SHiP: a new facility with a dedicated detector for studying ν_τ properties and nucleon structure functions

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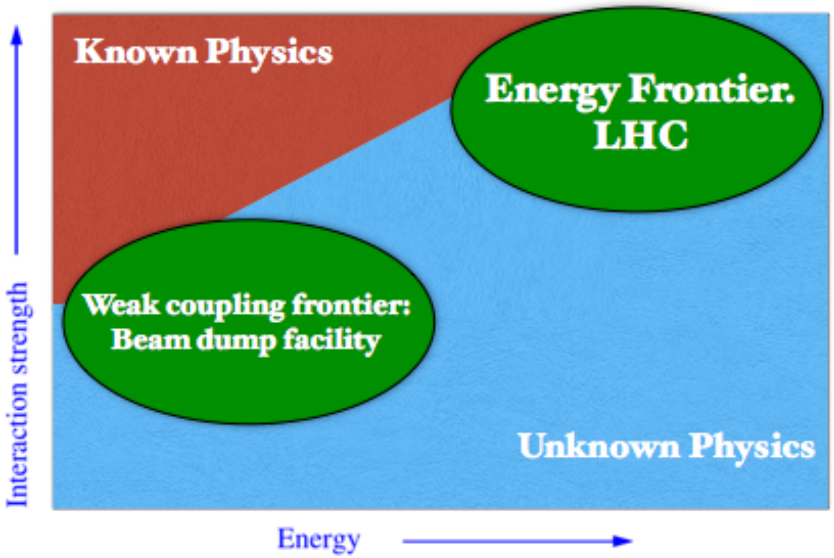
Physical Motivation

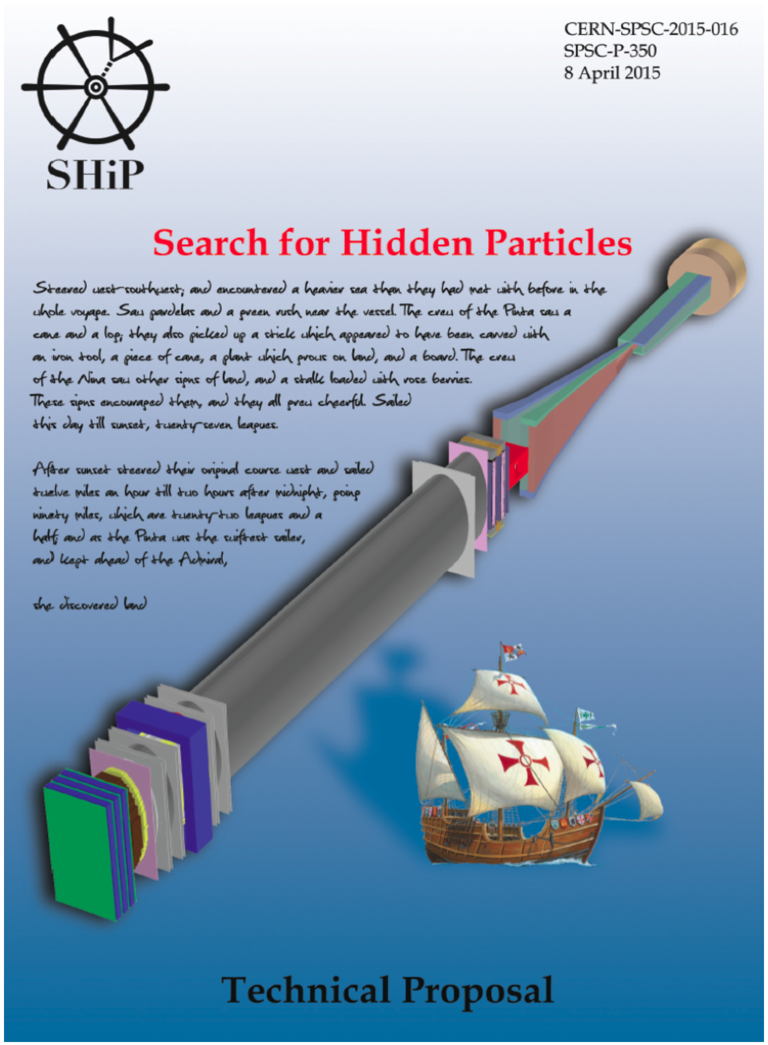
- Current model for description of particle physics world: Standard Model (SM)
- Three open questions:
  - Neutrino masses
  - Baryon Asymmetry in the Universe (BAU)
  - Presence of Non-baryonic Dark Matter



- Scale of new physics still unknown
- Long lived neutral (hidden) particles predicted in many BSM models.
- Two ways to search for new physics:
  - **energy frontier**
    - heavy particles
    - high energy events
  - **intensity frontier**
    - light particles
    - very rare events

SHiP experiment

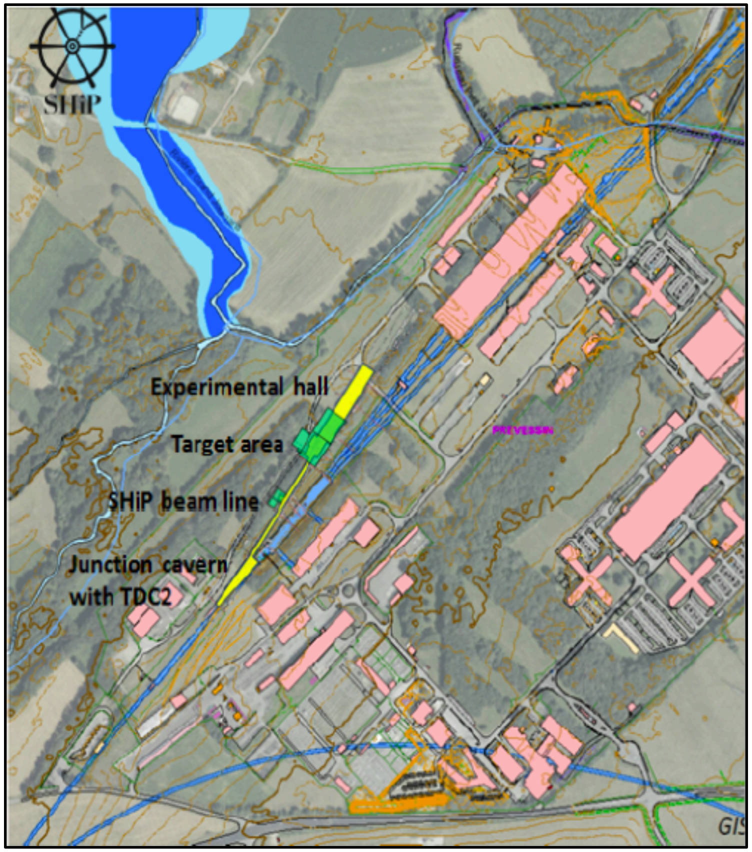
The SHiP experiment

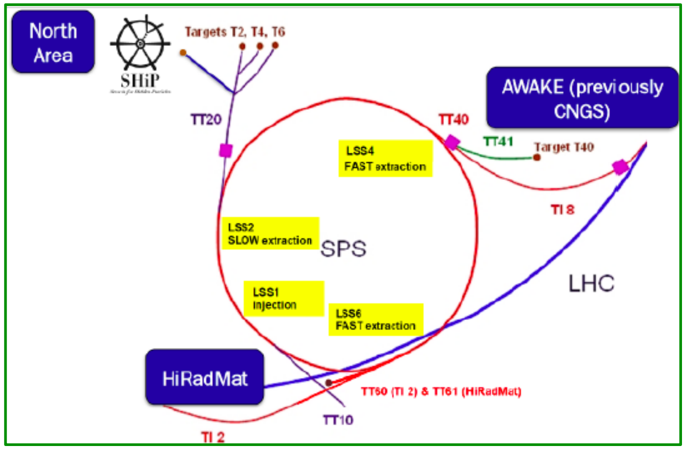


- Proposal for a new facility at the CERN SPS accelerator:
    - hidden sector detector
    - ν_τ facility
- 235 experimentalists from 45 institutes and 15 countries + CERN
- **Techinical Proposal submitted in April 2015** (arxiv.org/abs/1504.04956)
- **Physics Proposal signed by 85 theorists** (arxiv.org/abs/1504.0855)
- ***SPSC positive recommendation in January 2016***

The SHiP Facility

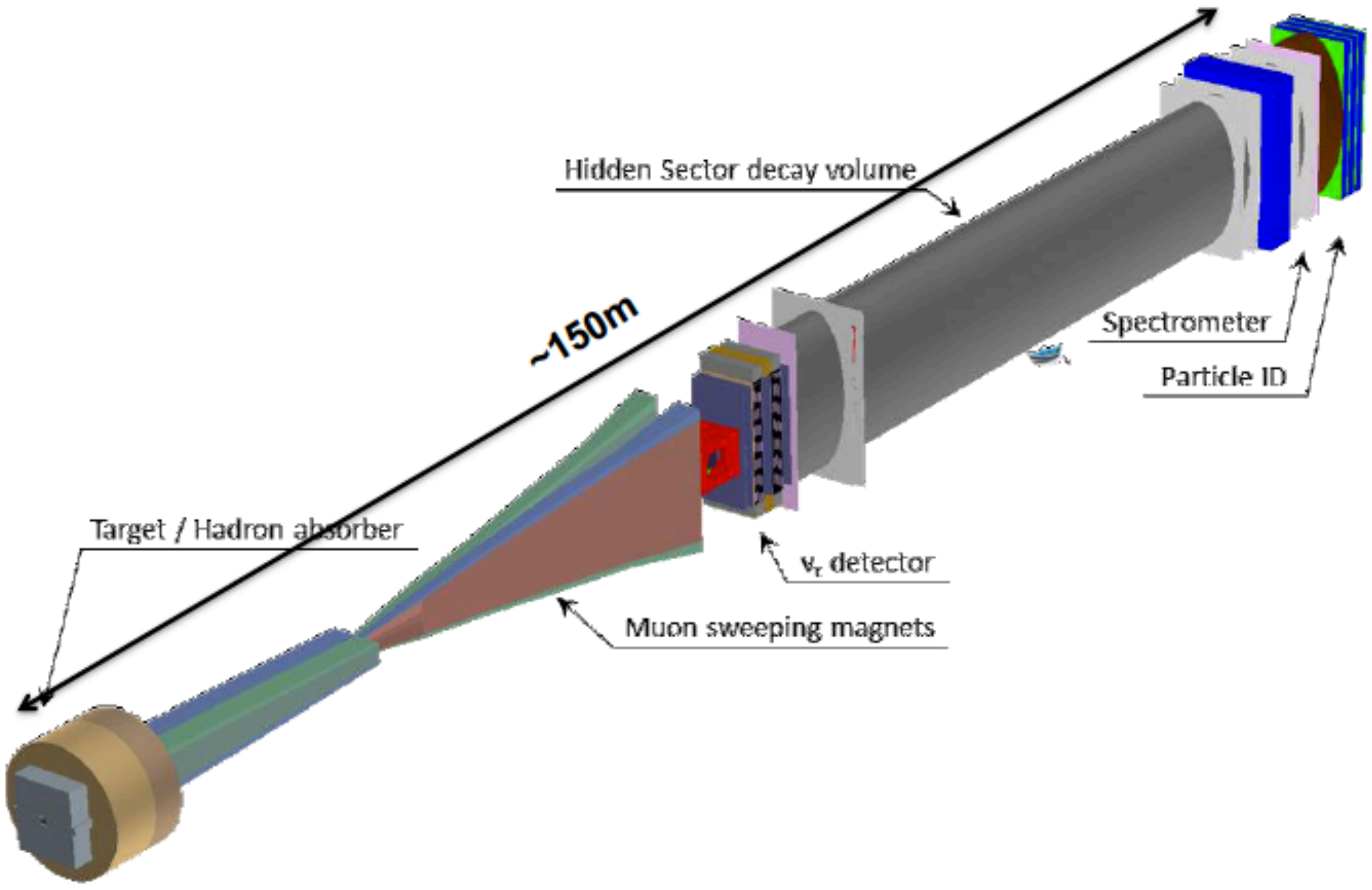
- General purpose fixed target facility at CERN
  - 400 GeV proton spills (4 x 10^{13} p.o.t.) from a dedicated beam line at the SPS accelerator





- Location: Prevessin North Area site
- Sharing of the TT20 transfer line and slow extraction mode with existing facilities
- Minimal modification to the SPS complex.

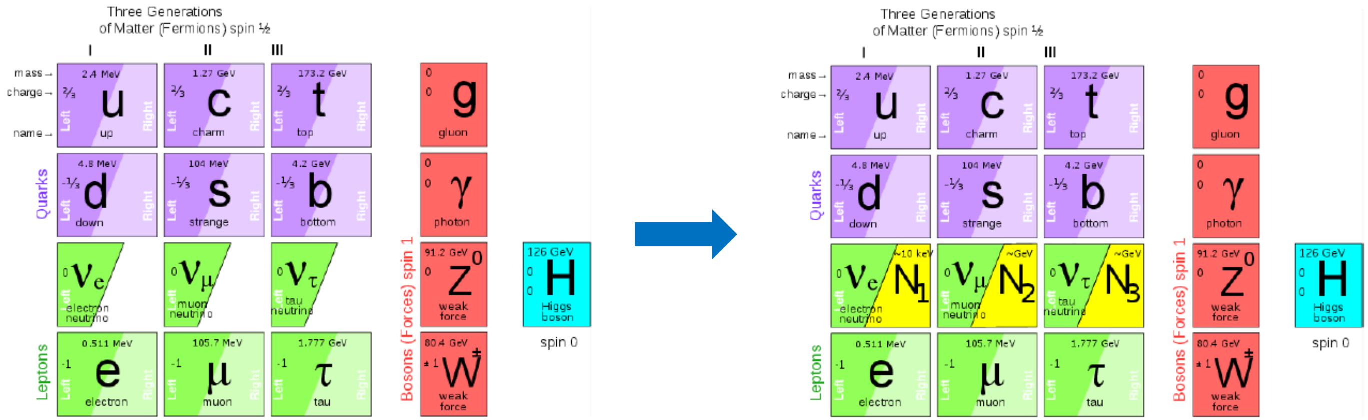
The SHiP detector layout



A DETECTOR TO SEARCH FOR HIDDEN PARTICLES

Physics goals

- Explore **Hidden Portals** and **extension of the SM** incorporating *long-lived and very weakly interacting particles*
  - Vector portal (dark, hidden, para-photons)
  - Scalar portal
  - Neutrino portal: *νMSM (Neutrino Minimal Standard Model)*[1]
    - Minimal extension of the SM fermion sector by_three RH (Majorana) Heavy Neutral Leptons (**HNL**): N_1, N_2, N_3.



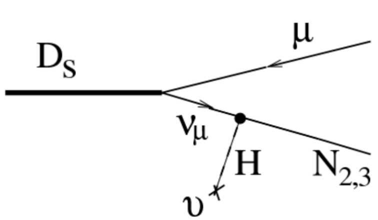
- Lightest singlet N_1 (mass ≈ KeV): good dark matter candidate.
- N_2, N_3 (mass in 100 MeV - GeV region):
  - "give" masses to neutrinos;
  - explain baryon asymmetry

[1] D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015

Experimental Requirements

PRODUCTION

Hidden particles produced in decays of charmed and beauty hadrons:



T.Asaka, M.Shaposhnikov PL B620 (2005) 17

- ***Maximize neutrinos from charmed hadrons***
- ***Minimize neutrinos from π and K***

↓

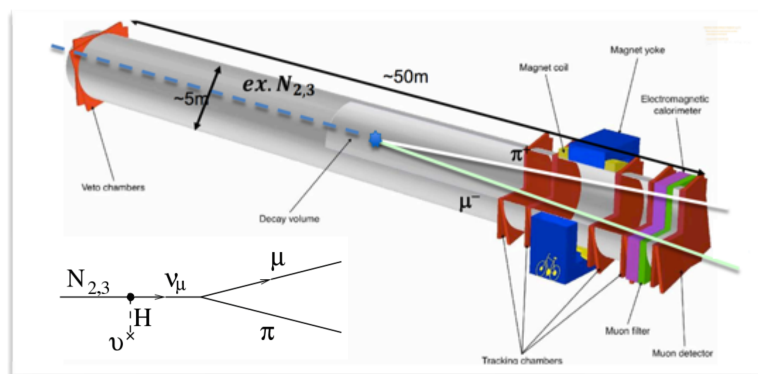
Hybrid target: blocks of titanium-zirconium doped molybdenum (TZM) followed by blocks of pure tungsten
Hadron Stopper: 5m of Fe

DETECTION

Hidden particles can decay in SM particles:

Final states	Models tested
$\pi l,\ Kl,\ \rho l,\ l=(e,\mu,\nu)$	ν portal, HNL, SUSY neutralino
$e^+e^-,\ \mu^+\mu^-$	V, S and A portals, SUSY s-goldstino
$\pi^+\pi^-,\ K^+K^-$	V, S and A portals, SUSY s-goldstino
$l^+l^-\nu$	HNL, SUSY neutralino

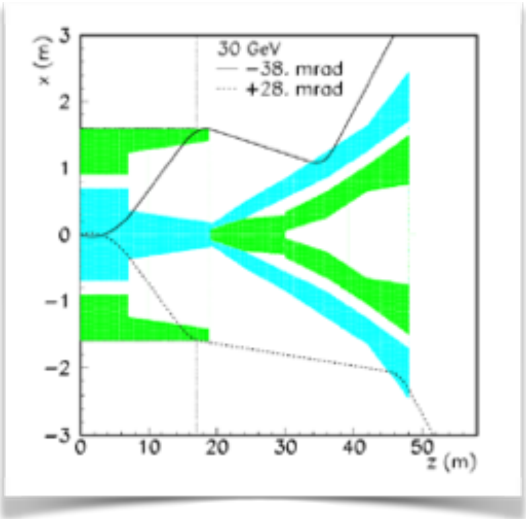
Typical lifetimes > 10 μs
$\Rightarrow$ Decay length O(km)

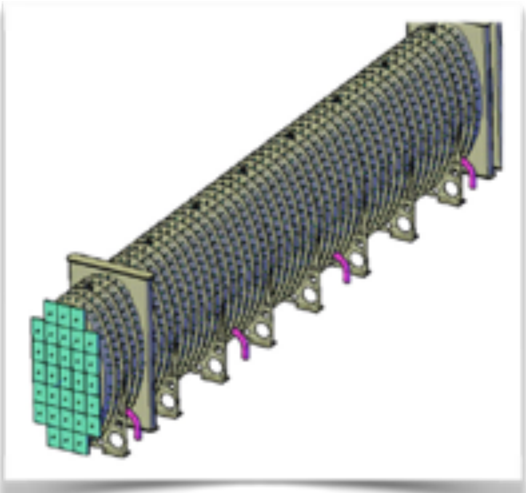


50 m long decay volume O(5)m diameter, equipped with detectors at the far end

Background rejection

- Muon Flux →
  - 48 m long active muon shield
  - veto system around the decay vessel
- Combinatorial →
  - Proton spills prepared with slow beam extractions (~1s)
  - Uniform extractions
- ν interactions inside the vessel →
  - Low pressure decay vessel
- ν interactions in the vessel proximity →
  - Light taggers located upstream and at the beginning of the HS fiducial volume



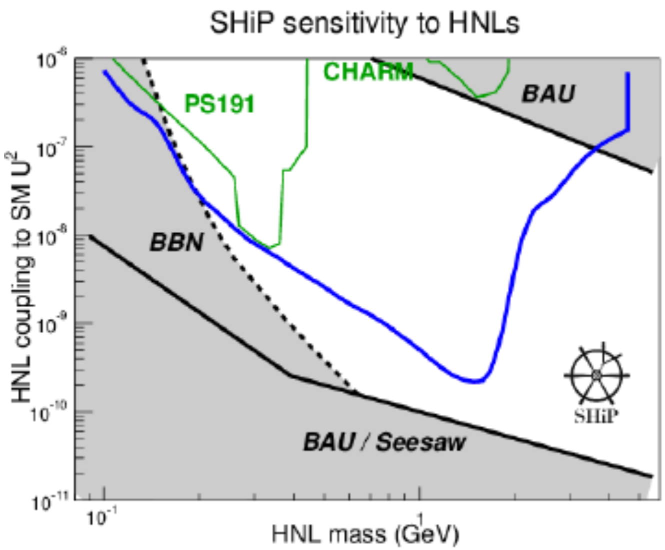


After selections:

≤ 0.1 bkg/ 5 y

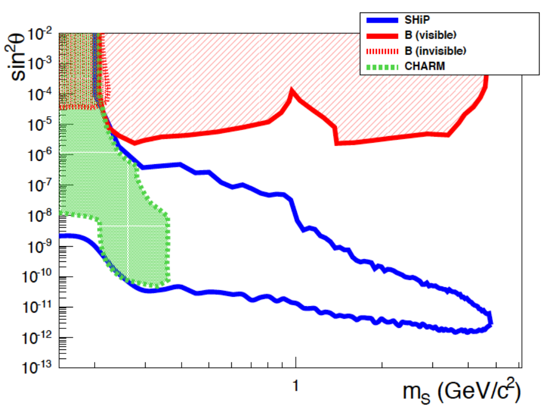
Sensitivities

Neutrino Portal (HNL)

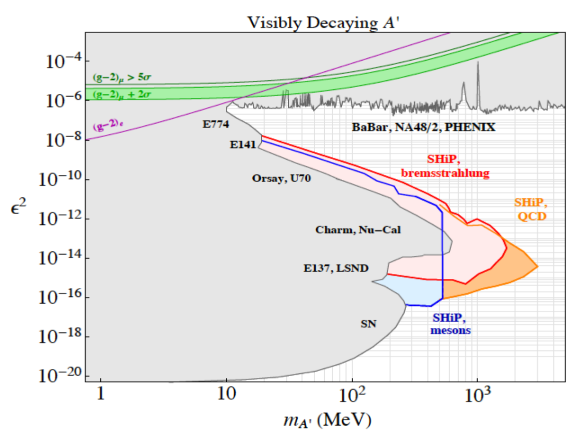


- Critically improving present limits in U^2
- Access masses up to m_B
- Probe region of special interest:
  - left open by cosmological observations (BBN)
- Sensitivity in all U_e, U_μ, U_τ channels

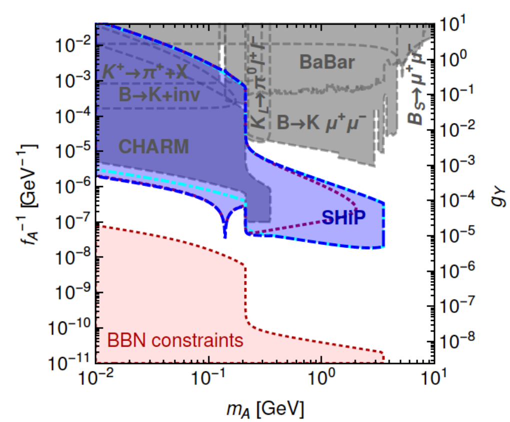
Scalar Portal



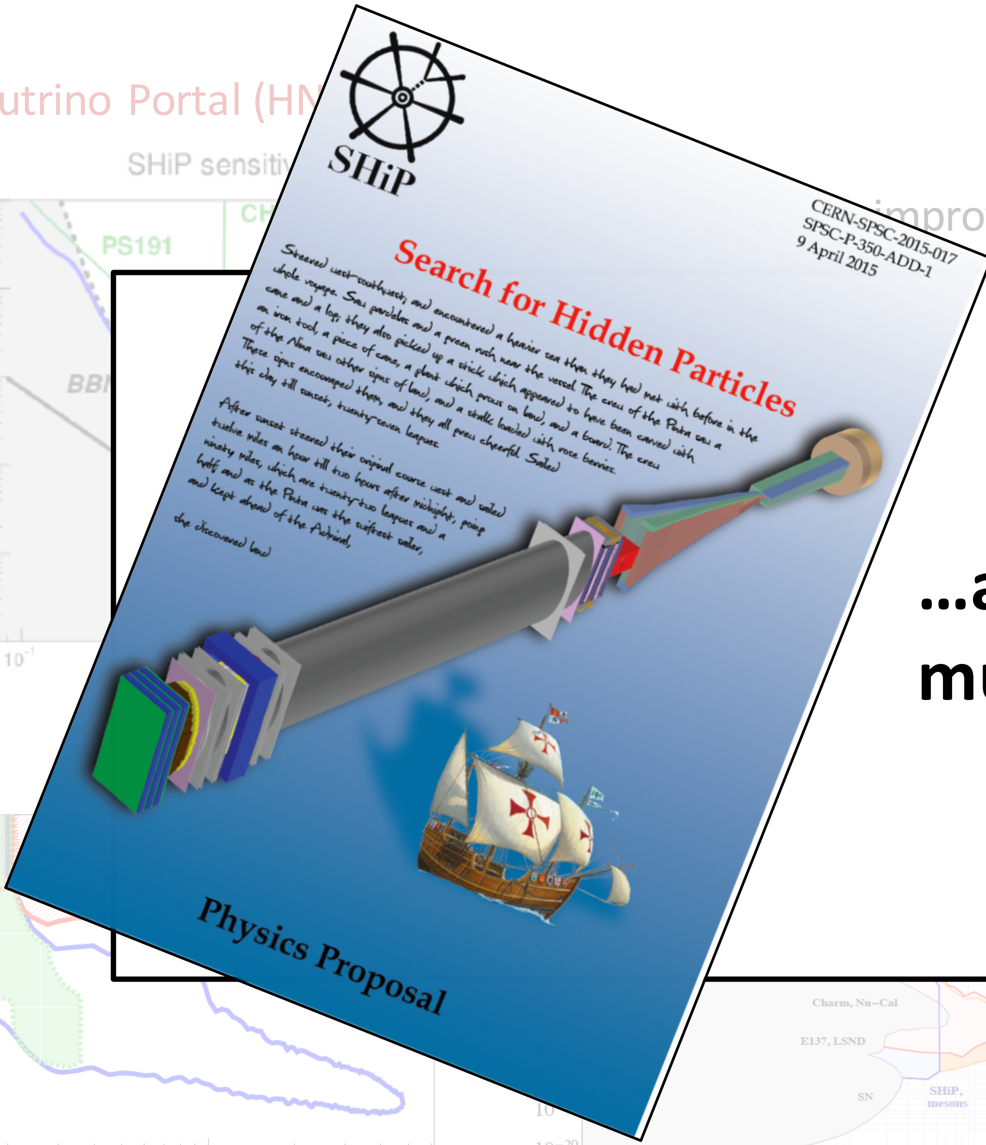
Vector Portal



Axion Portal



Sensitivities

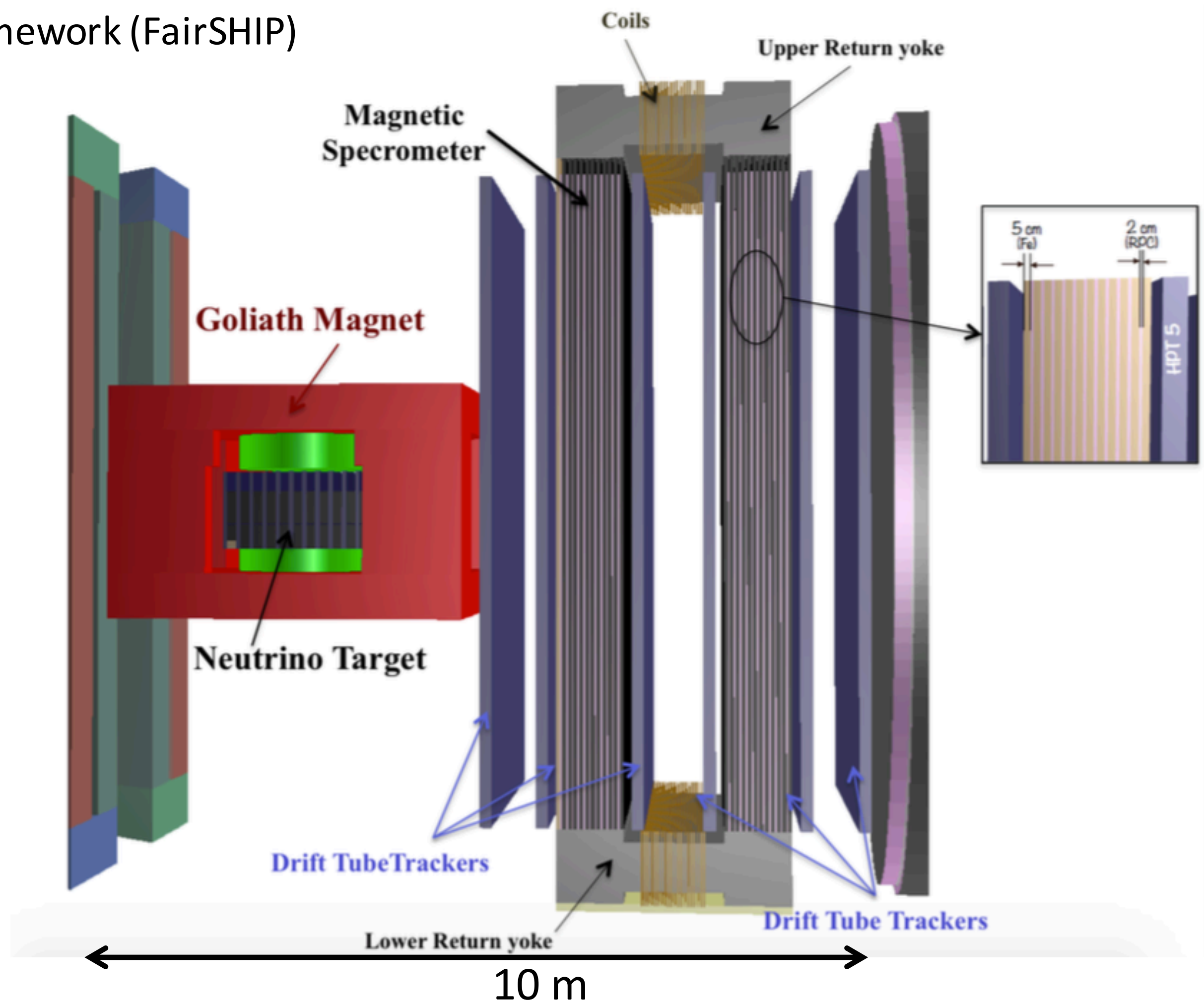


...and so much more...

NEUTRINO DETECTOR FOR A NEUTRINO PHYSICS PROGRAM

The neutrino detector

Implementation in dedicated CERN framework (FairSHIP)



ν_τ Physics Program

Motivation

- Less known particle in the Standard Model
- First observation by DONUT at Fermilab in 2001 with 4 detected candidates, *Phys. Lett. B504 (2001) 218-224*
- 9 events (with an estimated background of 1.5) were reported in 2008
- 5 ν_τ candidates reported by OPERA for the discovery (5.1σ result) of ν_τ appearance in the CNGS neutrino beam
- Anti- ν_τ never observed

SHiP neutrino program

- **~8k expected ν_τ and ~4k anti-ν_τ interactions in the target**
  - First observation of anti-ν_τ
  - Sufficient statistics to perform ν_τ and anti-ν_τ cross section measurement.
  - First measurement of structure function **F_4 and F_5 entering in DIS neutrino-nucleon cross section**

Experimental requirements

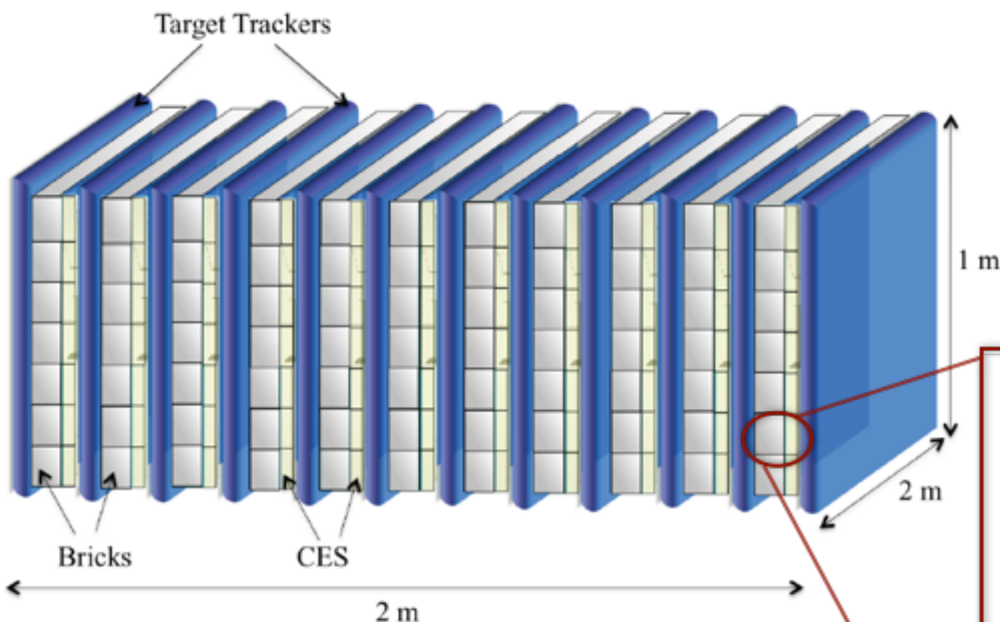
Target must be optimized to induce the maximum number of ν_τ interactions	Compact
Dimensions must be adapted to the region cleared by the muon active shield	High density
Disentangle τ production and decay vertices	Micron position resolution
Distinguish neutrinos from anti-neutrinos	Magnetised target
Muon identification, charge and momentum measurement to discriminate signal/background processes	Muon Magnetic spectrometer

Taking advantage of the OPERA experience

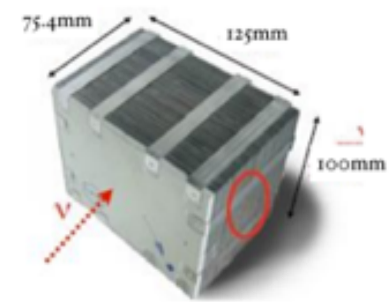
Identify all 3 neutrino flavour	Emulsion Cloud Chamber technique

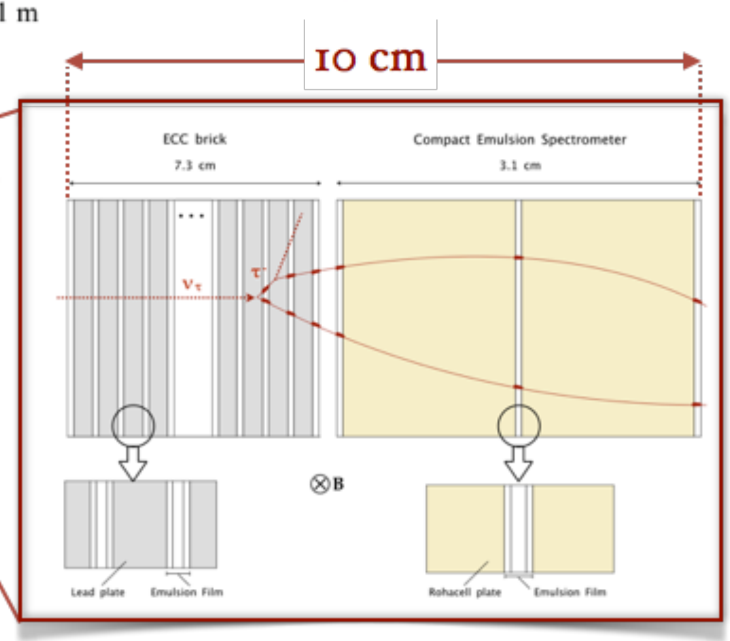
The neutrino target

ν target + vertex detector



Fundamental unit: **Brick**

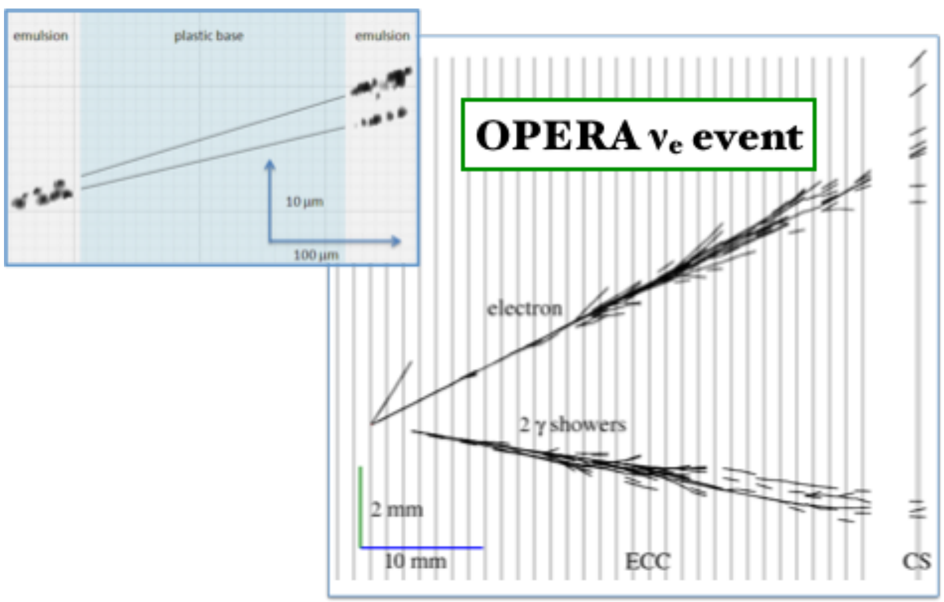


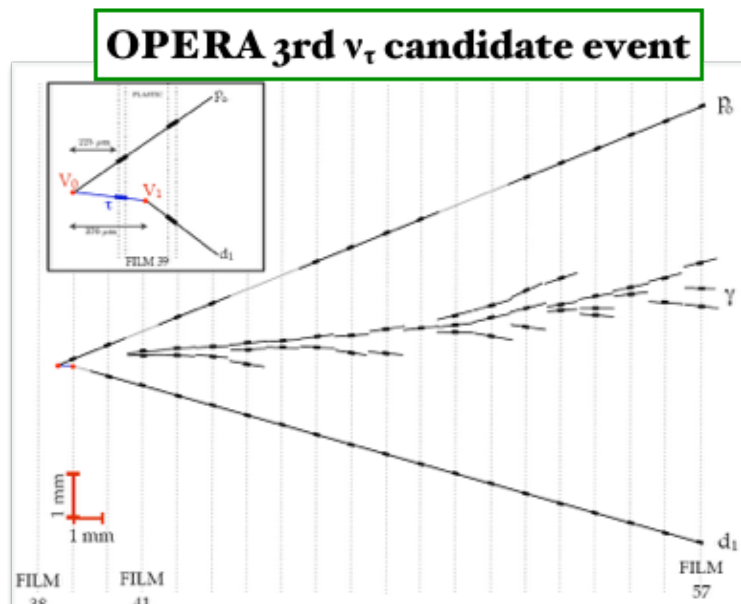


- **Emulsion Cloud Chamber technology**
- **Lead plates** (high density material for the interaction) interleaved with **emulsion films** (tracking devices with **µm resolution**)

Neutrino Flavour Identification in the ECC

- ν_μ identification: muon reconstruction in the magnetic spectrometer
- ν_e identification: electron shower identification in the brick
- ν_τ identification: disentanglement of τ production and decay vertices





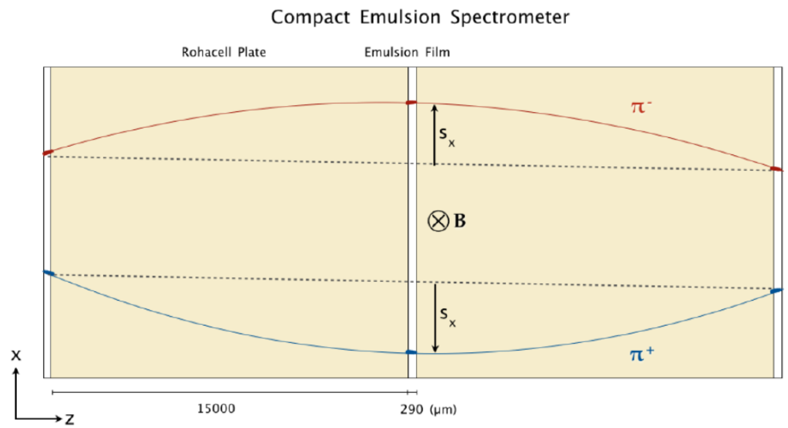
Separation ν_τ /anti-ν_τ

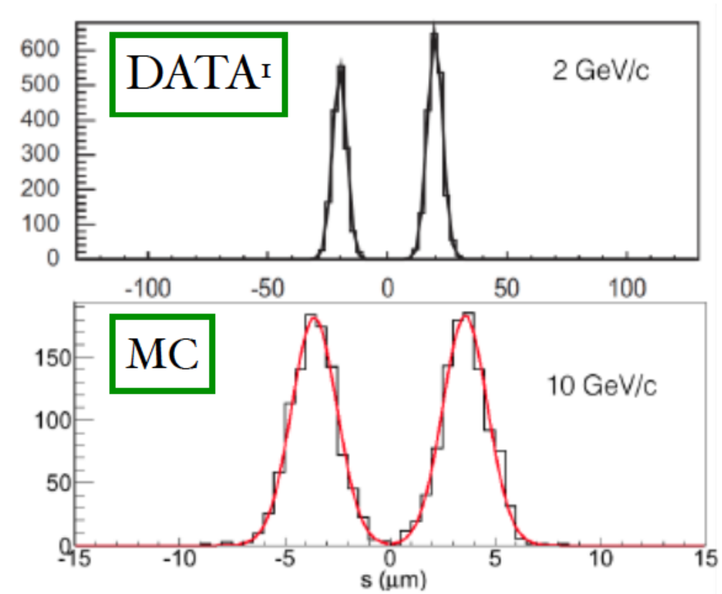
The Compact Emulsion Spectrometer

- three emulsion films interleaved with two, 15-mm thick, Rohacell layers
- capable of measuring the hadron track curvature
- 90% efficiency for hadronic τ daughters reaching the end of ECC brick in a 1 T field
- sagitta method used to discriminate between positive and negative charge

Performances

- electric charge can be determined with better than 3 σ level up to 10 GeV/c
- Momentum estimated from the sagitta Δp/p < 20% up to 12 GeV/c



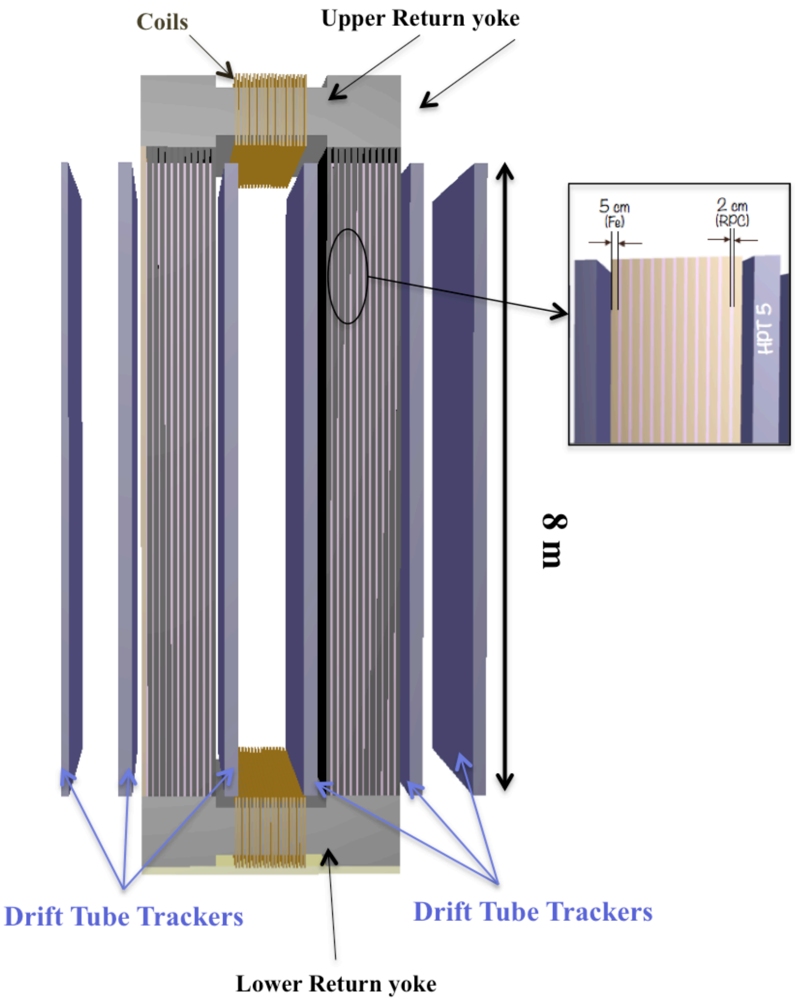


Event Time- Stamp

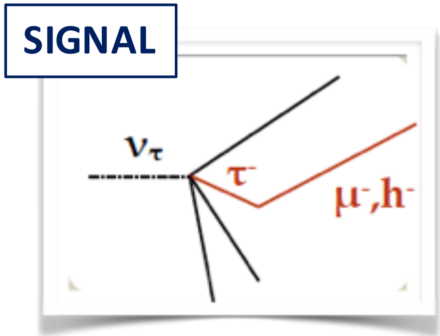
Target trackers (TT)

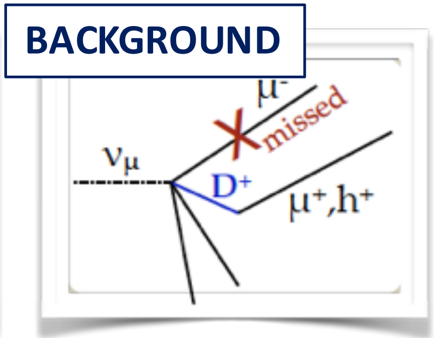
- ***Features:***
  - Provide Time stamp
  - Link track information in emulsions to signal in TT
  - Link muon track information in ν target to μ magnetic spectrometer
- ***Requirements in 1T field:***
  - 100 μm position resolution on both coordinates
  - high efficiency (>99%) for angles up to 1 rad
- ***Possible options:***
  - Scintillating fibre trackers
  - Micro-pattern gas detectors (GEM, Micromegas)
- ***Detector layout:***
  - 12 target planes interleaved by the 11 brick walls at a few mm distance
  - 1st plane used as veto
  - Transverse size of about 2 x 1 m2

μ Identification



- μ come from:
  - τ -> μ decays
  - ν_μ CC interactions
- **μ identification at 1ry vertex crucial for bkg rejection**



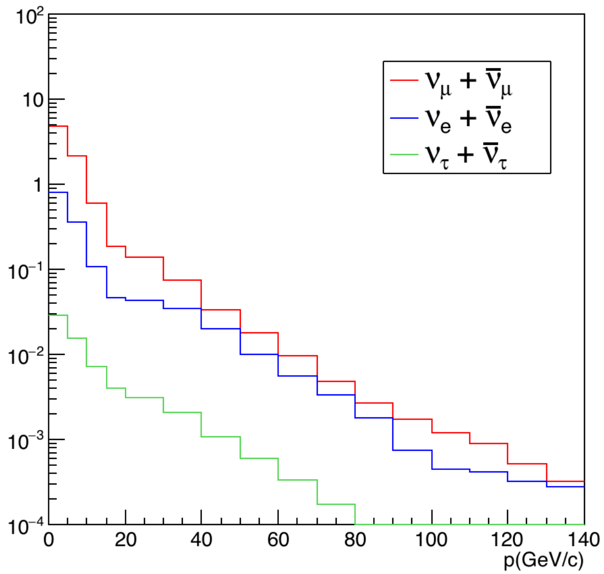


- **Dipolar magnetic (1.52T) spectrometer**
  - 12 iron layers/arm (5cm each)
  - 11 RPC layers/arm (2cm each)
  - 6 Drift Tube Tracker Planes
- Momentum resolution better than 25%
- Charge measurement efficiency ~ 94%

Neutrino Fluxes

- SHiP experimental setup ideally suited to perform studies on neutrino and anti-neutrino physics.
- High charmed hadrons decay rates $\Rightarrow$ high ordinary neutrino fluxes

ν energy spectra @ beam dump



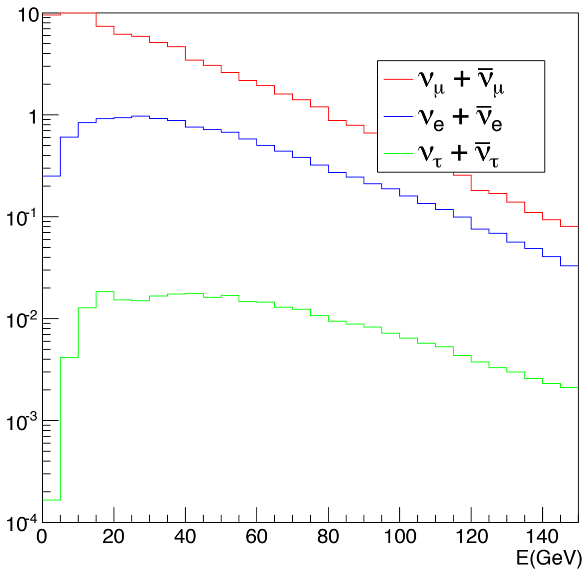
	Φ	<E> (GeV)
ν_μ	4.4×10^{18}	1.4
ν_e	2.1×10^{17}	3
ν_τ	3.3×10^{15}	9
Anti-ν_μ	2.8×10^{18}	1.5
Anti-ν_e	1.6×10^{17}	4
Anti-ν_τ	3.3×10^{15}	8

Rates for five years of nominal operation with 2×10^{20} protons on target

Neutrino Fluxes

- SHiP experimental setup ideally suited to perform studies on tau neutrino and anti-neutrino physics.
- High charmed hadrons decay rates $\Rightarrow$ high ordinary tau-neutrino fluxes

Energy spectra of DIS CC interacting ν



	Φ	<E> (GeV)
ν_μ	1.7×10^6	29
ν_e	2.5×10^5	46
ν_τ	7.6×10^3	59
Anti-ν_μ	6.7×10^5	28
Anti-ν_e	9.0×10^4	46
Anti-ν_τ	3.9×10^3	58

Rates for five years of nominal operation with 2×10^{20} protons on target

Physics with DIS

- High rates of Deep Inelastic Scattering interactions from all three neutrino flavours on target nucleons expected.

  - **Structure function estimation**

$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2\Bigg[\left(xy^2+\frac{m_l^2 y}{2E_\nu M_N}\right)F_1+\left(1-y-\frac{M_N xy}{2E_\nu}-\frac{m_l^2}{4E_\nu^2}\right)F_2$$
$$\pm\left(xy\left(1-\frac{y}{2}\right)-\frac{m_l^2 y}{4E_\nu M_N}\right)F_3+\frac{m_l^2(m_l^2+Q^2)}{4E_\nu^2 M_N^2 x}F_4-\frac{m_l^2}{E_\nu M_N}F_5\Bigg]$$

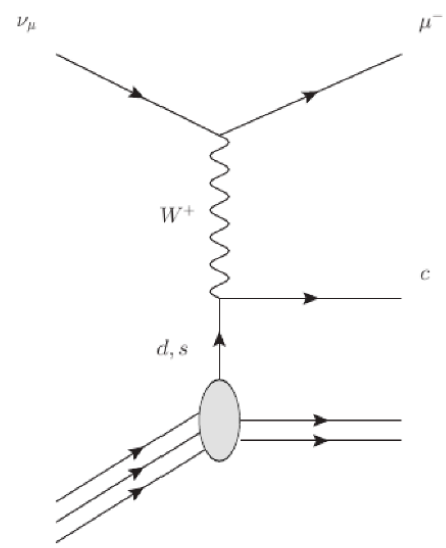
Estimation through ν/anti-ν data subtraction

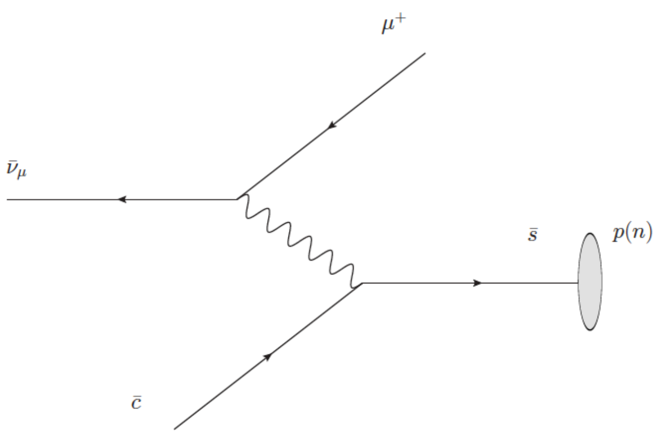
Dependent on the lepton mass.
Relevant only for ν_τ interactions

- From ν_τ and anti-ν_τ CC interactions:
  - *First evaluation of F_4 and F_5* not accessible with lighter neutrinos
- From ν_μ and anti-ν_μ CC interactions:
  - Estimation of F_3

Physics with DIS

- High rates of Deep Inelastic Scattering interactions from all three neutrino flavours on target nucleons expected
  - **Charm production with ν and anti-ν scattering**
    - Charmed hadrons produced at a level of a few % in ν_μ and ν_e CC interactions
    - s-quark content of the nucleon: both ν and anti-ν are a good probe in interactions where a charmed hadron is produced





  - **ν_e physics**
    - Study of ν_e cross section at high energies
    - Possibility to normalize the charm production at the beam dump

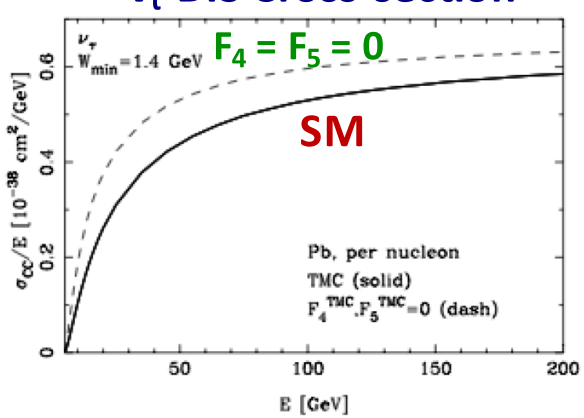
Sensitivity to F_4 and F_5

Through ν_τ and anti-ν_τ identification: unique capability of being sensitive to F_4 and F_5

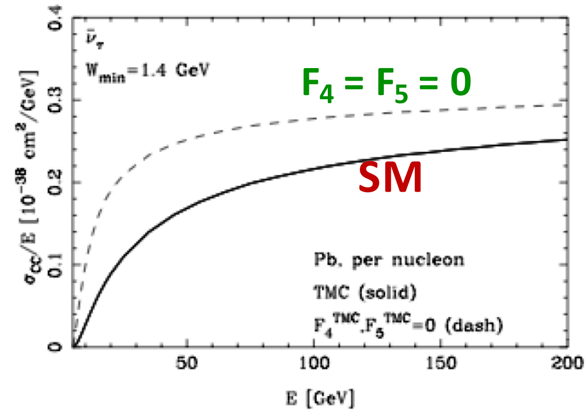
$F_4 = F_5 = 0$ hypothesis
Increases ν_τ and anti-ν_τ cross-sections

Differences larger for lower ν energies

ν_τ DIS Cross-section



Anti-ν_τ DIS Cross-section

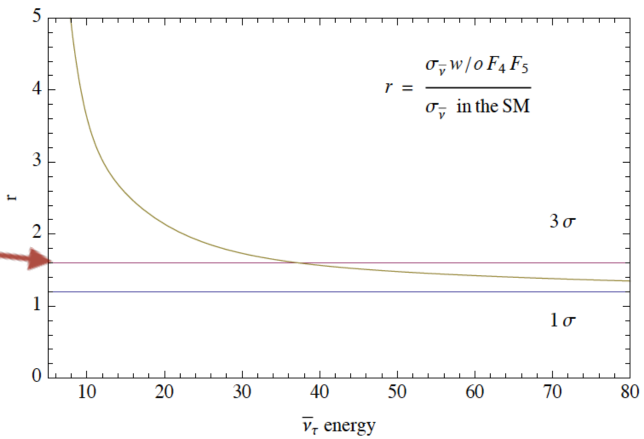


r = ratio between the cross section in the two hypotheses

E(anti-ν_τ) < 38 GeV (~300 evts)

E(ν_τ + anti-ντ) < 20 GeV (~420 evts)

r > 1.6
evidence for a non-zero value of F_4 and F_5



Sensitivity to s-quark

- Charmed hadrons identified through the observation of their decay.

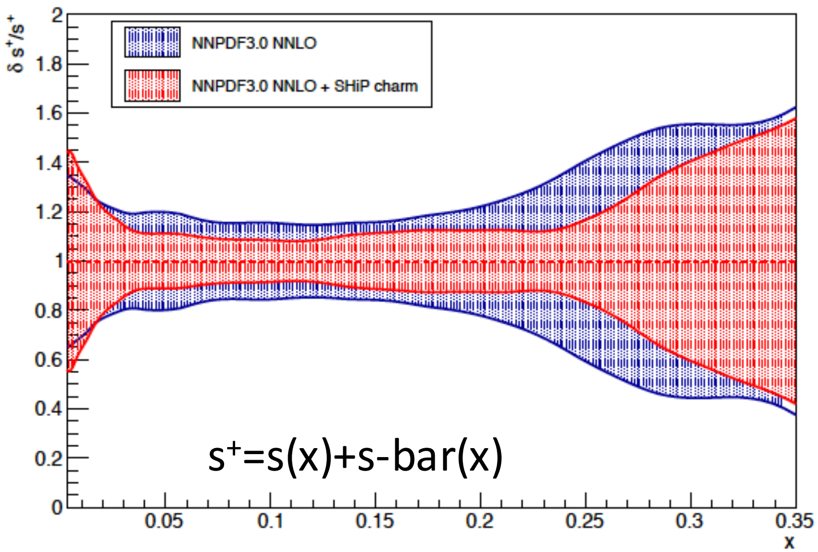
- Expected ν-induced charm yield in 5 years run:

$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}} \right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE} \approx 4\%$$

$$f(charm) = \frac{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_e}} \right) dE}{\int \Phi_{\nu_e} \sigma^{CC}_{\nu_e} dE} \approx 6\%$$

	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu_\mu}$	$2.7 \cdot 10^4$
$\bar{\nu_e}$	$5.4 \cdot 10^3$
total	$1.1 \cdot 10^5$

- Charmed hadron production in antineutrino interactions selects anti-strange quark in the nucleon
  - Improvement achieved on s+/s- versus x
  - Significant gain with SHiP data obtained in the x range between 0.03 and 0.35 complementary to that of ATLAS and CMS (sensitive at lower x)



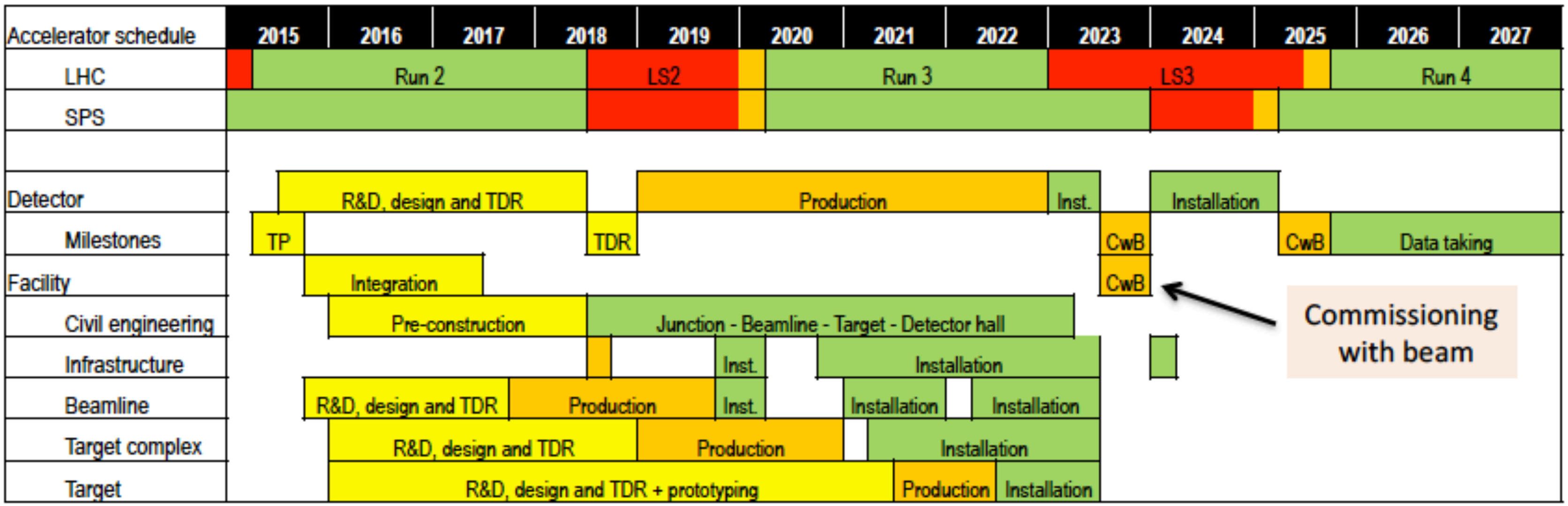
Annarita Buonaura, on behalf of the SHiP collaboration - DIS2016

CONCLUSIONS

- Unlike LHC exploring the energy frontier, SHiP intends to explore the intensity frontier
  - Long-lived and very weakly interacting particles are searched for
    - Sterile neutrinos (Heavy Neutral Leptons)
    - Dark photons
    - Paraphoton
    - SUSY: Sgoldstino, Light neutralino
  - Compact neutrino detector to perform SM physics studies
    - Cross-section measurement for ν_τ and anti-ν_τ interactions
    - Estimate structure functions (F_4 and F_5) from charged current neutrino nucleon deep-inelastic scattering
    - Study ν-induced charm events
    - Study s-quark content of the nucleon
- Technical and Physics proposal submitted to the SPSC in April 2015
- Positive recommendation from the SPSC in January 2016

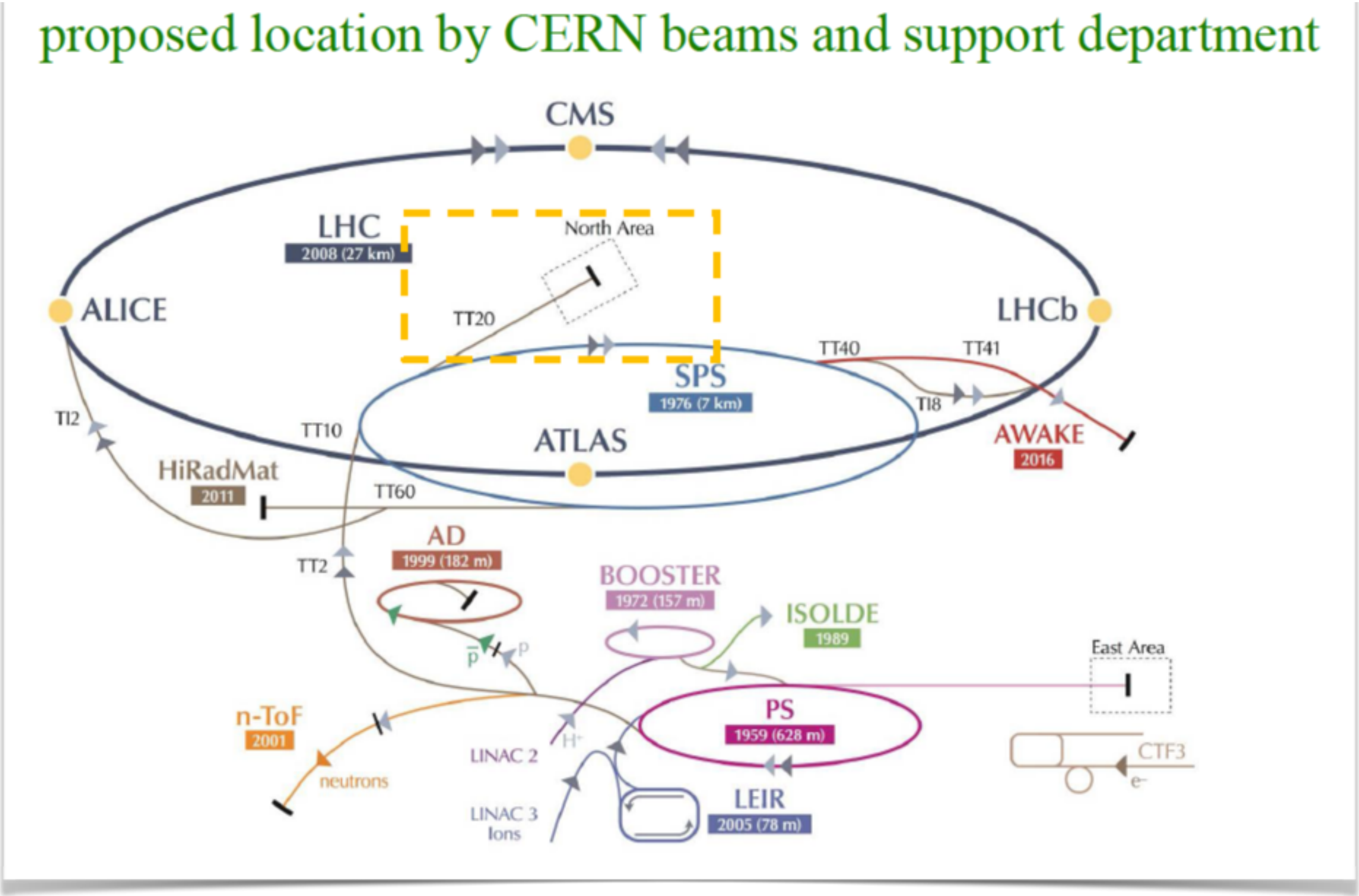
BACK-UP

Time scale



• Form SHiP Collaboration	December 2014 ✓
• Technical Proposal submission	April 2015 ✓
• Technical Design Report submission	2018
• Building and installation	2018-2023
• Commision	2023
• Data taking and analysis	2026

CERN Accelerator Complex



Hidden Particles Background

Expected number of background events from MC simulation for 5 years of data taking.

ratio between the equivalent MC statistics and the total expected number of events

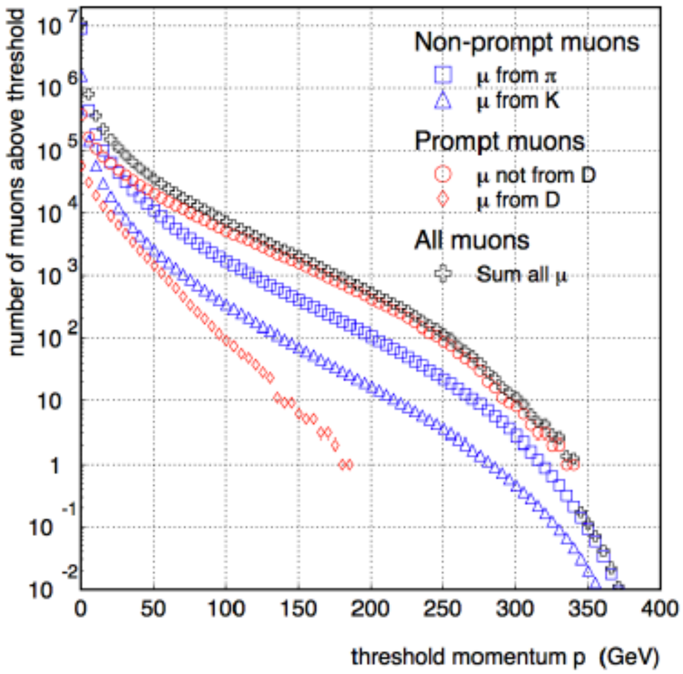
Background source	Statistical factor	Expected background
ν ($p >$ 10.0GeV)	35.	$<$ 0.07
ν (4.0GeV$< p <$ 10.0GeV)	~ 1	0 (MC)
ν (2.0GeV$< p <$ 4.0GeV)	0.07	0 (MC)
μ DIS HS	~ 1	0 (MC)
μ DIS wall	0.001	0 (MC)
μ Combinatorial	10^4	$<$ 0.1
μ Cosmics ($p <$ 100GeV)	0.2	0 (MC)
μ Cosmics ($p >$ 100GeV)	800.	$<$ 0.1
μ Cosmics DIS ($p >$ 100GeV)	10^3	$<$ 0.1
μ Cosmics DIS (10GeV$< p <$ 100GeV)	~ 1	0 (MC)

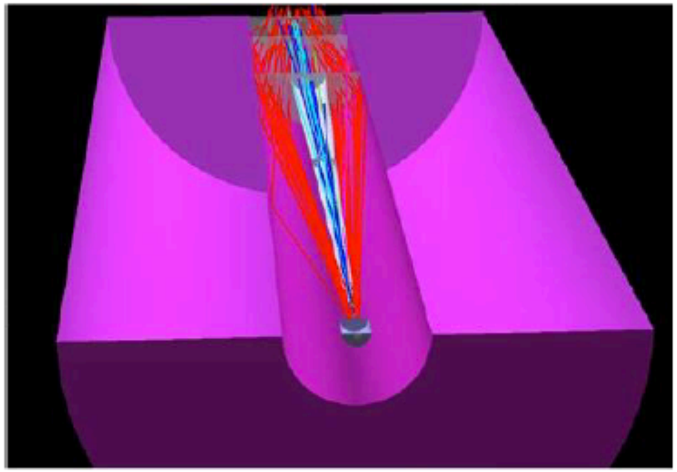
0 bkg events observed in the MC

- no evidence of significant impact of any of these backgrounds on the experiment
- any evidence for any source of irreducible background

Assumed a level of background of 0.1 events for the entire run of the experiment → 3σ evidence if 2 events of HNL are observed

Muon background

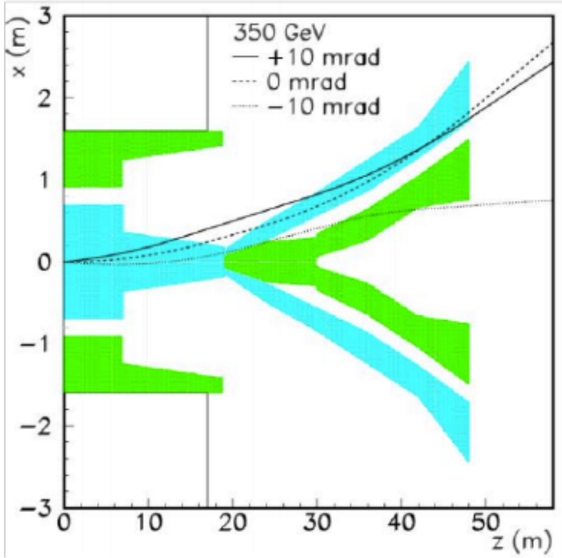


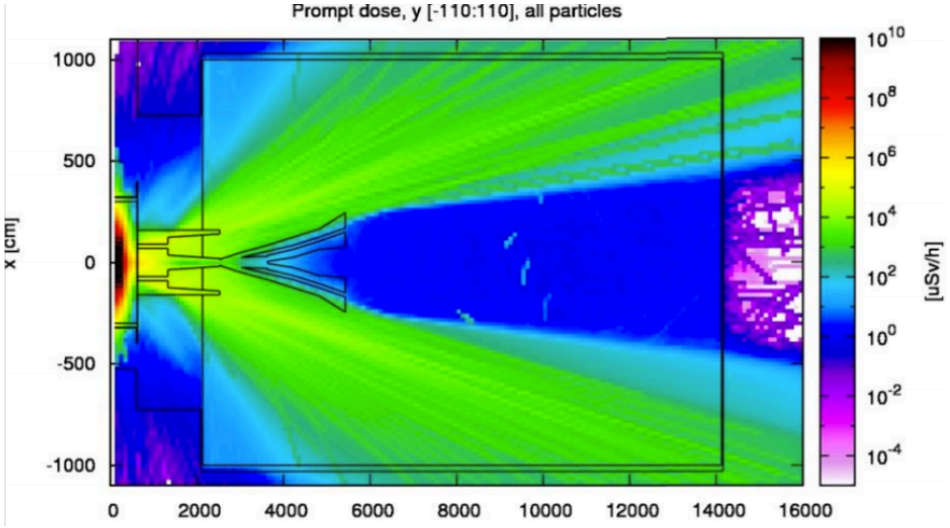


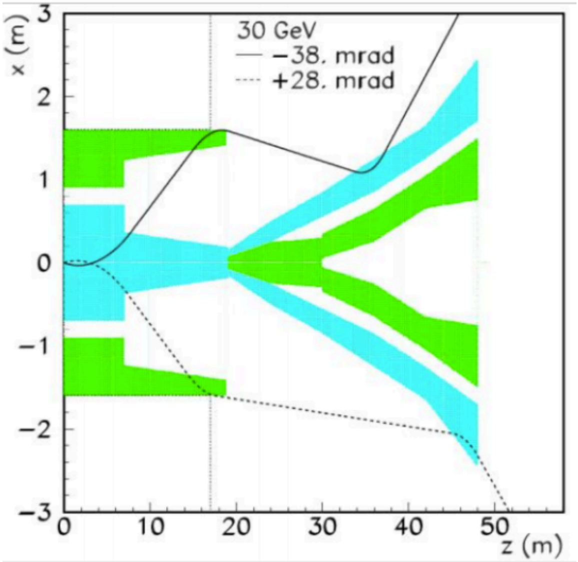
- Heavy target stops hadrons before they decay. After the target and the hadron absorber only muons survive
- Muons come mainly from η, η' and ω
- Without muon filter rate would be 5×10^{9}muons/spill (1 spill is 5×10^{13} POT)

Active Muon-Shield

- Muon flux driven by the HS background and emulsion-based neutrino detector
- Active muon shield based entirely on magnet sweeper with a total field integral B = 86.4 Tm
- Realistic design of sweeper magnets in progress
- Challenges: flux leakage, constant field profile, modeling magnet shape
- Rate reduction: from 1010 to 104 muons/spill
- Negligible flux in terms of detector occupancy





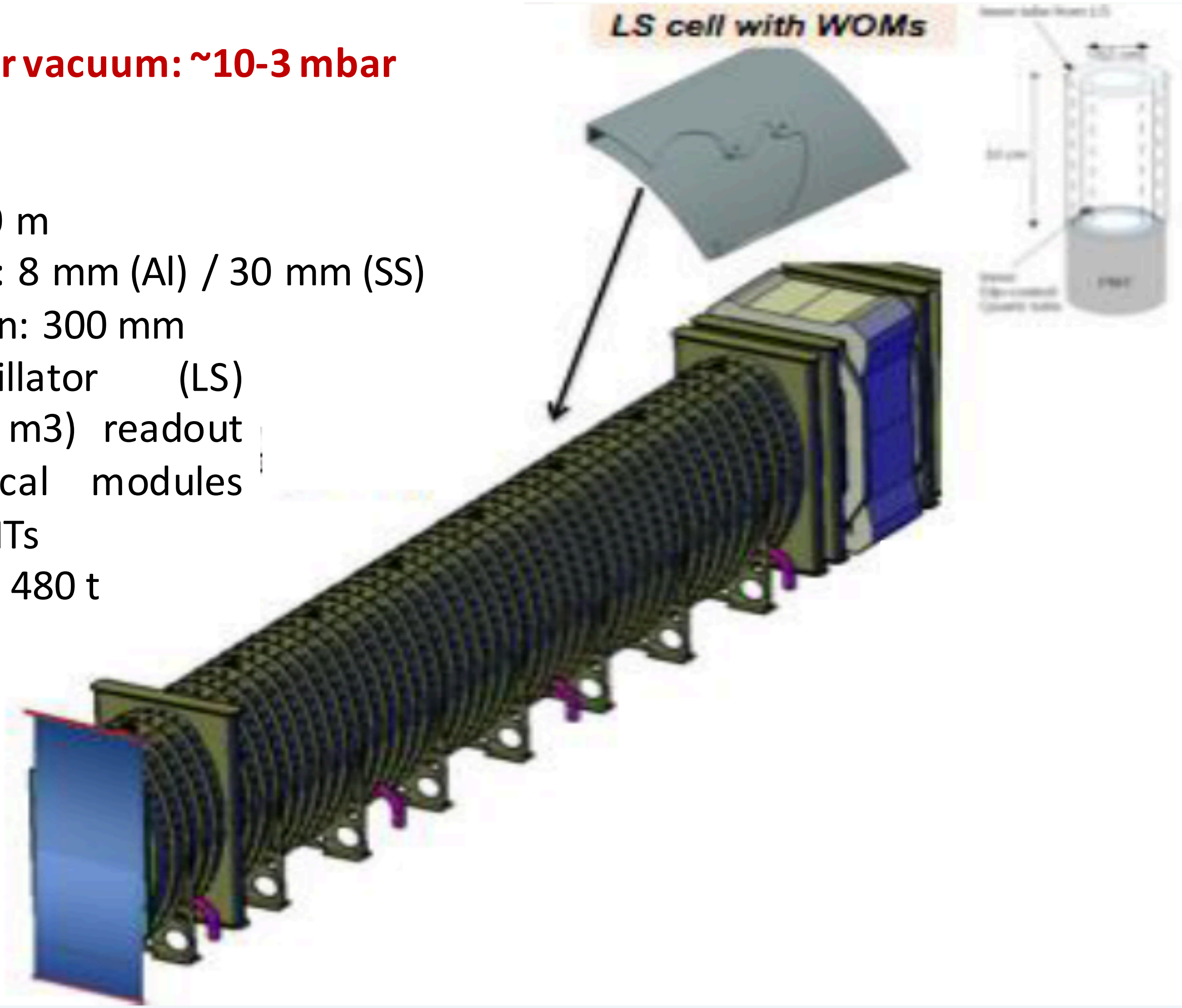


Decay volume and spectrometer

Estimated need for vacuum: ~10-3 mbar

Vacuum Vessel

- 10 m x 5 m x 60 m
- Walls thickness: 8 mm (Al) / 30 mm (SS)
- Walls separation: 300 mm
- Liquid scintillator (LS) volume (~360 m3) readout by WLS optical modules (WOM) and PMTs
- Vessel weight ~ 480 t

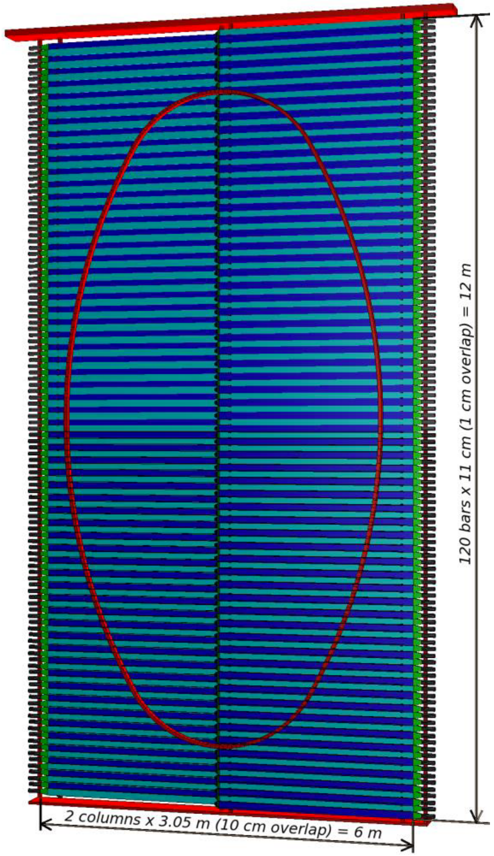


Timing detector

Challenges:

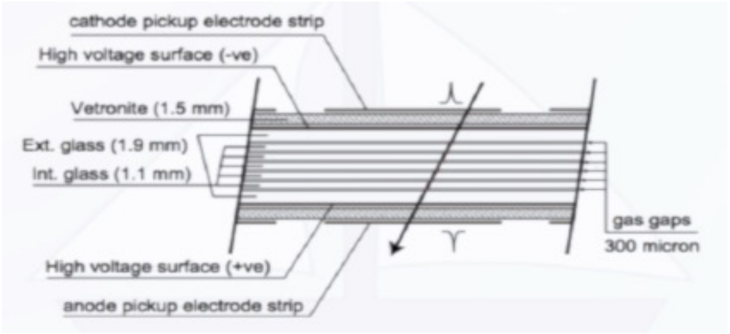
- large area
- required resolution < 100 ps

2 options considered



Multi-gap resistive plate chambers (MRPC)

- ALICE ToF and EEE project
- 61 chambers x 120 cm strips, 3 cm pitch
- 50 ps resolution achievable



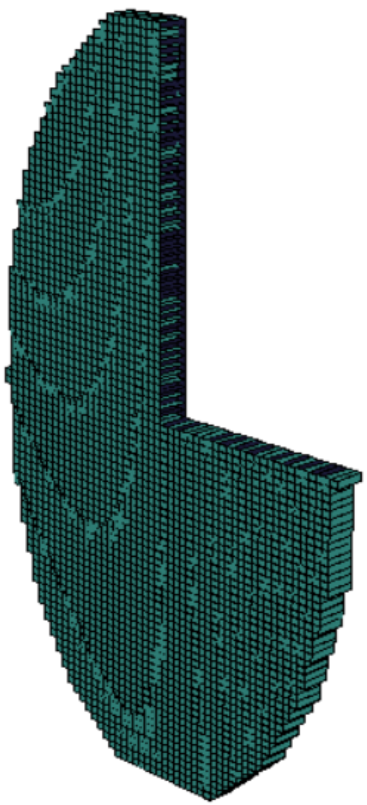
Scintillator bars

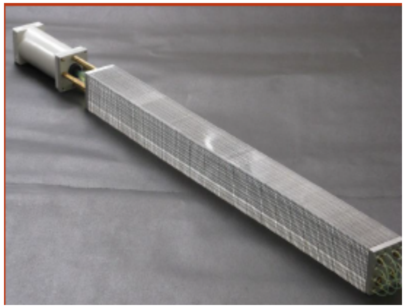
- NA61/SHINE ToF
- 100 ps resolution
- size of scint. counter 120 x 10 x 2.5 cm^3
- total active area 1.2 x 7.2 m^2

Calorimeters

ECAL

- Almost elliptical shape (5 m x 10 m)
- 2876 Shashlik modules
- 2x2 cells/modules, width=6 cm
- 11504 independent readout channels

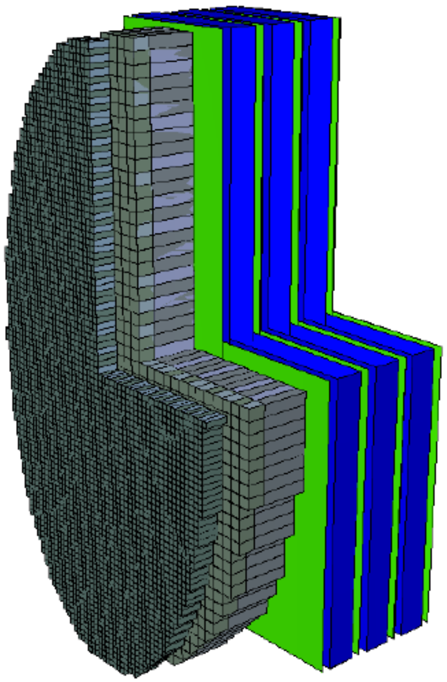




Dimensions	60x60 mm^2
Radiation length	17 mm
Moliere radius	36 mm
Radiation thickness	25 X_0
Scintillator thickness	1.5 mm
Lead thickness	0.8 mm
Energy resolution	1%

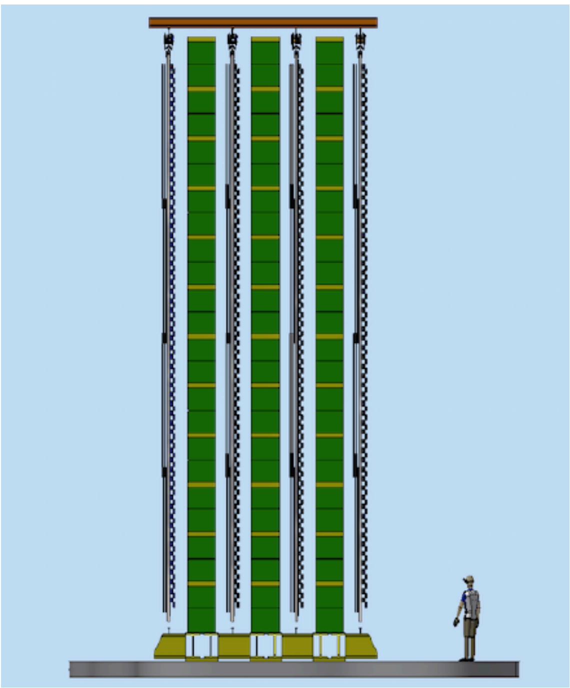
HCAL

- Matched with ECAL acceptance
- 2 stations
- 5 m x 10 m
- 1512 modules
- 24x24 cm^2 dimensions
- Stratigraphy: N x (1.5 cm steel+0.5 cm scint)
- 1512 independent readout channels



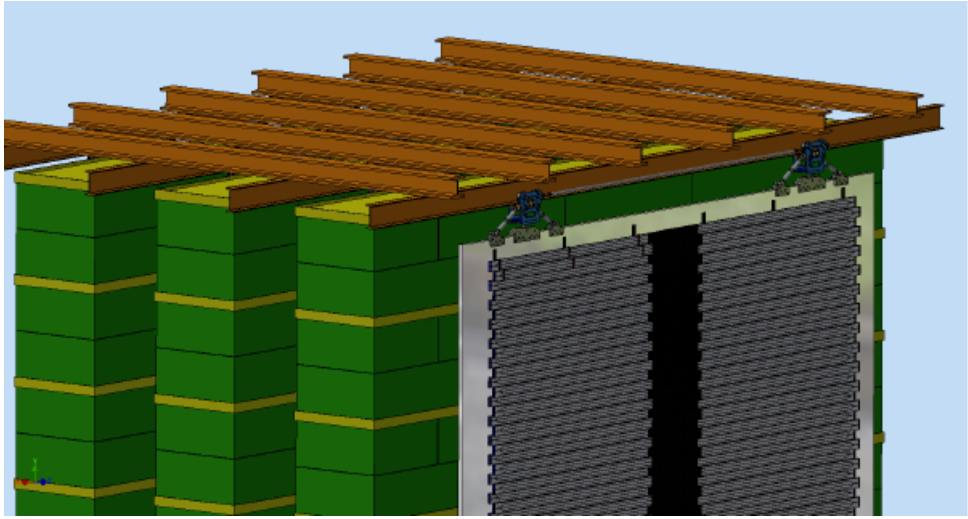
Muon System

Based on scintillating bars, with WLS fibers and SiPM readout



Requirements:
1) High-efficiency identification of muons in the final state
2) Separation between muons and hadrons/electrons
3) Complement timing detector to reject combinatorial muon background

Technical Proposal (preliminary design)
- 4 active stations
- transverse dimensions: 1200x600 cm2
- x,y view
- 3380 bars, 5x300x2 cm3/each
- 7760 FEE channels
- 1000 tons of iron filters



Neutrino fluxes

SHiP experimental setup ideally suited to perform studies on neutrino and anti-neutrino physics.

High charmed hadrons decay rates ⇒ high ordinary neutrino fluxes

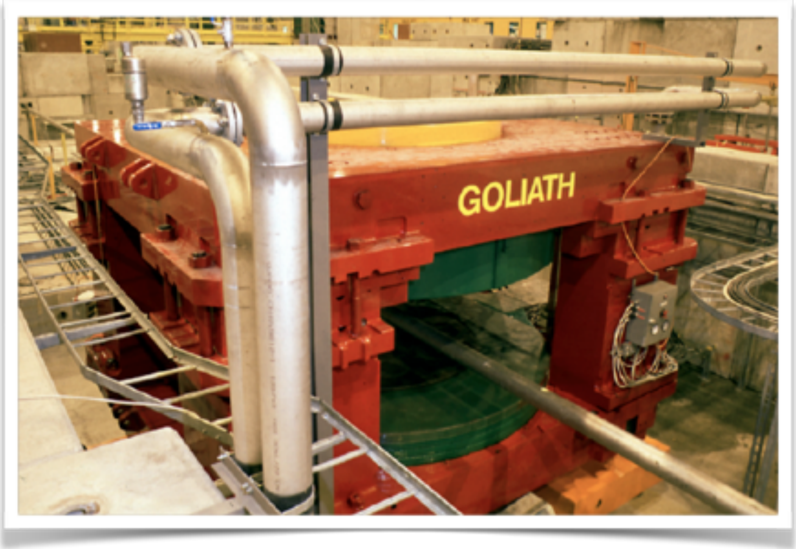
	<E> (GeV)	Beam dump	<E> (GeV)	Neutrino target	<E> (GeV)	CC DIS interactions
N_{ν_e}	3	$2.1 \cdot 10^{17}$	28	$3.6 \cdot 10^{15}$	46	$2.5 \cdot 10^{5}$
N_{ν_μ}	1.4	$4.4 \cdot 10^{18}$	8	$5.2 \cdot 10^{16}$	29	$1.7 \cdot 10^{6}$
N_{ν_τ}	9	$2.8 \cdot 10^{15}$	28	$1.4 \cdot 10^{14}$	59	$6.7 \cdot 10^{3}$
$N_{\overline{\nu}_e}$	4	$1.6 \cdot 10^{17}$	27	$2.7 \cdot 10^{15}$	46	$9.0 \cdot 10^{4}$
$N_{\overline{\nu}_\mu}$	1.5	$2.8 \cdot 10^{18}$	8	$4.0 \cdot 10^{16}$	28	$6.7 \cdot 10^{5}$
$N_{\overline{\nu}_\tau}$	8	$2.8 \cdot 10^{15}$	26	$1.4 \cdot 10^{14}$	58	$3.4 \cdot 10^{3}$

Rates for five years of nominal operation with 2×10^{20} protons on target

Target magnetization

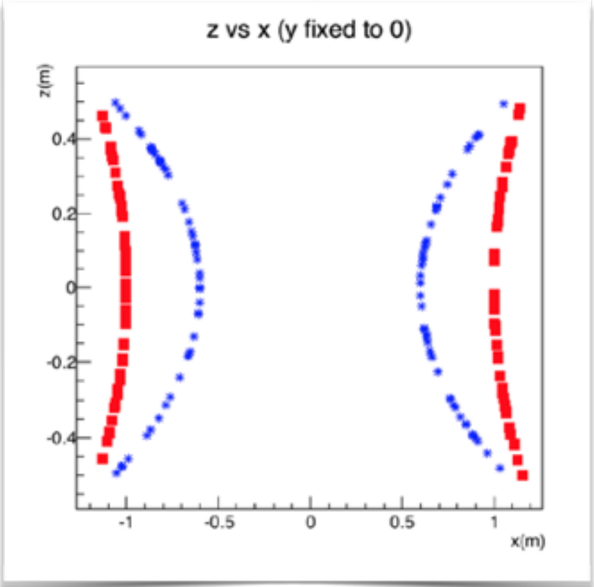
GOLIATH MAGNET

CERN H4 beam line inside 2389 PPE 134 zone



- 1 Tesla vertical magnetic field
- few m³ volume with constant magnetization

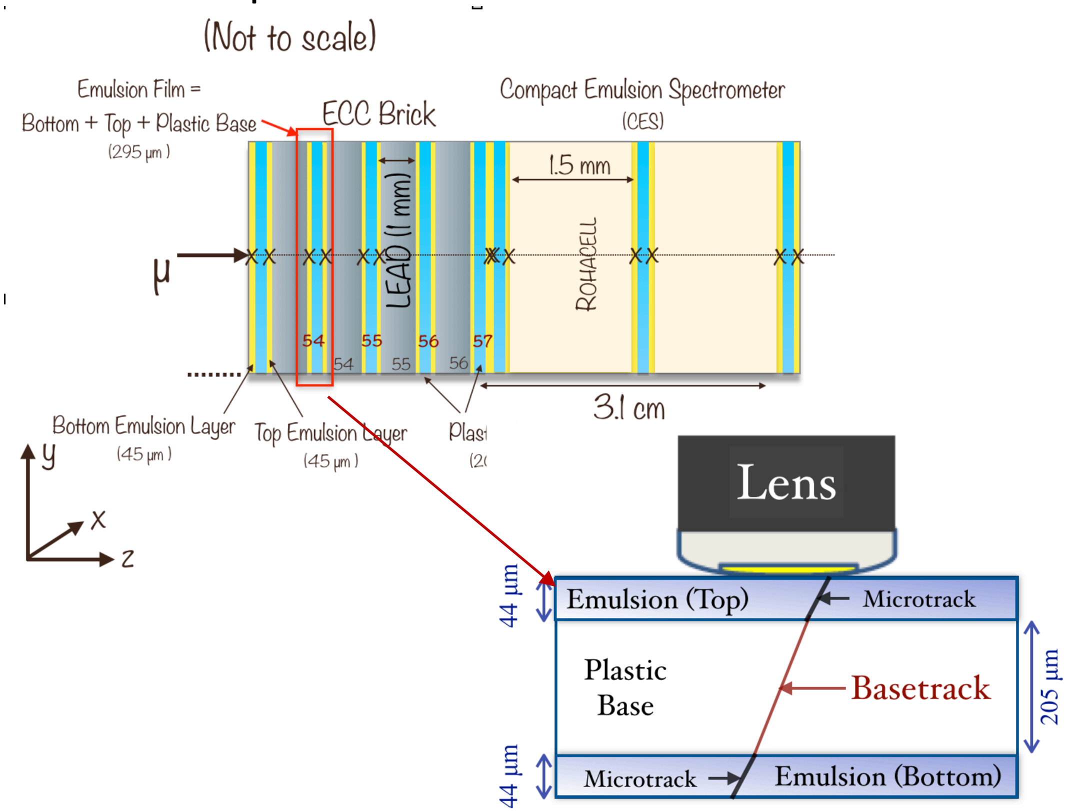
Magnetic field behavior in the target region



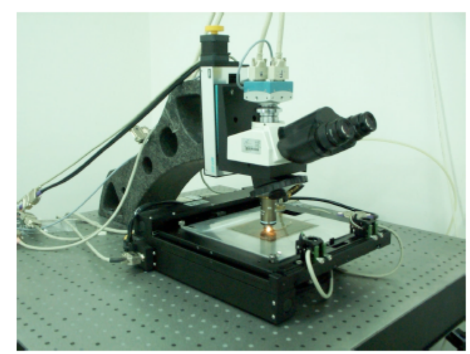
- Within the blue curves B ≈ 1.5 T
- Within the red curves B >=1 T

Track reconstruction in Emulsion Films

- Nuclear emulsions consist of AgBr crystals scattered in a gelatin binder.
- Passage of charged particles sensitises AgBr crystals along the path.
- Sensitesed crystals act as latent image centers.
- With development there is the growth of silver clusters => visible to optical microscope



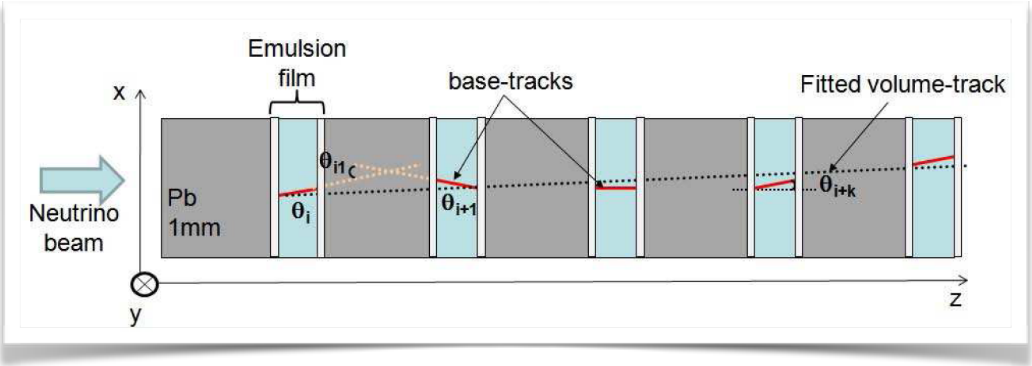
European Scanning System ESS



Measuring Momentum with ECC

- Total length of a brick ~ 10 X_0 (X_0 = 5.6 mm).
- Scattering is dominated by the lead
- Momentum measurement by MCS can be carried out in 2 ways:
  - track position (coordinate method)
  - track angle (angular method)

Deviation of the trajectory from a straight line



$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{x}{X_0}} \times \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

Momenta up to 8 GeV/c can be measured with a resolution better than 30%

Electron/pion identification

- The high granularity of the emulsions allows excellent e.m. shower identification.
- The separation of electrons and pions obtained by exploiting different behavior in passing through and interacting in an ECC.
- 2 complementary approaches:
  - study total number of tracks and different longitudinal and transverse profiles
  - study of Multiple Coulomb Scattering longitudinal profiles
    - going through a material, the energy remains almost constant for pions while strongly decreases for electrons

π contamination

e^- efficiency

E (GeV)	$\varepsilon_{e\to e}$ %	$\eta_{\pi\to e}$ %
	Data	
0.5	—	—
1	—	—
2	—	0.5±0.1
3	80±18	—
4	—	0.3±0.1
5	—	—
6	94.7±0.9	0.2±0.1
8	—	—

Detector performances

μ identification

- Requirements:
  1. track crossing 3 RPC layers in the ARM1 of the Magnetic Spectrometer
  2. track crossing the Goliath Iron and reaching at least the first HPT plane
- The usage of the HPT plane for the muon identification in case 2. increases the muon identification efficiency of about 2%
- Muon identification efficiency of about 90% for both charm events (and for the muonic decay channel of the τ lepton)

Charge measurement

- Charge of the hadrons is measured by the Compact Emulsion Spectrometer (CES)
- Charge of the muons by the magnetic spectrometer and the CES

$\epsilon^{h}_{charge} = 70\%$ $\quad \epsilon^{\mu}_{charge} = 94\%$ $\quad \epsilon^{3h}_{charge} = 49\%$

Correct assignment efficiencies

$\omega^{h}_{charge} = 0.5\%$ $\quad \omega^{\mu}_{charge} = 1.5\%$ $\quad \omega^{3h}_{charge} = 1.0\%$

Charge Misidentification probabilities

Costs

Table 6.2: Overall cost of the SHiP facility and the detectors.

Item	Cost (MCHF)	
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.1	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**