Development of the SHiP Timing Detector Based on Scintillating Bars Readout by SiPMs

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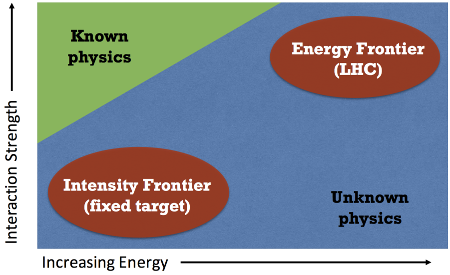
Motivation

- The Standard Model provides an explanation for many subatomic processes
- Although very successful, it fails to explain many observed phenomena

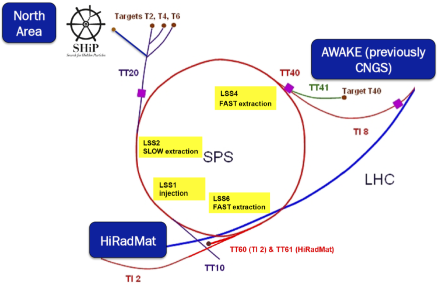
  Dark Matter
  Neutrino oscillation and masses
  Matter/antimatter asymmetry in the universe
- May have a whole Hidden Sector of weakly interacting particles BSM
- Energy Frontier
  Heavy particles → High energy events
- Intensity Frontier
  Light particles → Rare events

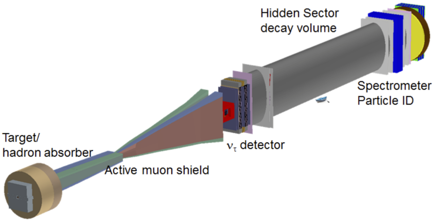


The SHiP experiment

- The SHiP (**S**earch for **Hi**dden **P**articles) experiment is a proposed fixed target facility at the CERN SPS
- SPS proton beam:

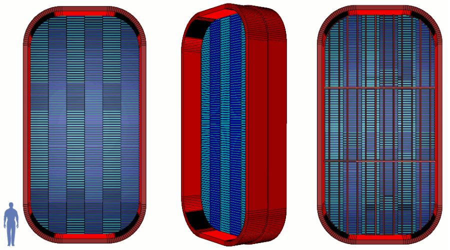
  4×10^{13} protons per spill @ 400 GeV
  $\rightarrow 2 \times 10^{20}$ collisions in 5 years
- Will probe long lived exotic particles with masses below $\mathcal{O}(10)$ GeV
- Programme will include searches of very weakly interacting low-energy SUSY states as well as direct searches for Dark Matter, Sterile Neutrinos and Dark Photons
- Neutrino detector consists emulsion target with tracking in a magnetic field followed by a muon spectrometer
  $N_{\nu_\tau} \sim 10^4$
- Hidden particle detector will consist of a long evacuated decay volume with a magnetic spectrometer, calorimeters, and a muon detector located on the far end

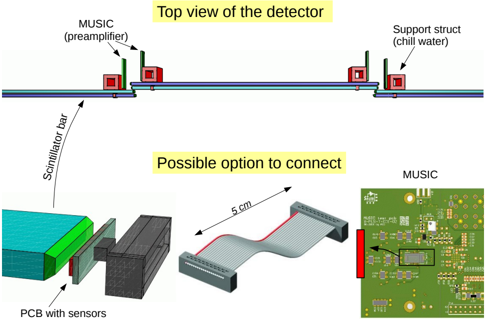




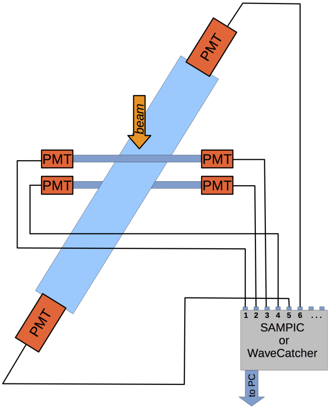
The SHiP timing detector

- A dedicated timing detector can be used to reduce random crossing in the detector
- Combinatorial di-muon background can be reduced to an acceptable level by requiring a timing resolution of 100 ps or less
- Two options have been proposed for the timing detector
  plastic scintillators
    1. plastic scintillators read-out by PMTs or SiPMs
    2. multigap resistive plate chambers
- This study focuses on the plastic scintillator option read-out by SiPMs



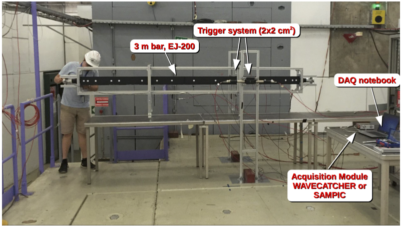


PMT option: Set-up

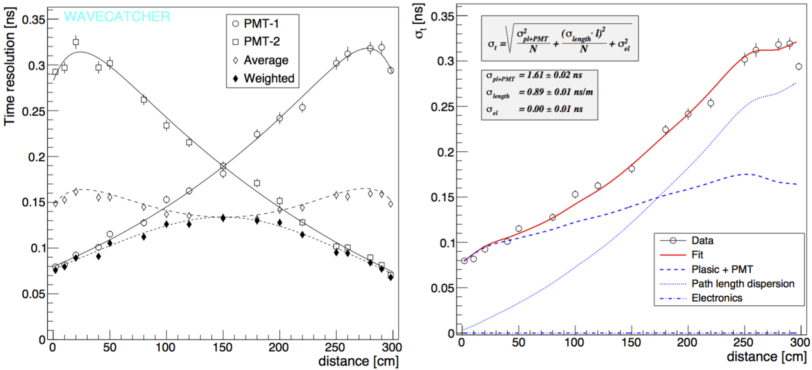


[arXiv:1610.05667]

- 10 GeV/c muon beam produced from the CERN PS (T9 beamline)
- 3 m long bar (EJ-200) readout by PMTs
- 2 reference counters used for trigger
  $\rightarrow$ 40 ps resolution
- Two DAQ systems are studied
  1. WAVECATCHER: 8 channel, hardware trigger $\sim$ few kHz
  2. SAMPIC: 16 channel, self triggering $\sim$ 150 kHz
- Time resolution of entire system is taken as Gaussian width of the following
  $\Delta t = \frac{t_1+t_2+t_3+t_4}{4} - t_{5,6}$



PMT option: Results



- 135 ps resolution halfway between bar (1.5 m)
- About 130 p.e./PMT when interaction is at middle of the bar
- Path length dispersion in the bar dominates time resolution at large distances
  $\rightarrow$ Main limiting factor for long bars
  $\rightarrow$ Faster electronics won't help

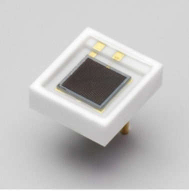
SiPM characterization

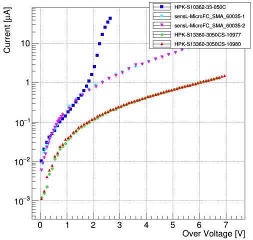
- SiPMs from two manufacturers:

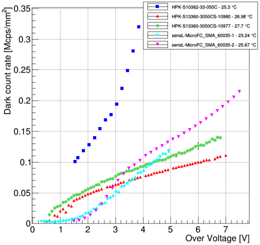
  Hamamatsu Photonics
  SensL

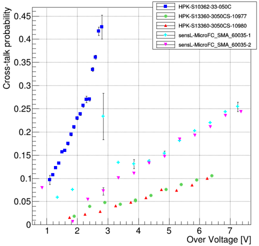
- SiPM characterized by:

  Current-Voltage behavior
  Dark count rate
  Cross-talk probability
  Single photon time resolution



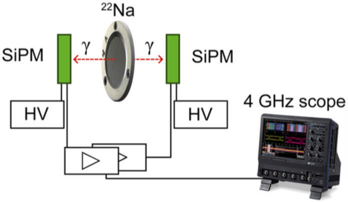




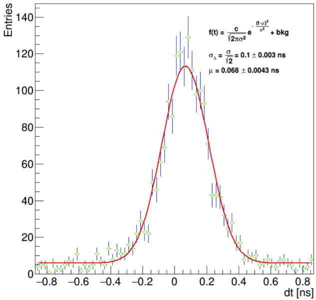


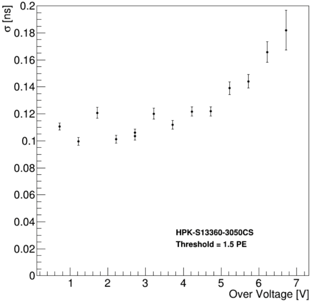
SiPM single photon time resolution

- Back-to-back γs from pair-annihilation in ^{22}Na is used as a source
- Single photon time resolution is taken as the Gaussian width in the time difference spectrum from coincidence signals
- Very good resolution $\sim$ 100 ps is observed in 3×3 mm HPK SiPM



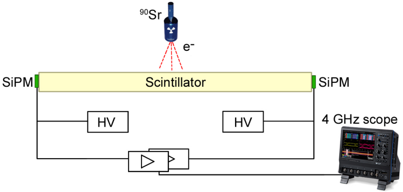
2.7 V - 1.5 photon level

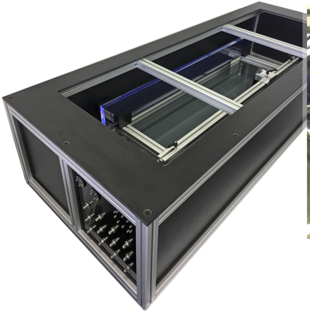


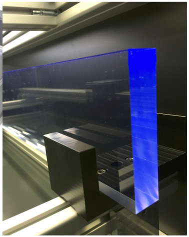


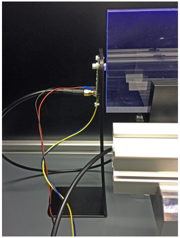
SiPM+bar: Set-up

- Signal generated by ^{90}Sr source
- Scintillating plastic bar: EJ-200, $120 \times 11 \times 2.5$ cm
- Read out on both ends by SiPMs / SiPM Arrays
- Signal sent to amplifier and readout out by 4 GHz oscilloscope



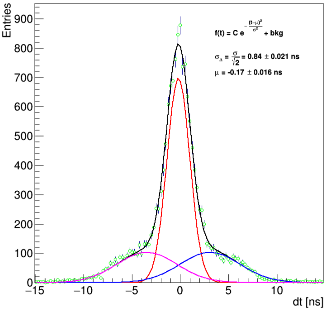


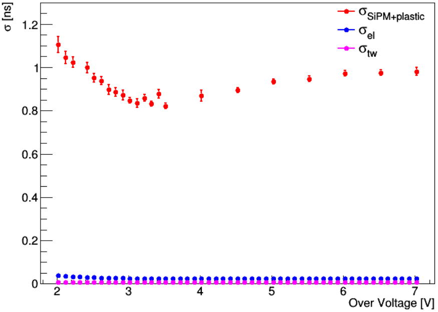




SiPM+bar: Time resolution

- ^{90}Sr pointed at bar center (60 cm)
- 3×3 mm^2 SiPM on either end of bar
- Initial measurements indicate time resolution of 800 ps
- Assuming $\sigma \propto 1/\sqrt{N}$
  $\sim$ 100 ps for 25% sensor coverage
  $\sim$ 50 ps for full sensor coverage





[C. Betancourt et al., *JINST* **12** 2 (2017)]

MUSIC: Multiple Use SiPM Integrated Circuit

Operational Modes

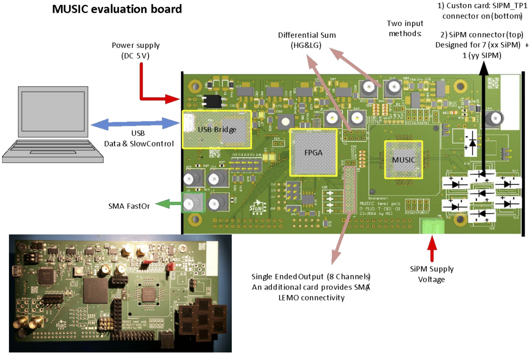
- Single channel: analog or discriminated
- Up to 8 ch summation
- Trigger output

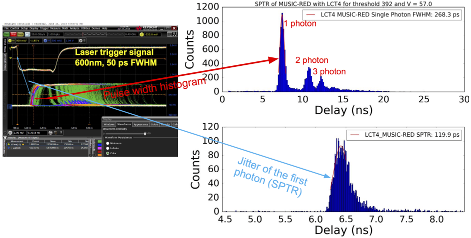
Performance

- Low noise
- High speed: $>$ 500 MHz without filtering
- Tuneable PZ cancellation
- SPTR 100 ps
- Dynamic range: from $<$ 1/5 to $>$2000 p.e.

Applications

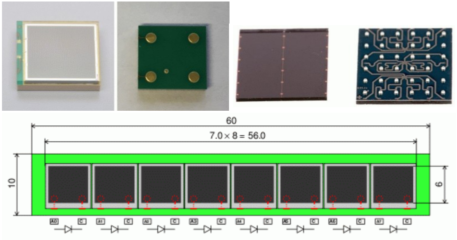
- Cherenkov Telescopes
- High Energy Physics and nuclear detectors
- Lab test benches for SiPM characterization: flexibility



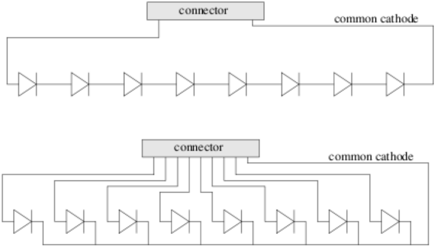


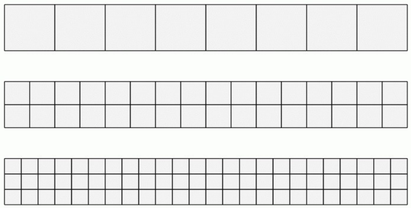
Sensor layout and connection

HPK SensL



- Array of 8 SiPMs (6×6 or 3×3 mm^2)
- Investigate different manufacturers (HPK, SensL, AdvanSiD?)
- Connection in series or parallel
- Increasing number of channels leads to better resolution





Summary & Outlook

- SHiP is a proposed fixed target experiment at the CERN SPS

  Tau neutrino physics
  Sterile neutrinos
  Dark Photon
  Dark Scalars/Dark Higgses
  Axion Like particles

  arXiv:1504.04855 (Physics), arXiv:1504.04956 (TP)

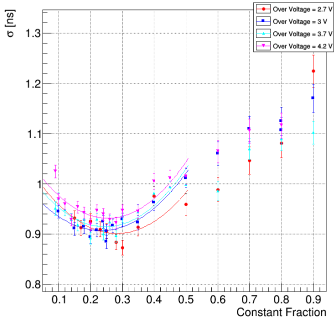
- Exploring scintillator based option for SHiP timing detector
- Readout by SiPMs

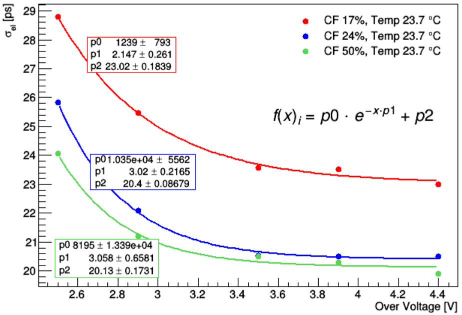
  $\sim$ 800 ps in bar center for 3×3 mm^2 sensors
  $\rightarrow$ 100 ps for 25% coverage, 50 ps for full coverage

- DAQ based on MUSIC board being investigated
- Optimization ongoing (series vs. parallel, small vs. large sensors)
- Finalize design by end of 2017

BACKUP

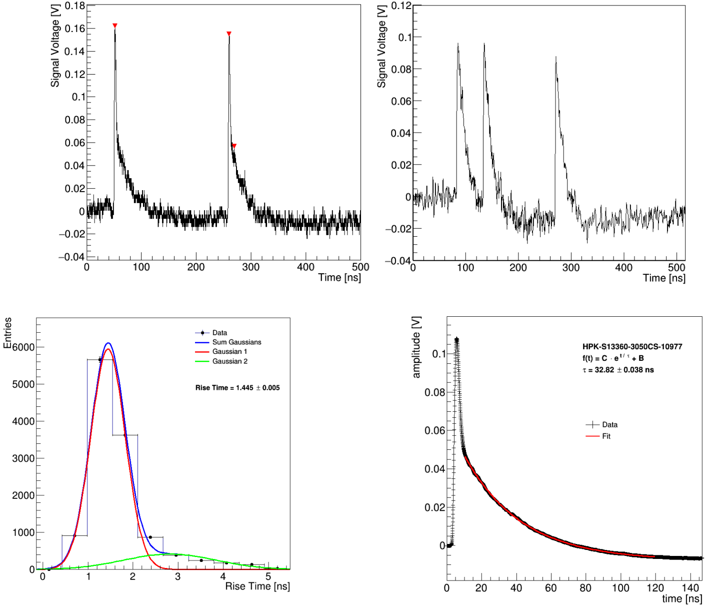
CFD optimization and electronic noise



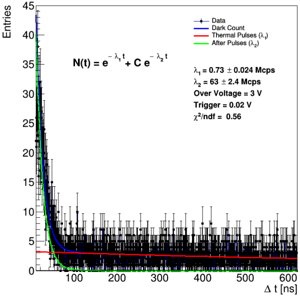


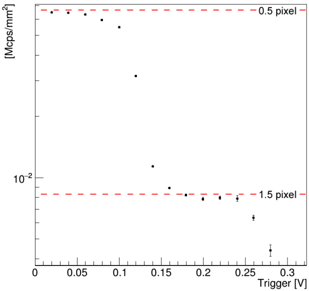
- Scan of CFD threshold indicated an optimal value of 24%
- Electronic noise at this value is $\sigma_{el} = 22$ ps for the optimal OV $= 3$ V

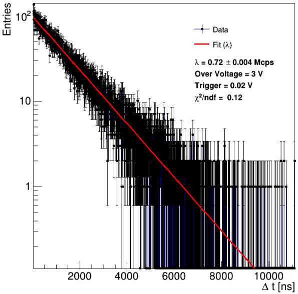
Waveforms, rise time and decay time

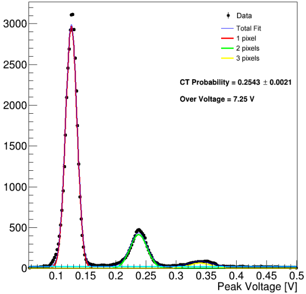


DCR and cross talk

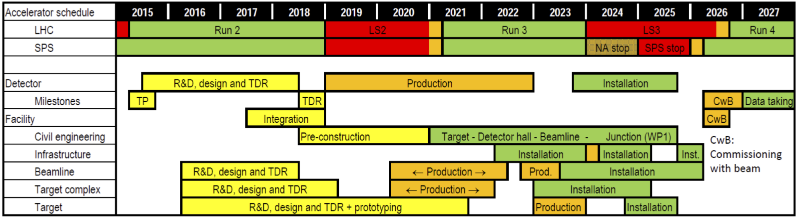


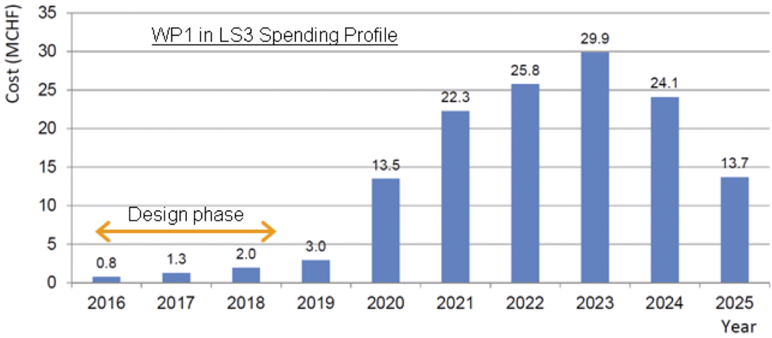






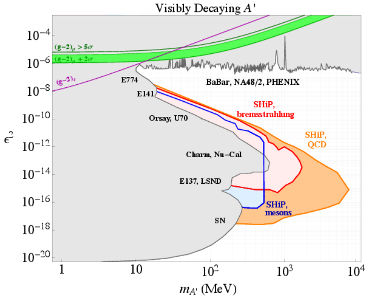
Timescale and costs

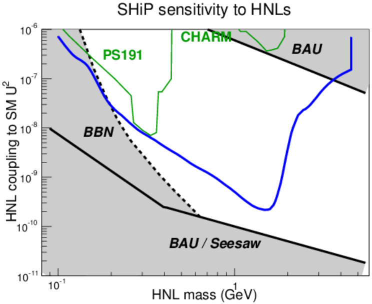




Hidden Sector particles can be explored by coupling to Standard Model particles

- Vector Portal (e.g. Kinetically mixed dark photons, HNL)
- Scalar Portal (e.g dark scalars, dark Higgses)
- Neutrino Portal (e.g. right handed neutrinos, sterile neutrinos)





Main decay modes and backgrounds

Main decay modes of hidden particles

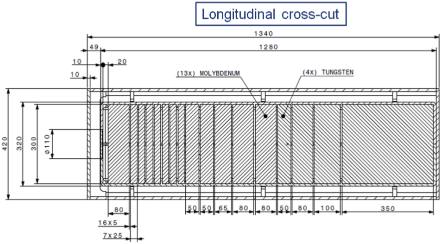
Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}$, $\rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}, \pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

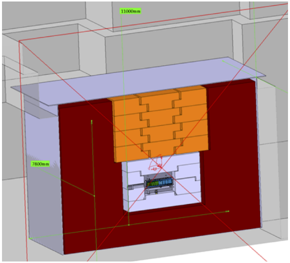
Background sources with V^0 particles

Background source	Decay modes
ν or μ + nucleon $\to X + K_L$	$K_L \to \pi e\nu, \pi\mu\nu, \pi^{+}\pi^{-}, \pi^{+}\pi^{-}\pi^{0}$
ν or μ + nucleon $\to X + K_S$	$K_L \to \pi^{0}\pi^{0}, \pi^{+}, \pi^{-}$
ν or μ + nucleon $\to X + K_\Lambda$	$\Lambda \to p\pi^{-}$
n or μ + nucleon $\to X + K_L$, etc	as above

The Target

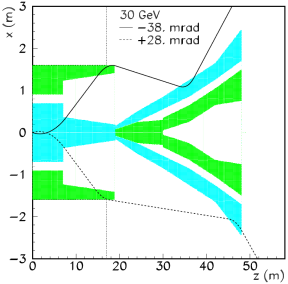
- SHiP target is very challenging due to high average beam power
  $\rightarrow$ 2.56 MW per 1 sec. spill
- Need heavy target to suppress π/Kaon decays
  $\rightarrow$ reduce the muon and neutrino induced backgrounds
- Longitudinally segmented hybrid target
  - Core of shower - four interaction lengths of titanium-zirconium doped molybdenum alloy
  - Followed by six interaction lengths of pure tungsten
  - Water cooling
- Neutral particle absorber protects upstream beamline from neutrons and other neutral radiation
- Target embedded in cast Iron bunker

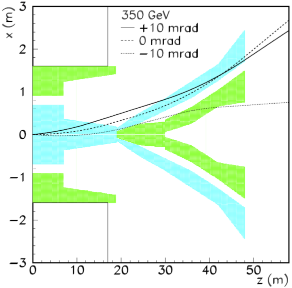




The Muon Shield

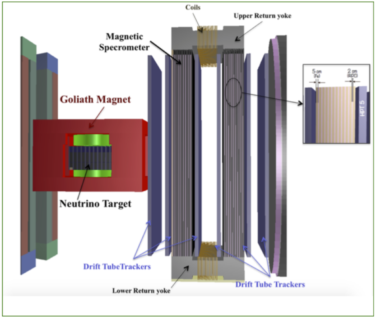
- $\sim 5 \times 10^9$ muons / spill
- Muon shield needs to be as compact as possible along beamline
- Both active and passive shields being investigated
- Active shield needs $B_y = 40$ Tm to bend 350 GeV muons away from the 5 m aperture of vacuum vessel
    1. Need to separate μ^+ from μ^-
    2. Bend muons further outward
- Passive shield uses dense material to slow down muons $\sim$ 40 m of tungsten
- Backscatter from wall of experimental hall still lead to an unacceptably large flux of muons

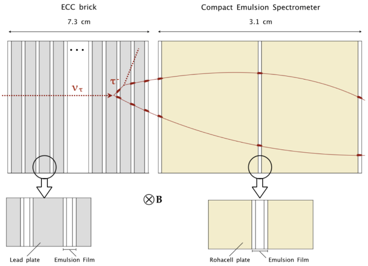




The Neutrino Detector

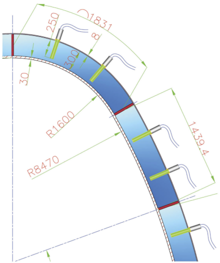
- Downstream of muon shield is the neutrino detector
- ν_τ and anti-ν_τ interaction detected by decay of τ lepton
- Detector consists of two parts
  - Neutrino Emulsion target in magnetic field
  - Muon Magnetic Spectrometer (MMS)
- Neutrino target based on Emulsion Cloud Chamber (ECC)
  - ECC brick - Lead as passive material
  - Compact Emulsion Spectrometer (CES) - sandwich of light material plates and emulsion film
- Muon Spectrometer
  - Resistive Plate Chambers (RPC)
  - Drift Tube Tracker (DTT)

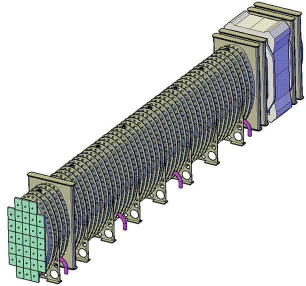




The Vacuum Vessel

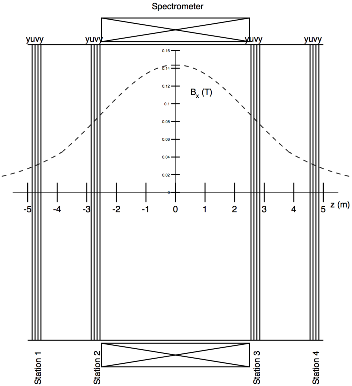
- Neutrino and muon interactions suppressed by 10^{-6} bar vacuum vessel
  $\rightarrow$ Vessel containing a helium filled ballon also under consideration, physics impact still under investigation
- Elliptical structure used to reject large muon flux entering the vessel horizontally by the active muon shield while maximizing geometrical acceptance
- Vessel is double walled structure
  $\rightarrow$ space filled with liquid scintillator that acts as a high efficiency background event tagger
- Charged particles passing through the background tagger is read out with photo-sensors
- Background tagger also offers possibility to decide offline if particles in tracker and calorimeter are entering from outside

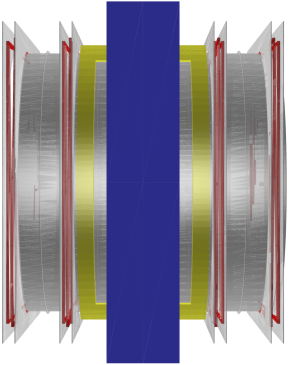




The Spectrometer Tracker and Magnet

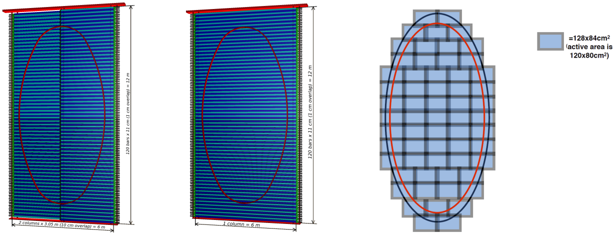
- Spectrometer used to reconstruct tracks from hidden particle decay products while rejecting backgrounds.
- Consists of large dipole magnet and two tracking telescopes on each side
- Straw tracker made up of thin polyethylene terephthalate tubes used for each station





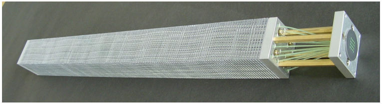
The Spectrometer Timing Detector

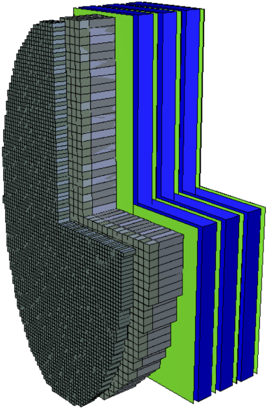
- A dedicated timing detector can be used to reduce random crossing in the detector
- Combinatorial di-muon background can be reduced to an acceptable level by requiring a timing resolution of 100 ps or less
  $\rightarrow$ Requires dedicated timing detector located after spectrometer and before calorimeters
- Two options have been proposed for the timing detector
  1. plastic scintillators read-out by PMTs or SiPMs
  2. multigap resistive plate chambers



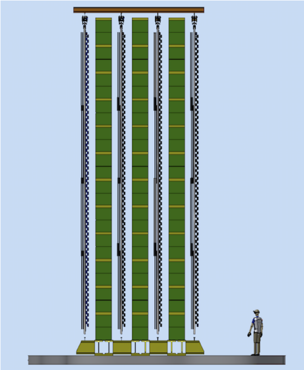
Calorimetry

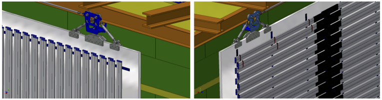
1. Electromagnetic calorimeter (ECAL)
    - Located right after timing detector
    - Provides electron, photon and pion identification and energy measurements
    - Cells made of scintillator-lead structure read out by plastic WLS fibers
2. Hadronic calorimeter (HCAL)
    - Right after ECAL
    - Provide pion identification
    - Pion/muon discrimination for low momentum
    - Tag neutral particles (K_L, n) for background rejection



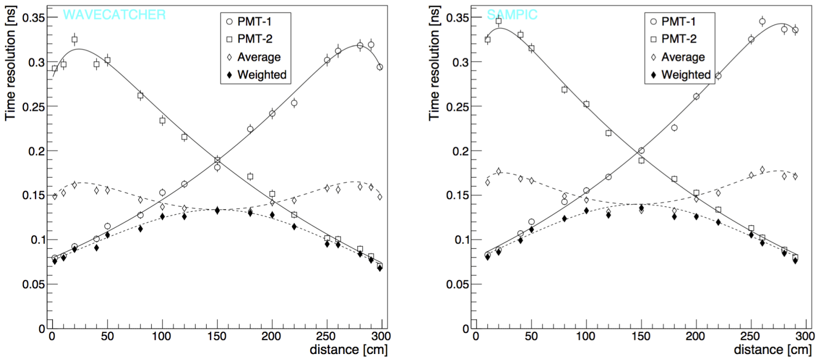


- Need to identify muons with high efficiency in signal channels
  $N \to \mu^+\pi^-, \mu^+\mu^-\nu_\mu$
  $V \to \mu^+\mu^-$
  $S \to \mu^+\mu^-$
- Separate signal from ν and μ induced backgrounds
- Downstream of the calorimeter system
- Four stations of active layers separated by three muon filters
- Granularity dictated by muon filters and multiple scattering in calorimeters (5-10 cm in the transverse direction)
- Active layers - extruded plastic scintillator strips with WLS fibers and opto-electronic readout



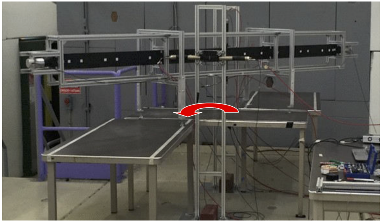


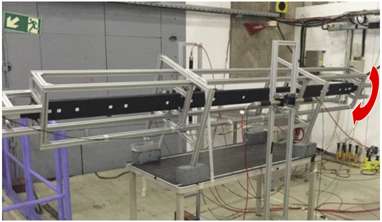
Time resolution vs. distance



- Very little difference between WAVECATCHER (135 ps in center) and SAMPIC (140 ps in center) using weighted average
- Degradation of time resolution is worse for SAMPIC at the far end $\rightarrow$ too small of an interval to fit baseline

Angular scans





Horizontal rotation

- 42°, 45°, 48°, 52°, 60°, 70°, 80°, 90°
- Track length increases, effective bar length decreases
  → time resolution improves

Vertical rotation

- 60°, 70°, 90°
- Track length increases
  → time resolution improves