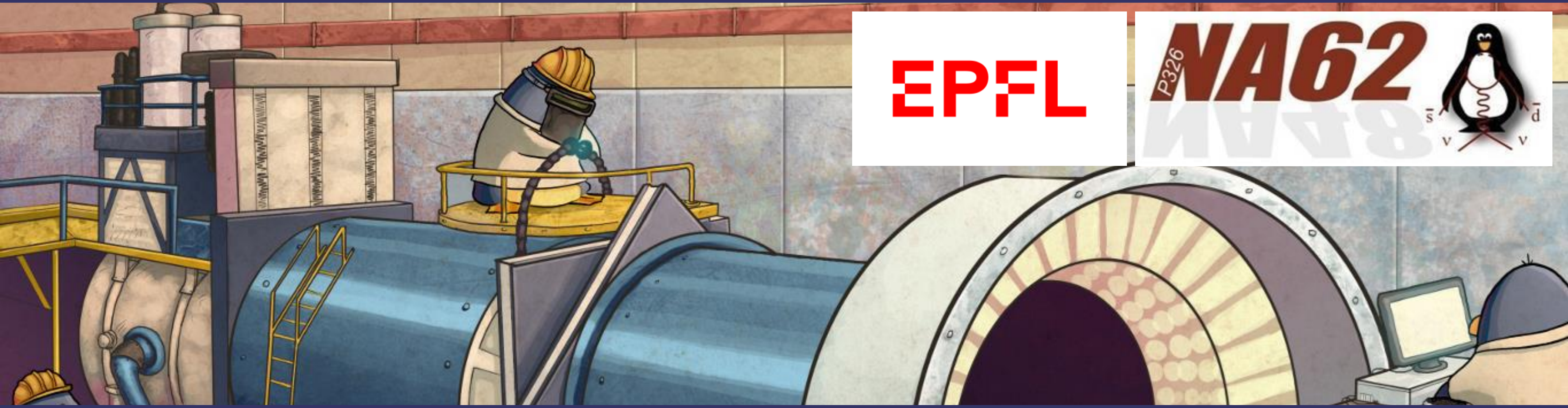

NA62 Gigatracker and silicon detector upgrade for HIKE

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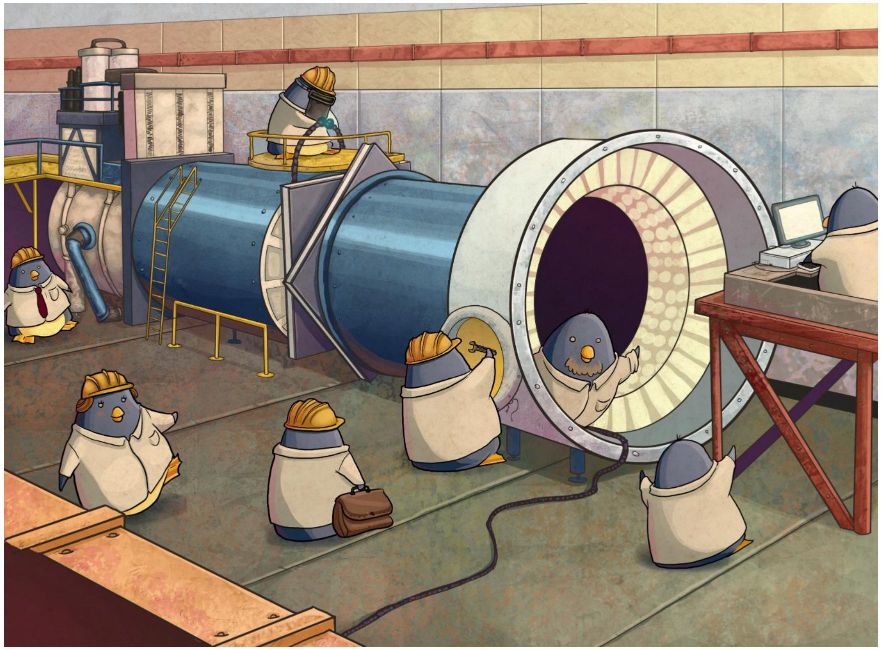
on behalf of GTK working group: CERN, UCL Louvain, Università/INFN Ferrara, Università/INFN Torino

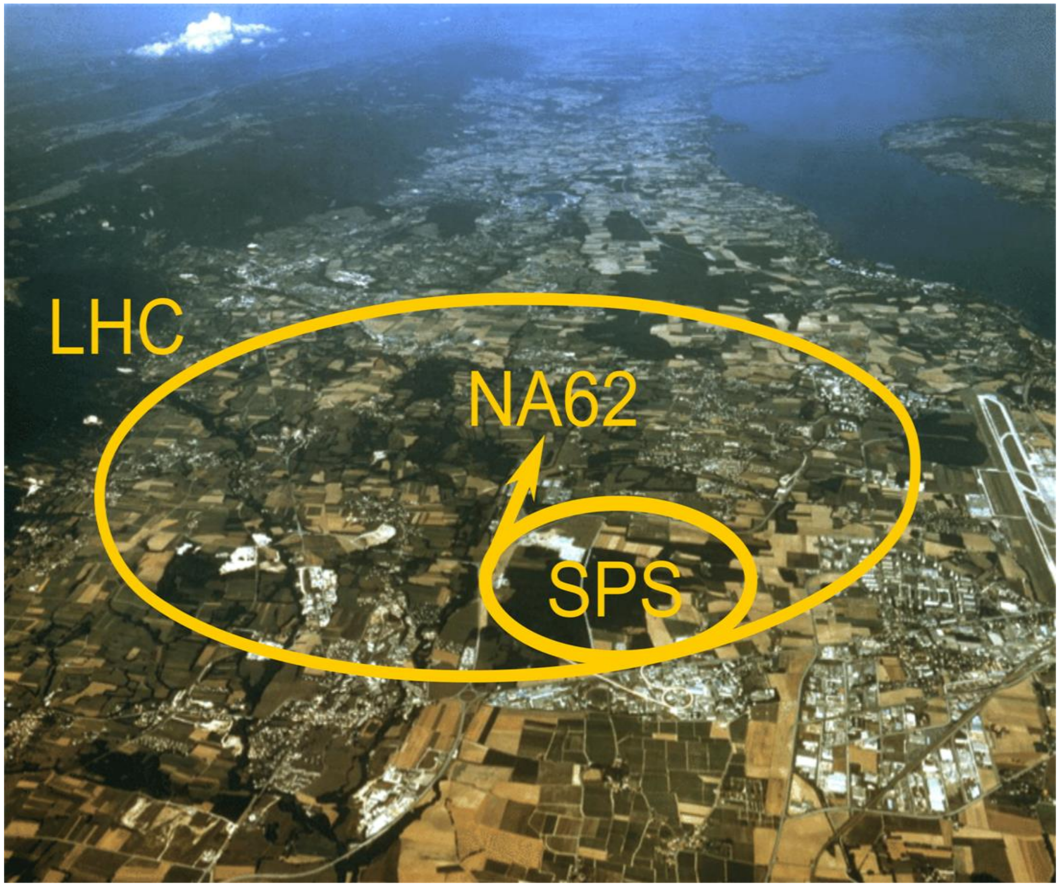
London 2023, 8th November

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 $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% precision using novel kaon-in-flight technique

Current SM prediction:

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

[arXiv:2109.11032]

Experimental values:

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

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

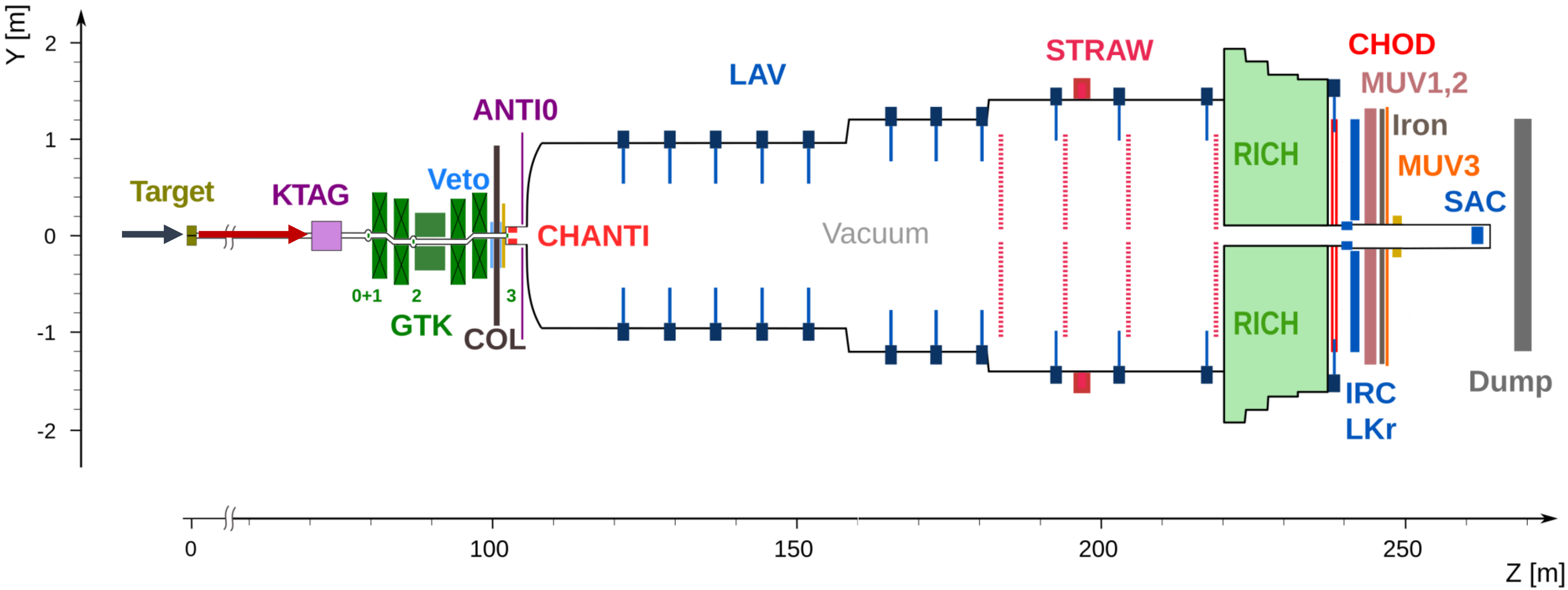
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{3.4\,stat} \pm 0.9_{syst}\right) \times 10^{-11}$$

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:

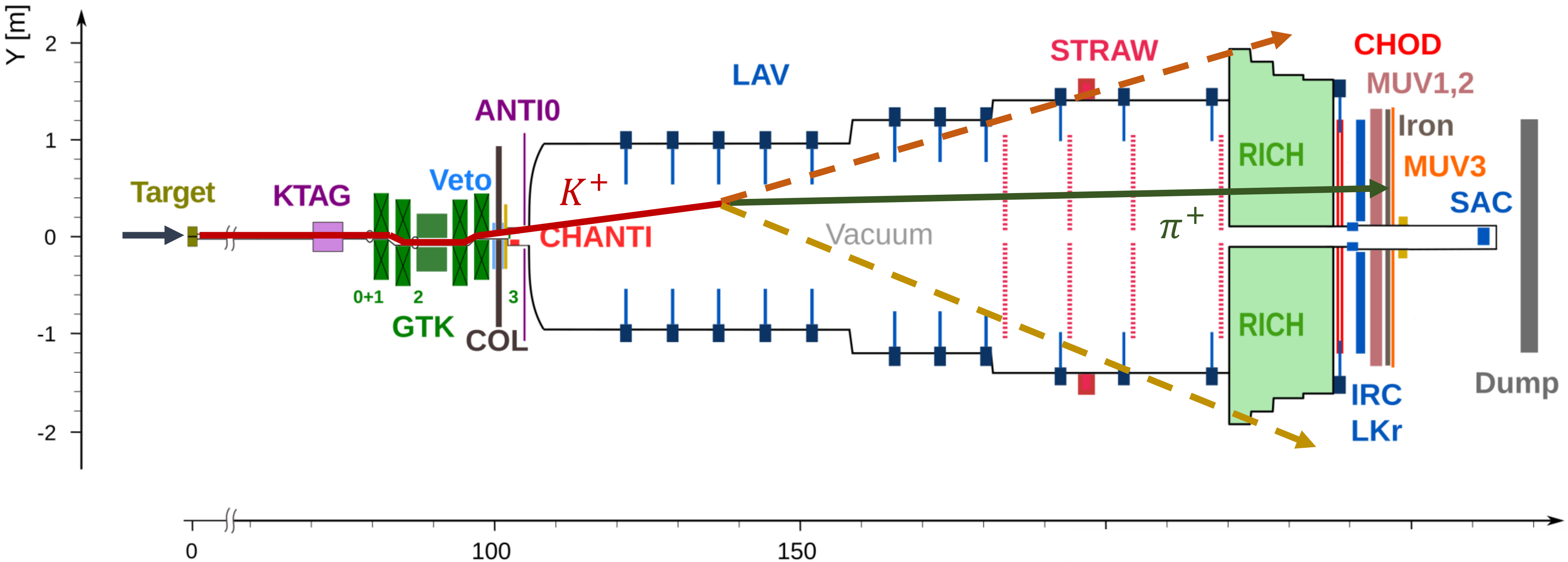
- 400 GeV protons from SPS
- $\sim 3.3 \times 10^{11}$ protons per spill
- average spill length ~4s

Secondary beam:

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

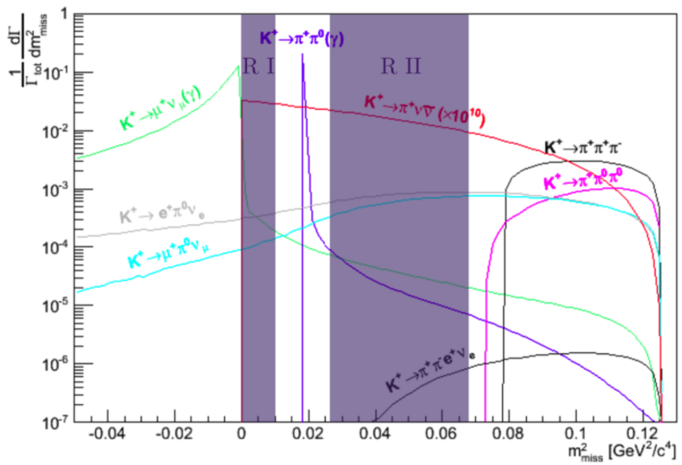
[NA62 Detector Paper, JINST 12 (2017), P05025]

Detector overview



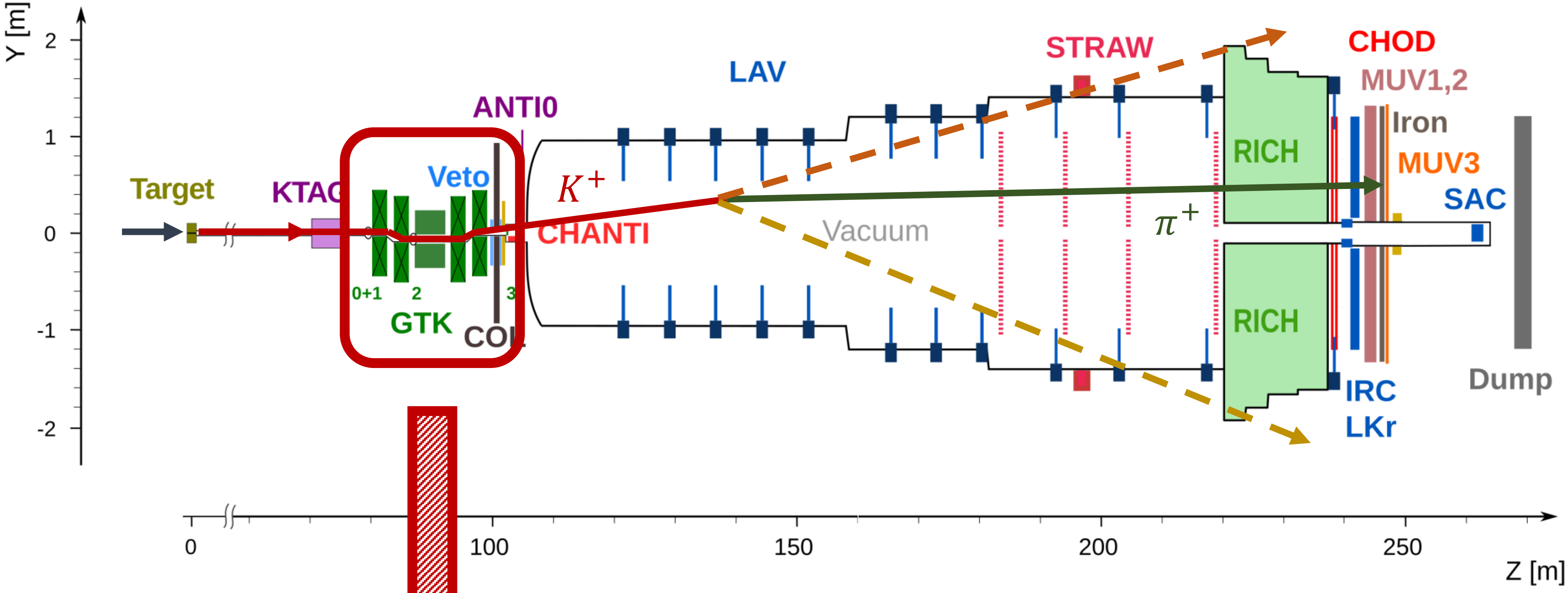
Performances:

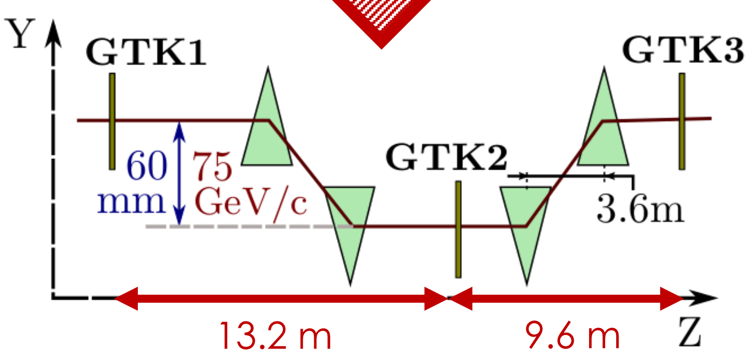
- GTK-KTAG-RICH time resolution: $\mathcal{O}$(100 ps)
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for 15 <p(π^+)< 35 GeV
- $\mathcal{O}(10^8)$ π^0 rejection of for E(π^0)> 40 GeV



[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

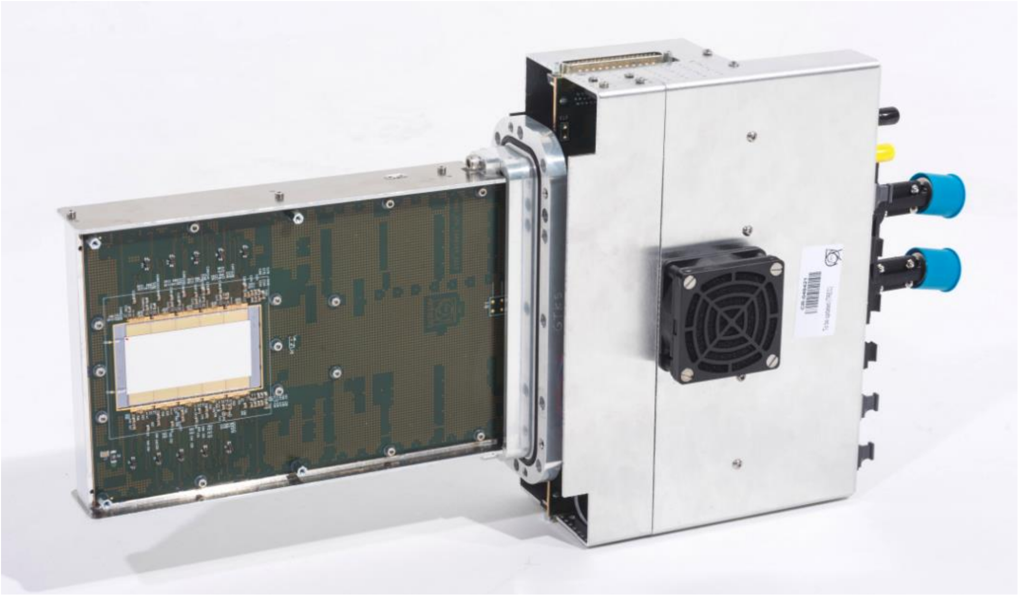
[NA62 Detector Paper, JINST 12 (2017), P05025]

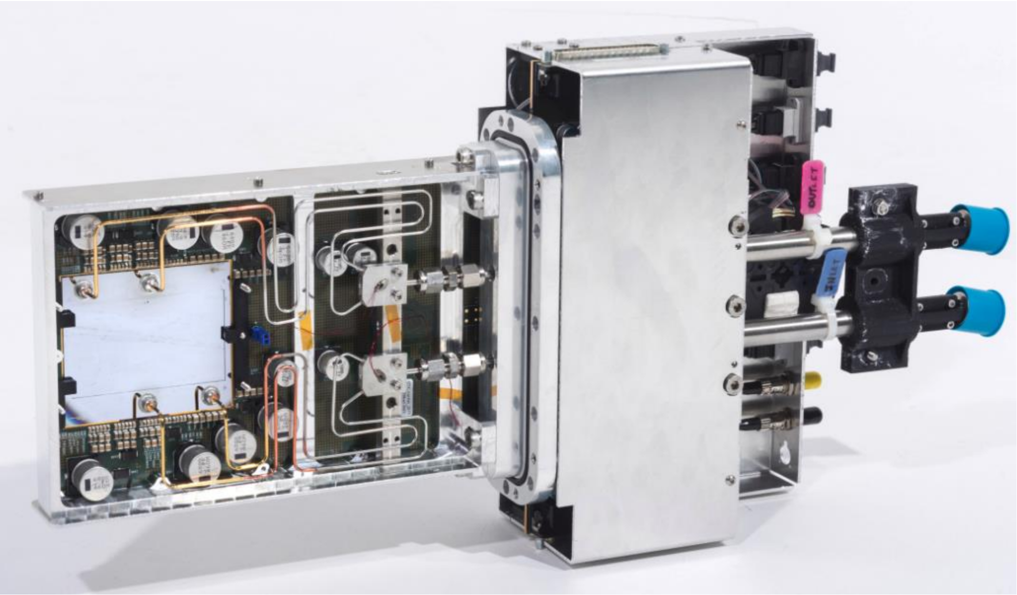
Design specifications

- Design started in 2007
- Three planes of Si hybrid pixels → 4^{th} layer (GTK0) was installed in 2021 in the same vessel with GTK1
- Installed in beam pipe vacuum: $\sim10^{-6}$ mbar
- Detectors are supposed to be replaced after 1 year at full intensity

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

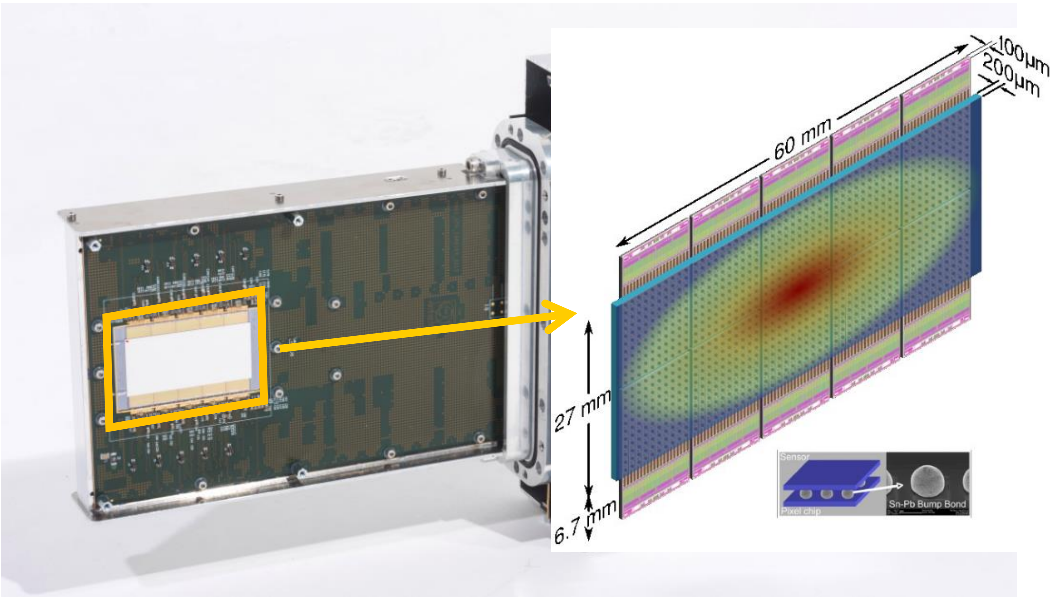
The GigaTracKer detector





Detailed description can be found [JINST14 P07010]

The pixel matrix



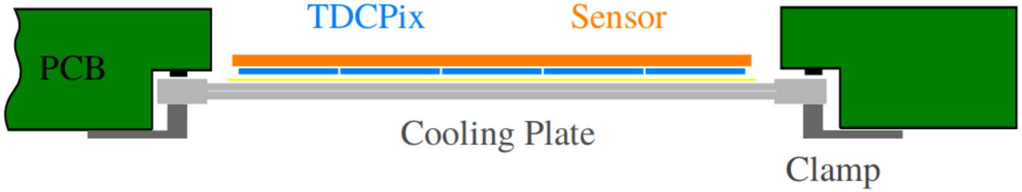
Sensor:
- Planar n-in-p/p-in-n
- 27×60.8 mm^2
- 200 µm thick (0.2% X_0)
- MPV of charge per MIP: 2.4fC, ~15000e

Bump-Bonding:
- Sn-Ag bumps
- Benzocyclobutane deposited to avoid discharges

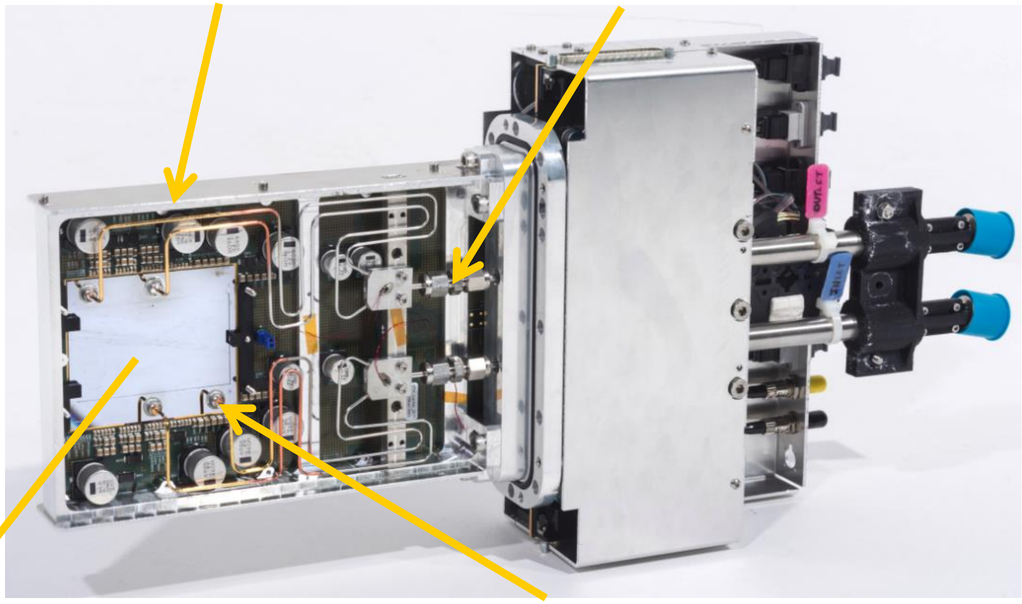
TDCPix:
- IBM 130nm CMOS technology
- 100 µm thick (0.1% X_0)
- 1800 pixels of 300 × 300 µm^2
- Time resolution: <200ps
- Peaking time: 5ns
- TDC bin size: 97ps
- SEU mitigation
- ECN <250e

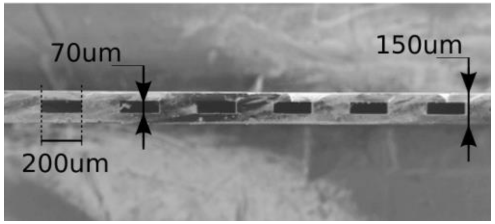
See more in [NIMA.2023.168331]

Cooling plate



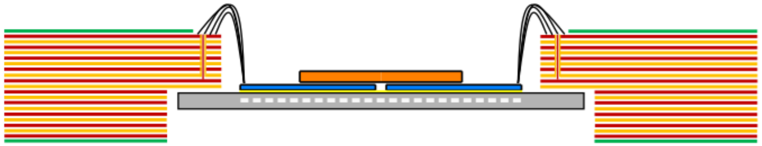
- Micro-channel technology – first application in HEP
- Fabricated by CEA Leti
- Dimensions: 70x80 mm^2, design thickness - 210 μm (0.2% X_0)
- 2 groups of 75 microchannels, 70x200μm^2
- Liquid coolant C_6F_{14} (~3g/s @ 3bars)
- Front-end electronics and sensor at <5°C





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

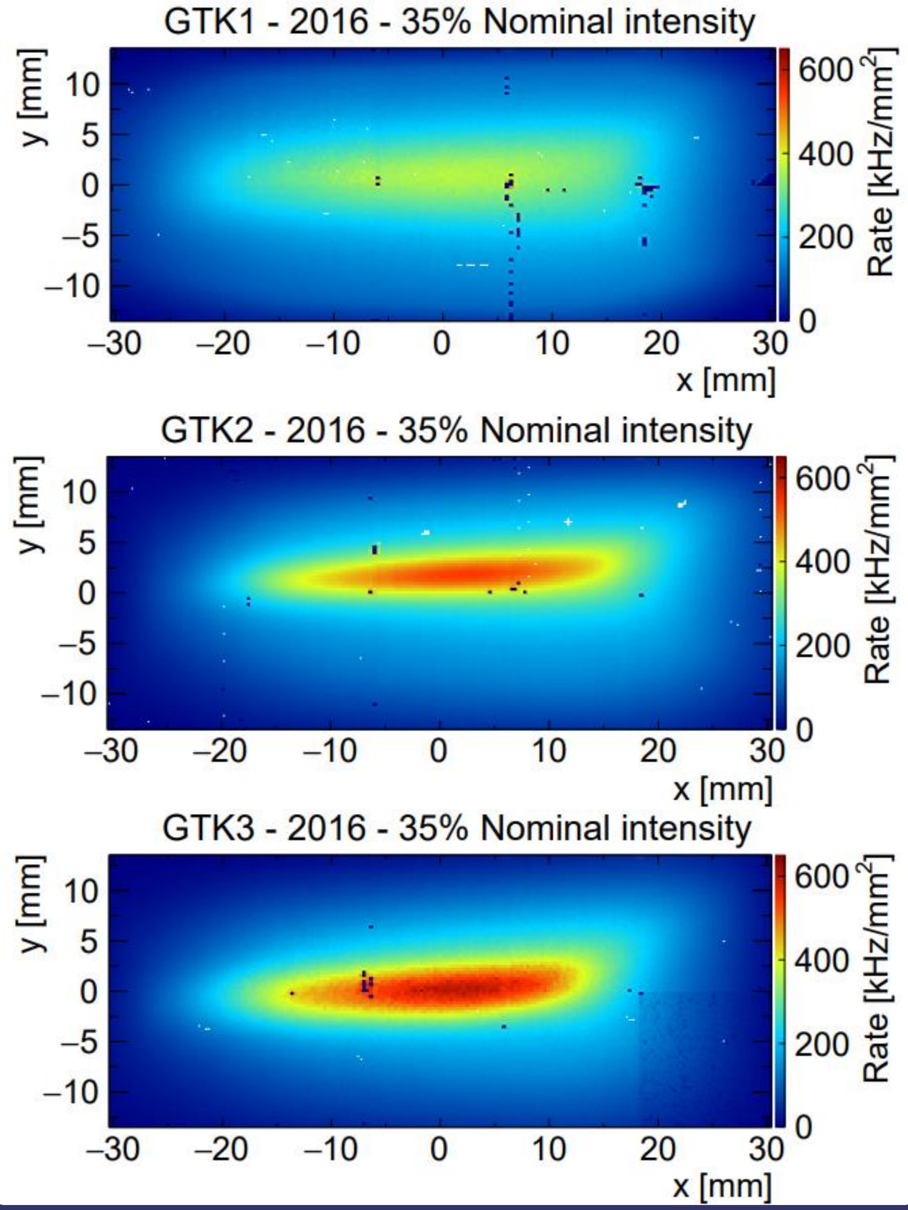
Wire bonding:

- TDCPix wired bonded to PCB
- Dense bonding scheme with 73 μm pitch on TDCPix (1450 bonding pads in PCB)
- Power, Clock, Config, Data transmitted

Detailed description can be found JINST14 P07010

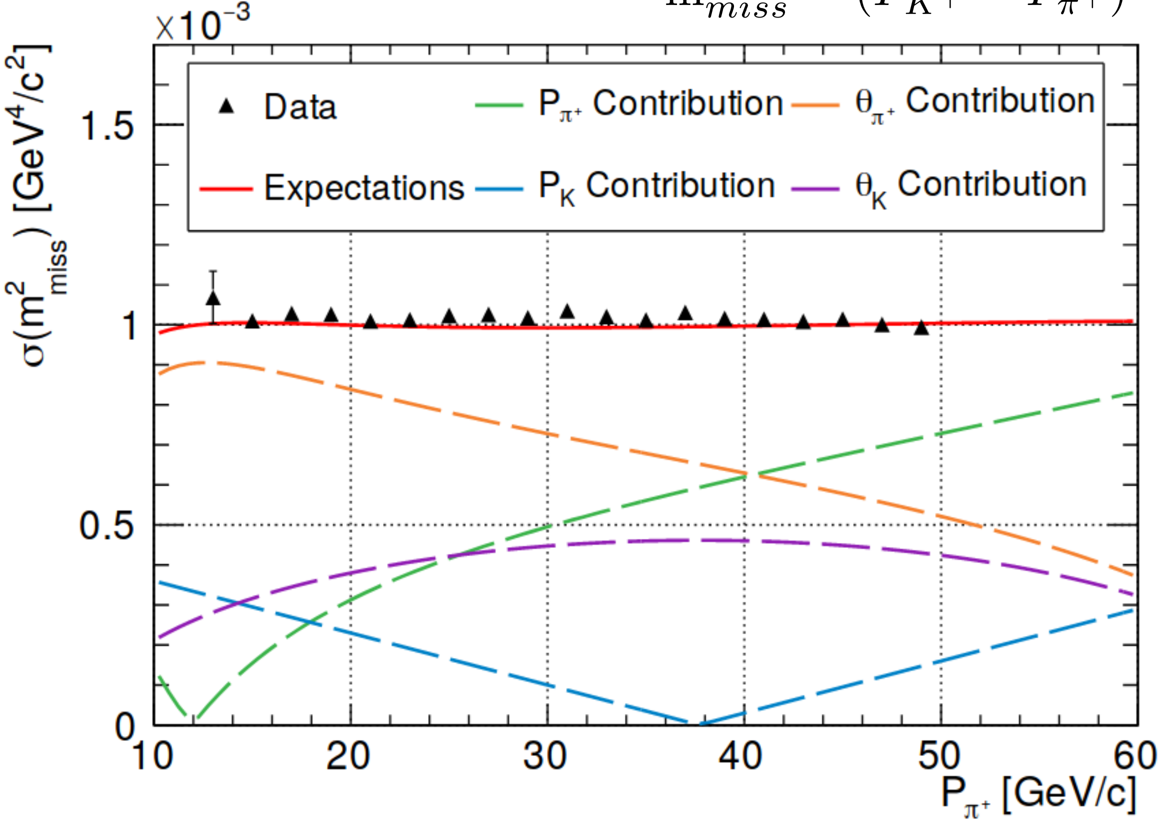
GigaTracKer in operation

- 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

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



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

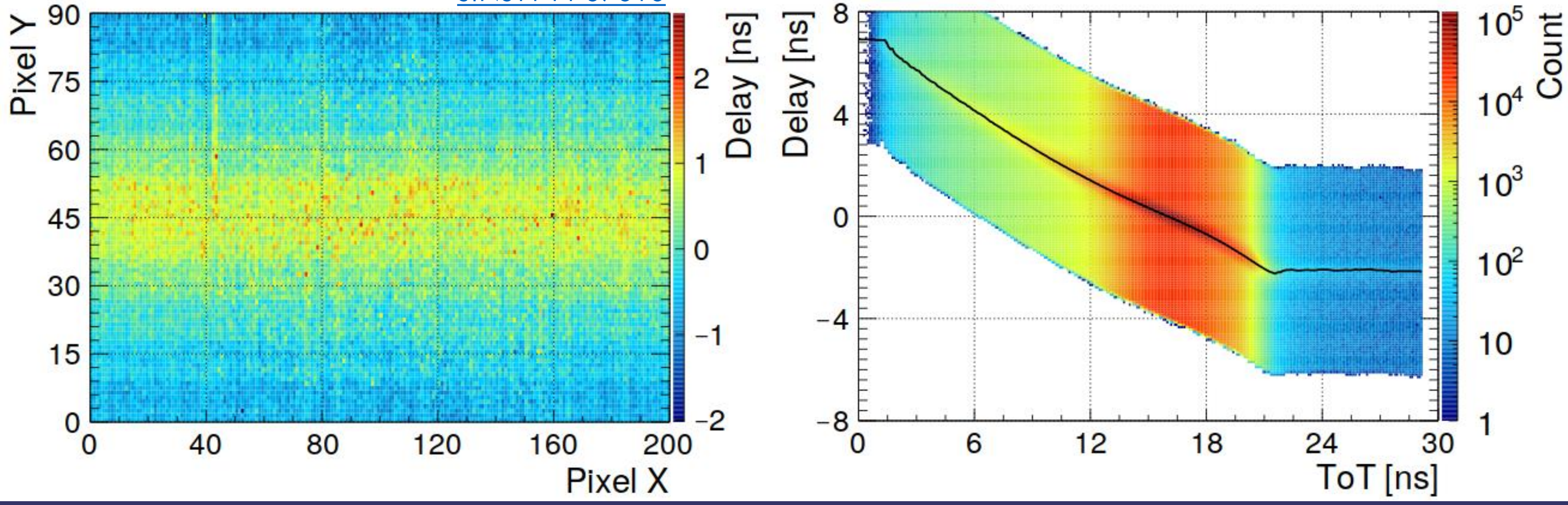
JINST14 P07010

Precise time measurement with GTK

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

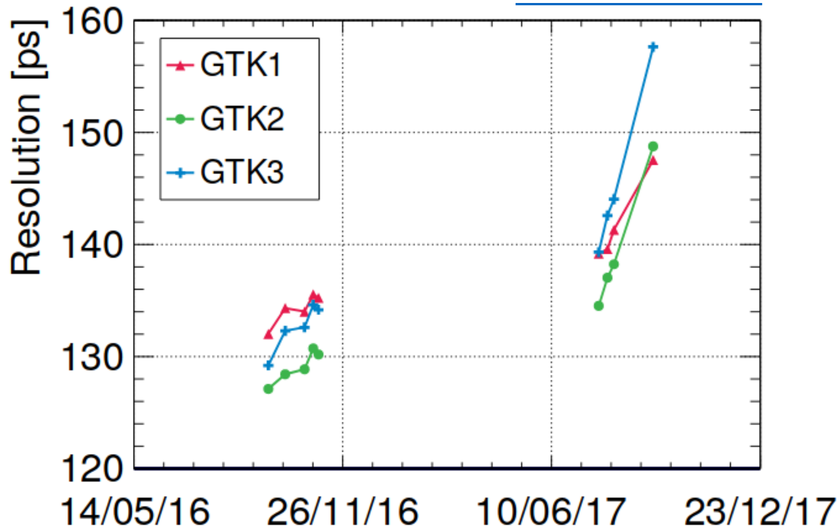
- Pixel time offsets extracted at MPV of ToT for each pixel (~3ns variation along a column)
- Time walk correction computed per chip (~300 ps/1ns ToT)
- Reference time: KTAG (70 ps resolution)
- Calibration is done once for each group of ~1500 spills

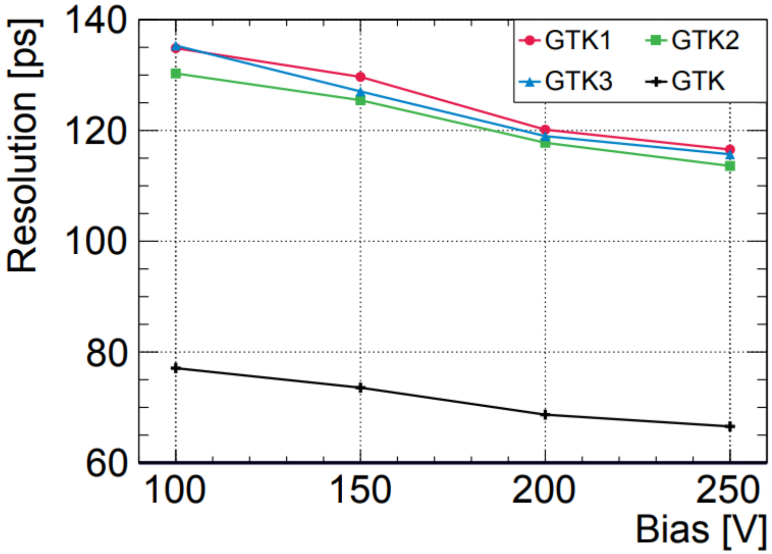
JINST14 P07010



GTK performance in 2016-2017

JINST14 P07010





Conditions:

- n-in-p sensors @100 V

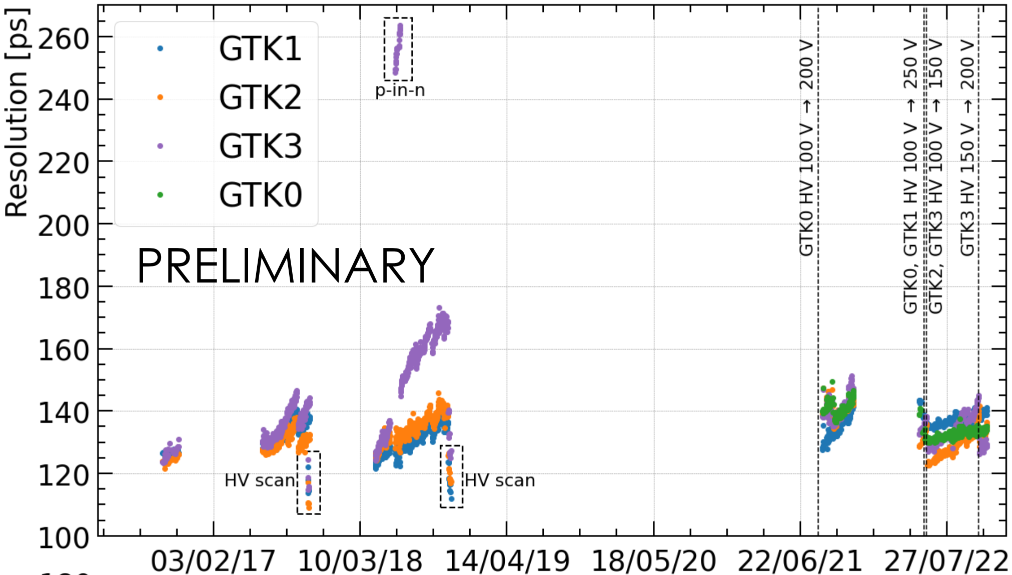
Measurement methods:

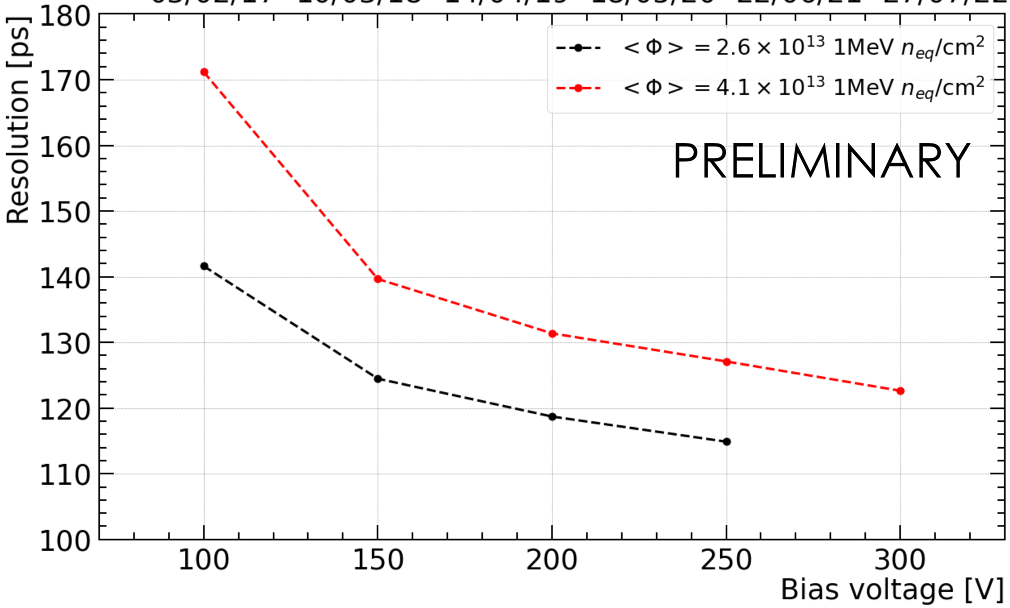
- Time difference between GTK stations, KTAG and RICH (σ_t < 100 ps)
- Time difference between the 3 GTK stations

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: $1.3(0.26) \times 10^{14}$ 1 MeV n_{eq}/cm^2
- Overall efficiency: 97%, 99% per station

GTK performance in 2018-2022





Conditions:

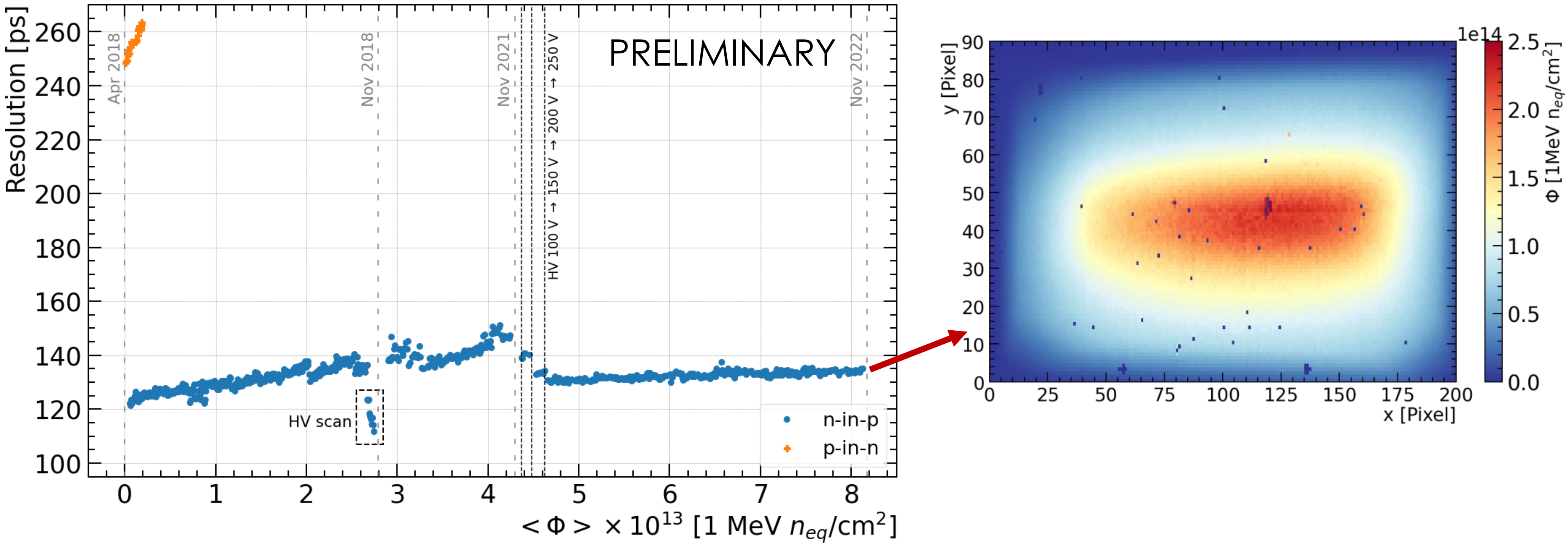
- 15 modules in total were used as GTK1,2, 3 and 0 from 2016 to 2023, a few modules were used for several years
- All modules, except one are n-in-p
- Nominal bias volage (HV) is 100 V
- After the end of each data taking period, modules are removed and stored in cold

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

*Only the most irradiated n-in-p module is shown



- 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 a factor of 2 worse than n-in-p and scales differently with fluence

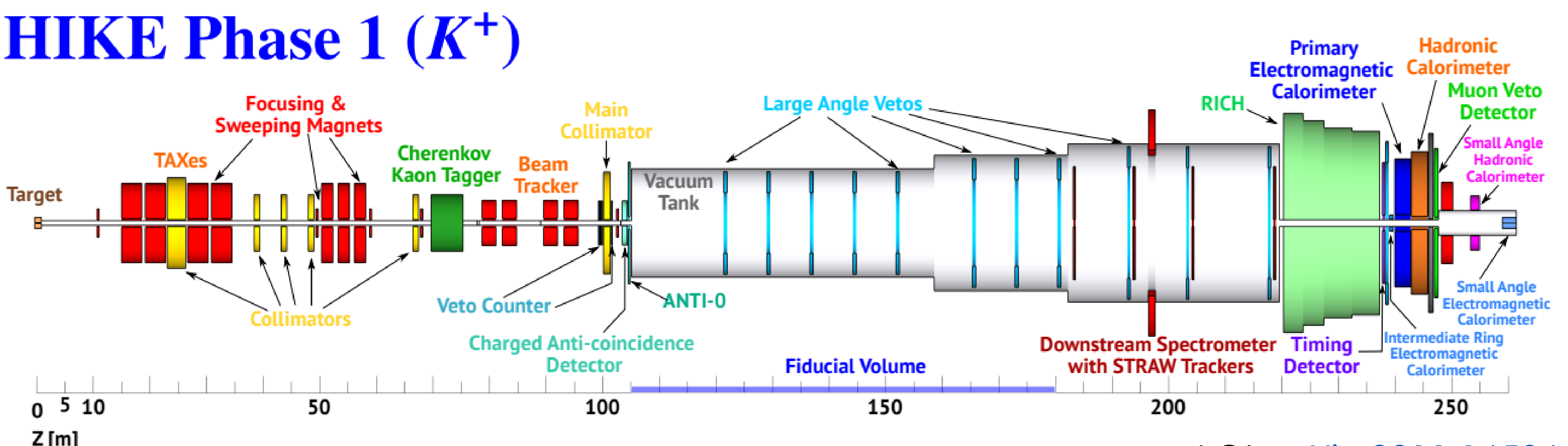
HIKE: High-Intensity Kaon experiments

- Long-term rare kaon decay programme @ CERN SPS (>~2030)
- K^+(Phase 1) and K_L(Phase 2) decay experiments
- Similar experimental layouts for charged and neutral beams: smooth transition between the two phases
- Beam line upgrade: intensity ×4 to × 6 larger than NA62 ($\sim 1.5 \times 10^{19}$ POT/year)

LOI: arXiv:2211.16586

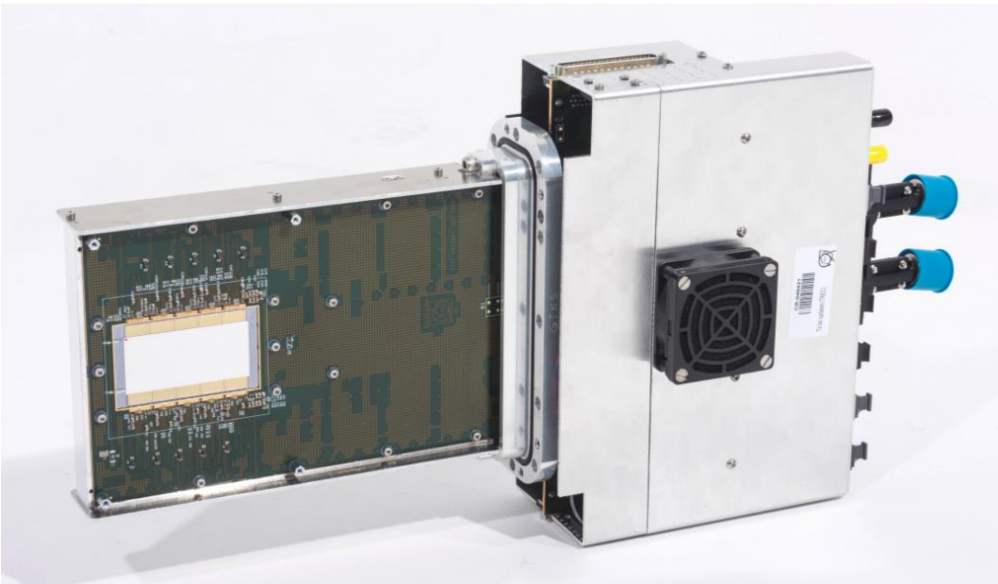
HIKE phase 1

- Detector optimised for measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) at 5% precision in 4 years
- Full tracking @ 3GHz beam
- Advanced detectors with $\mathcal{O}$(20ps) time resolution
- Minimize material



LOI: arXiv:2211.16586

Beam tracker for HIKE



4x intensity

New challenging specifications

Beam rate	>3GHz
Peak particle flux	>8.0 MHz/mm^2
Peak radiation	2.35×10^{15} 1MeV n_{eq}/cm^2/200 days
Efficiency	99%
Pixel size	<300 μm
Pixel time resolution	<50ps
Material budget	0.3-0.5%X_0
Detector size	60.8x27mm^2

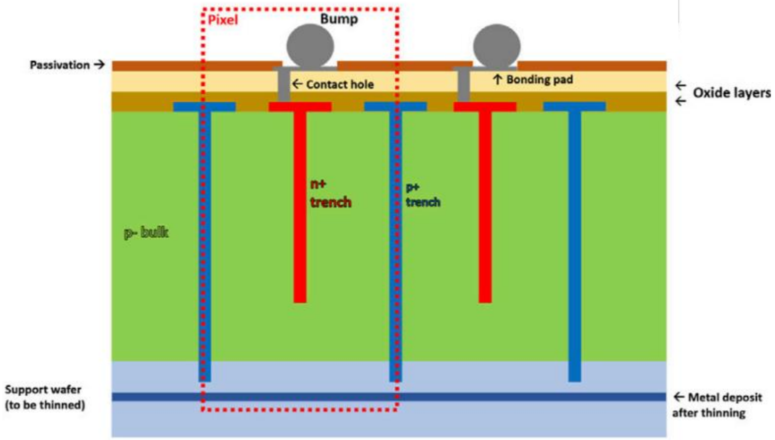
LOI: arXiv:2211.16586

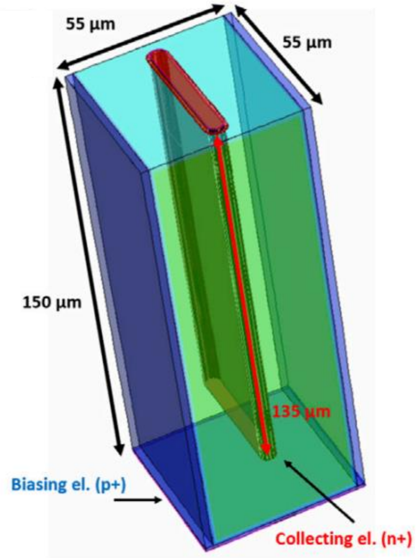
TimeSPOT 3D trench-type pixels

Can satisfy all requirements for HIKE tracker:

- Time resolution < 30 ps
- Radiation hardness > 10^{16}MeV n_{eq}/cm^2
- Spatial resolution $\mathcal{O}(10\mu m)$
- Detection efficiency >99%
- Data throughput > 1 TB/s

Sensor size 2×2 cm^2 can be produced and technical solution like stitching are being explored to produce larger devices

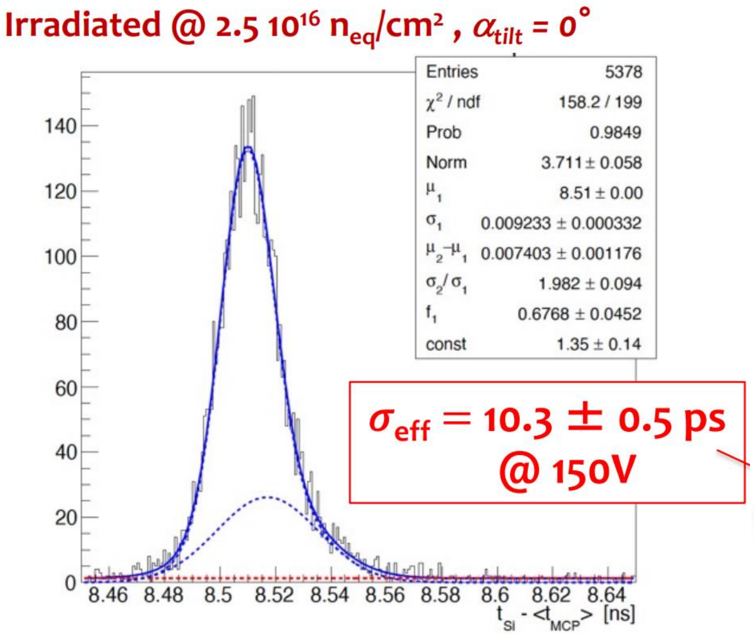


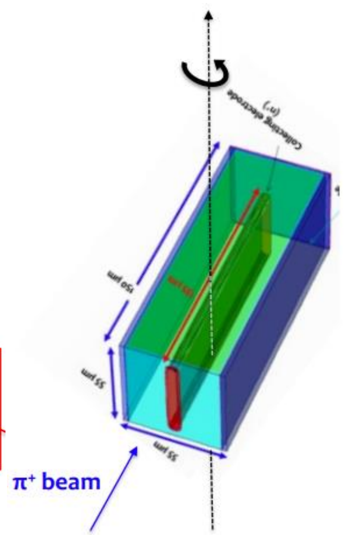


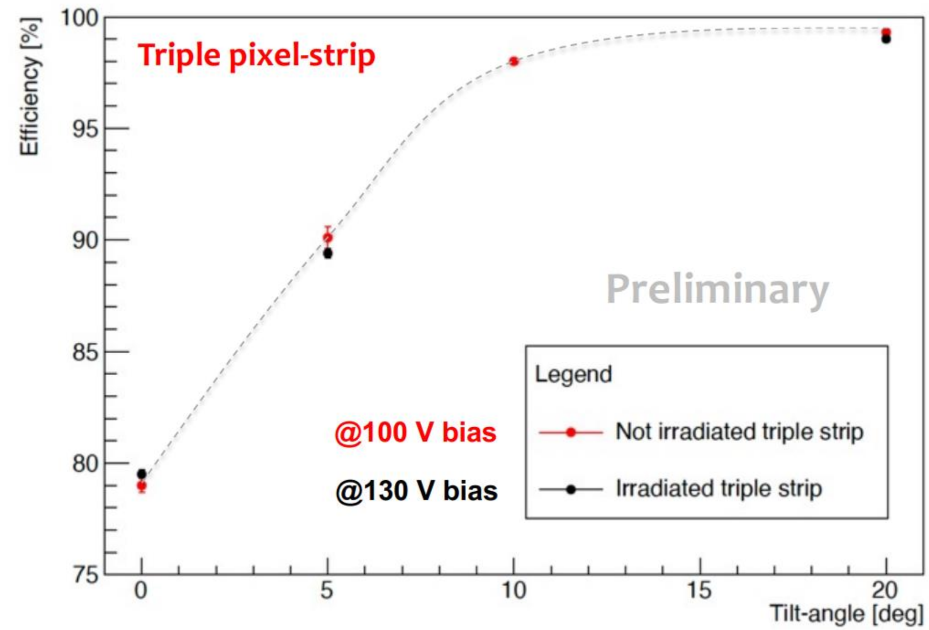
Trench geometry improves charge collection uniformity

F. Borgato et al. Frontiers in Physics 11 (2023) 1117575

TimeSPOT 3D trench-type pixels







- 99% detection efficiency can be achieved by tilting the sensor around the trench axis → same efficiency is demonstrated after the sensor irradiation
- 10 ps time resolution up to $2.5 \times 10^{16}\ n_{eq}/cm^2$

F. Borgato et al. Frontiers in Physics 11 (2023) 1117575

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 $2.5(0.81) \times 10^{14}$ 1MeV n_{eq}/cm^2, corresponding to ~120 days at nominal intensity.

Prospects:

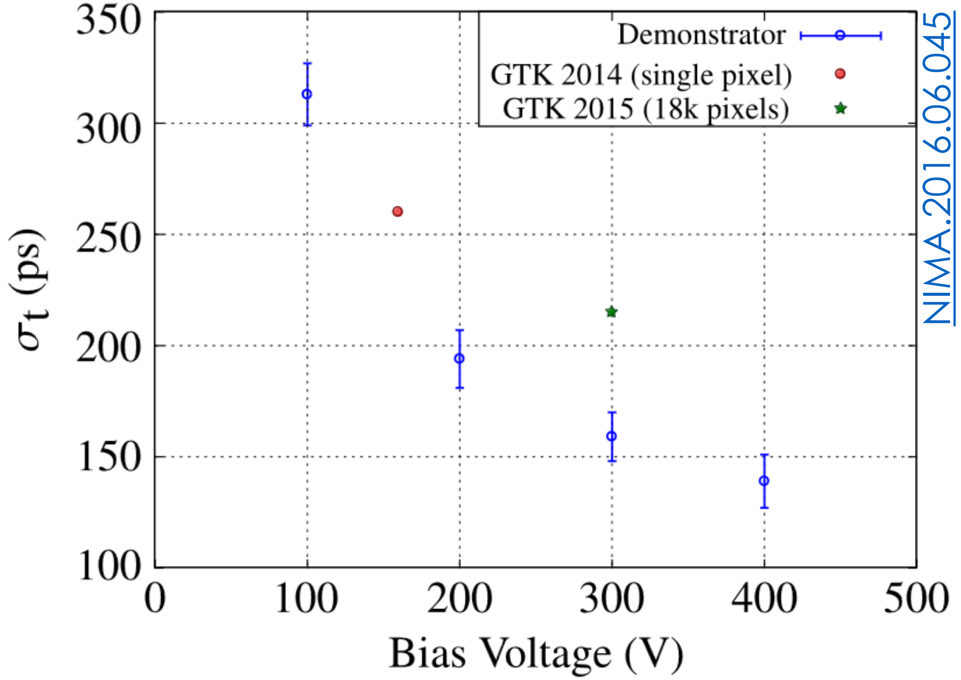
- Analysis of data is ongoing + preparing to restart data taking again next year
- New experimental challenges ahead: GTKx4 for HIKE experiment @ CERN SPS


Thank you!

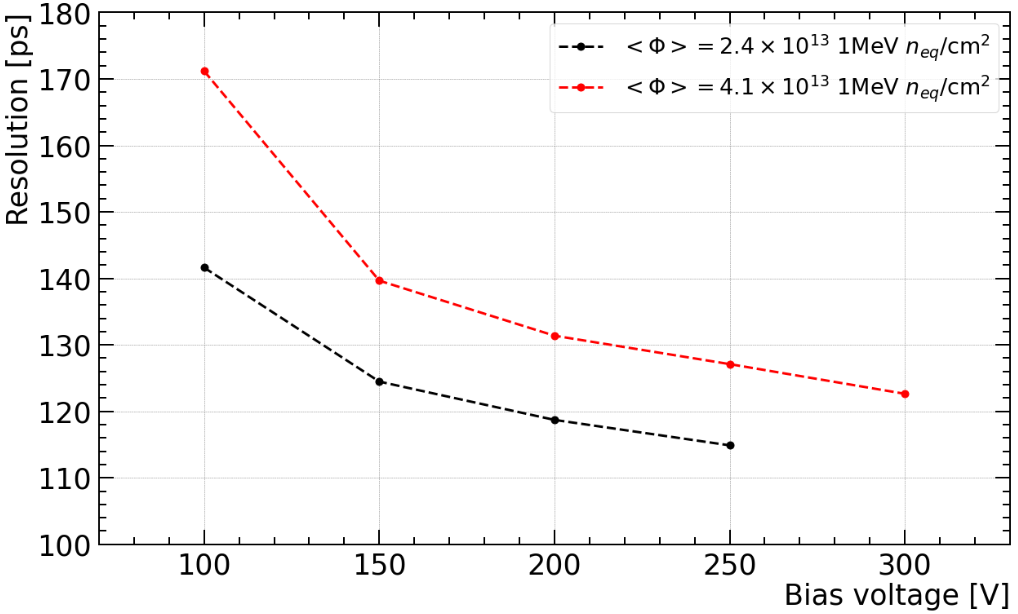
Backup slides

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

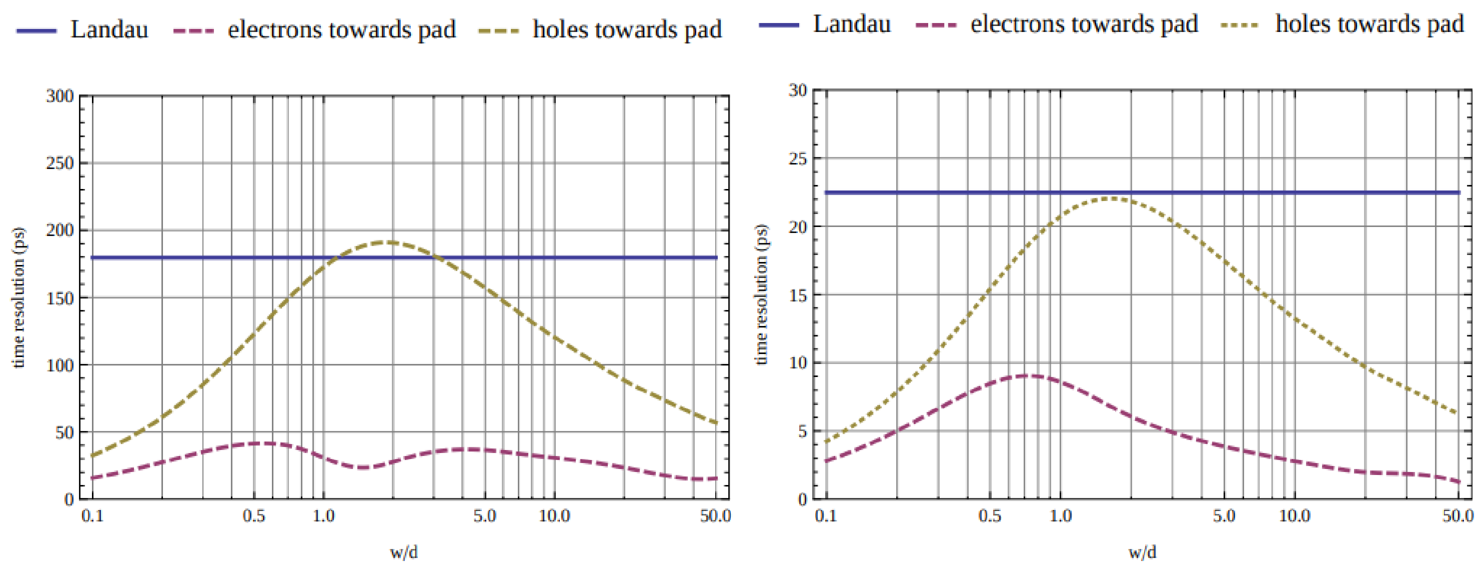
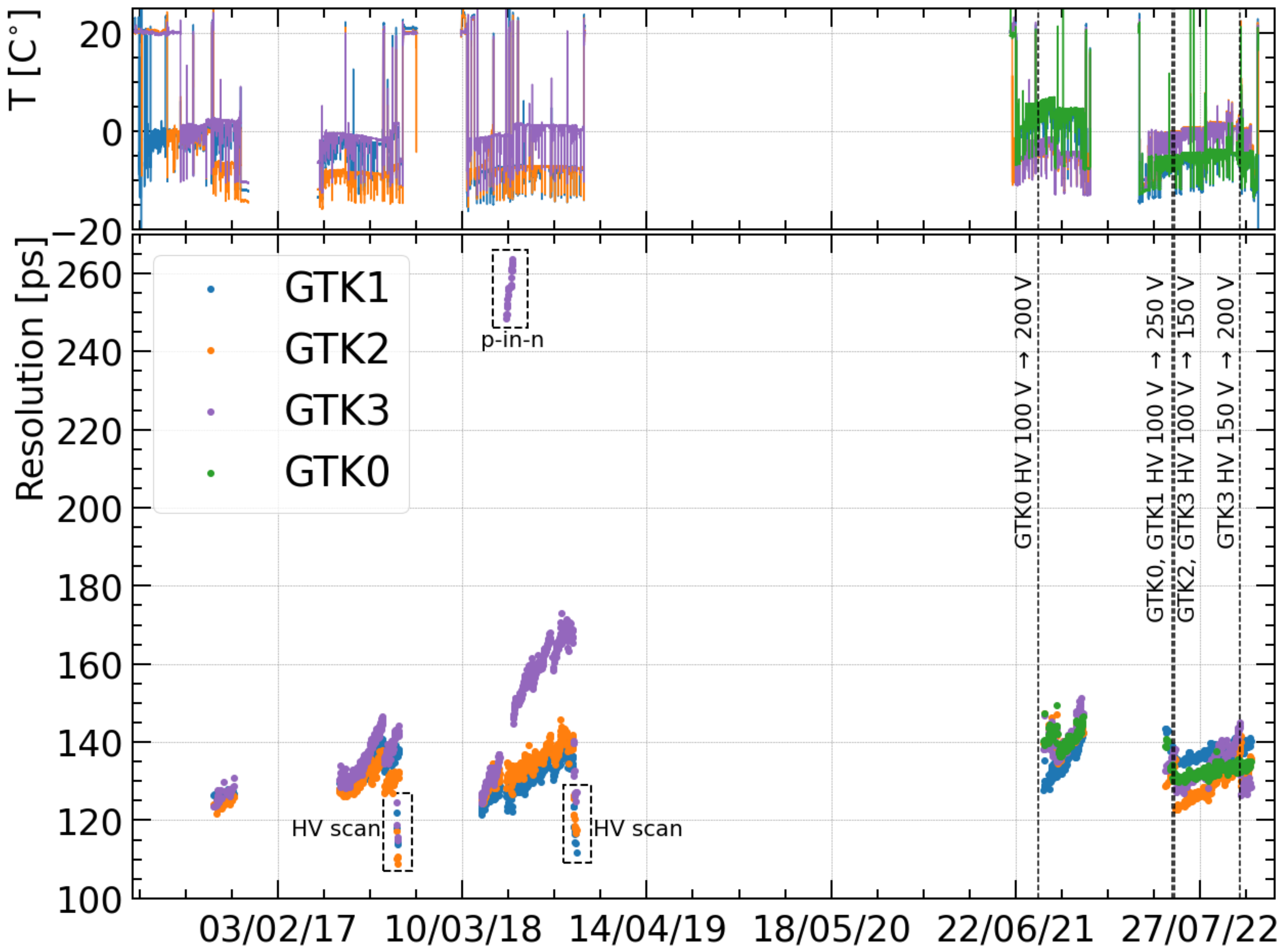
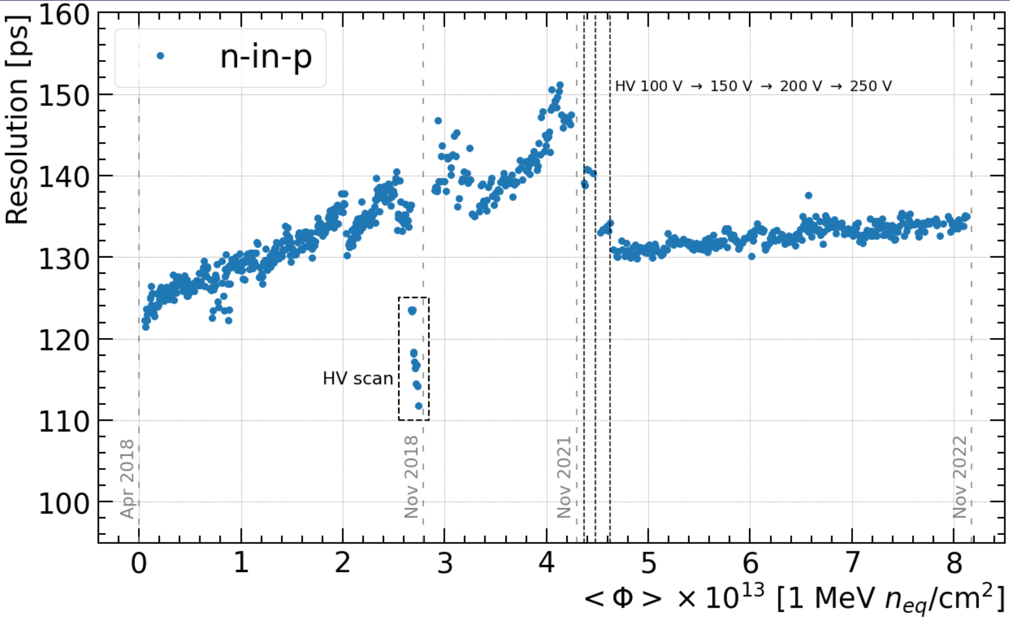


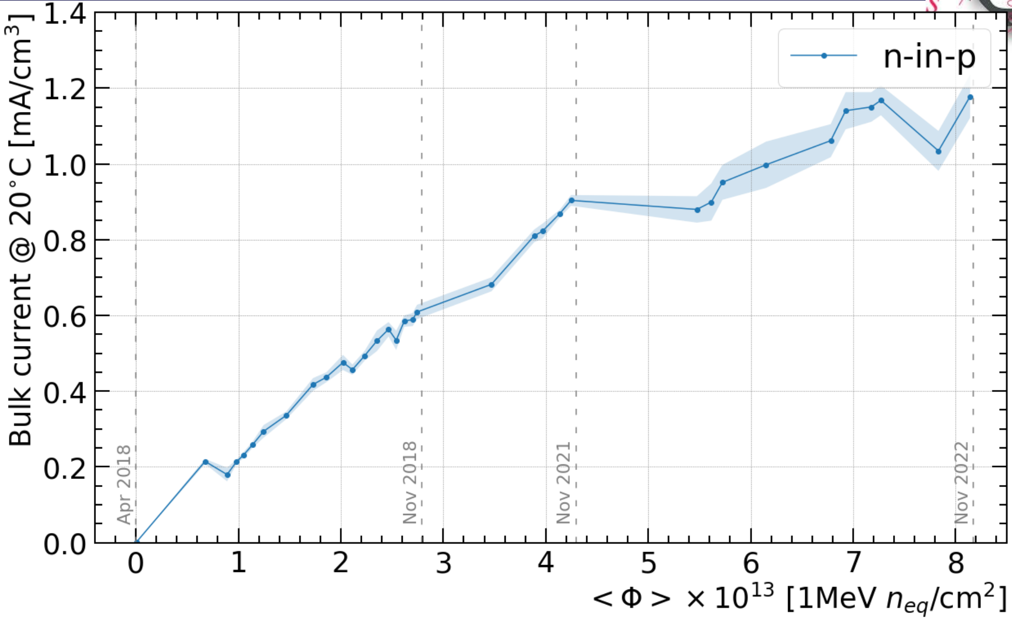
Figure 13. Standard deviation for the centroid time for sensor thickness of a) $d = 200\ \mu$m and b) $d = 50\ \mu$m and $V = 200$ V, assuming uniform charge deposit and a square readout pad. The horizontal line represents centroid time resolution from eq. (4.5) due to Landau fluctuations only. The two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

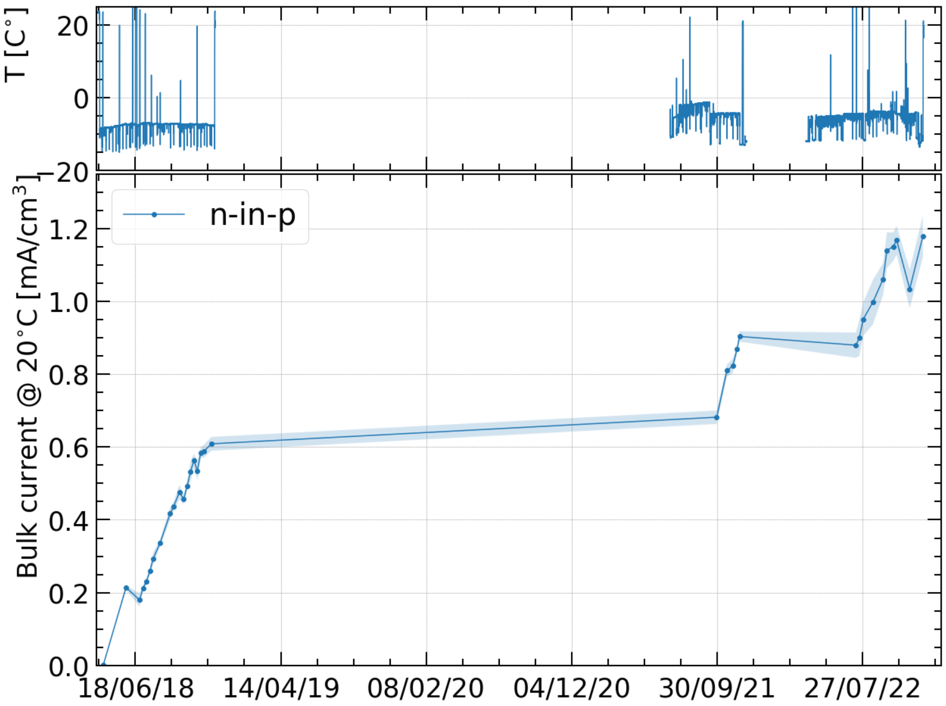
2017 JINST 12 P11017

Time resolution+temperature



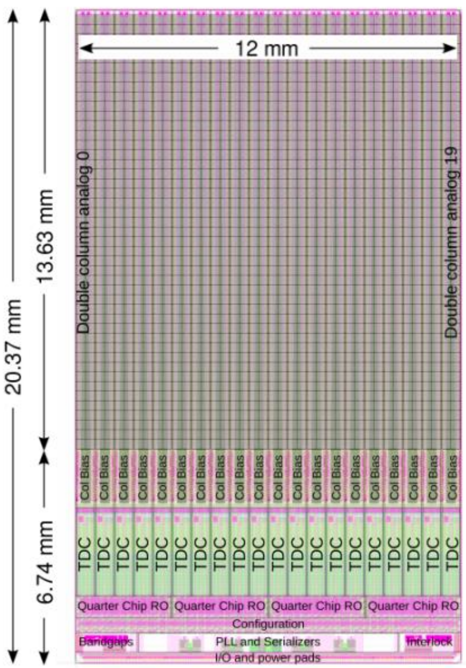


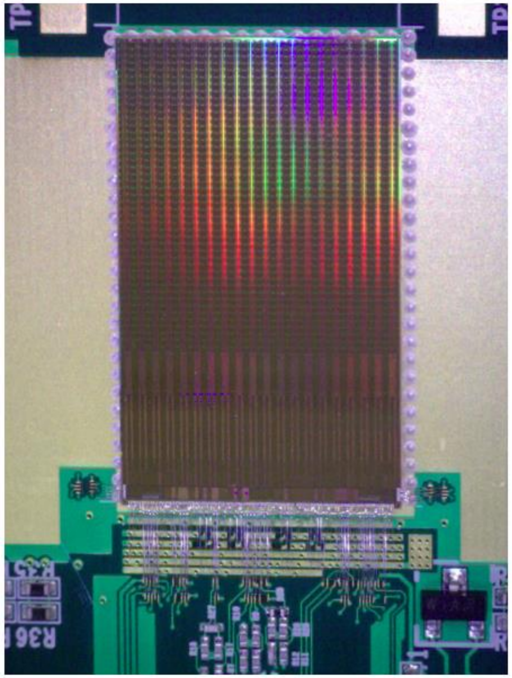




Time resolution, bulk leakage current and fluence of the most irradiated module

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)