SHiP
Search for Hidden Particles

The SHiP experiment at CERN

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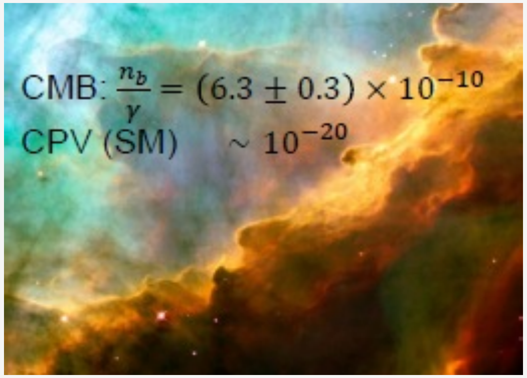
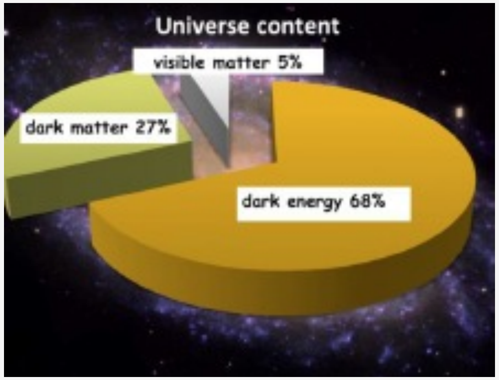
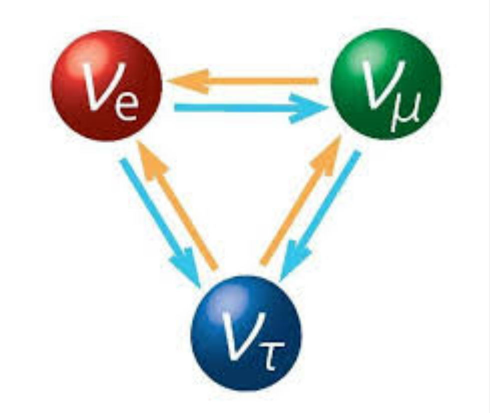
On behalf of the SHiP Collaboration

Physics Motivation

- Standard Model provided consistent description of Nature's constituents and their interactions.
  - No significant deviation from SM.
- But the Standard Model can not explain
  - Neutrino masses and oscillations
  - Dark matter
  - Baryon asymmetry

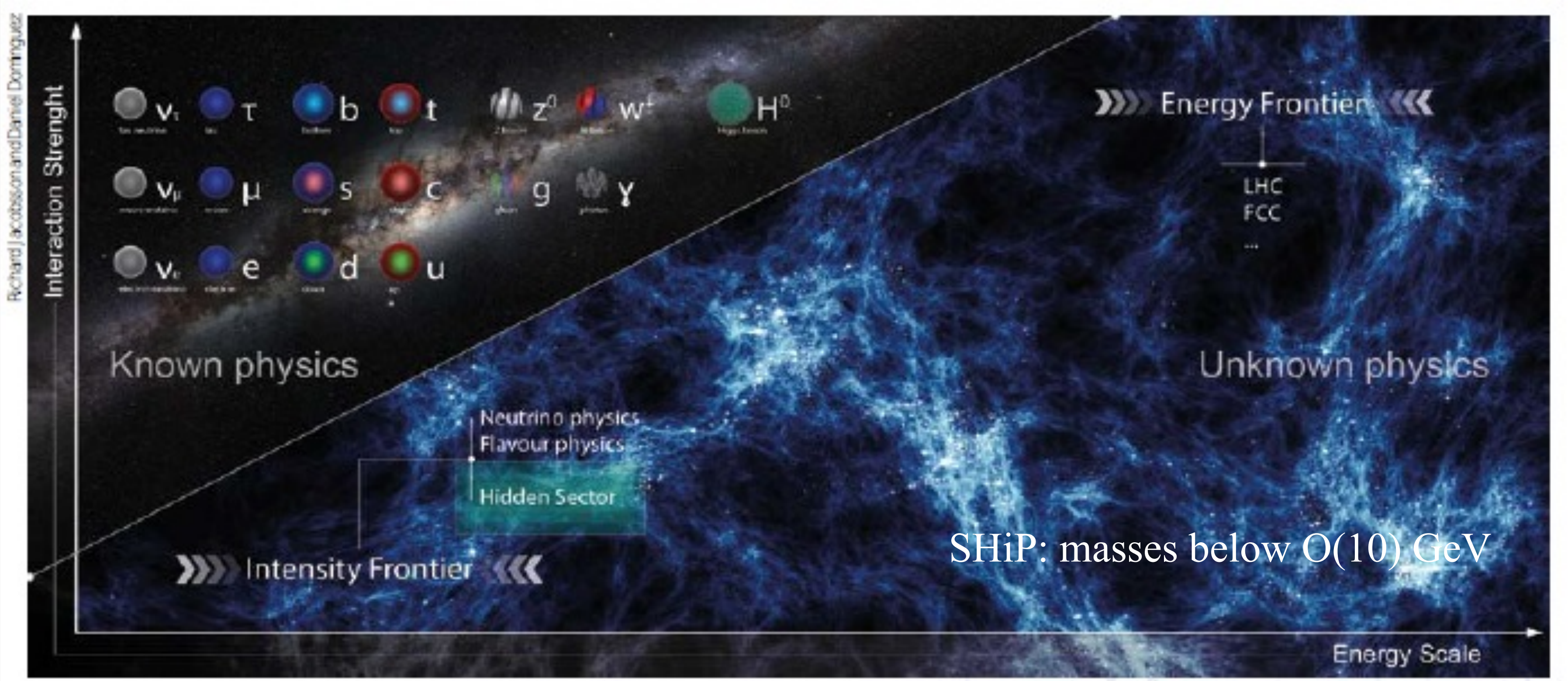






Physics Motivation

- If the *hidden* particles have very feeble interaction with standard model particles. The only way to observe these interactions is to go high intensity.
- The SHiP is proposed to explore the domain of hidden particles in intensity frontier.



Physics Goals

- Hidden particles are coupled to the Standard Model sector via renormalizable "portals".

$$L = L_{SM} + L_{mediator} + L_{HS}$$

- HP production and decay rates are strongly suppressed relative to SM
  - Production branching ratios $O(10^{-10})$
  - Long-lived objects

- Large number of models investigated.
- Tau Neutrino Physics.

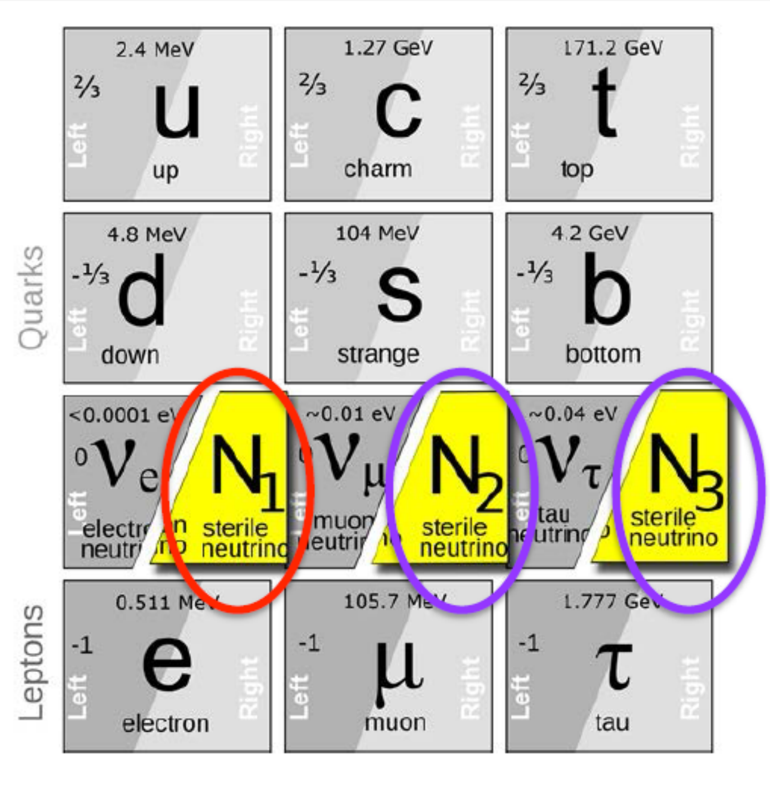
Physics Goals

- Production through hadron decays (π, K, D, B, proton bremsstrahlung, …)

Models tested	Final states
Neutrino portal, SUSY neutralino	$l\pi$, lK, $l\rho$ ($l=e,\mu,\nu$) ($\rho^+ \rightarrow \pi^+\pi^0$)
Vector, scalar, axion portals, SUSY sgoldstino	e^+e^-, $\mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
Neutrino portal, SUSY neutralino, axino	$l^+ l^- \nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\ \pi^0$

- Full reconstruction and PID are essential to minimize model dependence
- Experimental challenge is background suppression
  - It requires O(0.01)

Neutrino Portal



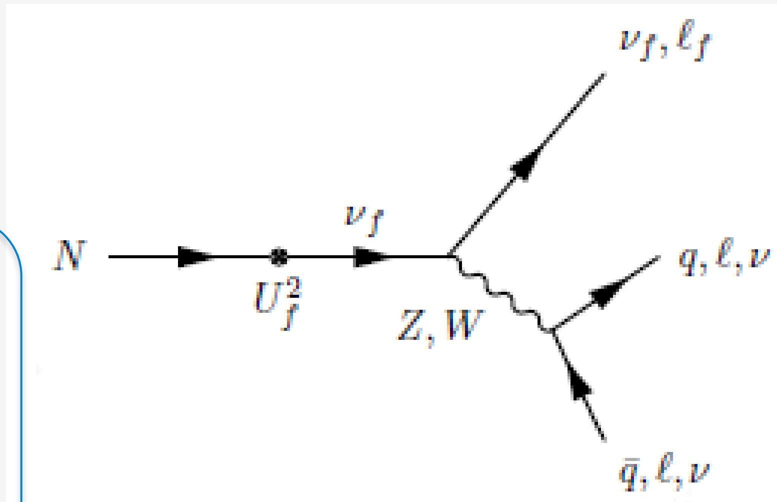
The neutrino Minimal Standard Model (υMSM) aims to explain.

T. Asaka, M. Shaposhnikov PLB620 (2005), 17.

- Matter anti-matter asymmetry in the Universe, neutrino masses and oscillations, non-baryonic dark matter.
- Adds three right-handed, Majorana, Heavy Neutral Leptons (HNL), N1, N2 and N3.

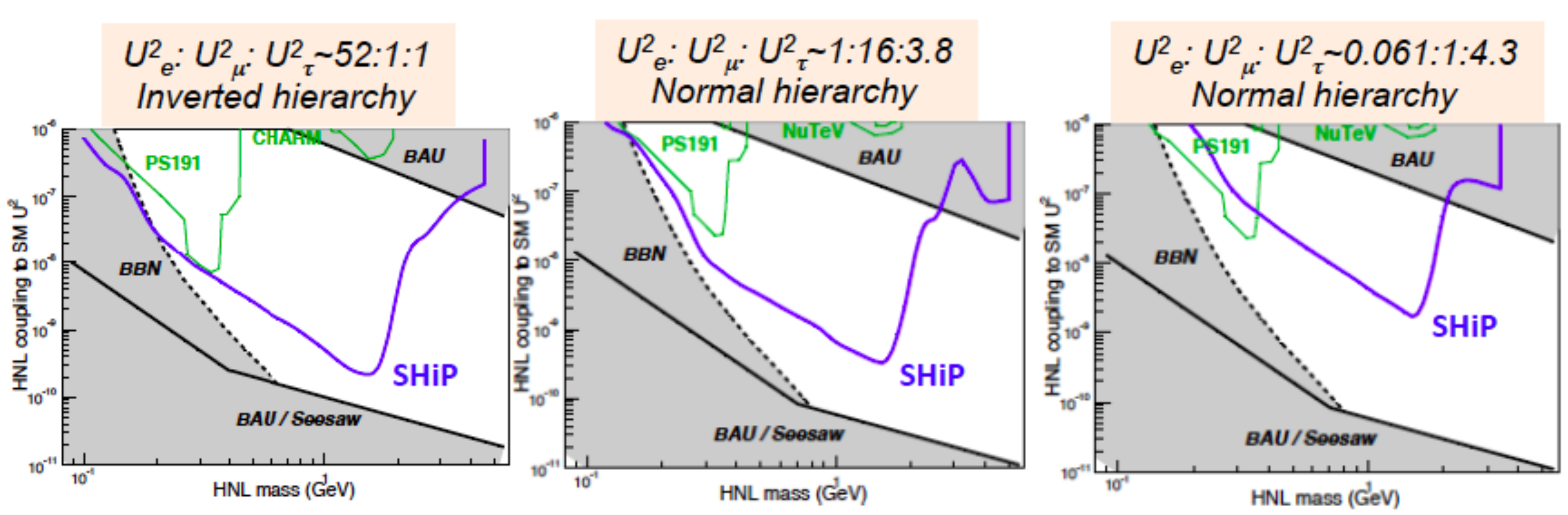
- N1 is a dark matter candidate (m≈ O(1) keV).
- N2, N3 give masses to neutrinos and produce baryon asymmetry of the Universe

  m≈ O(100 MeV-GeV)



HNL Sensitivity

- Production in charm and beauty meson decays
- Decay into *hl* and *llν*
- νMSM parameter space almost totaly explored for $m_N \leq 2$ GeV

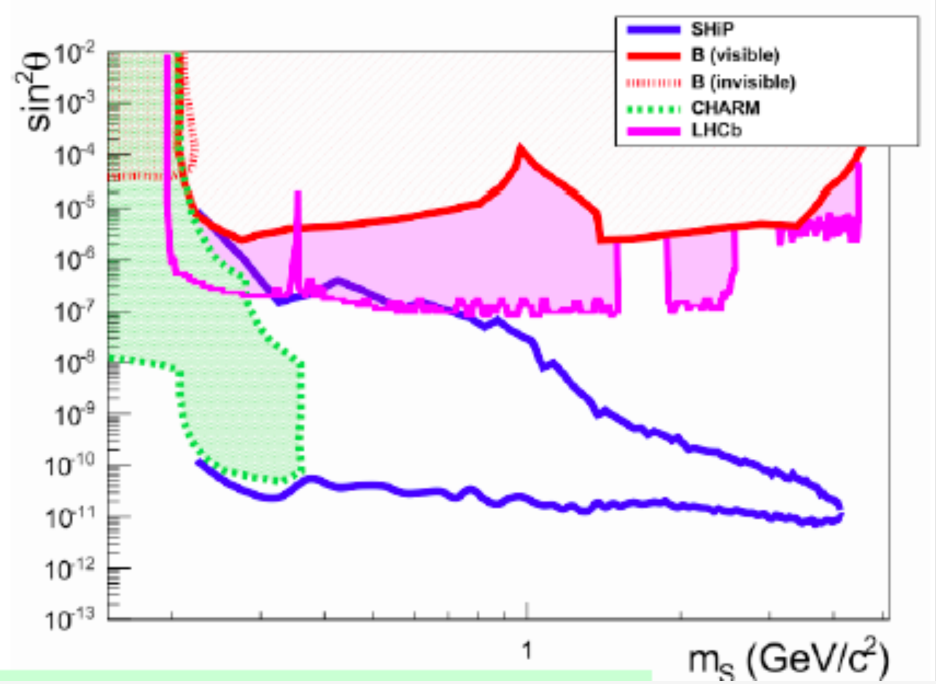


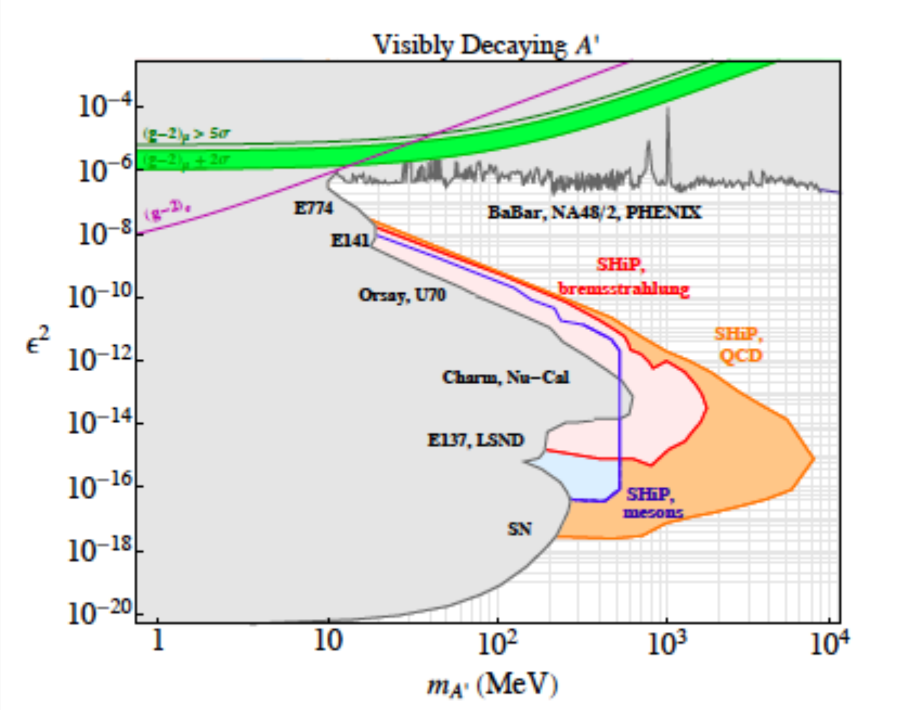
- SHiP sensitivity covers large area of parameter space below the B mass &moving down towards the ultimate see-saw limit

The Scalar and Vector Portals

- **Scalar Portal :** Hidden scalar can mix with the SM Higgs. Mostly produced in penguin-type decays of B and K decays
- Decay into a pair of SM particles $S \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$, KK, ηη, ττ, DD

- **Vector portal :** dark photon (A') produced in QCD processes or in decays of $\pi^0 \rightarrow \gamma'\gamma$, $\eta \rightarrow \gamma'\gamma$, $\omega \rightarrow \gamma'\pi^0$ and $\eta' \rightarrow \gamma'\gamma$
- Decay into SM particles through a virtual photon: $\gamma' \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}$





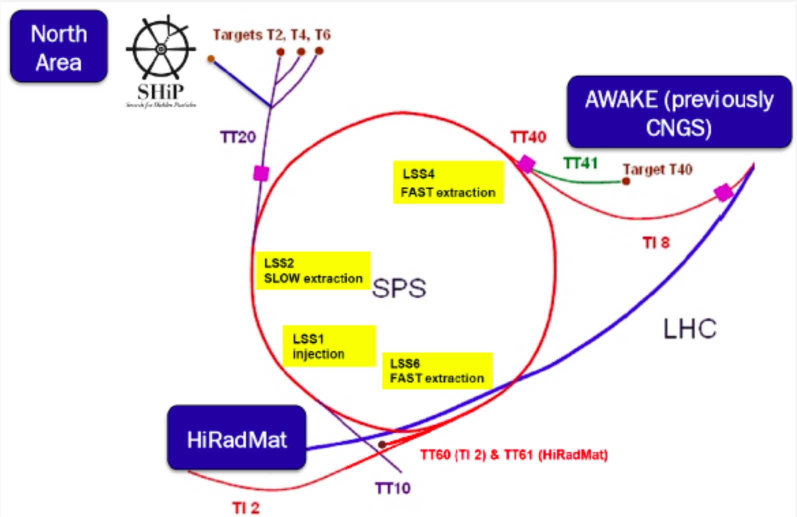
Physics Program

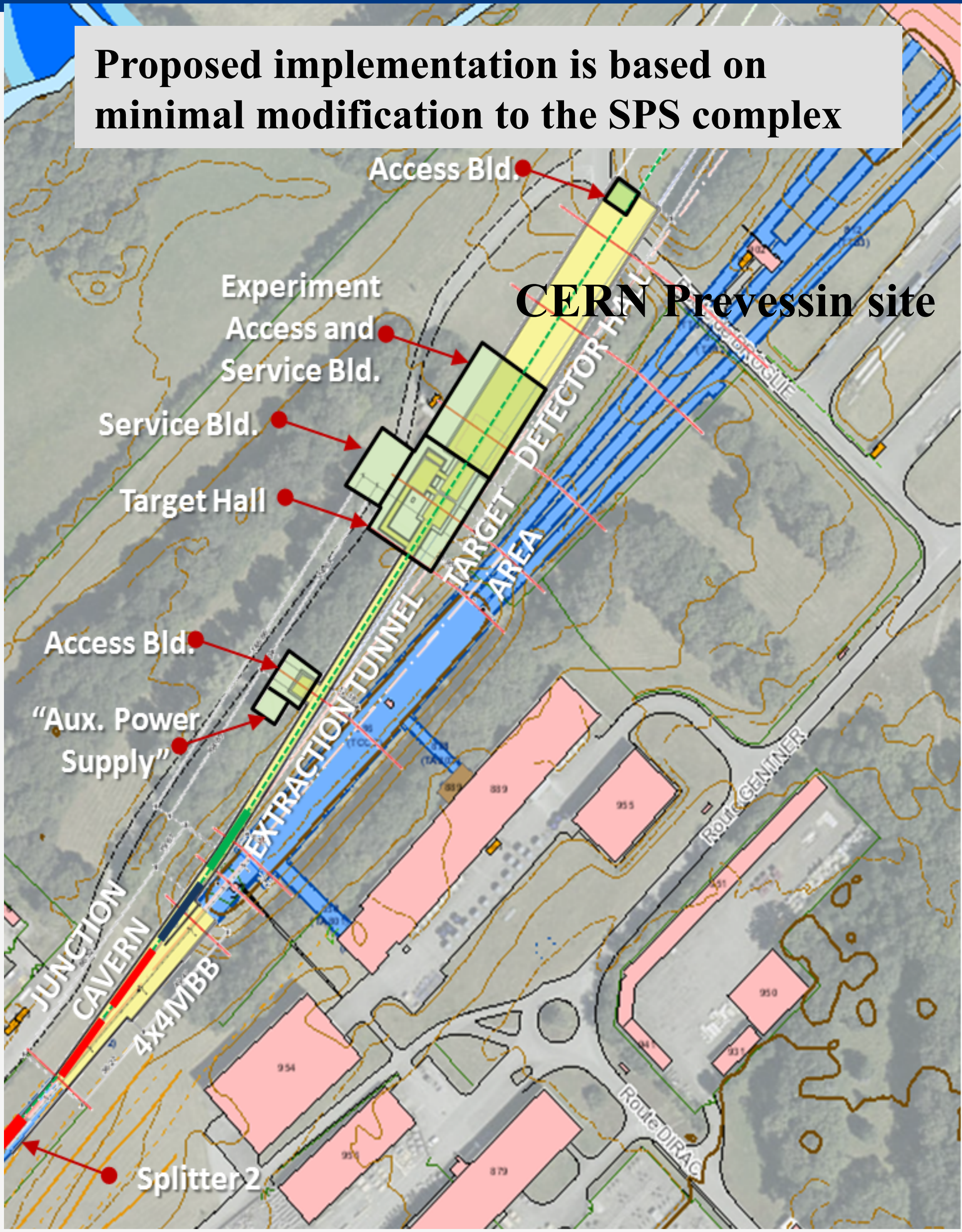
A facility to search for hidden particles (SHiP) at the SPS: the physics case

85 theorists
arXiv: 1504.0855

Contents

SHiP: a fixed-target facility at the SPS



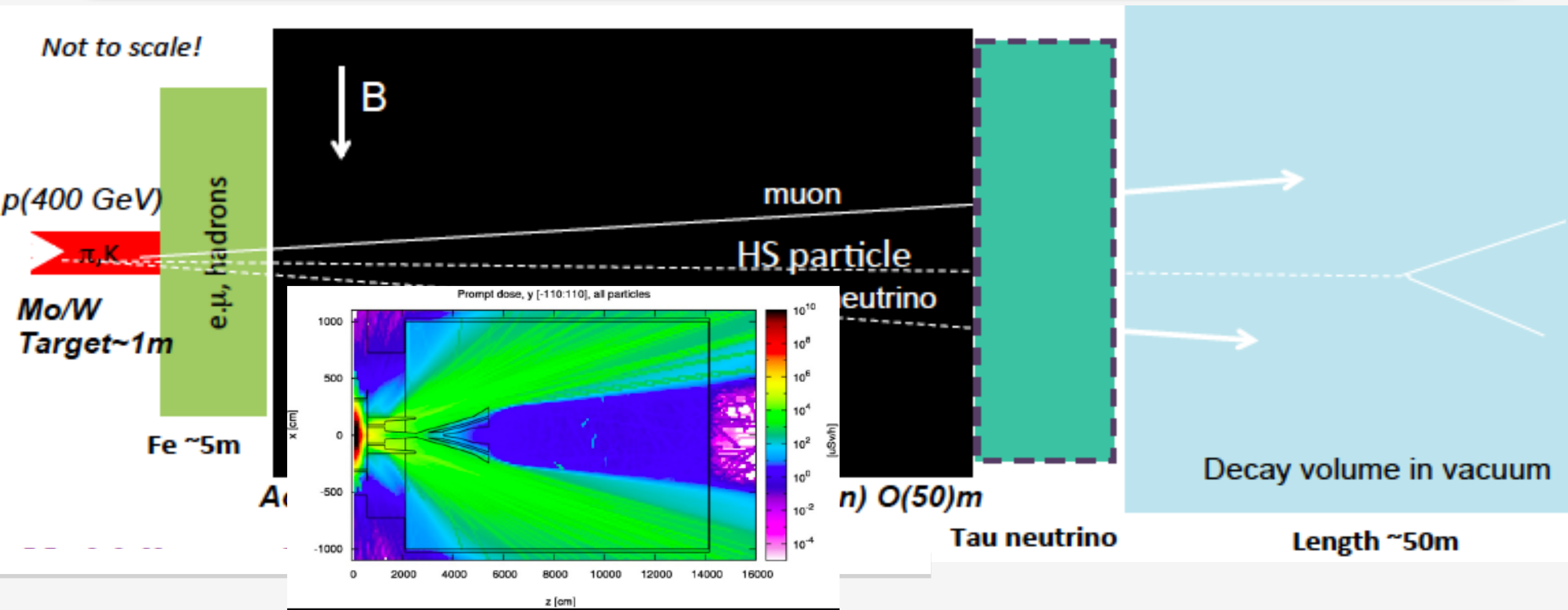


- The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode.
  - 400 GeV protons from SPS
  - 4×10^{19} pot/year (~200 days of running)
  - Spill = 4×10^{13} pot per cycle of 7.2 s with slow beam extraction (1s)

Experimental Requirements

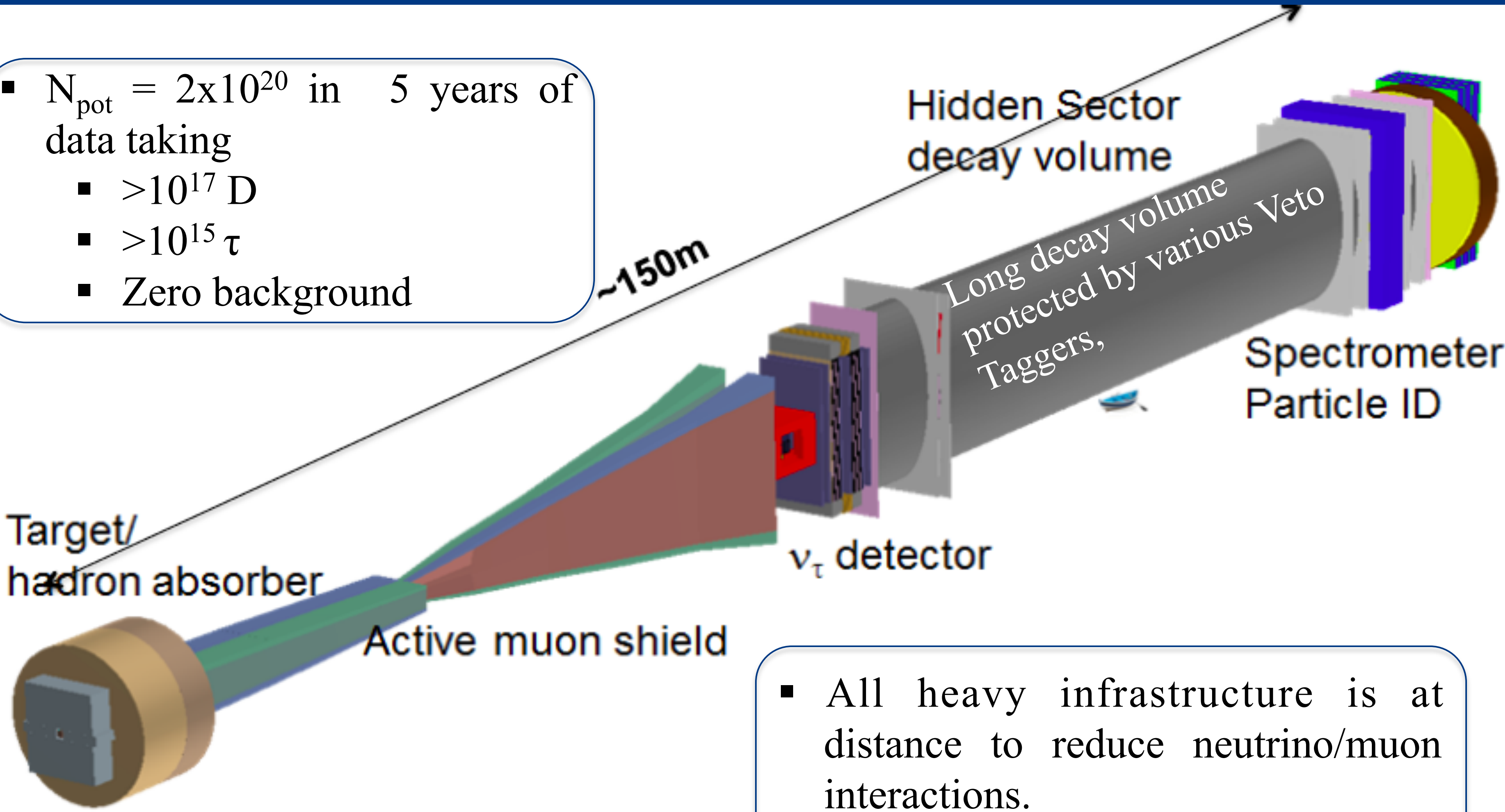
➢ **Initial reduction of beam induced backgrounds**

- Heavy target to maximize Heavy Flavour production (large A) and minimize production of neutrinos in π/K ➔μν decays (short λ_{int})
- Hadron absorber
- Effective muon shield (without shield: muon rate ~10^{10} per spill of 4×10^{13} pot)
- Slow (and uniform) beam extraction ~1s to reduce occupancy in the detector



The SHiP Detector

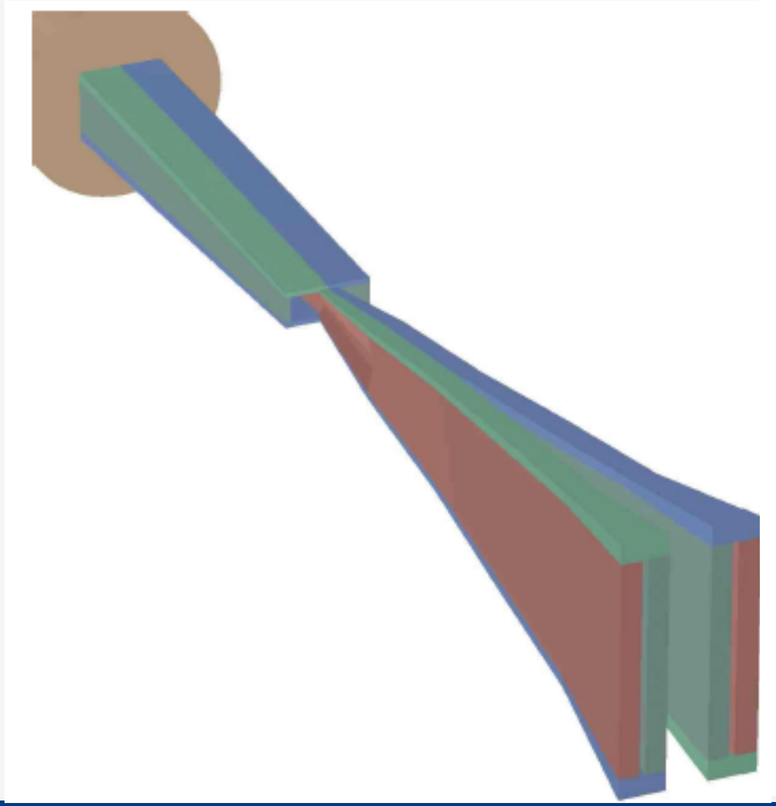
- N_{pot} = $2x10^{20}$ in 5 years of data taking
  - $>10^{17}$ D
  - $>10^{15}$ τ
  - Zero background

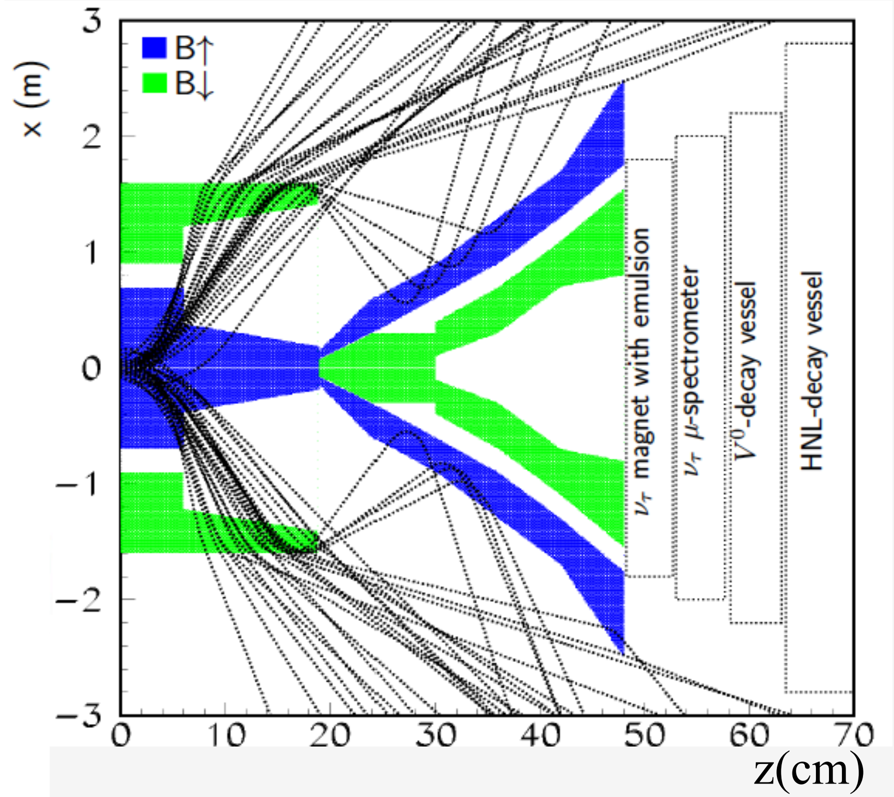


- All heavy infrastructure is at distance to reduce neutrino/muon interactions.

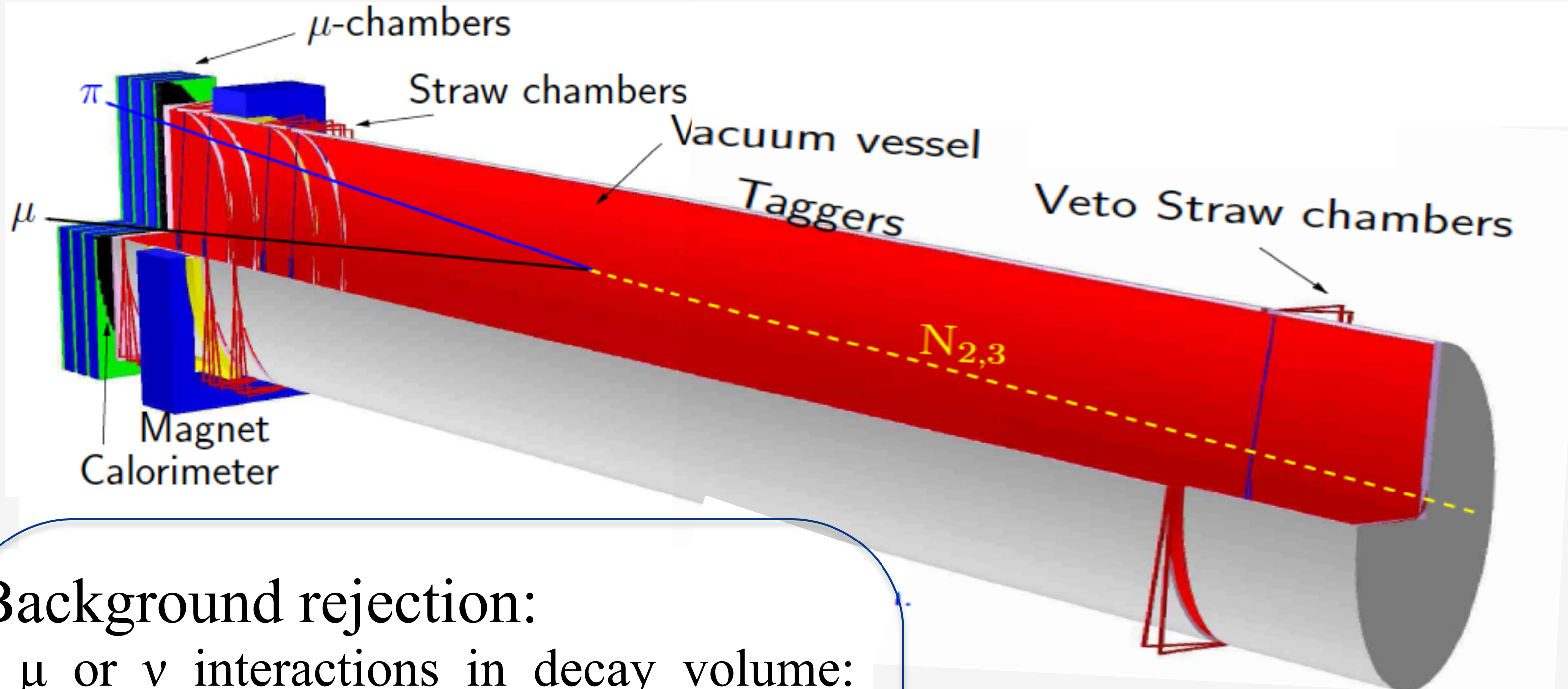
Active Muon Shield

- Active muon shield based entirely on magnet sweeper with a total field integral B_y = 86.4 Tm
- Realistic design of sweeper magnets in progress
- < 7k muons / spill (E_μ > 3 GeV), from 10^{10}
- Negligible flux in terms of detector occupancy





HNL Detector



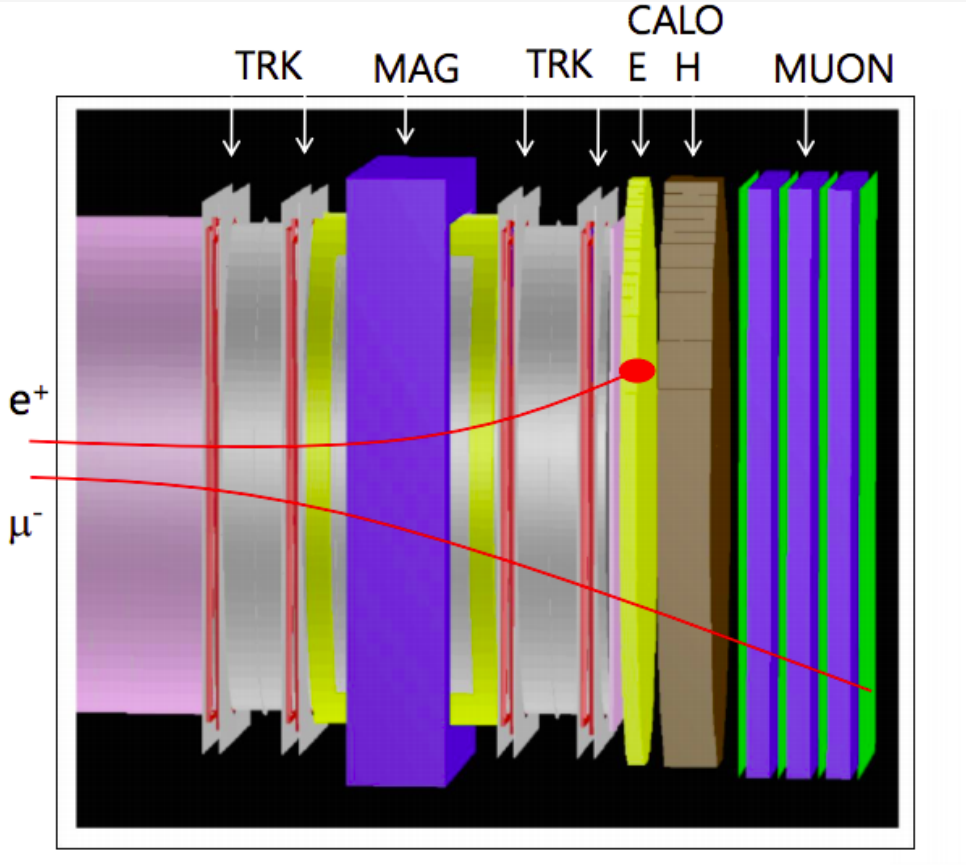
Background rejection:

- μ or ν interactions in decay volume: evacuated vacuum vessel: (10 μbar)
- K/Λ-decays produced in surrounding material in μ, ν-interaction:
  - Taggers: liquid scintillator in double walled vessel to veto candidates with accompanying particles.
  - Veto: veto short lived K_S, Λ, or candidate with accompanying particles.

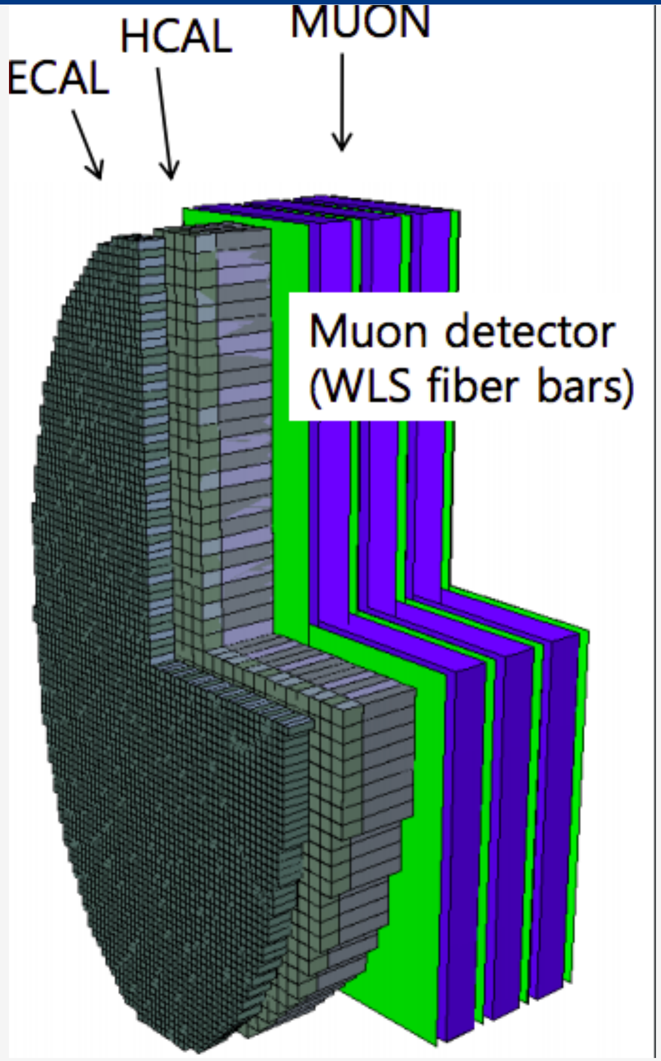
Spectrometer to reconstruct signal:

- Ecal and muon filter/chambers at the end.
- Tracking straw chambers and magnet for reconstruction.

Particle Identification

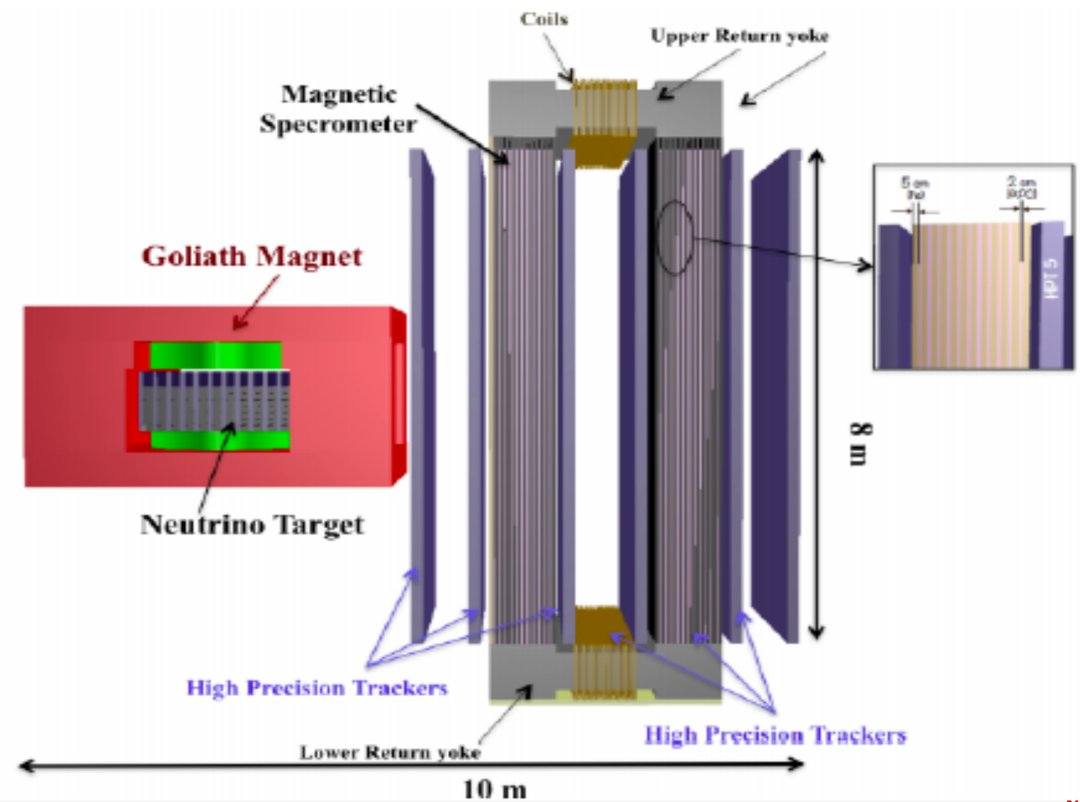


ECAL: e/γ, π^0 and η reconstruction
(Shashlik technique)



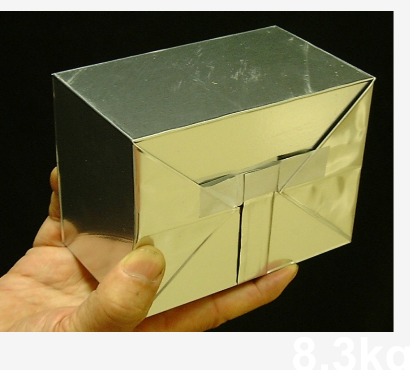
HCAL: π/μ separation

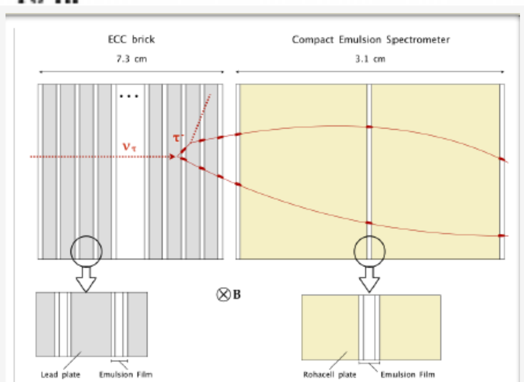
SHiP Neutrino Detector

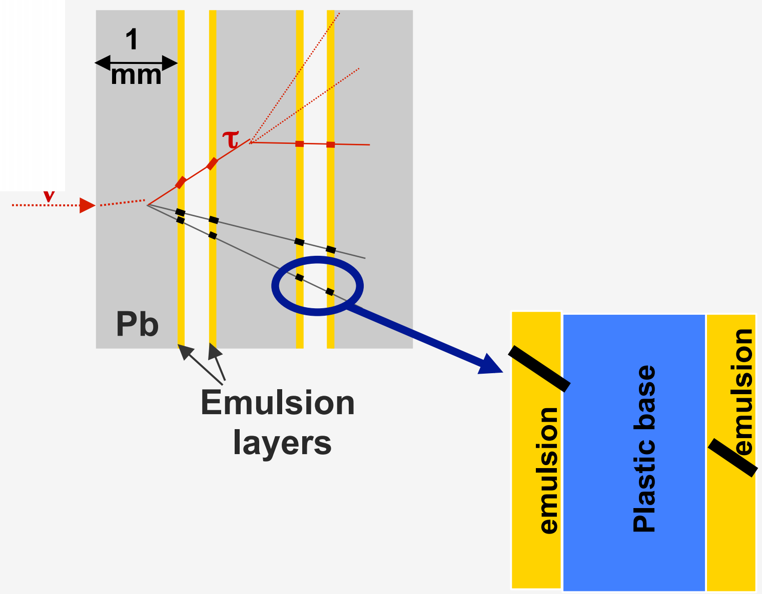


Emulsion Target

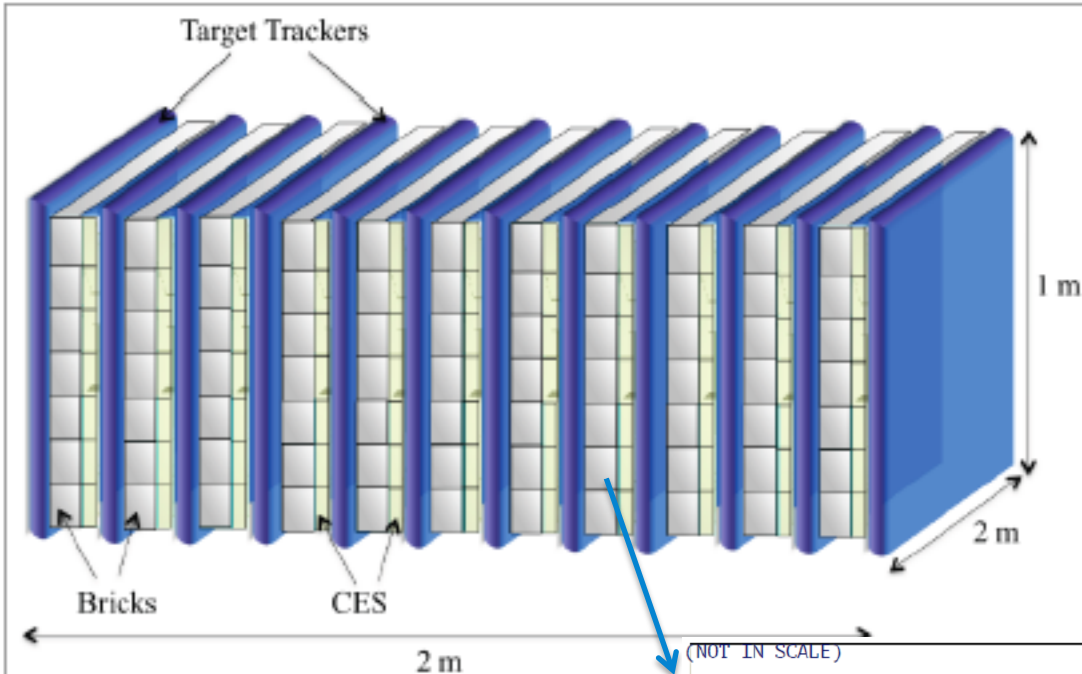
- Dimensions: 0.8 x 2 x 1.6 m^3
- Number of ECC bricks: ~900
- Modular structure made of a sandwich of passive material plates interleaved with emulsion films.
- Total mass: ~7 tons







The Neutrino Target

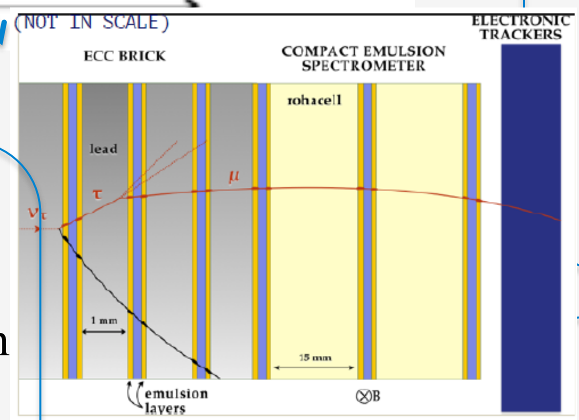


Target Trackers

- Provide time stamp
- Link track information in emulsion to signal in TT.

Dipolar Magnet & Compact Emulsion Spectrometer

- To measure the charge of the decay products .
- ν_τ/anti-ν_τ seperation, charge measrument



ECC

- Primary and secondary vertex recostruction with µm resolution
- Momentum measurement by multiple Coulomb Scattering
- Electron/pion identification.

~230 events/brick

Muon Spectrometer

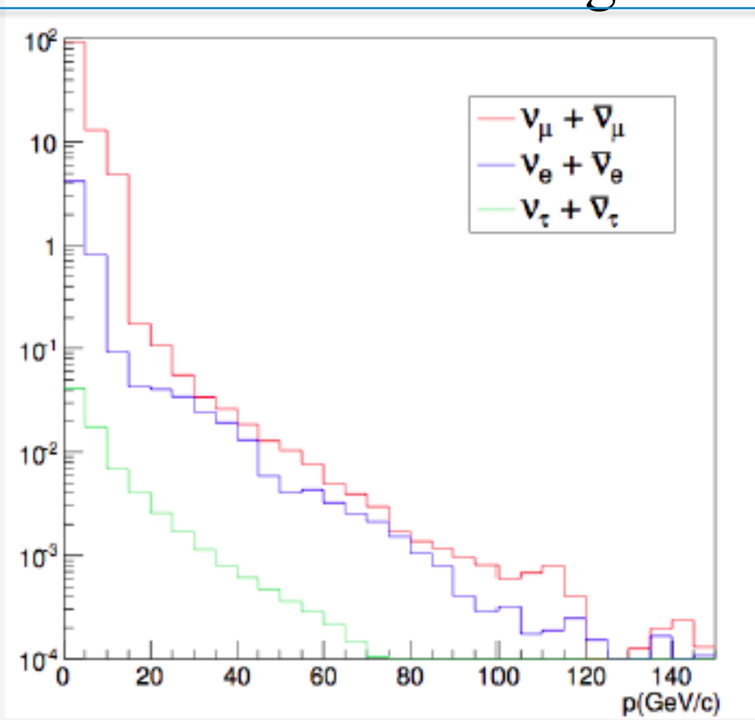
- Perform the muon identification and measure its charge and momentum.

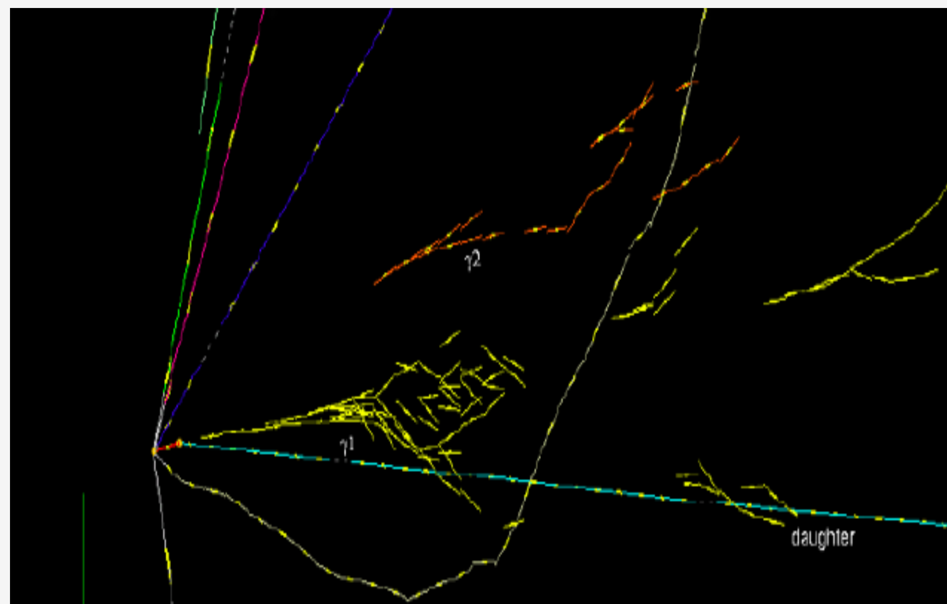
SHiP Neutrino Program

- SHiP setup ideally suited to study neutrino and anti-neutrino physics for all three active flavours.
- High charmed hadrons production rates ⇒ high neutrino fluxes from their decays, including remnant pion and kaon decays.

- Energy spectrum of different neutrino flavors at target

- Anti-ν_τ is not detected!





$\nu_\mu \rightarrow \nu_\tau$ *candidate observed by the OPERA experiment*

ν_τ/anti-ν_τ yield

- Number of υ_τ and anti-υ_τ produced in the beam dump.

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 3.26 \times 10^{-5} N_p = 6.5 \times 10^{15}$$

- Main background in υ_τ and anti-υ_τ searches is the charm production in υ_μCC (anti-υ_μCC) and υ_eCC (anti-υ_eCC) interactions, when the primary lepton is not identified.

SIGNAL EXPECTATION

BACKGROUND

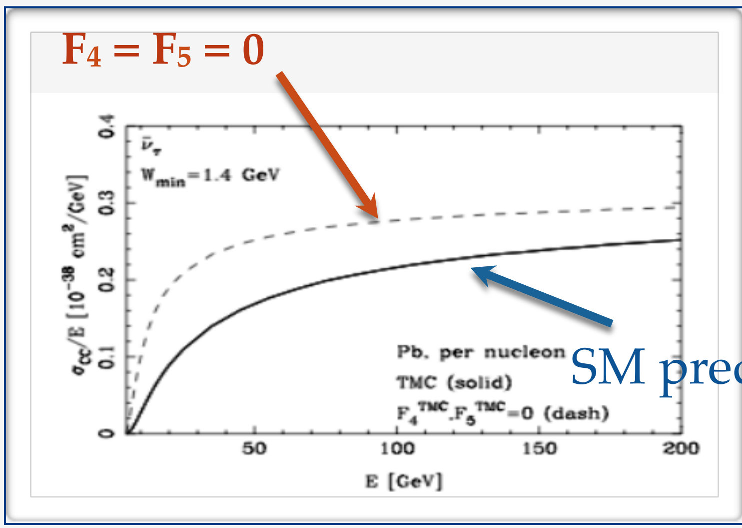
R=S/B RATIO

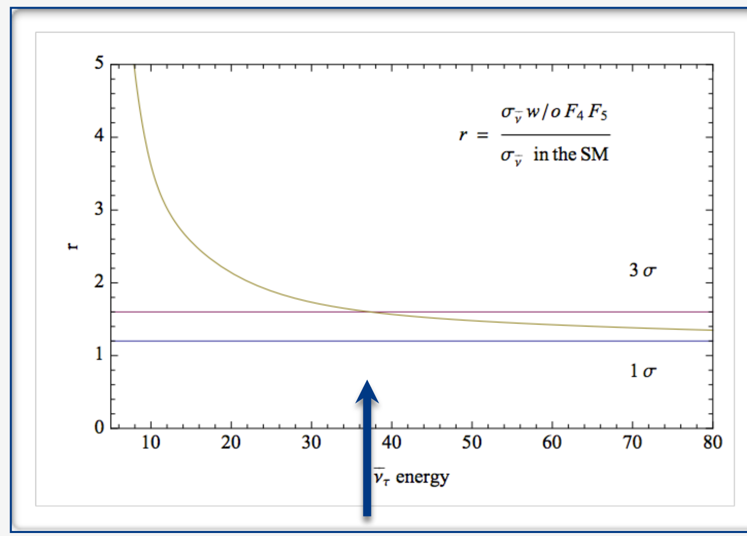
decay channel	ν_τ			$\bar{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \to \mu$	570	30	19	290	140	2
$\tau \to h$	990	80	12	500	380	1.3
$\tau \to 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

F_4 and F_5 Structure Functions

- Through ν_τ and anti-ν_τ identification: unique capability of being sensitive to F4 and F5

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2 x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right] F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right),$$





- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

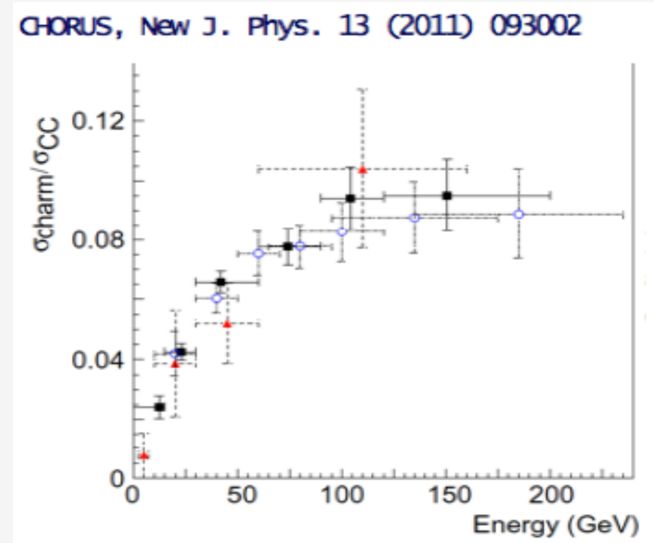
$E(\overline{\nu_\tau}) < 38$ GeV

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

Charm Physics

- Expected charm exceeds the statistics available in previous experiments by more than one order of magnitude

In NuTeV ~5100 ν_μ , ~ 1460 anti-ν_μ
In CHORUS ~2000 ν_μ , 32 anti-ν_μ



	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	$1.1 \cdot 10^5$

ν_μCC

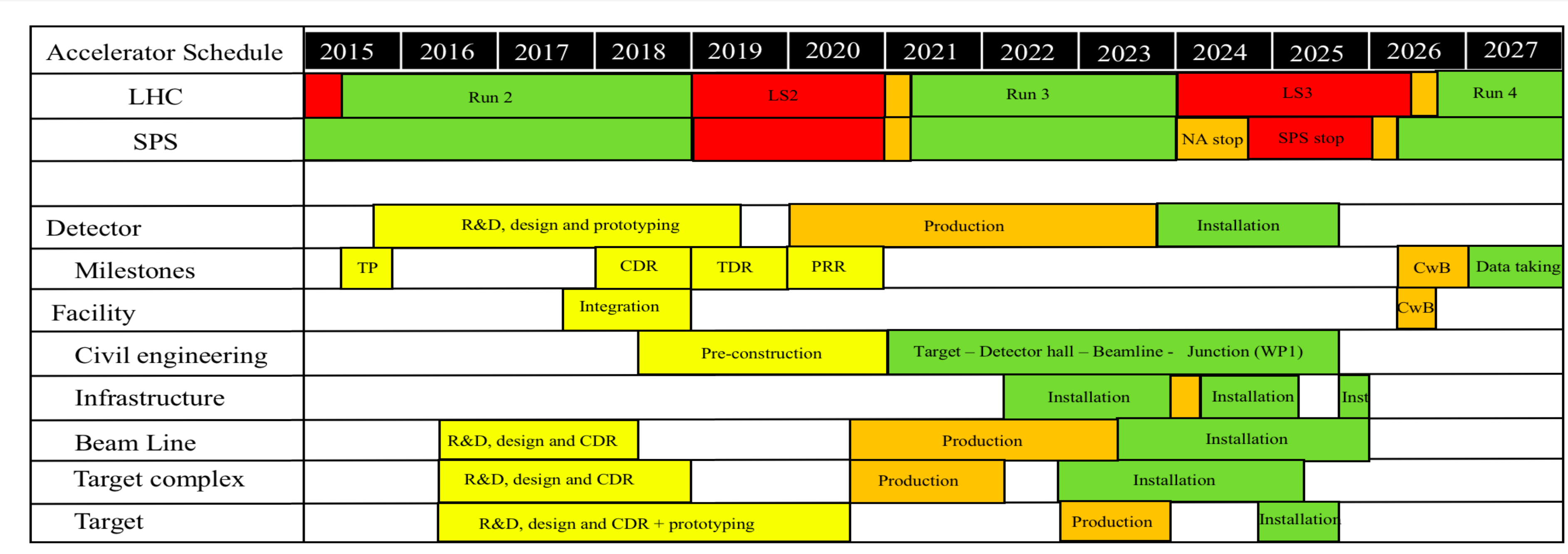
$$f(charm) = \frac{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} \left(\frac{\sigma_{charm}}{\sigma^{CC}_{\nu_\mu}}\right) dE}{\int \Phi_{\nu_\mu} \sigma^{CC}_{\nu_\mu} dE} \approx 4\%$$

ν_eCC

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

- **No charm candidate from ν_e and ν_τ interactions ever reported!**

Project Schedule



- Form SHiP Collaboration December 2014
- Technical Proposal April 2015
- Positive SPSC recommendation for CDS September 2016
- **Comprehensive Design Study 2018**
- **Construction and Installation 2021-2025**
- **Commissioning and data taking 2026**

SHiP: Search for Hidden Particles

- SHiP is a new proposed fixed-target experiment at the CERN SPS accelerator to search for hidden, very weakly interacting new particles.
- At the same time, also ideal for ν_τ physics.

Collaboration

- 49 institutes from 16 Countries, plus CERN


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

arXiv:1504.04956v1 [physics.ins-det] 20 Apr 2015

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

The SHiP Collaboration[1]

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

Summary

- SHiP is a fixed target experiment proposal at CERN SPS.
- SHiP is proposed to search for New Physics in the largely unexplored domain of new, very weakly interacting particles with mass O(10) GeV.
- SHiP will perform a complement searches for new searches at energy frontier at CERN.
- SHiP is also unique detector for neutrino/charm physics.
- Positive recommendation from the SPSC in January 2016.
- Comprehensive Design Report expected for European HEP strategy 2019.

Costs

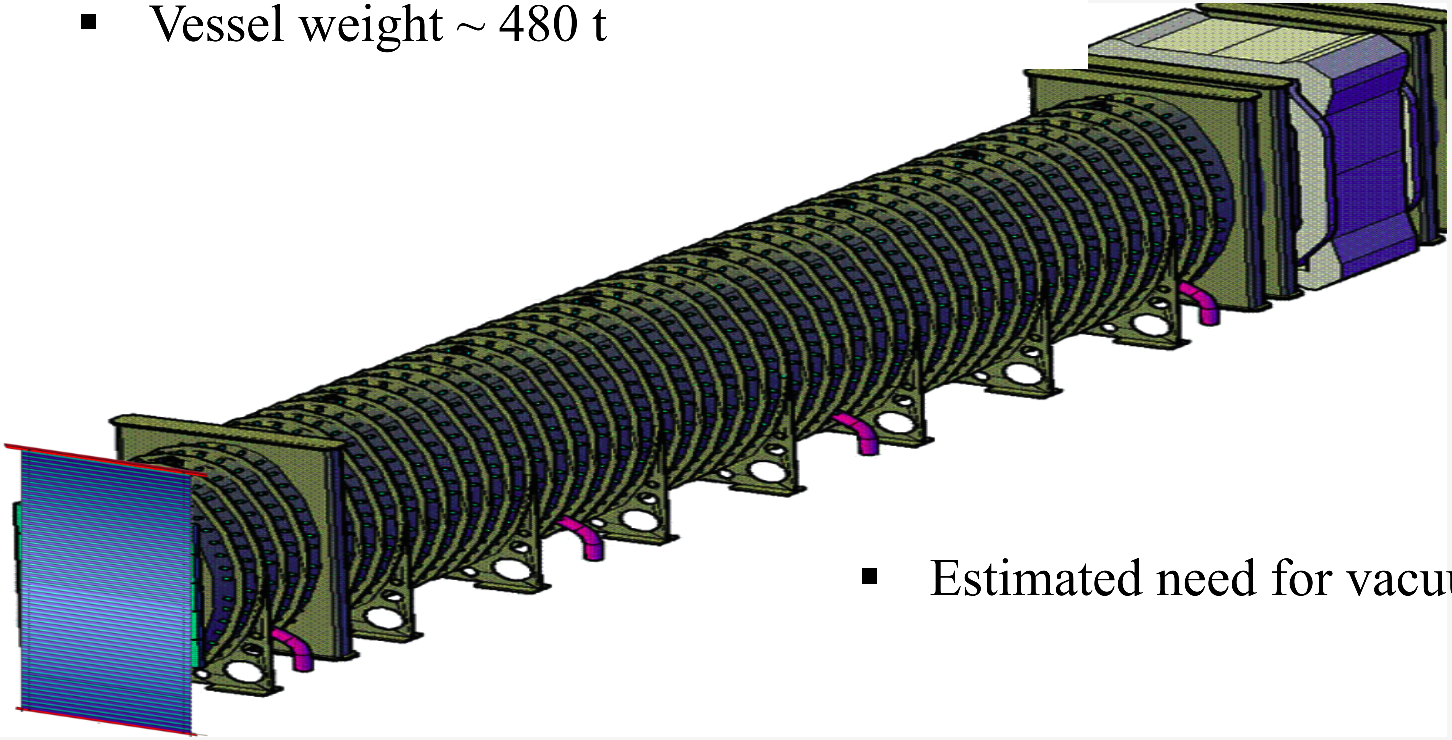
Item	Cost (MCHF)	
Facility		**135.8**
Civil engineering	57.4	
Infrastructure and services	22.0	
Extraction and beamline	21.0	
Target and target complex	24.0	
Muon shield	11.4	
Detector		**58.7**
Tau neutrino detector	11.6	
Hidden Sector detector	46.8	
Computing and online system	0.2	
Grand total		**194.5**

Decay Volume

- 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 (~$36m^3$) readout by WLS optical modules (WOM) and PMTs
  - Vessel weight ~ 480 t

Magnet designed with an emphasis on low power

- Power consumption < 1 MW
- Field integral: 0.65Tm over 5m
- Weight ~800 t
- Aperture ~50 m^2



- Estimated need for vacuum: ~10^{-3} mbar

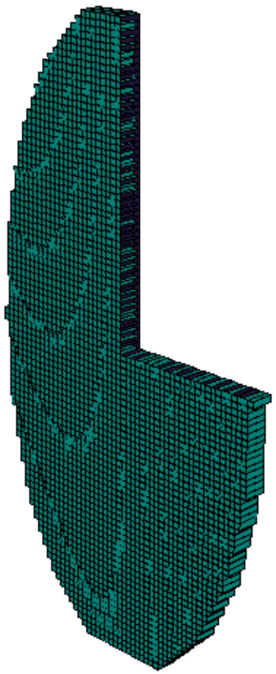
PID

- Tracking
  - – TT, Straw tracker(polyethylene terephthalate tubes), Emulsion
- Particle ID
  - – ECAL, HCAL, Muon spectrometer, Emulsion
- Reconstruction
  - – Decay vtx, IP, mass
- Momentum
  - – ECC, CES with magnet, Muon spectrometer
- Charge
  - – CES with magnet, Muon spectrometer
- Timing detector
  - – Plastic scintillator or MRPC (multigap RPC), TT

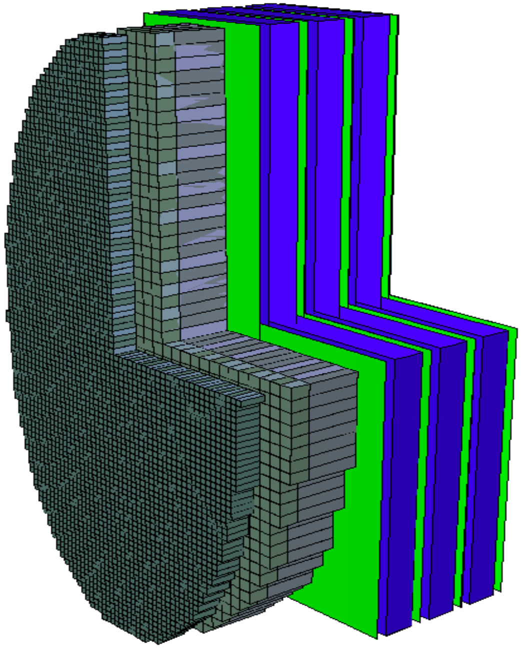
Calorimeters

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

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

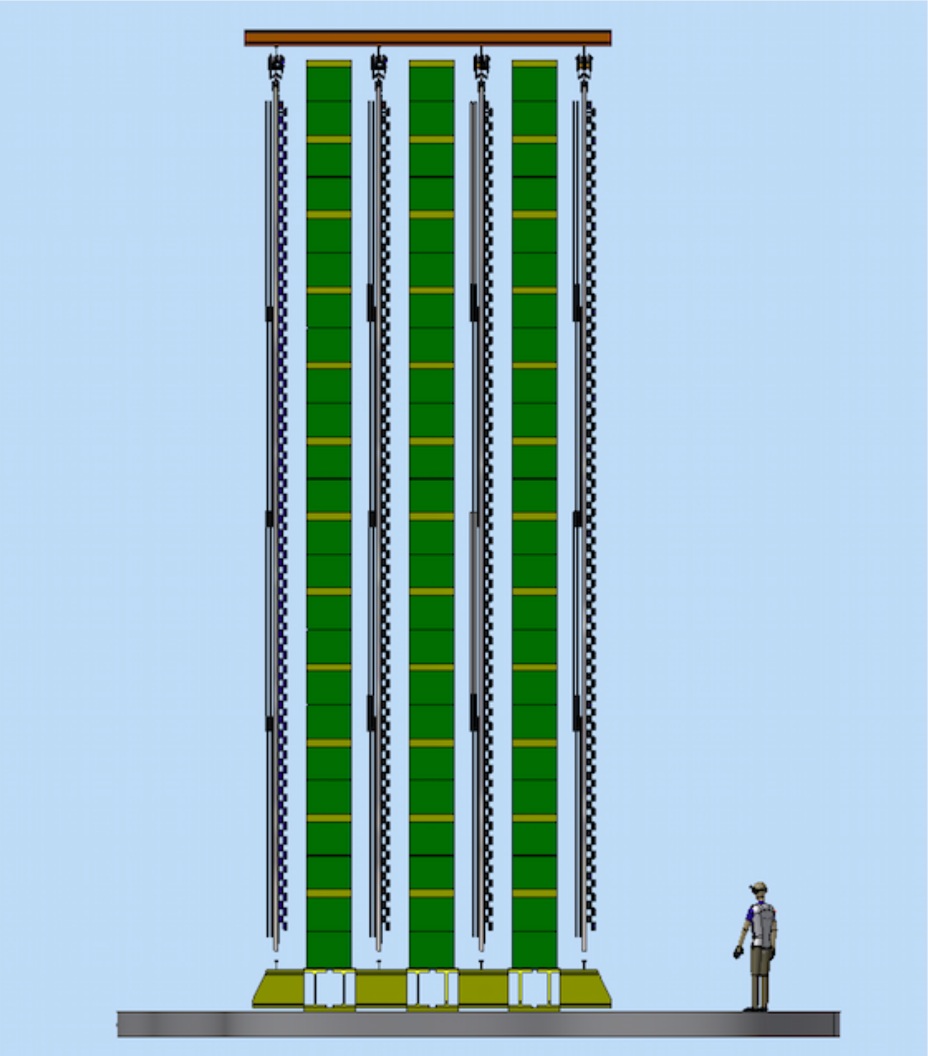


Dimensions 60x60 mm^2
Radiation length 17 mm
Moliere radius 36 mm
Radiation thickness 25 X_0
Scintillator thickness 1.5 mm
Lead thickness 0.8 mm
Energy resolution 1%



Muon System

- Based on scintillating bars, with WLS fibers and SiPM readout

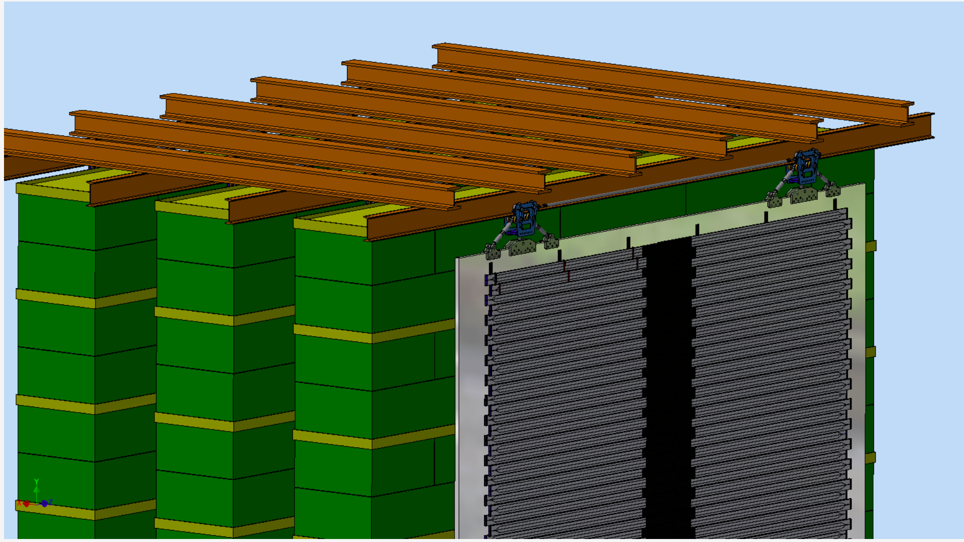


Requirements:

1) High-efficiency identification of muons in the final state

2) Separation between muons and hadrons/ electrons

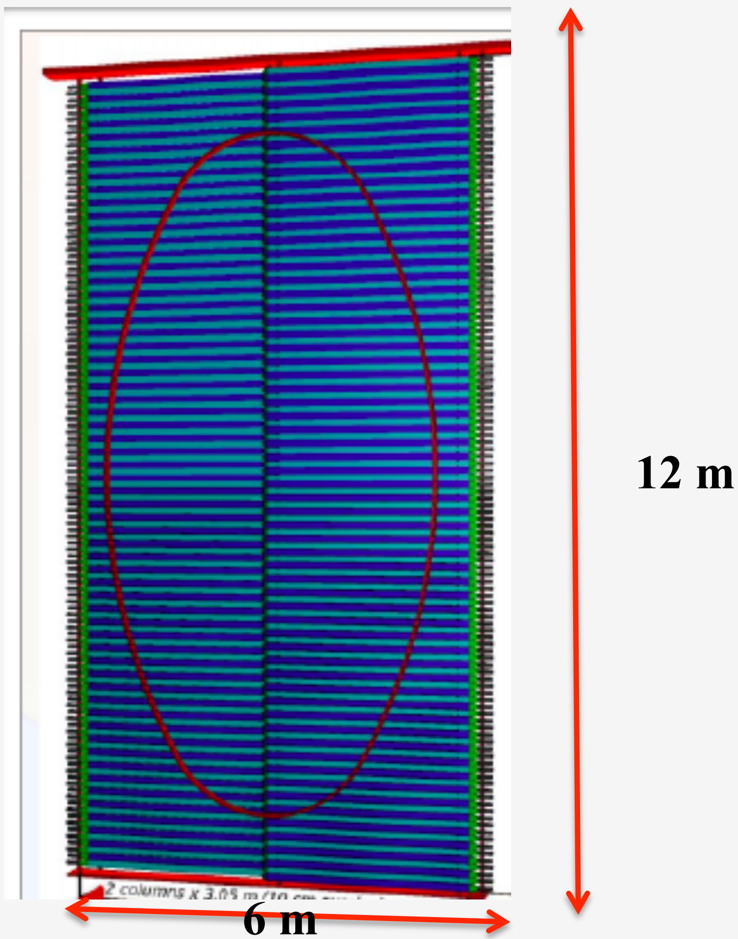
3) Complement timing detector to reject combinatorial muon background



Timing Detector

Challenges:

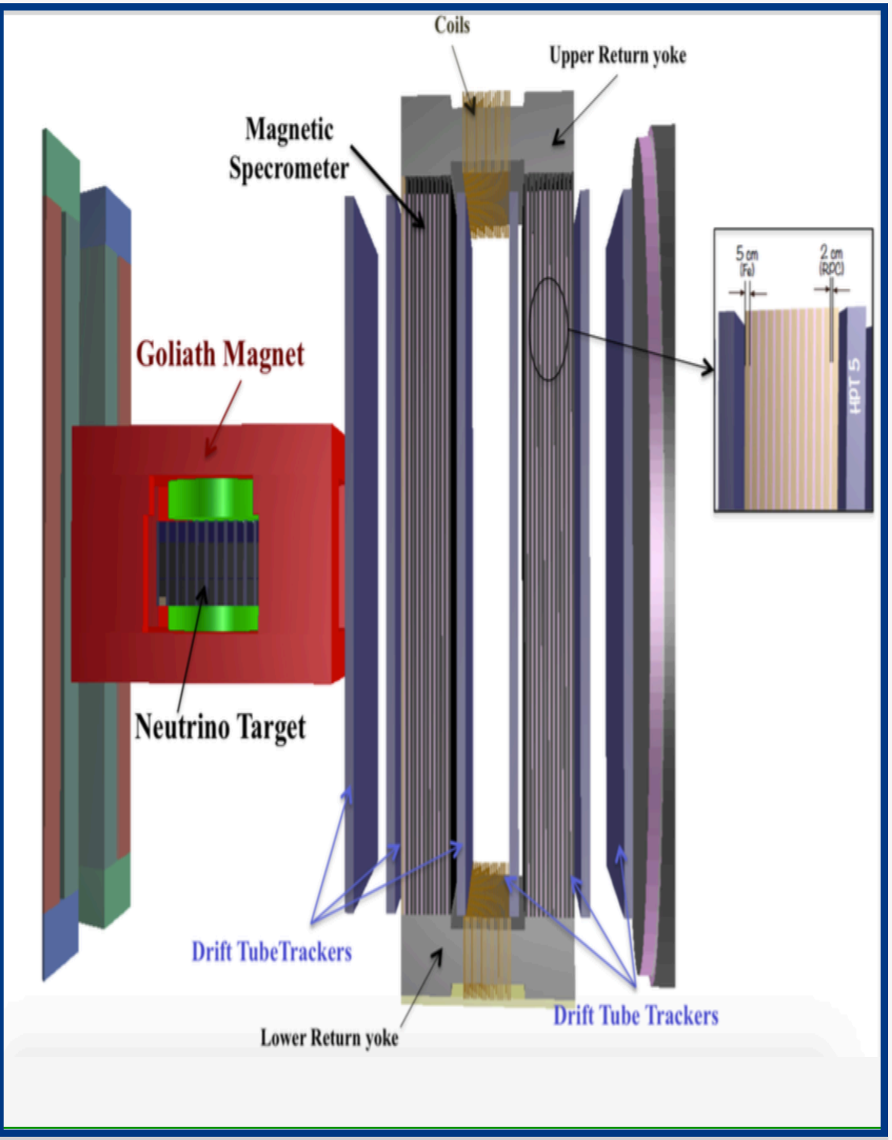
- Large area
- Required resolution < 100 ps
- Spatial resolution under study



Two options considered:

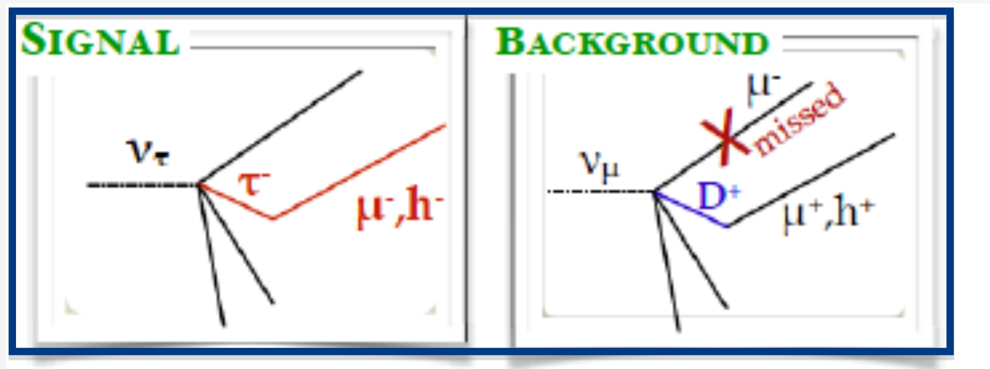
- Scintillator bars (NA61/SHINE, COMPASS)
  - NA61/SHINE ToF
  - 100 ps resolution
  - Long scintillator bars
- Multi-gap resistive plate chambers (MRPC)
- 61 chambers x 120 cm strips, 3 cm pitch
  - Used in ALICE TOF
  - 50 ps resolution achievable

Muon Identification



Muon come from

- $\tau \rightarrow \mu$ decays
- ν_μ CC interactions
- μ identification at primary vertex for background rejection



12 iron layers
11 RPC layers
6 Drift Tube Trackers Planes

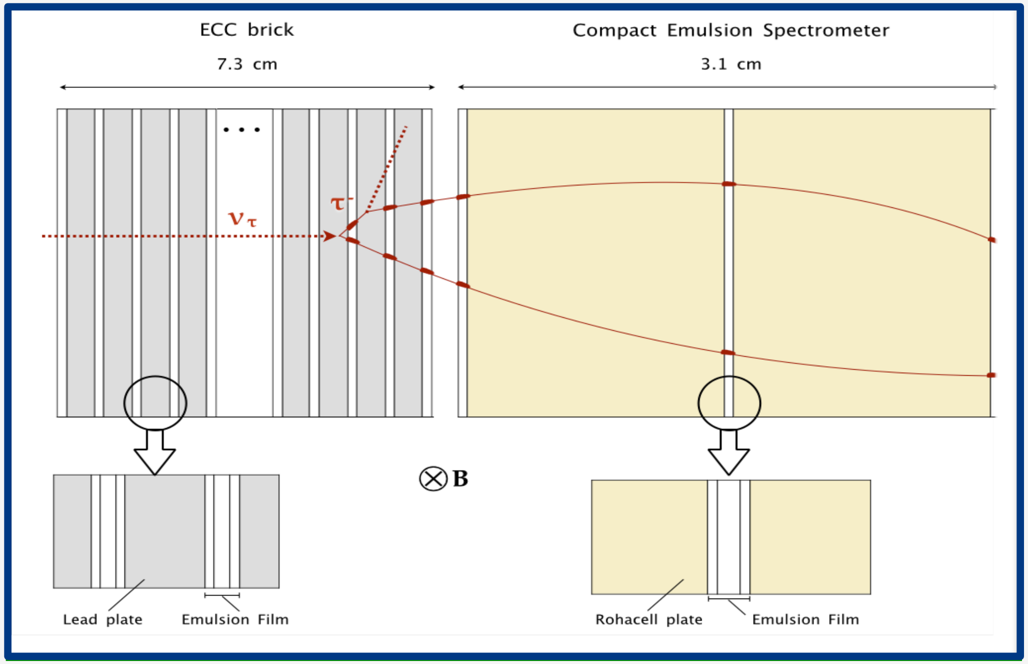
Tau/anti-tau Separation

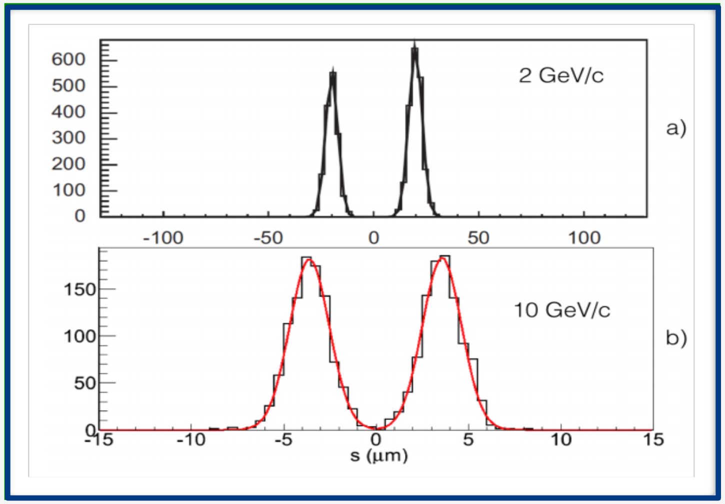
TASK

- Electric charge and momentum measurement of τ lepton decay products
- Key role for the τ→h decay channel

↓

- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field





PERFORMANCES

- Electric charge determined up to 10 GeV/c.
- Momentum estimated from the sagitta.
- Δp/p < 20% up to 12 GeV/c

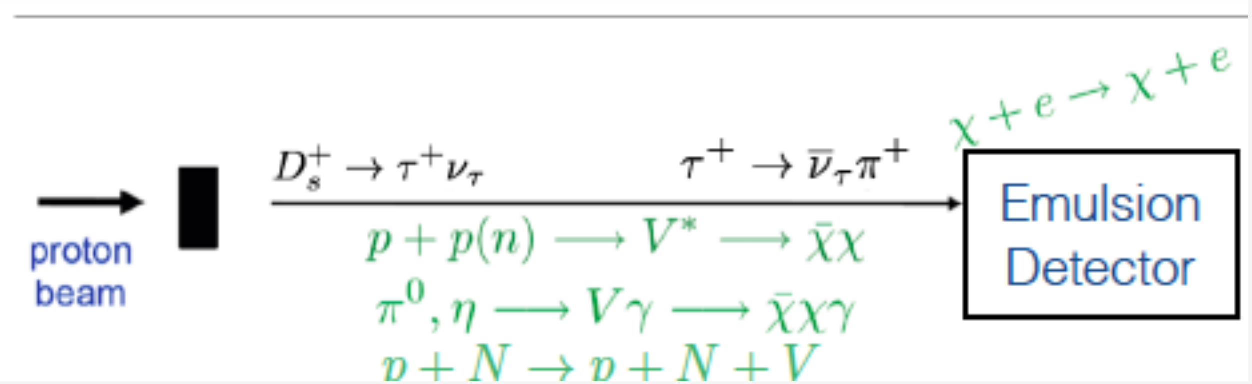
LHM Search

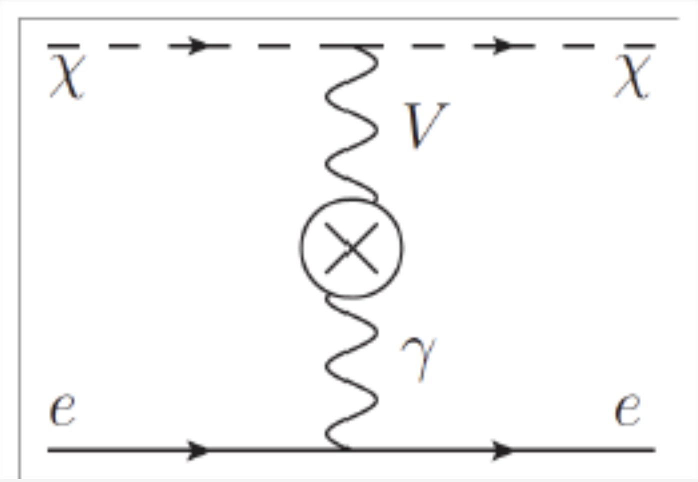
- Generated in the beam-dump, e.g. via light dark photon mediators (V)
- Main production modes

  1) direct production

  2) decay in flight

  3) resonant vector meson mixing





LDM elastic scattering on atomic electrons of the target

High energy beam dump:
➞ LDM-electron scattering is highly peaked in the forward direction

Strange Quark Content

- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon.
- Strangeness important for precision SM tests and for BSM searches.
- W boson production at 14 TeV: 80% via *ud* and 20% via *cs*.