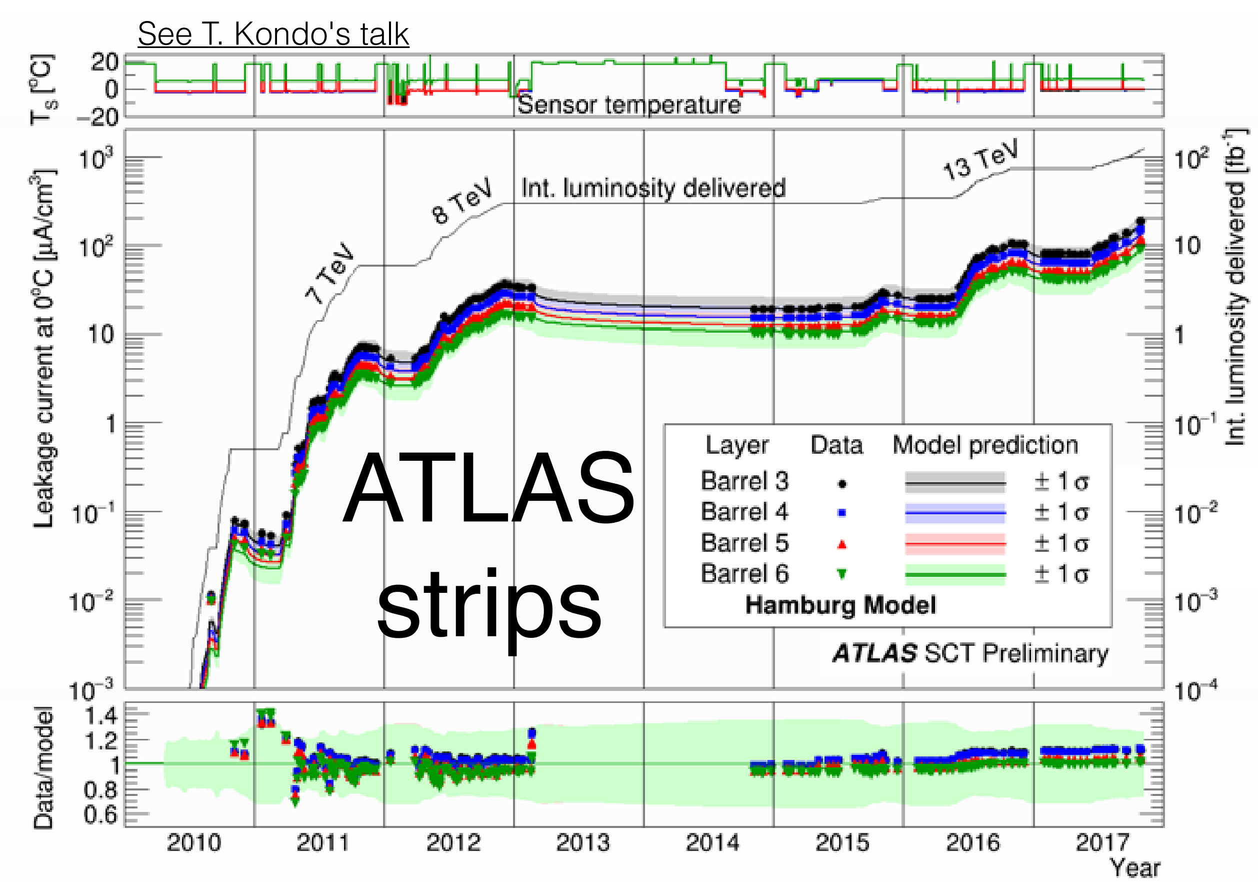
There are many parameters, each with a large (and in some cases, unknown - see previous slide) uncertainty

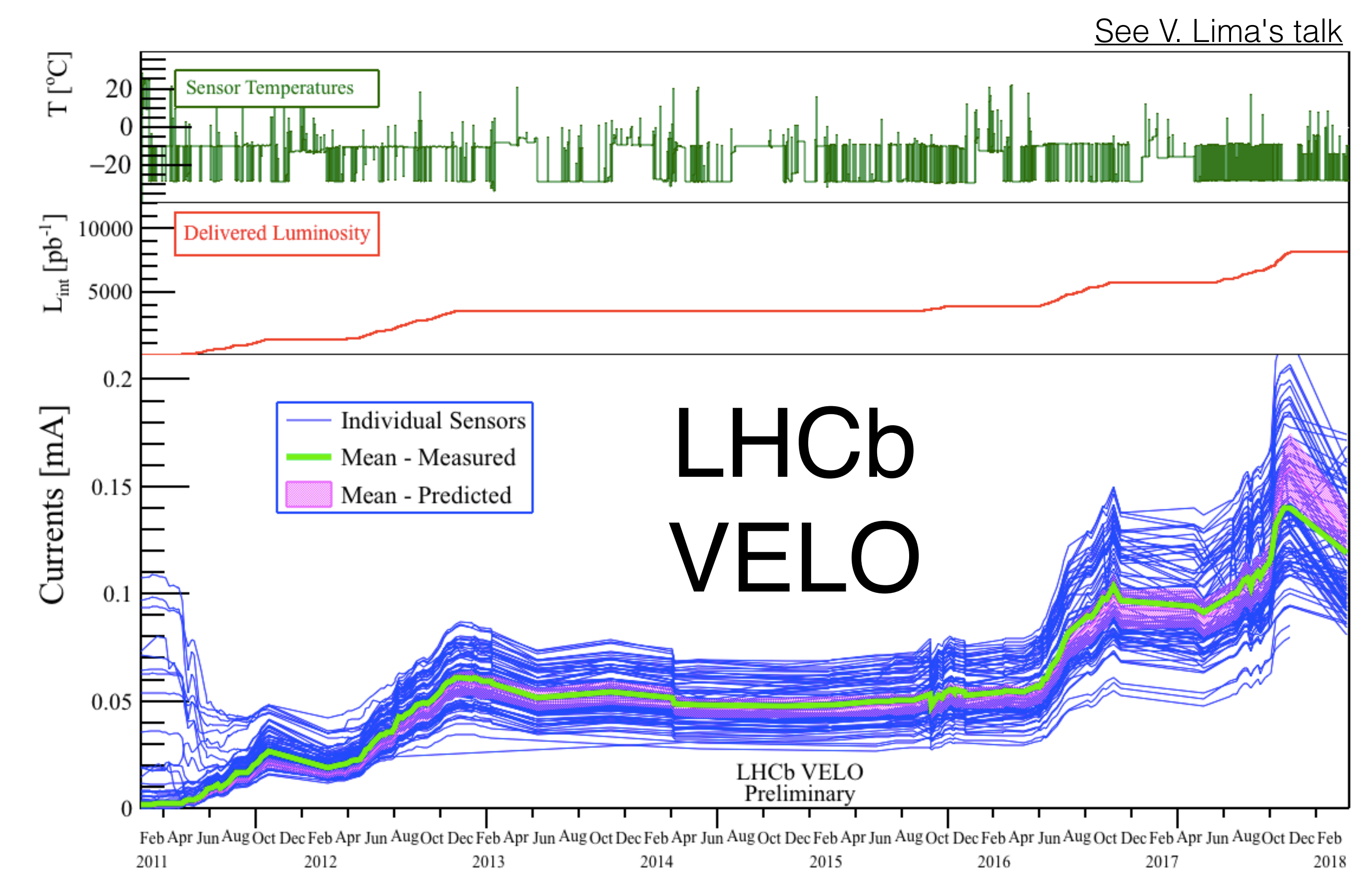
Leakage Current	Depletion Voltage
Raw leakage current	Measure charge versus HV
↓	↓
Temperature correction	Define $V_{dep.}$ = saturation point
↓	↓
Fit Φ/L in Hamburg/ Sheffield-Harper model	Fit Φ/L in Hamburg model
↓	↓
Measured Φ	Measured Φ

Fluence Monitoring: Leakage Current

ATLAS, CMS, LHCb have measured the leakage current for all silicon detectors.

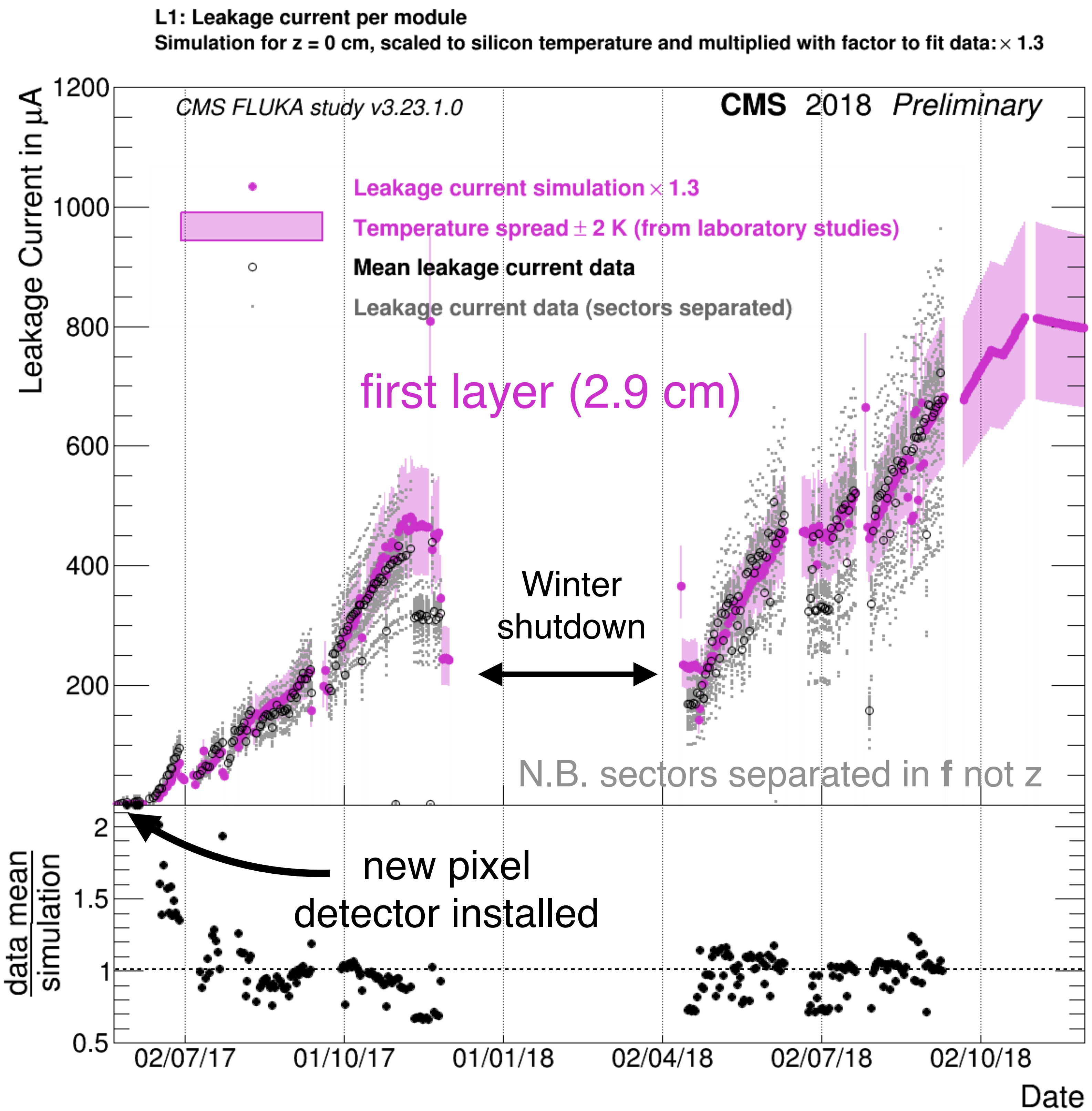
It is interesting to study the current across **time** and as a function of **z** & **radius**.





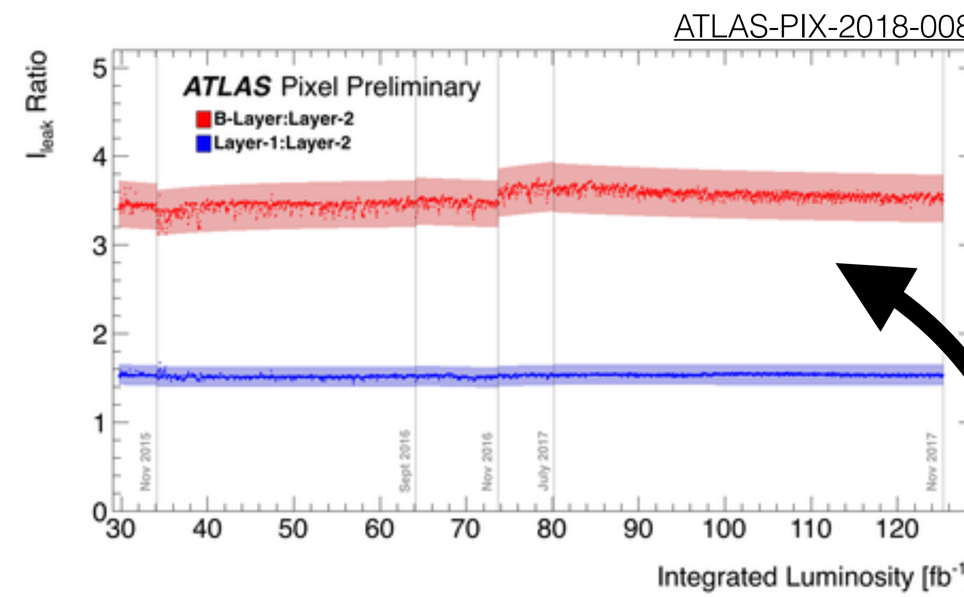
We now have ~8 years of data!

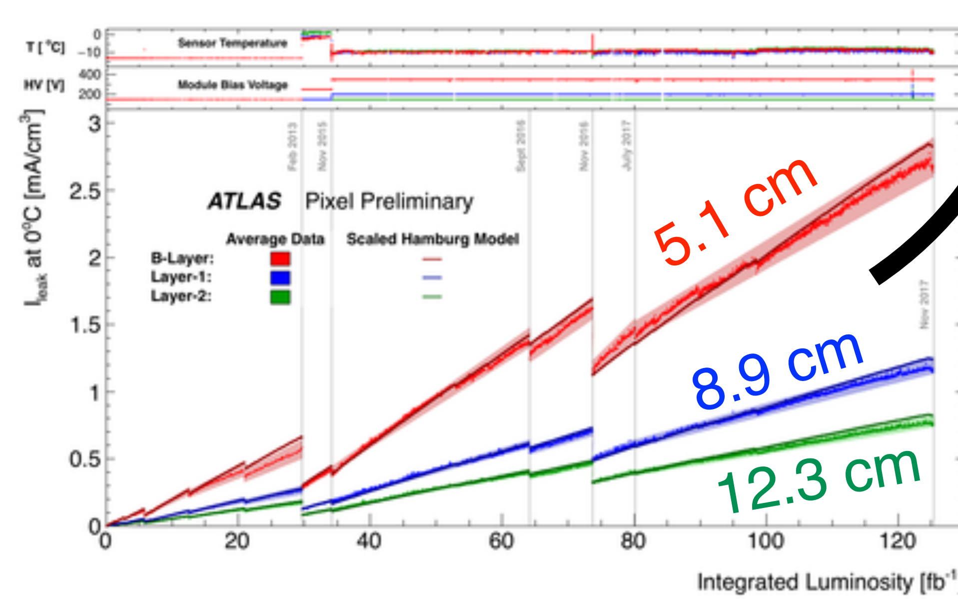
Leakage current across time



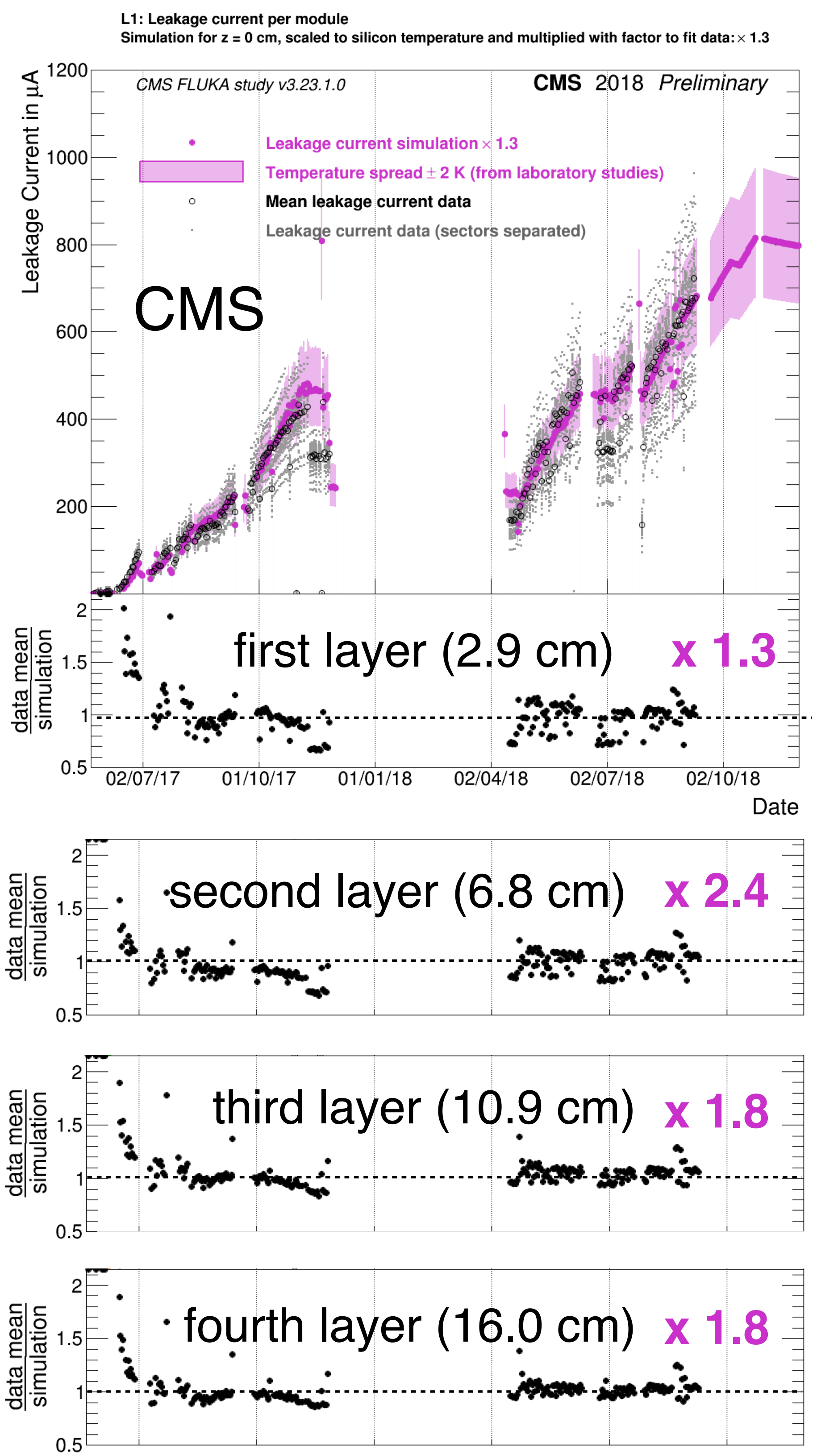
So far, excellent stability across time, even with significant annealing.

ATLAS-PIX-2018-008

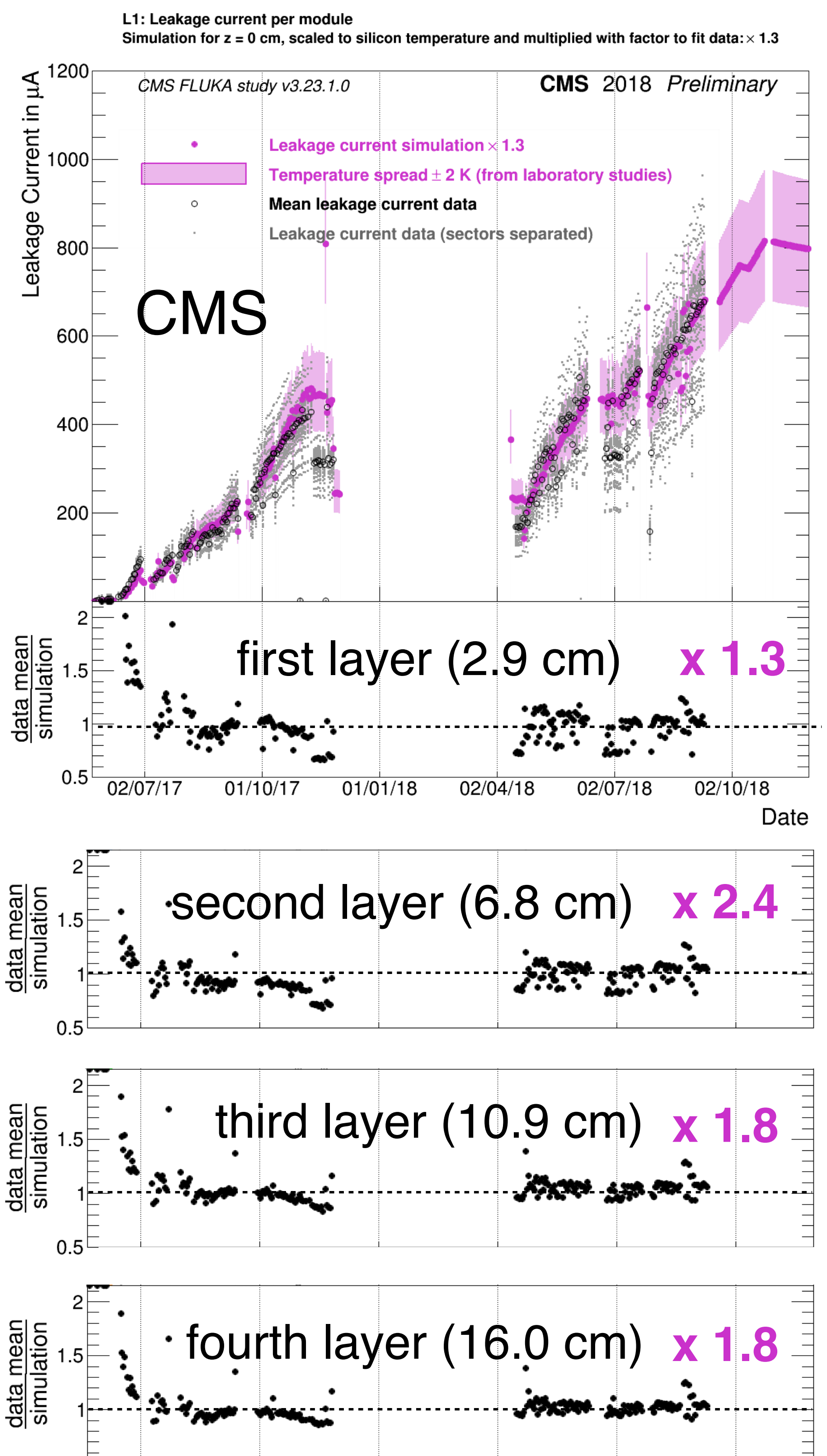




Leakage current across radii



Leakage current across radii



ATLAS
@ z = 0

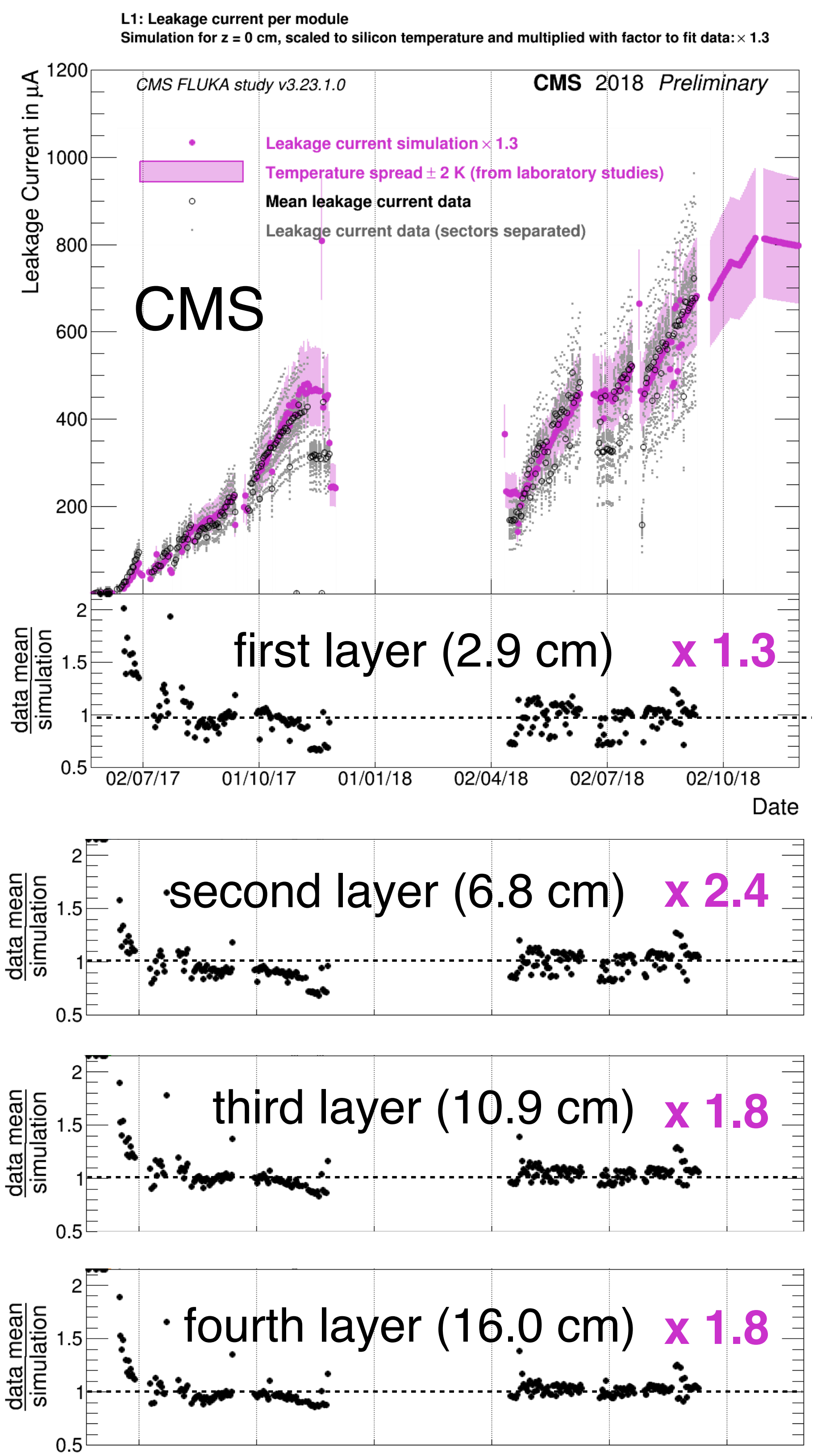
x (0.90 +/- 0.1)
3.3 cm

x (1.4 +/- 0.1)
5.1 cm

x (1.4 +/- 0.1)
8.9 cm

x (1.4 +/- 0.1)
12.3 cm

Leakage current across radii



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x (1.4 +/- 0.1)
12.3 cm

Overall, ATLAS and CMS observe a higher fluence in data than in simulation

with some weak evidence for radius dependence:

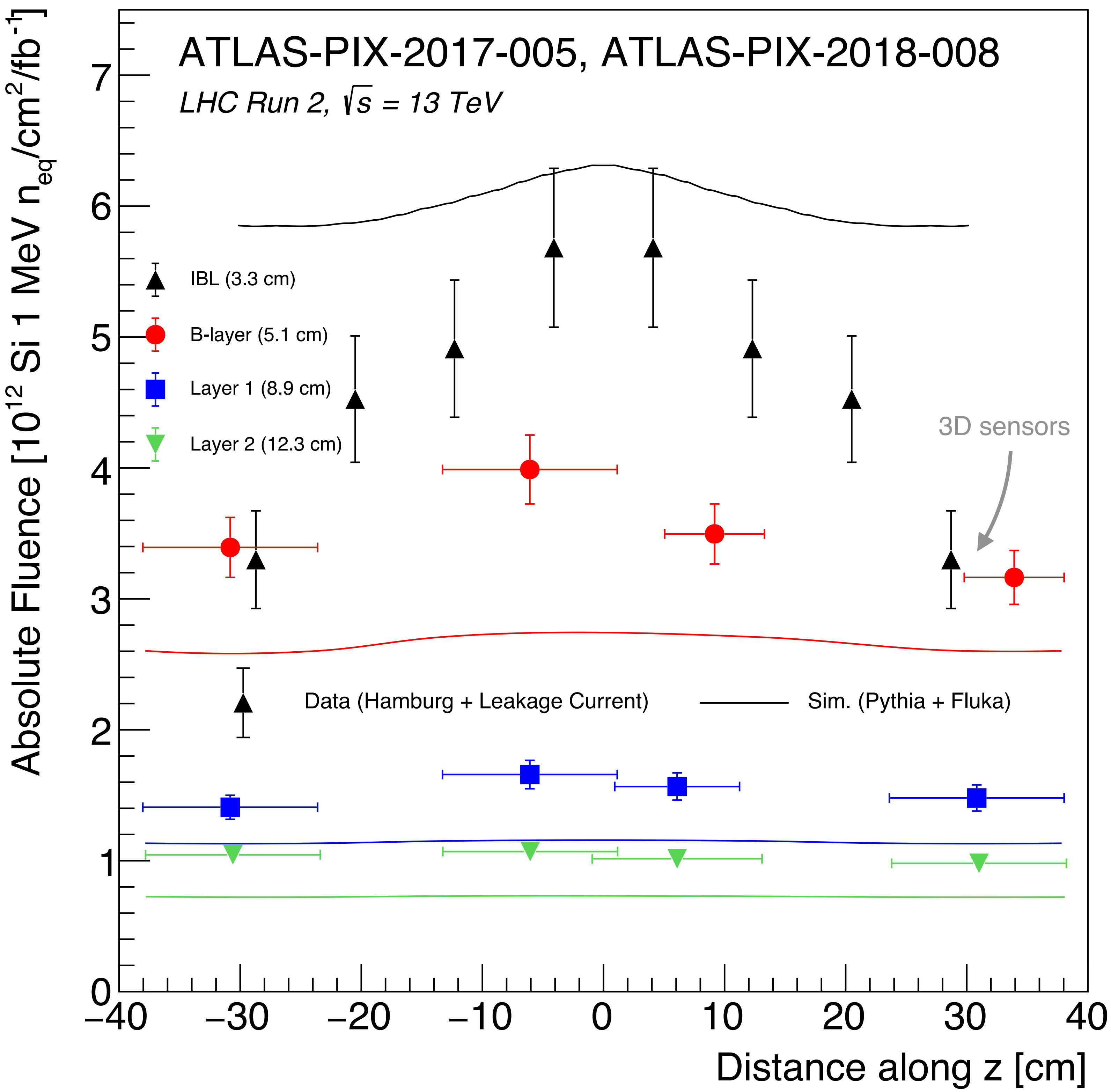
data ~ sim. for innermost

data ~ 1.5 - 2.5 x sim. for other pixels

data ~ 1.0 - 1.2 x sim. for strips

N.B. data > prediction … important to **take note for safety factors** !

Leakage current along z



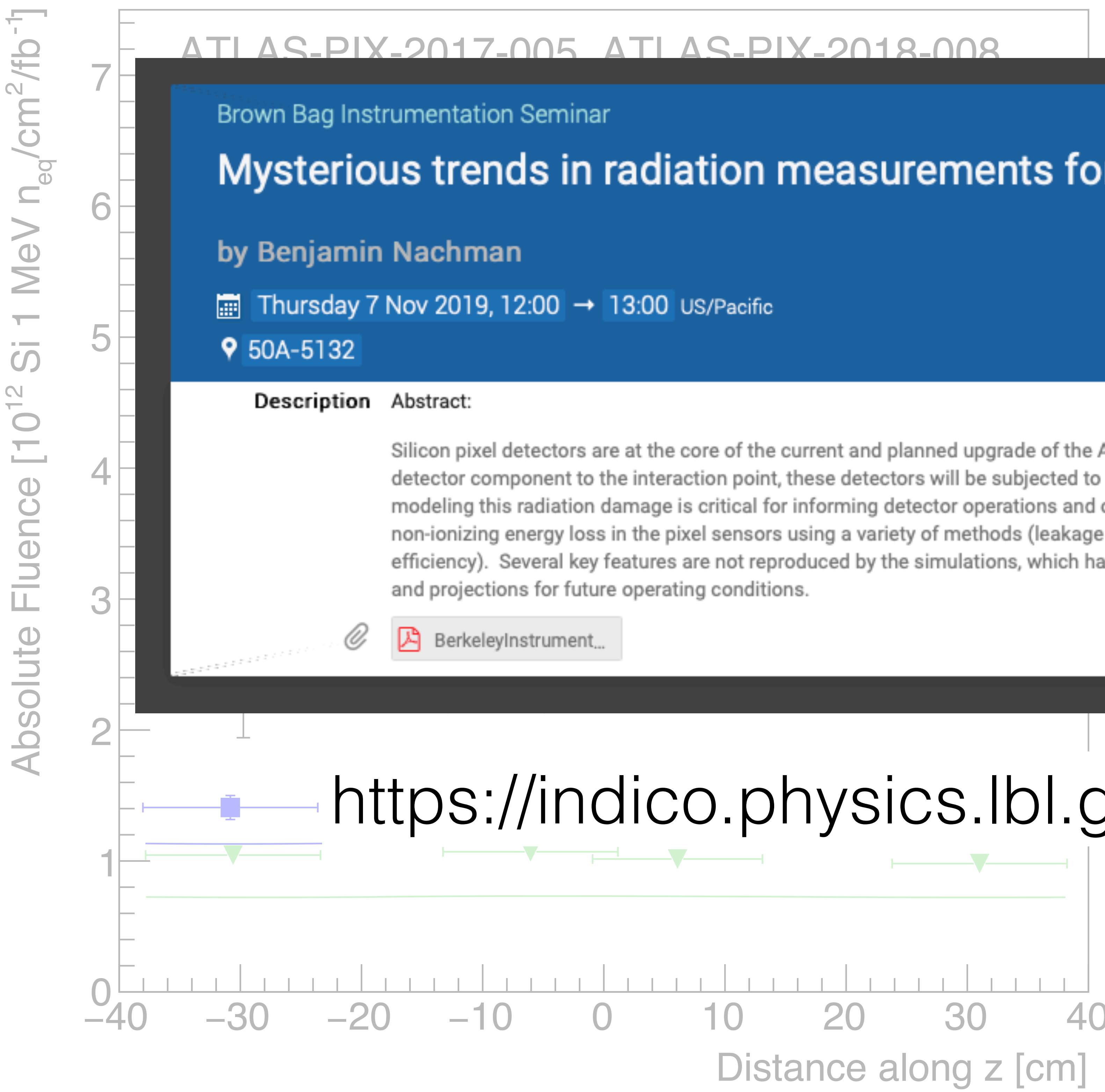
ATLAS measurement indicates (much) stronger z-dependence in data than simulation.

discrepancy seems to decrease with increasing radius.

…would be great to see confirmation from other measurements / experiments!

This is hard for CMS to measure, but some preliminary results indicate ~consistency with ATLAS

Leakage current along z



Brown Bag Instrumentation Seminar

Mysterious trends in radiation measurements for the ATLAS pixel detector

by Benjamin Nachman

Thursday 7 Nov 2019, 12:00 → 13:00 US/Pacific

50A-5132

Description Abstract:

Silicon pixel detectors are at the core of the current and planned upgrade of the ATLAS detector at the Large Hadron Collider (LHC). As the closest detector component to the interaction point, these detectors will be subjected to an extreme amount of radiation over their lifetime. Monitoring and modeling this radiation damage is critical for informing detector operations and offline data analysis. I will discuss recent measurements of the non-ionizing energy loss in the pixel sensors using a variety of methods (leakage current, depletion voltage, Lorentz angle, charge collection efficiency). Several key features are not reproduced by the simulations, which has important implications for safety factors for detector upgrades and projections for future operating conditions.

BerkeleyInstrument...

measurements / experiments!

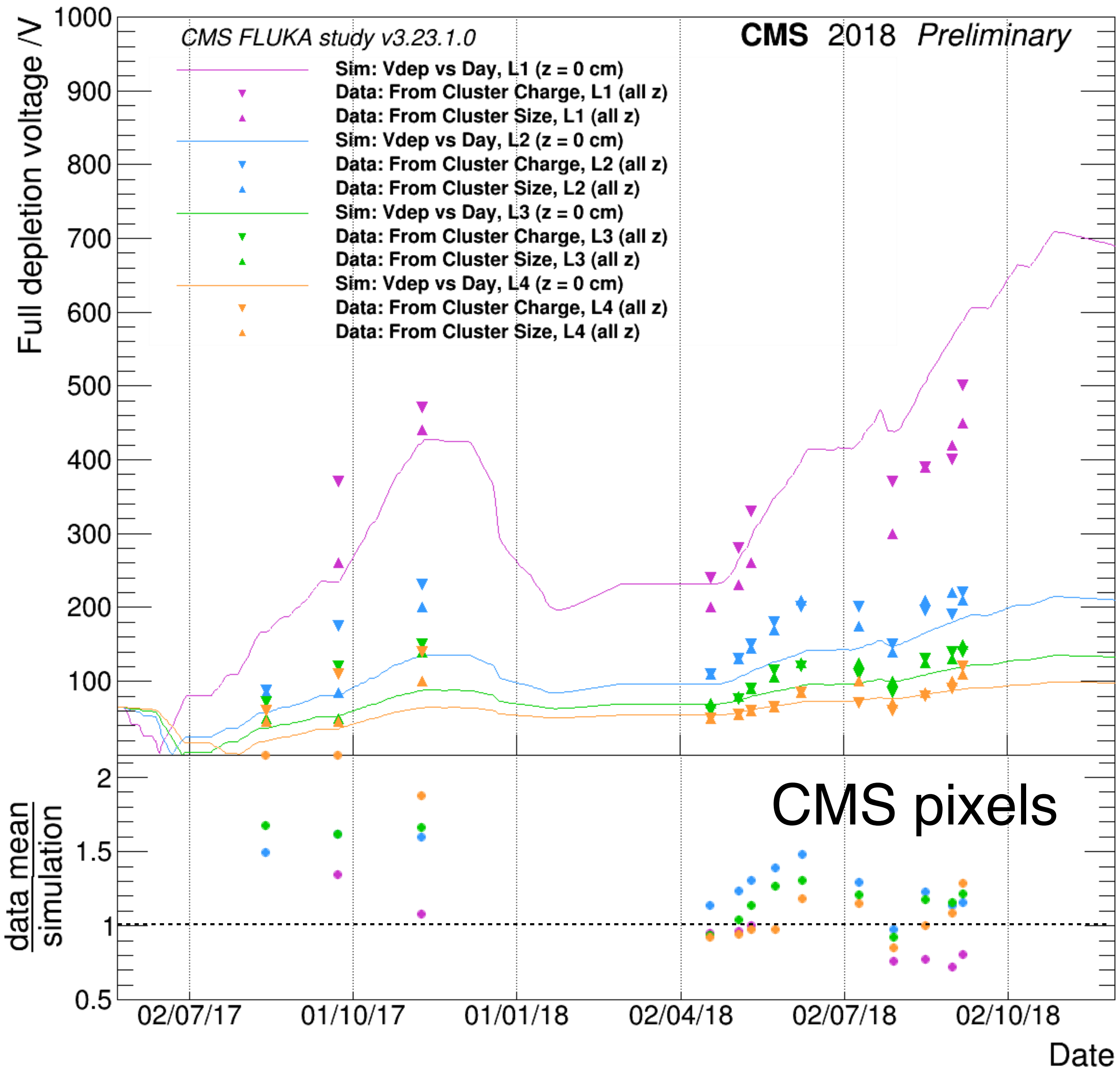
https://indico.physics.lbl.gov/event/1032/

This is hard for CMS to measure, but some preliminary results indicate ~consistency with ATLAS

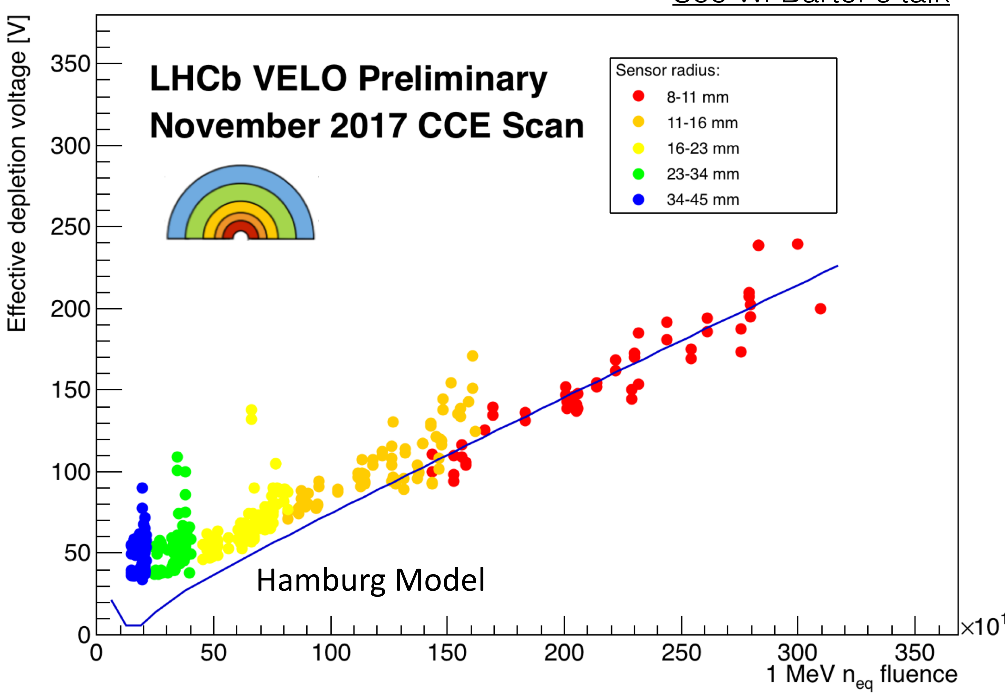
Depletion voltage across time and r

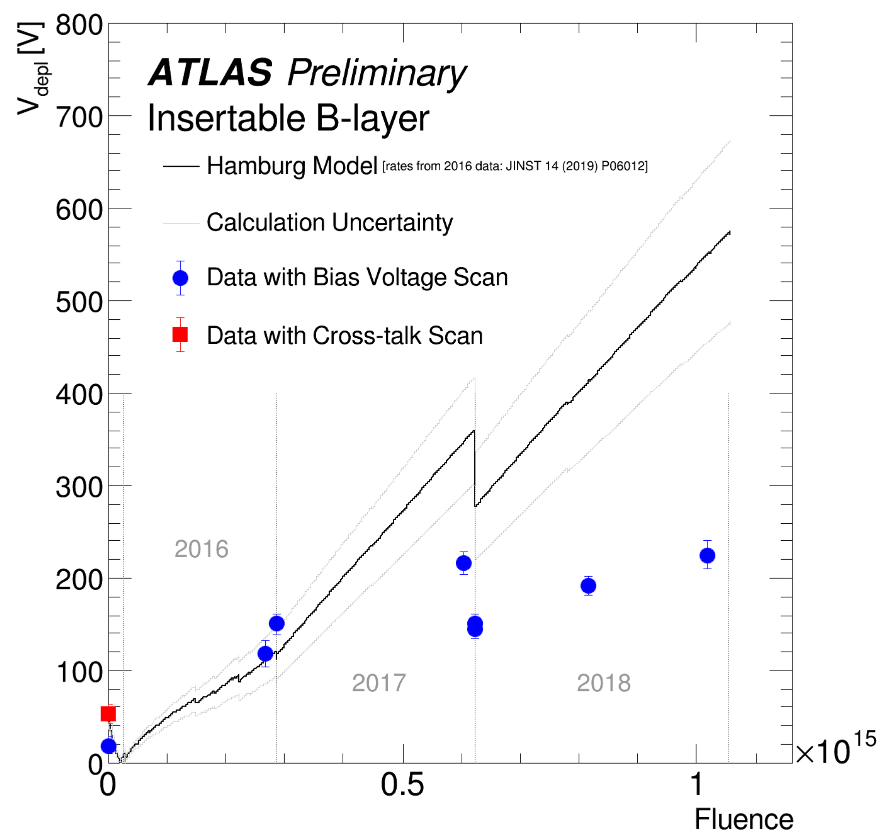
Difficult to fit all data points - challenging for extrapolation!

…do we need to modify the Hamburg model?



See W. Barter's talk





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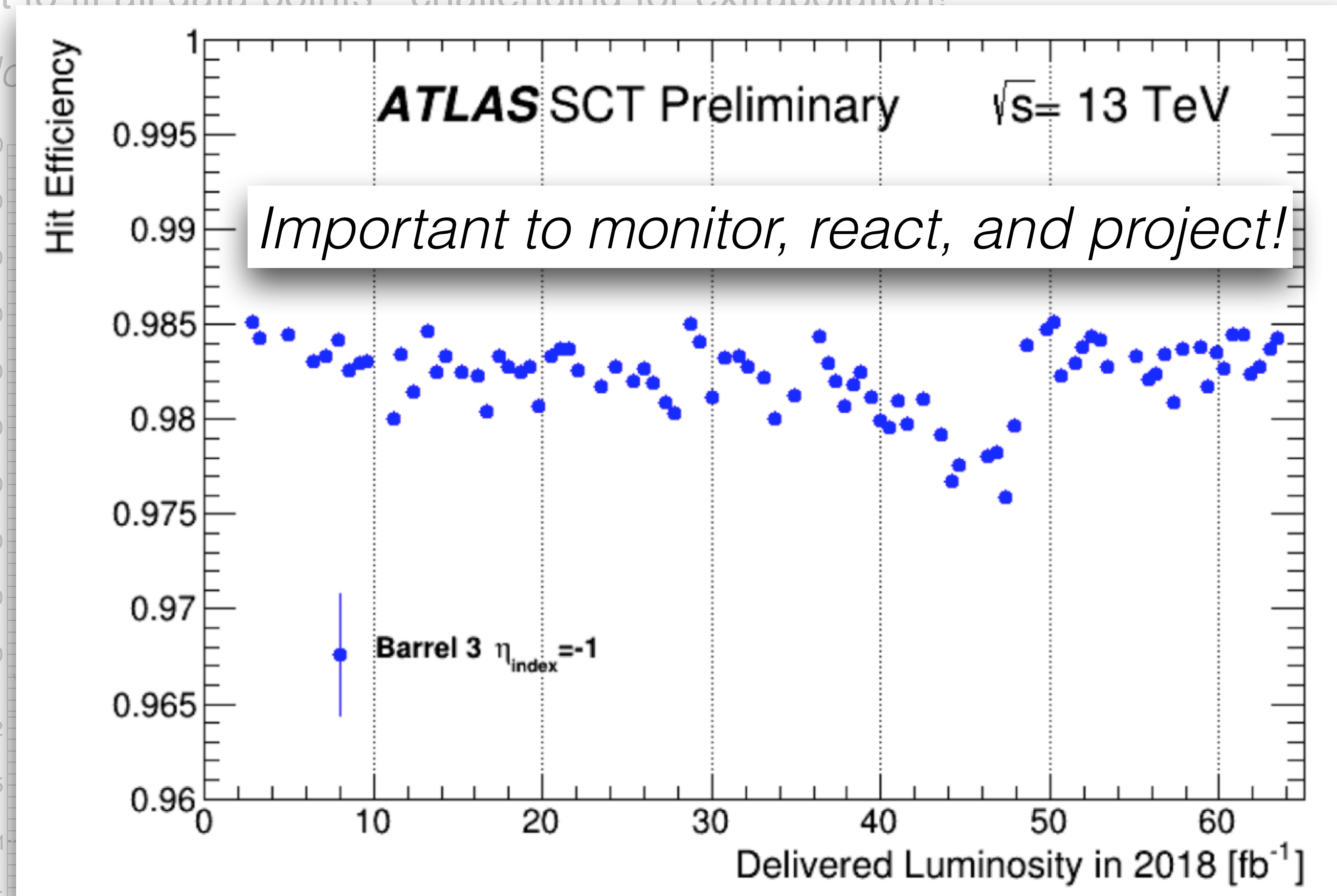
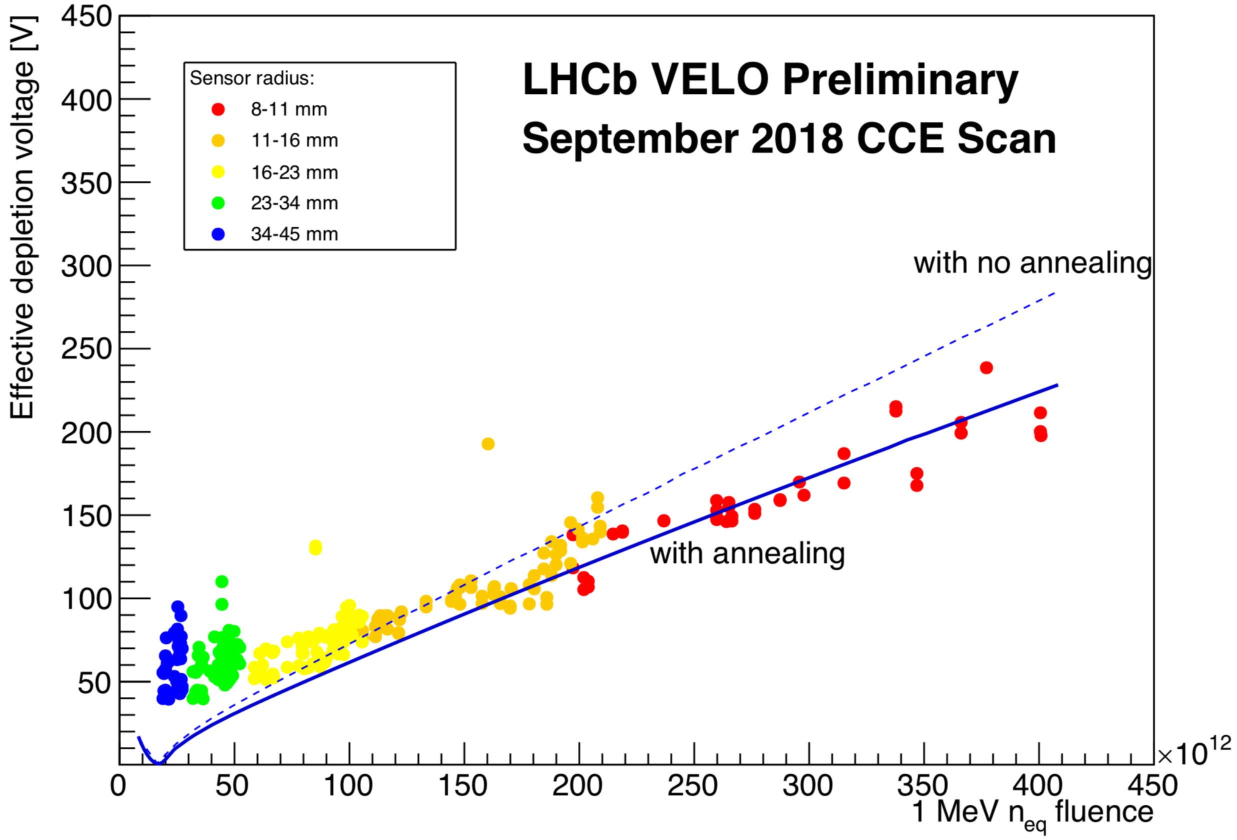
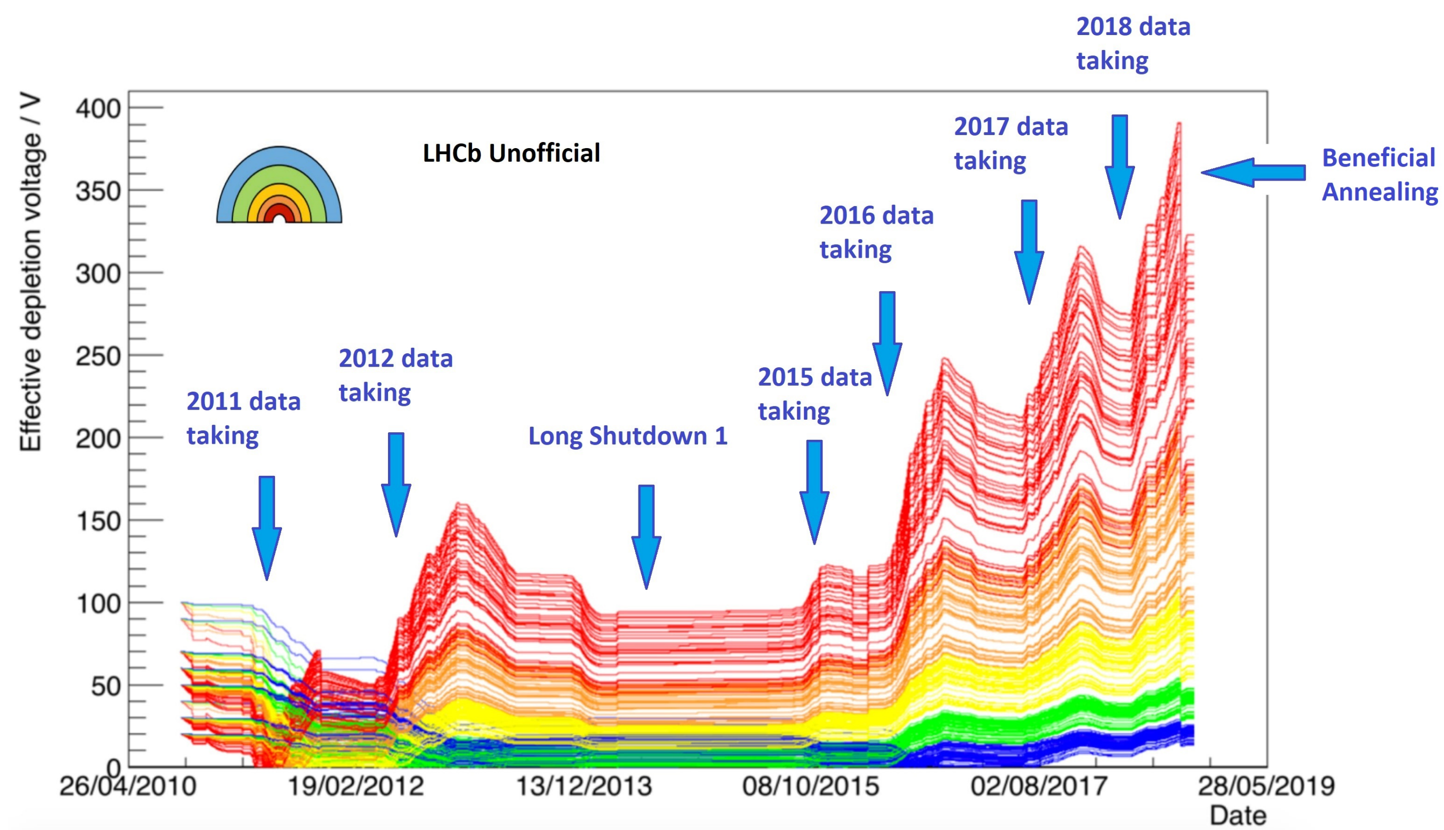


Important to monitor, react, and project!

LHCb highlight I



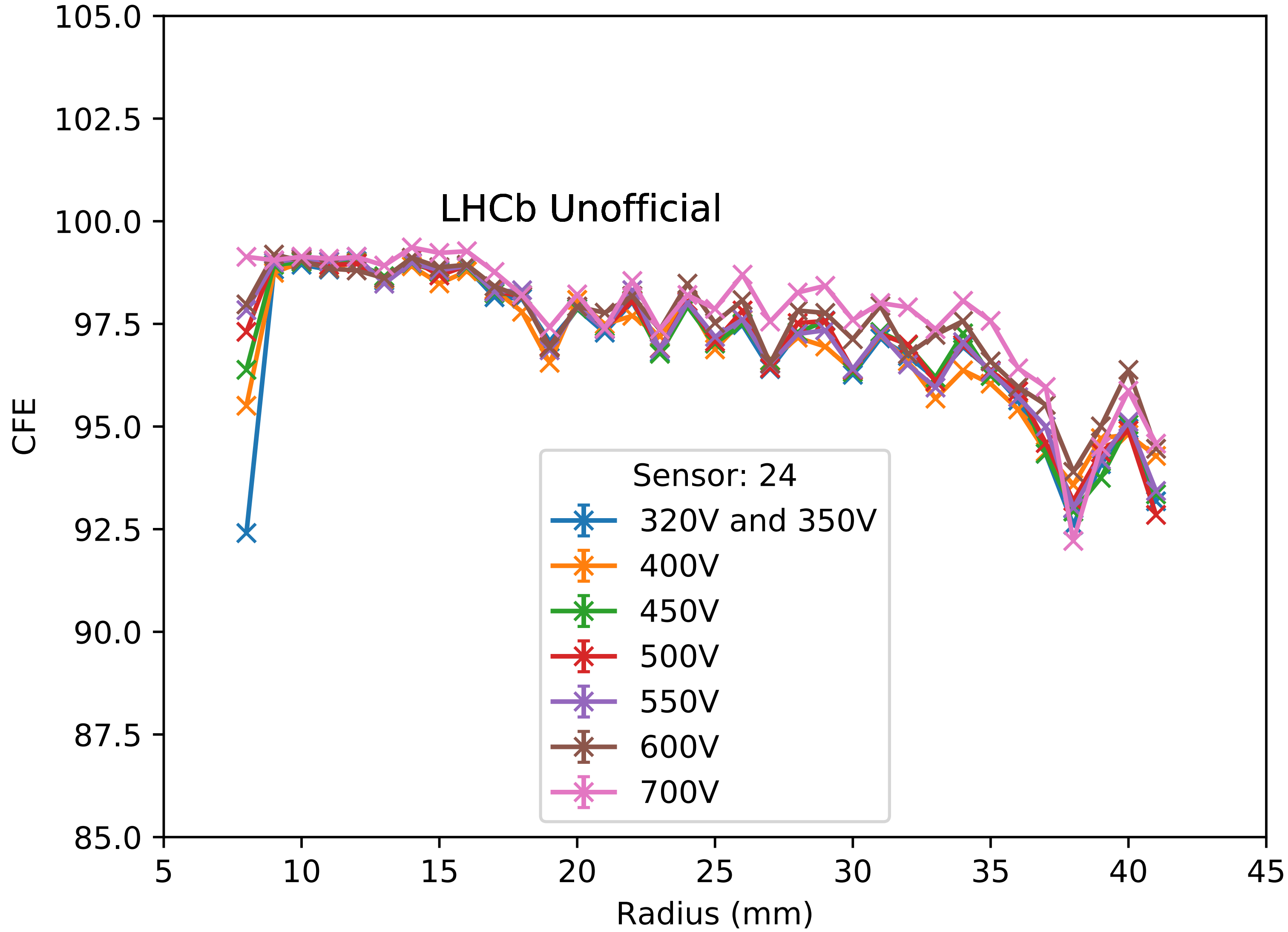
Radiation engineering: kept VELO at room temperature for 3 days in order to induce beneficial annealing and reduce depletion voltage by ~70V



LHCb highlight II

What to do with end of life? Stress test!

Just before removing the VELO, LHCb cranked up the HV well beyond the depletion voltage to if some of the charge (CFE = charge fraction efficiency) could be recovered



Can ATLAS/CMS do something like this at the end of Run 3?

Design HV = 500 V

(3) Impact on (Opto-)Electronics

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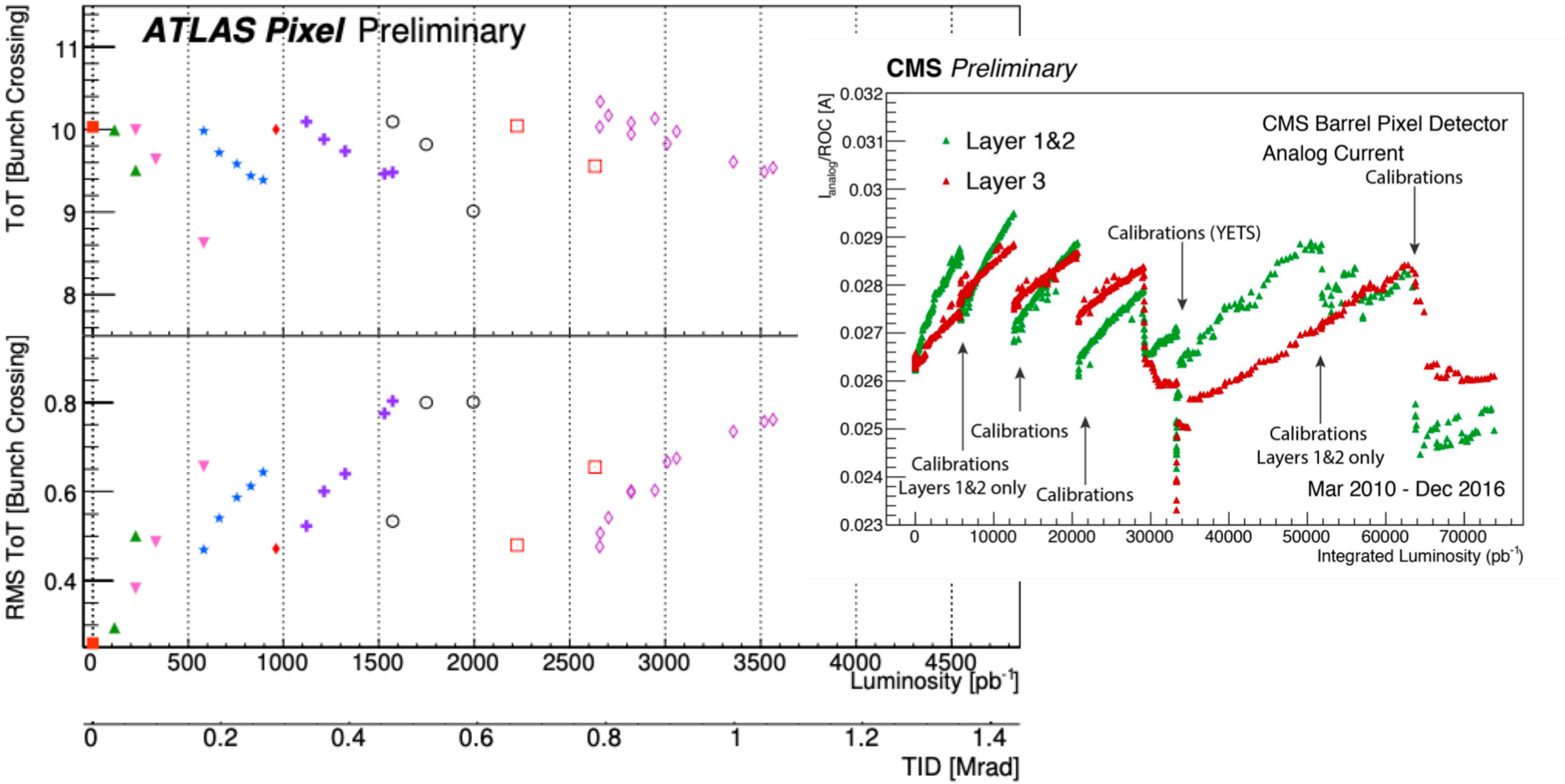
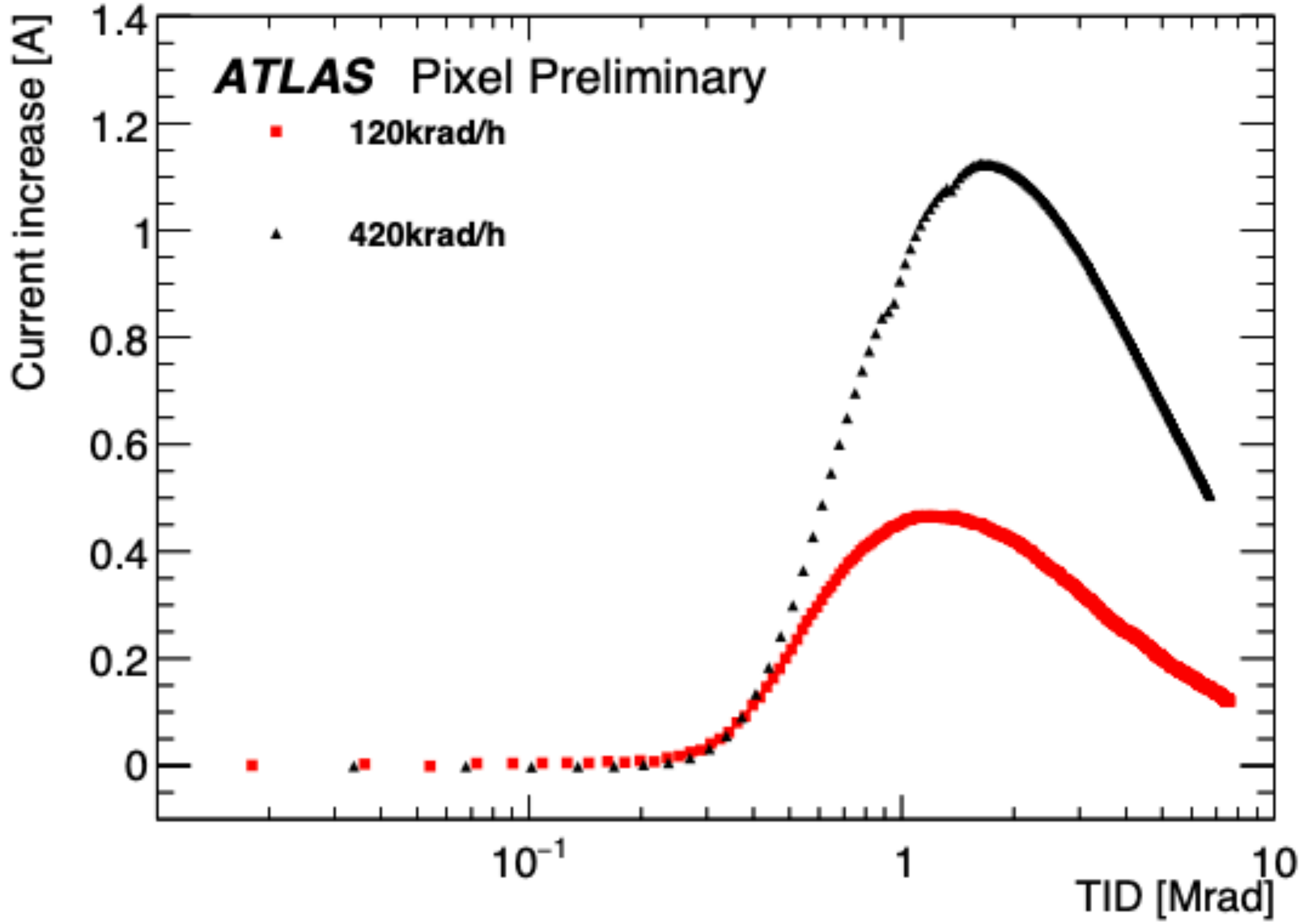


Calibration drifts with time and needs to be recalibrated.

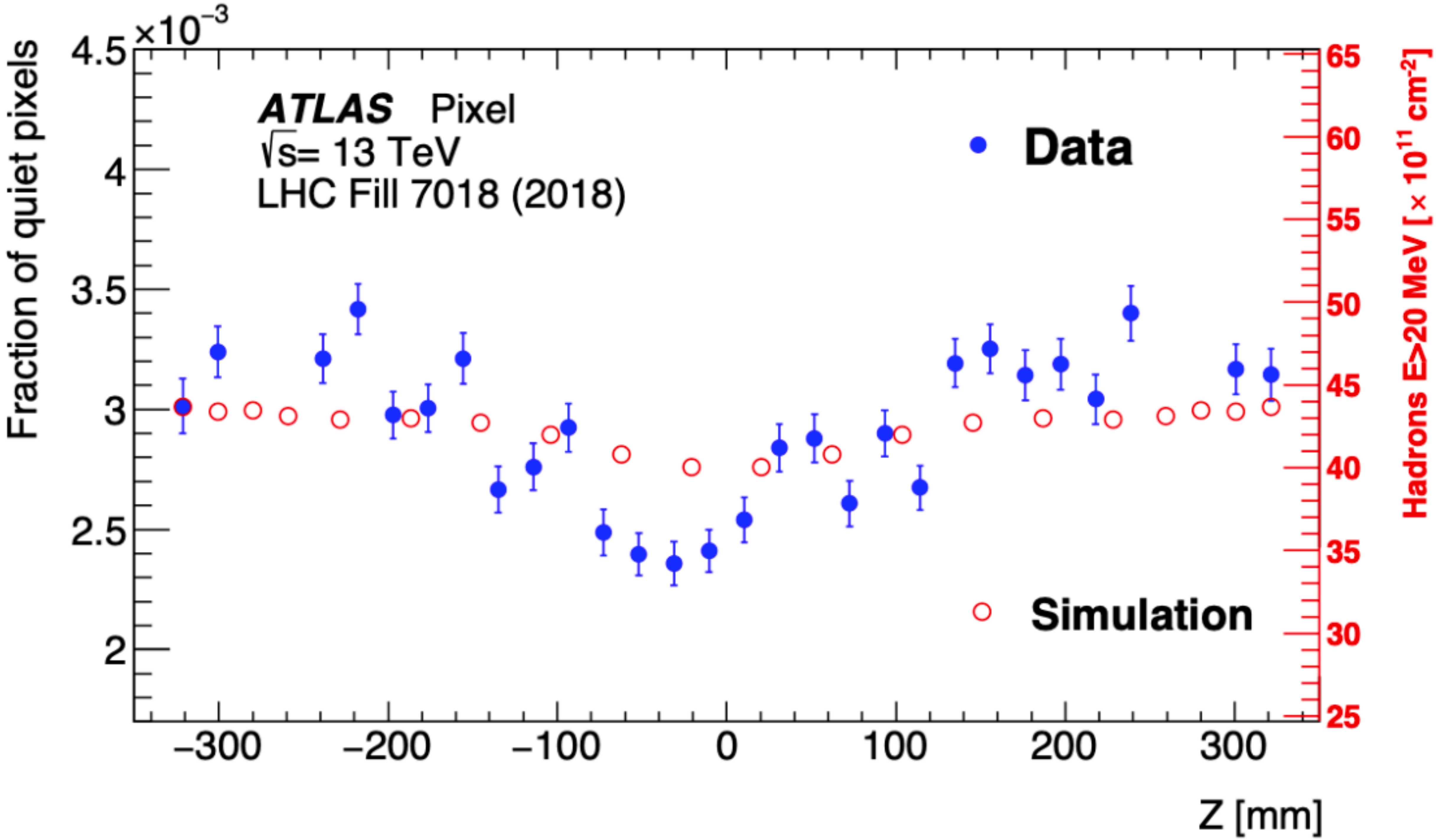
Some "surprises"



See studies by [A. Dimitrievska et al. for RD53]()

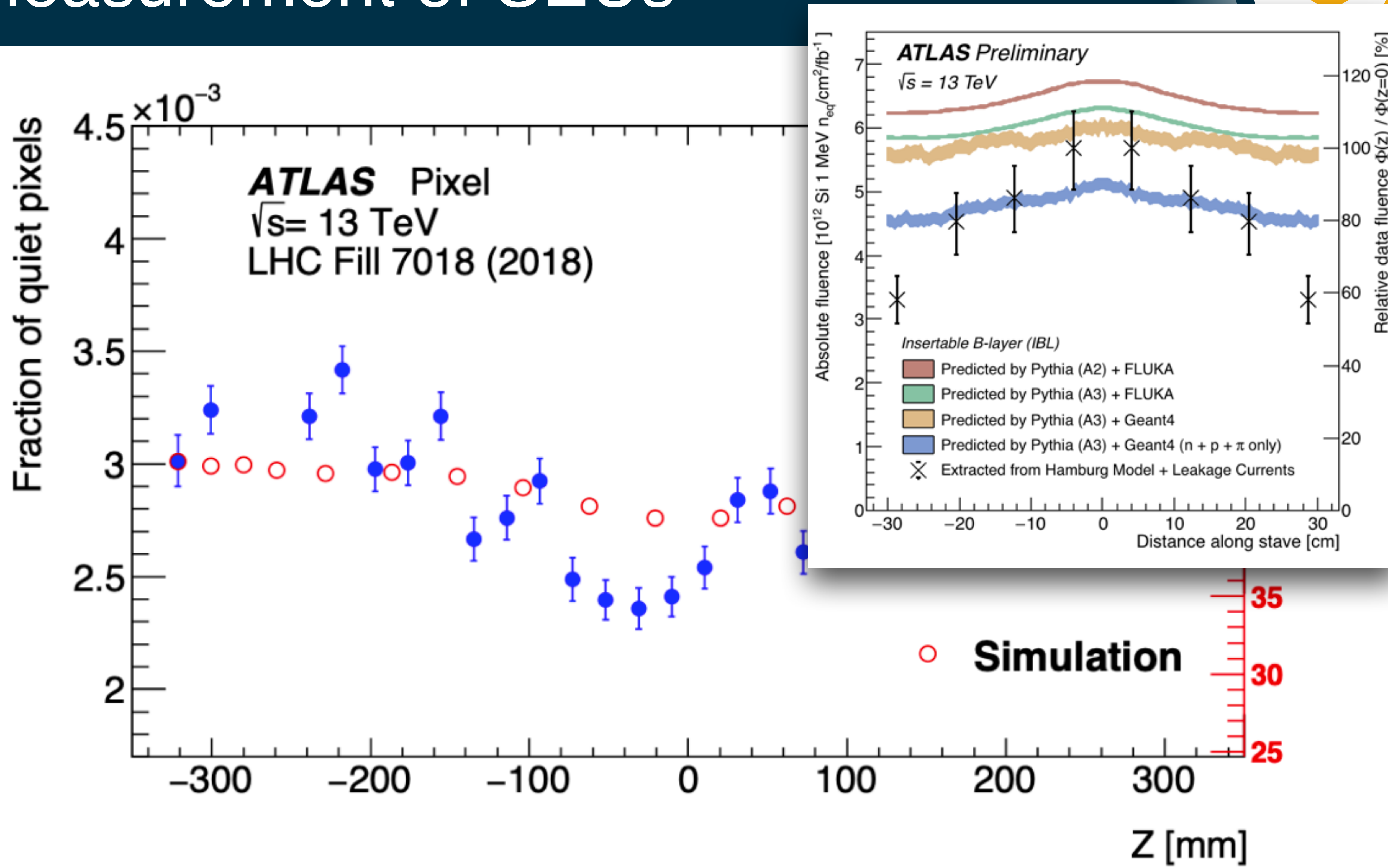
Low TID "bump" was a challenge for the IBL when it was first inserted. ATLAS upgrade: pre-irradiate (!)

Measurement of SEUs



Stronger |z|-dependence than simulation?

Measurement of SEUs



Stronger |z|-dependence than simulation?

(4) Detector Response Simulation

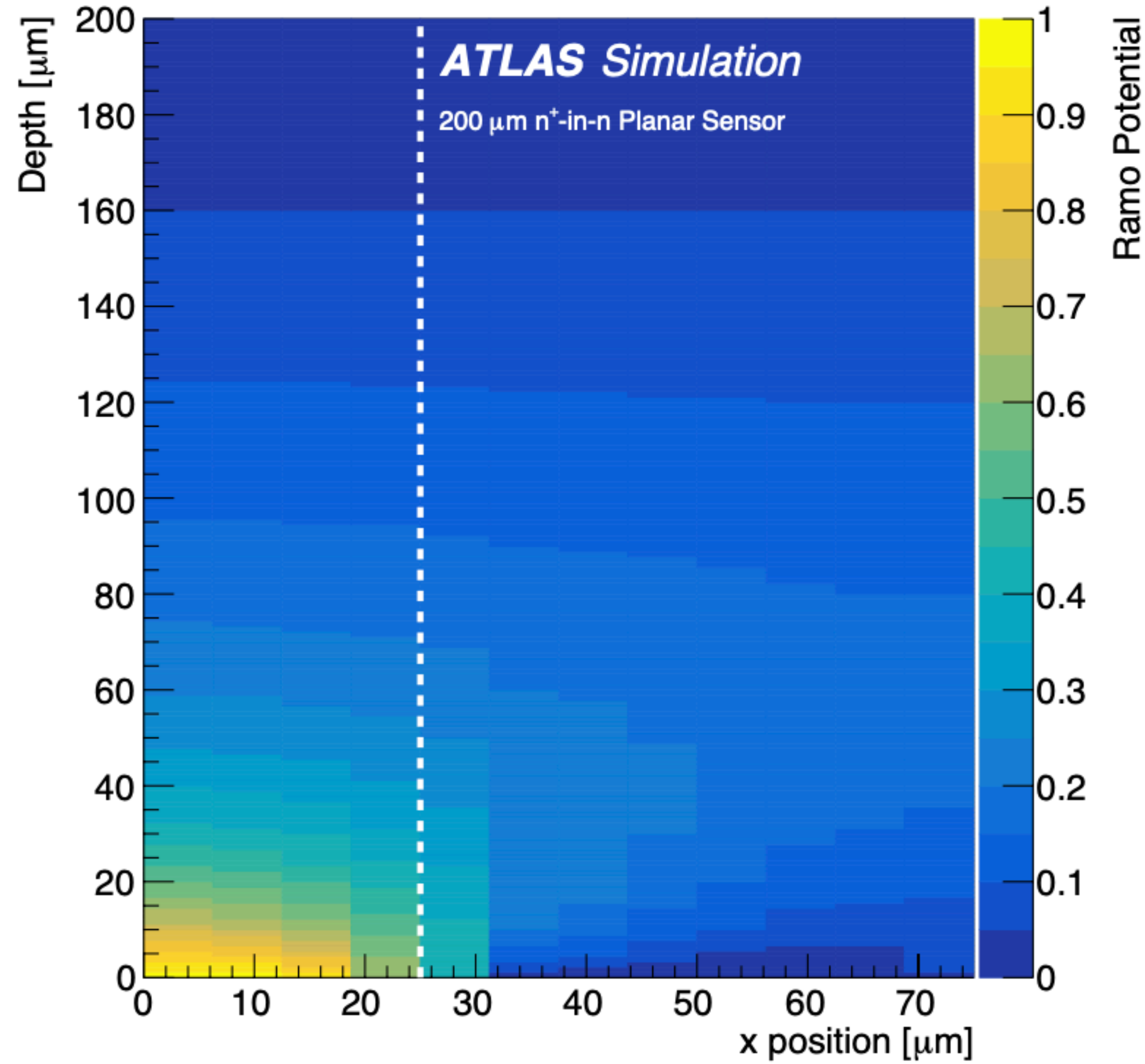
(4) Detector Response Simulation

Two levels of detail:

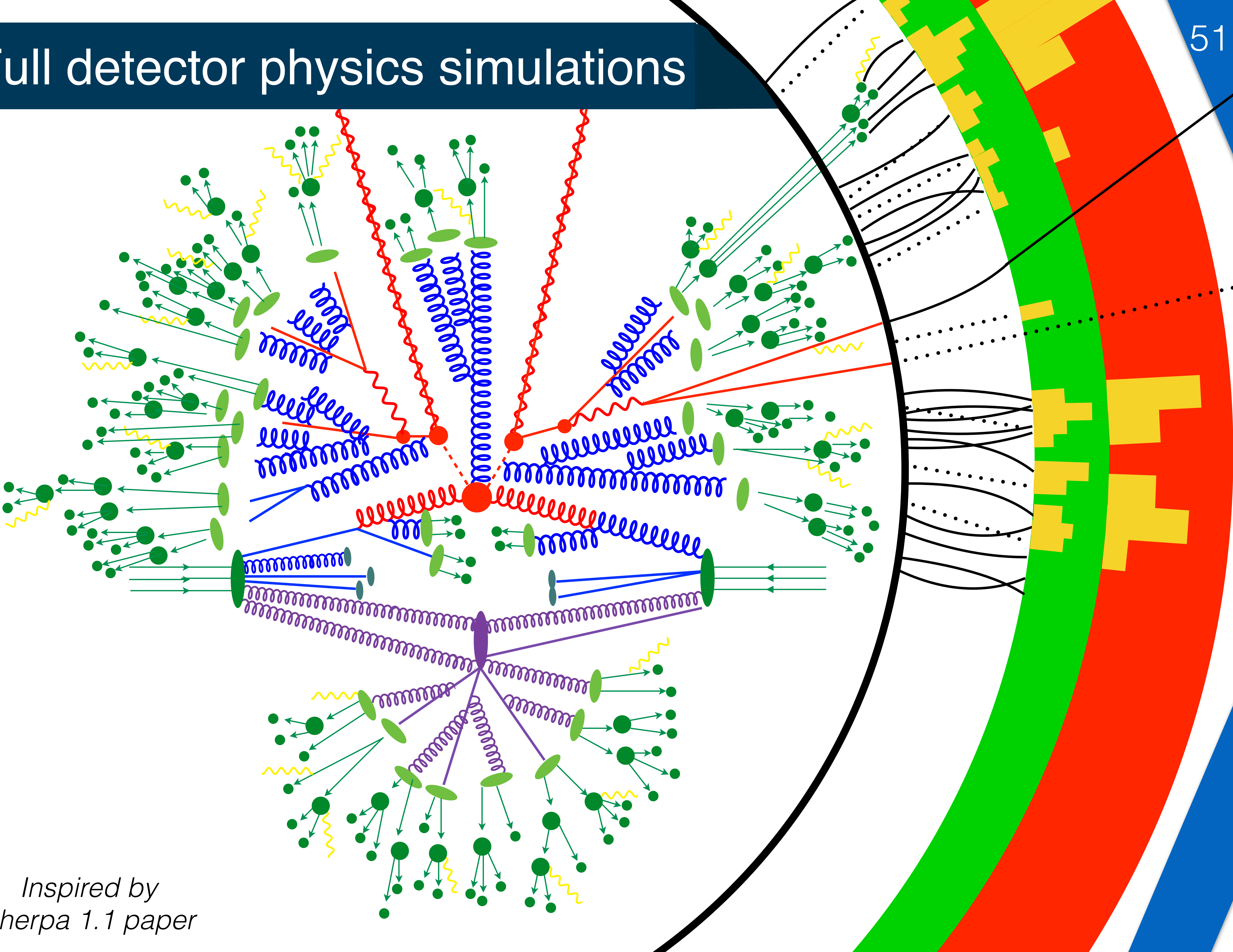
TCAD simulations of individual sensors

Monte Carlo simulation of entire detector systems

(used for physics analysis)



Full detector physics simulations



Inspired by Sherpa 1.1 paper

Full detector physics simulations

Hard-scatter
MadGraph 5 / aMC@NLO
POWHEG-BOX

↓

Fragmentation
Pythia, Herwig, Sherpa

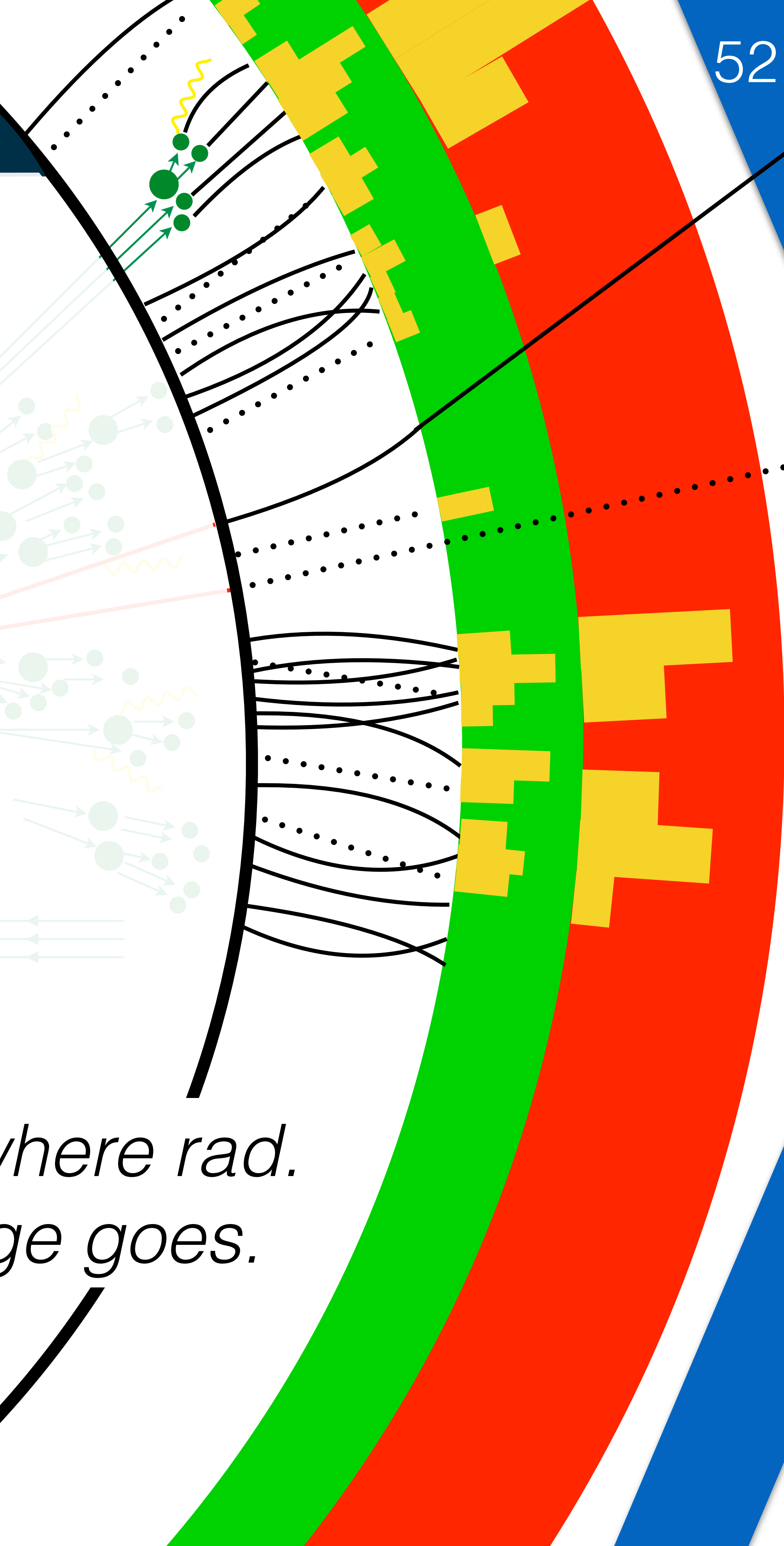
↓

Material Interactions
Geant 4

↓

Digitization
Custom code

this is where rad. damage goes.



Inspired by Sherpa 1.1 paper

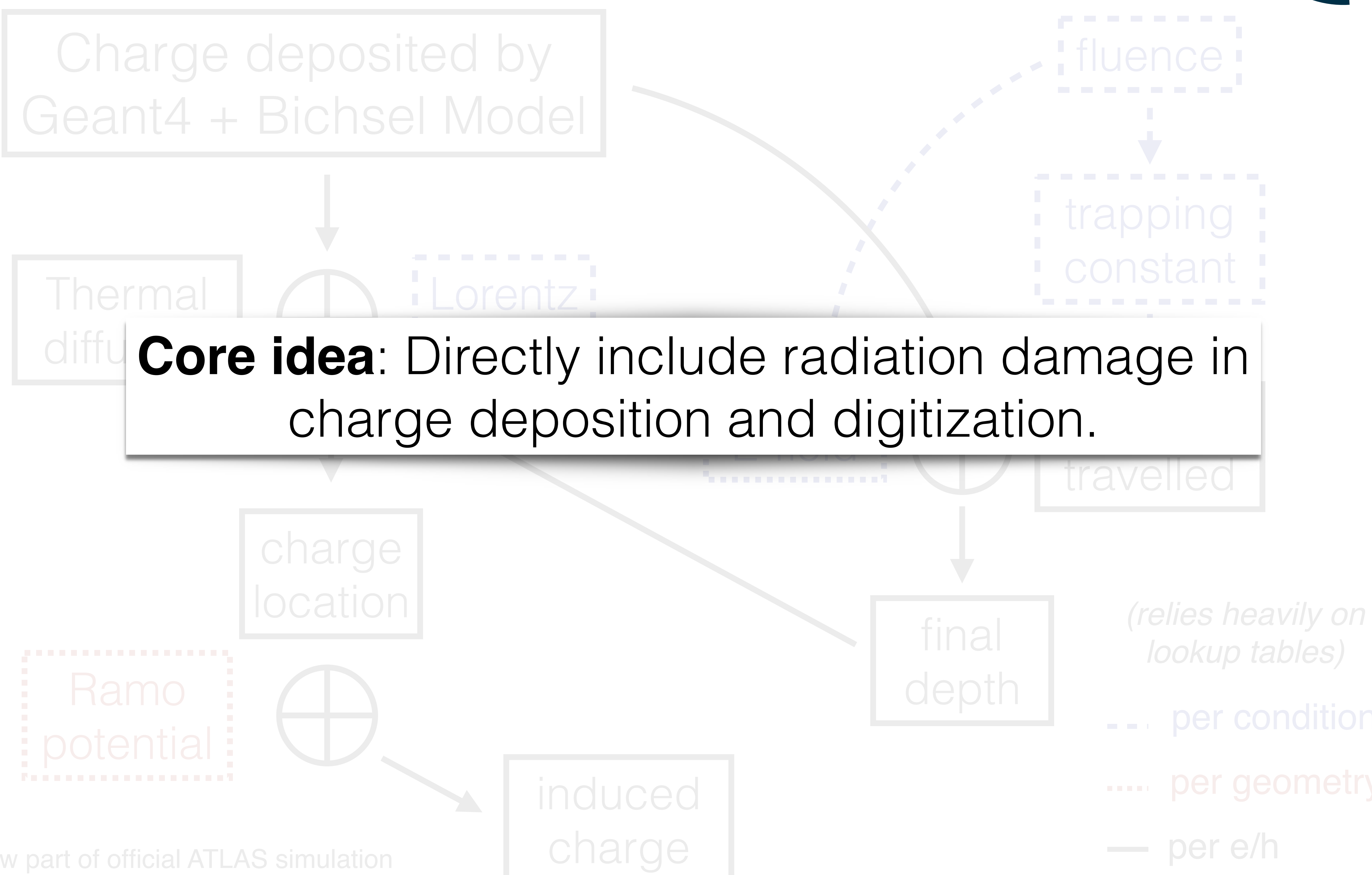
Current Run 2 (Si) Simulation

	ATLAS EXPERIMENT	CMS	LHCb
Energy Deposition	Bichsel Model + G4 ($\boldsymbol{\delta}$-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	readout noise	capacitive coupling + noise
Radiation damage	**none**	**none**	**none**

Next Generation (Si) Simulation

	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	readout noise	capacitive coupling + noise
Radiation damage	**trapping + charge induction**	**trapping + charge induction**	**charge & 'diffusion' corrections**

New ATLAS Pixel Simulation Details

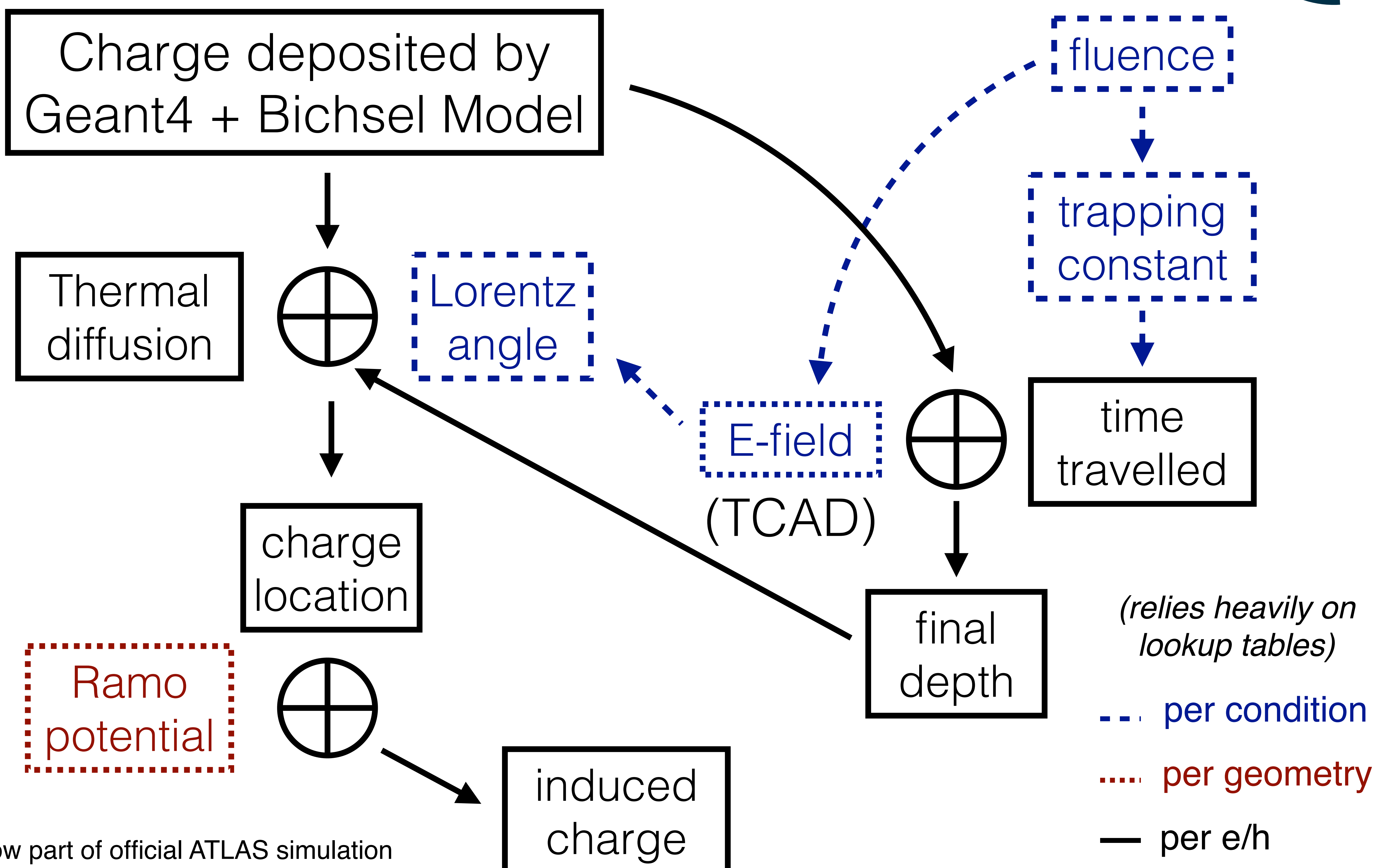


Core idea: Directly include radiation damage in charge deposition and digitization.

Now part of official ATLAS simulation (but currently off by default)

JINST 14 (2019) P06012 - 1905.03739

New ATLAS Pixel Simulation Details



Now part of official ATLAS simulation
(but currently off by default)

New CMS Pixel Simulation Details

The TCAD+Pixelav simulations are tuned to measured distributions

Measure E_z vs z profile → TCAD model E-field with 2-traps → Pixelav (detailed sim) T, r_H, Φ → electronic response (6 params) → Simulated Data: – charge distribution – size distributions – shape probabilities – Lorentz angle cals *clust size vs cot(α) *grazing angle → Calibrations: – Standard Reco * Lorentz corrs * error estimates – Template Reco *1D cluster shapes *error estimates …bability info …cluster shapes

Adjust these to match simulated data to measurements

Core idea: Detailed standalone simulation used to apply corrections to simulation.

Different approach:

instead of modifying primary simulation, perform detailed independent simulation and apply correction factors.

…ke clust

New CMS Pixel Simulation Details

The TCAD+Pixelav simulations are tuned to measured distributions

Measure E_z vs z profile → TCAD model E-field with 2-traps → Pixelav (detailed sim) T, r_H, Φ → electronic response (6 params) → Simulated Data: → Calibrations:

Simulated Data:
- charge distribution
- size distributions
- shape probabilities
- Lorentz angle cals
  - *clust size vs cot(α)
  - *grazing angle
- extracted E-field profiles

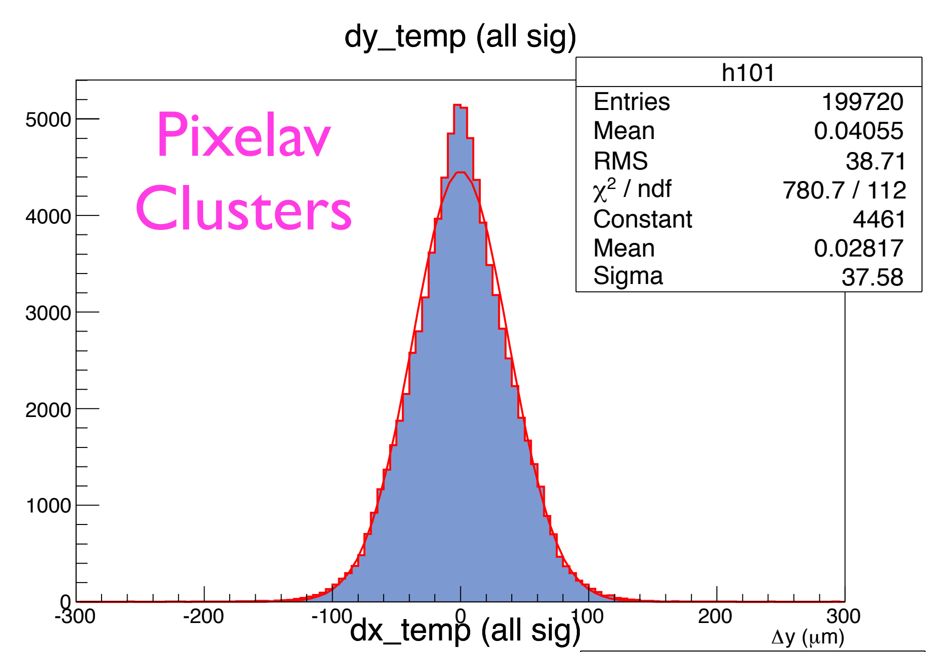
Calibrations:
- Standard Reco
  - * Lorentz corrs
  - * error estimates
- Template Reco
  - *1D cluster shapes
  - *error estimates
  - *probability info
  - *2D cluster shapes

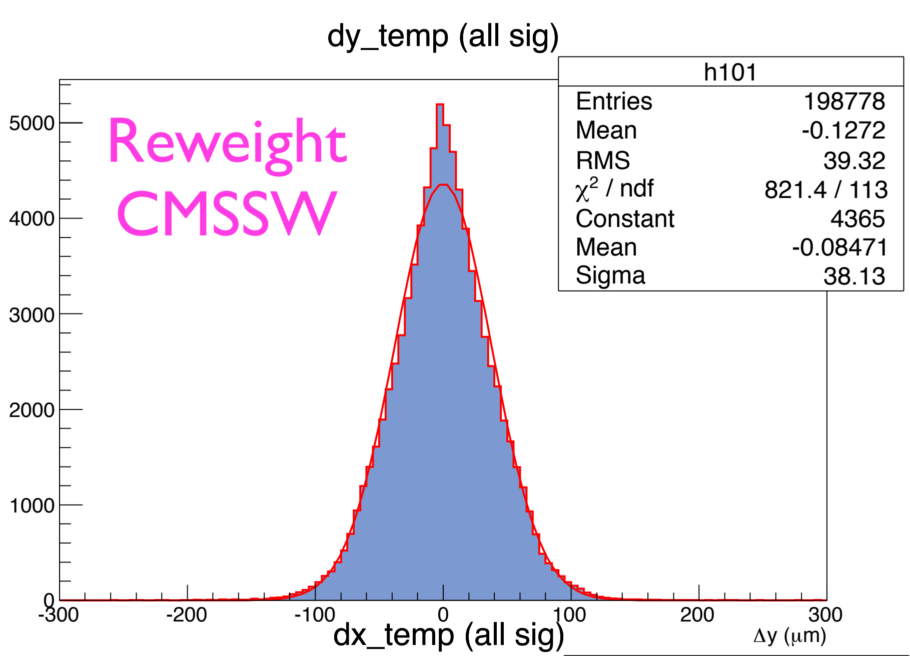
Adjust these to match simulated data to measurements

Different approach:

instead of modifying primary simulation, perform detailed independent simulation and apply correction factors.

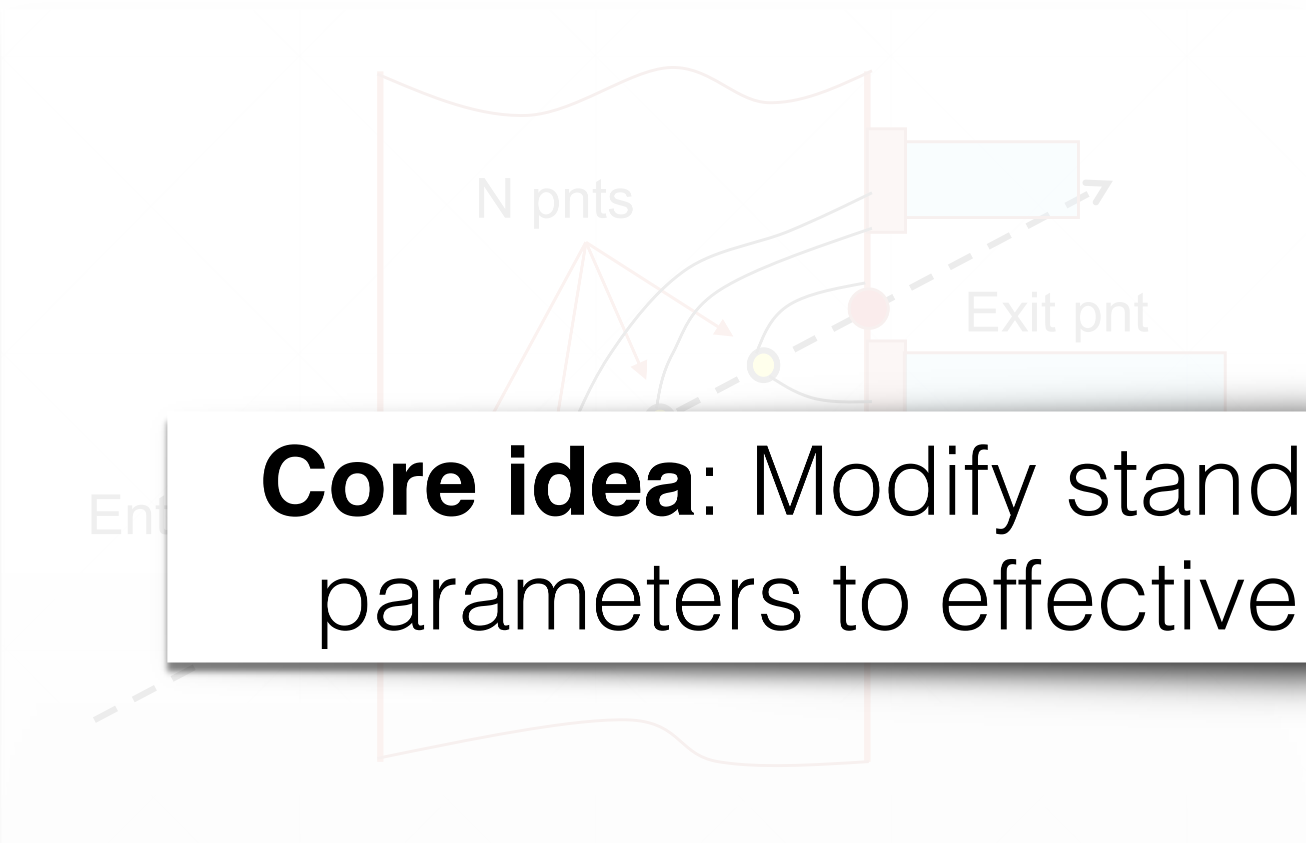
Fully simulated Φ=1.2x10^{15} n_{eq}/cm^2 clust vs reweighted CMSSW-like clust





See M. Swartz's talk for more details.

New LHCb Pixel Simulation Details



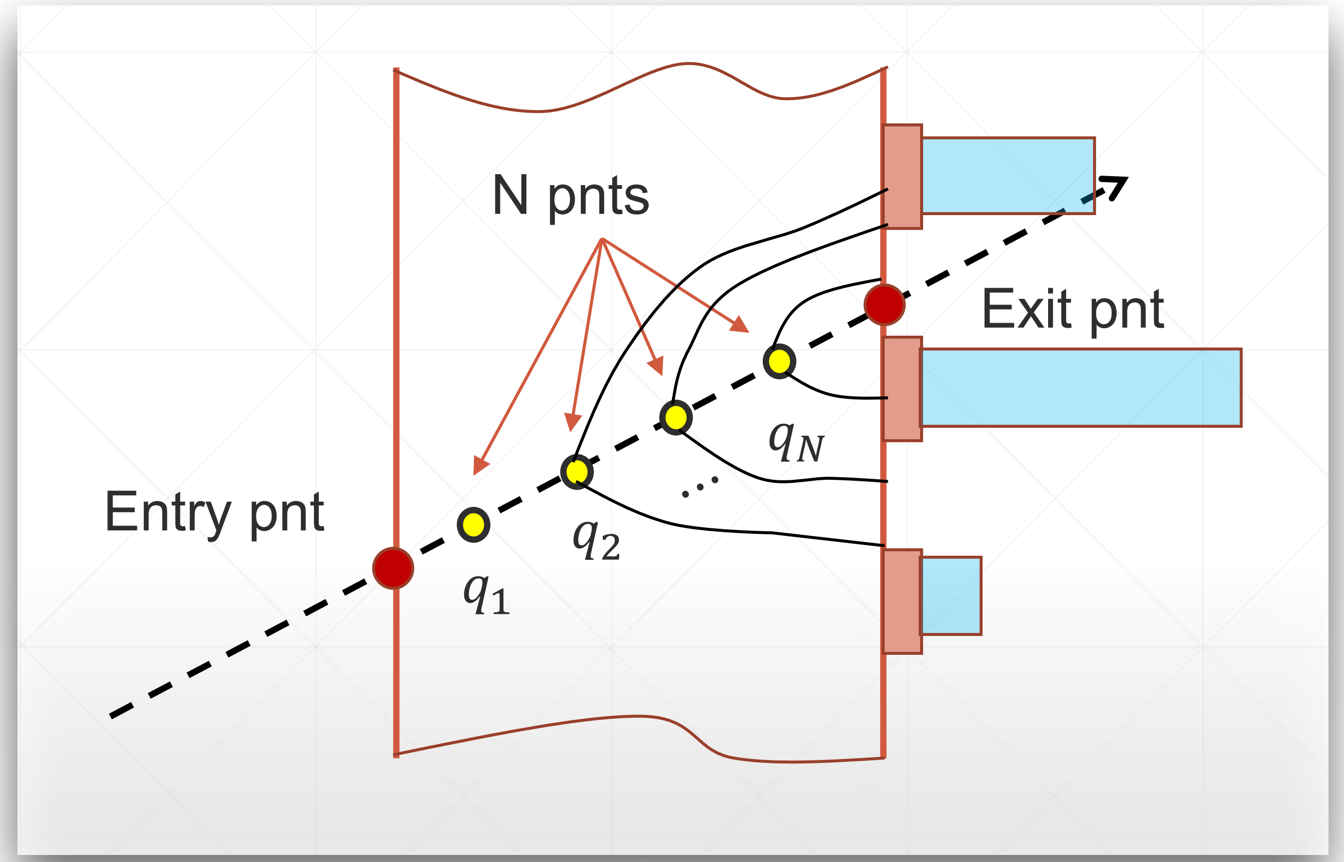
Different than both ATLAS/ CMS: reduce charge and increase “diffusion length”

Core idea: Modify standard charge propagation parameters to effectively model rad. damage.

Tuned once/year.

Preliminary results look promising and validation with bigger simulations is ongoing.

New LHCb Pixel Simulation Details



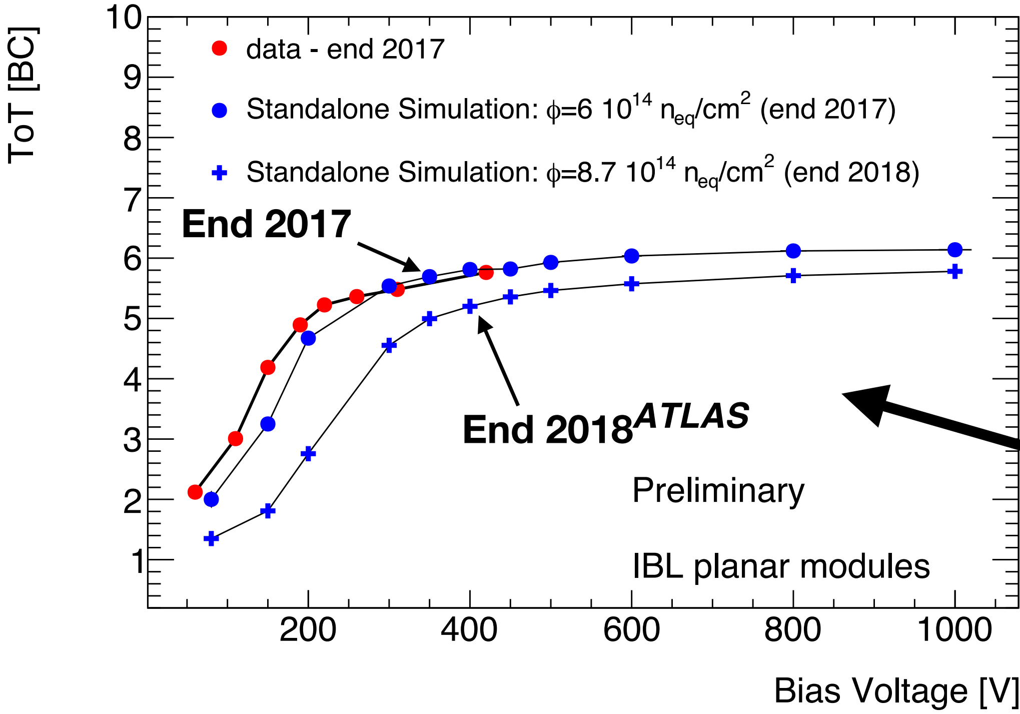
Different than both ATLAS/CMS: reduce charge and increase “diffusion length” to match data.

Tuned once/year.

Preliminary results look promising and validation with bigger simulations is ongoing.

See T. Szumlak's talk for more details.

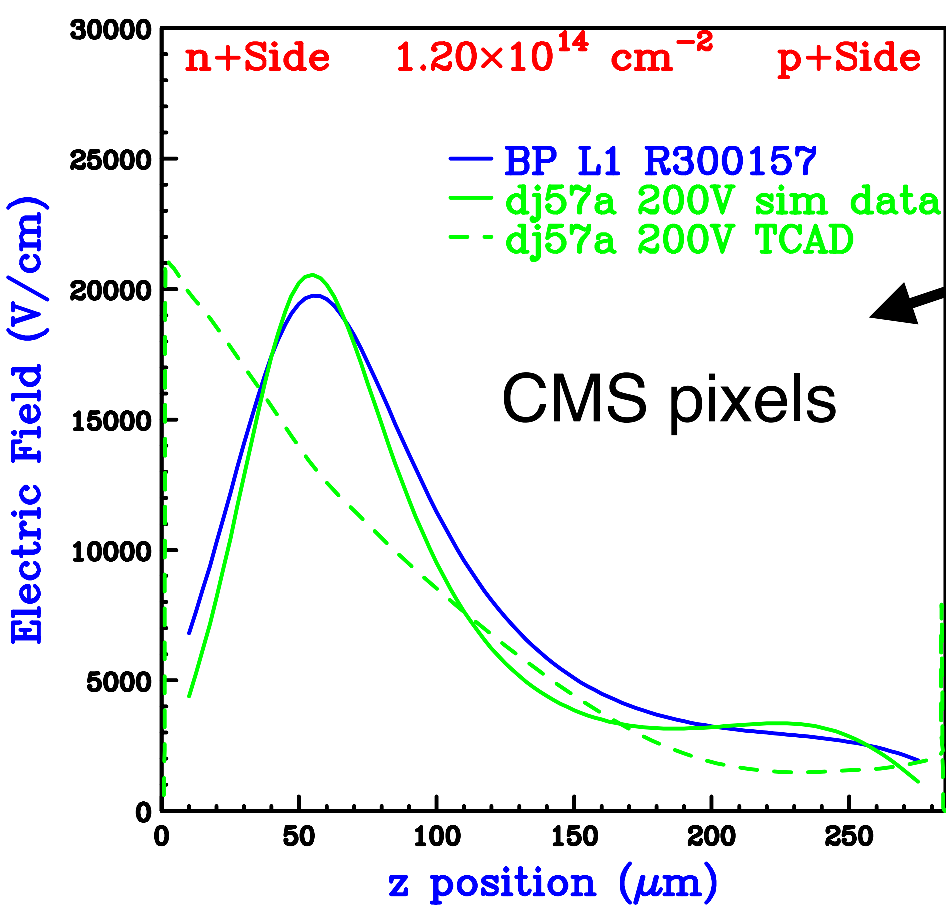
Validation with data



See L. Rossini's talk for details.

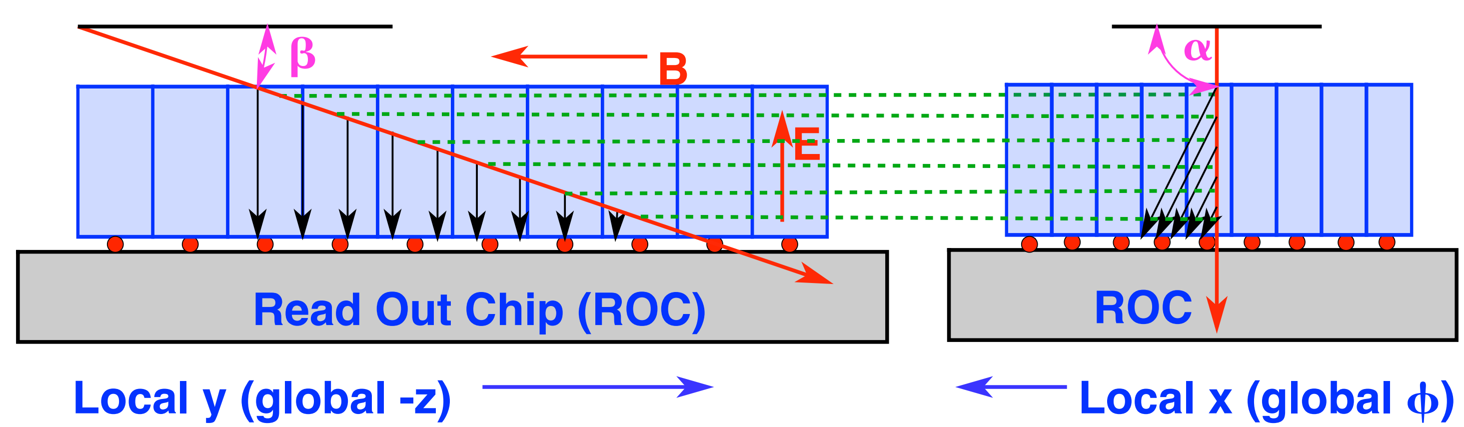
We have probes which are sensitive to the detailed structure of the E-field.

Charge collection efficiency for "under-depleted" sensors.



See M. Swartz's talk for details.

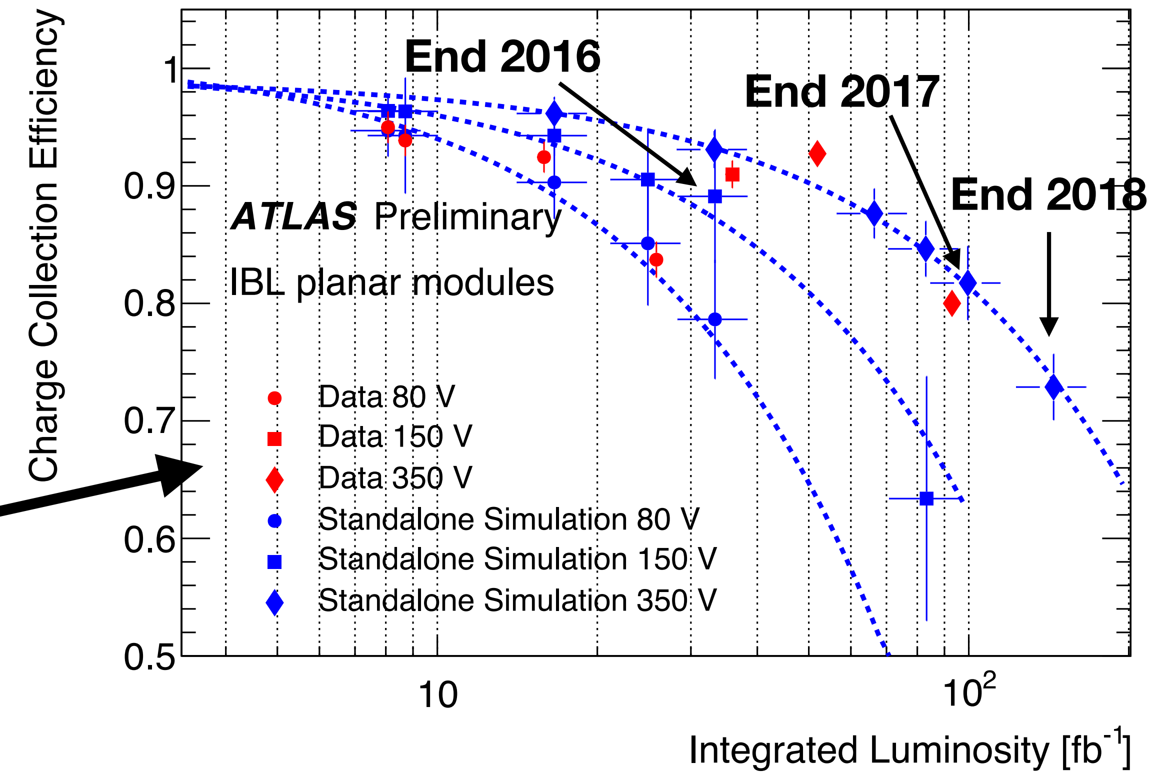
Charge drift depth-dependence using long clusters.
(invert mobility to get E-field)



Validation with data

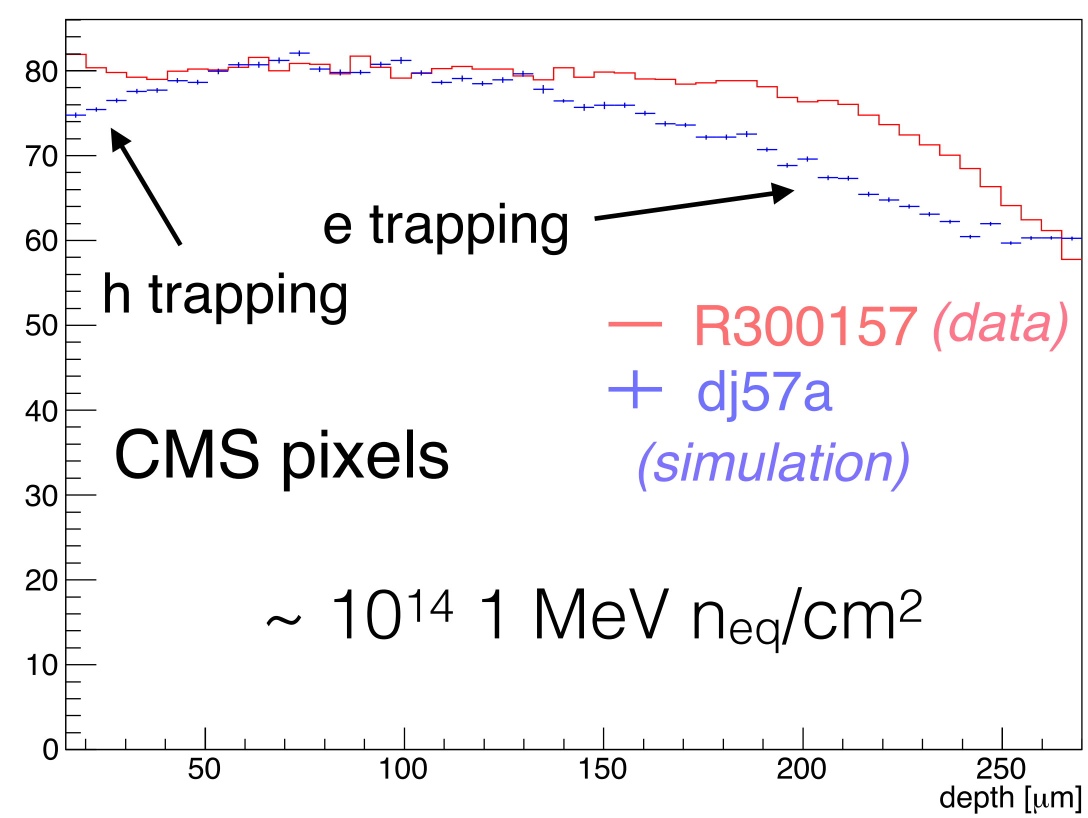
We also have probes that are very sensitive to charge trapping.

MPV of the deposited charge, normalized to unity at zero fluence.

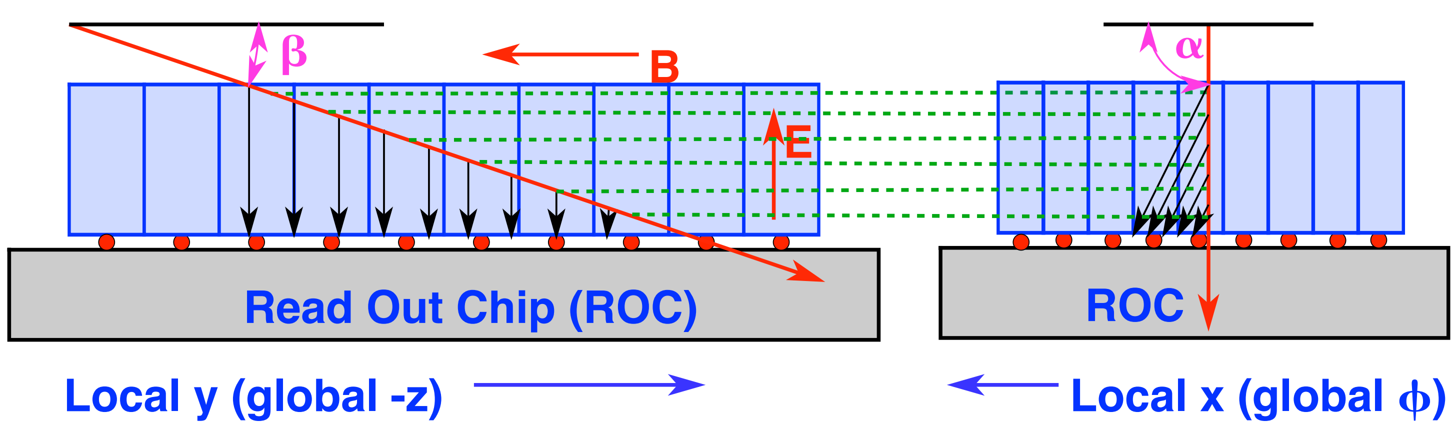


See L. Rossini's talk for details.

Using long clusters again, look at the charge versus depth.



See M. Swartz's talk for details.



Validation with data

ATLAS: Qualitative agreement in many cases, but uncertainties are large - need to profile!

CMS: E-field evolving faster than predicted; trapping rates evolving slower than expected (~60% fluence)

Future: use each other's analyses?

… also, can we check z-dependence of fluence?

more complicated as need to correct for angle effects, but possible!

Grand Challenges for the Future

…where I'd like to see progress for the years ahead:

Understand the mysterious |z| dependence of the fluence

Incorporate physics measurements into fluence predictions

RD50 radiation damage model parameter set + uncertainty

Progress toward a combination of TCAD + annealing

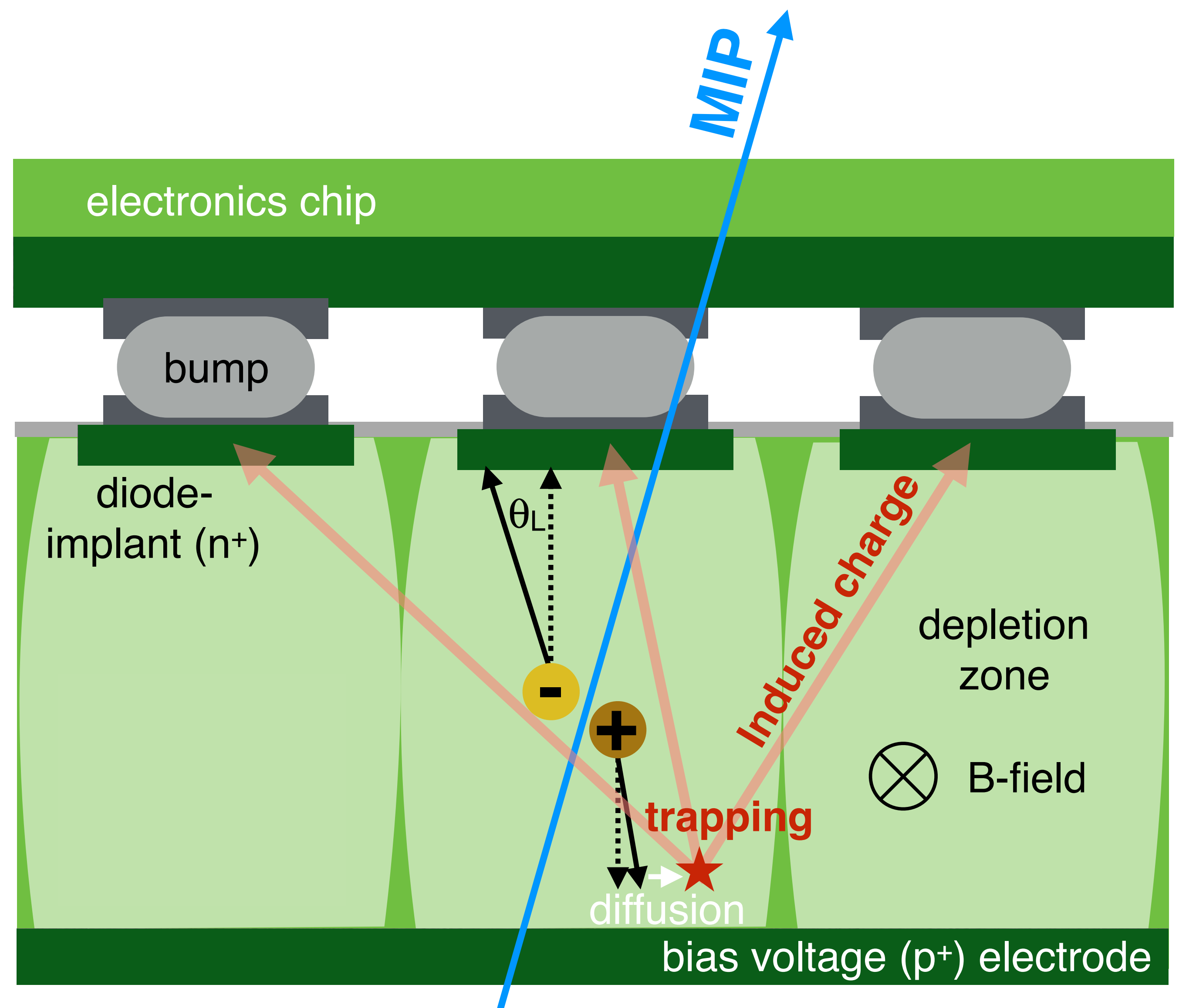
Impact on physics / analysis observables (e.g. flavor tagging)

Compare methods between ATLAS/CMS/LHCb

Conclusions and Outlook

The current LHC detectors are a great laboratory for radiation damage effects and are in great need of input from the community!

This Yellow Report marks the end of a chapter in the LHC history which will hopefully serve as an important reference for the HL-LHC and future colliders



Questions?