Position Sensitive Scintillating Muon Detector with Silicon Photomultiplier Readout

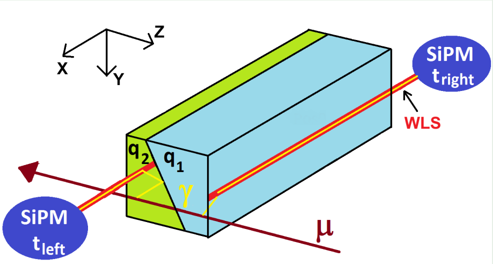
Ralph Müller

Ludwig-Maximilians-Universität
LS Schaile

July, 8^{th} 2013
26^{th} IMPRS Workshop
Max Planck Institute for Physics

Operation Principle (Basic Study)

Prototype: Two Trapezoids

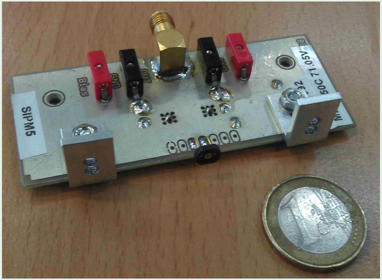


$$x = \frac{t_{left} - t_{right}}{t_{left} + t_{right}}; \; y = \frac{q_1}{q_1 + q_2}$$

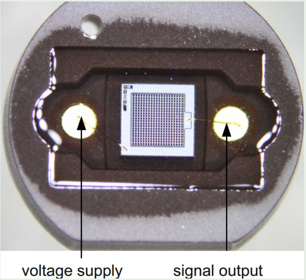
- Plastic scintillator BC-400
- Two optically insulated trapezoids
- Proportionality between path length of the muon and photon production (q_i)
- Light collection with wavelength shifting fiber (WLS)
- Silicon photomultipliers (SiPM)
- Two dimensional spatial resolution

Silicon Photo Multiplier(SiPM)

Amplifier board with SiPM



SiPM with 400 *px*

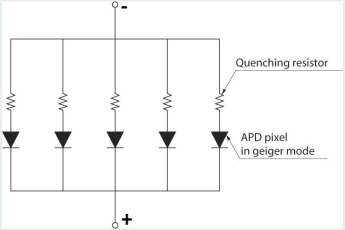


- Hamamatsu SiPMs
- Array of silicon Avalanche Photo Diods
- Pixel sizes: $25\,\mu m\left(\frac{40\times40}{mm^2}\right)$, $50\,\mu m\left(\frac{20\times20}{mm^2}\right)$ and $100\,\mu m\left(\frac{10\times10}{mm^2}\right)$
- Active area: $1\times1\ mm^2$ (and $3\times3\ mm^2$)

Silicon Photo Multiplier (SiPM)

- Photodiods: reversed bias voltage (V_{bias}) above breakdown voltage
- Creation of electron-hole pairs by photons (signal) or thermal excitation (background)
- Avalanche due to high E-field
- Voltage drop across quenching resistor
  $\Rightarrow V_{bias} < V_{BD}$
  $\Rightarrow$ Stop of the avalanche
- Recharge of the diode

Equivalent Circuit Diagram



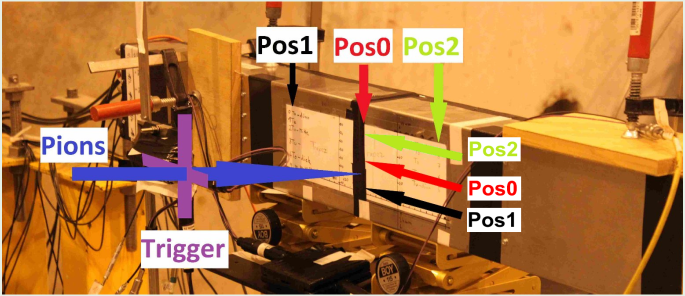
Advantages:

- Detection of single photons
- Extremly good time resolution $\approx 30\ ps$
- Insensitive to magnetic fields
- $V_{bias} < 100\ V$

Outline

1. Experiment:
   CERN (Fall 2012, H6 Beamline, 120 *GeV* Pions)
   - Position Resolution in X
   - Position Resolution in Y
2. Optimization of Light Yield
   - Computer Monte Carlo Simulation
   - Experimental Simulation

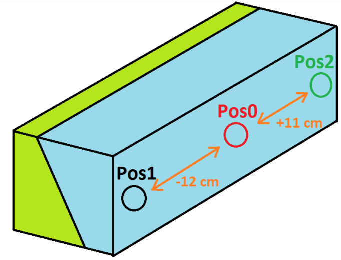
Setup at CERN (120 *GeV* Pions)



- $(5\ mm)^2$ coincidence trigger area
- Five wavelength shifting fibers per scintillator
- Single sided readout

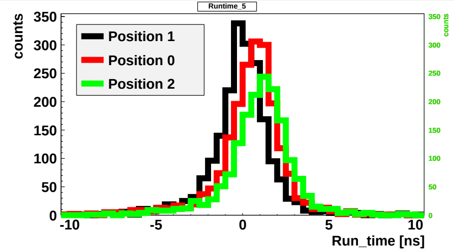
Scan in X-Directions (Time of Flight)

Scheme of Positions



- $(5\ mm)^2$ trigger area
- $x = \frac{t_{left} - t_{right}}{t_{left} + t_{right}}$
- Expected: $\Delta t \approx 0.6\ ns$

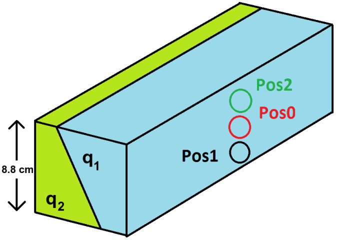
Result of Measurement



$$t_{max,\ Pos1} = (0,03 \pm 1,3)\ ns$$
$$t_{max,\ Pos0} = (0,69 \pm 1,3)\ ns$$
$$t_{max,\ Pos2} = (1,10 \pm 1,4)\ ns$$
$$\Rightarrow \Delta x_{Pos_1,\ Pos_0} \approx -12\ cm$$
$$\Rightarrow \Delta x_{Pos_0,\ Pos_2} \approx\ 8\ cm$$

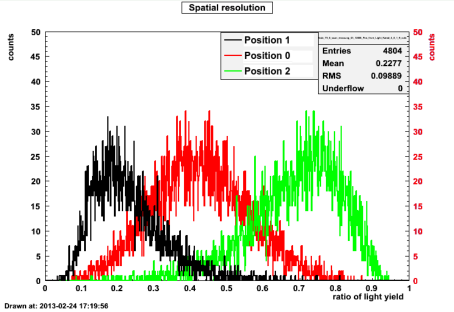
Scan in Y-Direction (Pulseheight)

Scheme of Positions



- $(5\ mm)^2$ trigger area
- $y \propto \frac{q_1}{q_1+q_2}$

Result of Measurement



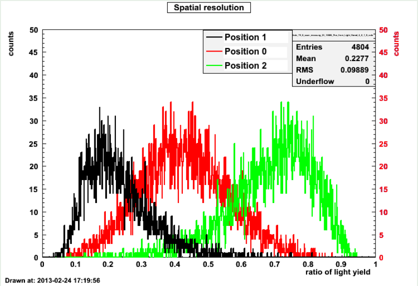
- Position resolution of $\approx 3\ cm$ (FWHM)
- $\Delta y \propto \frac{1}{\sqrt{N_{Ph}}}$

Simulation General

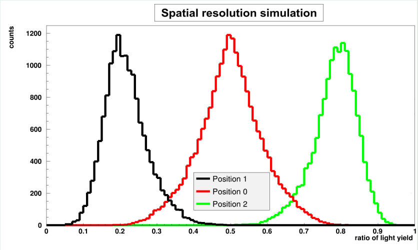
- Monte Carlo Simulation of photon propagation in a trapezoid
- $N_{Ph} = \dfrac{\left.\frac{\mathrm{d}E}{\mathrm{d}z}\right|_{\mu} \cdot \Delta z}{w}$
- Simulation of a $5 \times 5\ mm^2$-Trigger-Sensitive-Area
- φ-Direction: Uniform distribution: $\varphi = \mathrm{rand}\,[0,\ 2\pi]$
- ϑ-Direction: $\cos^2\vartheta$ distribution: $\vartheta = \arccos\left(\sqrt{\mathrm{rand}\,[0,\ 1]}\right)$
- Total reflection at scintillator surface ($\sphericalangle\,(\mathrm{tot.\ refl.}) = 40°$)
- Diffuse or directed reflection on cover material

Comparisson between Measurement and Simulation

CERN Result



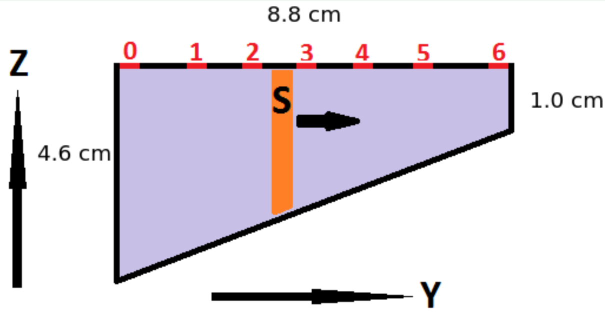
MC Simulation Result



- Measurement and Simulation basically show same results
- Photon production in simulation is preliminary

Scheme of the Simulation

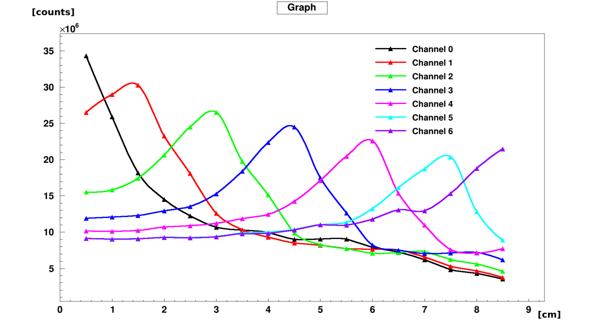
Design of First Prototype



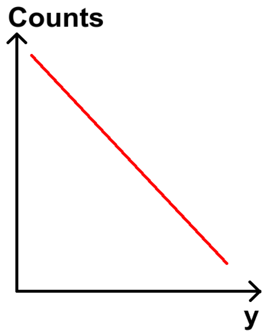
- 0 . . . 6: WLS fiber
- Moving the source in 5 *mm* steps from left to right
- 17 steps in total
- Label of a step corresponds to the mid of source position

Response of the Seven Channels at the 17 Steps

Light Output of the Seven Channels



Ideal Response Ch0

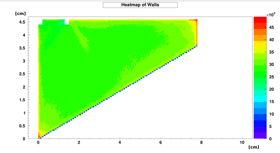


- Channel 0: measure for qualitiy of performance
- Channel 6: normalisation of light production? (MIP)

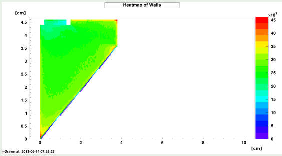
Computational Study for Optimal Trapezoidal Geometry

Compression in 1 cm steps: Constant height at thin side

Compression to 7.8 cm



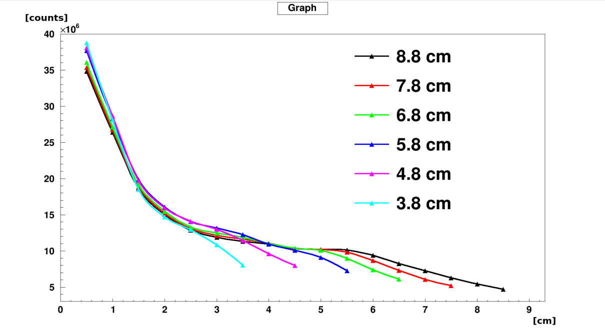
Compression to 3.8 cm



e.g.: step 7/17

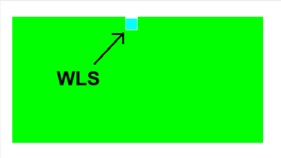
$\hat{=}\ y = 3.5\ cm$

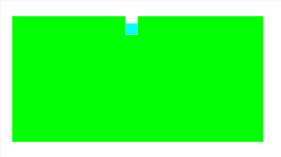
Result of the Compression Study

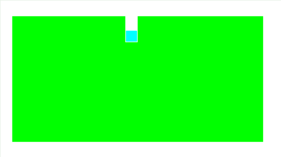


Position dependency over whole scintillator

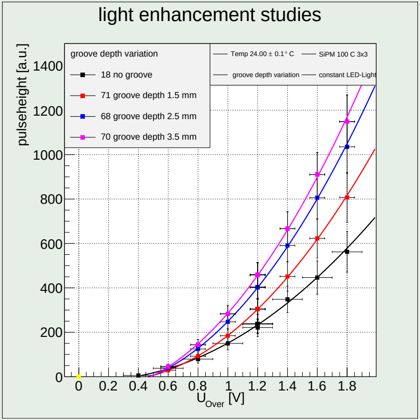
Experimental Study for Optimal Groove Depth







Varying Groove Depth



Increasing light output by increasing groove depth

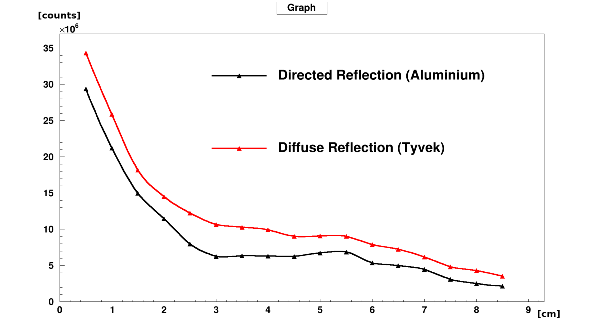
Summary and Outlook

1. Computational Studies of Cover Material (Aluminium, Tyvek)
   - Increased photon collection with diffuse reflective material
   - TODO: Perform measurements to check simulation results
2. Computational Geometry Studies
   - Best position dependency at the corners of the broad side
   - Improved position dependency with compressed scintillator
   - TODO: Built a second prototype to check simulation results
3. Experimental Studies
   - Increased light output by increased groove depth
   - Light propagation using LED-Driver:
     reproduction of Monte Carlo
     best position resolution at broad side
   - TODO: Measure various cover materials
   - TODO: Built a second prototype

Thank you !!!

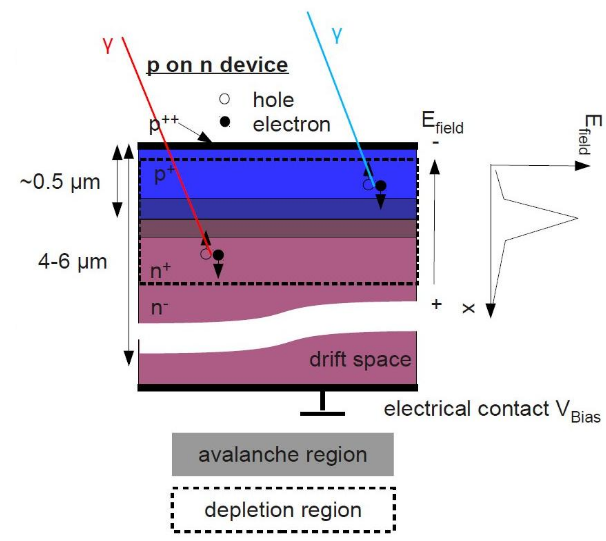
Results for Different Cover at Channel 0

Result of Cover Simulation for Channel 0



- Inceased light output by use of Tyvek-cover-material
- Same shape of the curves $\Rightarrow$ No change in position sensitivity

PN Junction


γ
γ
p on n device
hole
electron
p++
p+
~0.5 µm
4-6 µm
n+
n-
drift space
E field
-
+
x
E field
electrical contact V Bias
avalanche region
depletion region

Studies for Optimized Trapezoidal Geometry I

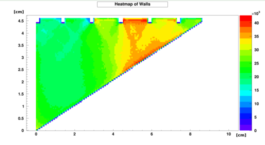
Motivation for Geometry Studies

Optimized light yield at the thin side of the trapezoid

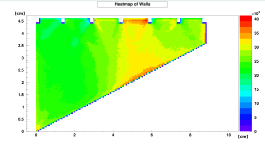
Studied with Channel 0

$\Rightarrow$ Variation of the trapezoidal geometry at thin side

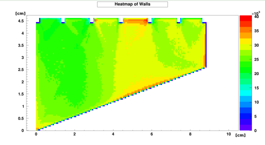
0.1 *cm*



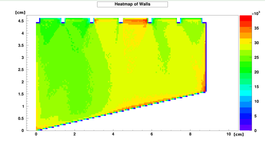
1.0 *cm* (CERN Geometry)



2.0 *cm*



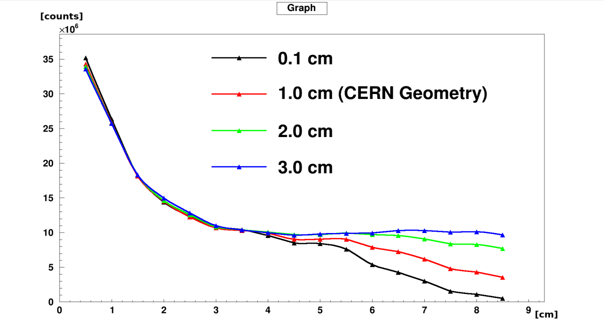
3.0 *cm*



As example: step $9/17 \,\hat{=}\, y = 4.5\ cm$

Optimal geometry: Width Study

Result for the Four Different Geometrys for Channel 0

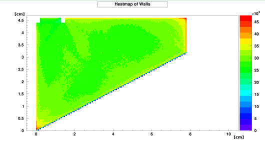
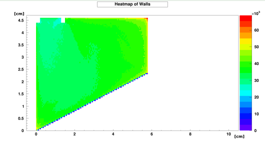
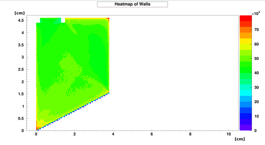


- Increasing photon detection at Channel 0 for a thicker end
- Decreasing position sensitivity at Channel 0 for a thicker end

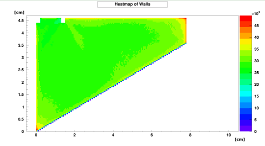
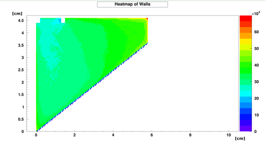
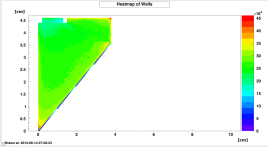
Possibility: Cut away the position insensitive part; $y > 4.5\ cm$

Studies for Optimal Trapezoidal Geometry II

1. Cut in 1 *cm* steps: Constant slope

Cut at 7.8 *cm*	Cut at 5.8 *cm*	Cut at 3.8 *cm*
		

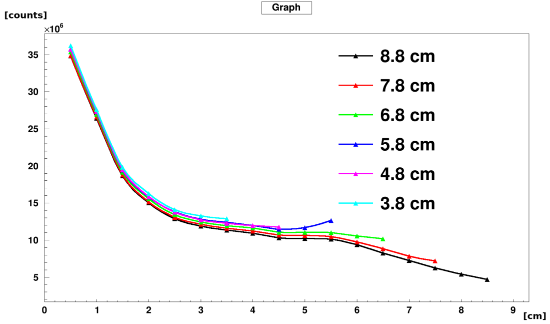
2. Compression in 1 *cm* steps: Constant height at thin side

Compression at 7.8 *cm*	Compression at 5.8 *cm*	Compression at 3.8 *cm*
		

As example: step $7/17 \hat{=} y = 3.5\ cm$

Optimal Geometry: Cut Study for Channel 0

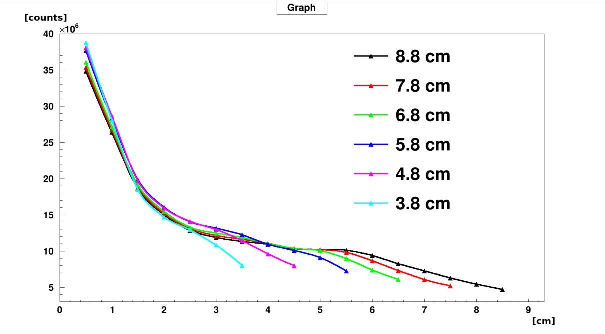
Result of the Cut Study



- Position independent part vanishes
- Slightly increased light output ($\rightarrow$ mean free path of the photons)

Optimal Geometry: Compression Study for Channel 0

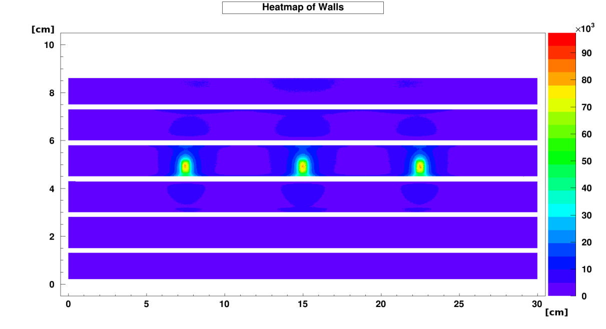
Result of the Compression Study



- Position independent part vanishes
- Position dependency over the whole scintillator (light-blue-curve)

Studies for Optimal Trapezoidal Geometry III

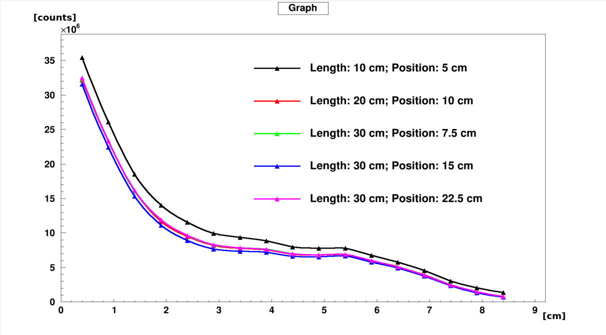
30 *cm* long Scintillator with Three Muon Positions



- Three scintillator sizes: 10 *cm*, 20 *cm* and 30 *cm*
- 10 *cm* and 20 *cm* scintillator: Photon source in the middle
- 30 *cm* scintillator: Photon source at 7.5 *cm*, 15 *cm* and 22.5 *cm*
- Standard dimension for the rest of the trapezoidal shape

Optimal Geometry: Length

Light Output for Various Length for Channel 0



- No bid effect on the position sensitivity
- Slightly less light output for longer scintillator
- Slightly more light output for positions closer to the edge