Radiation Damage Monitoring & Modeling with Full Detector Systems at the LHC

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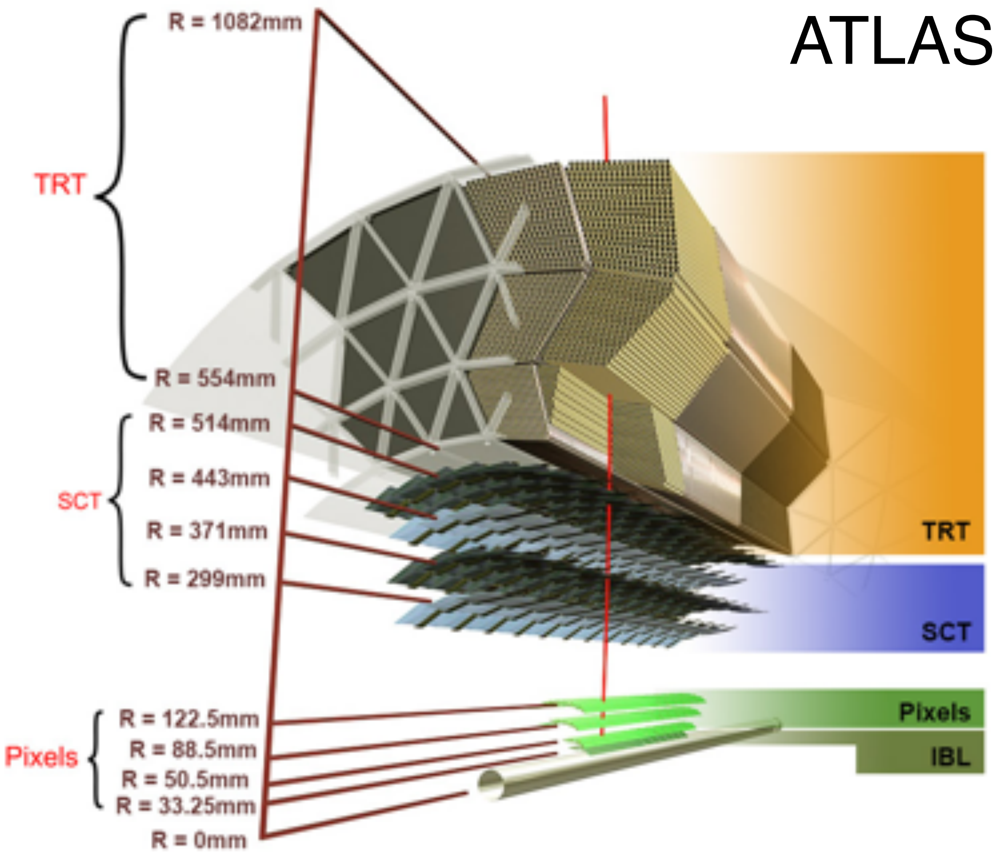
on behalf of the LHC experiments and the RD50 Collaboration

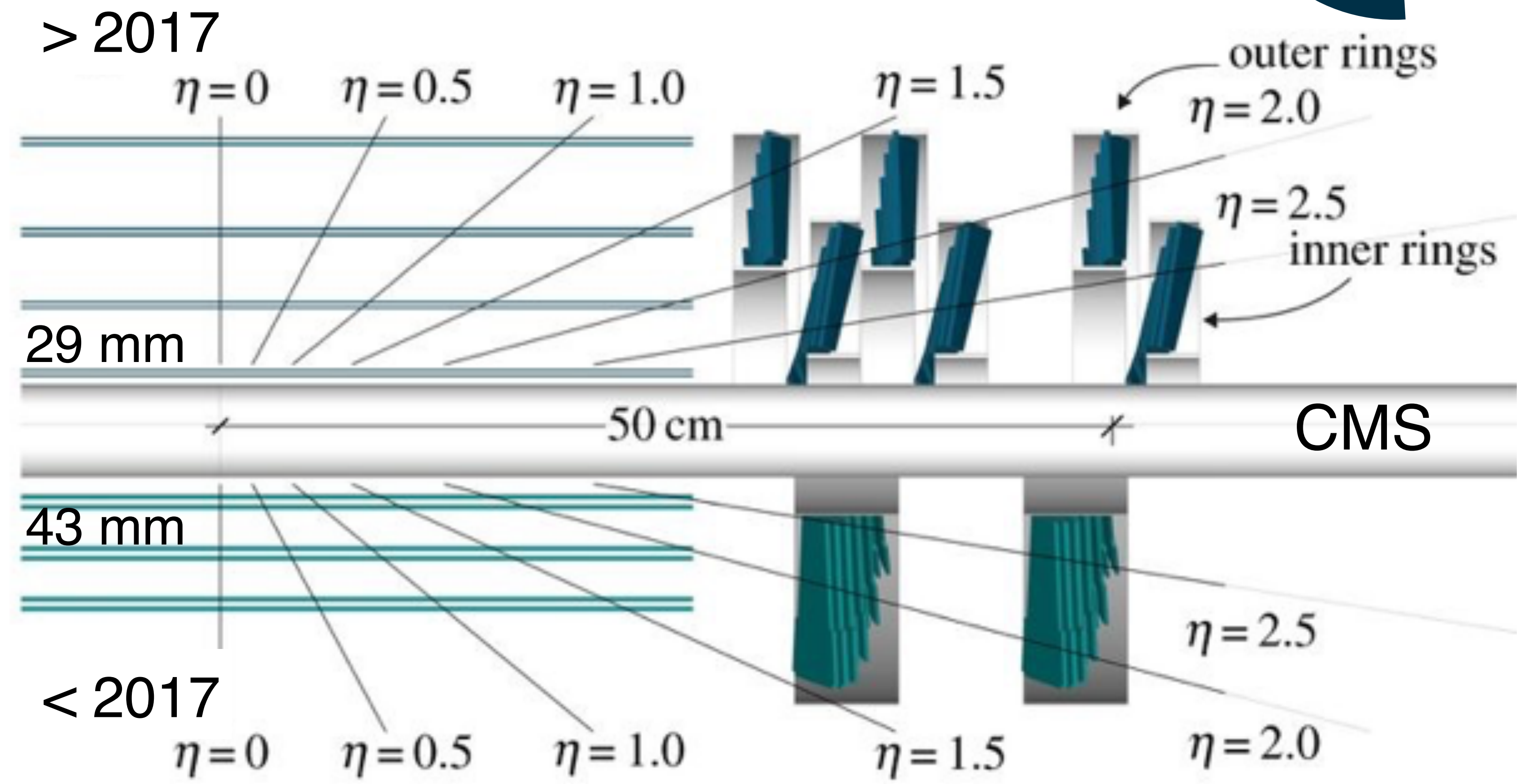
November 2018 RD50 Workshop

…and many thanks to Annapaola De Cosa, Jory Sonneveld, Finn Feindt, Julia Hunt, Martin Kocian,
Dave Robinson, Ian Dawson, Michael Moll, and all of the Feb. 2018 LHC Rad Damage Workshop Participants!

Our Full Detector Systems

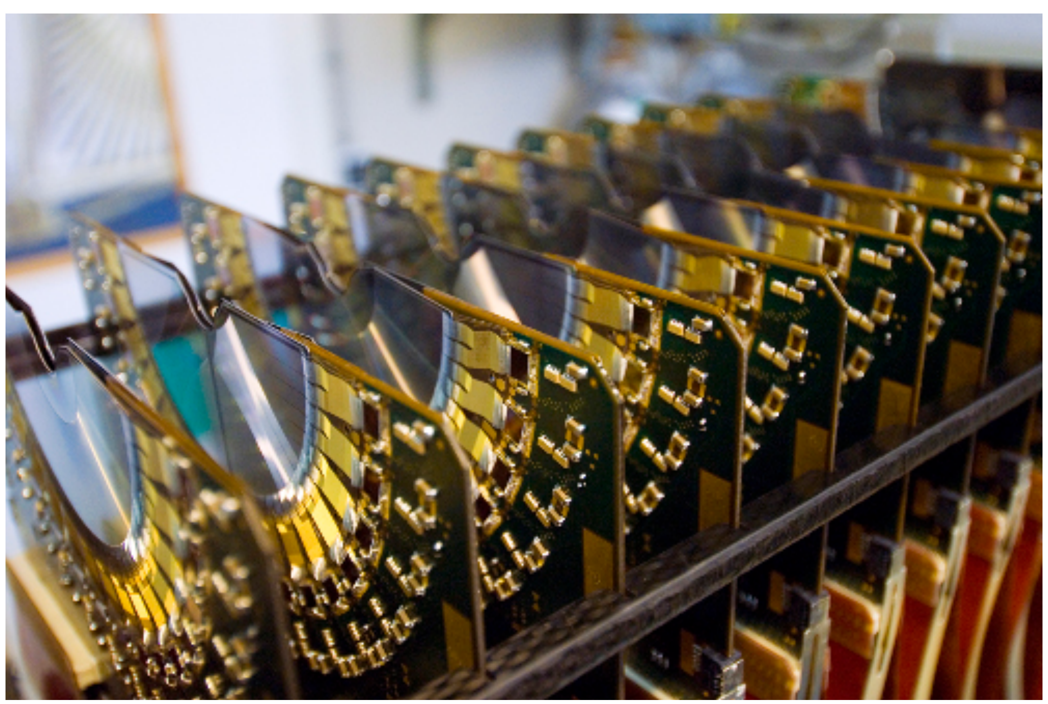
ATLAS

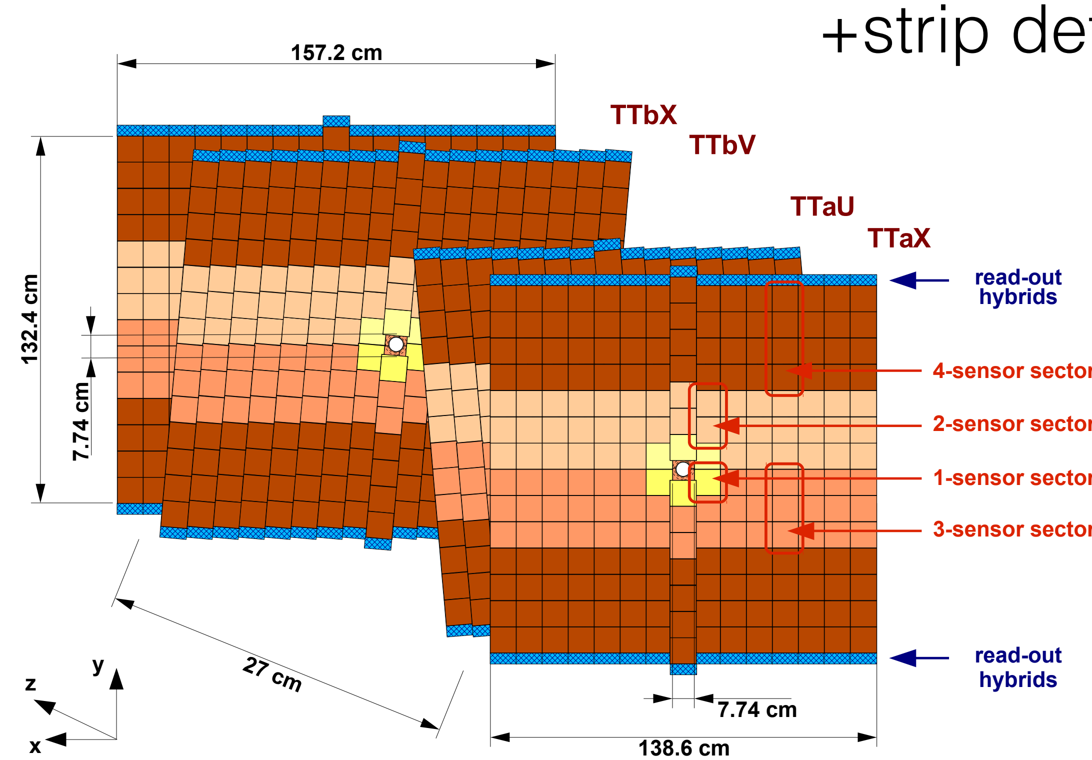




+strip detector

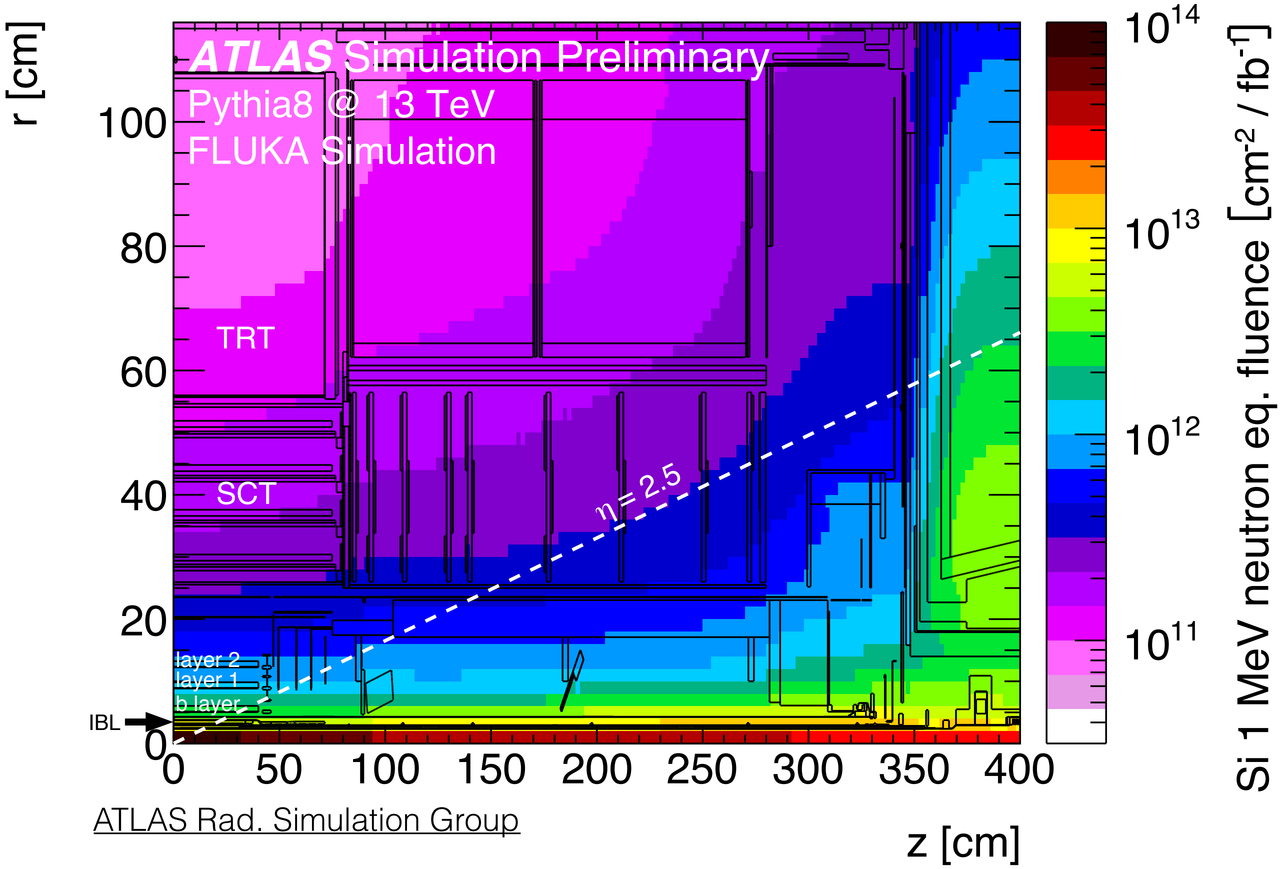
LHCb

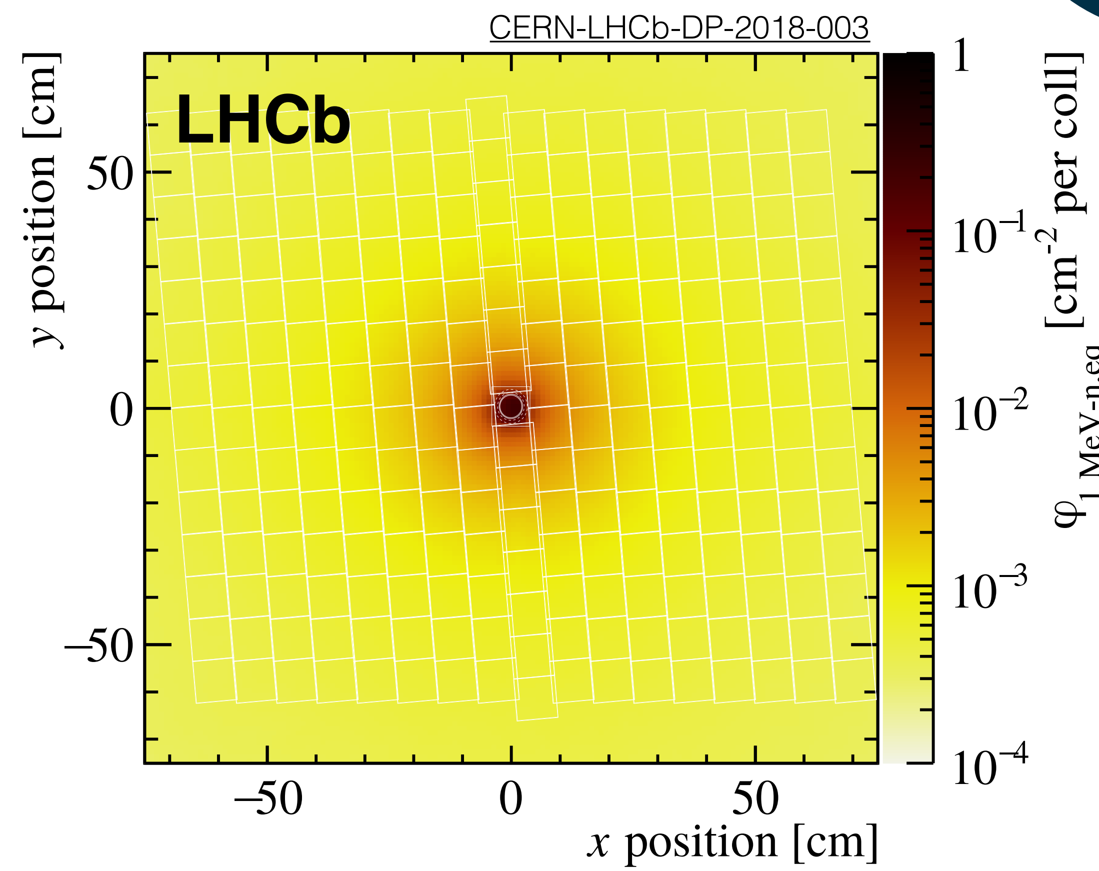


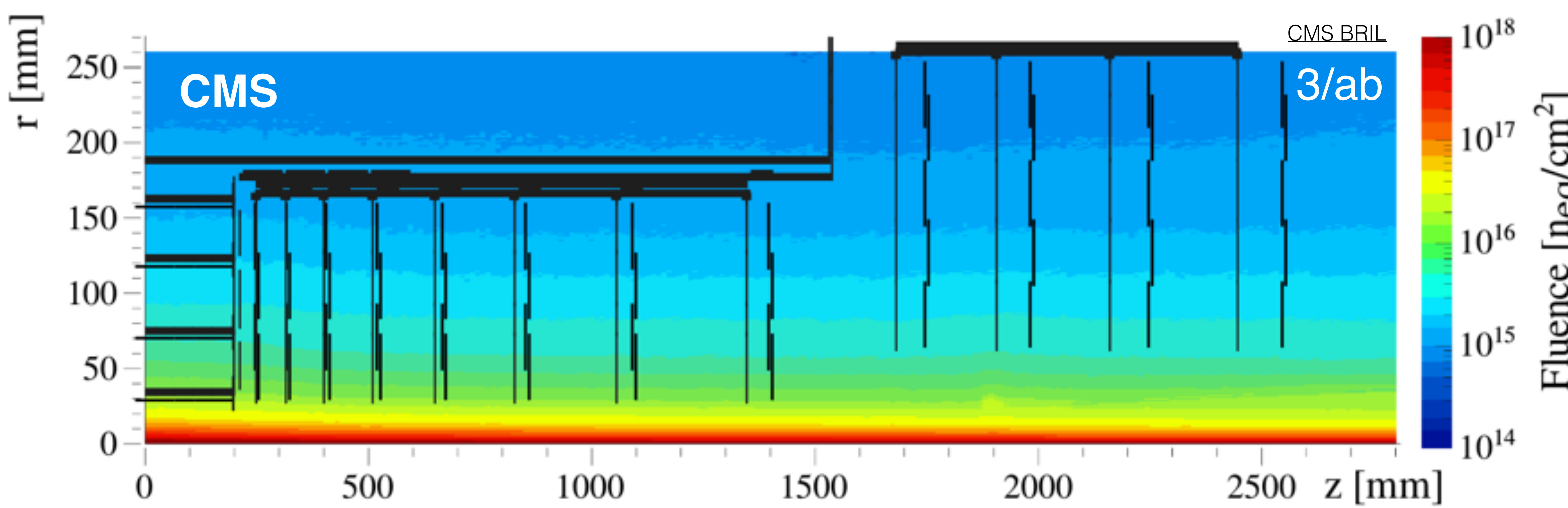


Not shown: ALICE tracking detector - more in a later slide

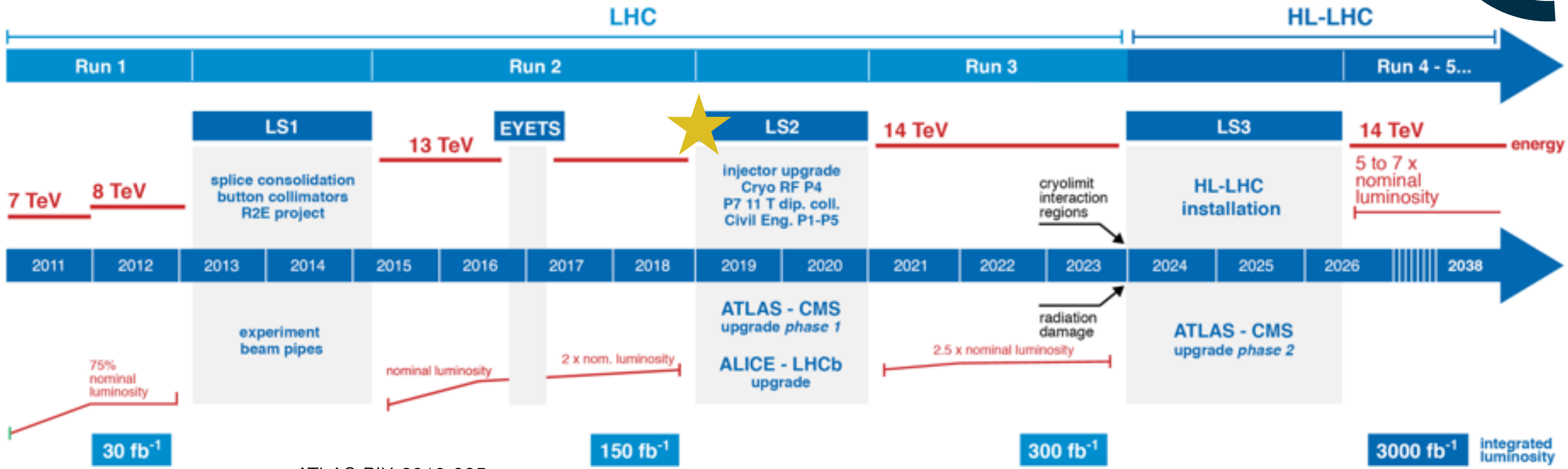
Our Full Detector Systems

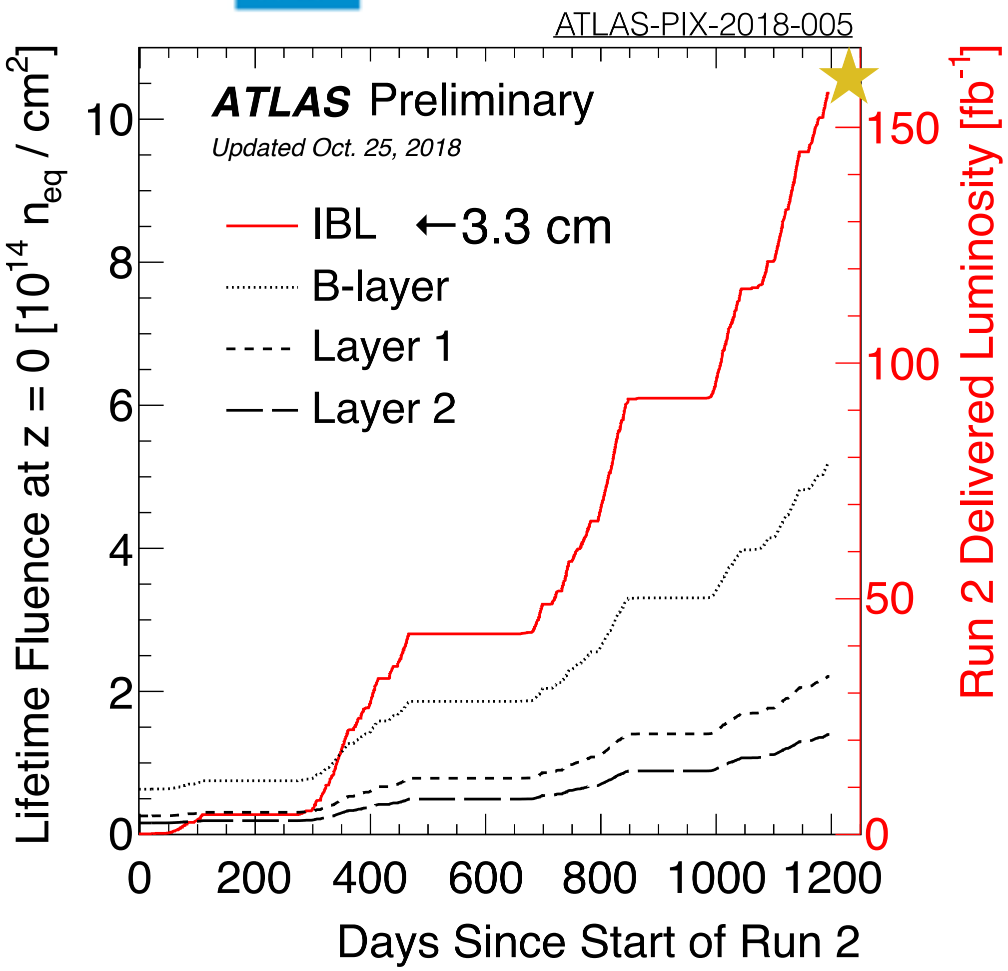






Motivation





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

We have huge, irradiated detectors. Non-trivial work to connect with single module studies, but critically important for Run 3 and the HL-LHC.

Radiation Damage in in Full Systems

Operations

Bias Voltage
Tuning frequency
Time spent warm

Simulation

Charge trapping
Deformed E-field

Track Reconstruction

Reduced Efficiency
Worse Resolution

Physics Analysis

Detector Upgrades

Choice of sensors
Electronics design
Detector layout

Radiation Damage in in Full Systems

Operations

Bias Voltage
Tuning frequency
Time spent warm

Today's focus:
NIEL & sensor damage

Simulation

Charge trapping
Deformed E-field

Track Reconstruction

Reduced Efficiency
Worse Resolution

Physics Analysis

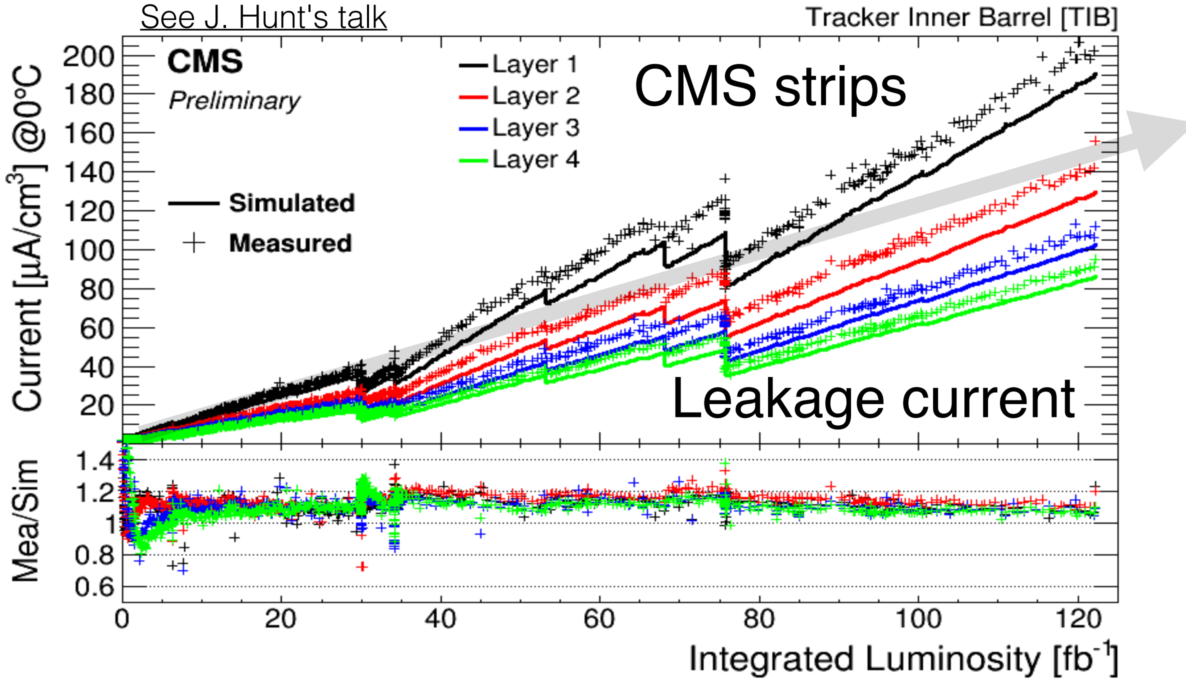
Detector Upgrades

Choice of sensors
Electronics design
Detector layout

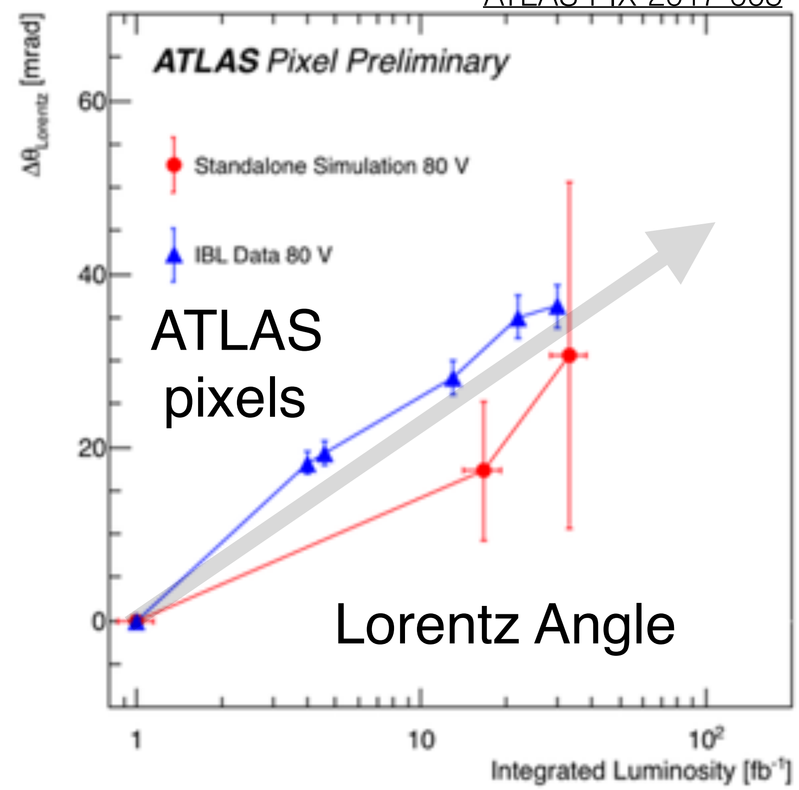
Fluence Monitoring

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

See J. Hunt's talk



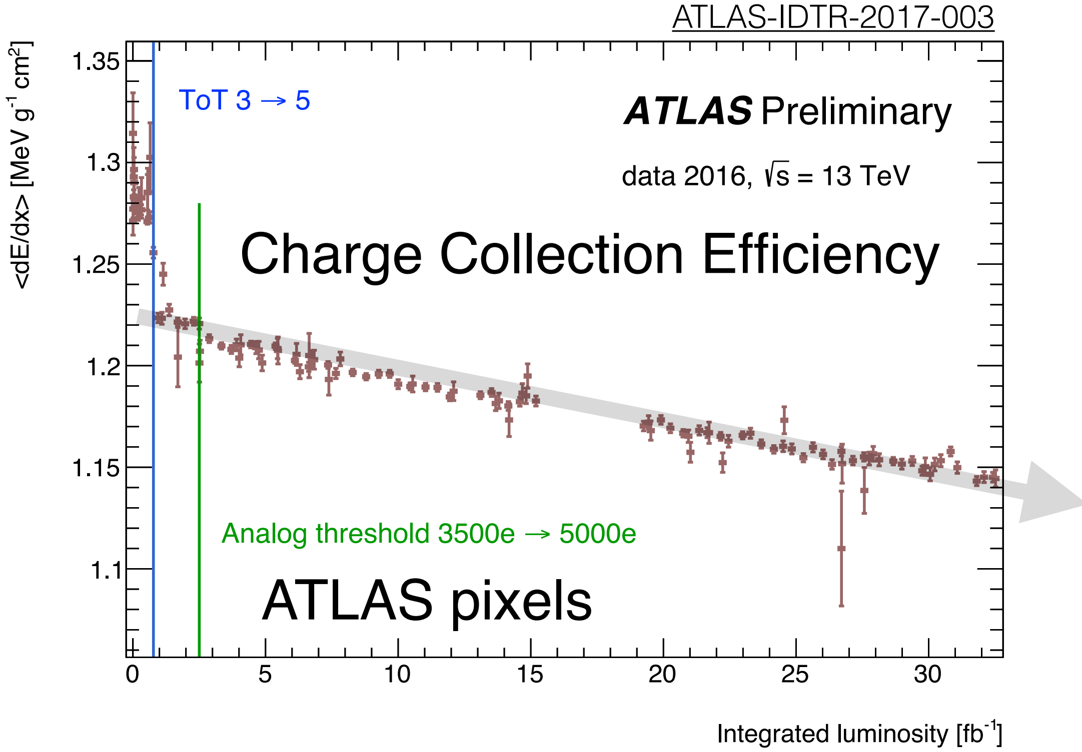
ATLAS-PIX-2017-005



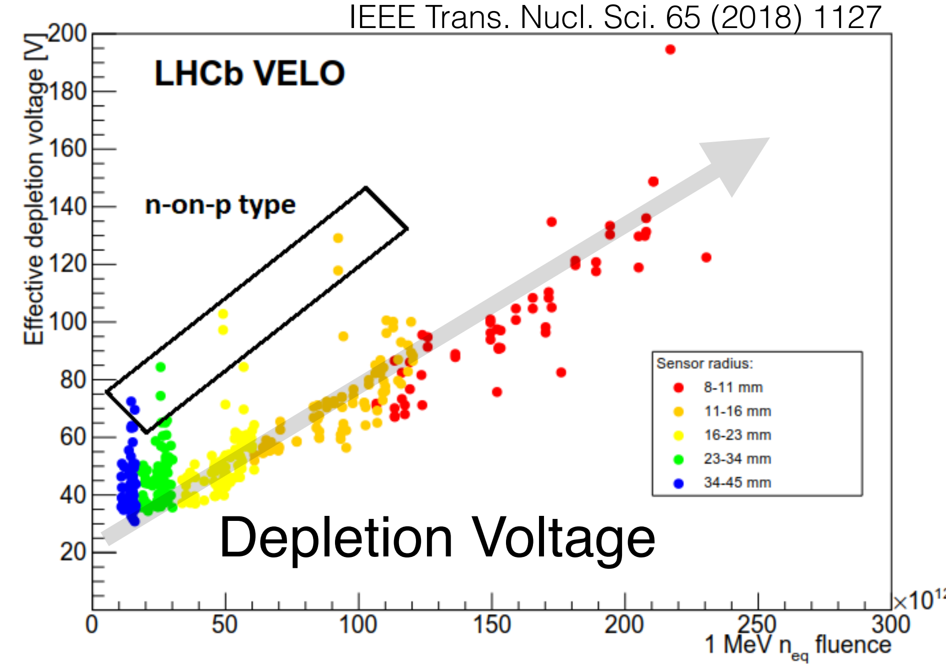
Many sensor properties are proportional to Φ

can use these for calibration and validation

ATLAS-IDTR-2017-003



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

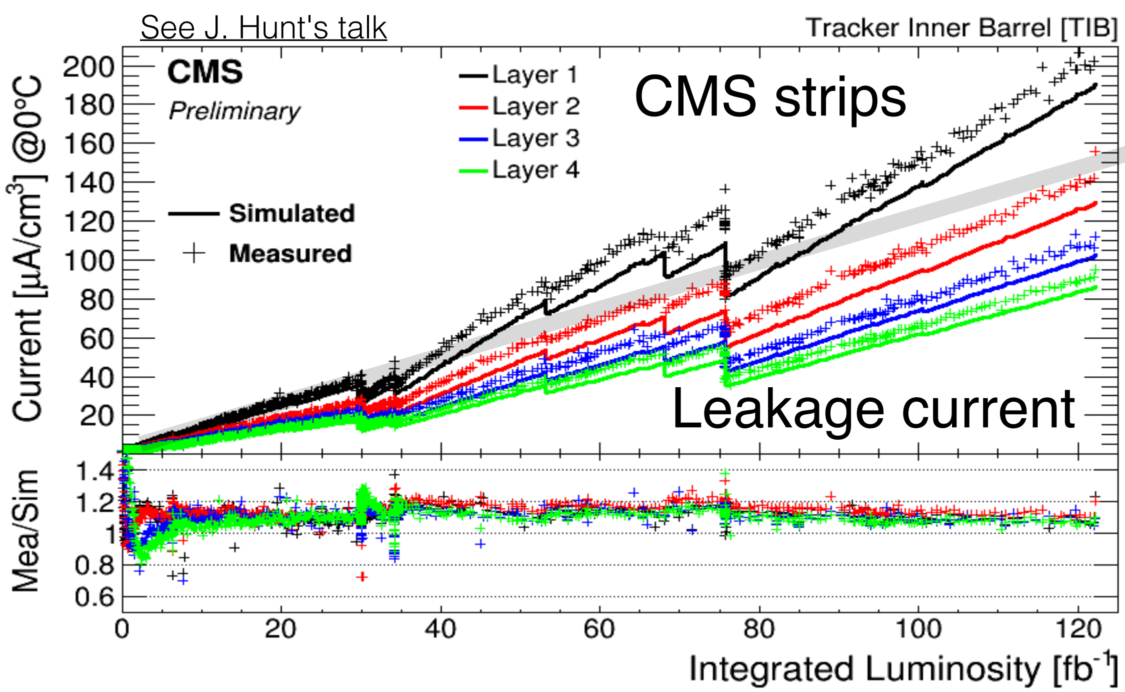


Caution:

Annealing can affect in different ways!

Fluence Monitoring

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



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

"Hamburg Model" or "Sheffield-Harper model"

Different approaches to time-dependence of annealing terms

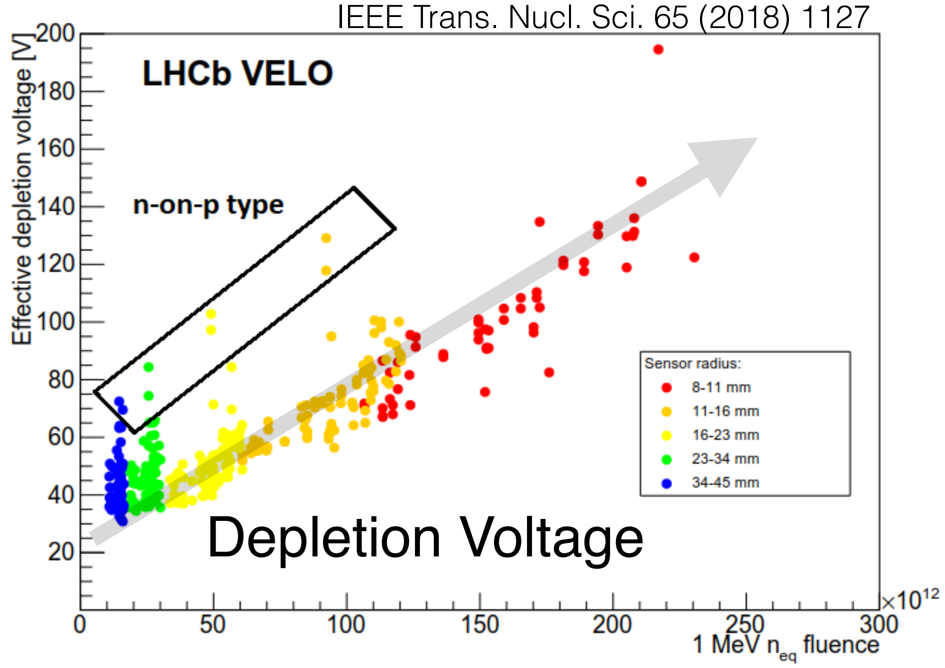
$$V_{\text{dep.}} = |N_{\text{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

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

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

"Hamburg Model"

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



Caution:

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

Given these assumptions, no need for TCAD (yet!)

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

Leakage Current

Raw leakage current

↓

Temperature correction

↓

Fit Φ/L in Hamburg/Sheffield-Harper model

↓

Measured Φ

Depletion Voltage

Measure charge versus HV

↓

Define $V_{dep.}$ = saturation point

↓

Fit Φ/L in Hamburg model

↓

Measured Φ

Comparing to Simulations

Radiation Simulation

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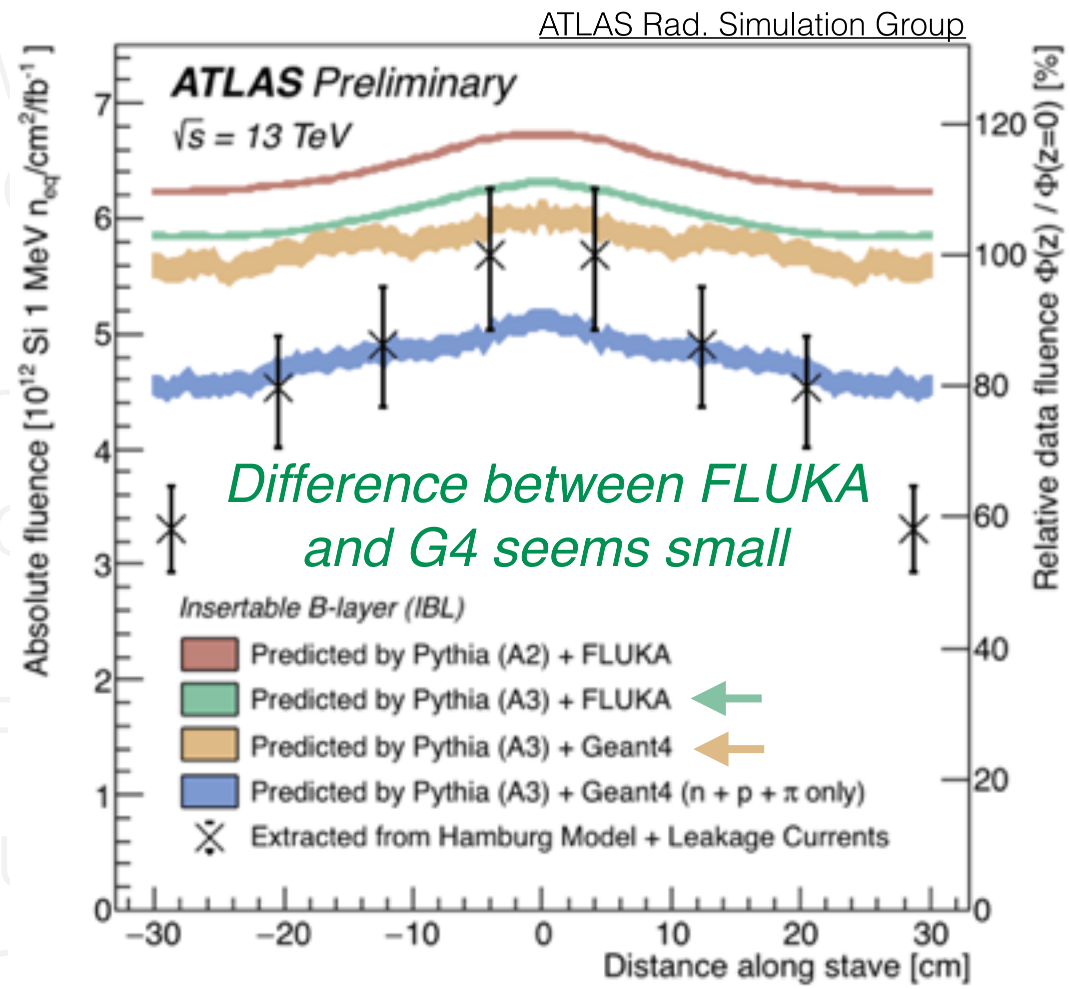
Non-ionizing damage

↓ *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!

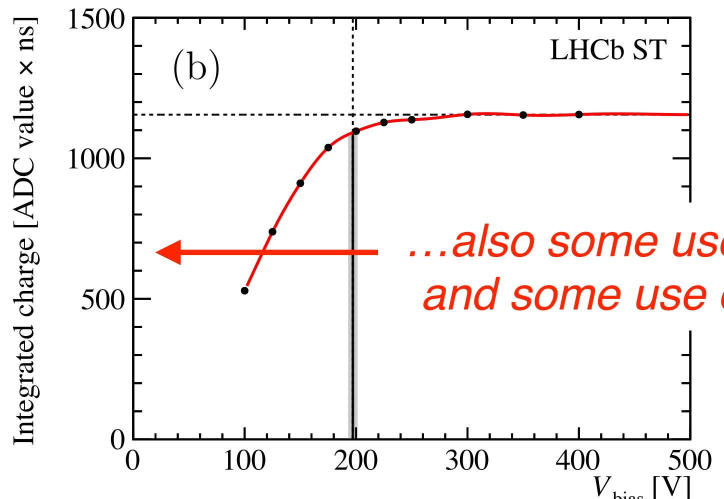
…due in part to the availability of monochromatic beams and uncertainty in converting to 1 MeV n_{eq}

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!



CERN-LHCb-DP-2018-003

…also some use ADCs and some use charge

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

Leakage Current

Raw leakage current

↓

Temperature correction

↓

Fit Φ/L in Hamburg/Sheffield-Harper model

↓

Measured Φ

Depletion Voltage

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↓

Define $V_{dep.}$ = saturation point

↓

Fit Φ/L in Hamburg model

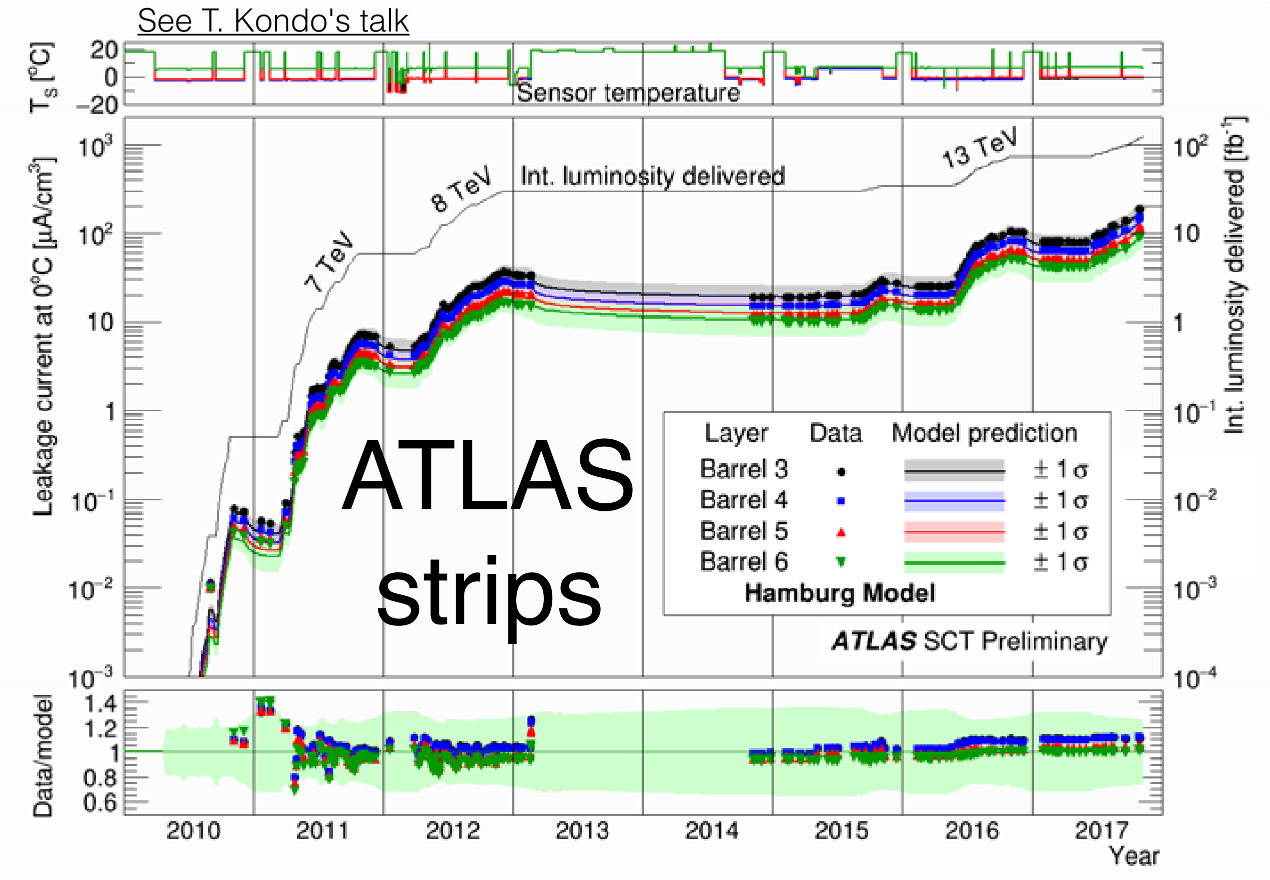
↓

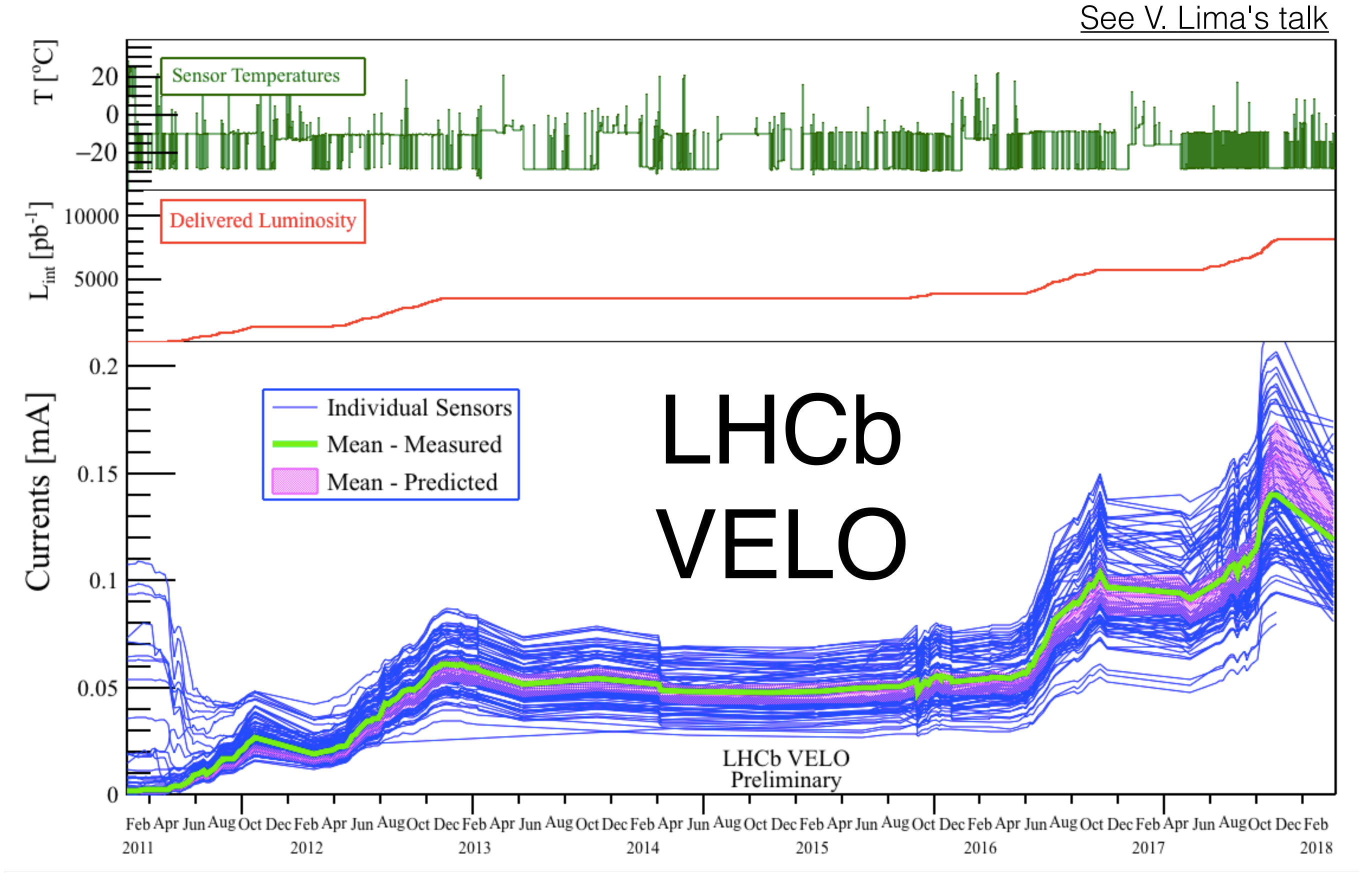
Measured Φ

Fluence Monitoring: Leakage Current

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

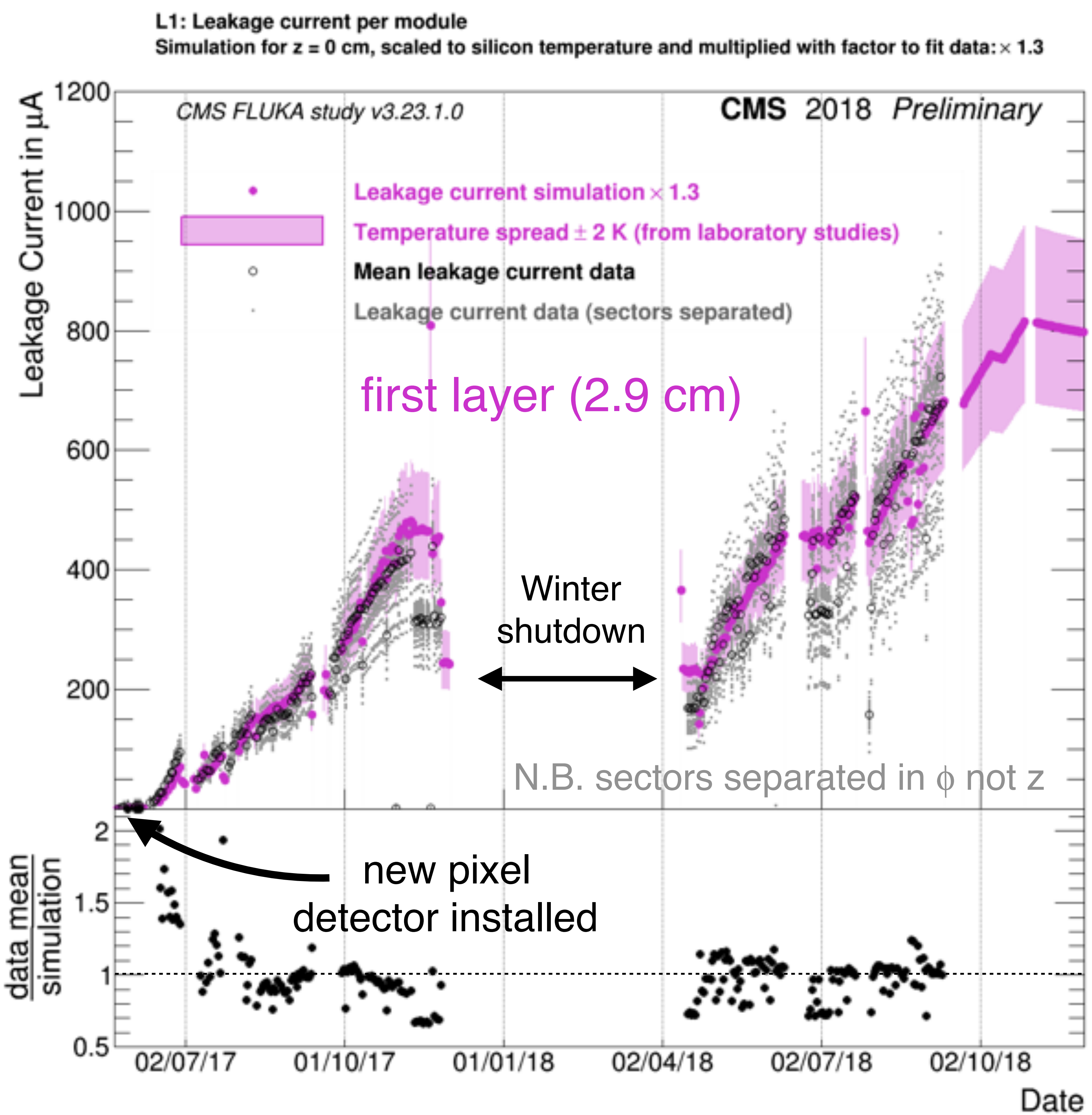
It is interesting to study the current across **time** and as a function of **z** & **radius**.



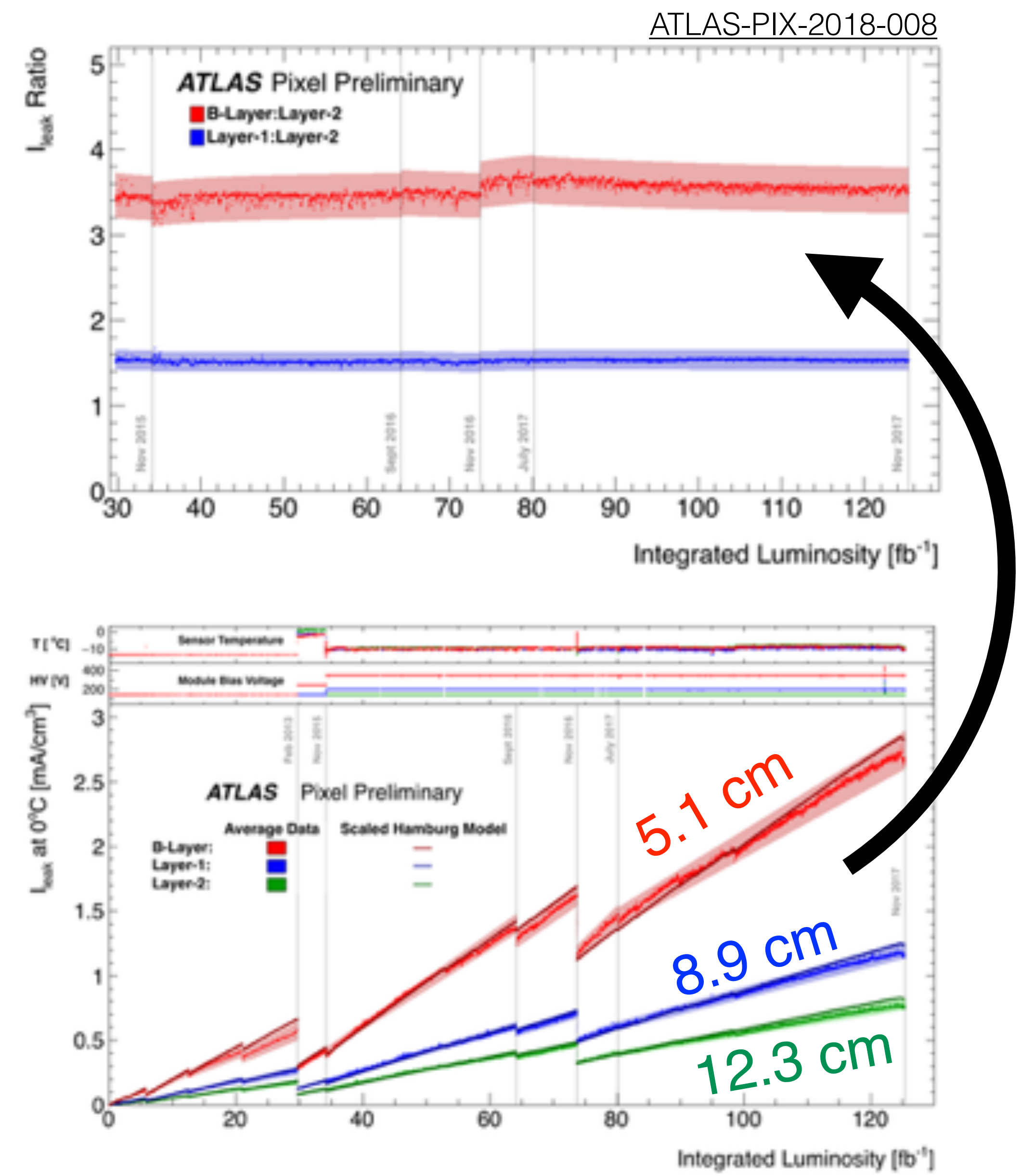


We now have ~8 years of data!

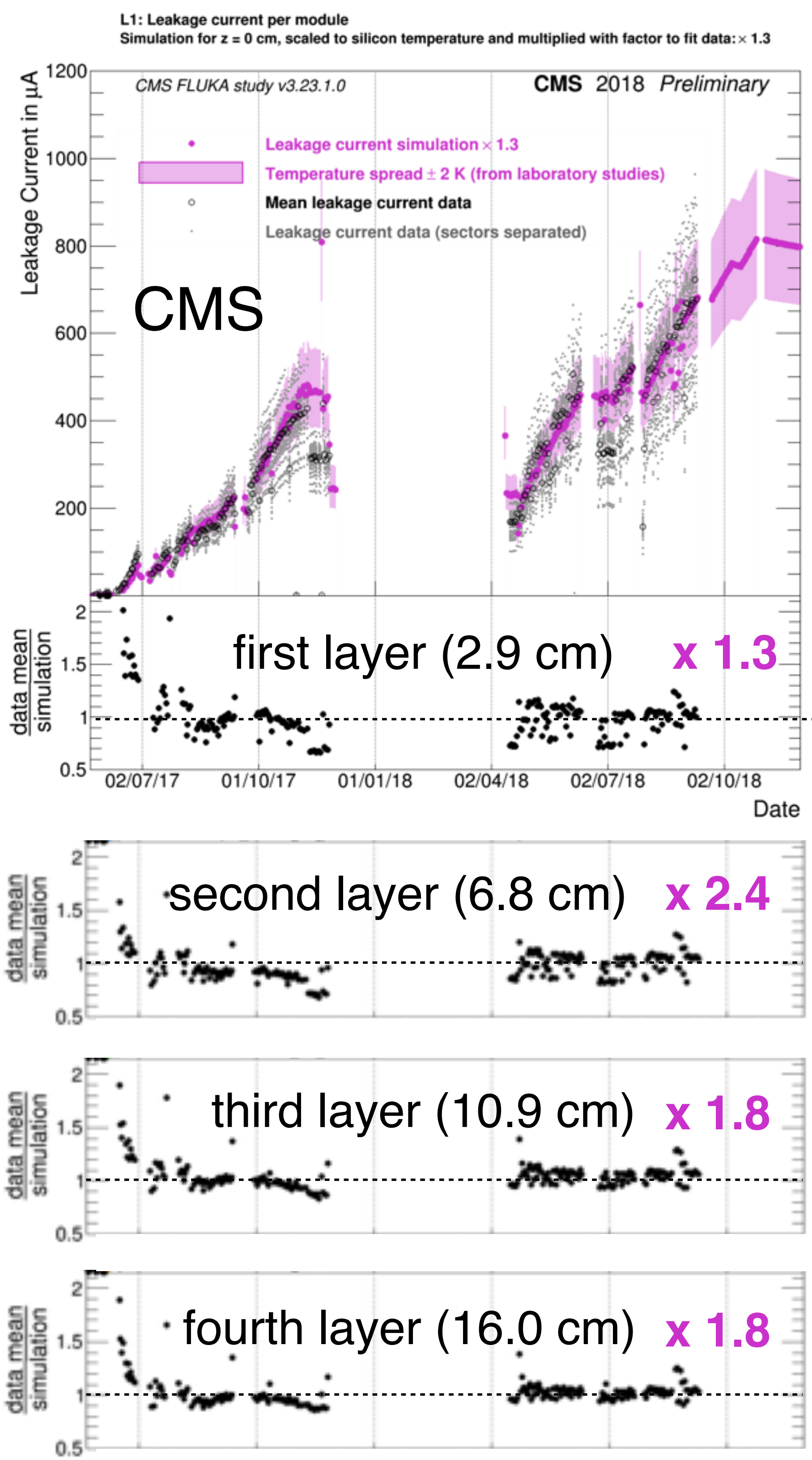
Leakage current across time



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



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

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

with some weak evidence for radius dependence:

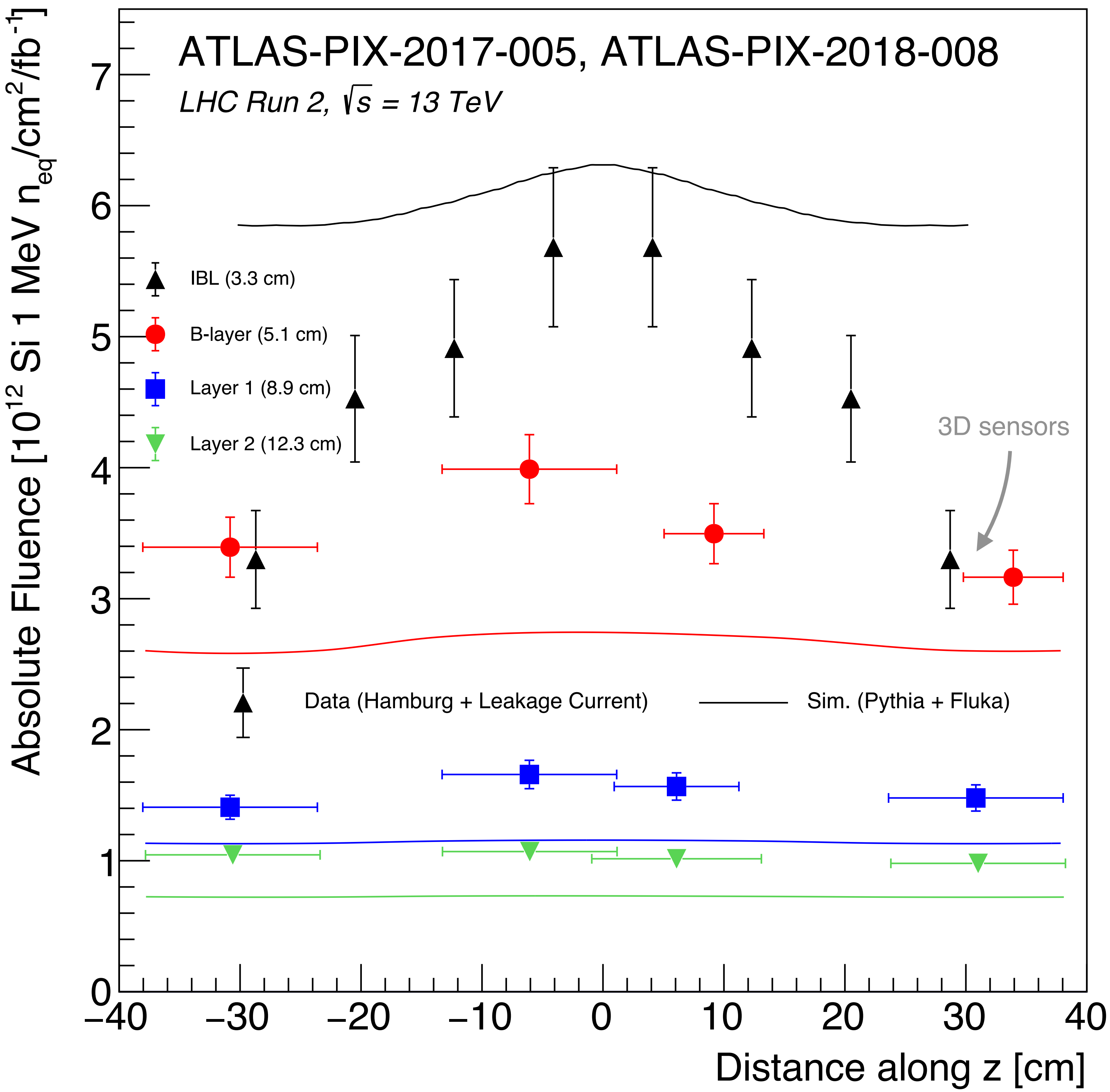
data ~ sim. for innermost

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.

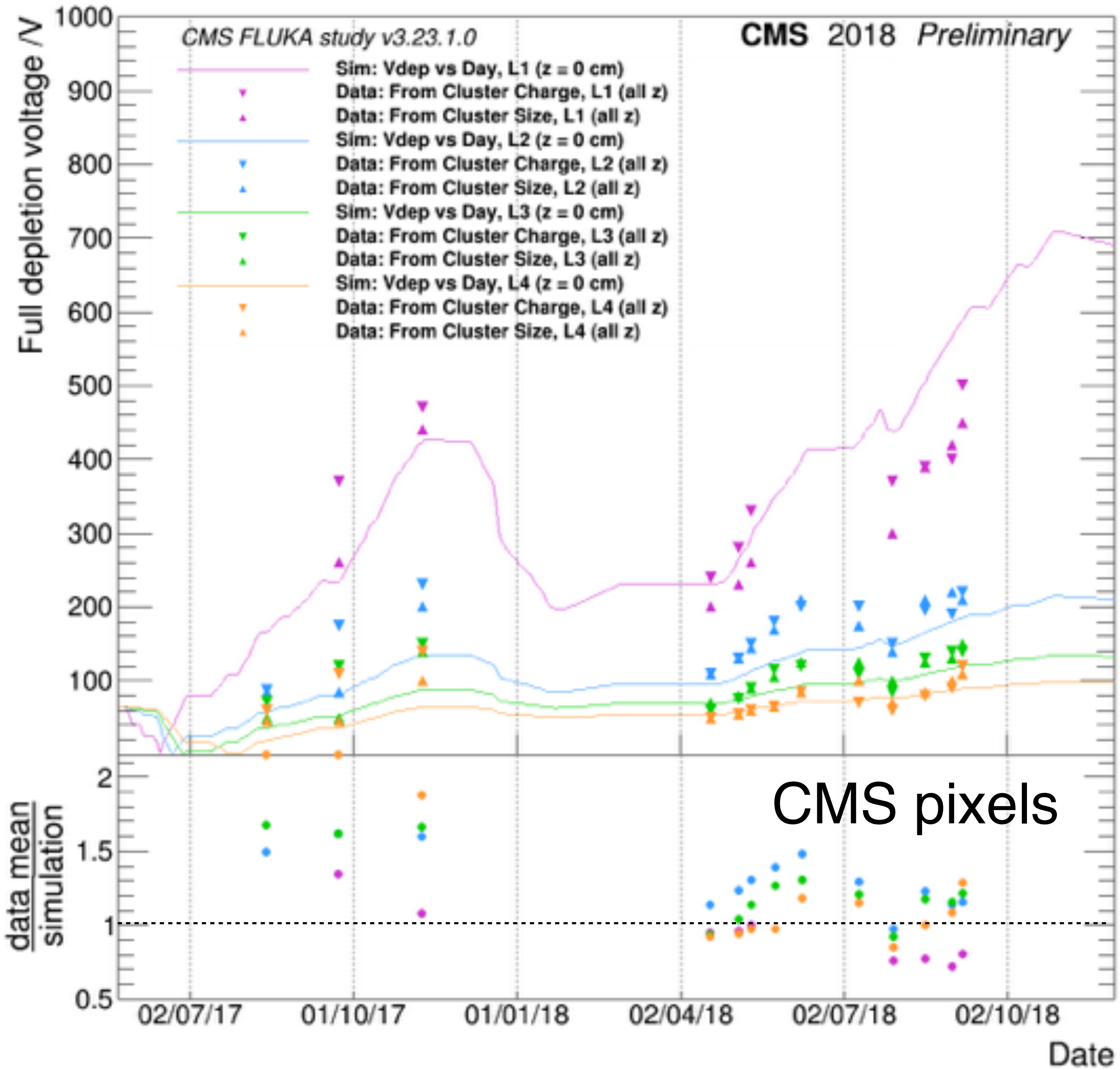
…would be great to see confirmation from other measurements / experiments!

Sneak preview: we see qualitative agreement with the z-dependence of depletion voltage and charge collection efficiency. Also studies on the simulation side to try to reproduce the trends. Stay tuned for Feb. workshop for details!

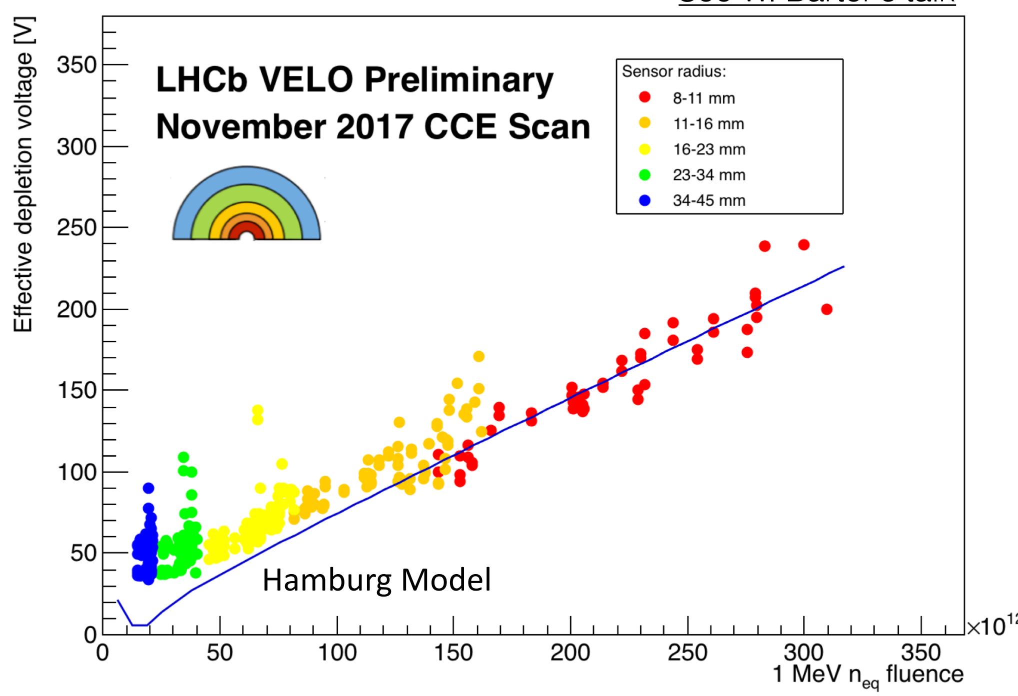
Depletion voltage across time and r

Difficult to fit all data points - challenging for extrapolation!

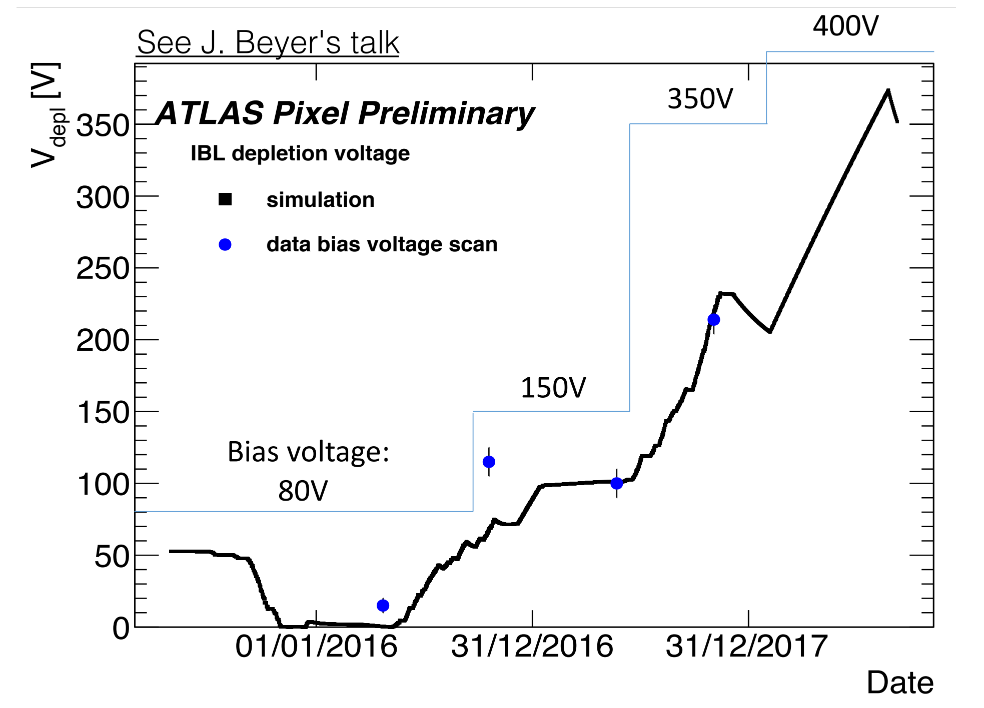
…do we need to modify the Hamburg model?



See W. Barter's talk



See J. Beyer's talk



So far, focus on operations…

…what about direct impact on physics analysis?

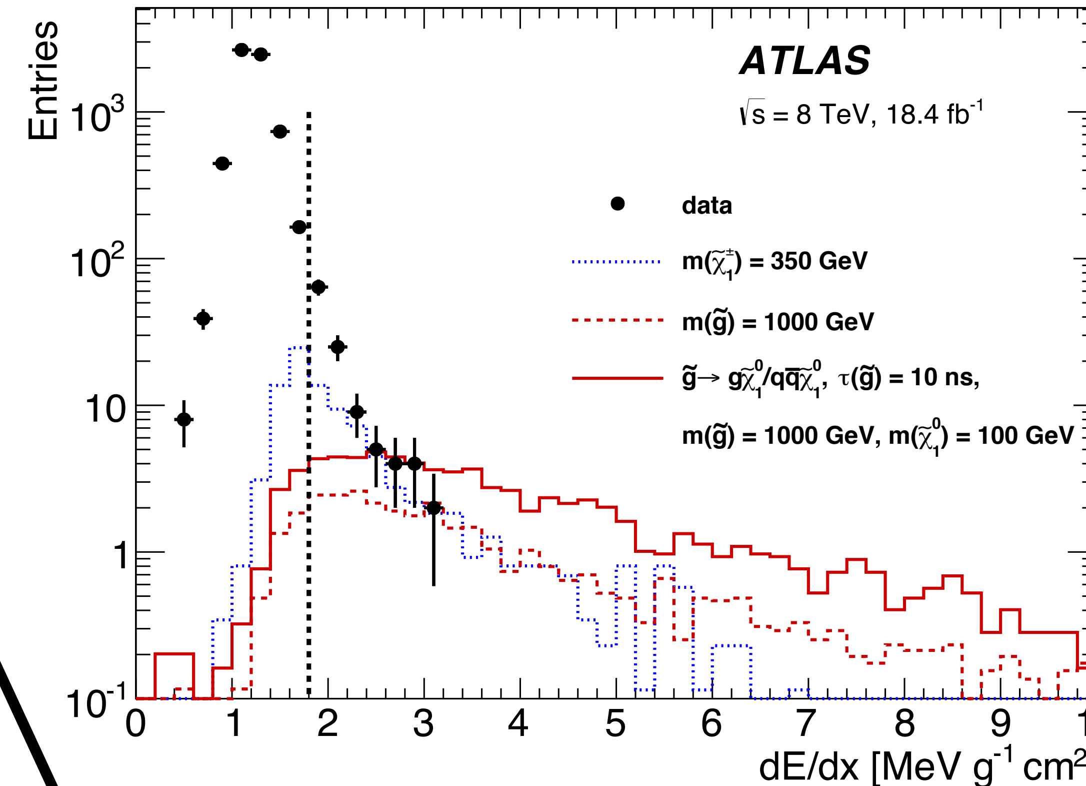
Impact on Physics and Performance

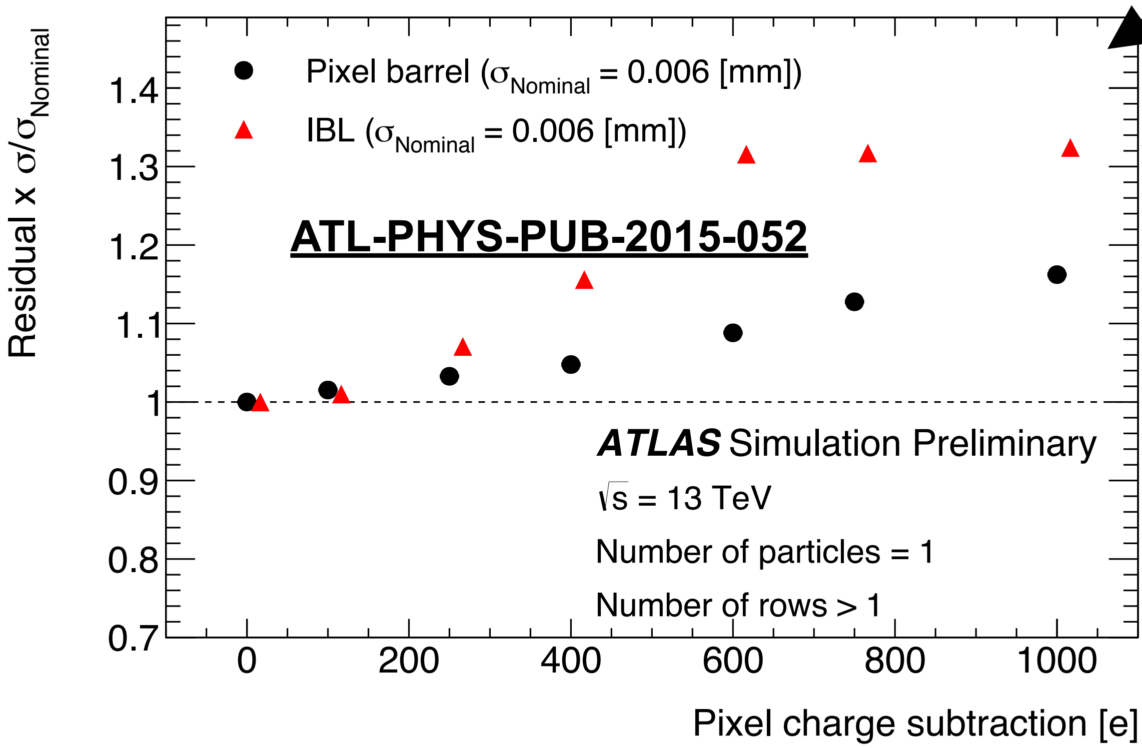
Charge loss directly effects searches for new highly ionizing particles →

We may be seeing a degradation in position resolution.

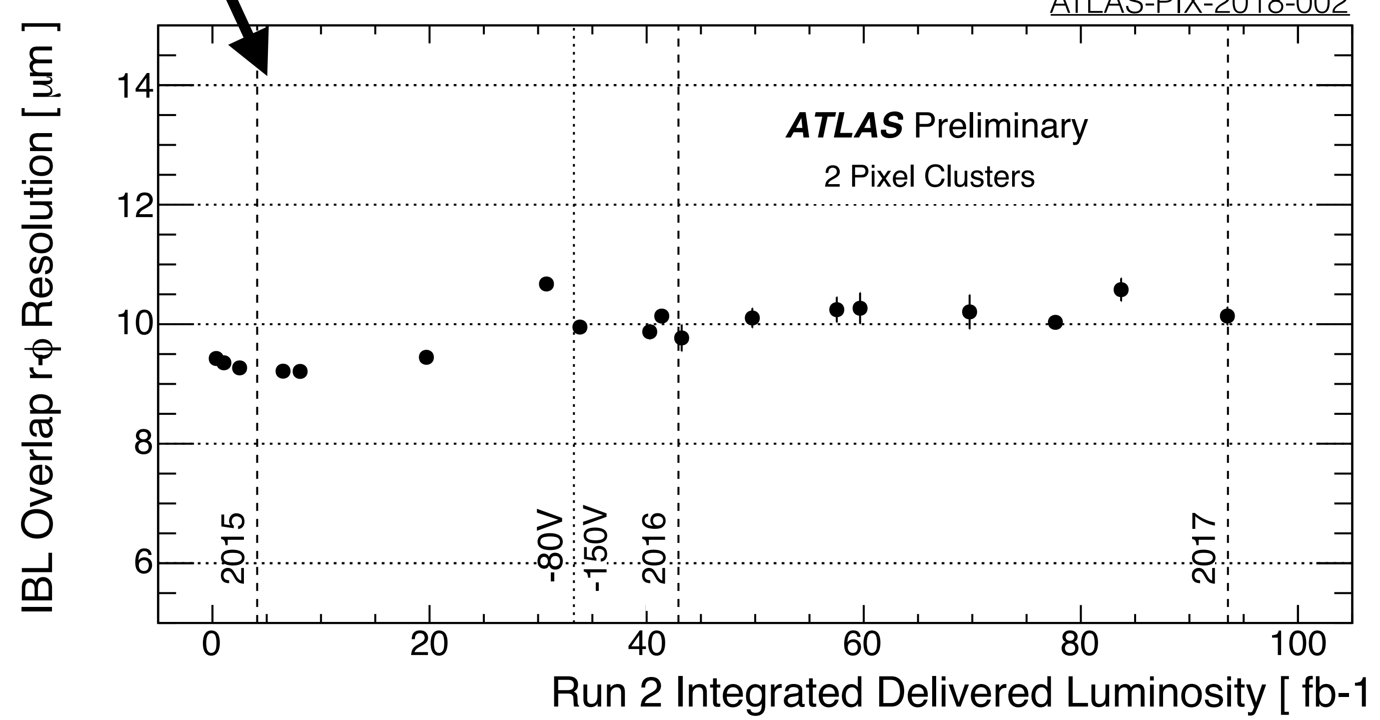
It is imperative that radiation damage effects are part of our **full detector physics simulations**!

Eur. Phys. J. C (2015) 75:407

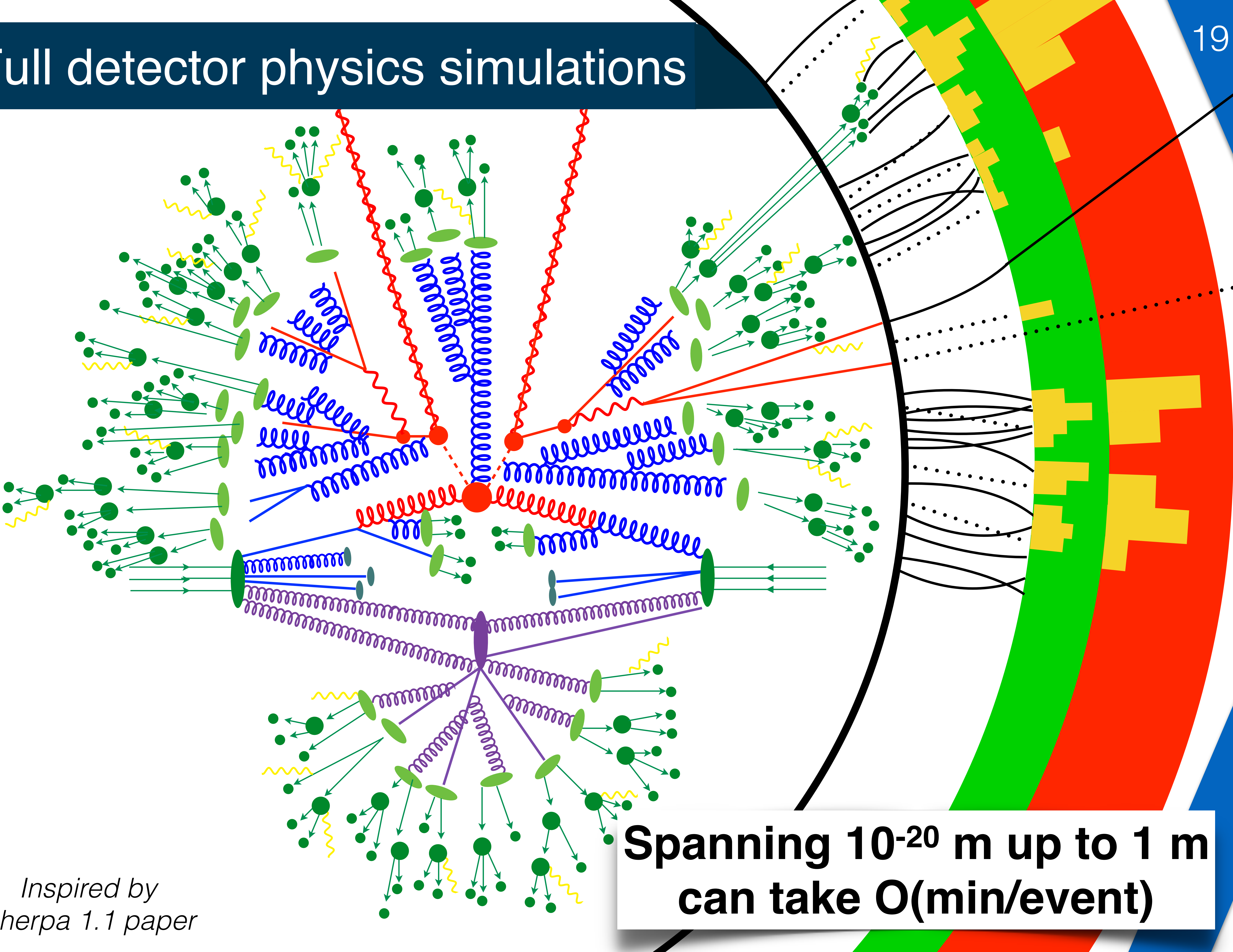




ATLAS-PIX-2018-002



Full detector physics simulations



Spanning 10^{-20} m up to 1 m can take O(min/event)

Inspired by Sherpa 1.1 paper

Full detector physics simulations

Hard-scatter

MadGraph 5 / aMC@NLO
POWHEG-BOX

↓

Fragmentation

Pythia, Herwig, Sherpa

↓

Material Interactions

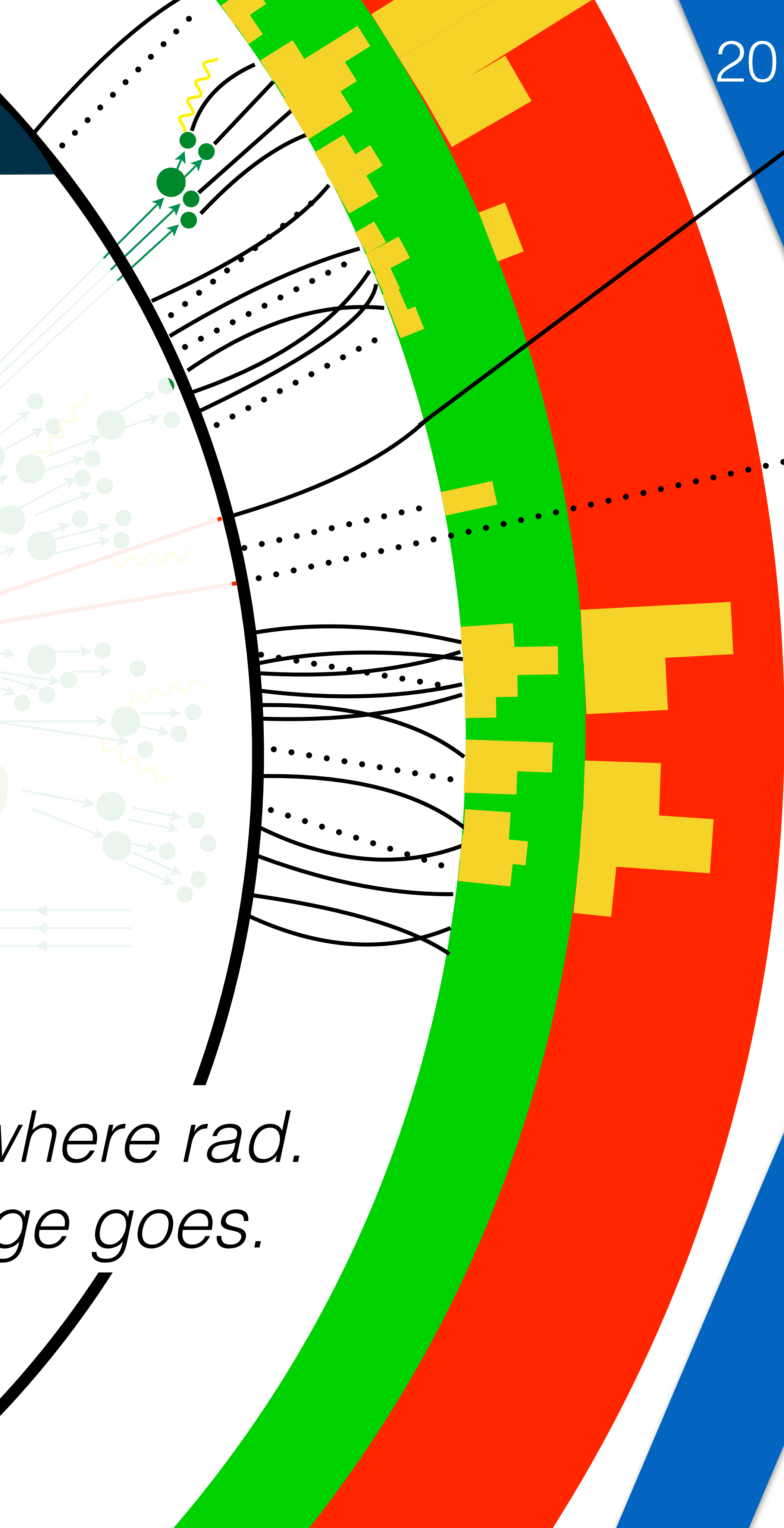
Geant 4

↓

Digitization

Custom code

this is where rad. damage goes.



Inspired by Sherpa 1.1 paper

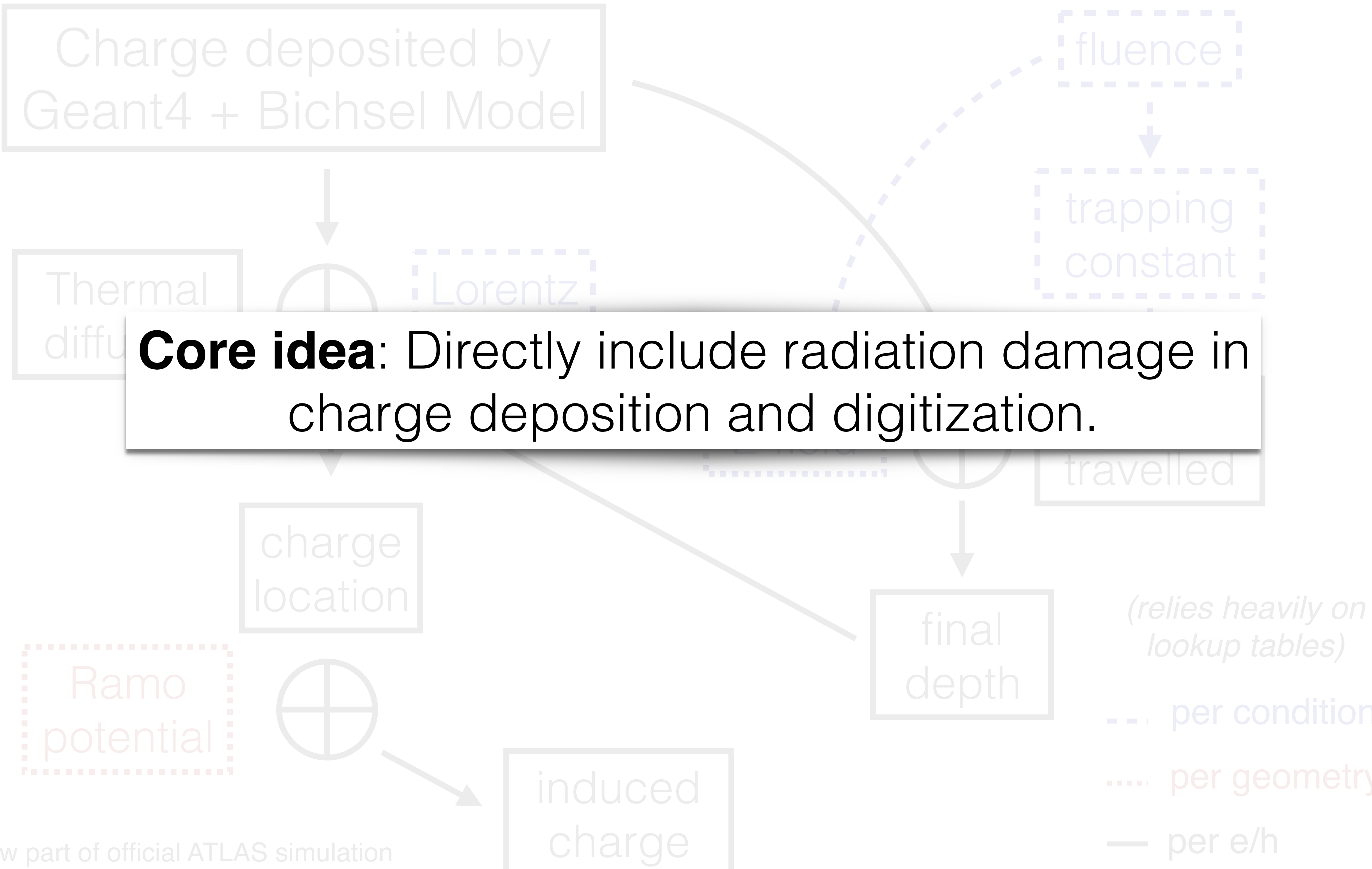
Current Run 2 (Si) Simulation

	ATLAS EXPERIMENT	CMS	LHCb
Energy Deposition	Bichsel Model + G4 (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	readout noise	capacitive coupling + noise
Radiation damage	**none**	**none**	**none**

Next Generation (Si) Simulation

	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**

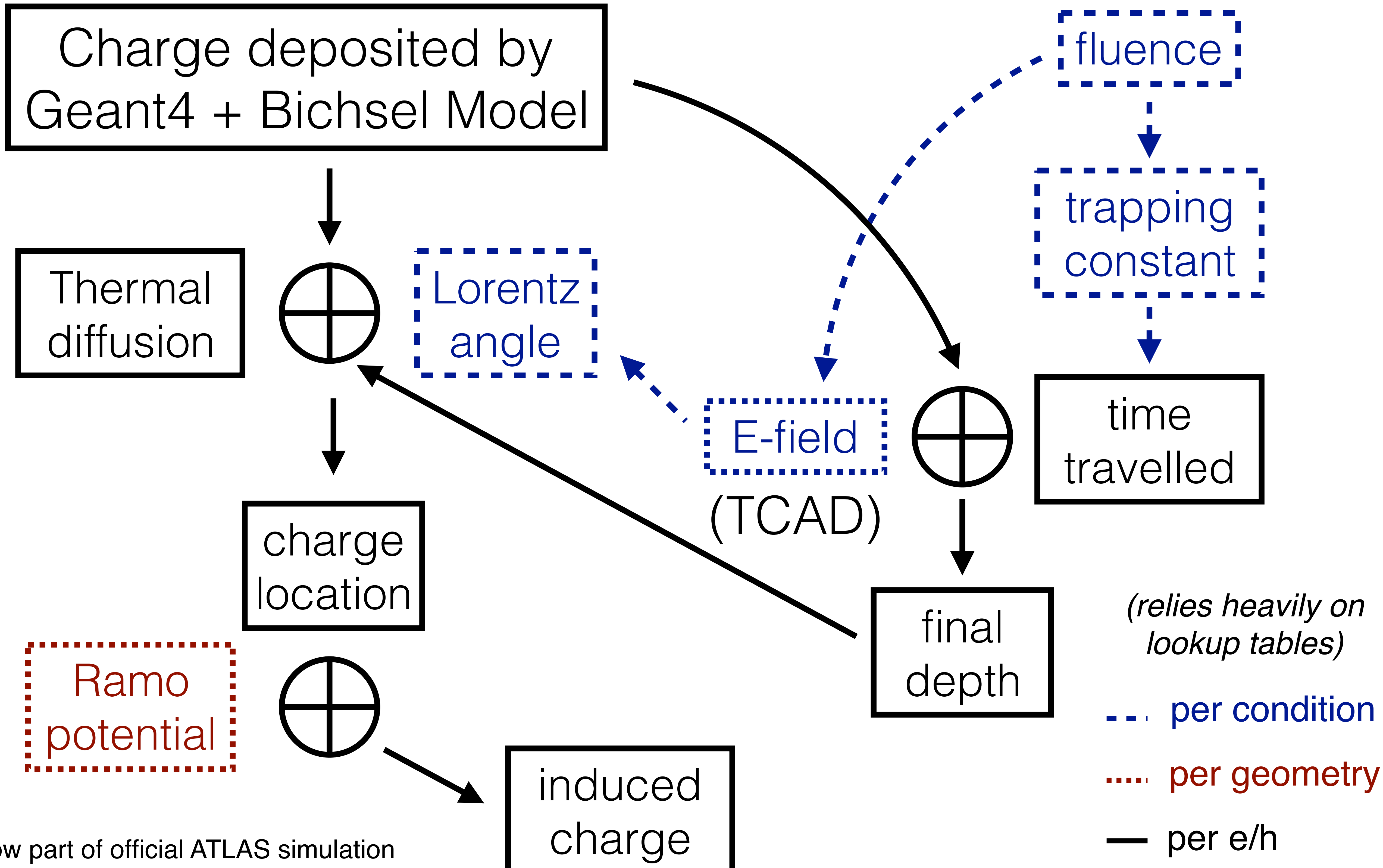
New ATLAS Pixel Simulation Details



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

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

New ATLAS Pixel Simulation Details



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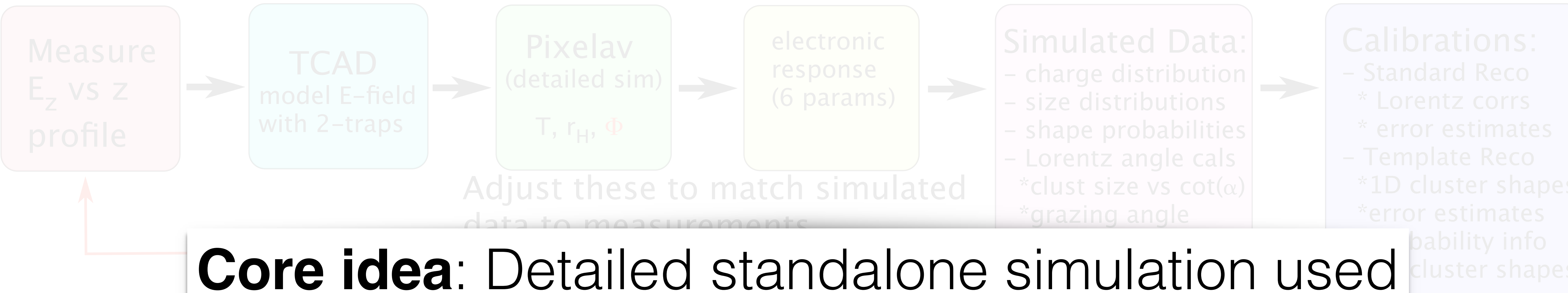
New CMS Pixel Simulation Details

The TCAD+Pixelav simulations are tuned to measured distributions



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.

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
- extracted E-field profiles

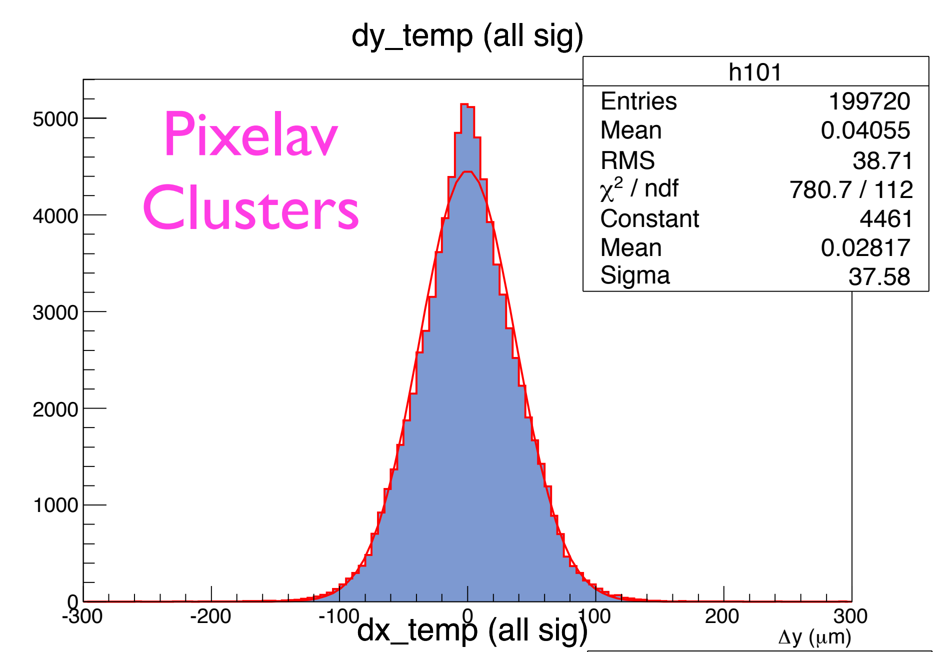
→ **Calibrations:**
- Standard Reco
  - * Lorentz corrs
  - * error estimates
- Template Reco
  - *1D cluster shapes
  - *error estimates
  - *probability info
  - *2D cluster shapes

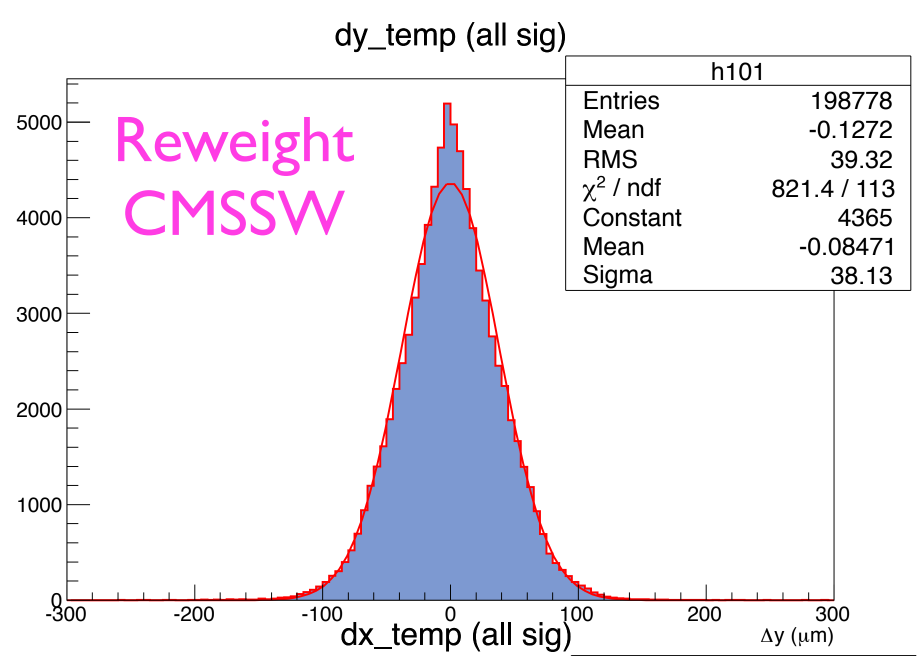
Adjust these to match simulated data to measurements

Different approach:

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

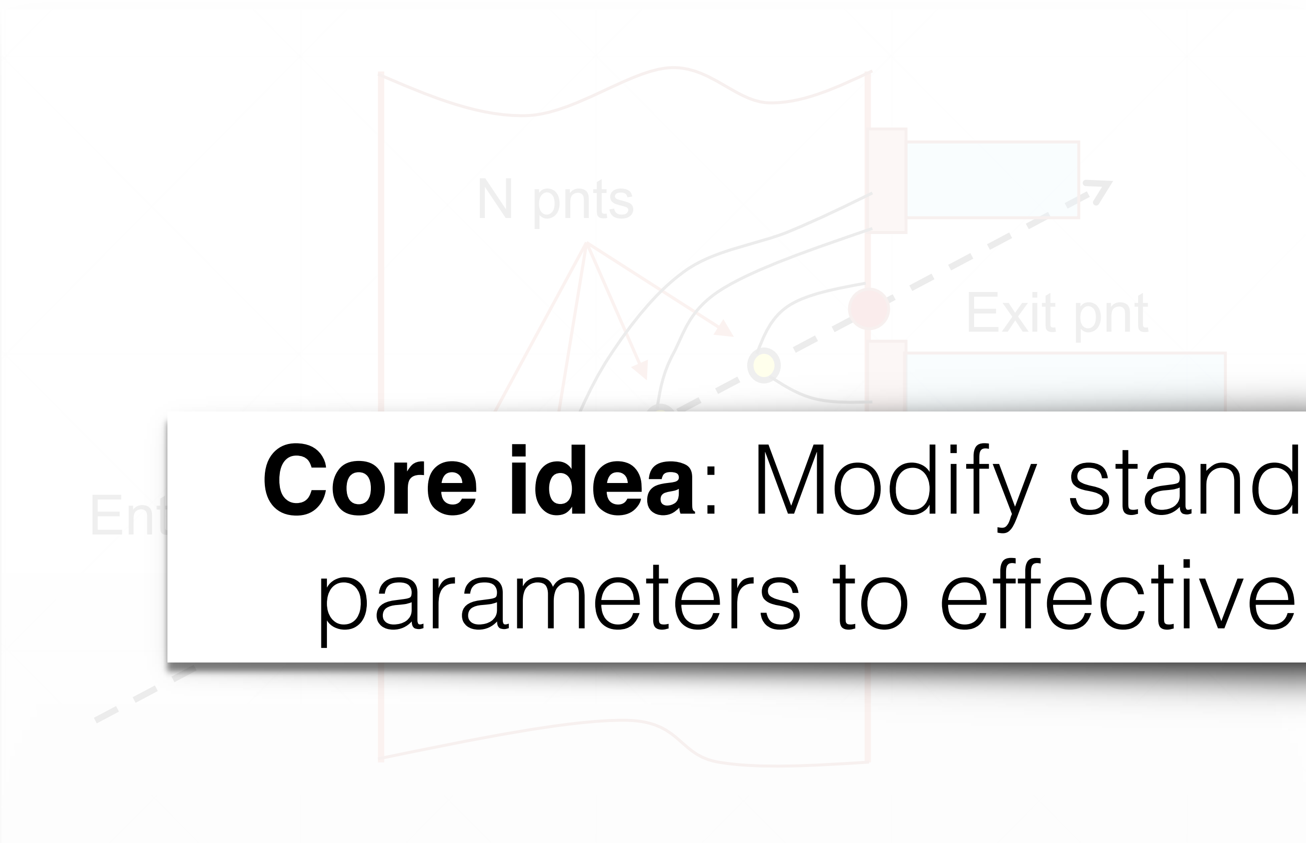
Fully simulated $\Phi=1.2\text{x}10^{15}$ n_{eq}/cm^2 clust vs reweighted CMSSW-like clust





See M. Swartz's talk for more details.

New LHCb Pixel Simulation Details



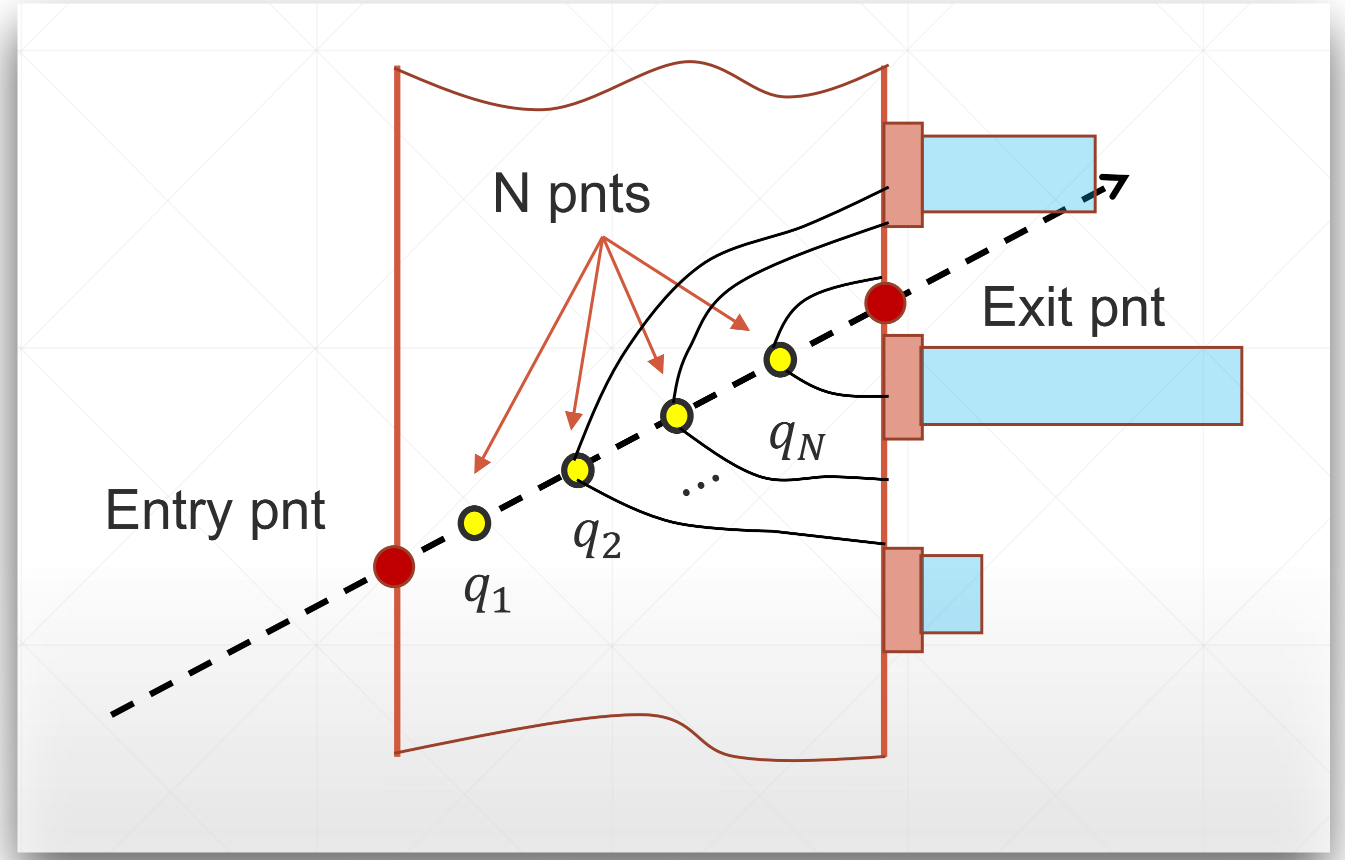
Different than both ATLAS/ CMS: reduce charge and increase “diffusion length”

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



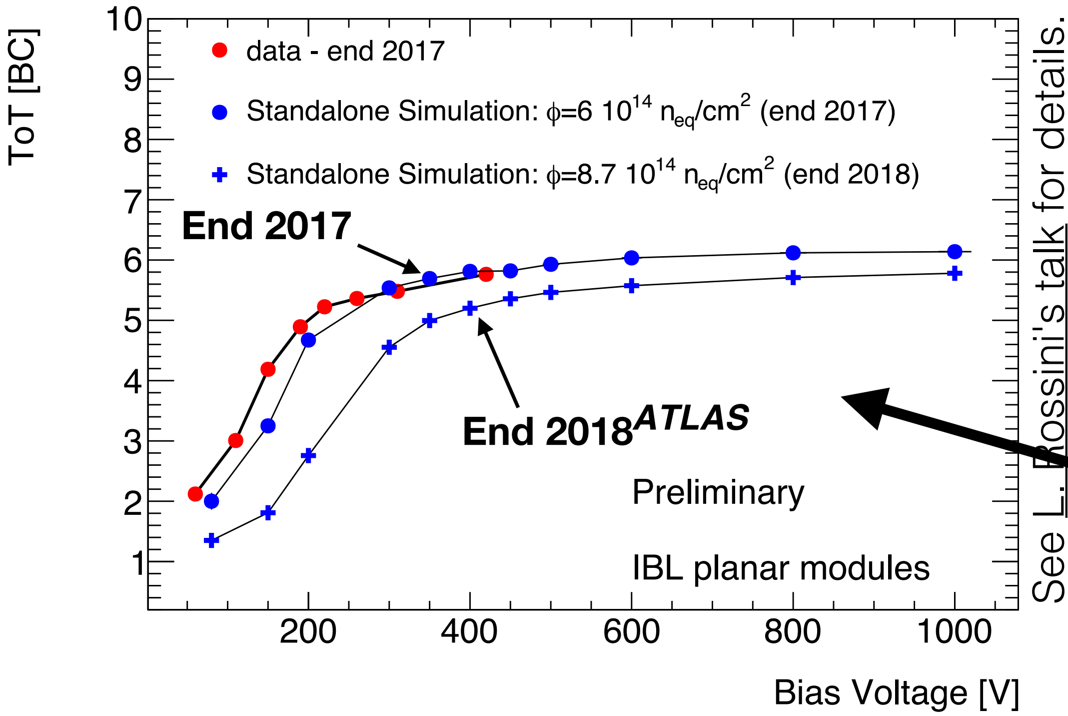
Different than both ATLAS/ CMS: reduce charge and increase "diffusion length" to match data.

Tuned once/year.

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

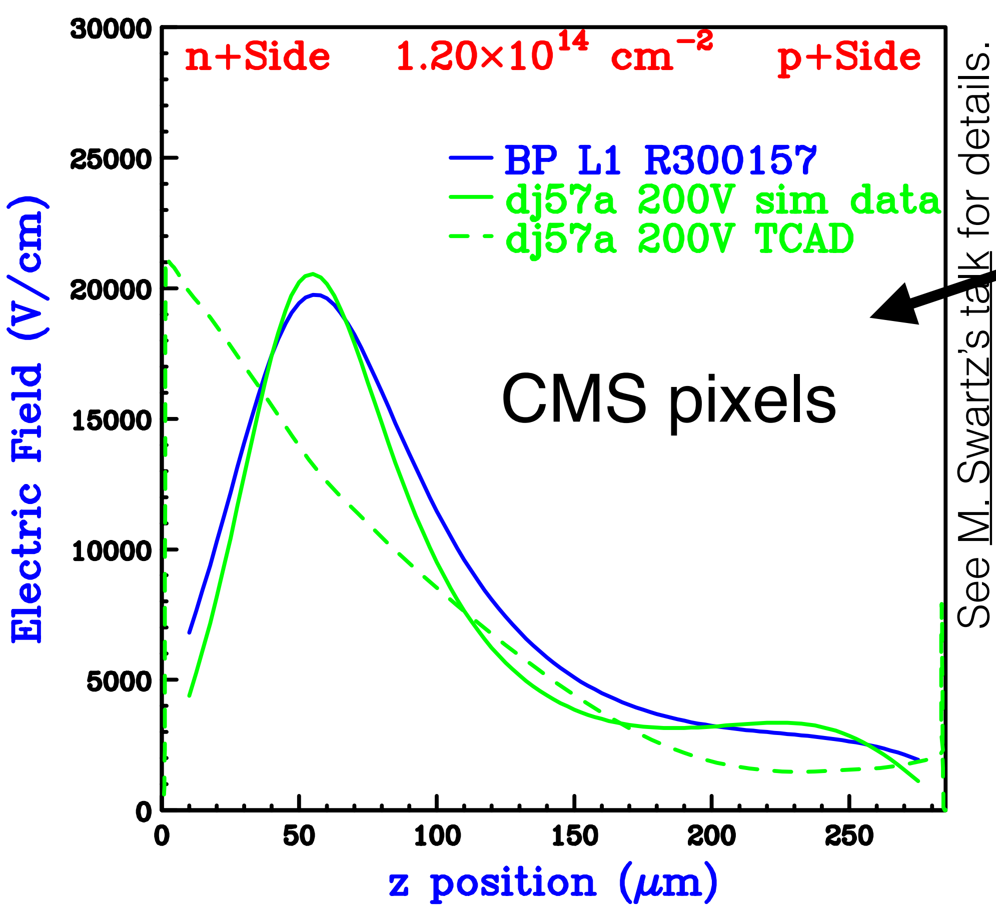
See T. Szumlak's talk for more details.

Validation with data

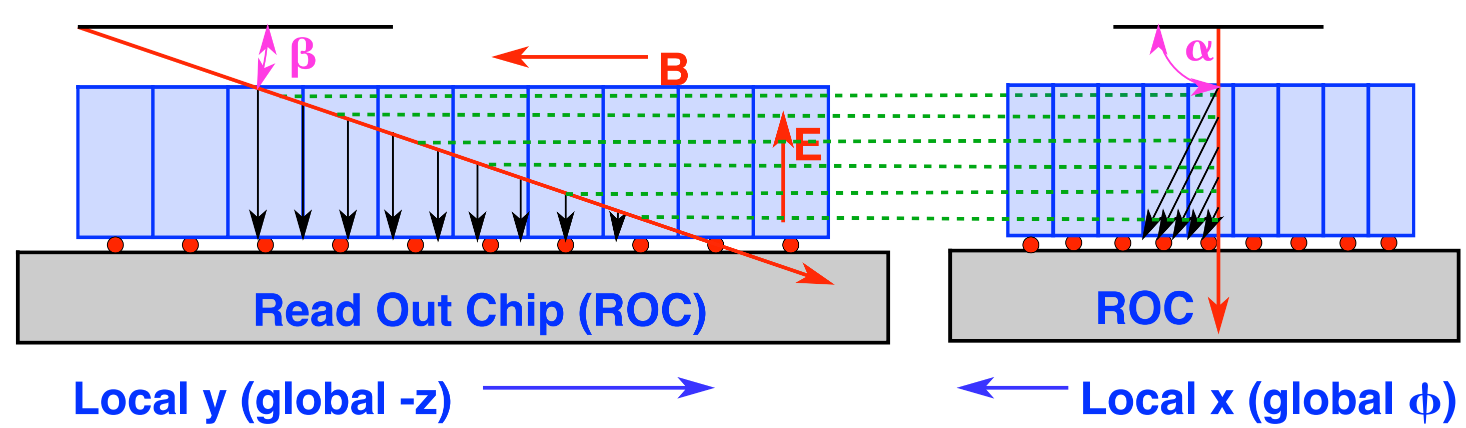


We have probes which are sensitive to the detailed structure of the E-field.

Charge collection efficiency for "under-depleted" sensors.



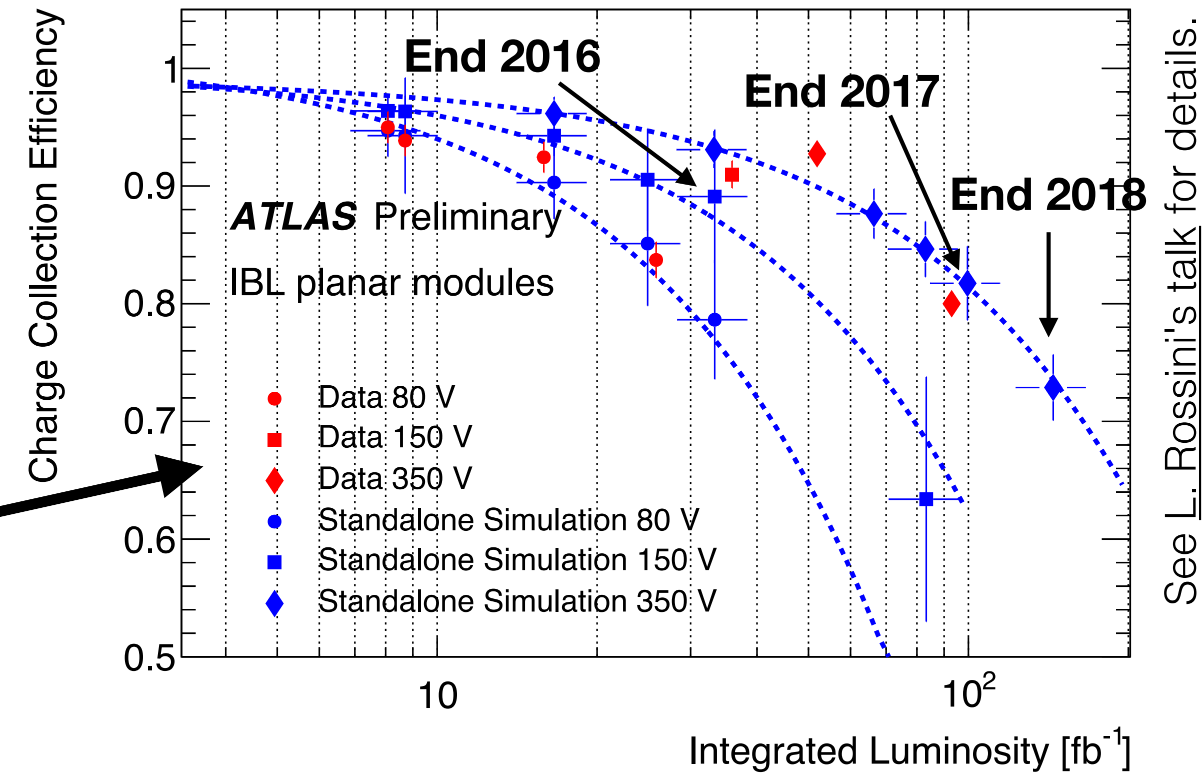
Charge drift depth-dependence using long clusters.
(invert mobility to get E-field)



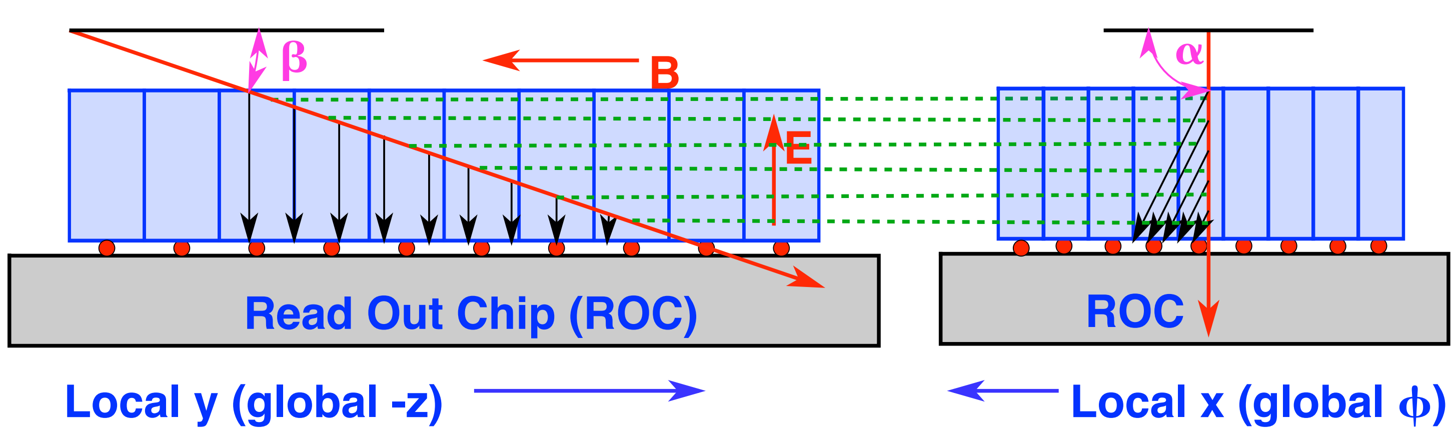
Validation with data

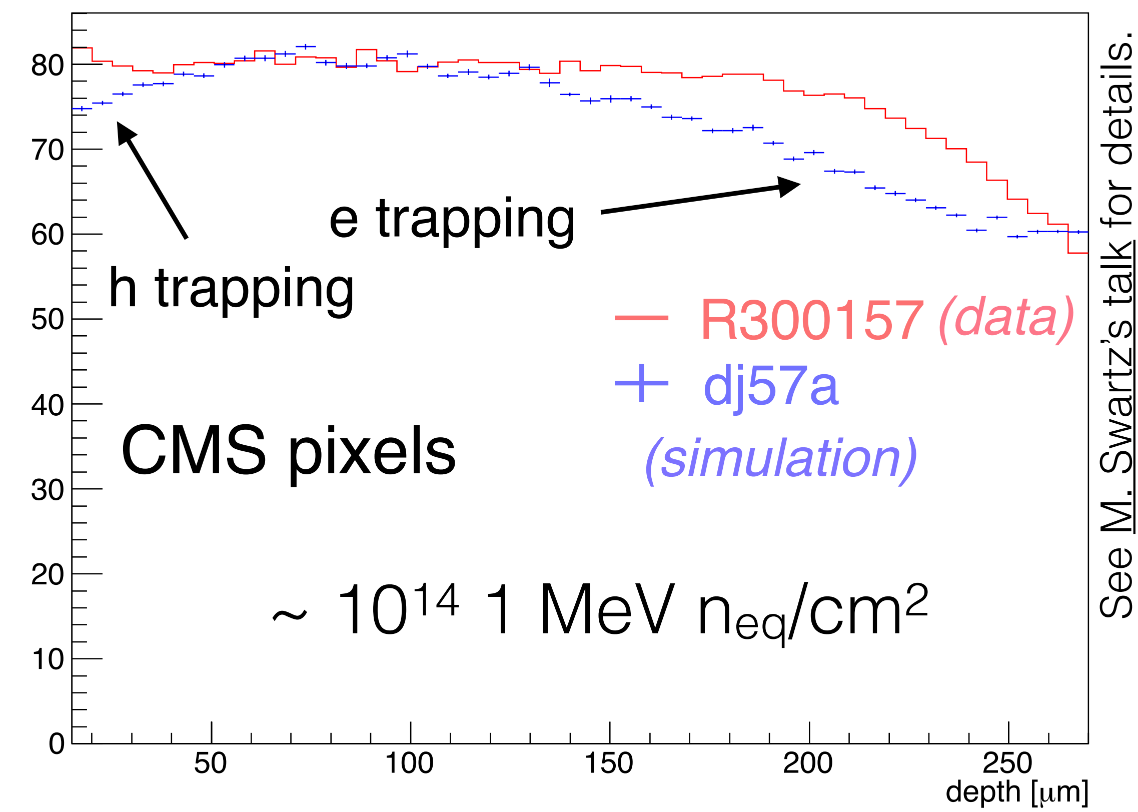
We also have probes that are very sensitive to charge trapping.

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



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





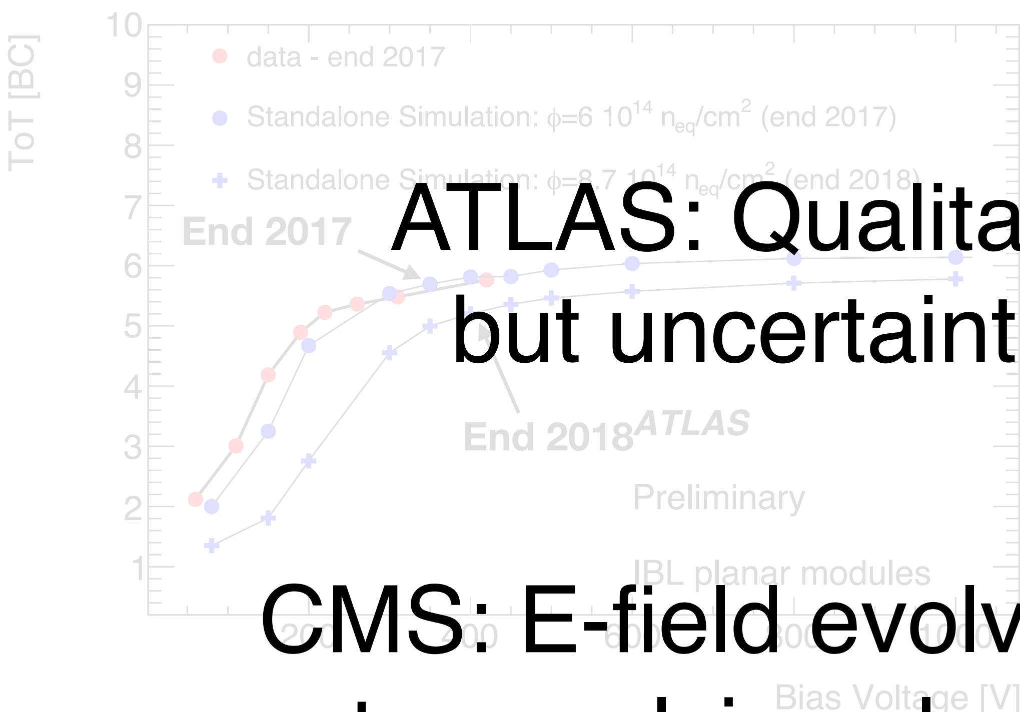
Validation with data

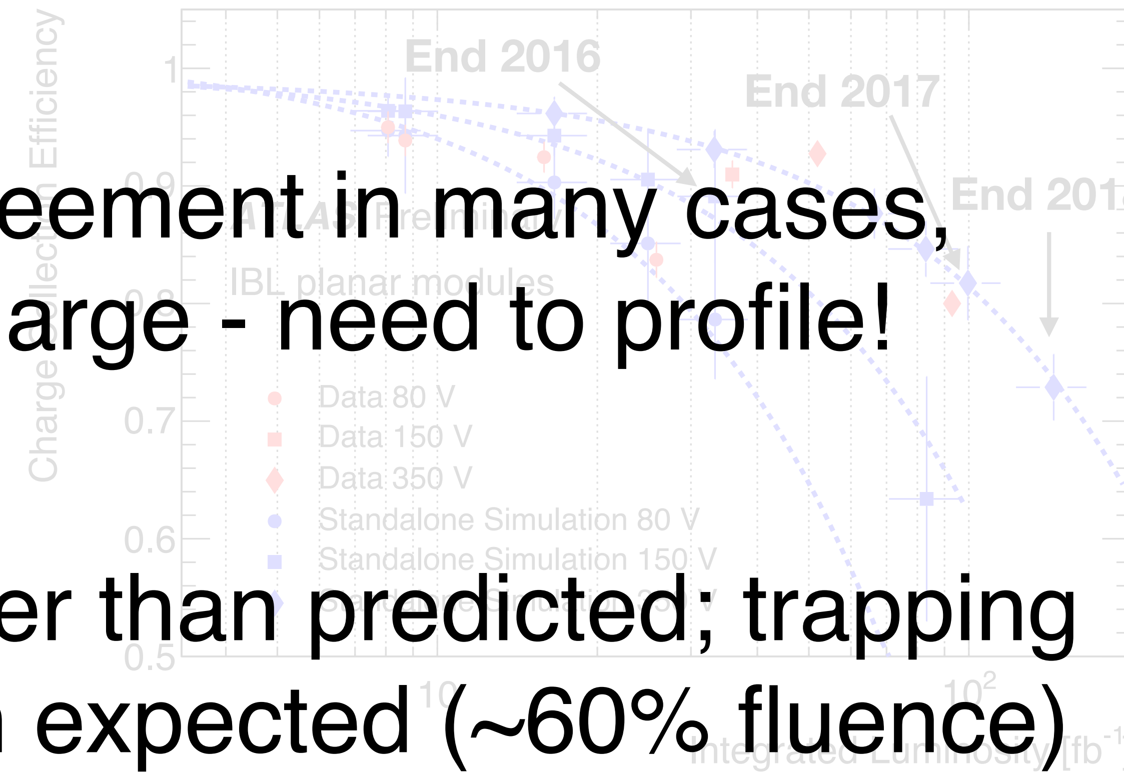
ATLAS: Qualitative agreement in many cases, but uncertainties are large - need to profile!

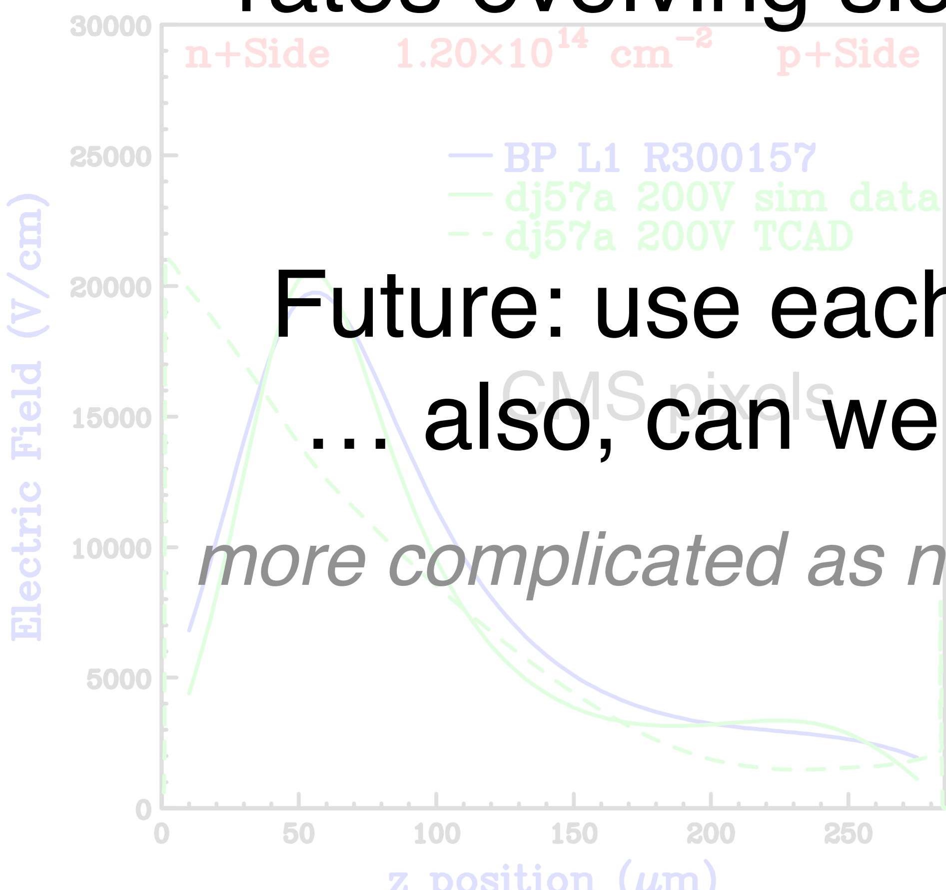
CMS: E-field evolving faster than predicted; trapping rates evolving slower than expected (~60% fluence)

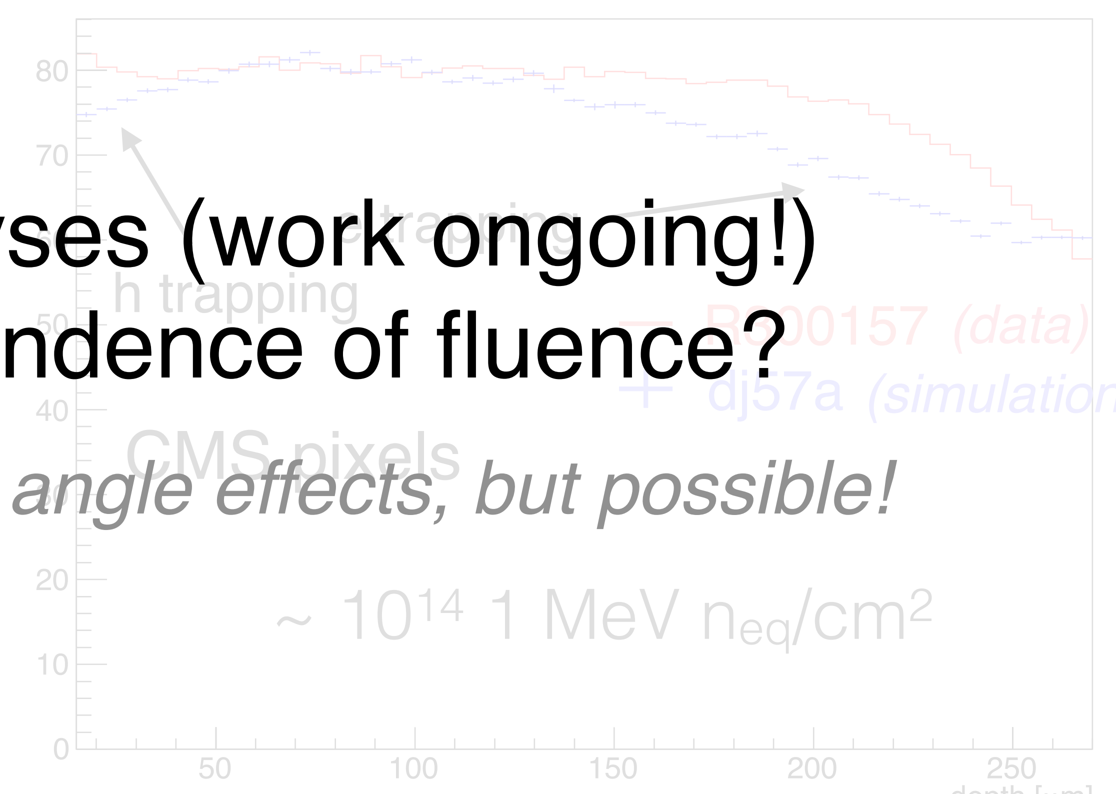
Future: use each other's analyses (work ongoing!)
… also, can we check z-dependence of fluence?

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







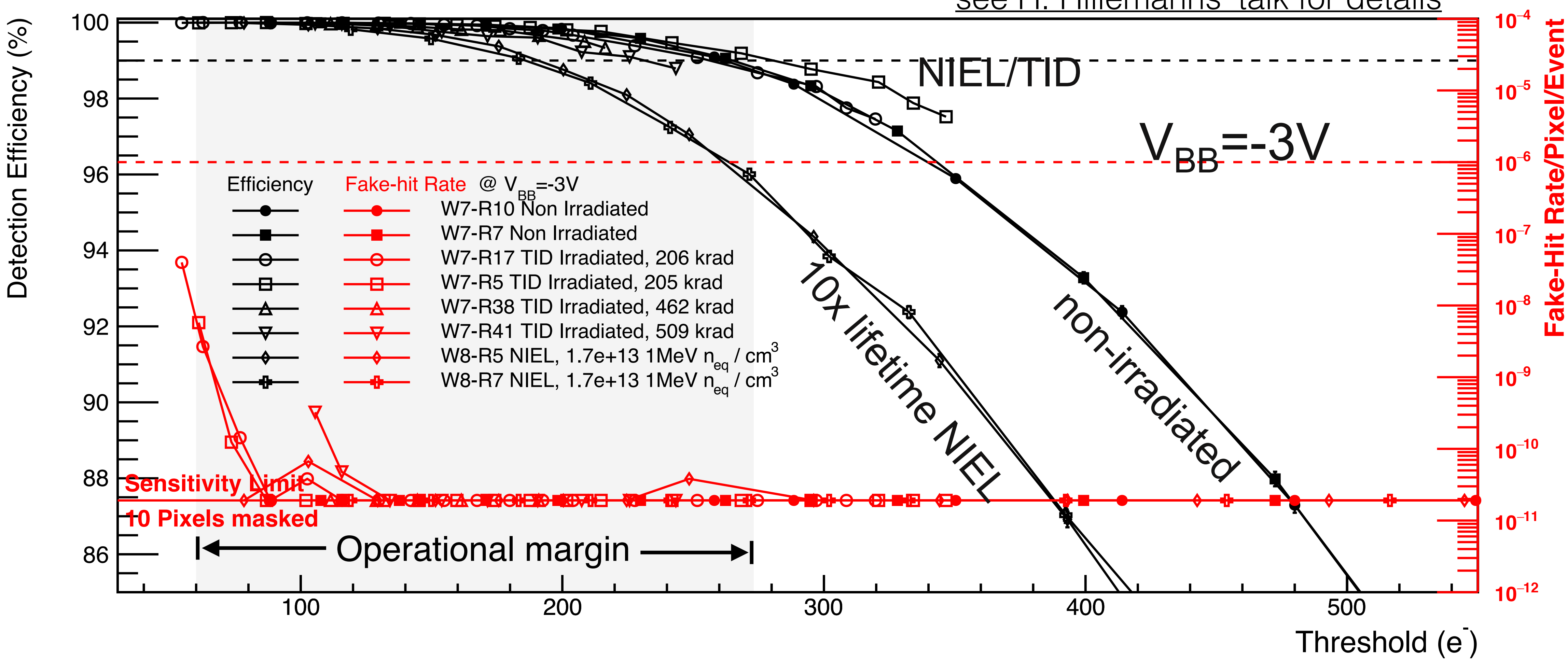


Radiation and detector upgrades

This is not a talk about the HL-LHC, but I have to say that that everything discussed so far provides critical input for the future.

…and since this talk covers all major exp's, I will say **ALICE** has an impressive **Run 3** pixel upgrade where rad. effects are relevant.

see H. Hillemanns' talk for details



Grand Challenges for the Future

…where I'd like to see progress by the next workshop(s):

Full study of z- and r-dependence of fluence

Full study of Si activation energy (simultaneous fit with fluence)

RD50 radiation damage model parameter set + uncertainty

Progress toward a combination of TCAD + annealing

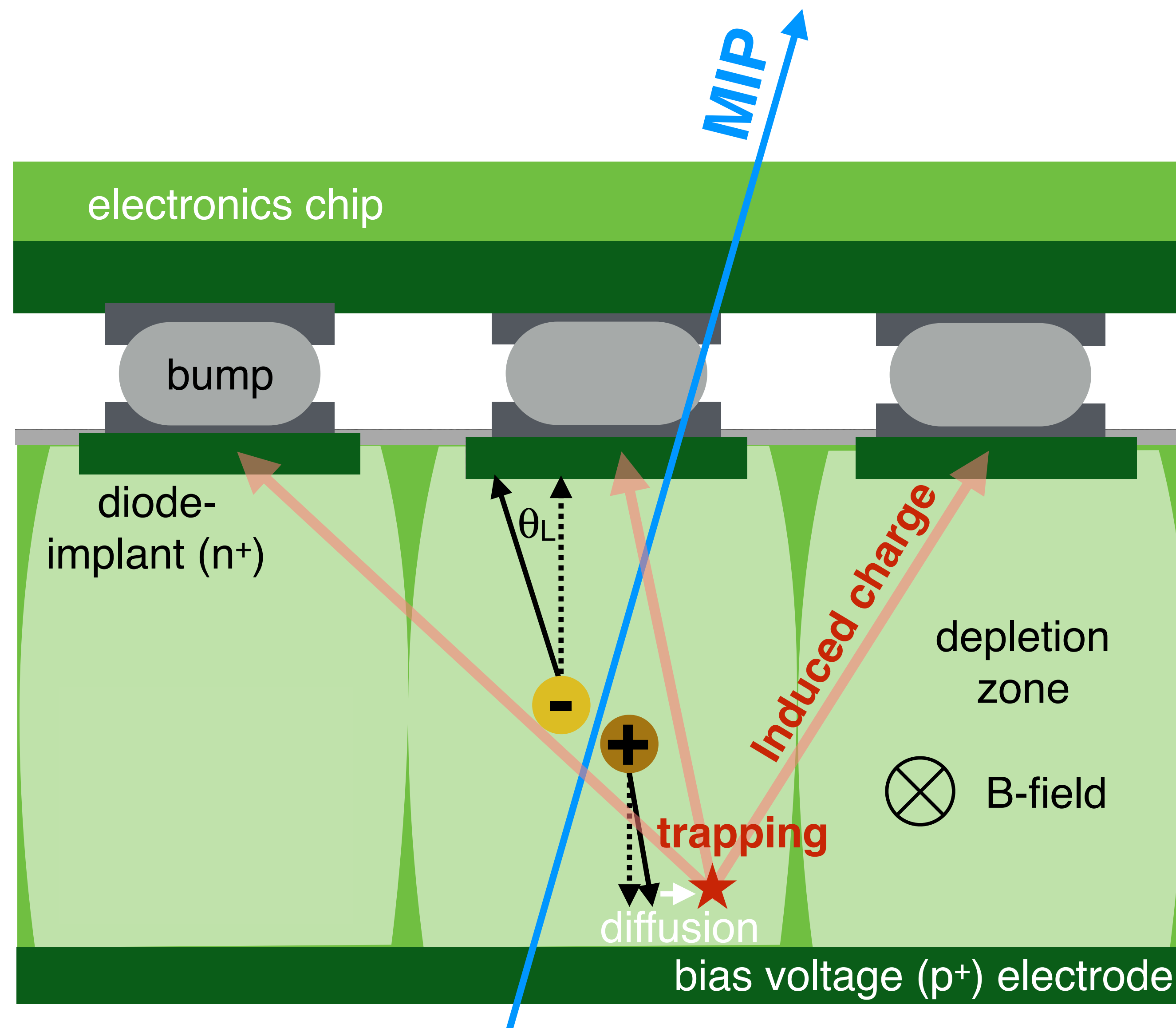
Impact on physics / analysis observables (e.g. flavor tagging)

Compare methods between ATLAS/CMS/LHCb

Conclusions

The current LHC detectors are a great laboratory for radiation damage effects and are in great need of input from the RD50 community!

Looking forward to the next gathering where there should be many interesting discussions with the full Run 2 dataset!



2nd workshop on radiation effects in the LHC experiments: impact on operation and performance

a post run 2 review, with focus on inner detector systems

11-12 Feb 2019 at CERN: indico.cern.ch/event/769192

Sessions on: sensor measurements & simulations; radiation background simulation & benchmarking; effects on electronics/optoelectronics

Organising Committee: E.Butz (KIT), M.van Beuzekom (Nikhef), J.Buytaert (CERN), M.Bomben (LPNHE), P.Collins (CERN), I.Dawson (Sheffield), S.Mallows (KIT), M.Moll (CERN), A.Mucha (AGH UST), B.Nachman (LBNL), D.Robinson (Cambridge), A.Rozanov (CPPM-IN2P3-CNRS)

Backup