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Results from the NA62 Gigatracker Prototype: a Low Mass and sub-ns Time Resolution Silicon Pixel Detector

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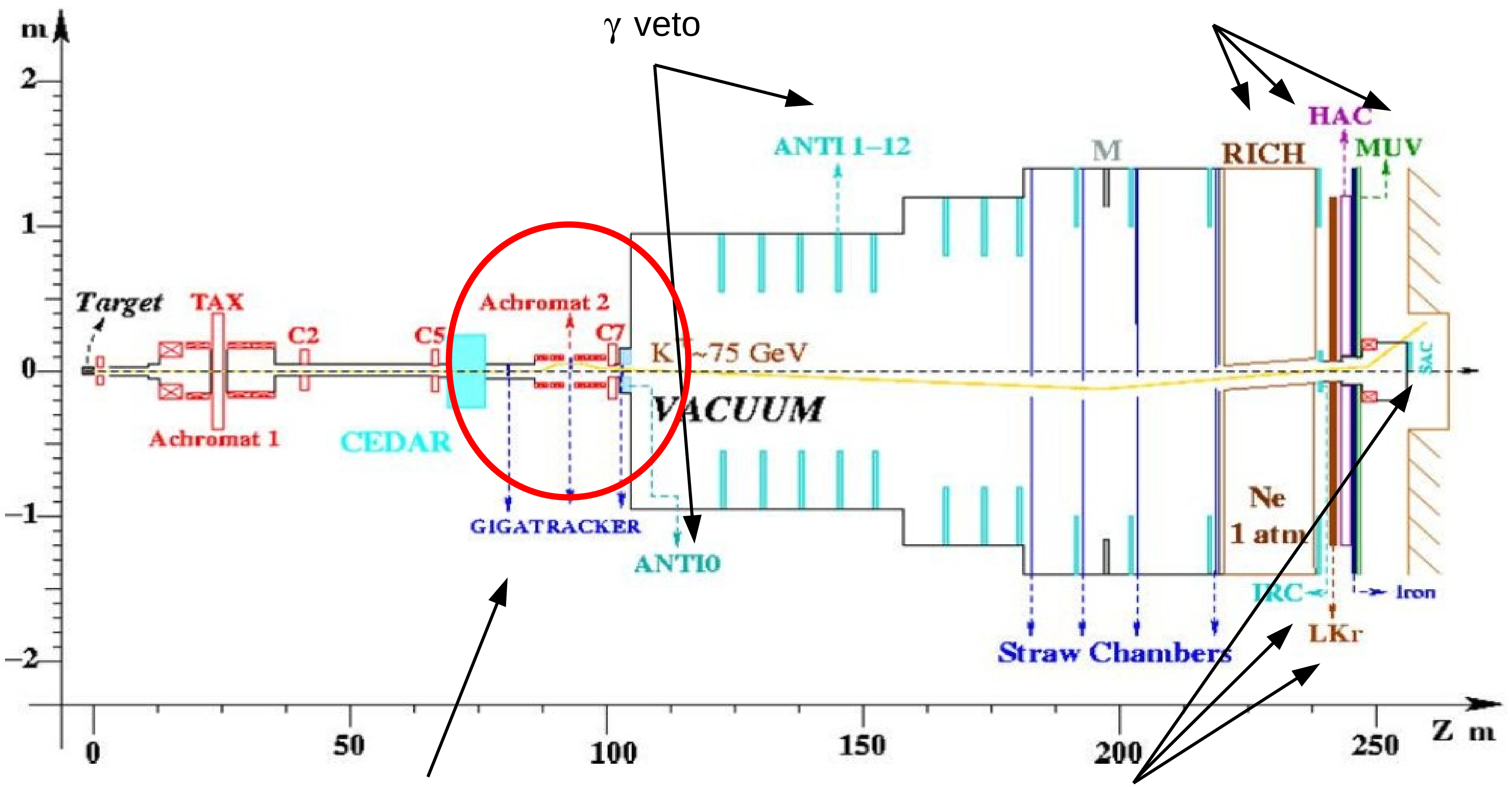
Context of the Work

- NA62 experiment at the CERN SPS accelerator
- $8{\cdot}10^8$ particles/s, 75 GeV/c
- Ultra-rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- Theoretically very clean: $|V_{td}|$ CKM (Cabibbo-Kobayashi-Maskawa) matrix can be related to the measured quantity
- It aims to measure 80 events with a branching ratio of $(8.5\pm0.7) \times 10^{-11}$ (SM prediction) and ~10% background
- Existing measurement based on 7 events (E787/E949): $BR=(1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Experimental Setup



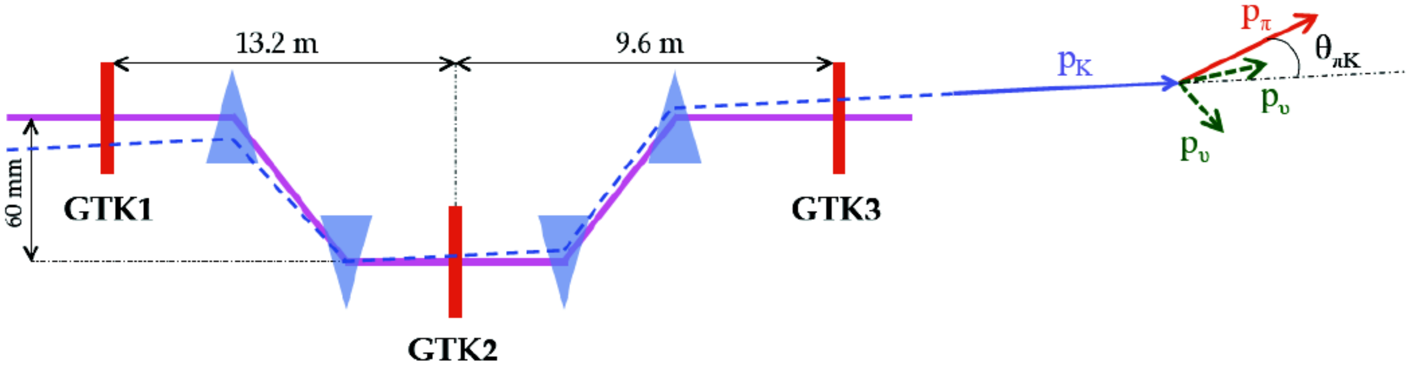
PID

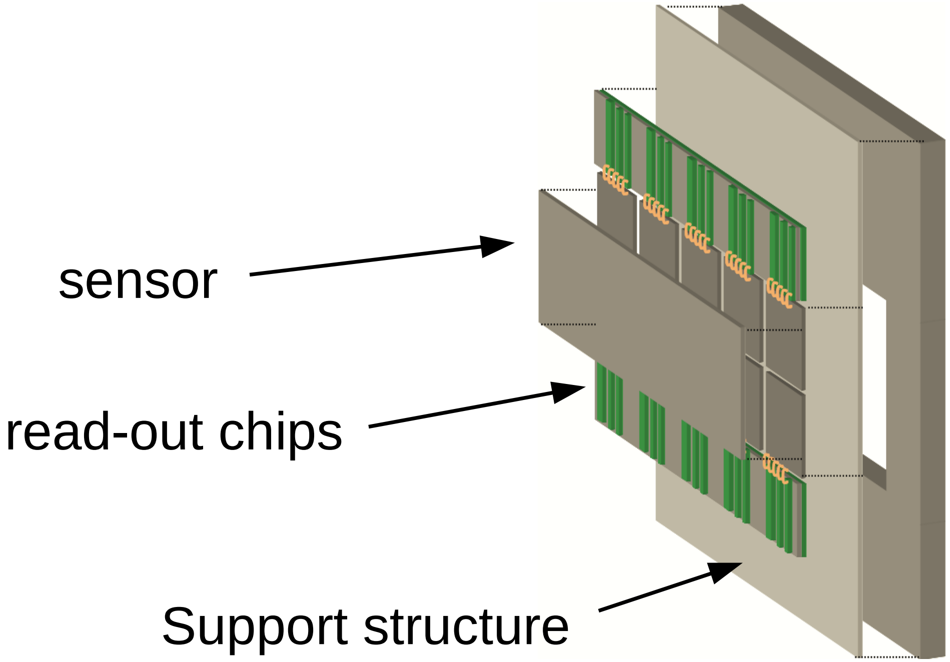
γ veto

P and t detection

γ veto

GTK




sensor

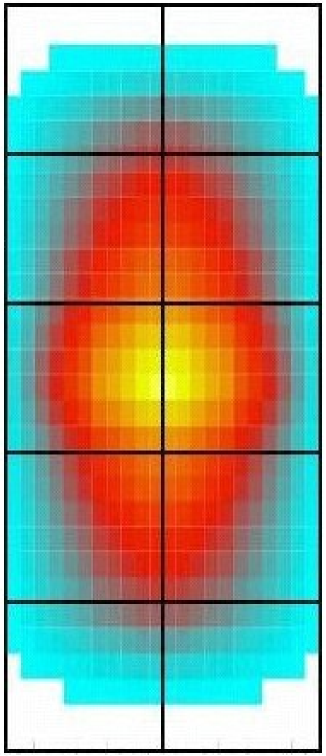
read-out chips

Support structure

- 3 GTK stations
- Single silicon sensor (60mm x 27mm x 200µm)
- 2 x 5 read-out chips
- Support and alignment structure outside the beam area

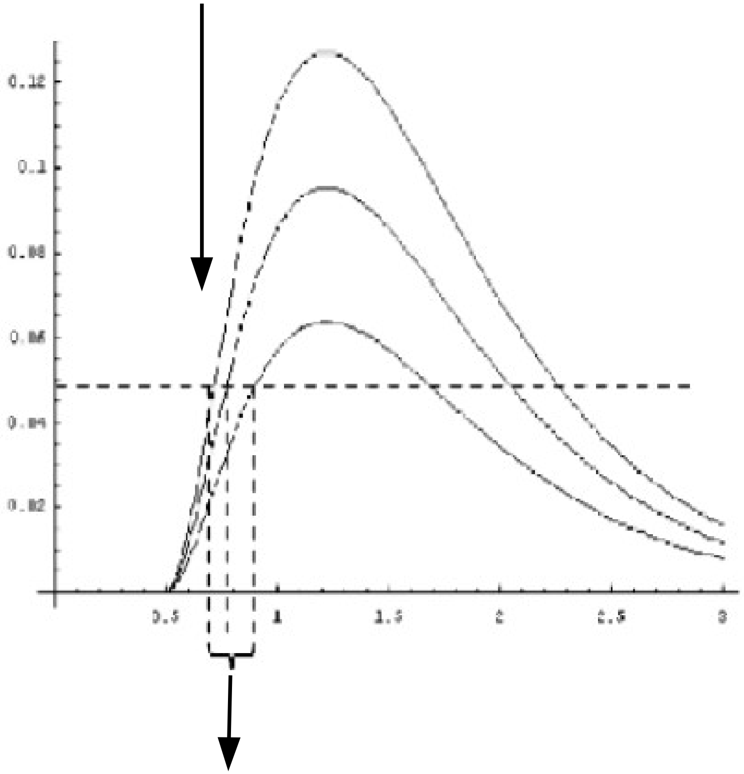
Read-out Chip Specifications

- $\Delta|P_K|/|P_K| \sim 0.3\%$, $|P_K| = 75$ GeV: 300μm x 300μm pixels
- Time resolution of 200ps (rms) on the single station (3 stations → $200/\sqrt{3}$=115ps): jitter, digitization and time walk
- Efficiency > 99%: 1fC threshold
- Dead time < 1%: max event rate of 150kHz/ch
- Power consumption < 2mW/ch
- Radiation tolerance: SEU and integral dose deterioration of the sensor



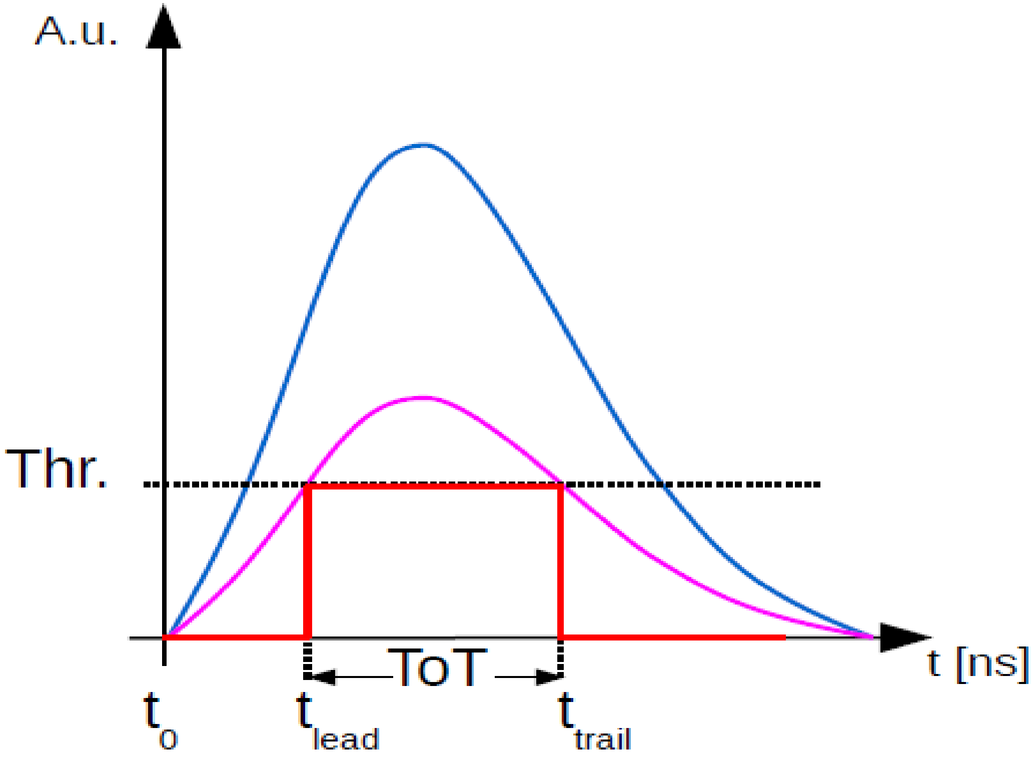
Time Walk

signals with constant rising time and different amplitudes



time walk error

Time Over Threshold



Time walk correction is based on an algorithm derived from the correlation between the pulse width and the experienced time walk. In this case two time measurements (rising and falling edge) are performed

Constant Fraction Discriminator

$$y(t) = \frac{At}{t_P}$$

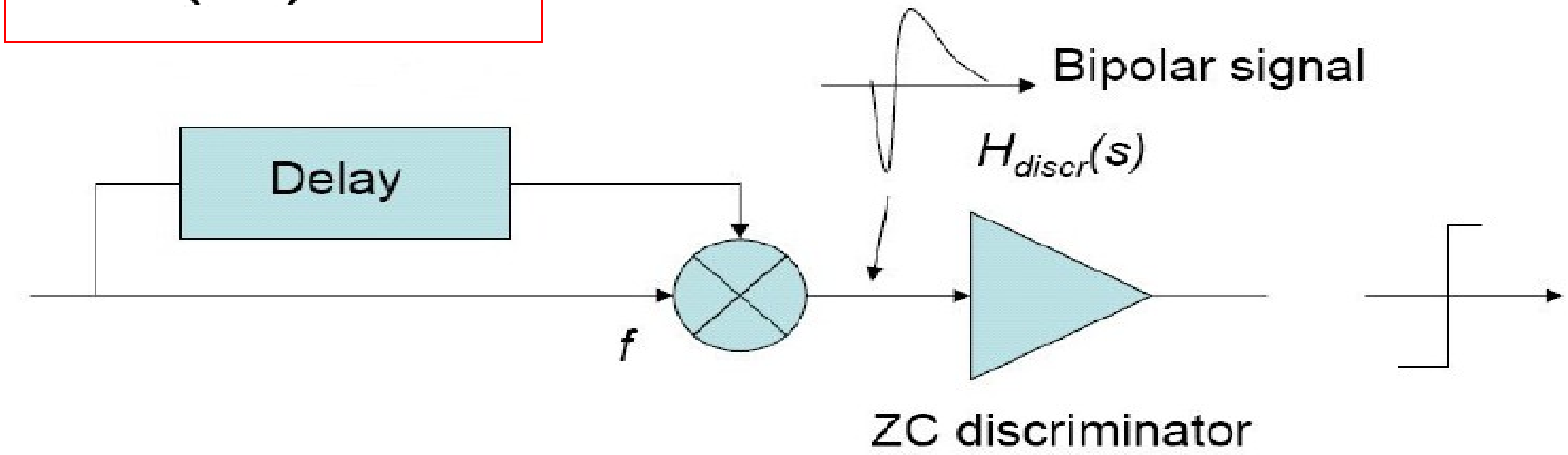
$$y(t-t_d) = fy(t)$$

$$\frac{A(t-t_d)}{t_P} = \frac{fAt}{t_P}$$

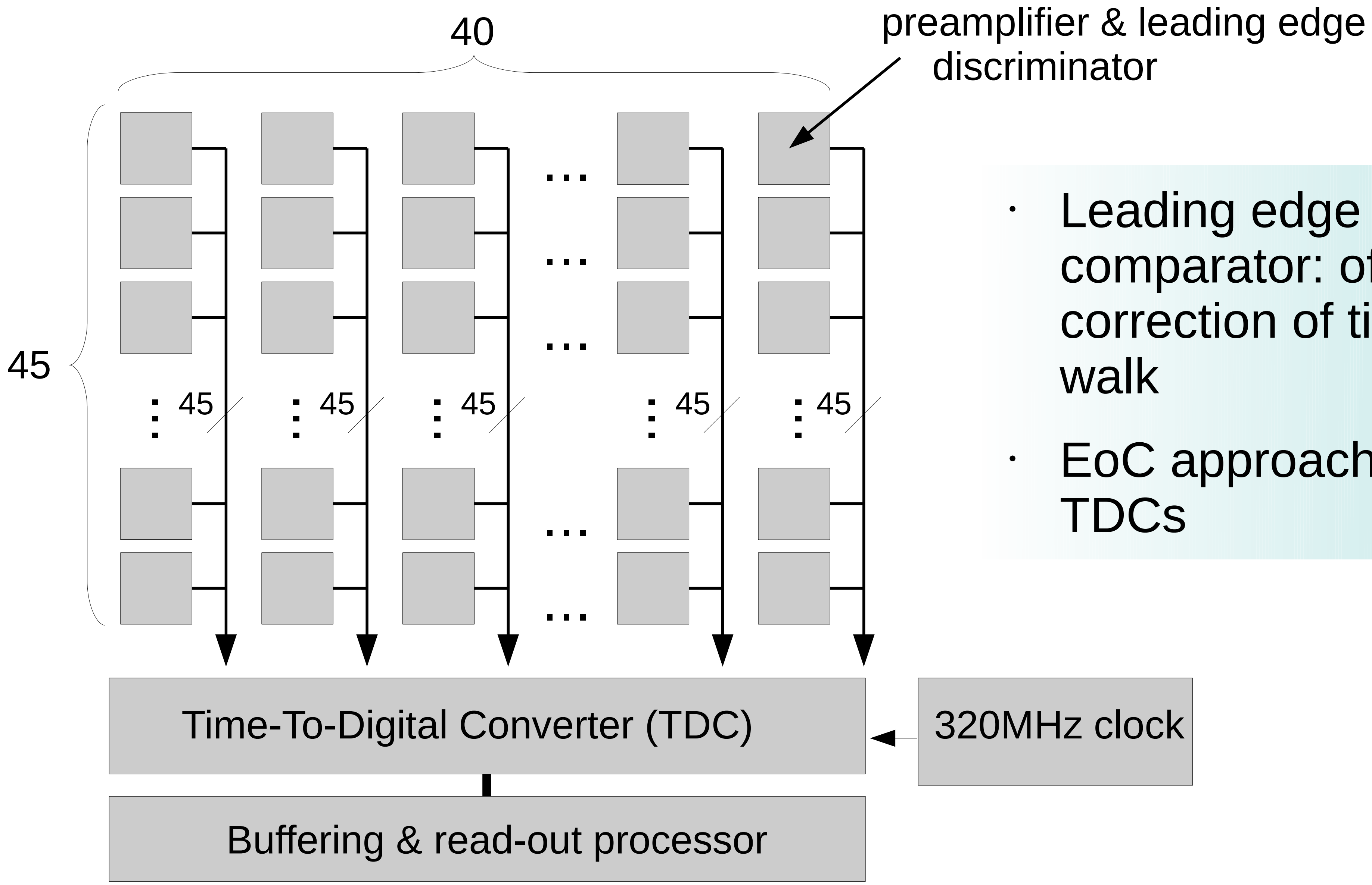
$$t = \frac{t_d}{(1-f)}$$

Approximation: triangular signal

Hypothesis: crossing point always on the linear rising portion of the input signal

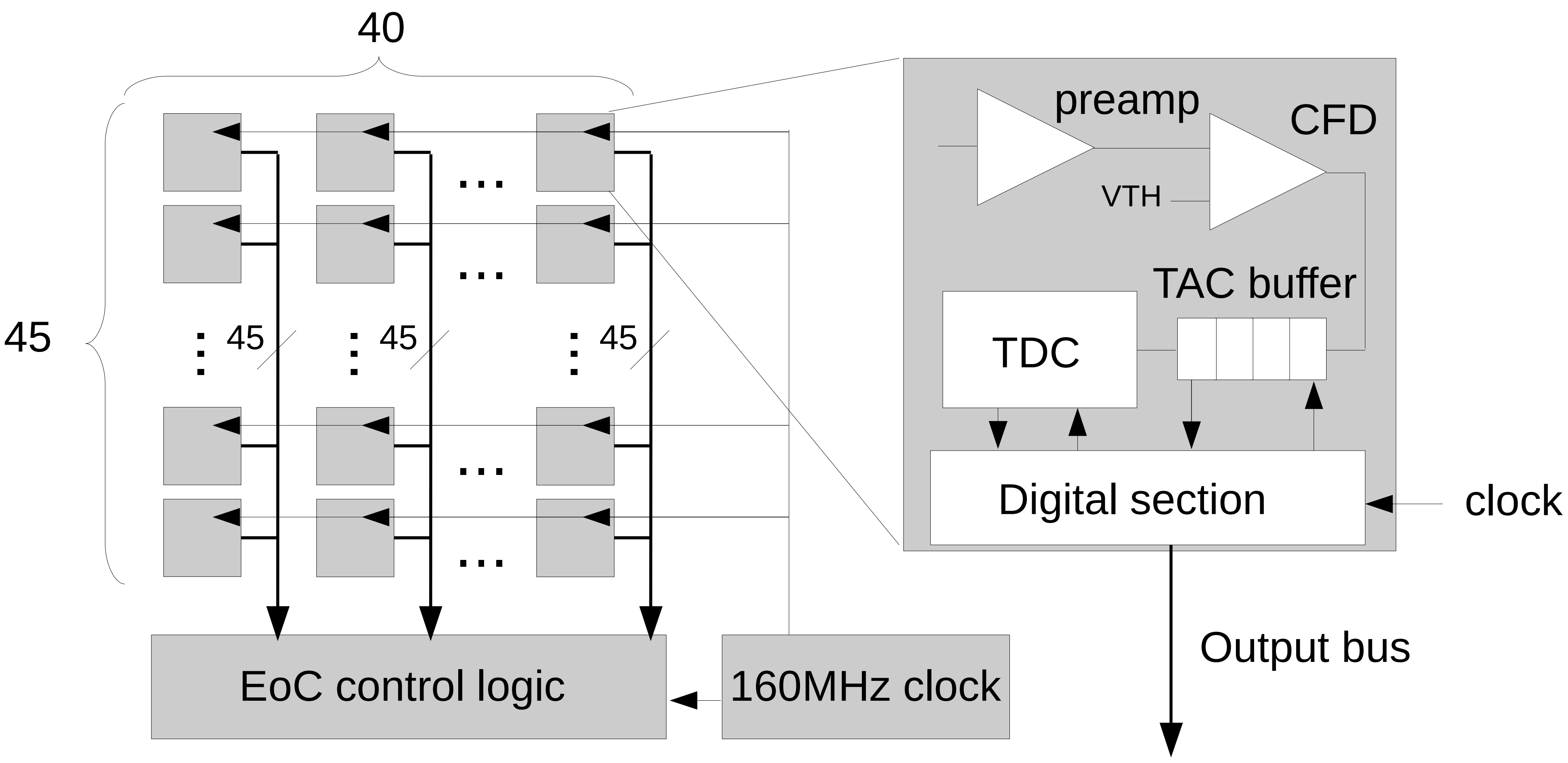


EoC Architecture



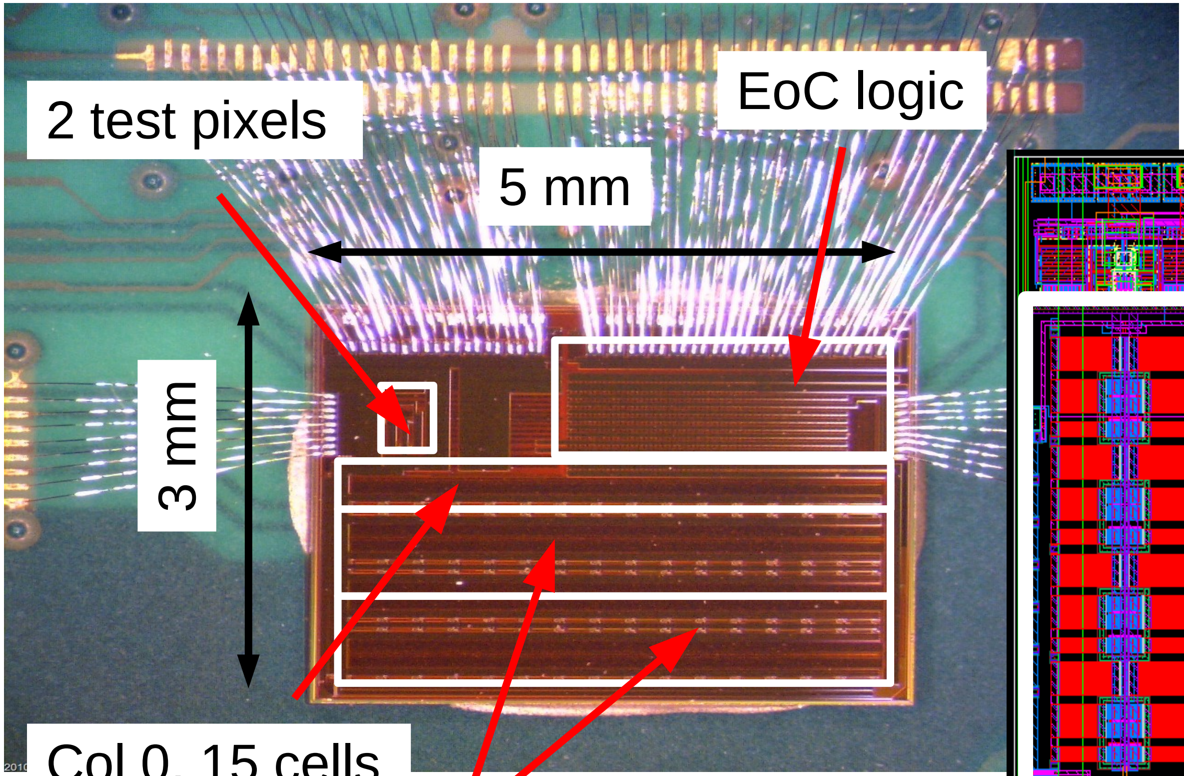
- Leading edge comparator: offline correction of time walk
- EoC approach: 40 TDCs

TDC per Pixel Architecture



- CFD: online correction of time walk
- local approach: 1800 TDCs

TDC per Pixel Demonstrator



2 test pixels

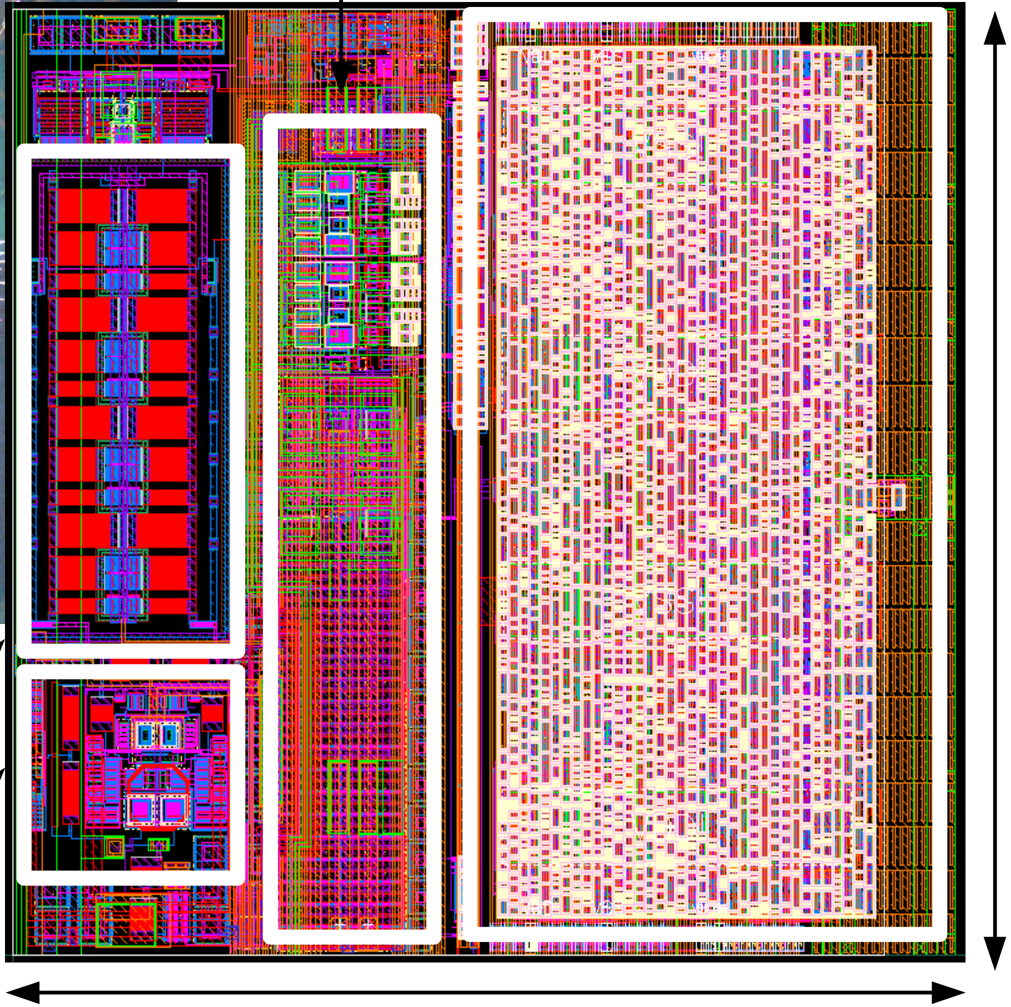
EoC logic

5 mm

3 mm

Col 0, 15 cells

Col 1 and 2, 45 cells



TDC

Digital section

CFD filter

preamplifier

300µm

300µm

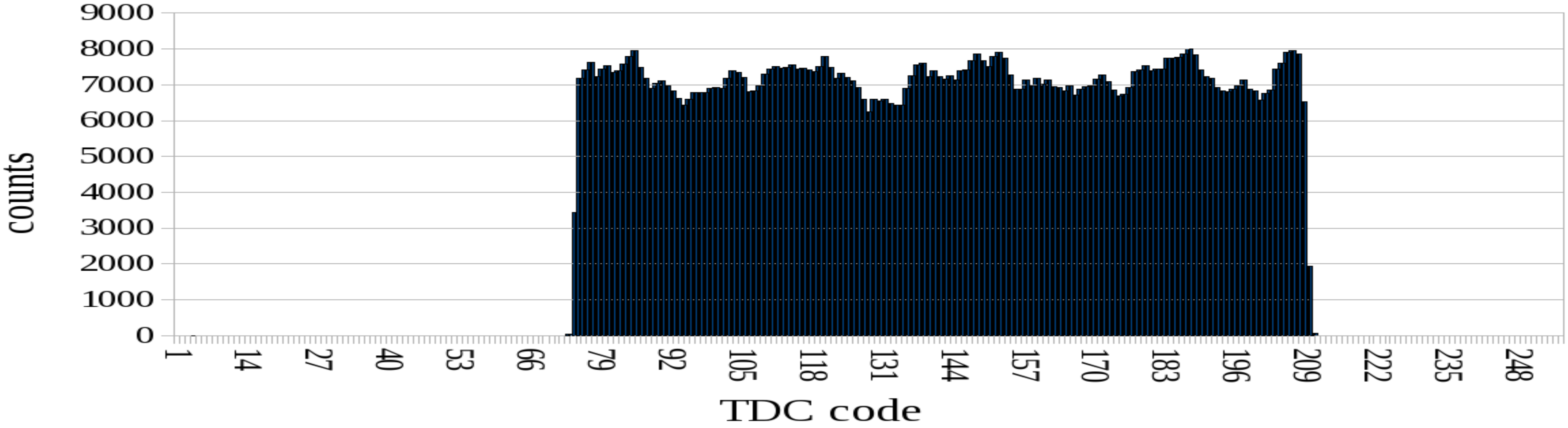
0.13µm DM
IBM CMOS
technology

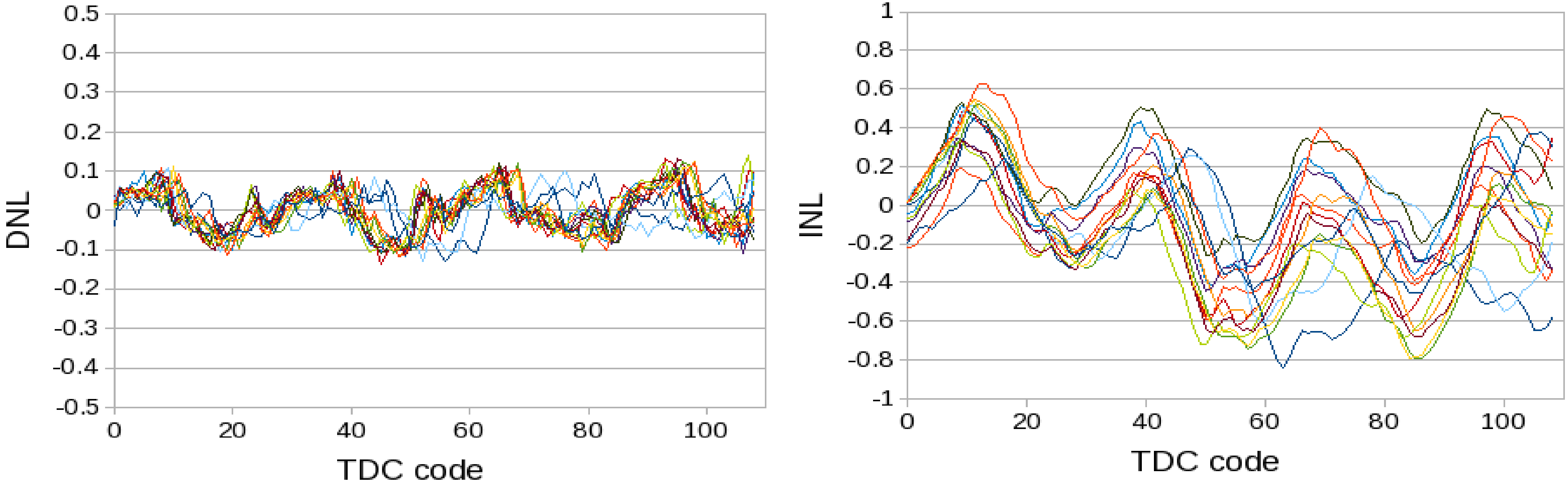
TDC Linearity (1)

10^6 random test pulses to the 7-bits TDC: $N_{th} = 10^6/2^7$

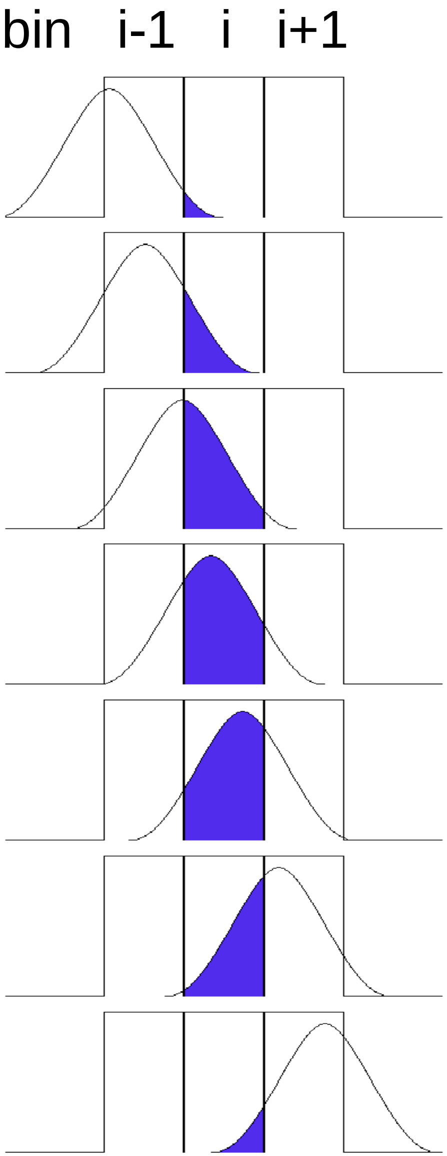
- $$-0.5 < DNL(i) = \frac{N_{exp}(i) - N_{th}(i)}{N_{th}(i)} < 0.5$$
- $$-1 < INL(i) = \Sigma_{i=0}^{k} \; DNL(i) < 1$$

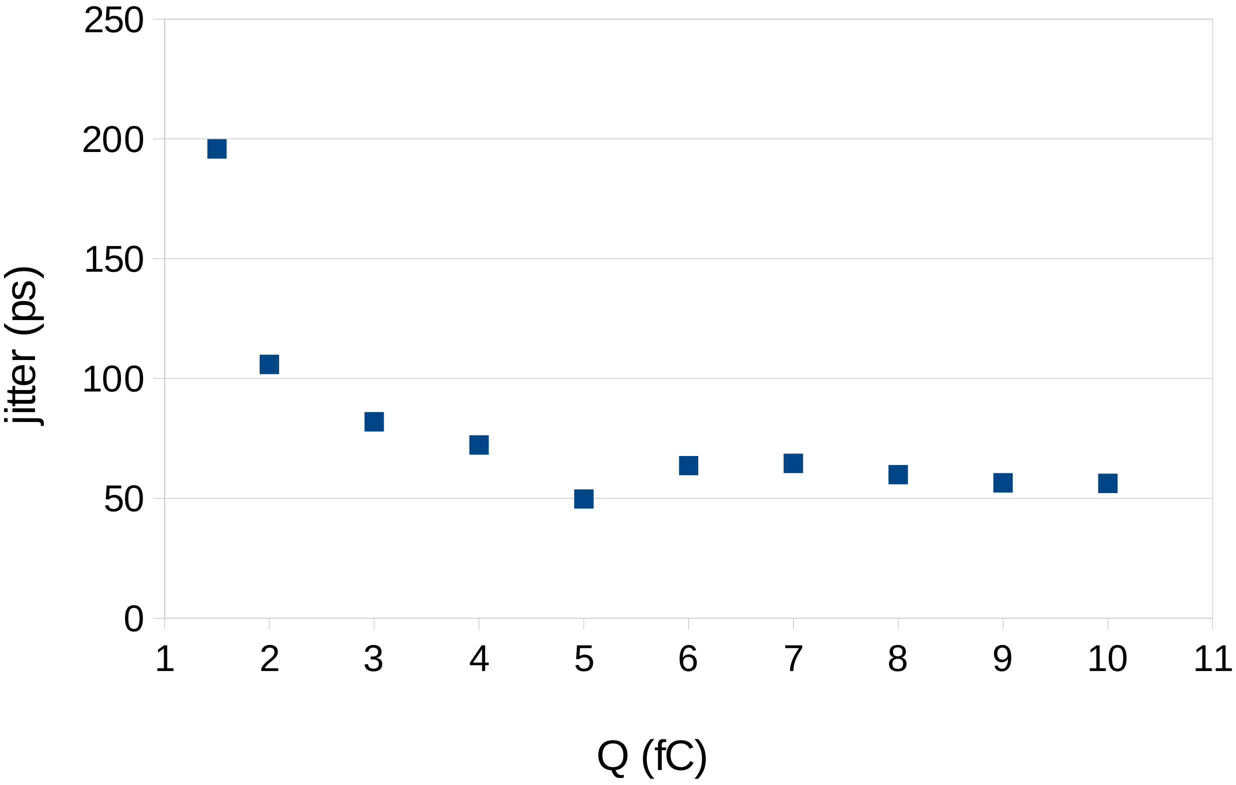
TDC Linearity (2)





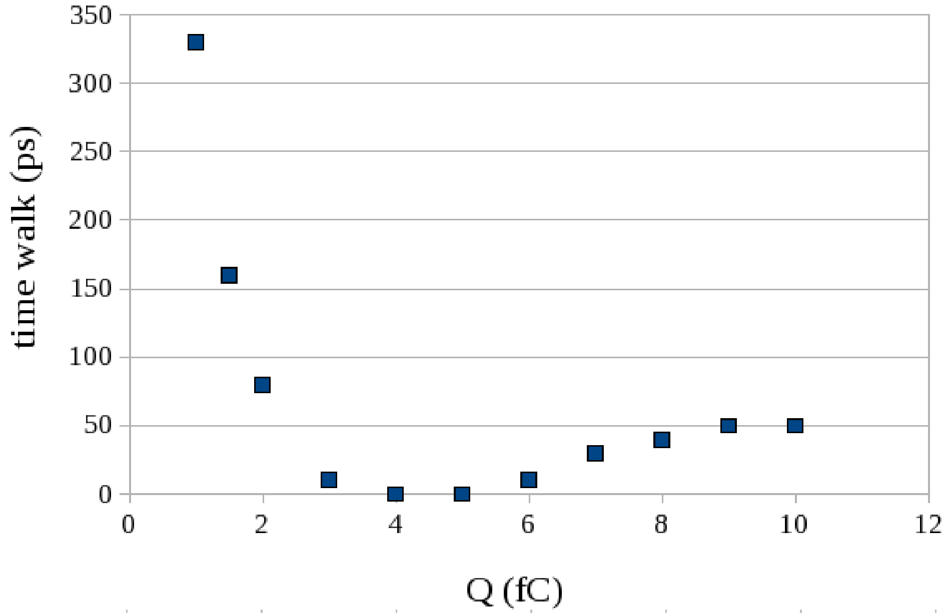
Jitter

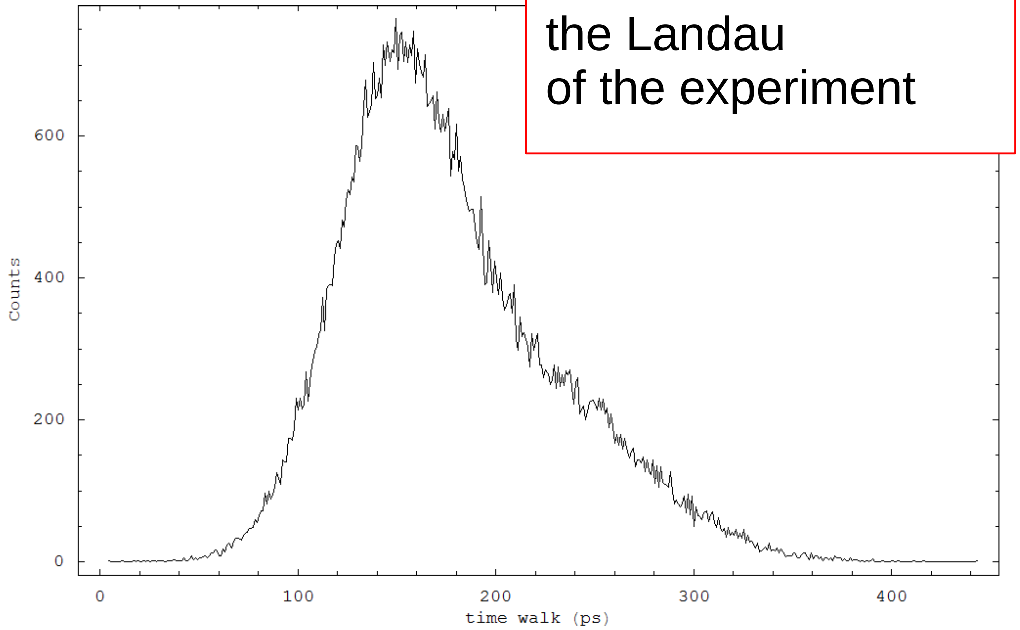




Jitter of ~90ps rms at 2.4fC measured at the output of matrix pixels

CFD (1)

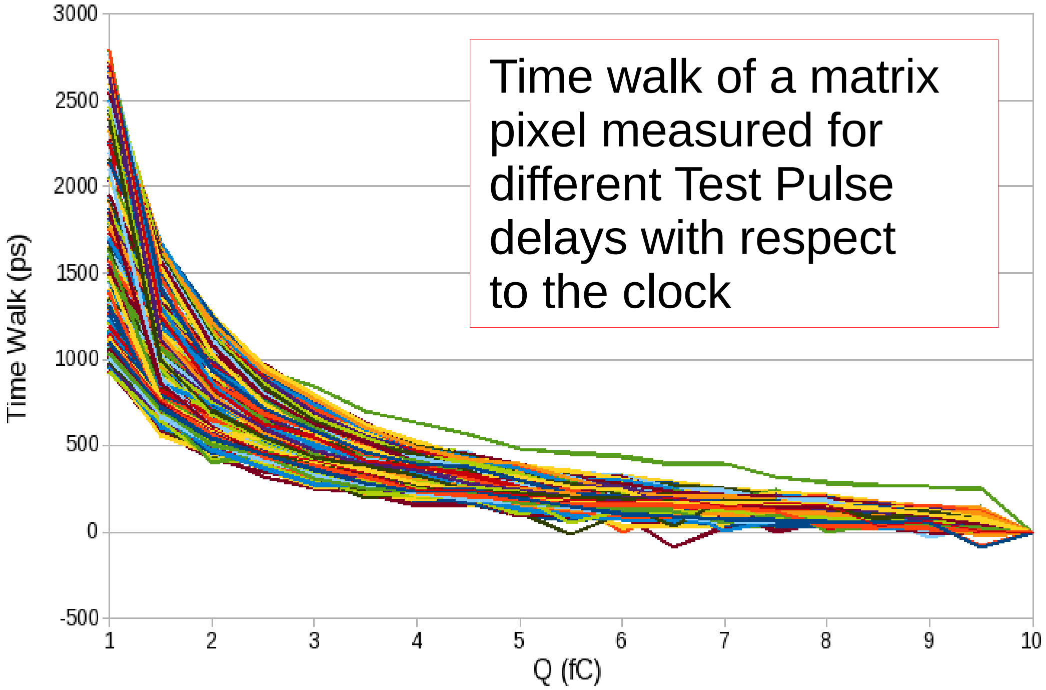




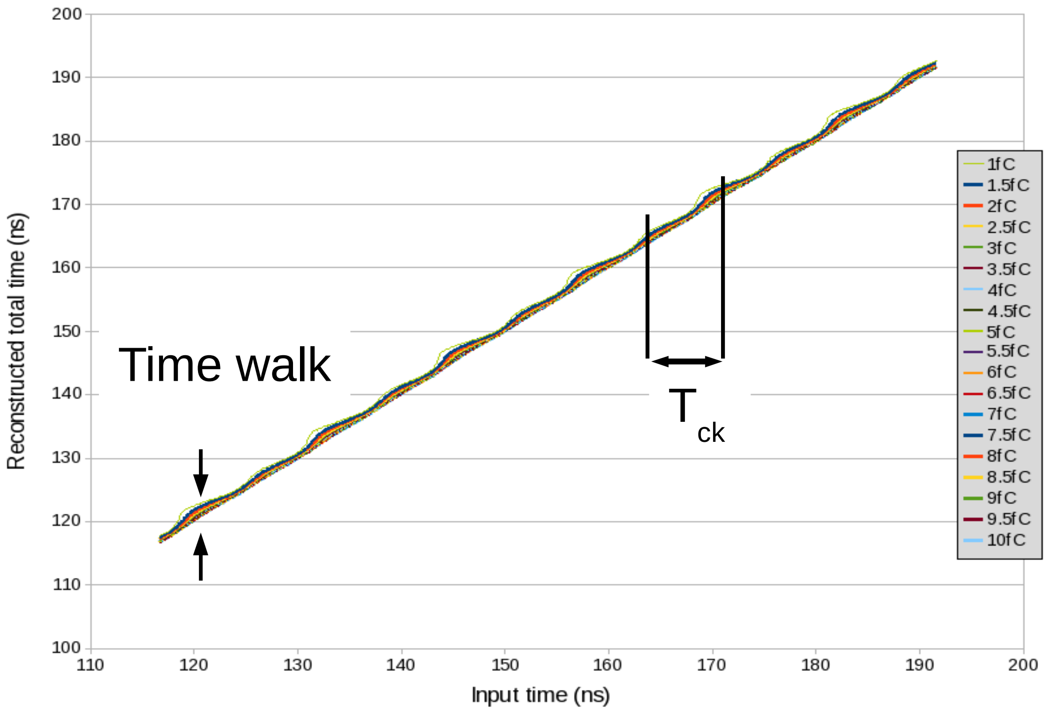
Convolution of the time walk curve with the Landau of the experiment

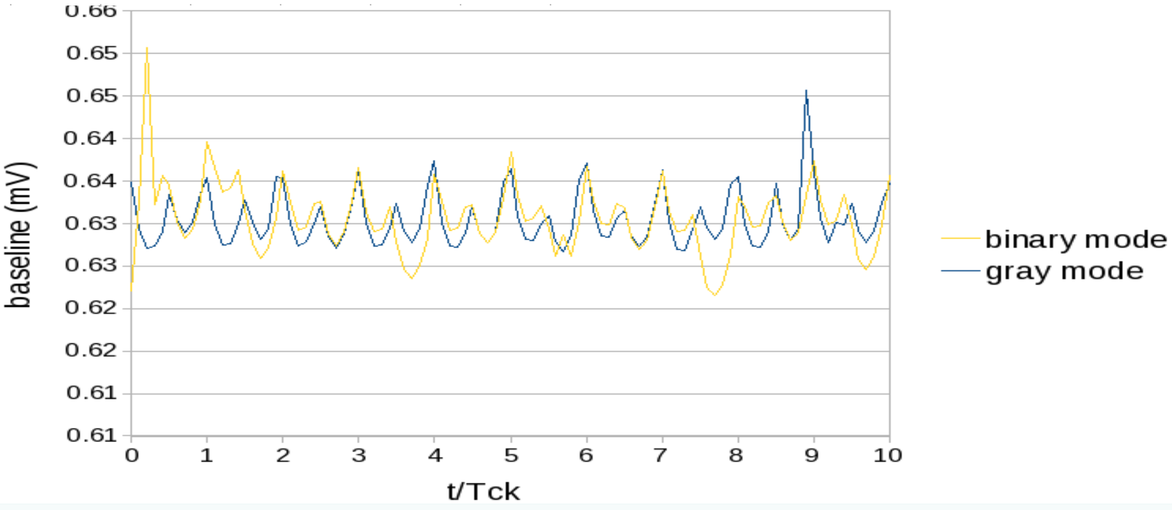
92ps rms time resolution measured at the oscilloscope on the test pixel <u>with the clock switched off</u>

CFD (2)

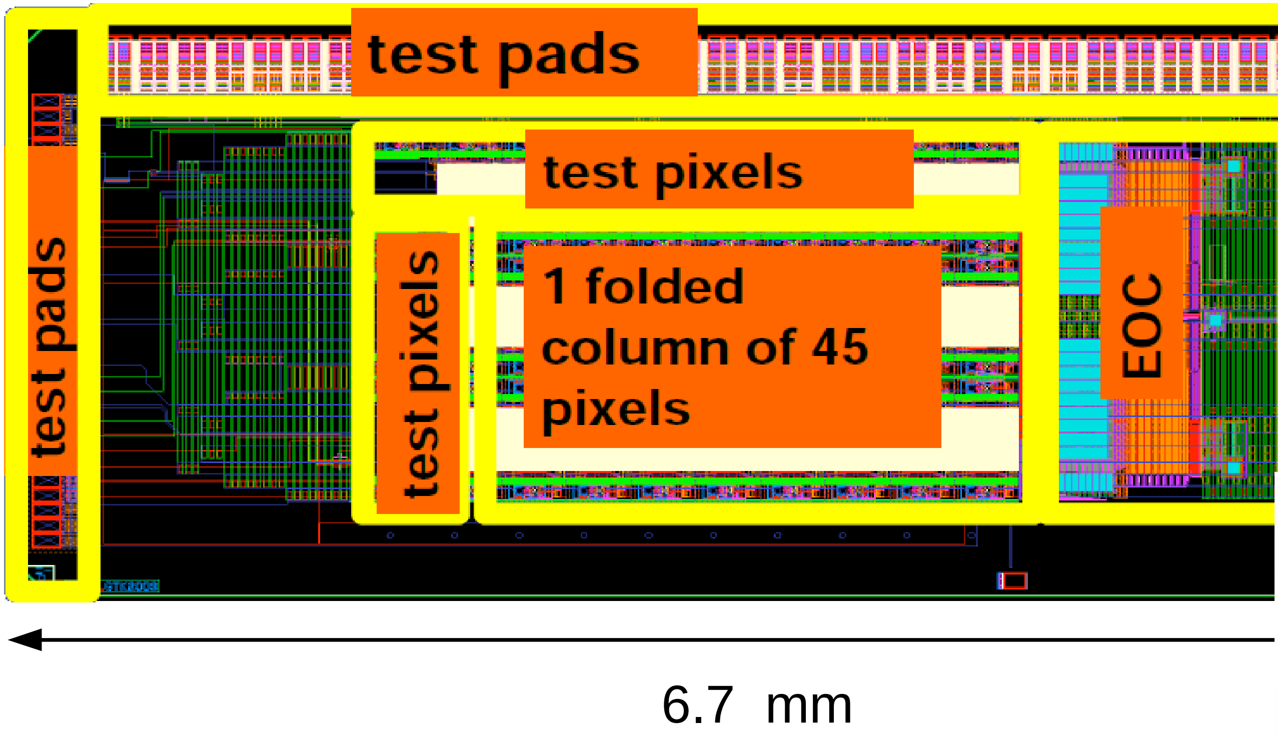


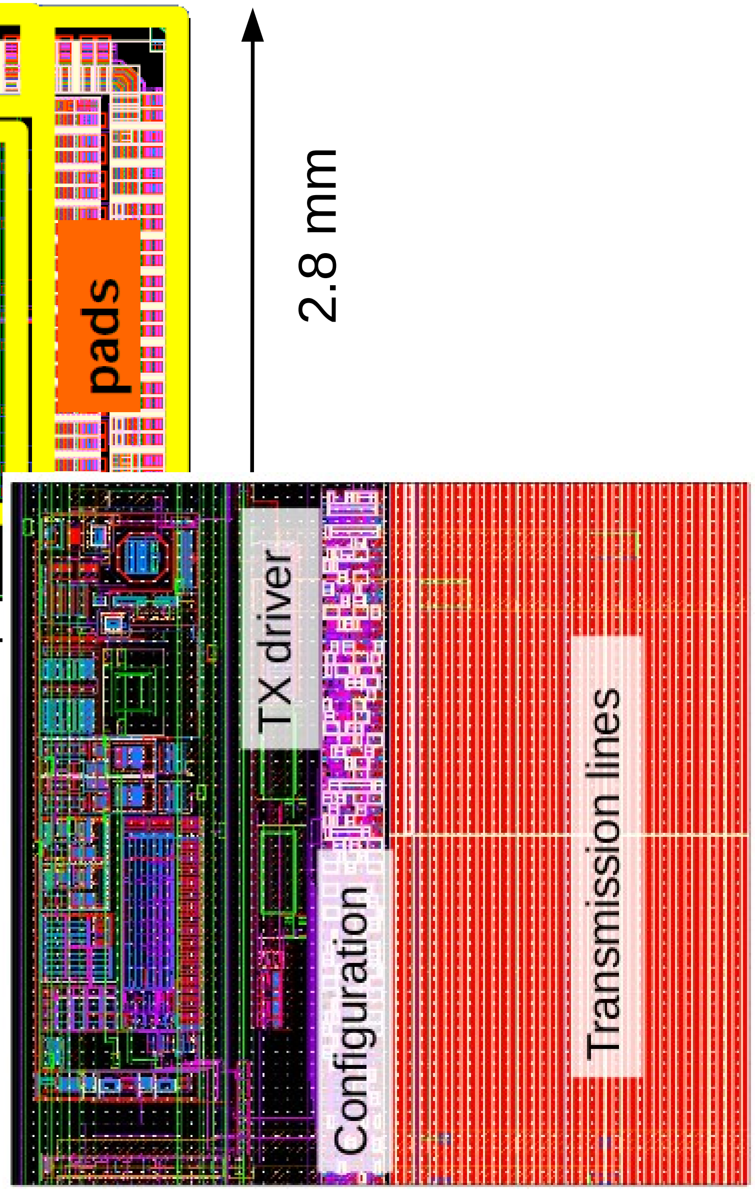
Time walk of a matrix pixel measured for different Test Pulse delays with respect to the clock

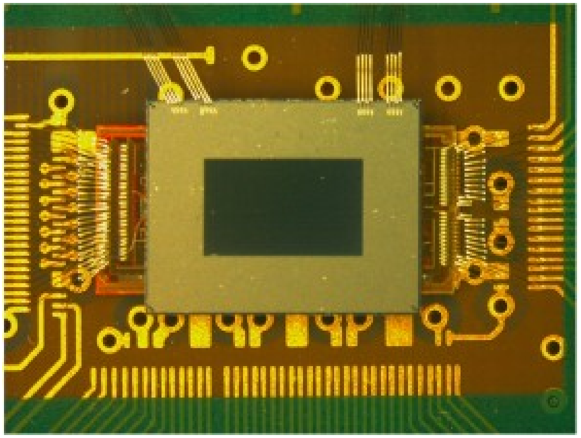




EoC Demonstrator

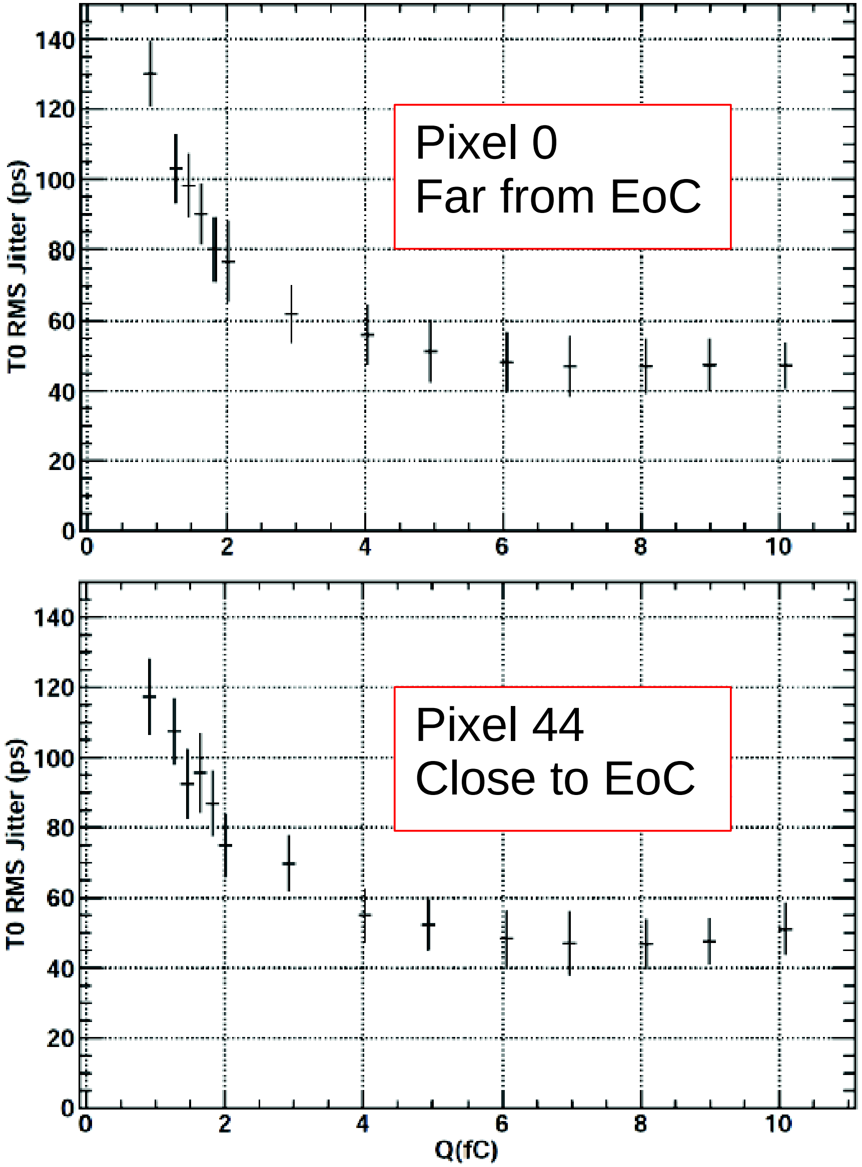






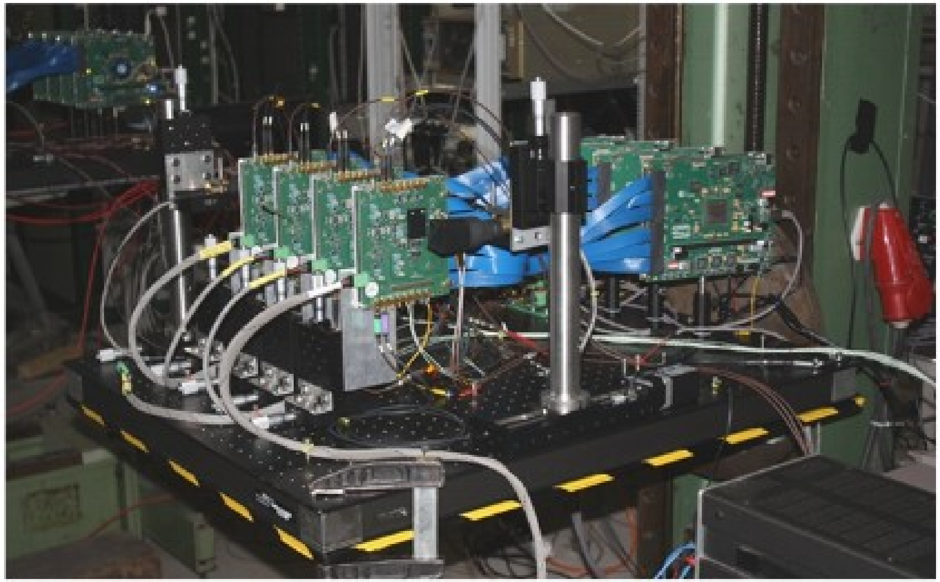
Laser Test

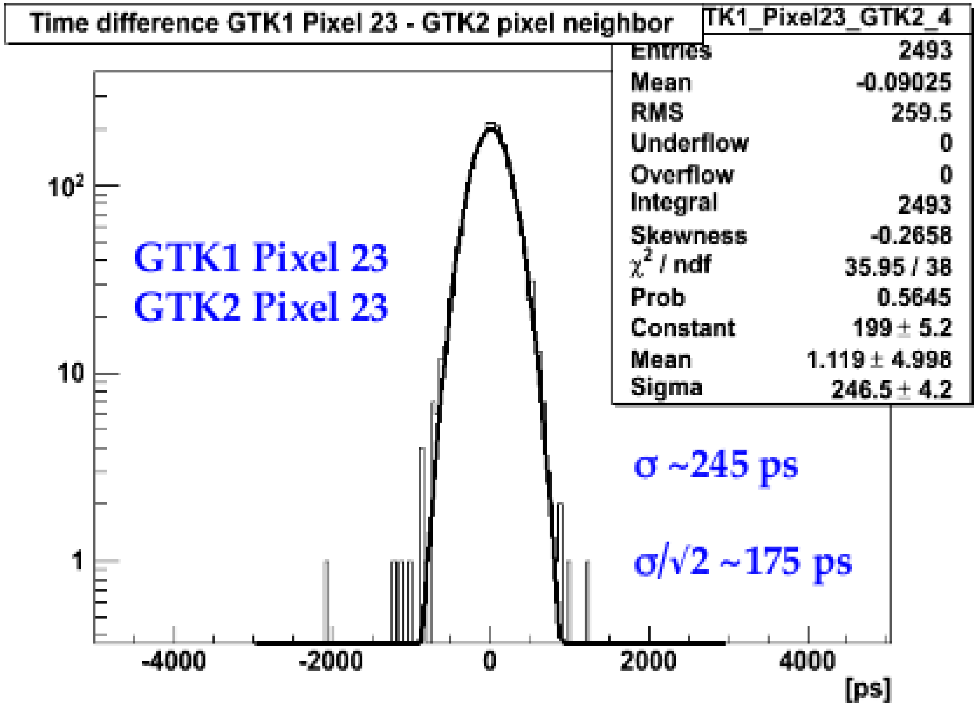
- Electronic noise from front-end chip ~180e^{-} (ENC) with sensor
- IR light (1060nm) to reproduce minimum ionizing particles
- Jitter of ~70ps rms at 2.4fC (charge injected at the pixel center)



Beam Test (1)

- Beam test at CERN T9 (10GeV/c π^+ and p)
- 4 consecutive GTK planes
- fast scintillators used as time reference



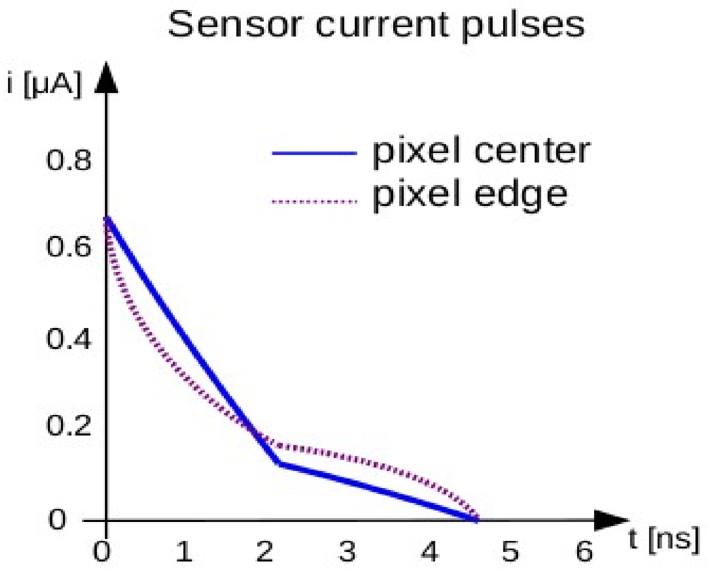


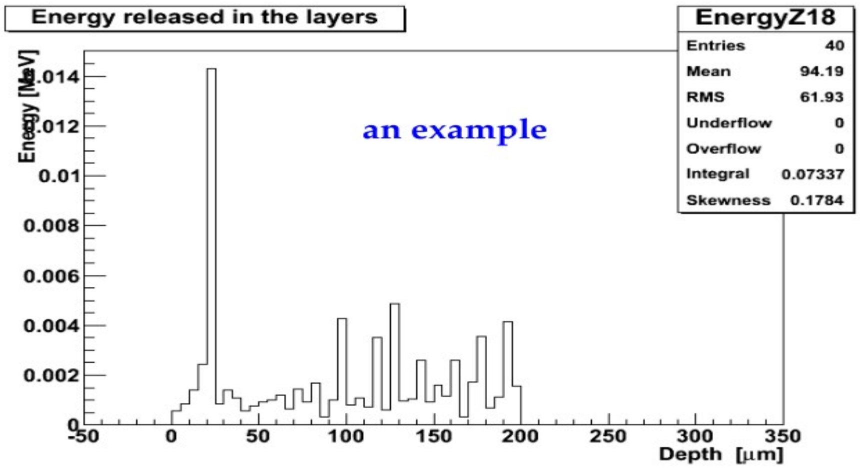
- measured time resolution of ~175ps σ at 300V of sensor bias voltage

Contributions to Timing Error (1)

Applying to any pixel front-end

- Electronic noise from front-end chip
- Impact position on pixel sensor: geometrical border effects

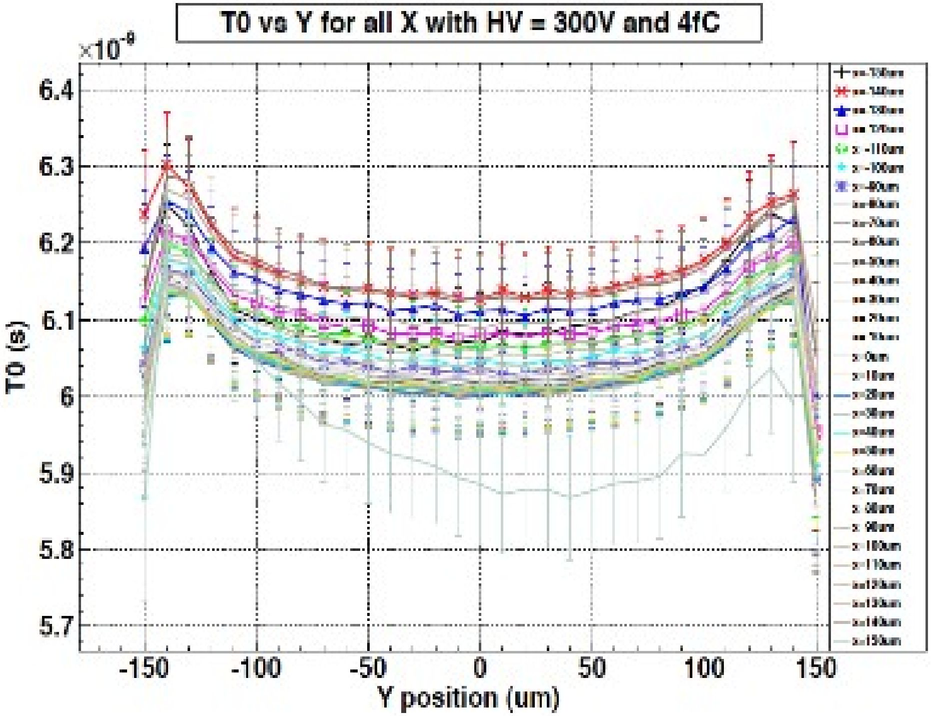




- Energy straggling in the sensor bulk: non uniform charge release along the sensor thickness

Contributions to Timing Error (2)

- Jitter: ~70ps rms @ 2.4fC
- ~85ps rms of variation of measured time with impact position inside the pixel (laser measurements)
- ~60ps rms from Geant simulations of charge straggling



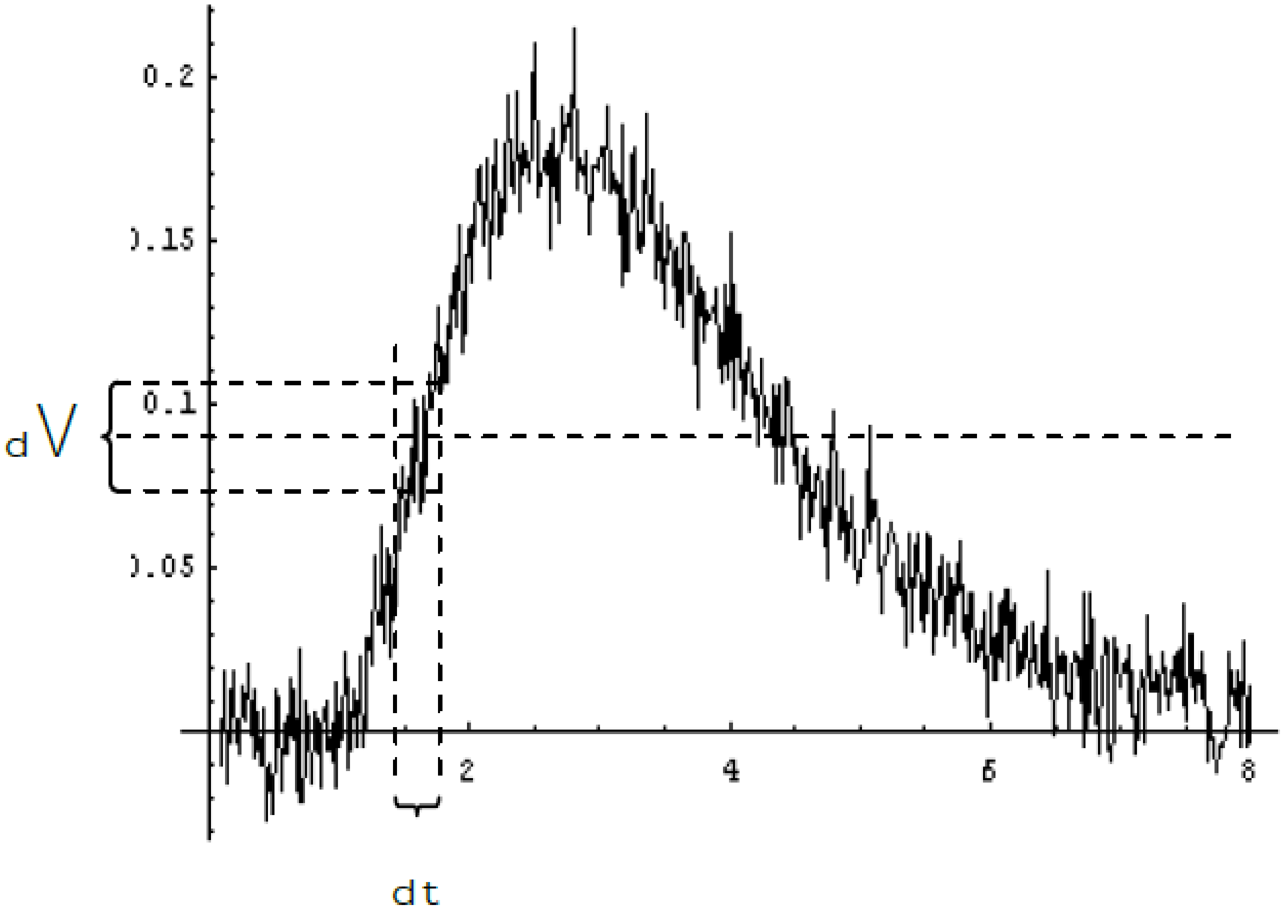
$$\sqrt{70^2+85^2+60^2}\sim 125\text{ps rms}$$

Conclusions and Outlook

- Extensive measurements (electrical, laser and beam tests) performed on prototype GTK bump-bonded assemblies
- A time resolution of ~175ps rms has been measured with minimum ionizing particles at 300V with EoC demonstrator
- For the TDC per pixel prototype the CFD has shown an intrinsic resolution of ~90ps rms, while a full system resolution higher than 500ps was measured at the beam test due to identified internal digital noise
- Also due to the tight schedule of the experiment the NA62 collaboration decided to adopt as baseline solution the EoC architecture
- One more prototype of TDC per pixel under development as a possible backup/upgrade solution

Jitter

$$\sigma_t = \frac{\sigma_n}{dV/dt}$$



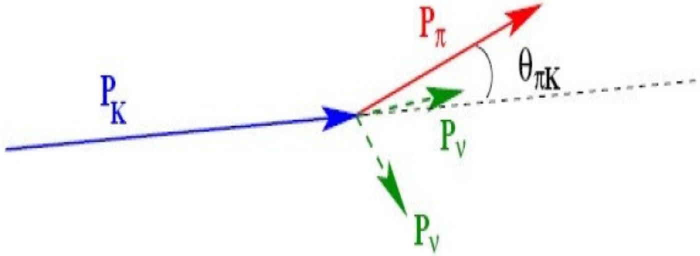
Physics Motivations

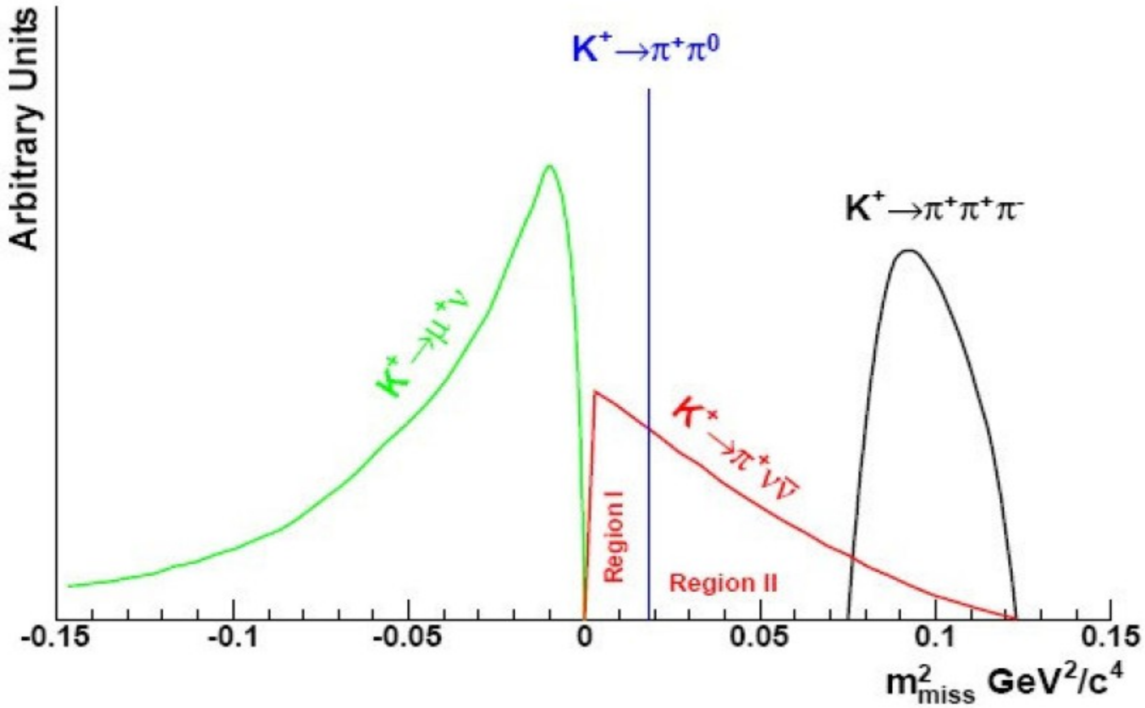
- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 6 r_{k^+} BR(K^+ \rightarrow \pi^0 e^+ \nu) \dfrac{|G_l|}{G_F^2 |V_{us}|^2}$
- $G_l = \dfrac{\alpha G_F}{2\pi \sin^2 \Theta_W} [V^*_{ts} V_{td} X(x_t) + V^*_{cs} V_{cd} X^l_{NL}]$
- V_{td} theoretical error of $\sim$5-7%

Background Rejection (1)

Decay mode	BR	Background rejection
$K^+ \rightarrow \mu^+\nu$	63%	μ PID, kinematics
$K^+ \rightarrow \pi^+\pi^0$	21%	γ veto, kinematics
$K^+ \rightarrow \pi^+\pi^+\pi^-$	6%	charged particle veto, kinematics
$K^+ \rightarrow \pi^+\pi^0\pi^0$	2%	γ veto, kinematics
$K^+ \rightarrow \pi^0\mu^+\nu$	3%	γ veto, μ PID
$K^+ \rightarrow \pi^0 e^+\nu$	5%	γ veto, E/p

Background Rejection (2)





- Region I: $0 < m^2_{miss} < m^2_{\pi^0} - (\Delta m)^2$
- Region II: $m^2_{\pi^0} + (\Delta m)^2 < m^2_{miss} < \min[m^2_{miss}(\pi^+\pi^+\pi^-)]$

Background Rejection (3)

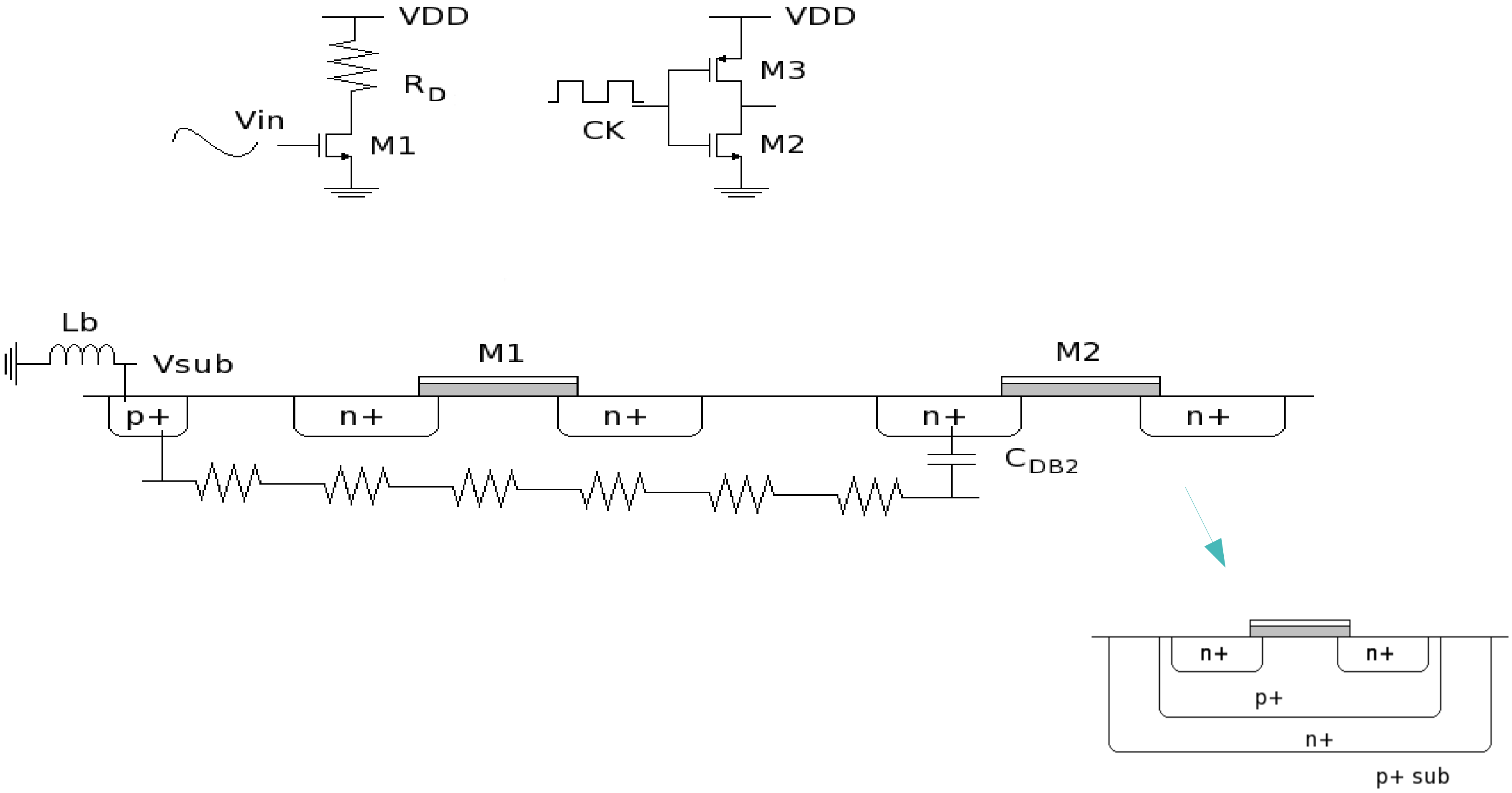
$$m^2_{miss} = m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right) + m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$

- $\Delta|P_K|/|P_K| \sim 0.3\%$, $|P_K| = 75$ GeV
- $\Delta|P_\pi|/|P_\pi| \sim 1\%$ at 30 GeV
- $\Delta\theta_{\pi K} \sim 50\text{-}60\ \mu\text{rad}$
- $(\Delta m^2_{miss}) \sim 8\times10^{-3}\ \text{GeV}^2/\text{c}^4$

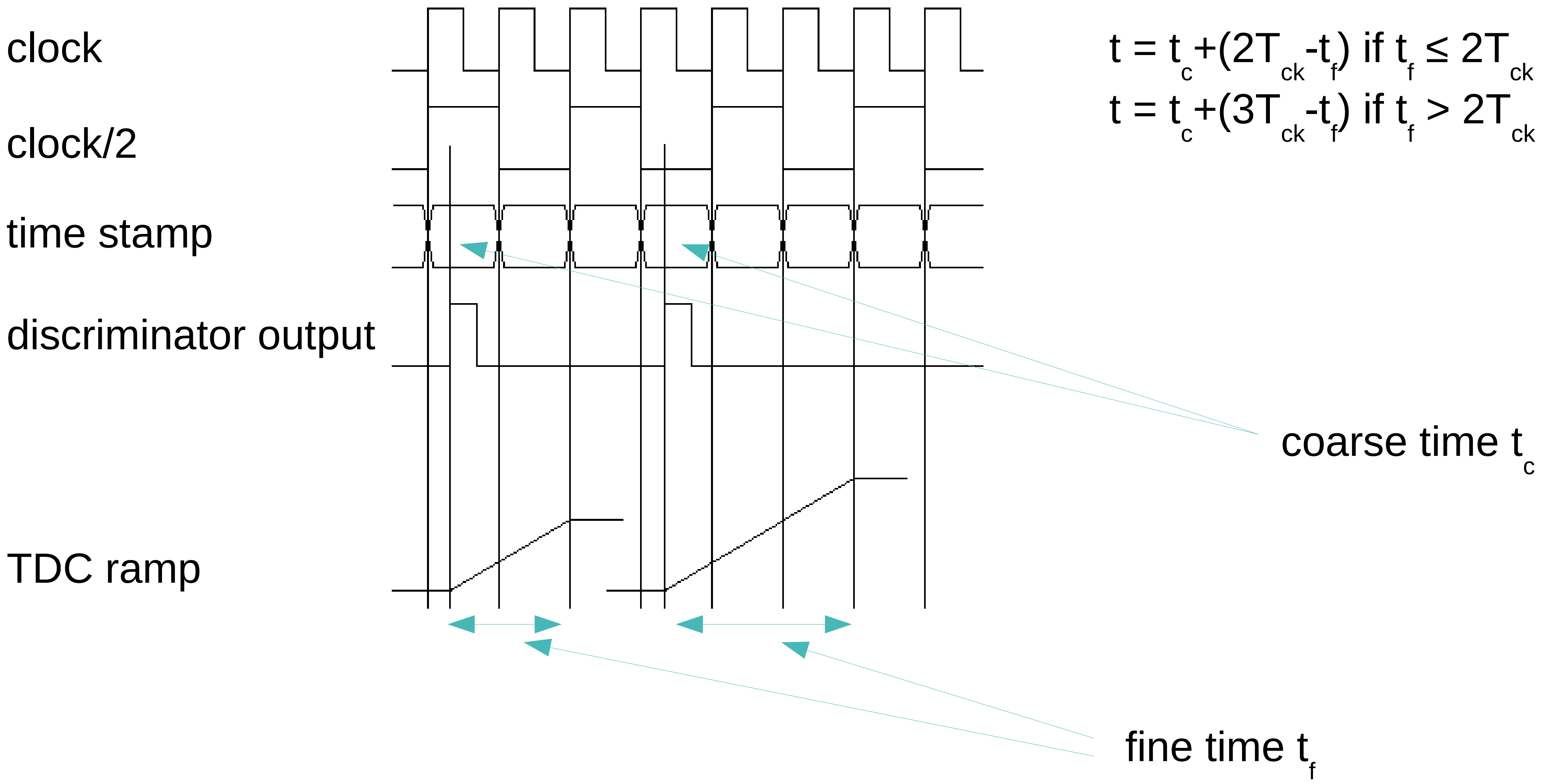
GTK

- 300µm x 300µm pixel
- ~ 100 ps time resolution due to high particle rate (60MHz/cm^2)

Substrate Noise



TDC



clock

clock/2

time stamp

discriminator output

TDC ramp

$t = t_c + (2T_{ck} - t_f)$ if $t_f \le 2T_{ck}$

$t = t_c + (3T_{ck} - t_f)$ if $t_f > 2T_{ck}$

coarse time t_c

fine time t_f