Position-dependent detector response of a liquid scintillation detector instrumented with wavelength-shifting optical modules and SiPMs using cosmic muons

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on behalf of the SBT collaboration

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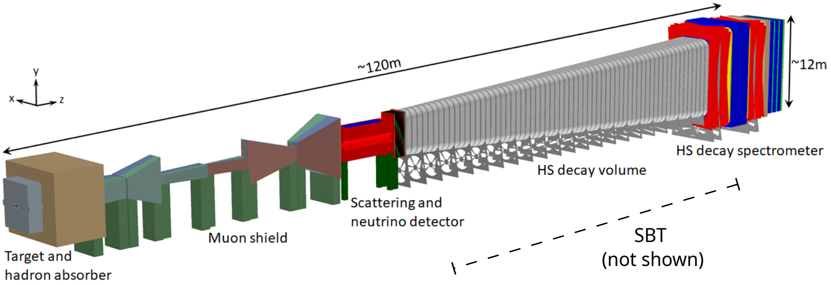
SHiP

Overview

1. SHiP Surround Background Tagger (SBT)
2. Liquid Scintillator SBT
3. Spatial resolution studies with a small-scale SBT cell prototype
4. Results

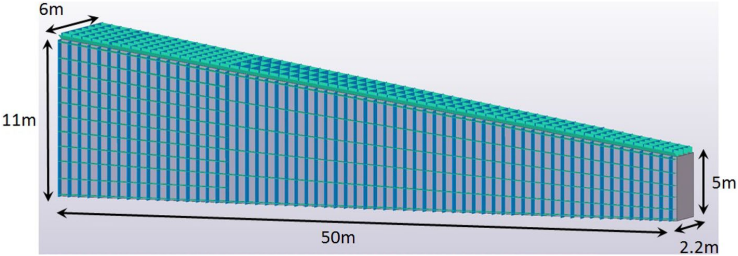
Search for Hidden Particles (SHiP)



Cr.: SHiP Collaboration [1].

- 'intensity frontier' experiment proposed at CERN SPS
- looking for long-lived exotic particles, $m < \mathcal{O}(10)\mathrm{GeV}\,c^{-2}$
- decay volume surrounded by liquid scintillator SBT

Surround Background Tagger (SBT)



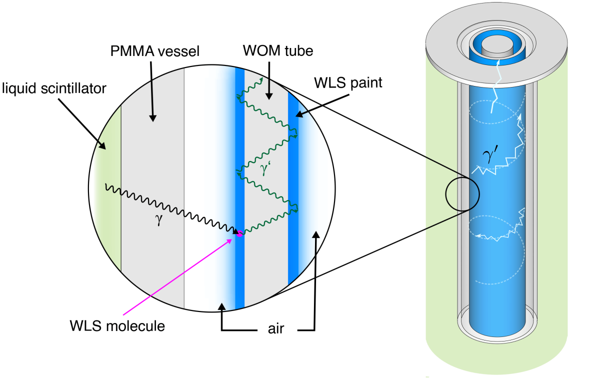
Cr.: Miano et al [2].

- requirements:
  - full coverage of surrounding area
  - high detection efficiency for charged particles (muons) entering decay vessel & deep inelastic scattering events induced by ν and μ from beam dump target

  $\Rightarrow$ liquid scintillator (LS): LAB + PPO ($2\,\mathrm{g\,L^{-1}}$)
- SBT made up of $\mathcal{O}(2000)$ detector 'cells'

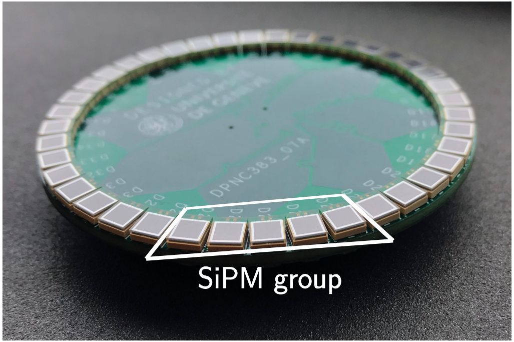
Wavelength-shifting Optical Module (WOM)

- LS UV light enters PMMA tube → wavelength-shifted → travels via total reflection
- WOM light-guide → detection area of WOM >> just SiPMs
- path of light to end of tube can be arbitrarily complex



Adapted from [3].

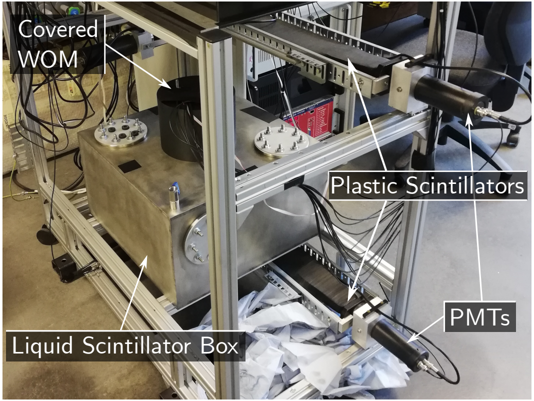
Electronics



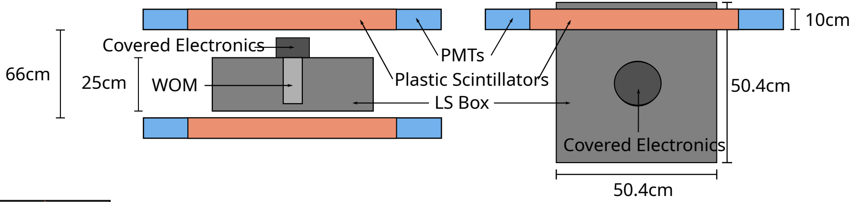
- WOM optically coupled to circular array of 40 SiPMs
- SiPMs mounted on PCB, PCB connected to eMUSIC board
  $\rightarrow$ 40 signals gathered in 8 analog channels à 5 SiPMs
- eMUSIC board connected to WaveCatcher (A-to-D converter)

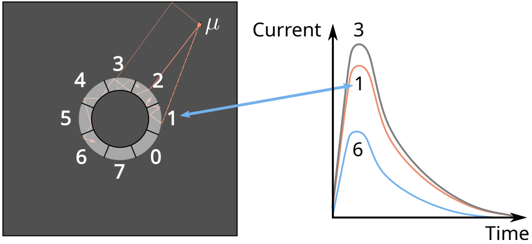
SBT Cell Prototype

- WOM and LS contained in 50.4 cm × 50.4 cm × 25 cm steel box
- SiPM array and electronics covered to prevent light leakage
- two sets of plastic scintillators + PMTs used to trigger on cosmic muons



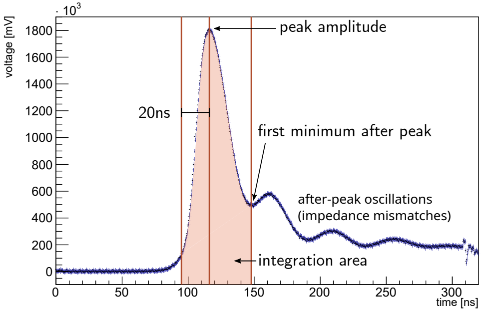
Position-dependent Detector Response





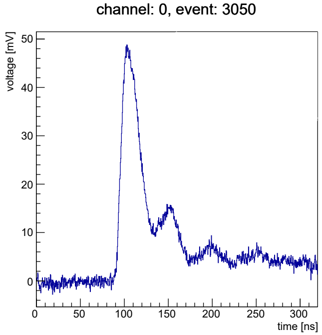
- muon generates scintillation light in LS box
- light gets collected, shifted by WOM $\rightarrow$ travels to SiPM array
- goal: study signal in 8 SiPM groups as function of muon incidence location

SiPM Signal



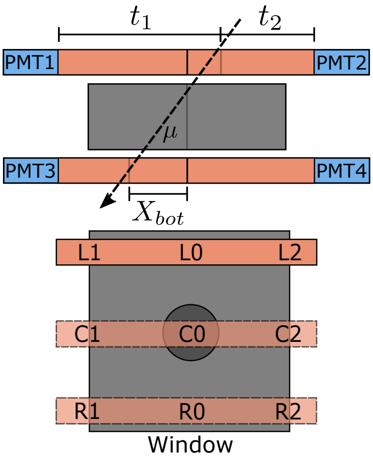
Light yield:

$$J = \int_{\Delta t} U(t)\, dt$$



- WaveCatcher records 320 ns voltage waveform per event and SiPM group
- 'main signal' integrated using ROOT-based software [4] → light yield measure for amount of light collected per group

Muon Incidence Location

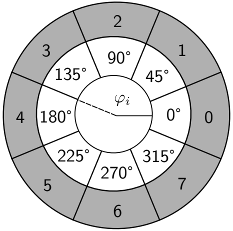


- muon location can be determined using speed of light inside plastic scintillators c_{PS}

$$X_{bot} = \frac{1}{2} \cdot c_{PS} \cdot (t_4 - t_3) = \frac{1}{2} \cdot c_{PS} \cdot \Delta t_{43}$$

- same for X_{top} $\rightarrow$ can filter Δt to set location
- compare detector signals for 8 + 1 positions
- use C-0 to determine non-uniformity of signal transmission

Event-dependent Mean Angle ϕ_{ew}



$$x_i = \frac{1}{N}\cos(\varphi_i)\cdot\frac{J_i}{\overline{J_i^{C0}}} \qquad y_i = \frac{1}{N}\sin(\varphi_i)\cdot\frac{J_i}{\overline{J_i^{C0}}}$$

$$\overline{J_i^{C0}} = \frac{J_i^{\text{C0, av.}}}{\frac{1}{8}\sum_{k=0}^{7} J_k^{\text{C0, av.}}}$$

- assign angle φ_i to each group i
- average all angles φ_i weighted by normalised light yield in respective group J_i $\rightarrow$ use vectorial addition

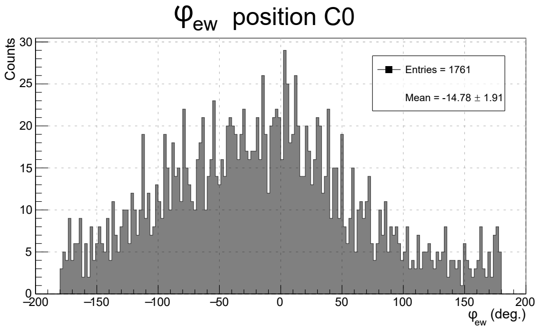
$$X = \sum_{i=0}^{7} x_i \qquad Y = \sum_{i=0}^{7} y_i$$

- correct for non-uniformity using C-0
- convert averaged vector back to polar angle ϕ_{ew}, project on $[-180°, 180°]$ interval

$$\phi_{ew} = \arctan\left(\frac{Y}{X}\right)$$

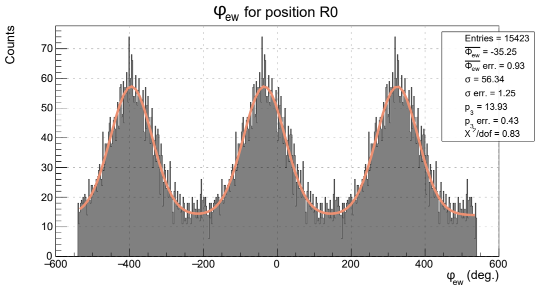
Central Position C-0

– with ideal optical coupling between WOM and SiPMs, expect uniform ϕ_{ew} distribution for C-0 $\rightarrow$ it is not



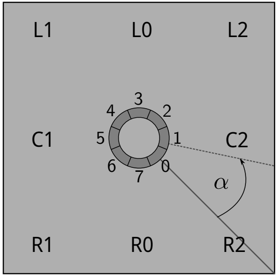
$\Rightarrow$ optical coupling and/or SiPM efficiency not uniform $\rightarrow$ use to normalise wrt. light yield

Position-dependent Mean angle $\overline{\Phi_{ew}}$

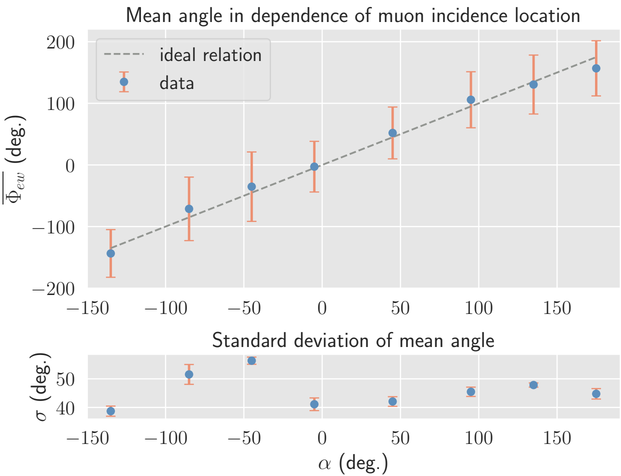


- sample corrected ϕ_{ew} distribution for position R-0
- barring shift of mean, similar for all positions
- fit Gaussian to determine position-dependent mean angle $\overline{\Phi_{ew}}$
- single Gaussian would require knowing mean (periodicity) $\rightarrow$ fit 3 Gaussians over $(0^{\circ}, \pm 360^{\circ})$ shifted values

Position-dependent Mean angle $\overline{\Phi_{ew}}$

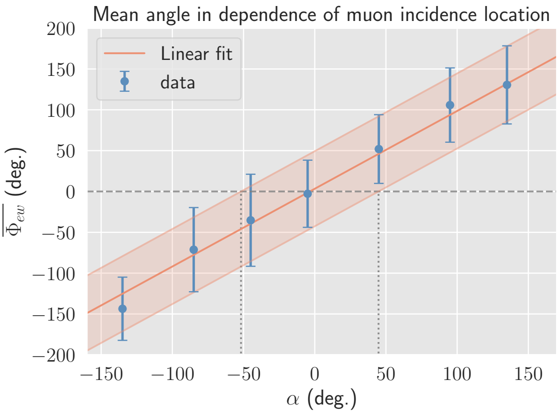


window



- assign angle α to each muon incidence location
- $\alpha \in [-180°, 180°]$, so that $\alpha = 0$ corresponds to corner of box

Conclusion



- For single event, can assign $\approx 100^\circ$ region at 1σ CL

We can determine the location of the primary light-source, i.e. the muon incidence, to a region of around 100° (at 1σ CL).

[1] SHiP Collaboration, "SHiP experiment - Comprehensive Design Study Report," Tech. Rep. CERN-SPSC-2019-049 ; SPSC-SR-263, Dec. 12, 2019.

[2] A. Miano, A. Fiorillo, A. Salzano, A. Prota, and R. Jacobsson, "The structural design of the decay volume for the search for hidden particles (SHIP) project," *Archives of Civil and Mechanical Engineering*, vol. 21, no. 1, Mar. 2021, ISSN: 1644-9665. DOI: `10.1007/s43452-020-00152-9`.

[3] Jan Zimmermann, "Efficiency studies of a liquid-scintillator detector based on wavelengthshifting optical modules," Master Thesis, Humboldt-University Berlin, 2020.

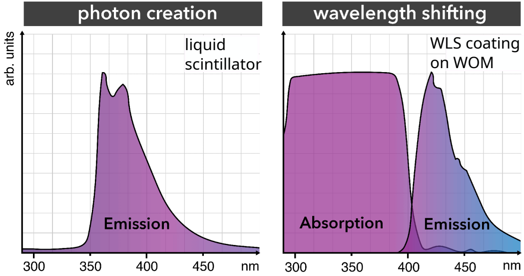
[4] Jan Zimmermann, *RootReader*, [Online]. Available: `https://github.com/Uni2K/RootReader` (visited on 03/03/2021).

[5] Joscha Hanel, "Determination of directional information from scintillation photons using SiPM-array-instrumented wavelength-shifting optical modules," Bachelor Thesis, Humboldt-University Berlin, 2020.

[6] M. Ruiz, “A fundamental study of organic scintillation for X-ray dosimetry in medical imaging,” Ph.D. dissertation, Université de Strasbourg, 2014.

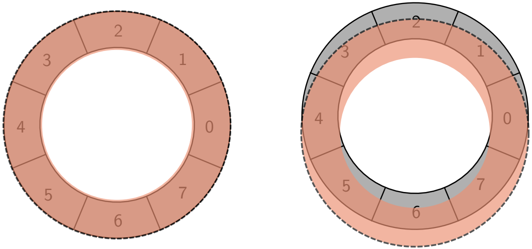
[7] Hamamatsu Photonics K.K., *Photomultiplier Tubes - Basics and Applications*, 2007. [Online]. Available: https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf (visited on 09/19/2021).

Wavelength-shifting Optical Module (WOM)

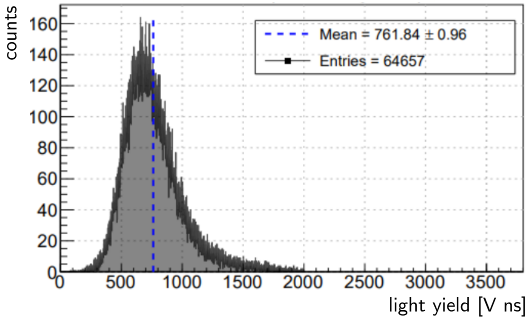


Adapted from [3].

- emission maximum of LS around 350 to 400 nm
- use wavelength-shifting paint on WOM → paint absorbs LS photons, re-emits in visible spectrum

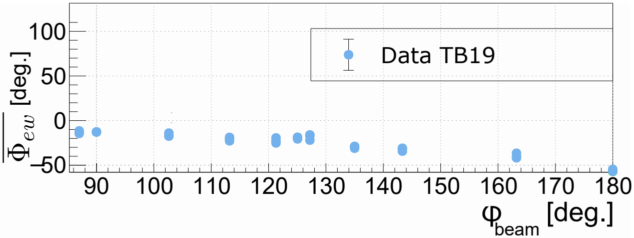


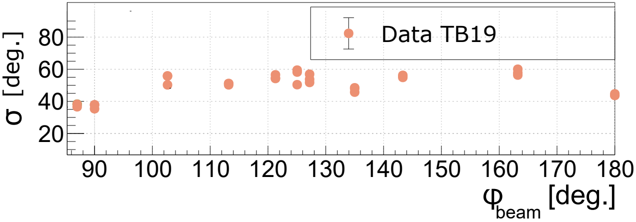
- imperfect coverage of WOM by SiPM array could favour some SiPM groups

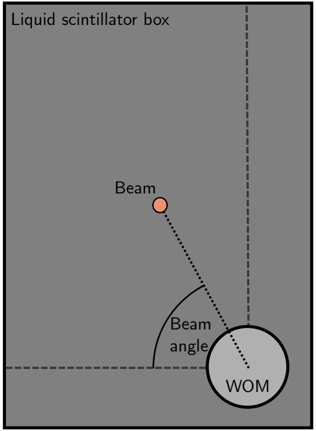


- light-yield from $\sim 65\,000$ events in one SiPM group

Cr.: Joscha Hanel [5].

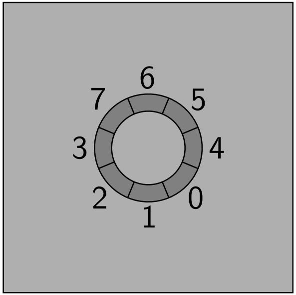




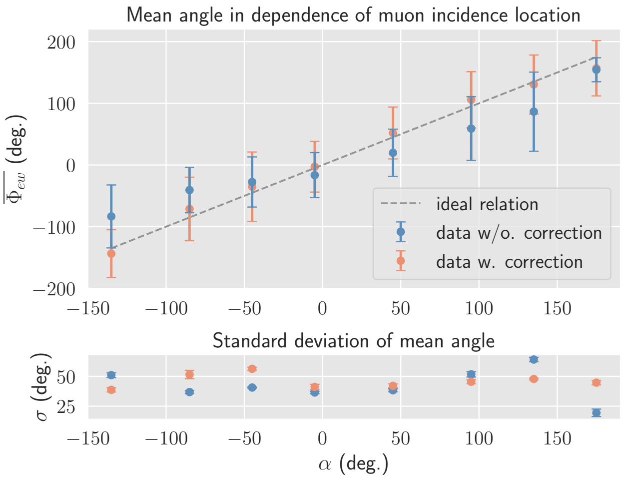


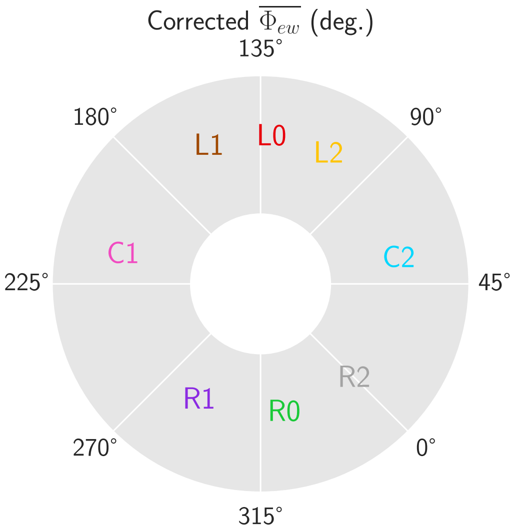
Sketch of TestBeam19 setup

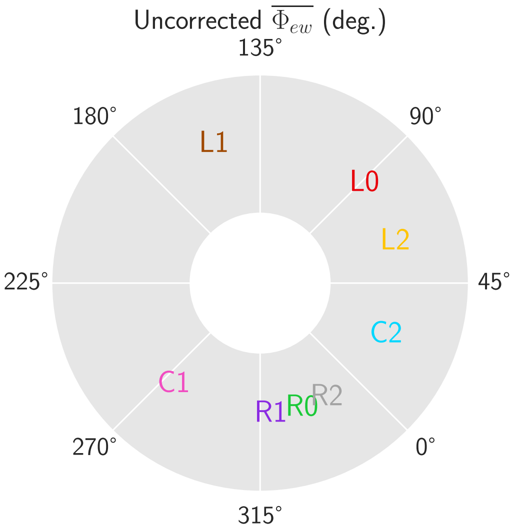
- $\Delta\phi_{beam} = 90^\circ \rightarrow \Delta\overline{\Phi_{ew}} = 45^\circ$



WaveCatcher channels' relative locations


Mean angle in dependence of muon incidence location
$\overline{\Phi_{ew}}$ (deg.)
200
100
0
−100
−200
−150
−100
−50
0
50
100
150
ideal relation
data w/o. correction
data w. correction
Standard deviation of mean angle
σ (deg.)
50
25
−150
−100
−50
0
50
100
150
α (deg.)


Corrected $\overline{\Phi_{ew}}$ (deg.)
135°
90°
45°
0°
315°
270°
225°
180°
L1
L0
L2
C1
C2
R1
R0
R2


Uncorrected $\overline{\Phi_{ew}}$ (deg.)
135°
90°
45°
0°
315°
270°
225°
180°
L1
L0
L2
C2
C1
R1
R0
R2