The experimental setup of BDF/SHiP proposed for ECN3

CERN Detector Seminar

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SHiP Search for Hidden Particles

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

October 13, 2023

The Hidden Sector

- We know there must be physics beyond the standard model

Mediators (portals) to the Hidden Sector

Visible Sector

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{\text{HS}}$$

Mediator/portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

- Ability to couple to SM gives constraints from theory
- Different options
  - c.f. arXiv:1504.04855v1

  - Dark photons
  - Scalar and pseudoscalar mediators
  - ALPs
  - Heavy Neutral Leptons

No new particles observerd, yet ▷ could be too heavy or too weakly interacting

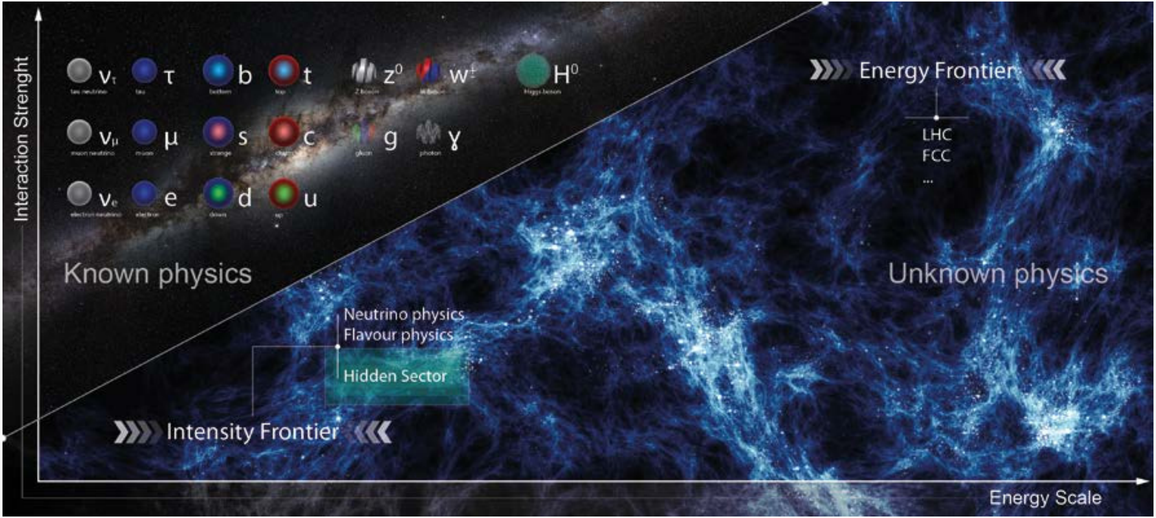


Image: CERN Courier 2/2016

How to the Explore the Hidden Sector?

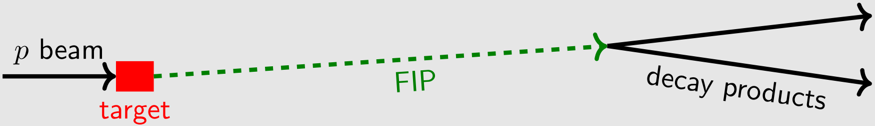
- Phenomenologies of HS models share a number of unique and common physics features
- ▷ Production through meson decays (π, K, D, B)
- ▷ Production and decay rates are strongly suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects $\mathcal{O}(\mu s)$
  - Travel unperturbed through ordinary matter
- ▷ Decay into two charged particles

Models	Final States
HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$
DP, DS, ALP (fermion coupling), SUSY sgoldstino	$\ell^{+}\ell^{-}$
DP, DS, ALP (gluon coupling), SUSY sgoldstino	$\pi^{+}\pi^{-}$, $K^{+}K^{-}$
HNL, SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
ALP (photon coupling), SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

Experimental Techniques

- Model independent search for Feebly Interacting Particles (FIPs)
- Production of FIPs in a high intensity proton beam

Decay of FIPs



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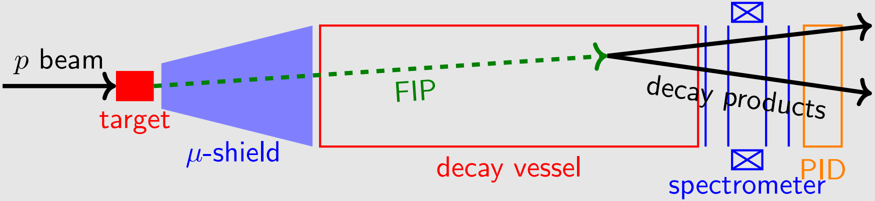
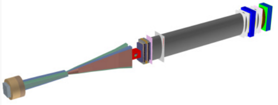


- Large decay volume followed by spectrometer and PID
- Shielding from SM particles: hadron absorber, muon-shield and veto detectors

The Ideo of SHiP

10.2013 EoI 🎉



October 7, 2013

Proposal to Search for Heavy Neutral Leptons at the SPS

CERN-SPSC-2013-024 / SPSC-EOI-010
07/10/2013

Executive Summary

A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a Dark Matter candidate.

Cosmological constraints on the properties of HNLs now indicate that the majority of the interesting parameter space for such particles was beyond the reach of the previous searches at the PS191, BEBC, CHARM, CCFR and NuTeV experiments. For HNLs with mass below 2 GeV, the proposed experiment will improve on the sensitivity of previous searches by four orders of magnitude and will cover a major fraction of the parameter space favoured by theoretical models.

The experiment requires a 400 GeV proton beam from the SPS with a total of 2×10^{20} protons on target, achievable within five years of data taking. The proposed detector will reconstruct exclusive HNL decays and measure the HNL mass. The apparatus is based on existing technologies and consists of a target, a hadron absorber, a muon shield, a decay volume and two magnetic spectrometers, each of which has a 0.5 Tm magnet, a calorimeter and a muon detector. The detector has a total length of about 100 m with a 5 m diameter. The complete experimental set-up could be accommodated in CERN's North Area.

The discovery of a HNL would have a great impact on our understanding of nature and open a new area for future research.

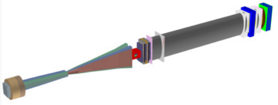
1 Introduction

The new scalar particle with mass ... GeV (ATLAS) [1], ... GeV (CMS) [2], recently found at the LHC, has properties consistent with those of the

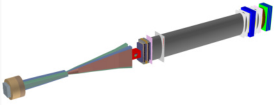
1

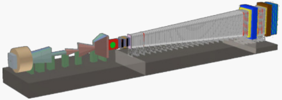
10.2013 EoI 🎉

04.2015 Technical Proposal and Physics Proposal



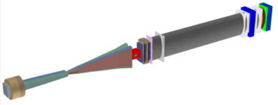
The Ideo of SHiP

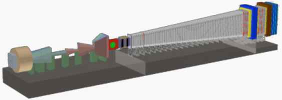




- 10.2013 EoI
- 04.2015 Technical Proposal and Physics Proposal
- 01.2016 Recommendation by SPSC to proceed to Comprehensive Design Study
- 04.2016 CERN launches Physics Beyond Collider group
  - SHiP facility included as Beam Dump Facility
- 12.2018 contribution to EPPSU together with BDF progress report to SPSC

The Ideo of SHiP





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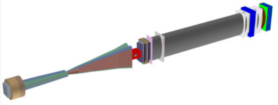

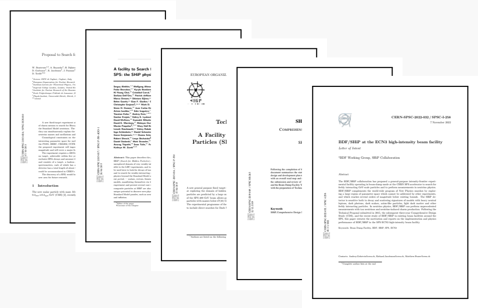

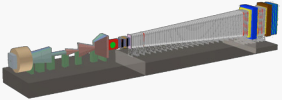

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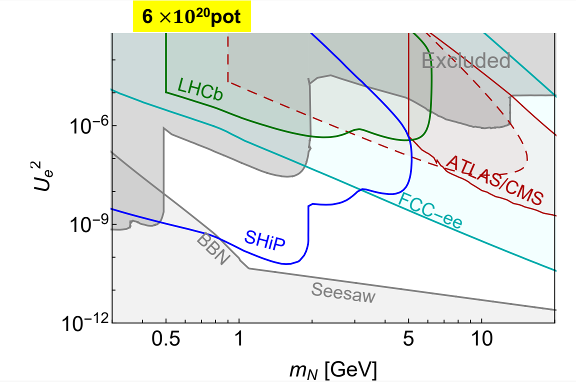
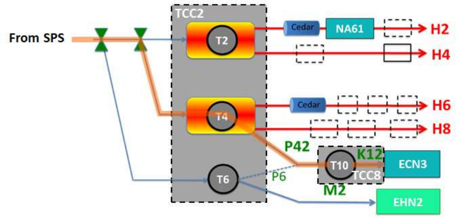
- 09.2020 CERN launches continued BDF/SHiP R&D
  - Location and layout optimization study recommending ECN3
- 07.2022 CERN launches dedicated decision process over 22/23 for the future of ECN3

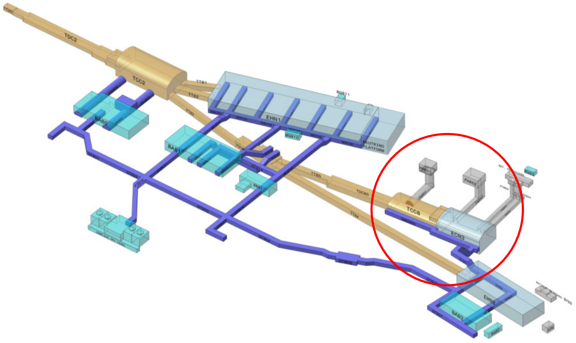
E.g. Heavy Neutral Leptons



- BDF/SHiP sensitive to a variety of models
- Covers a unique region that can only be explored by an optimized Beam Dump experiment
- Optimize for maximum production of charm, beauty and electromagnetic processes
- SPS energy and intensity provide unique direct discovery potential

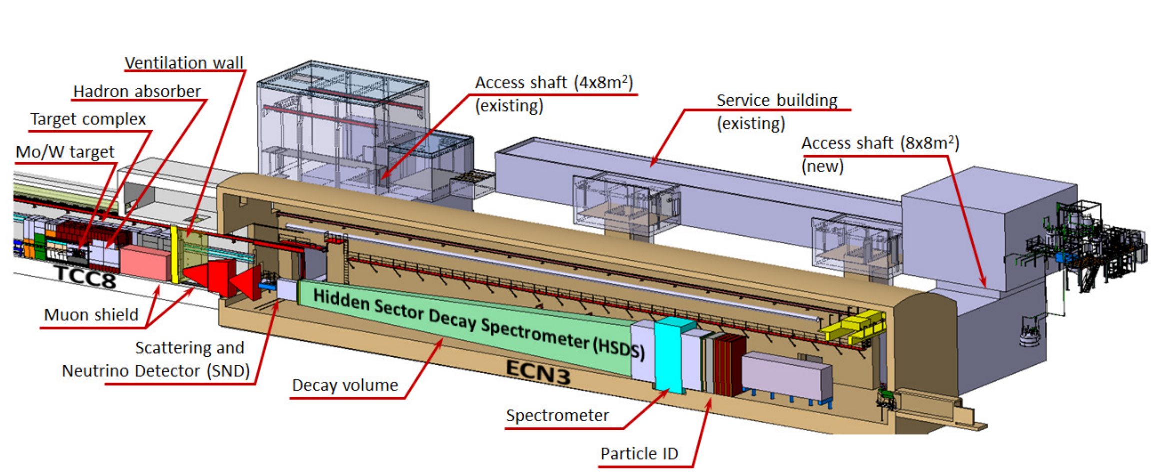
SPS ECN3 Beam Facility





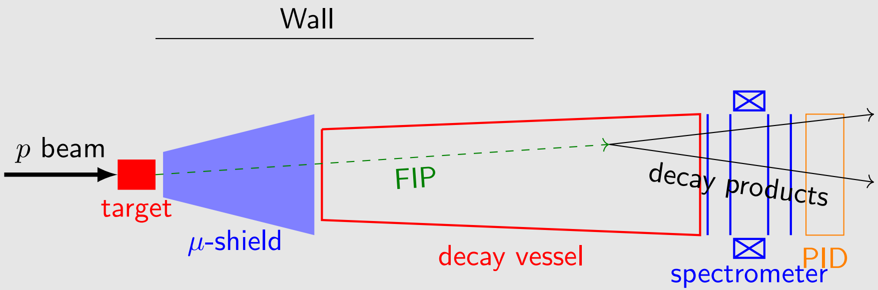
- Currently hosting NA62
- Profit a lot from existing infrastructure
- 1×10^6 spills of 4×10^{13} protons per year
- 6×10^{20} PoT for SHiP in 15 years

SHiP Implementation in ECN3



- Two complementary detecors: SDN and HSDS
- Low pressure decay vessel – optimized for zero-background

Background Sources



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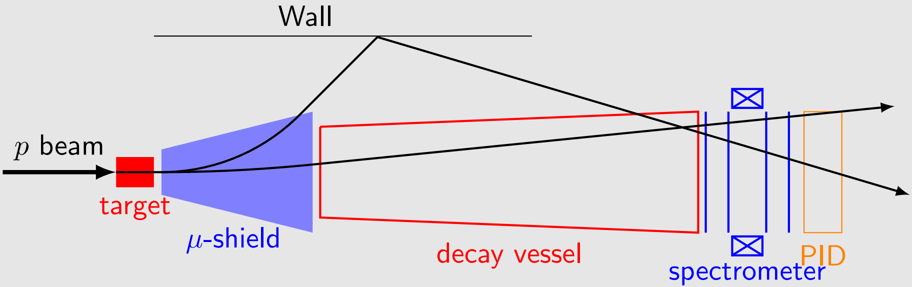
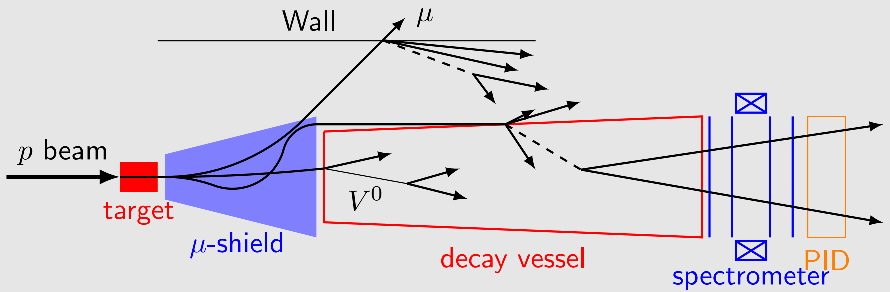


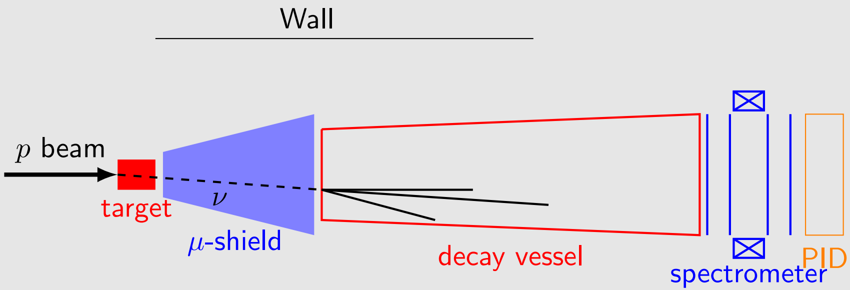
- Muon Combinatorial Background

Background Sources



- Muon Combinatorial Background
- Muon DIS

Background Sources



- Muon Combinatorial Background
- Muon DIS
- Neutrino DIS
- Background from muon and neutrino DIS dominated by random coincidences of secondaries, not V^0s

Background Selection and Events

Background estimation based on full GEANT-based MC

- Very simple and common selection for both fully and partially reconstructed events
- Model independent

Selection

Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	$< 1\,\mathrm{cm}$
Track pair vertex position in decay volume	$> 5\,\mathrm{cm}$ from inner wall
	$> 100\,\mathrm{cm}$ from entrance (partially)
Impact parameter w.r.t. target (fully reconstructed)	$< 10\,\mathrm{cm}$
Impact parameter w.r.t. target (partially reconstructed)	$< 250\,\mathrm{cm}$

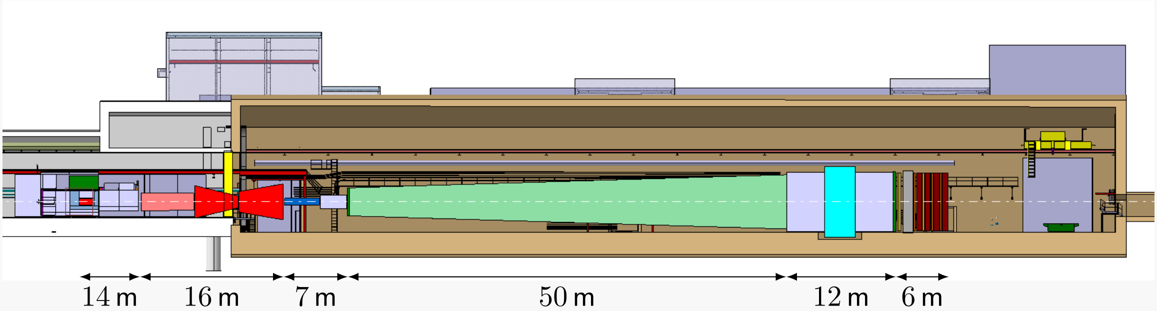
+Time coincidence +SBT

Events

Background source	Expected events
Neutrino DIS	< 0.1 (fully)/$<$ 0.3(partially)
Muon DIS (factorisation)*	$< 5 \times 10^{-3}$ (fully) / $<$ 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

- Expected background is < 1 event for 6×10^{20} pot in 15 years of operation

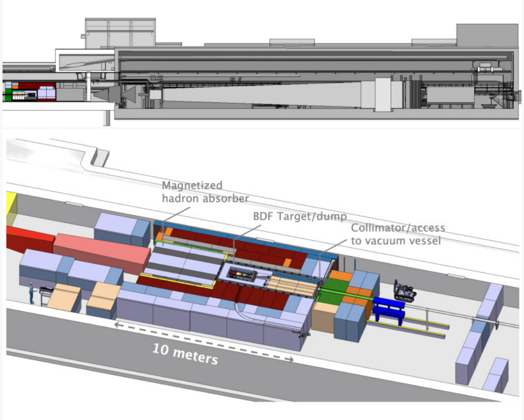
Experimental setup



- ECN3: Reduction of transversal size compensated by shortening distance to target
- Many distances object to change (optimization)

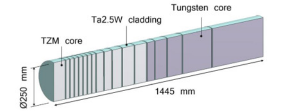
Target complex and Target

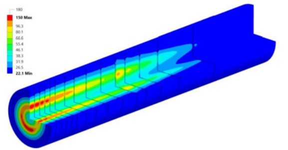
- High density proton target
  - effectively acting as beam dump and absorber
- Hadron absorber
  - already magnetized as part of muon shield
- First section of muon shield
  - integral part of overall shielding completely surrounding the target system



Target Design

- Long target made of high A/Z material
  - maximise production of heavy flavored hadrons and photons
  - suppress decay of pions and kaons for cleanest possible background
- 13 blocks **TZM** (Titanium-Zirconium-doped Molybdenum alloy)
- 5 blocks of pure **tungsten**
- Cladded by tantalum-alloy
- 5 mm gaps for cooling
- 12 interaction lengths
- Studies for further improvements ongoing by CERN





During CDS phase


Eur. Phys. J. C (2020) 80:284
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Measurement of the muon flux from 400 GeV/c protons interacting in a thick molybdenum/tungsten target

SHiP Collaboration

Received: 27 January 2020 / Accepted: 27 February 2020 / Published online: 29 March 2020
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EPJ C **80**, 284 (2020)

- Prototype built in 2017
- Test in H4 beamline in 2018
- Confirms expected muon flux
- Recent post irradiation confirmed robustness of design

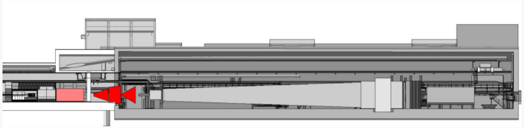
Muon Shield

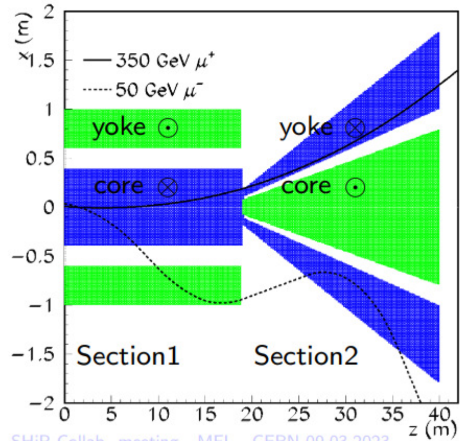
Purpose, Requirements and Challenges

- Deal with $\mathcal{O}(10^{11})$ muons per spill
- Suppress by 6 orders of magnitude!
  - ▷ Sweep out / absorb muons
- Try to keep it short

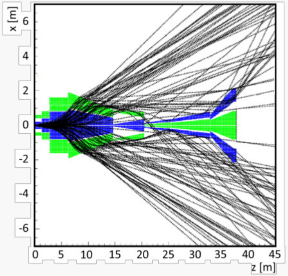
Technical implementation

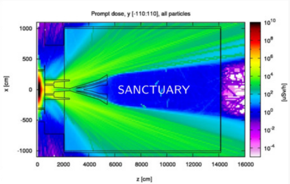
- Magnetic muon sweeper
- Alternate polarity scheme
- Shielding already starts in magnetized hadron absorber





Muon Shield Configuration





JINST 12 P05011

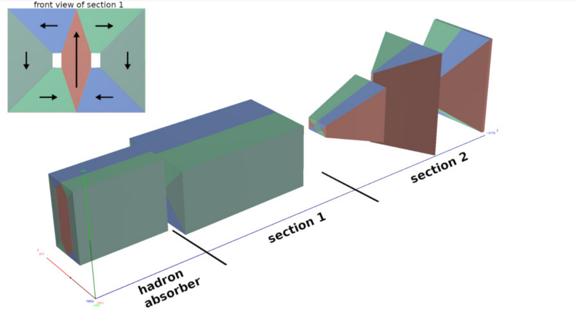
Moving to ECN3

- Reduced space for section in TCC8
  - ▷ Shorten space between target and experiment
  - ▷ Smaller experiment while **preserving physics reach**

- CDS: length $\sim 30\,\mathrm{m}$
- Reduces muon rate by about six orders of magnitude
- Intensive RP studies for target and shield
  - ▷ No problems for electronics

- Total length (LoI) $\sim 25\,\mathrm{m}$
  - ▷ Acceptable rate of muons
    - $67\,\mathrm{kHz}$ in SST
    - $2\,\mathrm{Hz/cm^2}$ in SND
- SND shorter by $3\,\mathrm{m}$
- Tracker: $4\,\mathrm{m} \times 6\,\mathrm{m}$, $8\,\mathrm{m}$ closer to target

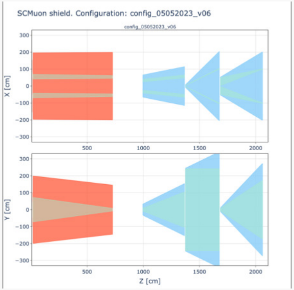
SC/NC Hybrid Muon Shield

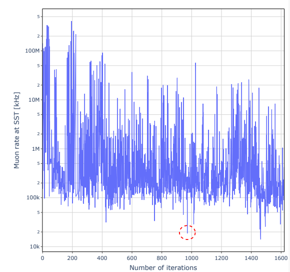


- 3 warm magnets and one SC magnet
- Further reduced in length by 5 m comapred to LoI
- HSDS decay volume closer to target by 13 m compared to CDS/ECN4 design

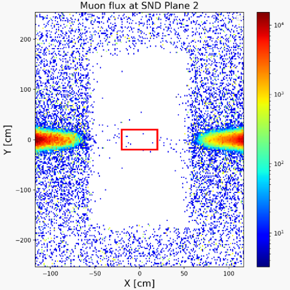
Conservative starting parameters

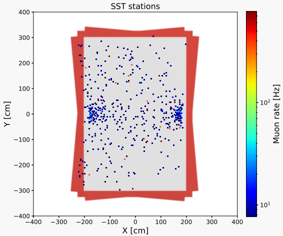
- Core aperture in range $0.5\,\mathrm{m} \times 0.5\,\mathrm{m}$ to $1\,\mathrm{m} \times 1\,\mathrm{m}$
- Iron/air core field $5\,\mathrm{T}$ over $4 - 8\,\mathrm{m}$
- NbTi @ $4.5\,\mathrm{K}$
- $\sim 50\,\mathrm{A/mm^2}$
- Low beam related heating (muons) - Fluka
- Cooling options under investigation
- Challenge in assembly





- Optimize for low rate in Tracker and SND acceptance





- Different configurations with similar performance
  - shows robustness against systematics
  - engineering studies will be used to select
- Optimization converges around 21 m

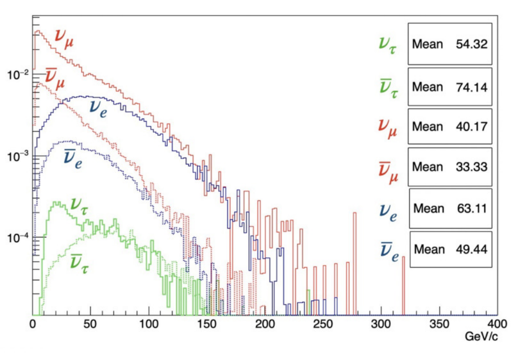
Shield configuration	Tracker rate [Muons/spill]	Shield length [m]
ECN4	45k	31
ECN3 Combi	160k	26
ECN3 Combi Optimized	67k	26
ECN3 SC Optimized	23k	21

Neutrinos Behind the Muon Shield

Take advantage of high neutrino flux emerging the beam dump

	<E> [GeV]	beam dump	<E> [GeV]	SND target acceptance	<E> [GeV]	CC DIS interactions
N_{ν_e}	6.3	4.1×10^{17}	30	1.3×10^{16}	63	2.8×10^{6}
N_{ν_μ}	2.6	5.4×10^{18}	8.4	1.5×10^{17}	40	8.0×10^{6}
N_{ν_τ}	9.0	2.6×10^{16}	22	1.0×10^{15}	54	8.8×10^{4}
$N_{\bar{\nu}_e}$	6.6	3.6×10^{17}	22	9.3×10^{15}	49	5.9×10^{5}
$N_{\bar{\nu}_\mu}$	2.8	3.4×10^{18}	6.8	1.2×10^{17}	33	1.8×10^{6}
$N_{\bar{\nu}_\tau}$	9.6	2.7×10^{16}	32	1.0×10^{15}	74	6.1×10^{4}

Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	



SND

- Heavy target for neutrino interactions
  - First observation of $\bar{\nu}_\tau$
  - ν_τ, $\bar{\nu}_\tau$ physics with high statistics
  - ν_τ magnetic moment
  - F4 and F5 structure functions
  - ν_e cross sections
  - ν-induced charm production
  - strange quark nucleon content
  - LFV
  - LDM via elastic scattering

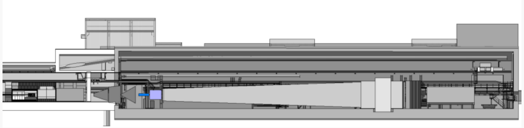
SND

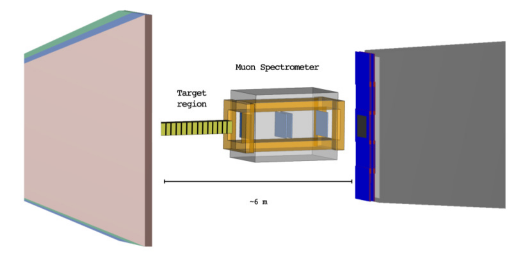
Purpose, Requirements and Challenges

- Target for LDM/neutrino interactions
- Radial dependence of flux - narrow and long neutrino target
- Followed by muon spectrometer
- Target tracker to predict location of neutrino interaction

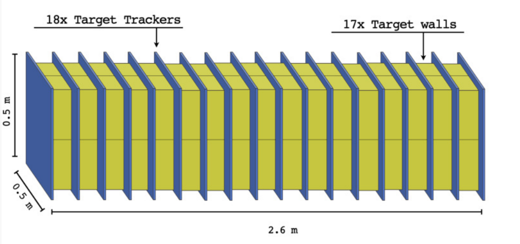
Technical implementation

- Emulsion Cloud Chamber (ECC)
- Alternated with tungsten plates
- Instrumented with vertexing capabilities





SND – Target Tracker



Requirements

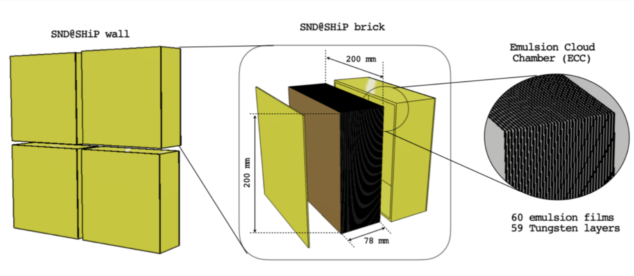
- Position resolution: $100\,\mu m$
- Time resolution: $50\,ps$
- High efficiency ($> 99\,\%$)

Features

- Provide time stamp to neutrino interactions in the emulsion target
- Link muon track in the emulsion target with the magnetic spectrometer
  - ▷ High energy muons also tracked in main spectrometer
- Sampling calorimeter for hadronic and electromagnetic energy measurement
- Complement emulsions for neutrino energy reconstruction

- Baseline Option: SciFi trackers

SND – Emulsion Target



- Vertex reconstruction with micrometric accuracy
- Identification of short-lived particle decays
- Momentum measurement with multiple coulomb scattering
- Electromagnetic shower identification with calorimetric technique

Emulsion Cloud Chamber (ECC)

- Sensitive Trackers: nuclear emulsions
- Passive material: Tungsten plates
- 17 walls
- Total mass: $3.1\,\mathrm{t}$

Emulsion Surface

- 1 brick: $2.4\,\mathrm{m}^2$
- 1 wall (4 bricks): $9.6\,\mathrm{m}^2$
- Full target (17 walls): $163\,\mathrm{m}^2$

SND – Emulsion Analysis

Replacement frequency depends on:

- maximum track density in emulsion $< 10^6\,\mathrm{cm}^{-2}$
- background rate

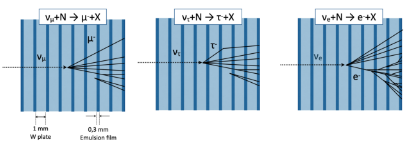
Desired Scenario

- Background rate $1\,\mathrm{Hz/cm}^2$
  - ▷ 1 to 2 replacements per year

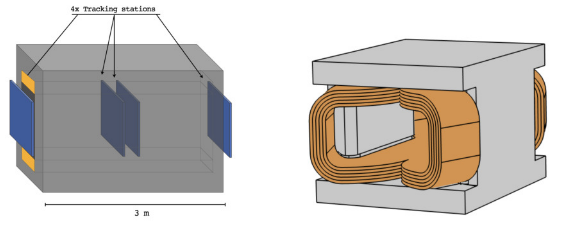
Emulsions will scanned with micrometer precision in dedicated scanning labs.

Lepton Flavor Identification

- ν_μ muon reconstruction in spectrometer
- ν_e electron shower identification in the emulsion target
- ν_τ disentanglement of τ production and decay vertices



SND – Muon Spectrometer



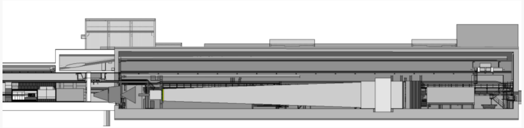
- Position resolution of tracking stations: $100\,\mu m$ in both coordinates
- High efficiency ($>99\,\%$)
- Baseline option: Drift tubes

- Identify muons produced in neutrino interactions and tau lepton decays
- Measurement of charge and momentum of muons produced in CC interactions and the muonic decay channel of the τ
- Air core dipole magnet $1\,T$ horizontal field
- Based on AdvSND design – to be optimized
- Four tracking stations

Upstream Background Tagger

Purpose, Requirements and Challenges

- Covers front cap window of vacuum vessel
- Tagging of time and position of muons and other charged particles
- Excellent time resolution $\mathcal{O}(50\,\mathrm{ps})$
- Complementing tracking in SND muon id

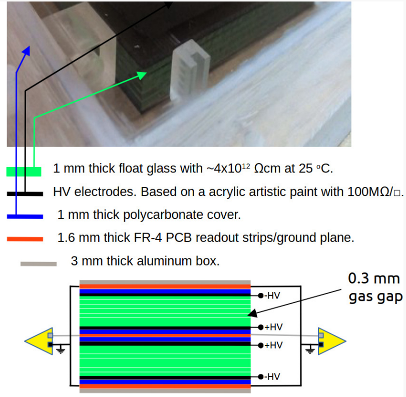


Technical implementation

- Multi-gap Resistive Plate Chambers

UBT Design

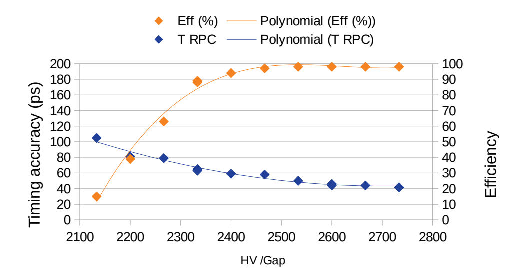
- Six gaps defined by seven 1 mm thick float glass electrodes
- Separated by 0.3 mm nylon mono-filaments
- HV electrodes applied to outer surface with airbrush technology
- Operated at ± 9000 V
- 98% $C_2H_2F_4$, 2% SF_6,
- Novel approach in design
  - very tight $5\,\mathrm{cm}^2/\mathrm{min}/\mathrm{m}^2$
  - or even sealed RPC technology

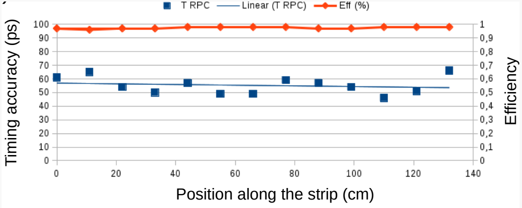


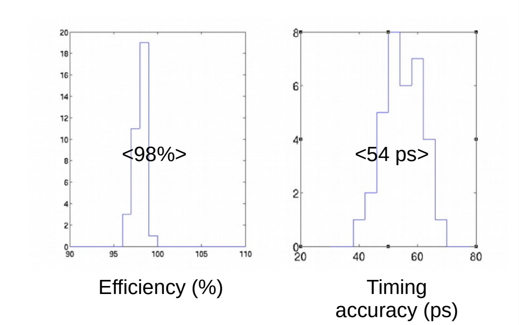
UBT Prototype

Testbeam at CERN

- Sandwich of two identical modules
- $1500\,\mathrm{mm} \times 1200\,\mathrm{mm}$
- $54\,\mathrm{ps}$ resolution
- 98% efficiency







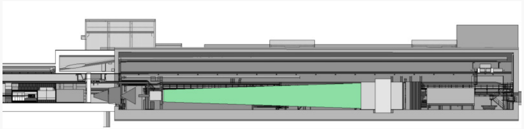
HS Decays Vessel and Surround Background Tagger

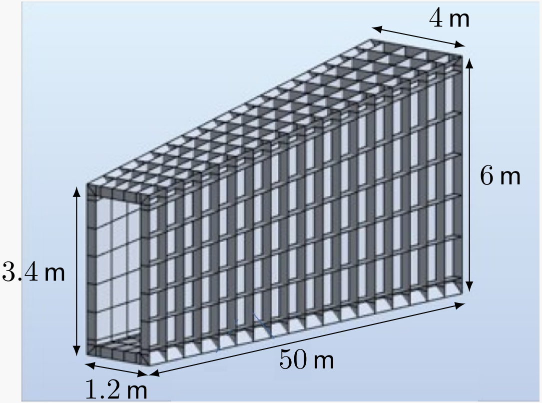
Purpose, Requirements and Challenges

- Low pressure environment for decay of FIPs
- Detect charged particles entering the vessel side walls from outside
- Detect charged particles produced in the interactions of muons and neutrinos in the vessel walls

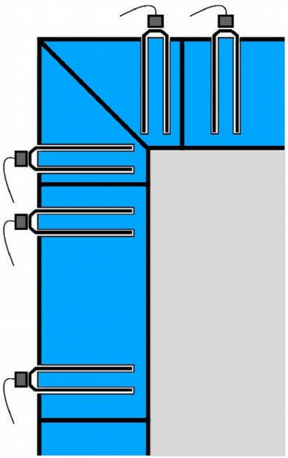
Technical implementation

- Pyramidal frustum with stiffening bars
- Cover walls with liquid scintillator

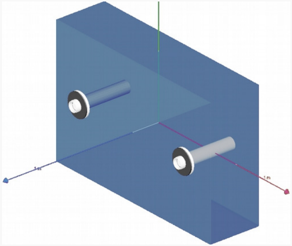




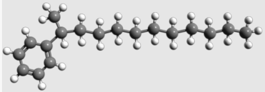
SBD – Detection Principle



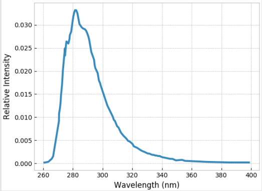
- Fill wall segments with liquid scintillator
  - ▷ High efficiency: $> 99.0\%$ for m.i.p.
  - ▷ Good time resolution: $\mathcal{O}(1\,\text{ns})$
- 2000 Segments: Filled with $150\,000\,\ell$ LS (LAB + PPO)
- Light Detectors: 4000 WOMs with SiPM readout



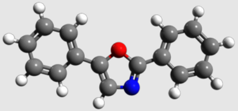
Solvent: Linear AlkylBenzene (LAB)



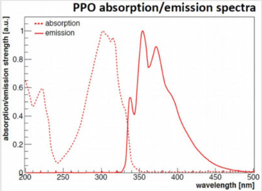
$\lambda_{scat} \sim 20$ m @ 400 nm



Flour: 2,5-diphenyl-oxazole (PPO)

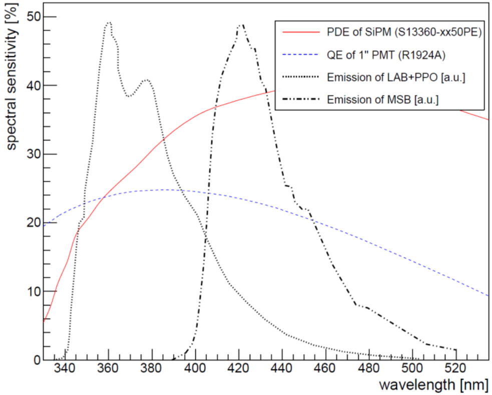


$\tau_{PPO} \sim 1.6$ ns, $\tau_{LAB+PPO} \sim 5$ ns



Scintillator emission spectrum:

- LAB + 2.0 g/l PPO: 350 nm – 380 nm
- WLS (Bis-MSB): 420 nm



SBT – Wavelength-Shifting Optical Module (WOM)

Transparent PMMA tube

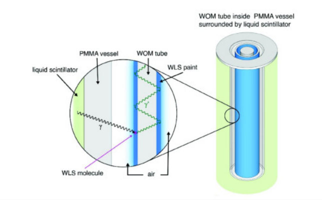
- $60\,\mathrm{mm}$ $\varnothing$, $200\,\mathrm{mm}$ $\leftrightarrow$, $3\,\mathrm{mm}$ wall
- Large effective area (compared to photo sensor)
- Low material budget

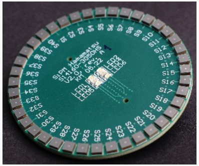
WLS paint coating: Bis-MSB

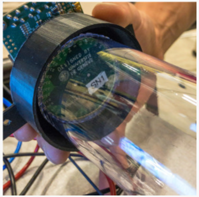
- UV / blue absorption [290 - $390\,\mathrm{nm}$]
- Isotropic visible light emission [$420\,\mathrm{nm}$]
- Internal total reflection: Up to 75% collection efficiency

SiPM readout

- Hamamatsu S14160-3050HS [$450\,\mathrm{nm}$]
- 40 $3\,\mathrm{mm} \times 3\,\mathrm{mm}$ SiPM on PCB array

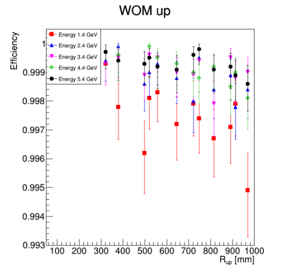


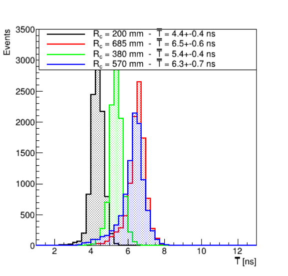


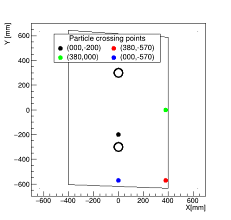


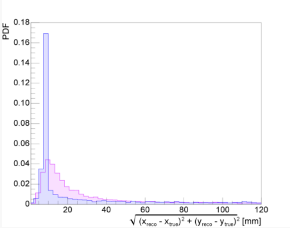
SBT Prototype

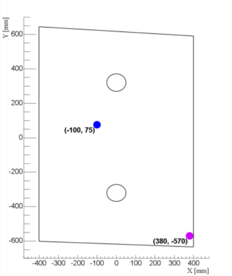
- Proof of principle shown in test beam 2017
  - ▷ time resolution of 1 ns
- Further test beams 2018-2022 with a 120 cm × 80 cm × 30 cm cell
- Serveral testbeams at CERN and DESY
- Detection efficiency close to 99.9%



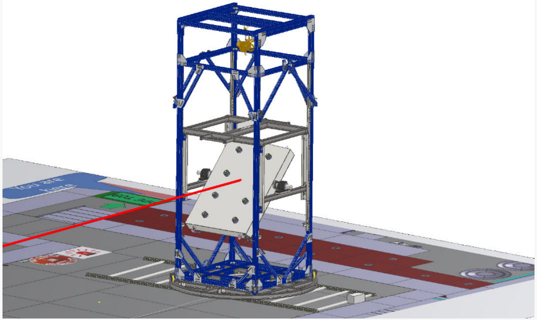




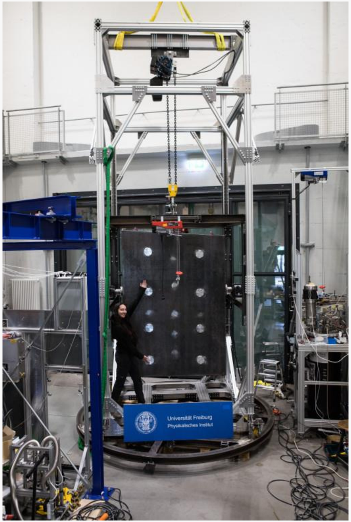




Four Cell Prototype



- 4 cell prototype to be tested at PS starting next week
- Improved reflective coating
- Orientation in any direction, cabled motors



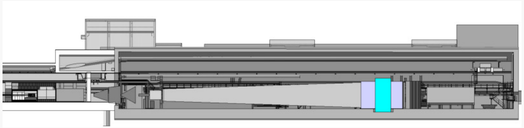
HS Spectrometer

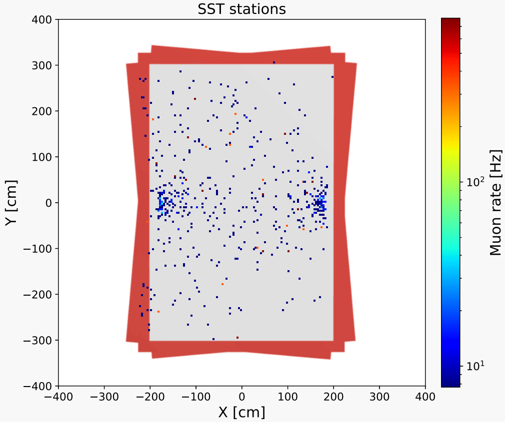
Purpose, Requirements and Challenges

- Reconstruct tracks with high precision (better $120\,\mu m$)
- Operation in low pressure environment
- Low material budget
- Large aperture $4\,m \times 6\,m$
- Moderate rate $\mathcal{O}(10\,kHz)$

Technical implementation

- Straw Tracker with ultra long tubes



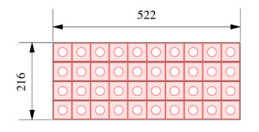


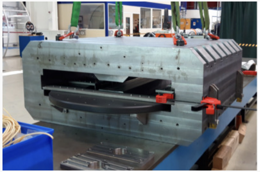
Spectrometer Magnet

- Physics aperture $4\,\text{m} \times 6\,\text{m}$
- Bending field $0.65\,\text{Tm}$, nominal on axis $\sim 0.15\,\text{T}$

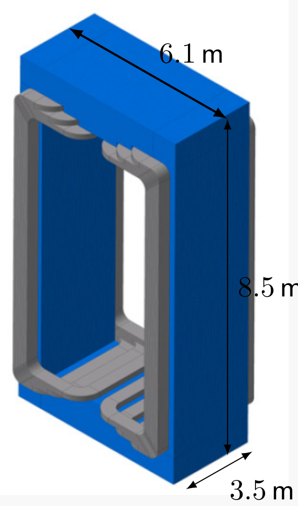
- Integrated in decay vessel
- Initial design: normal conducting option
- Square shaped hollow aluminium coils
- Steel yoke (50mm AISI 100)
- Requires $1.5\,\text{A/m}^2$
- Power consumption 0.5 to $0.6\,\text{MW}$

- Intermediate temperature superconductors (e.g. MgB_2)???
  - c.f. CERN Bulletin 11 September 2023
  - To be investigatet





CERN Bulletin 11.09.2023



Straw Tracker

Straw Tubes

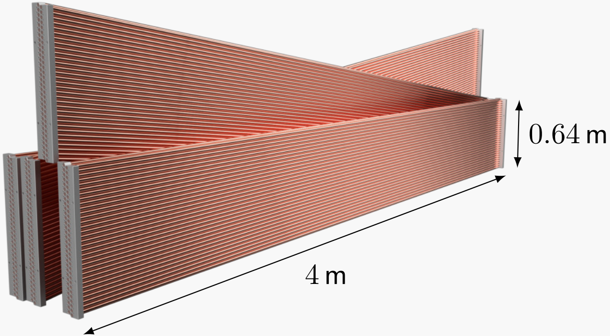
- Ultra-thin, ultra-long straws based on NA62 design.
- longitudinally **ultrasonically welded**.
  - high strength (pressure tests with 3 bar)
  - no glued layers
  - small gas leakage
  - ▷ suitable for use in vacuum
- Successful operation in NA62.
- Wall thickness $36\,\mu m$
- Coating: Au ($20\,nm$), Co ($50\,nm$)
- Diameter: $2\,cm$
- Length: $4\,m$

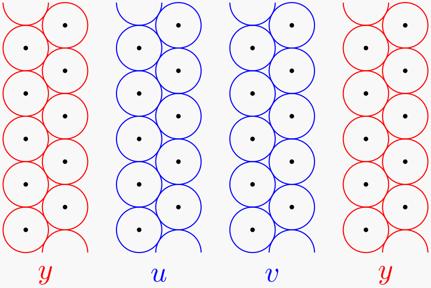
Tracker Stations

- 4 Stations
- $4\,m \times 6\,m$
- Horizontal operation of straws
- 4 Planers per station
- y-u-v-y setup, stereo angle $\sim 10^{\circ}$
- ▷ 10000 channels

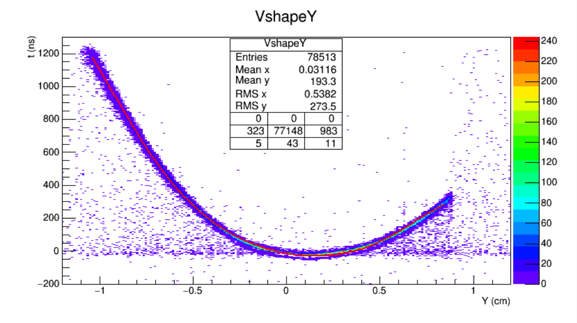
Modular Design

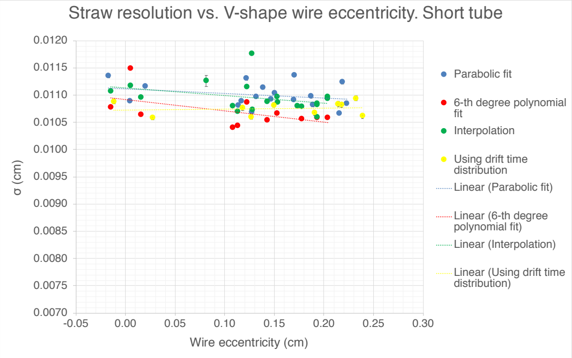
- Sub-division into modules of $2\,\text{Straws} \times 32\,\text{Straws}$
- Horizontal and stereo modules
- Can be produced off site, and later inserted into support frame
- Frame can then be side-loaded into decay vessel





- Hit resolution of short tubes (2 m) was measured in H2 testbeam
  - ▷ tested depending on wire eccentricity



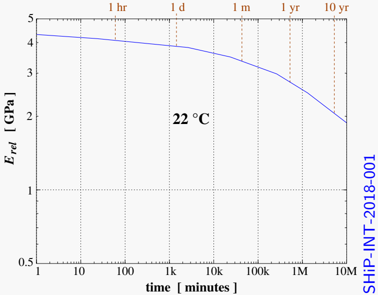


- Resolution <120 μm was achieved for wire eccentricities up to >2 mm

Main mechanical challenge:

Flowing of Mylar

- Reduction of tension to half over 10 years
- Problem for horizontal tubes



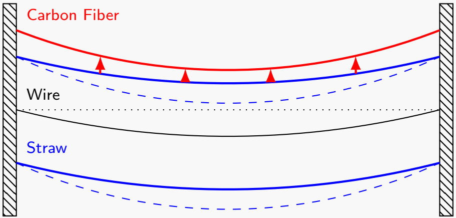
- Additional forces when vessel is evacuated and straws are under pressure

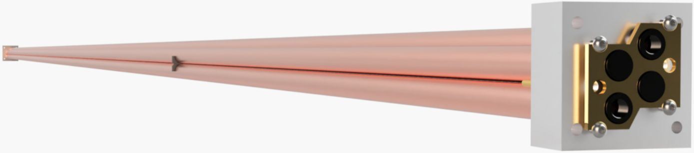
Implications

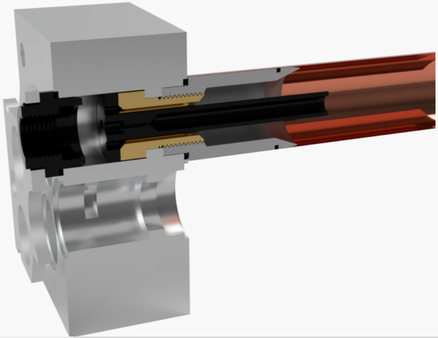
- Reduced tensions increase gravitational sagging of the straws over time
  $\Rightarrow$ changing the eccentricity of the wire
  $\Rightarrow$ electrostatic deflections!
- Reduced tensions relax load on any supporting frame, which would thus unbend
- An unbending frame pulls on the wire, which would thus rupture ($\Delta\ell_{\text{max}} \simeq 10\,\text{mm}$)

Mechanical Design

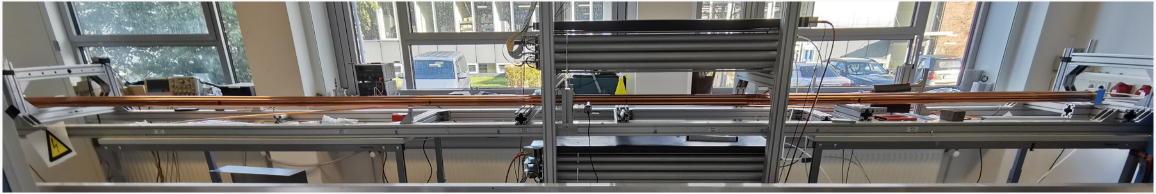
- Design option: support by thin carbon cables
- Carbon cable defines sagging.
- Two tubes share one cable, connection every meter.
- Gas distribution inside endplate (zig-zagging through tubes).
- Setup of first prototype with four tubes.
- Great to study long term effects (just started)

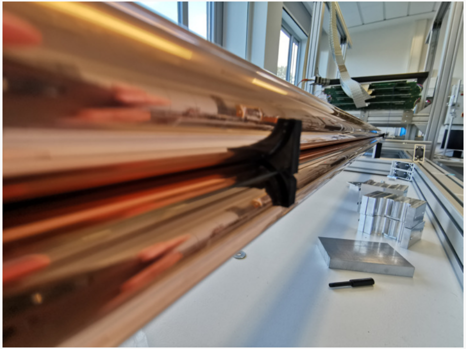




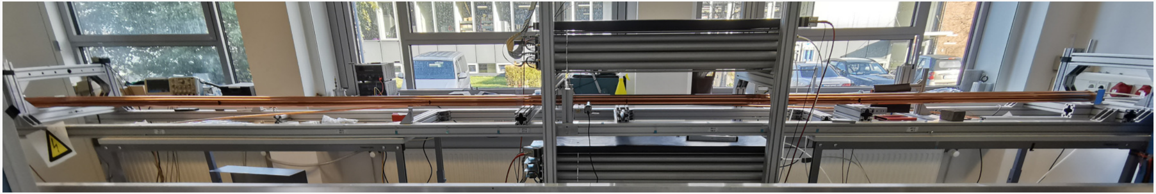


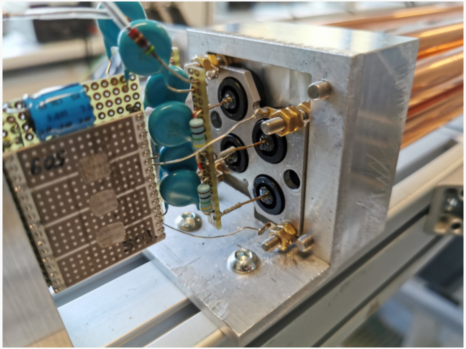
Prototype with Four Tubes

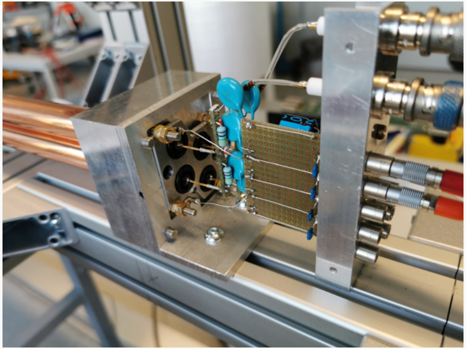




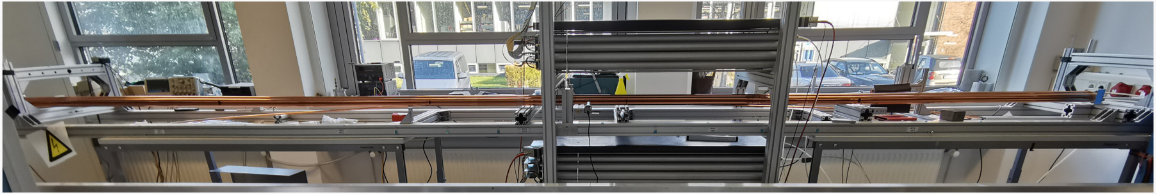
Prototype with Four Tubes

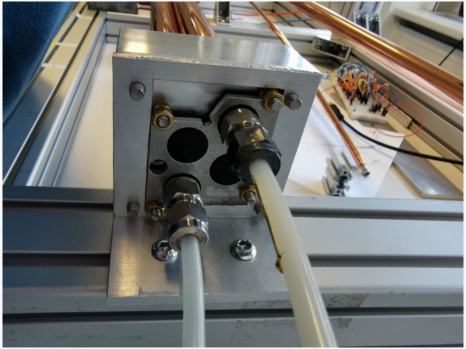






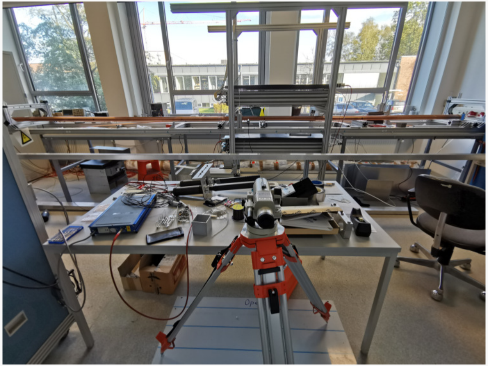
Prototype with Four Tubes

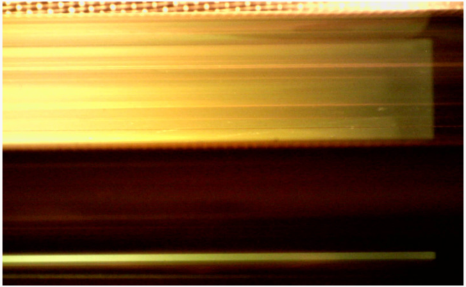


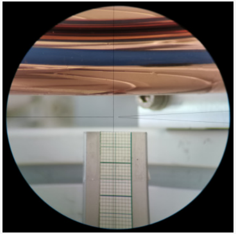


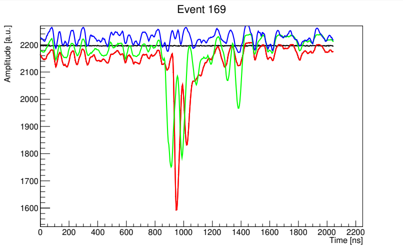
Sagging

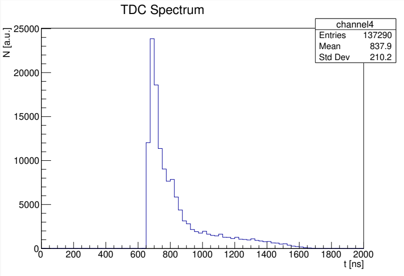
- Sagging monitored with optical level.
- Wire can be monitored with strong LEDs and optical microscope.
- Stable (working) over four years









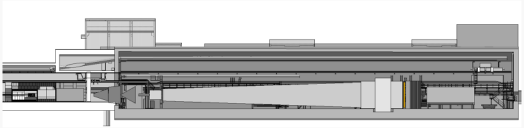


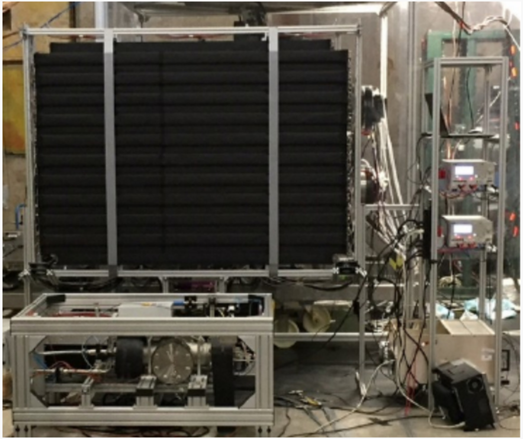
- Two different wire diameters ($30\,\mu m$ and $45\,\mu m$)
- Separate HV supply
- Signal amplified by L3 amplifier (used in OPERA)
- Signal readout by multi channel FADC
  - Auto trigger
  - External trigger (scintillators)
- Measurements with cosmics, Fe55, Sr90

Prototype works and technology is suitable for use in large spectrometer

- Study planed if recording of (simplified) waveforms is beneficial (justifying the cost)

Timing Detector





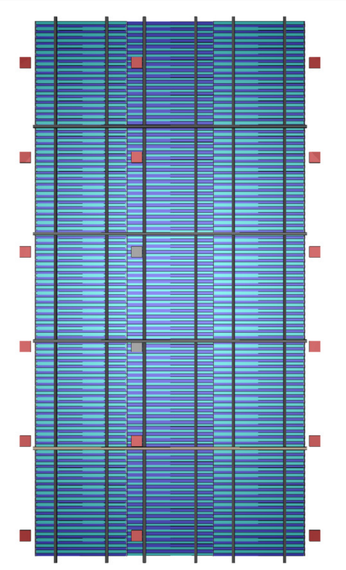
Purpose, Requirements and Challenges

- Reduction of the muon combinatorial background
- Provide time information for straw tubes
- Identification of particle decay products (ToF)
- Time resolution ≤ 100 ps

Technical implementation

- Three columns of vertically staggered scintillator bars

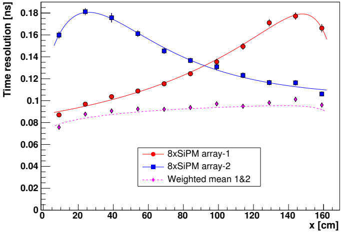
Timing Detector Characteristics



- 3 columns setup with EJ200 plasic bars
- $135\,\text{cm} \times 6\,\text{cm} \times 1\,\text{cm}$, providing $0.5\,\text{cm}$ overlap
- Summed readout on both ends by an array of eight $6\,\text{mm} \times 6\,\text{mm}$ SiPMs
- 330 bars $\rightarrow$ 660 channels

Test Beam at CERN

- Resolution of $\sim 80\,\text{ps}$ along the whole length of the bar over $2\,\text{m}^2$ prototype



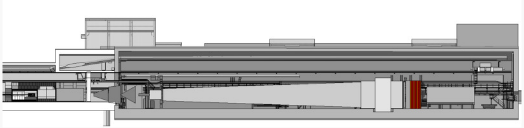
PID

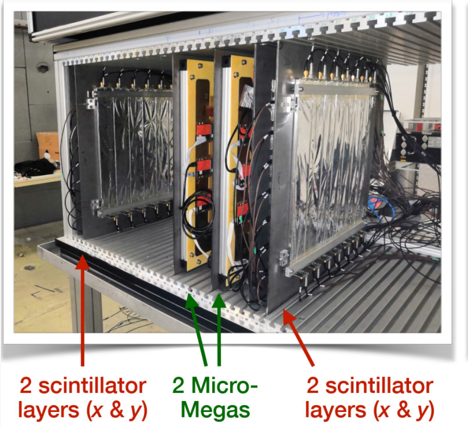
Purpose, Requirements and Challenges

- e/γ identification
- π^0 reconstruction,
- γ directionality
- Shower energy and angle

Technical implementation (CDS/ECN4)

- ECAL
- HCAL
- Muon Detector





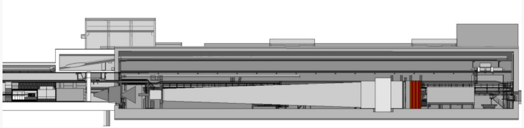
PID

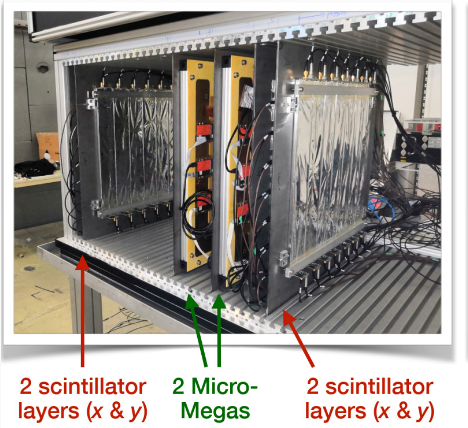
Purpose, Requirements and Challenges

- e/γ identification
- π^0 reconstruction,
- γ directionality
- Shower energy and angle

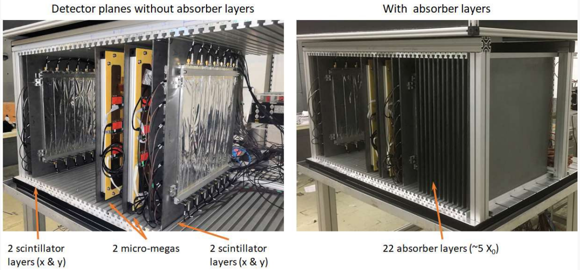
Technical implementation (CDS/ECN4)

- ~~ECAL~~
- ~~HCAL~~
- ~~Muon Detector~~
- Integrated solution ECAL/PID
  - Shorter detector

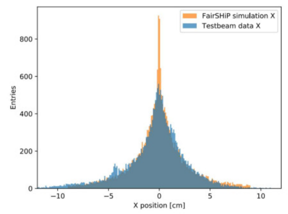


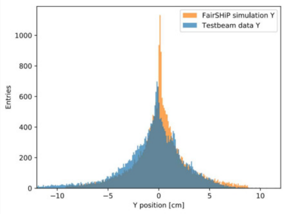


ECAL – *SplitCal*



Measured and simulated transverse e.m. shower distributions with 5 GeV electrons



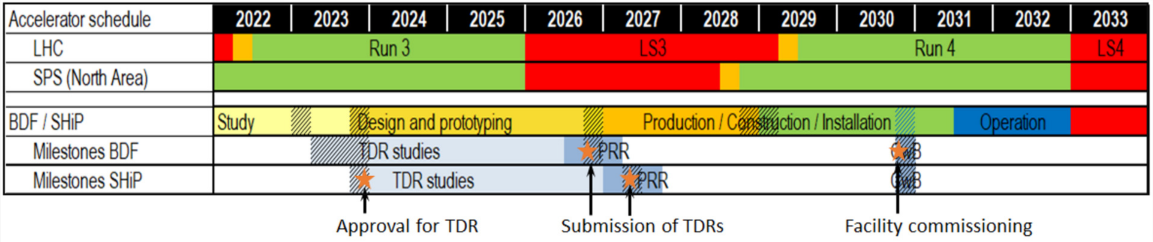


- Longitudinally segmented lead sampling calorimeter
- Lead absorber plates ($0.5X_0$ i.e. 0.28 cm)
- Sampling layers equipped with scintillating plastic bars, read out by WLS fibres (0.56 cm)
- ▷ 40 coarse layers $\rightarrow 20X_0$
- Three layers equipped with high resolution detectors ($\sim$200 µm resolution)
- ▷ reconstruct shower barycenter, provide photon angular resolution

PID Integrated Solution

- Setup has about one nuclear interaction length
  - sufficient for e/π separation
  - not enough for μ/π separation
- ▷ Four additional stations of active layers for muon id
  - interleaved by 60 cm iron walls
  - iron wall at front protecting form e.m. shower trails
  - thinner iron plate at back shielding from cavern background
- Expected muon id efficiency of $> 95\%$ in the momentum range of between 5 and 100 GeV with a mis-identification rate of 1 to 2 %
- Under study if suitable for SHiP

Schedule



- Approval in 2023 is critical to ensure timely funding
- ~ 3 years for detector TDR
- Availability of test beams challenging
- Important to start data taking more than one year before LS4

Collaboration

- 38 institutes from 15 countries and CERN
- Many young scientists
- Conceptual Design was well covered, more manpower welcome for TDR phase.

Sub-projects	Main lead	Involved groups
Muon shield		
Muon shield*	CERN[30]	RAL(UK)[38], CERN[30], ++
SND		
Emulsion system	Naples(IT)	LNGS(IT)[17], Naples(IT)[16,c], Aichi(JP)[18], Kobe(JP)[19], Nagoya(JP)[20], Nihon(JP)[21], Toho(JP)[22], Gyeongsang(KR)[23], Gwangju(KR)[24], Seoul(KR)[25], Gyeong Gi-do(KR)[26], METU(TR)[33]
Target tracker	Lausanne(CH)	Lausanne(CH)[31], Seigen(DE)[12]
Muon spectrometer	Naples(IT)	Bari(IT)[13,a], Naples(IT)[16,c]
HSDS		
Decay vacuum vessel + caps*	Naples(IT)	Naples(IT)[c], CERN[30]
Spectrometer vacuum vessel*	CERN[30]	CERN[30]
Spectrometer magnet*	CERN[30]	CERN[30], ++
Upstream background tagger	Lisbon(PT)	Lisbon(PT)[28]
Surrounding background tagger	Berlin(DE)	Berlin(DE)[7], Freiburg(DE)[8], Juelich(DE)[10], Mainz(DE)[11], Kiev(UA)[39]
Spectrometer tracker	Hamburg(DE)	Hamburg(DE)[9], Juelich(DE)[10], Kiev(UA)[39], CERN[30]
Timing detector	Zurich(CH)	Zurich(CH)[32]
Particle identification detectors		Mainz(DE)[11], Bologna(IT)[14], Cagliari(IT)[15,b], Bristol(UK)[35], ICL(UK)[36], UCL(UK)[37]
Online + offline		
Common electronics and online[(*)]	Orsay(FR)	Orsay(FR)[6], CERN[30]
Computing		CERN[30], Copenhagen(DK)[5]
Subdetector infrastructure, engineering, electronics		Sofia(BG)[1], Zurich(CH)[32], SAPHIR(CL)[2], UNAB-Santiago(CL)[3], ULS-Serena(CL)[4], Copenhagen(DK)[5], Siegen(DE)[12], Leiden(NL)[27], Belgrade(RS)[29], Ankara(TR)[34]

Summary

- BDF/SHiP provides a clear opportunity to discover FIPs in the decays of heavy mesons.
- Complementary to the FIP searches at HL-LHC and future e^+e^--colliders.
- Robust neutrino physics program, including fundamental tests of SM in tau neutrino interactions.

- A strong concept has been presented after the CDS phase
- Big support from the BDF working group

- Implemented detector into ECN3
- Ready for approval of TDR phase

BDF/SHiP is ready to set sails