GigaTracker, a Thin and Fast Silicon Pixels Tracker

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and Radiation Hardness of Semiconductor Detectors.
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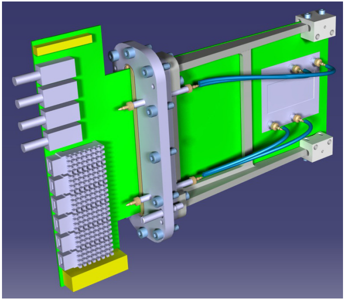
Everybody is looking for hints of physics **Beyond the Standard Model**.

Intensity frontier: Make precise measurements of rare processes.

Very good time and position resolution are needed for **background rejection**. Difficult to achieve while keeping a low material budget.



Outline

Introduction

GigaTracker Design
- Sensor and Read-Out
- Cooling
- Mechanical Integration

GigaTracker in Concrete Terms
- Bump-bonding
- Time Resolution
- Microchannel Cooling Performance
- Radiation Hardness

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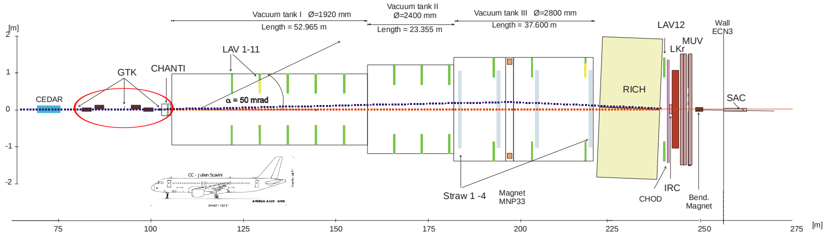
NA62 Experimental Setup

Our main goal is to measure $\mathrm{BR}\left(K^+ \to \pi^+\nu\bar{\nu}\right) \approx \mathcal{O}\left(10^{-10}\right)$.

- Fixed target experiment at CERN SPS,
- High intensity 75 GeV/c hadron beam, K^+ (7 %), π^+ and p
- Particle identification, particle vetos, kinematic measurements

The signal we looking for is one K^+ upstream, a π^+ downstream and nothing else.



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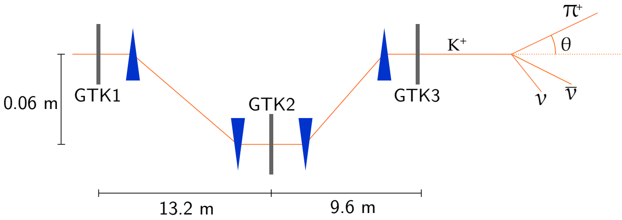
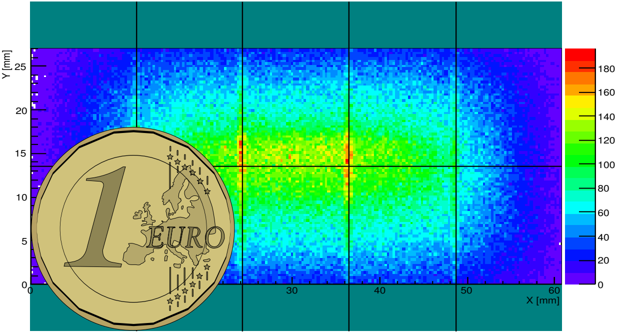
GigaTracker Key Requirement

GigaTracker has to provides momentum, time of passage and direction of beam particle. Crucial for kinematic background rejection,

- Sees all beam particles, must **sustain a high and non-uniform rate**, (1.3 $\mathrm{MHz/mm^2}$ in the center, 750MHz total),
- Has to be as **thin** as possible to avoid inelastic scatterings ($<$ 0.5 % X_0 or $<$ 470 um of Si),
- We need **good timing resolution** to match upstream K^+ track with downstream π^+ track ($<$ 200 ps / hit).



Sensor and Read-out Chips Layout



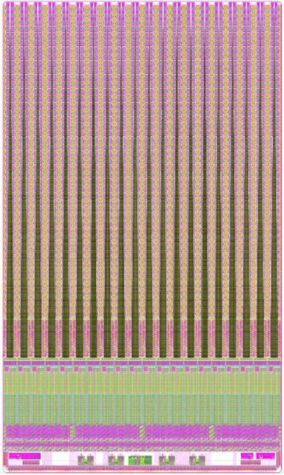
The 60 $\mathrm{mm} \times$ 27 $\mathrm{mm} \times$ 200 $\mathrm{\mu m}$ sensor is bump-bonded to ten read-out chips. This allows to spread the rate over the chips.

Each chip covers 1800 300 $\mathrm{\mu m} \times$ 300 $\mathrm{\mu m}$ pixels, digital part of the circuitry is at the extremity to migitate the radiation damages.

Read-out Chip Characteristics

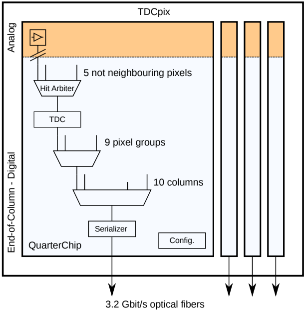
1800 pixels / front-end channels per chip.

Chip dimensions	$12 \times 19\ \mathrm{mm}^2$
Chip thickness	$50 - 100\ \mu\mathrm{m}$
Dissipated power (analog)	$\approx 0.4\ \mathrm{W/cm}^2$
Dissipated power (digital)	$\approx 2.95\ \mathrm{W/cm}^2$



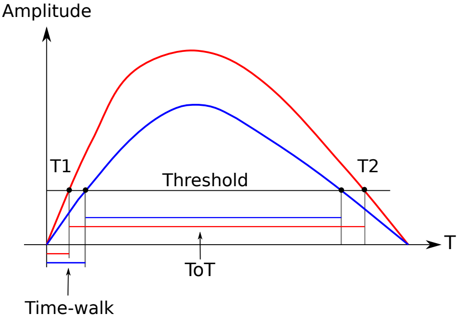
Read-out Electronics

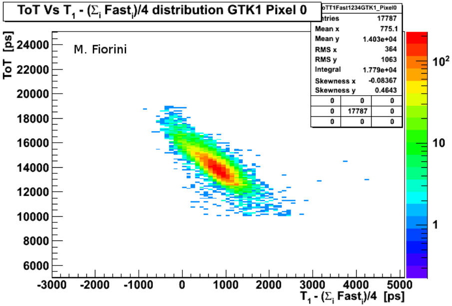
- Digital and analog part are well separated,
- Fast preamplifier-shaper in each pixel,
- Time-over-threshold discriminators.



Hit information: leading edge, trailing edge, address and pile-up flag.

Time-over-Threshold - Time-walk Correction



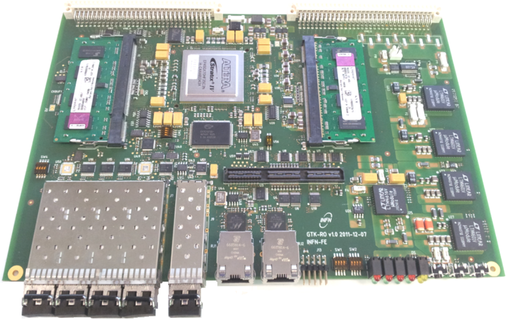


Time-walk correction takes advantage of the relation between time-walk and time-over-threshold.

Data Readout

Each chip send data off via four 3.2 Gbit/s optical fibers (40 links per station)

We store the full data-flow waiting for a L0 trigger decision (1 ms latency). We then only keep the data in 75ns window around the trigger.



Triggerless architecture.

Microchannel Cooling

The chips & sensor must be kept at low temperature ($< 5^\circ C$) to cope with radiation damages and keep the the leakage current small.

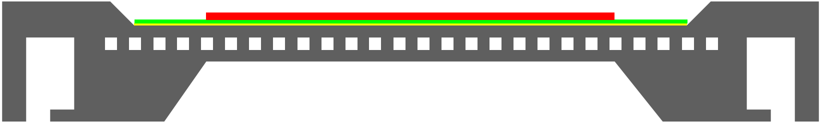
Solution, two bonded silicon wafers with liquid coolant ($\mathrm{C_6F_{14}}$) circulating in microchannels:

- Low material budget ($< 0.15\% X_0$),
- High thermal stablity,
- High thermal uniformity ($\pm 3^\circ C$),
- Reaction time to power/hydraulic failures (time to trigger the power interlook).

Full scale prototype available, characterization ongoing.

Microchannel Cooling - Baseline Option

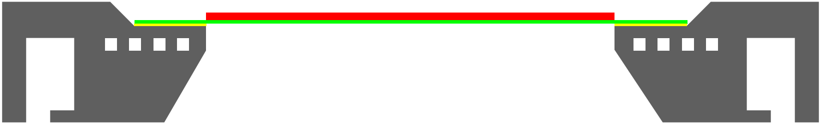
Drawing not to scale: $200 \times 70\ \mu\mathrm{m}^2$ channels separated by a $200\ \mu\mathrm{m}$ wall, $30\ \mu\mathrm{m}$ top and bottom covers.



Material in the acceptence area: $0.13\% X_0$ (130 um).

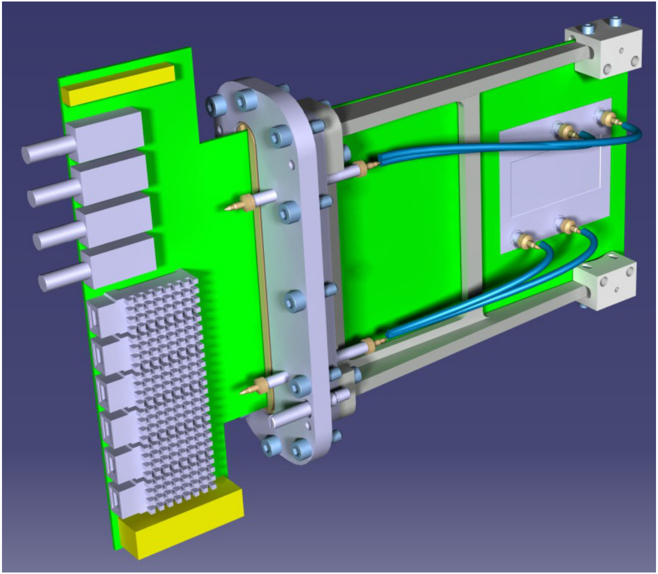
Microchannel Cooling - Frame Option

Takes advantage of the fact that the digital part of the chip has the highest power dissipation.

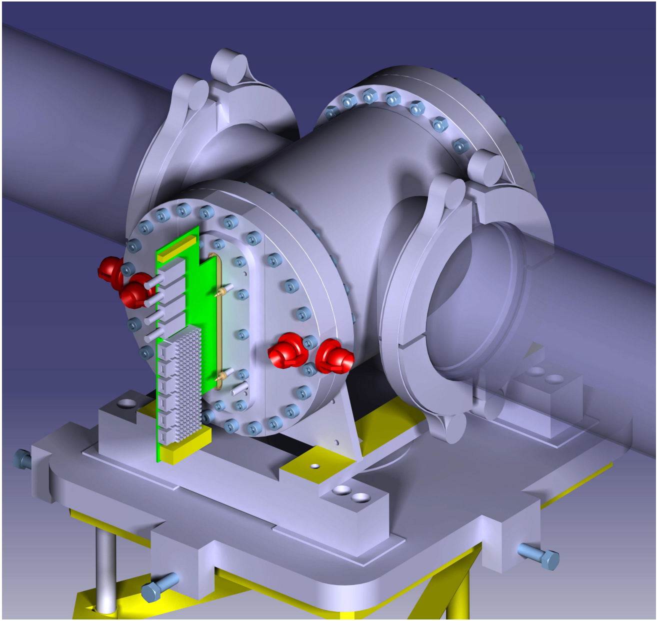


No material at all in the active area but requires a thicker chip (200 µm) to get a reasonable ΔT over the sensor.

Mechanical Integration



Mechanical Integration



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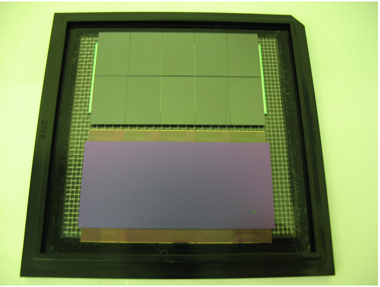
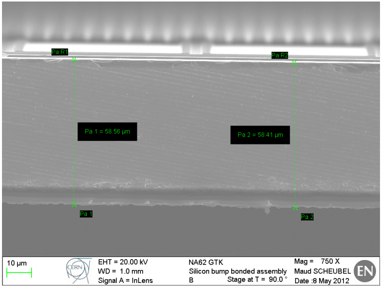
Bump-Bonding

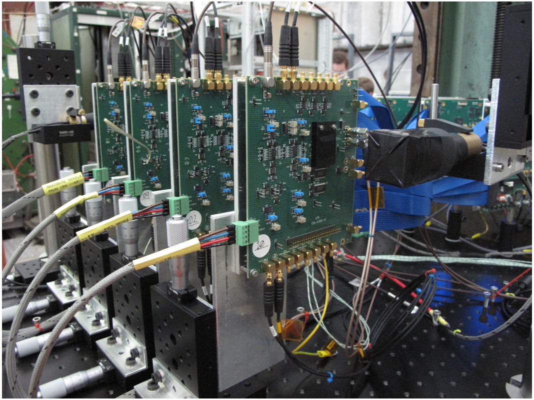
Thinning and bump-bonding studies on dummy components at IZM (Berlin, Germany).





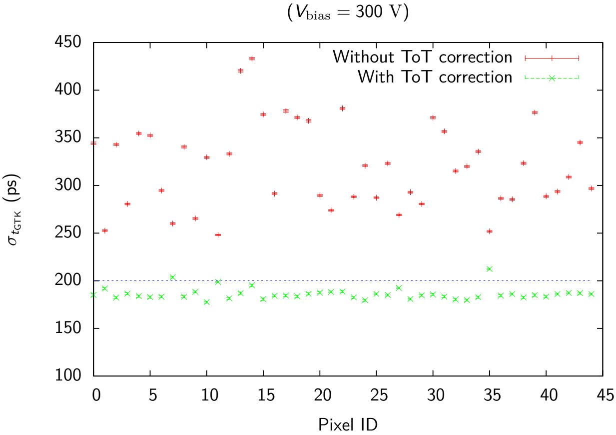
Readout chips thinned to 58 µm !

Demonstrator and Test Beam



- 10 GeV/c π^+ & p,
- 4 GigaTracker prototypes (45 pixels),
- Fast scintillators ($\sigma_t = 43\ \mathrm{ps}$) used as timing reference.

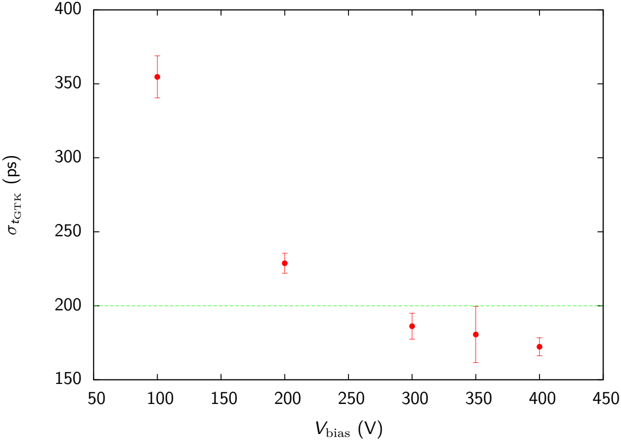
Test Beam - Main Results



Small variations mainly induced by pixel-by-pixel threshold variation.

After ToT correction: $V_{\mathrm{bias}} = 300\ \mathrm{V} \rightarrow \sigma_t = 175\ \mathrm{ps}$.

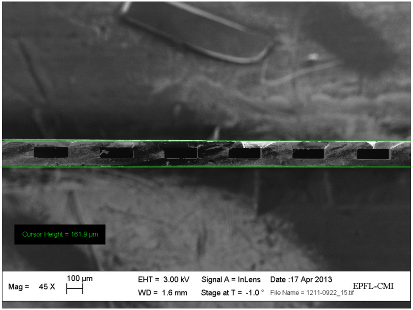
Test Beam - Main Results

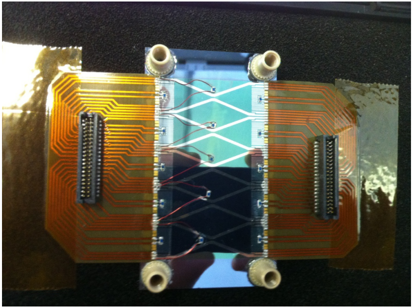


As expected, clear dependence on V_{bias}.

Microchannel Cooling

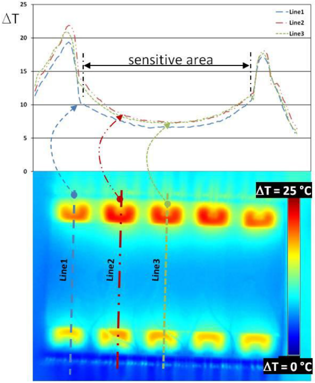
First Si-Si assembly delivered by IceMos and Si-Pyrex cooling plate with heater assembly.





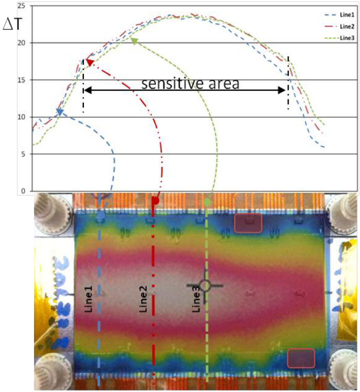
Microchannel Cooling - Main Results

Mass flow 8 g/s



Require $T_{in} = -25$°C to keep the sensor below 0°C.

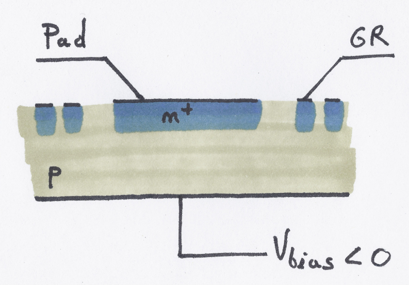
Mass flow 10 g/s



Require $T_{in} = -15$°C to keep the sensor below 0°C.

Radiation Hardness - Wafers & Diodes

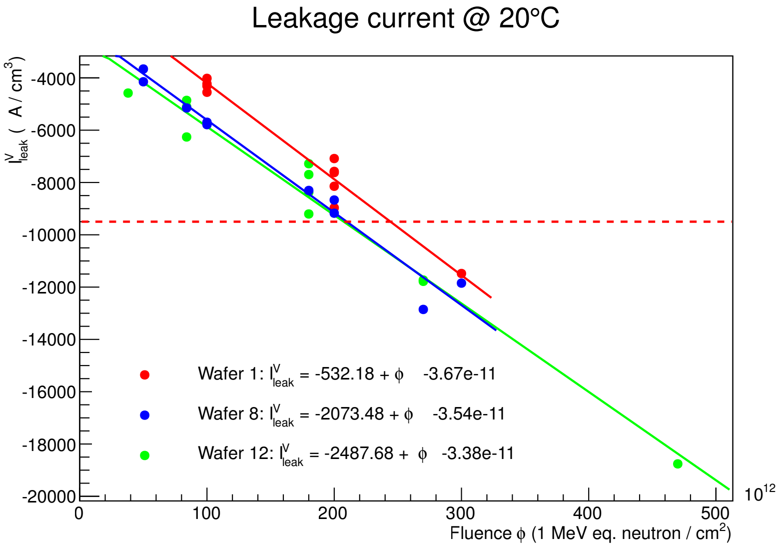
Wafers manufactured by FBK Trento, $\mathrm{n^+ - in - p}$ type.



Twelve $0.5 \times 0.5 \times 0.02\ \mathrm{cm}^3$ diodes were diced from each wafer and irradiated with 50 MeV protons at Louvain-la-Neuve cyclotron.

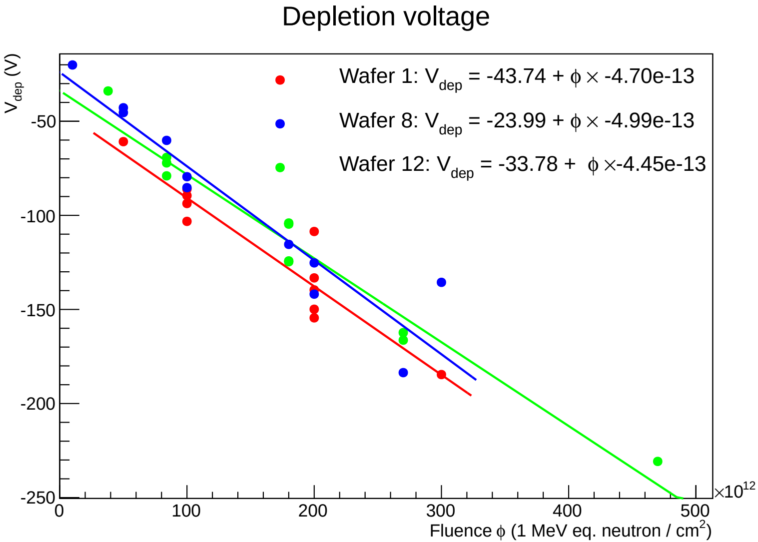
The expected fluence is $\approx 2 \times 10^{14}\ \mathrm{1\ MeV\ n_{eq}/cm^2}$ for 100 days of operation (sensor center).

Leakage Current (at 20°C and −400 V)



$\Delta I^V = \alpha \cdot \Delta\phi$ with $\alpha = 4 \times 10^{-11}\ \mu\ \mathrm{A\ cm}^{-1}$ in the literature.

Depletion Voltage



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GigaTracker is

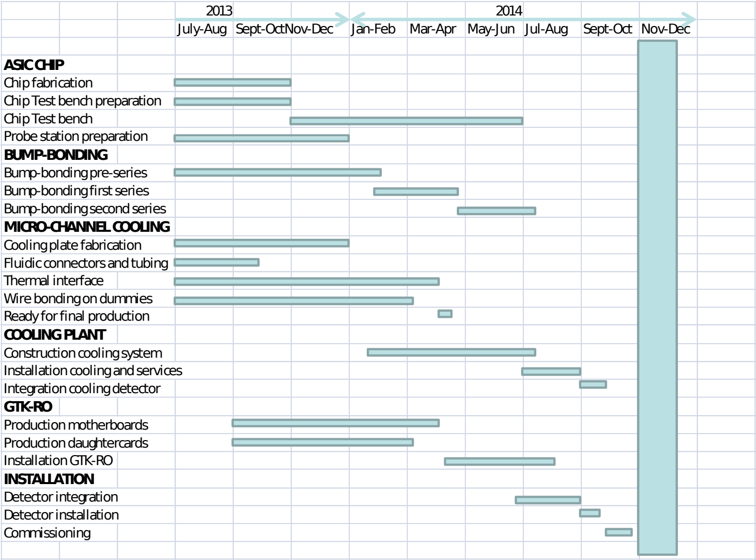
- Fast, $\sigma_t < 175\ \mathrm{ps}$ at $V_{\mathrm{bias}} = 300\ \mathrm{V}$,
- Thin, $X/X_0 < 0.5\%$,
- Innovative, it takes advantage of microchannel cooling.

The prototype meets all the specifications and is well tested
We are now building the full scale detector.

Data Taking due to start in fall 2014.

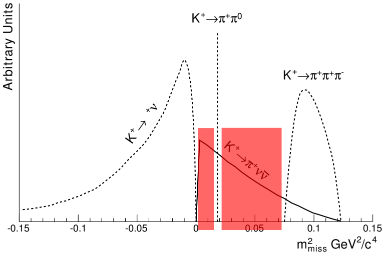
Backup slides

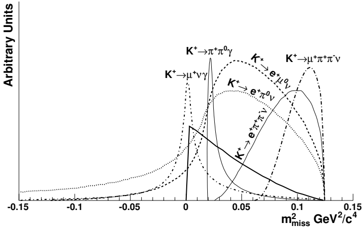
Schedule


2013
2014
July-Aug
Sept-Oct
Nov-Dec
Jan-Feb
Mar-Apr
May-Jun
Jul-Aug
Sept-Oct
Nov-Dec
ASIC CHIP
Chip fabrication
Chip Test bench preparation
Chip Test bench
Probe station preparation
BUMP-BONDING
Bump-bonding pre-series
Bump-bonding first series
Bump-bonding second series
MICRO-CHANNEL COOLING
Cooling plate fabrication
Fluidic connectors and tubing
Thermal interface
Wire bonding on dummies
Ready for final production
COOLING PLANT
Construction cooling system
Installation cooling and services
Integration cooling detector
GTK-RO
Production motherboards
Production daughtercards
Installation GTK-RO
INSTALLATION
Detector integration
Detector installation
Commissioning

Kinematical Background Rejection

92 % of background can be separated from the signal by kinematic cuts.





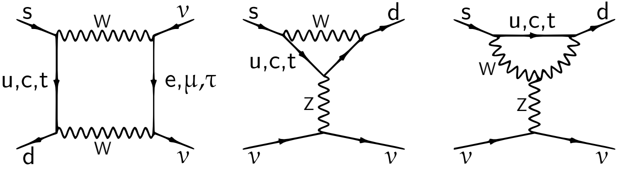
$$m^2_{\mathrm{miss}} = (p_k - p_\pi)^2 \approx m^2_{\mathrm{K}}\left(1 - \frac{|\mathbf{p}_\pi|}{|\mathbf{p}_{\mathrm{K}}|}\right) + m^2_\pi\left(1 - \frac{|\mathbf{p}_{\mathrm{K}}|}{|\mathbf{p}_\pi|}\right) - |\mathbf{p}_\pi||\mathbf{p}_{\mathrm{K}}|\theta^2_{\pi\mathrm{K}}$$

Background Rejection

- Particle identification
  - Tag the K^+ with **KTAG**,
  - π/μ with **RICH**.
- Particle vetoes
  - Photons vetos ($K^+ \to \pi^+\pi^0$ and radiative decays) with **LAV**, **LKr**, **SAC** and **IRC**,
  - Muons vetos ($K^+ \to \mu^+\nu$) with **MUV**,
  - Inelastic scattering products with **CHOD** and **CHANTI**.
- Kinematic measurements with **GigaTracker** and **STRAW** ($K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^-\pi^0$).

Why $K^+ \to \pi^+ \nu \bar{\nu}$?

Precise theoretical prediction and sensitive to new physics!



- Short-distance contributions dominates (internal top quark)[†],
- Hadronic Matrix elements is related to $K^+ \to \pi^0 e^+ \nu_e$ decay[‡],
- Long distance contribution suppressed (GIM mechanism).

[†] J. Brod et al. (Phys. Rev. D, 83, 034030).

[‡] F. Mescia and C. Smith (Phys. Rev. D, 76, 034017).

$K^+ \to \pi^+ \nu\bar{\nu}$ - What are we Hunting Down?

$$\mathrm{BR}\left(K^+ \to \pi^+\nu\bar{\nu}\right)_{\mathrm{SM}} = \left(7.81^{+0.80}_{-0.71} \pm 0.29\right) \times 10^{-11}$$

$$\mathrm{BR}\left(K^+ \to \pi^+\nu\bar{\nu}\right)_{\mathrm{E949}} = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

Our goal: detect $\mathcal{O}(100)$ $K^+ \to \pi^+\nu\bar{\nu}$ with ≈ 10% background over two years of data taking.

We'll try to put constraints on new physics models.

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[*] SM : Brod et al. (Phys. Rev. D, 83, 034030). E949 : Artamonov et al. (Phys. Rev. D, 79, 092004).

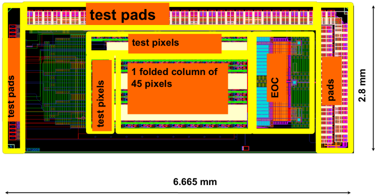
Leakage Current Rescaling

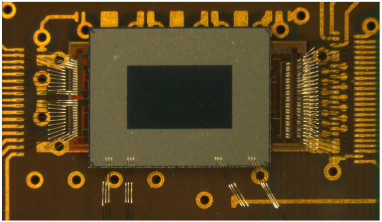
$$I(T) = I(T_{\mathrm{meas}}) \times \left(\frac{273.2 + T}{273.2 + T_{\mathrm{meas}}} \right)^{\frac{3}{2}} \times \exp \left\{ \frac{E}{k} \left(\frac{1}{273.2 + T_{\mathrm{meas}}} - \frac{1}{273.2 + T} \right) \right\}$$

With $k = 8.716 \times 10^{-5}\ \mathrm{eV}\ \mathrm{K}^{-1}$, the Boltzmann constant and $E = 1.12\ \mathrm{eV}$, the band gap energy.

GigaTracker Prototype

One full column folded into a 5 × 9 pixel array





Produced by IBM, bump-bonded and characterized in 2010