NA62, HIKE and NuTag

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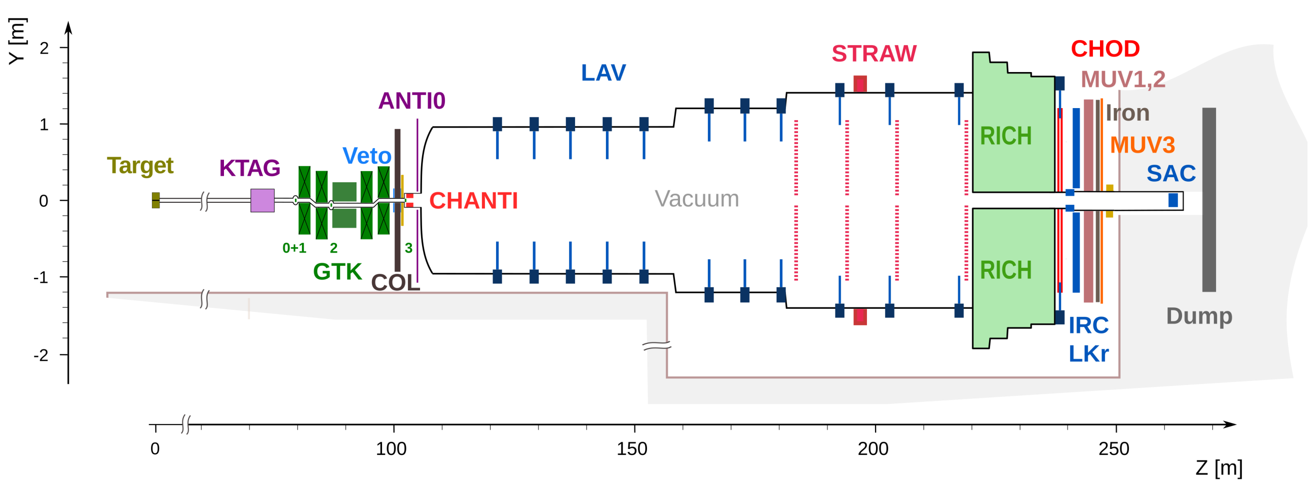
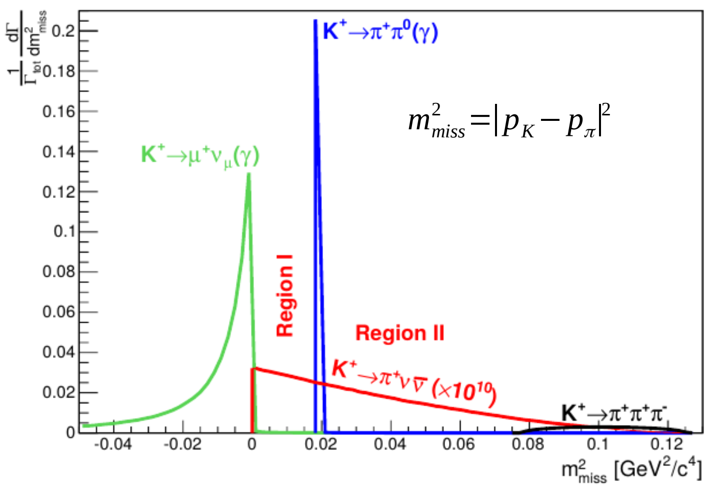
Outline

- NA62 and the GigaTracKer
- Results from NA62
- Future Projects
  - High Intensity Kaon Experiment (HIKE)
  - Tagged Neutrino Experiment (NuTAG)

NA62 and the GigaTracker

- **Kaon** physics experiment (CERN) aiming for BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) at 15% by 2025
  - Challenge: BR is $(8.4 \pm 1.0) \cdot 10^{-11}$ with **two neutrinos in final state**
  - Previous results from E787 (BNL) using **stopped beam**
  - Main kinematical variable is the squared missing mass: $m^2_{miss} = |p_K - p_\pi|^2$
- NA62: **decay in flight** technique at CERN SPS
  - Continuous beam: 750MHz, (6% K^+, 24% p, 70% π^+) at 75 GeV/c
  - **Decay in flight** technique requires a **beam spectrometer:** GigaTracker GTK

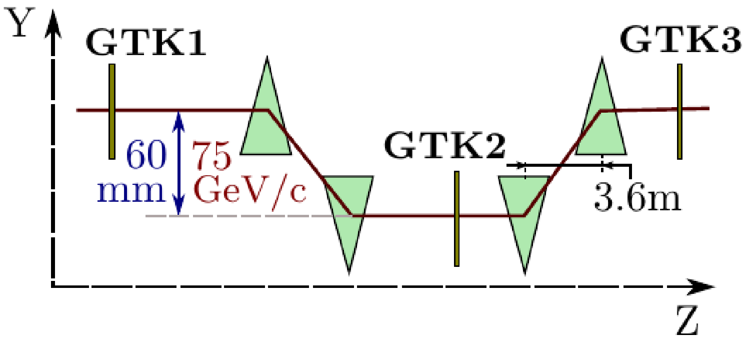


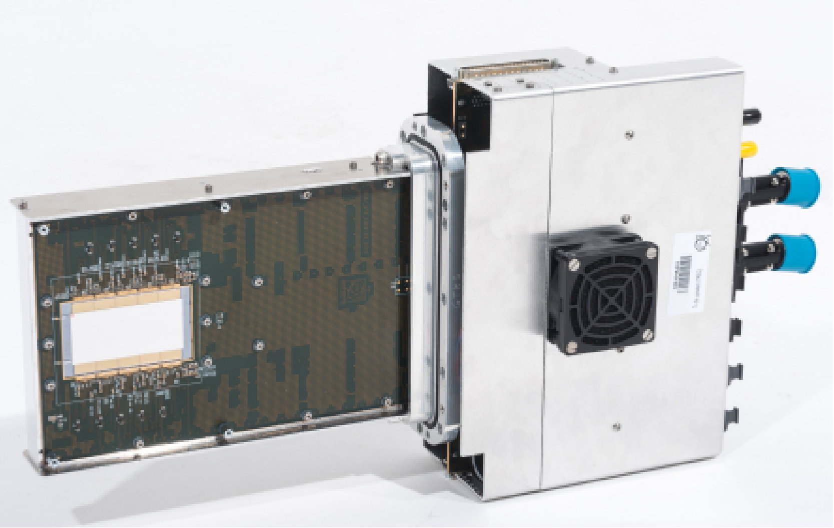


GTK

- **Beam Spectrometer**
  - Measures momentum, angle and time of all beam particles
  - Sustains high particle flux (750MHz)
  - Minimized material budget
- **Design (~2009)**
  - Three (four from 2021) planes of time resolved pixel

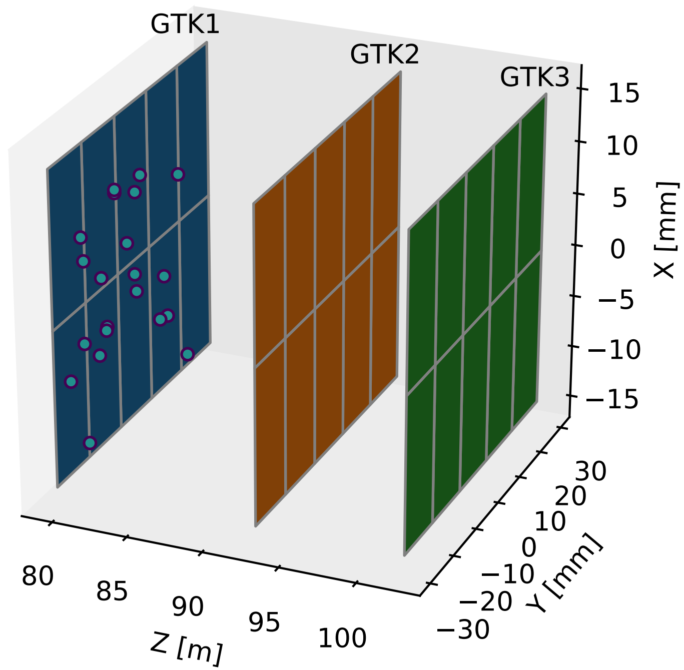
Beam Rate	800 MHz - 1 GHz 1.3 $\mathrm{MHz/mm^2}$
Peak Radiation	4.10^{14} 1MeV $\mathrm{n_{eq.}/cm^2}$ for 200 days
Efficiency	99%
Momentum Resol.	0.2%
Angular Resol.	16 µrad
Pixel Time Resol.	$<$ 200 ps RMS
Material Budget	0.5% X_0





Need for Timing

- **Association with other NA62** sub-detectors based on time coincidence
- **Tracking in GTK** relies on time (little geometrical redundancy with 3 planes)



Typical Event at 30% of nominal intensity

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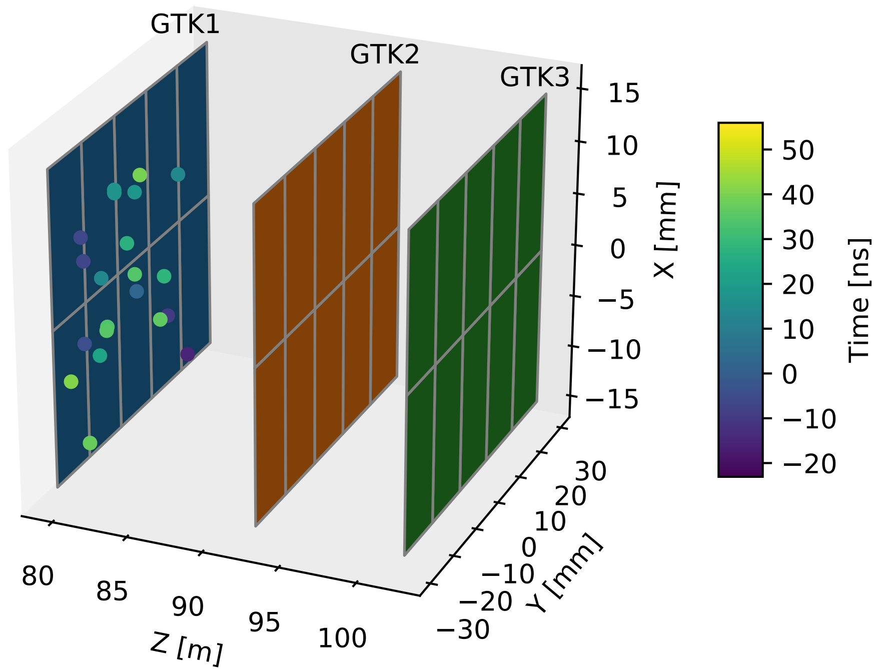

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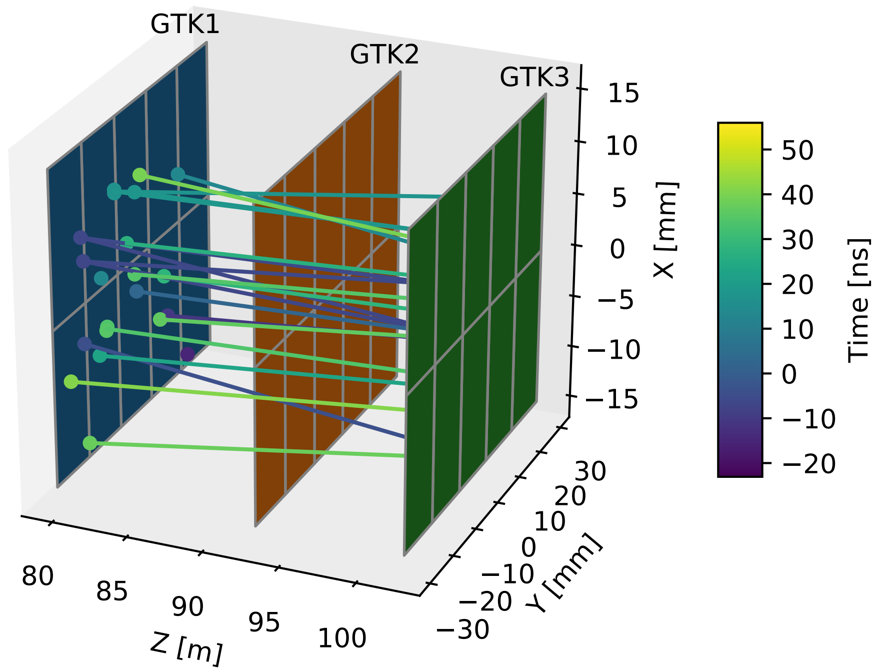

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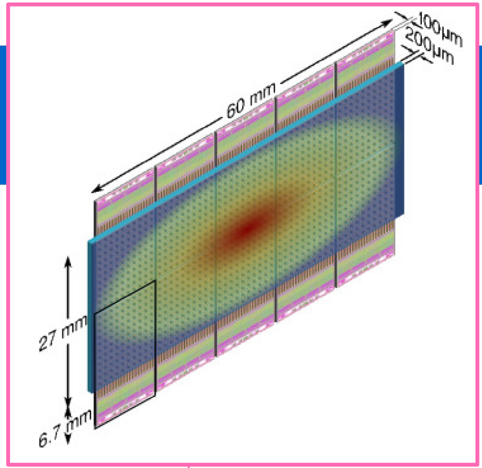
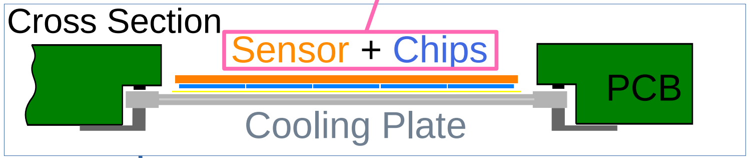
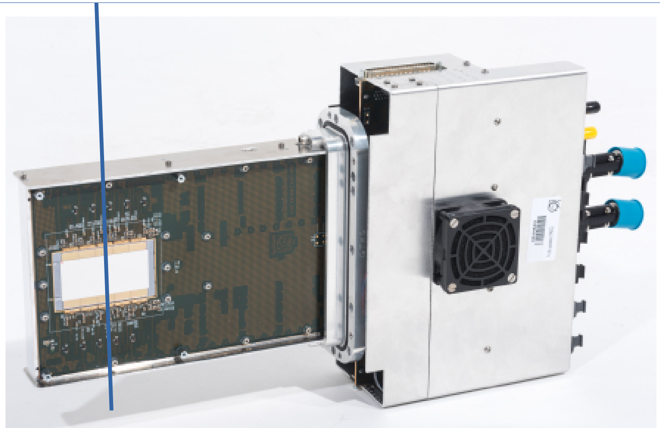
GTK Design



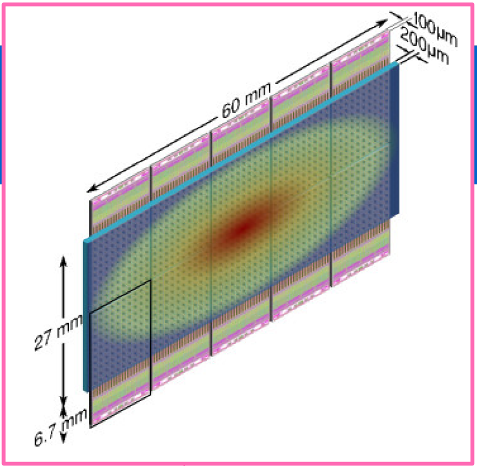
- Single 3×6 cm^2 **sensor** (n-in-p) hybridized to 2×5 TDCPix
- **TDCPix**:
  - a custom made chip with **97ps TDC bin** (the best time precision on the market since 2009)
  - significant **power consumption** (1.7W/cm^2)



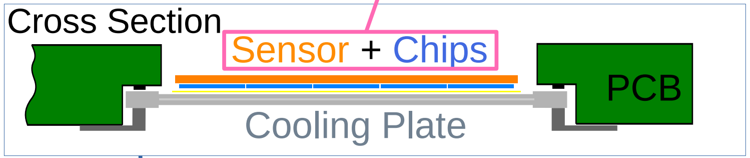


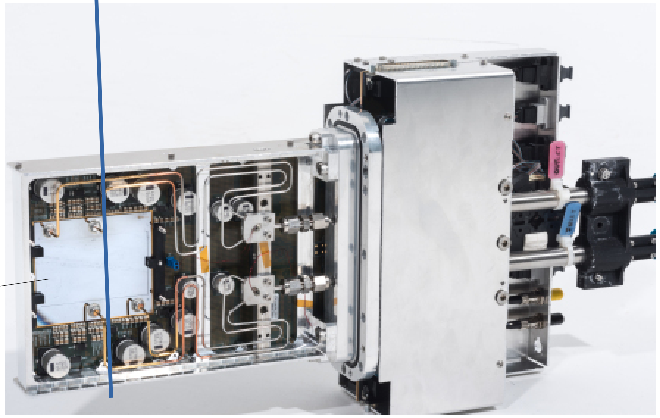
Sensor Side

GTK Design

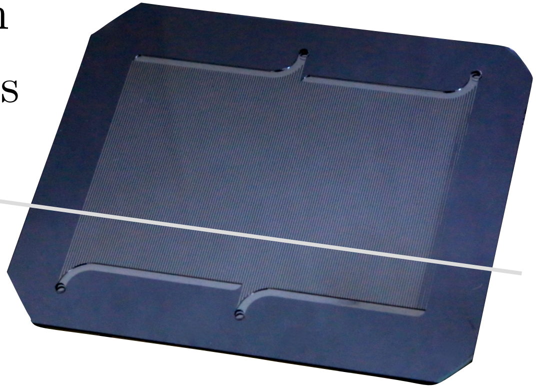


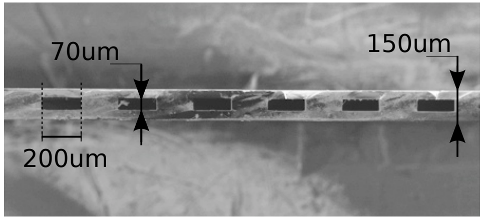
- Single 3×6 cm^2 **sensor** (n-in-p) hybridized to 2×5 TDCPix
- **TDCPix**
  - a custom made chip (IBM 130nm) with **97ps TDC bin** (the best time precision on the market since 2009)
  - 300×300 µm^2 pixels
  - significant **power consumption** (1.7W/cm^2)
- **Microchannel cooling** plate (1st implementation)
  - 200µm thick
  - 150 channels of 200×70µm
  - Liquid C_6F_{14} at -10°C, 3g/s





Cooling Side

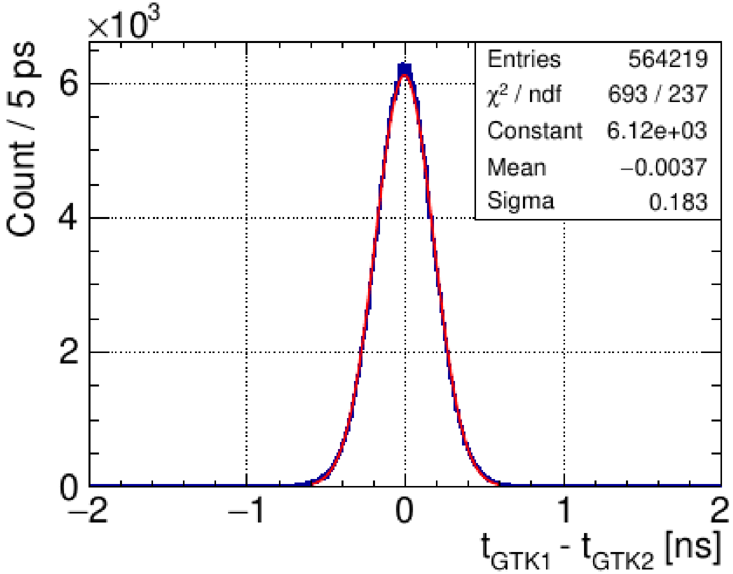


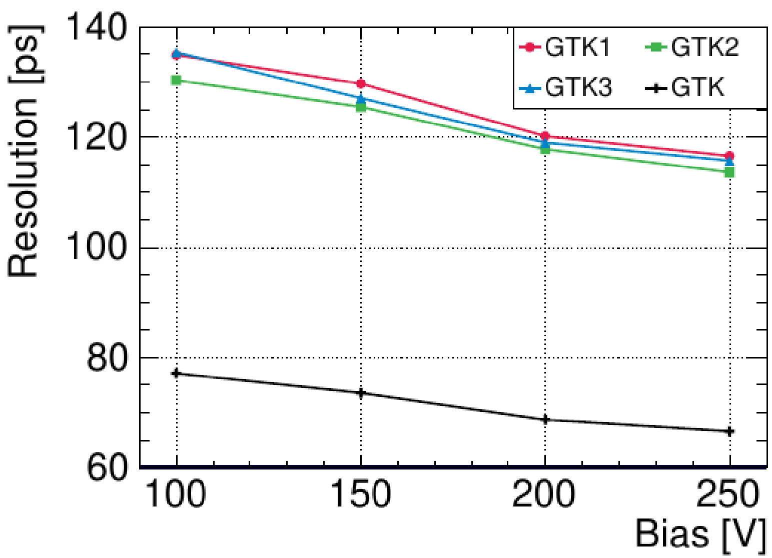


Cross Section

Time resolution

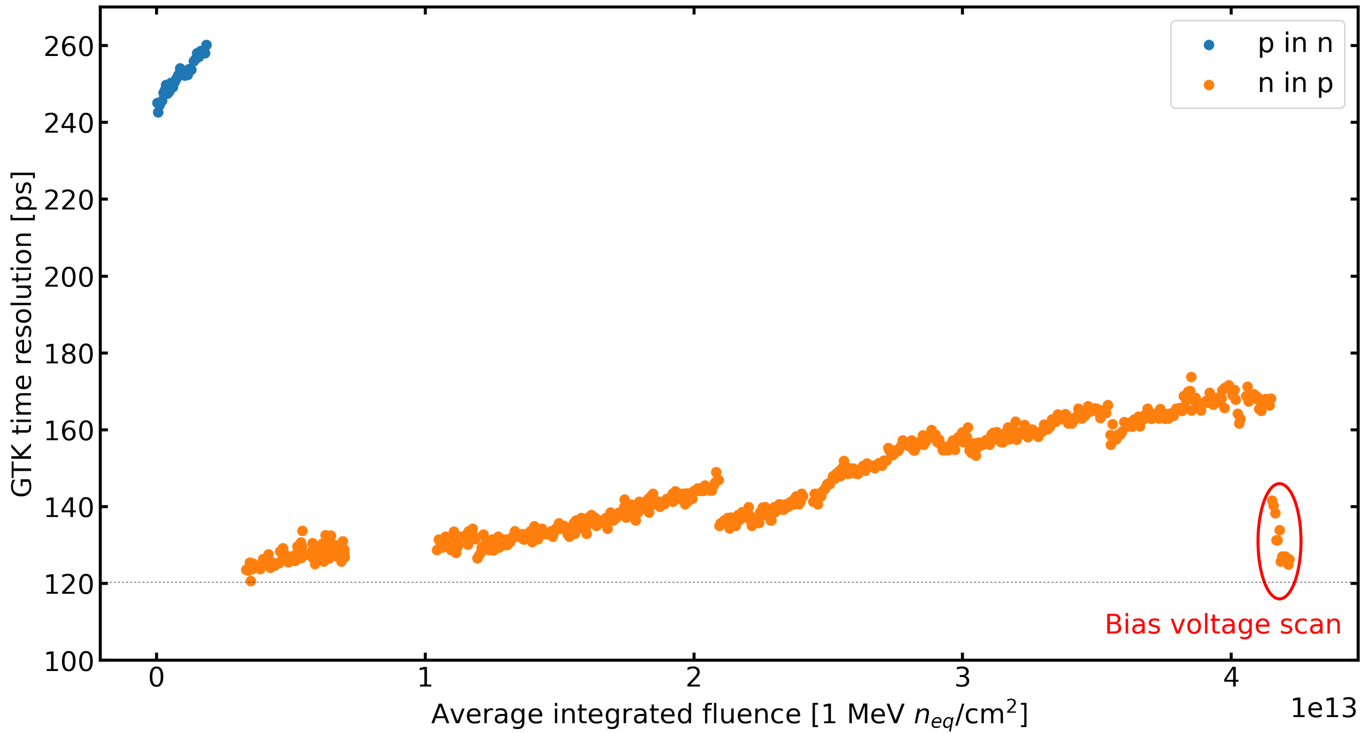
- Precise **time calibration** of the pixel is required to get good time resolution
- **Performance**
  - Track Time resolution: 75 ps
  - Hit Time resolution: 130 ps (gauss fit)
  - Dominant contribution is the **weighting filed potential** and **charge straggling**.
- Time resolution improve with **higher bias**





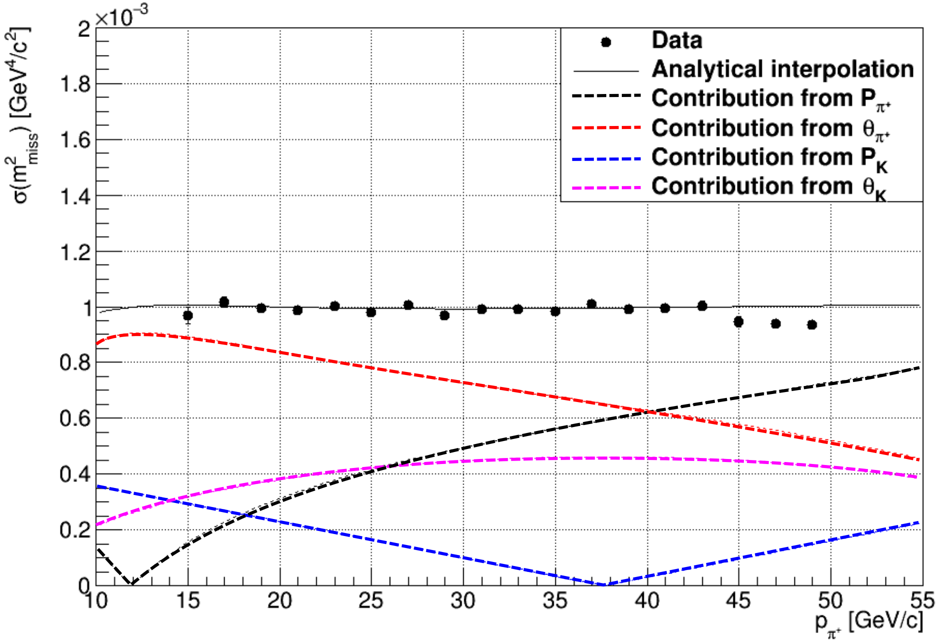
Time resolution stability

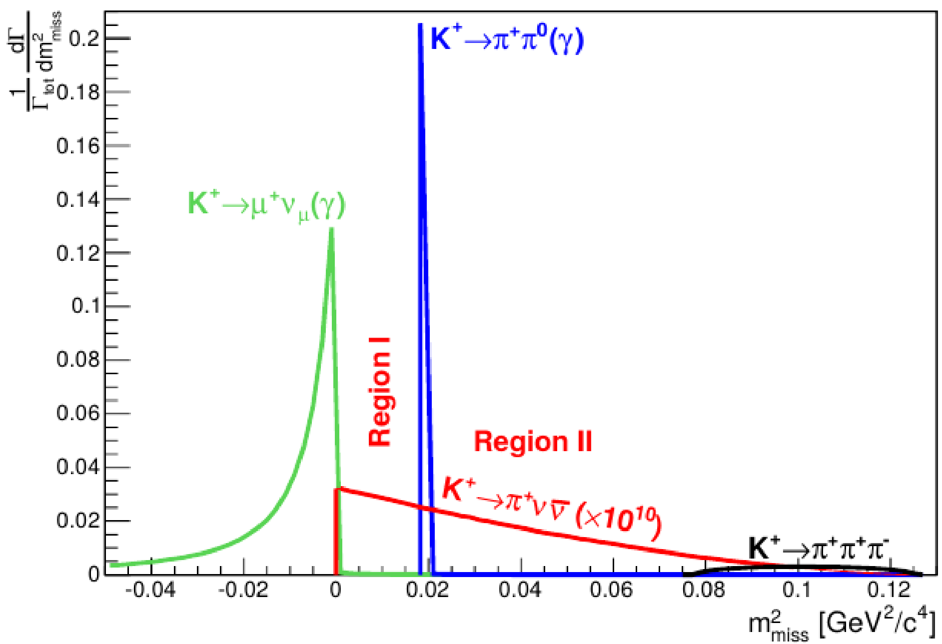
- TDCPix also accept **p-in-n sensor** which has much worse time resolution
- Time resolution degrades with **integrated fluence**
- Performance are recovered by increasing the **bias voltage** (and annealing)



Kinematics for $K^+ \rightarrow \pi^+ \nu\nu$

- **Recall:** main analysis variable is squared missing mass $m^2_{miss} = |p_K - p_\pi|^2$
- Resolution of the m^2_{miss} evaluated on a sample of $K^+ \rightarrow \pi^+ \pi^0$





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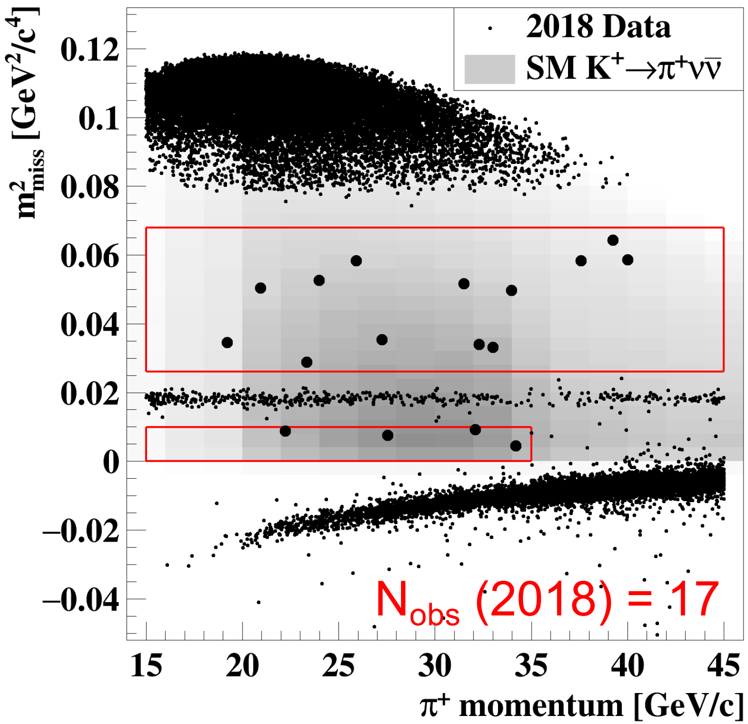
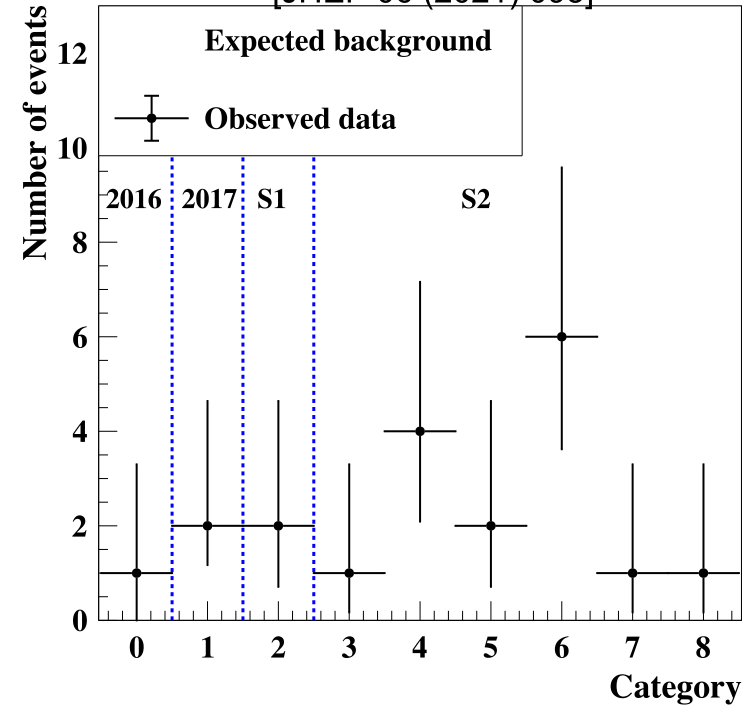
NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ RUN1=2016+2017+2018



[JHEP 06 (2021) 093]



N_{obs} (Run1) = 20 $\quad N^{exp}_{background} = 7.03^{+1.05}_{-0.82} \quad N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ at 68% CL $\quad$ **3.4σ significance**

Most precise determination of the decay rate to date

Prospects: Run 2 (2021-2025) with nominal beam intensity, modified beamline and additional detectors.

Aim to measure BR($K^+ \to \pi^+\nu\nu$) at O(15%) precision by LS3

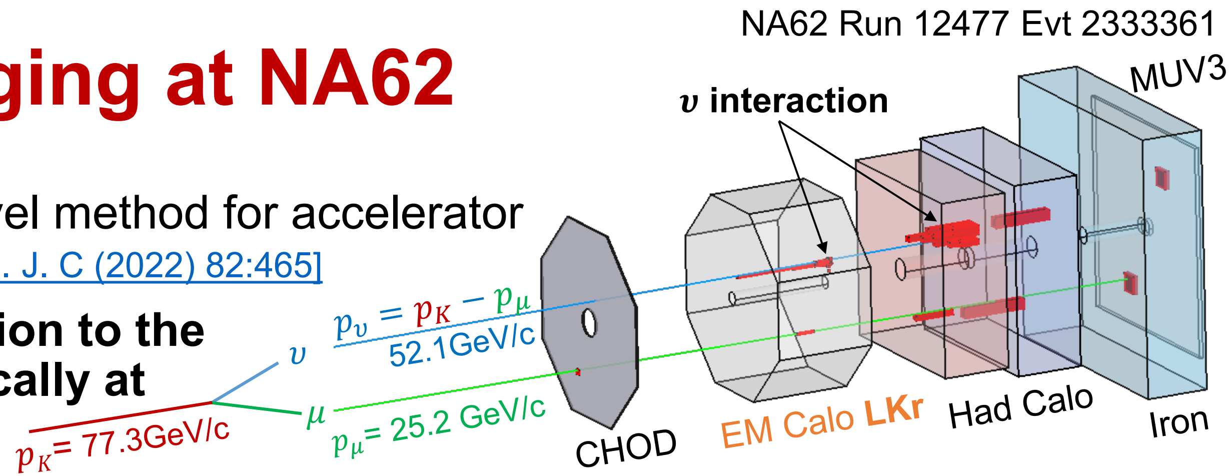
Something New (EPS-2023)

Neutrino Tagging at NA62

- **Proof-of-principle** of a novel method for accelerator based experiments [Eur. Phys. J. C (2022) 82:465]
- **Associate each υ interaction to the υ reconstructed kinematically at production** ($K^+,\pi^+ \to \mu^+ \nu_\mu$)

➢ Pristine access to neutrino **flux**

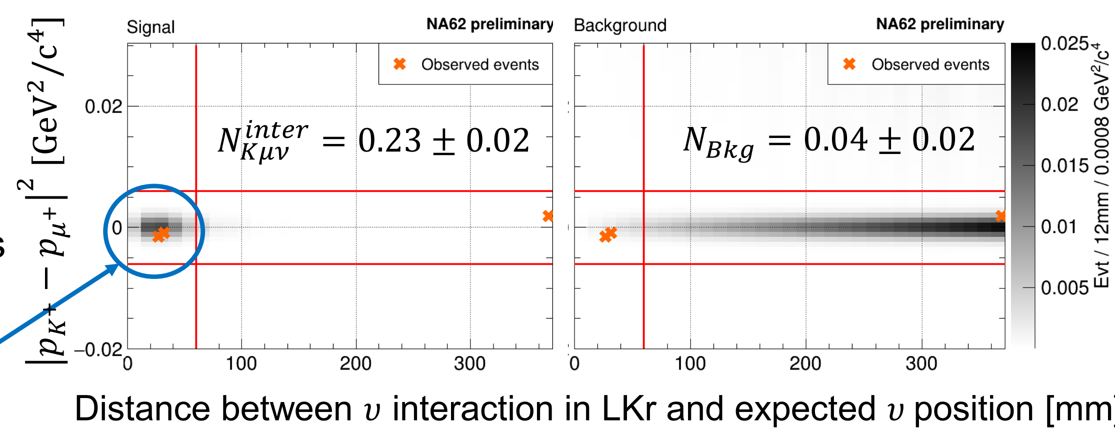
➢ Excellent υ **energy resolution:** <1%



Full details on B. De Martino Talk @ NuFact-23

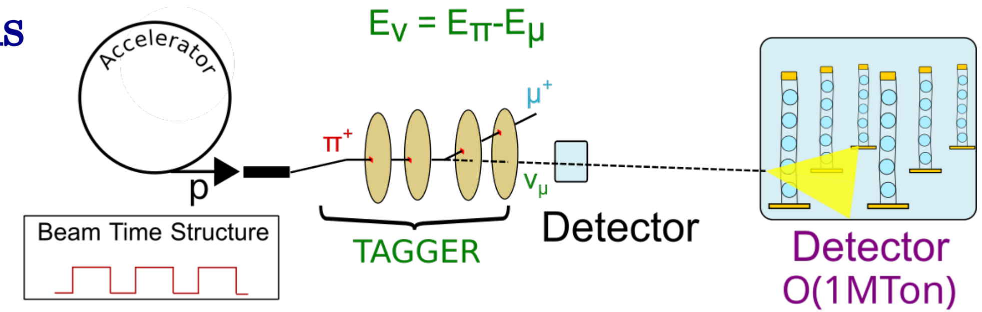
- **NA62 as tagged-υ experiment**
  - ➢ ~10^{12} $K^+ \to \mu^+ \nu_\mu$ per year
  - ➢ ν_μ interactions in the 20 ton of LKr
  - ➢ K^+ and μ^+ reconstructed in trackers

Two tagged υ candidates observed!

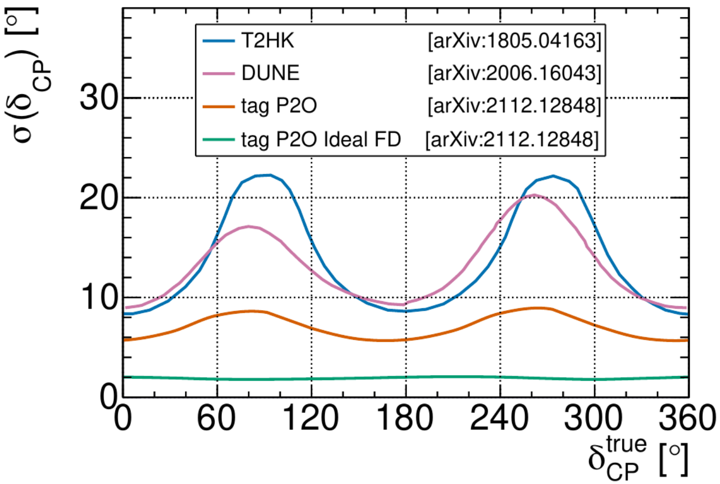


Toward a full scale tagged ν experiment

- Ideal tool to study **neutrino interactions** at a **short baseline experiment**
  - dominant systematics uncertainties for DUNE/T2HK



- Ideal tool to study **neutrino oscillations** at a **long baseline experiment**
  - excellent energy resolution (<1%)
  - low systematic uncertainties
  - oscillation studied event-by-event: ν tracked from creation to detection



Precision on δ_{CP} is up to 10 times better than at upcoming experiments

- **Need a tracker able to sustain very high beam particle flux 10-100 Mhz/mm^2, $10^{12}\pi^+$/s**

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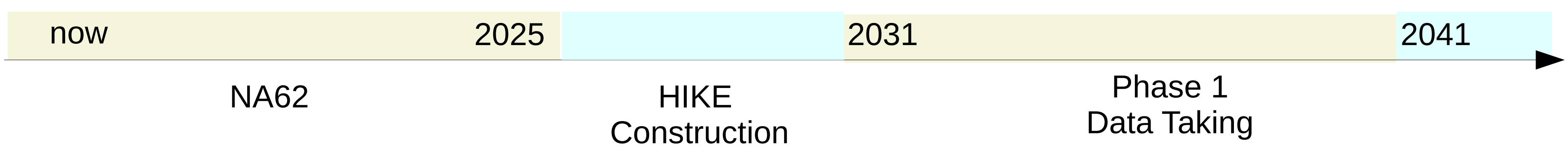
Future: NA62 → HIKE

- **HIKE** a multi-purpose high-intensity kaon decay-in-flight experiments
  - Phase 1: 2031-2041 ($K^+ \rightarrow \pi^+ \nu\nu$ at ~5% precision)
  - Phase 2: 2043-2048 ($K_L \rightarrow \pi^0 l^+ l^-$ at ~20% precision)

- **High intensity beam**
  - 4-6 times NA62
  - New beam tracker is needed

	NA62 GigaTracker	New beam tracker
Single hit time resolution	< 200 ps	< 50 ps
Track time resolution	< 100 ps	< 25 ps
Peak hit rate	2 MHz/mm^2	8 MHz/mm^2
Pixel efficiency	> 99 %	> 99 %
Peak fluence / 1 year [10^{14} 1 MeV n_{eq}/cm^2]	4	16



HIKE Beam Tracker

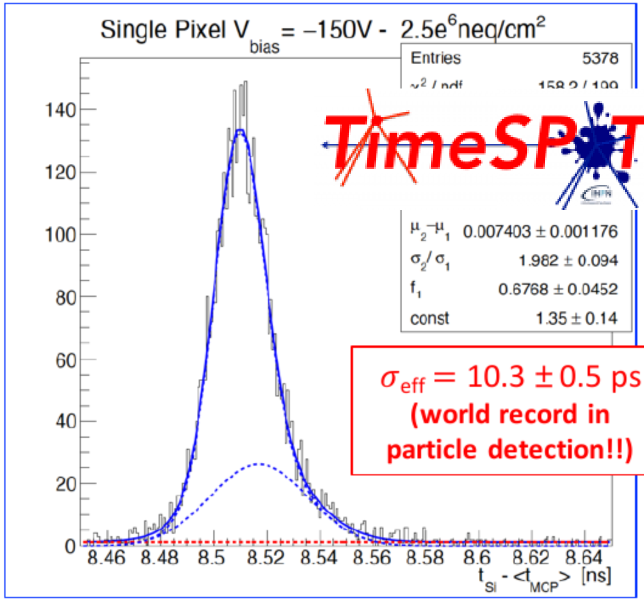
- Design similar to GigaTracKer, but using the timeSPOT technology (initially developed for LHCb)
  - new **sensor** with better time reso: 3D trench pixels

Charged-particle timing with 10 ps accuracy using TimeSPOT 3D trench-type silicon pixels. Front. Phys., 2023.

  - new **electronics** (28nm, $<1.5\text{W/cm}^2$)

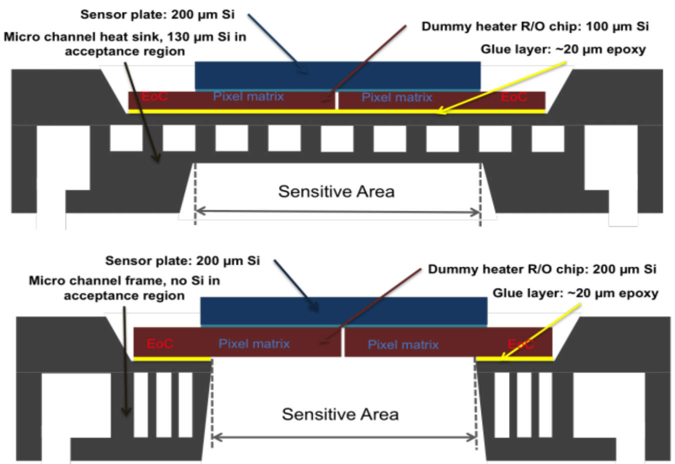
Timespot1: a 28 nm CMOS Pixel Read-Out ASIC for 4D Tracking at High Rates, JINST 18 P03034

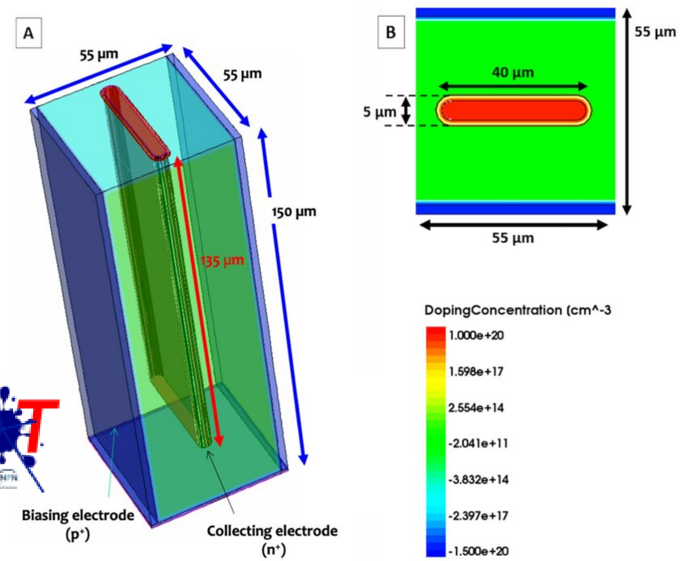
  - cooling **frame** instead of plate to reduce material budget to 0.3% X_0
  - operated **tilted** by 20° to get full efficiency



Plate

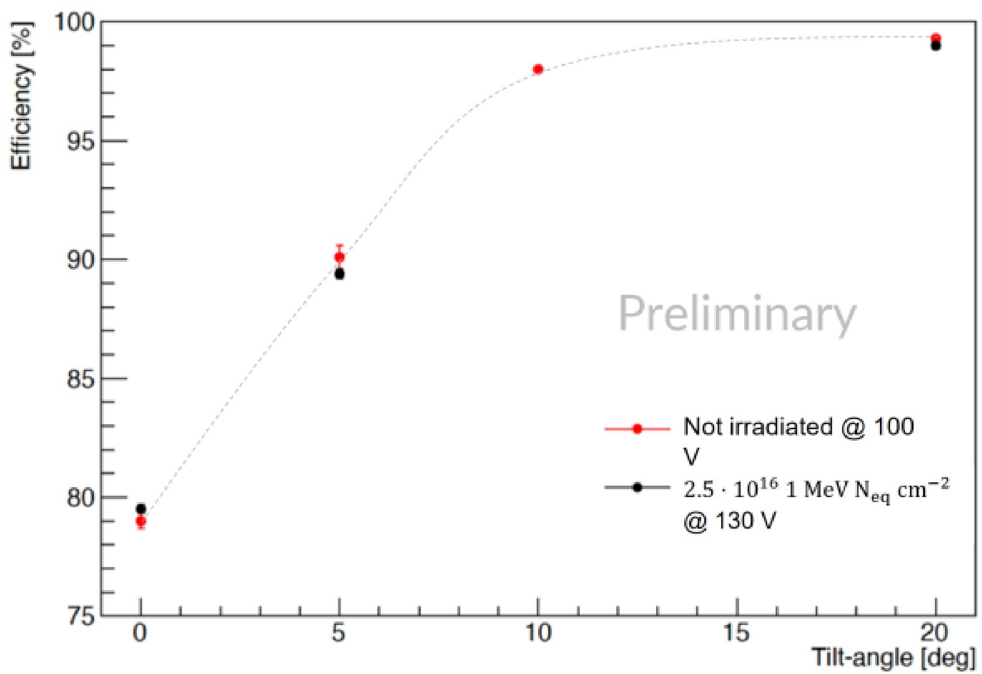
Frame

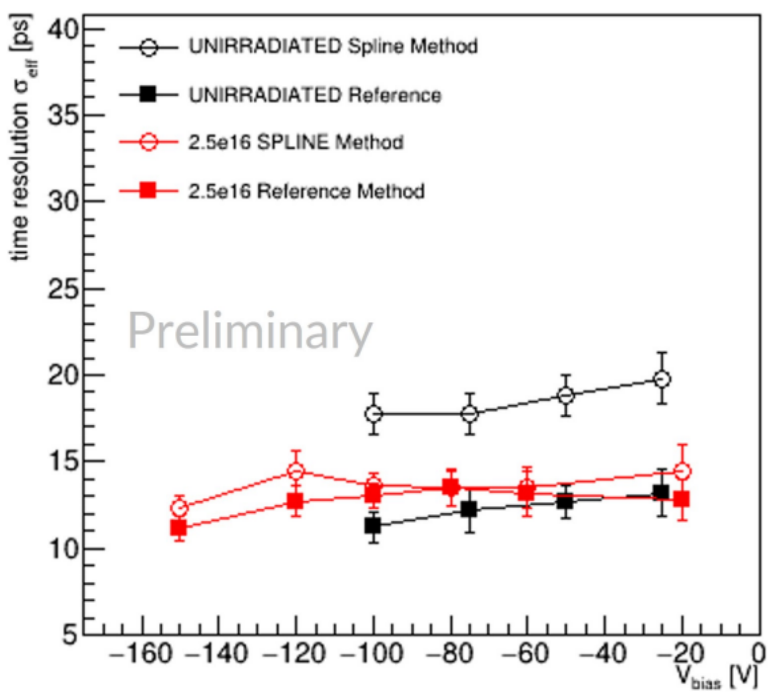




Radiation Hardness and Efficiency

- No significant performance degration observed up to $2.5 \cdot 10^{16}\ n_{eq}/cm^2$!
- Detection efficiency fully recovered with a 20° tilt angle



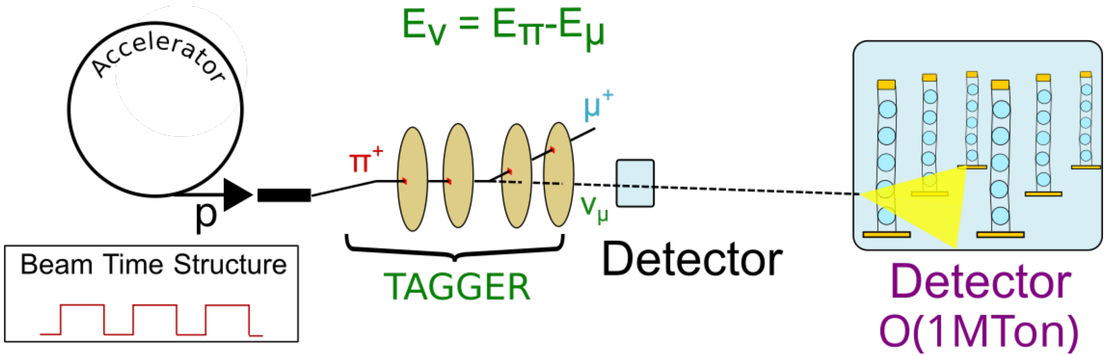


A. Lampis et al 2023 JINST 18 C01051

Neutrino Tagging

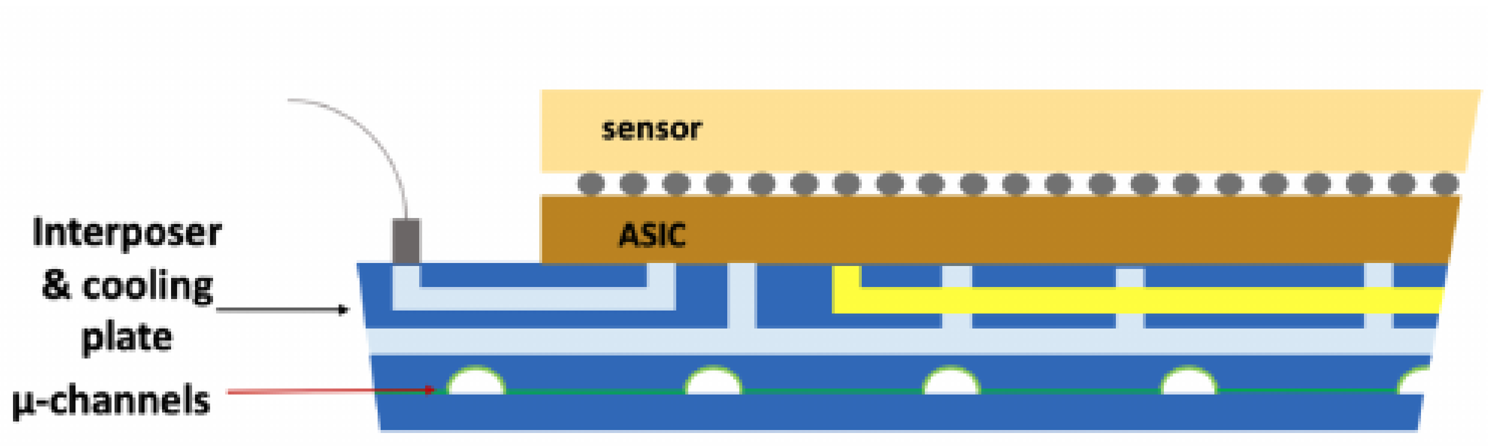
- **Specifications** are even more stringent than for HIKE, as to be competitive, a tagged neutrino experiment need to track about $\mathbf{10^{12}\ \pi/s}$

Specification	Neutrino Tagging	HIKE	NA62 (in operation)
Flux (MHz/mm^2)	$\mathcal{O}(10-100)$	8	2
Fluence (n$_{eq}$/cm^2)	10^{16-17}	$8 \cdot 10^{14}/y$	$2 \cdot 10^{14}/y$
Hit Time Reso. (ps)	< 20	50	200
Det. Efficiency (%)	> 99	> 99	> 99
Thickness (% of X$_0$)	< 0.5	< 0.5	< 0.5



Tracker for Neutrino Tagging

- **TimeSPOT technology** can allow to build such tracker, but requires very advanced integration techniques
- **Cooling power** will ultimately determine the time resolution (>1.5W/cm^2)
- **3D integration** is considered with an **active cooling plate** to distribute power, clock, data (10 Gbps/cm^2 with photonics intergrated circuits on cooling plate) and reach the desired efficiency and low material budget



Summary and Conclusions

- NA62 has open **a new road** to study **very rare decays** with **4D trackers**

- 4D tracker could also open **a new road** for **high precision neutrino physics** with the neutrino **tagging** technique
- The **first two tagged neutrino candidates** have been observed at NA62

- **Both projects are to be continued** with HIKE and the development of a tagged neutrino experiments (SBL and LBL)
- Impressive (σ_t=10ps) **technological achievements** have been reached and pave the way for the next generation of 4D trackers