Silicon trackers for neutrino tagging at long baseline experiments

Project-ANR-19-CE31-0009

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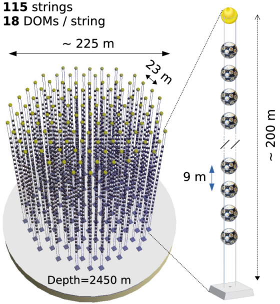
October 18, 2021

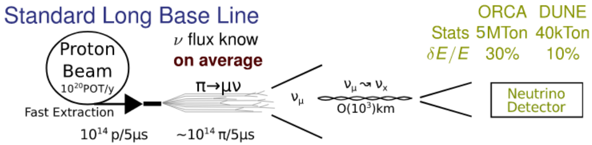
Outline

- Introduction
- Silicon sensors
- Analysis on sensors Time Resolution
- Next steps: neutrino tagging

Neutrinos experiments

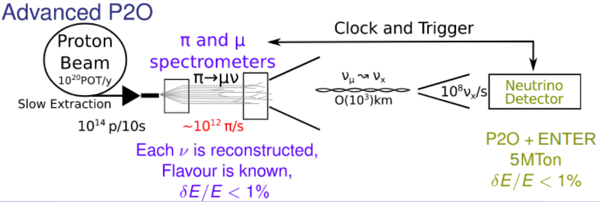
- Neutrino physics still has many fundamental parameters that have not been experimentally measured: mass ordering, oscillations parameters and Charge-Parity violation
- Can answer some of these questions by studying oscillations at long baseline experiments
- Set-up: near detector (initial energy spectrum and composition of neutrino beam), far detector (neutrino beam properties after oscillations).
- Example: P2O (Protvino to ORCA) would exploit the U70 beamline in Protvino and the KM3NeT/ORCA detector as far detector, baseline of 2600 km
- These experiments typically have many systematics → Tagged long baseline experiments: instrument the beamline with Si trackers





Framework: E.N.T.E.R. project

- E.N.T.E.R. = Enhanced Neutrino **Tagging** and Energy Reconstruction
- Goal: measure the energy of the neutrino using the two charged particles of the decay $\pi \to \nu\mu$
- Trackers reconstruct every pion and muon
- Far detector needs to tag the flavour of the oscillating neutrino
- Improvement in energy resolution ($\sim$ 10x better)
- Very high rate of π ($\sim 10^{12}\pi/s$)
- $\to$ important to have a tracker with a very good time resolution: need to make a one-to-one match between the tagged ν and the interacting ν
- It is crucial to study the timing performances of Silicon detectors and understand the elements that affect their time resolution.



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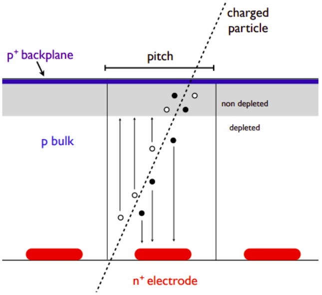
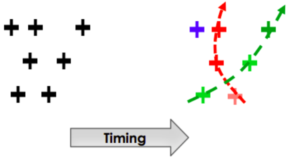
Time Resolved Silicon Detectors

- Silicon pixel detector functioning principle is based on p-n junction
- e^- near p-n interface drift in p region, holes drift towards n region → depletion region
- Reverse V_{bias} applied → depletion region grows: $w_{depl} \propto \sqrt{V_{bias}}$
- Signal induced by motion of e^- and holes produced by crossing ionizing particle → detection
- Different sensor types depending on the doping of bulk and strips: n-on-p and p-on-n

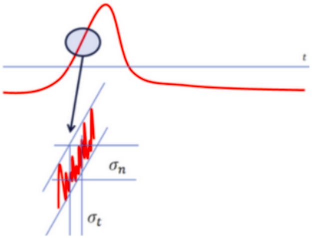




Time resolution budget in Silicon Pixel Detectors

$$\sigma_t^2 = \sigma_{electronics}^2 + \sigma_{straggling}^2 + \sigma_{WeightingField}^2 + \sigma_{TW}^2$$

- Electronics: TDC + noise ($\sigma_t \propto \frac{1}{dV/dt}$)
- Charge straggling: variation of charge deposit in the sensor
- Time Walk: for signals arriving simultaneously, the time needed to cross the threshold is shorter for signals with larger amplitudes than for signals with smaller ones → very large contribution, corrected offline
- Weighting Field: depends on the pixel geometry → differences in signal shape between center and edge of the pixel



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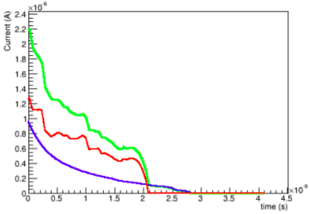

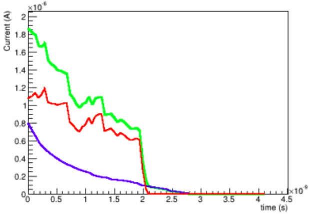

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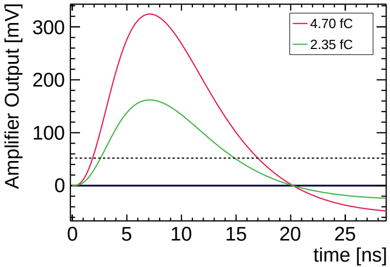

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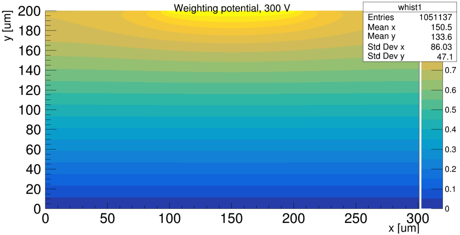
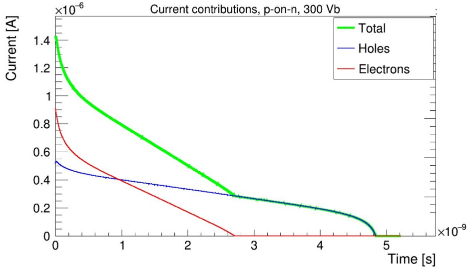
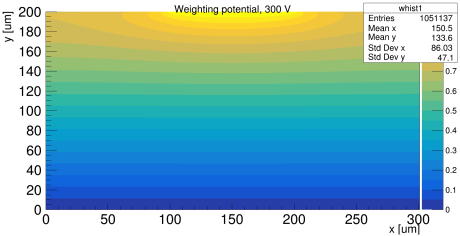
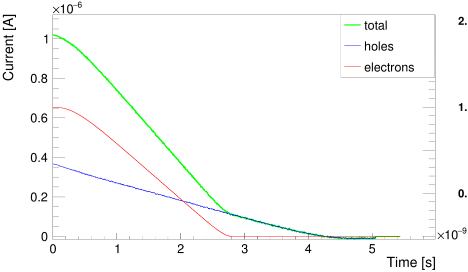


Charge position: WF contribution

- WF not uniform on the pixel area → difference in pulse shape at center and at edges
- Degradation of the time resolution due to:
  - worsening of the signal quality at edges (less steep and intense)
  - different time walk on center and on edges







TDCPix and previous test campaigns

- TDCPix: time resolved readout chip of Silicon tracker of NA62 experiment (GigaTracker)
- 200 µm thick planar sensors, p-in-n or n-in-p, 40 × 45 pixels of 300 × 300 μm^2
- From previous test campaign have been experimentally measured
  - electronics contribution from laser test with TDCPix demonstrator: ∼ 80 ps
  - WF contribution with laser tests with TDCPix: ∼ 85 ps
- Simulation of charge straggling contribution → ∼ 100 ps
- Missing:
  - experimental measures of charge straggling
  - experimental confirmation of WF effect with MIPs
  - systematic study on performances of n-on-p and p-on-n sensors

$$\sigma_t = \sqrt{\sigma^2_{electronics+TDC} + \sigma^2_{weightingfield} + \sigma^2_{straggling}} = \sqrt{80^2 + 85^2 + 100^2} = 150ps.$$

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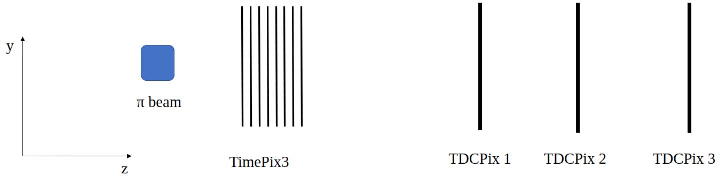
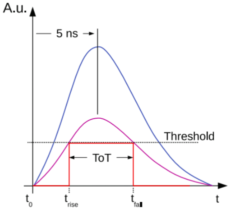
Beam Test Setup

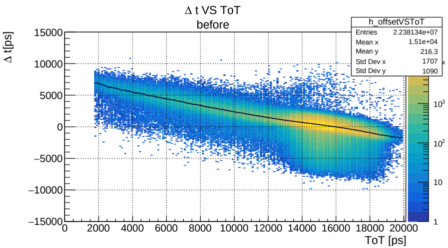
- Beam test taken at CERN SPS in 2017 with π^+ at 180 GeV/c: 3 planes of TDCPix + 8 planes of TimePix3
- No external time reference
- TPX telescope has very small pixels (55 µm) → can resolve the position inside the TDCPix pixel
- Goal: study of time resolution contributions.

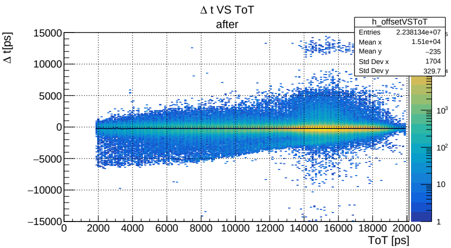


Time Walk Correction

- Procedure to be done on plane couples in absence of time reference
- Both planes are to be corrected → iterative procedure
- Use Time over Threshold ($ToT = t_{fall} - t_{rise}$) as a proxy to the signal amplitude
- Derive delay of detection at threshold as function of ToT thanks to $\Delta t = t_2 - t_1$ VS ToT distributions
- Effect of correction: flatten and shrink Δt VS ToT distribution

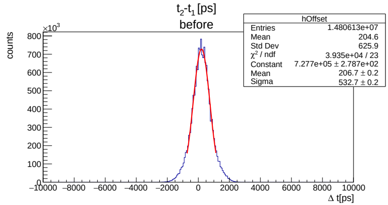


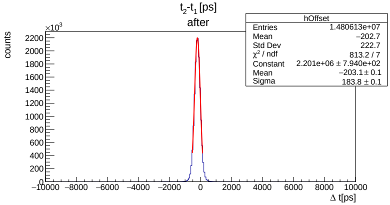


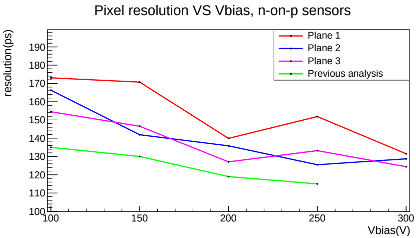


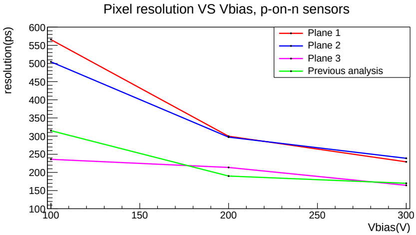
Time Resolution

- By taking the projections of Δt VS ToT distributions we can access the resolutions
- Width of the Δt distributions will be $\sigma^2_{i-j} = \sigma^2_i + \sigma^2_j$
- Resolution of a plane: $\sigma_i = \sqrt{\frac{1}{2}\left(\sigma^2_{i-j} + \sigma^2_{i-k} - \sigma^2_{j-k}\right)}$



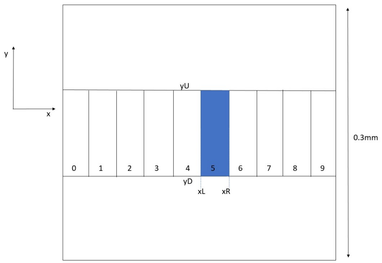






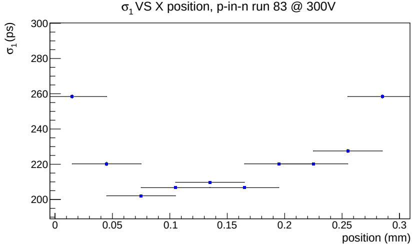
Time resolution and position inside the pixel

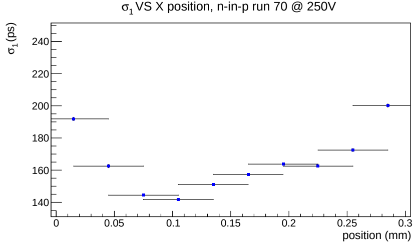
- Goal: see how the time resolution changes in different regions of the pixels (WF effect)
- Use tracks from TPX telescope to resolve position inside the TDCPix pixel
- Align in space and time the track intercept and the hits of the TDCPix, association in space and time
- Pixel "slicing" thanks to intercept position



Estimation of WF contribution to the time resolution

- For each slice build Δt distribution → access WF contribution to time resolution
- $\sigma_{1S} = \sqrt{\sigma_{21-S}^2 - \sigma_2^2}$, where σ_2 is the resolution of plane 2 and σ_{21-S} is the width of the Δt distribution of each slice
- for n-in-p: $\Delta\sigma_{WF} \sim 40$ ps
- for p-in-n: $\Delta\sigma_{WF} \sim 100$ ps





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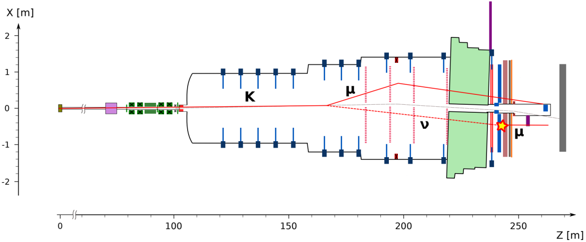
Neutrino tagging feasibility study

- Goal: use data from the NA62 experiment to perform neutrino tagging
- NA62: experiment that study rare Kaon decays
  - Use the 2 body kaon decay $K^+ \rightarrow \mu^+ \nu$
  - Use Silicon tracker to precisely reconstruct the tracks of the charged particles of the decay
  - ν interacts in LKr calorimeter via CC interaction producing a μ
  - The 2 in-time μs are detected by an electromagnetic calorimeter
  - $\rightarrow$ full reconstruction of $K^+ \rightarrow \mu^+ \nu$



Conclusions

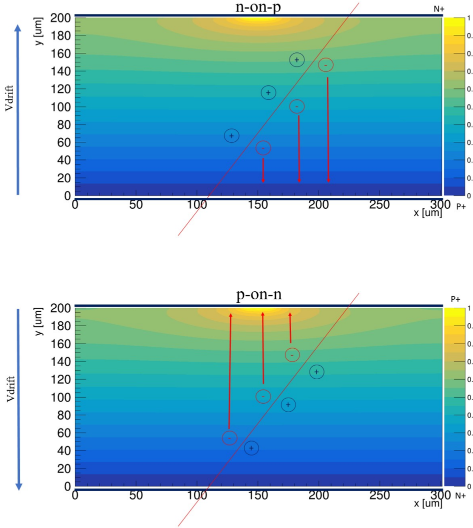
- Neutrino tagging can revolution the way we design experiments for neutrino physics
- In order to be able to perform it, we need time-resolving Si trackers with very good time resolution
- It is important to understand and estimate all the contributions to the tracker's time resolution in order to be able to design one for this project
- It is crucial to show the feasibility of this technique → analysis of data from NA62 with its performing Si detector
    - Trigger line to collect these events from July 2021, now being improved

Thank you for your attention!

Backup

Hypothesis: another WF effect?

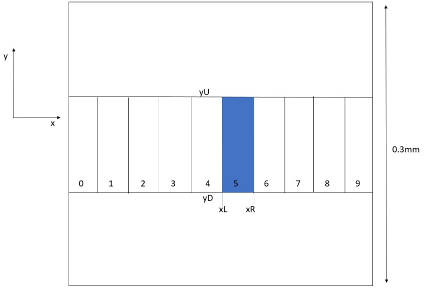
- Main signal contribution comes from electrons
- n-on-p: electrons collected on bottom part of sensor (WF less intense but homogeneous)
- p-on-n: electrons collected on top part of sensor (WF more intense but inhomogeneous)
- A more homogeneous WF could mean less variability in signal shape

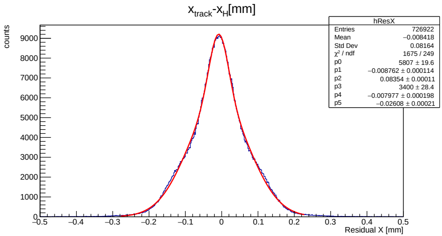


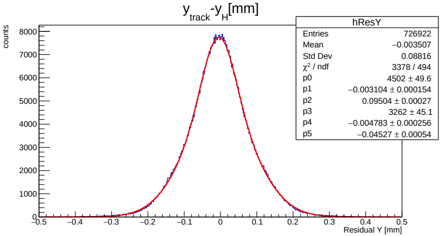
Disclaimer: the understanding of this effect is still in a very preliminary phase!

Alignment and spatial resolution

- Goal: see how the time resolution changes in different regions of the pixels (WF effect)
- Association in space and time between tracks from TPX and hits of plane 1 of TDCPix
- It is possible to access space resolution of tracker thanks to residual plots
- Resolution along X $\sim 30\mu m$, resolution along Y $\sim 50\mu m$ $\rightarrow$ pixel slicing

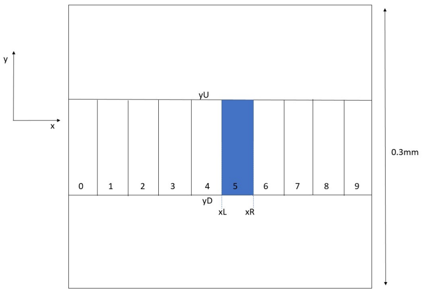






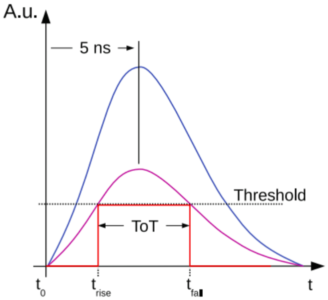
Resolving hit position inside the pixel

- Goal: see how the time resolution changes in different regions of the pixels (WF effect)
- Use tracks from TPX telescope to resolve position inside the TDCPix pixel
- Align in space and time the track intercepts and the hits of the TDCPix
- Spatial resolution of tracks: along X $\sim 30\mu$m, along Y $\sim 50\mu$m
- Plane 1: pixel "slicing" thanks to the position of the intercept associated to the hit
- For each slice build Δt distribution $\rightarrow$ access WF contribution to time resolution



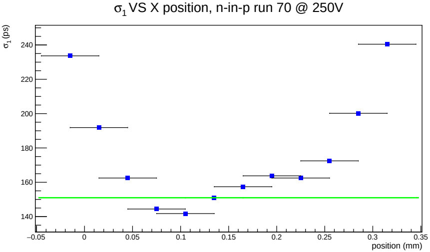
Time Walk Correction

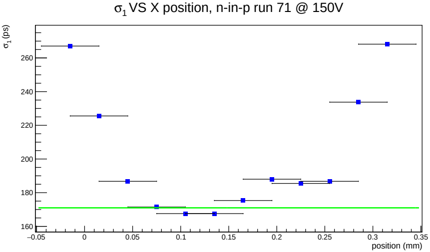
- Goal: measure the corrected resolution of the slices of plane 1 (closest to telescope)
- Reuse time walk correction previously derived on the **whole** pixels of plane 1 and 2 (**average** TW)
- Apply correction to each slice of plane 1
- Plot Δt histograms and access resolutions

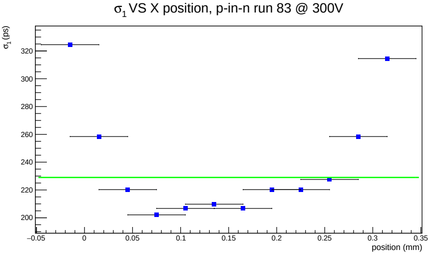


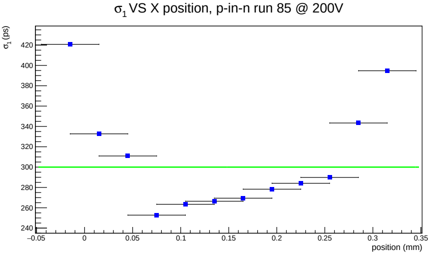
Results: resolution VS X position

- For each slice: $\sigma_{1S} = \sqrt{\sigma^2_{21-S} - \sigma^2_2}$, where σ_2 is the resolution of plane 2 and σ_{21-S} is the width of the Δt distribution of each slice









Estimation of WF contribution

- WF contribution: $\sigma^2_{WF} = \sigma^2_{WF-degradation} + \sigma^2_{WF-TW}$
- Comparison between:
  - the σ_1 of the central slice (4) corrected with a custom TWC (σ_{1C})
  - the σ_1 of the full plane 1 corrected with the average TW (σ_{1F})
- for n-in-p:
  - $\Delta\sigma^{250V}_{WF} = \sqrt{\sigma^2_{1F} - \sigma^2_{1C}} = 39\text{ps}$
  - $\Delta\sigma^{150V}_{WF} = \sqrt{\sigma^2_{1F} - \sigma^2_{1C}} = 44\text{ps}$
- for p-in-n:
  - $\Delta\sigma^{300V}_{WF} = \sqrt{\sigma^2_{1F} - \sigma^2_{1C}} = 102\text{ps}$
  - $\Delta\sigma^{200V}_{WF} = \sqrt{\sigma^2_{1F} - \sigma^2_{1C}} = 170\text{ps}$
- Here the custom TWC for the central slice and its Δt distribution are computed on a restricted ToT range (very low statistics at low ToT → algorithm not stable)

Comparison with previous results

M Noy, M Aglieri Rinella, Gianluca Ramusino, A Fiorini, Massimiliano Jarron, P. Kaplon, J Kluge, Alexander Martin, Erwann Morel, Maximo Perktold, L Poltorak, Karolina Riedler, P. (2011). Characterisation of the NA62 GigaTracker End of Column Demonstrator Hybrid Pixel Detector. Journal of Instrumentation. 6. C11025. 10.1088/1748-0221/6/11/C11025.

- In this paper the results of pixel scan with laser on a p-in-n TDCPix demostrator are shown.
- Charge injected in the pixel in steps of 10μm across the pixel, look at the behavior of the reconstructed time → shows a systematic error in the reconstruction time as the edge is approached
- Plot histogram with **mean values** for each X-Y point → RMS of $\sim 85ps$ → what Matt calls weighting potential contribution to the time resolution.
- This results only accounts for the variation of the average time in each step across the pixel, therefore underestimating the WF effect: the broadening of the Δt distributions is not taken into account