SHiP: a new facility to search for heavy neutrinos and study ν_τ properties

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On behalf of the SHiP Collaboration

Physics motivation

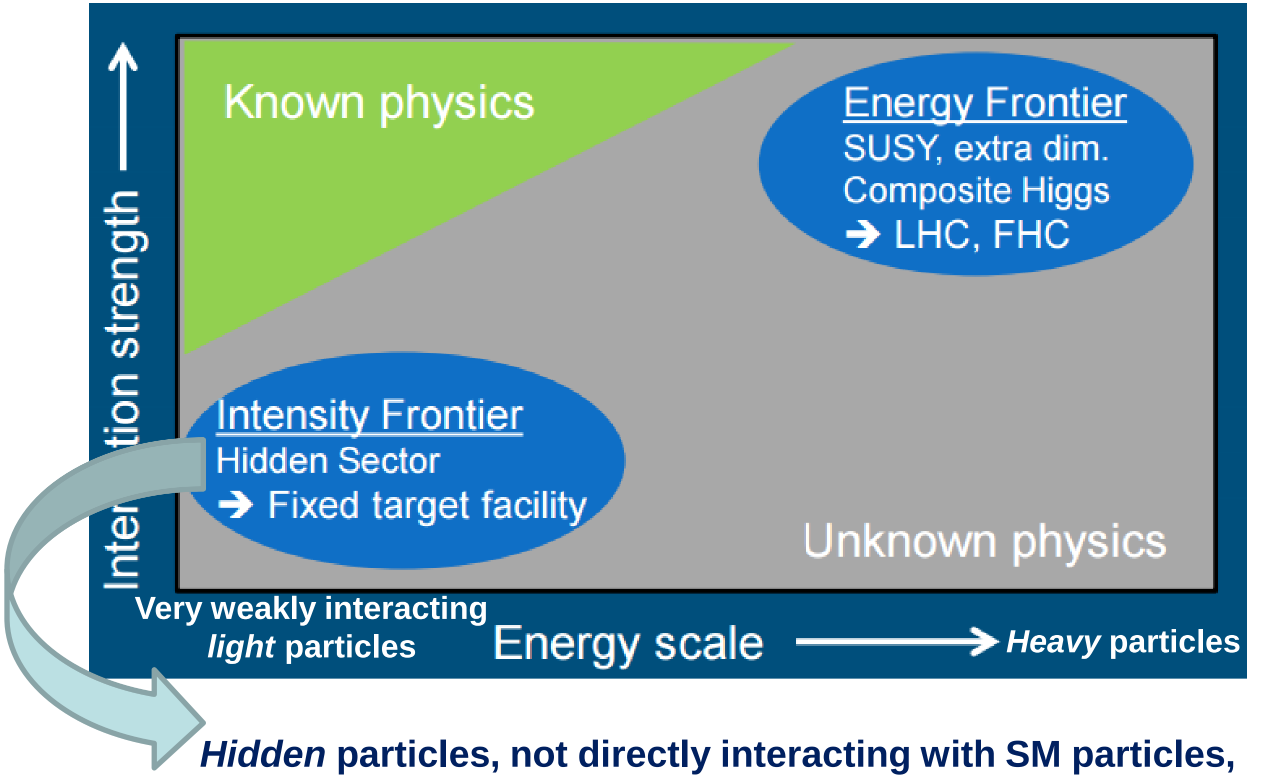
The Standard Model provides a consistent description
of Nature's fundamental constituents and their interactions.

Although largely tested and confirmed by several experiments,
the SM cannot be regarded as the ultimate theory of Nature,
since it cannot account for a number of established
experimental facts, such as:

- Neutrino masses and oscillation
- Excess of matter over antimatter in the Universe
- Dark matter

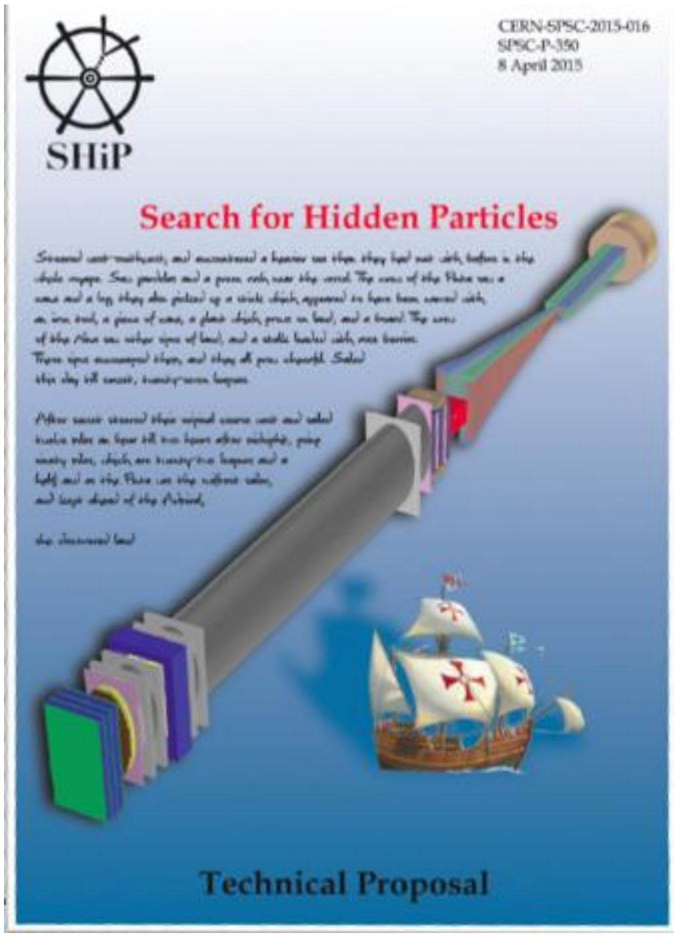
Physics motivation

New, yet unknown particles and/or interactions should exist.



***Hidden* particles, not directly interacting with SM particles, could be coupled to the *visible* sector via gauge-singlet operators (portals).**

The SHiP experiment



Proposal of a beam dump facility at CERN SPS designed to investigate the *hidden sector* in the GeV mass region and study ν_τ physics

Technical Proposal (arXiv:1504.04956) submitted last April, signed by 235 experimentalists from 45 institutes

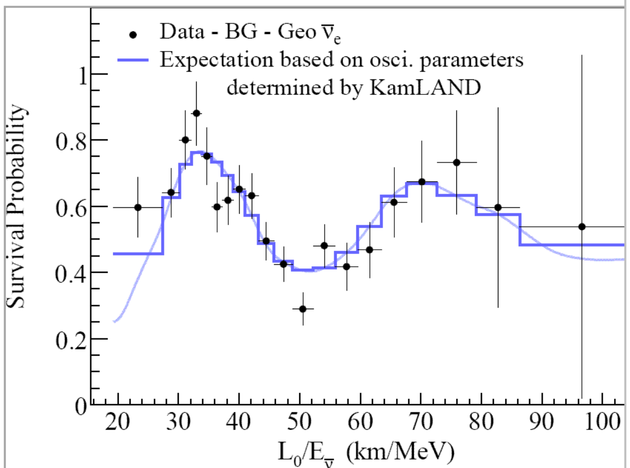
Physics Proposal (arXiv:1504.04855) signed by 80 theorists

The SHiP physics program

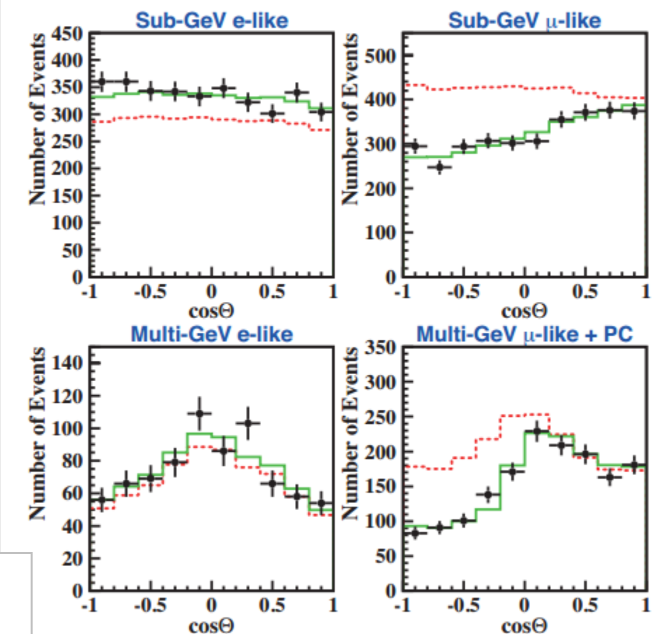
Rich physics program

This talk:
focus on ν portal and ν_τ physics

Neutrinos: current picture

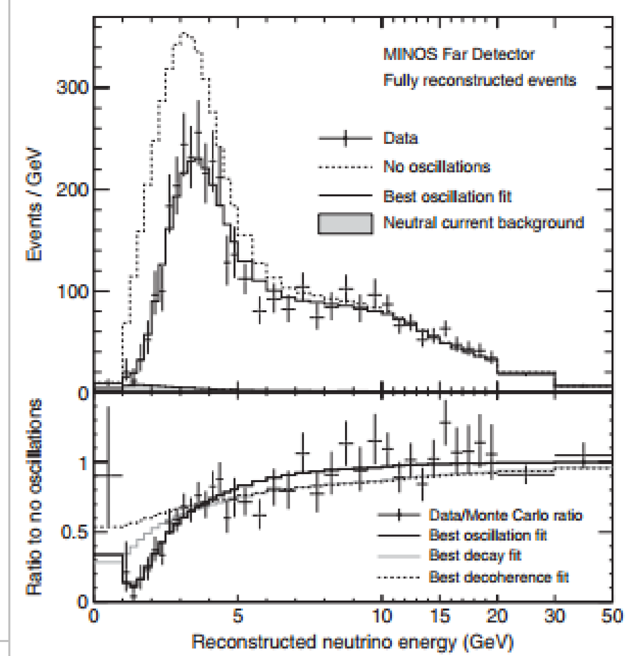


Phys. Rev. **D83**, 052002 (2011)

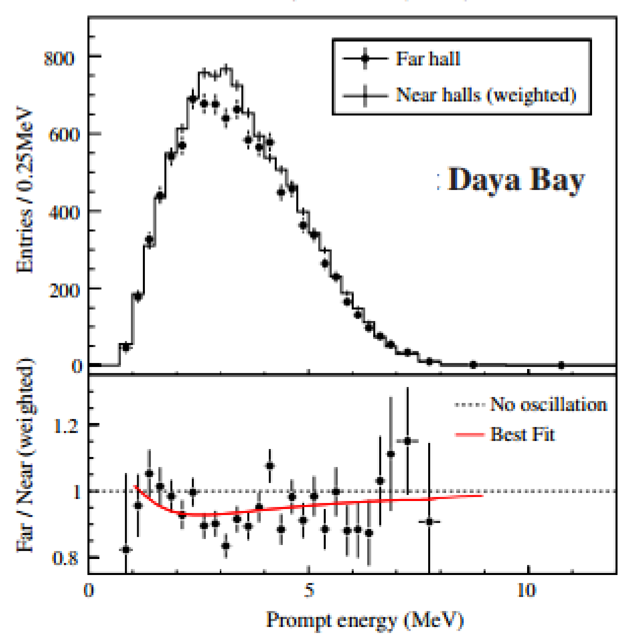


[Super-Kamiokande Collab.]

PRL **106**, 181801 (2011)



PRL **108**, 171803 (2012)



Oscillation mechanism among active neutrinos well established after several decades of experimental searches, described in terms of two mass splittings and three mixing angles

⇒ Non-zero ν masses ⇒ Beyond SM physics

Neutrino portal

Most general renormalizable Lagrangian (see-saw generation of neutrino masses):

$$L_{singlet} = i\bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c + L_{SM}$$

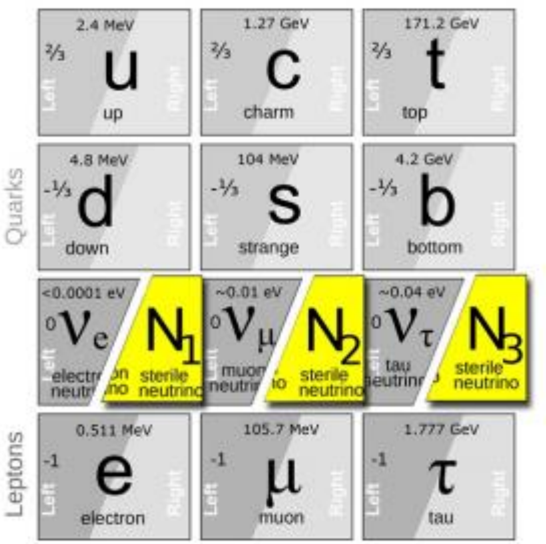
Majorana mass term

$N_I \,(I = 1,2,\ldots,n)$ gauge-singlet fermions

Yukawa term: mixing with active neutrinos

If $n = 3$ and $M_I < M_W$: Neutrino Minimal Standard Model (νMSM)

Neutrino portal

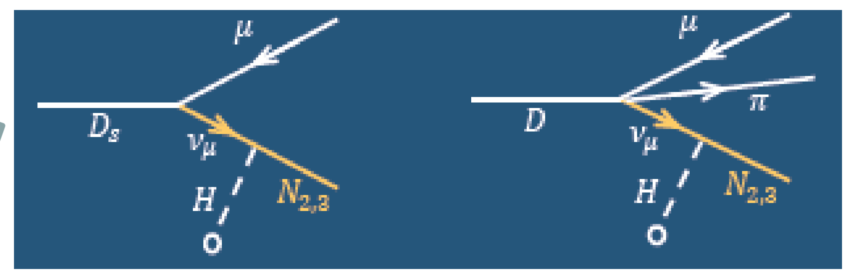


T.Asaka e M.Shaposhnikov, PLB620 (2005) 17

νMSM:
3 additional sterile right-handed neutrinos,
Majorana partners of active neutrinos with masses < M_W
(*Heavy Neutral Leptons*, HNL)

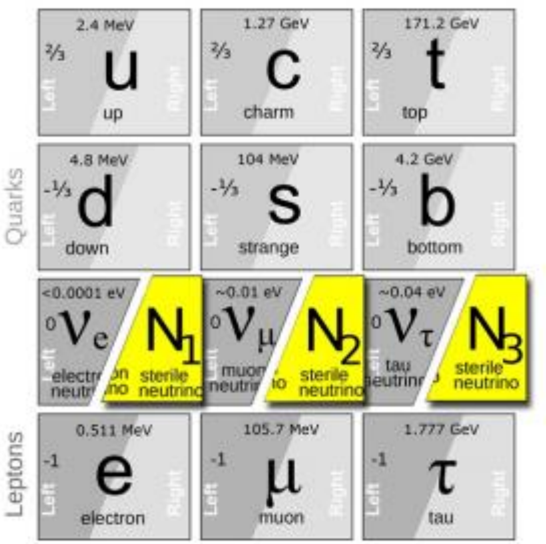
N_1 with mass in the keV region: dark matter candidate

$N_{2\text{-}3}$ with mass in the GeV region : allow for the explanation of ν masses and oscillation and baryon asymmetry



Production: semi-leptonic decay of mesons

Neutrino portal



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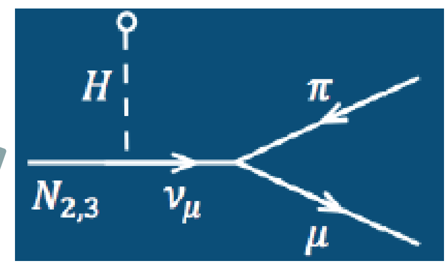
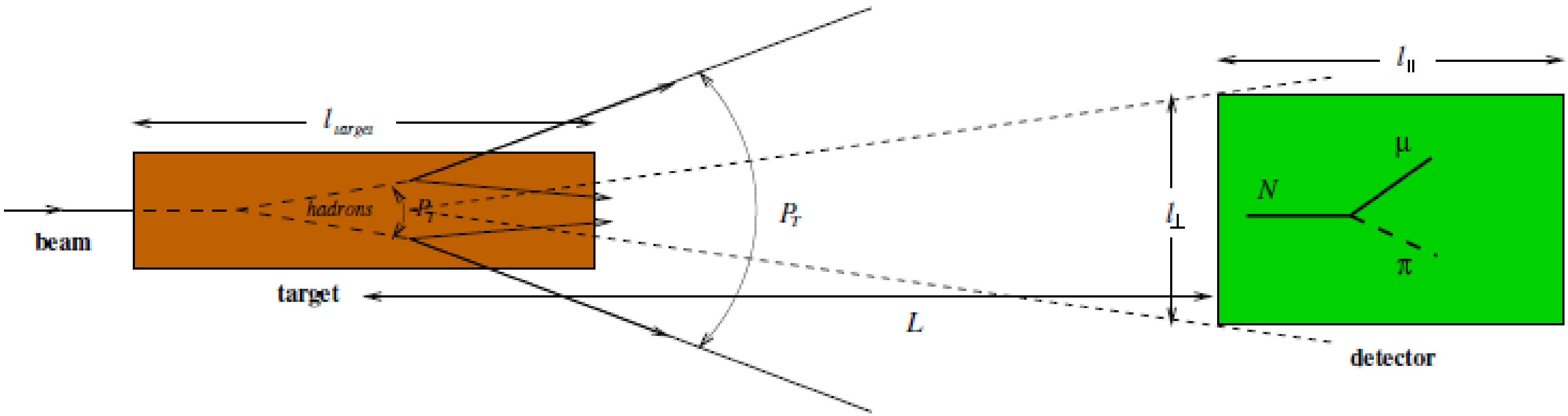


Very small HNL – active ν coupling:
HNL long-lived particles (flight length *O*(km))

Experimental requirements

Search for HNLs produced in charmed hadron decays

Detection of HNL decays to SM particles



Requirements:

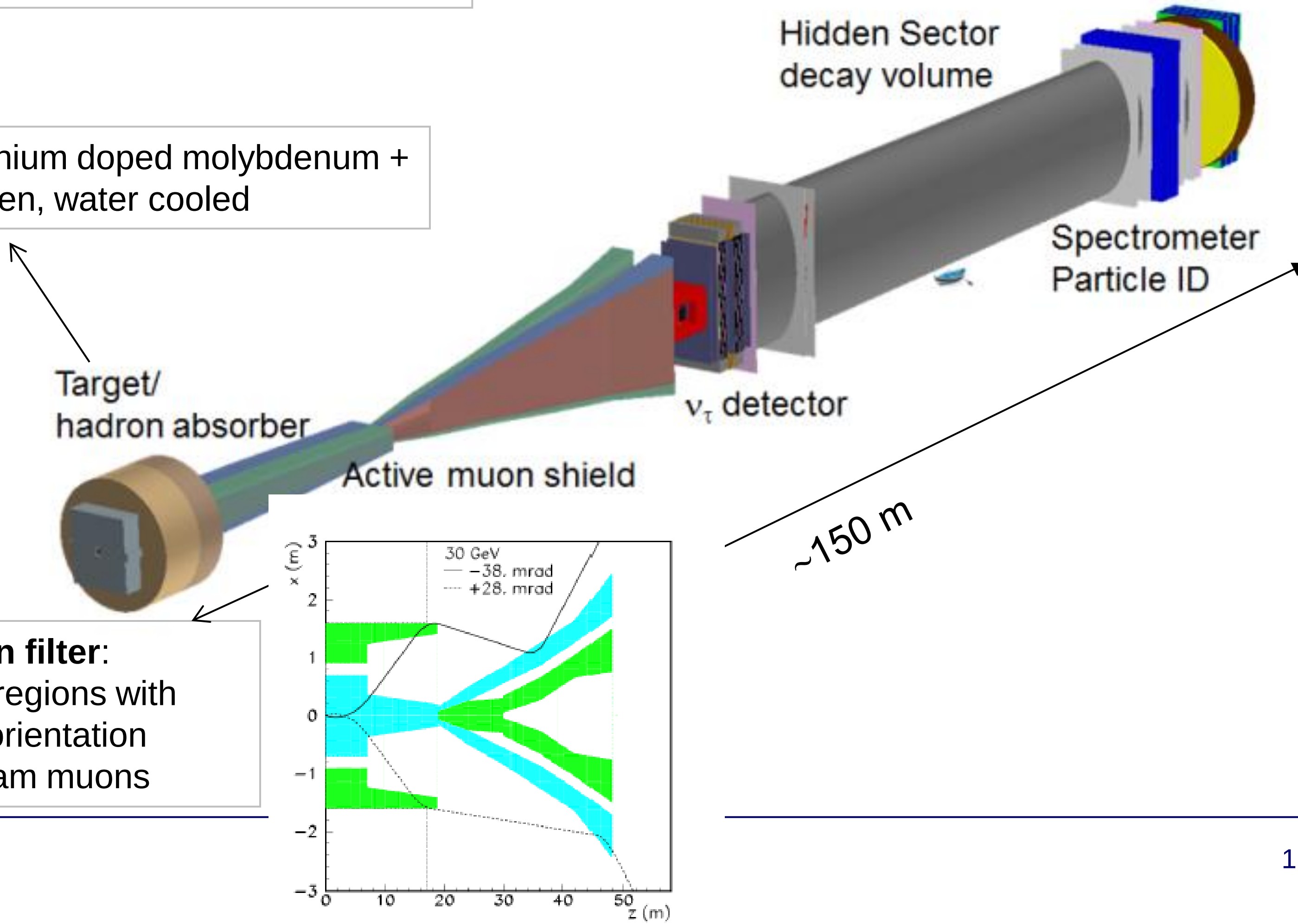
- Maximize production of charmed hadrons
- Minimize neutrinos from π and K decays
- Effective and compact muon shield
- Hadron and electron/gamma absorber
- Detector *close* to target to maximize geometrical acceptance (large P_t)

The SHiP facility

SHiP
Search for Hidden Particles

Beam: $4x10^{13}$ p.o.t. / cycle (7.2s)
with slow extraction (1s) to reduce detector occupancy (combinatorial background);
$4x10^{19}$ p.o.t. / year

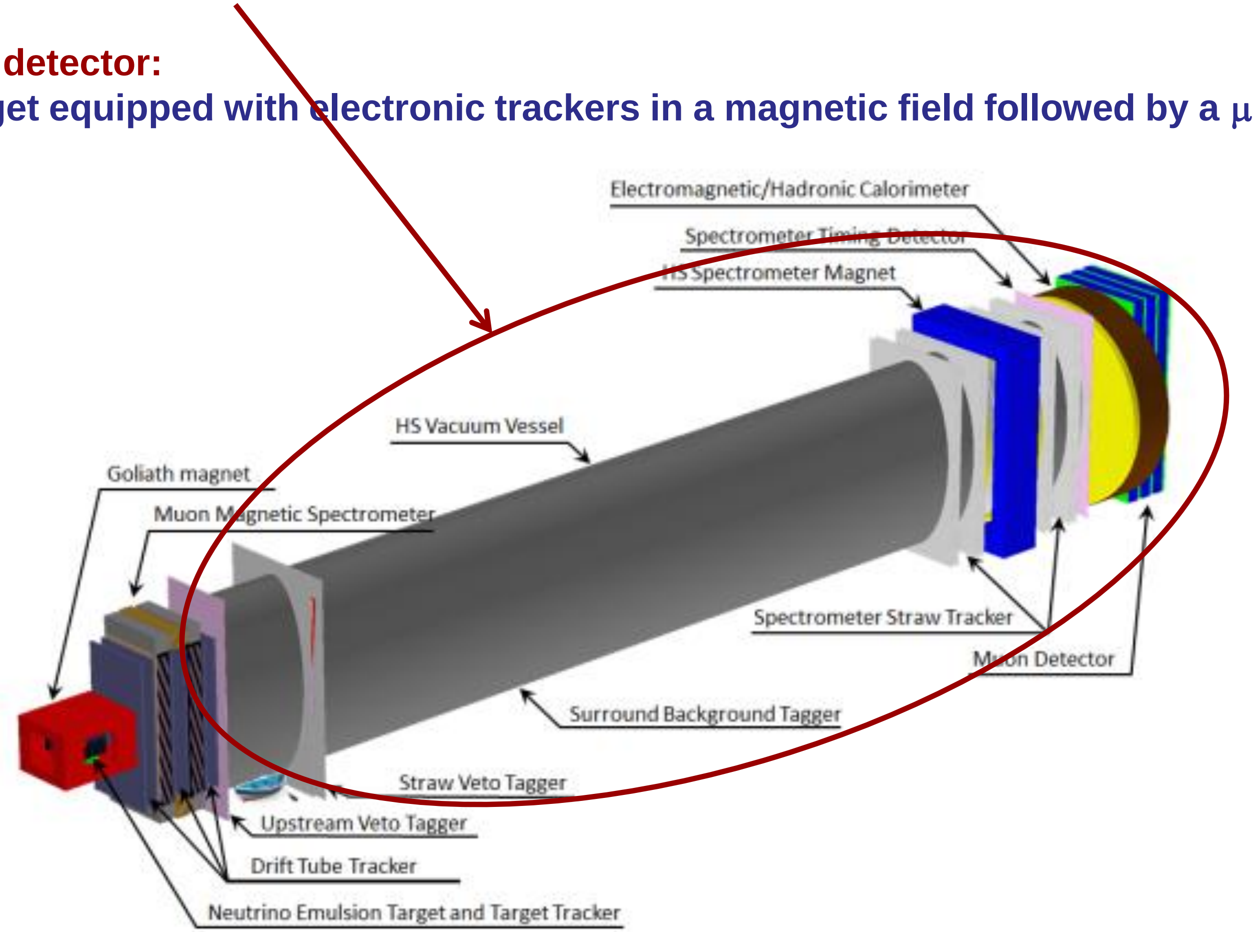
Target: titanium-zirconium doped molybdenum + pure tungsten, water cooled



Active muon filter:
two magnetized regions with opposite field orientation
to bend out beam muons

The SHiP detector

- **Hidden particle detector:**
  long, evacuated decay volume with a magnetic spectrometer, calorimeters and μ detectors
- **Tau neutrino detector:**
  emulsion target equipped with electronic trackers in a magnetic field followed by a μ spectrometer

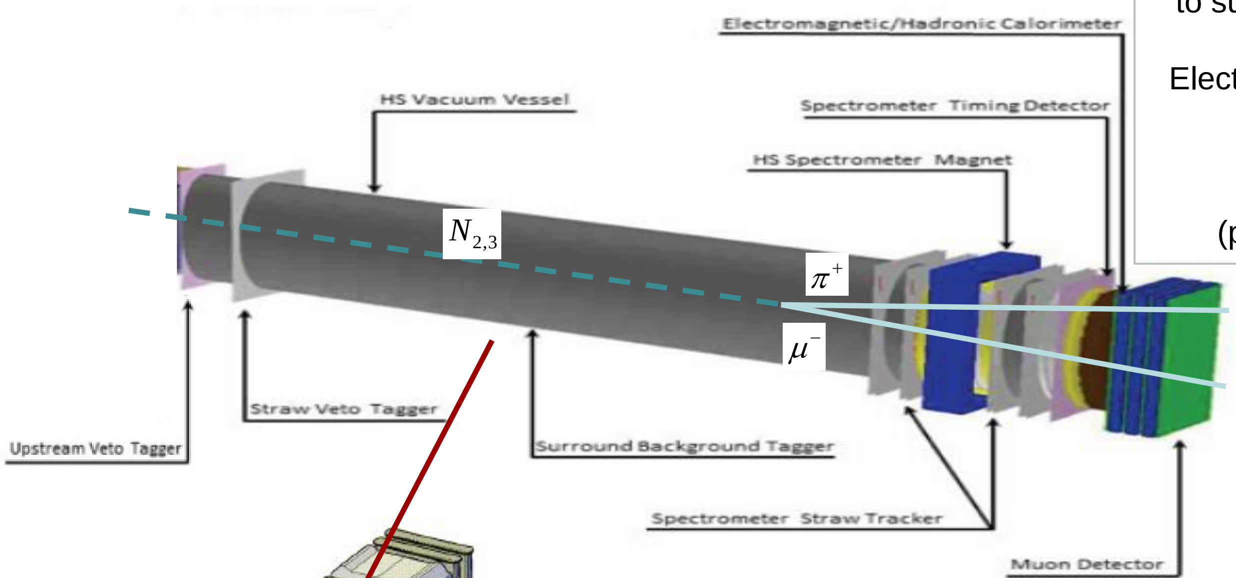


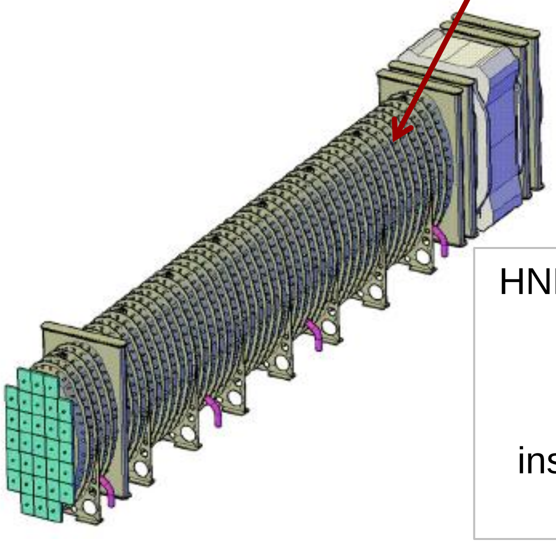
HNL detector

Large aperture dipole magnet instrumented with Straw Tracker planes + timing detector (~ 100 ps resolution) to suppress combinatorial background

Electromagnetic / hadronic calorimeter (Shashlik technique, LHCb)

Muon detector (plastic scintillator bars, MINOS)

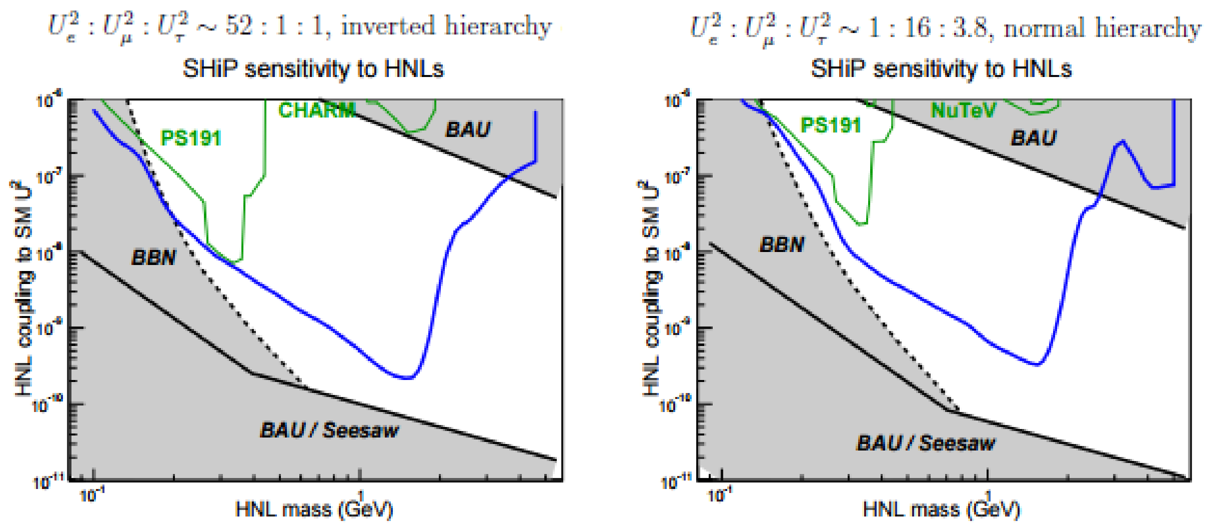


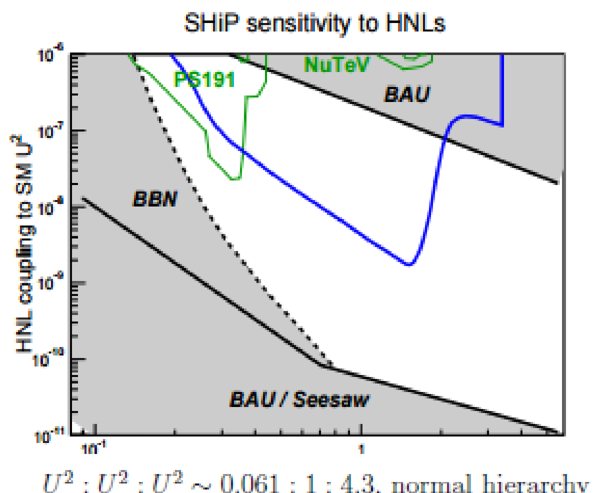


HNL discovery potential critically dependent on background rejection:

5m x 10m x 50m evacuated elliptical decay volume (pressure ~ 10^{-6} bar) to suppress ν and μ interactions, instrumented with surrounding liquid scintillator background tagger + upstream veto tagger

HNL: sensitivity





2×10^{20} p.o.t. @ 400 GeV
5 years

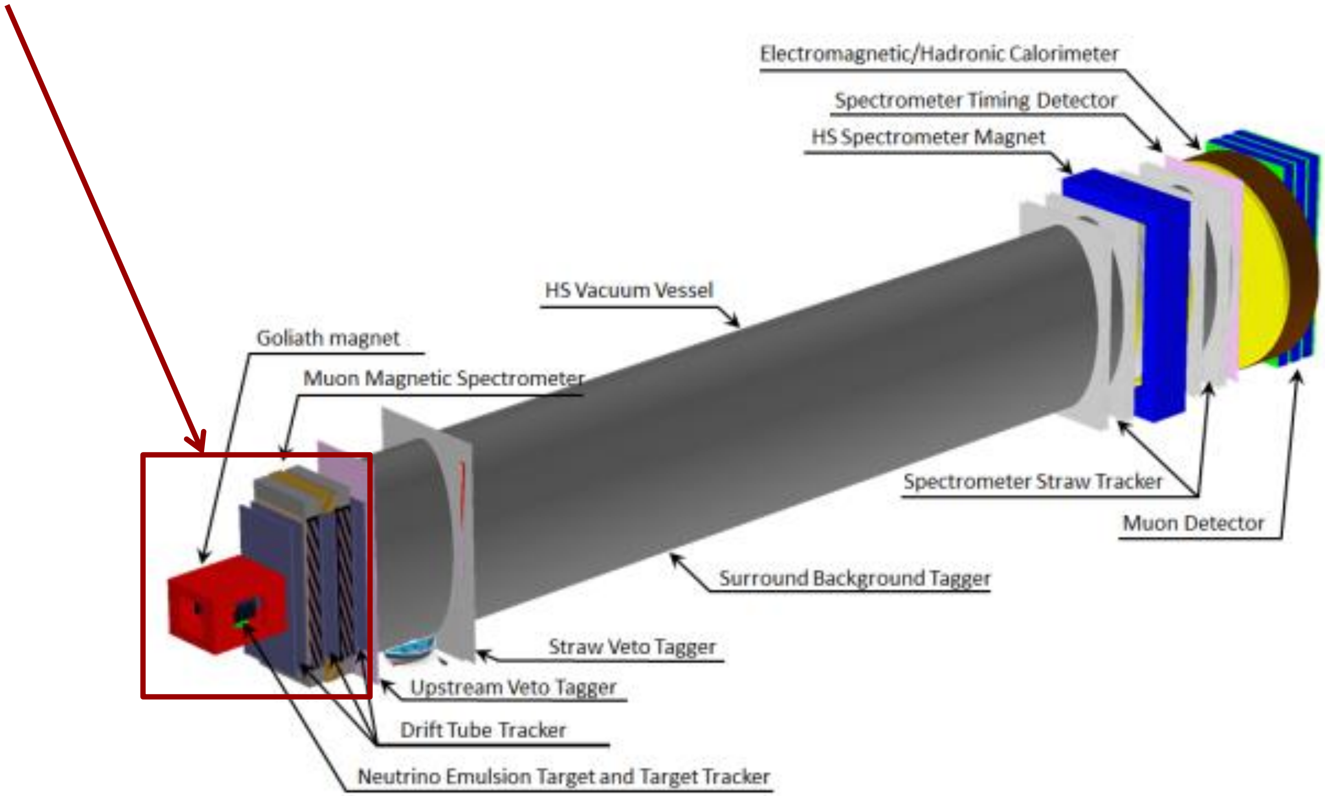
$Br(N \to \mu/e\ \pi) \sim 0.1 - 50\%$
$Br(N \to \mu/e\ \rho) \sim 0.5 - 20\%$
$Br(N \to \nu\mu e) \sim 1 - 10\%$

- **Significant improvement of present limits**
- **Largely unexplored region above m_K up to m_B**

The SHiP detector

- **Hidden particle detector:**
  long, evacuated decay volume with a magnetic spectrometer, calorimeters and μ detectors

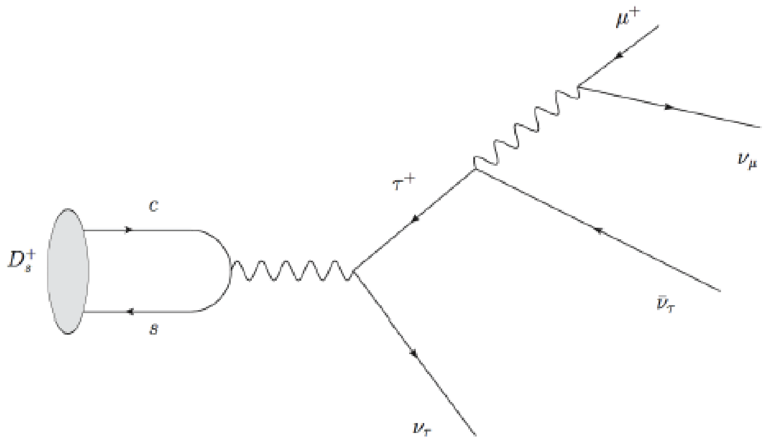
- **Tau neutrino detector:**
  emulsion target equipped with electronic trackers in a magnetic field followed by a μ spectrometer



ν_τ physics

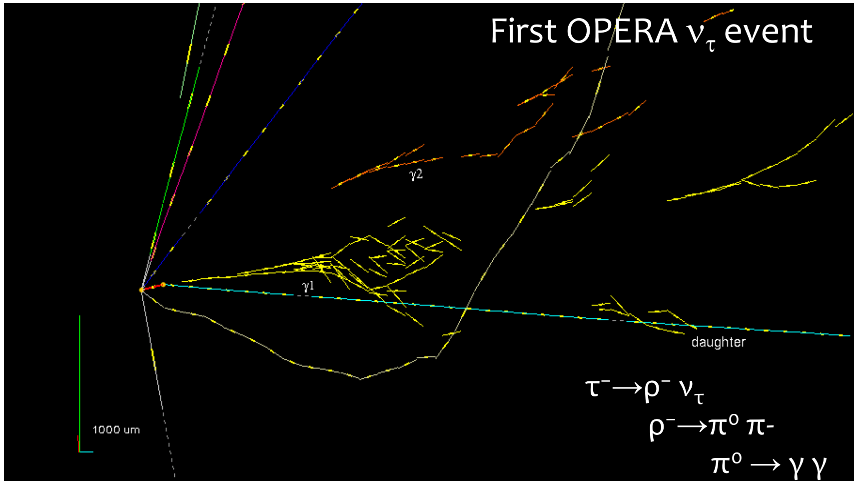
Abundant production of neutrinos in charmed hadron decays

SHiP ideally suited for studying ν physics

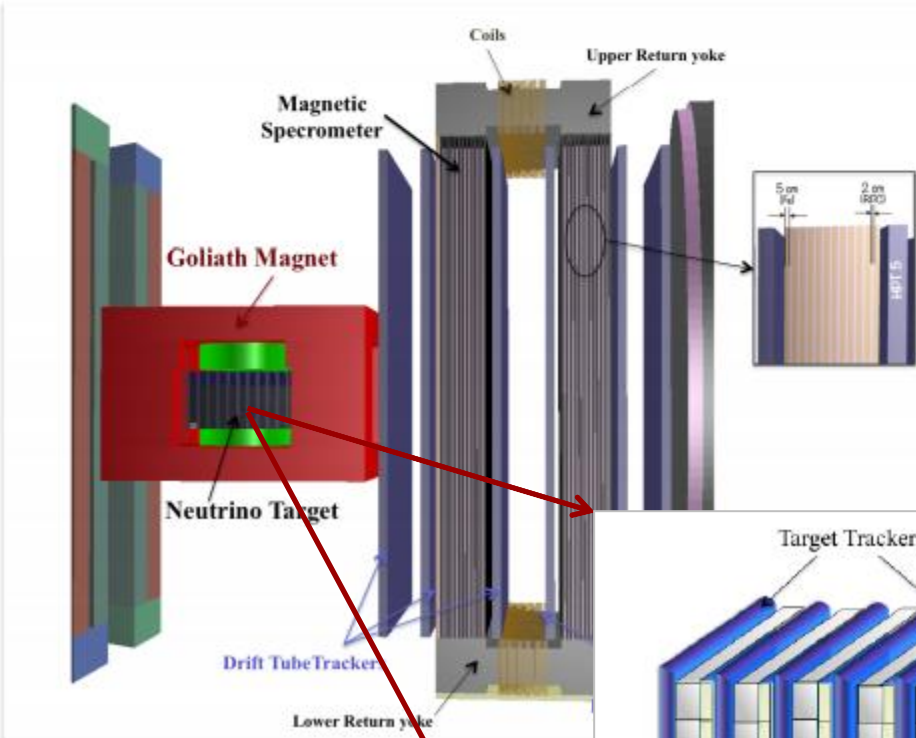


- **First direct observation of anti-ν_τ**
- **Measurement of ν_τ and anti-ν_τ cross section**

Only 9 ν_τ events (with 1.5 background events) observed in DONUT and 5 ν_τ events (from ν_μ oscillation) observed so far in OPERA

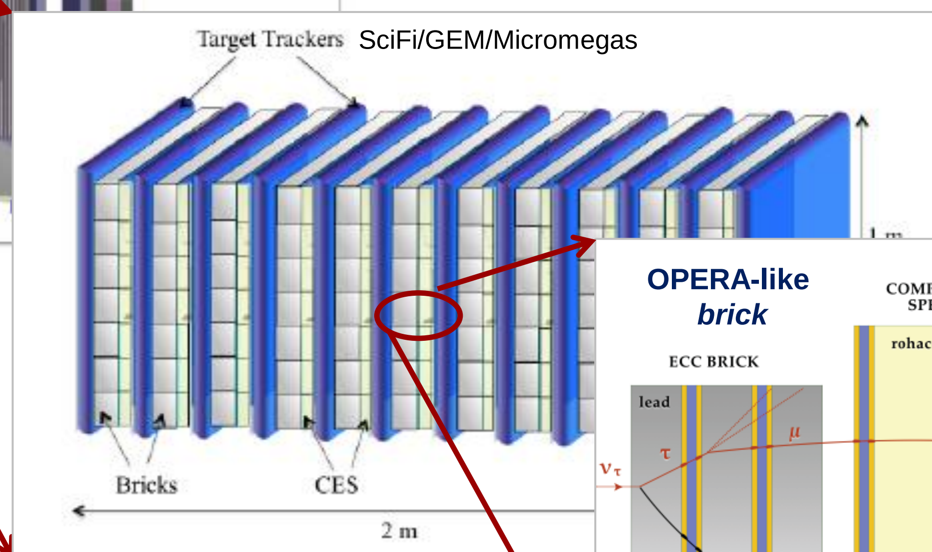


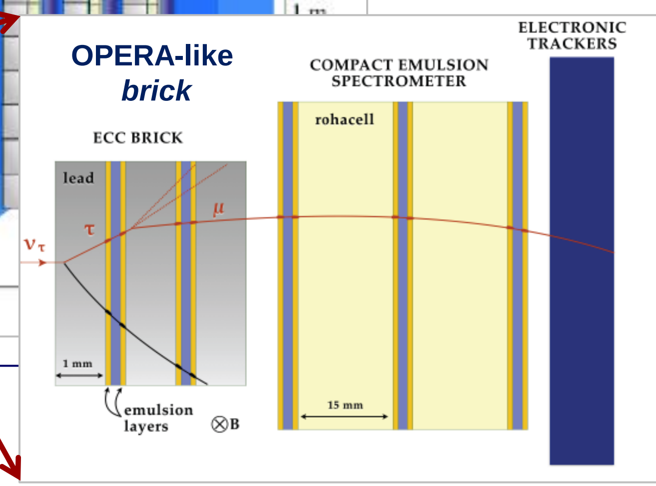
ν_τ detector



Requirements:

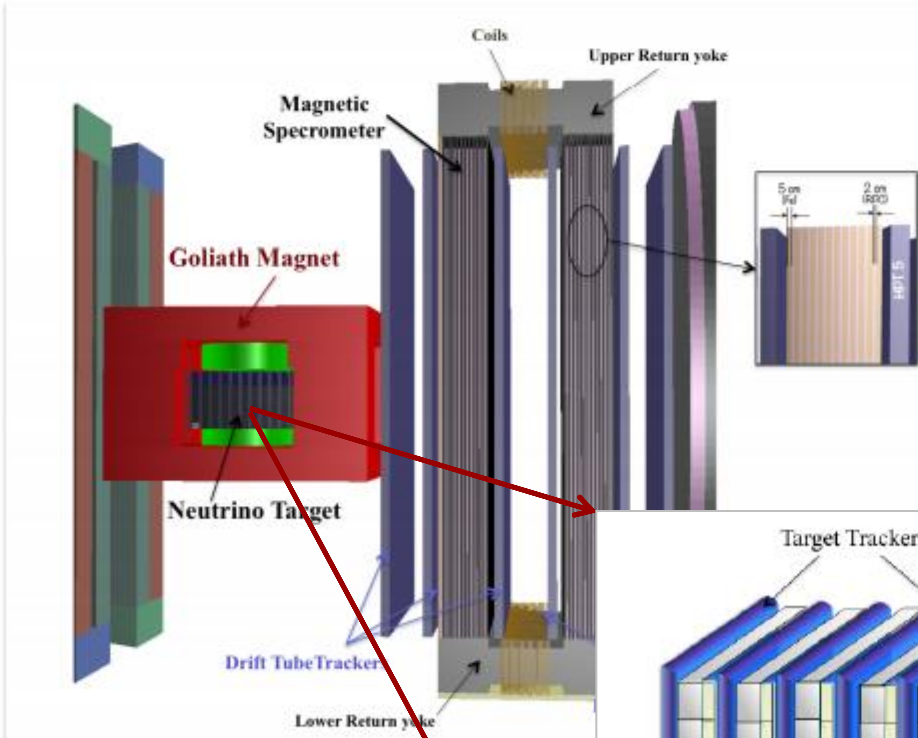
- Compact high-density magnetized target with sub-micrometric position resolution
- Muon magnetic spectrometer

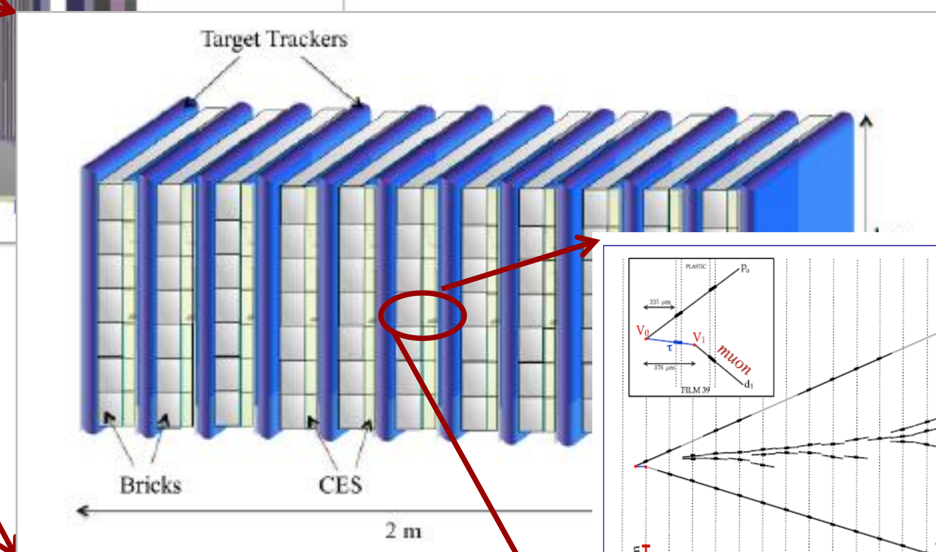


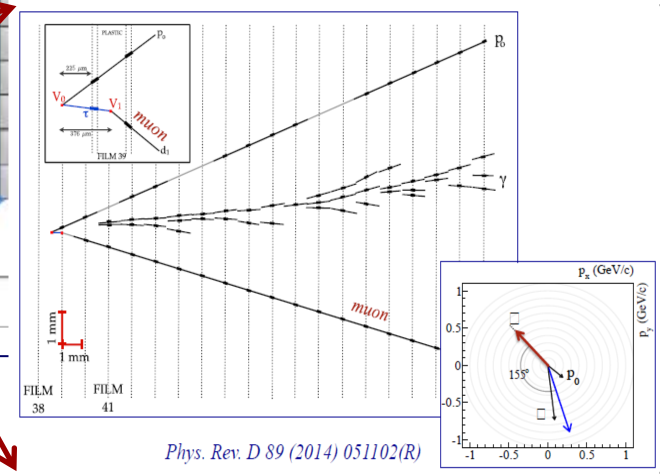


- **Magnetized nuclear emulsion – lead target**
- **Electronic trackers (time stamp)**

ν_τ detector







Phys. Rev. D 89 (2014) 051102(R)

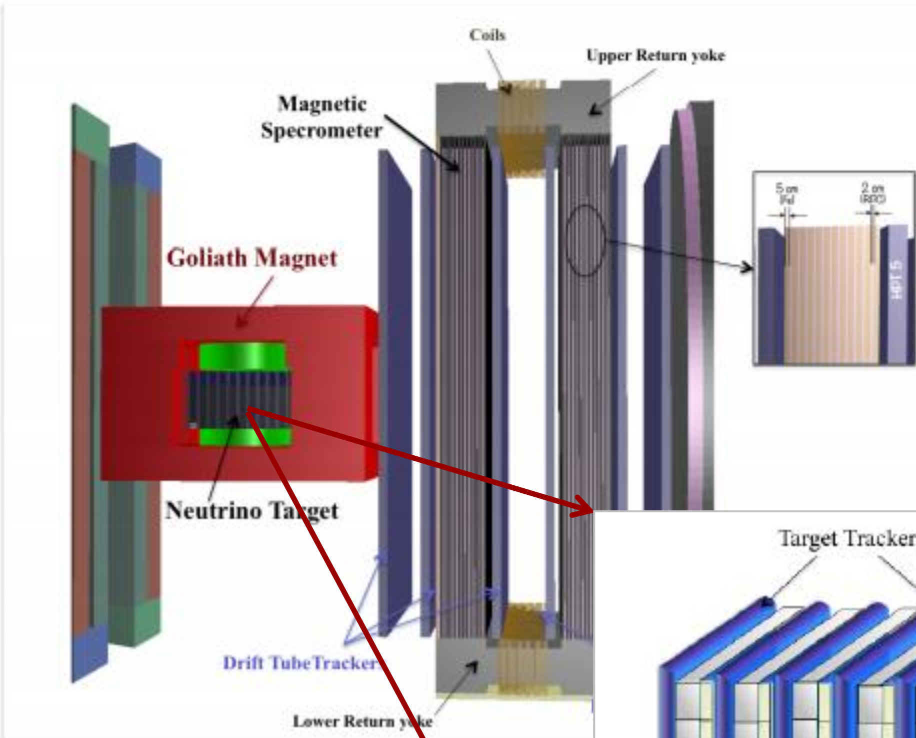
- **<u>Unique capability of detecting all ν flavors</u>**

  ν_μ: muon reconstruction in the magnetic spectrometer

  ν_e: e.m. shower reconstruction in the brick

  ν_τ: observation of ν interaction and τ decay vertices in the brick

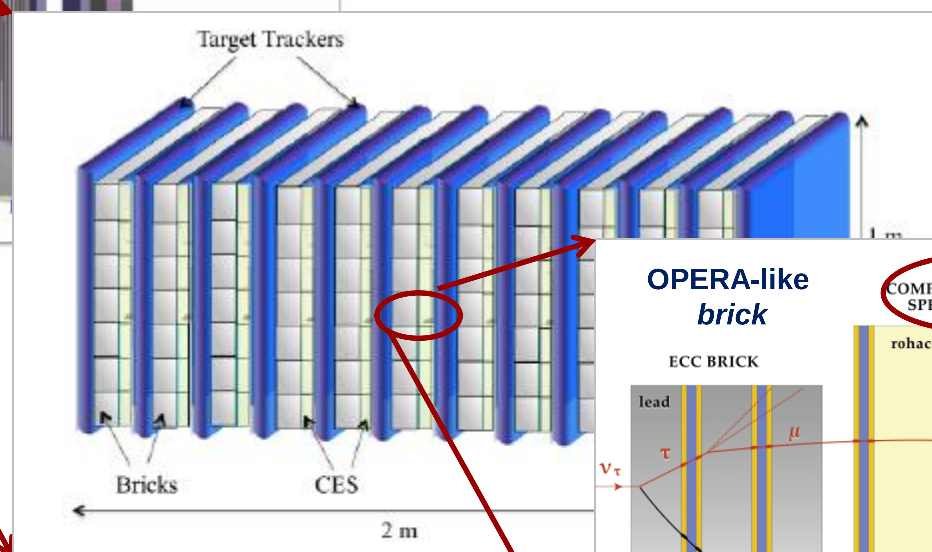
ν_τ detector

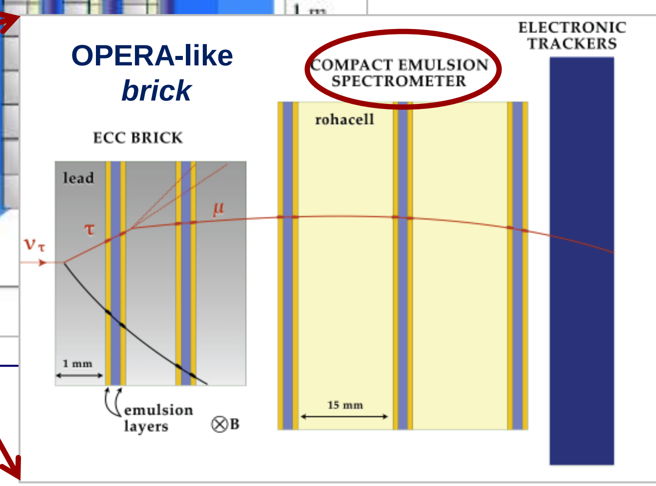


- ν_τ / anti-ν_τ separation

  $\tau \to \mu$: muon charge measurement in the magnetic spectrometer

  $\tau \to h$: hadron charge measurement in the *Compact Emulsion Spectrometer*





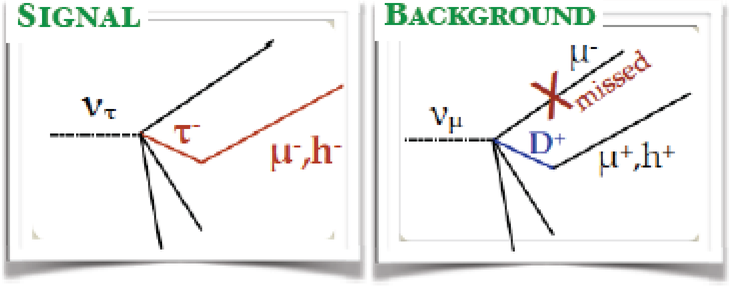
ν_τ physics performance

Expected number of signal and background events

decay channel	ν_τ			$\overline{\nu}_\tau$		
	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

2×10^{20} p.o.t. @ 400 GeV
5 years
Target mass: 9.6 t

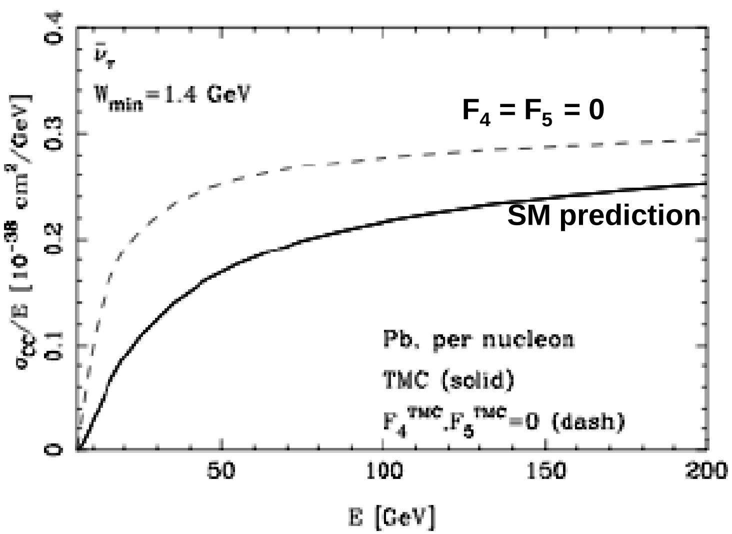
Main background source:
charm production in ν CC interactions
with unidentified primary lepton

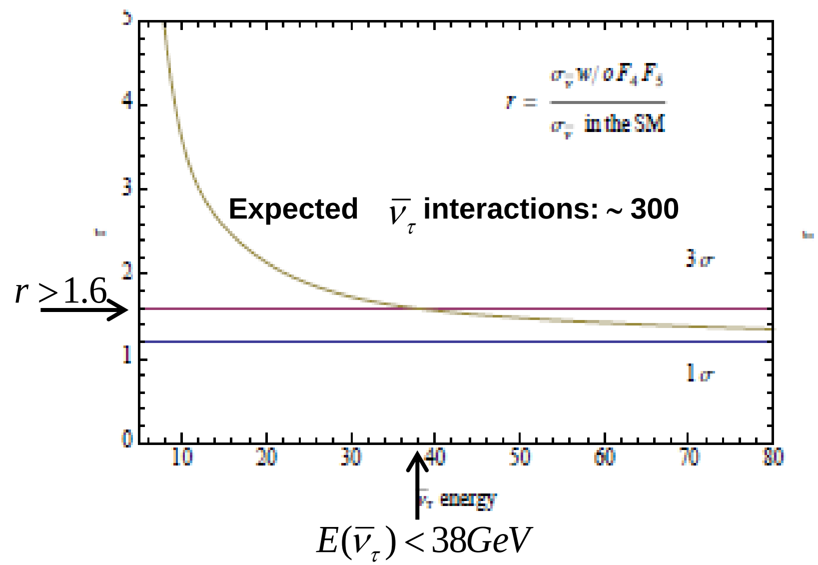


ν_τ physics performance

Structure functions F_4 and F_5, neglected in ν_μ / ν_e interactions, contribute to ν_τ cross section (higher τ lepton mass)

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





ν physics performance

SHiP ideally suited to study ν and anti-ν physics for all three active flavours

Expected ν-induced charm production

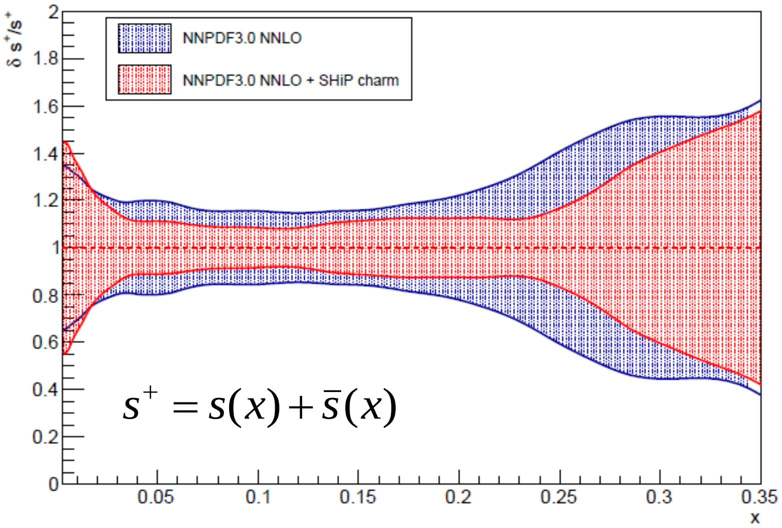
	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu}_\mu$	$2.7 \cdot 10^4$
$\bar{\nu}_e$	$5.4 \cdot 10^3$
Total	$1.1 \cdot 10^5$

Expected charm yield exceeds available statistics from previous experiments by more than one order of magnitude

NuTeV: ~5100 (ν_μ) and ~1460 (anti-ν_μ)
CHORUS: ~2000 (ν_μ) and 32 (anti-ν_μ)

Charm production in anti-ν interactions *selects* the anti-strange quark in the nucleon

Significant improvement in the knowledge of nucleon s-quark content with SHiP data in the range 0.03 < x < 0.35



Conclusions

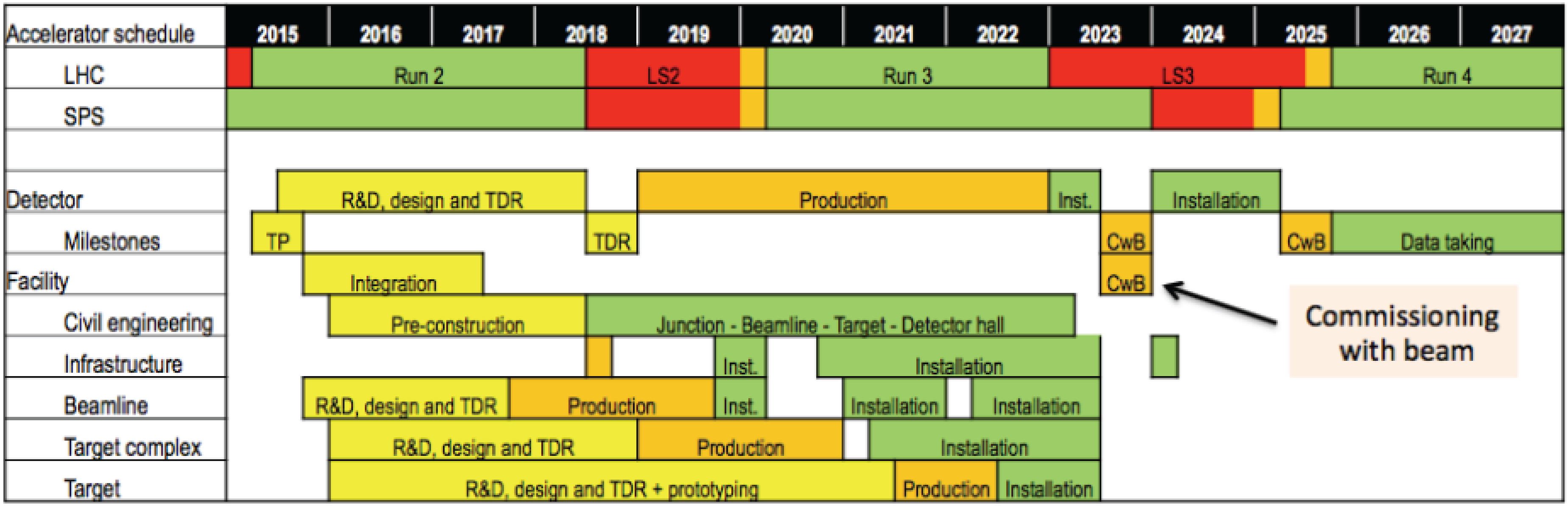
- **SHiP designed to complement searches for New Physics at LHC by probing a largely unexplored domain at the *intensity frontier*: search for new, very weakly interacting particles with masses *O*(GeV)**

- **Technical and Physics proposals submitted to the SPSC in April 2015**

- **Rich physics program including *Heavy Neutral Leptons* and ν_τ physics with unprecedented sensitivities**

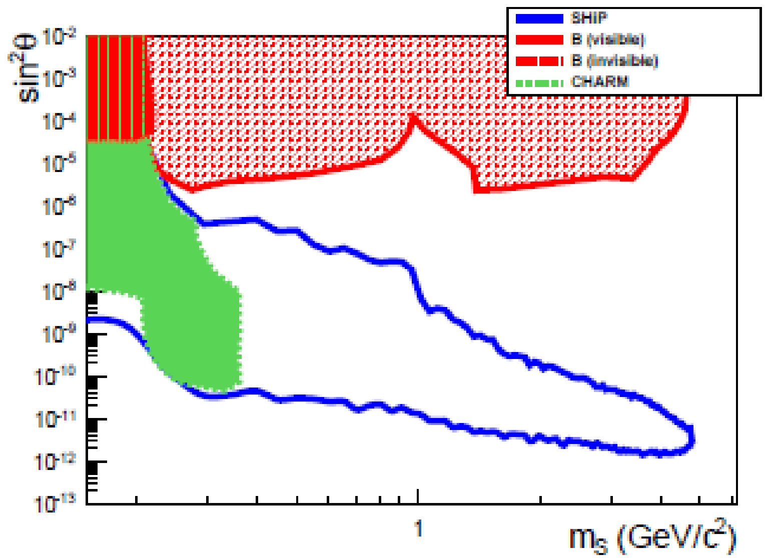
BACKUP SLIDES

Time schedule



- TDRs by end of 2018
- Detector construction (4 years) + installation (2 years)
- Commissioning in 2023 (beam line, target, muon shield)
- Data-taking in 2026

Scalar and vector portals: sensitivity



Exclusion limit at 90 % C.L.
for a light hidden scalar particle of mass m_S
coupling to the Higgs with $\sin^2\theta$ mixing parameter
and decaying in ee, $\mu\mu$, $\pi\pi$, kk

Dark photon