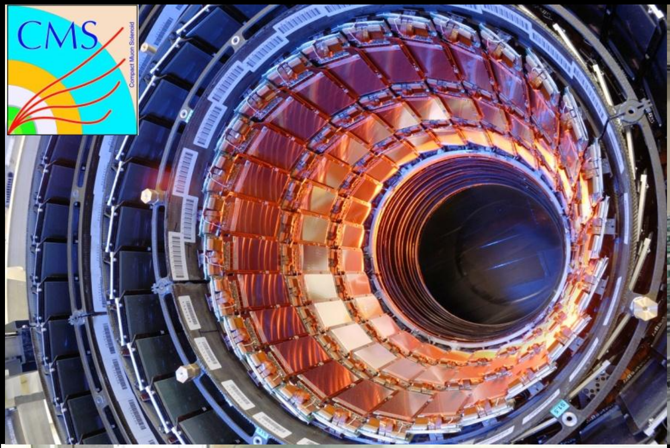
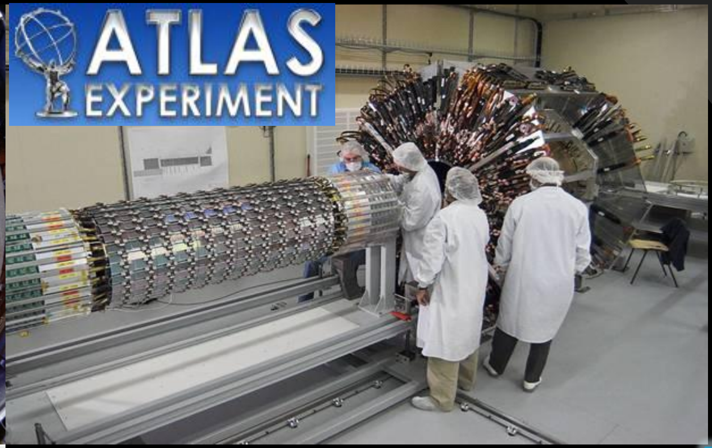


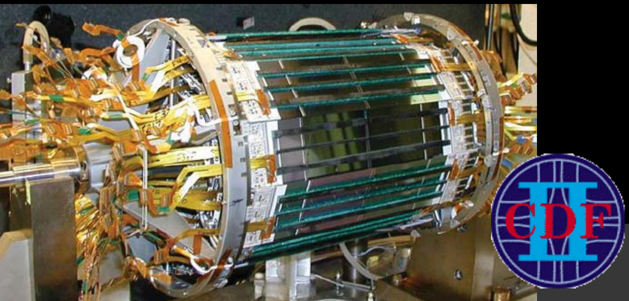


Karlsruhe Institute of Technology

Frank.Hartmann@CERN.CH

03.02.2012

EVOLUTION OF SILICON PARAMETERS DUE TO IRRADIATION AT THE LHC



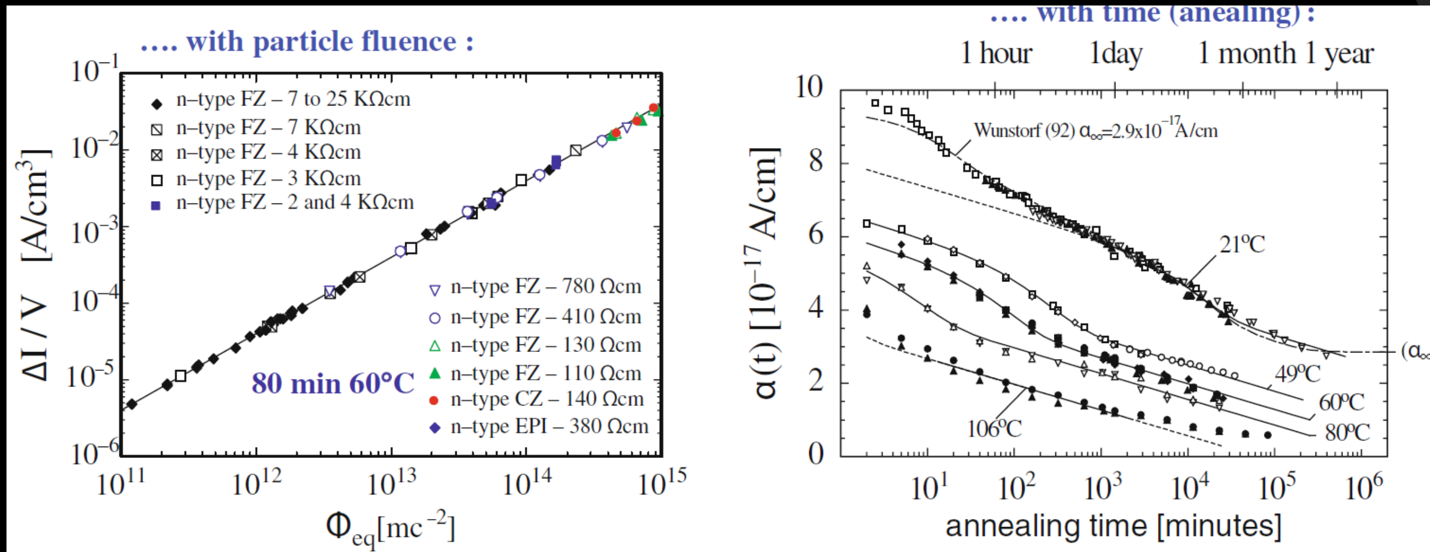
Content & Disclaimer

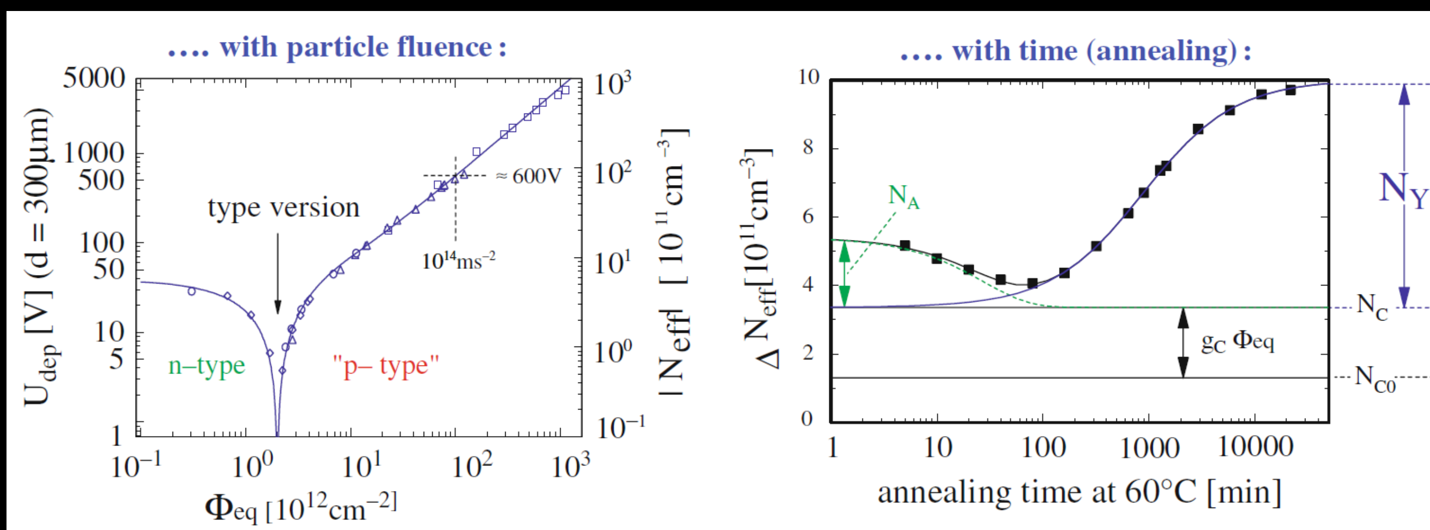
- Different Strategies
- FLUKA
- Leakage currents
- Depletion Voltage

Not always the latest plots – @LHC everything needs approval

- Each experiment is following the same goal but with slightly different strategies
  - An inter-experiment working group on radiation damage started
    - Comparison of tools
    - Standard plots/presentation (e.g. current scaling to volume and 0° C)
  - With almost $\mathcal{L}_{int}$=5fb^{-1} detectors see changes in leakage currents and innermost detectors (VELO & pixel) see changes in depletion voltage

What Happens in a Nutshell





From M. Moll and R. Wunstorf and others

Test Strategies

- **Pixel**
  - Currents:
    - Some high res. current measurement boards (10nA)
    - Single pixel res. 0.125 nA
  - Vdep:
    - Single pixel cross talk vs. voltage;
      - TS, now more often
      - non-beam
    - Monitor depletion depth – threshold -no scan
- **SCT**
  - In-situ radmon sensors
    - Dose & Fluence
  - Noise vs. voltage
  - Efficiency and depletion depth vs. voltage;
    - non-beam

ATLAS

- **Pixel**
  - Currents:
    - IV scan
    - I-Temperature scan
  - Vdep:
    - Small # of channels (0.5%) Signal vs. bias
      - Several times per year
      - Stable Beam
- **SST**:
  - Currents:
    - Current per sensor via DCU
  - Vdep:
    - Noise vs. bias scans (IV)
      - 4/year
      - non-beam
    - Full signal vs. bias scan (IV)
      - 2/year
      - Stable beam
    - Small (0.25%) Signal vs. bias scan
      - monthly
      - Stable Beam

CMS

- **VELO**
  - Currents:
    - IV scan
      - Weekly
    - I-Temperature scan during technical stops
  - Vdep:
    - Noise vs. bias
      - Monthly
      - Non-beam
    - Signal vs. bias – layer scanning
      - Few times per year
      - Stable beam

LHCB VELO

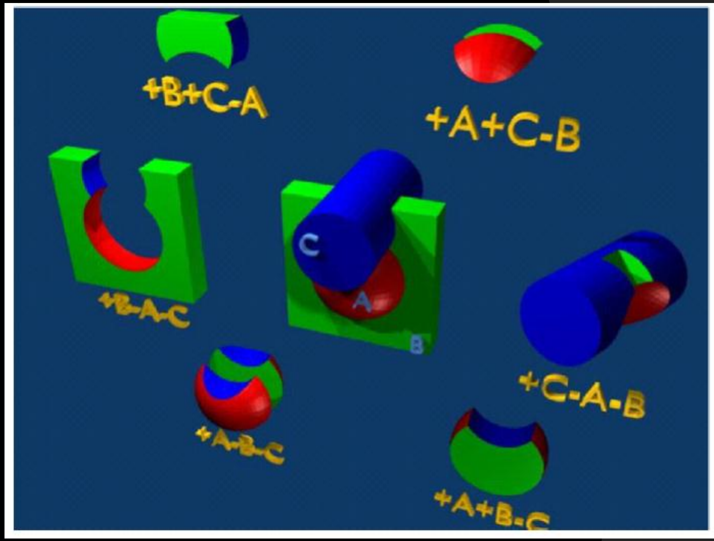
More or less continuous archiving of currents and temperature

Experiment measure luminosity but we need local fluences to allow comparison of measurements with prediction

FLUKA

FLUKA

- FLUKA: Fully integrated particle physics MonteCarlo simulation package. [1]
- Events generated by DPMJET-3.
- No tracking of particles.
- Many different predefined scorings
  - Flux of different particles types
  - Energy spectra
  - Dose
  - Radiation damage
  - Activation
  - Etc.

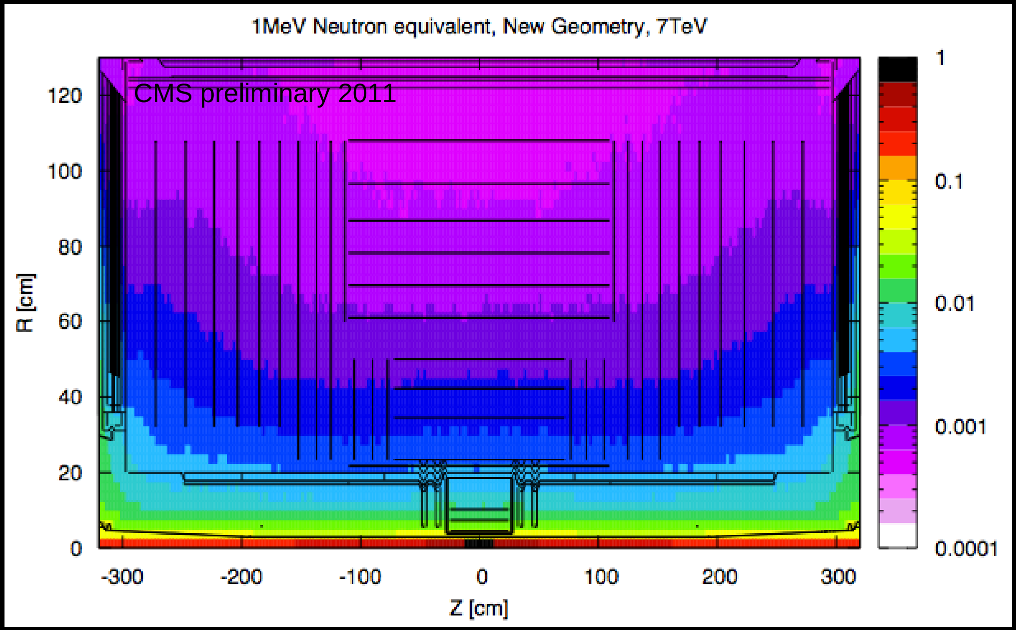


- Geometry described with mathematical combination of geometric elements.
  - Import of mechanical drawings not possible

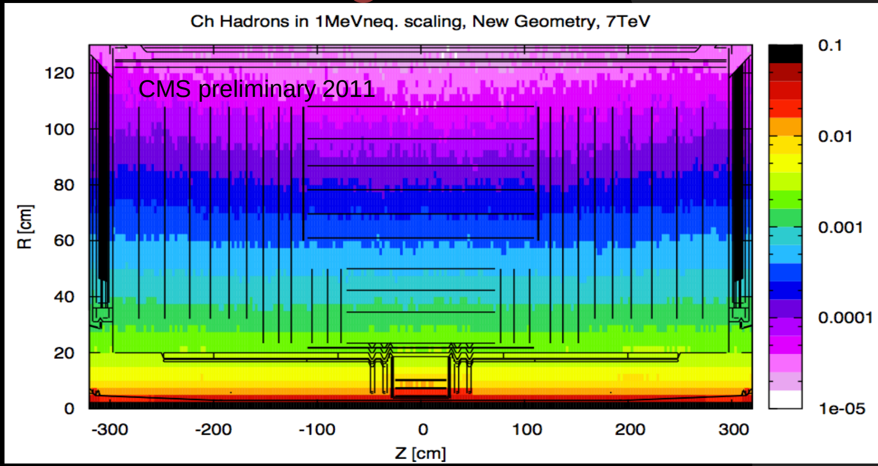
[1] A. Fasso, A. Ferrari, J. Ranft, P.R. Sala: FLUKA: a multiparticle transport code, CERN-2005-10

Flux in Tracker Region

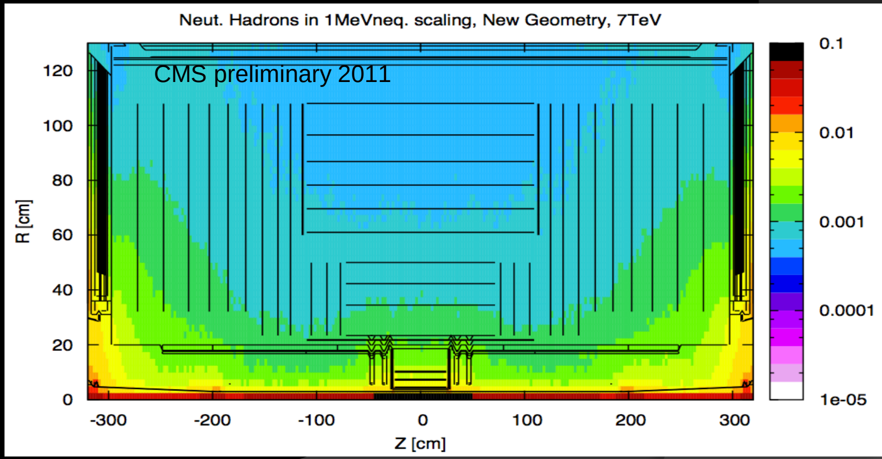
Total 1MeV neutron equivalent



charged hadrons



neutral hadrons



- For analysis of radiation damage the 1MeV neutron equivalent (n-eq.) scaling is most important.
- The left plot shows the total 1MeV n-eq. flux, the right plots show the contributions from charged hadrons and neutrons.

Comparisons and Uncertainties

- Leakage current:

Temperature

Luminosity | FLUKA → Fluence | Effective α(t,T) | Leakage current (T)

measurement

Temperature parameterization

Material description
GRID

- Depletion voltage:

In-situ measurement

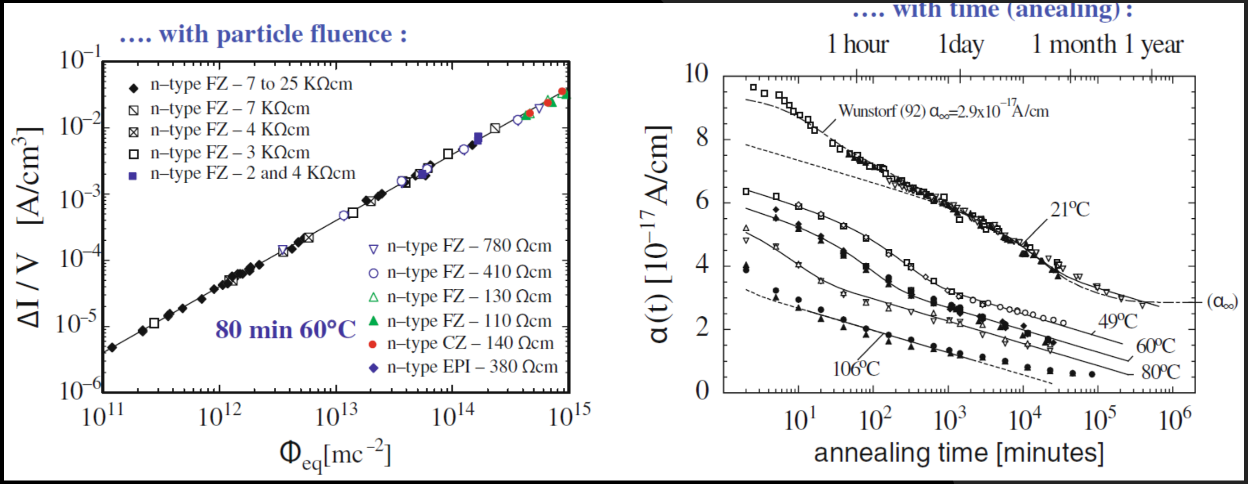
Luminosity | FLUKA → Fluence | *Dedicated* HH model parameter | Depletion Voltage

measurement

parameters

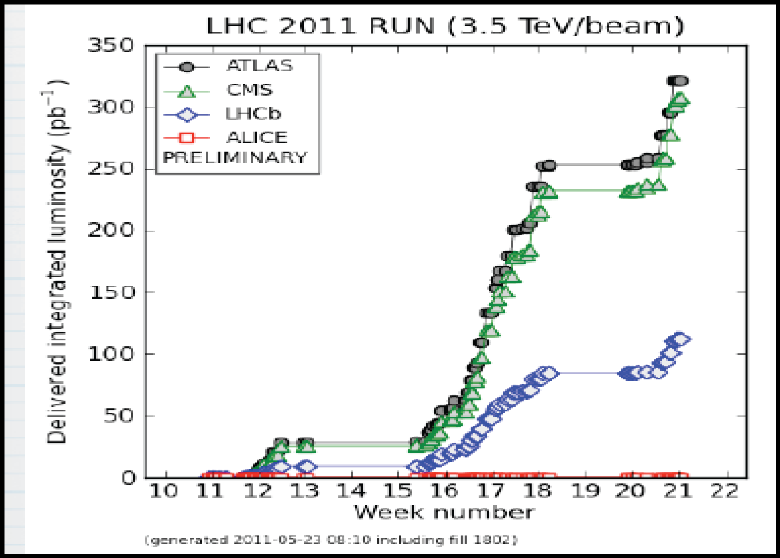
Not to forget Annealing

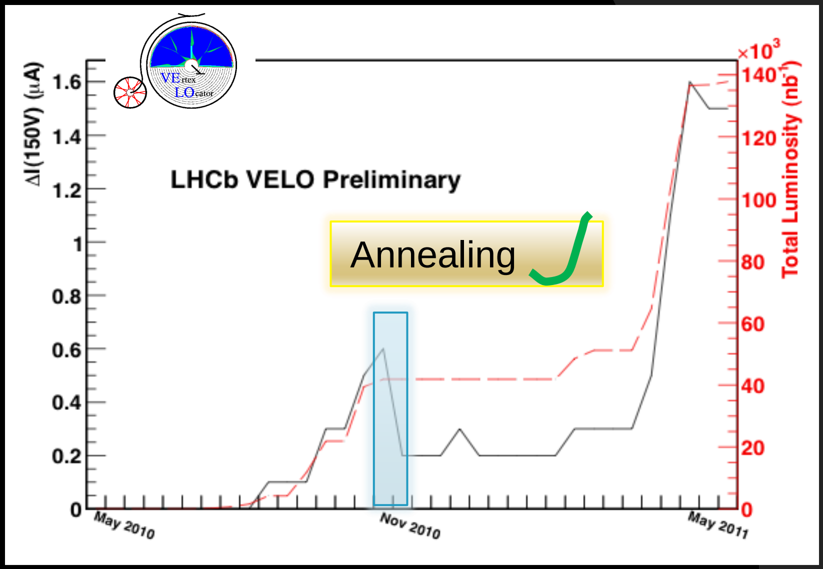
Leakage Currents

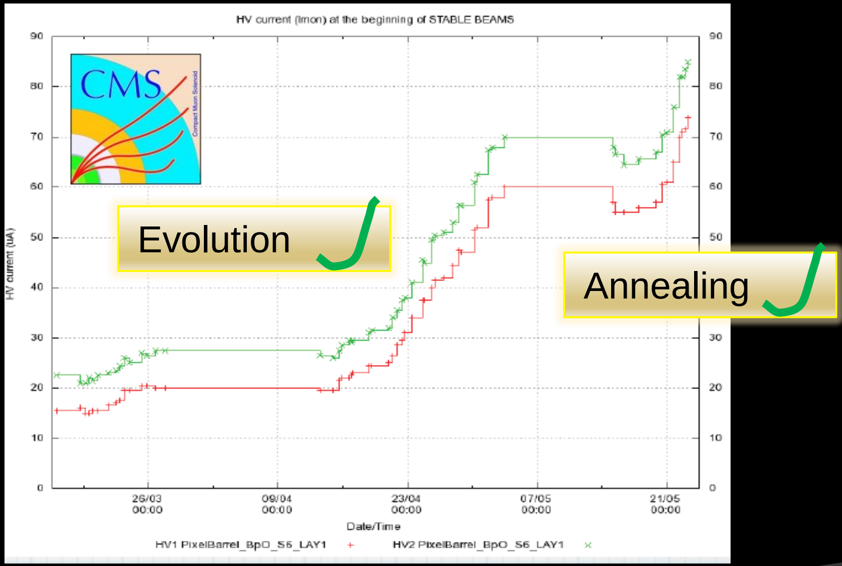


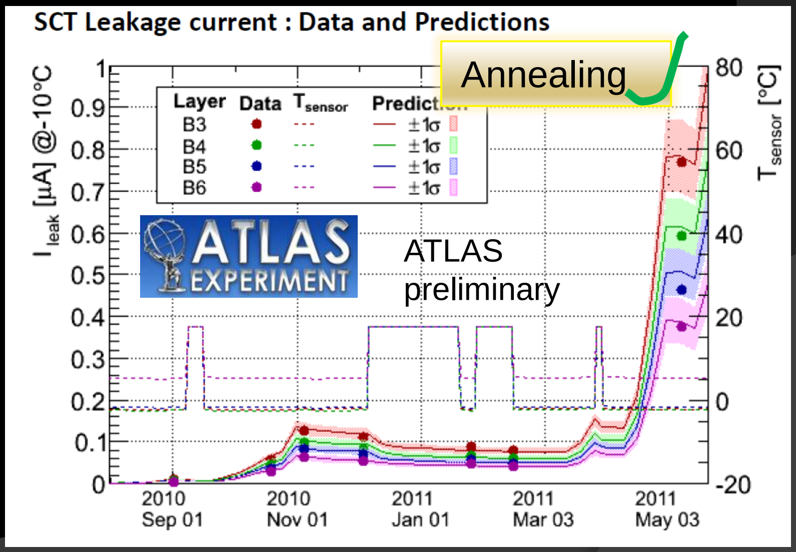
Does it increases?
Alpha?
Annealing?
Comparison with simulation?
Surface Currents?

Evolution of Sensor Currents



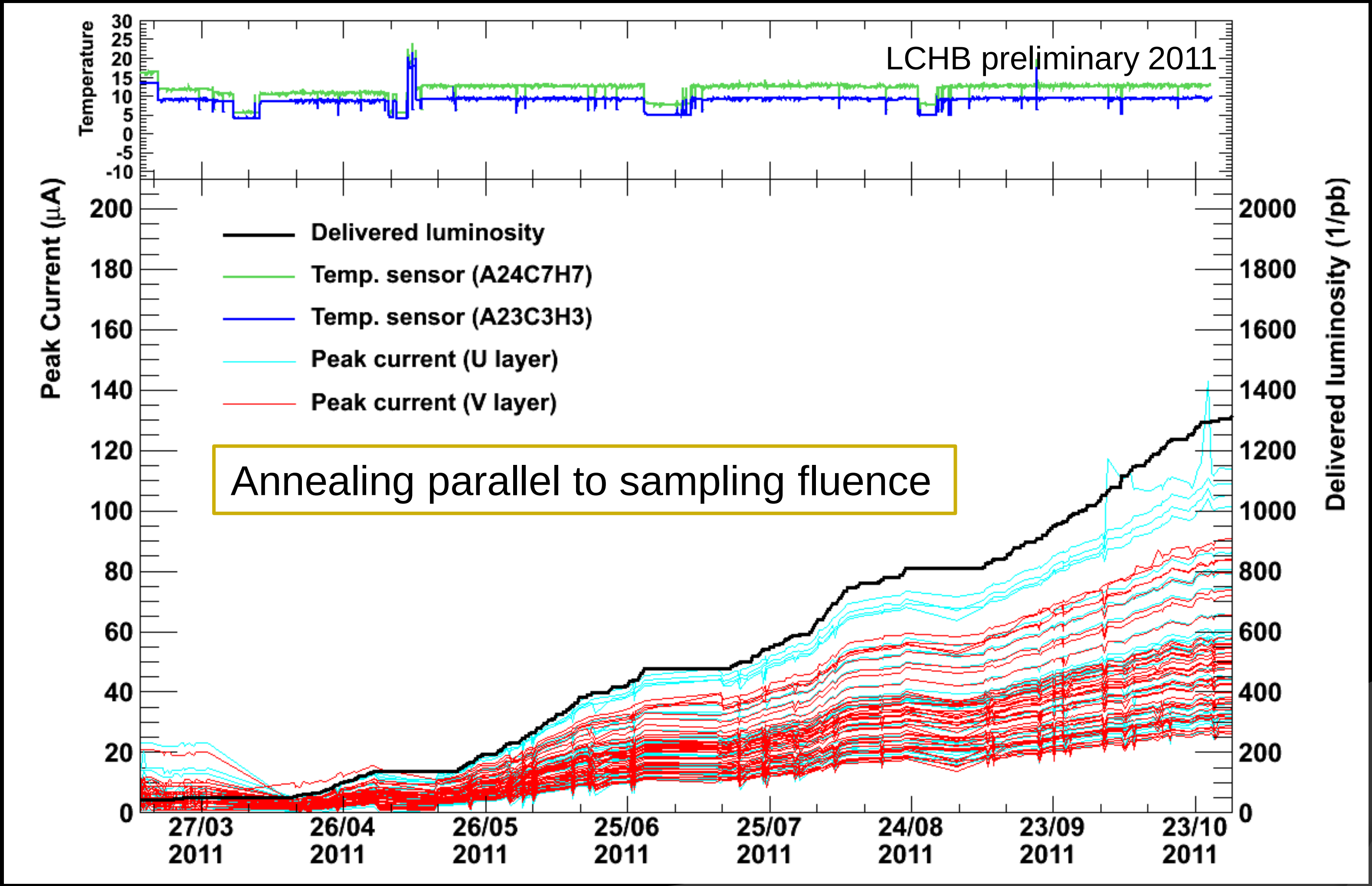




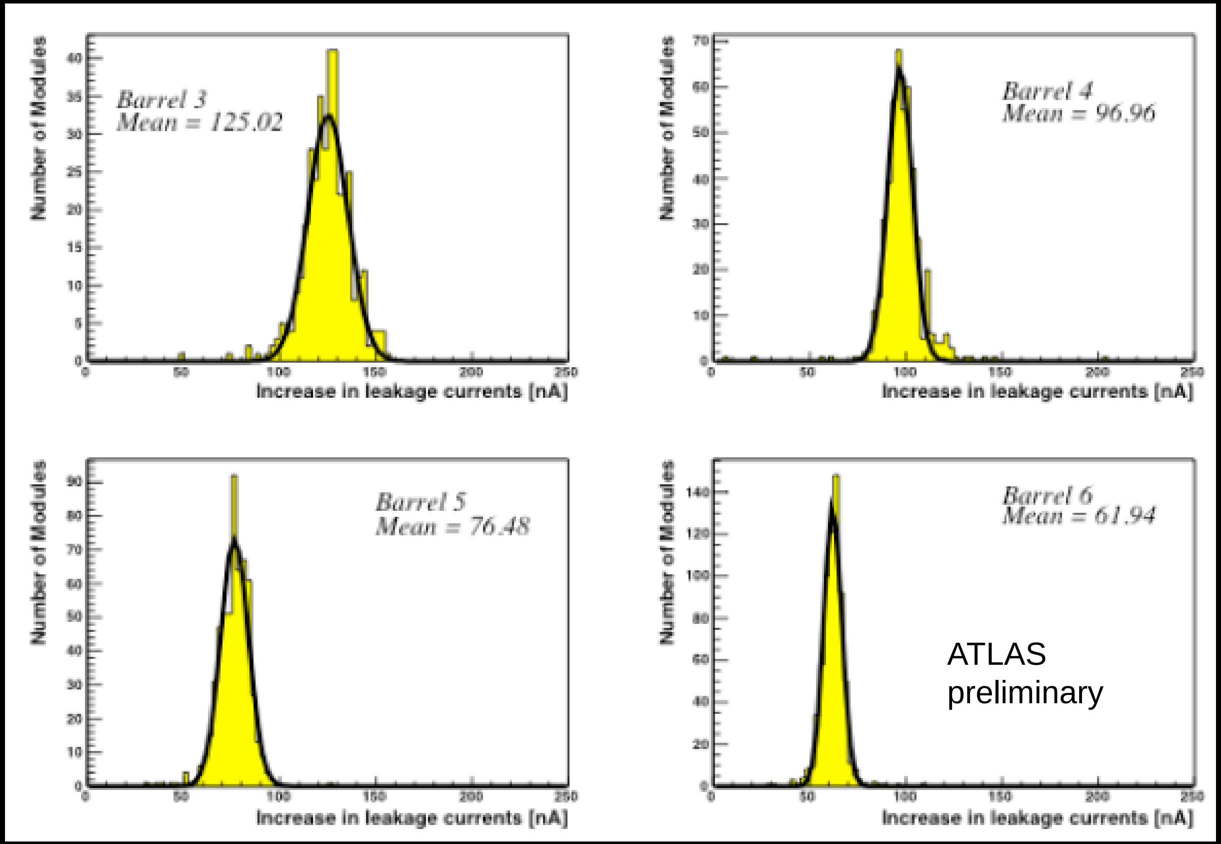


Yes, current changes and at least it qualitatively follow the delivered luminosity

Leakage Current vs. Time ~Luminosity LHCB-TT



ATLAS SCT at the end of pp 2010



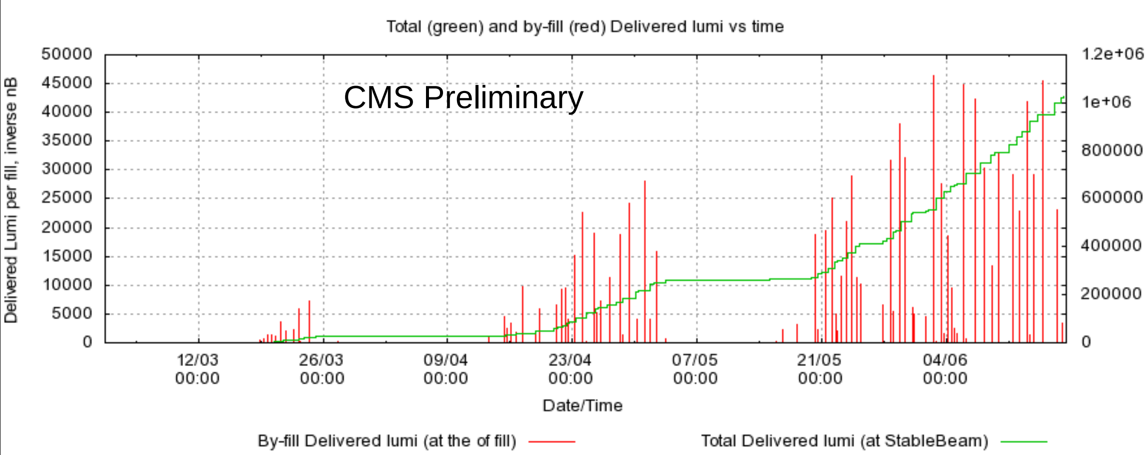
Histograms showing increases in SCT barrel module leakage currents (*normalized to -10C*) from

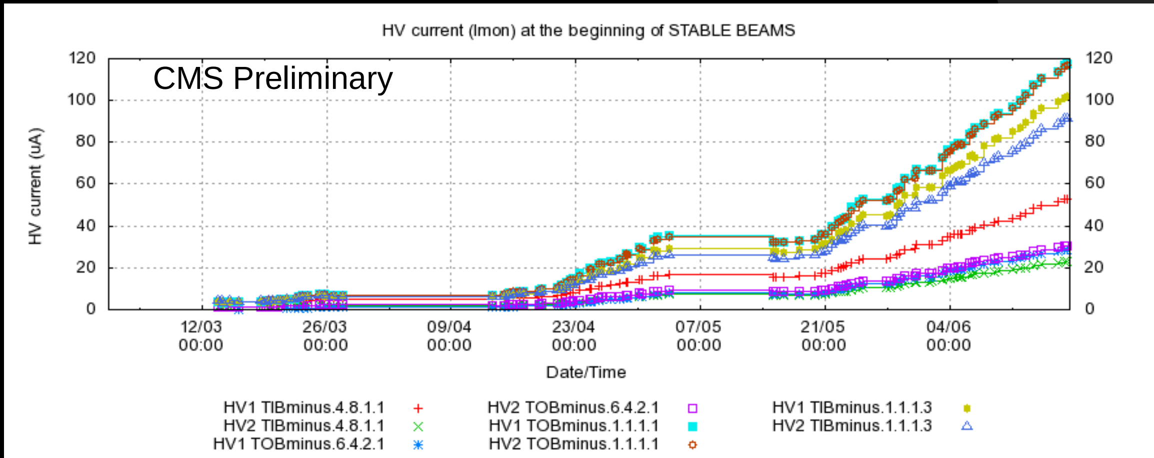
Begin of operation to end 2010.

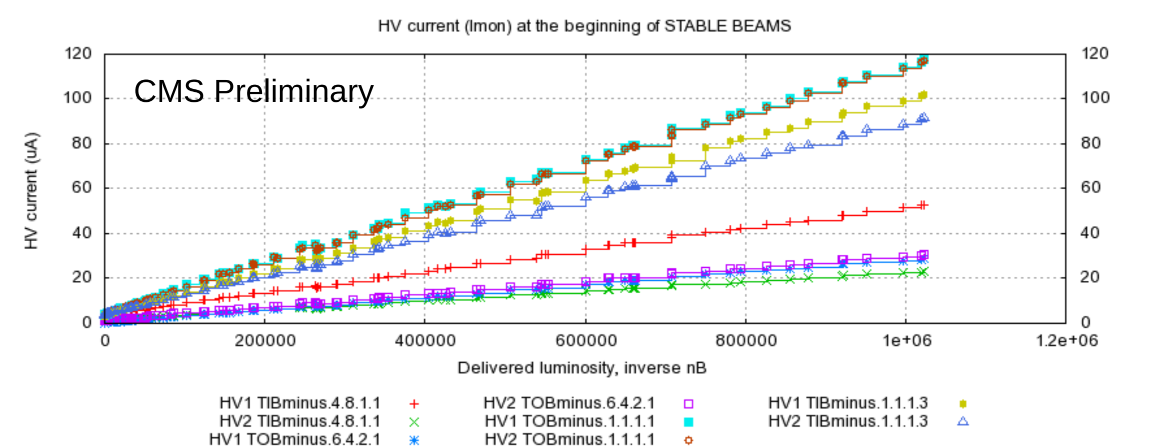
- Very impressive current resolution (10nA), much better than CMS or LHCb
- At that time CMS SST only quoted: “in the noise”

DB Query

- WEB-based online tool
  - No dedicated measurement
  - Standard DB query
- Power supply I value, begin of each fill (10min)
  - Different layers – different ϕ
  - Different # of modules
  - Different T
    - ➔ different curves
- ➔ Offline analysis
  - Normalize volume & T
  - Normalize to slope [$\mu A/1fb^{-1}/cm^3$]

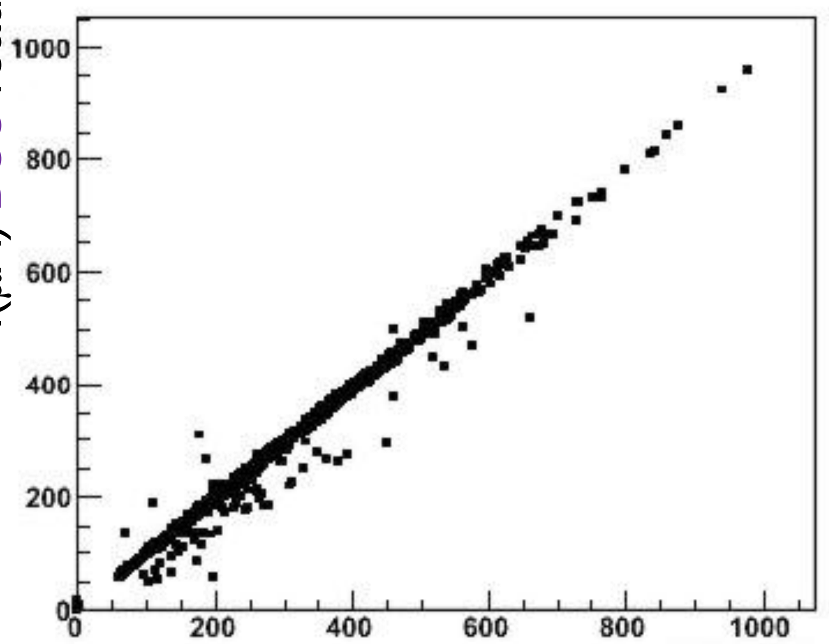






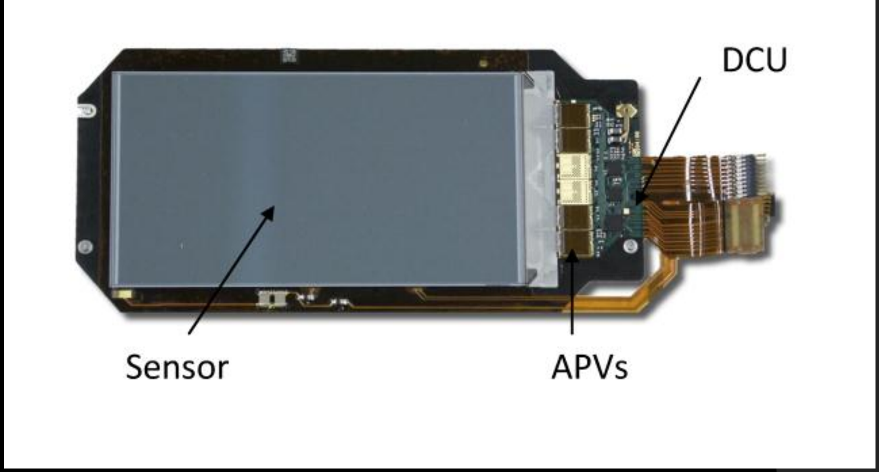
DCU

DCU readout of the leakage current vs. the corresponding power supply measurements after 4.7fb^{-1}.



I(μA) DCU readout

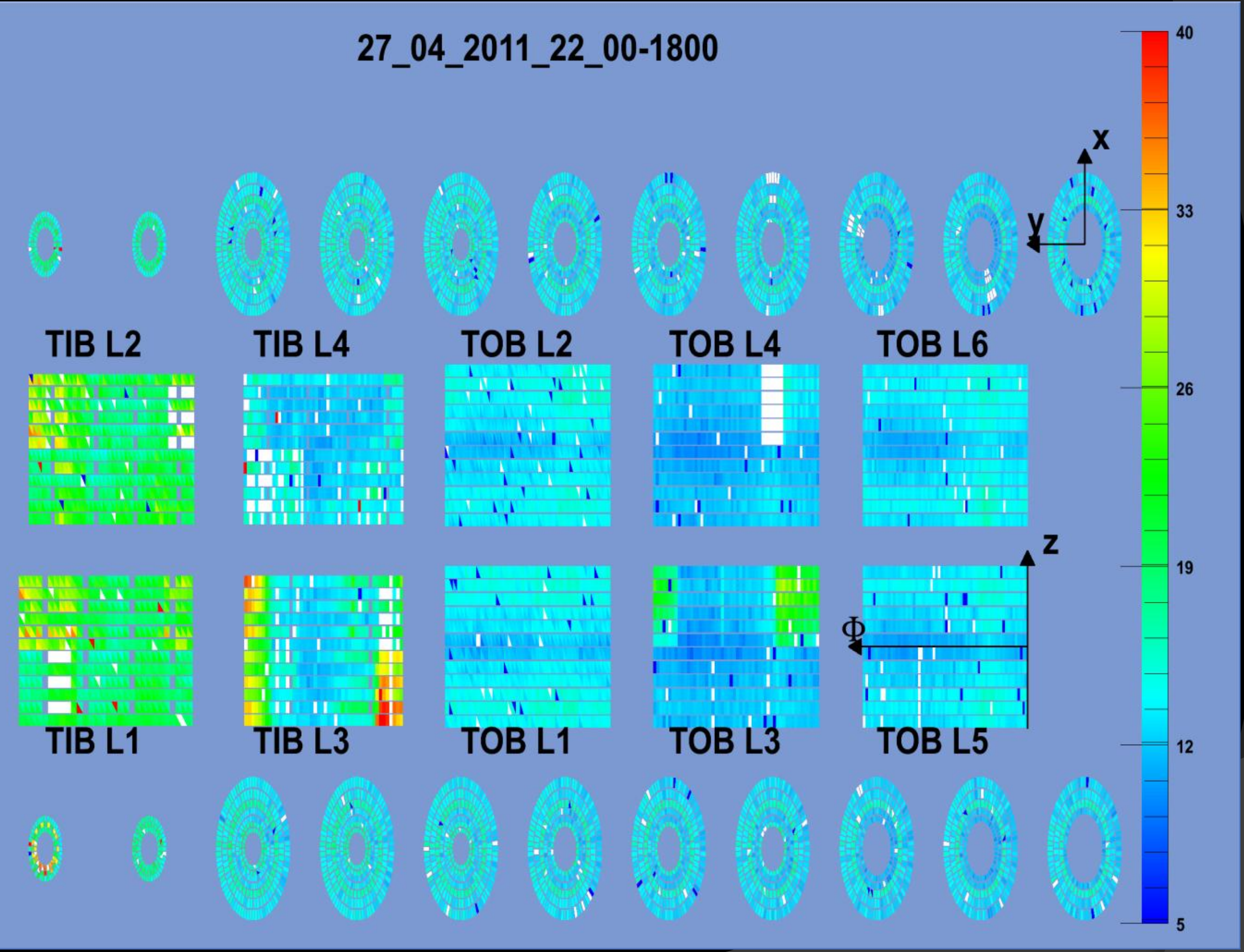
I(μA) Power Supply readout



The detector control unit is a ASIC sitting on each of the tracker modules, with the ability to measure the <u>temperature</u> of the module as well as the <u>leakage current</u> and LV voltages applied.

Each high voltage line of our power supply system is connected to 3-12 modules, to achieve higher granularity CMS needs to use the DCU information.

CMS Silicon Temperatures

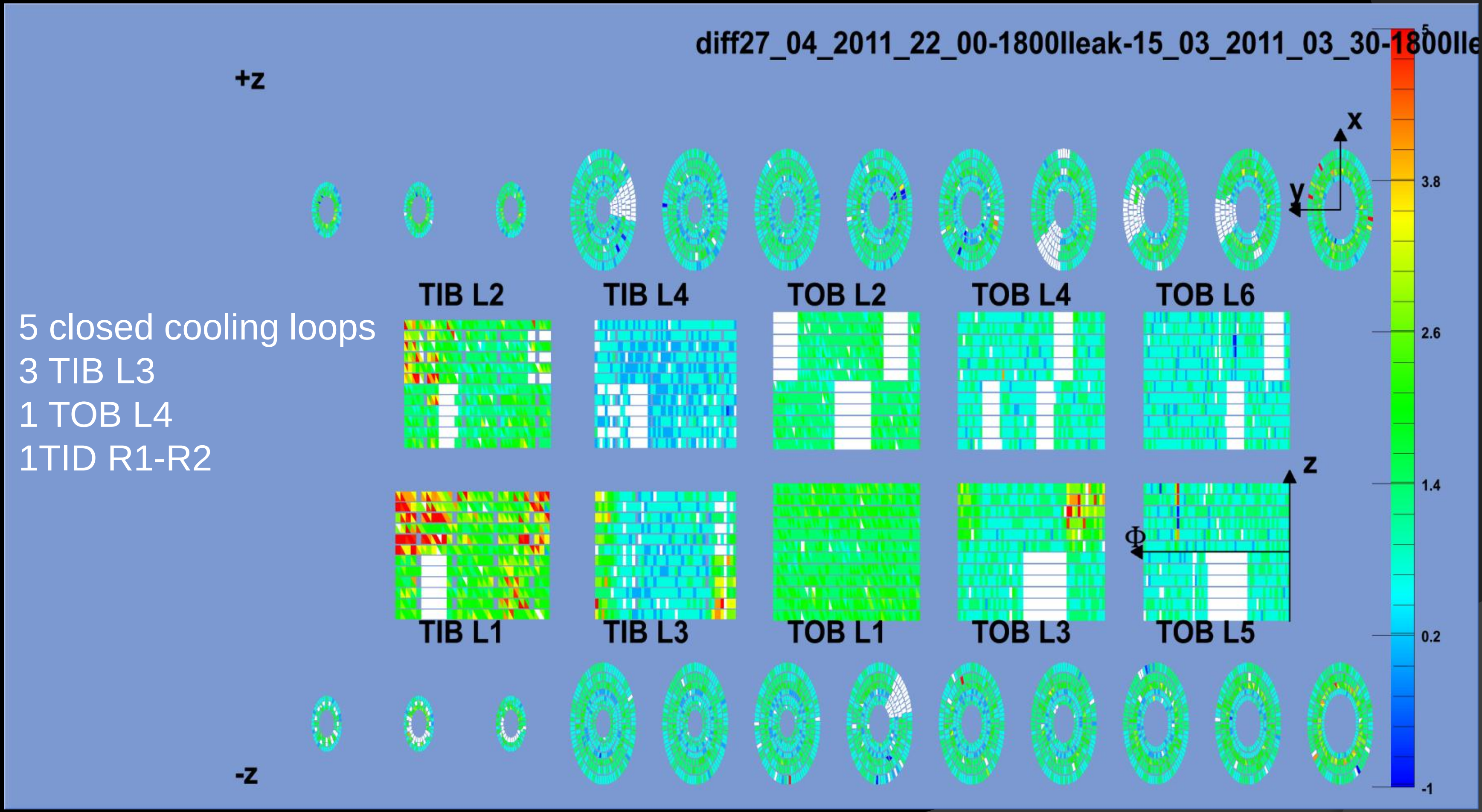


5 closed cooling loops
3 TIB L3
1 TOB L4
1TID R1-R2

DCU measurements of individual modules

Delta $I_{Leakage}$

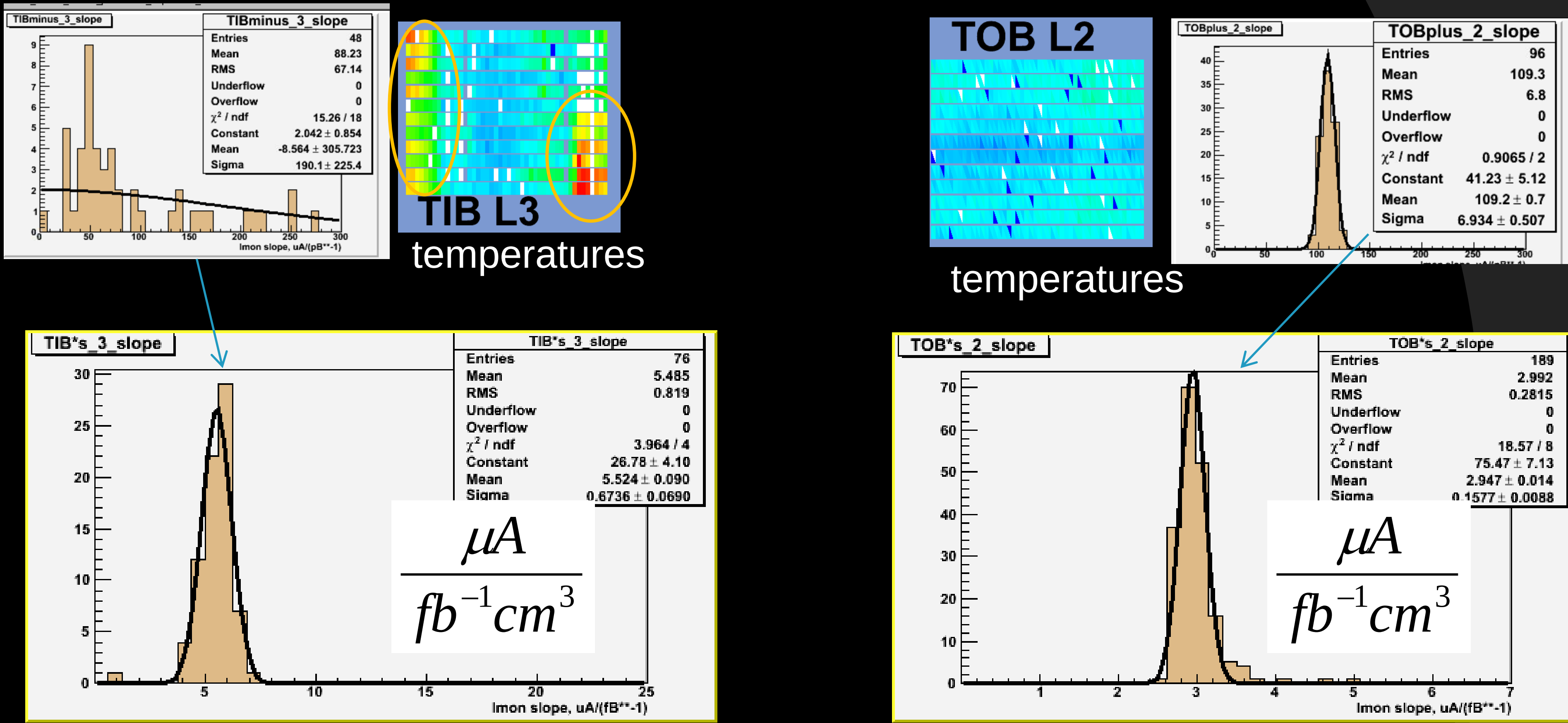
27/04/2011 and 15/03/2011



5 closed cooling loops
3 TIB L3
1 TOB L4
1TID R1-R2

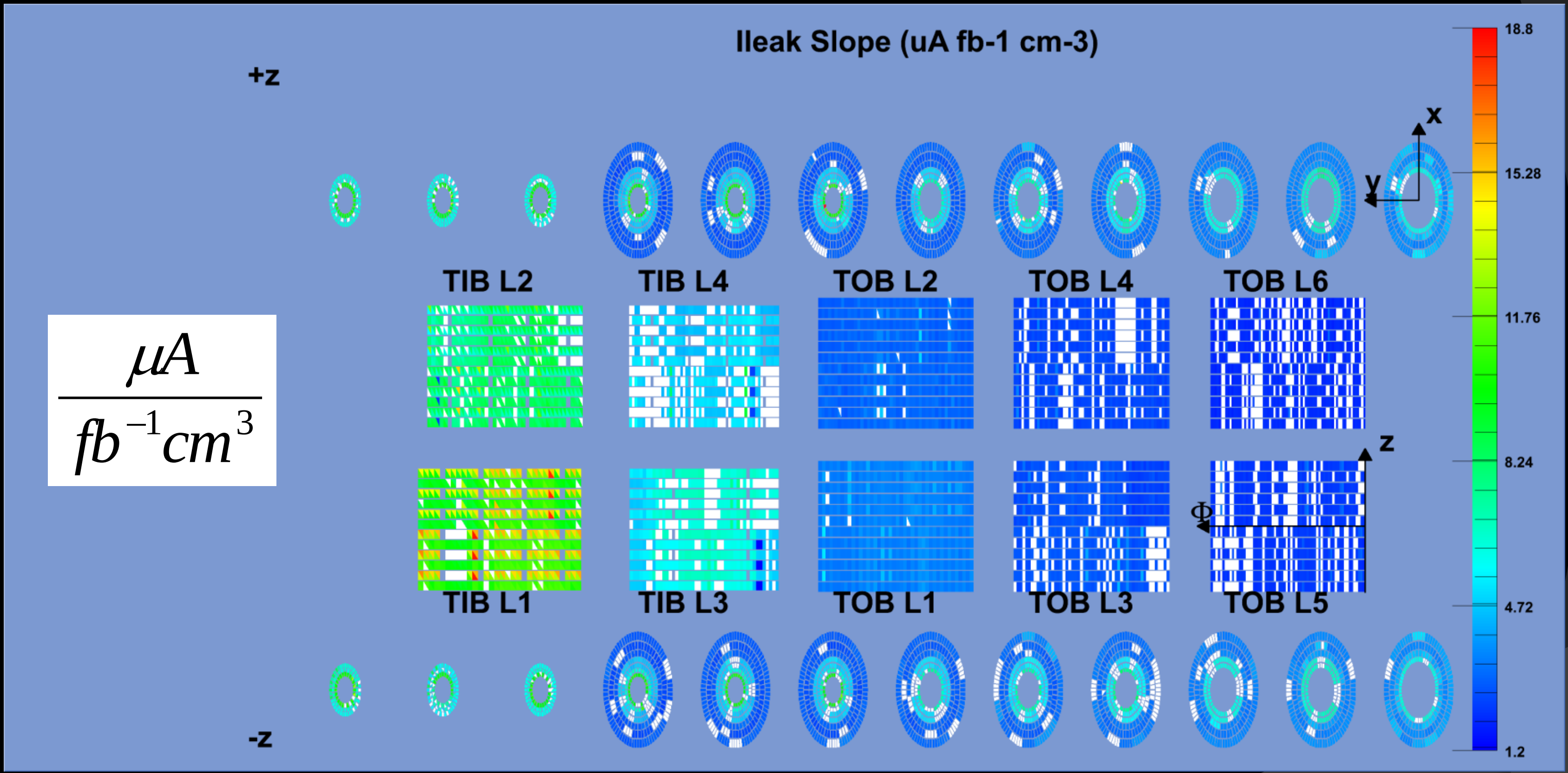
Hot regions see higher current - not a real surprise

Leakage Currents Normalized



- Normalization with respect to volume and temperature
- → Radial dependence
- → Comparison with expectation

Leakage Current Slopes Normalized

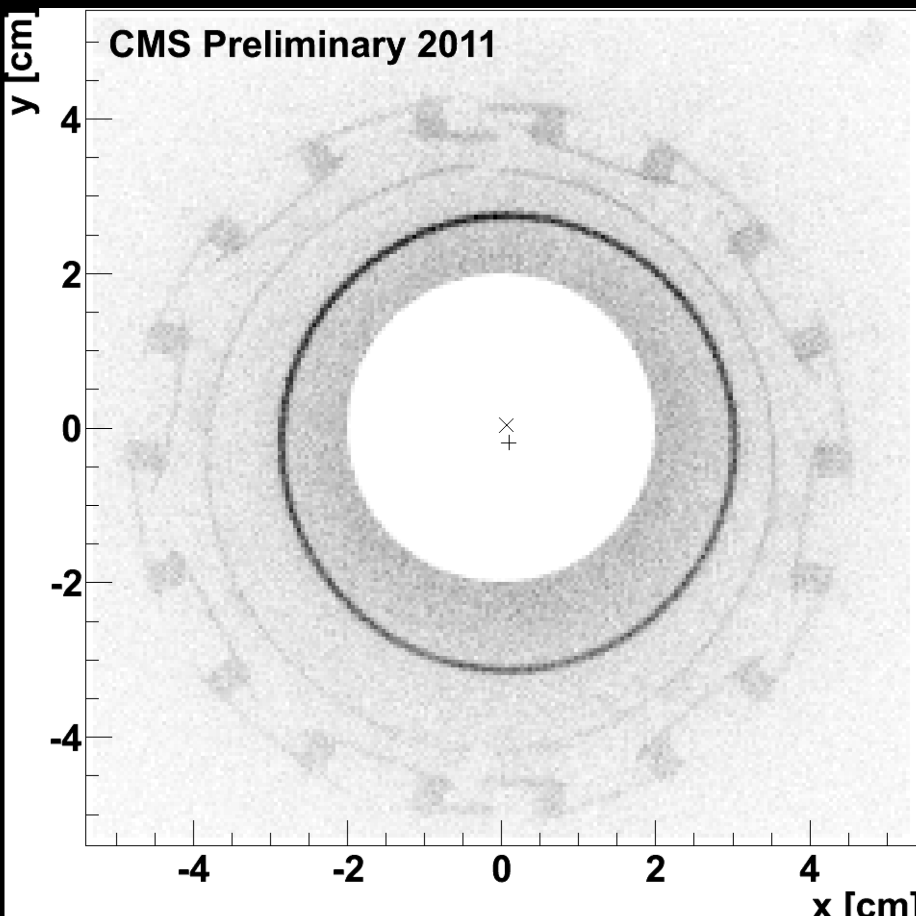


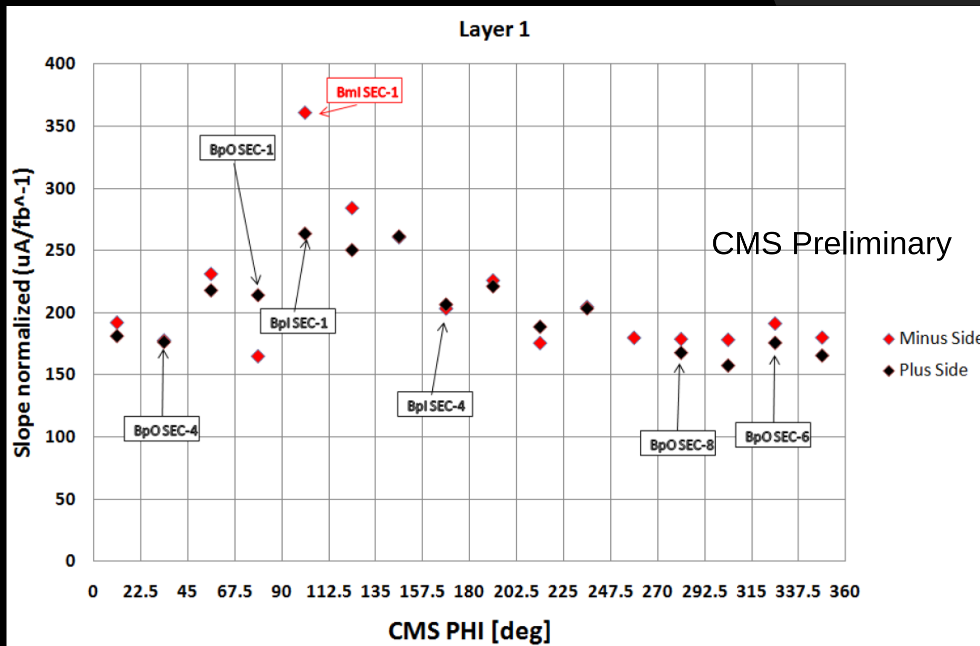
$$\frac{\mu A}{fb^{-1}cm^{3}}$$

Radial dependence! ✓

Inter-experiment working group proposal: scale to cm^3 and to 0°C

A Peculiarity:
Where is the Beam?





Also staggered geometry visible in dark current profile

Discussion started for 2012 to steer the beam off–center “to center” inside detector

Radial dependence

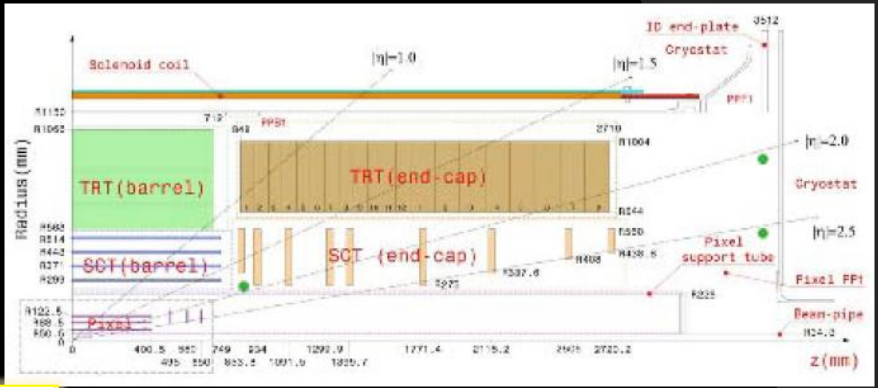
FLUKA

Annealing

A Try to Compare Results with Expectation

ATLAS Current Data vs. Simulation

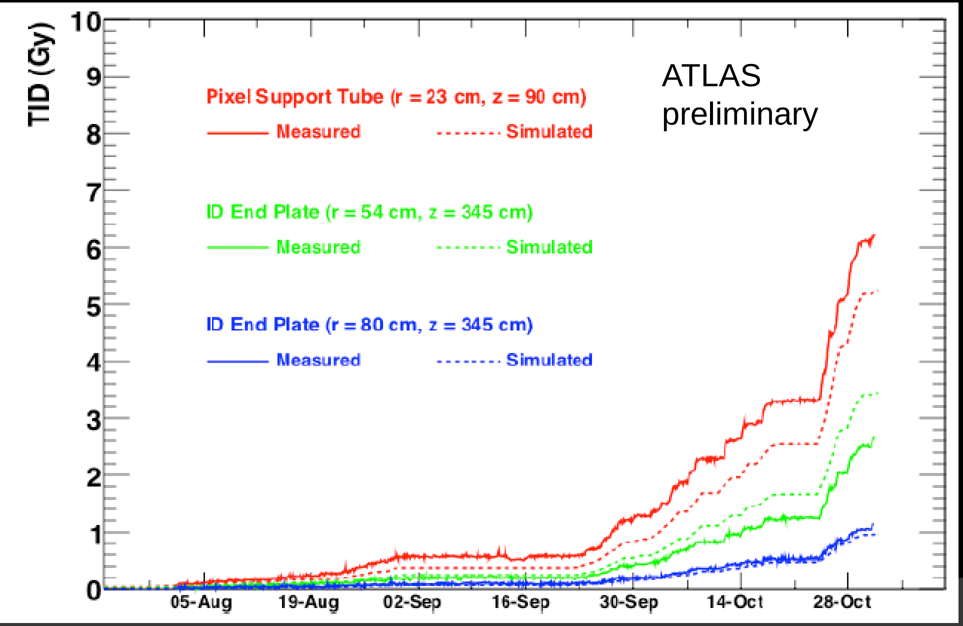
- **Dedicated** RADmon sensors readout via DCS
  1. Radiation sensitive p-MOS transistors (RADFETs).
  2. Calibrated diodes

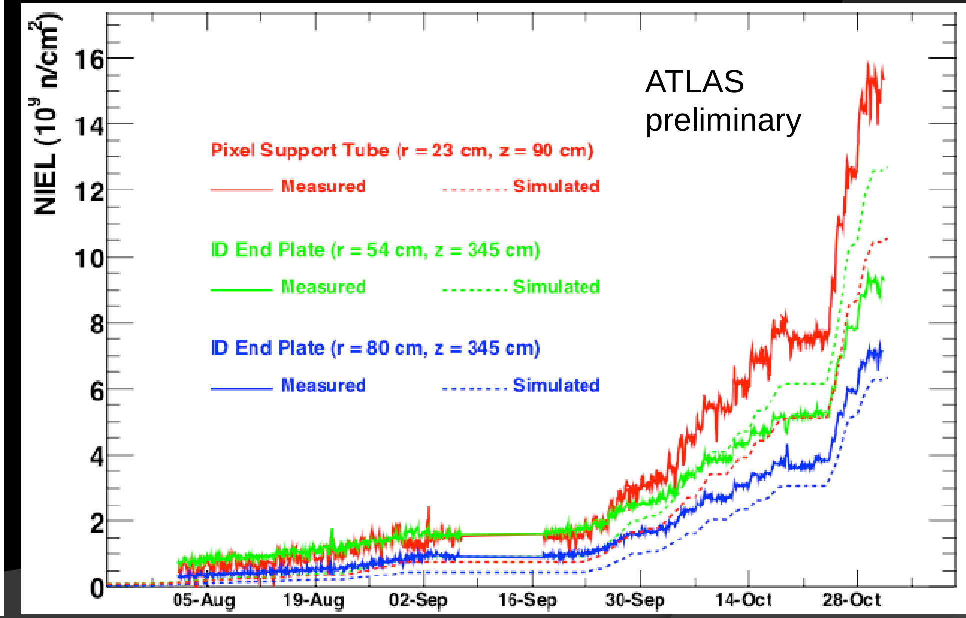


Comparison

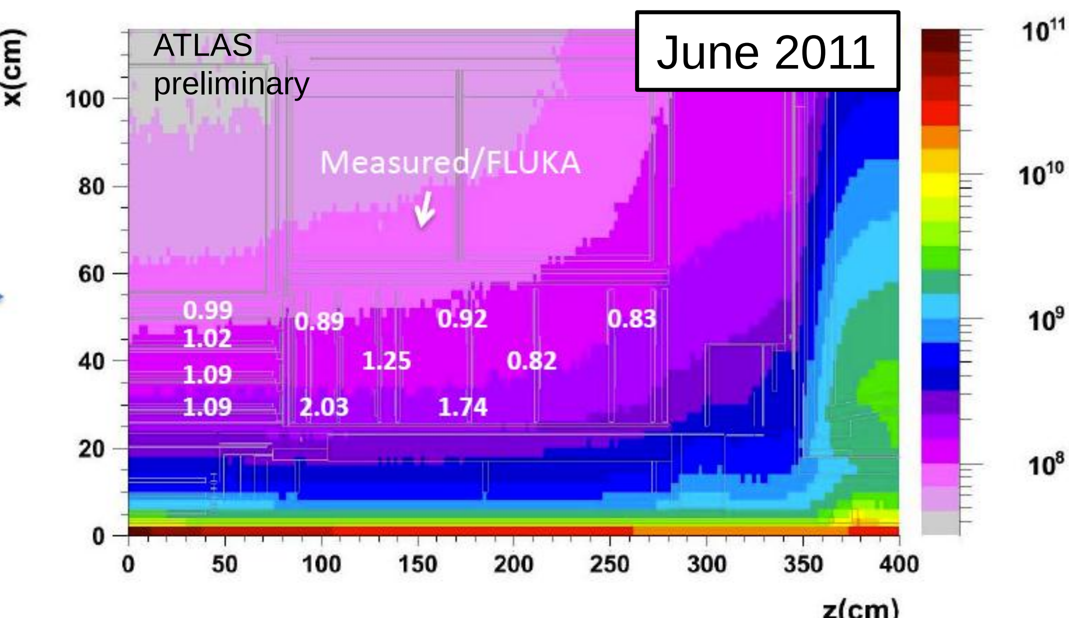
Comparison of ionising-dose measurements and simulated predictions

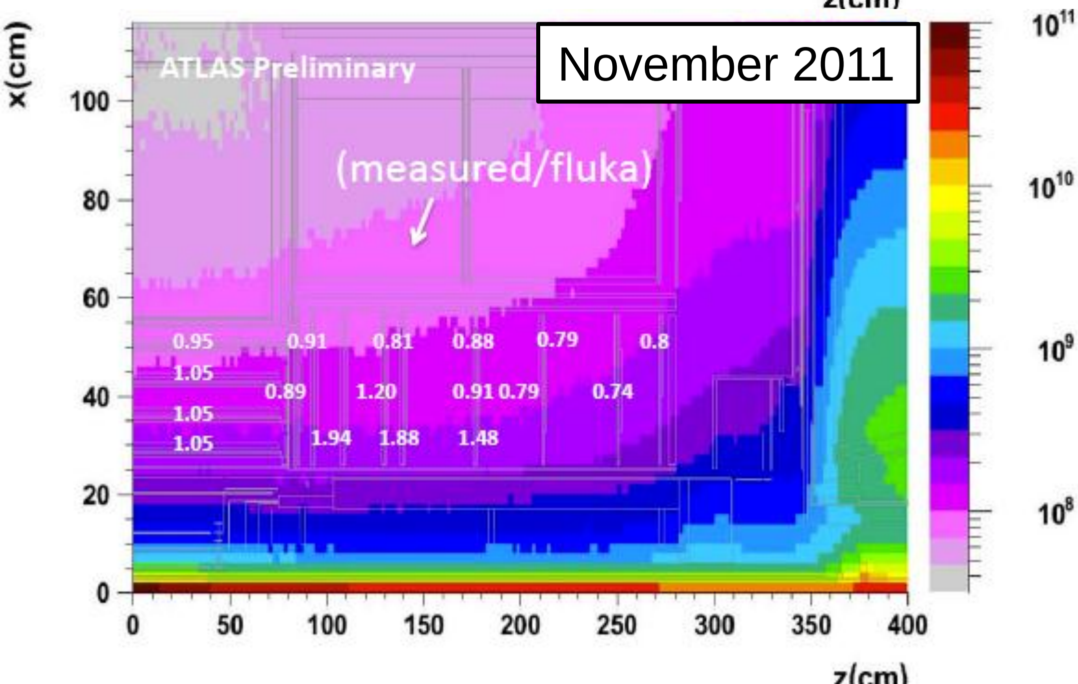
Comparison of NIEL (1MeV neutron equivalent) measurements and simulated predictions





ATLAS Current Comparison with FLUKA





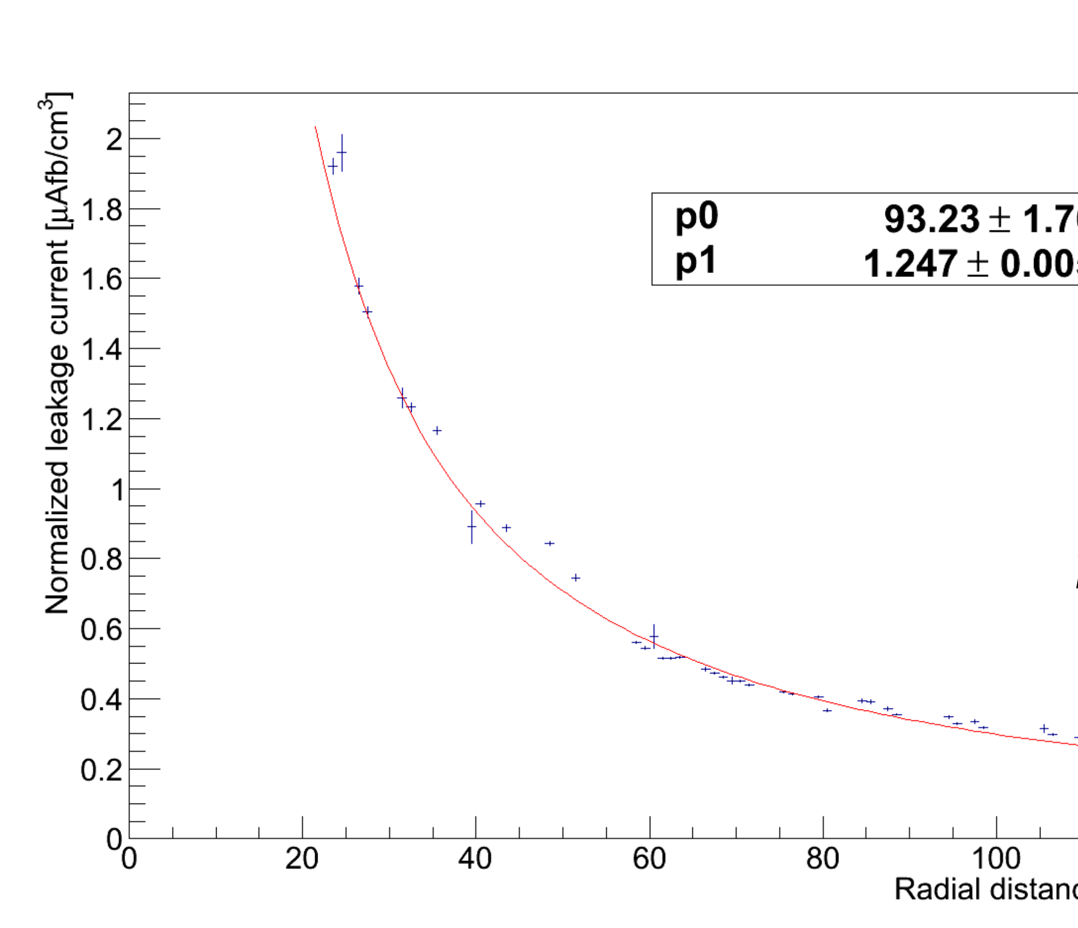
- Approach: normalize averaged currents for temperature and then calculate fluence in 1MeV n_equiv (with standard alpha); then compare derived fluence with FLUKA Sim
- Larger differences in the inner endcap regions
- Comparison gets better with time (and of course more fluence)

Numbers are ratio Measured/FLUKA

Comparison

Radial Dependency of Leakage Currents

Slope of leakage current increase per fb^{-1} after 4.7 fb^{-1}
[normalized to 1cm^3 and 0°C]



$$f(r) = \frac{\text{p0}}{r^{\text{p1}}}$$

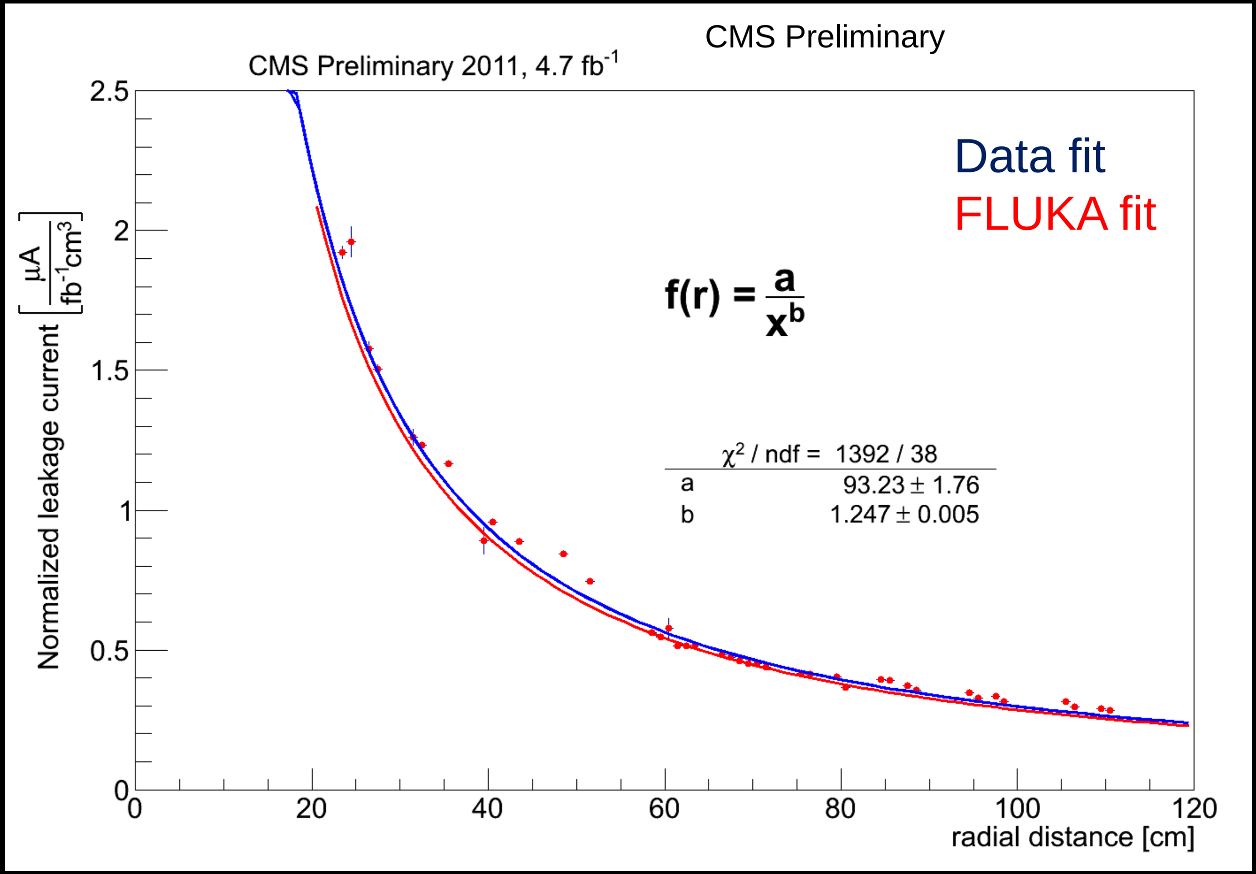
The normalized leakage current is averaged within each bin of a given radial distance r

Remember TDR assumption: $\sim \frac{1}{r^{1.6}}$ today: $\sim \frac{1}{r^{1.24}}$

Attempt to Compare with Simulation

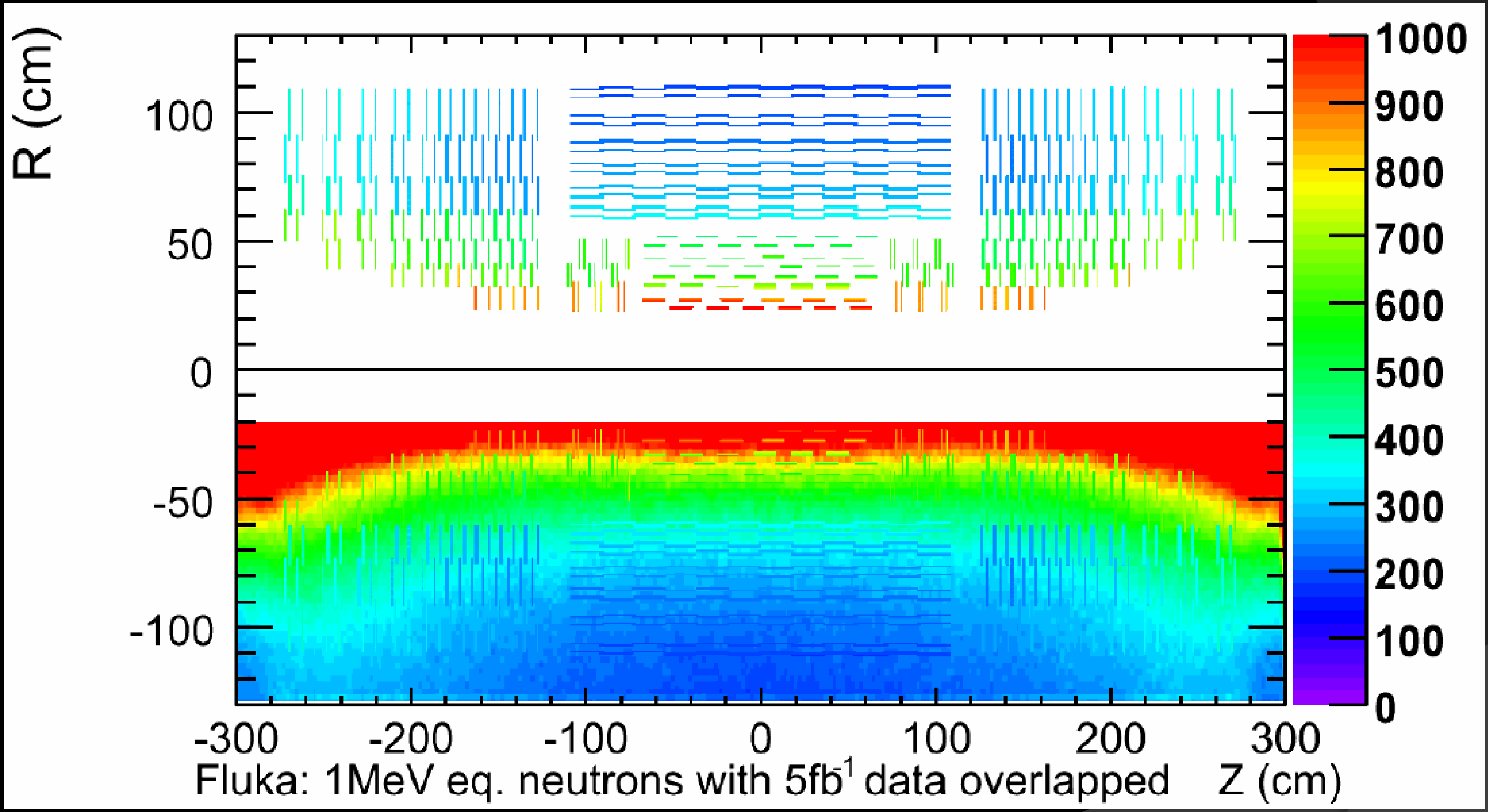
Approach: calculate current increase from simulated fluence (α=7.1 e-17 A/cm @0°C)

- Simulation: Fluka 7TeV scored to 1MeVn_equivalent per pp collision
- With the above zero temperature we have continuous parallel annealing and α(t,T) is not directly obvious
- Mind also that the radial dependence also changes a bit with Z (here we used central region)
- FLUKA given in grid of 2.5 x 2.5 cm (linear interpolation used)



Comparison ✓

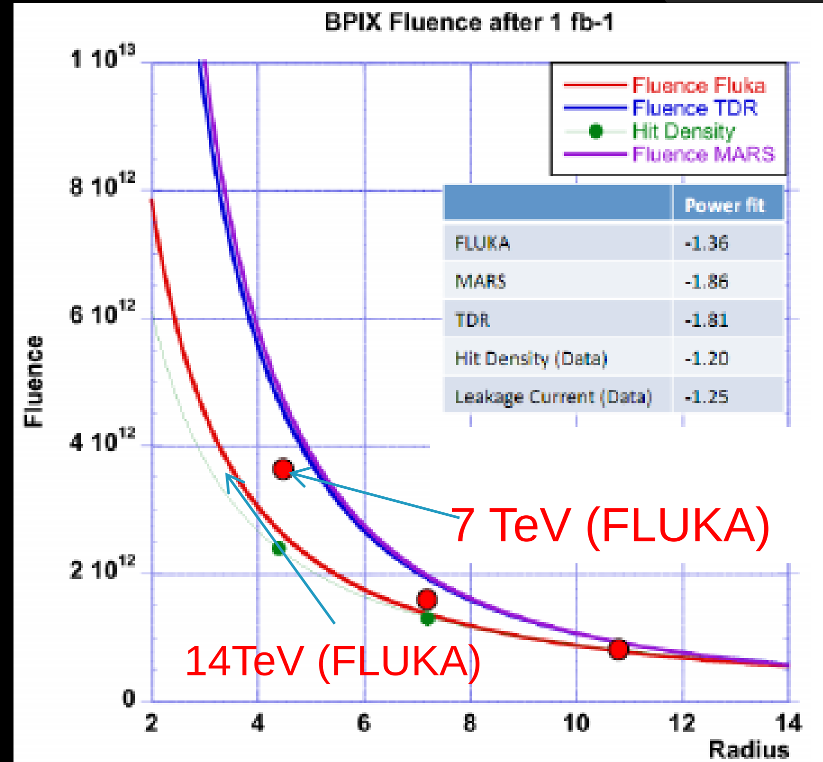
Hide & Seek -- Localized Comparison

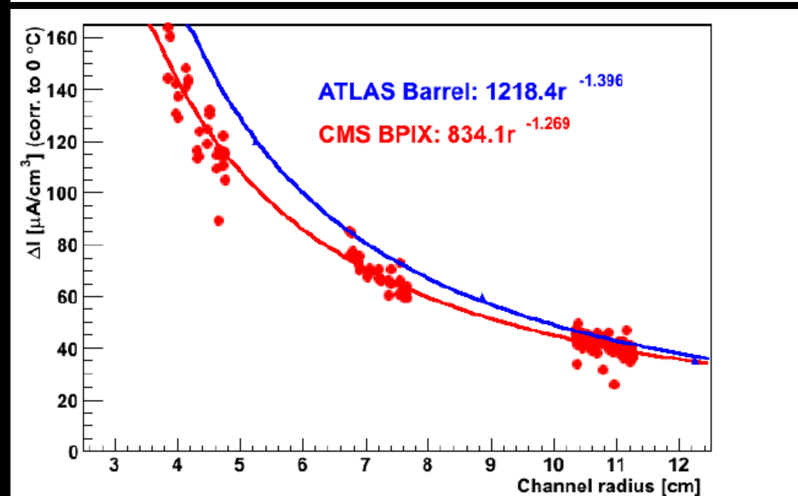


Comparison

CMS Pixel

- Still uncertainties in FLUKA
  - Coarse grid
  - Material description...
- Hit density matches leakage current
- Power law similar to strips





ATLAS from RD50 workshop

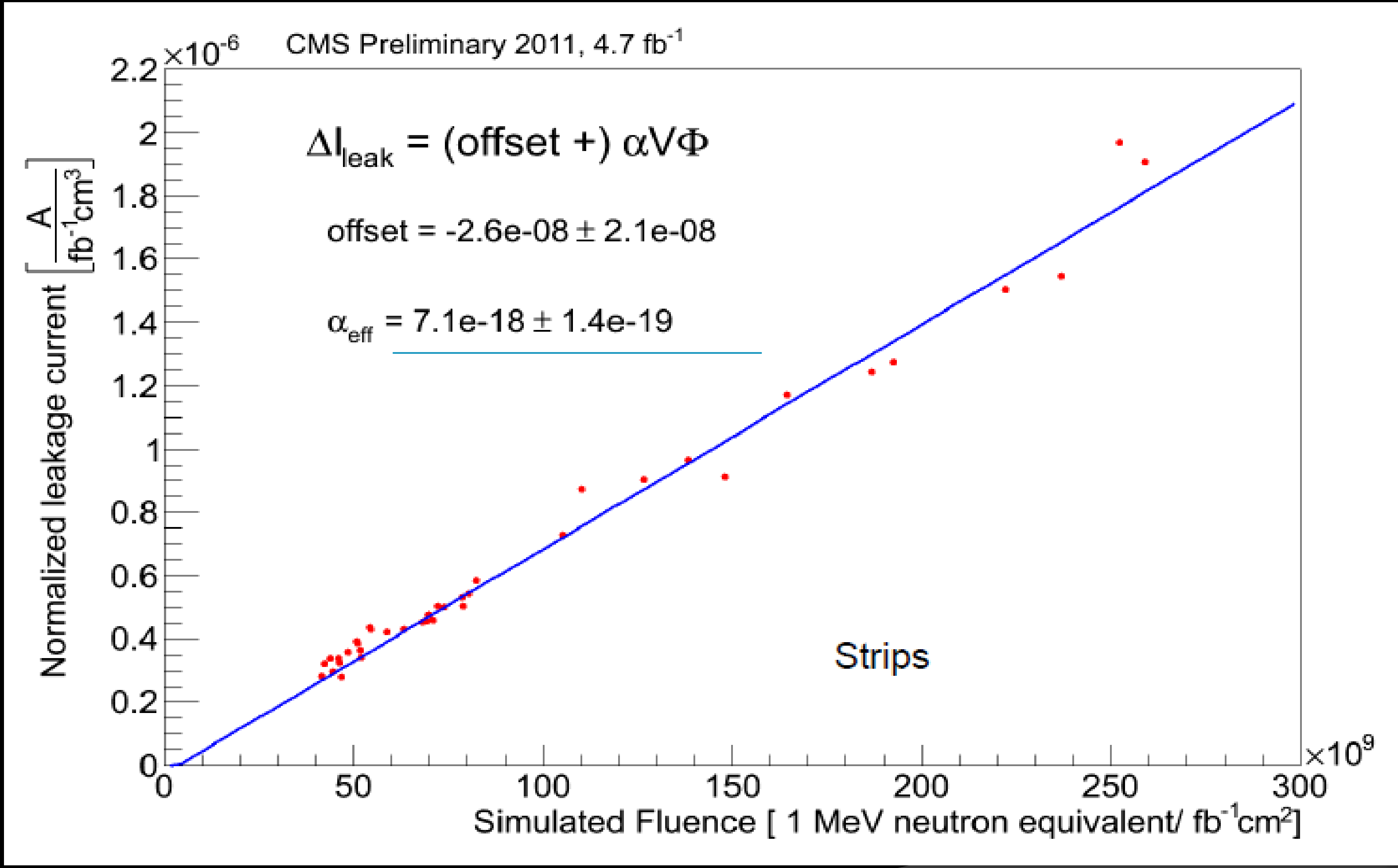
Radius of channel includes offset w.r.t. Beamspot but NOT staggered geometry

Is it visible?
How to treat it correctly?
How to treat it when active during irradiation (operating above ZERO degree?)?
Effective $\alpha(t,T)$

Excursion: Annealing

Effective a(t,T) at α=4.7 fb^{-1}

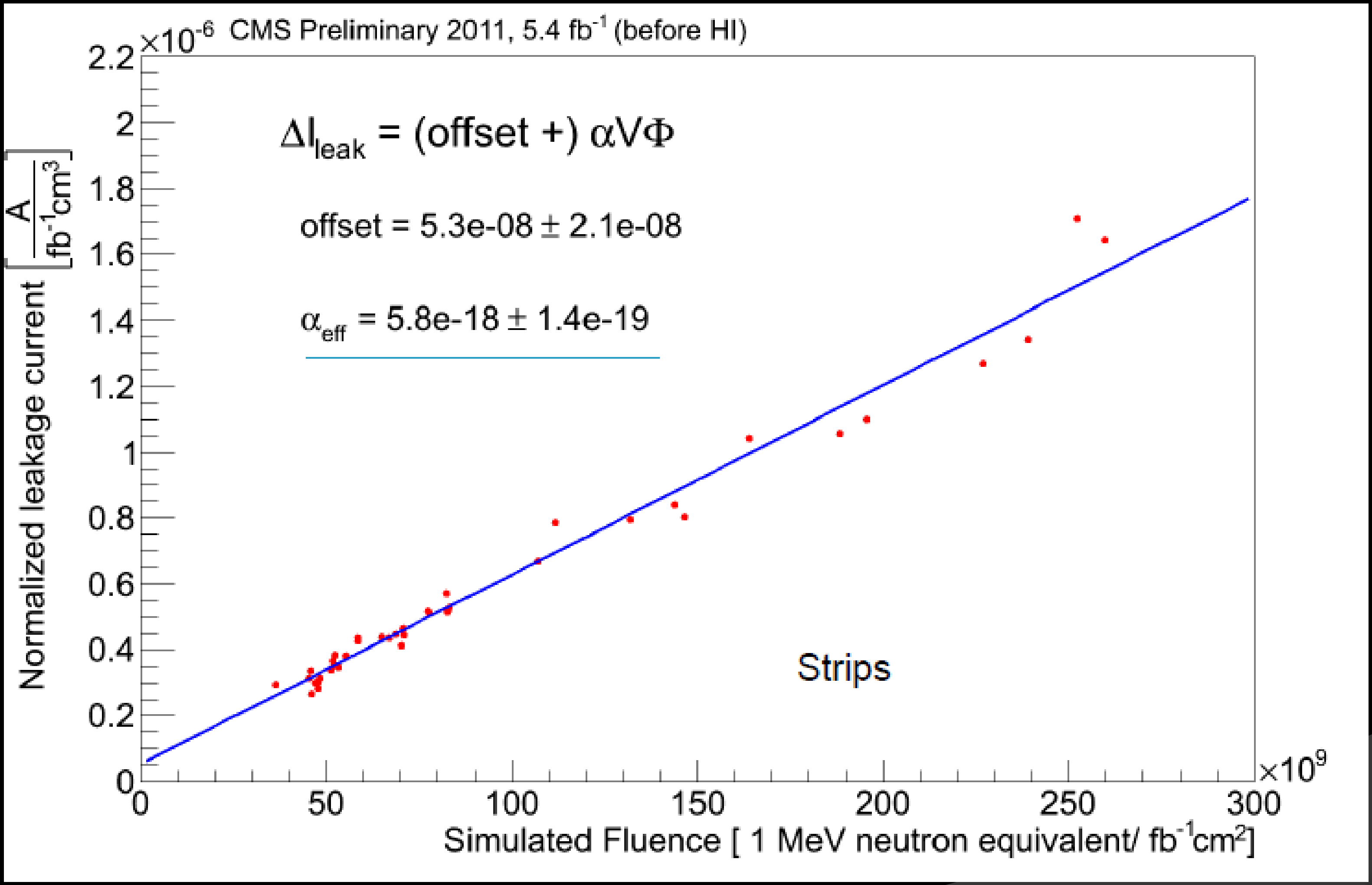
Slope of leakage current increase per fb-1 after 4.7 fb-1
normalized to $1cm^3$ and 0°C



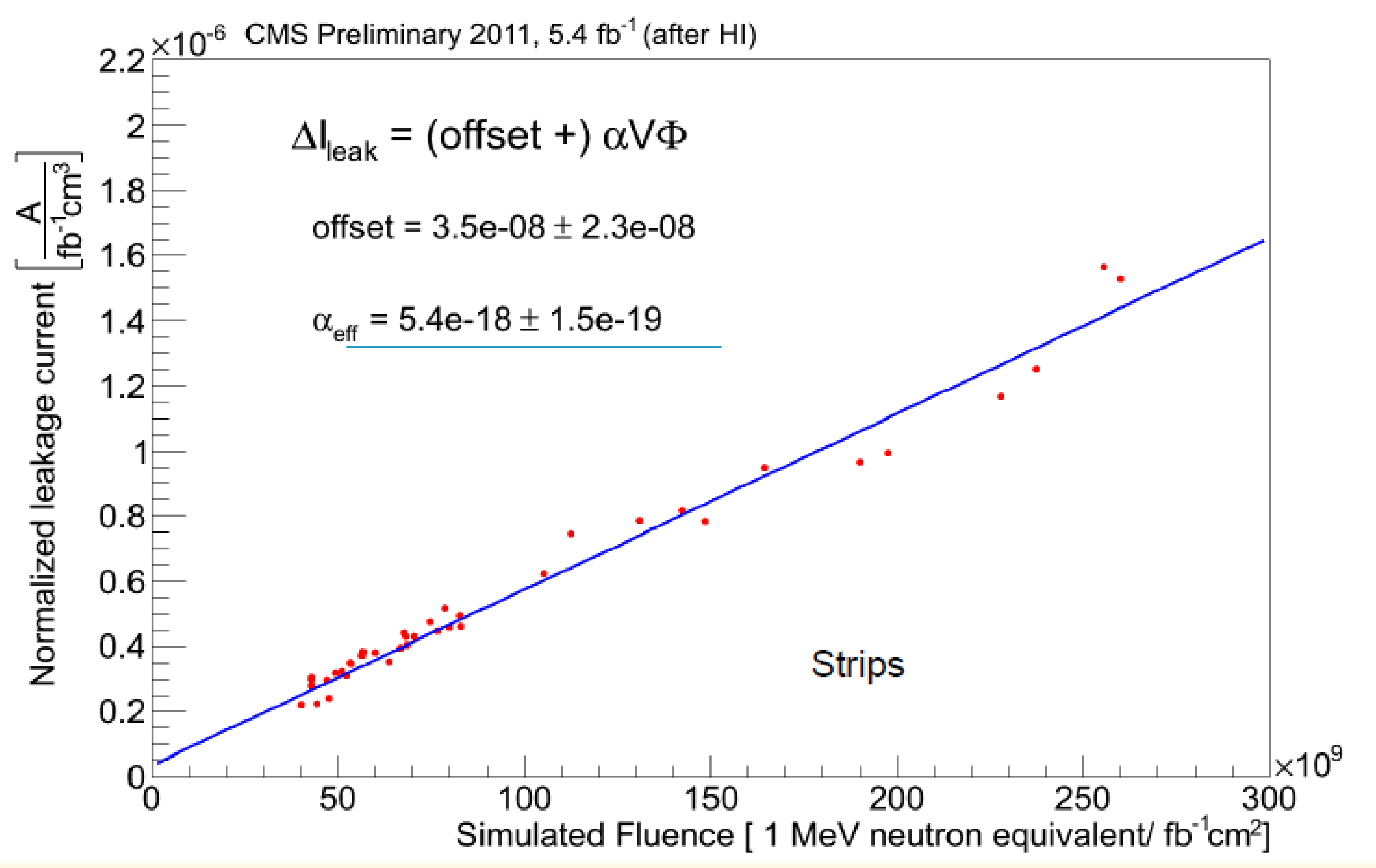
Fluence derived from 7TeV FLUKA simulation scored to 1MeV neutron equivalent.

Slope → α_{eff}

Effective a(t,T) at α=5.4 fb^{-1} before HI



Effective a(t,T) at α=5.4 fb^{-1} after HI



➔ **Need to use effective α(t,T) and model on a daily basis in an integral way**

Example: CMS

Inputs:

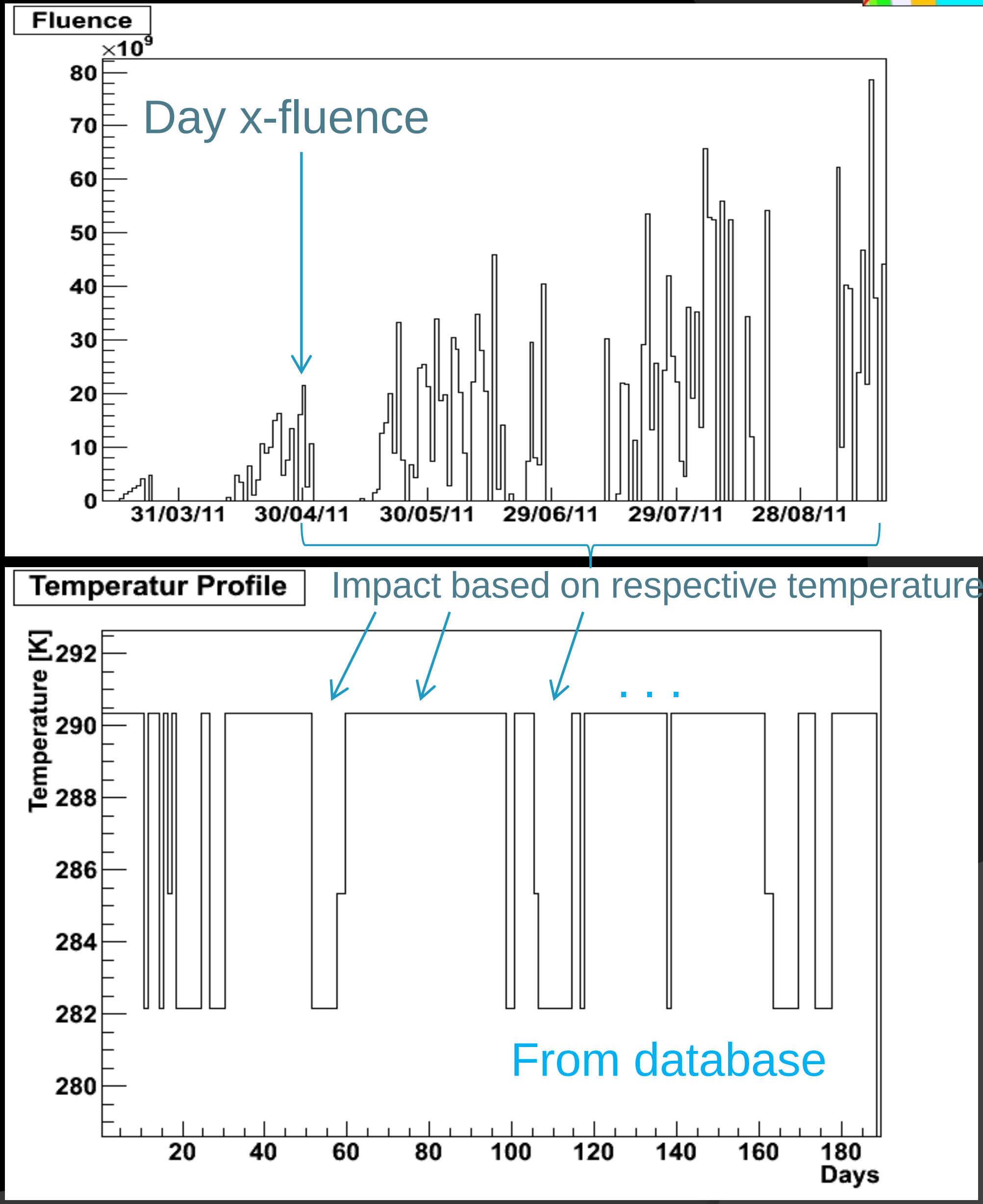
- Fluence at indiv. module position
- Temperature of indiv. modules
  - Measured by DCU

Method/Tools:

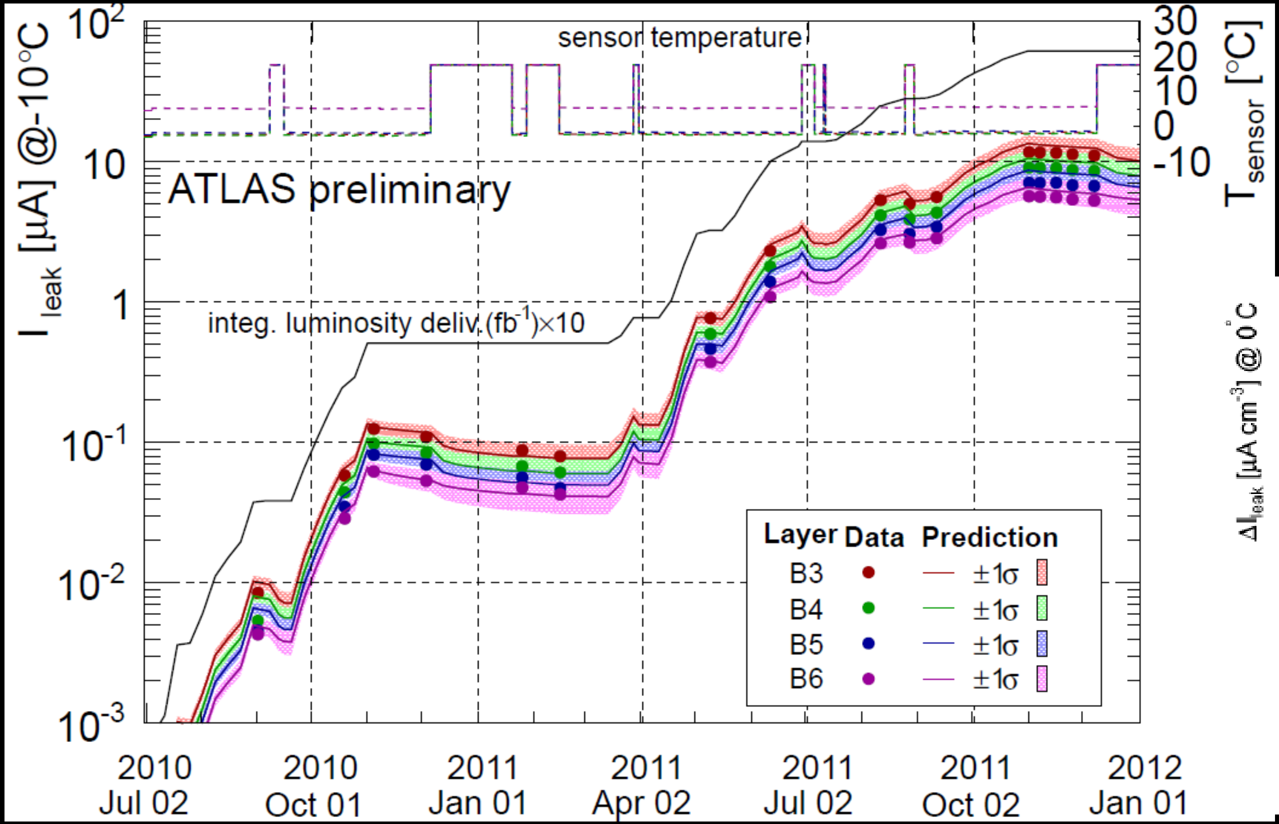
- Histograms filled with one bin per day for the temperatures and fluences
- Afterwards the impact of each day's fluence to all consecutive days is computed with the annealing time constants based on the given temperature at the respective day.
- The integrated sum over all days gives the result
- Sensor self heating included

Output

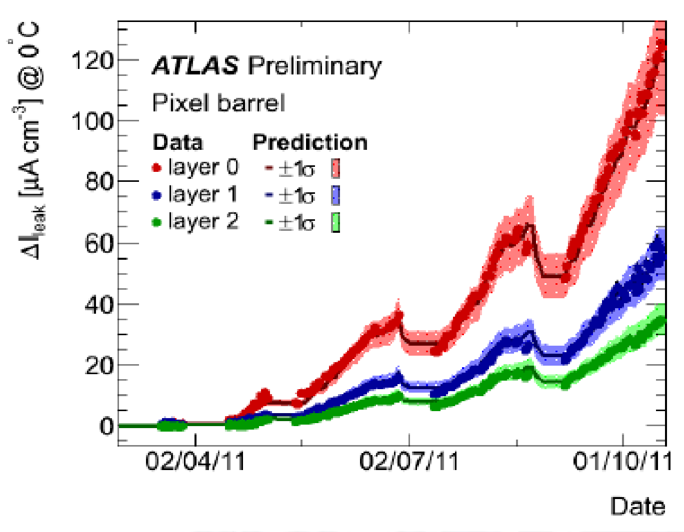
- Leakage current
  - Leakage current of modules for comparison
    - Measured by DCU, cross checked by PS values
- Same for depletion voltage



Leakage Current Evolution in ATLAS and Comparison with Model

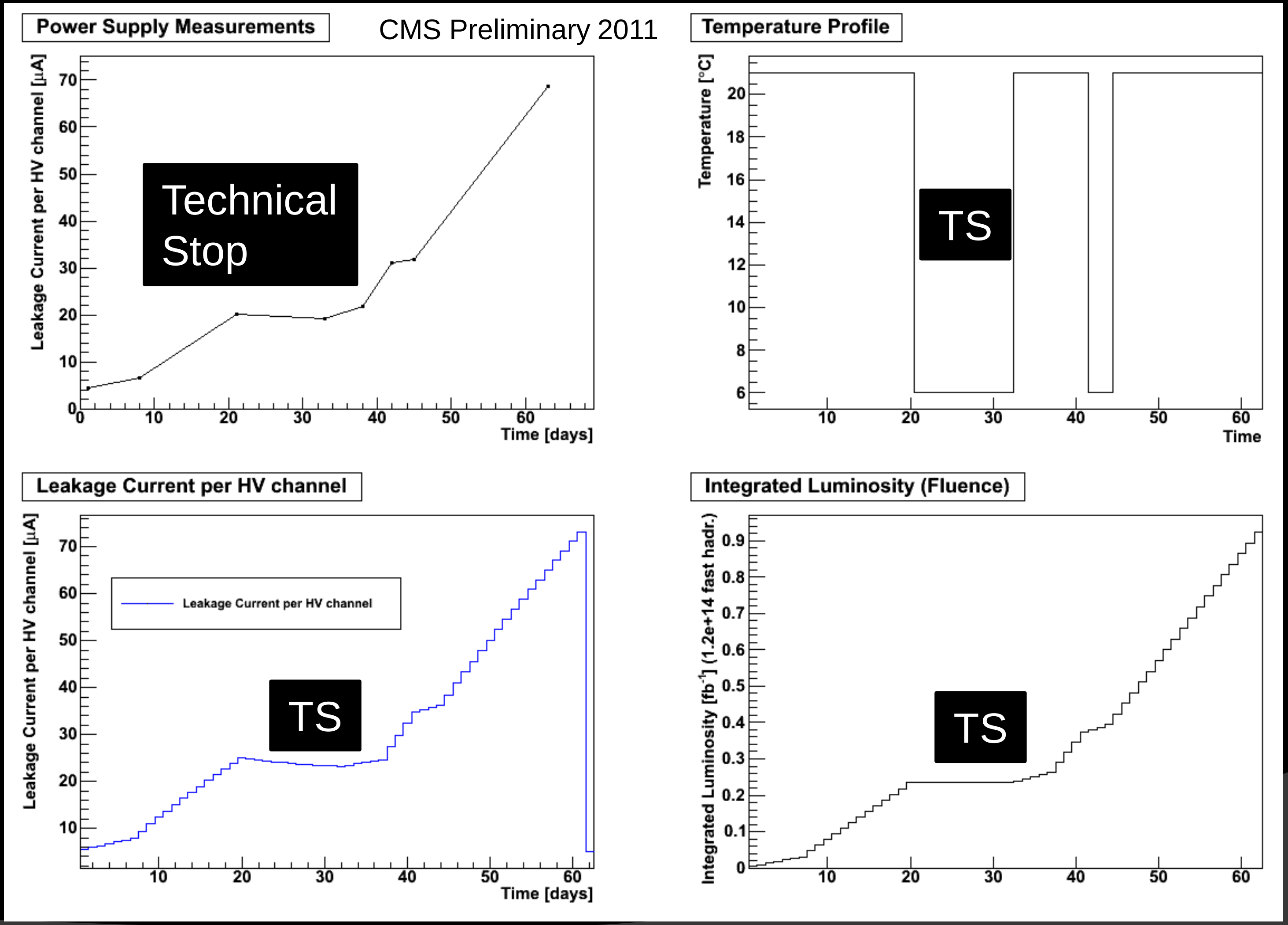


Comparison ✓



- Prediction is based on the total 7-TeV luminosity profile and the FLUKA simulations, taking the self-annealing effects into account.
- The prediction uncertainties are mostly due to errors in the fraction of the slowest annealing component (11%) and luminosity measurement (4.5% in 2011). The uncertainty of FLUKA simulation is not included.
- Scaled to -10°C for SCT (0°C for pixel)

Match Data with Simulation in a Timely Fashion

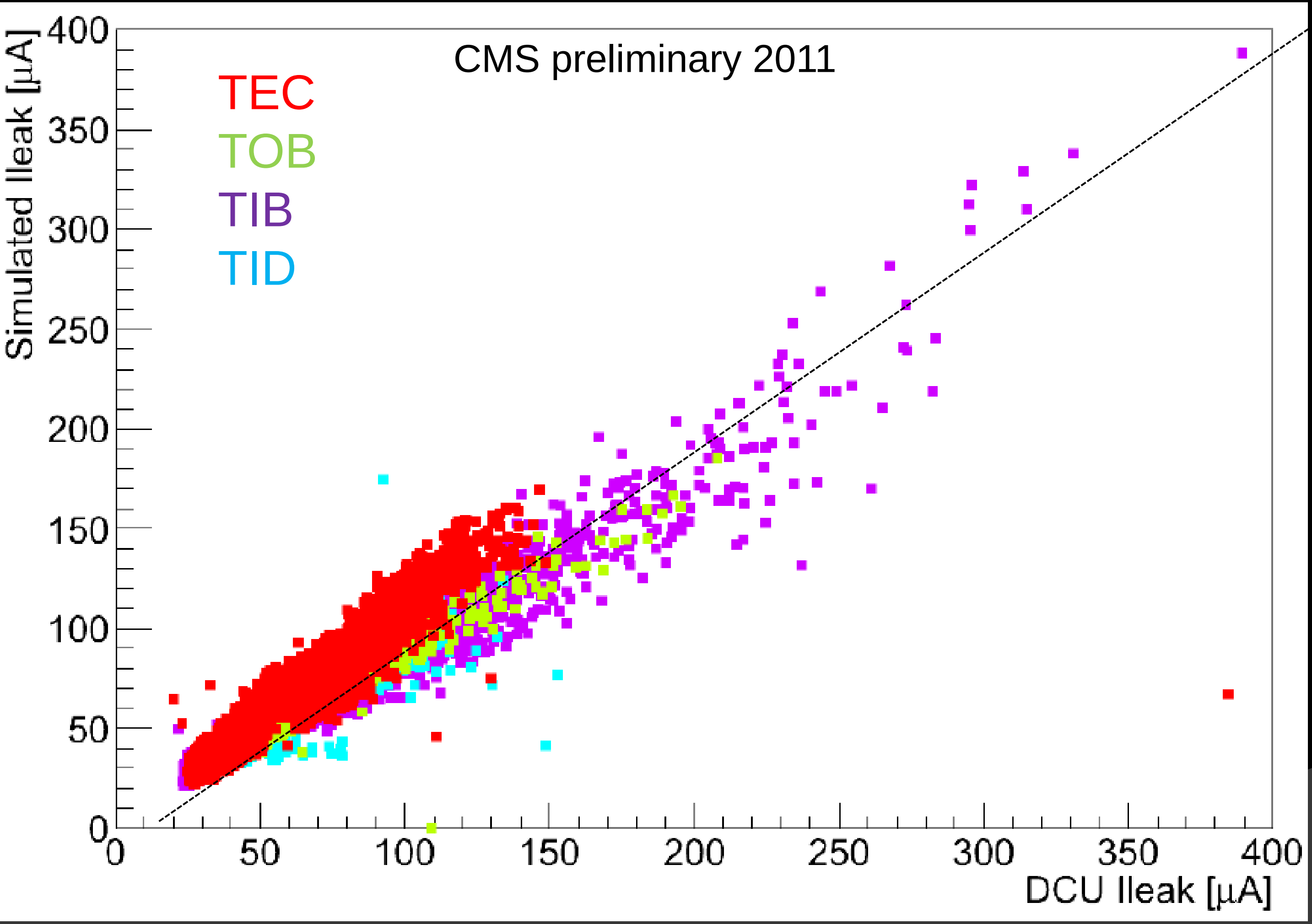


- CMS SST
  - Starting point
  - To be used for extrapolation
  - α(T,t)

Annealing alpha

The Whole Strip Tracker: Simulation and Measured Values

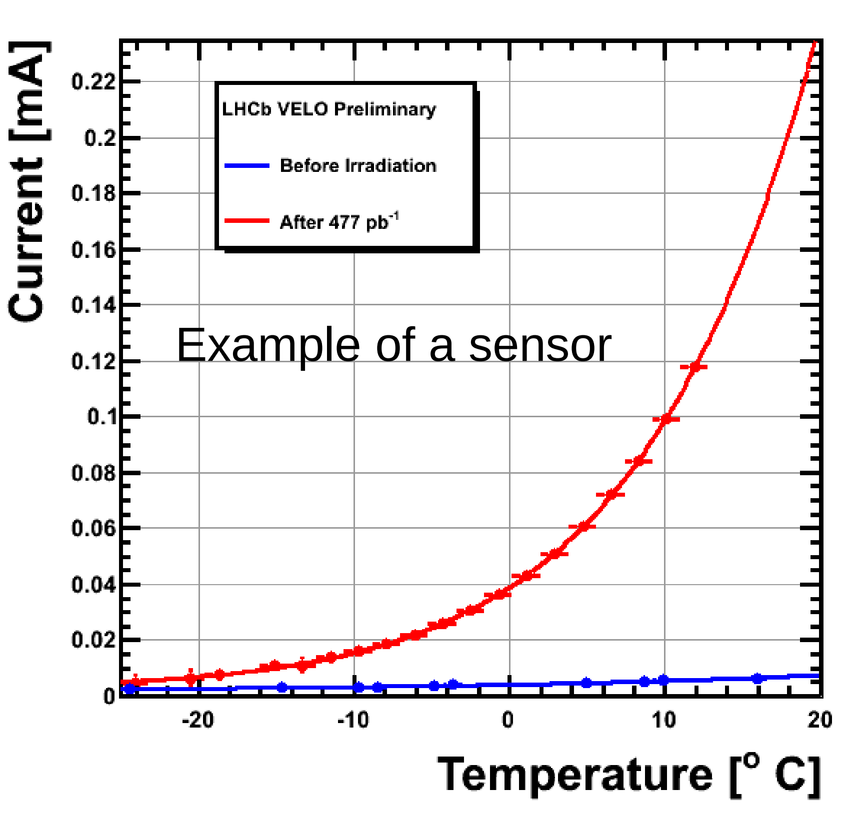
$\mathcal{L}$=5fb^{-1} (before HI period)

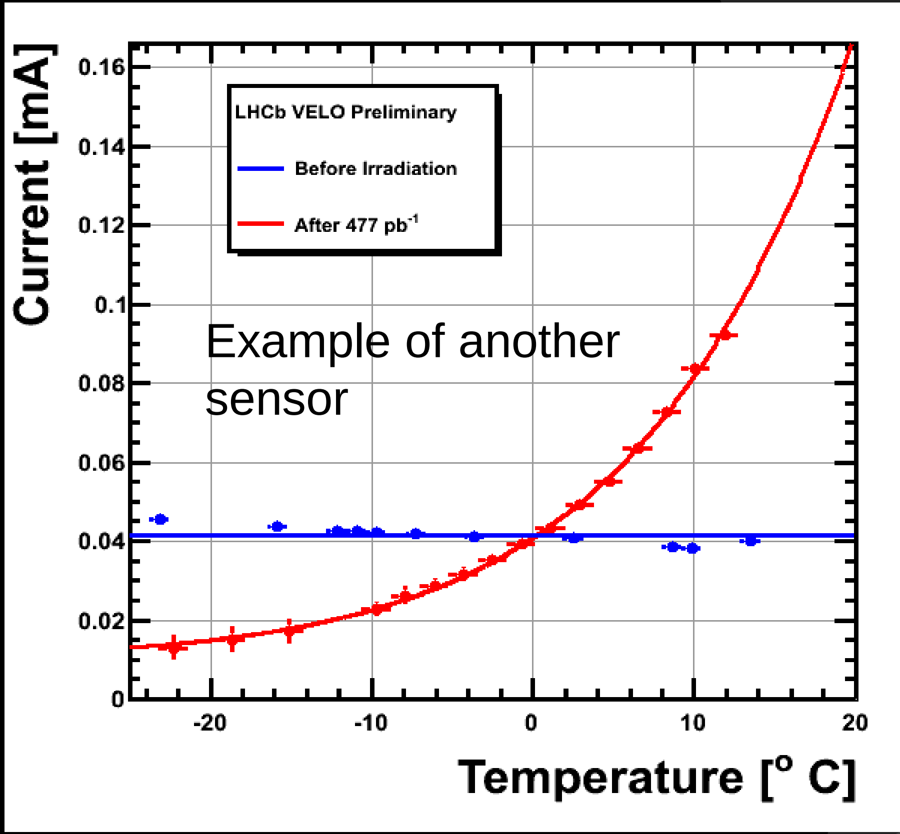


- Day by day
- Module granularity
- Annealing
- Self-heating

Surface Current

Bulk or Surface? / Bulk & Surface?

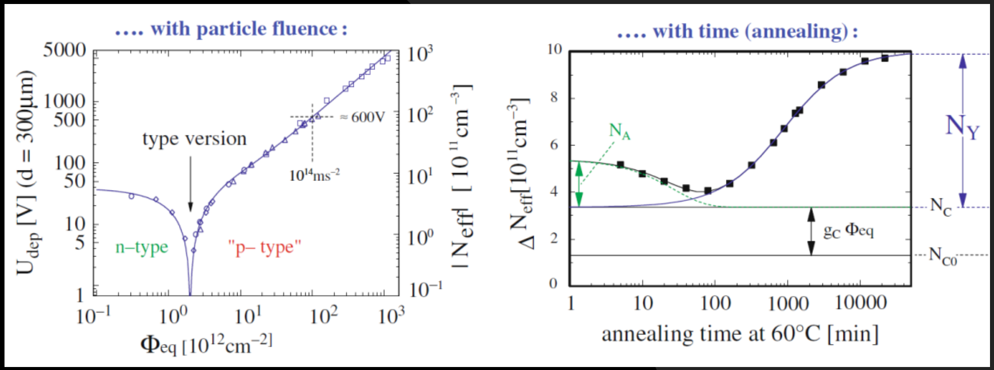




Bulk current dominated this sensor before and after irradiation

Surface current dominated this sensor before irradiation, Bulk dominated after

➔ Looks like, surface current is irrelevant after irrad



Do we see already effects?

Can we *(do we need to)* tune the HH model parameters?

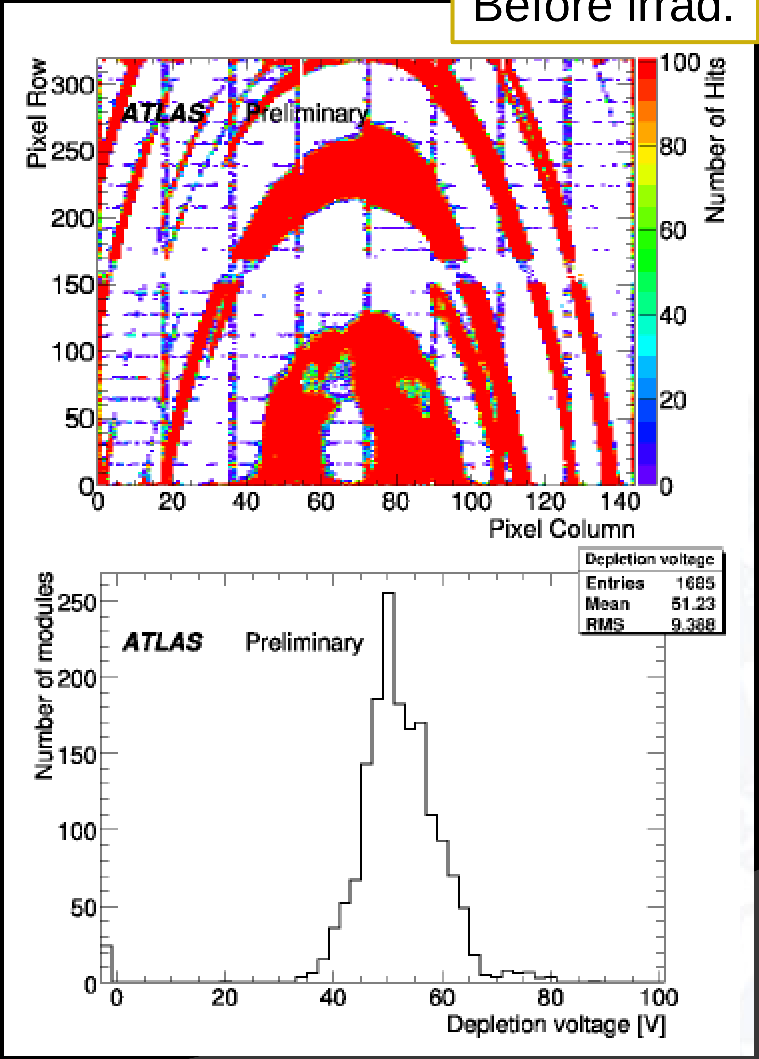
Former design strategies ok?

Depletion Voltage

ATLAS Pixel

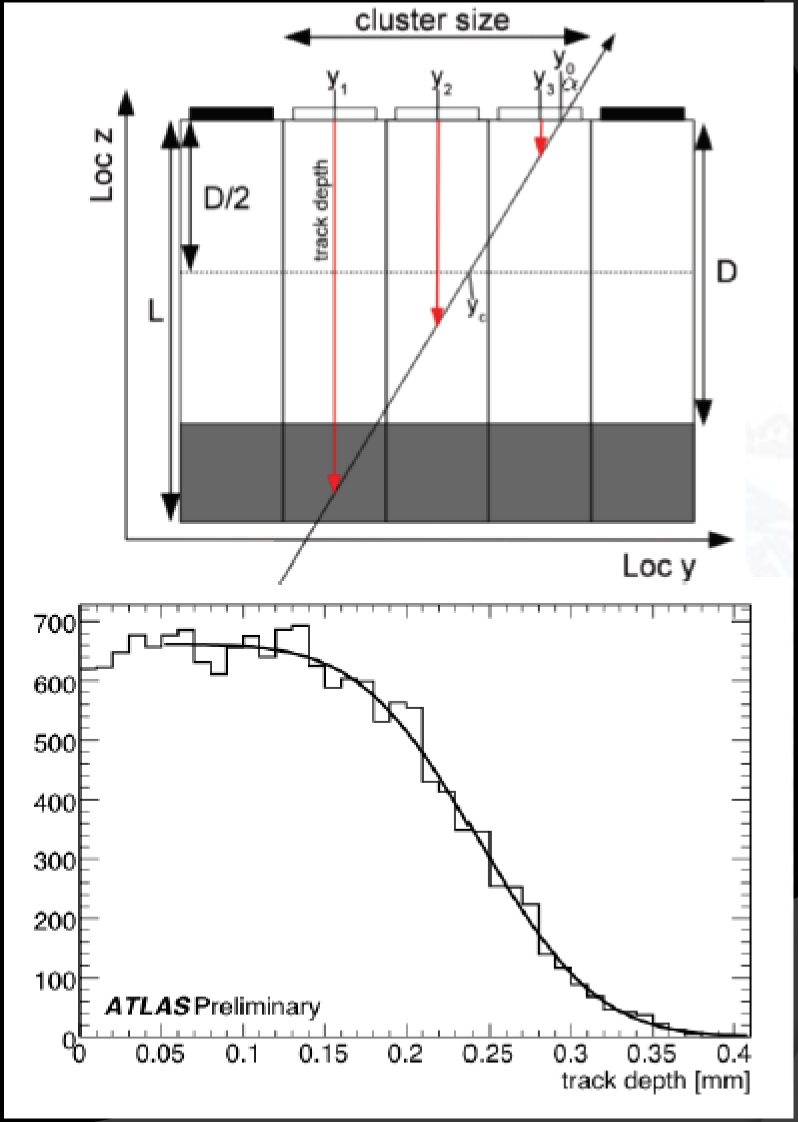
- Strategy **before** type inversion
  - Scan based on inter-pixel cross talk
    - No beam
  - High ohmic short in under-depleted case
  - Capacitive coupling when depleted
  - Inject enough charge into pixel to cause hit in neighbour when below depletion voltage

Before irrad.

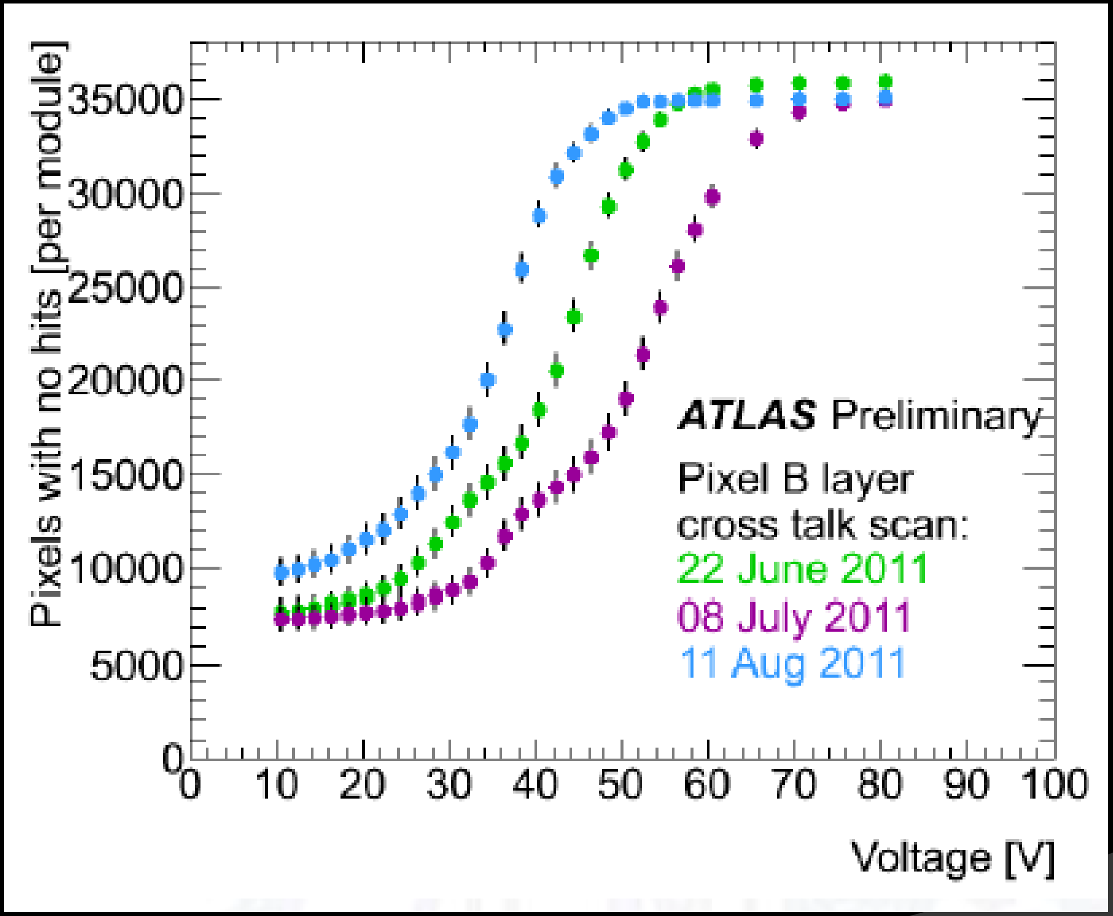


ATLAS Pixel

- **Strategy after type inversion**
  - Determine track segment depth
    - No scan
  - Validation:
    - Before type inversion: hits only if sensor fully depleted
    - Validation yields ~250μm in agreement with sensor thickness



ATLAS Pixel
Evolution of Depletion Voltage



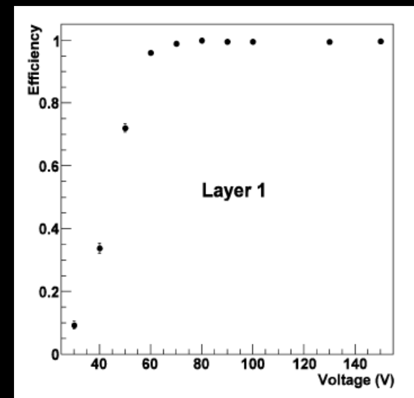
Vdep evolution

Signal vs. Voltage Scans during STABLE BEAM

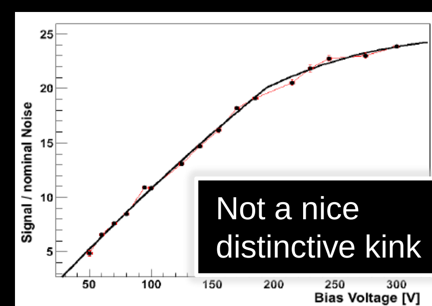
- **Pixel**
  - None
- **SCT**
  - None

ATLAS

- **Pixel**
  - Scan sample modules
    - All sensors from one ingot
  - Semi manual
- **SST**
  - Scan full detector at once
  - Semi manual
  - Use pixel for track seeding
  - Model chip response

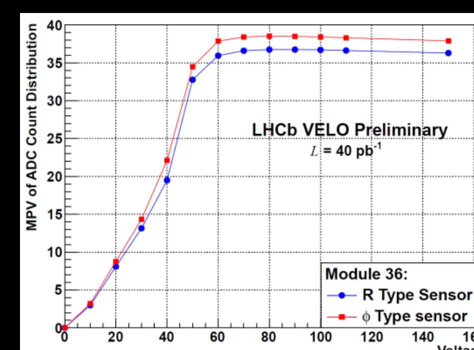


Bpix_BmO_SEC6_LYR1-2_HV1



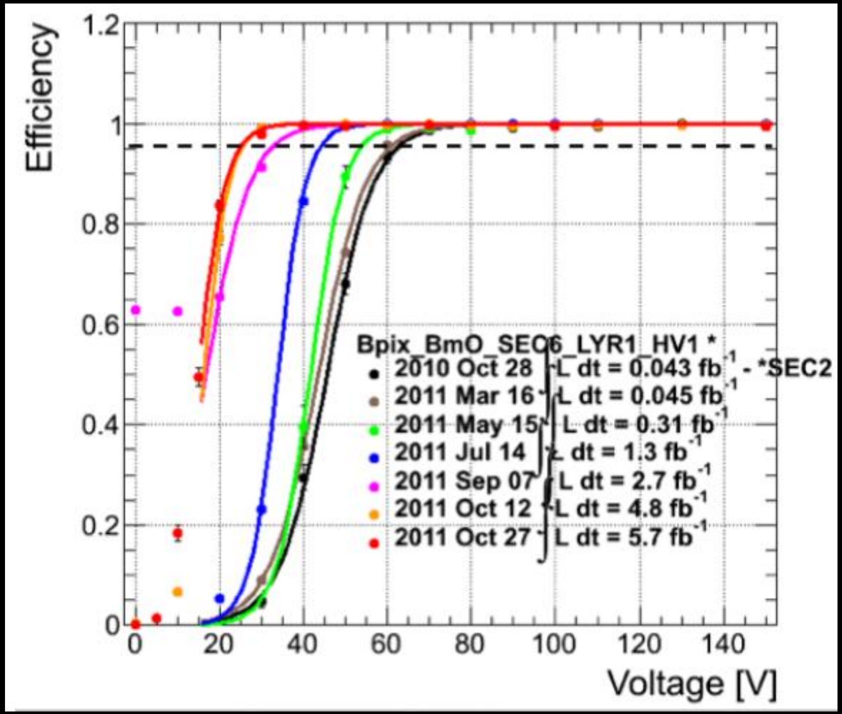
CMS

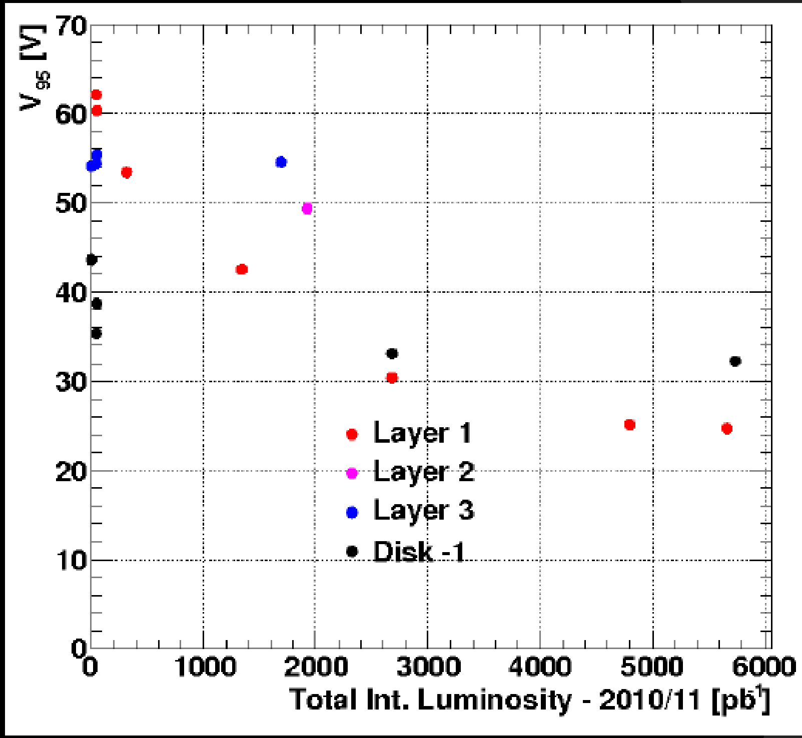
- **VELO**
  - Scan 3 double layers at once
  - Cycle through the layer combinations
  - Fully automated
    - 80% value used matching lab CV



LHCb VELO

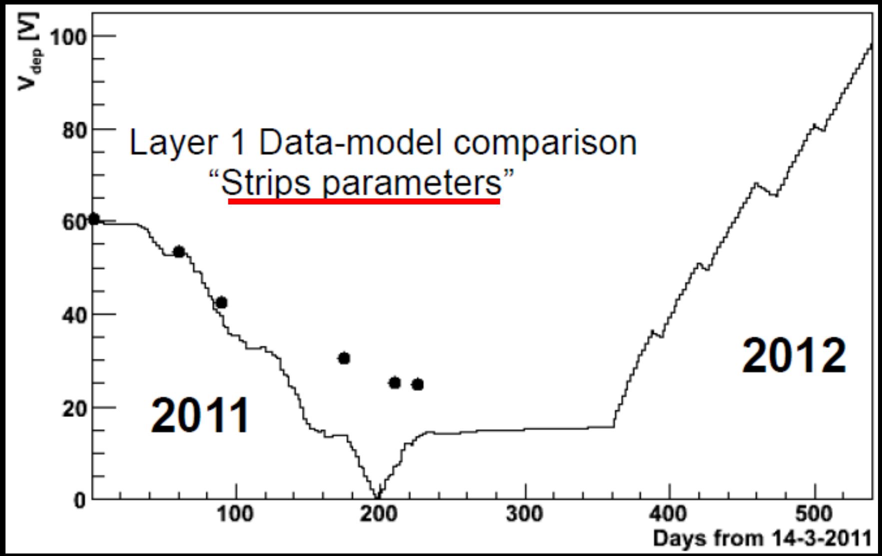
CMS Pixel – Evolution of Depletion Voltage

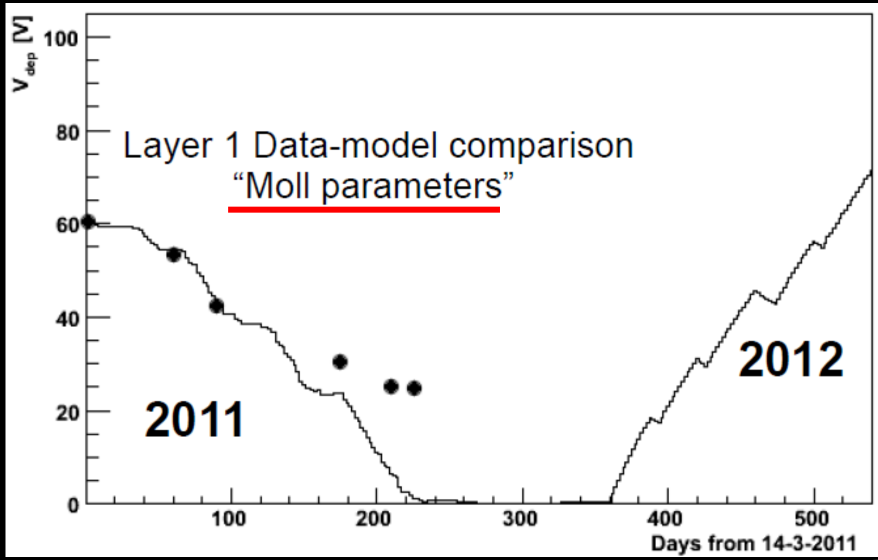




- Voltage scan during Stable Beam
- Take voltage corresponding 95% hitt efficiency $V_{95\%} \sim V_{dep}$

Compare with Model

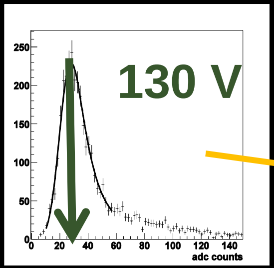


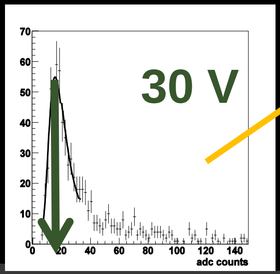


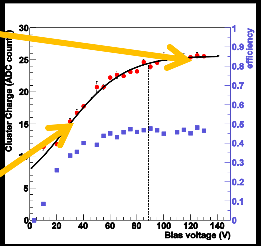
- Model depends on input parameter!
- Which parameters are the correct ones?
  - To be extracted from data
- Do we see signs of inversion?
- Comparing with results from CDF and LHCB VELO we do not expect to arrive at V_{dep}=0V
- Room for improvement

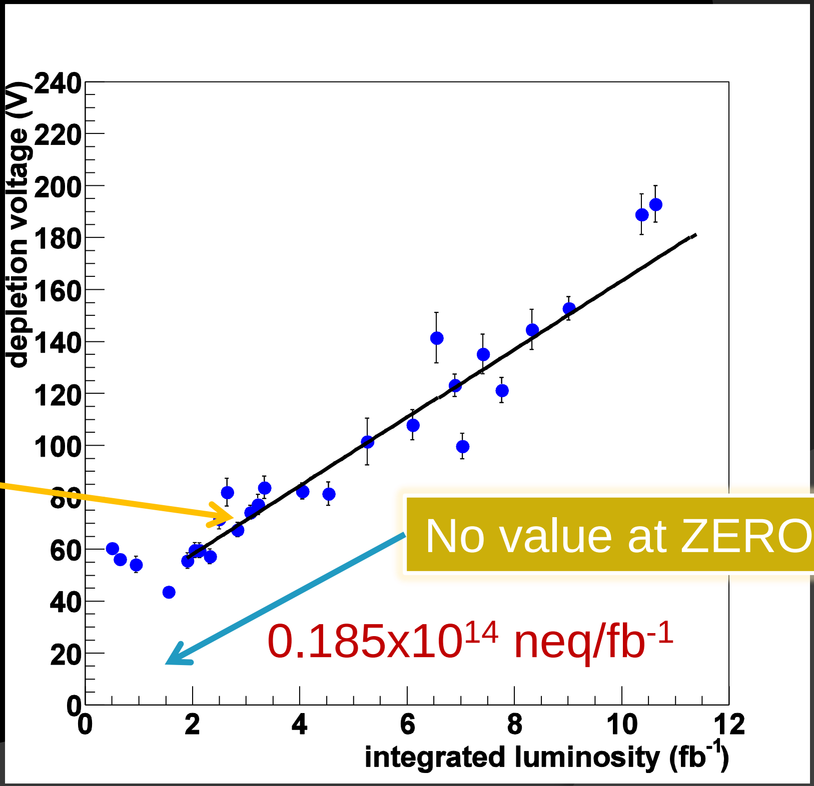
Depletion Voltage Measurement

- Plot collected charge for different bias voltages
- Determine depletion voltage as the minimum voltage that collects 95% of the charge at the plateau
- Extrapolate into the future - linear fit after inversion point









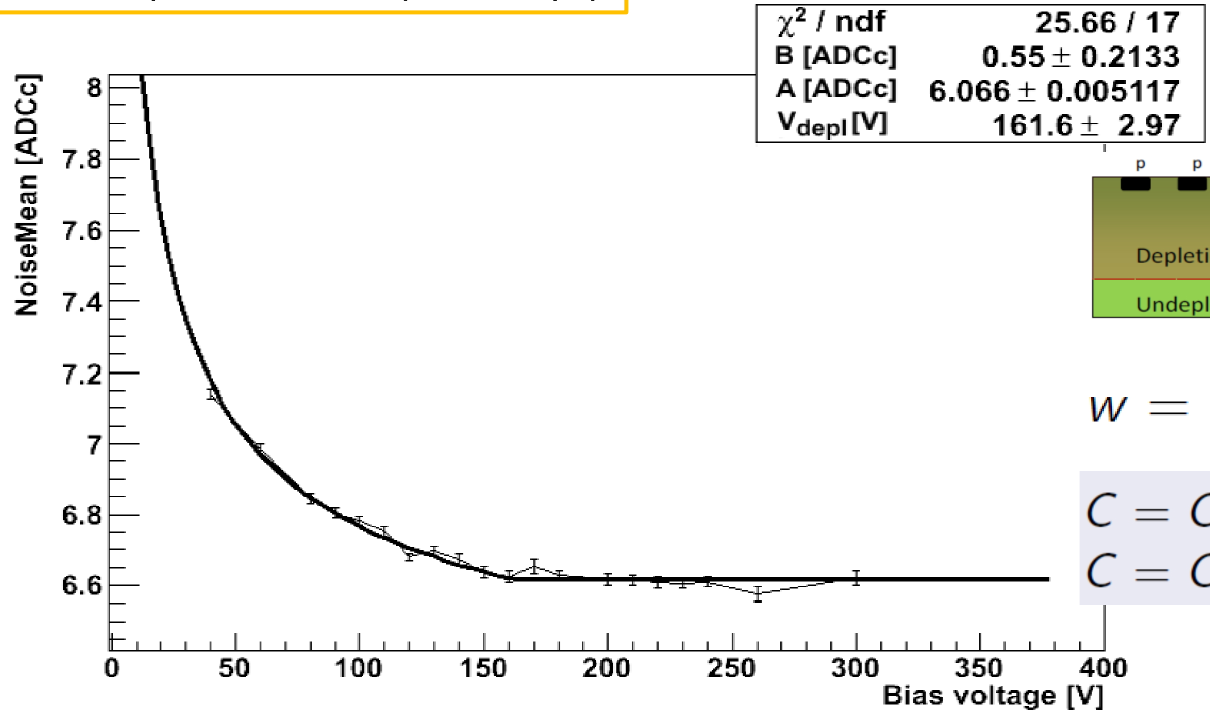
For CMS SST – Case by Case

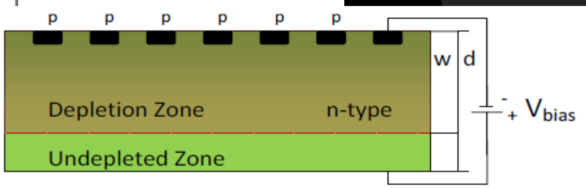
Mind large number of modules/sensors with large variety of initial depletion voltages at many different radii (fluences)

More Detailed Example of Method to Determine Depletion Voltage

$V_{depletion}$ via Noise Measurement

It was not clear from the beginning that we can use this method in p-in-n sensors (CMS strips)





$$w = \sqrt{\frac{2\epsilon_{Si} V}{q|N_{eff}|}} = d\sqrt{\frac{V}{V_{depl}}}$$

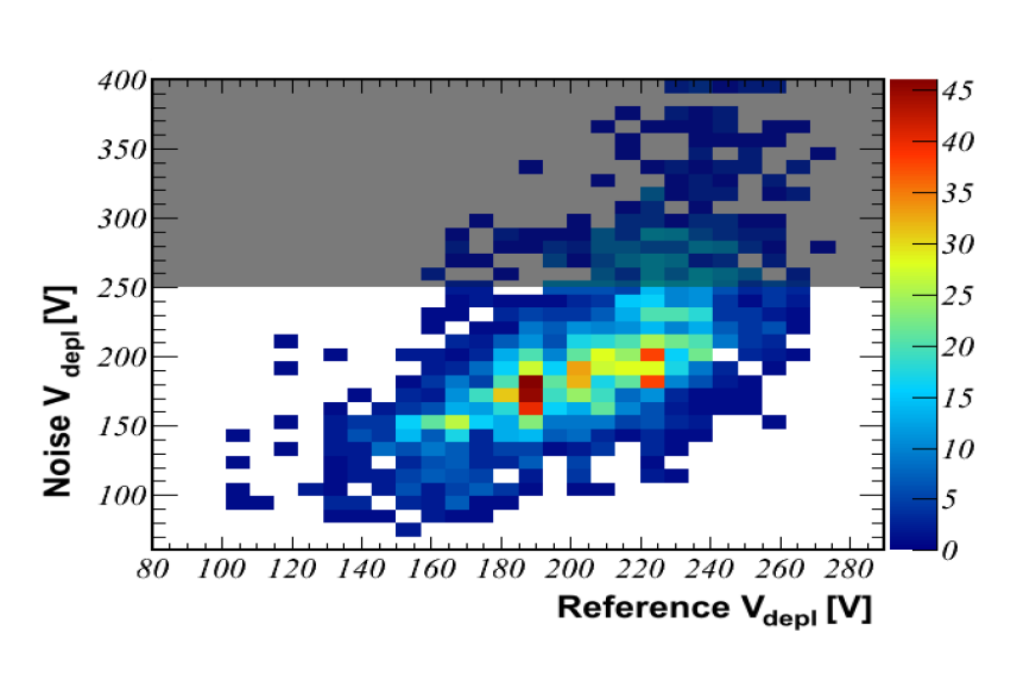
$$C = C_0\sqrt{\frac{V_{depl}}{V}} \quad for \quad V < V_{depl}$$
$$C = C_0 \quad for \quad V \geq V_{depl}$$

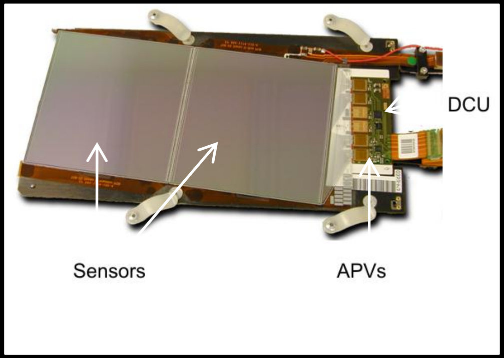
The noise is fitted with

$$n = \sqrt{(A + B \cdot \sqrt{\frac{V_{depl}}{V}})^2 + others^2} \ \ for \ \ V < V_{depl} \quad ; \quad n = n_0 \quad else.$$

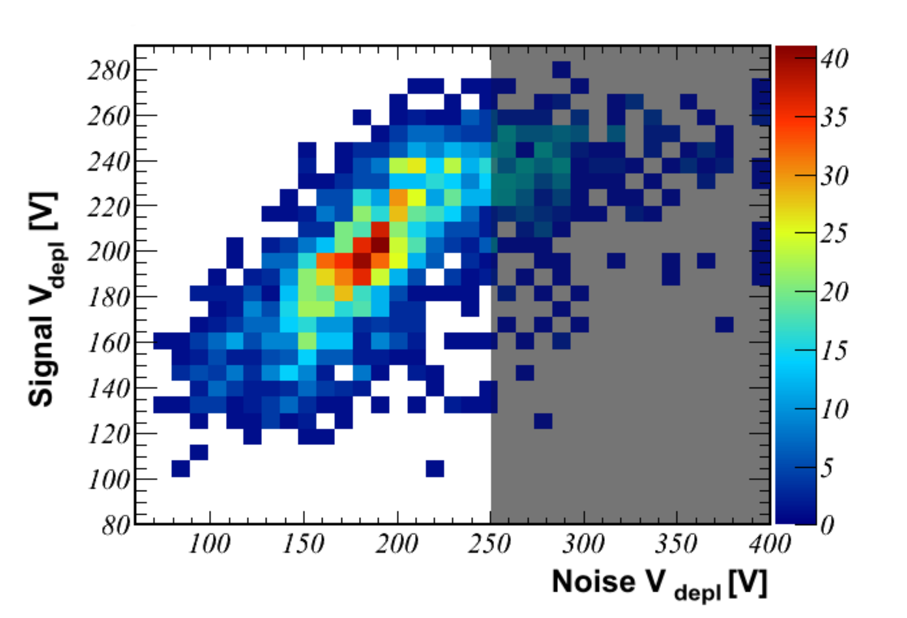
Due to the range of the measurement this leads only to reliable results up to depletion voltages of about 250V.

$V_{depletion}$ from Noise in p-in-n Sensors





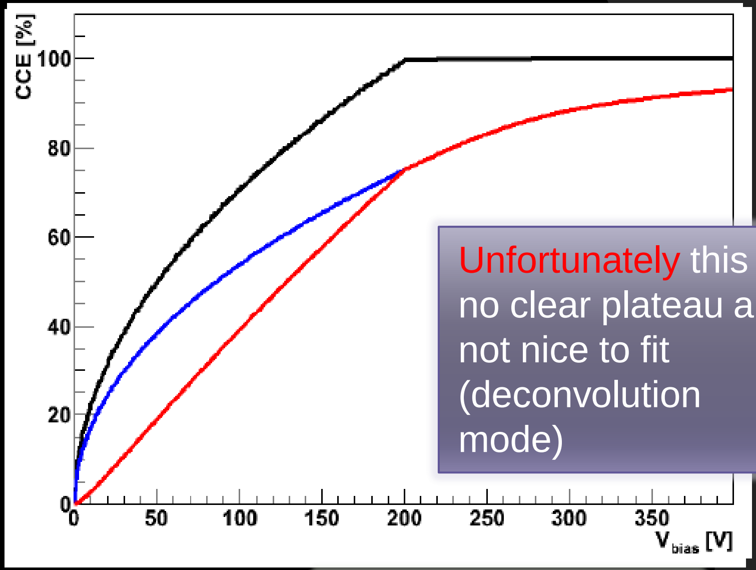
TOB



Reference measurements are from lab CV measurements on full sensor or company CV on diodes

$V_{depletion}$ in the CMS Case from Signal vs. Voltage

- Variation of depletion width changes the amount of charge collected

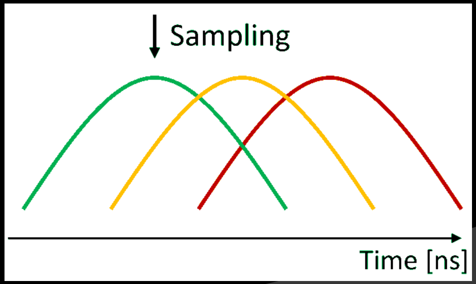


Unfortunately this is no clear plateau and not nice to fit (deconvolution mode)

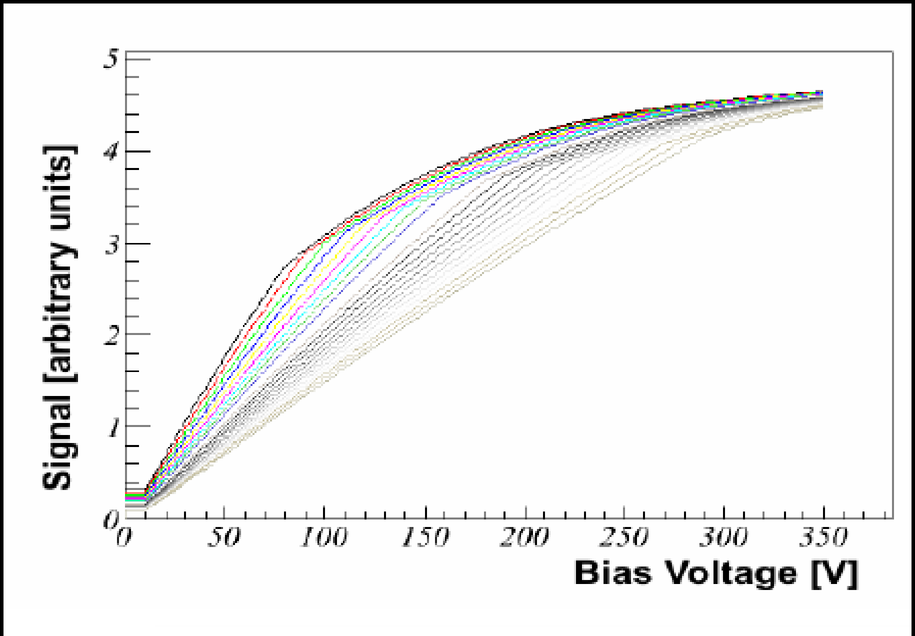
- Change of charge carrier mobility

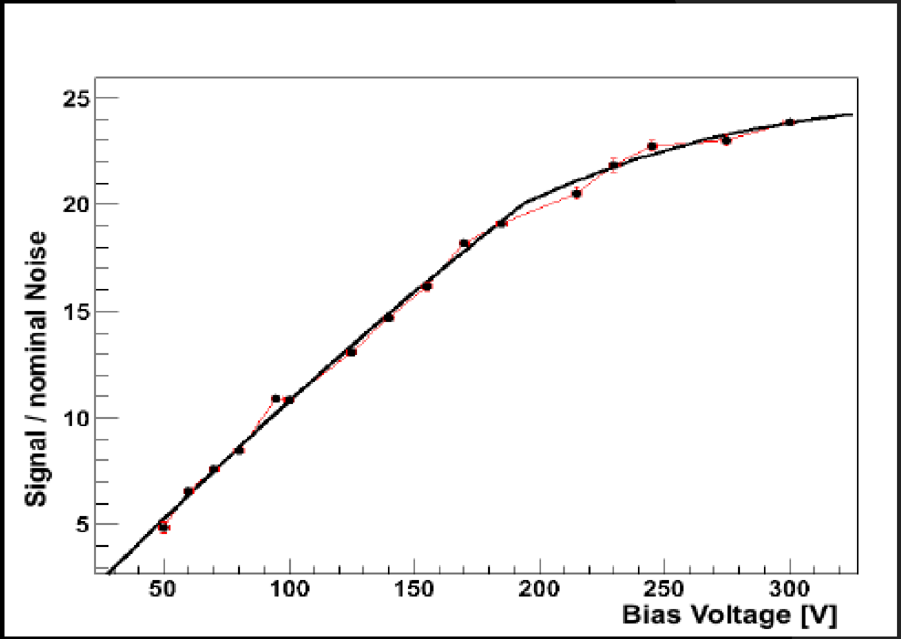
But fortunately the deconvolution mode is very sensitive to the effects

- Change in load capacitance change the signal shaping of the signal pulse thus the measured signal



$V_{depletion}$ from Signal vs. Voltage

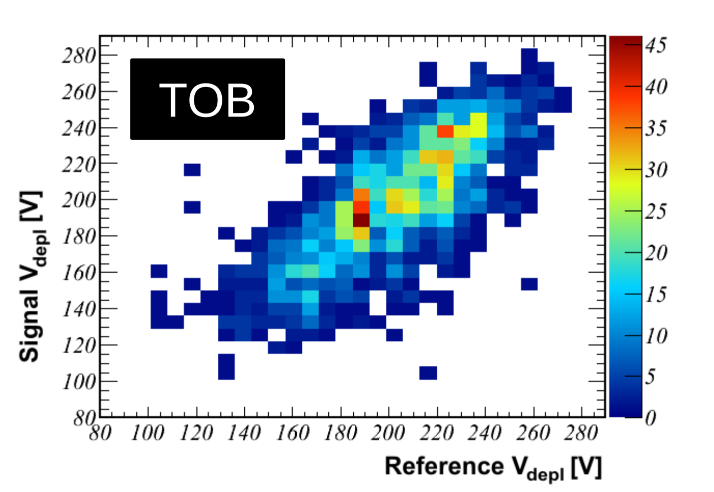


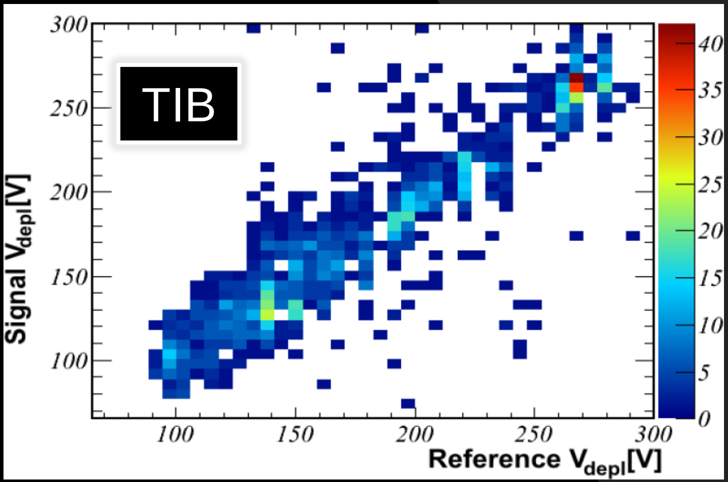


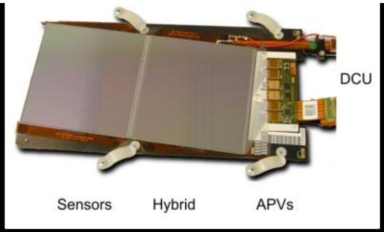
- onTrack cluster with good Landau fits
- Fit graph with pre-modeled curve
  - One for each given voltage

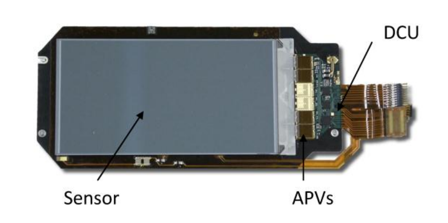
- Frequency:
  - Small bias scan 1/month (0.25% of detector)
  - Full detector scan 2/year

Signal vs. Voltage (during STABLE BEAM)



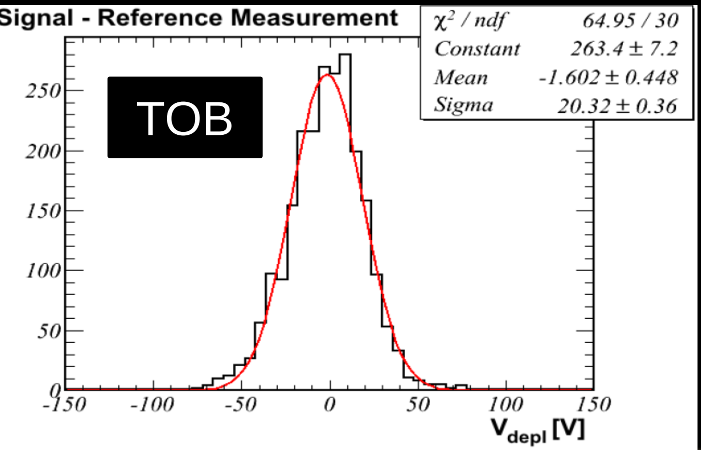


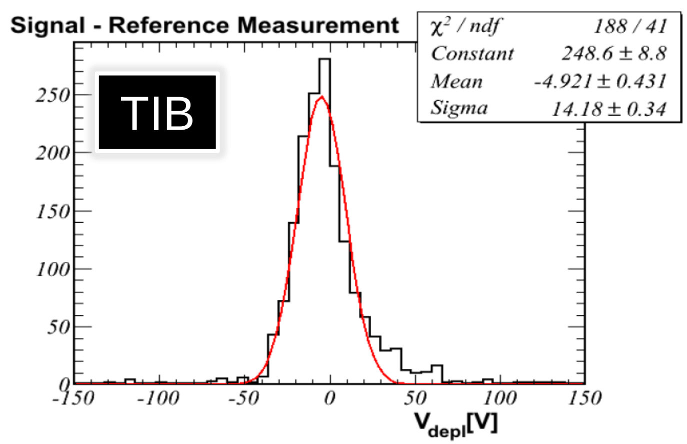




Very good agreement between the results from the signal scan and the reference measurements (especially in TIB partition with only one sensor per module)

➔ Anchor measurement for the future





Within to the accuracy of the measurement “no” significant change in V_{dep} is visible so far (Dec12).

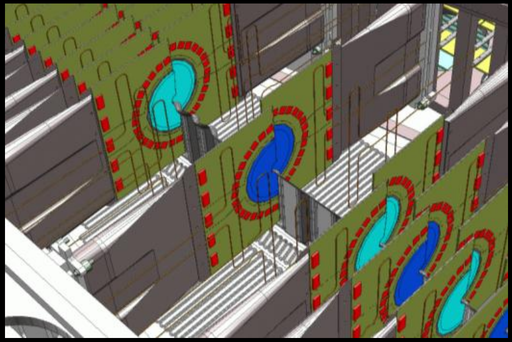
To me the most interesting

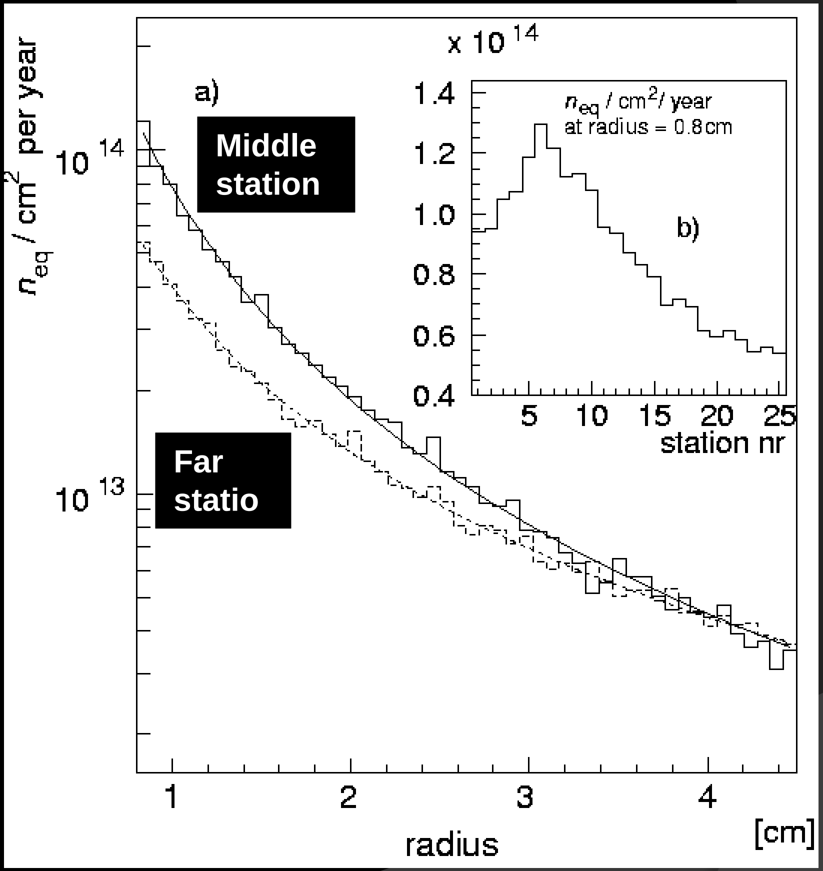
OLEV – VELO *Inverted*

And now to LHCb - VELO

TDR Prediction

- First Strip only 8mm from LHC beam
  - Outer strip 40mm
- Maximum Fluence predicted at 14TeV
  - 1.3×10^{14} 1MeV $n_{eq}/cm^2/2\ fb^{-1}$
- Strongly non-uniform
  - Dependence on $1/r^{1.9}$ and station (z)

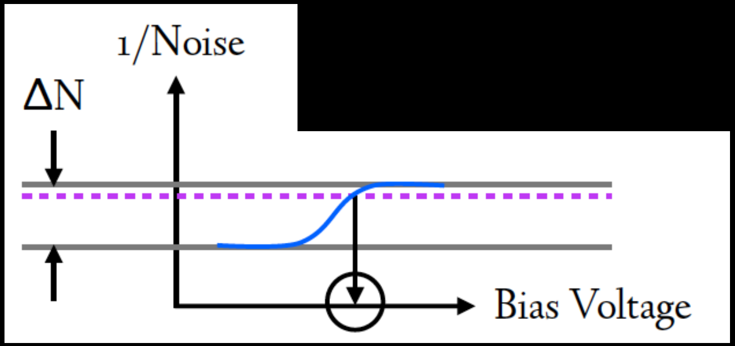




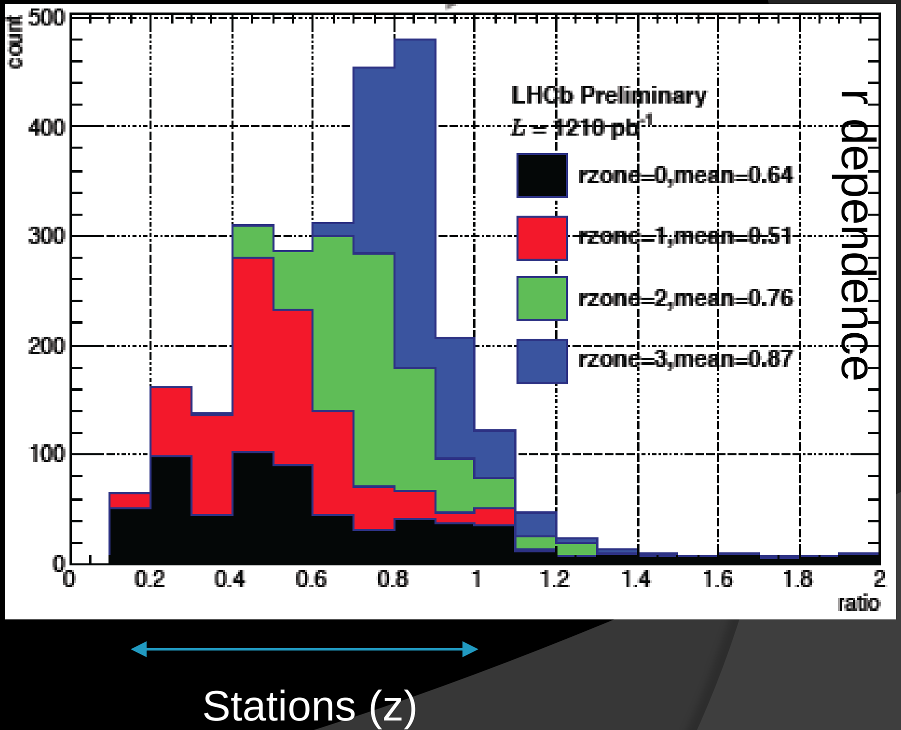
Tips of VELO sensors already inverted

Strategy - Noise vs Voltage

Measure voltage required to get noise to reduce by a specified fraction of the total depleted/undepleted change in noise

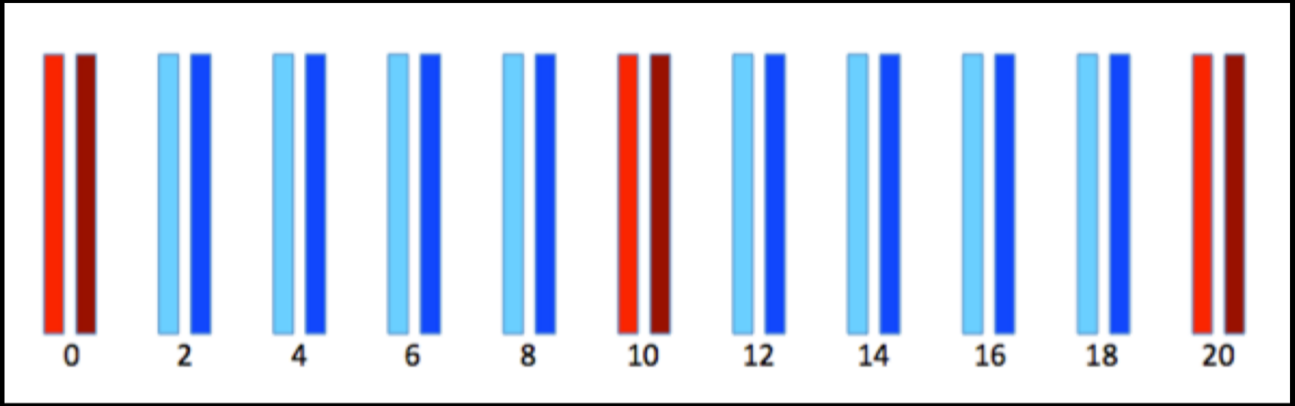


Dependence on $1/r^{1.9}$ and station (z)



- Allows localized analysis
- n-in-n sensor
- Strategy after SCSI to be defined/tested

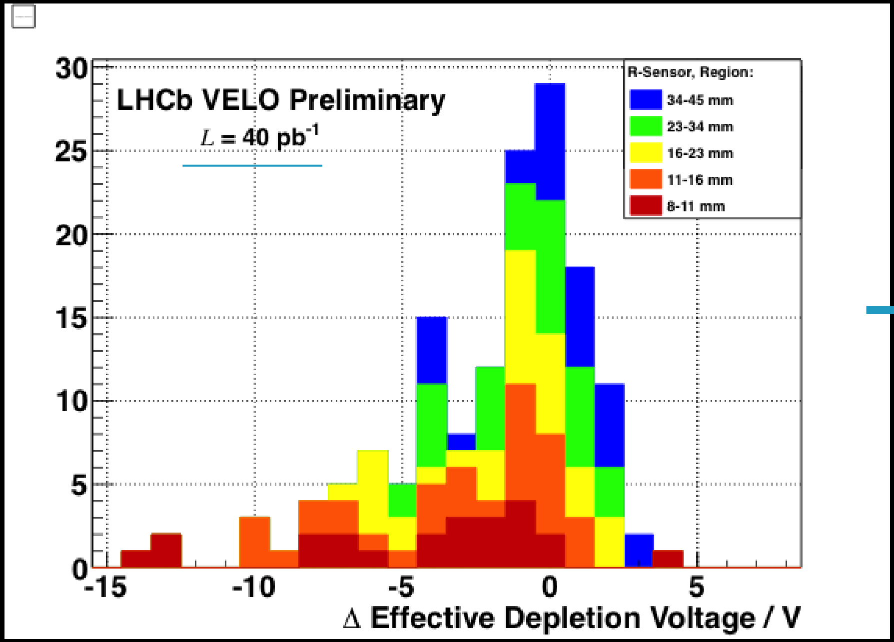
Strategy - Signal vs. Voltage



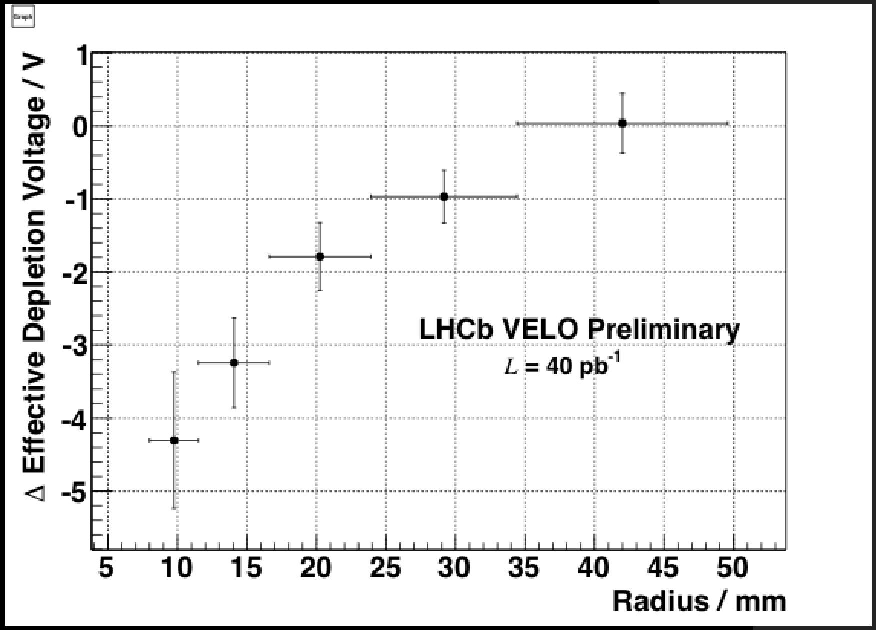
- Blue – tracking sensors – at full bias voltage
- Red – test sensors – bias voltage ramped
  - 10V steps, 0V-150V
  - Rotate through patterns, fully automatic scan procedure

- Tracks fitted through tracking sensors
  - Charge collected at intercept point on test sensors measured as function of voltage
    - Non-zero suppressed data taken so full charge recorded
  - Can study regions of sensor

Signal vs. Voltage
Vdep Changes Clearly Visible



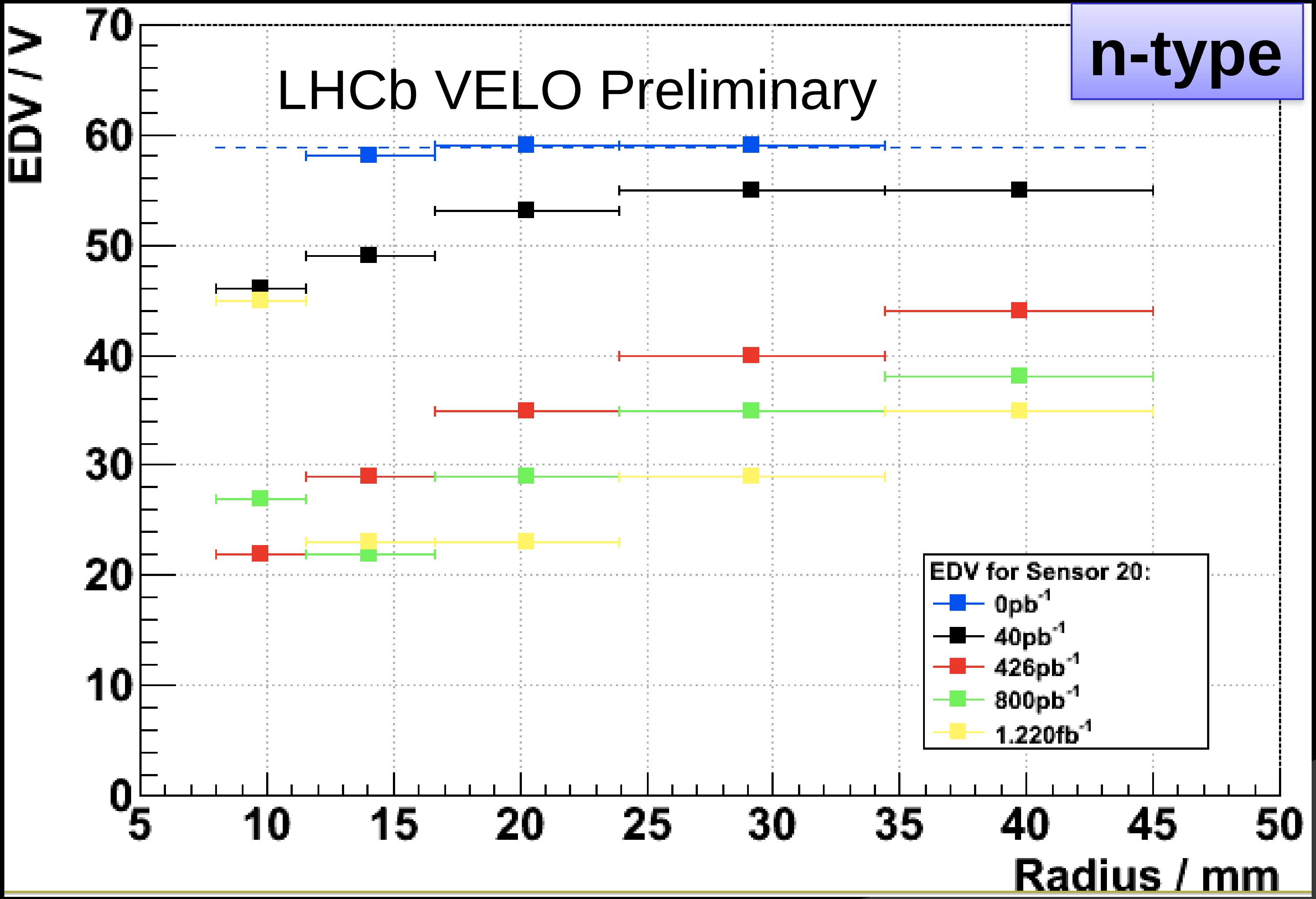
mean



- Charge collection efficiency vs. voltage measured.
- Voltage at which CCE is 80% extracted
  - 80% chosen as gives best agreement un-irradiated with depletion (CV)

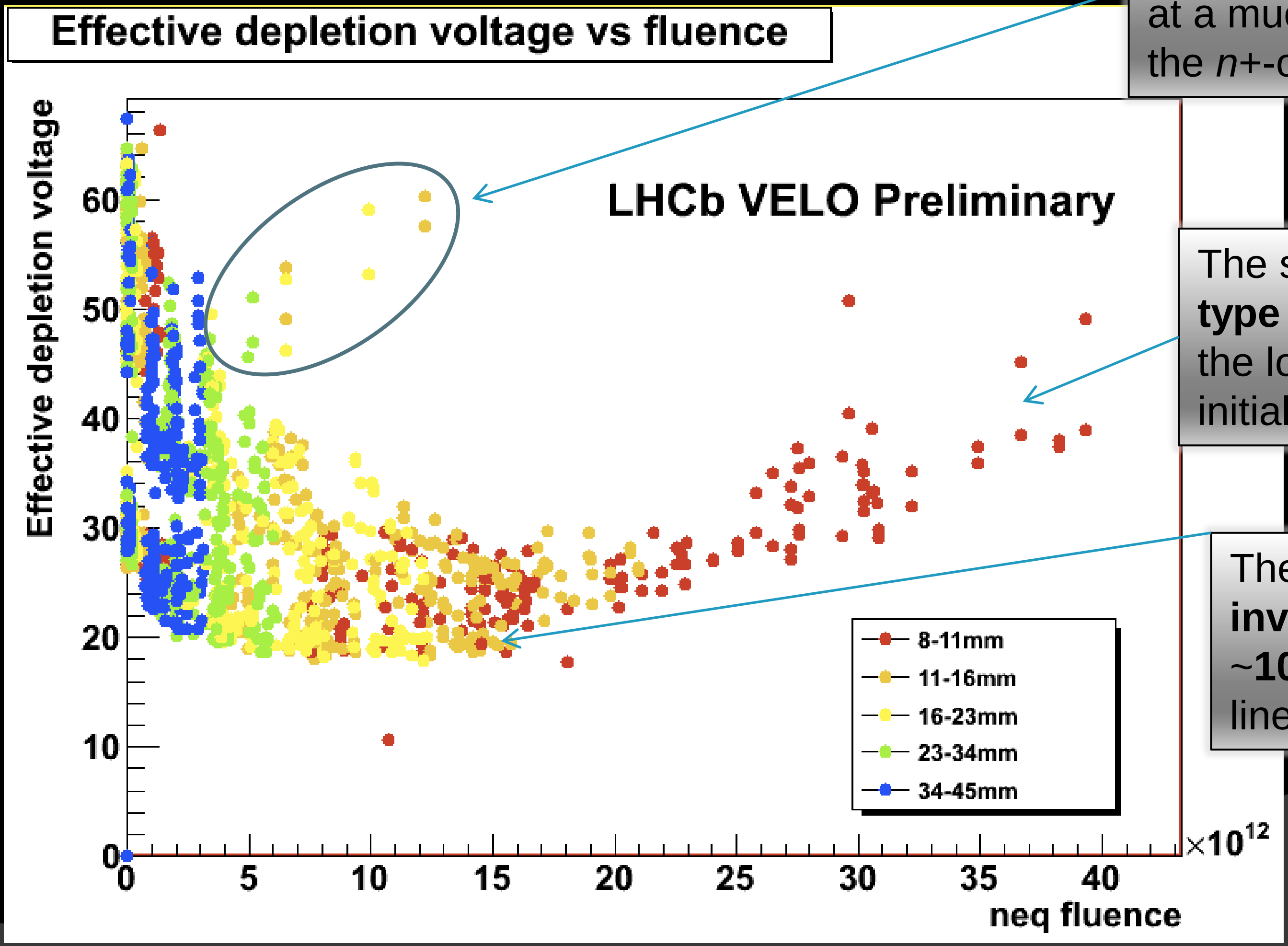
- Dependence on $1/r^{1.9}$ and station (z)

Eff. Depletion Voltage vs. Radius



Eff. Depletion Voltage vs. Fluence

- Measured Effective Depletion voltage versus radius
- Fluence per region per sensor

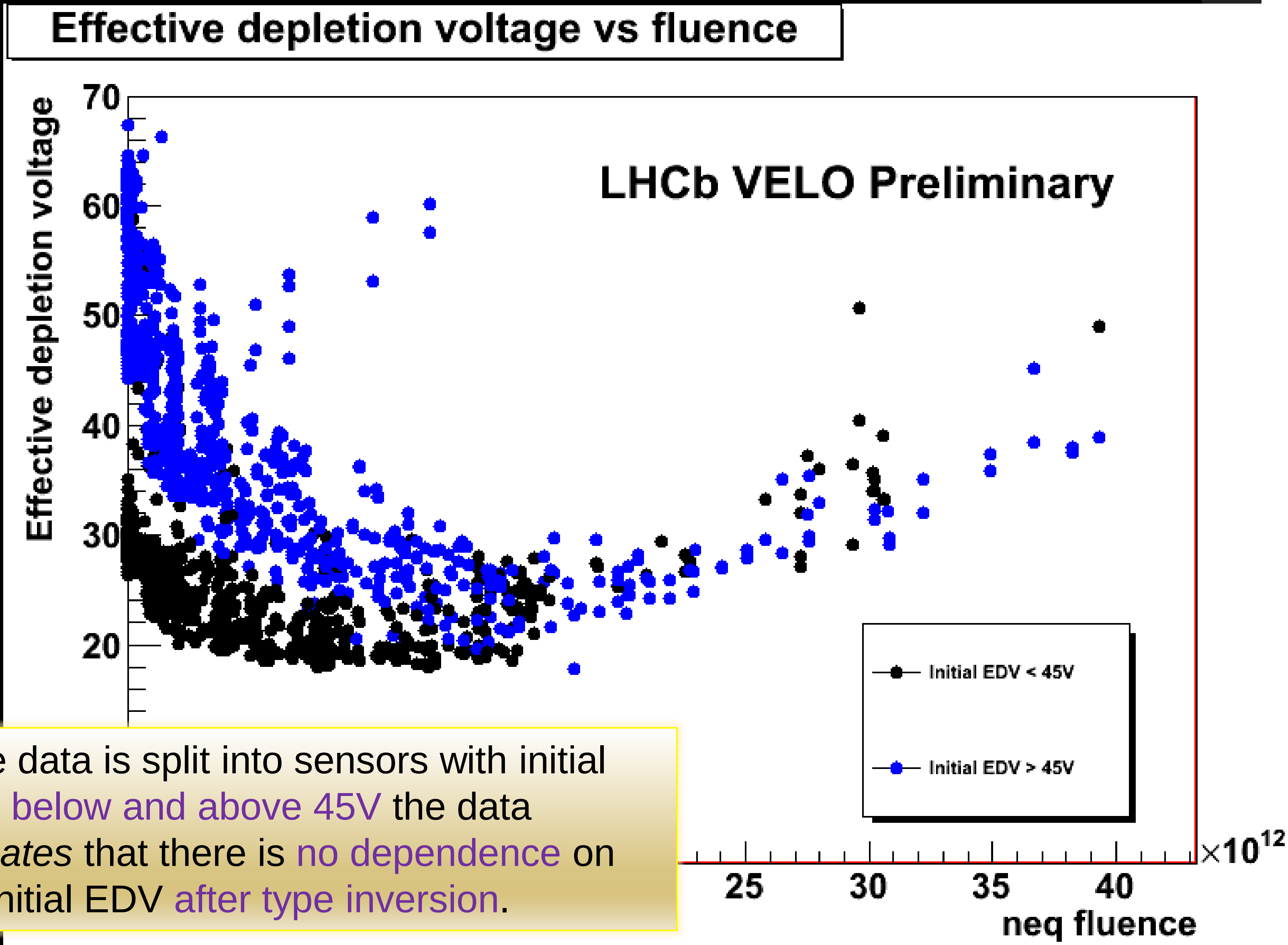


The ***n*+-on-*p* sensors** also see a drop in EDV before increasing at a much lower fluence than the *n*+-on-*n*.

The sensor tips have clearly **type inverted**, as the EDV of the lower radius regions has initial EDV started increasing.

There is a **common inversion point** around **~10^{13} 1 MeV** neq fluence, in line with expectations

Eff. Depletion Voltage vs Fluence

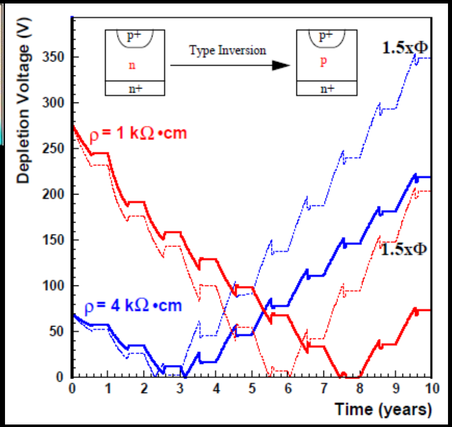


If the data is split into sensors with initial EDV below and above 45V the data *indicates* that there is no dependence on the initial EDV after type inversion.

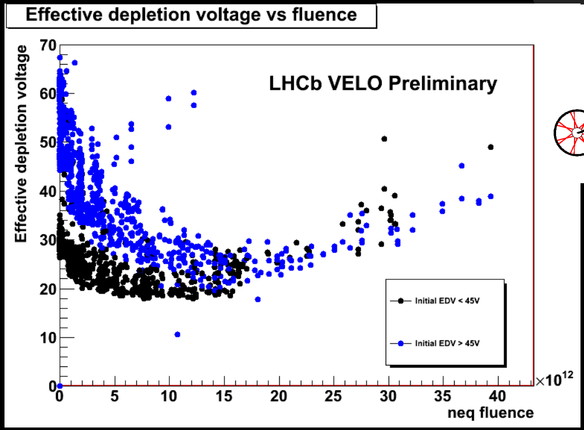
Comments and Conclusion

History and Future - Comment

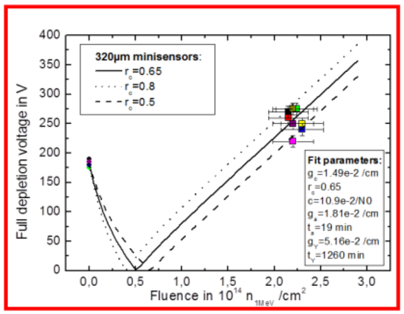
- CMS strategy: Low resistivity silicon to start with a high depletion voltage and end after inversion with a "not so high" depletion voltage
- VELO hint: after inversion the initial doping is washed out.

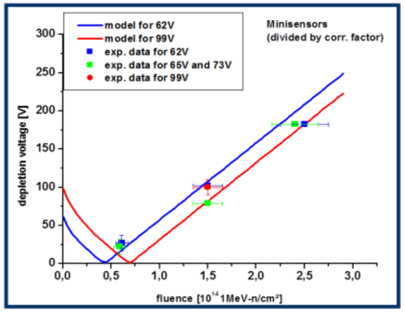


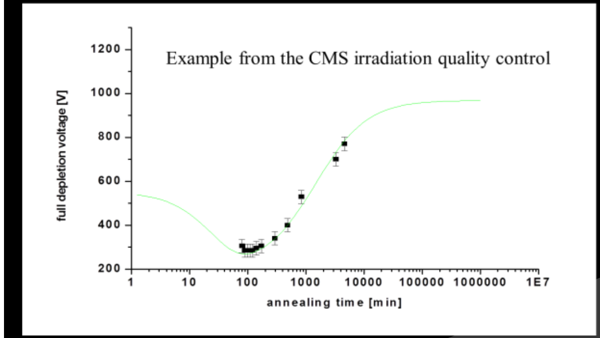
What is the donor removal?
For CMS?
For LHCB?



- CMS did extensive radiation studies during construction to establish the "respective CMS" HH parameters – donor removal not 100%!







- Let's see how much we can constrain the model and corresponding future extrapolation? Useful for upgrade?!?!

How can 10 LHC years in 10 minutes (Zyklotron) be compared with 10 LHC year in 10 years?

Conclusion

The effects of radiation on the silicon sensor is clearly visible in the first 5fb $^{-1}$

- Currents ~ integrated luminosity
  - Normalization for temperature and volume is necessary to allow comparison
  - Annealing clearly visible and needs to be taken into account
    - In a day by day basis
  - First comparison of data to simulation looks ok
  - Uncertainties in
    - FLUKA, multiplicity, scaling and alpha - especially in the annealing term (temperature parametrization!)

- Effects on $V_{depletion}$ are clearly visible
  - VELO partially inverted already
  - Methods to determine $V_{depletion}$ are established
    - Number of scans will remain small – cut into data taking
    - Comparison and HH parameter tuning for $V_{depletion}$ is not yet possible or difficult
      - Annealing not yet seen
    - What is the effective donor removal factor?

- Projections are underway to
  - estimate lifetime or define environment during technical stops or shutdowns
    - CMS: Projections supported the possibility to operate 2012 still at elevated temperatures but not after LS1
  - support the upgrade planning

Big thanks to ATLAS and LHCb to allow me to show and compare strategies & results