

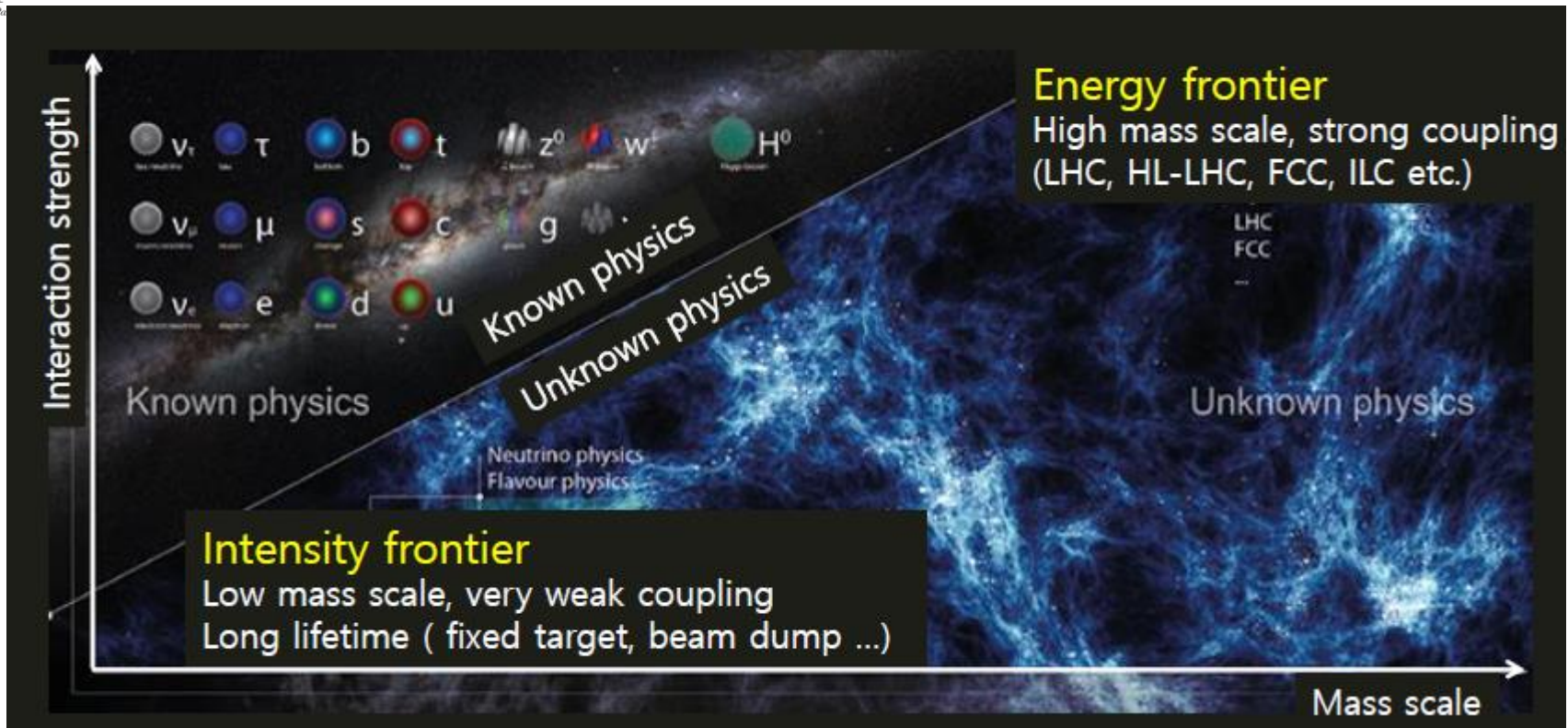


Neutrino Physics with the SHiP experiment at CERN

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University of Bari & INFN Bari

On behalf of the SHiP Collaboration

(NEW) PHYSICS LANDSCAPE



Two complementary approaches to search for New Physics

Several theoretical models postulate the existence of light particles with masses around the GeV scale, very feebly interacting with SM particles

New physics might be *hidden* at low masses → need to probe the *intensity frontier*

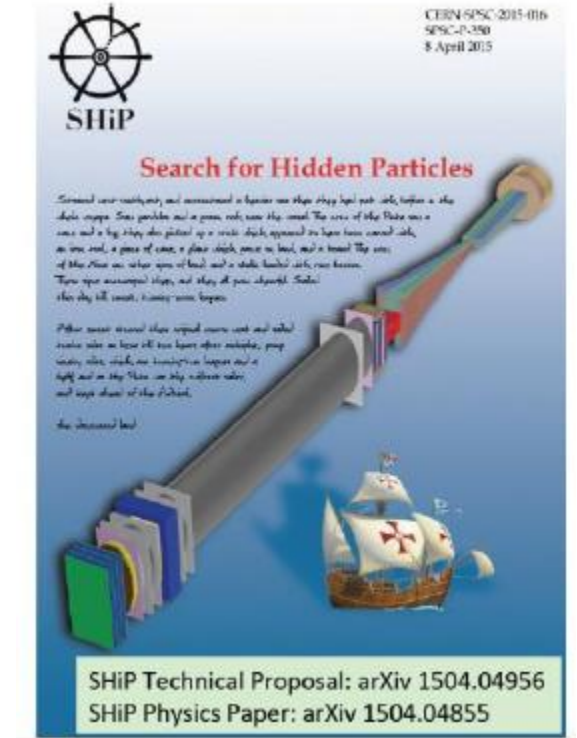
SHiP: Search for Hidden Particles

Proton-beam dump experiment proposed at CERN

Fixed target facility (BDF) in the SPS North Area

Physics goals:

- search for *hidden* particles
(Heavy Neutral Leptons, Dark Photon, Axion-like particles)
- study ν (ν_τ) physics, search for light dark matter



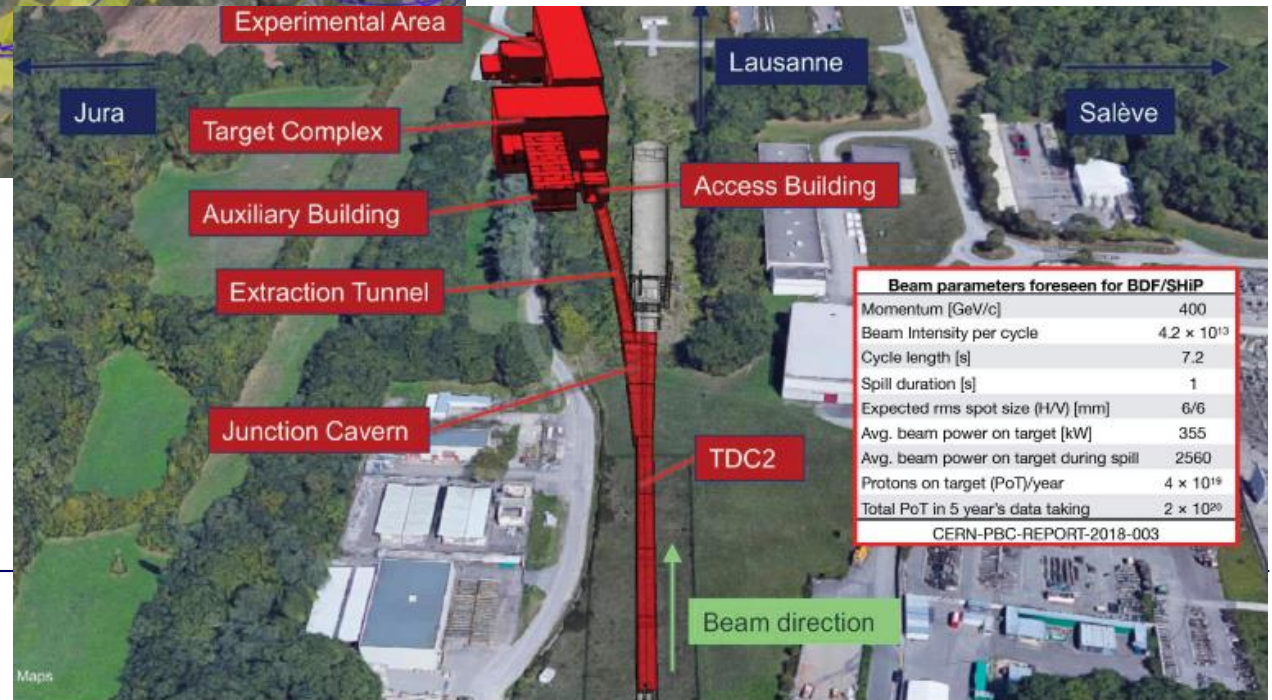
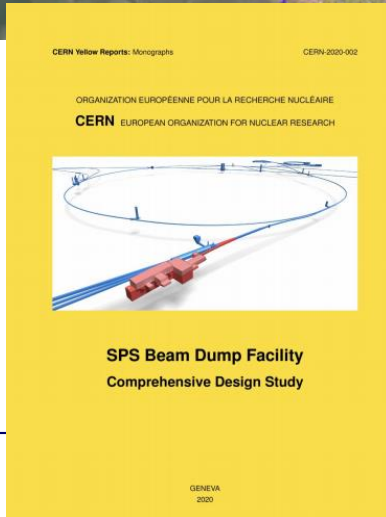
**Comprehensive Design Study Report
submitted in Dec. 2019**

BEAM DUMP FACILITY @ CERN



Well advanced design:

- Extraction and beam transfer
- Target and target complex
- Radiation protection
- Safety engineering
- Integration
- Civil engineering

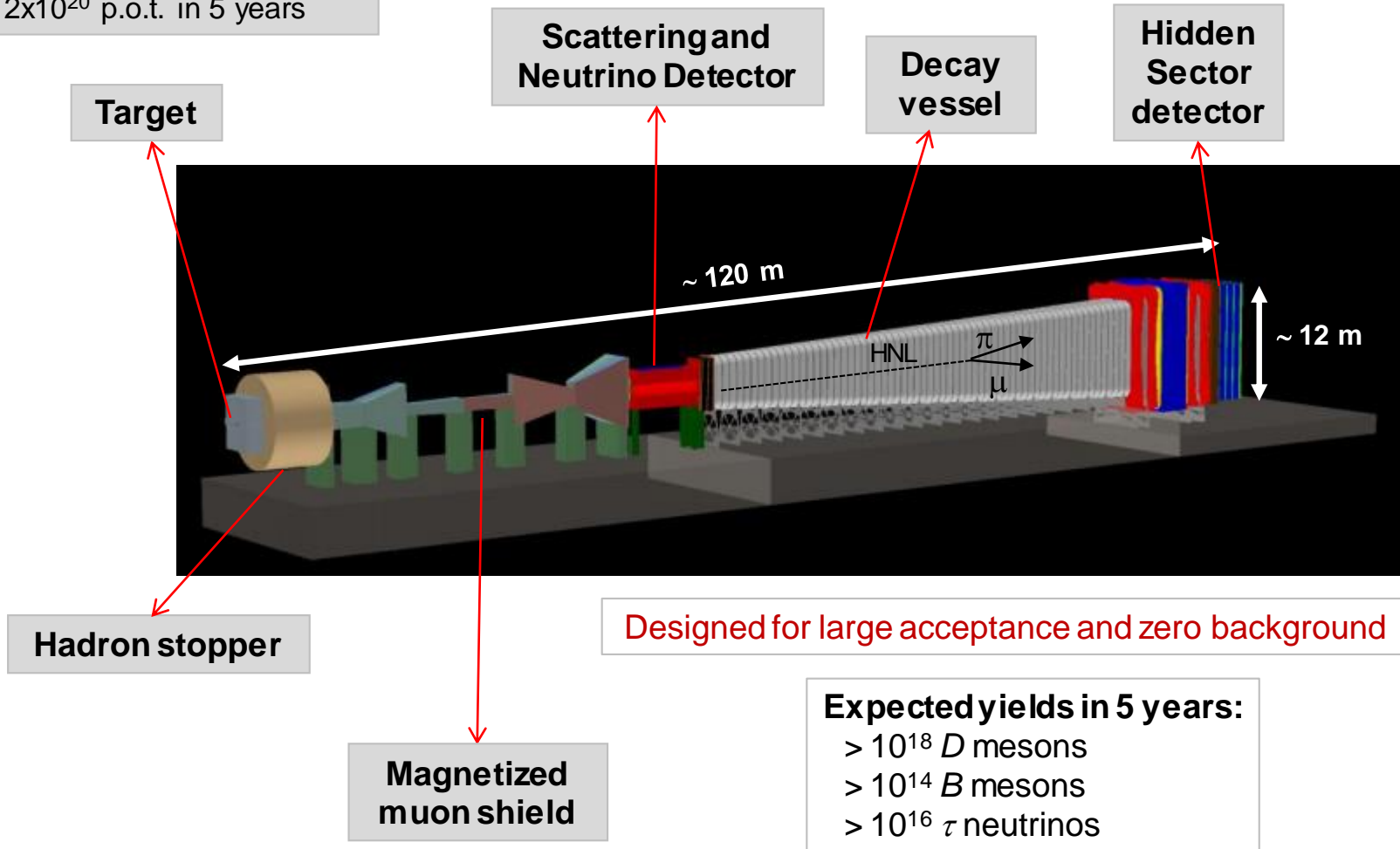


Beam parameters foreseen for BDF/SHiP	
Momentum [GeV/c]	400
Beam Intensity per cycle	4.2×10^{13}
Cycle length [s]	7.2
Spill duration [s]	1
Expected rms spot size (H/V) [mm]	6/6
Avg. beam power on target [kW]	355
Avg. beam power on target during spill	2560
Protons on target (PoT)/year	4×10^{19}
Total PoT in 5 year's data taking	2×10^{20}

CERN-PBC-REPORT-2018-003

SHiP DETECTOR LAYOUT

Beam: 400 GeV/c protons
slow extraction (1s)
 2×10^{20} p.o.t. in 5 years

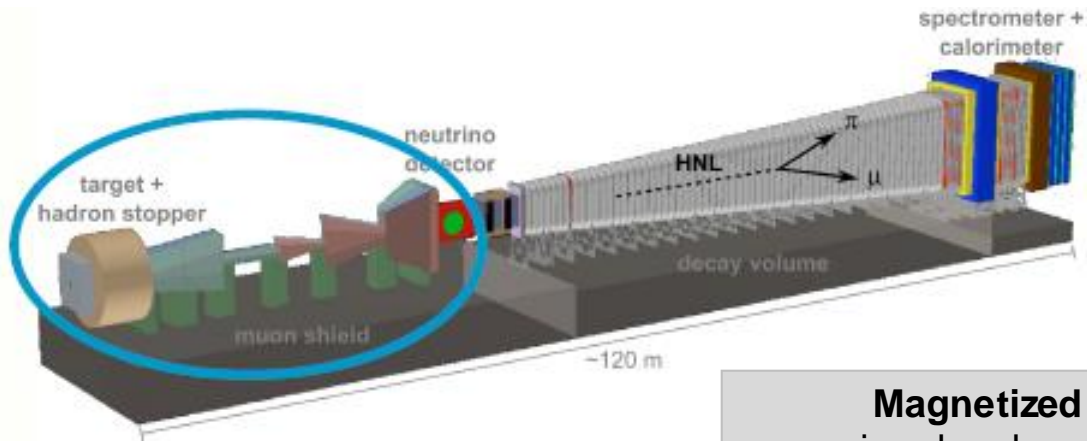


Designed for large acceptance and zero background

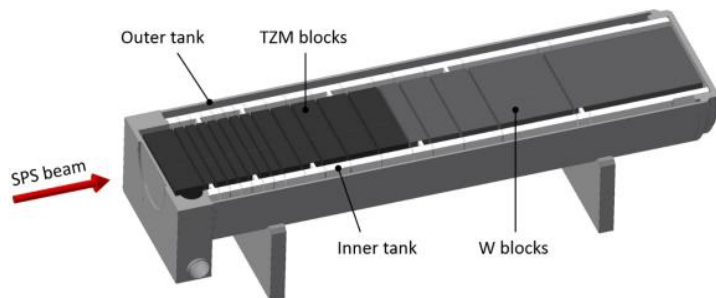
Expected yields in 5 years:

- $> 10^{18}$ D mesons
- $> 10^{14}$ B mesons
- $> 10^{16}$ τ neutrinos

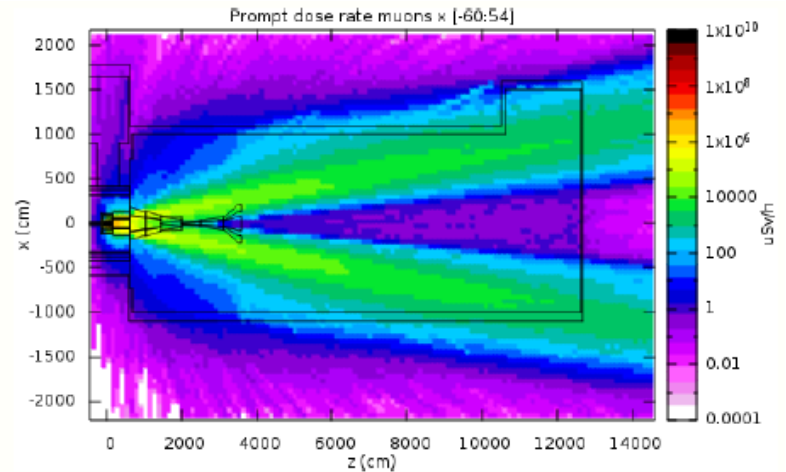
TARGET AND MUON SHIELD



Target: titanium-zirconium-molybdenum (TZM) alloy + pure tungsten, water cooled; total thickness $\sim 12\lambda_{\text{int}}$ (~ 1.5 m); optimised for heavy meson production while minimizing neutrinos from π/K decays



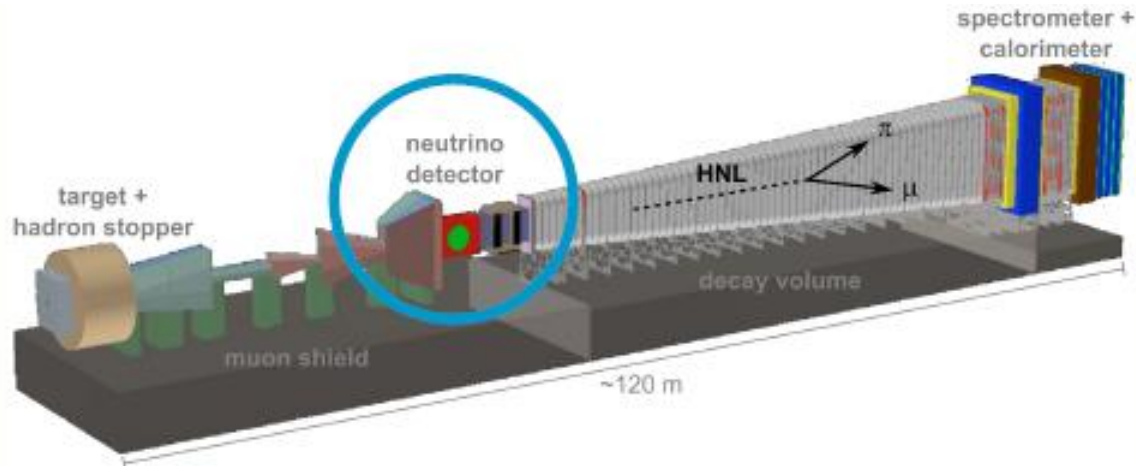
Magnetized muon shield:
passive absorber and active deflection (1.7T magnetic field)
 $\sim 10^{11}$ muons in 1 spill reduced to $< 10^5$



K. Kershaw et al, JINST 13 (2018) P10011

JINST 12 (2017) P05011

SCATTERING AND NEUTRINO DETECTOR

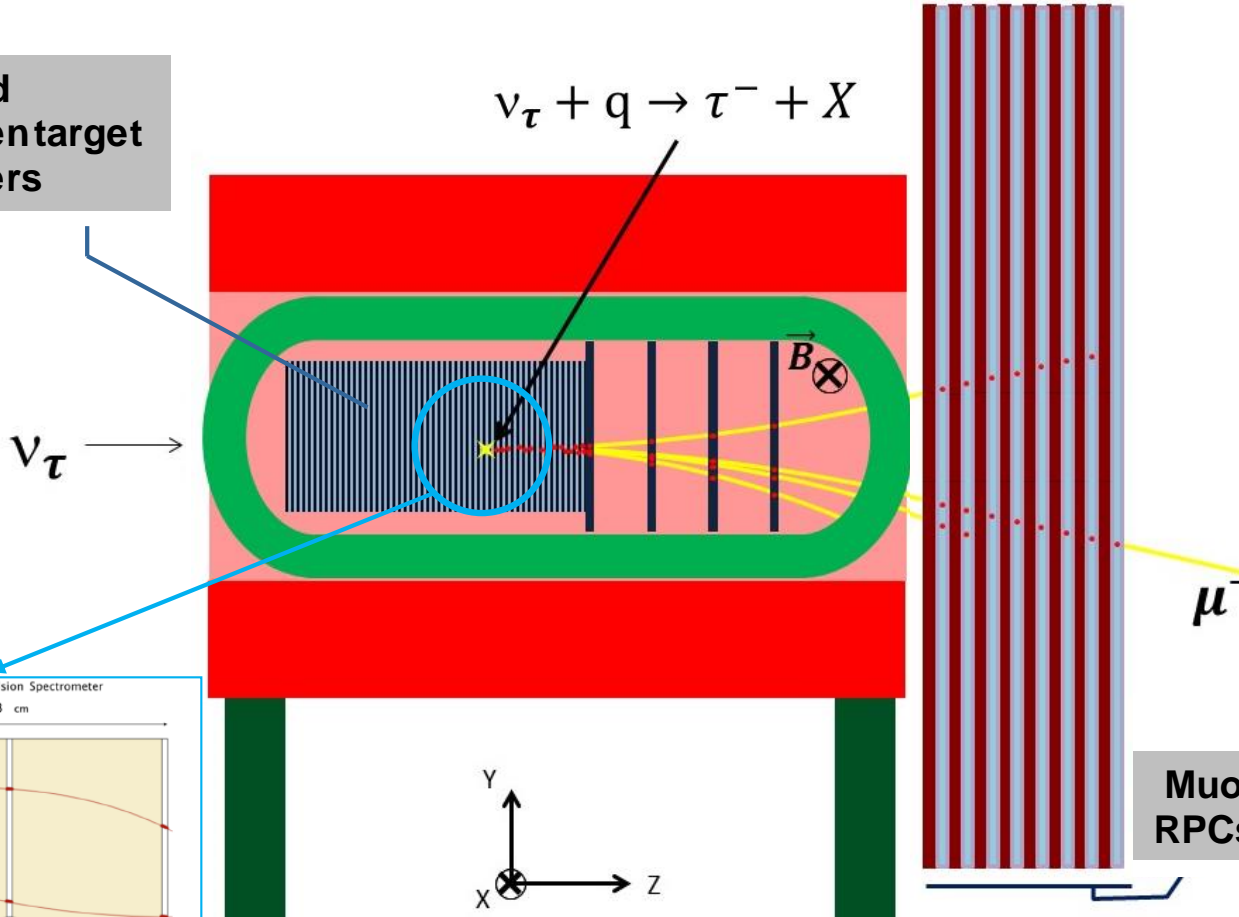


Physics goals:

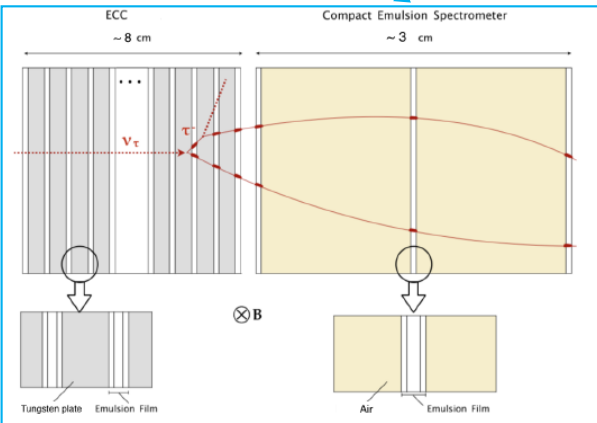
- Cross section measurements of all ν flavors
- ν_τ and of anti- ν_τ physics with high statistics
 - First detection of anti- ν_τ
 - ν_τ magnetic moment
 - F4 and F5 structure functions
- ν -induced charm production studies
- Light dark matter searches

SCATTERING AND NEUTRINO DETECTOR

Magnetized emulsion - tungsten target + SciFi trackers



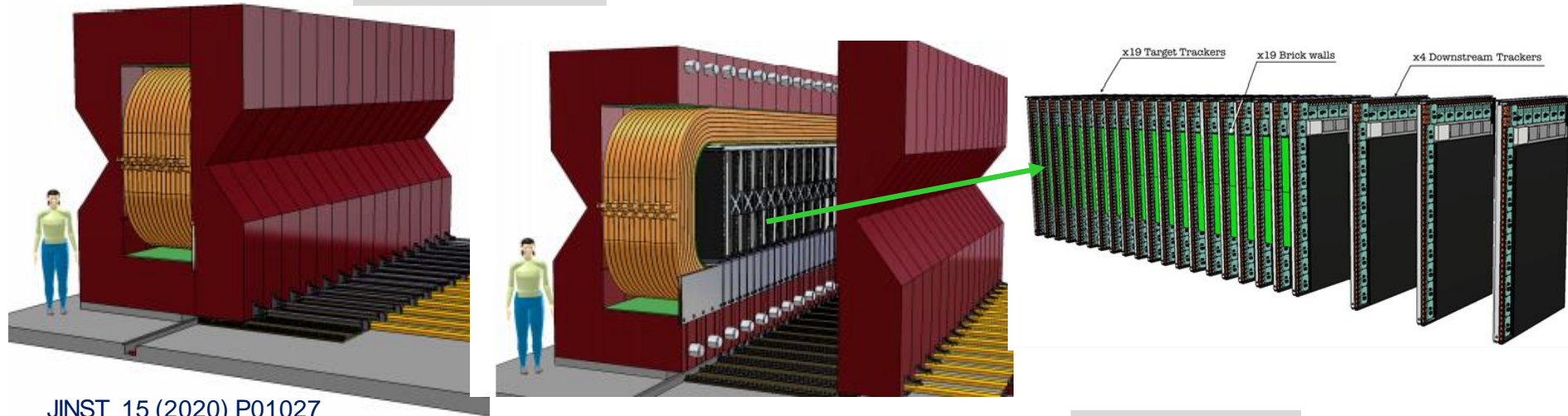
ECC bricks à la OPERA



Muon ID system:
RPCs + iron filters

SCATTERING AND NEUTRINO DETECTOR

Magnetized target



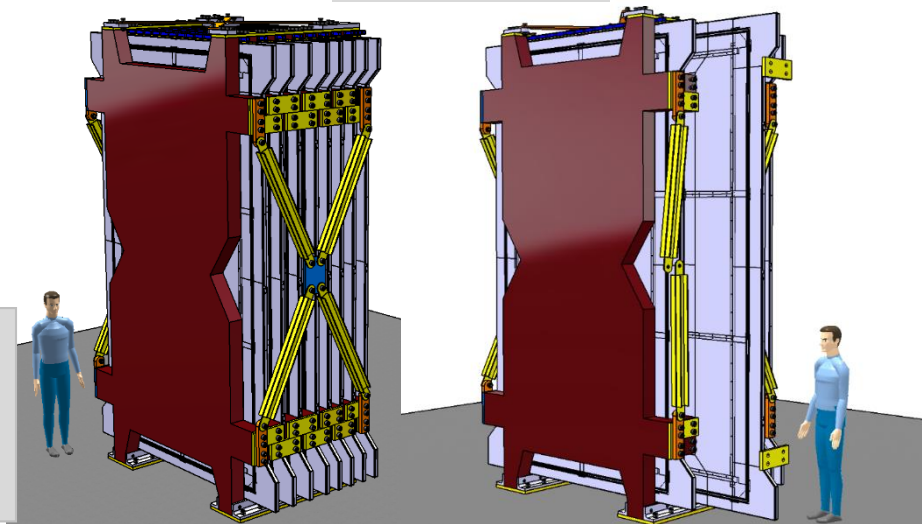
JINST 15 (2020) P01027

Magnetized volume of $\sim 10 \text{ m}^3$ ($B \cong 1.2 \text{ T}$);
 stray field outside the magnet at % level;
 internal volume temperature: 18°C ;
 opening / closing mechanism to allow for
 emulsion film replacement during run

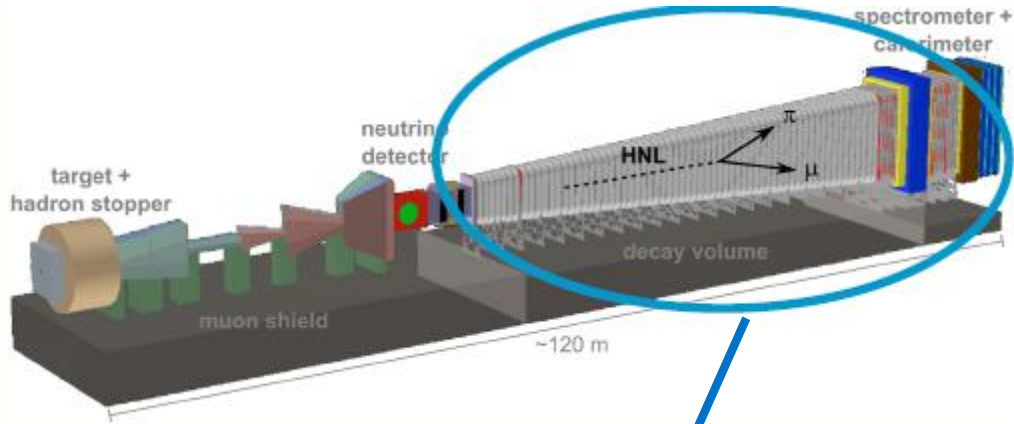
Muon ID System

RPC tracking planes hanging from top;
 upper trails for insertion / extraction

Steel plates tied through brace systems
 transmitting seismic actions to the ground



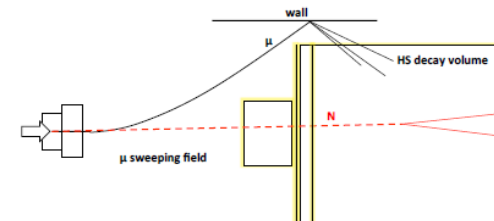
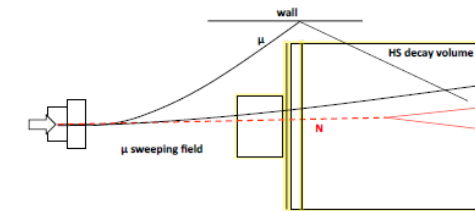
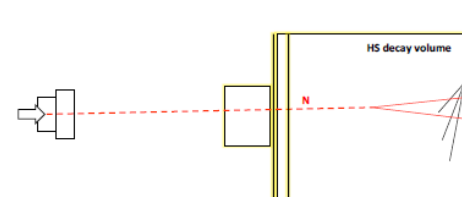
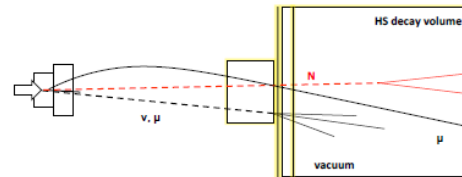
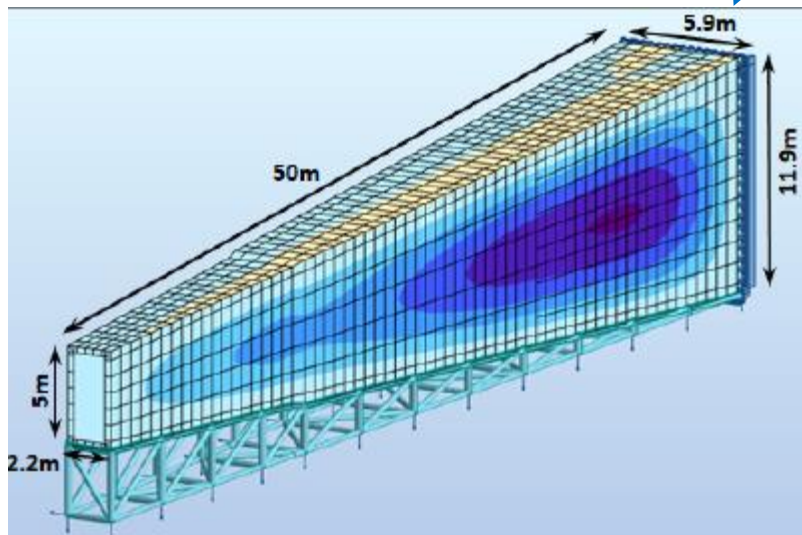
DECAY VESSEL



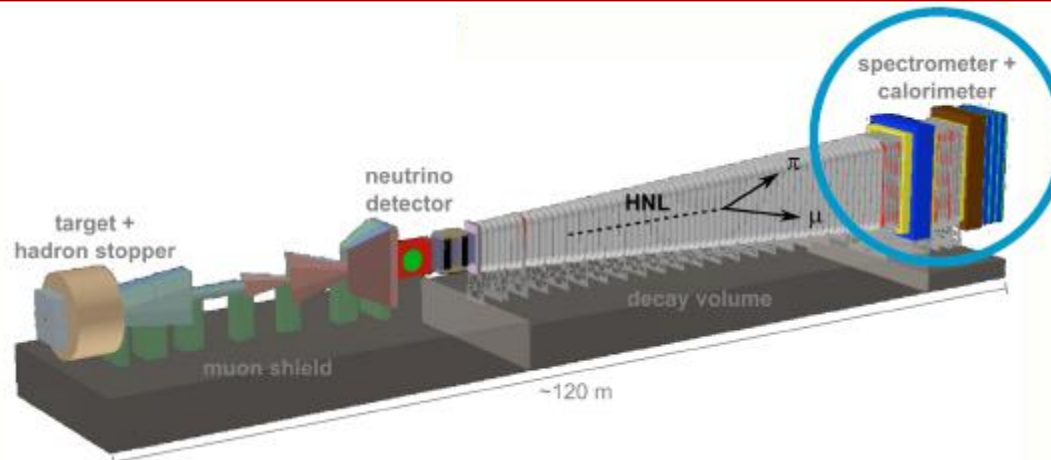
Pyramidal frustum shape, length 50 m
1 mbar, volume 2040 m³

Double-layer steel structure
with strengthening ribs

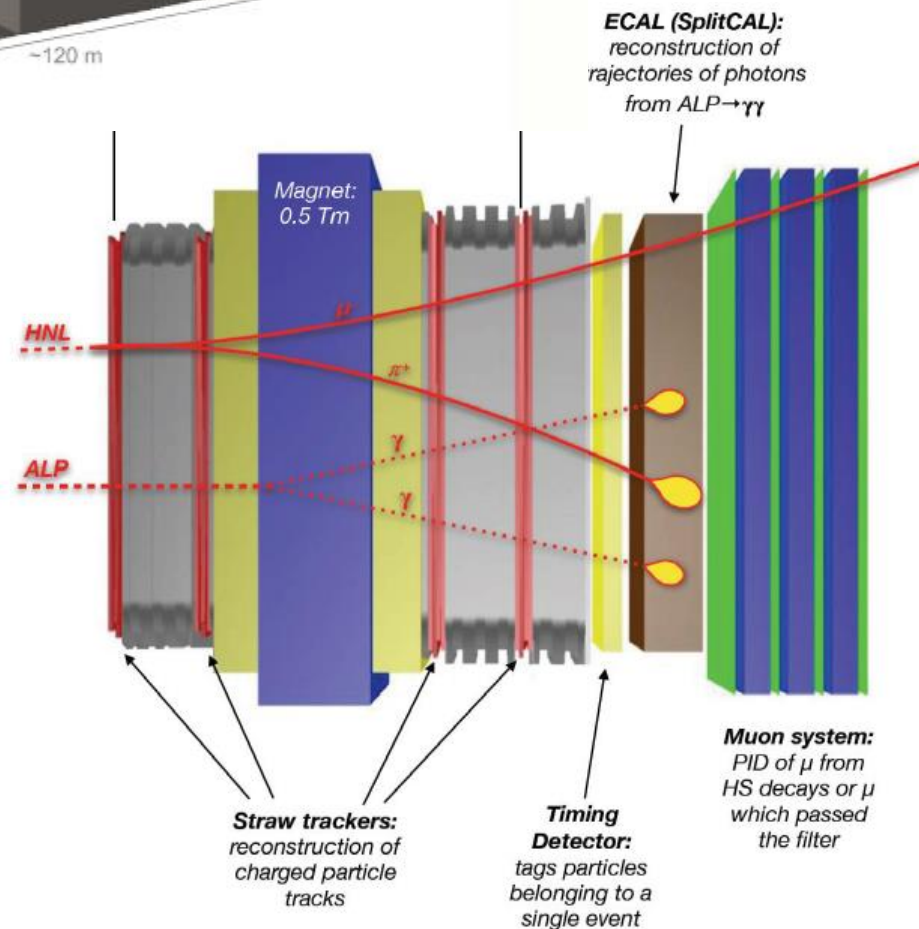
Surrounding background tagger:
480 t of liquid scintillator



HIDDEN SECTOR SPECTROMETER



- Straw tracker ($\sigma_x < 120 \mu\text{m}$ per straw) inside the evacuated decay volume
 - Timing detector ($\sigma_t < 100 \text{ps}$)
 - plastic scintillators + SiPM or MRPCs
 - ECAL (SplitCal)
 - sampling lead/scintillator + SiPM
 - high-precision layers (MicroMegas)
 - Muon system
 - four active stations equipped with scintillating tiles + SiPM + iron or concrete



PROTOTYPING

Intense prototyping activities



Small-scale replica of the SHiP target



Prototype of the SND muon ID system



Prototype of a complete cell of the SBT



Prototype of MRPC (HS timing detector)



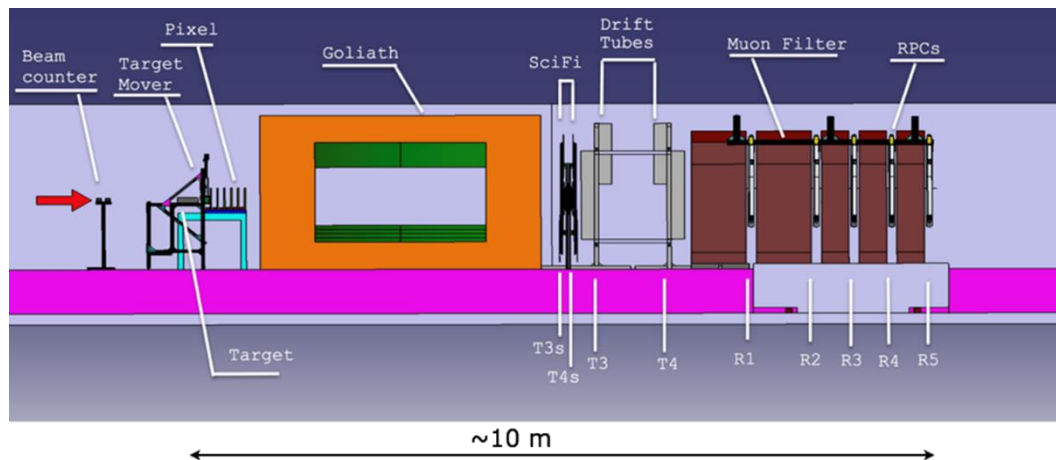
Prototype of a scintillating fibre module
of the SND target tracker



Prototype of the ECAL

Measurement of the differential charm production cross section (incl. cascade production)

- Knowledge of the associated charm production yield in 400 GeV/c proton interactions crucial for SHiP both for Hidden Sector searches and Neutrino Physics studies

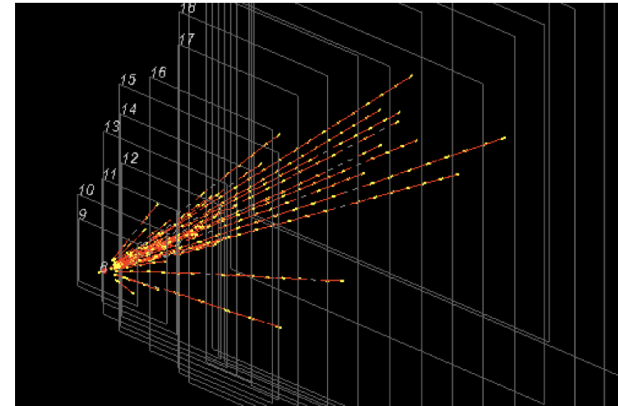
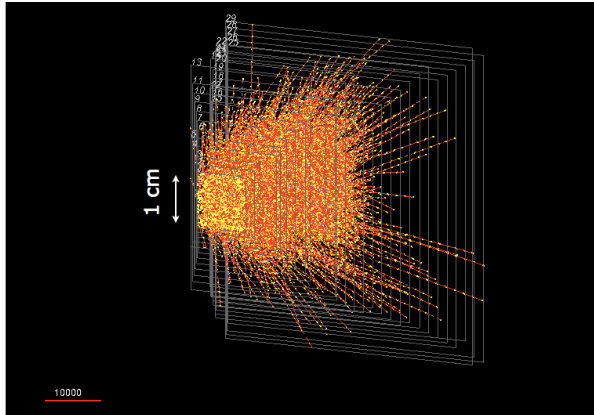


- Proton collisions in a lead target instrumented with **nuclear emulsions** as tracking detector
- Charm daughters charge and momentum measured by a **spectrometer** instrumented with silicon pixel detectors, SciFi and drift tubes
- Muon identification performed by RPCs + iron absorbers

Optimization run performed in July 2018 at SPS - H4



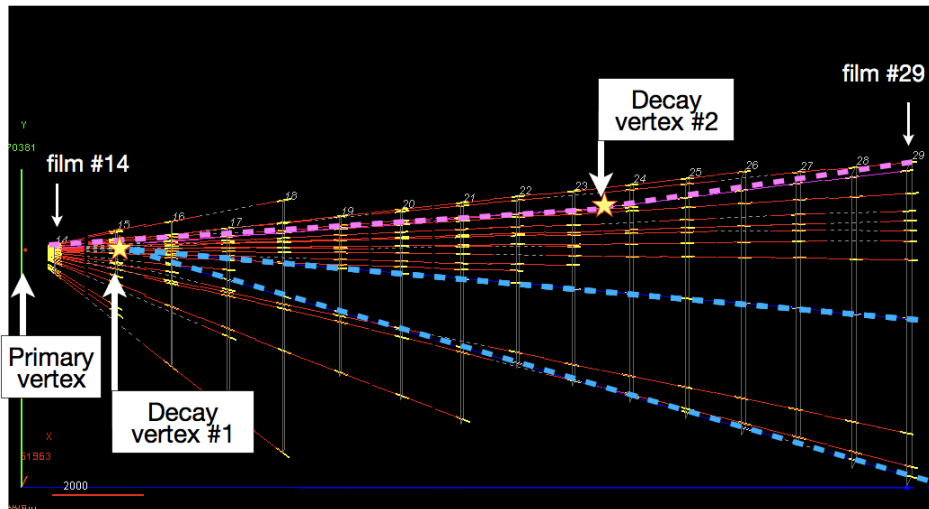
Final measurement foreseen after LS2



Reconstructed tracks in 1x1 cm², 29 emulsion films

- Total number of integrated p.o.t.: 1.5×10^6
- Density of track segments in a single emulsion film: **up to $10^5/\text{cm}^2$**
- Number of reconstructed vertices in a brick: **5×10^5**

Capability of reconstructing vertices
in a high density and high background
environment demonstrated



Primary vertex multiplicity: 31

Decay vertex #1: *V0-like* topology
(FL 2.1 mm)

Decay vertex #2: *kink-like* topology
(FL 12.7 mm, kink angle 31mrad)

NEUTRINO PHYSICS WITH THE SND

	$\langle E \rangle$ [GeV]	CC DIS interactions
N_{ν_e}	59	1.1×10^6
N_{ν_μ}	42	2.7×10^6
N_{ν_τ}	52	3.2×10^4
$N_{\bar{\nu}_e}$	46	2.6×10^5
$N_{\bar{\nu}_\mu}$	36	6.0×10^5
$N_{\bar{\nu}_\tau}$	70	2.1×10^4

Expected CC DIS interactions

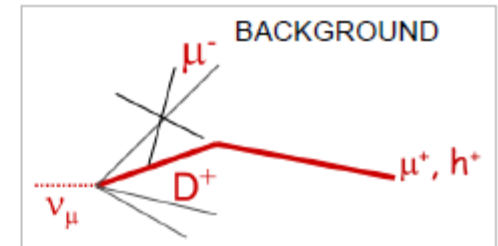
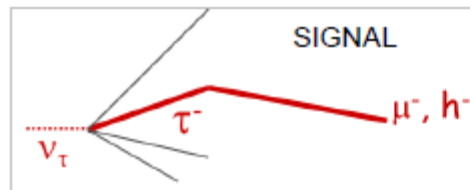
Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \rightarrow \mu$	1200	1000
$\tau \rightarrow h$	4000	3000
$\tau \rightarrow 3h$	1000	700
Total	6200	4700

Expected number of ν_τ and $\bar{\nu}_\tau$
for 2×10^{20} protons on target.

So far, only 9 ν_τ events (DONUT experiment),
no separation ν_τ - anti ν_τ ,
+ 10 events from ν_μ oscillation
measured by the OPERA experiment

Similar experimental technique in SHiP

Statistics $\times 10^3$ w.r.t. previous exps

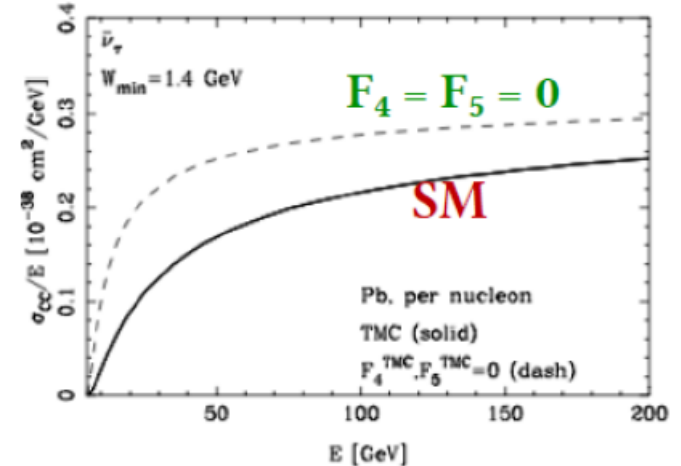


NEUTRINO PHYSICS WITH THE SND

Unique capability of measuring structure functions
F4 and F5, not accessible with ν_μ/ν_e

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

Anti- ν_τ DIS cross-section



	$\langle E \rangle$ [GeV]	CC DIS w. charm prod
N_{ν_μ}	55	1.3×10^5
N_{ν_e}	66	6.0×10^4
$N_{\bar{\nu}_\mu}$	49	2.5×10^4
$N_{\bar{\nu}_e}$	57	1.3×10^4
Total		2.3×10^5

Expected CC DIS neutrino interactions
with charm production
for 2×10^{20} protons on target.

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

$\bar{\nu}$ -induced charm production sensitive to s-quark
content of the nucleon \Rightarrow

significant reduction of the uncertainty on s-quark
distribution with SHiP data in the range
 $0.03 < x < 0.35$ for $s^+(x) = s(x) + \bar{s}(x)$

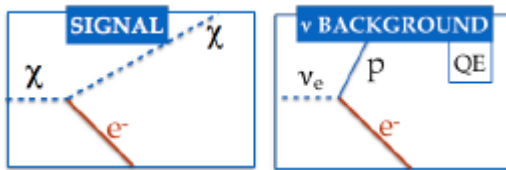
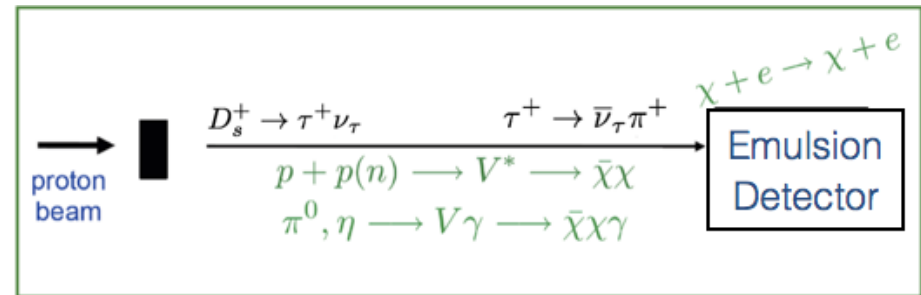
LIGHT DARK MATTER SEARCH WITH THE SND

LDM PRODUCTION

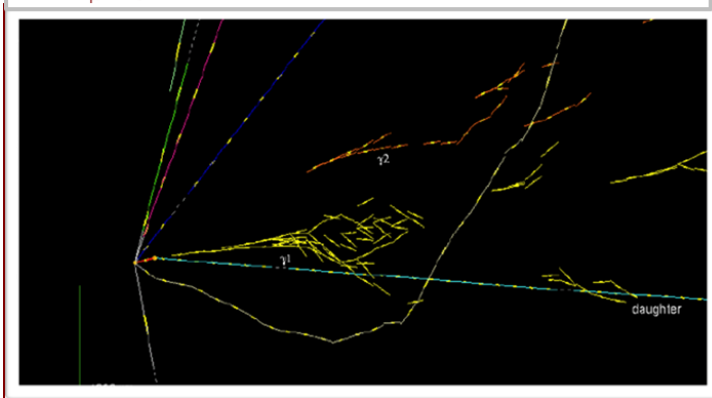
- Generated in the beam-dump, e.g. via light dark photon mediators (V)

LDM DETECTION

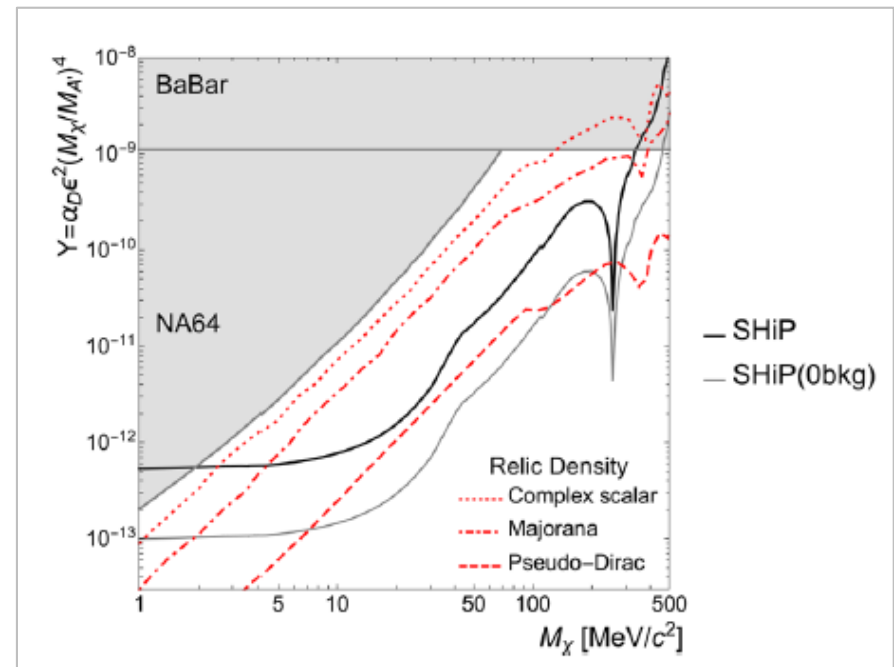
- LDM elastic scattering on atomic electrons of the brick target



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



ECC brick as a sampling calorimeter ($10 X_0$) with sub-micrometric accuracy



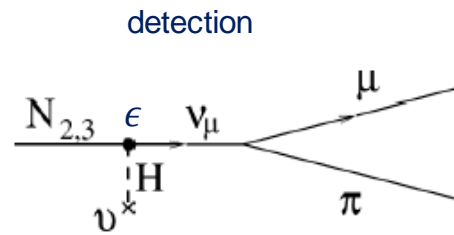
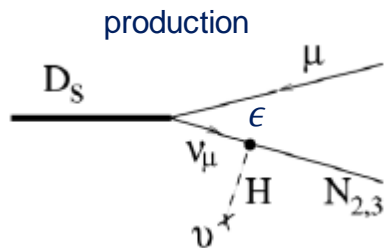
SEARCH FOR HEAVY NEUTRAL LEPTONS

	2.4 MeV $\frac{2}{3}$ Left u up Right	1.27 GeV $\frac{2}{3}$ Left c charm Right	171.2 GeV $\frac{2}{3}$ Left t top Right
Quarks	4.8 MeV $-\frac{1}{3}$ Left d down Right	104 MeV $-\frac{1}{3}$ Left s strange Right	4.2 GeV $-\frac{1}{3}$ Left b bottom Right
	<0.001 eV 0 Left ν_e electron neutrino Right	\sim keV \sim 0.01 eV Left N_1 sterile neutrino Right	\sim GeV \sim 0.04 eV Left N_2 sterile neutrino Right
			\sim GeV Left N_3 sterile neutrino Right
Leptons	0.511 MeV -1 Left e electron Right	105.7 MeV -1 Left μ muon Right	1.777 GeV -1 Left τ tau Right

T.Asaka, M.Shaposhnikov PLB 620 (2005) 17

ν Minimal Standard Model (ν MSM): Extension of the SM by 3 right-handed Heavy Neutral Leptons (HNLs)

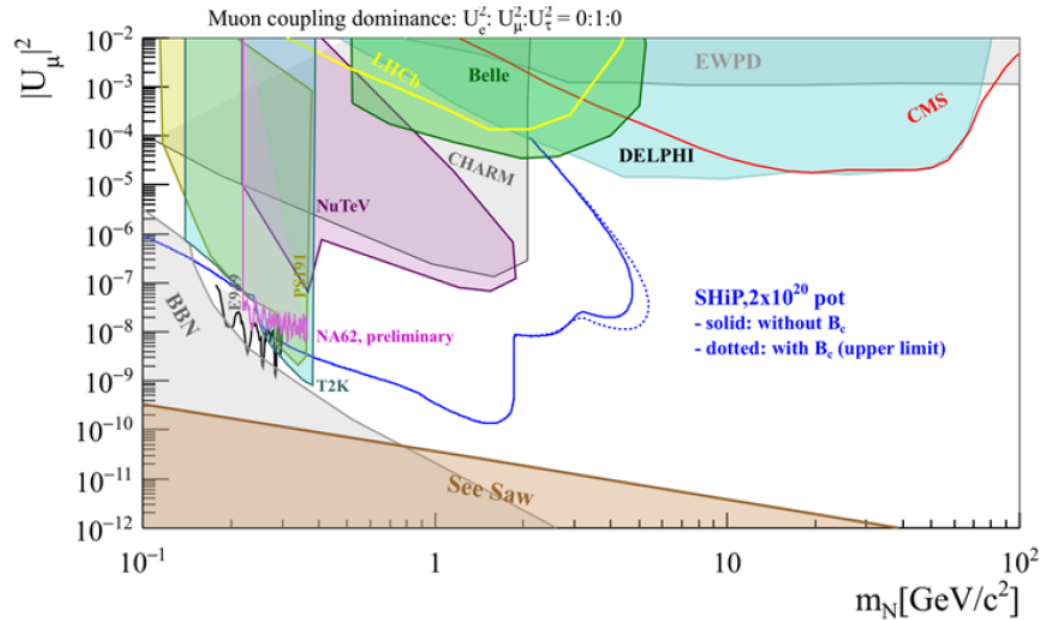
- *Light* N_1 :
Mass $O(\text{keV})$
Dark Matter candidate
- *Heavy* $N_{2,3}$:
Mass $O(\text{GeV})$
Could explain ν masses (through see-saw)
and baryon asymmetry



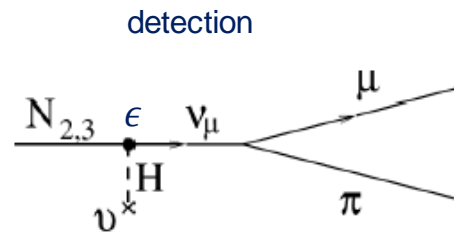
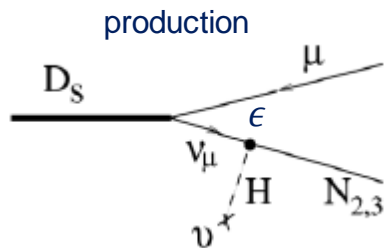
probability $\propto \epsilon^4$
 \Rightarrow Requires high intensity

SEARCH FOR HEAVY NEUTRAL LEPTONS

	2.4 MeV Left $\frac{2}{3}$ u Right up	1.27 GeV Left $\frac{2}{3}$ c Right charm	171.2 GeV Left $\frac{2}{3}$ t Right top
	4.8 MeV Left $-\frac{1}{3}$ d Right down	104 MeV Left $-\frac{1}{3}$ s Right strange	4.2 GeV Left $-\frac{1}{3}$ b Right bottom
Quarks	<0.0001 eV Left 0 ν_e Right electron neutrino	\sim keV Left 0 N_1 Right sterile neutrino	\sim 0.01 eV Left 0 ν_μ Right muon neutrino
	\sim keV Left 0 N_1 Right sterile neutrino	\sim GeV Left 0 N_2 Right sterile neutrino	\sim 0.04 eV Left 0 ν_τ Right tau neutrino
	\sim GeV Left 0 N_3 Right sterile neutrino		
Leptons	0.511 MeV Left -1 e Right electron	105.7 MeV Left -1 μ Right muon	1.777 GeV Left -1 τ Right tau



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probability $\propto \epsilon^4$
 \Rightarrow Requires high intensity

CONCLUSIONS

SHiP: *Proton-beam dump* experiment proposed at CERN to probe the intensity frontier: search for new, very fleebly interacting particles with masses $O(\text{GeV})$

Rich physics program including Heavy Neutral Leptons, Light Dark Matter and ν_τ physics with unprecedented sensitivities

Beam Dump Facility and SHiP Comprehensive Design Studies finalized in Dec. 2019, next steps towards TDR to be defined