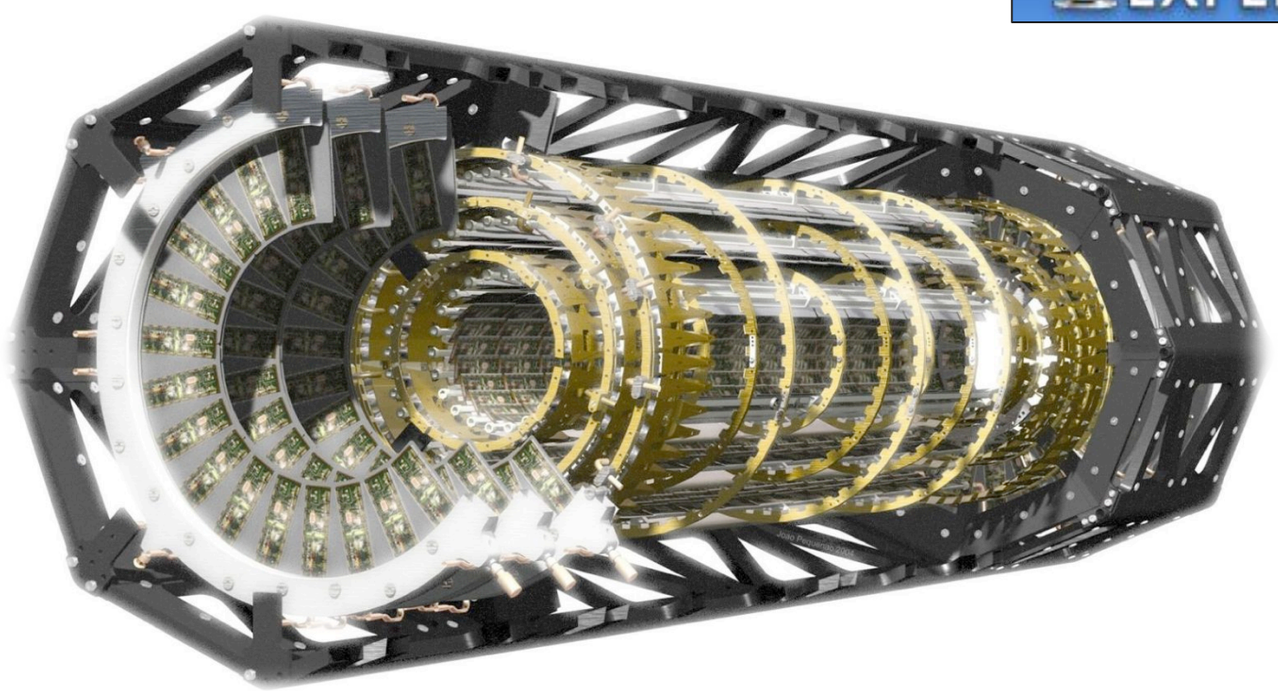
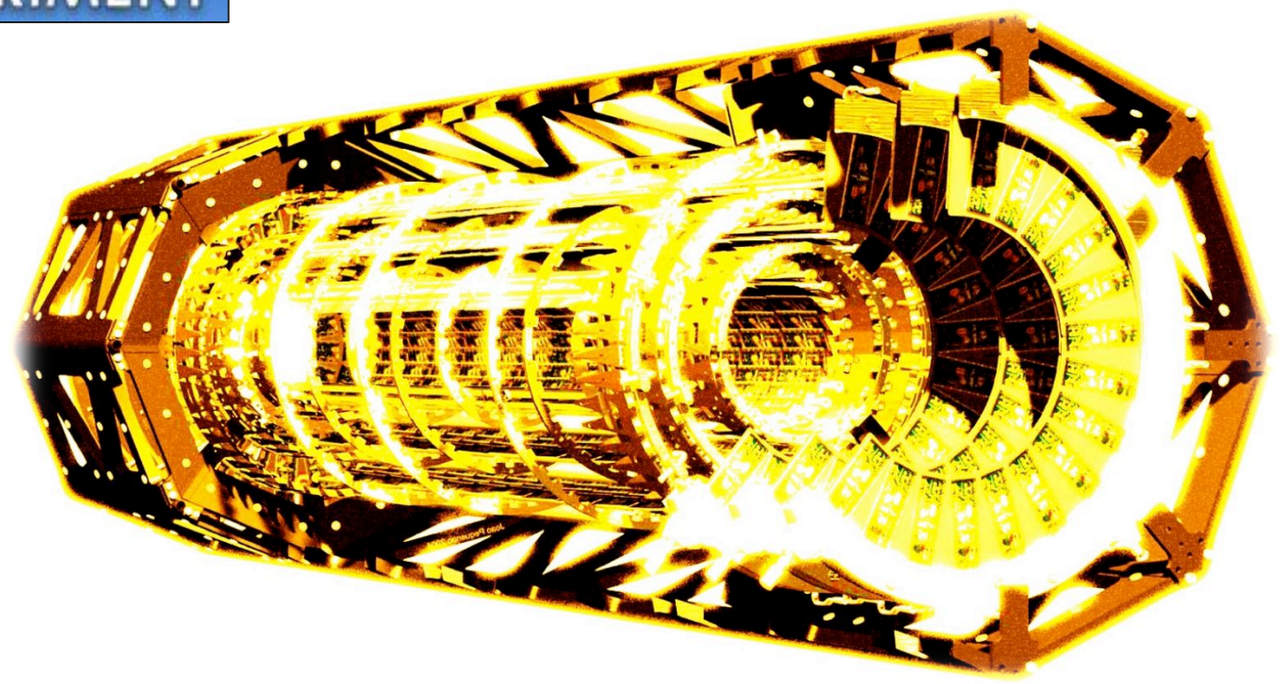
Observation of type-inversion in the innermost tracking layer of the ATLAS Pixel Detector





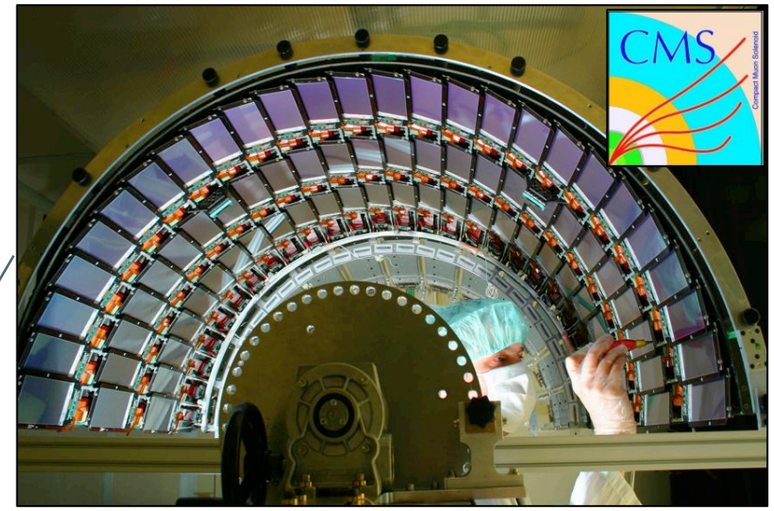
Stephen Gibson
& André Schorlemmer
on behalf of the
ATLAS Inner Detector
Radiation Damage Group

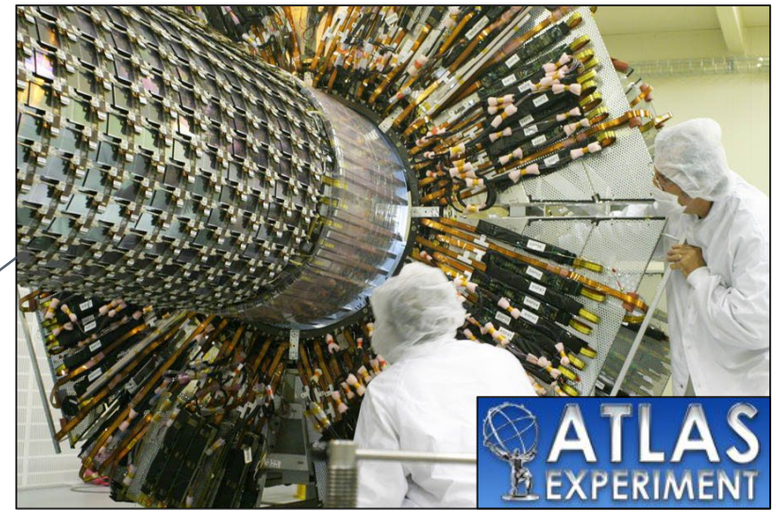
The 21st RD50 Workshop.
CERN | 14 – 16 November 2012

Outline

- Motivation and the ATLAS Pixel Detector
- Fluence, leakage current and annealing effects
- Effective Depletion Voltage
  - Cross-talk method
  - Track based method
- Inter-experiment working group

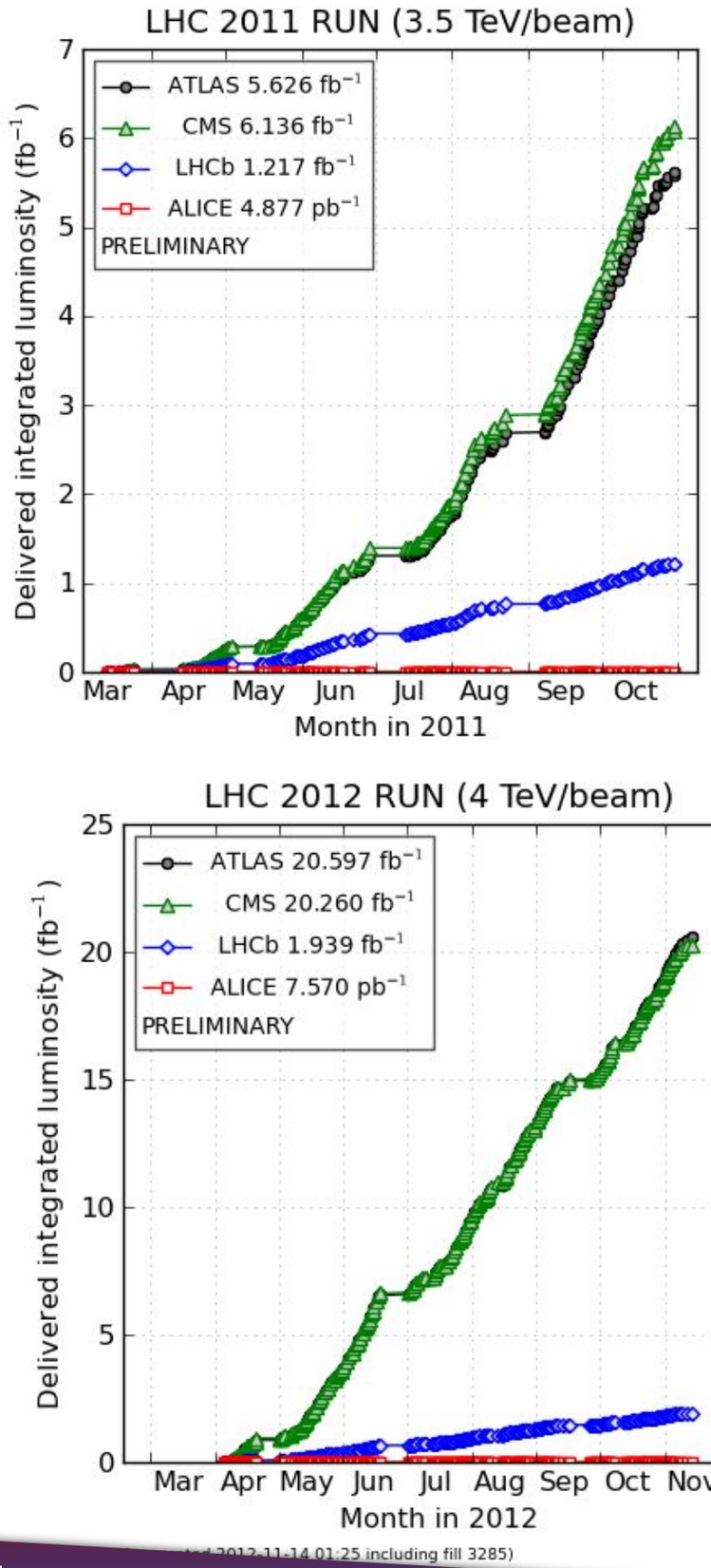
?



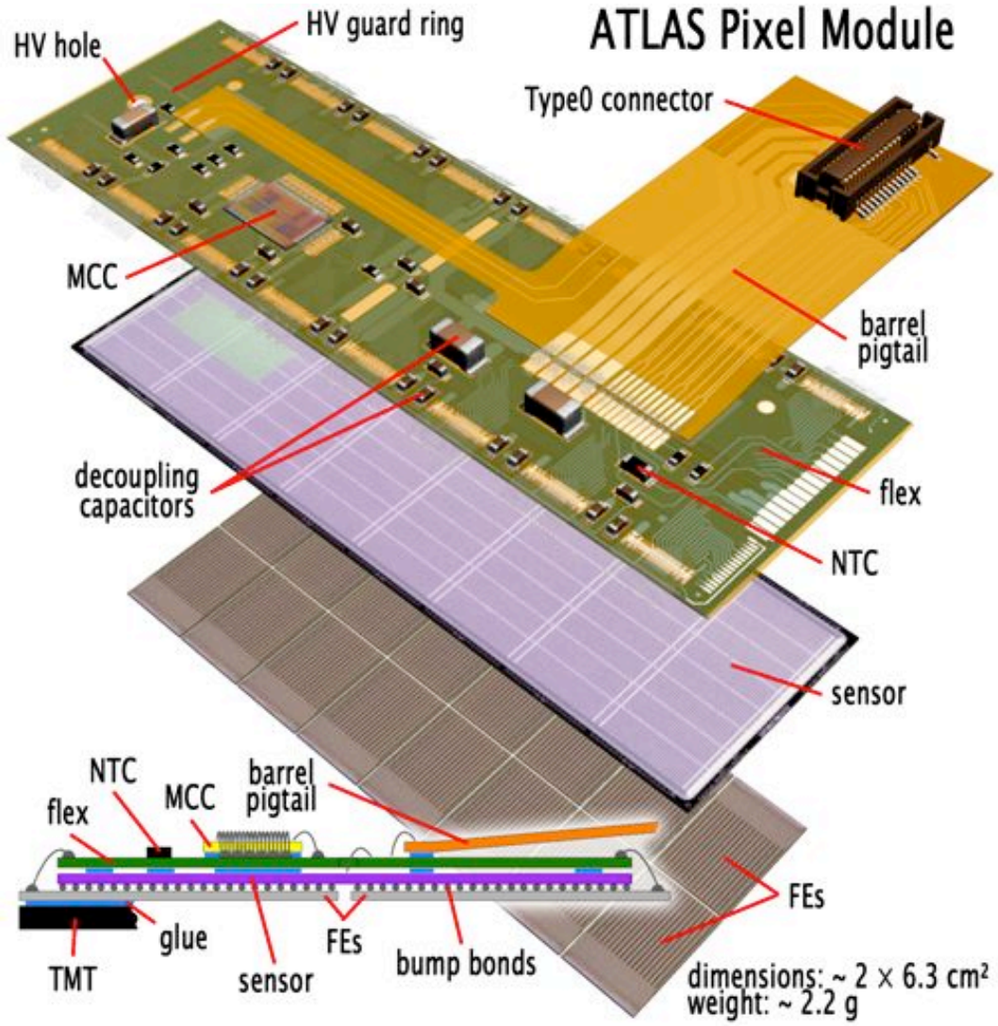


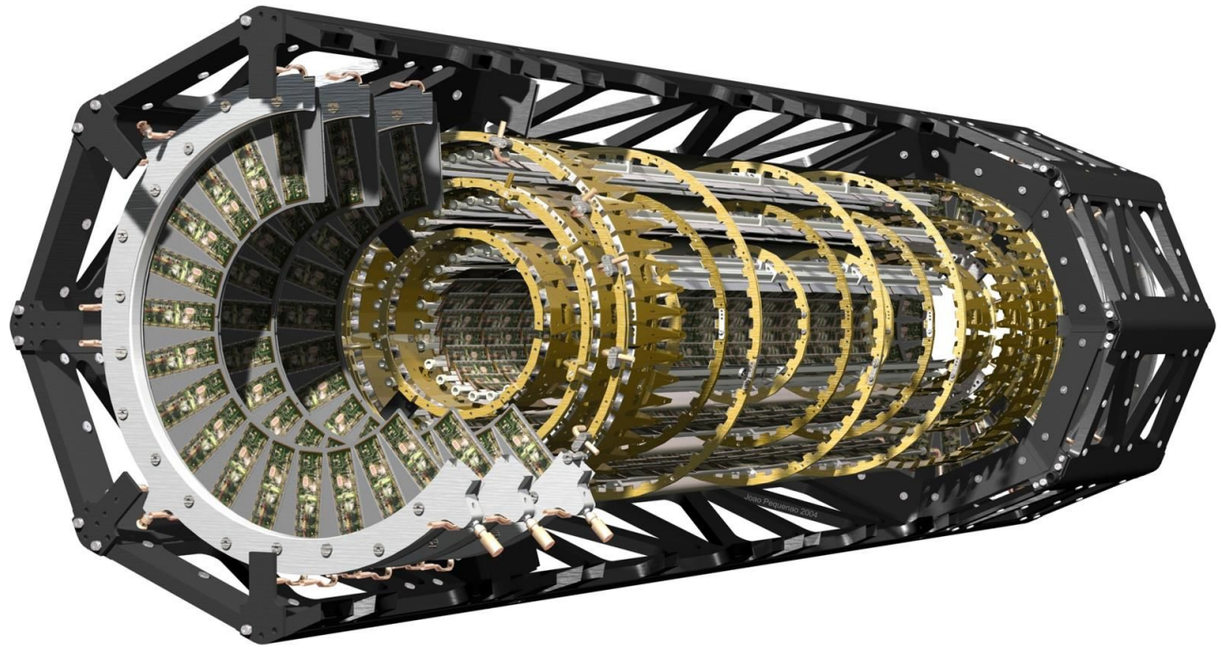
Motivation

- The LHC has delivered 25 fb^{-1} to ATLAS and CMS to date, corresponding to a fluence of over ~6x10^{13} 1 MeV n_{eq} cm^{-2} at the innermost Pixel layers.
  - This is now more than double the threshold required for type inversion.
- The LHCb VELO is subject to an even higher fluence of ~6x10^{13} 1 MeV n_{eq} cm^{-2} *per* fb^{-1} at the inner tips of sensors only 8.2 mm from the beam.
- The evolution of silicon parameters in all experiments is regularly monitored:
  - Do the new measurements match former model predictions?
  - How to mitigate reverse annealing and optimize detector performance?
  - Future extrapolations: how long will our detectors last?



ATLAS Pixel Detector module





- **Readout:** FE = Front End, MCC = Module Control Chip
  - 16 FE chips with zero suppression, MCC builds module event. Date rate of 40-160 MHz depending on layer.
  - Deposited charge measured by Time over Threshold.

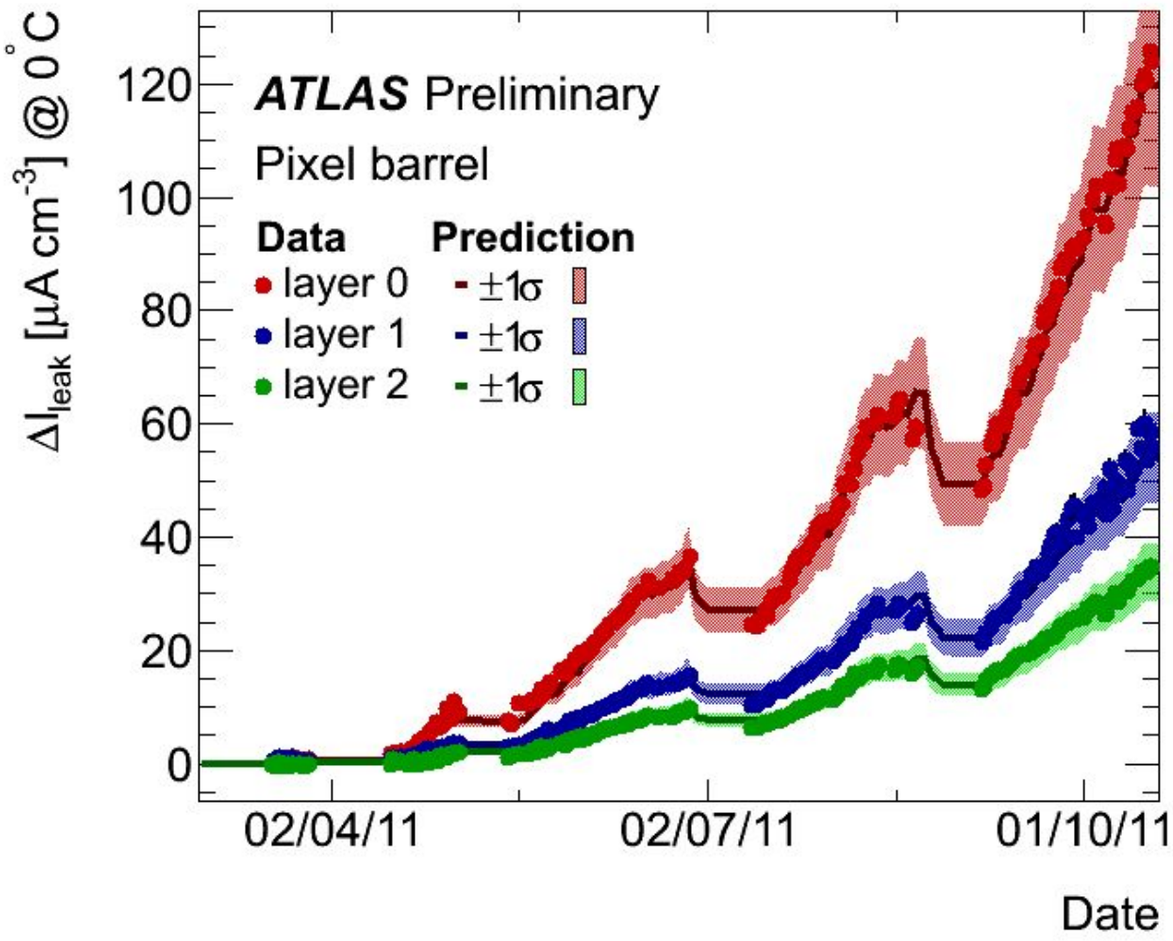
- **Innermost layer at 50.5mm:**
  - Radiation tolerance 500kGy/ 10^{15} 1MeV n_{eq} cm^{-2}
- **Evaporative cooling integrated in support structure:**
  - Modules cooled to average of -13 °C.
- **Sensor:**
  - 250 μm thick n-on-n type silicon, with typical pixel granularity, 50x400 μm.
  - 47232 (328 x144) pixels per module (46080 pixels bump-bonded to 16 FE readout chips).
  - V_{bias} = 150 V (600 V)

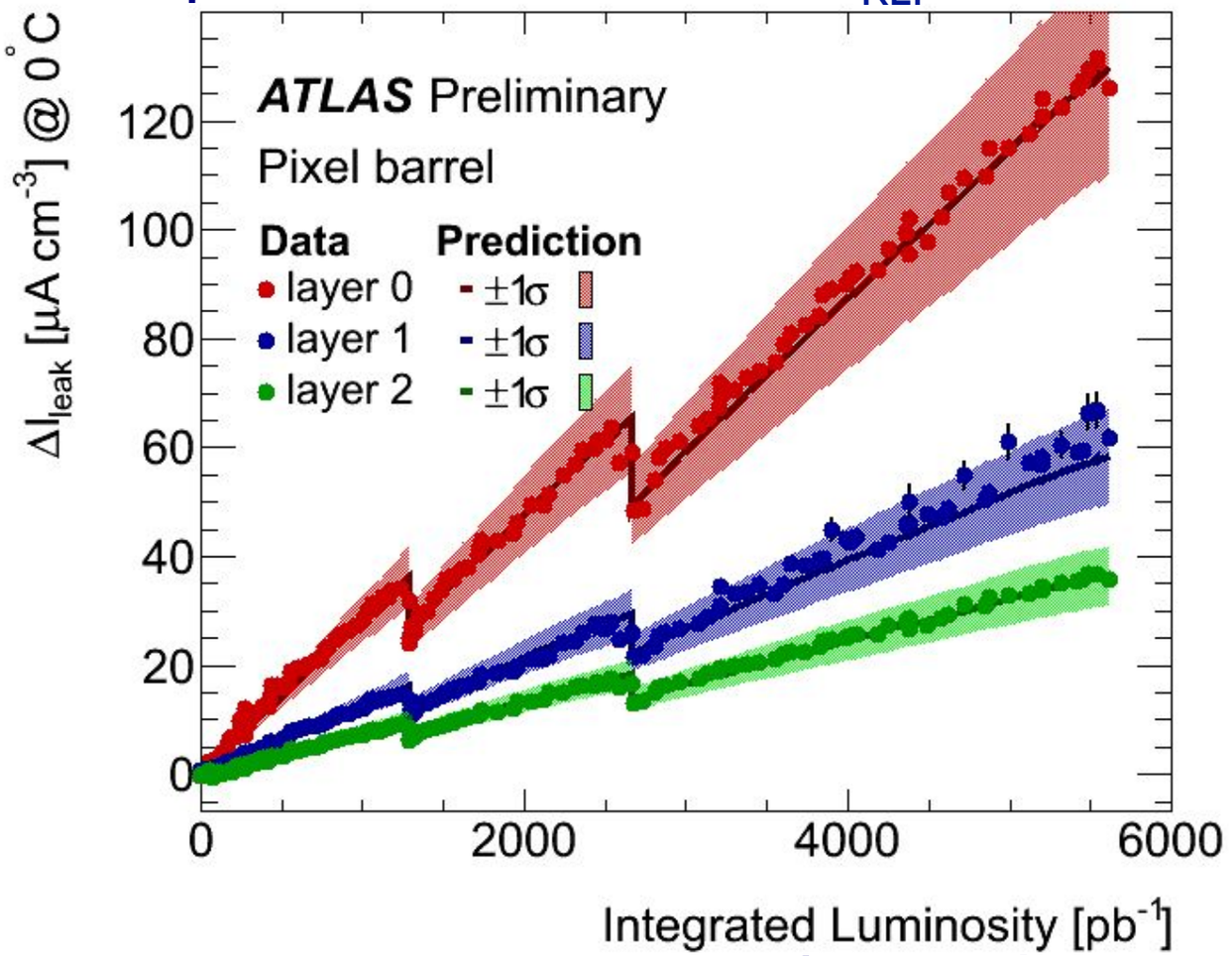
Monitoring radiation damage

- Radiation damage in the Pixel Detector became observable in early 2011 and continues to be tracked by complementary methods:
- Leakage current is monitored with three granularities:
  - ***Per pixel*** measurement exploits capabilities of FE-chip. Regular calibration scans with resolution LSB ~ 0.125nA per pixel. } see talk by Markus Keil, 20th RD50
  - **Per module** using dedicated current measuring boards on certain modules (10nA). Continuous. High / low range settings. } see talk by Rui Wang
  - **Per half stave** of 6 or 7 modules; measure reverse-bias current via each (ISEG) power supply with a precision of ~80 nA per half stave. Continuous.
- Depletion depth and effective depletion voltage:
  - Regular ***cross-talk scans*** to measure depletion voltage of each module.
  - ***Track-based depletion depth measurements*** using track incidence angle, geometry and threshold.

2011 data at 7 TeV

- Average power supply currents by layer; temperature corrected to T_{REF} = 0 °C

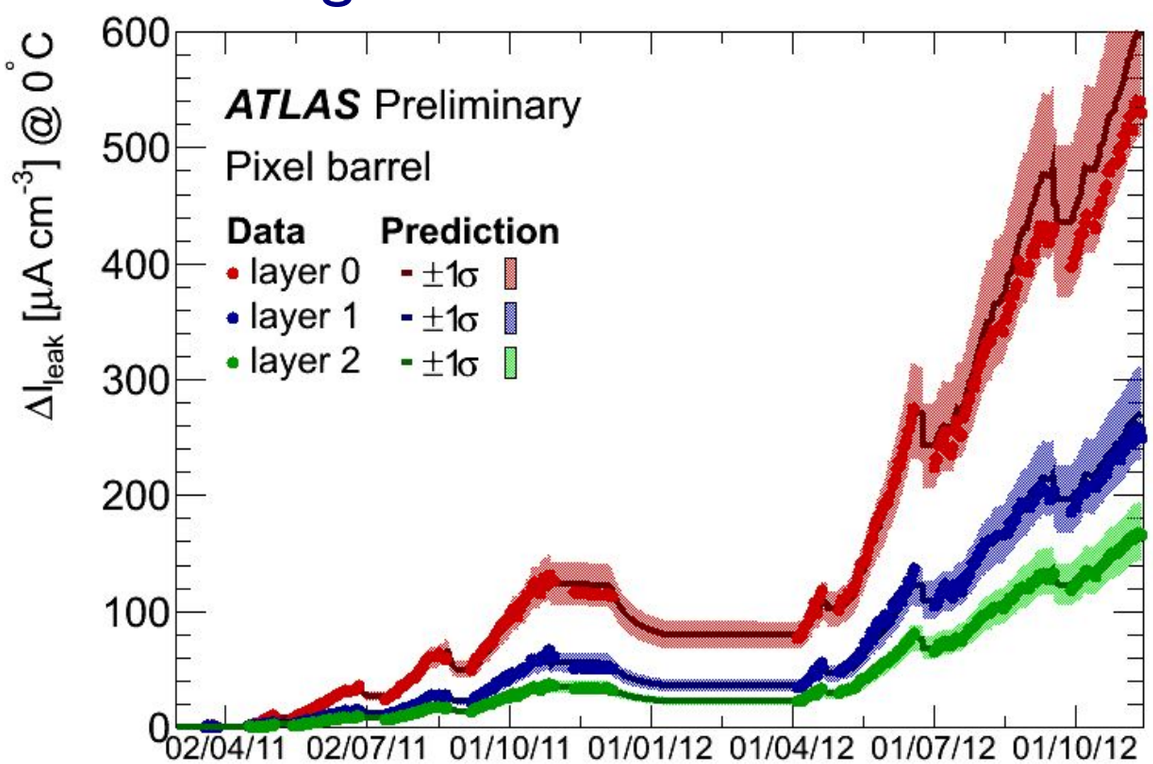


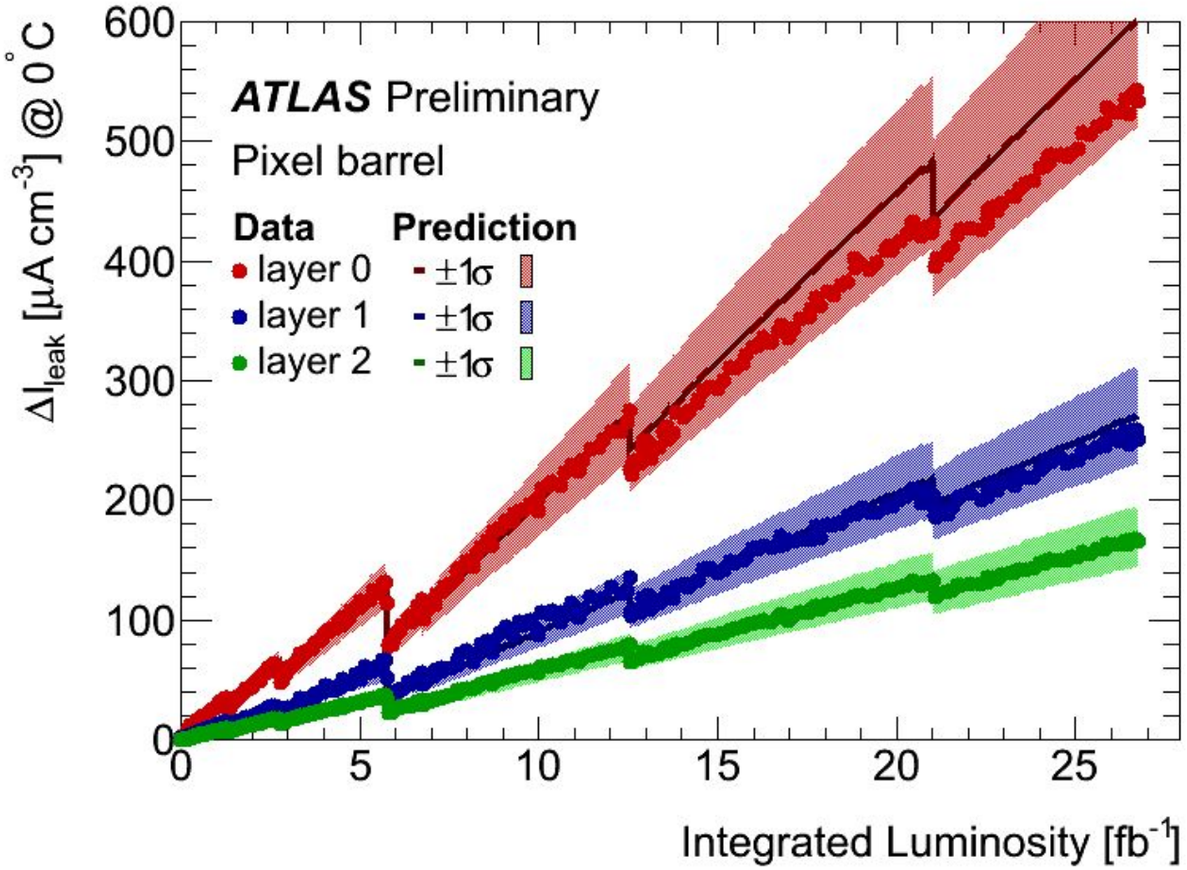


- Leakage current follows integrated luminosity; steps consistent with annealing during detector warm-up periods.
- Prediction is based on delivered luminosity, the expected fluence by barrel layer from Phojet + FLUKA simulations and the Dortmund (Hamburg) model [O. Krasel]
- Qualitatively very good agreement; however, the prediction underestimates the data and had to be scaled up: L0 (1.15) L1, L2 (1.25).

2011/2012 fluence at 7 TeV / 8 TeV

- Adding the latest 2012 data…

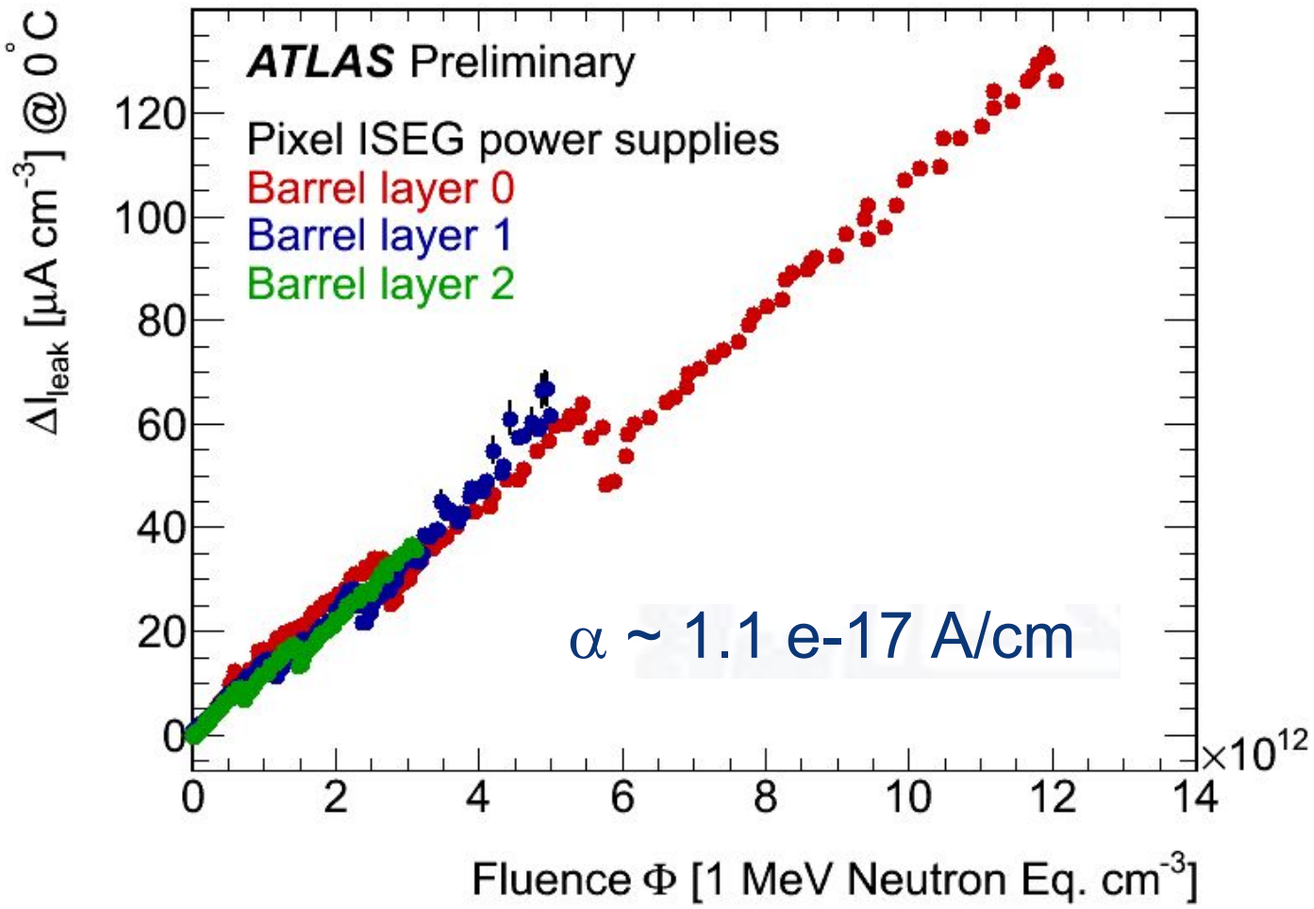




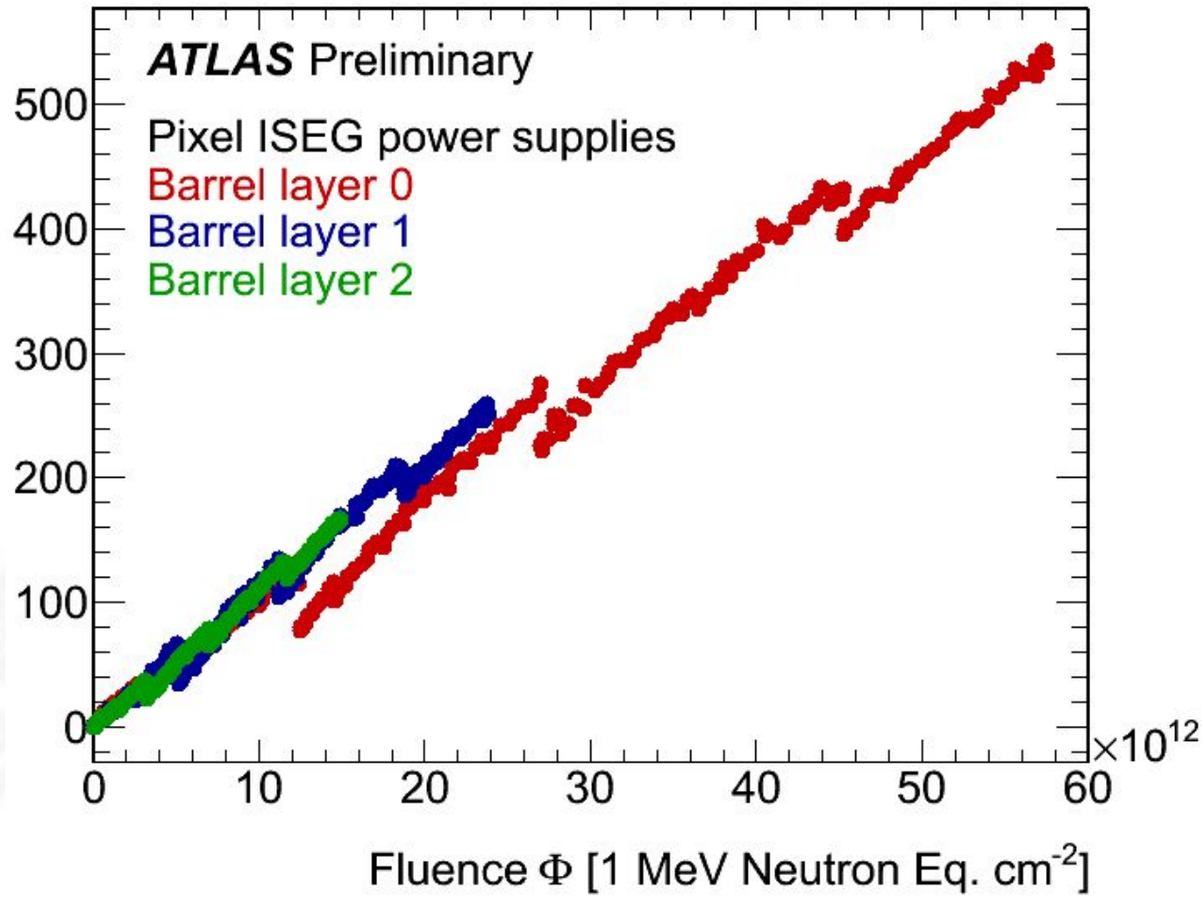
- Prediction for both years is based on 7 TeV FLUKA for 2011 and an estimated 8 TeV fluence for 2012 by an interpolation between 7 TeV and 14 TeV FLUKA simulations. The same scaling factors are applied: L0 (1.15) L1, L2 (1.25).
- Agrees well until June 2012, after which L0 data show a slightly shallower slope.
- Thought to arise from an underestimate of annealing effects in the model: the time binning in the Dortmund (Hamburg) model needs to be finer to capture warm up time structure (per day to per hour or less).

Leakage current vs fluence

2011



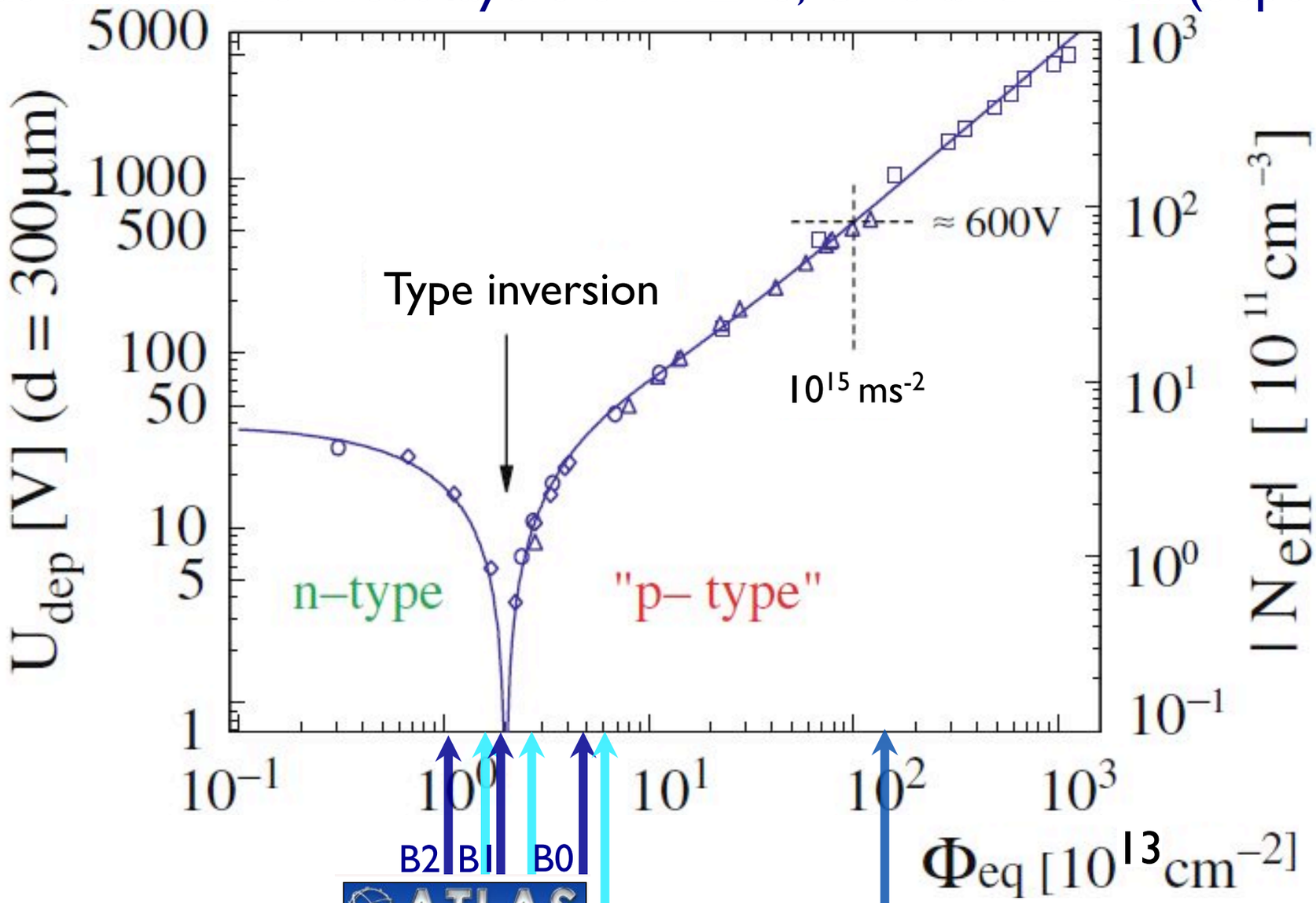
2011+2012



- Leakage current shows the expected rise in proportion to the fluence (FLUKA).
- ATLAS Pixel sensors operate for months at low temperature (-13° C), which freezes the annealing until the cooling stops (20°C): this novel regime for alpha, (togther with FLUKA fluence conversion) may contribute to the underestimate in leakage current model predictions.

Fluence status and type inversion

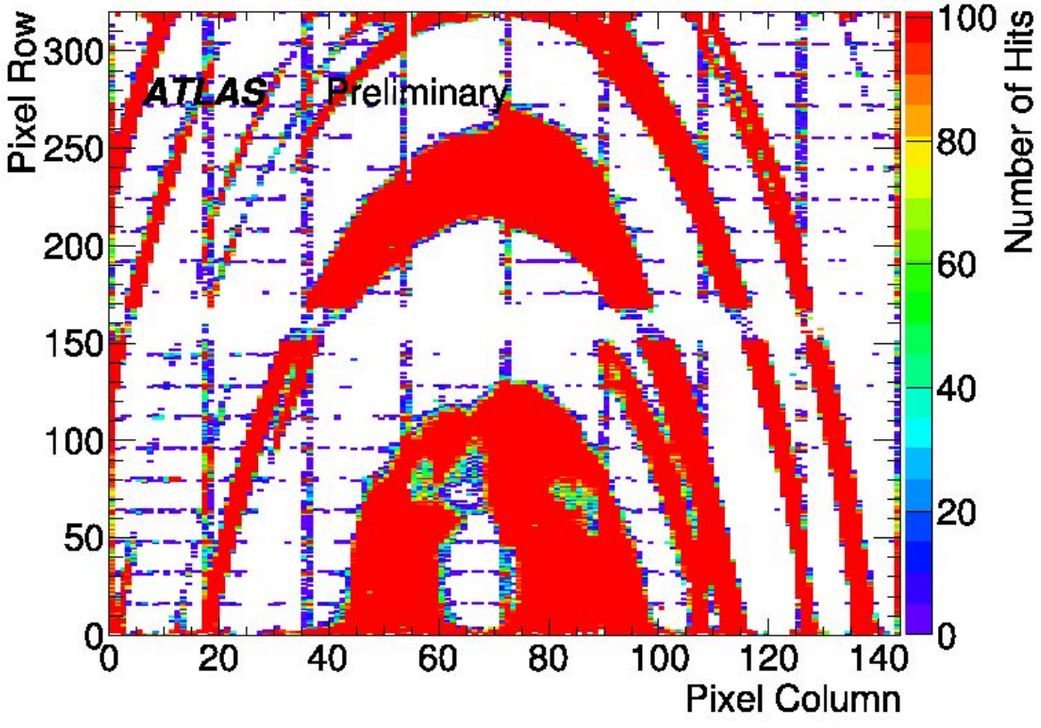
- The status of the innermost layers of ATLAS, CMS and LHCb (Sept 2012)

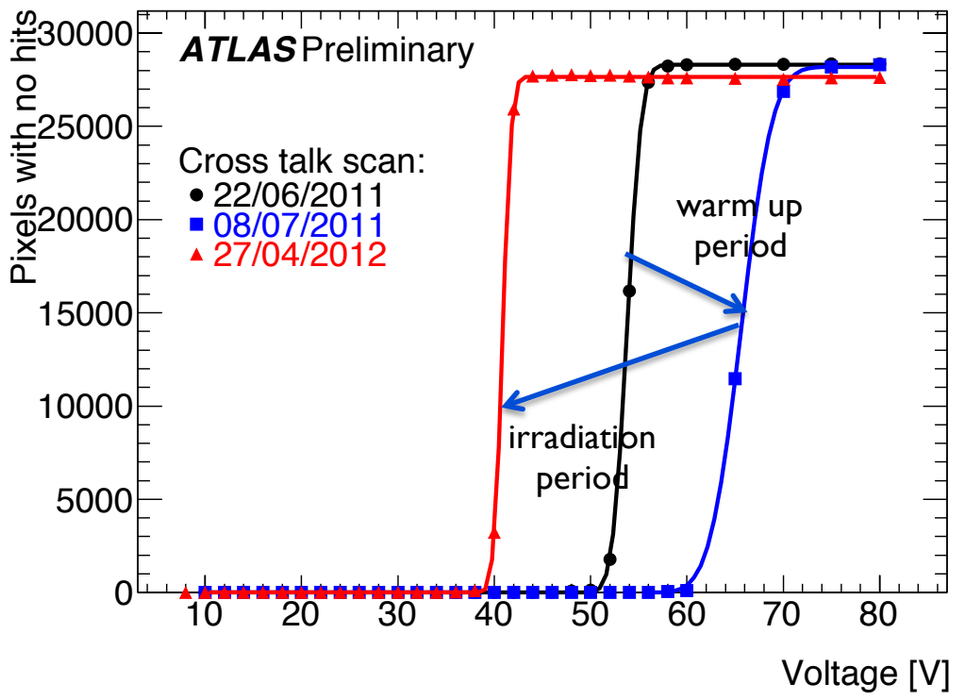


Innermost layers now type inverted.
Second Pixel layers approaching type inversion

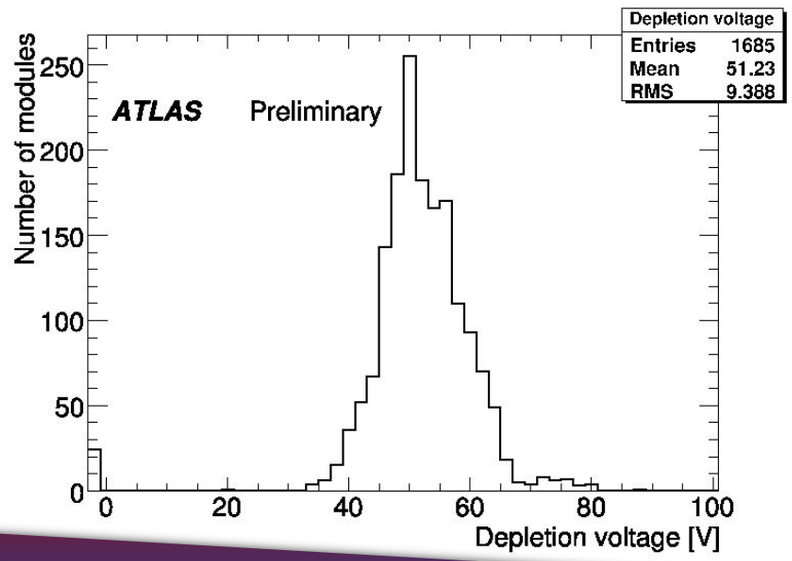
Effective depletion voltage

- Before type-inversion, use inter-pixel cross talk to determine depletion voltage:
  - Sequentially inject charge into pixels and read out neighbour;
    - If not fully depleted, high-ohmic short between pixels. (cross-talk)
    - If fully depleted, pixels are isolated from each other (no hits)



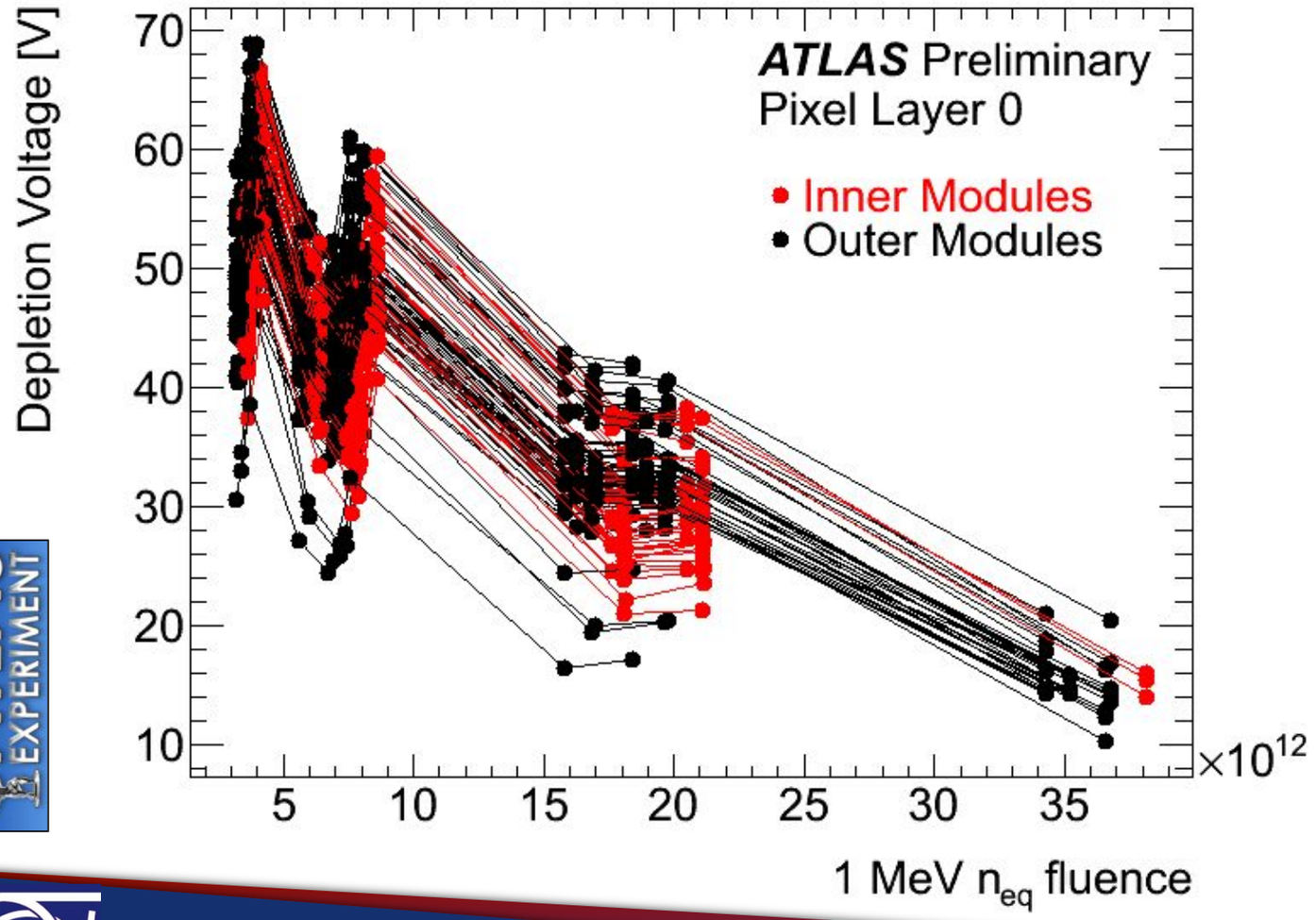


Example: single module close to V_{FD}
White: depleted pixels with no cross talk.
Reveals structure of sensor production.

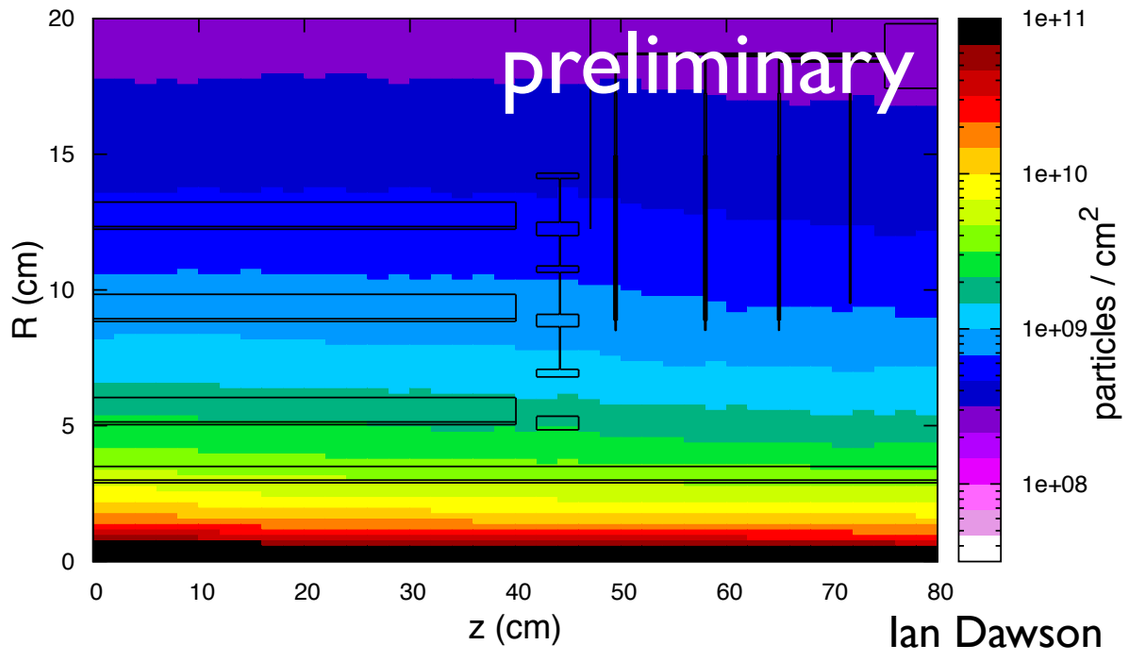


Effective depletion voltage

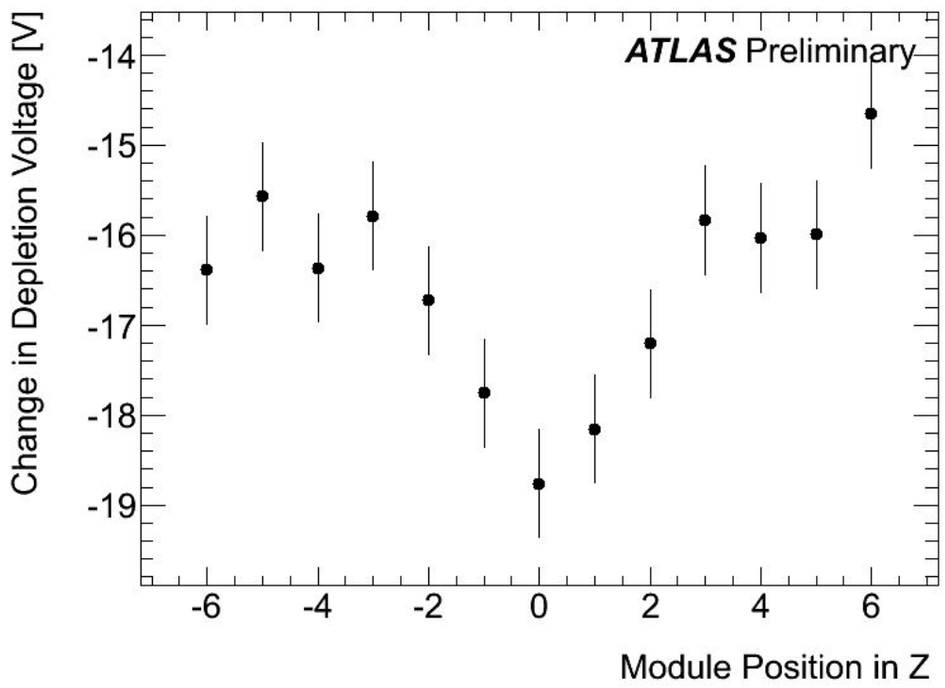
- ATLAS measurements using cross-talk scans.
- Fluence is largest for module closest to the interaction point.
- Reduction in depletion voltage is largest for inner modules.



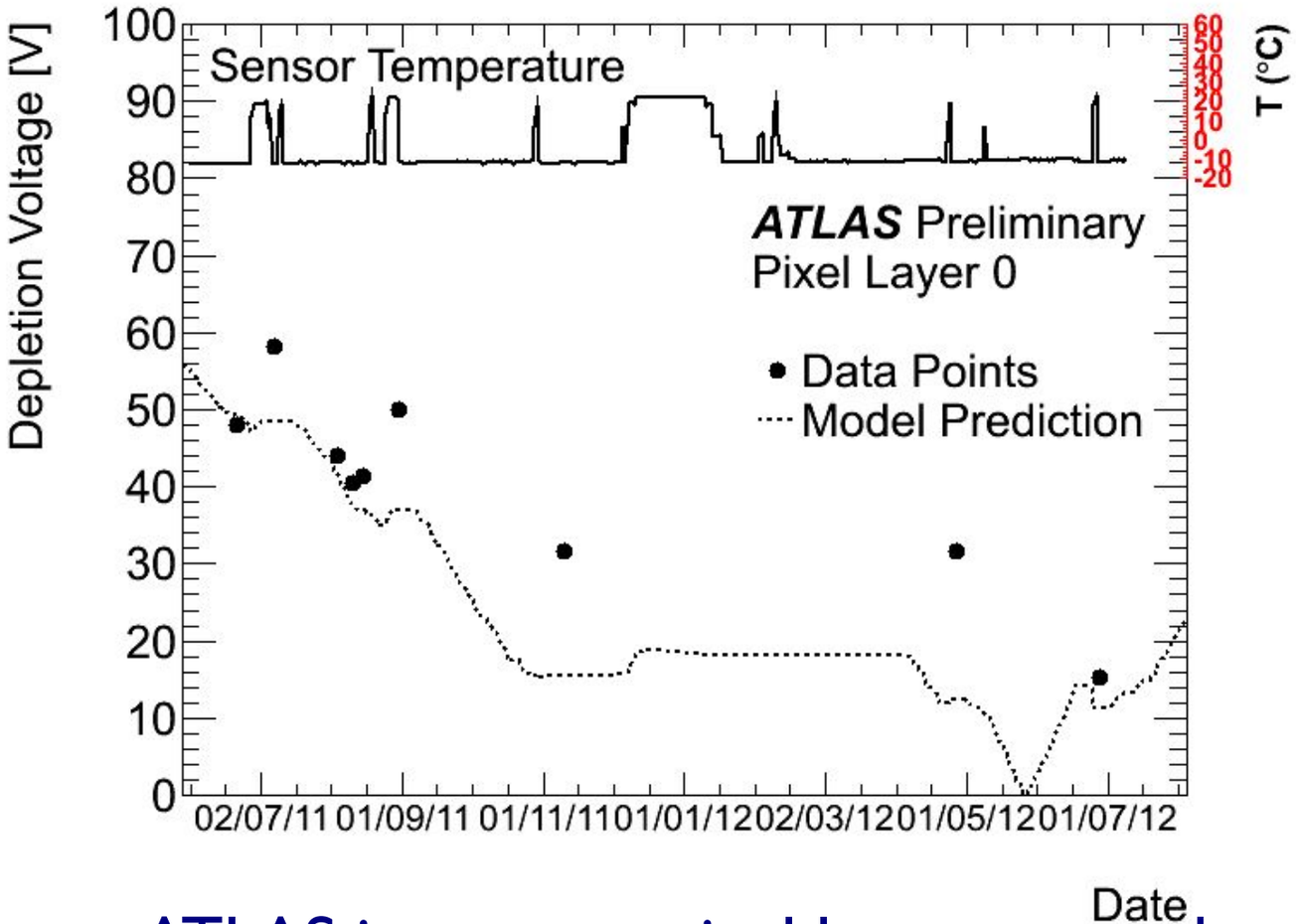
7 TeV FLUKA fluence prediction in Pixel



Ian Dawson

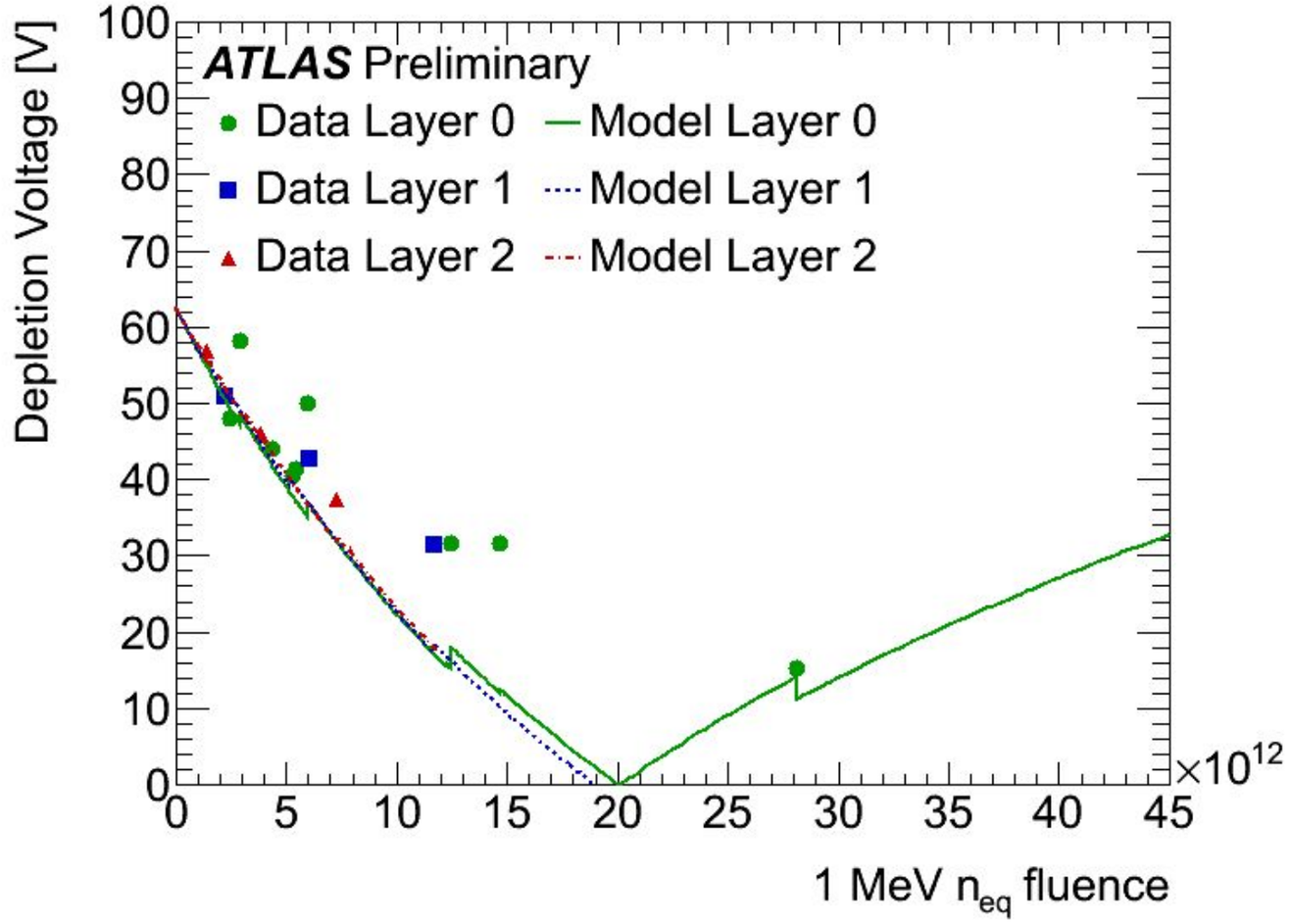


Effective depletion voltage



- Measurements as ATLAS innermost pixel layer approaches type inversion in the summer 2012.
- Model appears to underestimate the data close to type inversion:
  - An artifact that the theoretical value goes to zero, where as in reality the measured value goes close to an offset before rising.
- Beneficial annealing is observed at the cooling stops (higher than present model prediction).

Effective depletion voltage

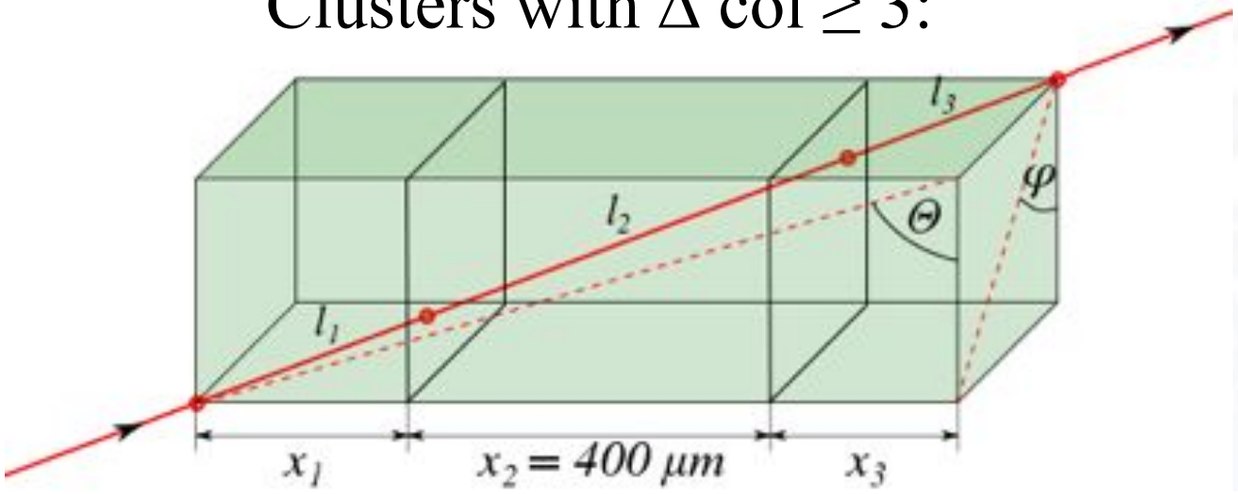


- Evolution of the depletion voltage by layer using cross-talk scan:
  - Model prediction for ATLAS is shown at Sept 2012 luminosity and fluence:
  - layer 0 predicted to be type inverted.
- Next data points would be most interesting to check rate of increase, however…
- Cross-talk method must be replaced by track-based method after type inversion.

ATLAS track based method

- *Determine depth from charge distribution in clusters with special geometry:*

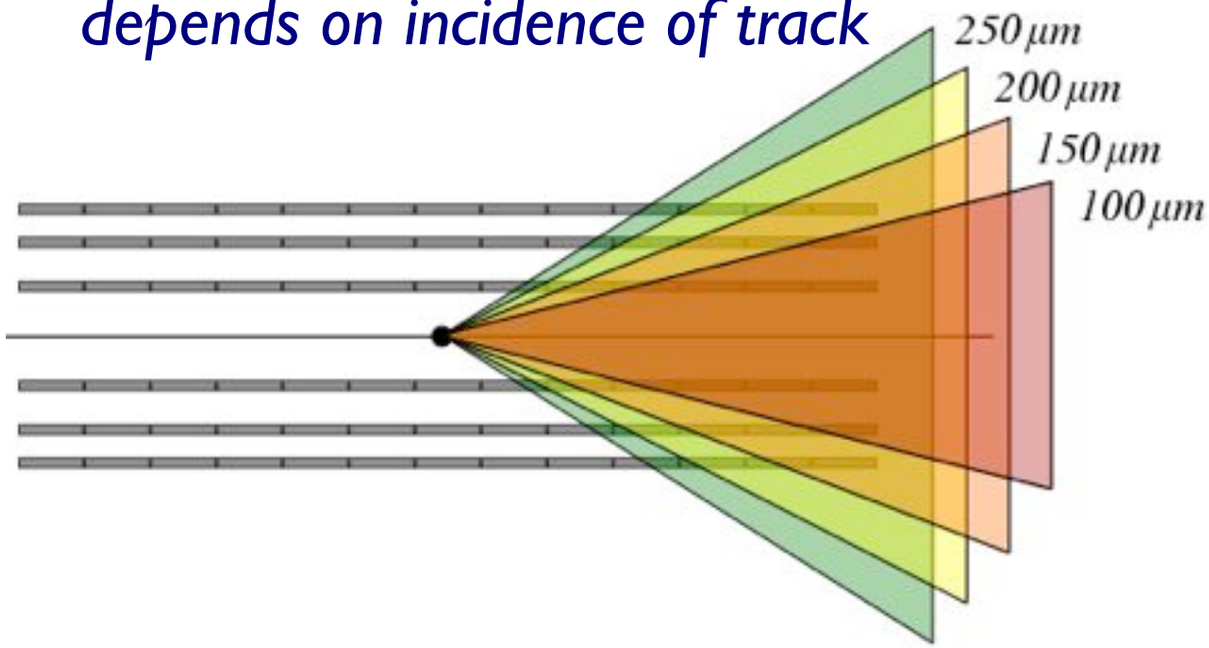
Clusters with Δ col ≥ 3:



- *Calculate l_2 in the central pixel from known pixel dimensions:*
- *Weight l_1 and l_3 by the charges in the pixels; Bethe Bloch proportional to track length:*

$$d_{depl} = \left(\frac{Q_1}{Q_2} + n + \frac{Q_3}{Q_2} \right) \cdot \frac{x_2}{\tan\theta}$$

- *Covered region and depths depends on incidence of track*

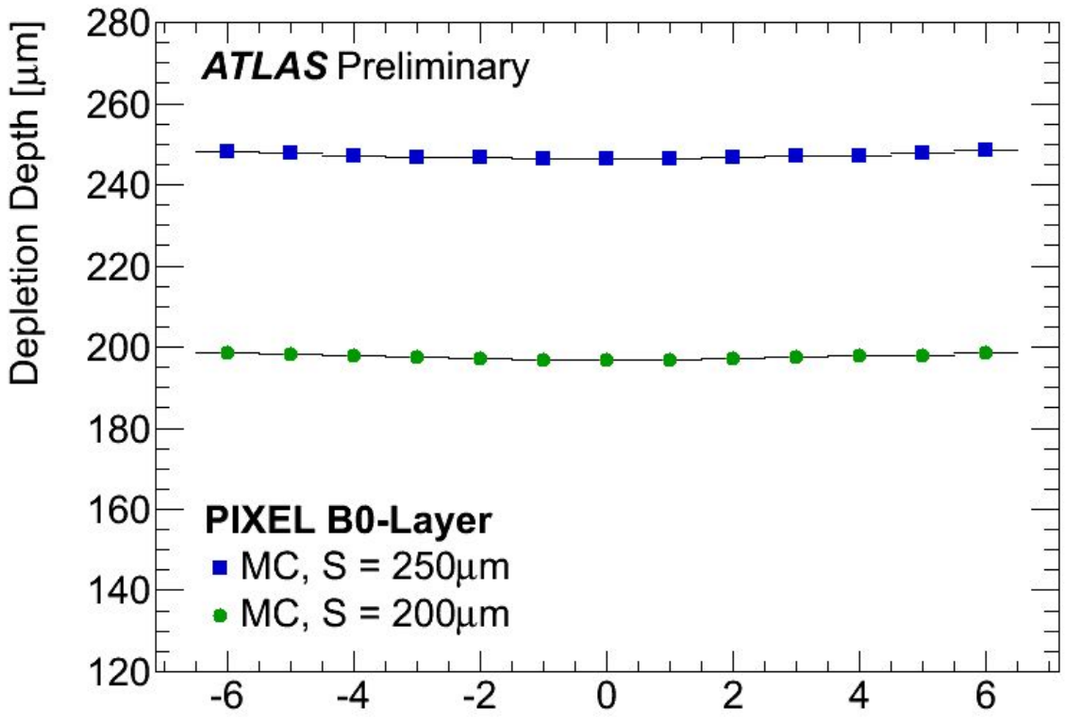


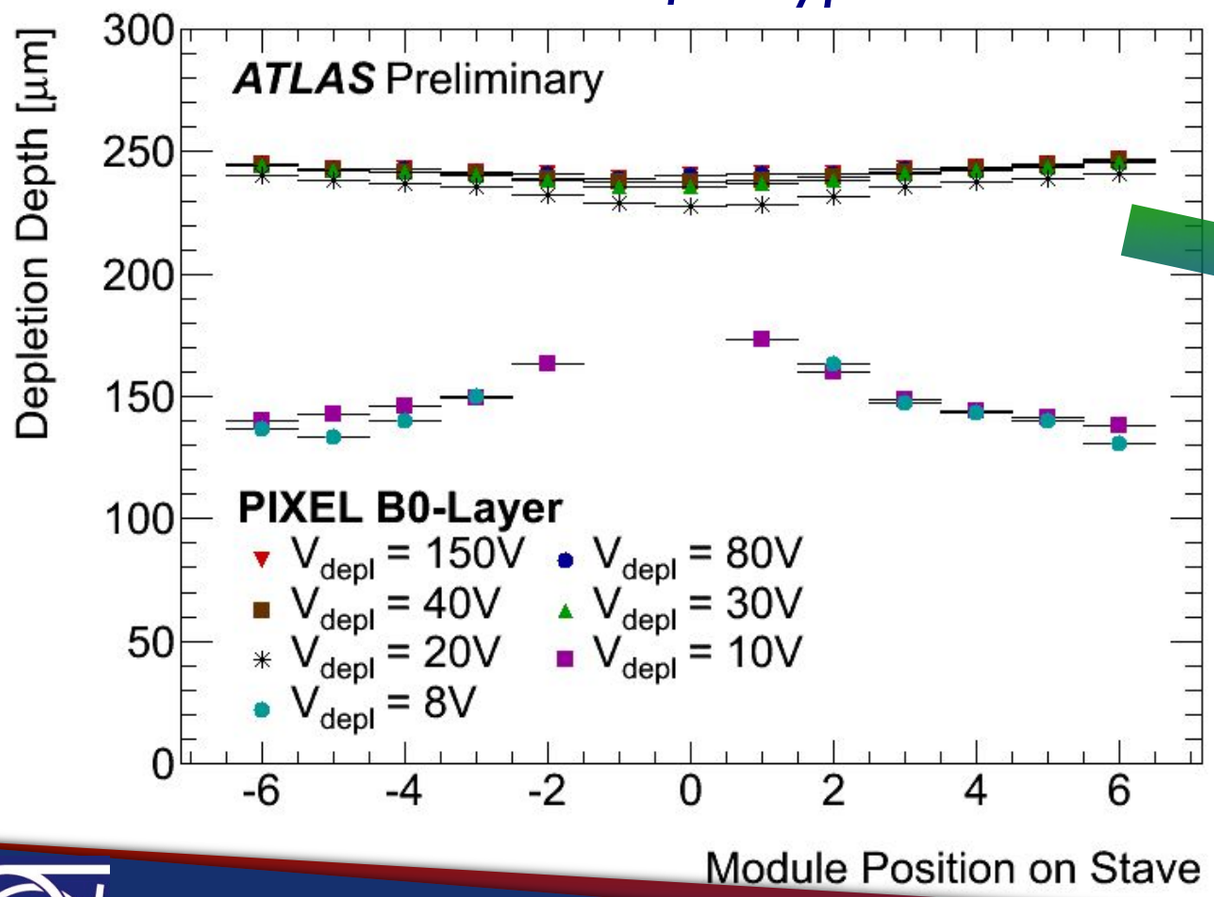
- *Fraction of layers covered at certain depletion depths*

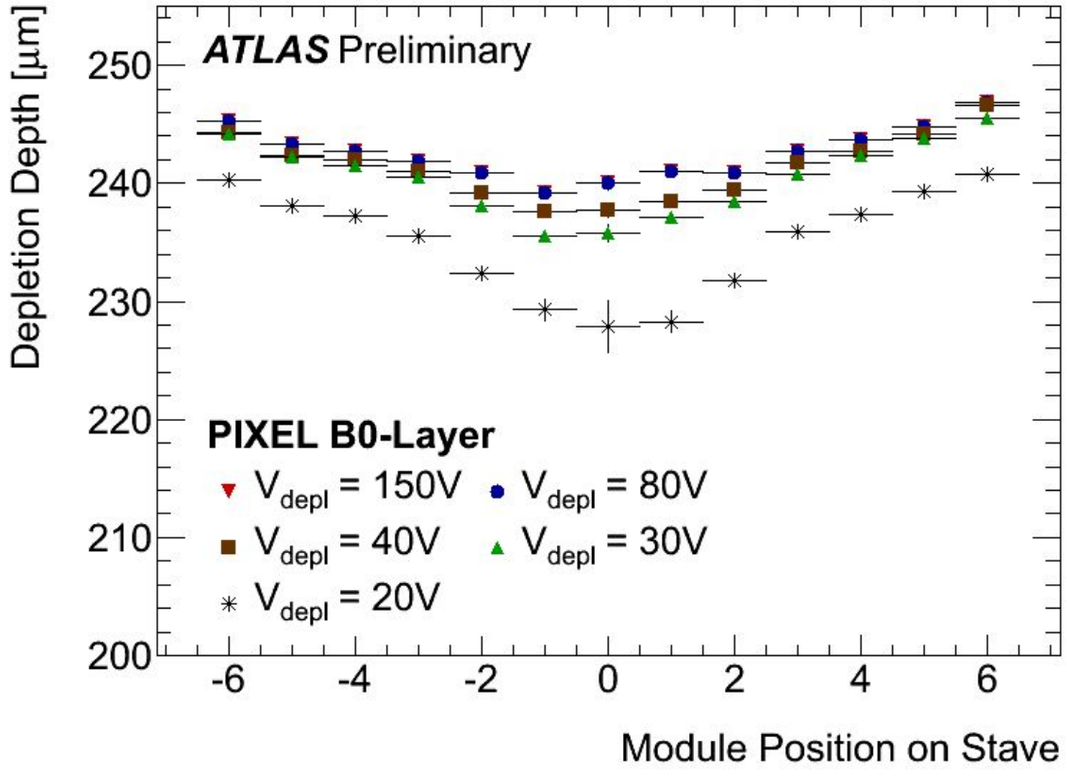
d_{depl}	b-Layer	Layer 1	Layer 2
250 μm	95%	78%	66%
200 μm	90%	69%	54%
150 μm	81%	54%	33%
100 μm	64%	23%	0%

ATLAS track based method

- *High Voltage Bias scanned on the innermost layer only during non-physics data taking.*
- *Reconstruct depletion depth as a function of module position along the beam line.*
- *Monte Carlo agrees well with input sensor thickness.*
- *Central modules with highest fluence are the most advanced after type inversion.*

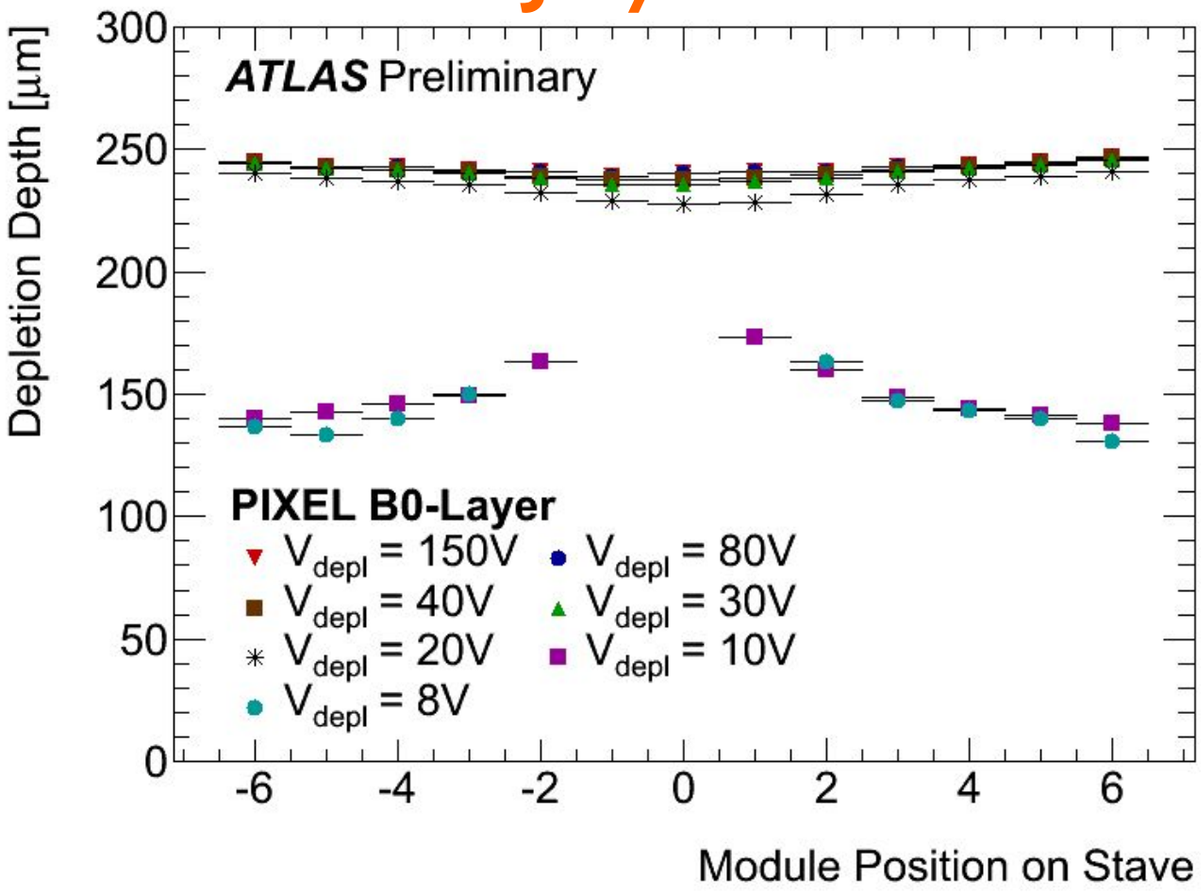




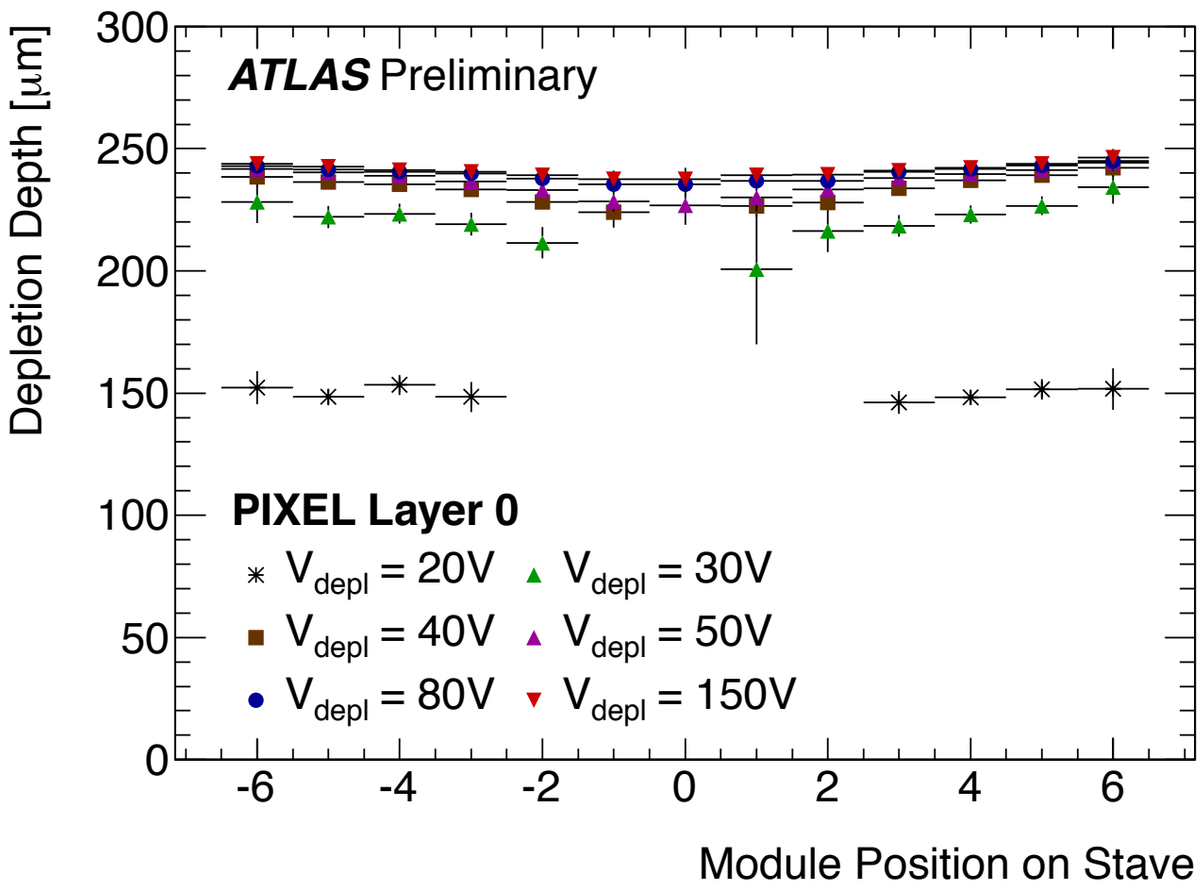


ATLAS track based method

2 July 2012



1 November 2012



- *A comparison of two voltage scans taken at and well after type inversion of layer 0.*
- *In the first scan the 10V line is not well depleted - the effective depletion voltage lies between 10 and around 20V (depending on EDV % definition)*
- *In the second scan, the 20V is now not fully depleted – the effective depletion voltage has **risen** to between 20V and around 30V.* ***Type-inversion has occurred.***

ATLAS track based method

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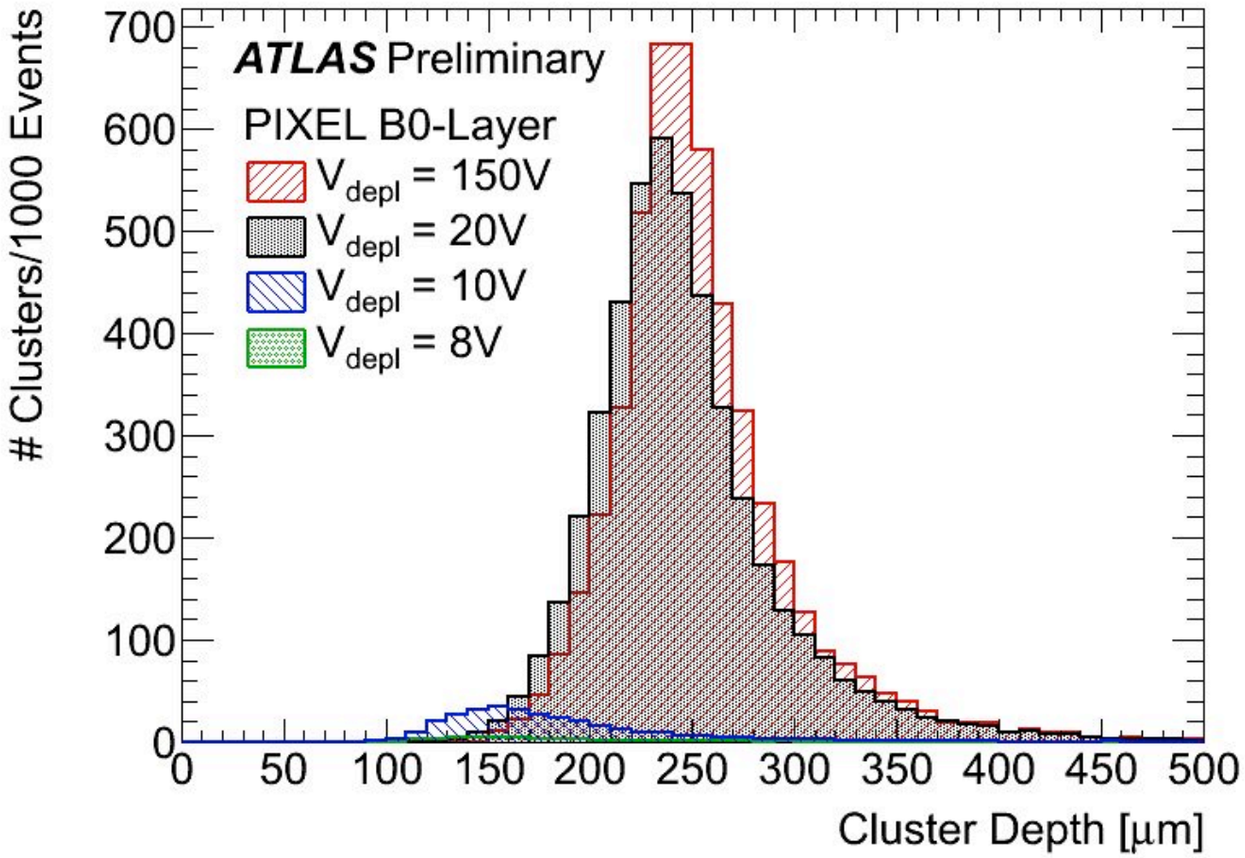

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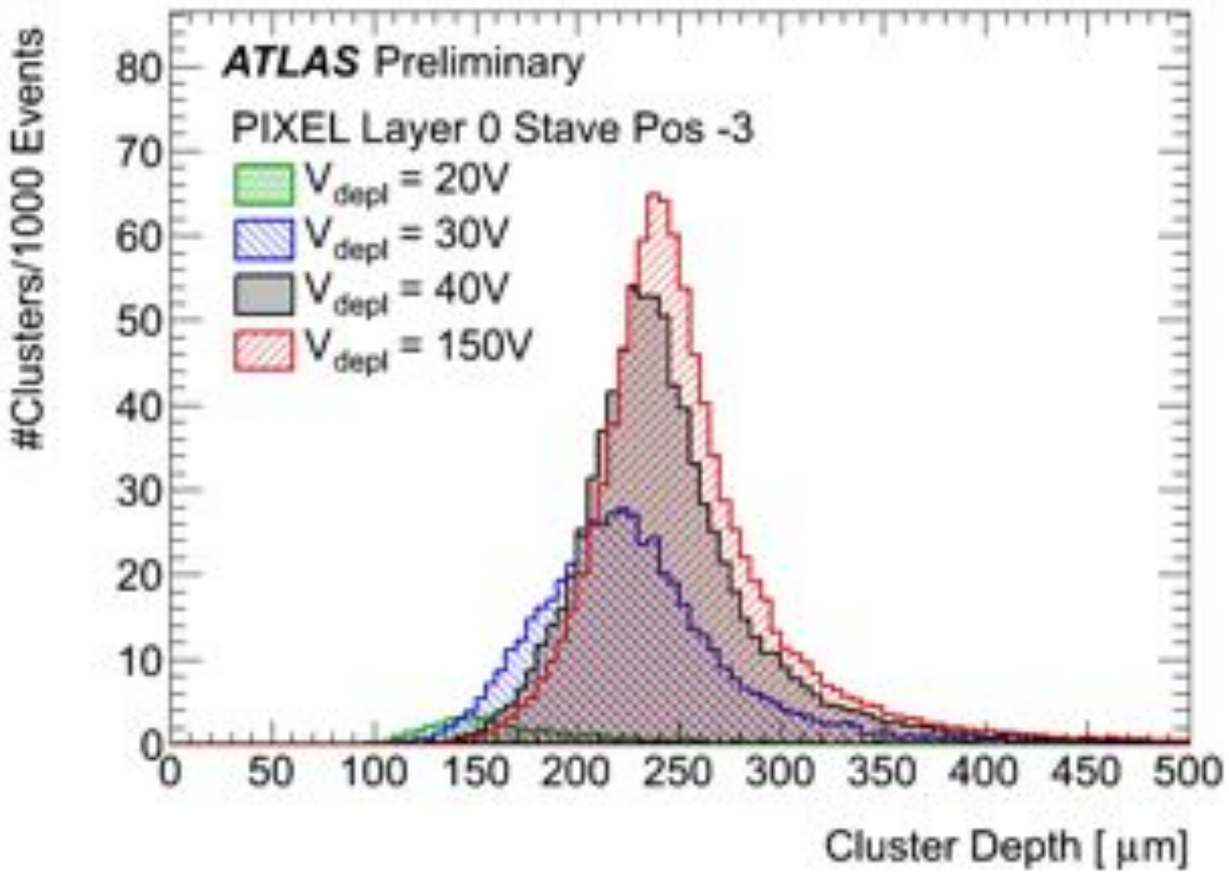

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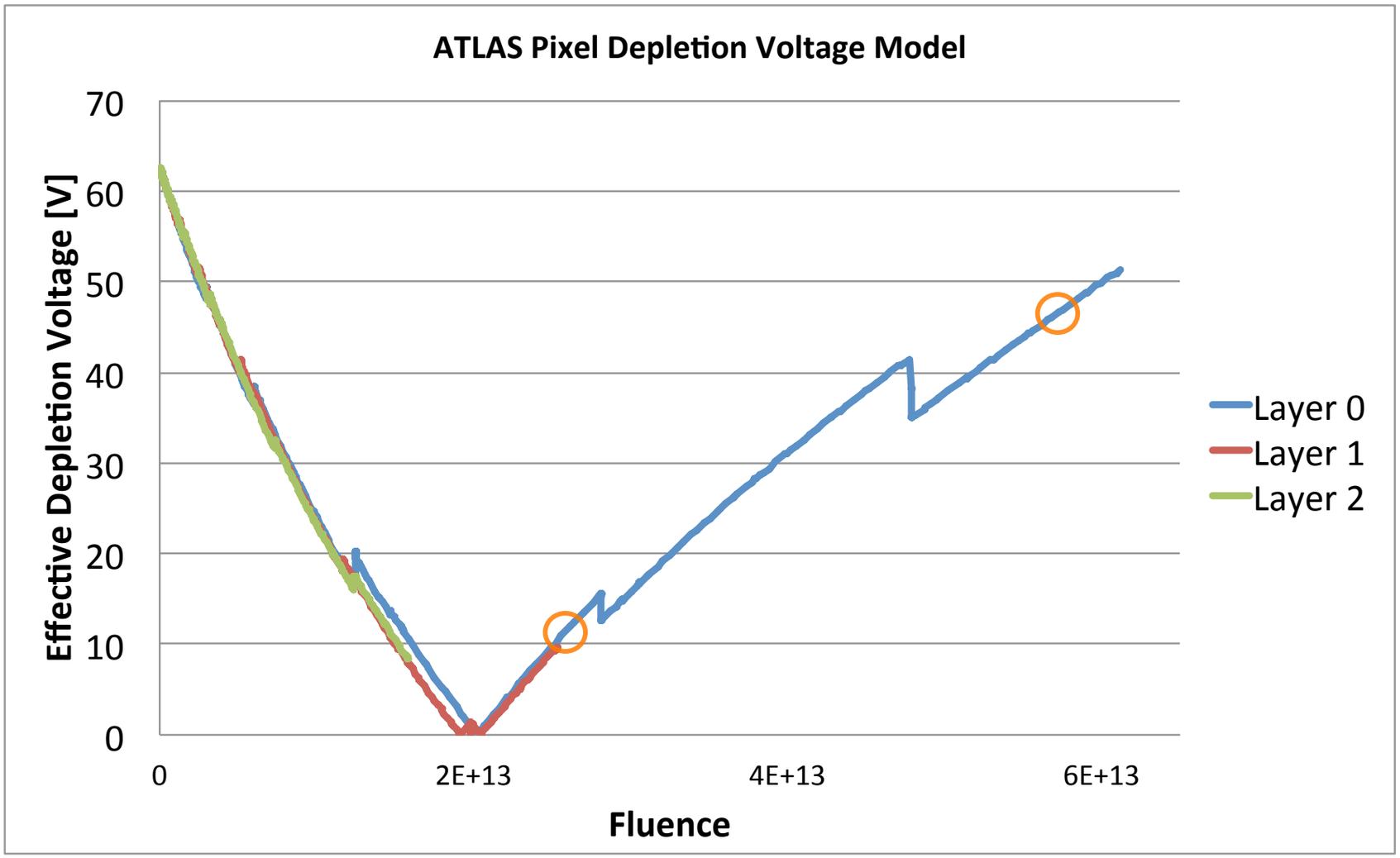
Comparison with model



- The Dortmund (Hamburg) model predicts a depletion voltage of ~47.5 V in the innermost layer on 1/11/2012, the date of the last track depth HV scan.
- The data indicate an effective depletion voltage of around 30V, suggesting the data are slightly behind the model prediction.
- The data lagging the model is also consistent with CMS.

Conclusions

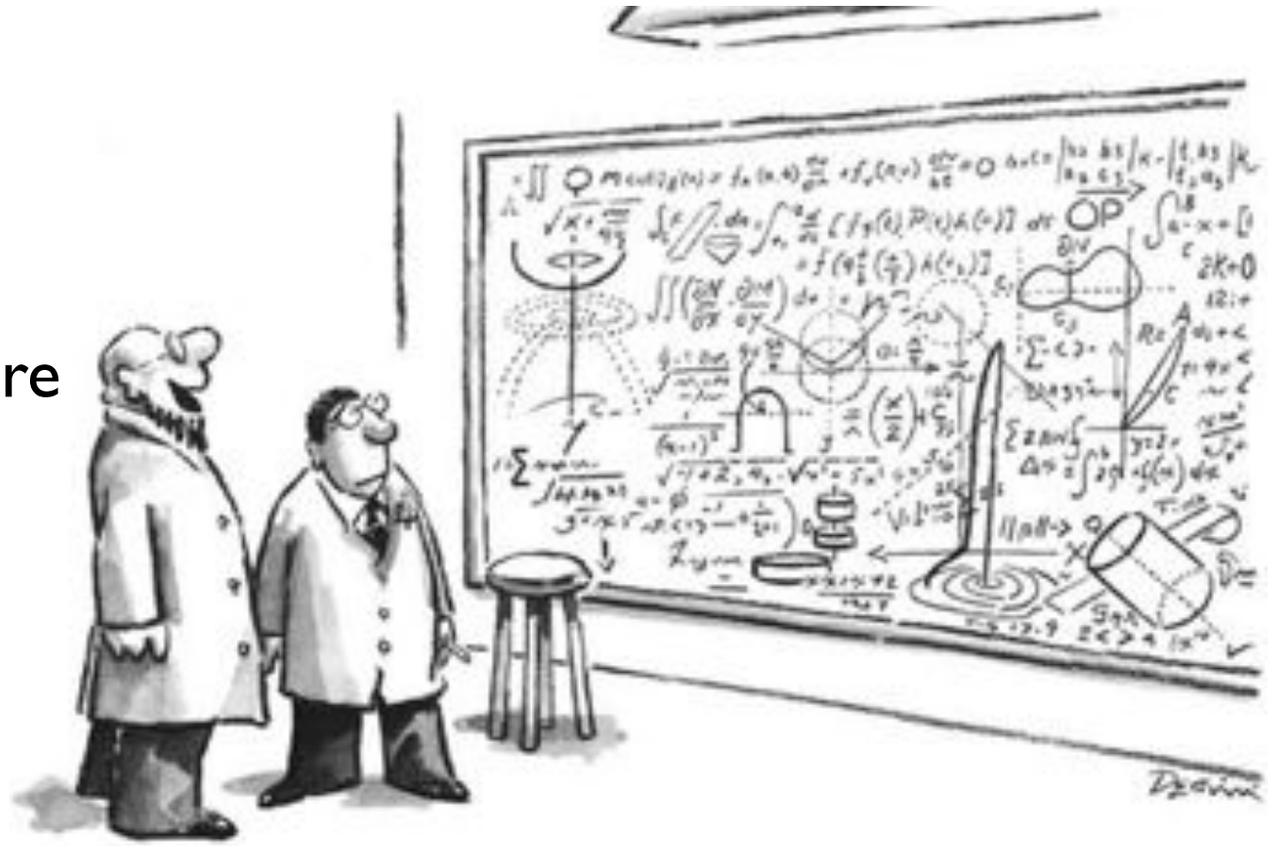
- Monitoring of radiation damage is well established by ATLAS.
- No major surprises so far: the leakage current evolves as expected with luminosity and annealing, generally agreeing remarkably well with the model.
- The ATLAS (and CMS) measurements are upto ~30% higher than the model at low radii: the fluence model can be improved by 8 TeV FLUKA simulations and finer time bins.
- Cross talk measurements indicate a reduction in depletion voltage up to type inversion for the innermost pixel layers.
- Track based depletion voltage methods developed for continued monitoring reveal a subsequent rise in the effective depletion voltage, indicating type-inversion has occurred in the innermost layer of the Pixel Detector.
- The rate of depletion voltage evolution is slightly slower than model predictions.

Making sense of it all…

Thanks to Paula C.

Inter-experiment radiation damage working group set up in 2011

- Pool ideas, tools resources
- Find a common language to compare results across experiments
- Develop a common approach
- Special sessions at the RD50 workshops



Meetings and mailing list are open for consultation - please join the party!

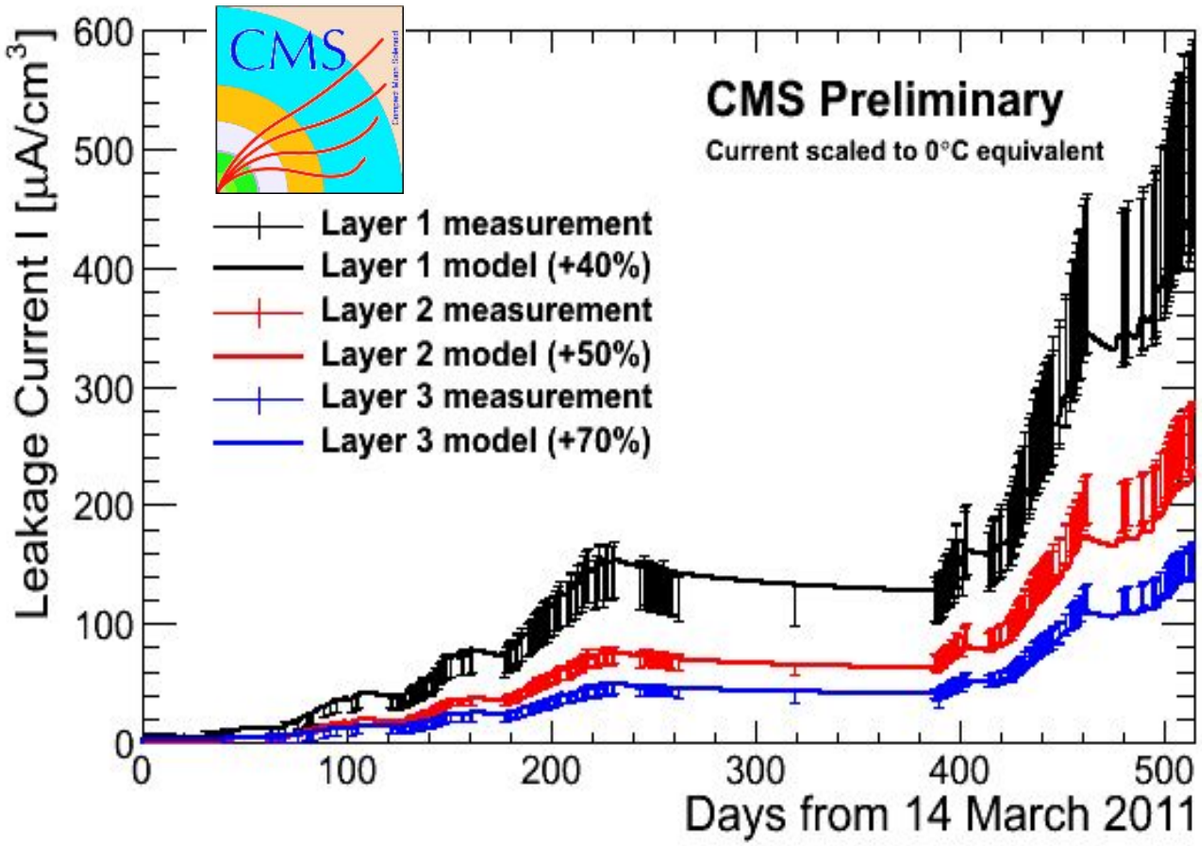
- Mailing list: rad-damage-iewg Sharepoint: https://cern.ch/rad-damage-iewg/

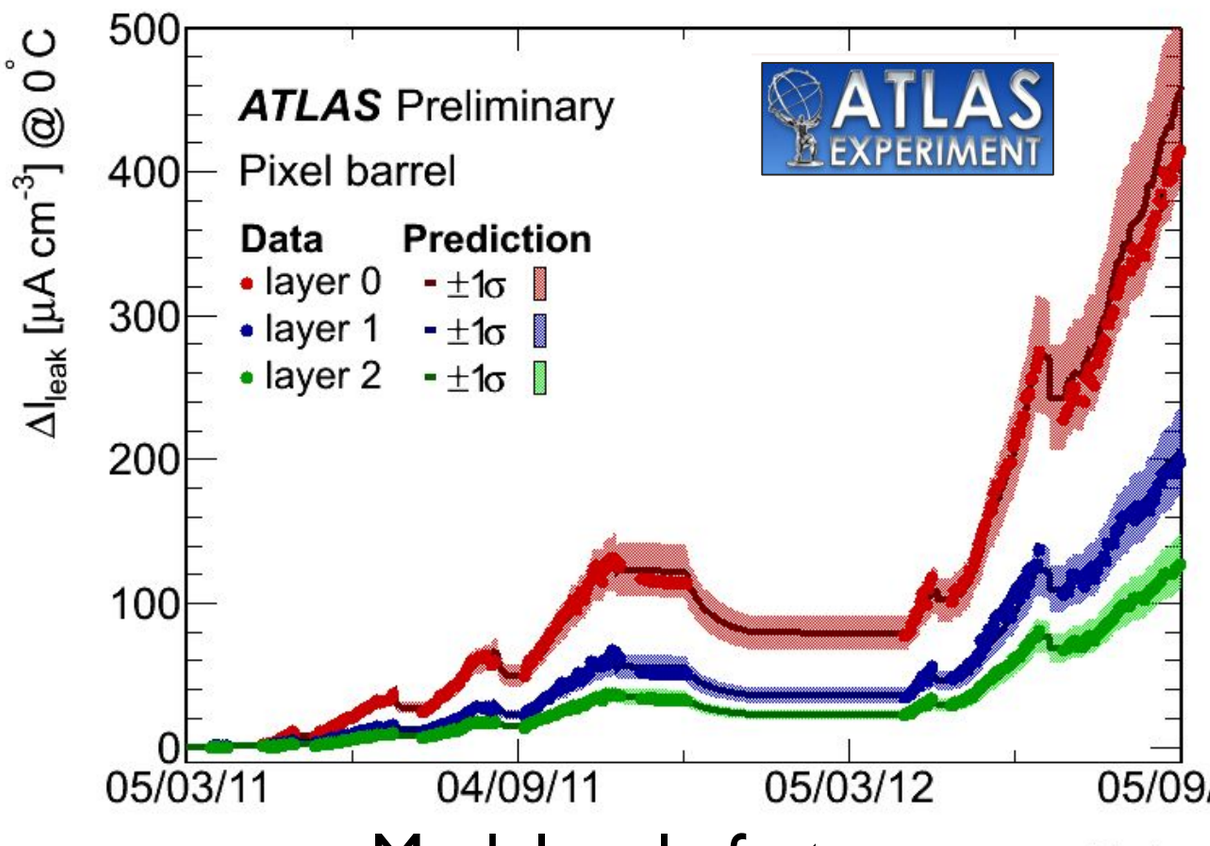
Latest meetings

- https://indico.cern.ch/conferenceDisplay.py?confId=178194
- https://indico.cern.ch/conferenceOtherViews.py?confId=148833
- https://indico.cern.ch/conferenceOtherViews.py?confId=175330

Leakage current at low radii

- Radiation damage is clearly visible from leakage currents which rise with the fluence profile and anneal with temperature.
- The model describes the data well qualitatively, with the expected shape:
  - Best agreement is for high radii detectors (ATLAS / CMS strips)
  - Some scaling up of the model is required for certain low radii detectors for the model(s) to describe the data – why?

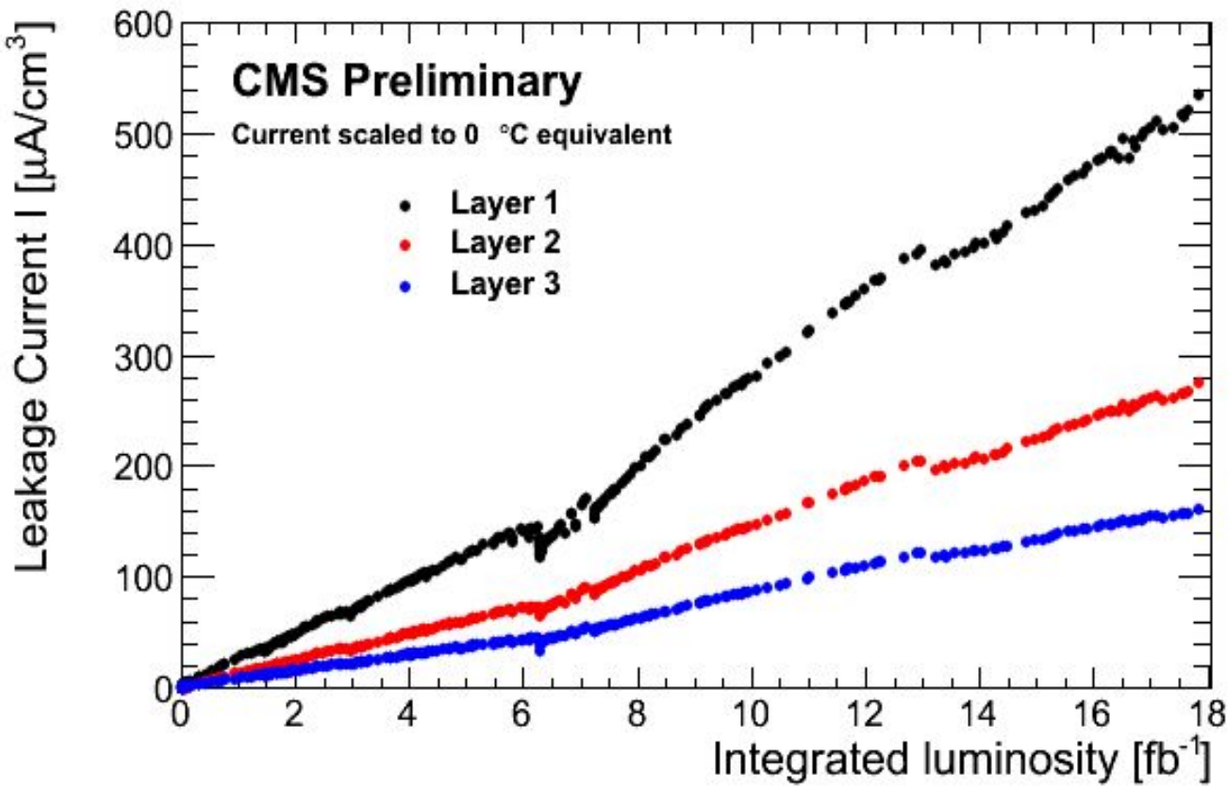


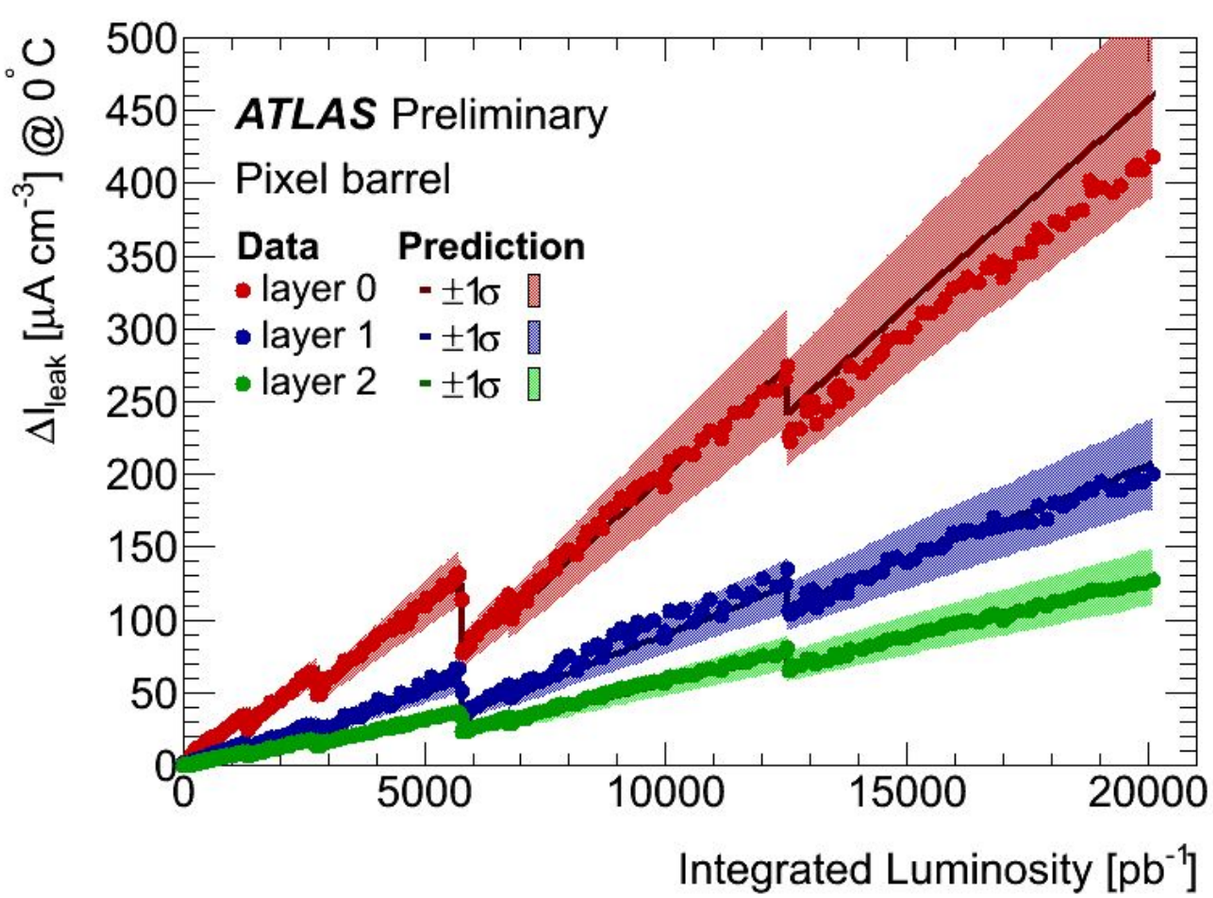


Model scale factors:
L0(1.15), L1(1.25), L2(1.25)

2011/2012 fluence at 7 TeV / 8 TeV

- Rate of increase of current in 2012 is higher than in 2011, due to higher fluence in changing from 7 TeV to 8 TeV collisions.
  - Leakage current model includes a very preliminary interpolation of ATLAS 7 TeV and 14 TeV FLUKA simulations to 8 TeV: this underestimates the data. Ideally new 8 TeV simulations or improved parameterisation is needed.
  - Can alternatively measure the gradient between cooling stops, to determine the relative 7 TeV and 8 TeV fluence factors:





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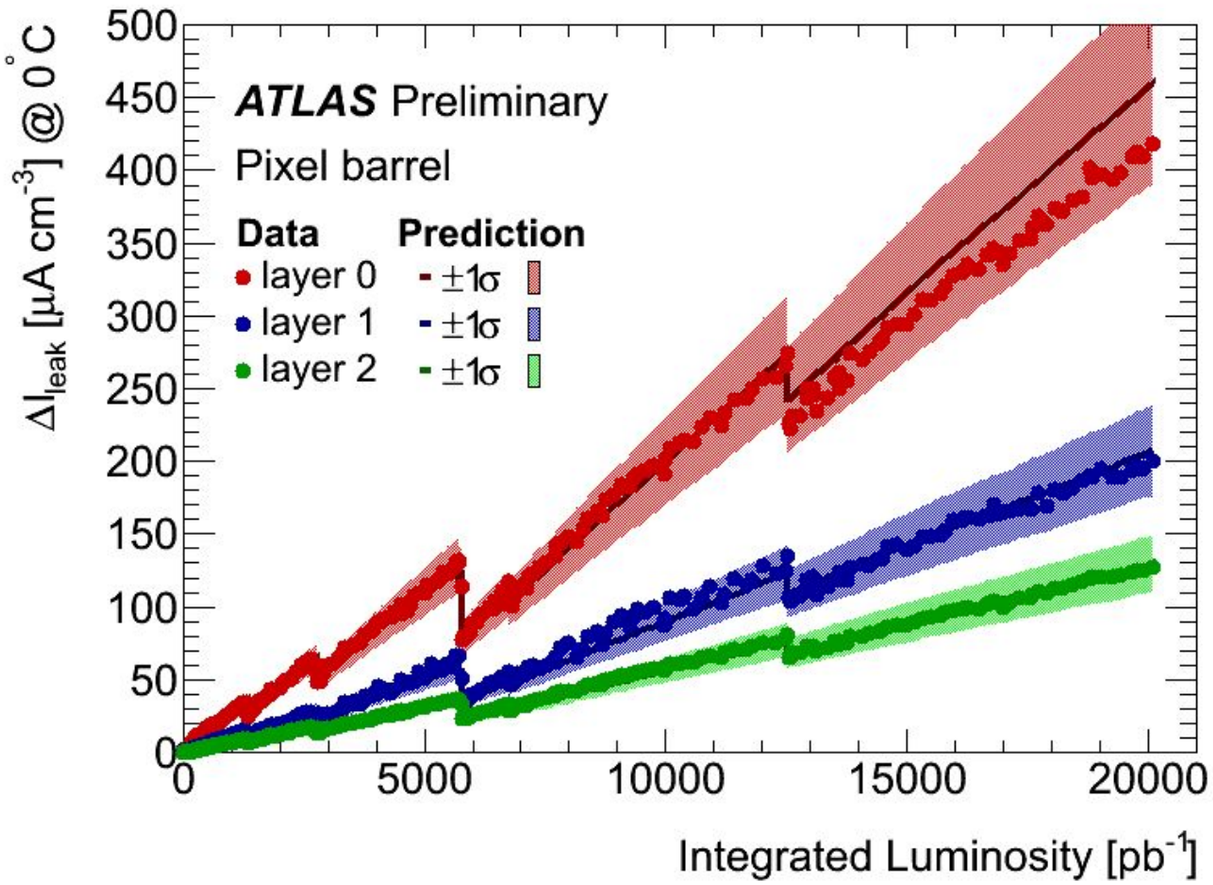
  - Can alternatively measure the gradient between cooling stops, to determine the relative 7 TeV and 8 TeV fluence factors:

- The ATLAS Pixel Detector operates at -13 °C, so annealing during each operation period is frozen / negligible.
- Annealing steps are apparent due to warm up to 18.5 °C during maintenance periods.



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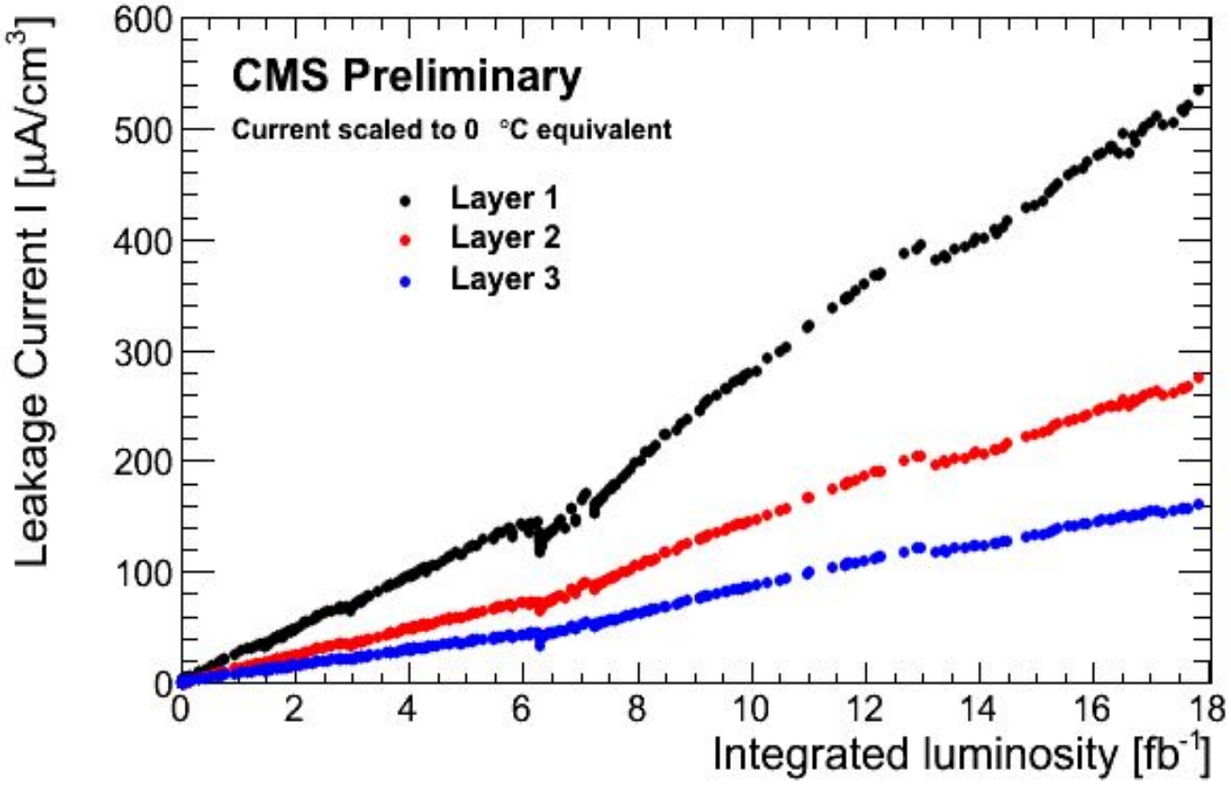
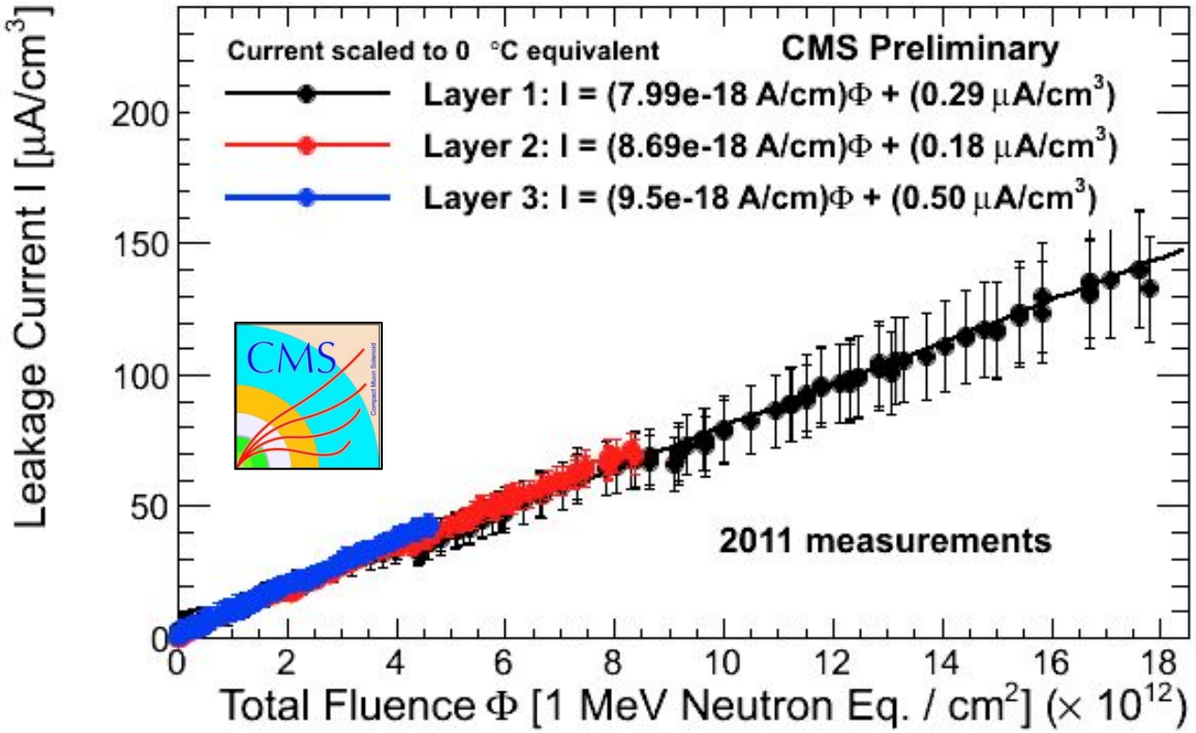
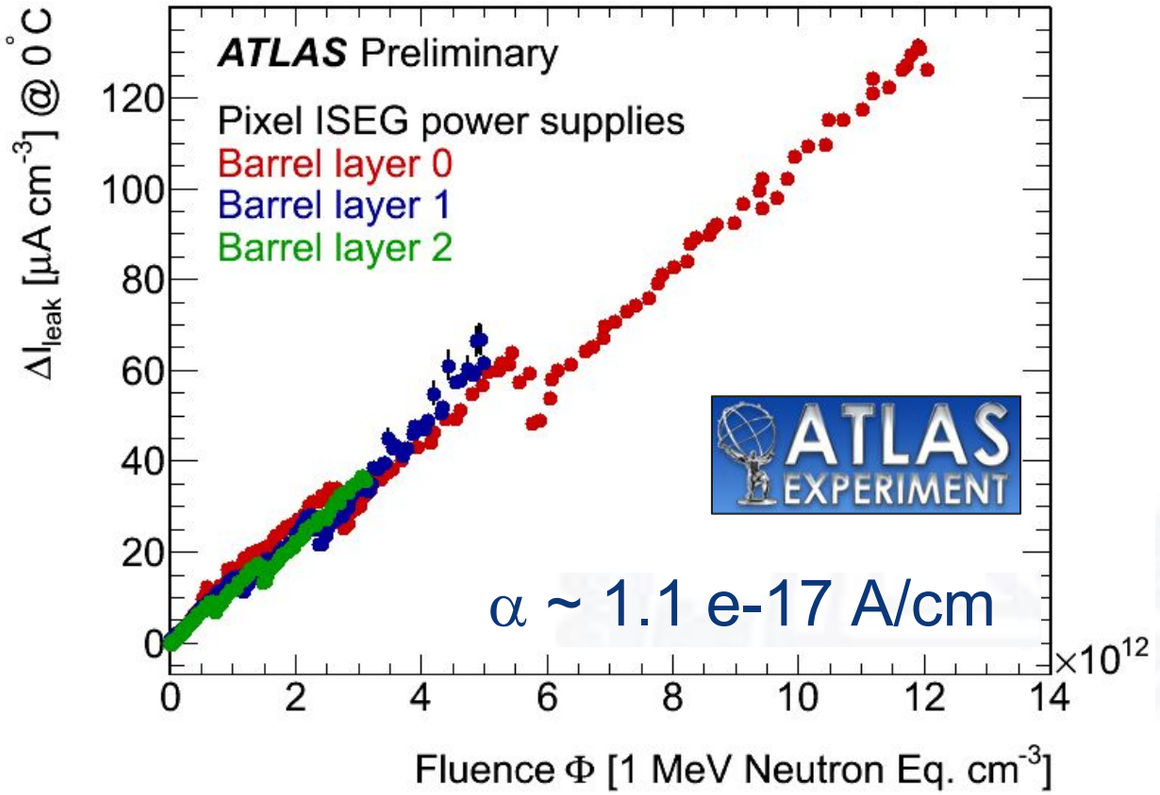
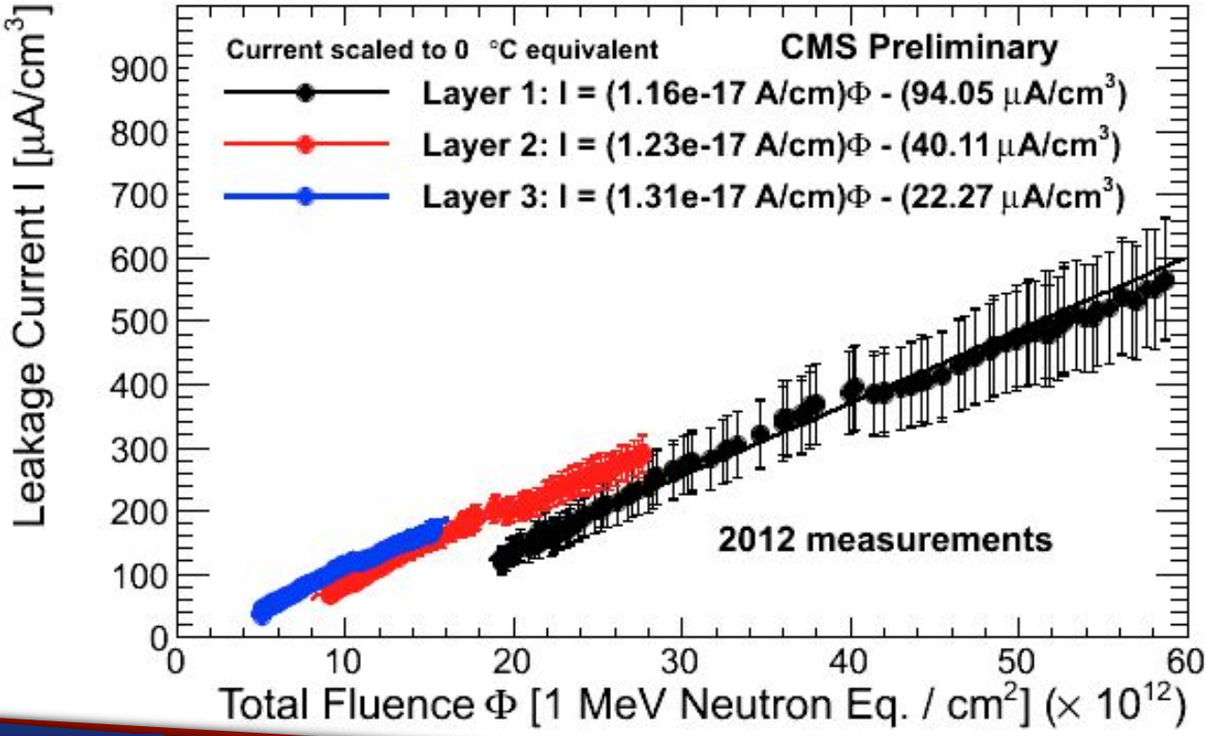


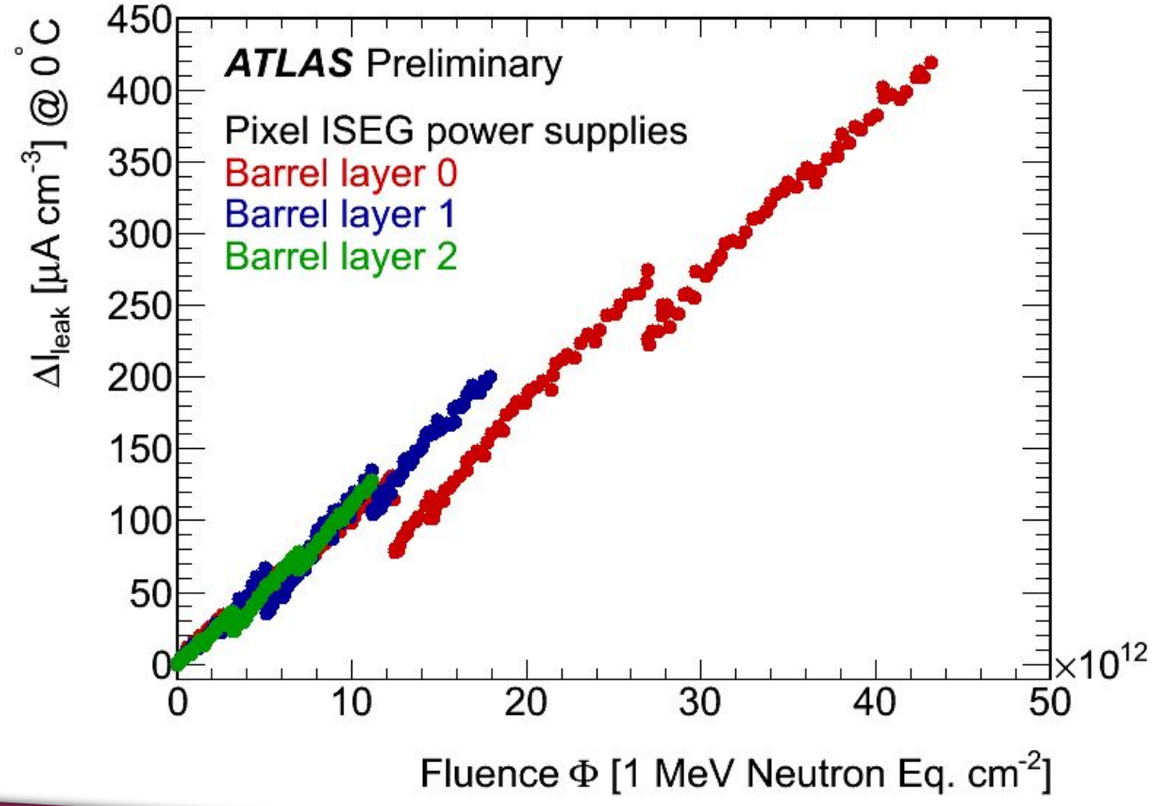
- CMS Pixel is relatively warm, resulting in parallel annealing during operation.
- The operating temperature changed:
  - 2011: On [Off] = 17 [9] °C
  - 11/12 Winter Shutdown: 11 °C
  - 2012: On [Off] = 10 [3-4] °C
- The temperature effect would need to be decoupled from the change in 7/8 TeV pp fluence.

Leakage current vs fluence



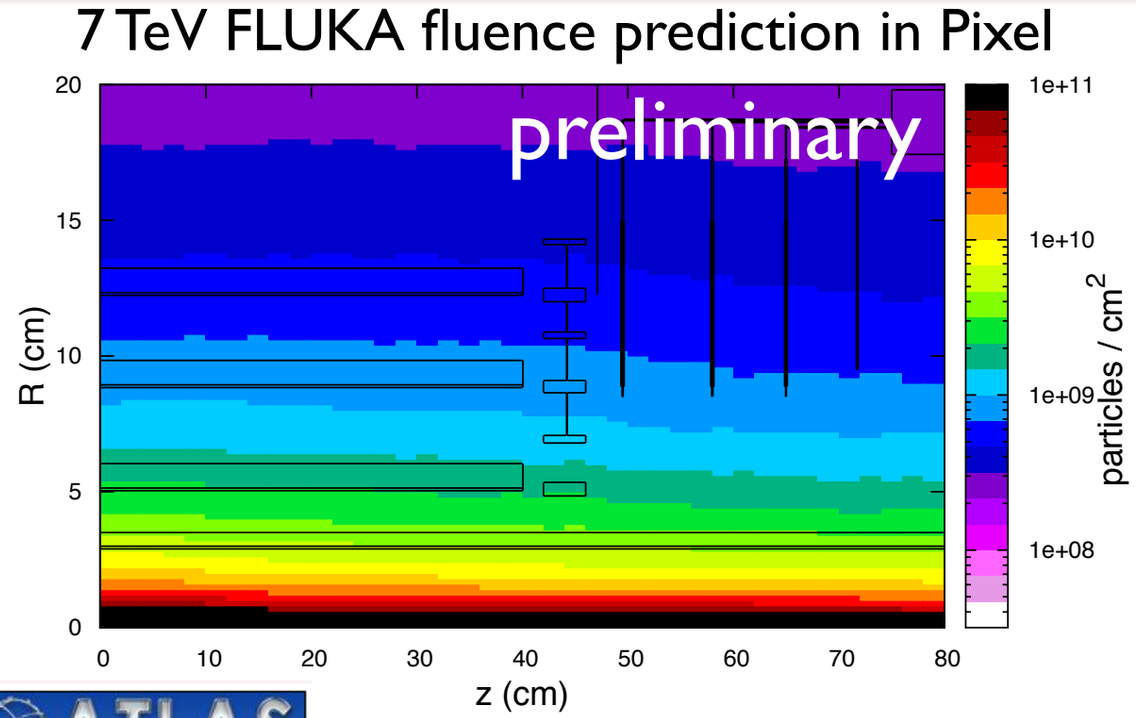


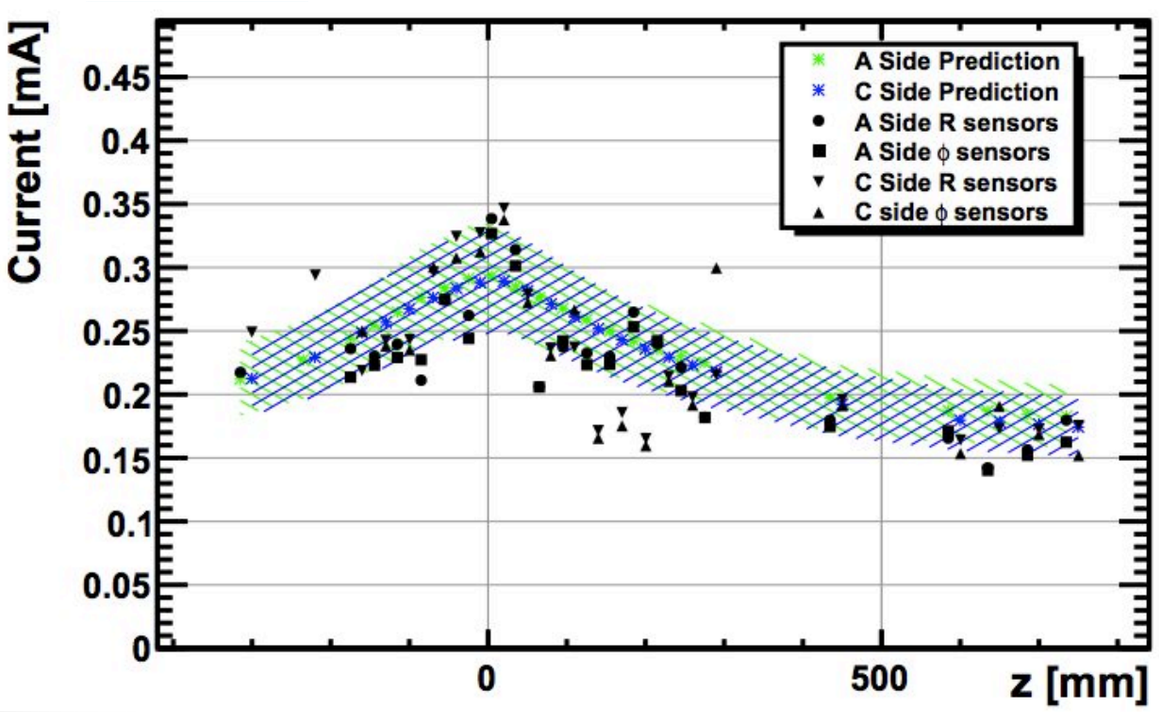


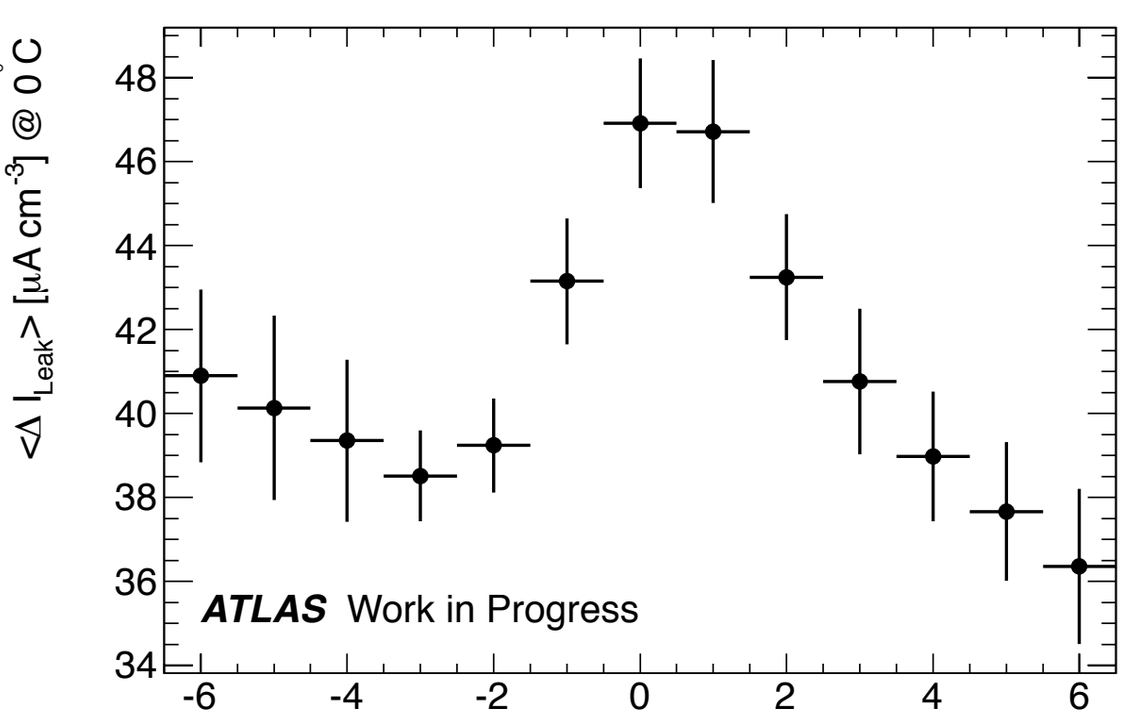


Leakage current Z distributions

- Slightly larger fluences in central regions, at a given radius, reflected in leakage current distributions.
- Next steps?
  - Normalized comparisons at RZ positions between experiments.
  - Check of fluence prediction models.



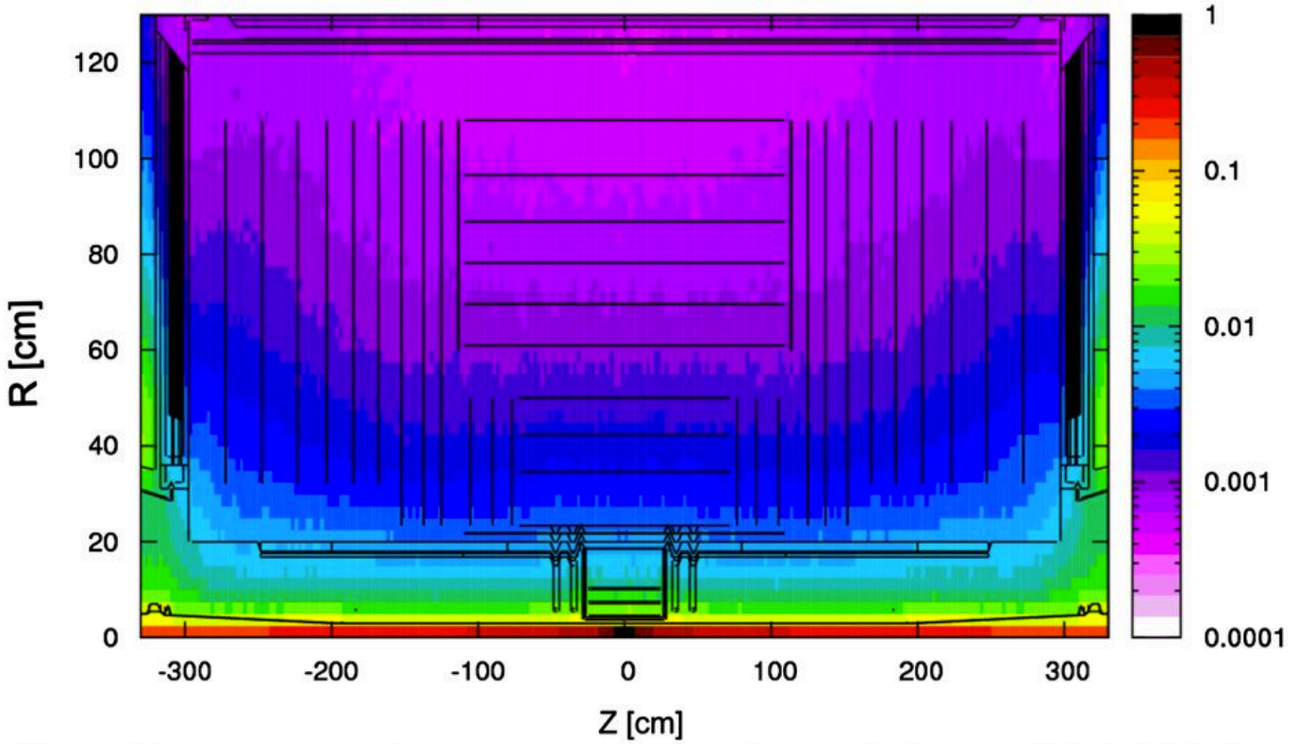




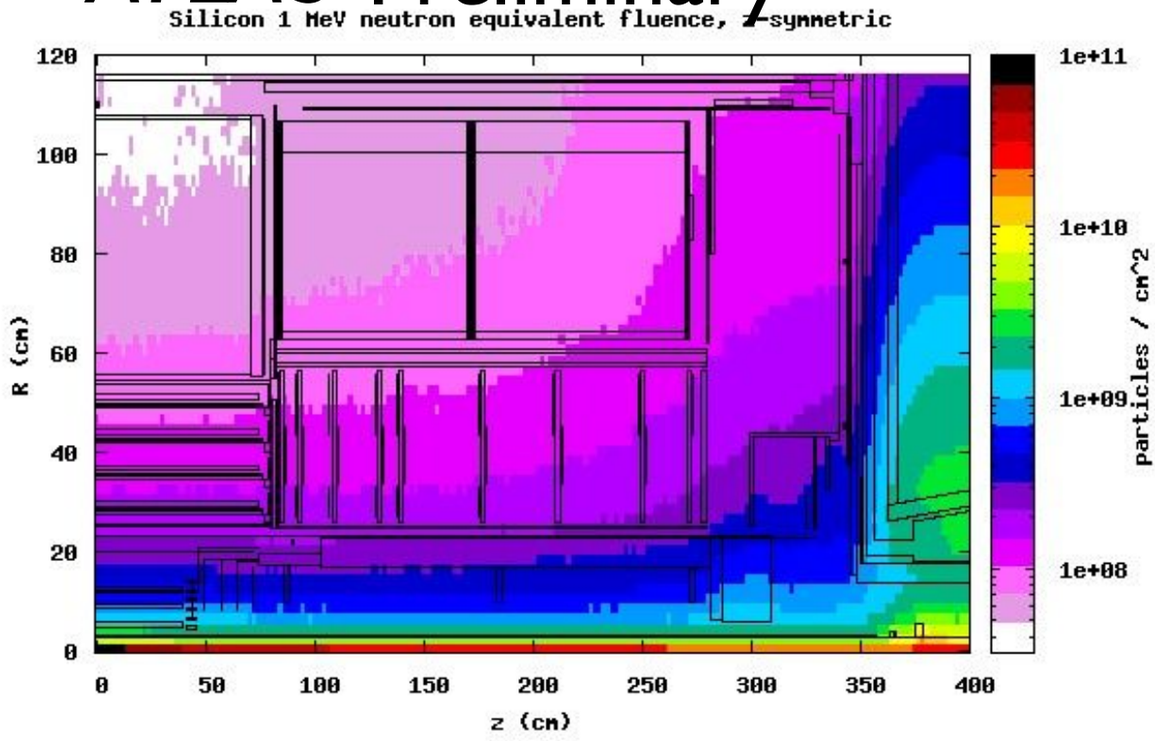
Also seen in Vdep

FLUKA fluence comparison

CMS



ATLAS Preliminary



Earlier work toward checking FLUKA models between experiments:

- Radial dependence at different Z slices compared for 7 TeV and 14 TeV FLUKA simulations in CMS and ATLAS.
- Initial studies show reasonable agreement at low radii, despite effects of material and different magnetic fields (low p_T loopers).
- Next step: 8 TeV simulation needed for 2012 data.
- A radial parameterisation is envisaged: See Ian Dawson's talk at Vertex2012