# Development of the CMS Phase-1 Pixel Online Monitoring System and the Evolution of Pixel Leakage Current

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On behalf of CMS Pixel Collaboration

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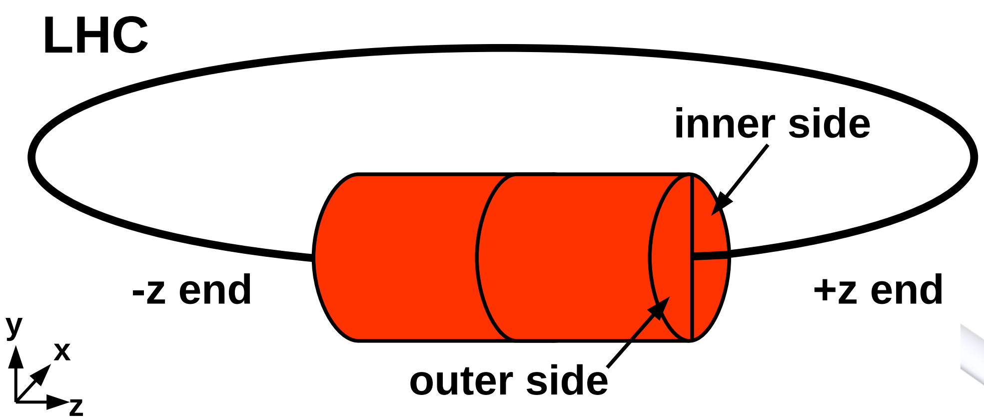
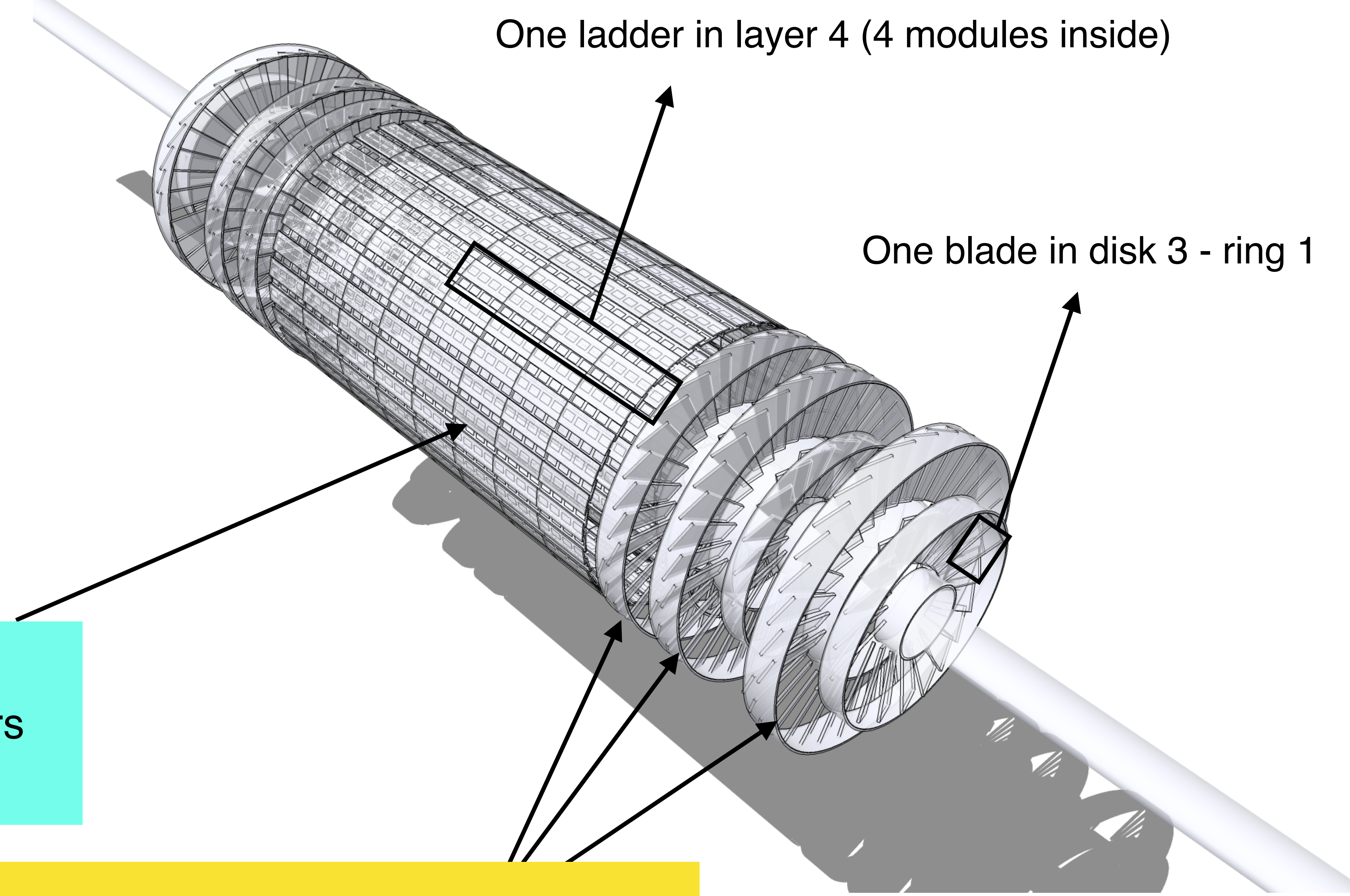
# CMS Phase-1 pixel detector




- LHC coordinates: four half cylinders:
  - Inner side +z end (BpI)
  - Inner side -z end (BmI)
  - Outer side +z end (BpO)
  - Outer side -z end (BmO)




- Pixel barrel:
  - 4 concentric layers
  - Array of ladders

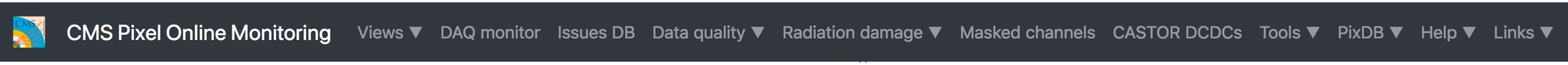
- Pixel endcap:
  - 3 disks with 2 concentric rings
  - Array of blades (modules in each blade panel)

**124 million pixels in total**

# Pixel detector

# Online Monitoring Development

# Motivation of Pixel Online Monitoring Development




- **A webpage for monitoring the following parameters online/offline:**

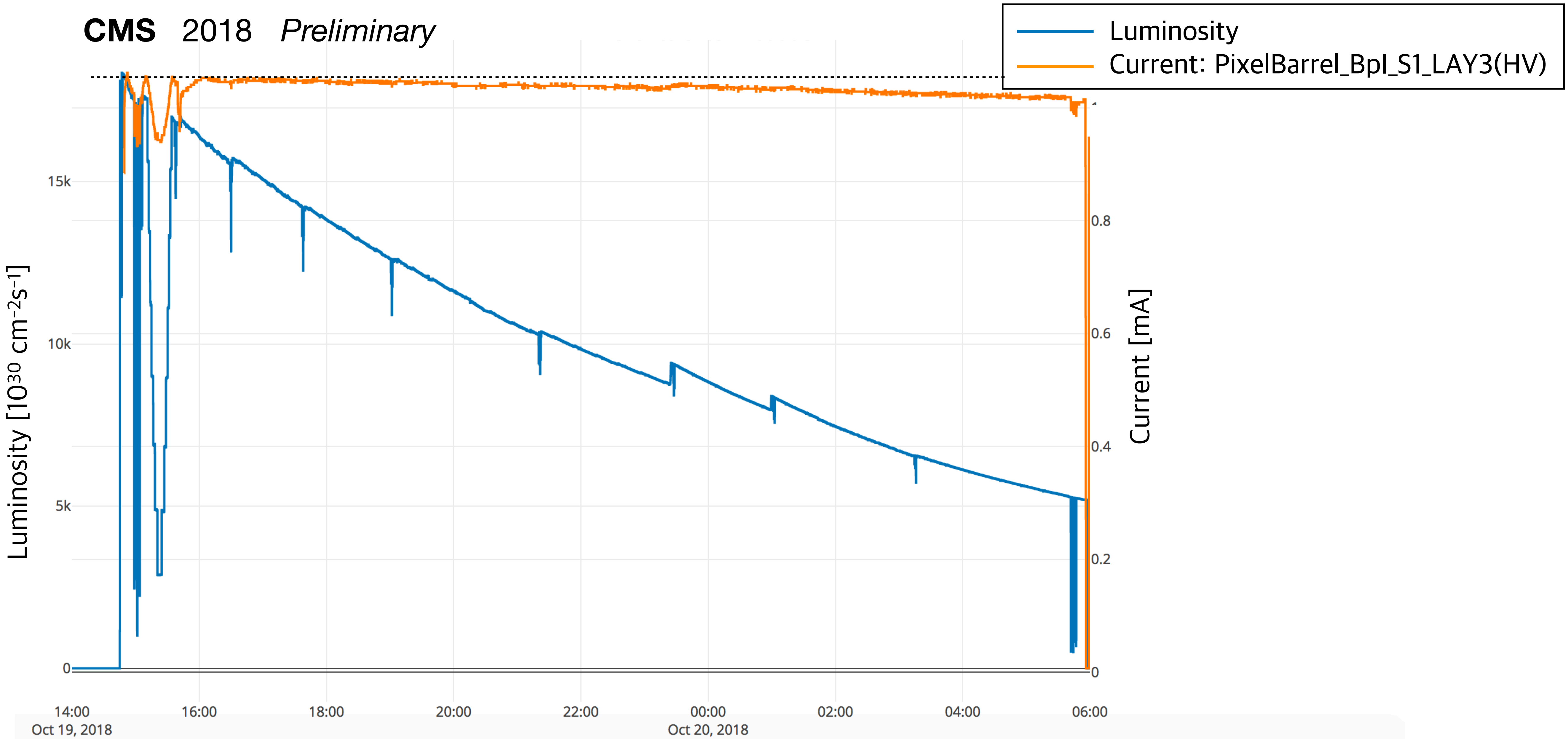
- Environment variables:
  - Dew point
  - Air pressure
  - Air temperature
  - Humidity
  - …

- Detector variables:
  - Power supply voltage
  - Current in power supply group
  - Module temperatures
  - Cooling flow status
  - …

- CMS detector run property:
  - Instantaneous / integrated luminosity
  - Detector run status
  - Data acquisition status
  - Data quality monitoring
  - …

- **Function of online monitoring system:**
  - **Correlate these information to have a good overview of the detector status**
  - **Centralize the above information**
  - **Have an easily accessible user interface**

# View of online quantity in the monitoring system



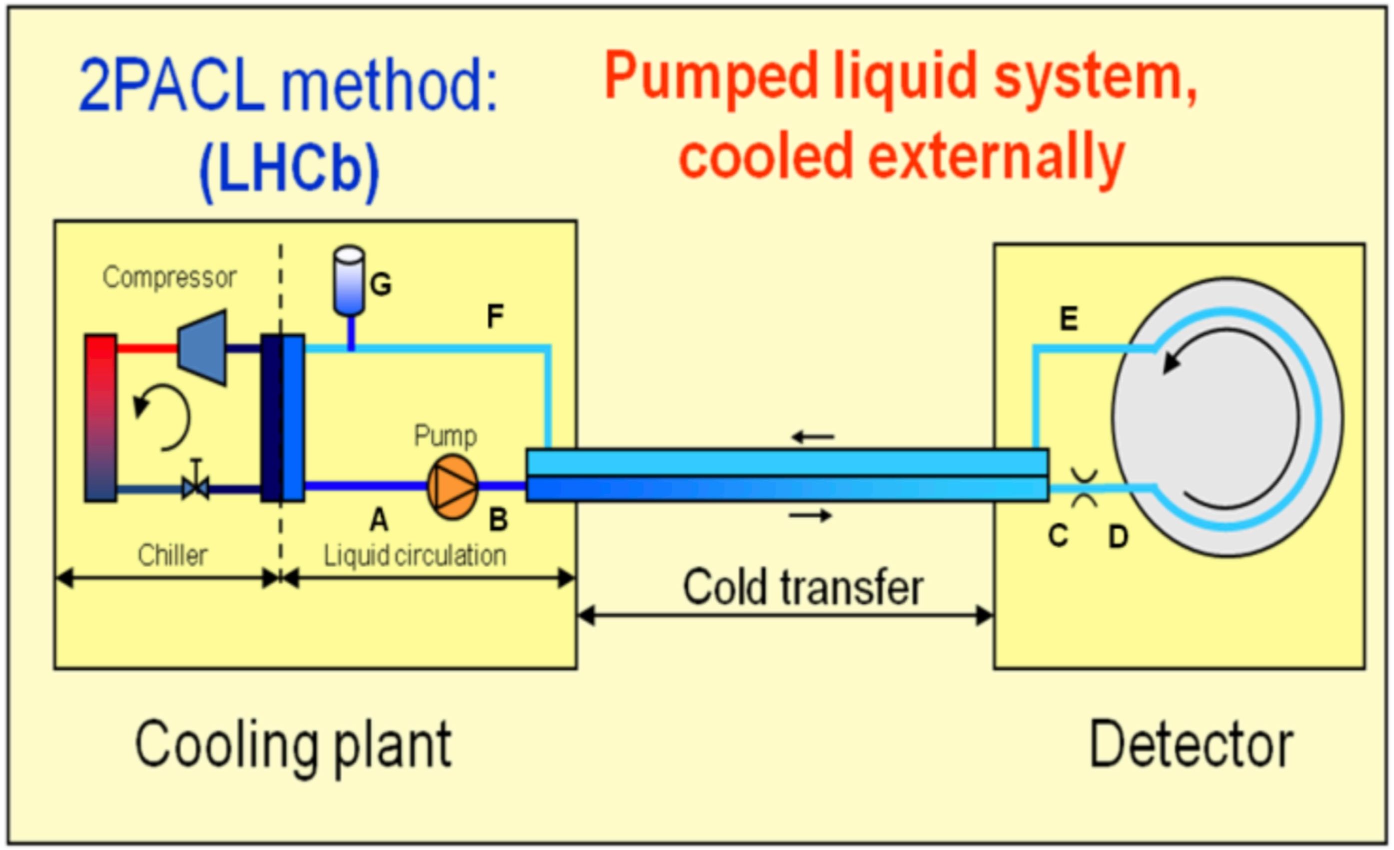

- During an LHC fill:
  - Instantaneous luminosity & leakage current (one power sector in layer 3 of Pixel Barrel)

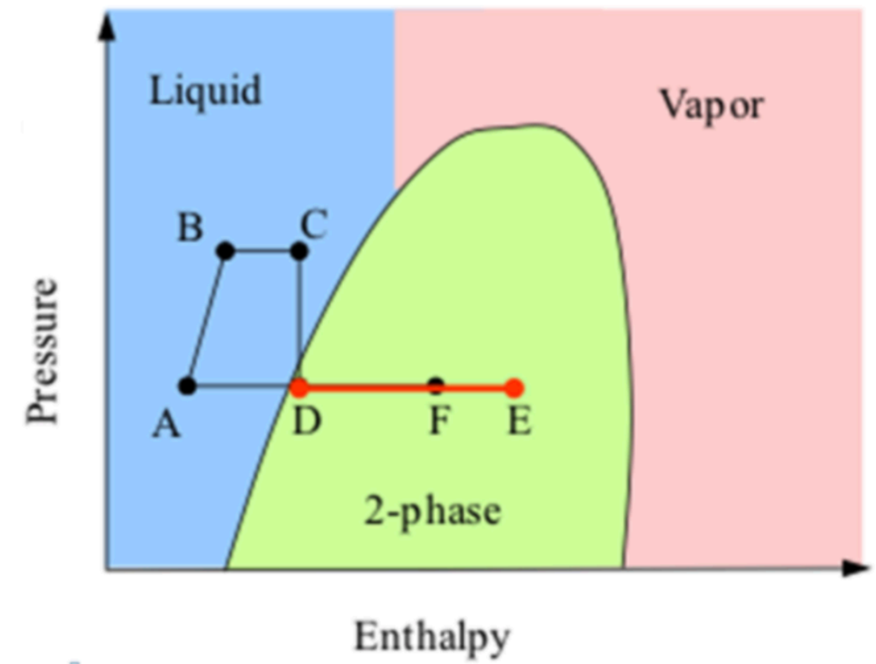
- **The monitoring system correlates the instantaneous luminosity and the leakage current at the same time**

# Pixel detector

# Cooling schematics & temperature distribution

# Pixel detector cooling loop schematics & flow



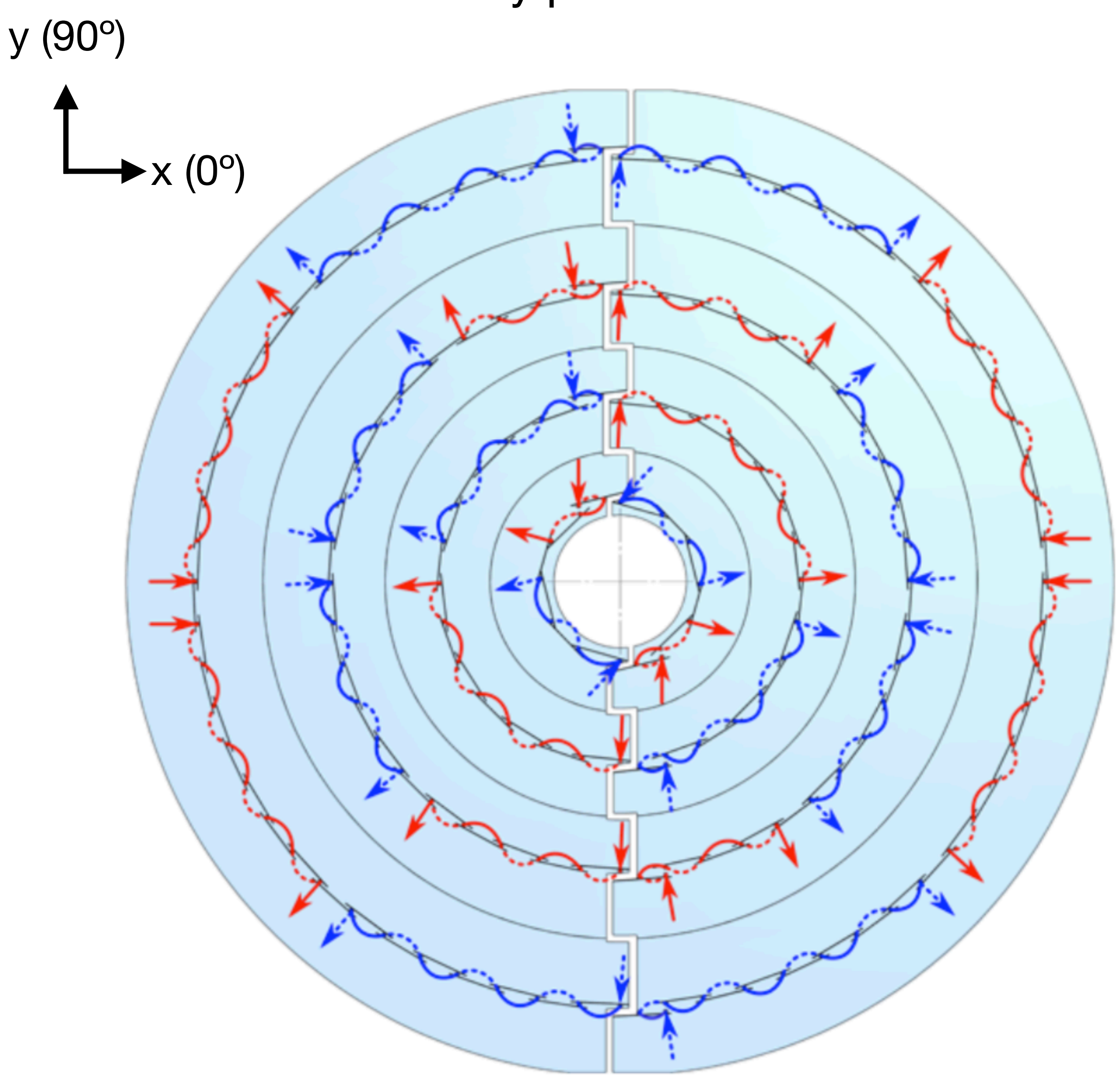




- 2-phase accumulator controller (2PACL):
  - **Point A**: $CO_2$ flow liquified by chiller
  - **Point B**: increase liquid pressure by pump
  - **Point B ~ C**: thermal exchange
  - **Point C ~ D**: decrease the pressure
  - **Point D**: reach 2-phase state at **inlet**
  - **Point D ~ E**: evaporation (absorbing heat in the detector)
    - **cooling becomes more efficient**
    - **temperature drops**
  - **Point E ~ F**: liquid/vapor mixture return to cooling plant from **outlet**
  - **Point G**: accumulator vessel

- $CO_2$ cooling flow was used since 2017 for the Phase-1 pixel detector

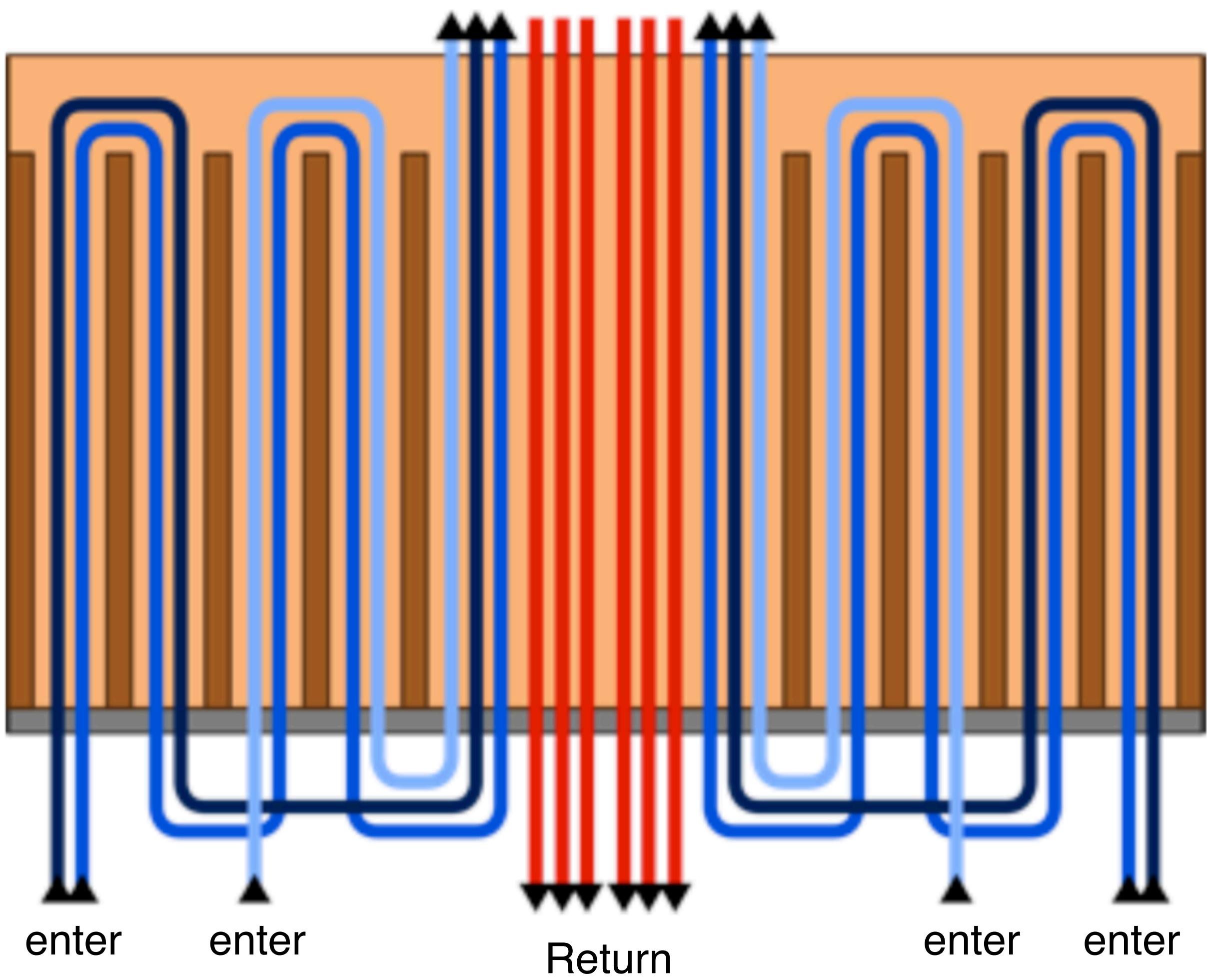
# Pixel barrel cooling loop schematics & flow

x-y plane section




View along z on the supply line

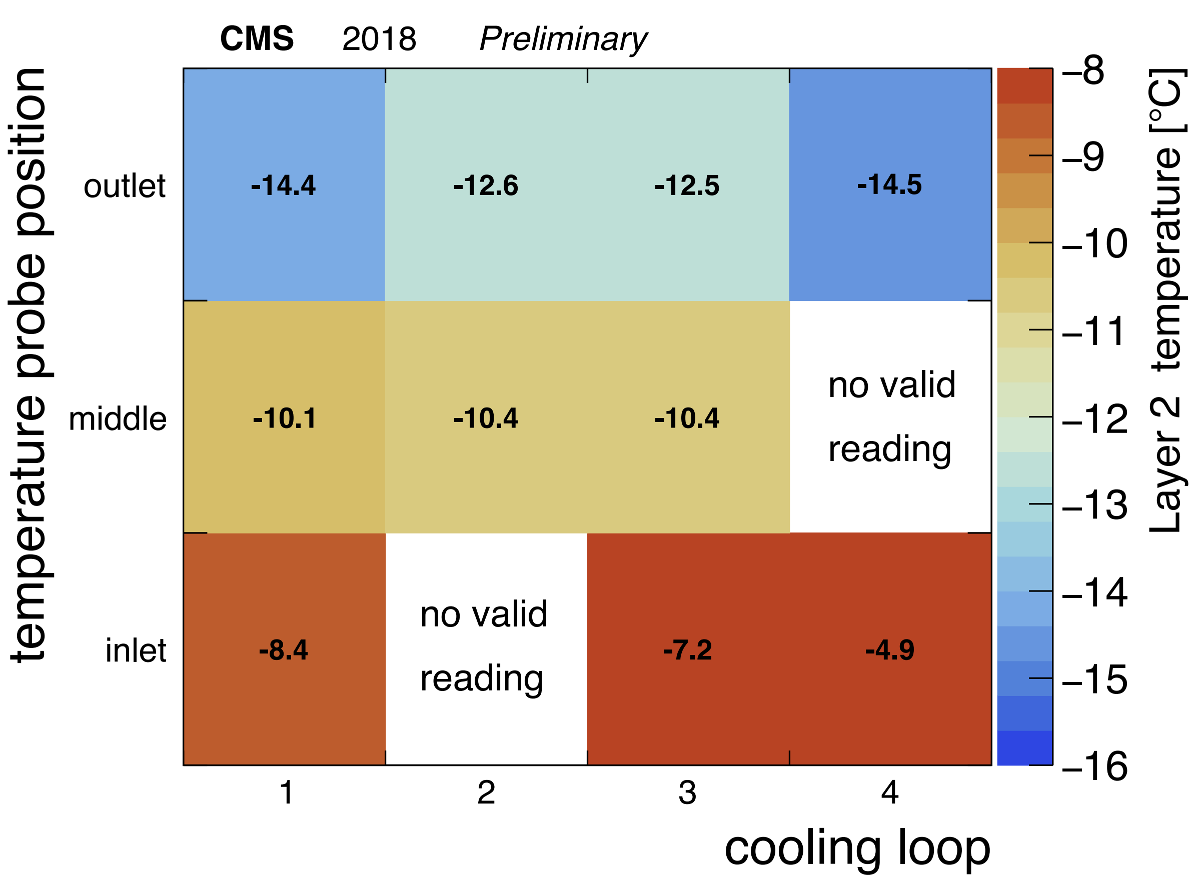
(Pre-heating of pixel detector)



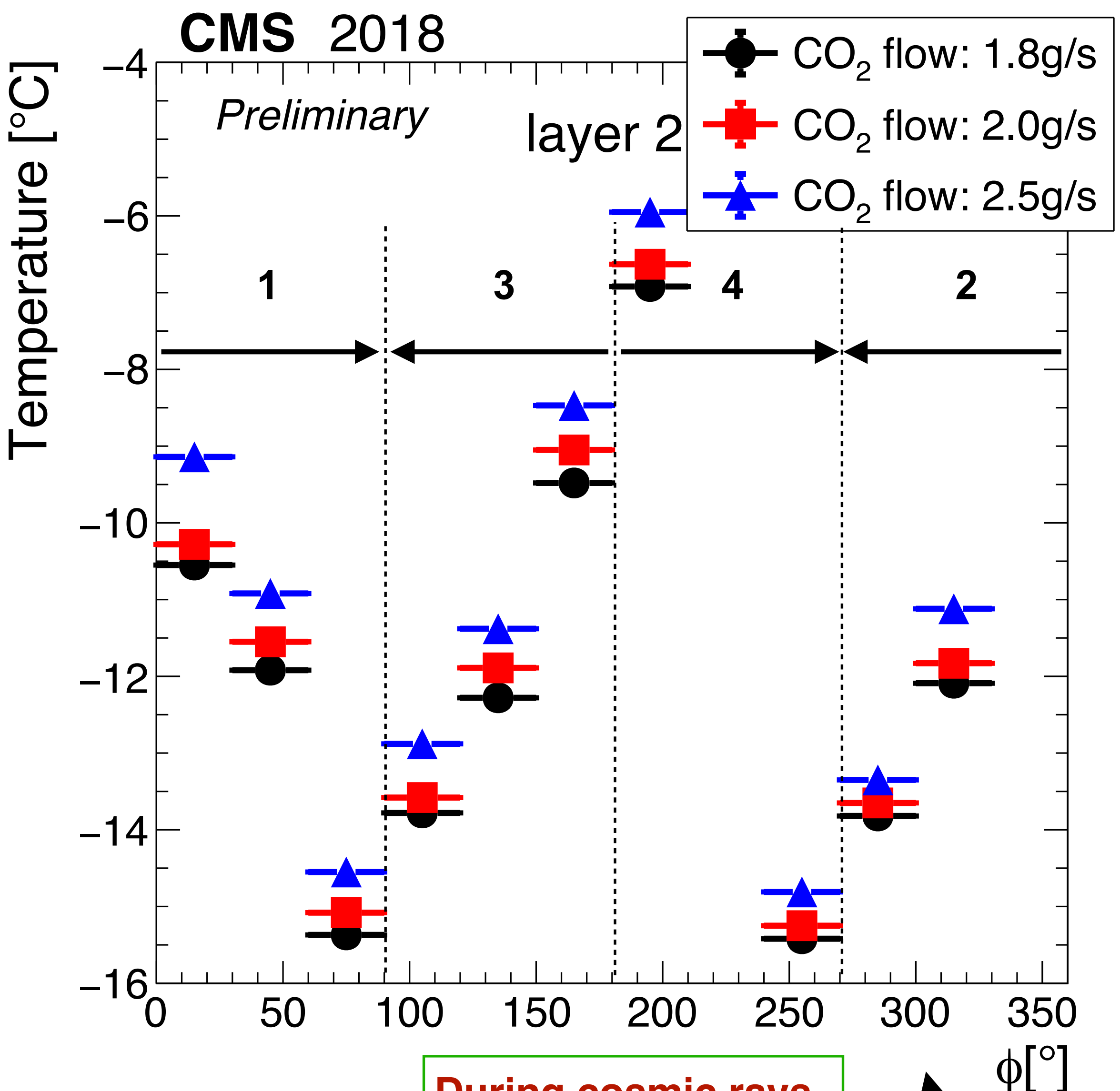

- Each loop cools down the full barrel length over a given azimuthal (ϕ) range
- Arrows: direction of $CO_2$ flows

Average temperature accuracy:
± 0.5 degree celsius

# Pixel barrel temperature (layer 2)




**During p-p collisions**



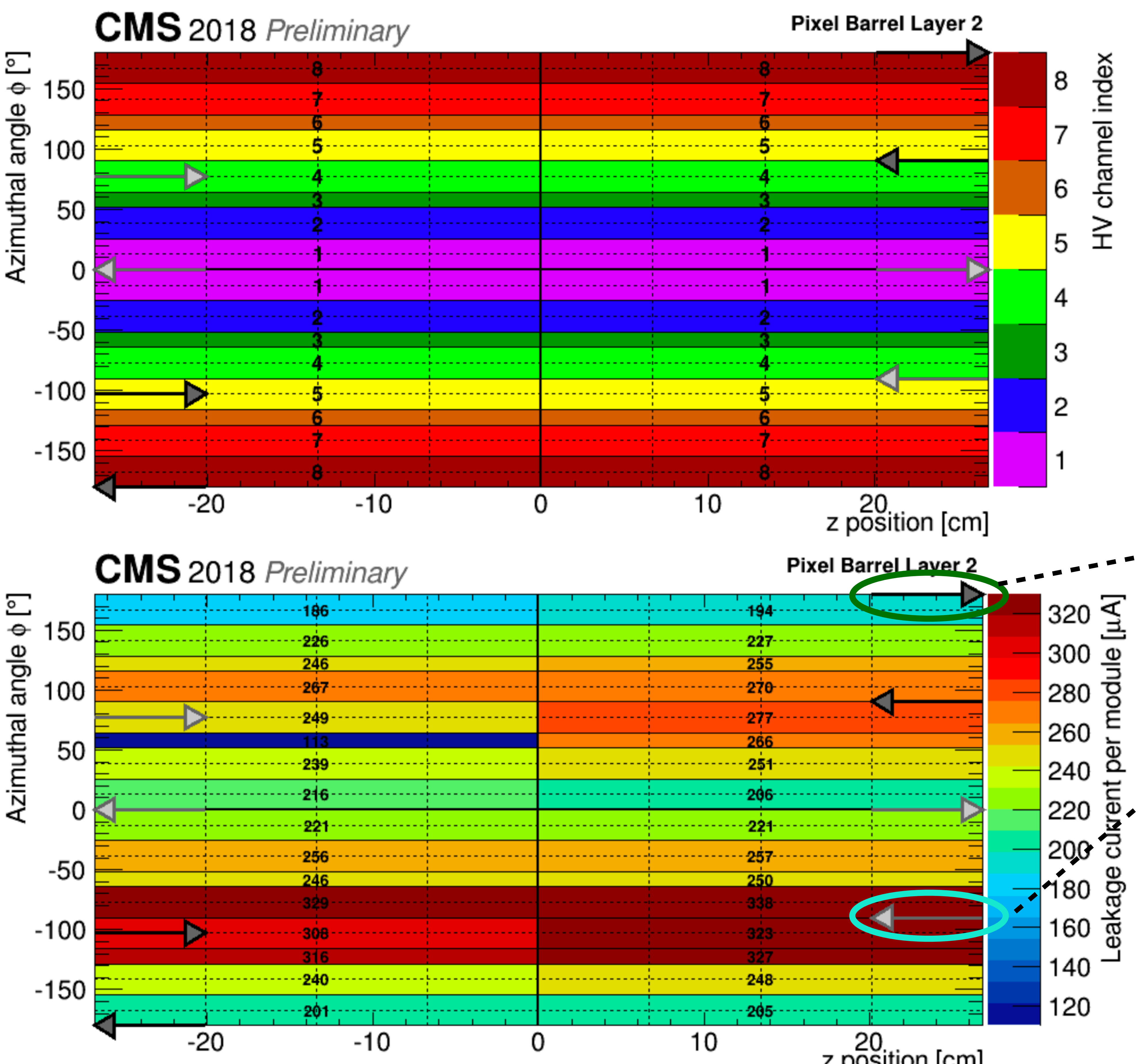

**During cosmic rays**

- As a result of $CO_2$ flow feature (slide 9), temperature gradient: inlet > middle > outlet
- Temperature measured during p-p collisions is higher than the measured temperature in cosmic rays

- **Decreased $CO_2$ flow leads to a better heat exchange more sufficiently, resulting in more efficient cooling:**
  - **lower temperature, less temperature spread**

# Assignment of power groups & leakage current distribution

# Map of power sectors & leakage current (pixel barrel layer 2)




- Arrows indicate the inlet and outlet of $CO_2$ cooling lines
- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current
- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

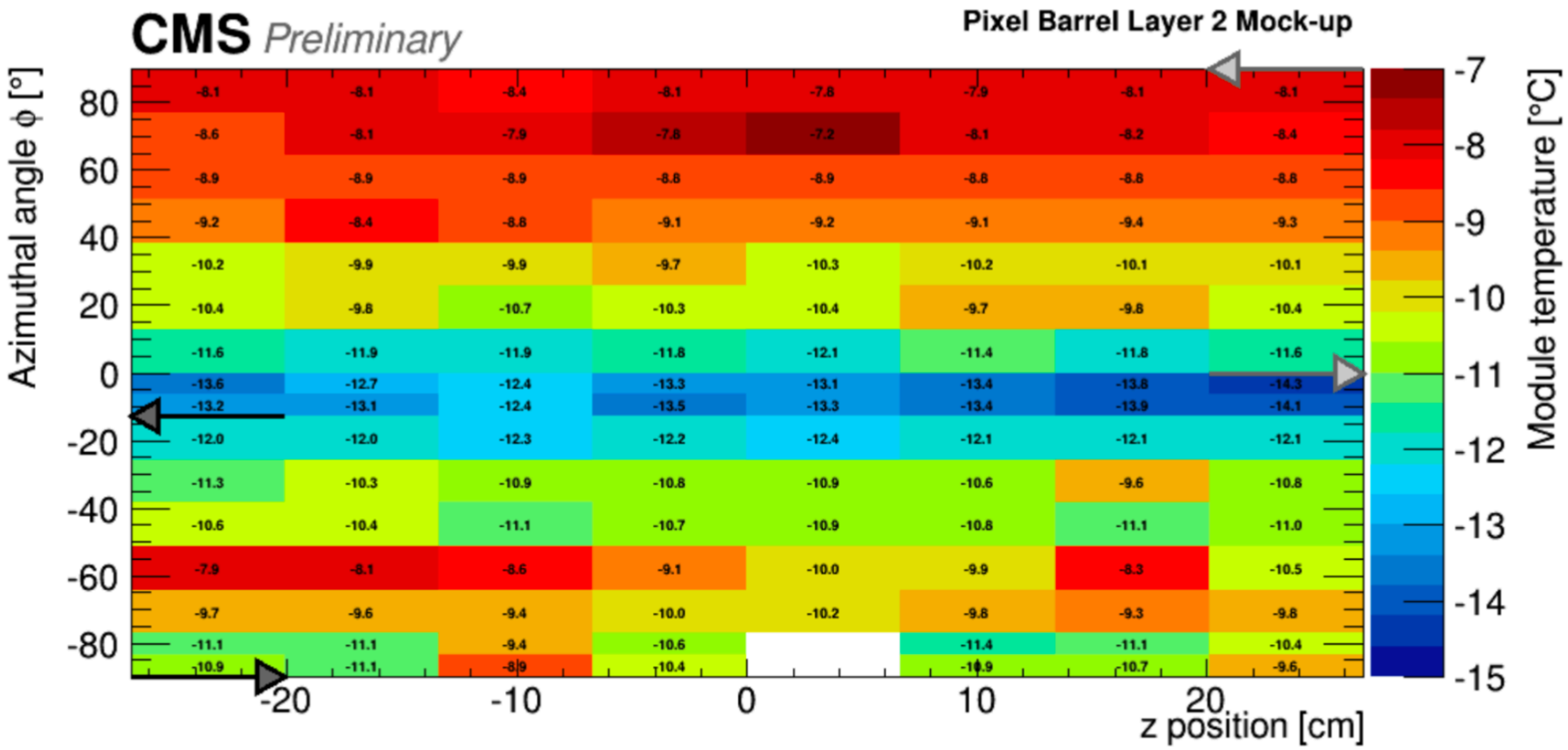
# Correlation of leakage current & temperature

- We can improve the temperature estimates by use of a thermal mockup

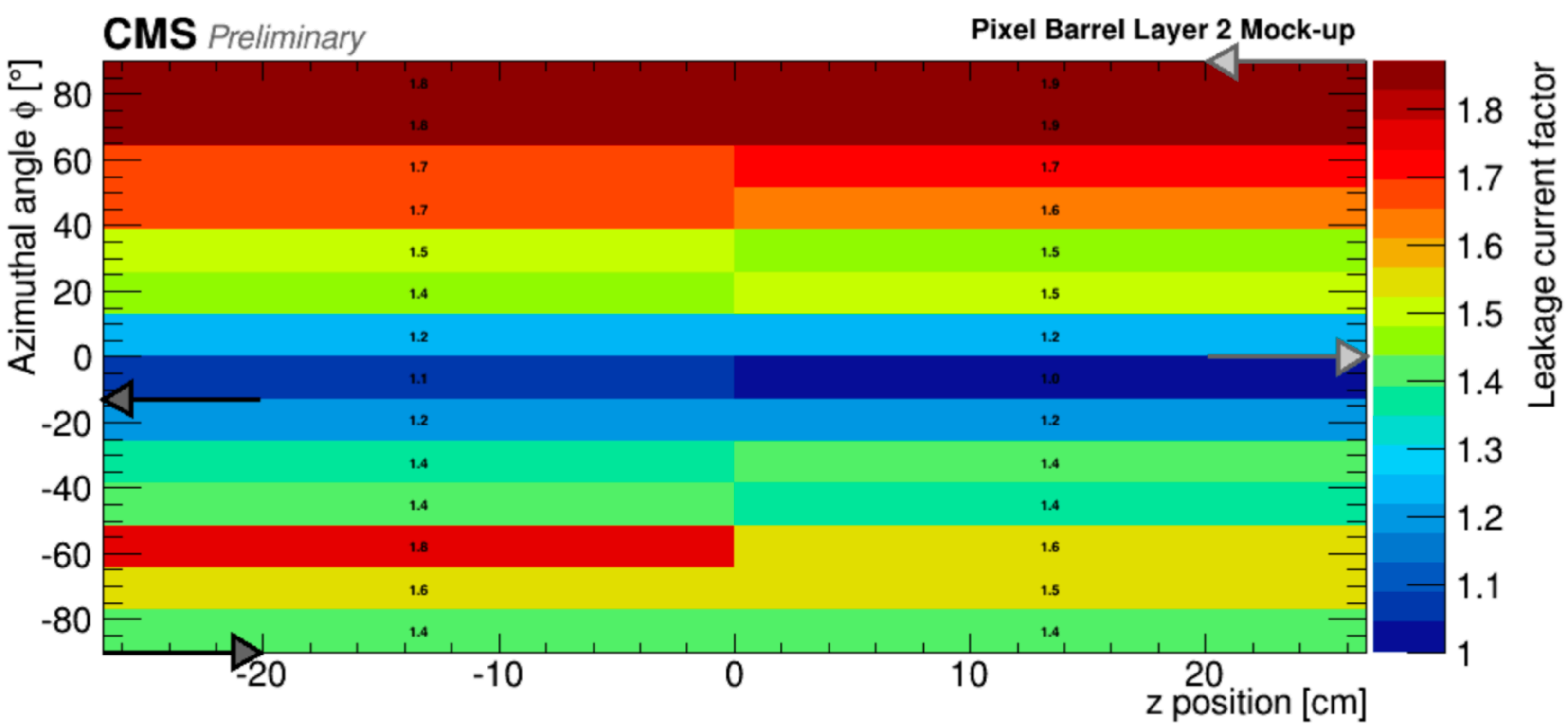
# Thermal Mockup

- Motivation:
  - Emulate the temperature distribution along pixel barrel layer 2
  - Estimate temperature spread in the real detector
  - Better model the correlation between pixel leakage current and temperature
- Setup: simulate the second layer of real pixel barrel detector
  - Same as a half shell of layer 2
  - Same cooling loop as the real detector
  - Same silicon sensors as the real detector
  - Every module has a heater instead of readout chip
  - Each module has a temperature probe — precise measurement of temperature

# Leakage current & temperature dependence (thermal mockup)




Temperature distribution

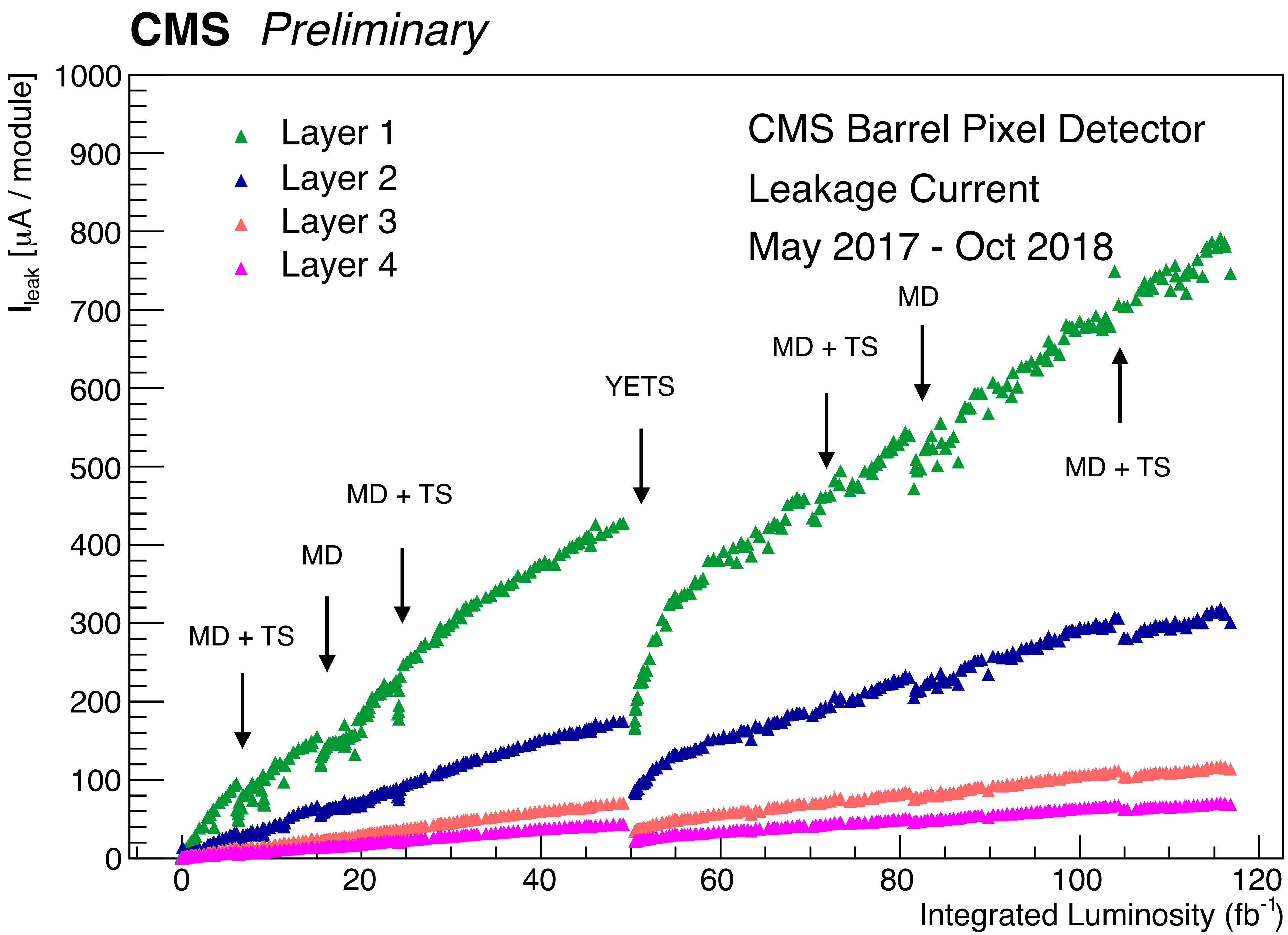



Leakage current factors (1.1 ~ 1.9)

- We expect to have a spread of temperature of factor 2, which matches with the above plot
- Formula relating leakage current & temperature: $$\text{leakage current factor} = \frac{I}{I_0} = \frac{1}{N_{\text{modules}}} \sum_i \frac{T_i^2}{T_0^2} \exp\left[-\frac{\Delta E}{2\,k_B}\left(\frac{1}{T_i} - \frac{1}{T_0}\right)\right]$$
- Good agreement with the measured leakage currents in the real detector — We understand the cooling in the detector

# Pixel module leakage current evolution

# Pixel barrel module leakage current evolution (measurement)




During p-p collisions

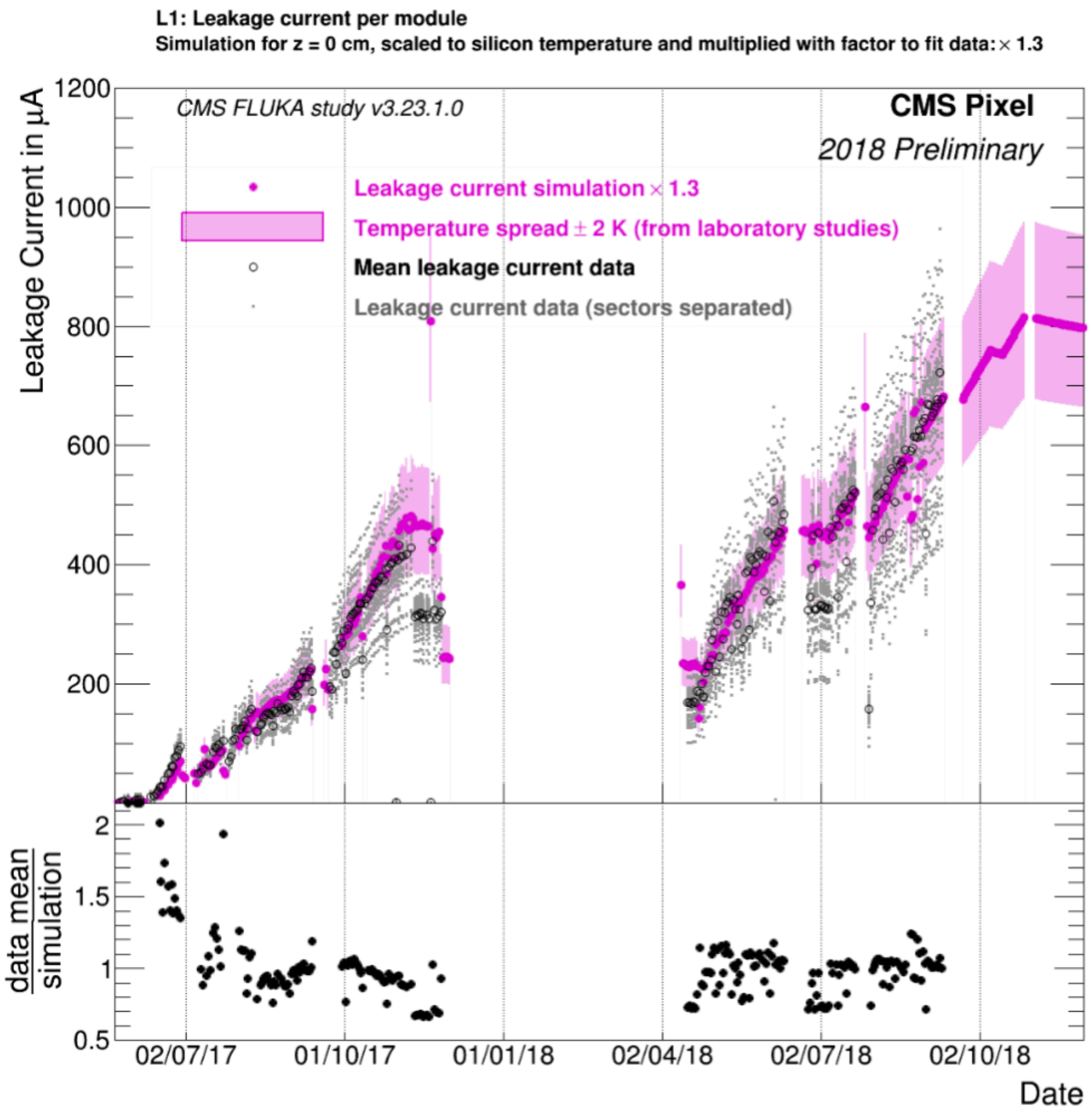
- MD: Machine development
- TS: Technical stop
- YETS: Year-End technical stop

- Leakage current increased gradually due to accumulated radiation dose through the year
- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (layer 1 > layer 2 > layer 3 > layer 4)
- Leakage current drop during MD/TS/YETS: annealing or changed high voltage settings

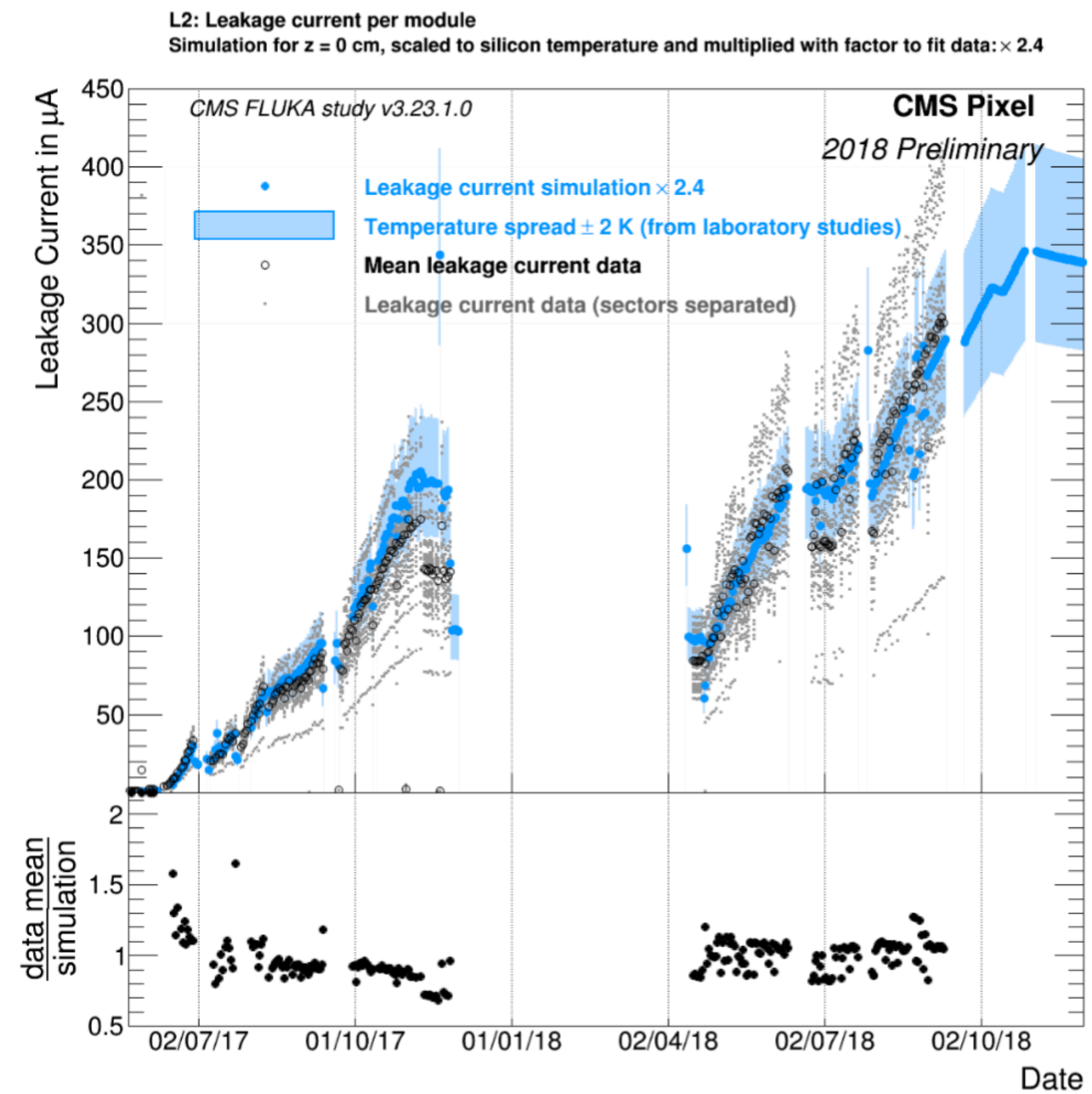
# Pixel module leakage current simulation

- The expected leakage current in each pixel barrel layer is calculated based on the temperature and irradiation history
- Empirical radiation damage model is used by including the parameters: fluence, temperature, time, sensor volume
- **Reference: DESY-THESIS-1999-040 (Hamburg model)**

# Pixel barrel leakage current simulation




layer 1

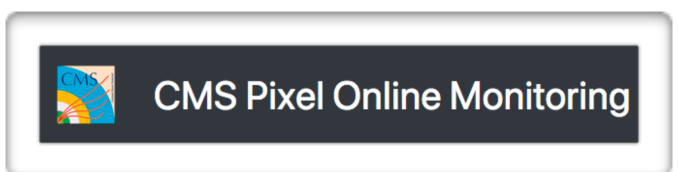


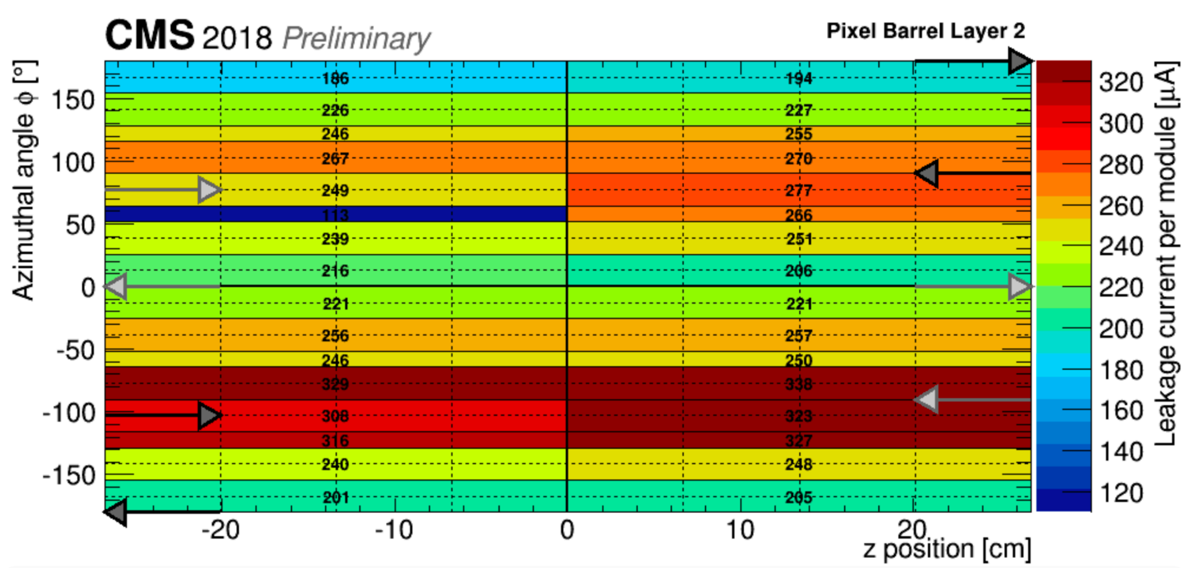

layer 2

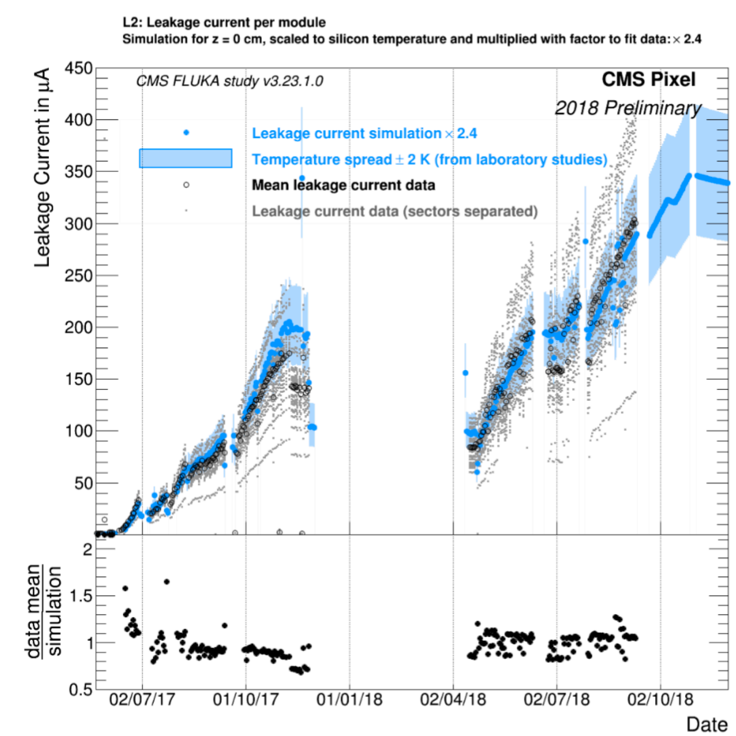
- Good agreement between measurement and simulation on module leakage current evolution

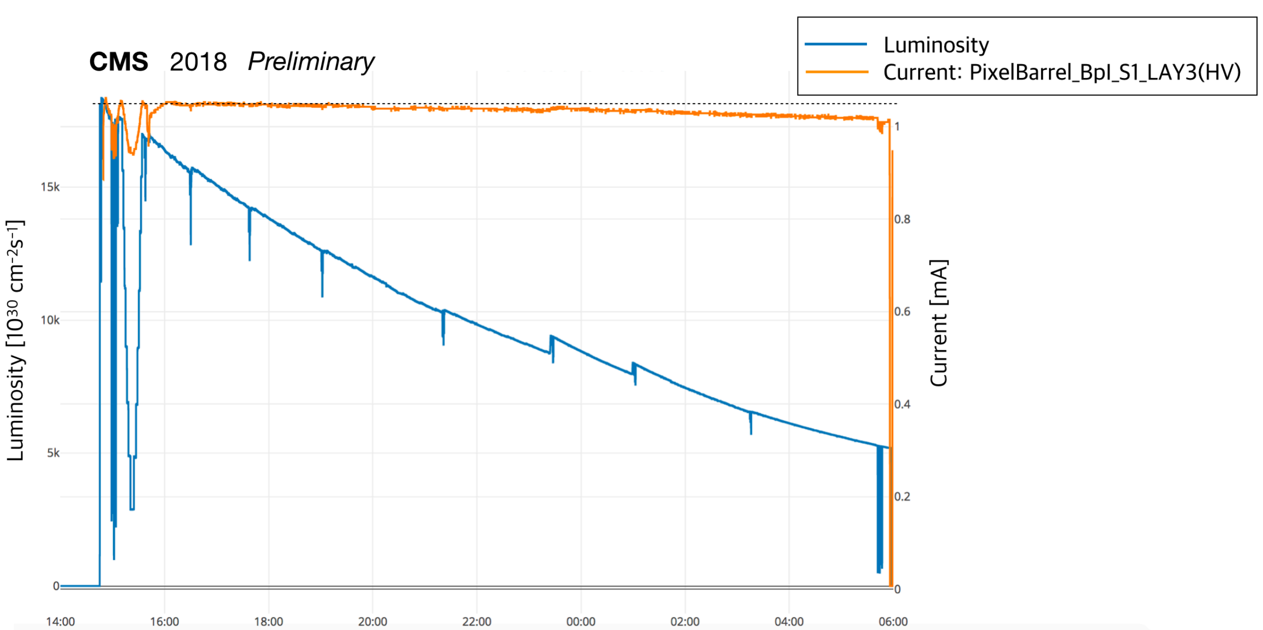
# Conclusion

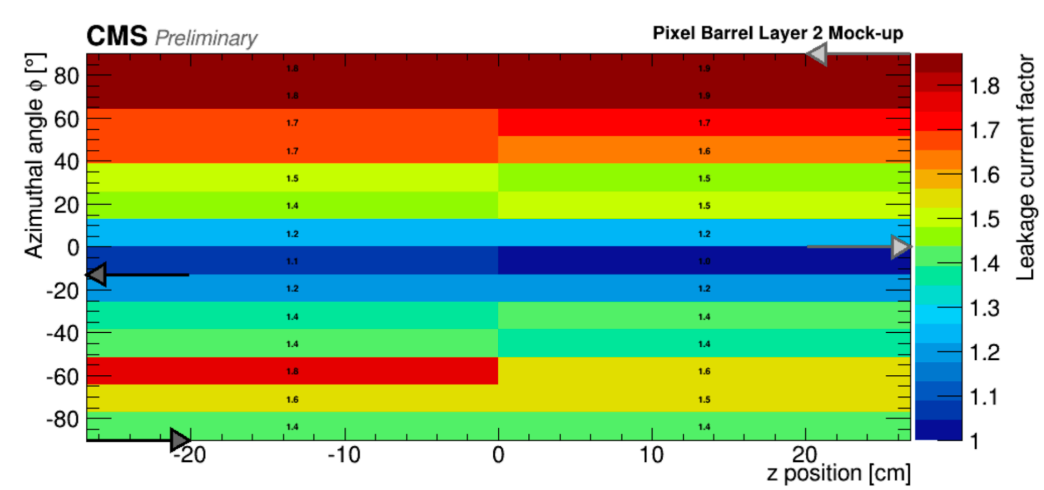
- We have developed an awesome monitoring system for CMS Phase-1 pixel detector
- We have achieved a good understanding on the cooling of the pixel detector
- The study on the correlation between pixel leakage current and temperature has been successful
- We have realized a precise prediction on the module leakage current evolution



Thanks for your attention!

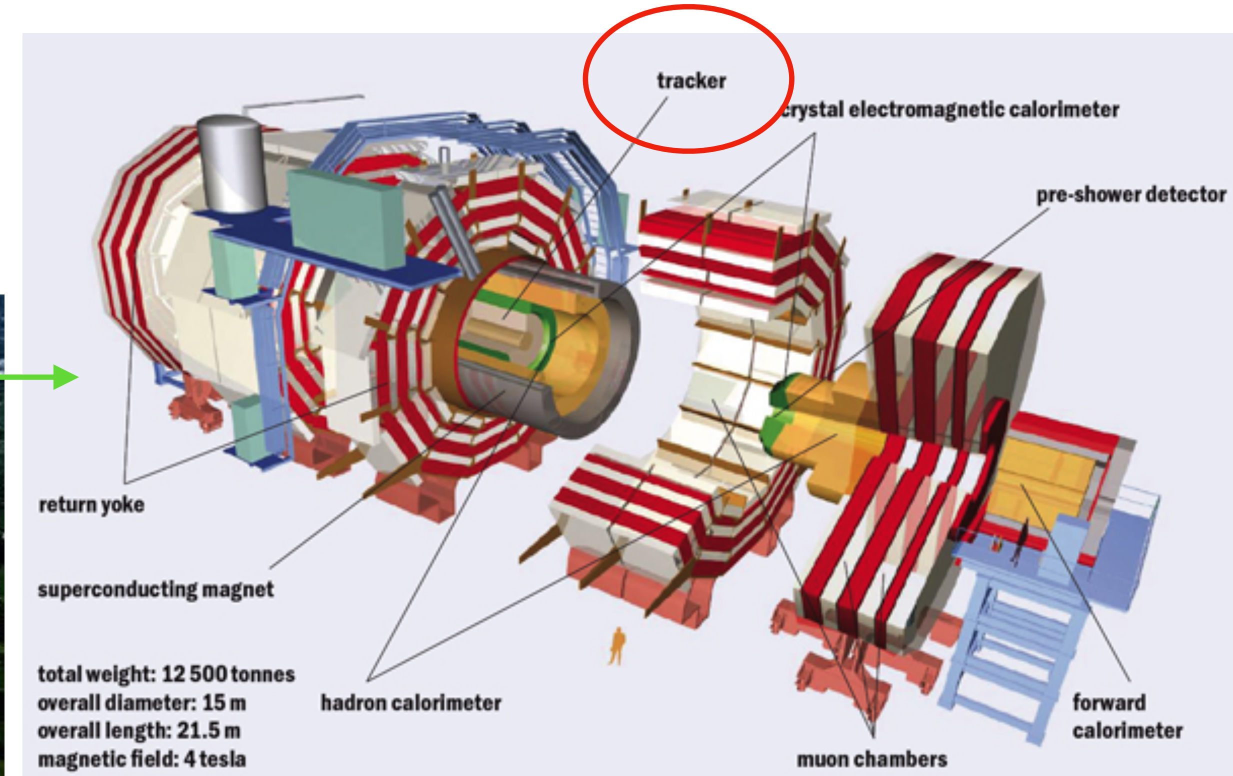
# Backup

# Introduction

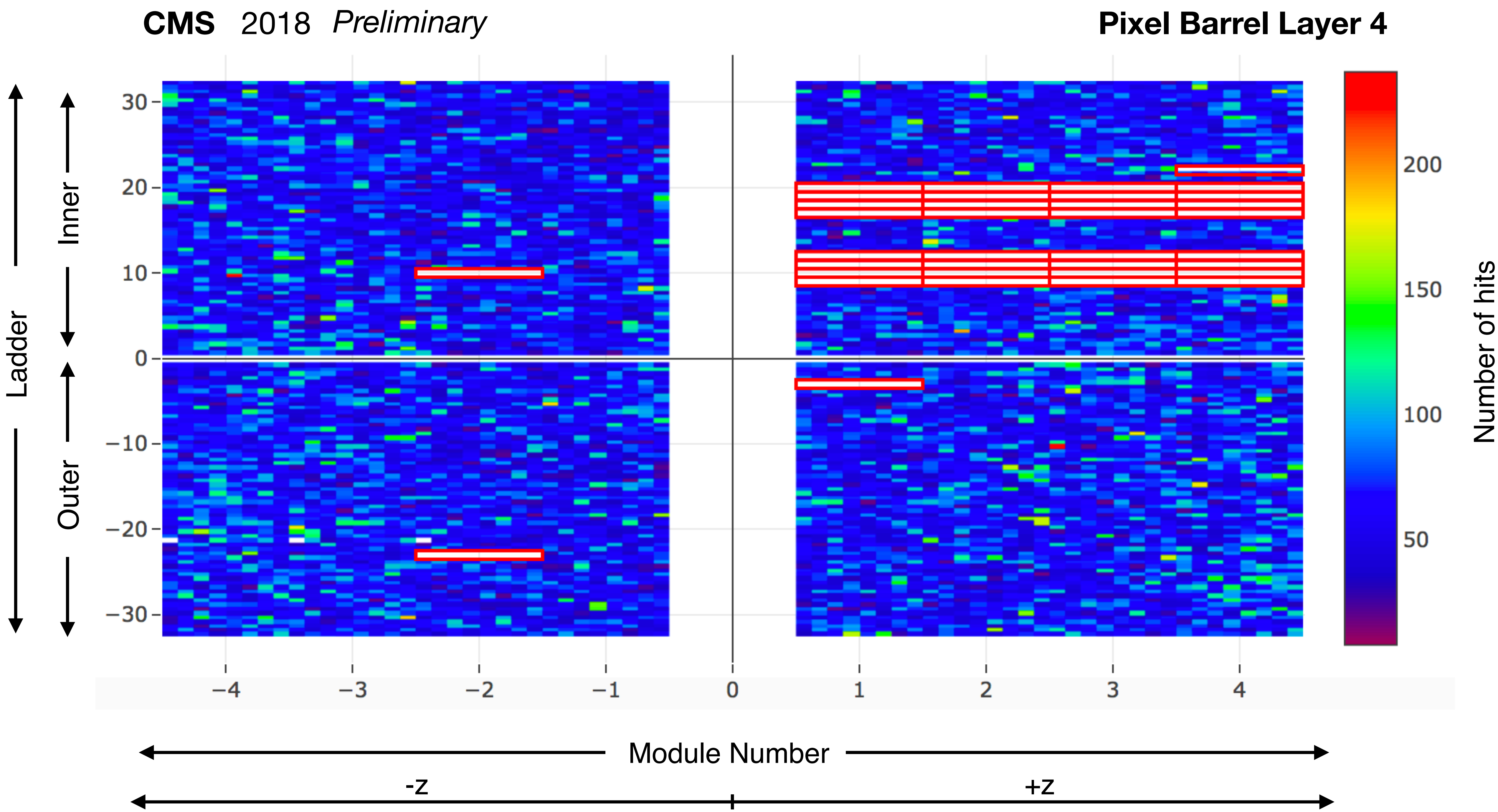
- **Pixel monitoring system**
- **Cooling schematics & Temperature**
- **Leakage current & correlation with temperature**
- **Prediction on pixel leakage current**

- Pixel detector is the inner detector of silicon tracker
- Shortest distance: **2.9 cm** to the beam pipe

- LHC: proton-proton collision in 13 TeV
- CMS :Integrated luminosity ~ 120 $fb^{-1}$ (2017 ~ 2018)

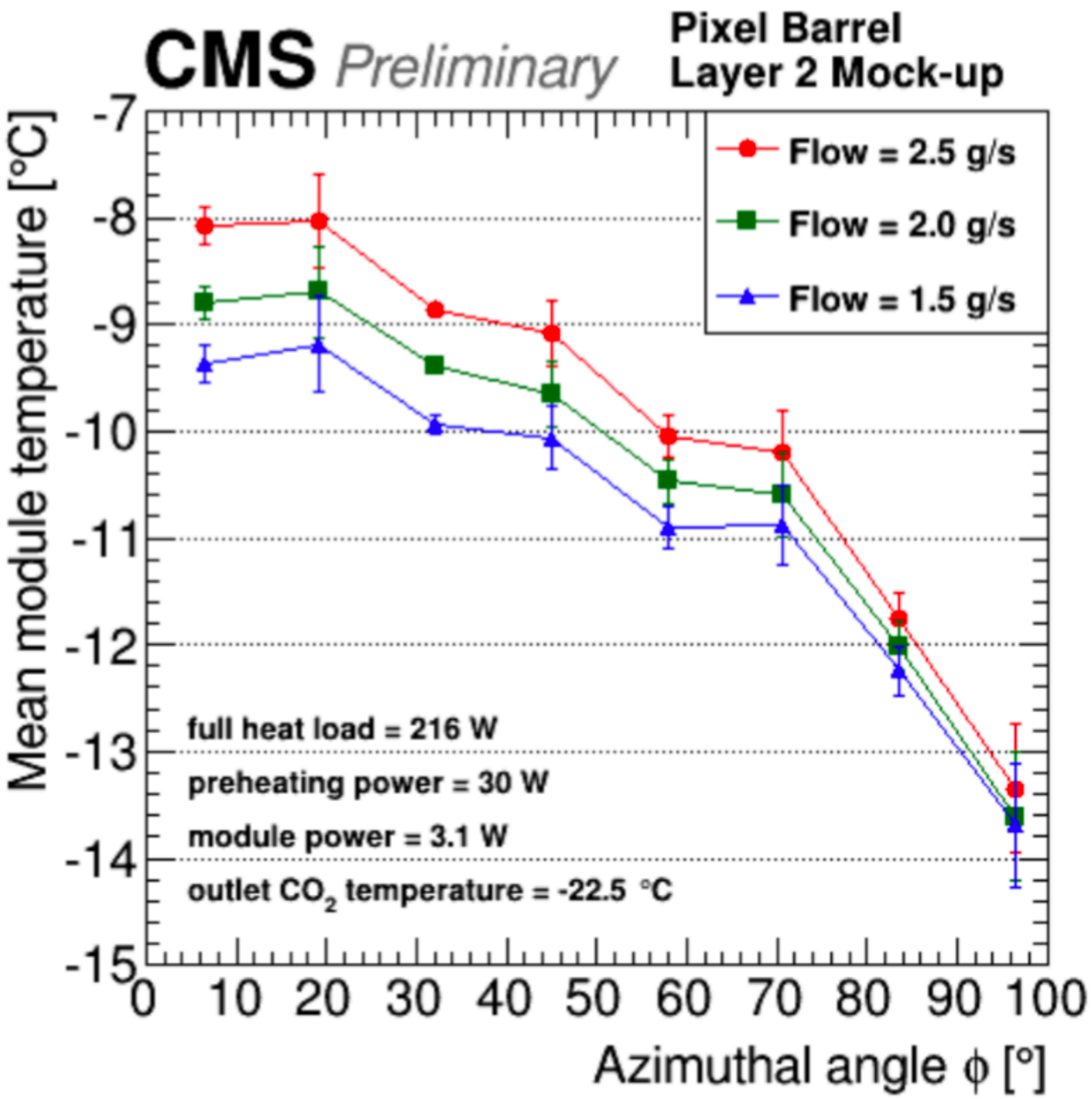



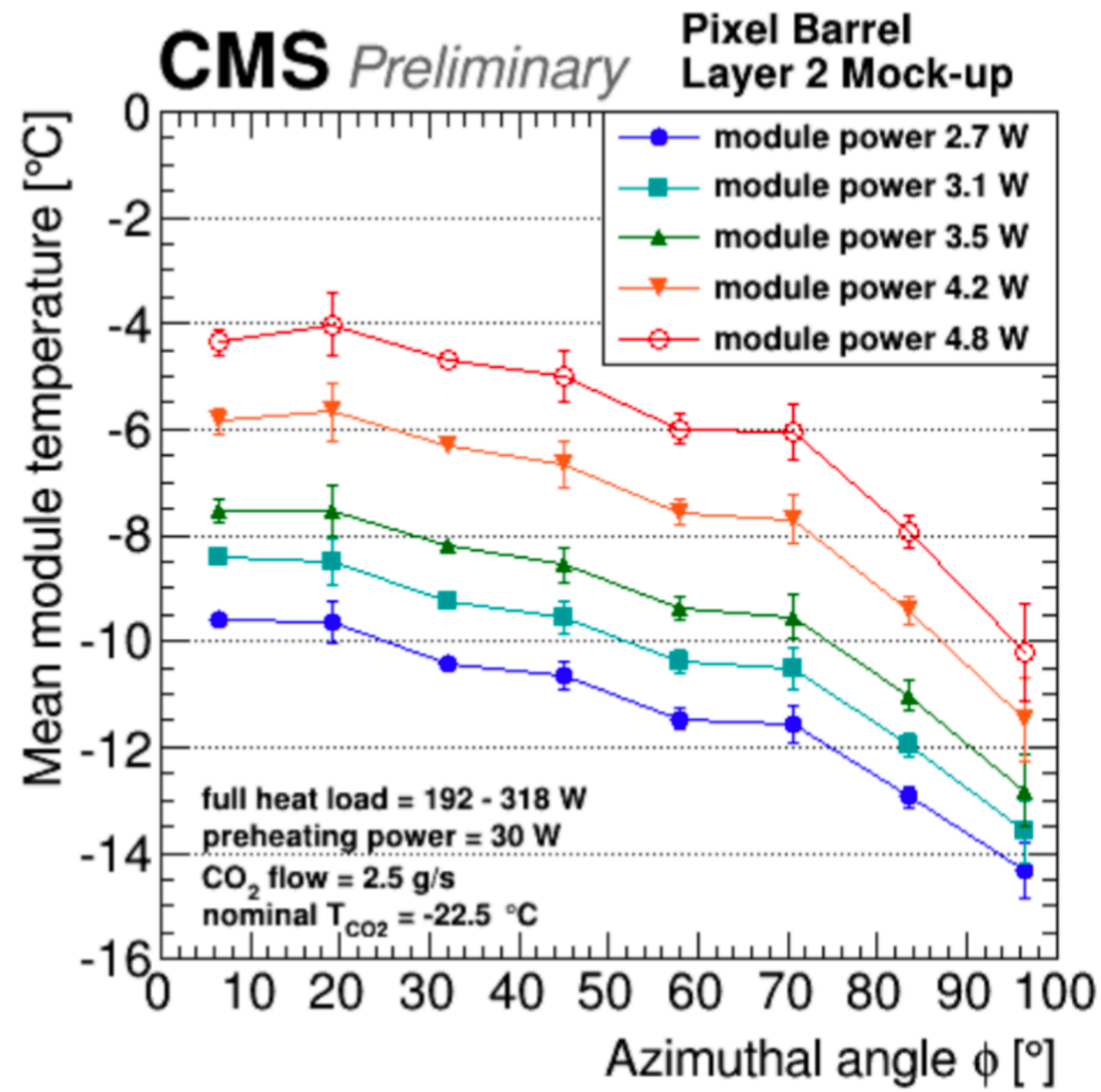
# Pixel module occupancy




- Each module has 16 readout chips
- In the plot, one bin corresponds to one readout chip (ROC)
- The monitoring system has **a database** recording the **problems associated to the detector occupancy**
  - Red marked rectangles

# Temperature & cooling flow dependence (thermal mockup)




- The effect observed is due to the properties of the $CO_2$ in 2-phase state
- The temperature at the return point (ϕ = 90º) stays nearly constant, the differences (spreads) depending the full heat load
- $CO_2$ mass flow reduction can decrease the temperature and leakage current in the detector
- A significant higher module power also affects the temperature

# Silicon module temperature estimation

1. Measurements from carbon fibre (near cooling loop):
Taking the average of all sensors and average over a day.
Temperature is around -11.5 °C when low voltage is on.

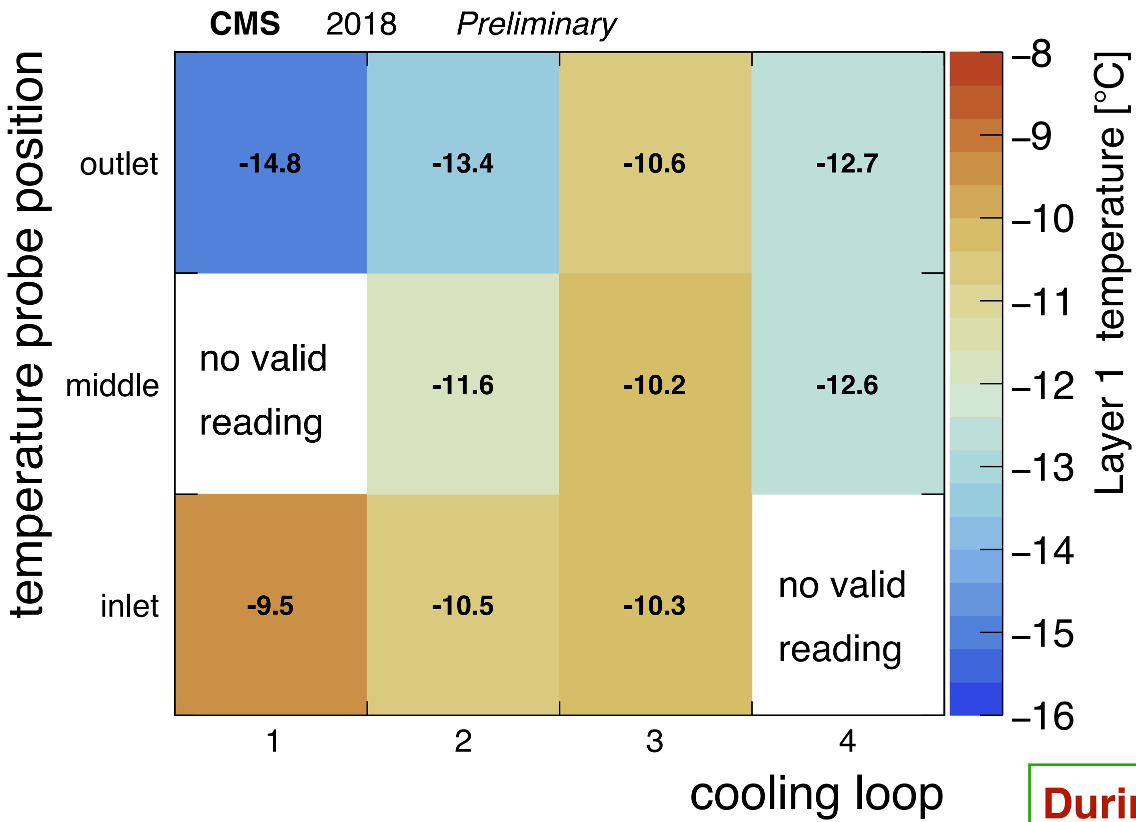
2. Actual silicon temperature is higher than measurements near cooling loop when module power (low voltage) is on.
Estimation from mock-up layer 2 in laboratory:
+ 2-3 K offset to carbon fibre measurements.

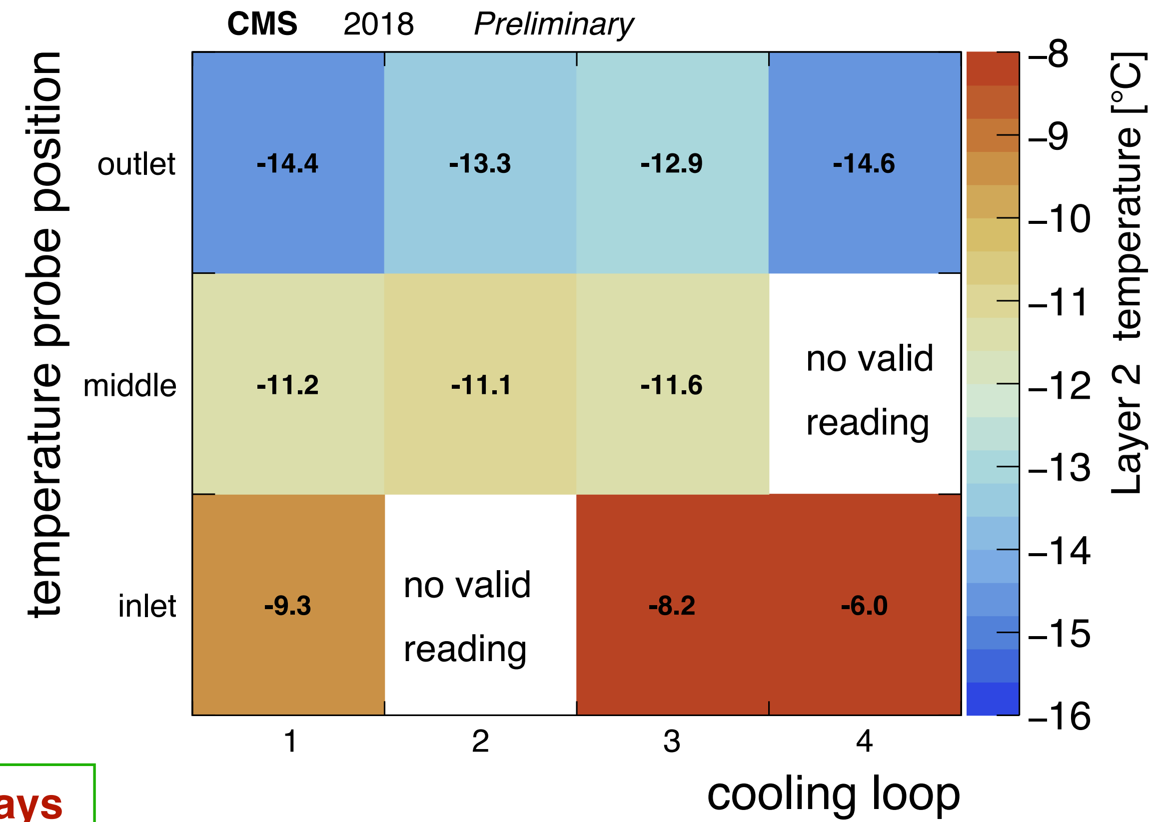
| | L1 | L2 | L3 | L4 |
|---|---|---|---|---|
| 1. Avg. carbon fibre temperature per day | fluctuating around -11.5 °C | | | |
| 2. Estimated offset | +3 K | +3 K | +3 K | +4 K |
| **Silicon temperature** | **-8.5 °C** | **-8.5°C** | **-8.5°C** | **-7.5°C** |

Layer 4:
Warmed by the adjacent strip tracker, assuming +1 K

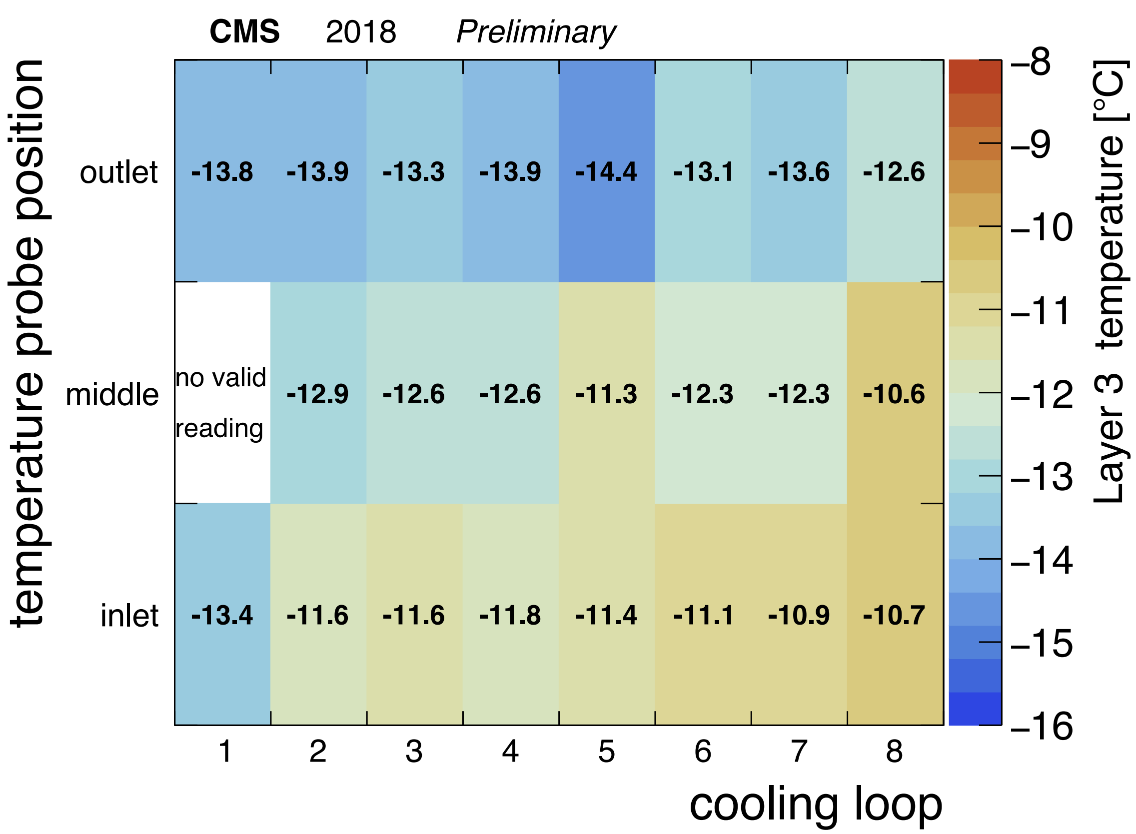
Layer 1: Better thermal contact (no base strips),
but also higher digital activity.
We estimate that these effects cancel each other out.

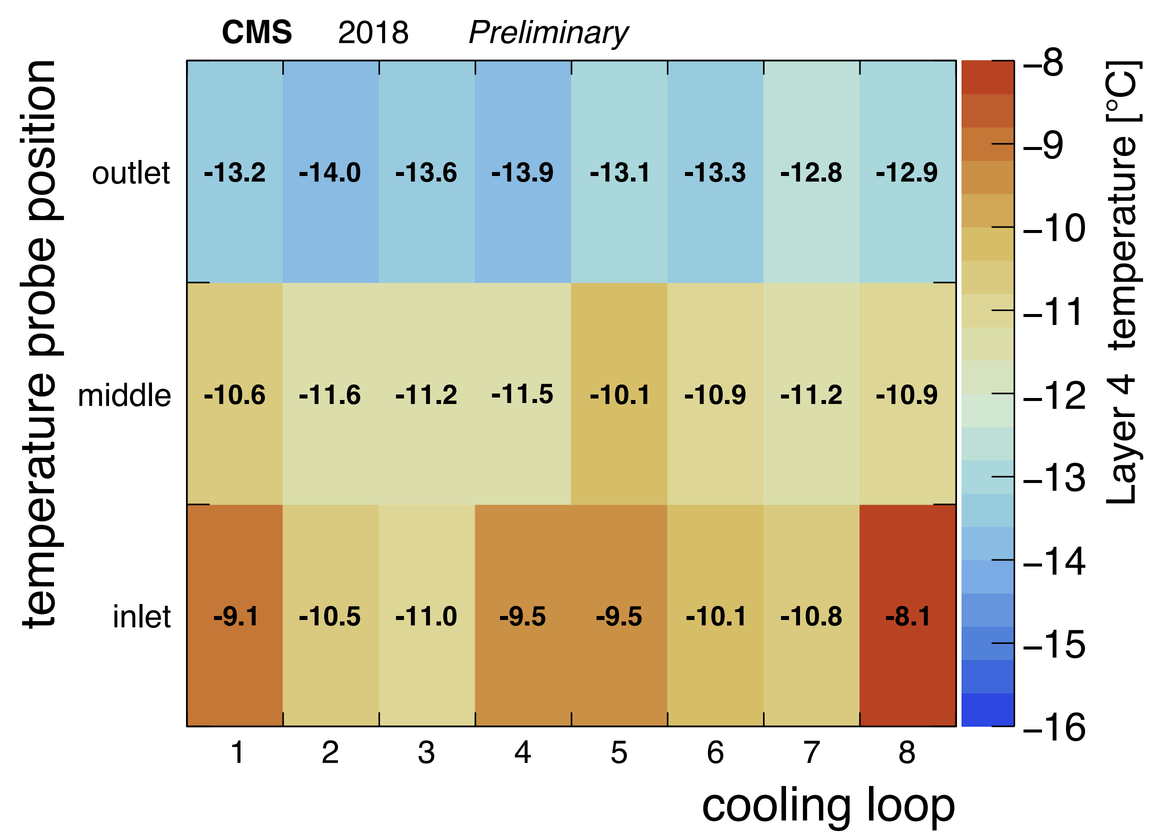
# Pixel barrel temperature gradient along each cooling loop



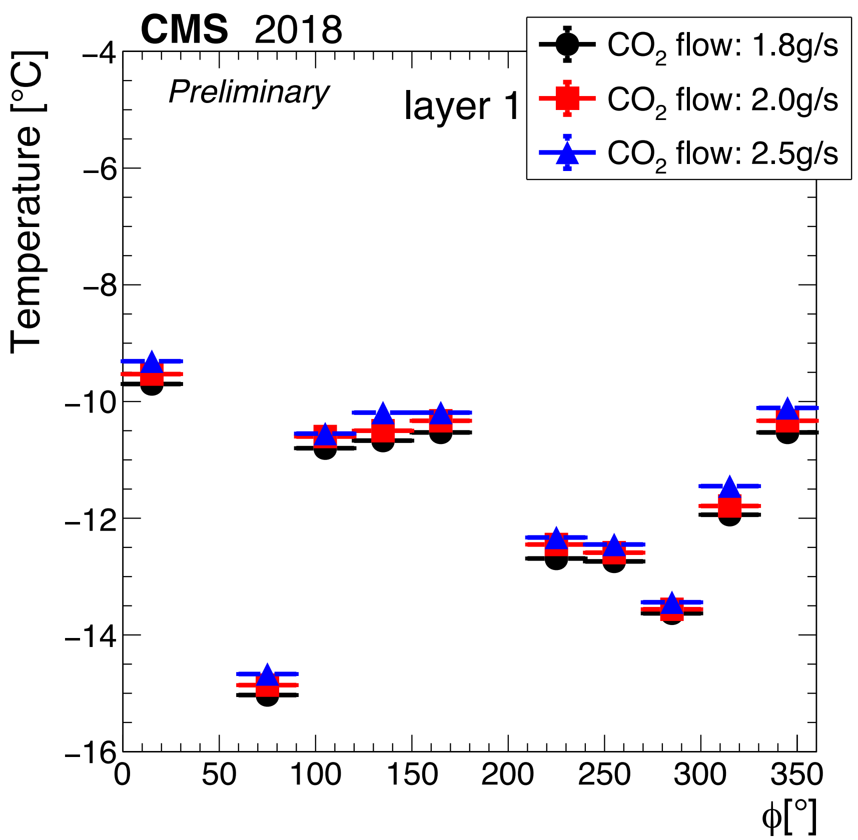

**During cosmic rays**

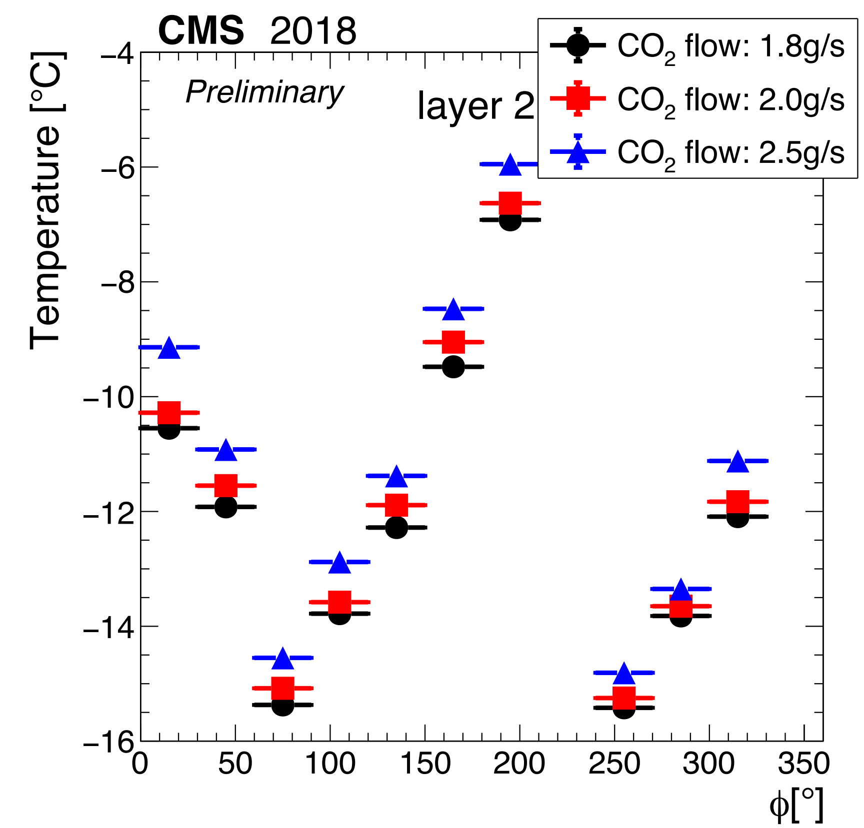


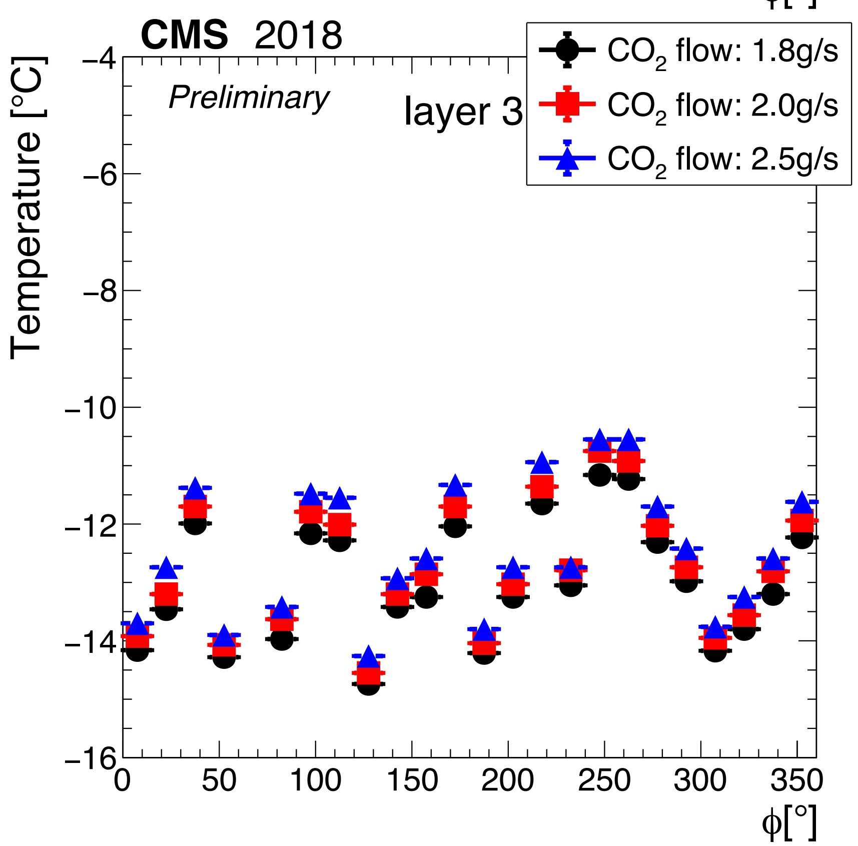

- Each cooling loop has three temperature probes, which are located respectively at the beginning (inlet), middle, end (outlet) positions
- As expected for $CO_2$ cooling, the temperature at the outlet is lower than at the inlet

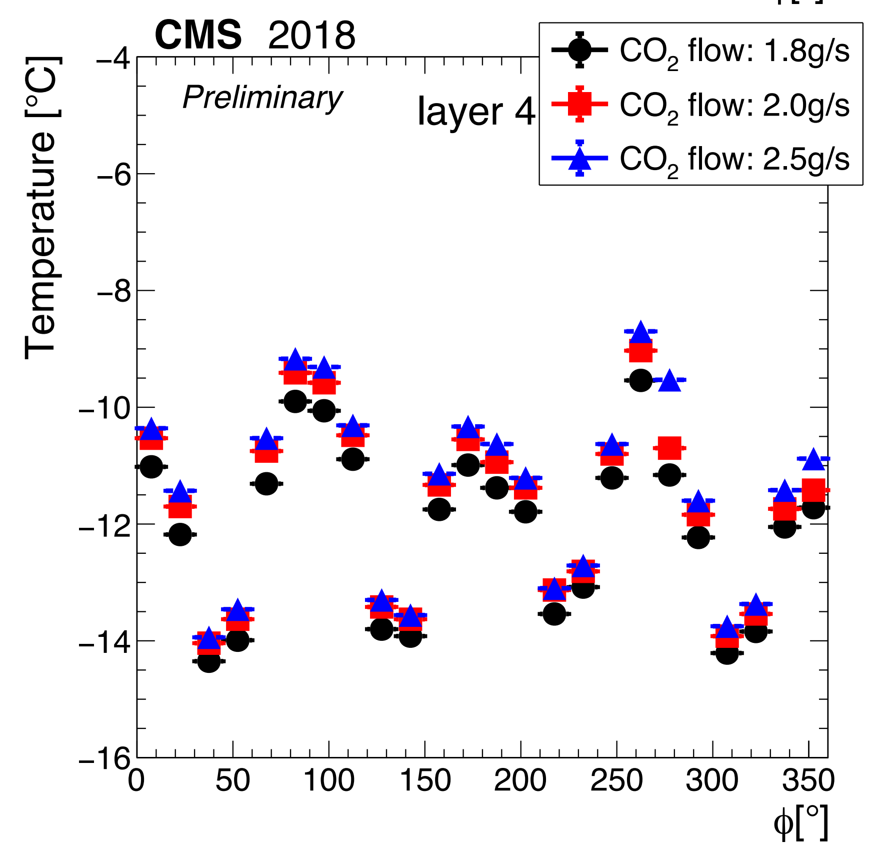
# Pixel barrel temperature w.r.t azimuthal coordinate



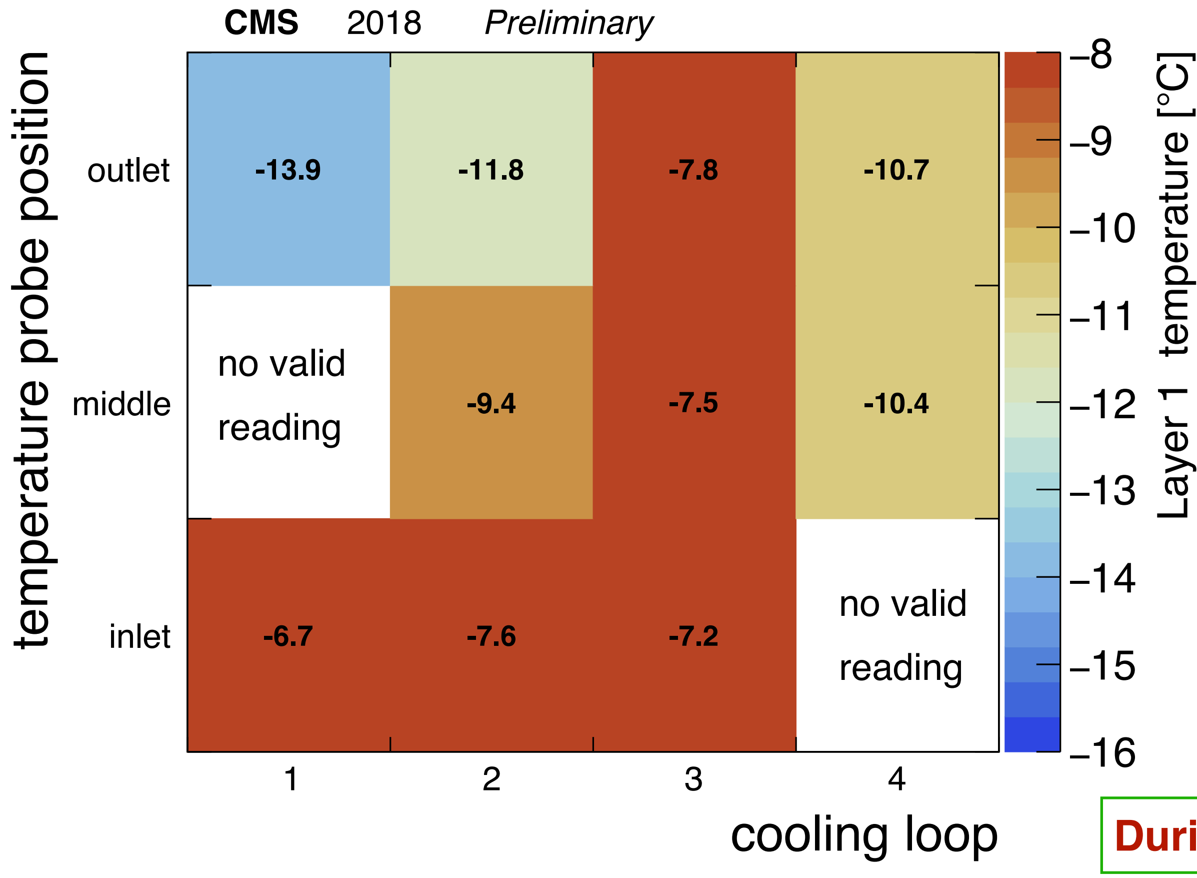

During cosmic rays

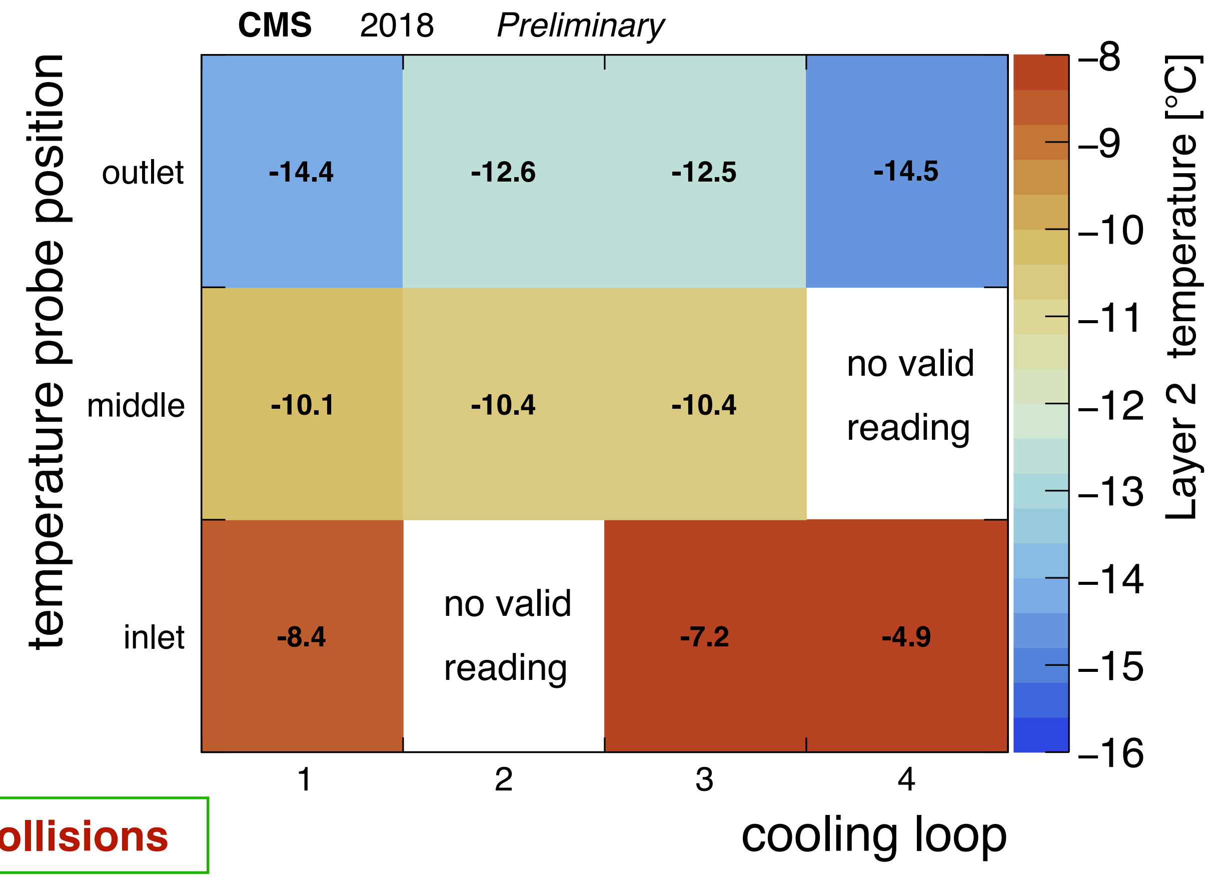


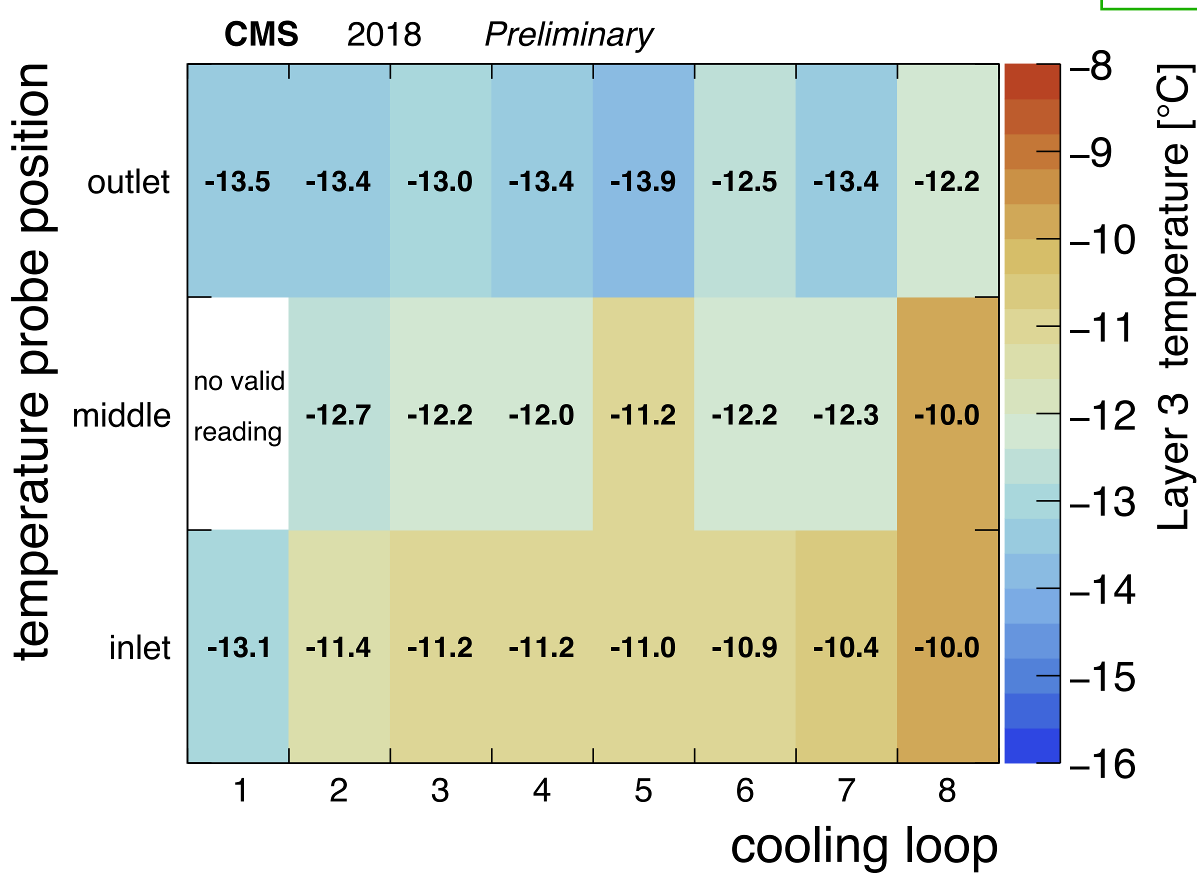

- **As a result of the 2-phase state of $CO_2$ cooling flow, decreased $CO_2$ flow leads to its absorbing heat more sufficiently, resulting in more efficient cooling, lower temperature, less temperature spread (explanations in slide 9)**

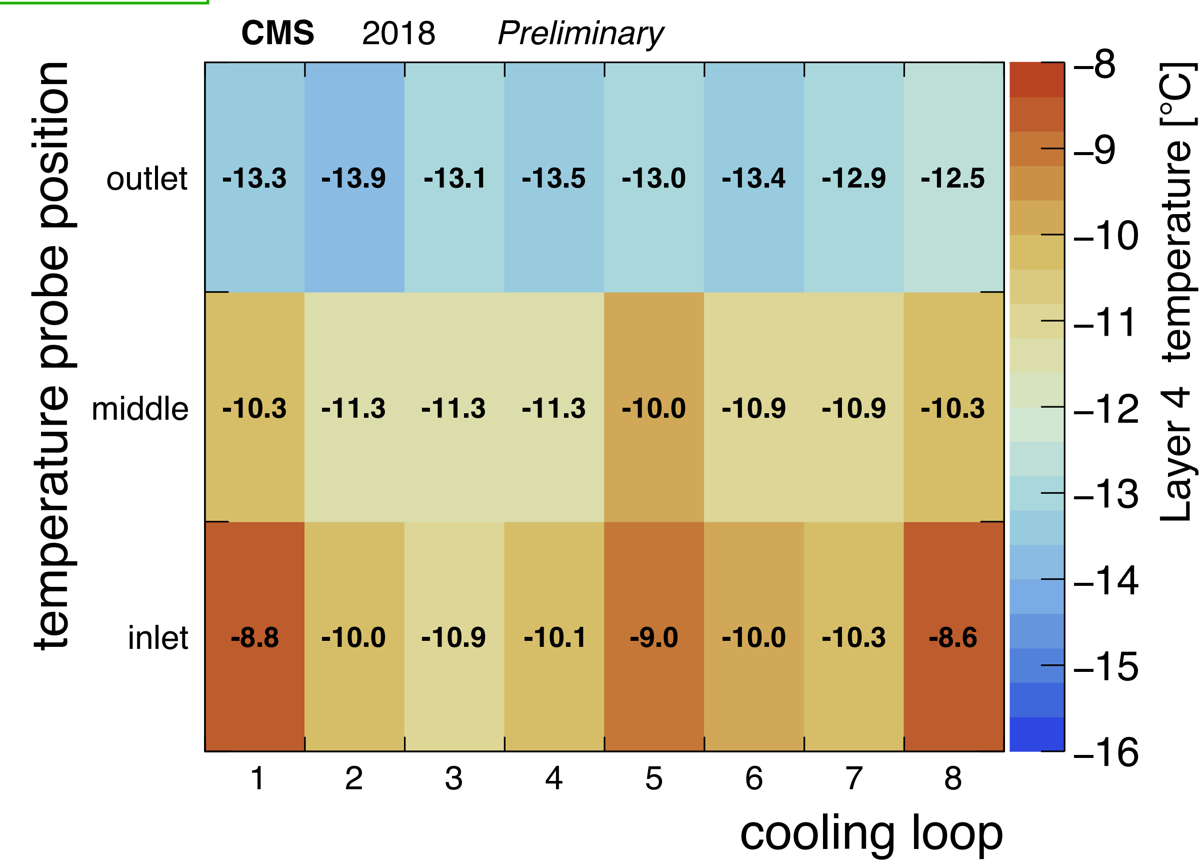
# Pixel barrel temperature gradient along each cooling loop



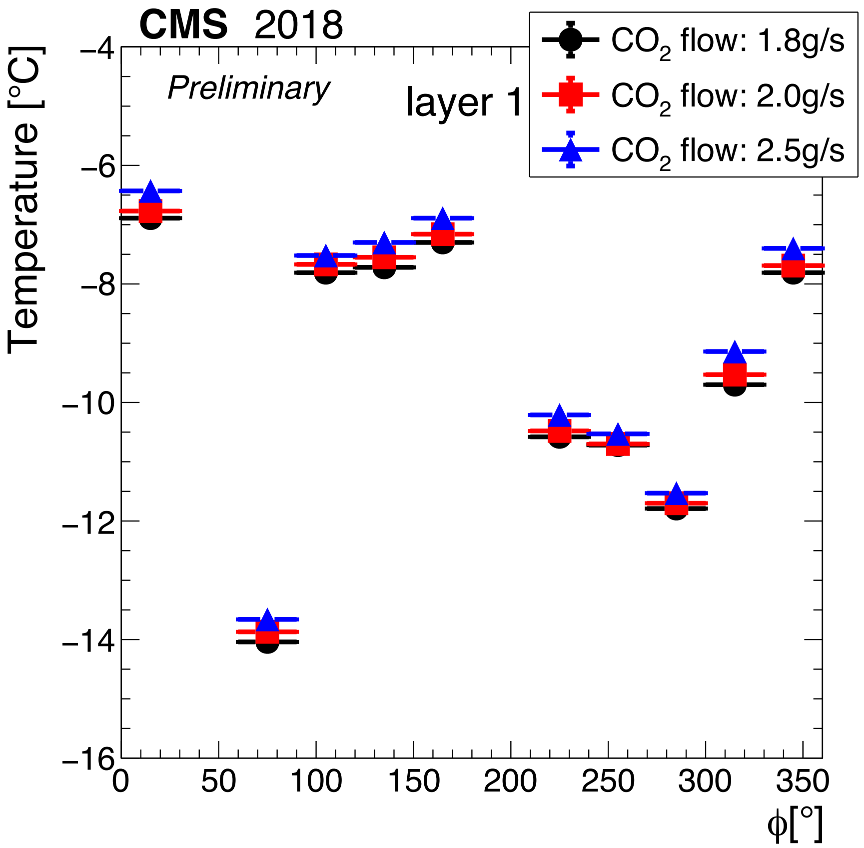

**During p-p collisions**

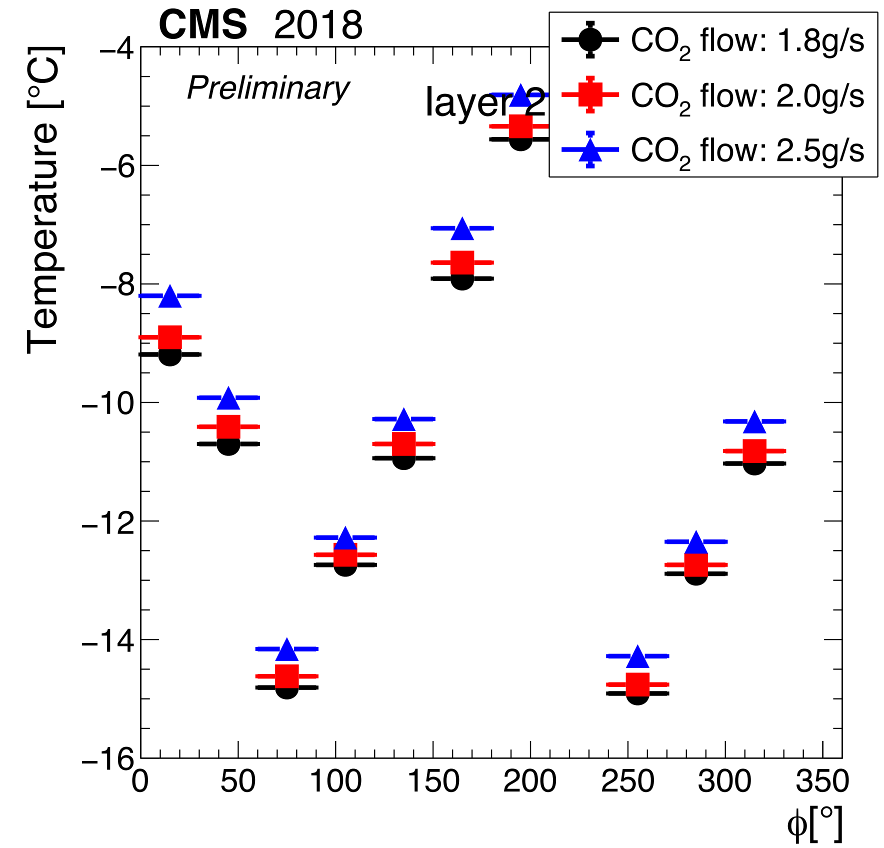


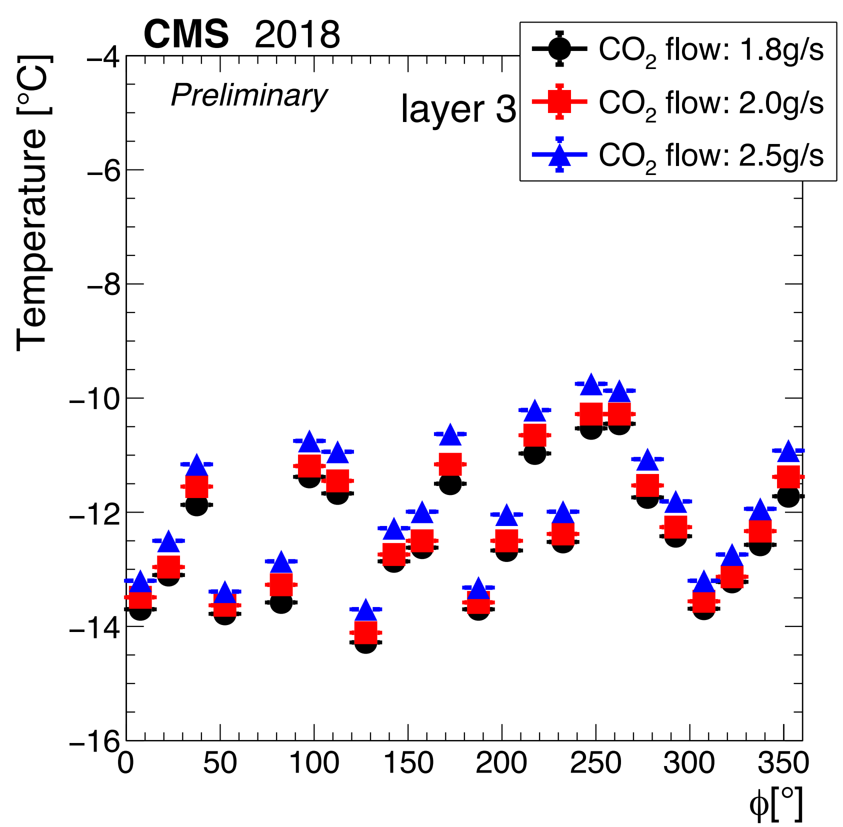

- Each cooling loop has three temperature probes, which are located respectively at the beginning (inlet), middle, end (outlet) positions
- As expected for $CO_2$ cooling, the temperature at the outlet is lower than at the inlet

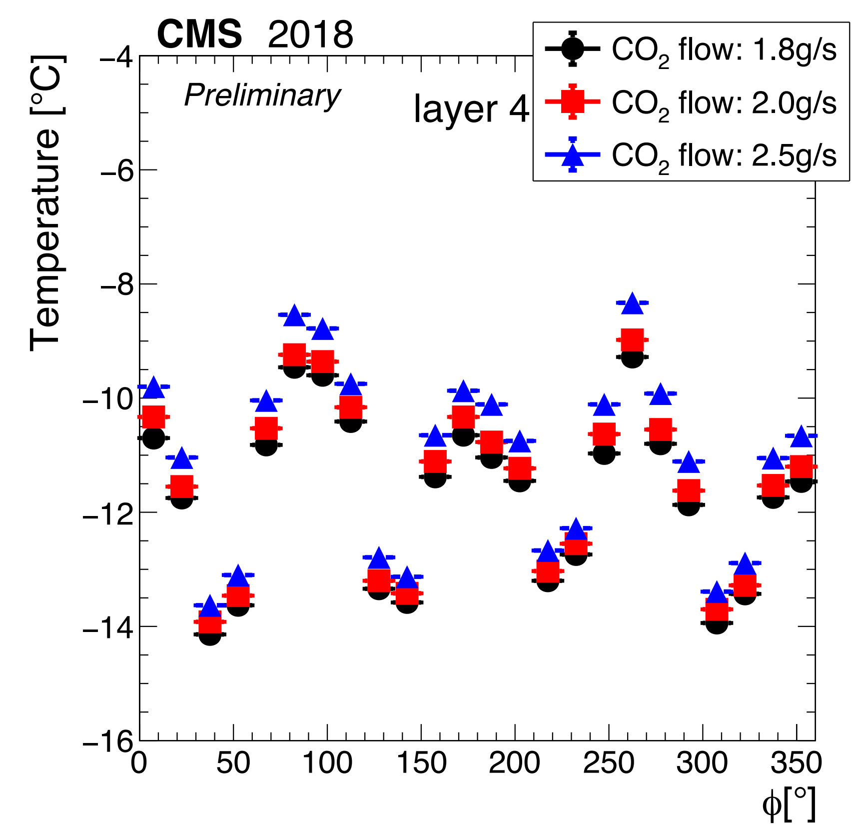
# Pixel barrel temperature w.r.t azimuthal coordinate




**During p-p collisions**

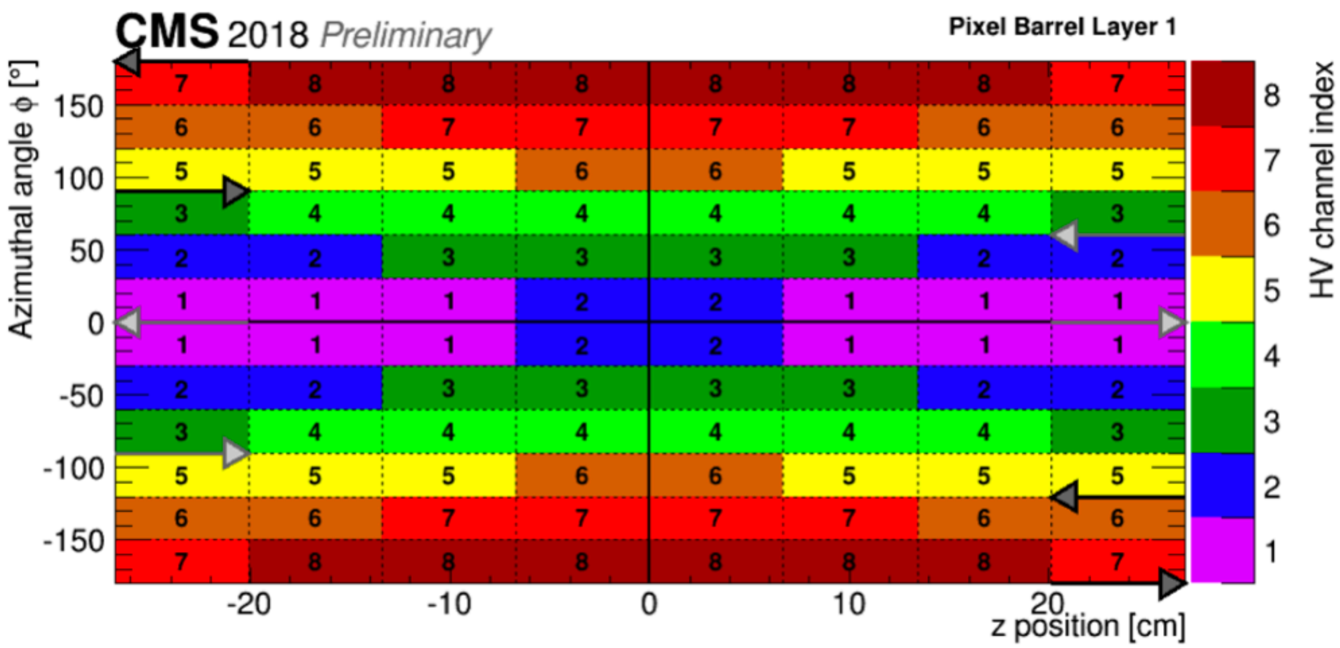


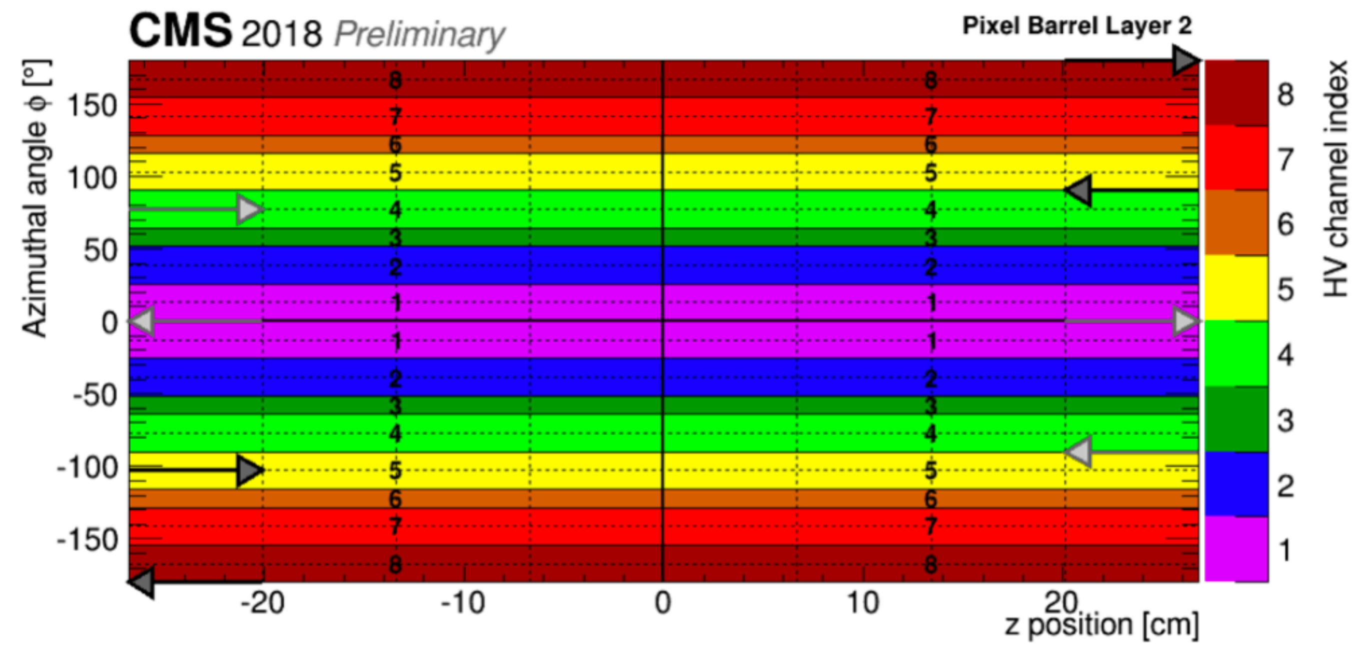



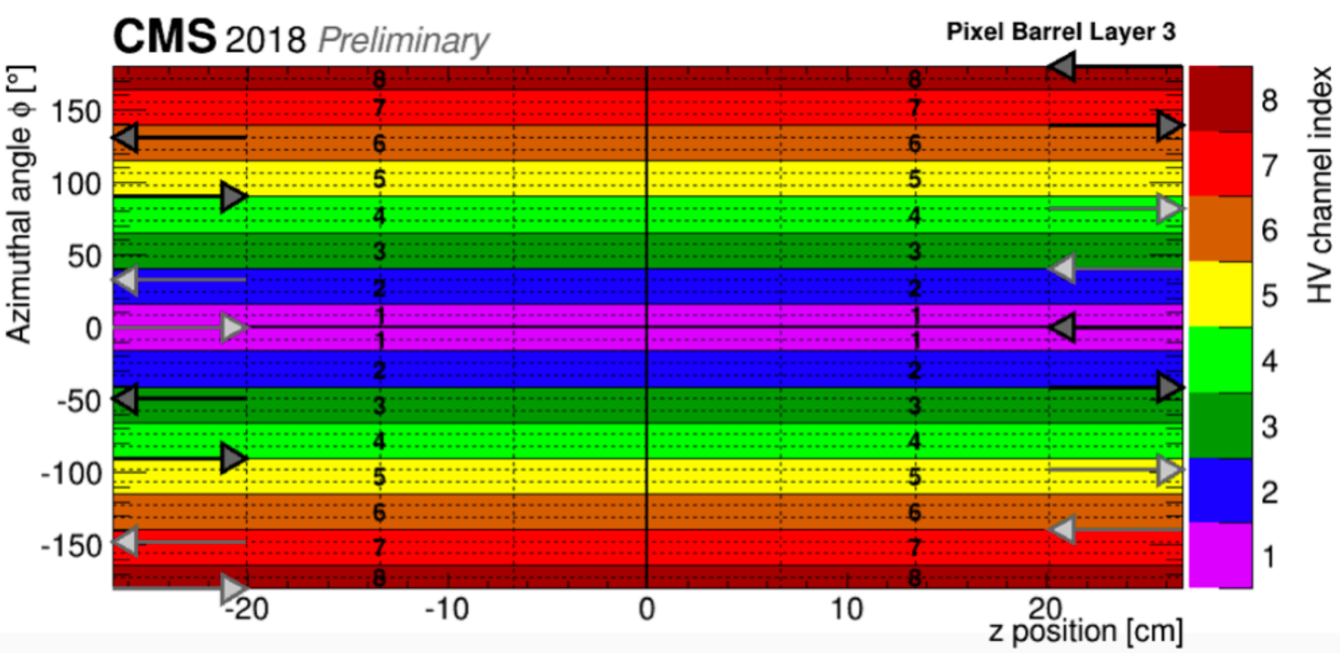

- **As a result of the 2-phase state of $CO_2$ cooling flow, decreased $CO_2$ flow leads to its absorbing heat more sufficiently, resulting in more efficient cooling, lower temperature, less temperature spread (explanations in slide 9)**

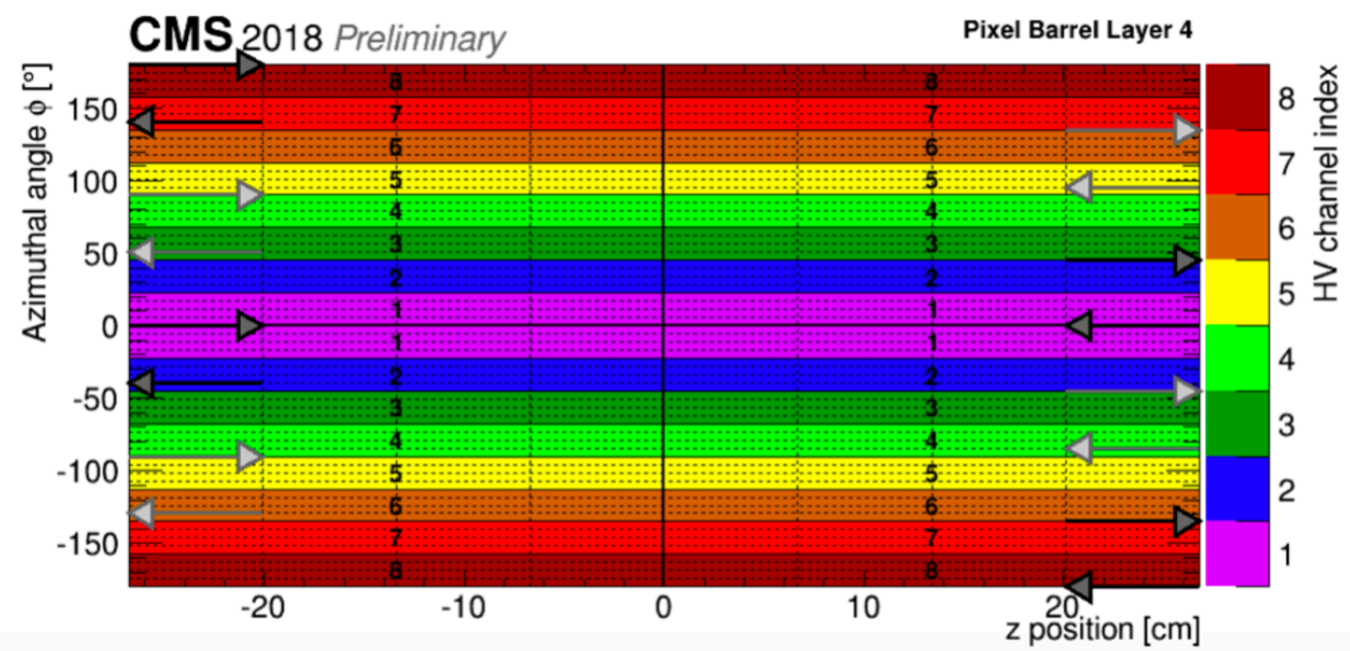
# Map of pixel barrel power sectors

- Each layer has 8 power sectors
- Arrows indicate the inlet and outlet of $CO_2$ cooling lines

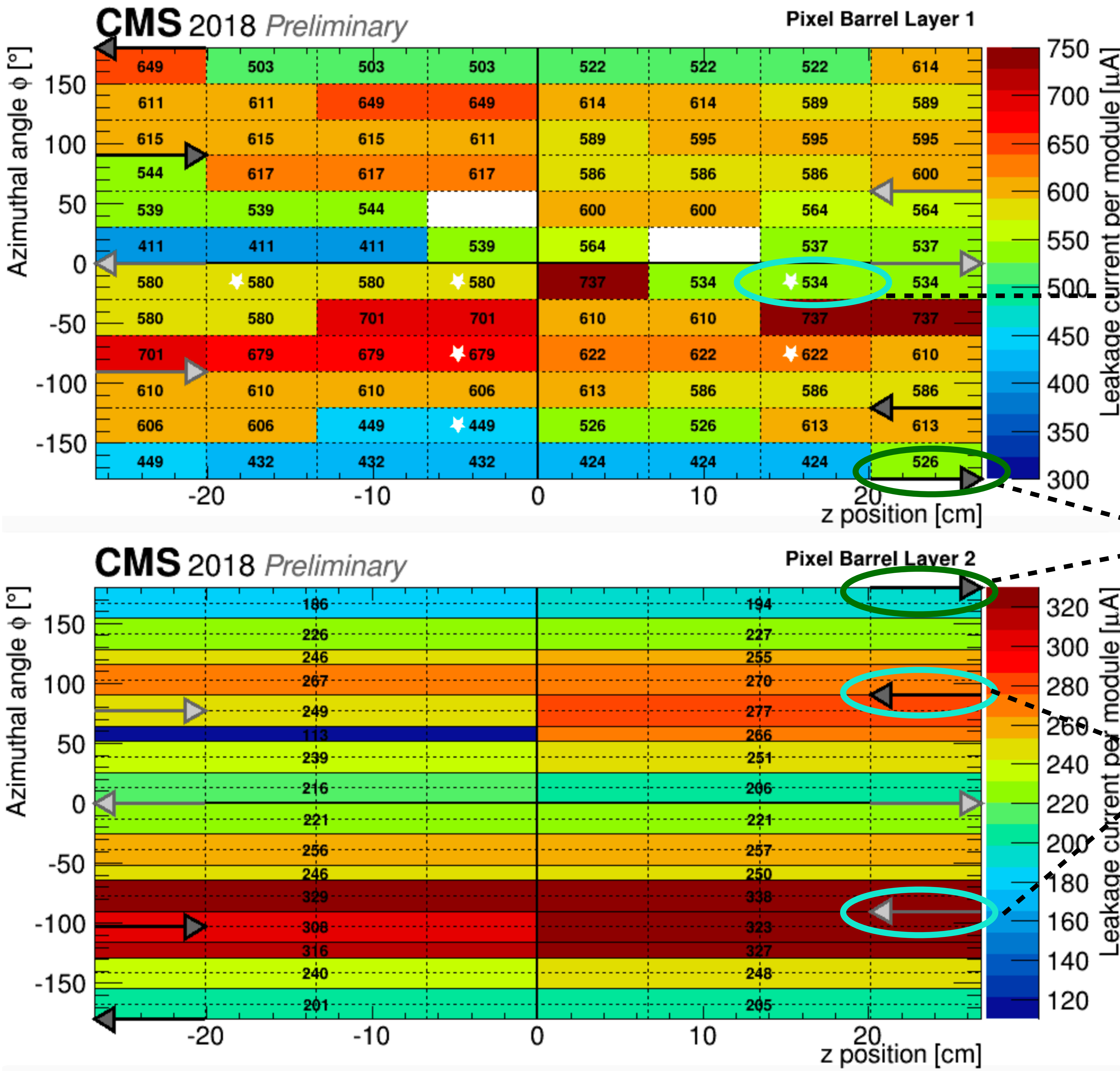


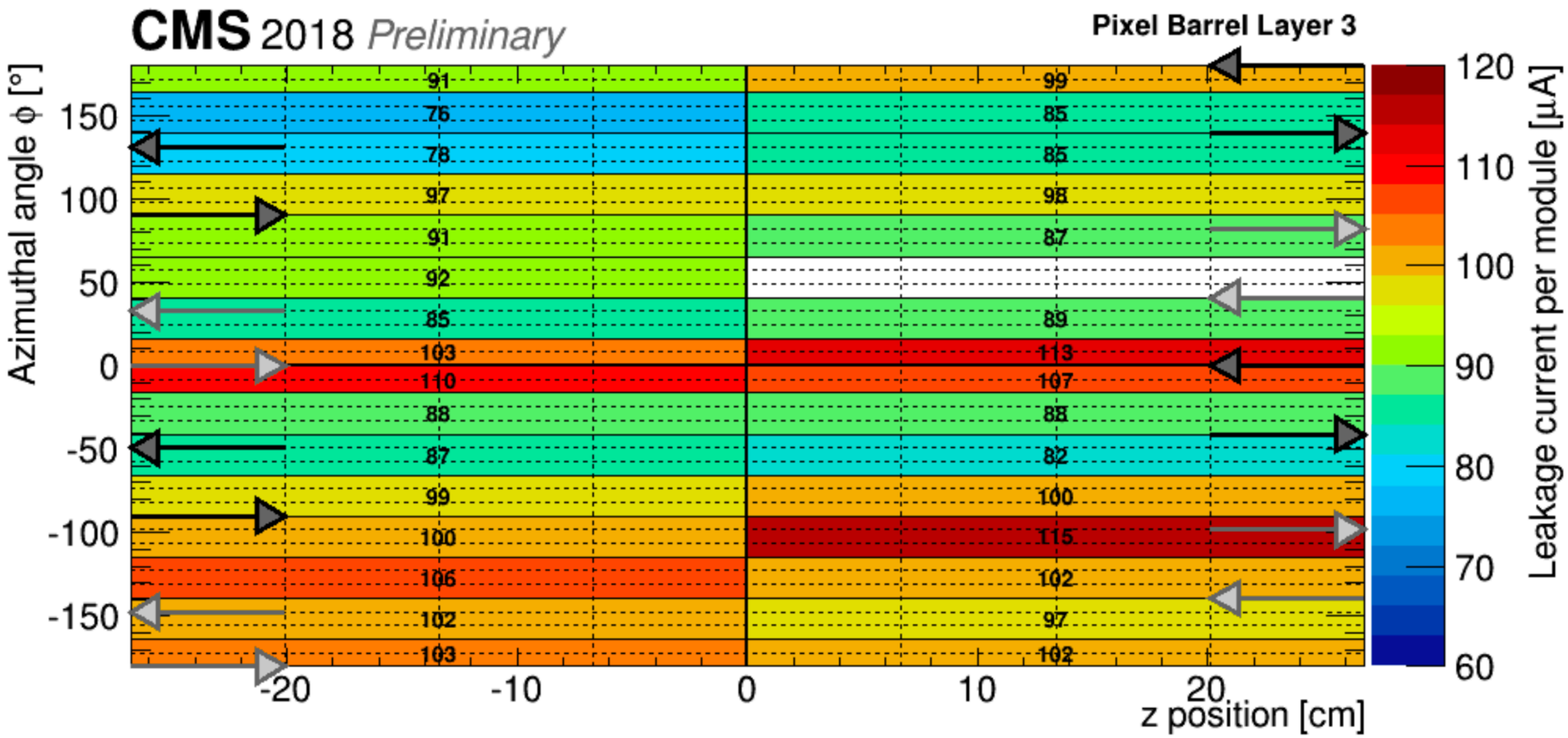



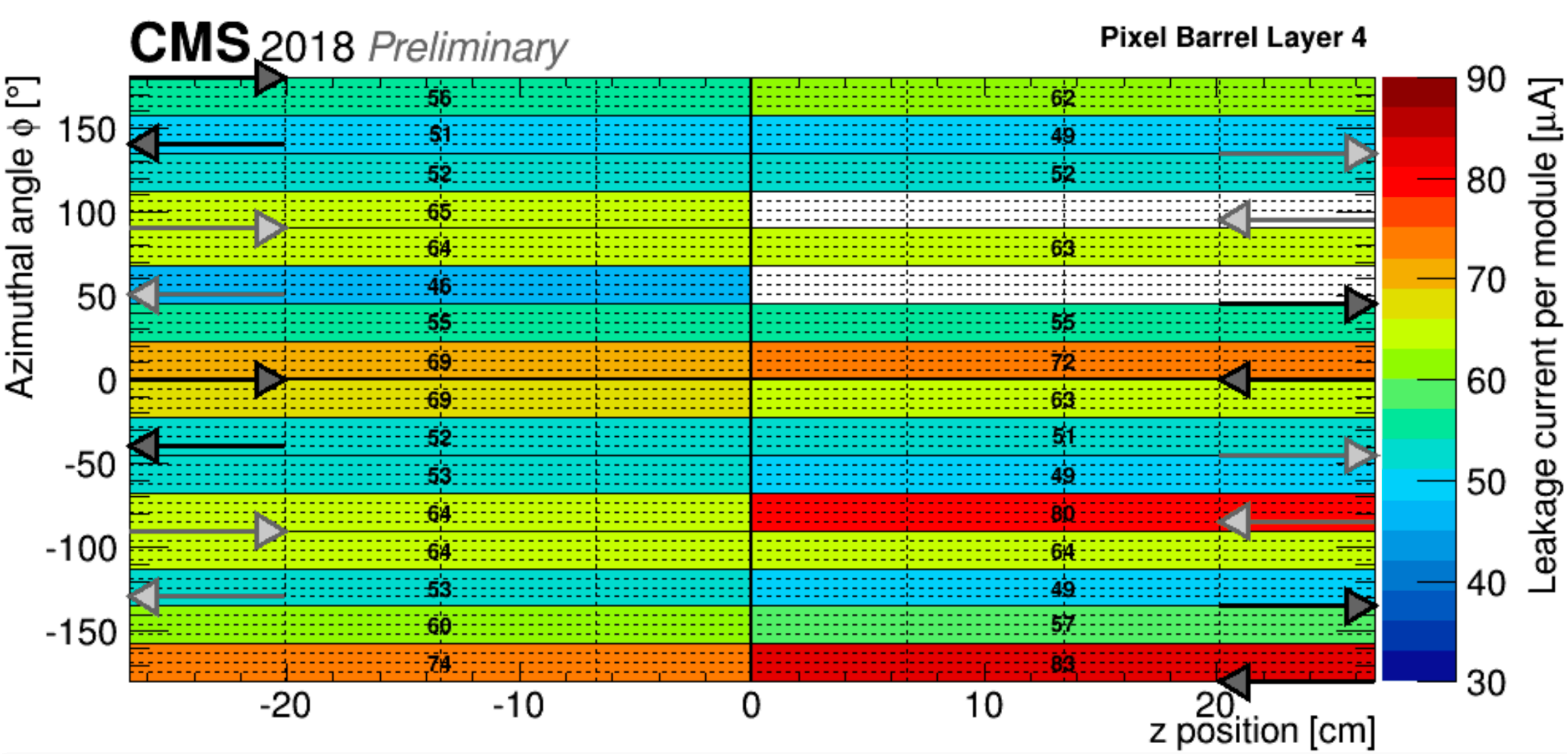
# Pixel barrel leakage current distribution (average per sector)




- White asterisk:
  - Modules exchanged between 2017 and 2018
- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current
- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

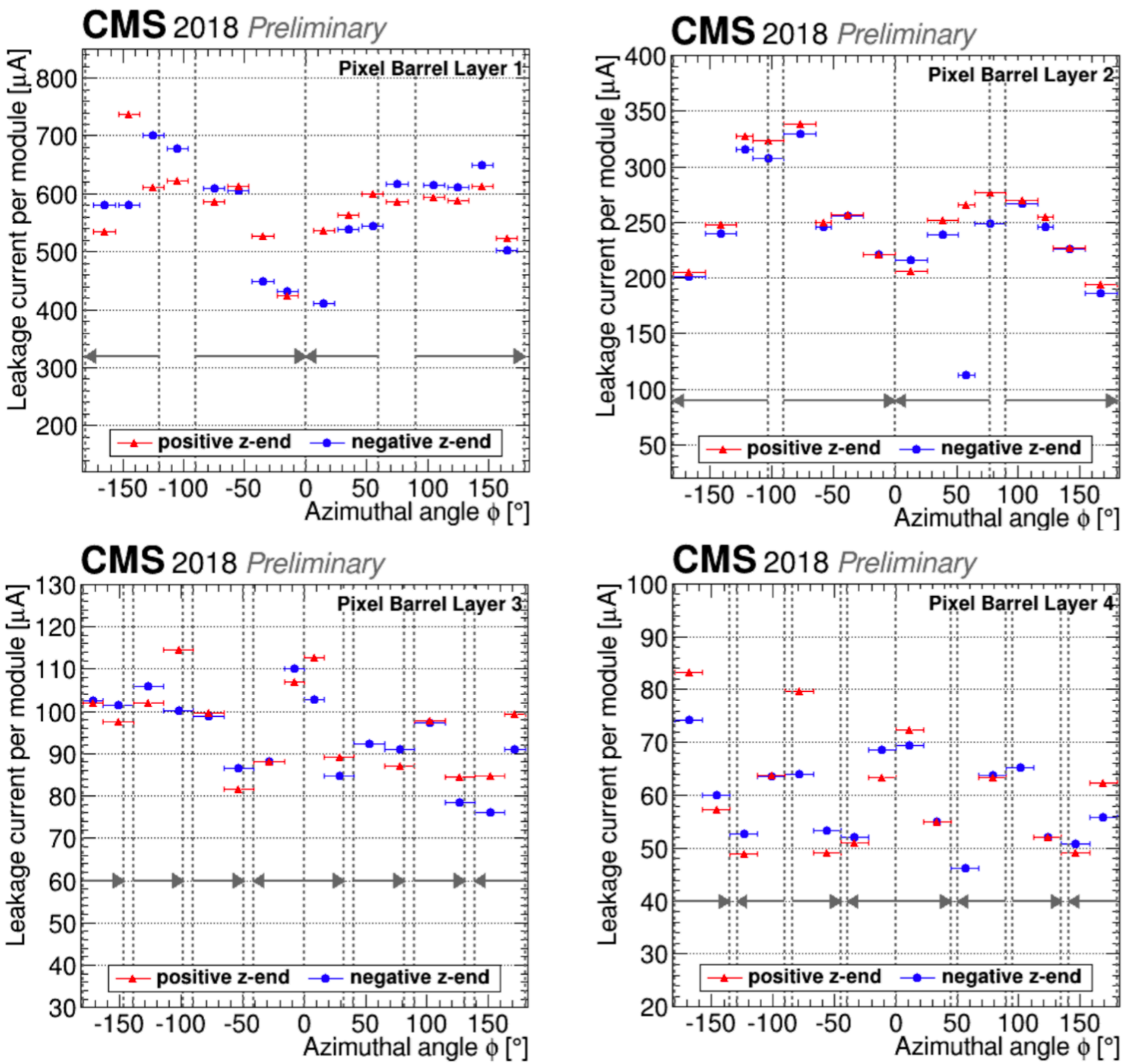
# Pixel barrel leakage current distribution (average per sector)




- Layer 3/4 are more distant from beams than layer 1/2 —> lower leakage current
- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current
- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

# Pixel barrel leakage current w.r.t azimuthal coordinate

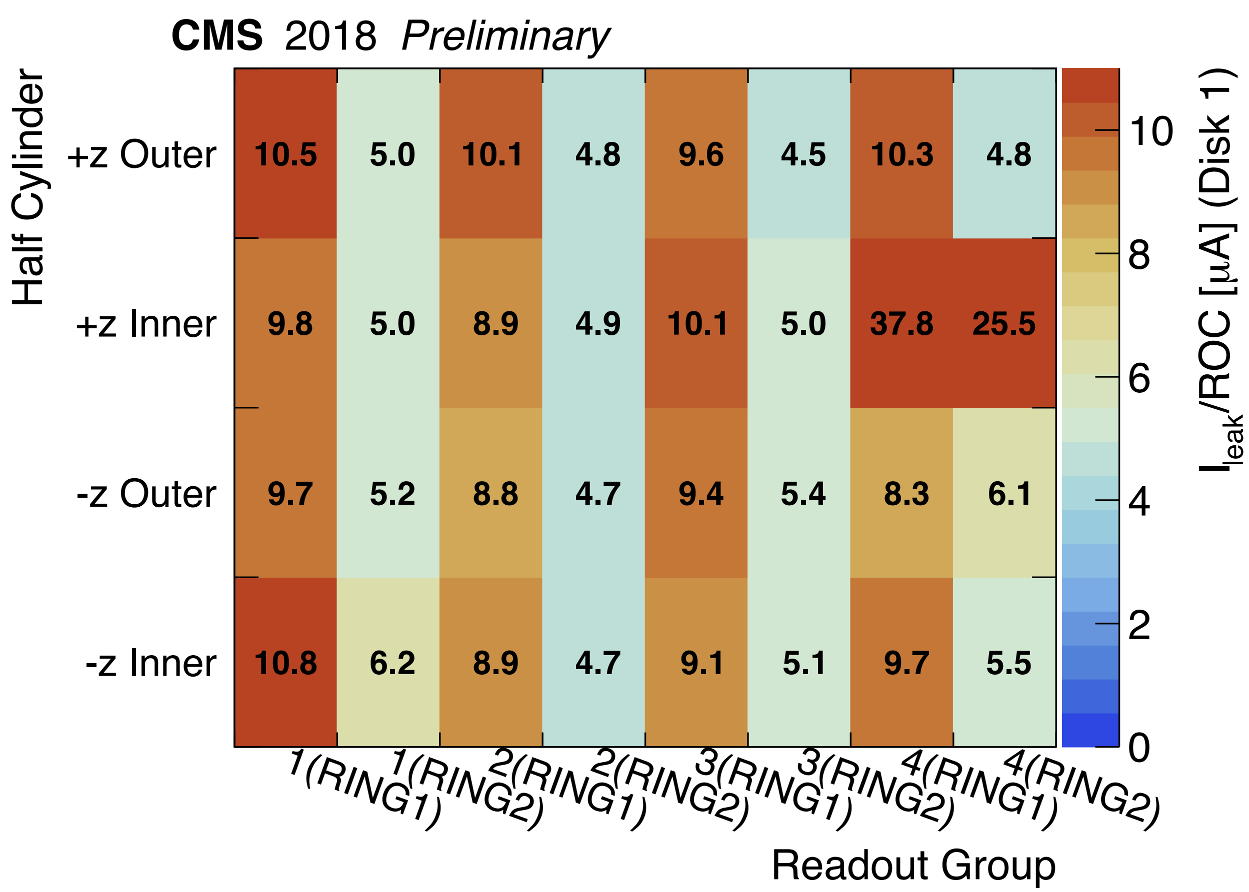


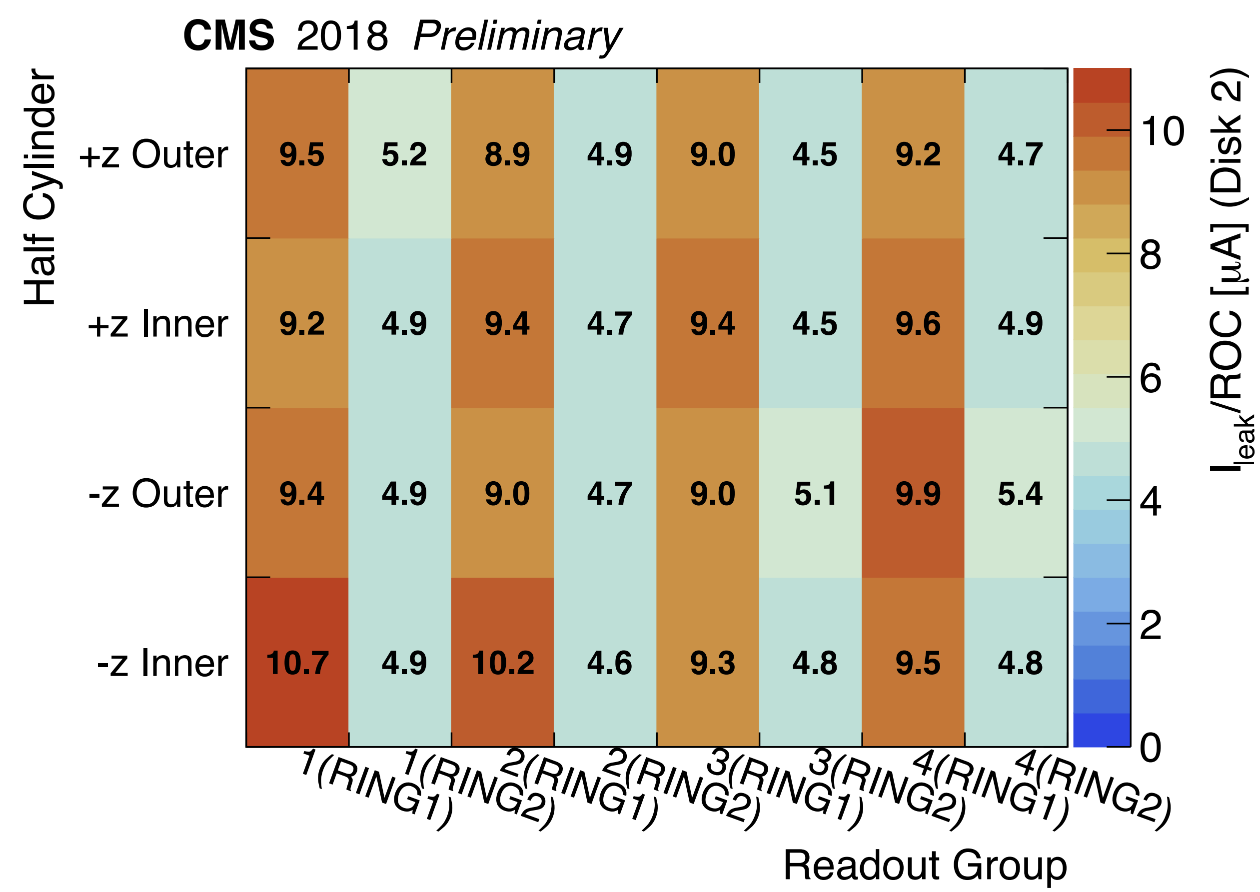

- Gray arrows: $CO_2$ cooling direction
- Dashed lines: inlet or outlet

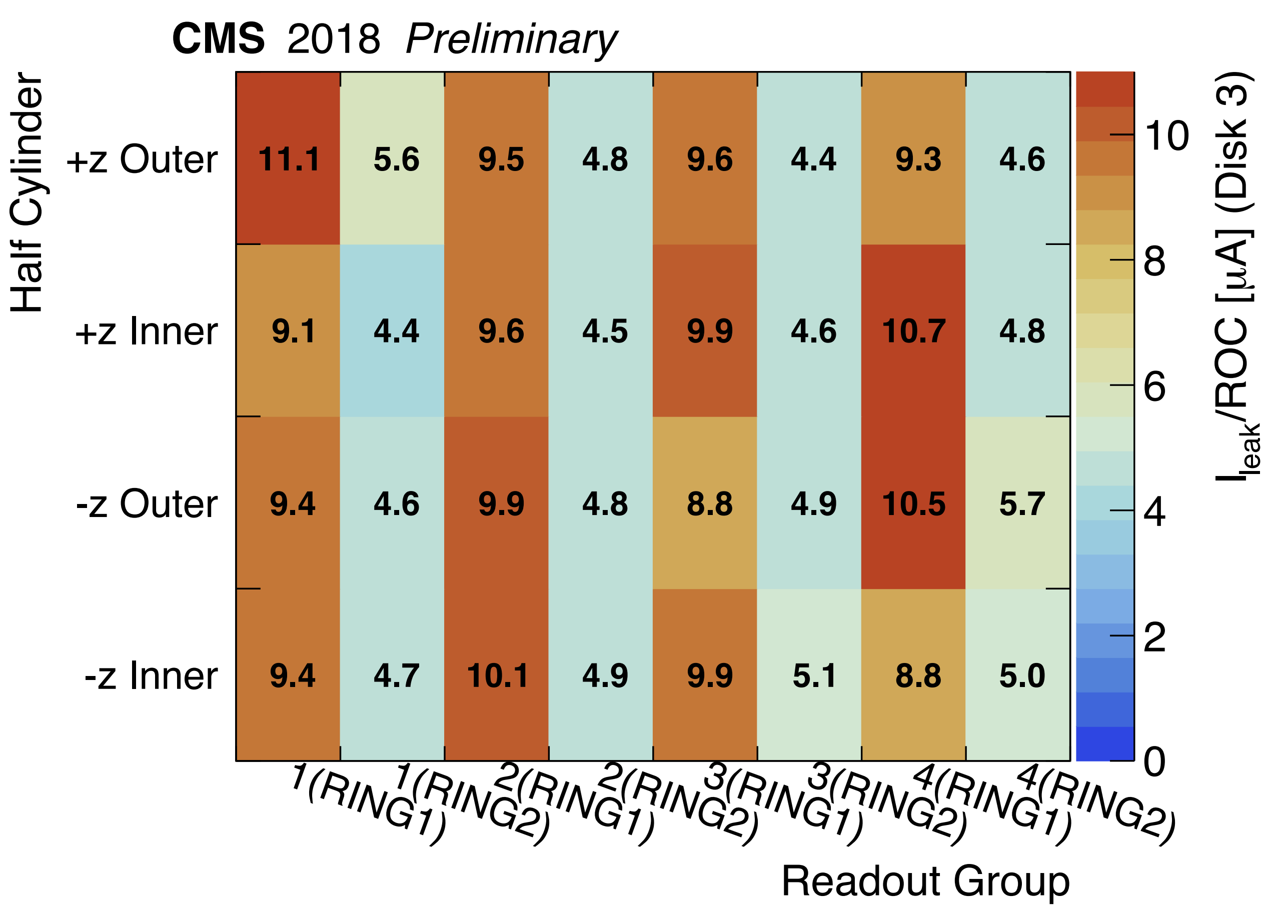
- Outlet of cooling loop
  - Lower Temperature drop
  - Lower leakage current

- Inlet of cooling loop
  - Higher Temperature drop
  - Higher leakage current

# Pixel endcap leakage current distribution



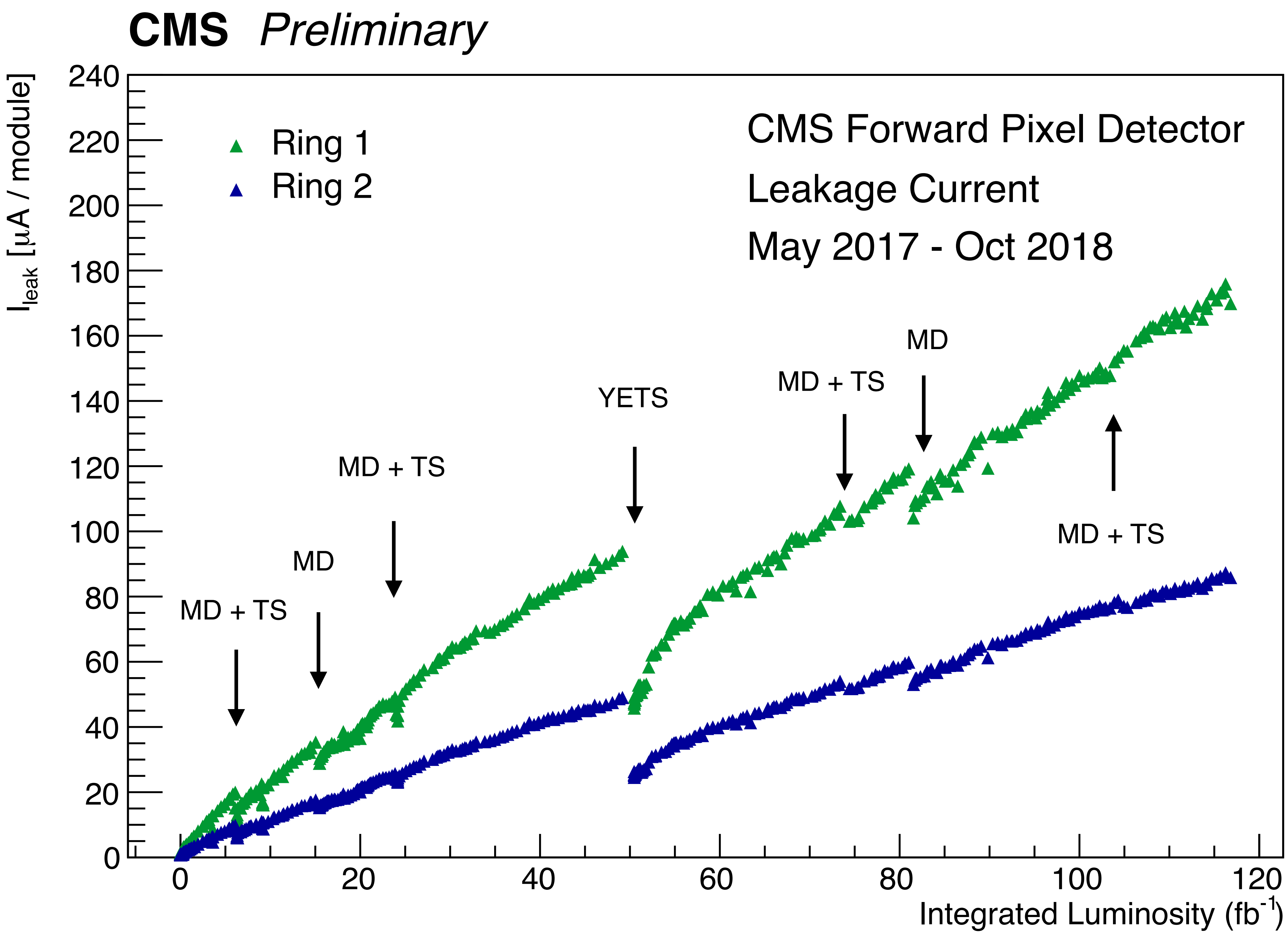




**During p-p collisions**

- **Uniform leakage current distribution in each ring!**
- **RING 1 is closer to beams —> higher leakage current than RING 2**

# Pixel endcap module leakage current evolution (measurement)

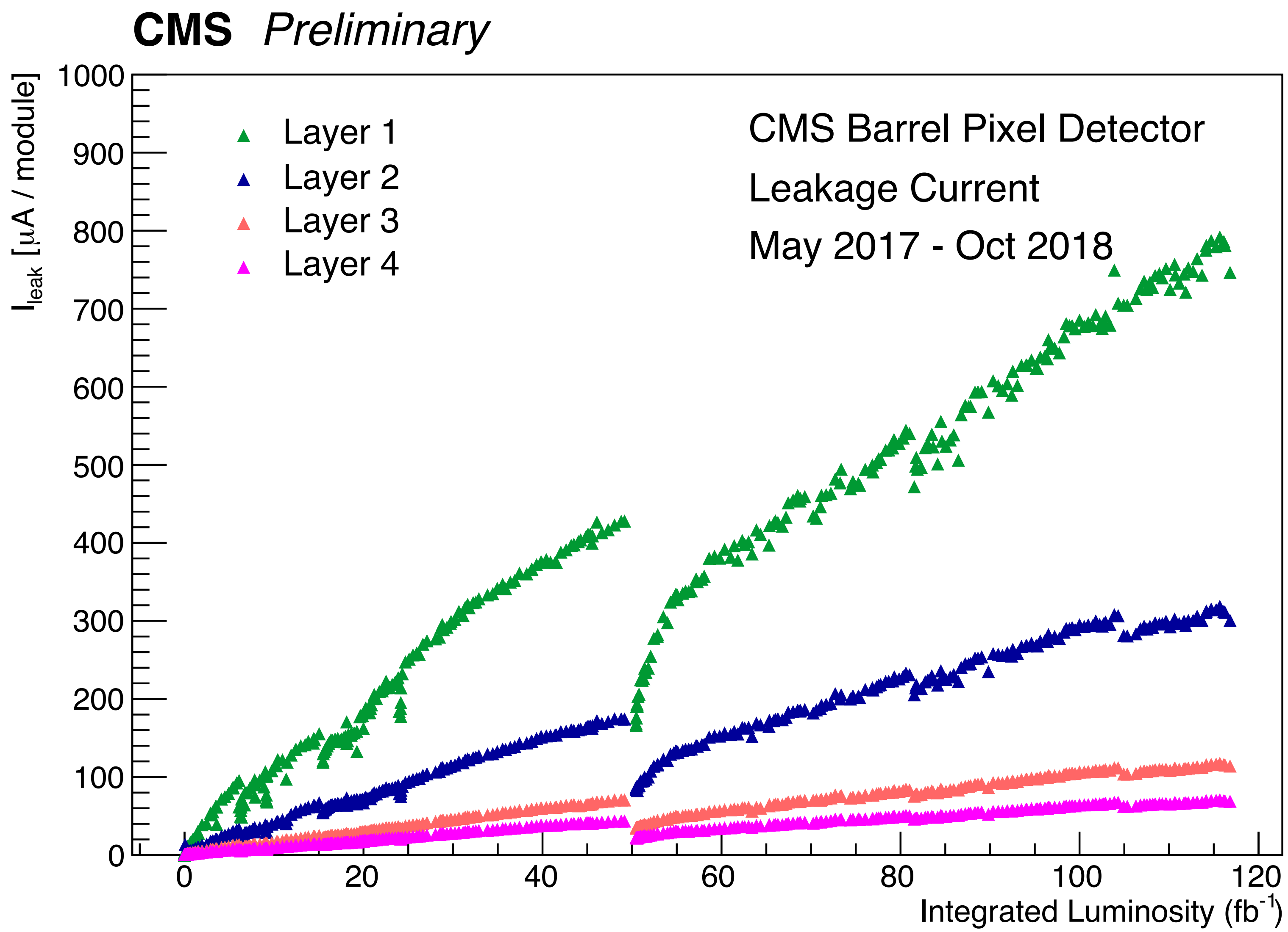



During p-p collisions

- MD: Machine development
- TS: Technical stop
- YETS: Year-End technical stop

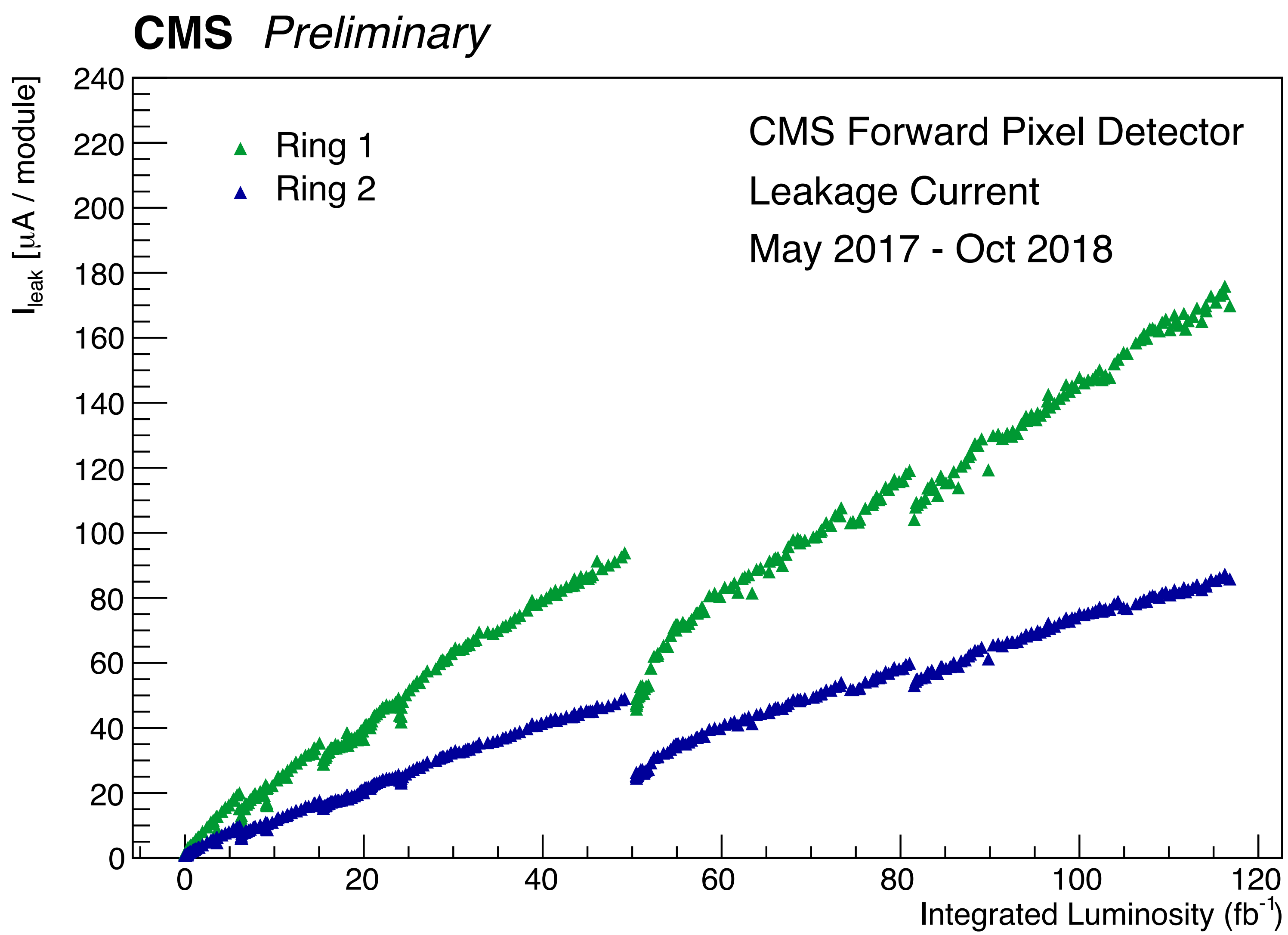
- Leakage current increased gradually due to accumulated radiation dose through the year
- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (ring 1 > ring 2)
- Leakage current drop during MD/TS/YETS: annealing or changed high voltage settings

# Pixel barrel module leakage current evolution



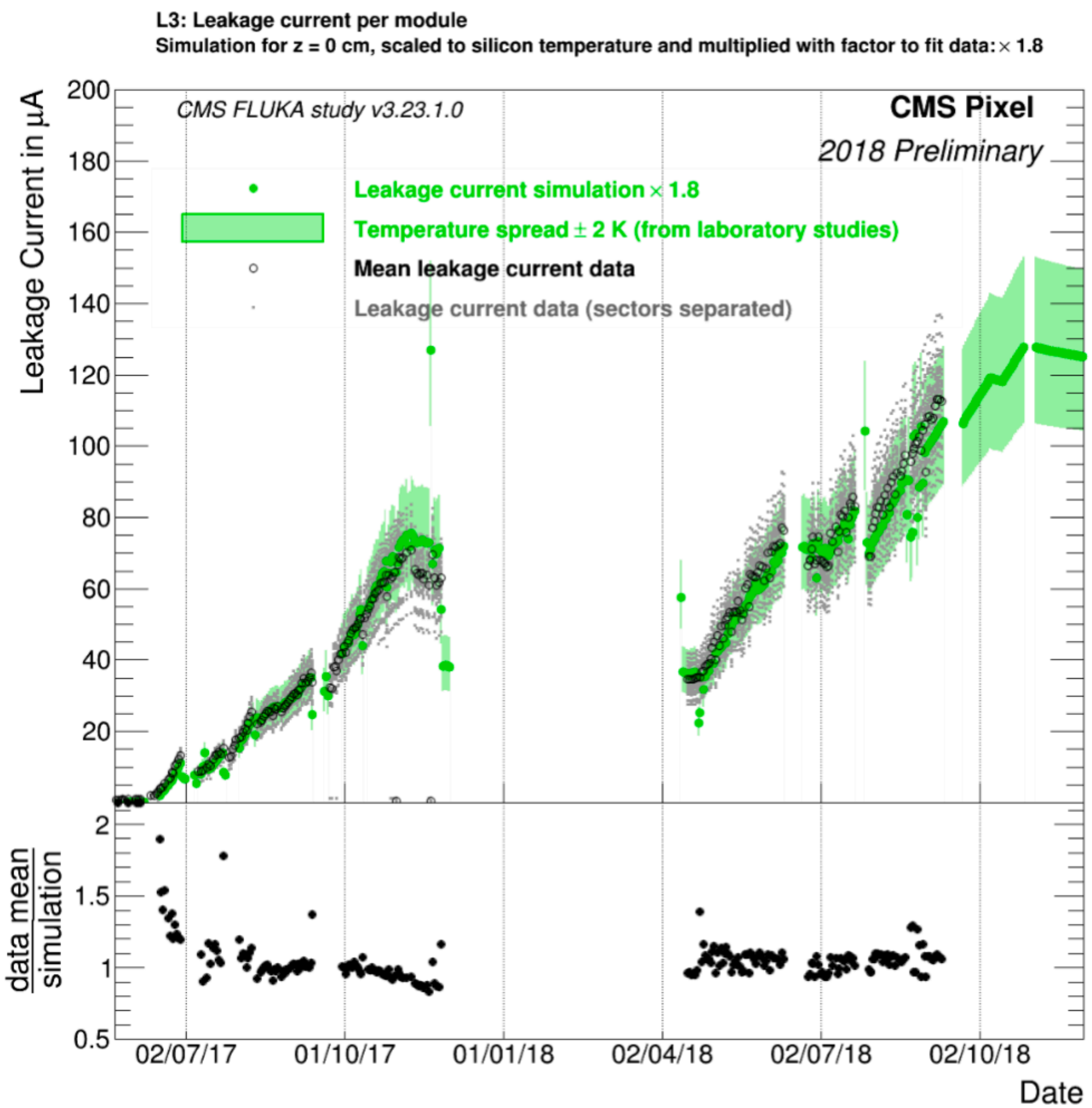

- LHC fills from beginning of 2017 until end of October in 2018 data-taking are employed (proton-proton collisions)
- Currents measured within 20 minutes from Stable Beam declaration
- Average current per pixel module measured from power groups (**no temperature correction**)
- Leakage current increased gradually due to accumulated radiation dose through the year
- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (layer 1 > layer 2 > layer 3 > layer 4)
- There are some drops of leakage current from the global trend because of:
  - Annealing during Machine development or technical stop period
  - Power supply replacement
  - HV setting change

# Pixel endcap module leakage current evolution

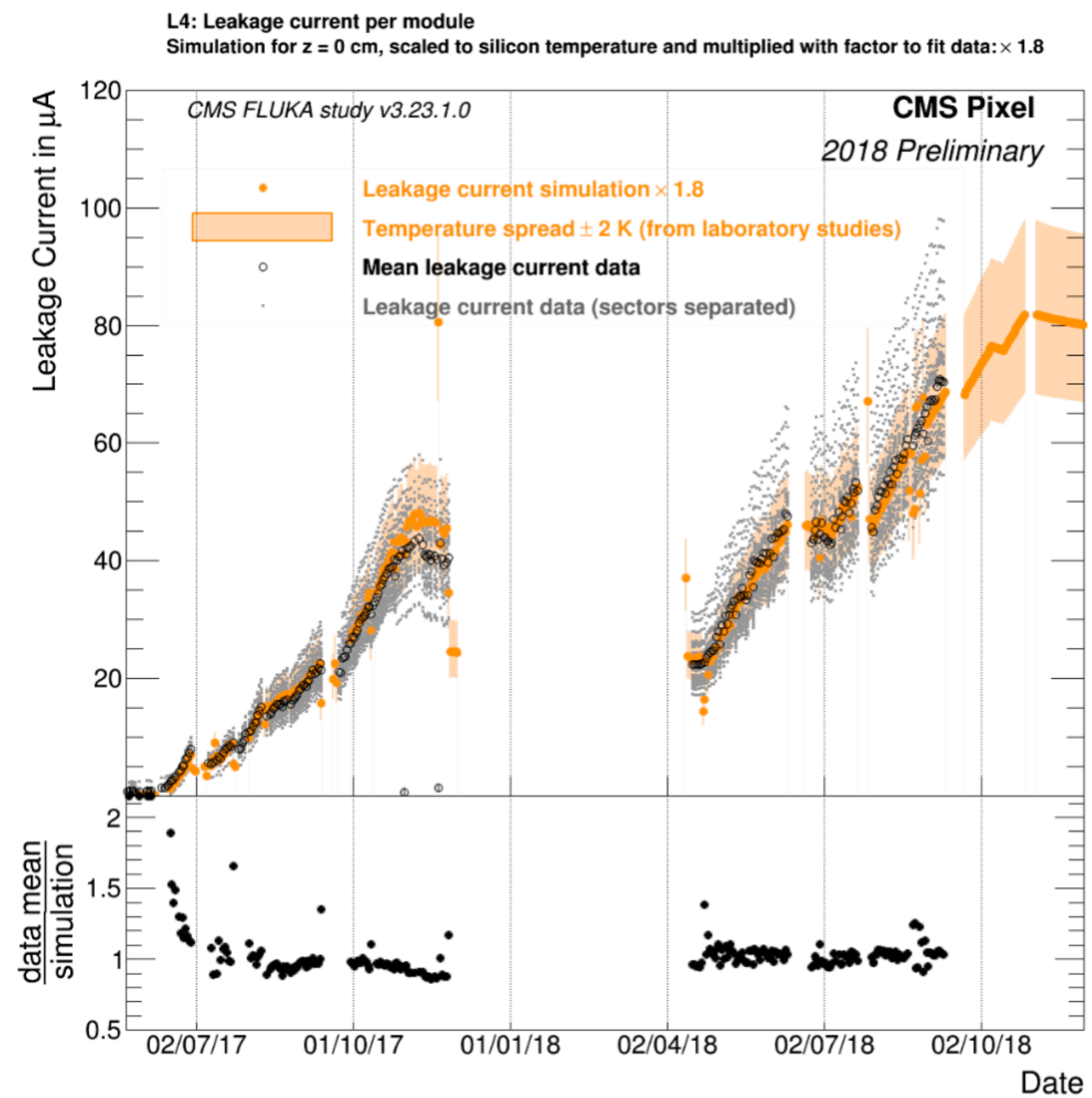



- LHC fills from beginning of 2017 until end of October in 2018 data-taking are employed  (proton-proton collisions)
- Currents measured within 20 minutes from Stable Beam declaration
- Average current per pixel module measured from power groups (**no temperature correction**)
- **Note: The 4th power group giving much higher current in disk 1 (seen in slide 25) is removed from the average**
- Leakage current increased gradually due to accumulated radiation dose through the year
- Closer to beam spot -> more accumulated radiation dose -> higher leakage current (ring 1 > ring 2)
- There are some drops of leakage current from the global trend because of:
    - Annealing during Machine development or technical stop period
    - Power supply replacement
    - HV setting change

# Pixel barrel leakage current simulation




layer 3




layer 4

- Good agreement between measurement and simulation on module leakage current evolution