High-Resolution Micromegas Telescope for Pion- and Muon-Tracking

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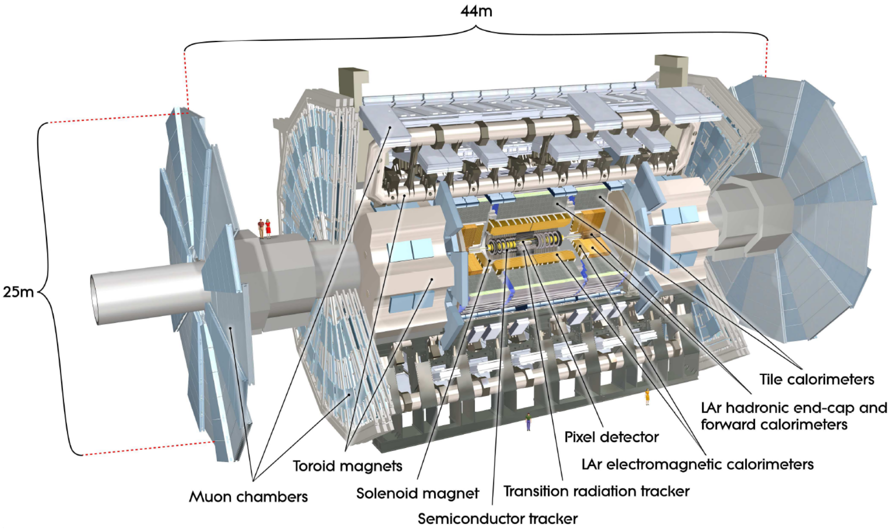
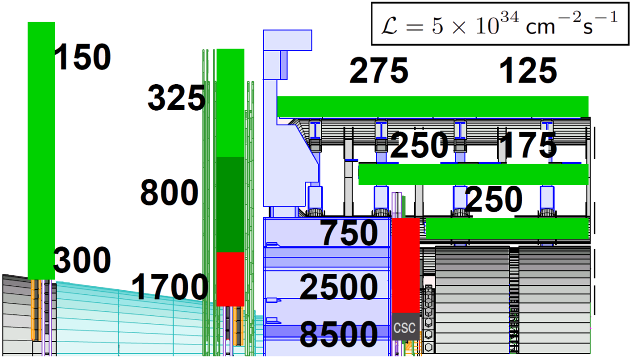
Motivation

- development & comissioning of muon tracking detectors
  - high-energy physics (ATLAS upgrade)
  - medical imaging i.e. photon detectors
  - neutron-physics (^{3}He-shortage)
- investigate properties & performance of micro-pattern gaseous detectors: Micromegas
  $\rightarrow$ Application: tracking telescope for test beams: high resolution, high efficiency, good double hit resolution, high rate capablity

The ATLAS Experiment at LHC



HL-LHC: Why New Muon Detectors?



J. v. Loeben, IEEE Nucl. Sc. Symp. 2010

expected background rates [Hz/cm²], including safety factor of 5

high-rate neutron- & γ-background:

- **occupancy** $\leftrightarrow$ low efficiency
- **degradation of spatial resolution** $\leftrightarrow$ worse momentum resolution

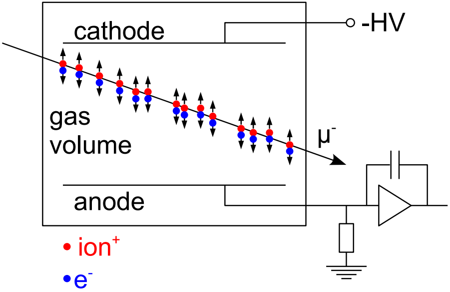
Properties of a “good” muon detector for ATLAS

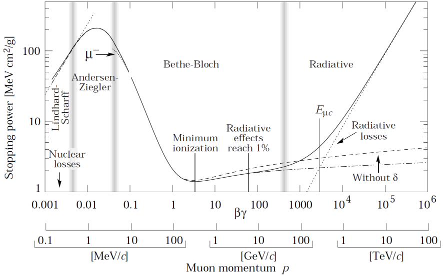
- high **efficiency** to muons
- good **spatial resolution** $\Delta r \lesssim 50\,\mu\text{m}$
- high rate capability
  - low occupancy
  - little degradation of spatial resolution in high flux γ- and neutron-background
- large area coverage
- cost effective
- **reliable** $=$ no or at least little aging

Outline

1. Introduction
2. Setup
3. Performance & Optimization
4. Spatial Resolution
5. Summary

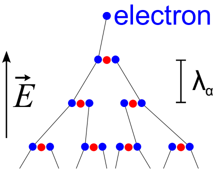
Ionization Chamber

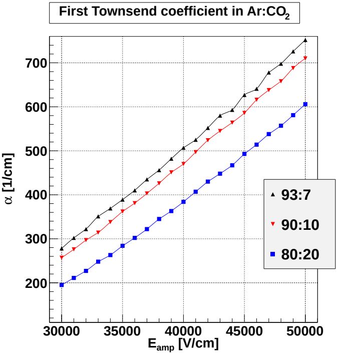




- charged particles: el.-magn. interaction dominant in gas detectors → excitation and **ionization**
- incident particle deposits energy in gas, Bethe-Bloch → $\langle dE/dx \rangle$
- $\langle dE/dx \rangle_{MIP} = 2.53\,\mathrm{keV/cm}$ in Ar @ NTP
- $\#_{e-\text{ion pairs}} = \frac{\langle dE/dx \rangle}{W_I}$
- $W_I \sim 25\,\mathrm{eV}$ in Ar (also accounts for excitation) →∼**100 e-ion-pairs/cm**
- measureable but really difficult!

Gas Amplification

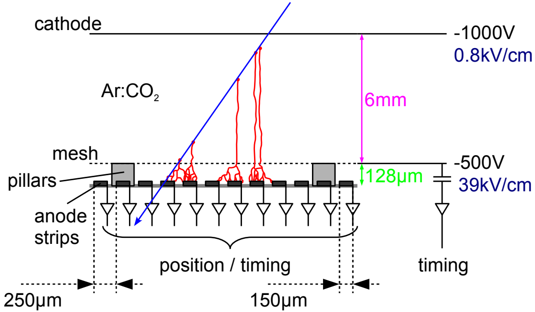


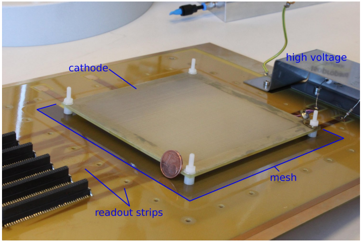


- in **strong electric fields**, e^- gain enough energy to further ionize the gas
- mean free path $\lambda_\alpha = 1/\alpha$
- first Townsend coefficient $\alpha = \#_{e-\text{ion pairs}}/\text{cm}$
- $N(x) = N_0 \exp(\alpha x)$
- **gain factors of 3000 - 20000** sufficient

Setup

Micromegas Setup & Functional Principle



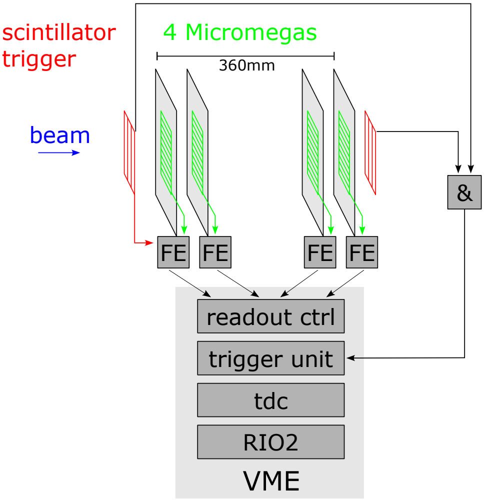


- **ionization** in 6 mm drift region
- **gas amplification** in 128 µm amplification region
- $90 \times 100\,\mathrm{mm}^2$, 360 copper strips (150 µm width and 250 µm pitch)
- gas: Ar:CO_2 93:7, 85:15 @ NTP

Calibration Experiments for Track Telescope

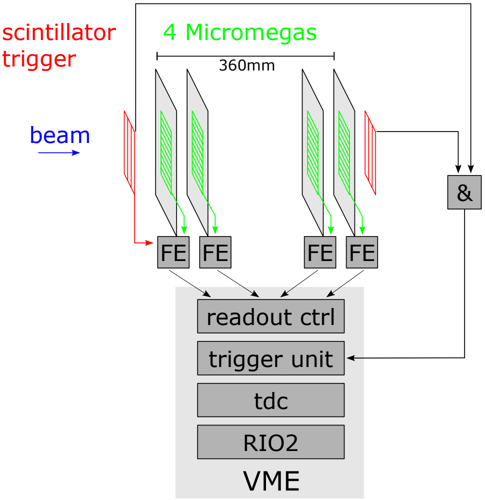
- π^-: 120 GeV - 300 GeV @ H6 SPS CERN
- μ^-: $\lesssim$ 160 GeV @ H8 SPS CERN
- rates up to $\mathbf{4.2 \times 10^3}$/cm^{2}s
- two Ar:CO_2 gas mixtures **93:7** and **85:15**
- statistics: $\sim$ 6M pion and $\sim$ 14M muon tracks

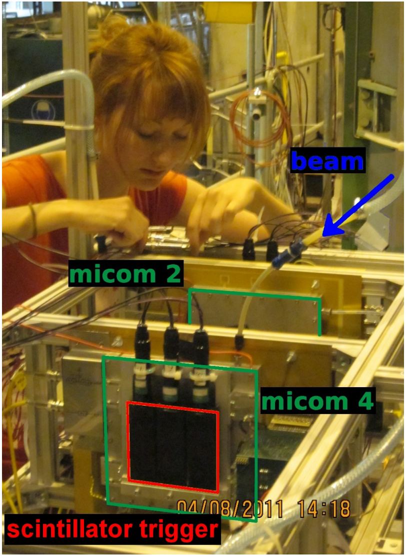
Testbeam Setup



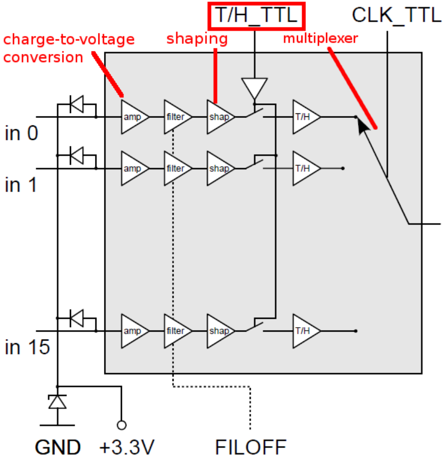
- 4 Micromegas with 360 strips each, all strips parallel
- trigger: 2×3 scintillators → 3rd coordinate
- readout by Gassiplex frontends, 1500 channels in total
- gas-flux ∼ 1 ln/h @ 1013 mbar stabilized pressure

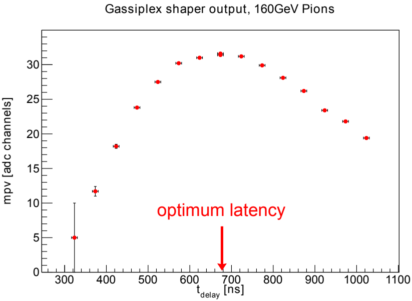
Testbeam Setup





Trigger Latency



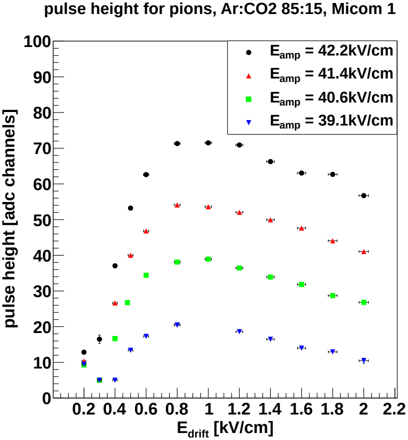


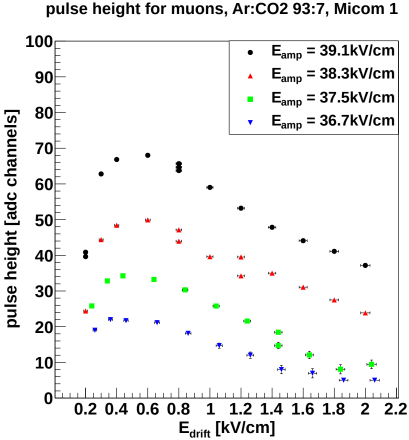
Performance & Optimization

Performance & Optimization

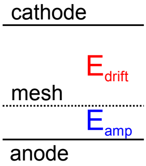
- optimize readout electronics w.r.t. speed, pulse height, stability
- optimize particle detection **efficiency**
- investigate **stability** (discharges) in high-rate hadron and muon beams
- determine and investigate **spatial resolution**
- investigate gas properties (drift velocity, diffusion $\leftrightarrow$ spatial resolution)
- optimize reconstruction algorithms

Pulse Height & Drift Field

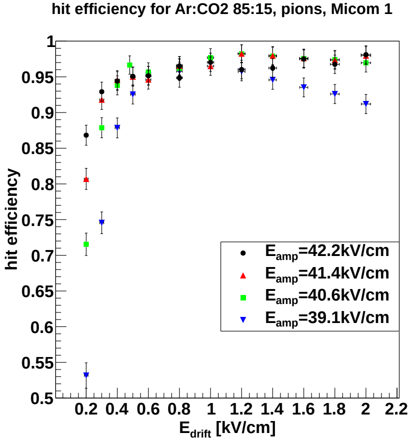


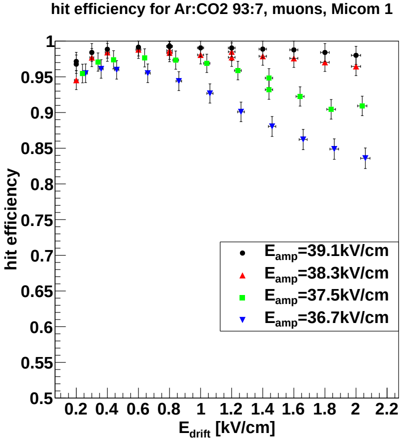


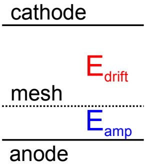
- **separation** of e^- & Ar^+ high ↔ E_d high
- electric **transparency of mesh** high ↔ E_d low



Efficiency vs Drift Field



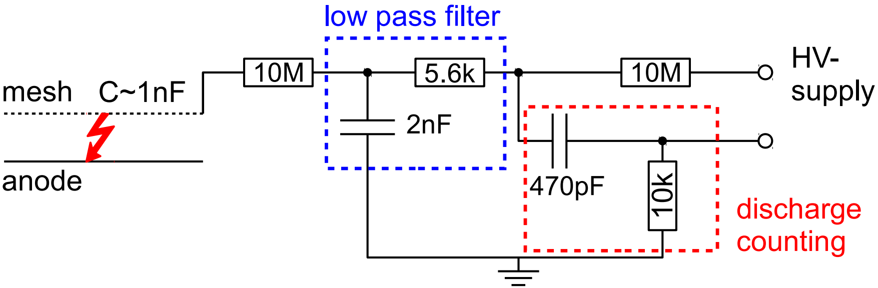




- $\varepsilon_{max} = 98.5\%$, limited by geometric effects

Discharges & Discharge Counting

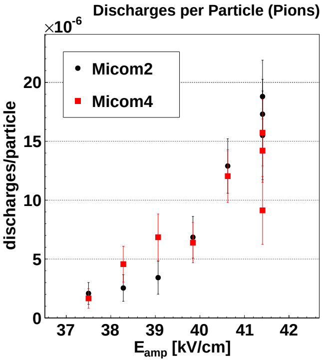
- discharges between mesh (-HV) and anode strips (ground), induced by large ionisation clusters ($> 1000e^-$)
- non destructive, **dead time** < 20ms
- detect the mesh recharge
- **pions:** discharge probability $\sim 10^{-5}$ per particle, similar for all detectors



Discharges in Pion- and Muonbeams

pions:

- particle flux $4.2 \times 10^3/\text{cm}^2\text{s}$
- discharges dominated by incident particles
  $\rightarrow$ similar for all detectors
- discharge probability $\sim \mathbf{10^{-5}}$/particle
- ~ 2 discharges per SPS spill ($= 10\,\text{s}$)
  $\rightarrow < 0.4\%$ deadtime
  $\rightarrow$ **negligible**



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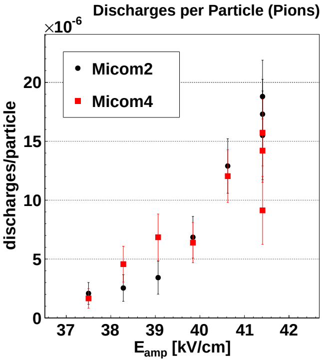
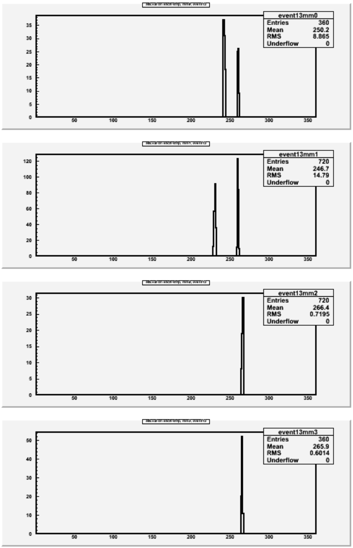


muons:

- particle flux $> 4/\text{cm}^2\text{s}$
- discharges dominated by small detector defects, factor 6 difference between detectors
- discharge rates $1/30\text{min}$ to $1/5\text{min}$ $\rightarrow < 0.04\%$ deadtime
  $\rightarrow$ **completely negligible**

Spatial Resolution

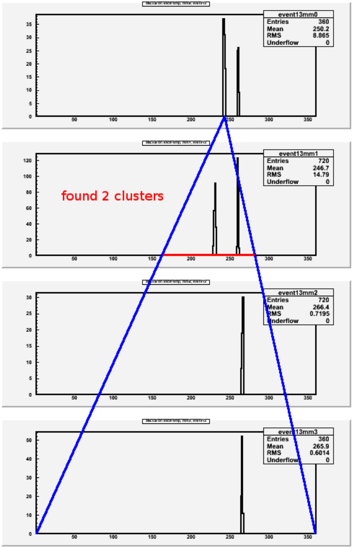
Track-Building



initial situation:

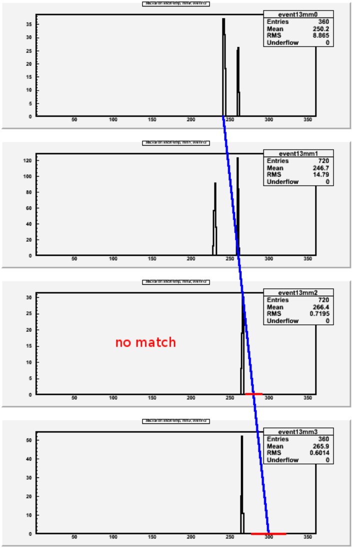
- two hits in the first two detectors, secondary low energetic particle
- using leading clusters gives bad track

Track-Building



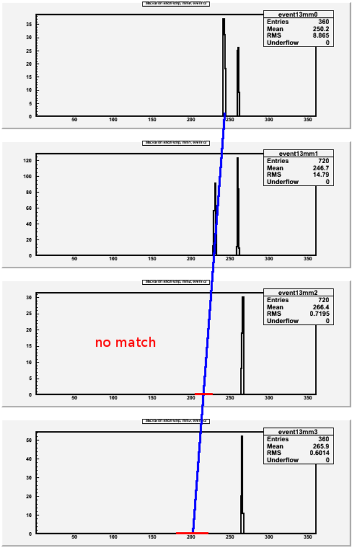
- use leading cluster in layer 1
- look for matching clusters in layer 2, within the overall geometric acceptance
- if more than one is found, use the leading cluster

Track-Building



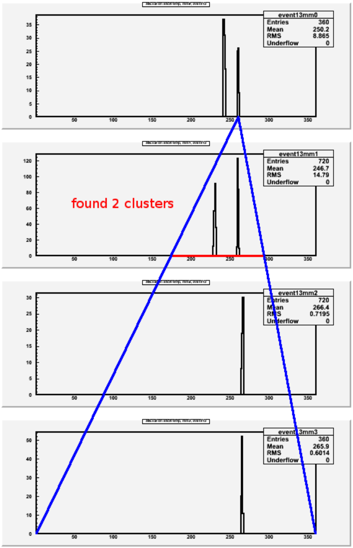
- build a track from the two clusters
- look for matching hits in layer 3
- if no hits are found ...

Track-Building



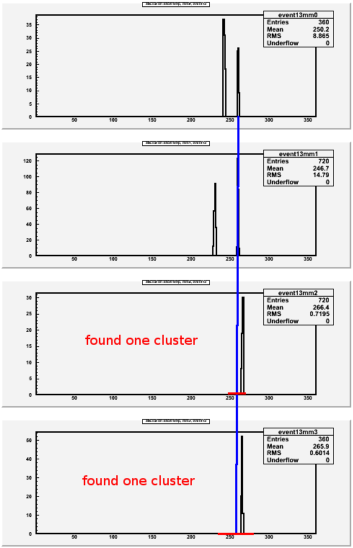
- … use the next to leading cluster in layer 2
- again build a track from the two clusters
- look for matching hits in layer 3
- if no hits are found and no further clusters in layer 2 match …

Track-Building



- ... use different start cluster in layer 1
- look for matching clusters in the layer 2, within the overall geometric acceptance
- if more than one is found, use the leading cluster

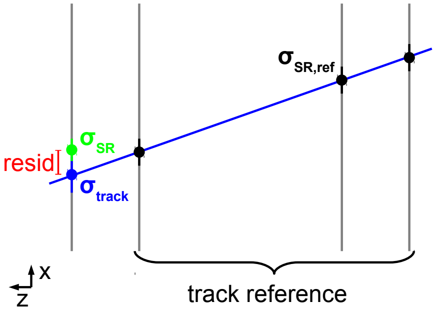
Track-Building



- build a track from the two clusters
- look for matching hits in layer 3
- if one is found, build a track from the three clusters
- look for matching hits in layer 4
- if one is found ...

found track!

Single Detector Spatial Resolution – Track Extrapolation



the method:

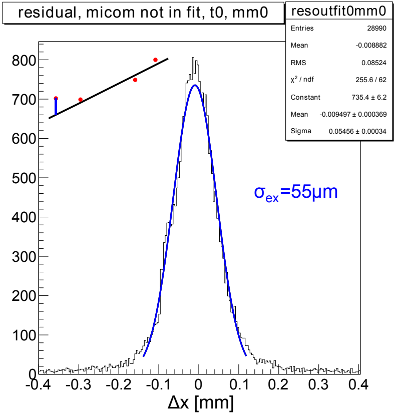
- **extrapolate track** from $n-1$ detectors into the nth
- determine residual between measured hit and track prediction
- $\sigma^2_{\text{resid}} = \sigma^2_{\text{track},n} + \sigma^2_{SR}$

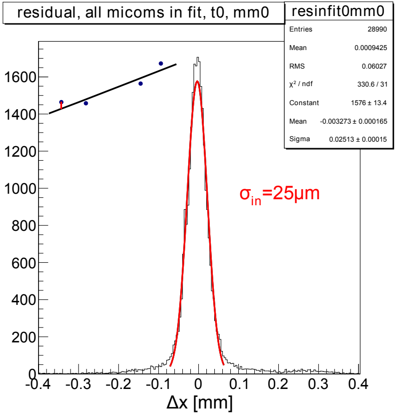
details:

- fit line $x(z) = az + b$ to $n-1$ detectors ↔ minimize $\chi^2 = \sum_{i=1}^{n-1} \left(\frac{x_i - az_i - b}{\sigma_{SR,i}} \right)^2$ → a and b
- $\sigma_{\text{track}}(z)^2 = \left\langle \left(x(z) - \langle x(z) \rangle \right)^2 \right\rangle = \sigma_{\text{track}}(z, \sigma_{SR,i})^2$

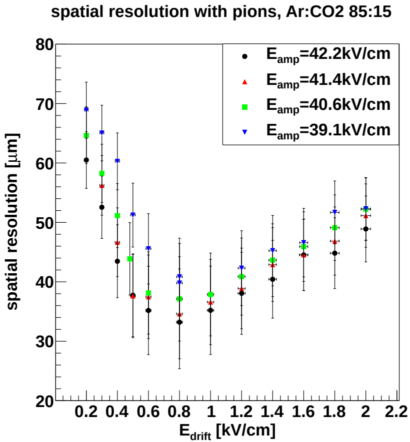
Track Resolution – NIMA 538, 372

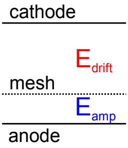
- determine σ_{in} and σ_{ex}, i.e. the residual for the detector included in the fit and excluded respectively
- Carnegie et al.: spatial resolution $\sigma_{SR} = \sqrt{\sigma_{\text{in}} \times \sigma_{\text{ex}}}$
- **equal operation parameters** in all detectors $\rightarrow \sigma_{\text{track}}\left(\sigma_{\text{SR,i}}\right)$





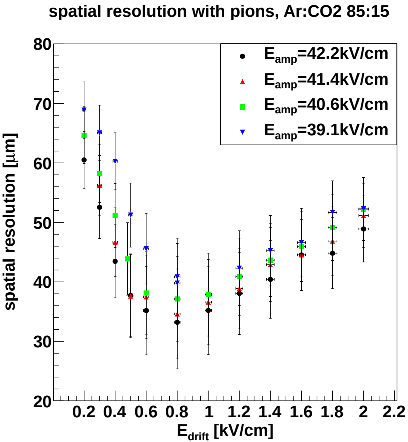
Spatial Resolution & Drift Field, Ar:CO_2 85:15

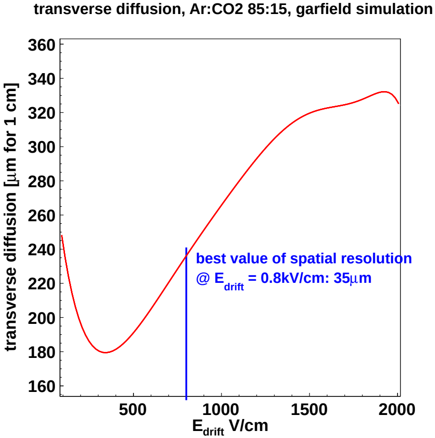


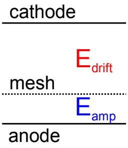


- larger resolution @ small & large E_{drift}
- **optimum resolution 35 μm @** $E_{drift} = 0.8\,kV/cm$
- idea: resolution best when charge distribution is smoothest $\leftrightarrow$ hit position is represented best
- two effects can smooth charge distribution:
    - **diffusion** of electrons
    - increasing the **number of electrons**, entering the amplification region

Spatial Resolution & Drift Field, Ar:CO_2 85:15

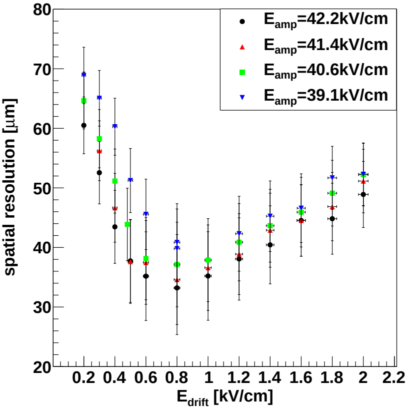


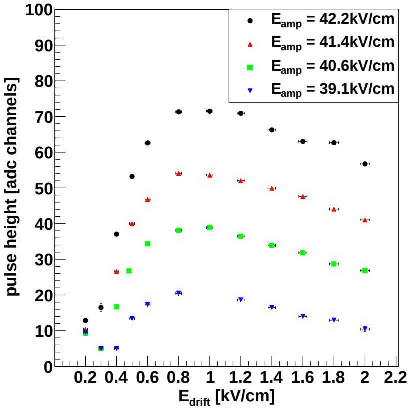


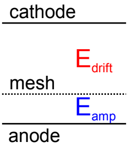


no clear dependance visible

Spatial Resolution & Drift Field, Ar:CO_2 85:15

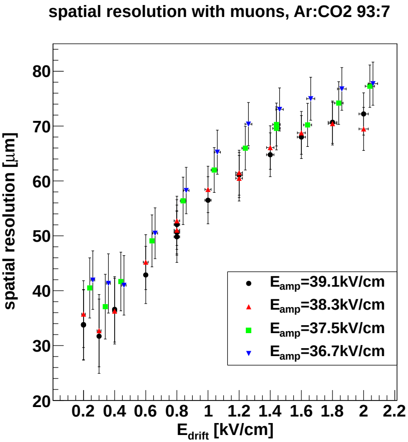


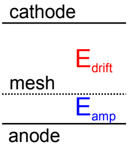




spatial resolution depends on the **number of electrons**, entering the amplification region

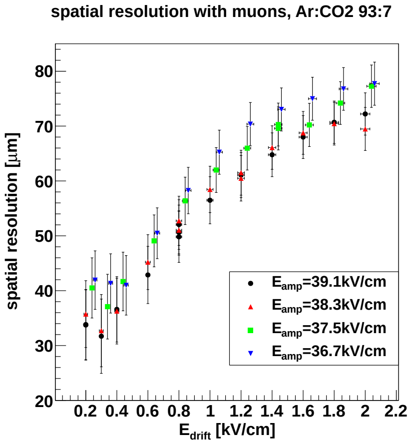
Spatial Resolution & Drift Field, Ar:CO_2 93:7

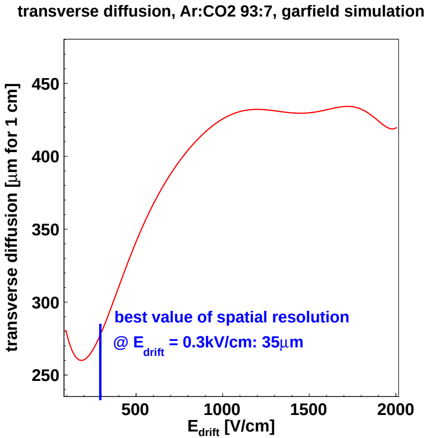


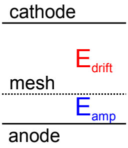


- larger resolution @ small & large E_{drift}
- optimum resolution 35 μm @ $E_{\text{drift}} = 0.3\,\text{kV/cm}$
- resolution should also depend on number of electrons in amplification region

Spatial Resolution & Drift Field, Ar:CO_2 93:7

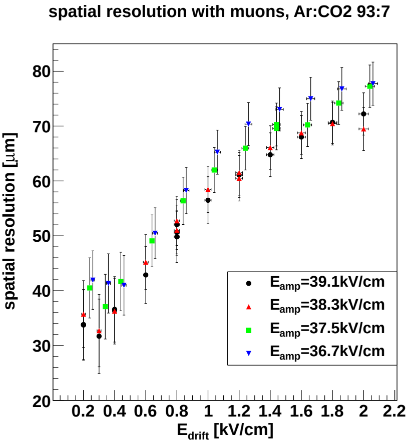


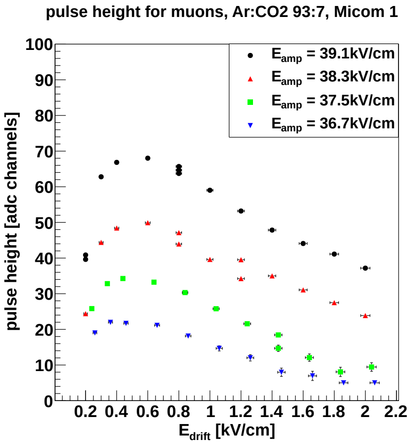


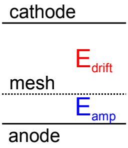


behaviour looks similar BUT absolute values don't match

Spatial Resolution & Drift Field, Ar:CO_2 93:7

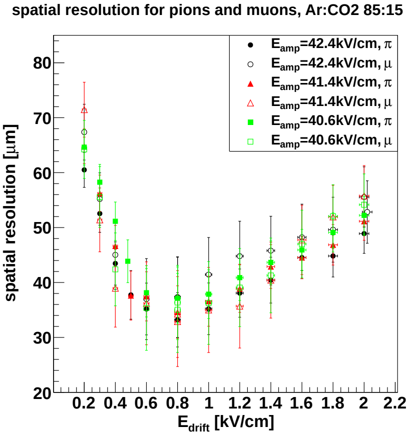


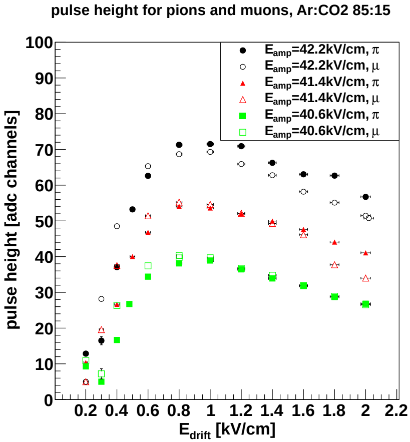




spatial resolution depends on the number of electrons, entering the amplification region

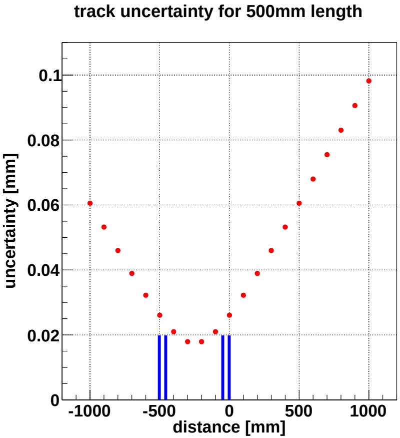
Spatial Resolution for Pions and Muons

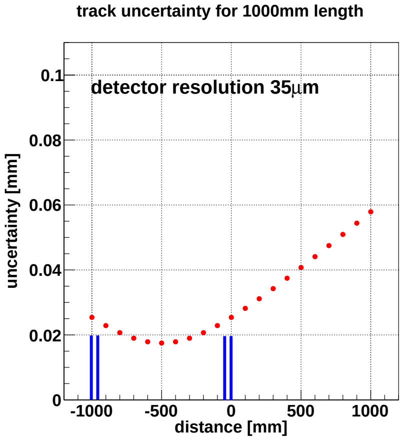




- **equivalent** behavior for pions & muons
- pulse height fluctuation ↔ temperature variation

Tracking Accuracy of the Telescope





Summary & Outlook

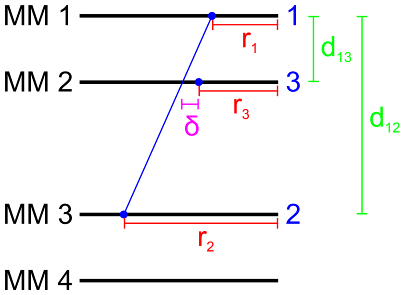
- stable operation in pure hadron and muon beam over weeks, $p_{\mathrm{spark},\pi} \lesssim 10^{-5}$
- but: in high background environment discharge counter-measures needed (resistive strips, floating strips)
- optimization w.r.t. gas gain, drift field, trigger latency, readout configuration
- spatial resolution $\leftrightarrow$ number of electrons entering amplification gap
- single detector spatial resolution $\sigma_{\mathrm{opt}} \sim 35\mu m$
  $\Rightarrow$ overall tracking resolution $\sigma \sim 20\mu m$
- track merging with additional DAQ systems possible (analog trigger tag)

Summary & Outlook

Thank you!

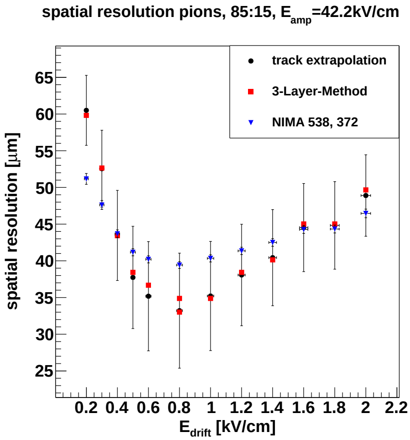
backup

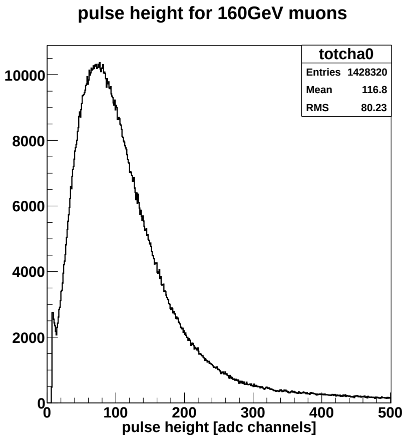
backup: Single Detector Spatial Resolution II – 3 Layer Method



- interpolate track prediction by two detectors into 3rd and compare with measured hit in that detector
- $\delta = r_3 - r_2 \frac{d_{13}}{d_{12}} - r_1 \left(1 - \frac{d_{13}}{d_{12}}\right) \rightarrow$ $(\Delta\delta)^2 = (\Delta r_3)^2 + \left(\frac{d_{13}}{d_{12}} \Delta r_2\right)^2 + \left[\left(1 - \frac{d_{13}}{d_{12}}\right) \Delta r_1\right]^2$
- 4 Δr_i & 4 different triplett-equations $\rightarrow$ solvable system

backup: Comparison of the Three Methods





- method I and II equivalent
- method III tends to decrease the difference of spatial resolution for different detectors ($\sigma_{\mathrm{SR,ref}} = 44 \pm 2\mu\mathrm{m}$)