Neutron Damage of ATLAS Endcap Alignment CCDs

Camila Pazos, Brandeis University
on behalf of the ATLAS Muon collaboration

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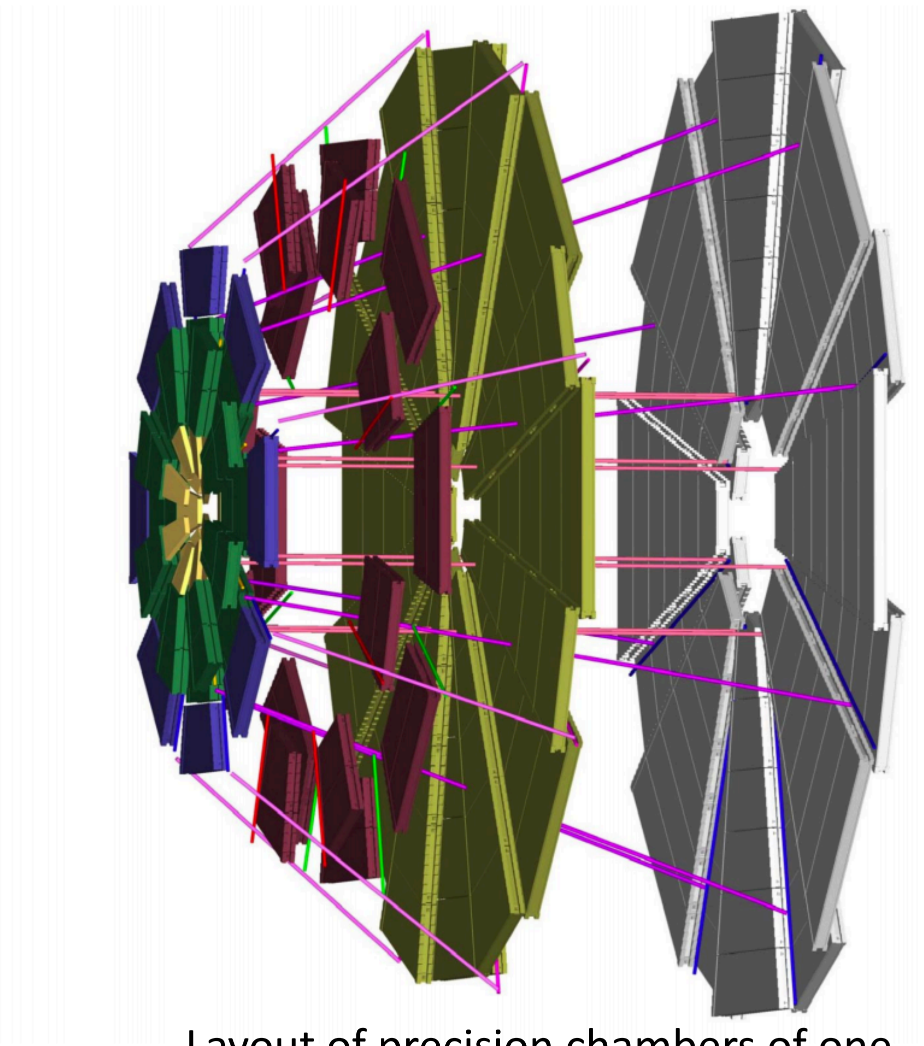
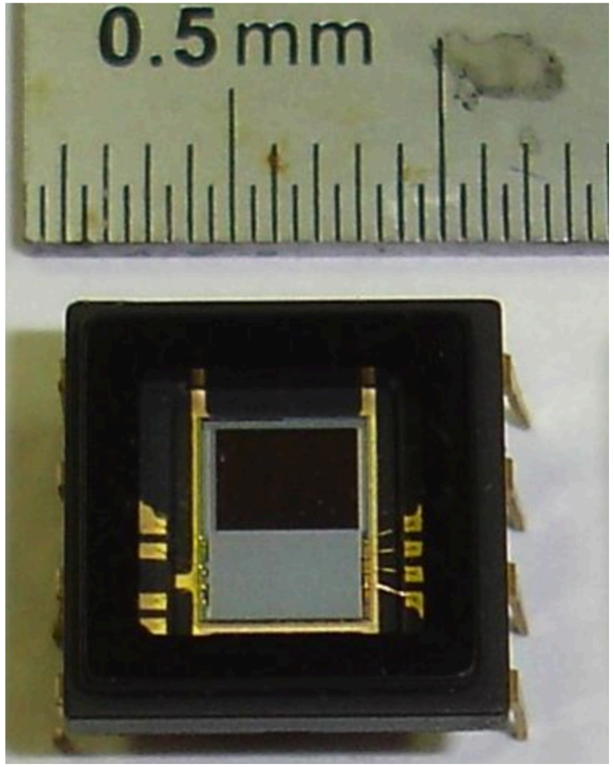


Layout of precision chambers of one ATLAS muon spectrometer endcap

ATLAS Endcap Alignment System & CCDs

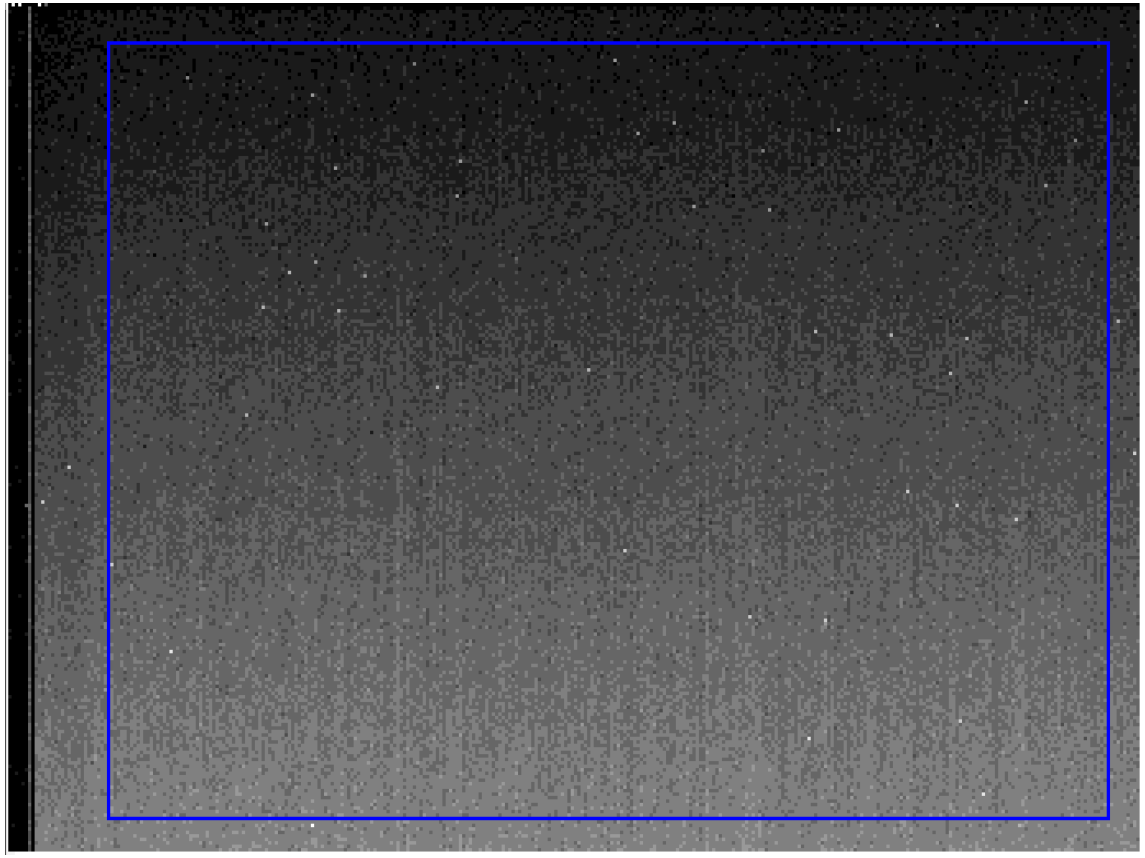
- ATLAS endcap alignment system is based on optical sensors.
  - TC255P image sensors, which are charge-coupled devices (CCDs).
  - In our CCD readouts, pixel intensity is digitized and recorded in ADC counts.
- CCDs can experience a build up of charge in pixels from thermally generated electrons, which is called dark current.
- CCDs have a Silicon crystal lattice structure.
- Neutron irradiation can knock out Si atoms from the crystal lattice, leaving defects that generate dark current.
- Measurements of the amount of dark current in the ATLAS endcap muon alignment system CCDs could be used to measure neutron flux!



TC255P image sensor

Measuring Dark Current

- One way to measure the dark current is by using the vertical slope of the intensity-gradient of an image, which is a result of the 48 ms row-by-row readout.
- We measure dark current in ADC *counts/(pixel*millisecond)* [cnts px^{-1} ms^{-1}].
- We measure neutron equivalent fluence in *10^{12} Si 1 MeVNE cm^{-2}*, which we abbreviate to Tn.
- In order to measure the total neutron flux, we need to know the dark current per neutron equivalent fluence, i.e. [cnts px^{-1} ms^{-1} Tn^{-1}].



Vertical intensity gradient of a neutron-irradiated CCD.

Measuring Dark Current

We model the relationship between dark current and neutron equivalent fluence with the equation

$$I = \alpha\, D\, e^{(T-20°\mathrm{C})/(12°\mathrm{C})} \quad \text{cnts px}^{-1}\ \text{ms}^{-1}$$

where,

I is dark current in cnts px^{-1} ms^{-1}

D is the 1 MeV neutron equivalent fluence in Si in 10^{12} cm^{-2} [Tn]

T is temperature in Celsius [°C]

α is a rate constant that describes the dark current generated per Si 1 MeV neutron equivalent fluence in cnts px^{-1} ms^{-1} Tn^{-1}

Pre-ATLAS Experiments

Lowell Experiment:

- In 1998, four TC255P CCD heads were subjected to varying neutron doses (between 2.0 Tn and 8.0 Tn) over 9 hours with a neutron source at University of Massachusetts at Lowell.

$$I = 0.28\ D\ e^{(T - 20°\mathrm{C})/(12°\mathrm{C})}\ \mathrm{cnts\ px^{-1}\ ms^{-1}}$$

PROSPERO Experiment:

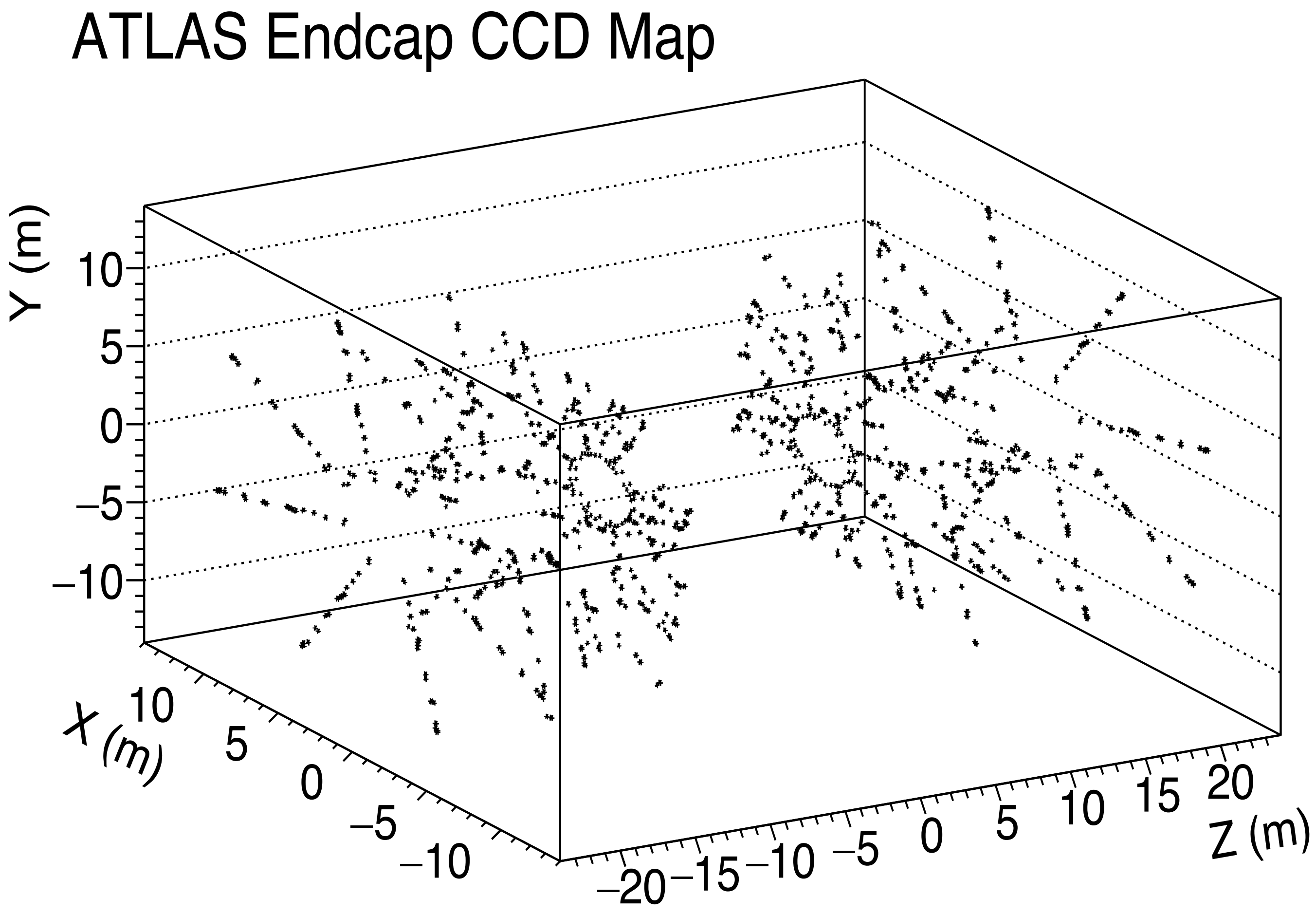
- The following year, 8 TC255P CCD heads were sent to the PROSPERO reactor in France. They received neutron doses between 0.5 Tn and 10.0 Tn.

$$I = 0.26\ D\ e^{(T - 20°\mathrm{C})/(12°\mathrm{C})}\ \mathrm{cnts\ px^{-1}\ ms^{-1}}$$

ATLAS Endcap Alignment CCDs

Data Set Information

- Dark images were captured with 100 ms exposure by each CCD in the ATLAS endcap alignment system and analyzed to find dark current due to neutron damage.
- Images from 2670 CCDs per data set.
- We record the average temperature in the ATLAS endcaps for each data set.
- 30 data sets collected between 2016 - 2018.

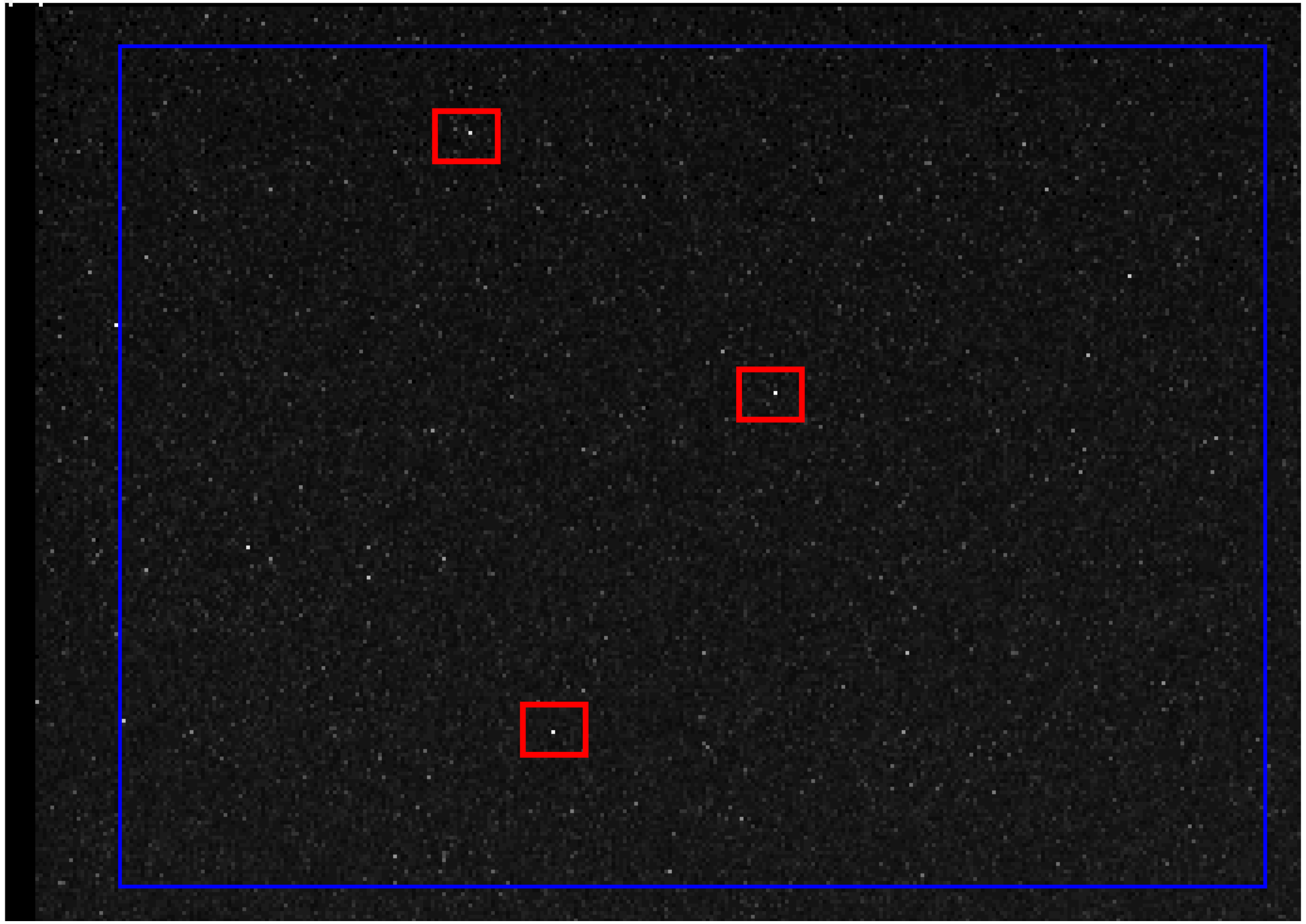


Dark Current Measurement Method in ATLAS Endcap Alignment CCDs

- Simulated neutron equivalent fluence in the ATLAS endcaps is below 0.01 Tn where most of our CCDs are located.
- At low neutron equivalent fluence (<0.01 Tn), the intensity-gradient due to neutron damage is not steep enough to measure dark current with the slope.
- The intensity-gradient slope method can be reliably used on 247 out of 2670 ATLAS endcap alignment CCDs.
- We use a combination of the intensity-gradient method and the bright-pixel method to measure dark current in ATLAS endcap alignment CCDs.
- The bright-pixel measurement method:
  - Has better dark current measurement for CCDs exposed to low neutron equivalent fluence
  - Allows us to follow specific damaged pixel over time
  - Can filter out single-event occurrences
  - Gives a dark current factor that is linearly correlated to the dark current as measured by the intensity-gradient slope

Bright-Pixel Measurement Method

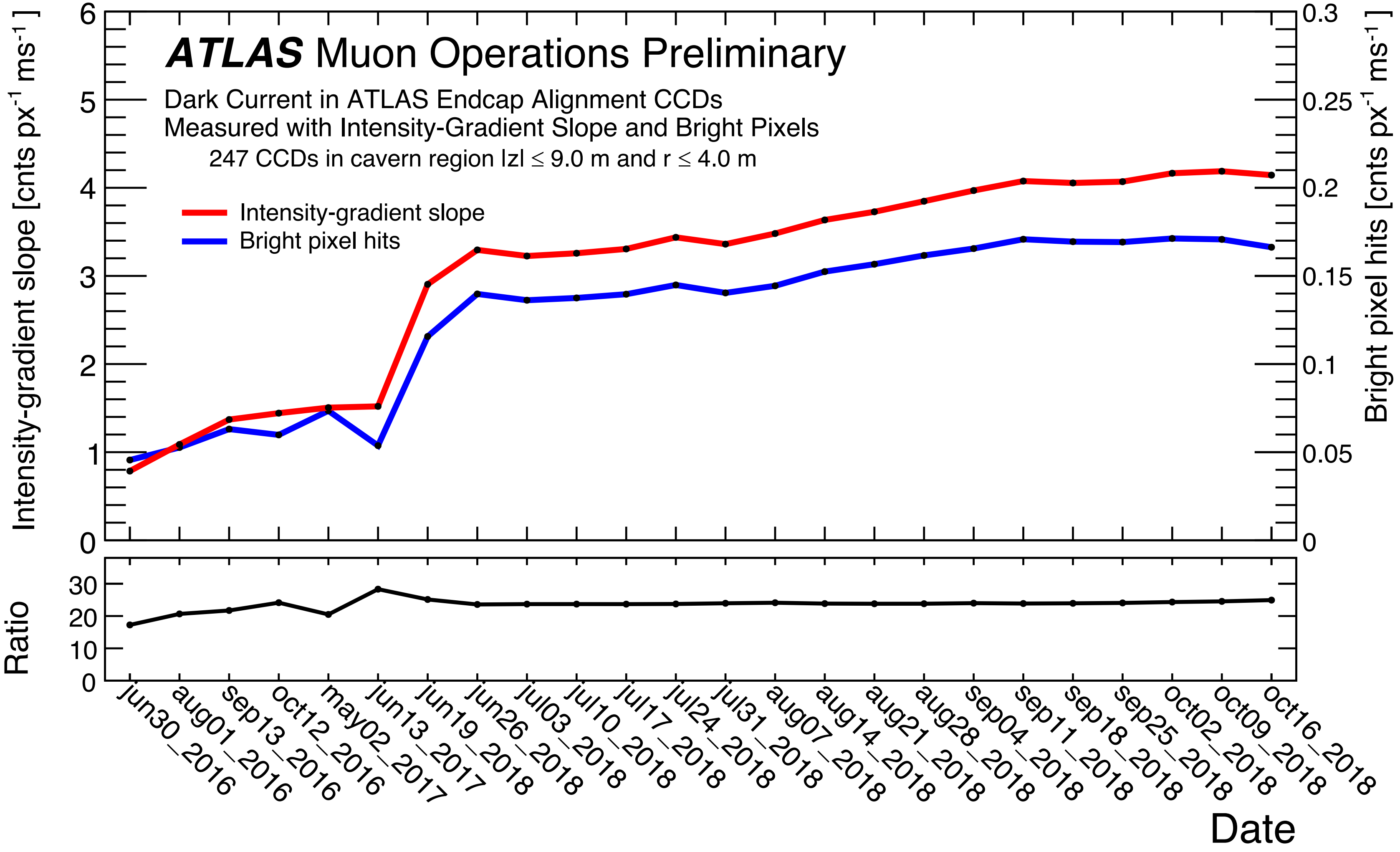
- When a damaged CCD is exposed in darkness, bright pixels appear in the dark image as a result of dark current.
- The bright-pixel measurement records pixels with an intensity more than 10 counts above average. The sum of these intensities across a CCD, divided by the number of pixels and by the exposure time gives a dark current measure in cnts px^{-1} ms^{-1} .
- This bright-pixel measurement is linearly correlated to the CCD dark current as measured with the intensity-gradient slope.



Dark current image at 100 ms exposure with 3 pixels marked.

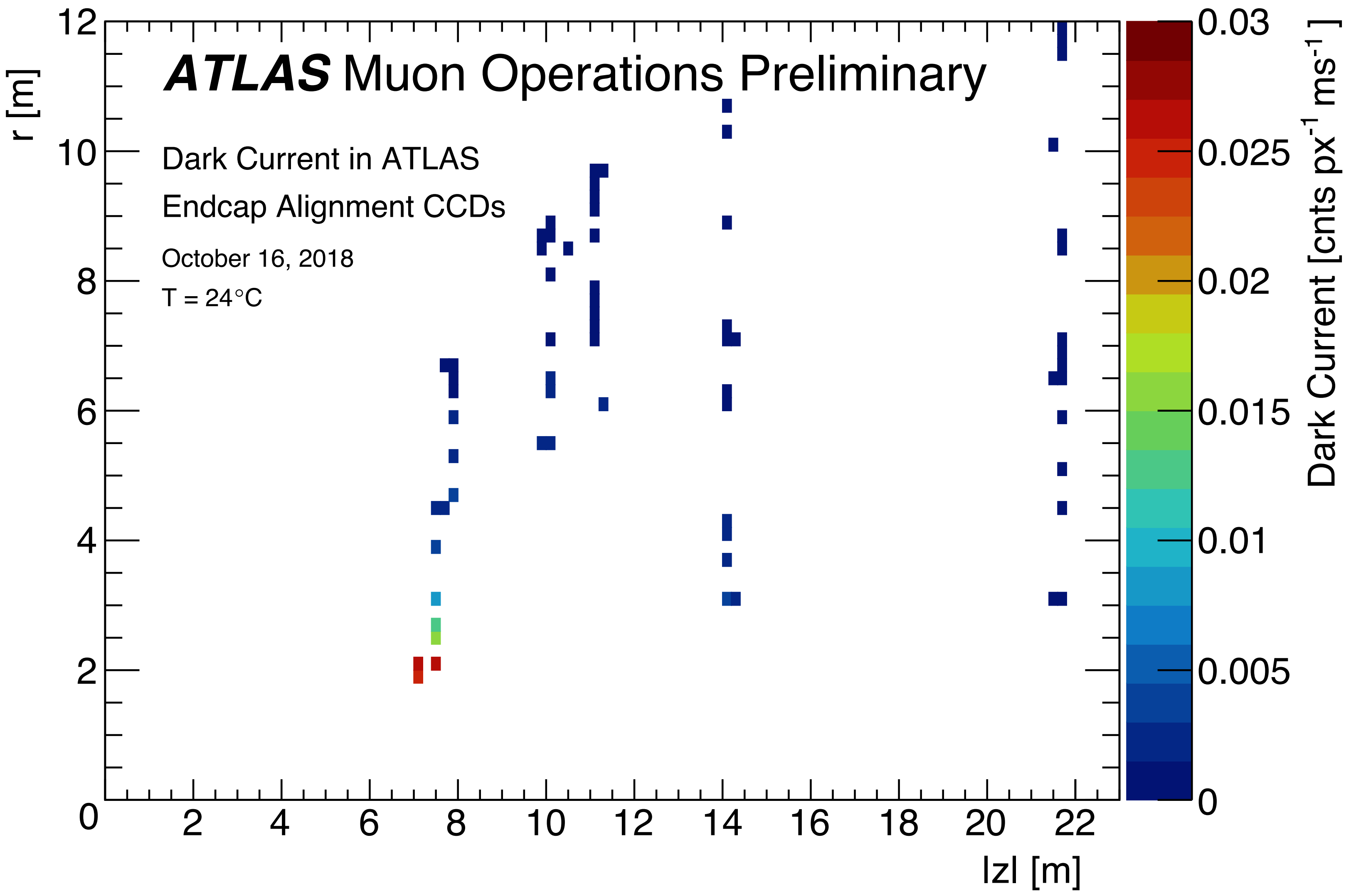
Dark Current Measured in ATLAS Endcap Alignment CCDs

- Data sets from a set of 247 ATLAS endcap alignment CCDs that received at least 0.02 Tn were analyzed using both methods.
- We find a linear relationship between the bright-pixel dark current and the intensity-gradient slope, and use the ratio to calibrate our ATLAS endcap alignment CCD bright pixel measurements.



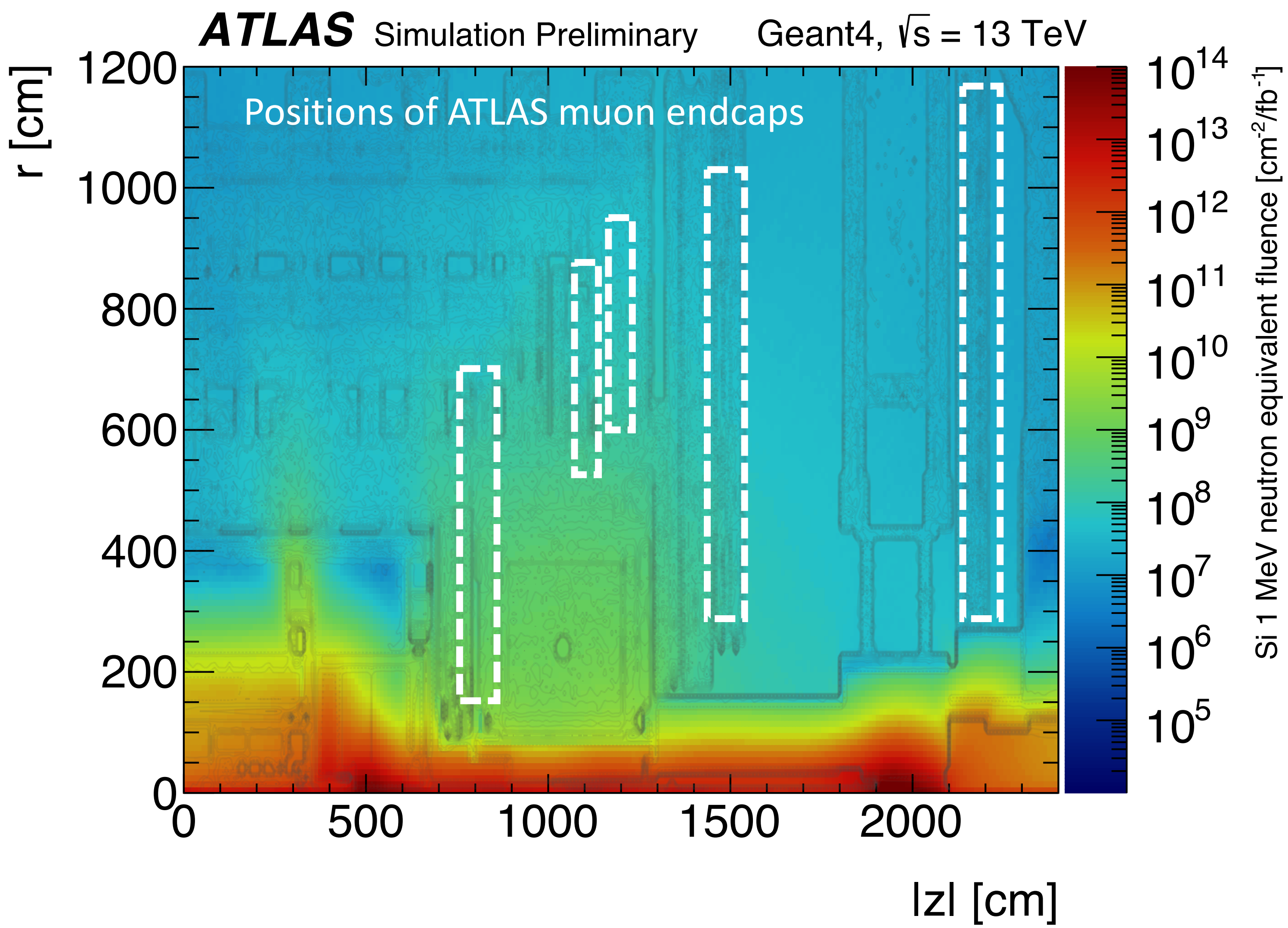
Dark Current Measured in ATLAS Endcap Alignment CCDs

- We measured all dark current (using bright pixels) present in endcap alignment CCDs in ATLAS on October 16, 2018.
- We scaled the measurement by our calibration constant (x24) to obtain the intensity-gradient slope equivalent measure of dark current.
- The dark current decreases with distance from IP along the beam line and radius from the beam line as expected.
- Max = 0.027 cnts px^{-1} ms^{-1}
  Min = 0.0002 cnts px^{-1} ms^{-1}



Geant4 Simulated Neutron Equivalent Fluence in ATLAS

- Using a simulated Geant4 neutron equivalent fluence (shown on the right) we can find the total neutron equivalent fluence at our CCD locations in ATLAS.
- We scale the simulated neutron equivalent fluence by the total delivered integrated luminosity.
- The total ATLAS delivered integrated luminosity for combined Run1 (scaled for $\sqrt{s} = 13$ Tev) and Run2 was 170 fb^{-1} on October 16, 2018.

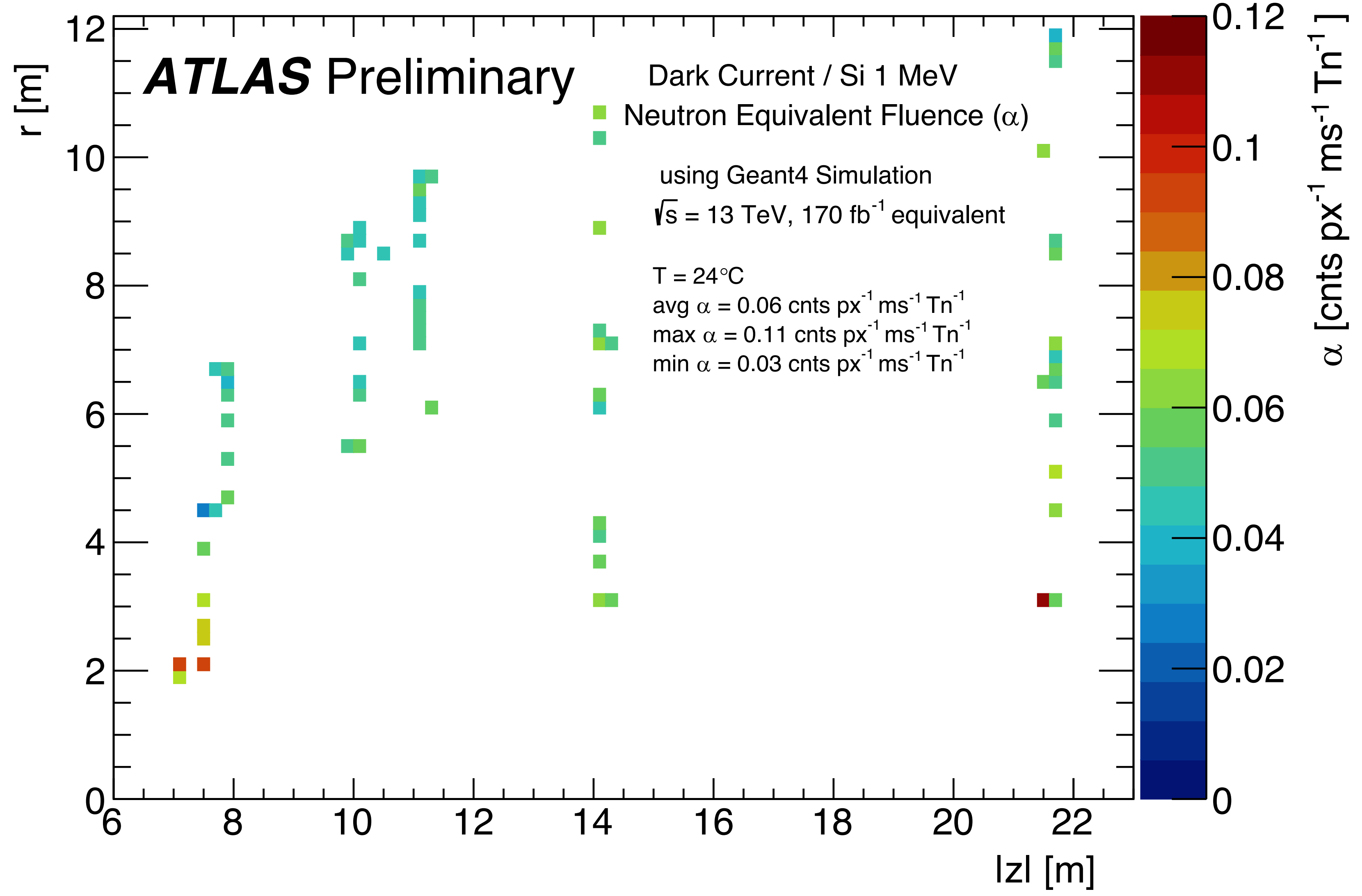


Dark Current / Geant4 Simulated Neutron Equivalent Fluence

The α values of ATLAS endcap muon alignment CCDs mapped in r and |z|. Averages over all CCDs within any 20 × 20 cm² bin are shown on a color scale.

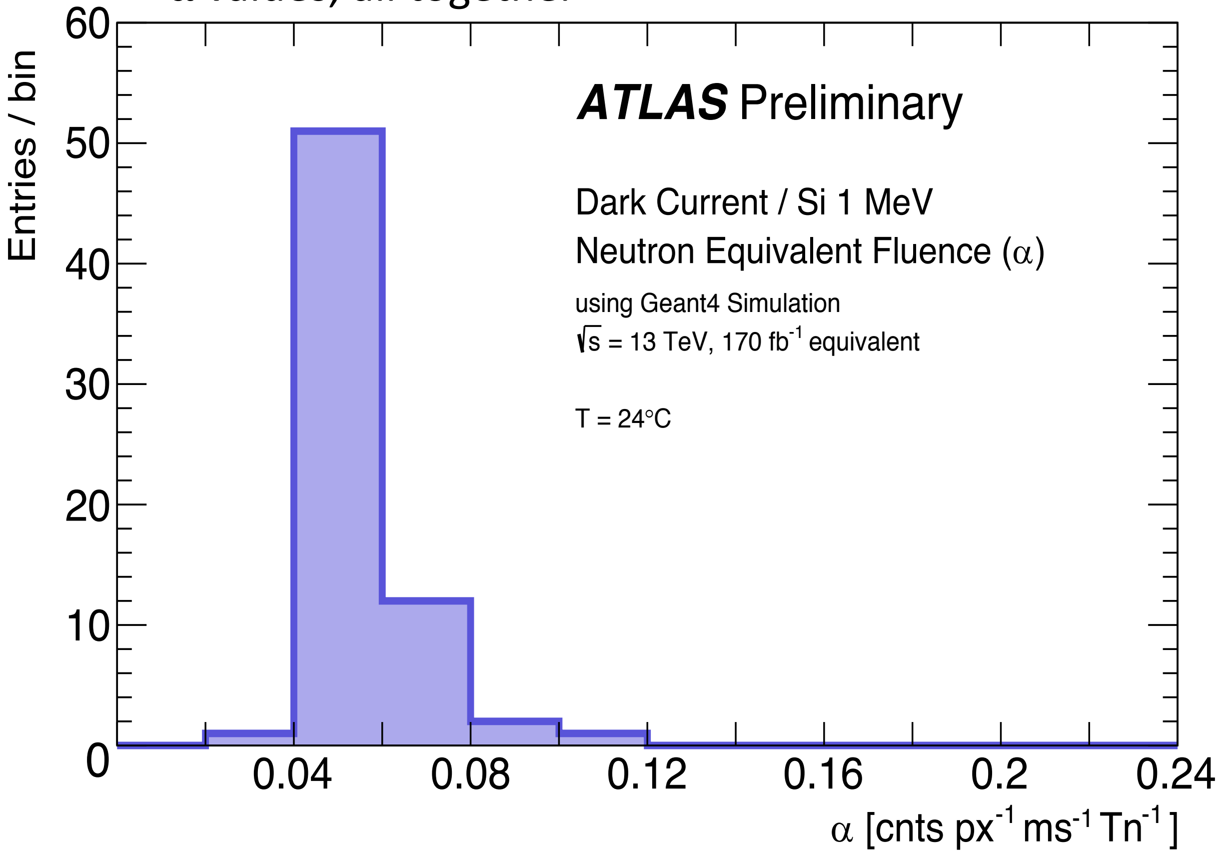
$$I = 0.06\, D\, e^{(T-20°C)/(12°C)}$$
$$\text{cnts px}^{-1}\ \text{ms}^{-1}$$

The relation between neutron fluence and dark current as seen in ATLAS endcap alignment CCDs, where *D* is the neutron equivalent fluence in 10^{12} Si 1 MeVNE cm^{-2} (Tn) and *T* is temperature in Celsius.

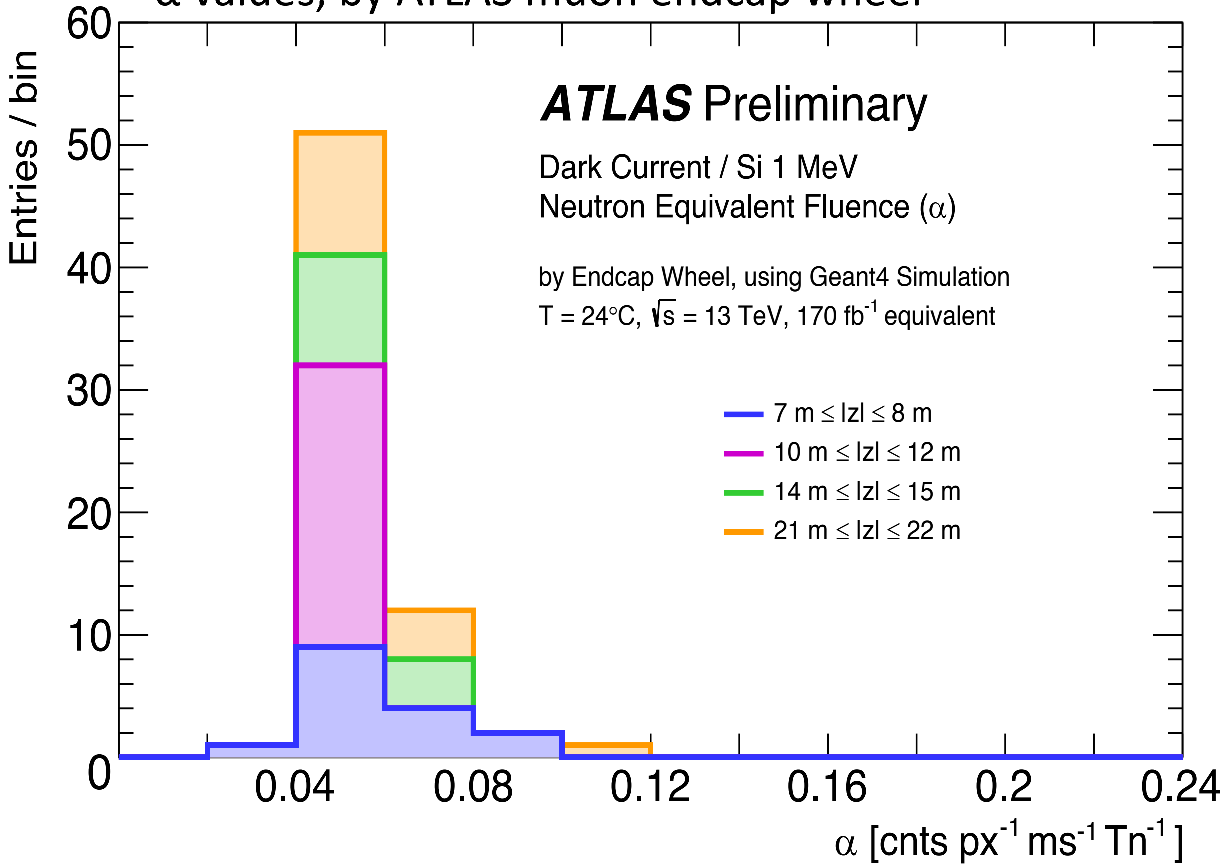


α Value Distribution

α values, all together



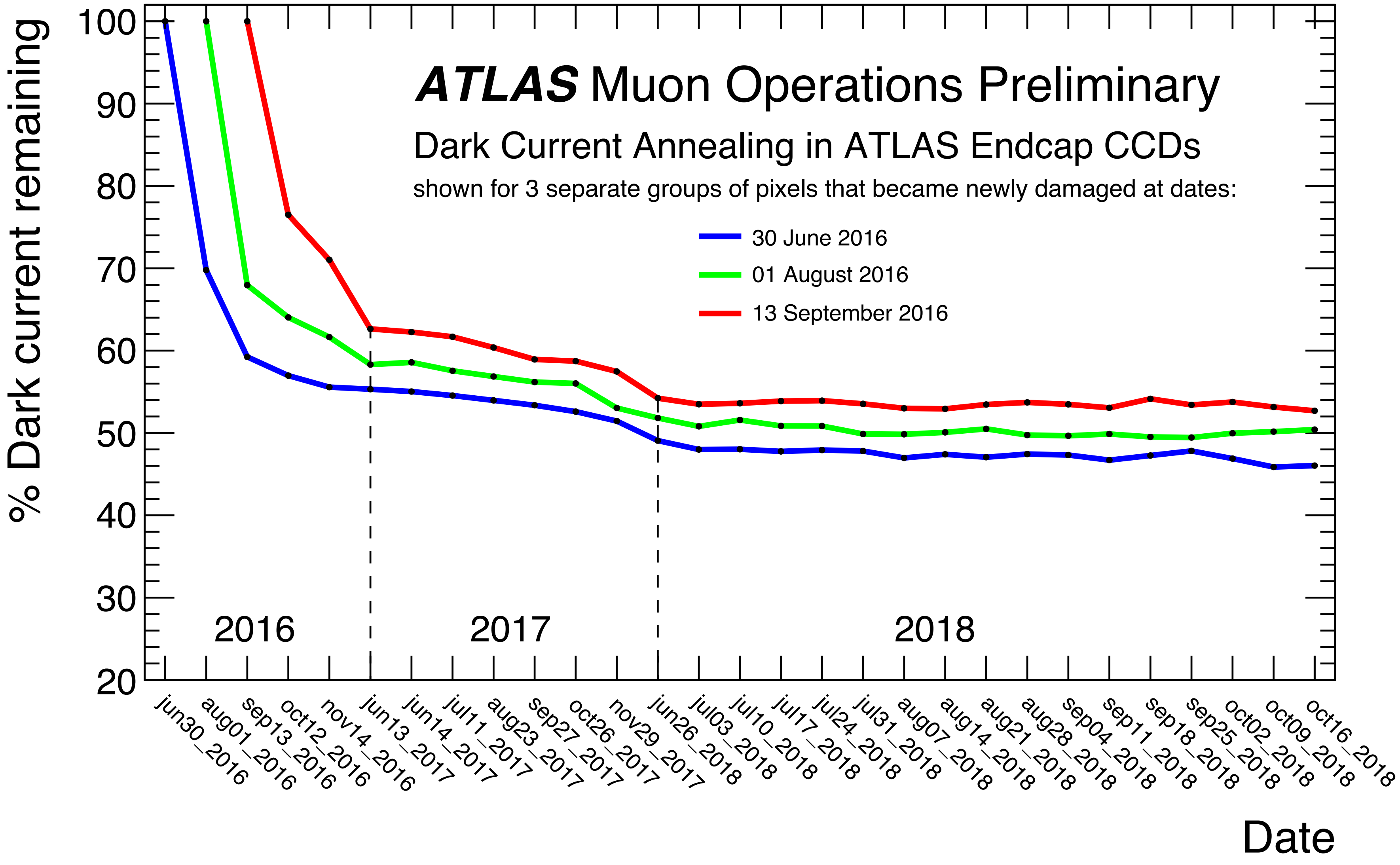
α values, by ATLAS muon endcap wheel



The distribution of α values, where α is the dark current (in cnts px^{-1} ms^{-1}) per 10^{12} Si 1 MeV neutron equivalent fluence cm^{-2} (in Tn). The entries are the averages over all CCDs within any 20 × 20 cm^2 bin in ATLAS endcap mapping (see slide 13). The α values are binned in 0.02 [cnts px^{-1} ms^{-1} Tn^{-1}].

Annealing Effects

- Neutron damaged pixels can anneal over time, reducing the total dark current in a CCD.
- Three separate groups of pixels from different data sets taken in 2016 each show about 45%-50% annealing of dark current over 2 years.
- In 2019, we remeasured the dark current in the CCDs sent to PROSPERO in 1999 and found 46% of the dark current had annealed, giving a new $\alpha = 0.14$.



Conclusion

- The dark current was measured in 2670 ATLAS endcap alignment CCDs. Using a Geant4 simulation of neutron fluence, we calculate the dark current per neutron equivalent fluence. We compare these measurements to the results obtained in previous controlled experiments.

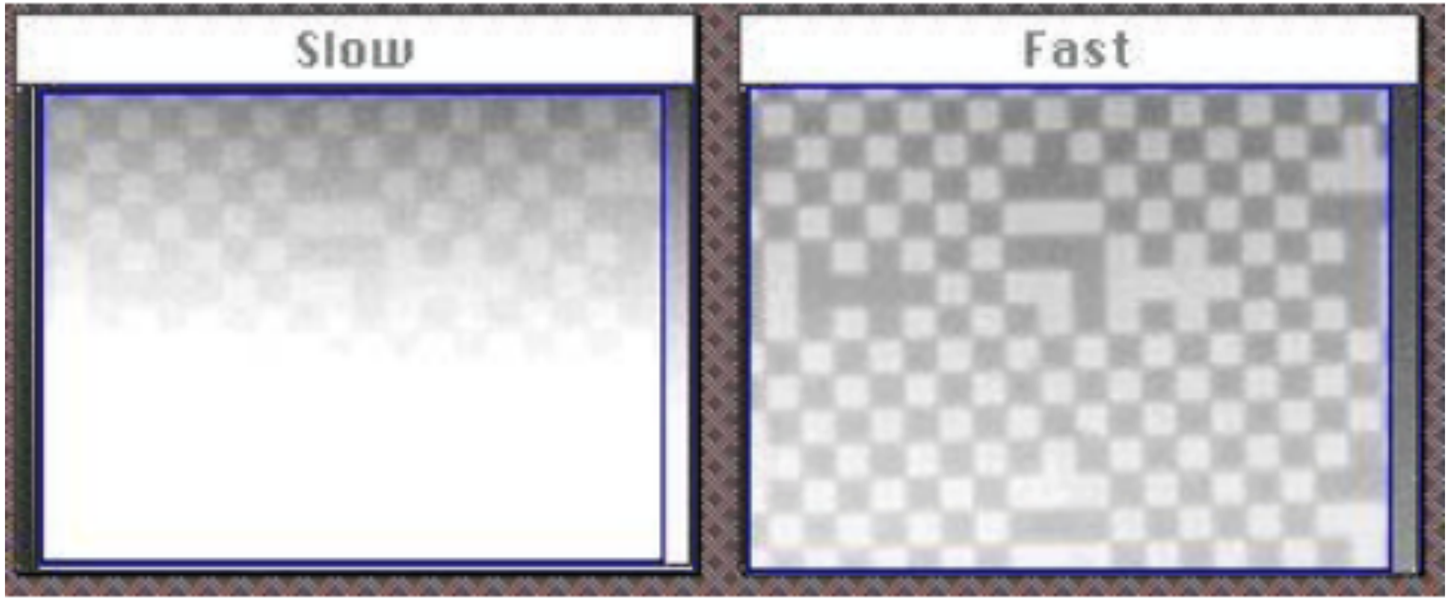
  - 1998 Lowell — $\alpha = 0.28$ cnts px^{-1} ms^{-1} Tn^{-1}
  - 1999 PROSPERO — $\alpha = 0.26$ cnts px^{-1} ms^{-1} Tn^{-1}
  - 2018 PROSPERO, annealed — $\alpha = 0.14$ cnts px^{-1} ms^{-1} Tn^{-1}
  - 2018 ATLAS endcap, using Geant4 simulation — $\alpha = 0.06$ cnts px^{-1} ms^{-1} Tn^{-1}

- ATLAS results show a reasonable agreement with the neutron equivalent flux simulation and with the results of our controlled experiments.
- We are still investigating annealing effects and other factors to improve our understanding of these measurements and simulations.
- We hope to be able to provide reliable neutron flux measurements throughout the ATLAS endcap in the future.

Backup

Dark Current Gradient

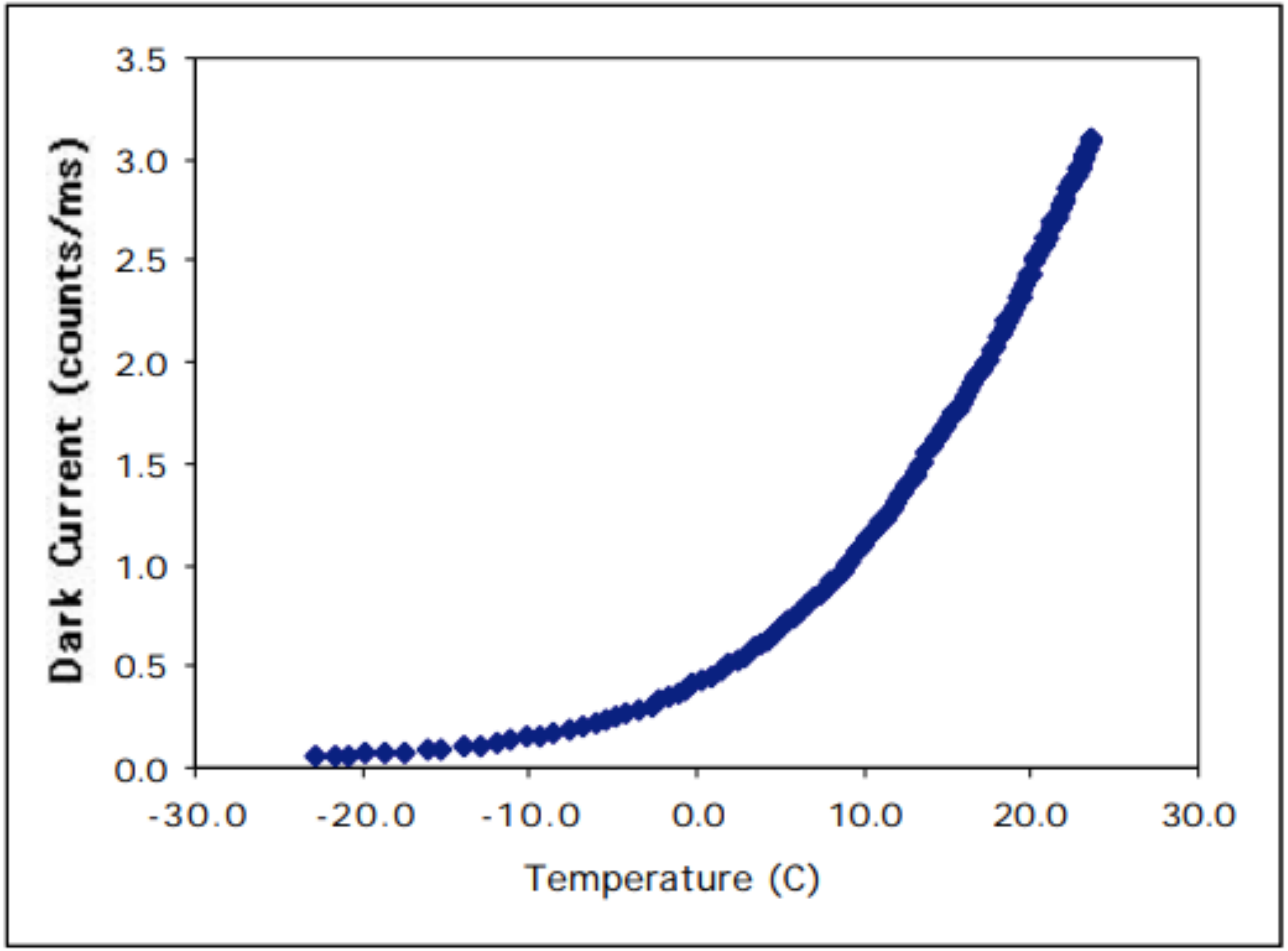
- The contrast gradient of these images matches an asymmetry in the image transfer time of pixels within a CCD.
- After exposure, the image is moved into the CCD's light-shielded storage area, and then transferred from the storage area into its own RAM.
- Pixels in the top row of the image are transferred out of the storage area first, while the top rows are transferred last and accumulate more dark current in the meantime.



Images taken by a damaged CCD head at different readout speeds

Temperature & Dark Current

- Dark current decreases at low temperatures since fewer electrons are thermally generated.
- Following the Lowell experiment, one of the CCD heads was cooled and its dark current measured alongside its temperature, giving the plot shown on the right.
- The dark current approximately doubles every 8°C.



Run-1 and Run-2 Integrated Luminosities

- Run-1 and Run-2 total delivered integrated luminosities are considered for the total neutron equivalent fluence.
- The simulated neutron equivalent fluence is taken from a GEANT4 simulation of the ATLAS detector in a configuration for Run-2 at a center-of-mass energy of 13 TeV.
- Neutron equivalent fluence scales approximately with center-of-mass energy and cross-section.
  - 2011: $\sqrt{s}$ = 7 Tev σ_inel = 71.39 mb L_del = 5.46 fb^{-1}
  - 2012: $\sqrt{s}$ = 8 Tev σ_inel = 72.85 mb L_del = 22.8 fb^{-1}
  - 2015-18: $\sqrt{s}$ = 13 Tev σ_inel = 78.42 mb L_del = 154 fb^{-1} (October 16, 2018)
- In order to include the Run-1, the delivered integrated luminosities at 7 Tev and 8 TeV are scaled by the Run-2 center-of-mass energy and cross-section:
  - Run-1 2011: 5.46 fb^{-1} * (7 TeV/13 TeV) * (71.39 mb/78.42 mb) = 2.67 fb^{-1}
    2012: 22.8 fb^{-1} * (8 TeV/13 TeV) * (72.85 mb/78.42 mb) = 13.0 fb^{-1}
  - Run-2 On October 16, 2018 (date of last dark current measurement) = 154 fb^{-1}

  Total = 2.67 fb^{-1} + 13.0 fb^{-1} + 154 fb^{-1} = 170 fb^{-1} equivalent luminosity at $\sqrt{s}$ = 13 Tev.

Links and References

- TC255P data sheet: http://alignment.hep.brandeis.edu/Electronics/Data/TC255P.pdf
- Lowell experiment: http://alignment.hep.brandeis.edu/ATLAS/MUON-98-253.pdf
- PROSPERO experiment: http://alignment.hep.brandeis.edu/ATLAS/MUON-2000-011.pdf
- GEANT4 simulated neutron flux map: https://twiki.cern.ch/twiki/bin/view/Atlas/RadiationMapsGeant4