



# Operation and performance of the NA62 GigaTracker

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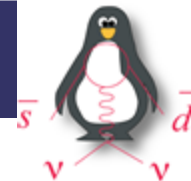
on behalf of GTK working group:  
CERN, UCL Louvain,  
Università/INFN Ferrara,  
Università/INFN Torino

**EPFL**



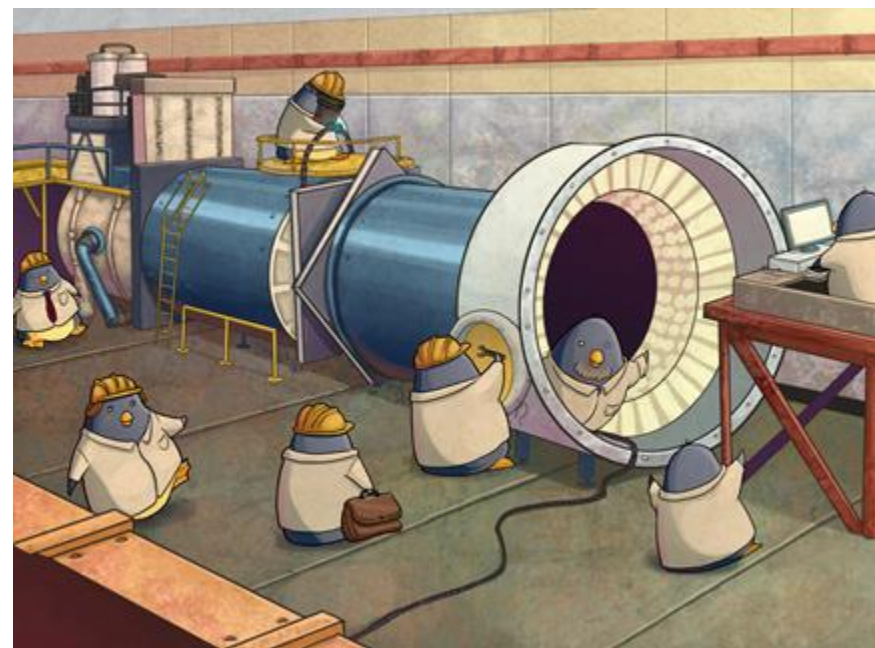
[www.cinqueterre5.com](http://www.cinqueterre5.com)

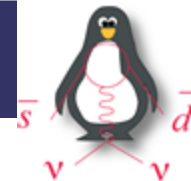
Sestri Levante 2023, 16<sup>th</sup> October



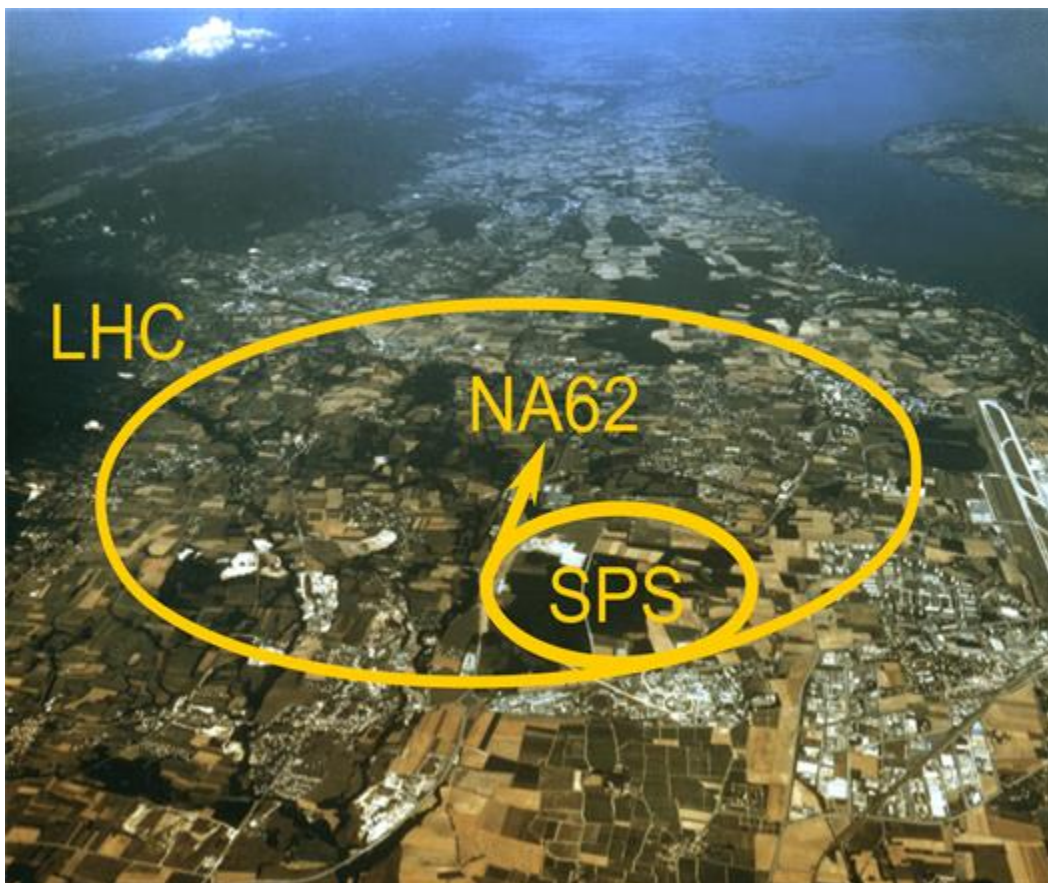
# Outline

- Overview of the NA62 experiment
- GigaTracker, the beam spectrometer of NA62
- Performance
- Prospects
- Summary





# The NA62 experiment



~30 institutes, ~200 participants

**NA62** is a fixed-target experiment at CERN SPS

**Main goal:** measure  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  with 10% precision using novel kaon-in-flight technique

**Current SM prediction:**

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

[[arXiv:2109.11032](https://arxiv.org/abs/2109.11032)]

**Experimental values:**

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3_{-10.5}^{+11.5}) \times 10^{-11}$$

E949/E787 [Phys. Rev D 79, 092004 (2009)]

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$

$$= (10.6_{3.4}^{+4.0} \text{stat} \pm 0.9_{\text{syst}}) \times 10^{-11}$$

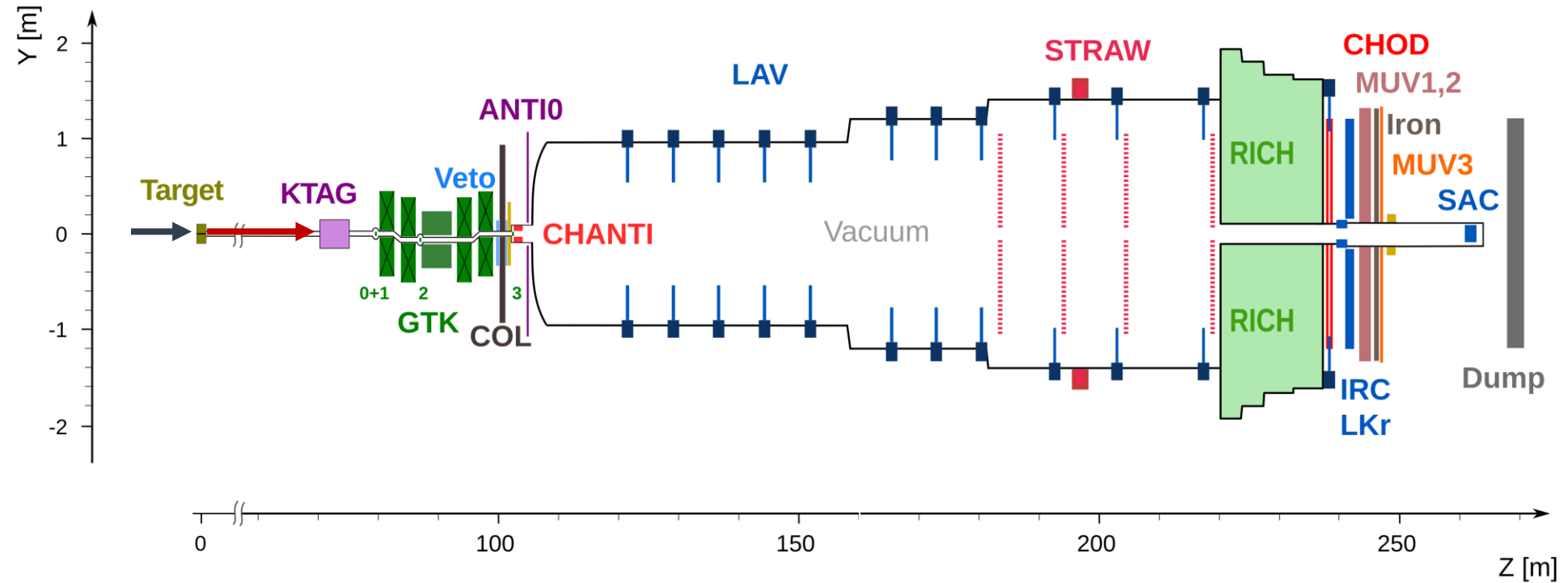
NA62 [JHEP06 (2021) 093]

**Broader physics programme:**

- **Rare/forbidden** kaon decays
- Searches for **exotic particles** in kaon decays and in **beam dump** mode



# Detector overview



## Primary beam:

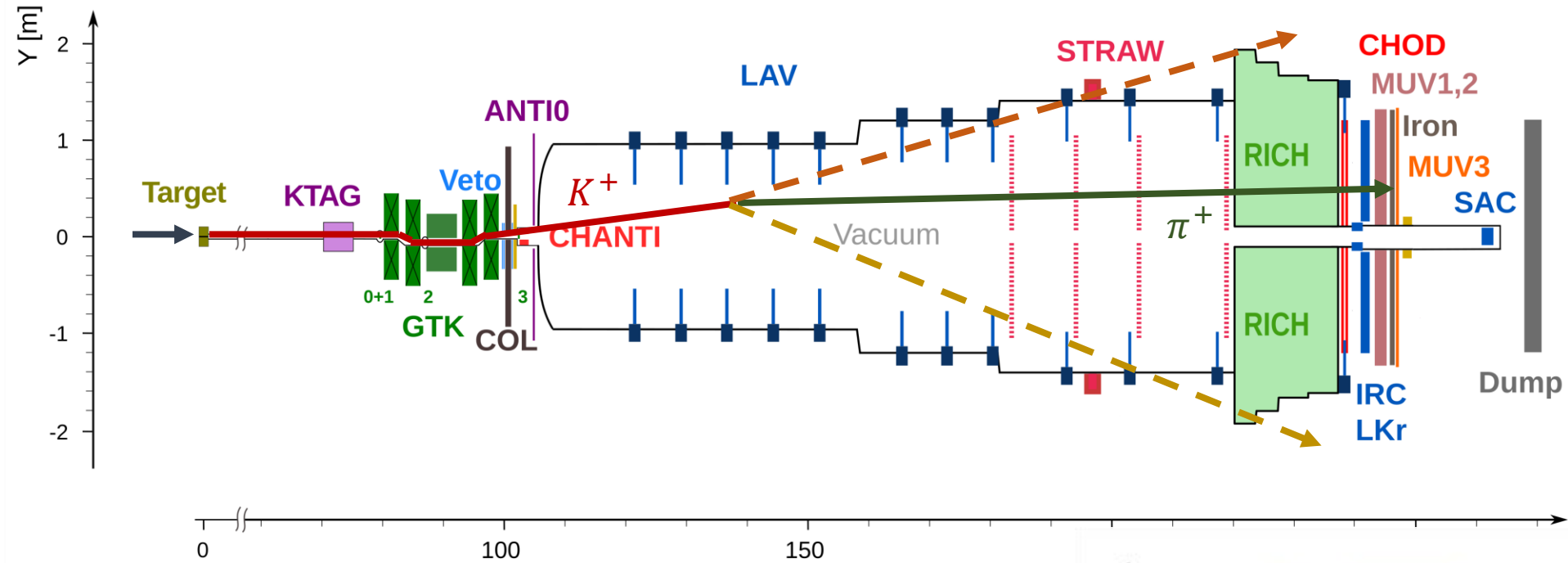
- 400 GeV protons from SPS
- $\sim 3.3 \times 10^{11}$  protons per spill
- average spill length  $\sim 4\text{s}$

## Secondary beam:

- 75 GeV hadron beam,  $\frac{\Delta p}{p} = \sim 1\%$  (rms)
- 6% of the beam are kaons

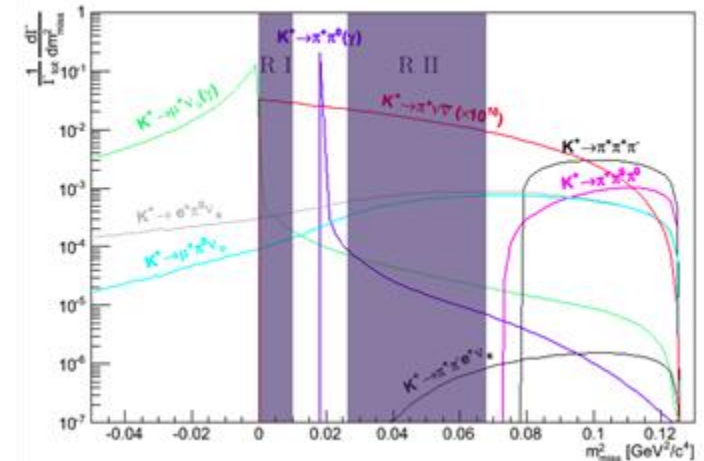


# Detector overview



## Performances:

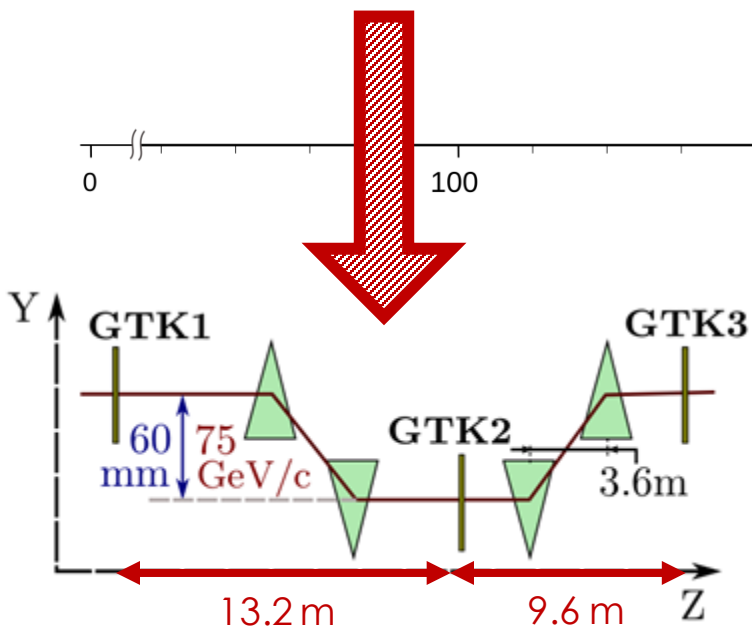
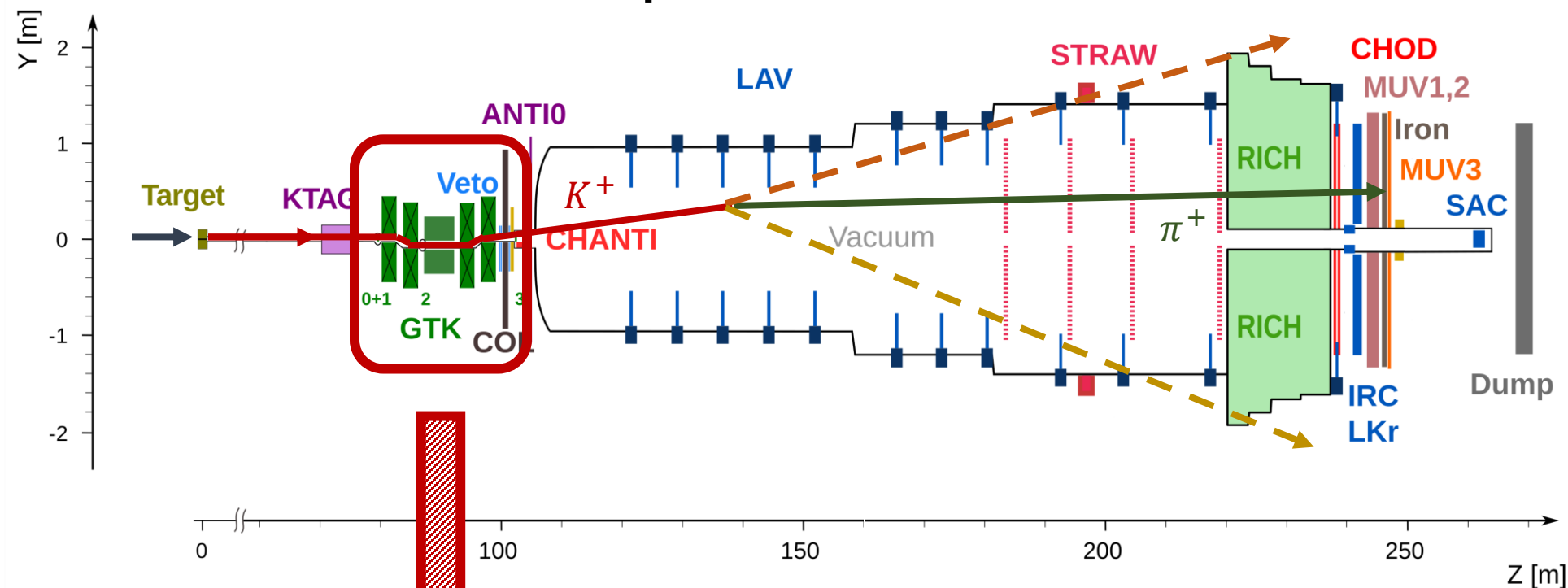
- GTK-KTAG-RICH time resolution:  $\mathcal{O}(100 \text{ ps})$
- $\mathcal{O}(10^4)$  background suppression from kinematics
- $\mathcal{O}(10^7)$  muon rejection for  $15 < p(\pi^+) < 35 \text{ GeV}$
- $\mathcal{O}(10^8)$   $\pi^0$  rejection for  $E(\pi^0) > 40 \text{ GeV}$



[NA62 Detector Paper, JINST 12 (2017), P05025]

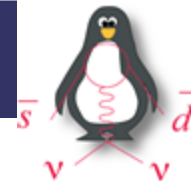


# The beam spectrometer of NA62



- Measures momentum, angle and time-stamp of all beam tracks
- Sustains high particle flux
- Minimized material budget

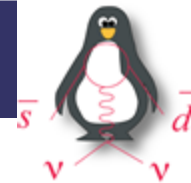
[NA62 Detector Paper, JINST12 (2017), P05025]



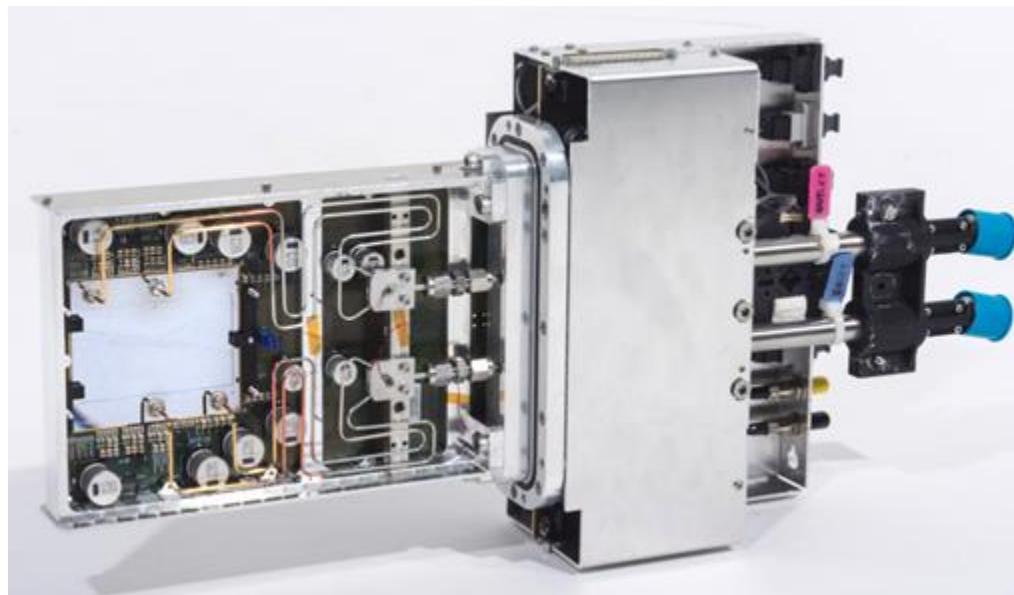
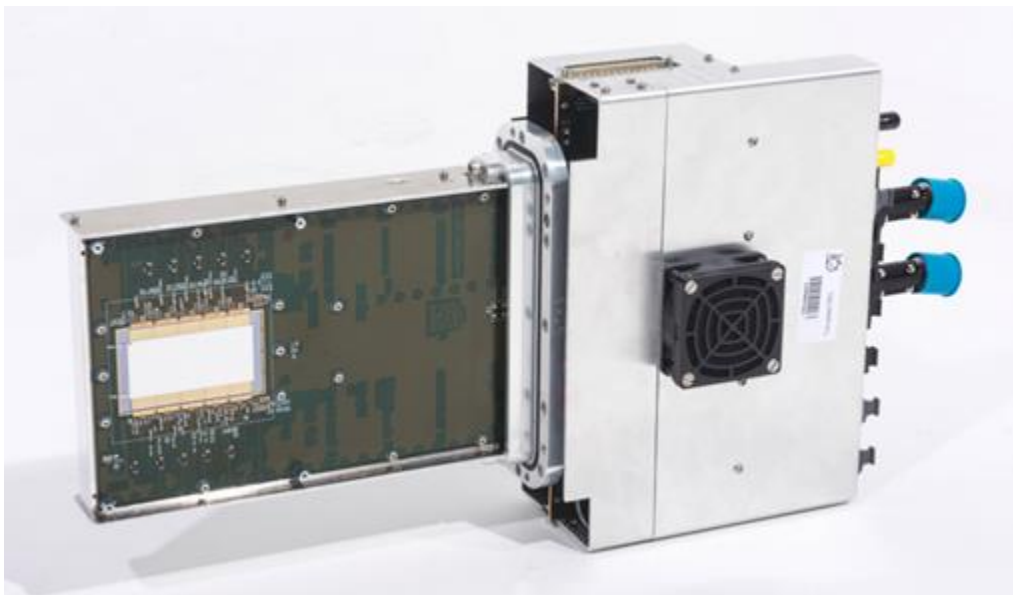
# Design specifications

- Design started in 2007
- Three planes of Si hybrid pixels → 4<sup>th</sup> layer (GTK0) was installed in 2021 in the same vessel with GTK1
- Installed in beam pipe vacuum:  $\sim 10^{-6}$  mbar
- Detectors are supposed to be replaced after 1 year at full intensity

Beam rate	750MHz-1GHz
Peak particle flux	2.0 MHz/mm <sup>2</sup>
<b>Peak radiation</b>	$4.5 \times 10^{14}$ 1MeV $n_{eq}/\text{cm}^2/200$ days
Efficiency	99%
Momentum resolution	0.2%
Angular resolution	16 $\mu\text{rad}$
<b>Pixel time resolution</b>	<200ps RMS
<b>Material budget</b>	0.5% $X_0$
<b>Detector size</b>	60.8x27mm <sup>2</sup>

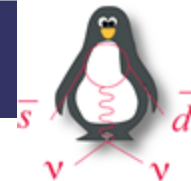


# The GigaTracker detector



Detailed description can be found [JINST14 P07010](#)





# The pixel matrix

TDCPix

Sensor



## Sensor:

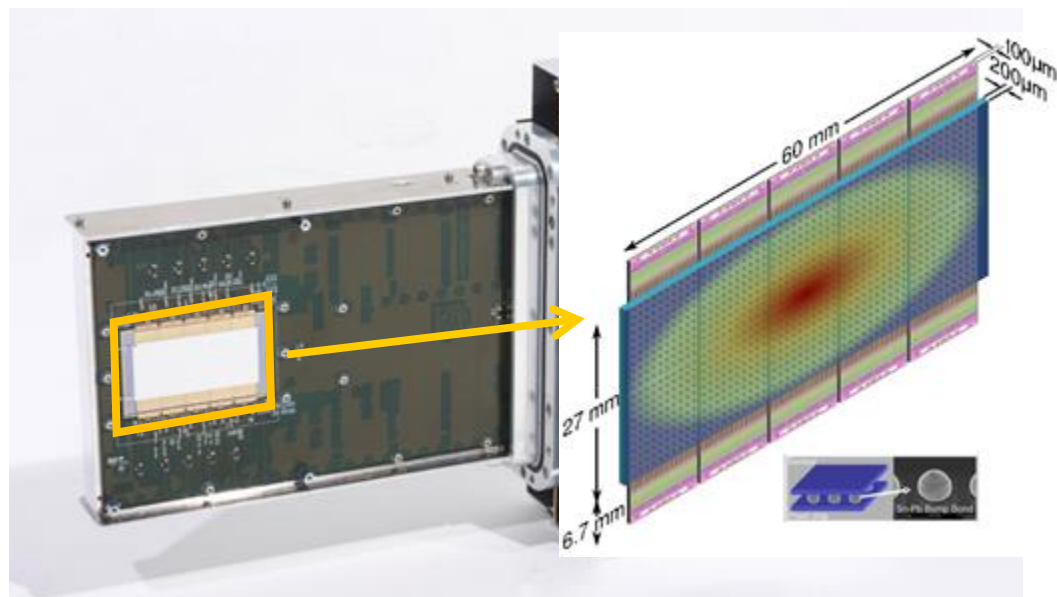
- Planar n-in-p/p-in-n
- $27 \times 60.8 \text{ mm}^2$
- $200 \mu\text{m}$  thick ( $0.2\% X_0$ )
- MPV of charge per MIP:  $2.4 \text{ fC}$ ,  $\sim 15000e$

## Bump-Bonding:

- Sn-Ag bumps
- Benzocyclobutane deposited to avoid discharges

## TDCPix:

- IBM 130nm CMOS technology
- $100 \mu\text{m}$  thick ( $0.1\% X_0$ )
- 1800 pixels of  $300 \times 300 \mu\text{m}^2$
- Time resolution:  $< 200 \text{ ps}$
- Peaking time:  $5 \text{ ns}$
- TDC bin size:  $97 \text{ ps}$
- SEU mitigation
- ECN  $< 250e$



See more in [NIMA.2023.168331](https://arxiv.org/abs/2301.16833)



# Cooling plate

- Micro-channel technology – first application in HEP
- Fabricated by CEA Leti
- Dimensions: 70x80 mm<sup>2</sup>, design thickness - 210 μm (0.2% X<sub>0</sub>)
- 2 groups of 75 microchannels, 70x200μm<sup>2</sup>
- Liquid coolant C<sub>6</sub>F<sub>14</sub> (~3g/s @ 3bars)
- Front-end electronics and sensor at <5°C



Capillaries

Manifold



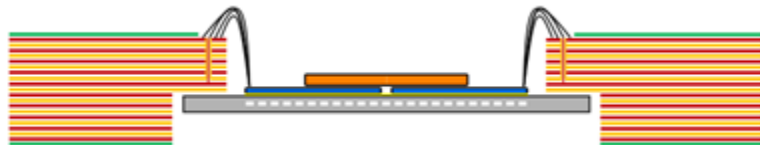
KOVAR connectors



Detailed description can be found [JINST14 P07010](#)



# Electrical Integration



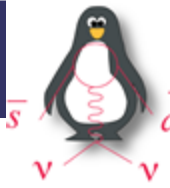
## PCB:

- Chips, sensor and cooling plate assembly hosted in the countersink of the carrier board
- 14 layers T-shaped PCB
- 40 differential 3.2 Gb/s signals over 30cm

## Wire bonding:

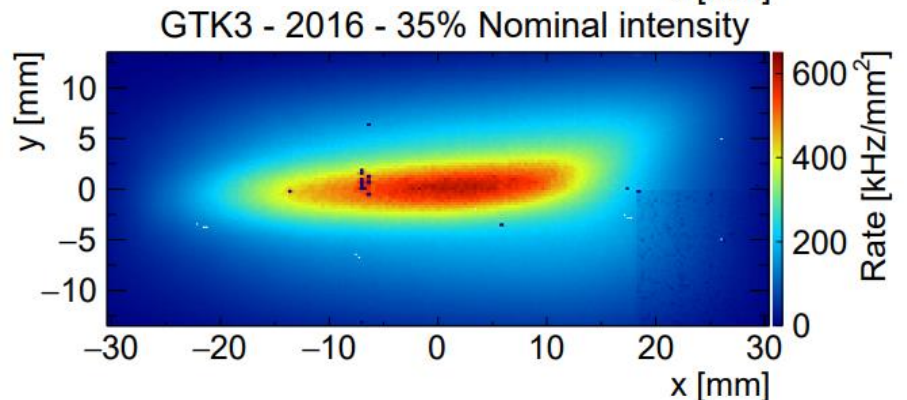
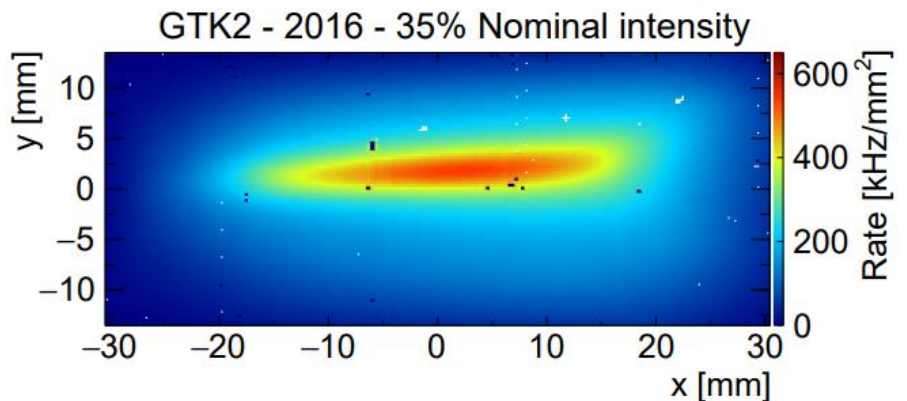
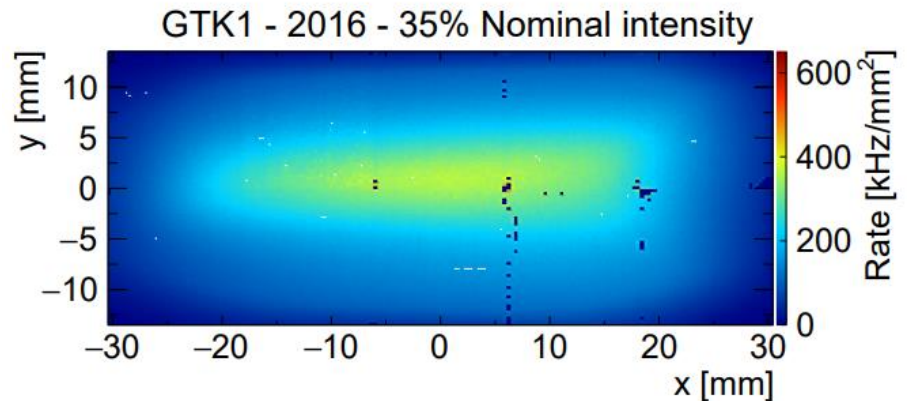
- TDCPix wired bonded to PCB
- Dense bonding scheme with 73  $\mu\text{m}$  pitch on TDCPix (1450 bonding pads in PCB)
- Power, Clock, Config, Data transmitted

Detailed description can be found [JINST14 P07010](#)



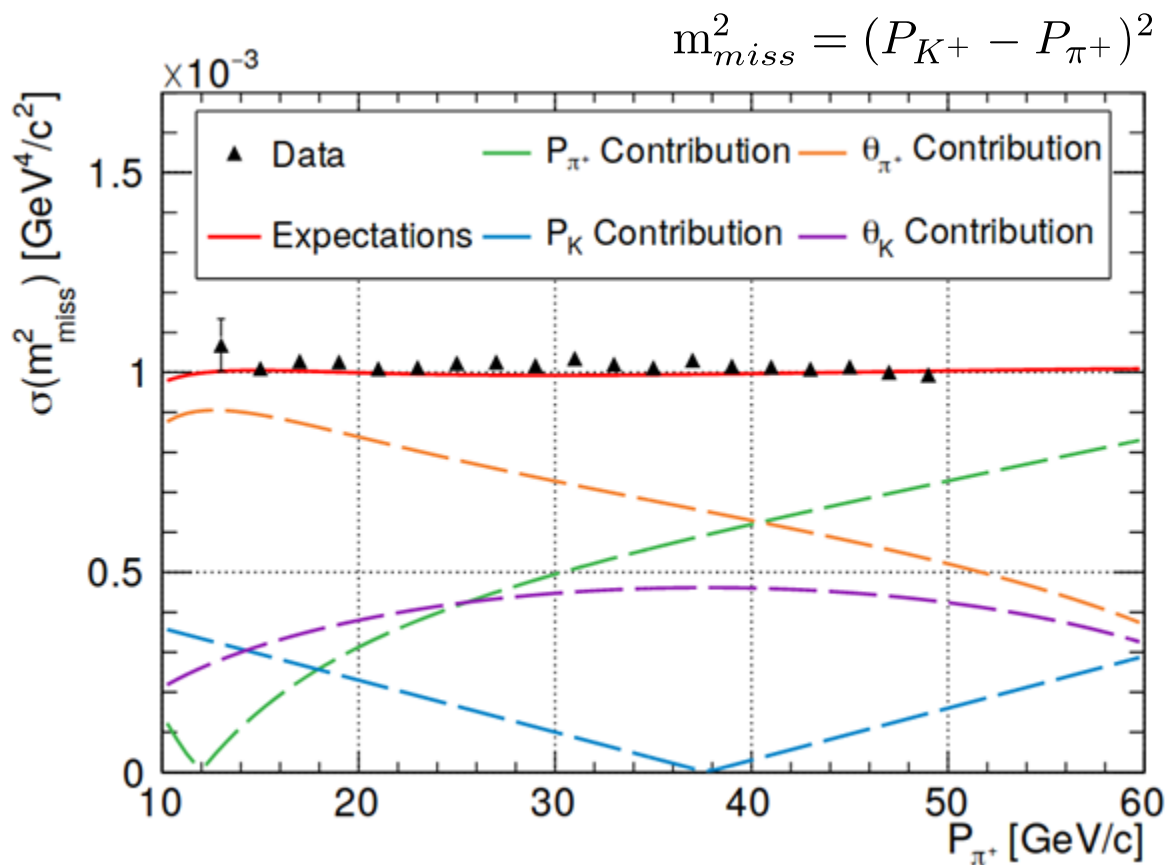
# GigaTracker in operation

- Fully operational since September 2016 (first station installed in 2014)
- Few noisy/dead pixels (< 1% per station)
- Nominal bias voltage – 100V
- Beam intensity was increasing over the years of data taking, being 35% of nominal in 2016 and reaching 100% in 2018.





# Kinematic performance



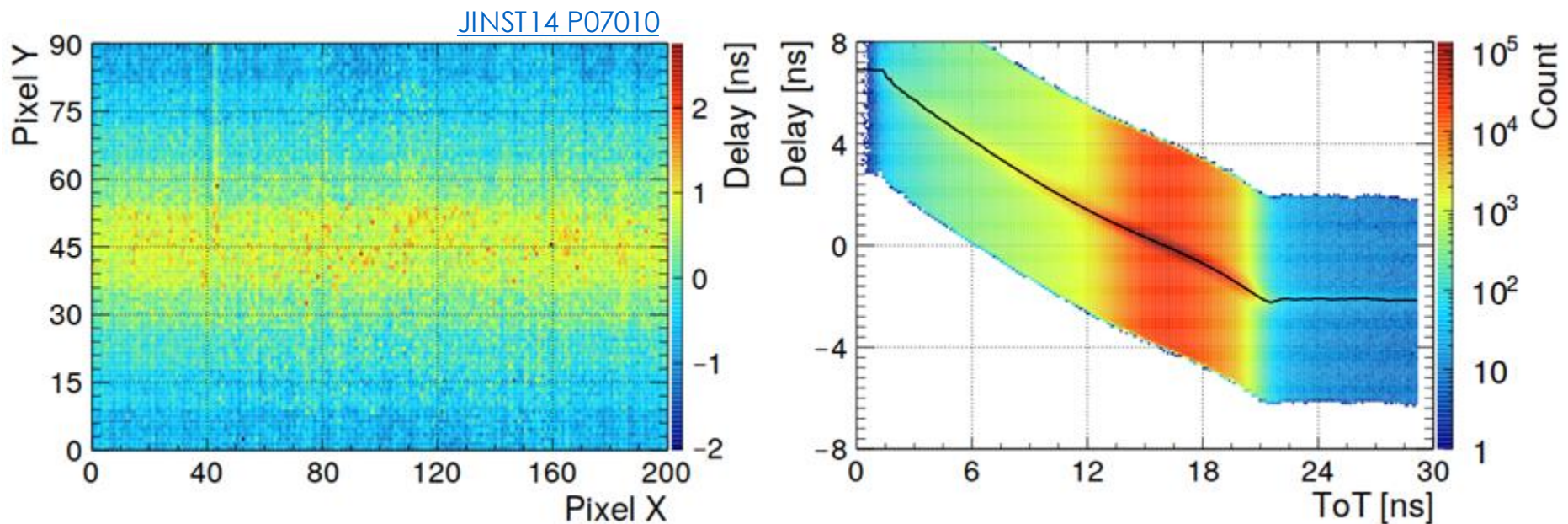
- Sample of  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  is used to align GTK and STRAW spectrometer and equalize measurement of momentum
- Physics performance from a sample of  $K^+ \rightarrow \pi^+ \pi^0$  matches design performance (16  $\mu\text{rad}$ )



# Precise time measurement with GTK

Offline calibration is necessary to correct for time walk and delays in the pixel matrix:

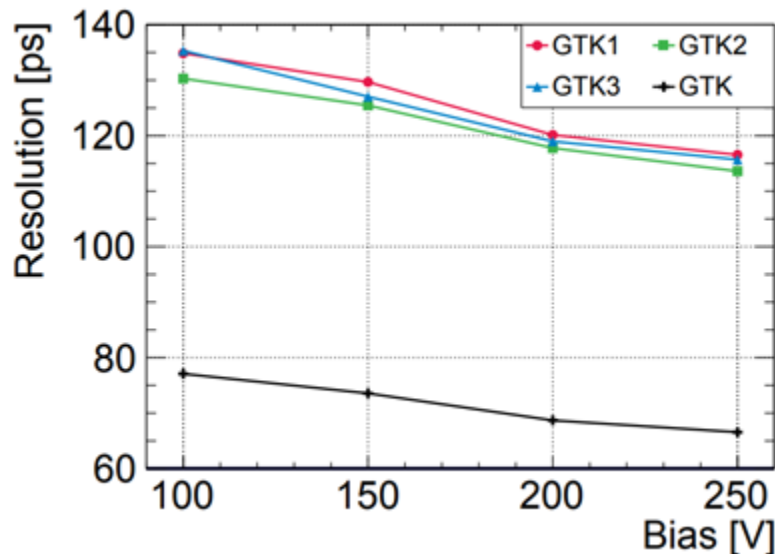
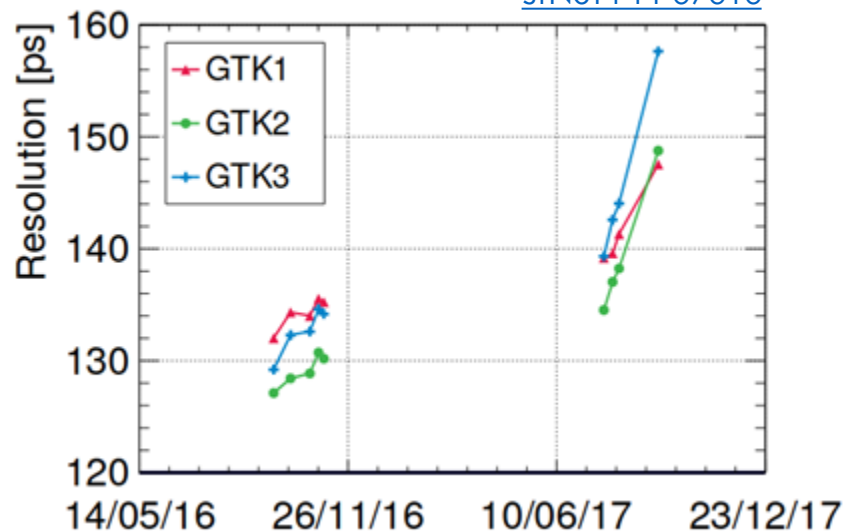
- Pixel time offsets extracted at MPV of ToT for each pixel (~3ns variation along a column)
- Time walk correction computed per chip (~300 ps/1ns ToT)
- Reference time: KTAG (70 ps resolution)
- Calibration is done once for each group of ~1500 spills





# GTK performance in 2016-2017

JINST14 P07010



## Conditions:

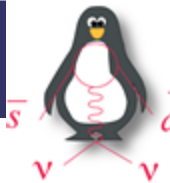
- n-in-p sensors @100 V

## Measurement methods:

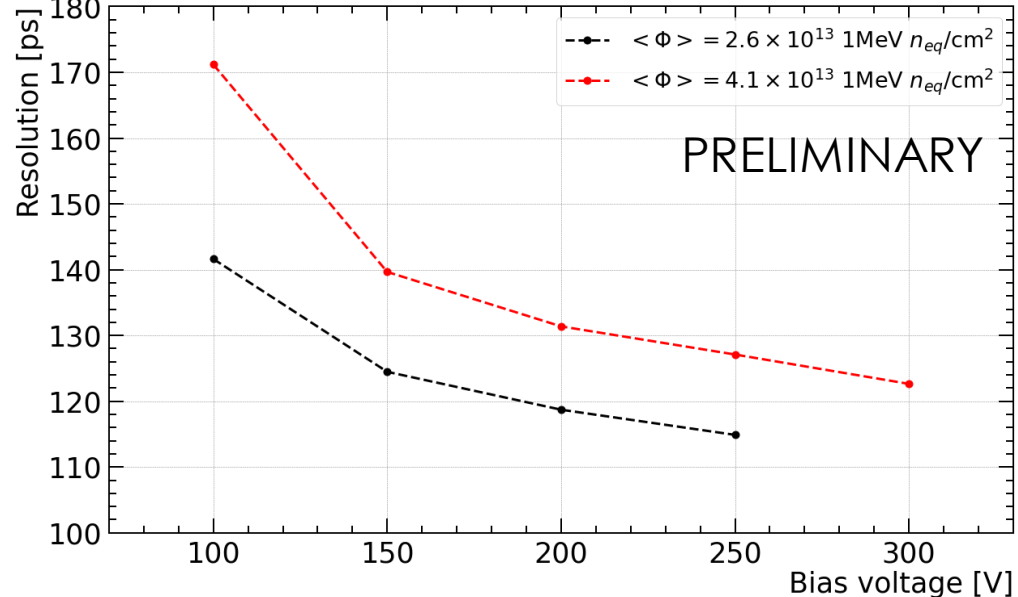
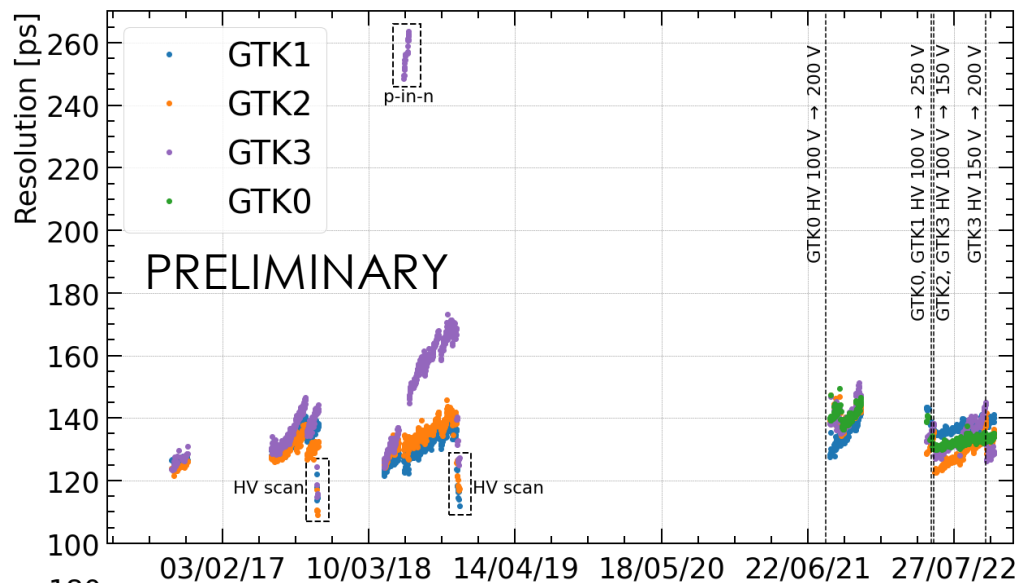
- Time difference between GTKs KTAG RICH ( $\sigma_t < 100$  ps)
- Time difference between the 3 GTK stations

## Observations:

- Hit time resolution: 130 ps (best 115 ps @250 V)
- Track time resolution: 75 ps (best 65 ps @250 V)
- ~20% time resolution degradation observed by the end of 2017, which is still better than the design requirements
- Peak(average) fluence by the end of 2017:  $1.3(0.26) \times 10^{14} \text{ 1 MeV } n_{eq}/\text{cm}^2$
- Overall efficiency: 97%, 99% per station



# GTK performance in 2018-2022



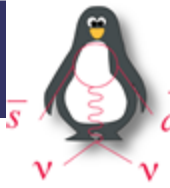
## Conditions:

- 15 modules in total were used as GTK1, 2, 3 and 0 from 2016 to 2023, a few modules were used for several years
- All modules, except one are n-in-p
- Nominal bias volage (HV) is 100 V
- After the end of each data taking period, modules are removed and stored in cold

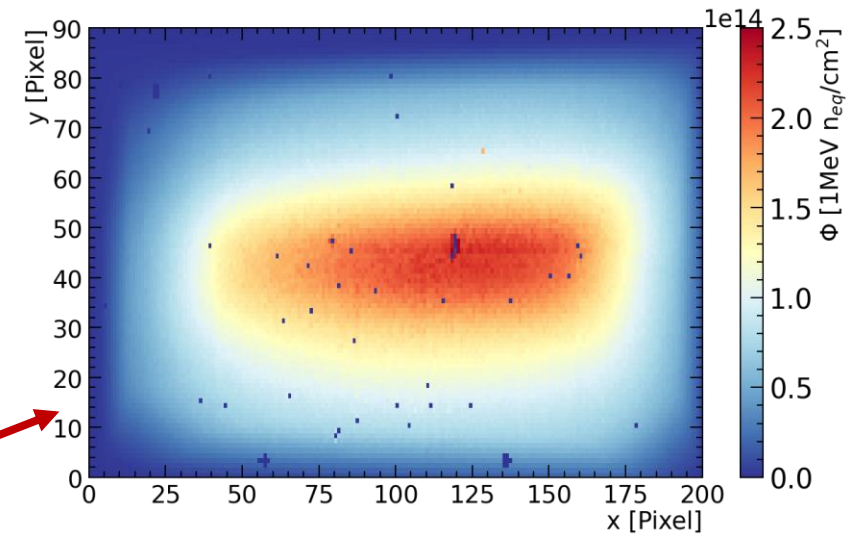
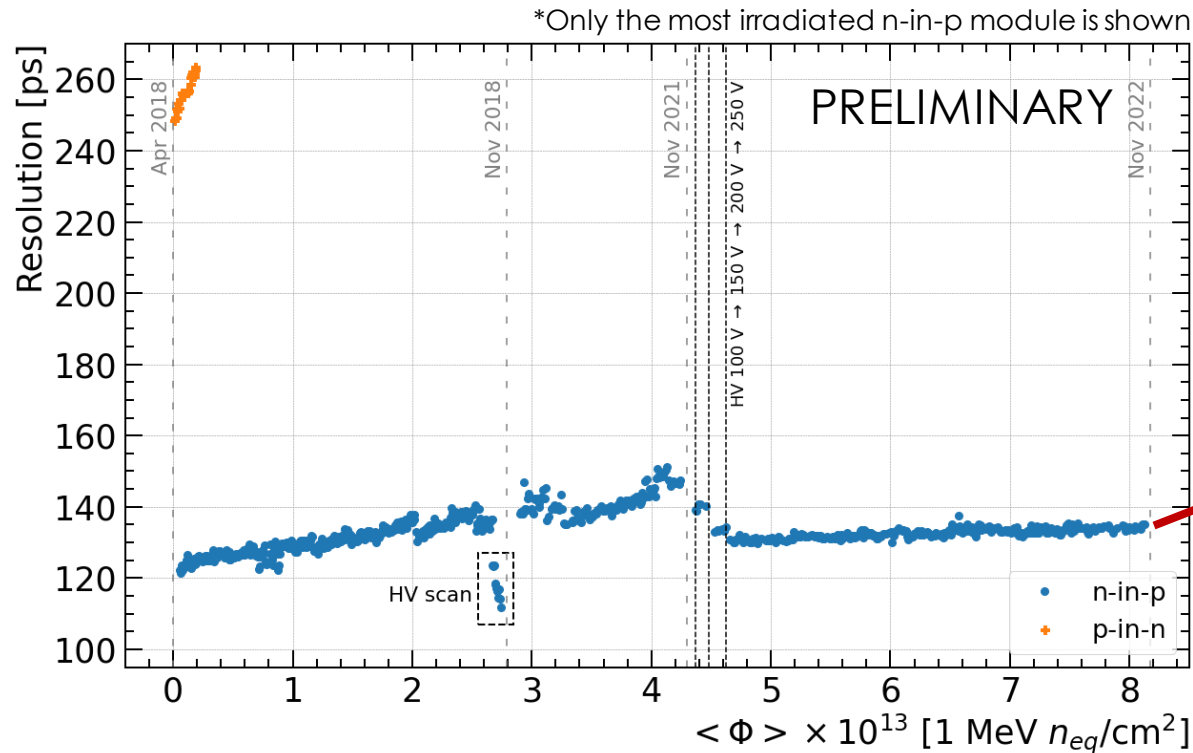
## Observations:

- Hit time resolution: 120 ps best, 260 ps worst( p-in-n @ 100V)
- ~30% time resolution degradation for the most irradiated module by the end of 2018:
  - Starting from 2021 bias voltage adjustment was used to improve performance of old modules and keep resolution stable





# GTK performance in 2018-2022



- The most irradiated module by 2023 with a peak(average) fluence of  $2.5(0.81) \times 10^{14}$  1MeV  $n_{eq}/cm^2$  provided 135 ps time resolution @250 V at the end of 2022 data taking
- Resolution of p-in-n sensors is factor of 2 of n-in-p and scales differently with fluence



# Prospects

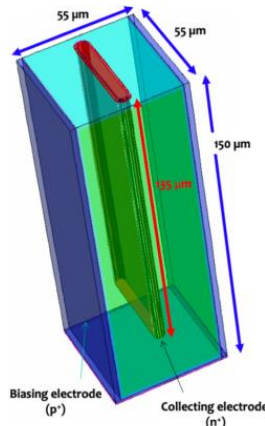
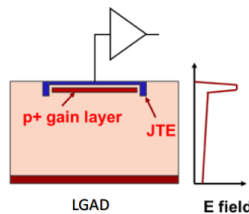
HIKE (High-Intensity Kaon experiments): a long-term rare kaon decay programme @ CERN SPS (>~2030)



- Multiple phases,  $K^+$  and  $K_L$  decay experiments

HIKE Phase 1:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  at 5% precision in 4 years:

- 4x intensity on GTK → new challenging specifications
- Possible synergies with ongoing developments:
  - TimeSPOT (3D sensors)
  - LGAD



Beam rate	>3GHz
Peak particle flux	>8.0 MHz/mm <sup>2</sup>
<b>Peak radiation</b>	2.35×10 <sup>15</sup> 1MeV n <sub>eq</sub> /cm <sup>2</sup> /200 days
Efficiency	99%
Pixel size	<300 μm
<b>Pixel time resolution</b>	<50ps
<b>Material budget</b>	0.3-0.5%X <sub>0</sub>
<b>Detector size</b>	60.8x27mm <sup>2</sup>

LOI: [arXiv:2211.16586](https://arxiv.org/abs/2211.16586)



# Summary

- The GigaTracker is the NA62 **4D beam tracker** and is **essential** for the precise measurement of  $BR(K^+ \rightarrow \pi^+ \bar{\nu} \nu)$
- The detector is fully operational since 2016 and successfully taking data
- The single hit time stamp resolution of **115 ps** was achieved, **surpassing** the design resolution.
- Analysis of data collected in 2018-2021 demonstrated that GTK can maintain **135 ps** hit time stamp resolution even after being irradiated up to  **$2.5(0.81) \times 10^{14} \text{ 1MeV } n_{eq}/\text{cm}^2$** , corresponding to  $\sim 120$  days at nominal intensity.

## Prospects:

- Analysis of data is ongoing + preparing to restart data taking again next year
- New experimental challenges ahead: GTKx4 for HIKE experiment @ CERN SPS



Thank you!

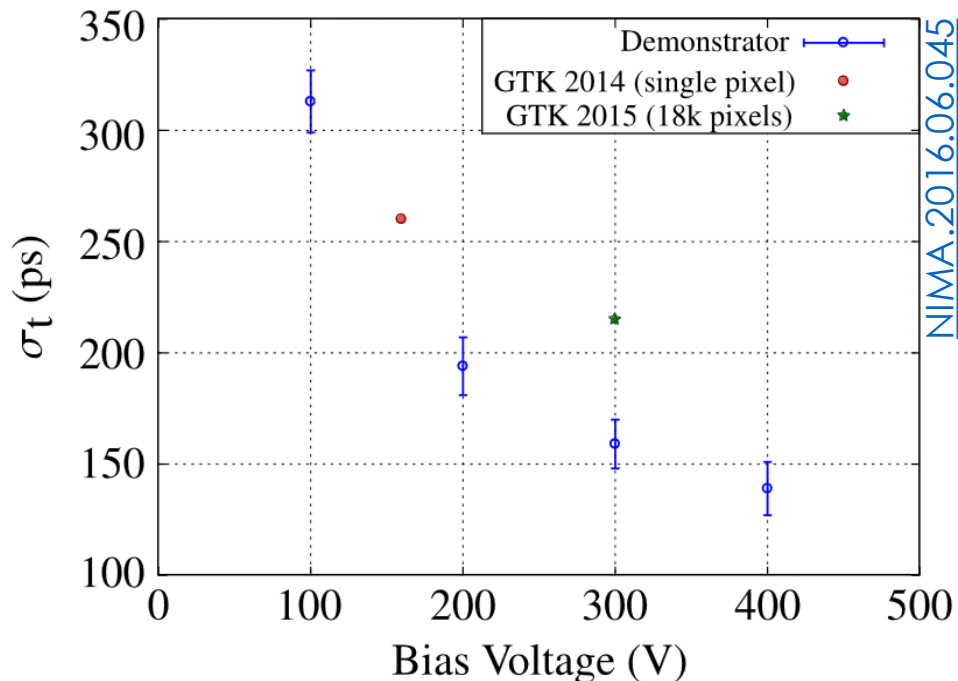


# Backup slides

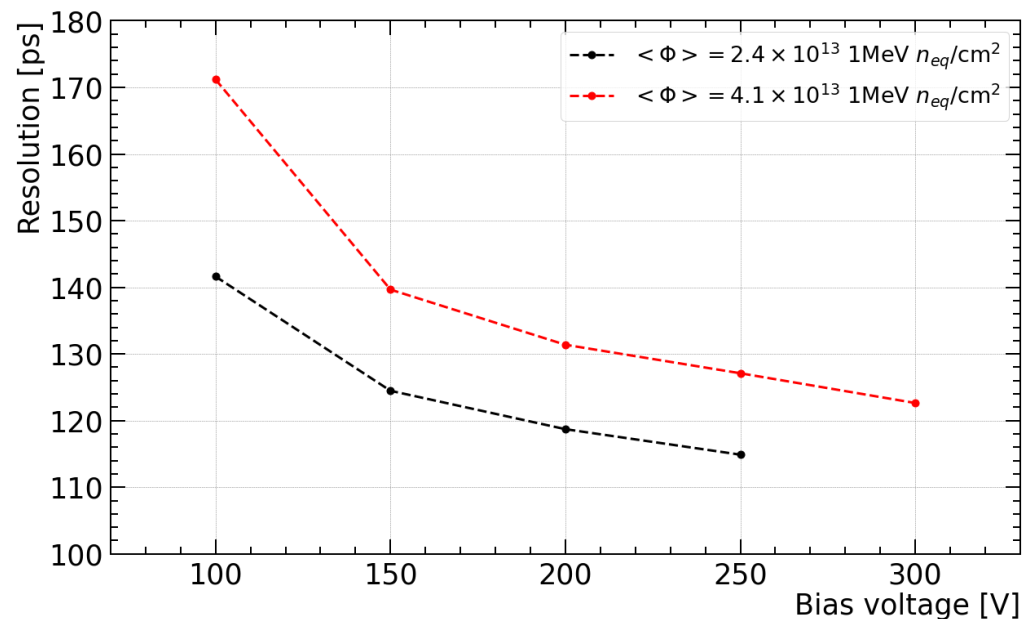


# Time resolution of p-in-n and n-in-p

GTK with p-in-n sensor

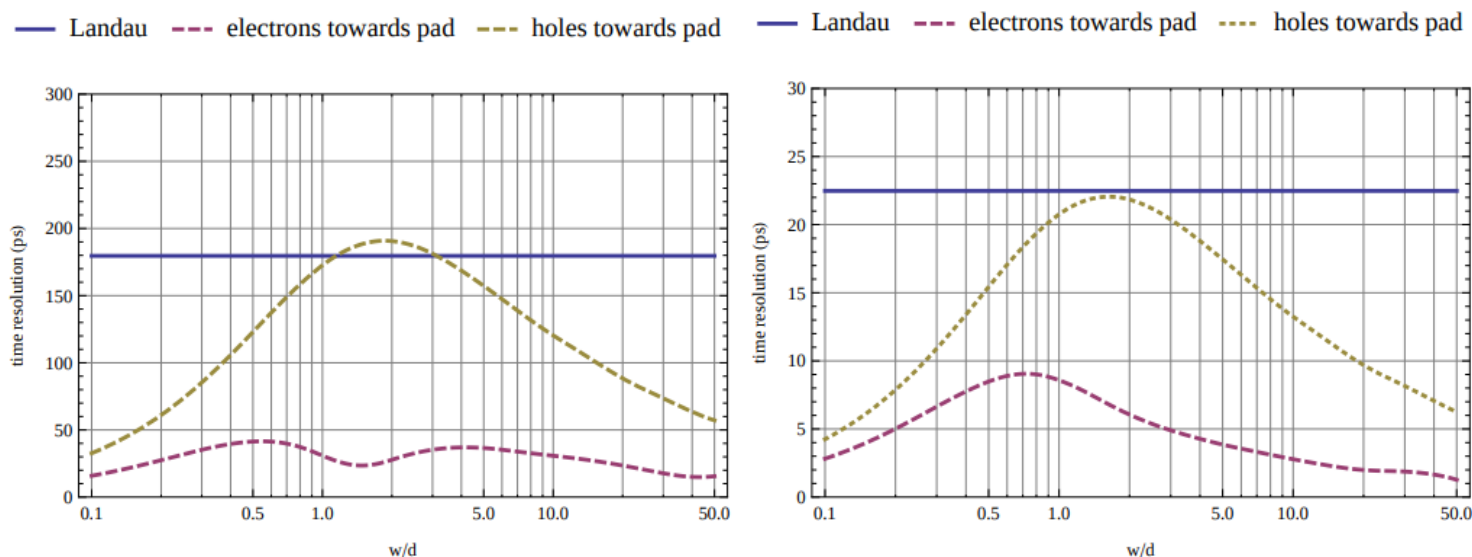


GTK with n-in-p sensor

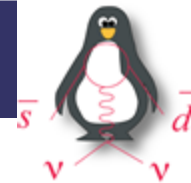




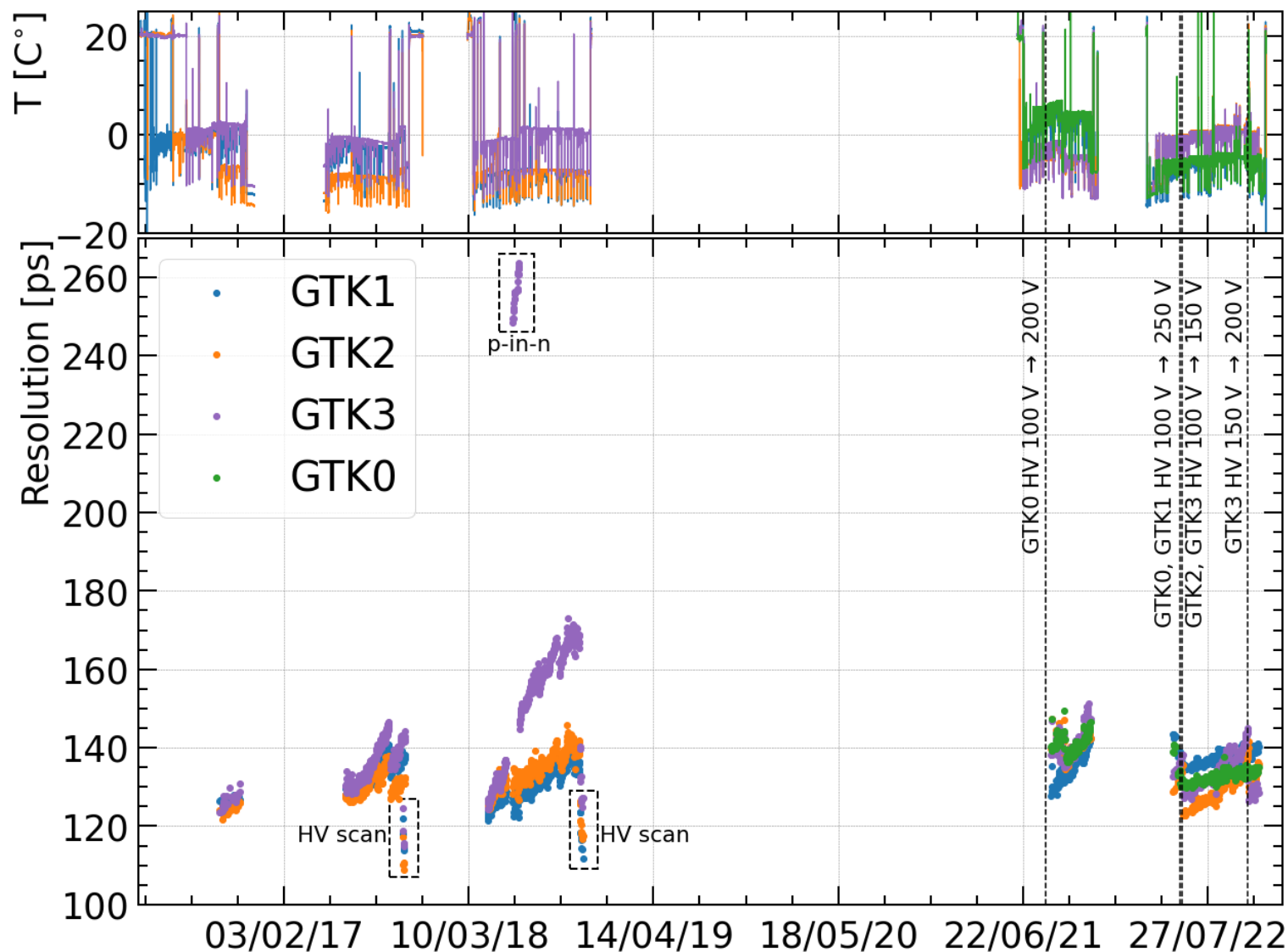
# Time resolution of p-in-n and n-in-p



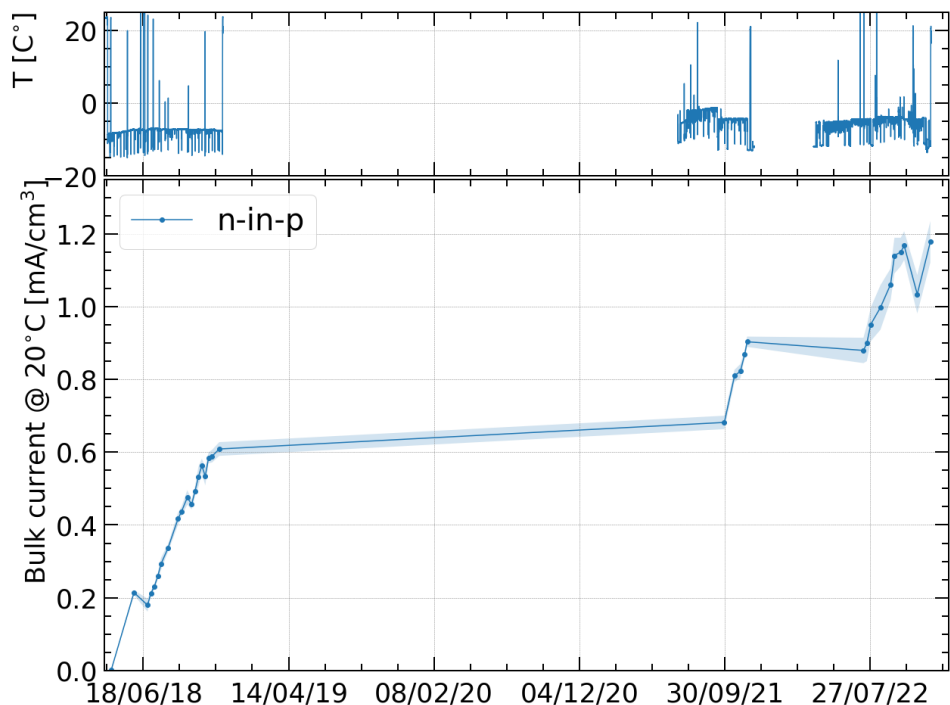
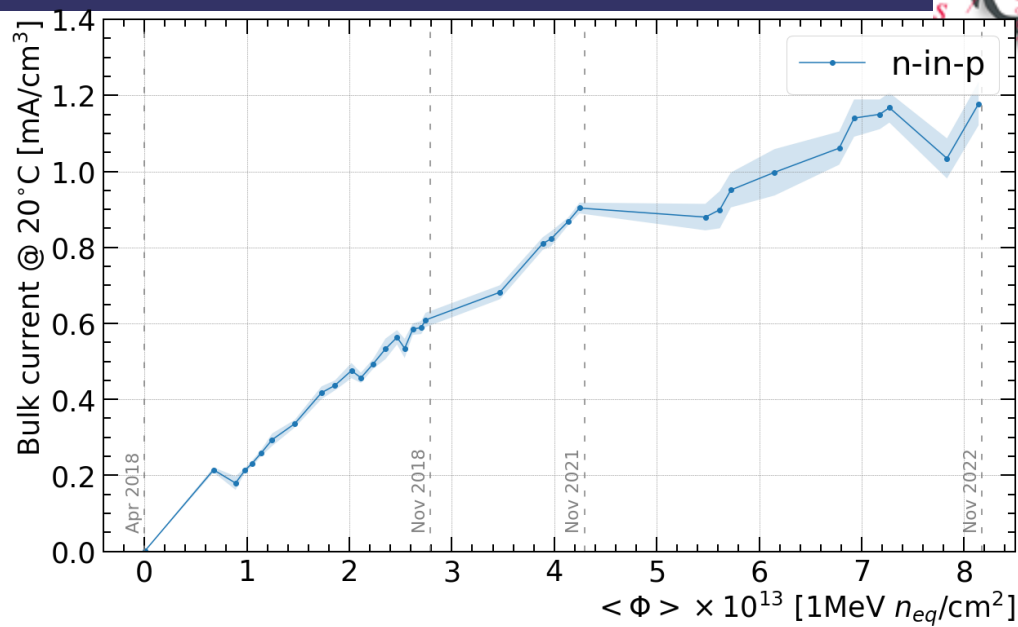
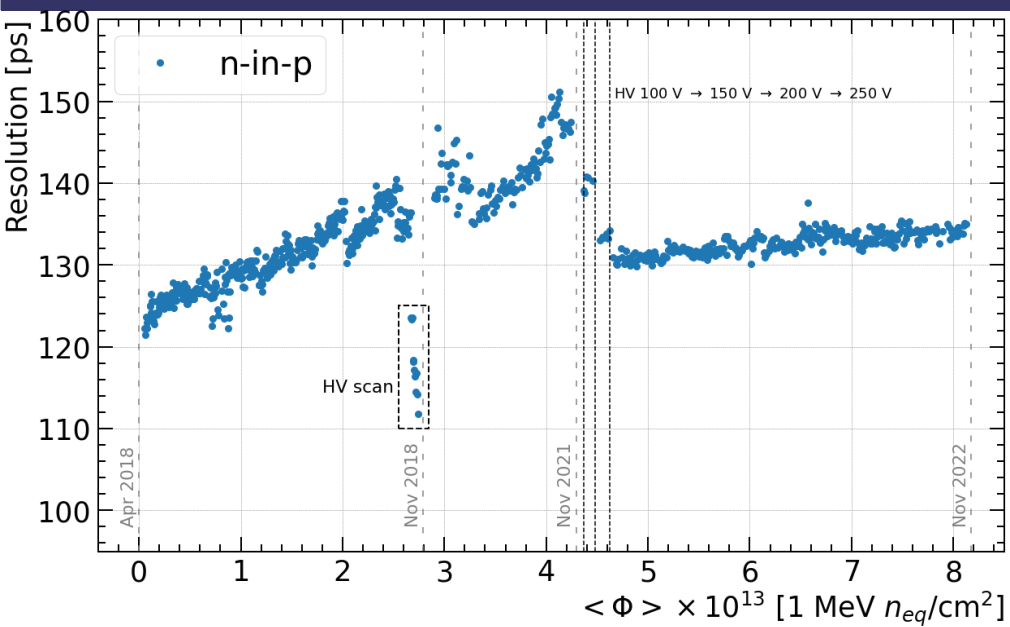
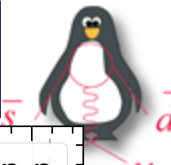
**Figure 13.** Standard deviation for the centroid time for sensor thickness of a)  $d = 200 \mu\text{m}$  and b)  $d = 50 \mu\text{m}$  and  $V = 200 \text{ V}$ , assuming uniform charge deposit and a square readout pad. The horizontal line represents centroid time resolution from eq. (4.5) due to Landau fluctuations only. The two curves in the plots represent the effect of weighting field fluctuations where either the electrons or the holes move towards the readout pad.



# Time resolution+temperature



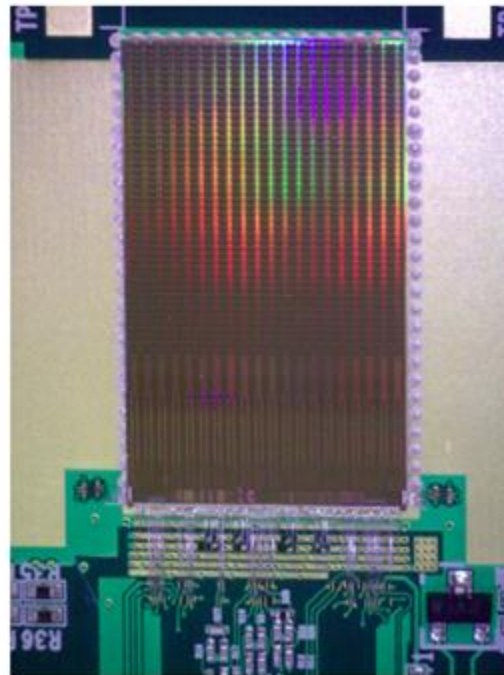
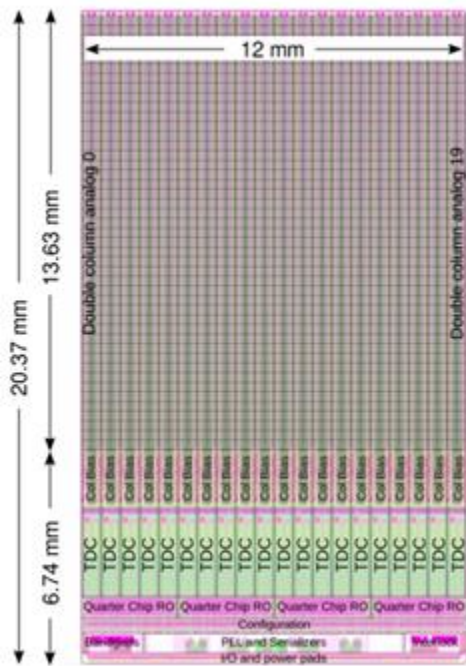




Time resolution, bulk leakage current and fluence of the most irradiated module



# TDCPix ASIC



Two sections:

- **40x45 pixel matrix**: preamplifier, discriminator (5 bit DAC), asynchronous transmission lines

- **end-of-column**: TDCs, digital logic

Organized by columns (1 column=45 pixels)

- group of 5 pixels send signals to 1 Hit Arbiter
- 1 Hit Arbiter sends signal to a dual TDC (leading and trailing edge): 9 TDCs per column/360 TDCs per chip

Per column pair:

- 1 DLL provides the fine timestamp, 97 ps bin of the TDC

Per groups of 10 columns: **3.2 Gb/s data transmitter**

Power consumption: **3.5W per chip** (>90% is in EOC region)