z-resolution in a TPC with a pixel readout

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LCTPC Analysis meeting

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Outline

1. z-resolution in single chip detector
2. z-resolution in the ILD TPC
3. Time stamping resolution of TPC tracks in ILD

Single chip Timepix3-based GridPix detector

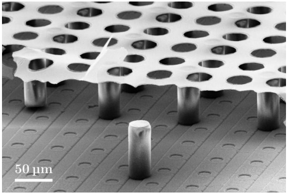
Timepix3-based GridPix:

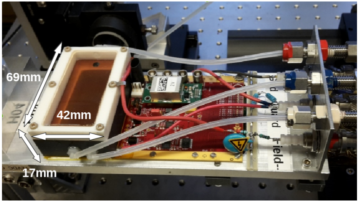
- Micro-pattern gaseous detector with grid aligned to pixels
- 65K 55 µm × 55 µm sized pixels

Timepix3 compared to its predecessor:

- Improved time resolution of 1.56 ns
- Simultaneous time and charge (ToT) measurement

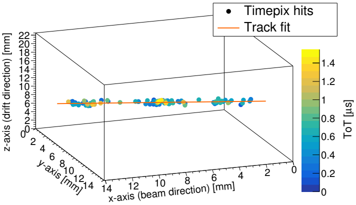
Single chip Timepix3 detector with field shaping, guard electrode, and T2K TPC gas (Ar:CF_4:iC_4H_{10} 95:3:2)

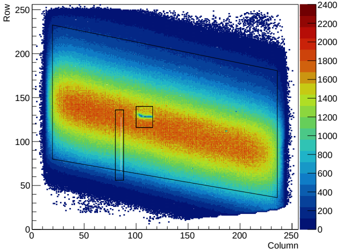


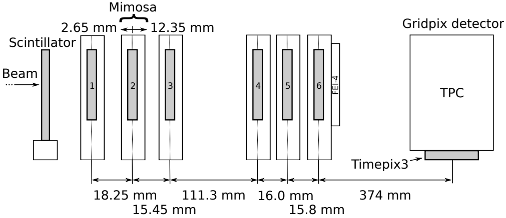


Test beam measurements

- Test beam using 2.5 GeV electrons at the ELSA facility (Bonn)
- Tracks are reconstructed by simple linear regression
- Drift field is 280 V/cm
  - $v_{\text{drift}} = 78.86(1)\ \mu\text{m/ns}$ from Magboltz



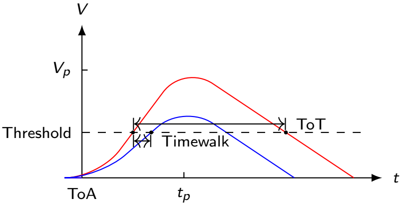


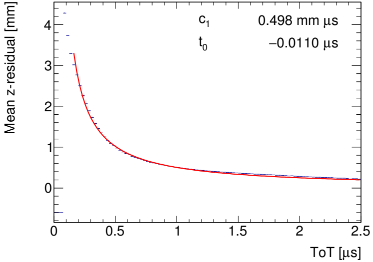


Time walk correction

Time walk error is caused by ToA depending on signal magnitude
This can be corrected using

$$z_{\text{tw}} = \frac{c_1}{t_{\text{ToT}} + t_0} \tag{1}$$





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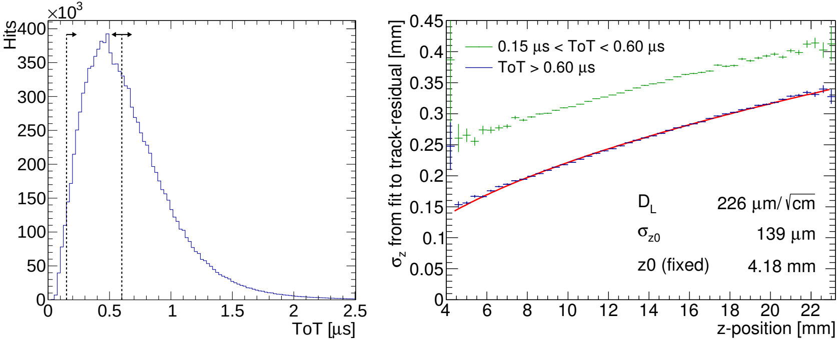
z-resolution

Resolution σ_z determined by longitudinal diffusion coefficient D_L and resolution at zero drift distance σ_{z0}: $\sigma_z^2 = \sigma_{z0}^2 + D_L^2(z - z_0)$

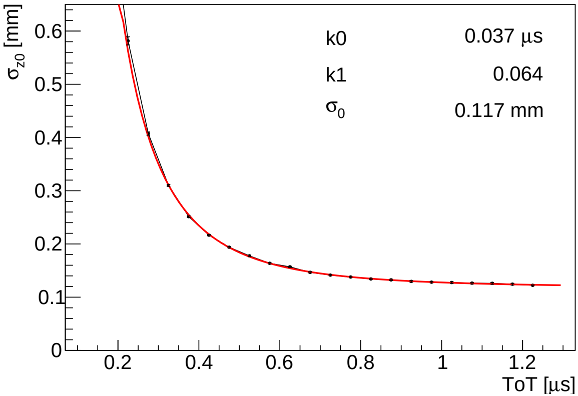


Measured $D_L = 226\,\mu\text{m}/\sqrt{\text{cm}}$ (Magboltz predicts $201(5)\,\mu\text{m}/\sqrt{\text{cm}}$) and $\sigma_{z0} = 139\,\mu\text{m}$ ($168\,\mu\text{m}$ if including ToT $< 0.60\,\mu\text{s}$)

ToT error is propagated to z-resolution

ToT error $\sigma_{ToT} = k_0 + k_1(t_{ToT} + t_0)$ causes error in z-position through time walk correction.

Fit $\sigma_{z0}^2 = \sigma_{ToT}^2 + \sigma_0^2$ for slices in ToT of width 0.05 µs



Fix c_1 and t_0 from time walk and fit k_0, k_1 and σ_0

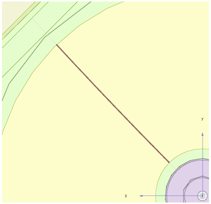
Contributions to z-resolution

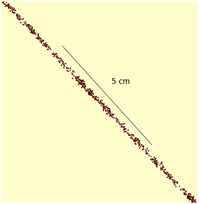
Contributions at zero drift distance

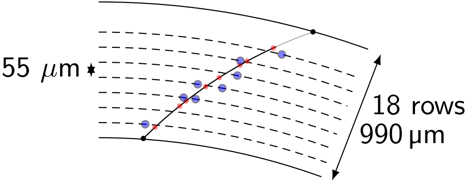
Time resolution: $\tau v_{\text{drift}}/\sqrt{12}$	34 µm
Systematics of the chip from a histogram	47 µm
Uncertainty in track position	30 µm
Fluctuations in ToT (117 µm for asymptotically high ToT)	154 µm
Total σ_{z0}	168 µm

Simulation of ILD TPC with pixel readout

- Pixel geometry is implemented in ILD DD4hep simulation (Geant4)
- Simulated in layers of ∼990 µm over which to track is interpolated to 55 µm pixels
- An energy deposit is converted to a hit if above 27 eV (Our tune)
- Hits are smeared with hit-resolution
  - $\sigma_z = \sqrt{\sigma_{z0}^2 + D_z^2 z_{\text{drift}}}$
  - From test beam: $\sigma_{z0} = 0.168\,\text{mm}$
  - From Magboltz: $D_L = 205\,\mu\text{m}/\sqrt{\text{cm}}$ (test beam $D_L = 226\,\mu\text{m}/\sqrt{\text{cm}}$)
- Tracks are reconstructed with a Kalman filter







Contributions to the z-resolution

- Uncertainty from position measurement

$$\sigma_{\text{me}}^2 = \frac{\sigma_z^2}{\sqrt{N}} \propto \frac{\sigma_z^2}{\sqrt{L_{\text{track}}}} \tag{2}$$

- Uncertainty from weighted measurement of angle

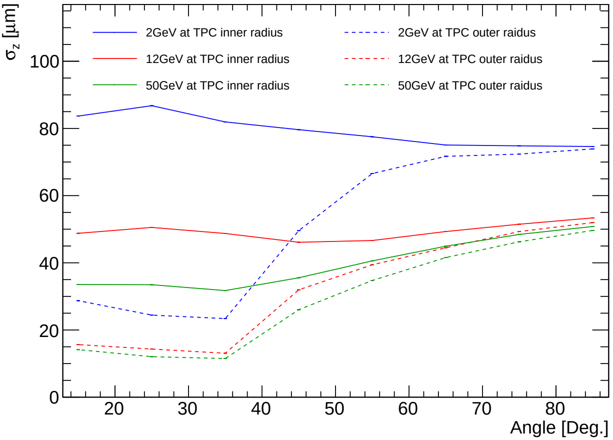
$$\frac{1}{\sigma_{\text{ms}}^2} \propto \frac{1}{\sigma_0^2} + \frac{p^2}{\sigma_1^2 L^3} \Rightarrow \sigma_{\text{ms}}^2 \propto \frac{1}{1/\sigma_0^2 + p^2/(\sigma_1^2 L^3)}, \tag{3}$$

where the first term captures the measurement error and the second term the multiple scattering

Equations under the assumption of constant hit errors (diffusion is missing)

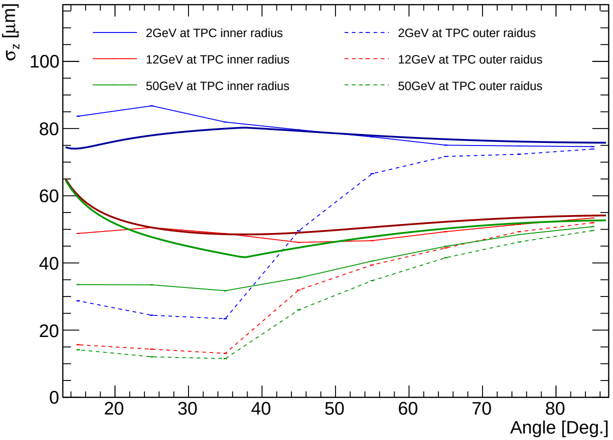
Resolution as a function of angle

for muons



Resolution as a function of angle

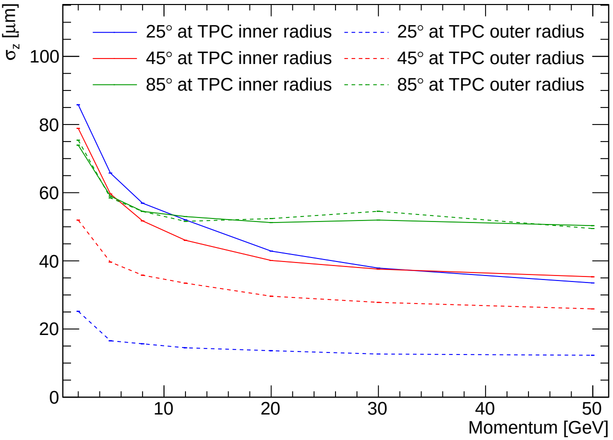
for muons



Parameters are set to $\sigma_z = 64\,\mu\text{m}$, $\sigma_0 = 76\,\mu\text{m}$, $\sigma_1 = 87\,\mu\text{m}(\text{GeV/c})^{-1}\text{m}^{-3}$

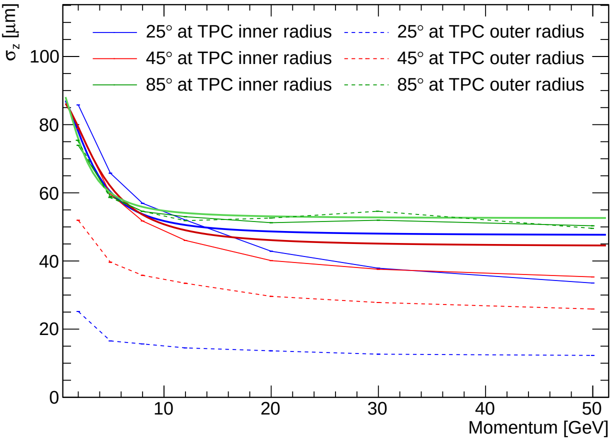
Resolution as a function of momentum

for muons



z-resolution as a function of momentum

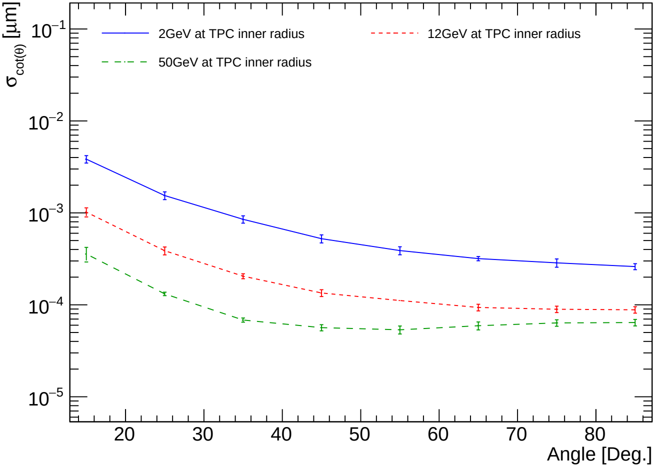
for muons



Parameters are set to $\sigma_z = 64\,\mu\text{m}$, $\sigma_0 = 76\,\mu\text{m}$, $\sigma_1 = 87\,\mu\text{m}(\text{GeV}/c)^{-1}\text{m}^{-3}$

Cot(θ) resolution

for muons



$$\cot(\theta) = \tan(\lambda)$$

z-resolution in the ILD TPC with pixel readout

	At inner radius	At outer radius
50 GeV muons at 85°	50 µm	50 µm
50 GeV muons at 25°	13 µm	35 µm
2 GeV muons at 85°	75 µm	75 µm
2 GeV muons at 25°	25 µm	85 µm

Without systematics errors

If instead of the Magboltz value of $D_L = 205\,\mu\text{m}/\sqrt{\text{cm}}$ the diffusion coefficient $D_L = 226\,\mu\text{m}/\sqrt{\text{cm}}$ from the test beam setup is used, σ_z is approximately 10 % greater: e.g. σ_z=55 µm for 50 GeV muons at 85°

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Time stamping of TPC tracks in ILD

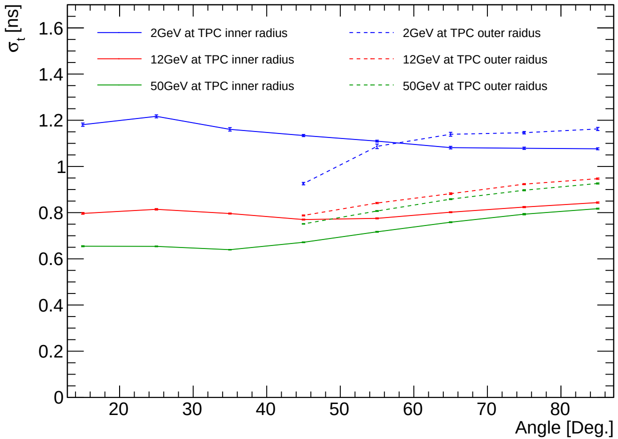
Tracks are time stamped by comparing their absolute z-position from the silicon trackers with the z-position determined from the drift time measurement in the TPC

The Silicon Internal Tracker (SIT) and the Silicon External Tracker (SET) will be build from respectively 2 and 1 layers of the same double strip planes with a $\sigma_z = 50\,\mu\text{m}$ resolution. So the SIT and SET resolution is approximately $50/\sqrt{2}\mu\text{m} = 35\,\mu\text{m}$ and $50\,\mu\text{m}$ respectively

The precision of the silicon trackers and hit resolution put stringent requirements on the relative precision of the drift velocity. In a study for the CLIC ILD detector the relative precision from electric field, temperature and pressure was estimated to be $7 \cdot 10^{-6}$, corresponding to $16\,\mu\text{m}$ [1]

[1] Martin Killenberg, Time Stamping of TPC Tracks in the CLIC ILD Detector, LCD-Note-2011-030

Time stamping of TPC tracks in ILD

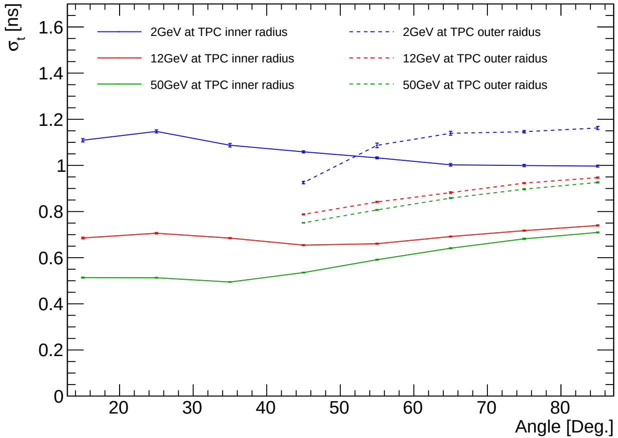


Assuming uncertainties of 16 μm from the drift velocity, 35 μm from the SIT, and 50 μm from the SET.

Multiple scattering from inner and outer TPC field was neglected

Time stamping of TPC tracks in ILD

If the SIT is instrumented with Silicon pixels instead of Silicon strips, the time resolution can be improved



Assuming an uncertainty of 15 µm from the SIT

Conclusion

- From test beam measurements sources of position errors in the z-direction are identified
- The uncertainty in a single chip Gridpix detector is given by $\sigma_z = \sqrt{\sigma_{z0}^2 + D_L^2 z}$, where $\sigma_{z0} = 168\,\mu\text{m}$ and $D_L = 226\,\mu\text{m}/\sqrt{\text{cm}}$
- The z-resolution of the ILD TPC with pixel readout is studied and from simulations found to be between 13 μm and 85 μm
- The time stamping resolution of the ILD TPC is estimated to range from 0.65 ns to 1.2 ns

The TPC as a time of flight detector

Time difference of particles is given by

$$\Delta t = \frac{Lc}{2p^2}(m_1^2 - m_2^2) \tag{4}$$

- Time resolution does not suffice for particle identification (for a 2 GeV/c proton/kaon at traversing the ILD TPC at 45° $\Delta t = 0.632\,\mathrm{ns}$)
- But is useful in searches

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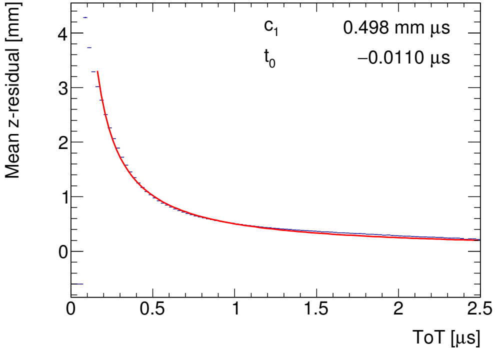
Time walk correction



Timewalk corrected with $z_{\text{tw}} = \frac{c_1}{t_{\text{ToT}} + t_0}$
The error in the ToT should be propagated to the z-coordinate:
$\sigma_z^2 = (\sigma_{z0}(t_{\text{ToT}}))^2 + D_L^2(z - z_0)$

Propagation of ToT error to σ_z

Propagate error:

$$\sigma_{z0}(t_{\mathrm{ToT}}) = \sigma_{ToT} \frac{\partial z_{tw}}{\partial t_{ToT}} \tag{5}$$

Derivative is:

$$\frac{\partial z_{tw}}{\partial t_{ToT}} = -c_1 (t_{ToT} + t_0)^{-2} \tag{6}$$

Assume:

$$\sigma_{ToT} = k_0 + k_1 (t_{ToT} + t_0) \tag{7}$$

Full error becomes:

$$\sigma_z(t_{ToT}) = \sqrt{\frac{(k_0 + k_1(t_{ToT} + t_0))^2 c_1^2}{(t_{ToT} + t_0)^4} + \sigma_0^2} \tag{8}$$