XIX International Workshop on Neutrino Telescopes

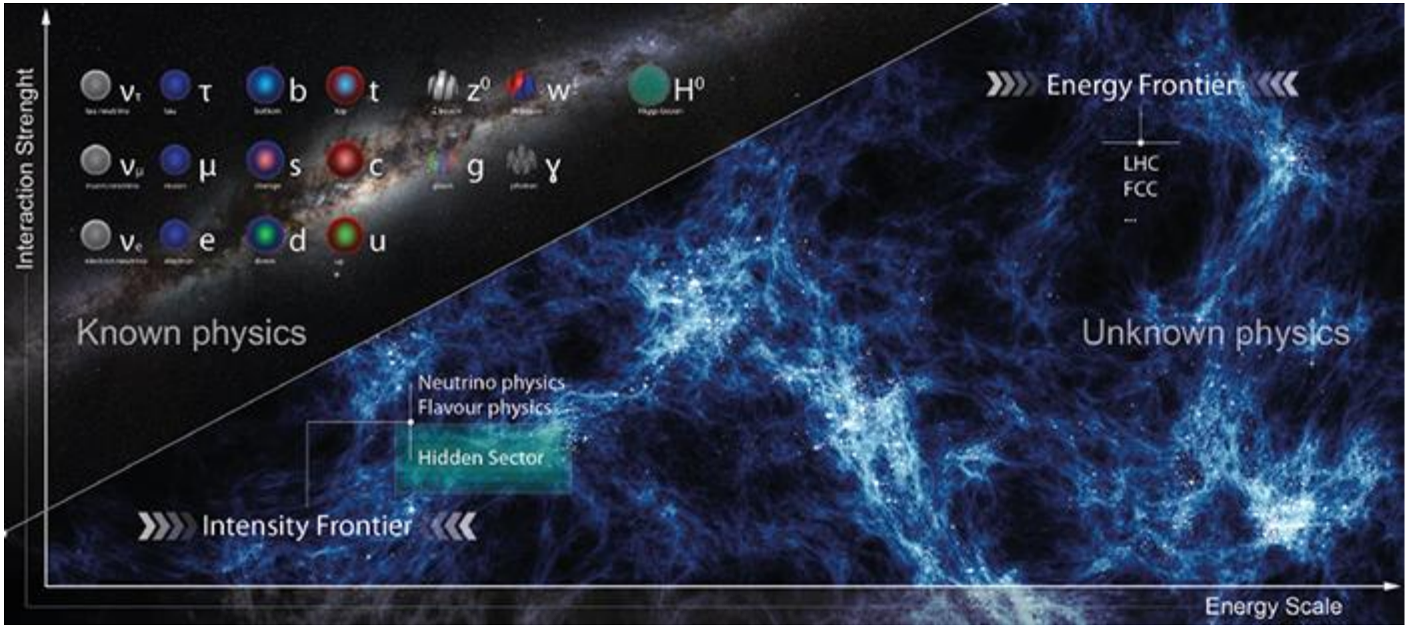
18-26 February 2021
Online

Neutrino physics with the SHiP experiment

Alessandra Pastore (INFN Bari)
on behalf of the SHiP Collaboration

Beyond Standard Model …

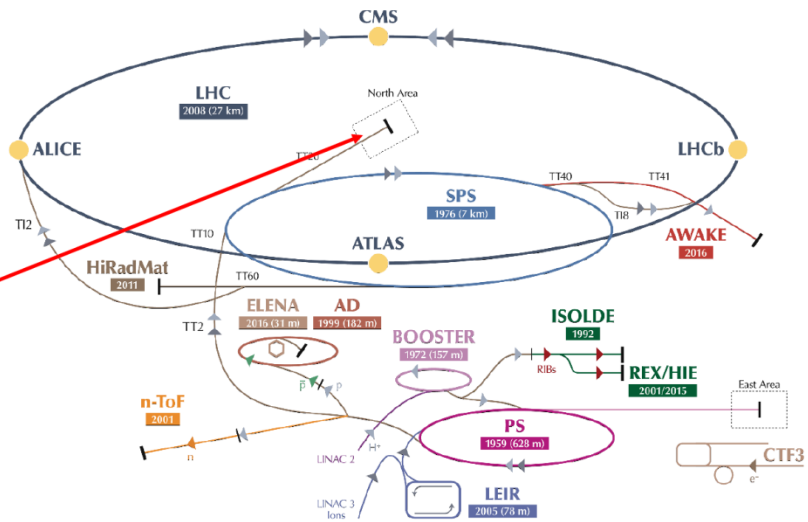
Experimental hints of BSM physics
- ν masses and oscillations
- Baryon Asymmetry of the Universe
- Dark Matter



New Physics can be hidden due to
very heavy masses → *Energy Frontier, high energy collisions*
or
very weak couplings → *Intensity Frontier, beam dump*

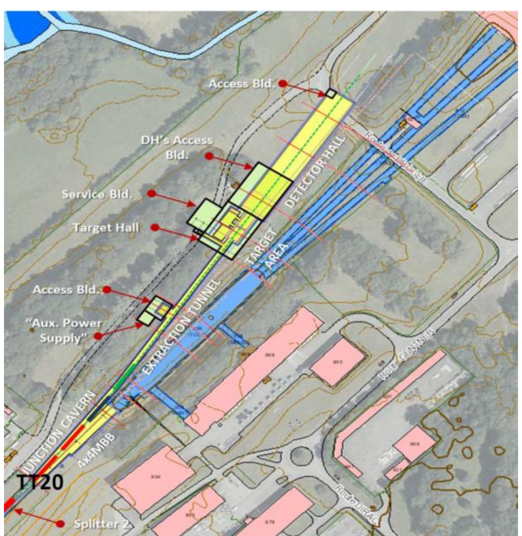
and beyond Colliders

Search for Hidden Particles (SHiP) @
CERN-based Beam Dump Facility (BDF)



Proposed siting of the SPS Beam Dump Facility

- *Slow extraction (1 sec)*
- *High intensity proton beam*
  $4*10^{13}$ p/spill , $4*10^{19}$ pot/year
  $2*10^{20}$ pot/5 years
- *O(400 GeV/c) optimal beam momentum*



existing tunnels
existing buildings
new installations

https://doi.org/10.23731/CYRM-2020-002


CERN Yellow Reports: Monographs CERN-2020-002

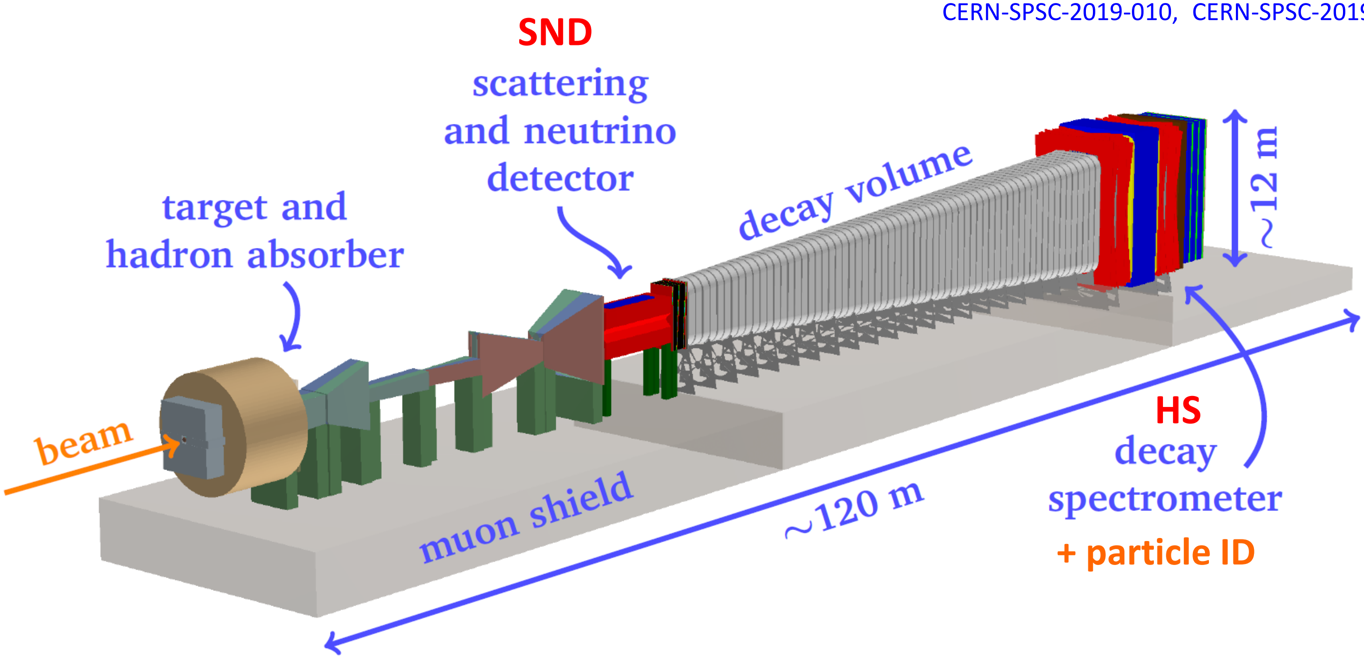
ORGANIZATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SPS Beam Dump Facility
Comprehensive Design Study

GENEVA
2020

The SHiP experiment

ins-det: 1504.04956, JINST 14(2019)03 P03025,
CERN-SPSC-2019-010, CERN-SPSC-2019-049 / SPSC-SR-263



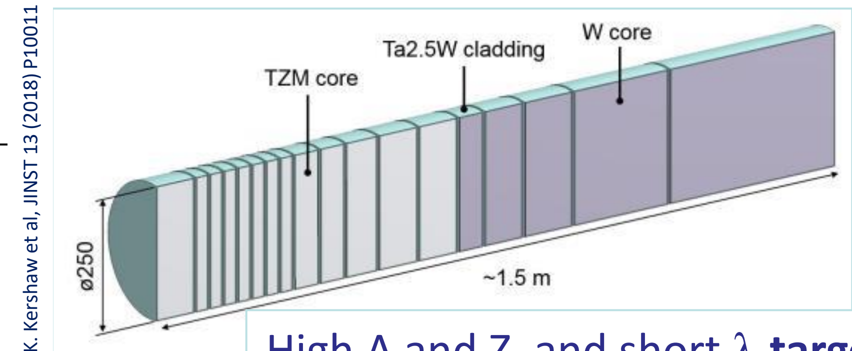
Dual detector system

- Scattering and Neutrino Detector (SND)
  → neutrino physics and Light Dark Matter searches

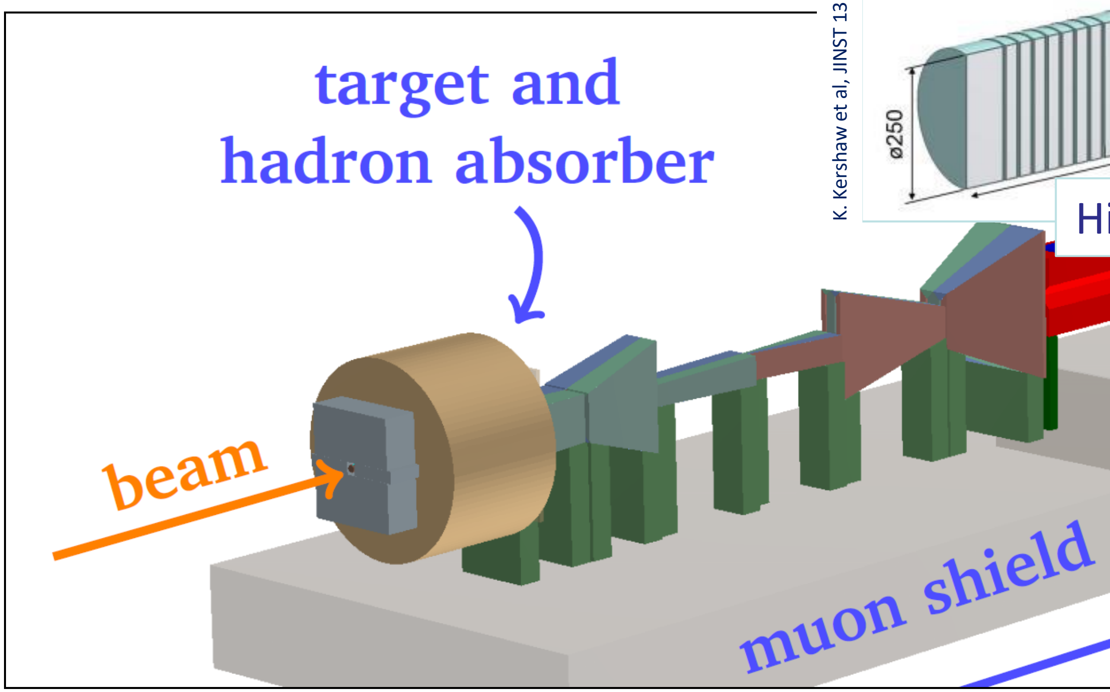
- Hidden Sector detector (HS)
  → search for new, weakly coupled, long lived particles from the Hidden Sector

The SHiP experiment : general requirements

driven by Hidden Sector phenomenology



High A and Z, and short λ **target**

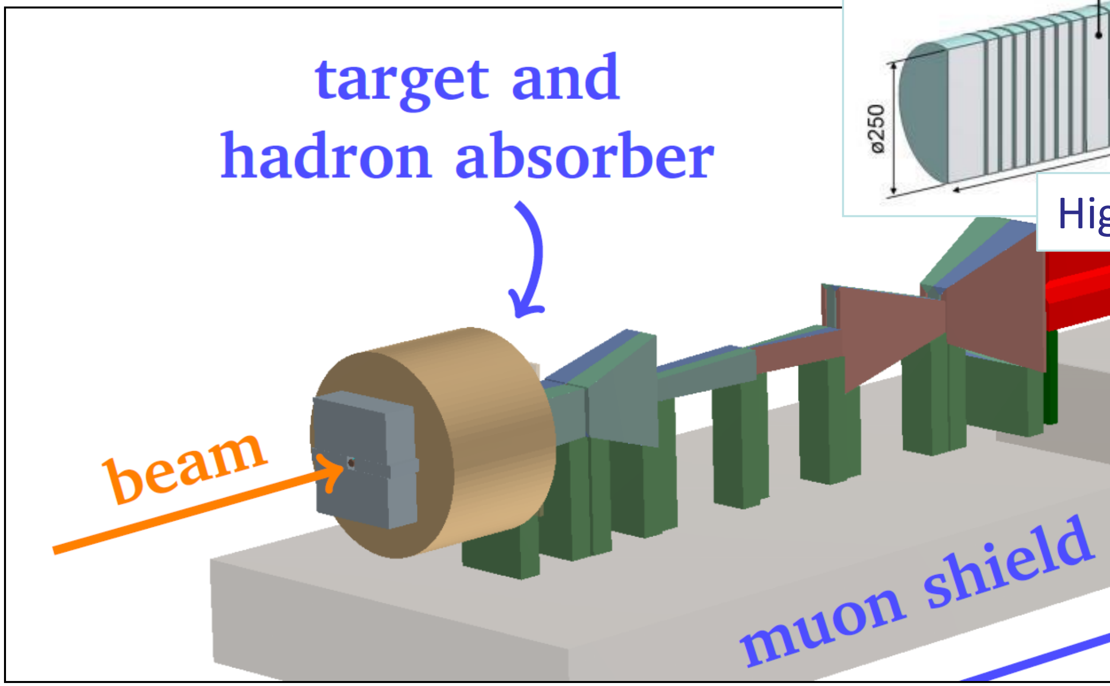


5 years of BDF@SPS (2*10^{20}pot):

- 10^{18} charm mesons
- 10^{14} beauty mesons
- 10^{16} tau leptons

The SHiP experiment : general requirements

driven by Hidden Sector phenomenology



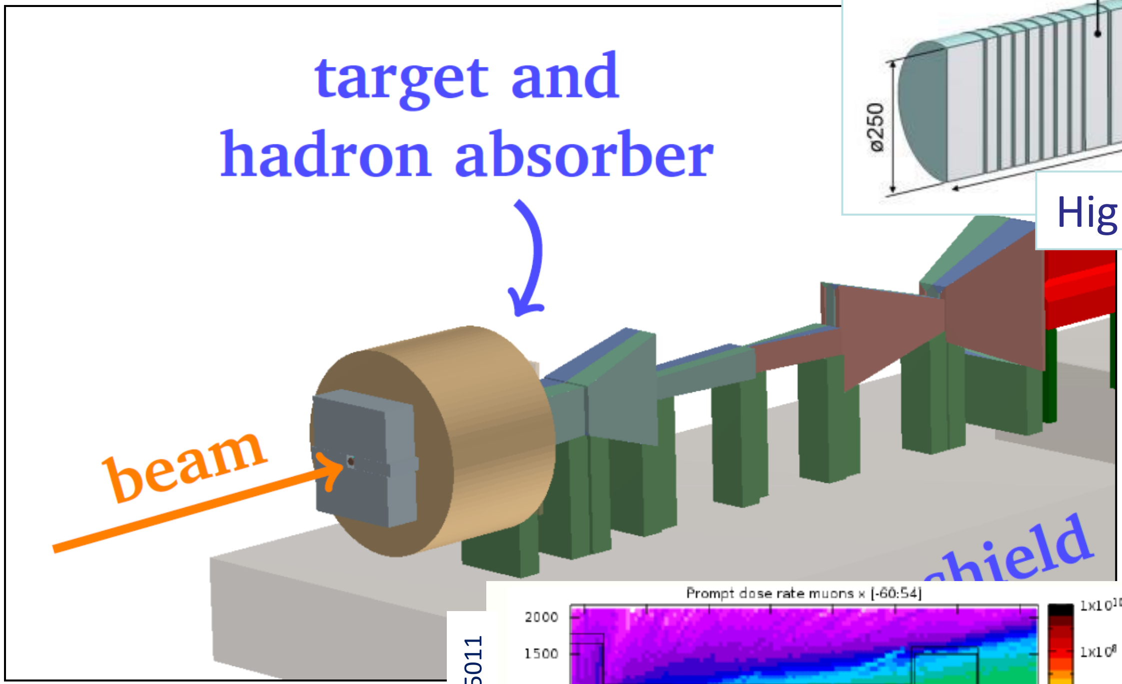
High A and Z, and short λ target

Hadron absorber

Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay

The SHiP experiment : general requirements

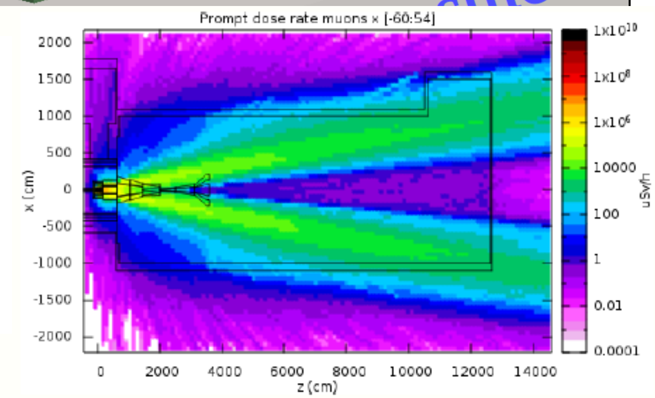
driven by Hidden Sector phenomenology



High A and Z, and short λ target

Hadron absorber

Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay



JINST 12 (2017) P05011

magnetised muon shield

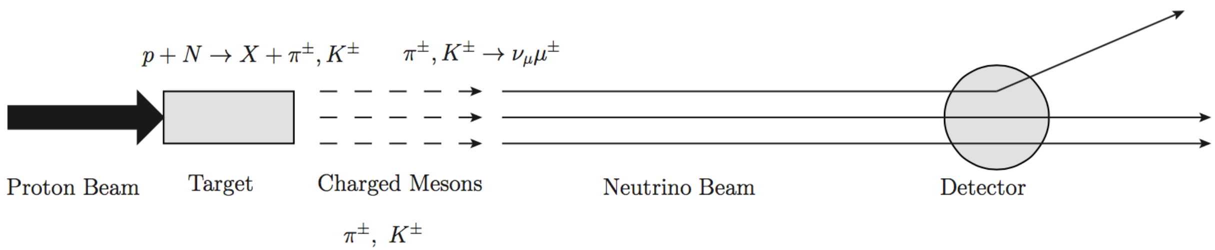
$\sim 10^{11}$ μ in 1 spill reduced to $< 10^5$

Muon spectrum validated with dedicated experiment in 2018

The Scattering and Neutrino Detector

High (anti-)ν flux expected@BDF

→ Unique opportunity to perform studies on ν_τ, ν_μ, ν_e (+ cc) @SHiP SND



ν Physics potential at SND:

- first ever observation of anti- ν_τ

- ν_τ and anti- ν_τ physics with high statistics

- ν induced charm production studies

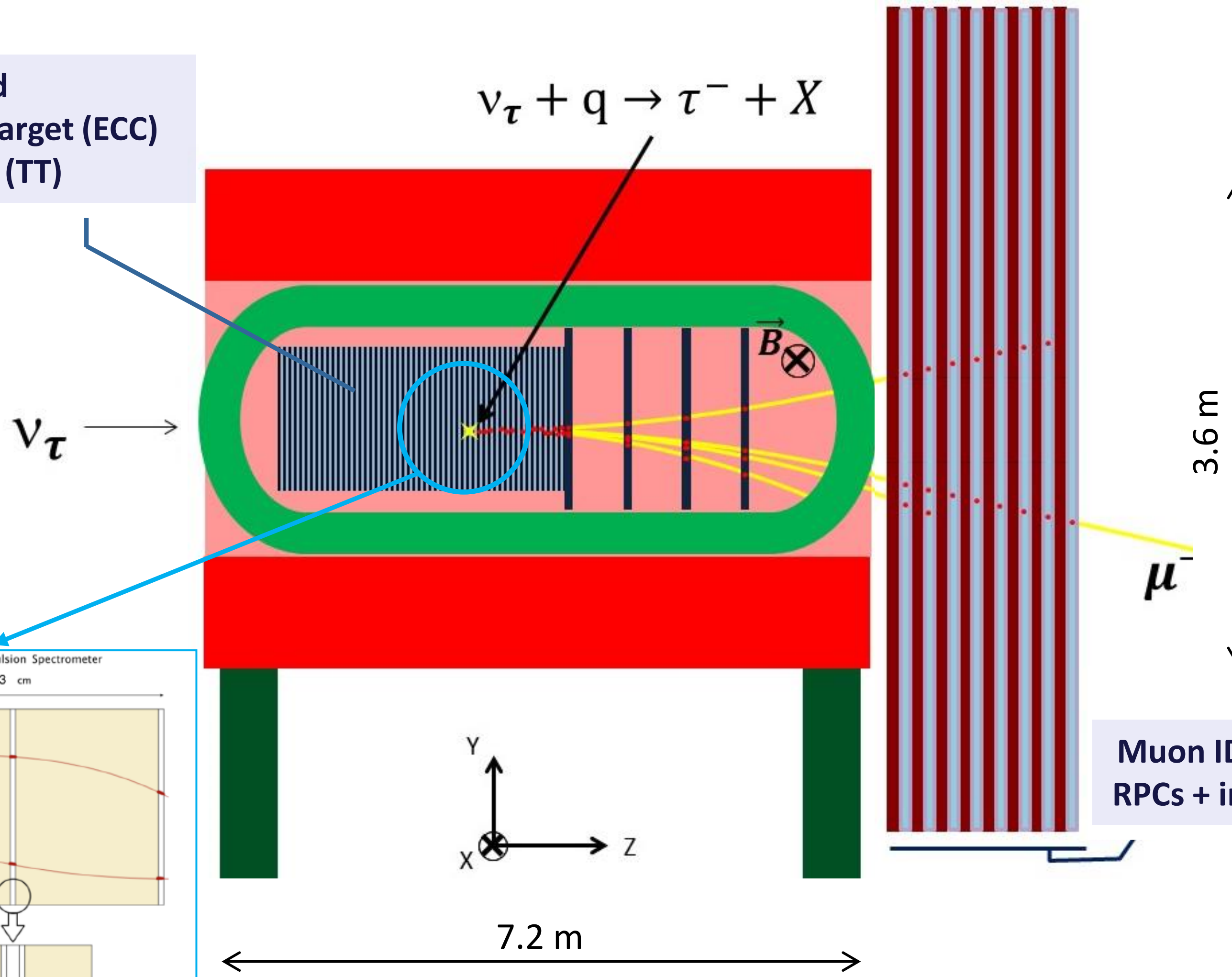
- ν_f cross sections measurements

# of ν CC DIS int. in SND target in $2\text{x}10^{20}$ pot

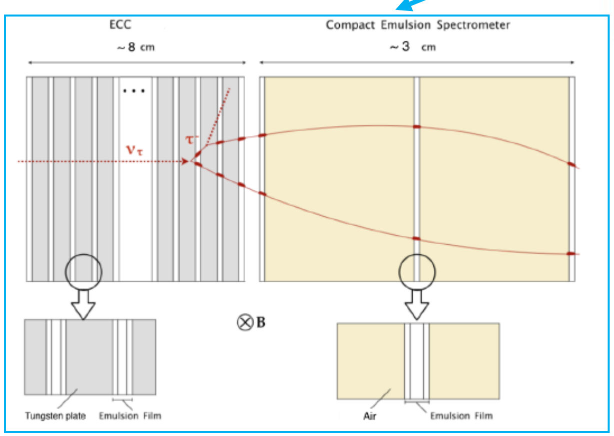
	$\bar{E}$ [GeV]	CC DIS int.
ν_e	59	1.1×10^6
ν_μ	42	2.7×10^6
ν_τ	52	3.2×10^4
$\bar{\nu}_e$	46	2.6×10^5
$\bar{\nu}_\mu$	36	6.0×10^5
$\bar{\nu}_\tau$	70	2.1×10^4

The Scattering and Neutrino Detector

Magnetized emulsion - tungsten target (ECC) + SciFi trackers (TT)



ECC bricks *à la OPERA*

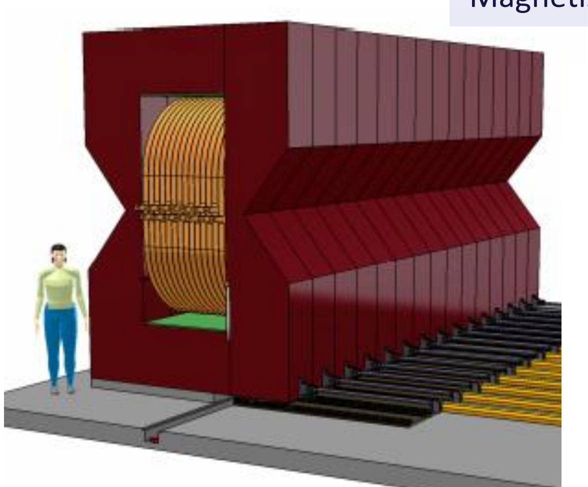


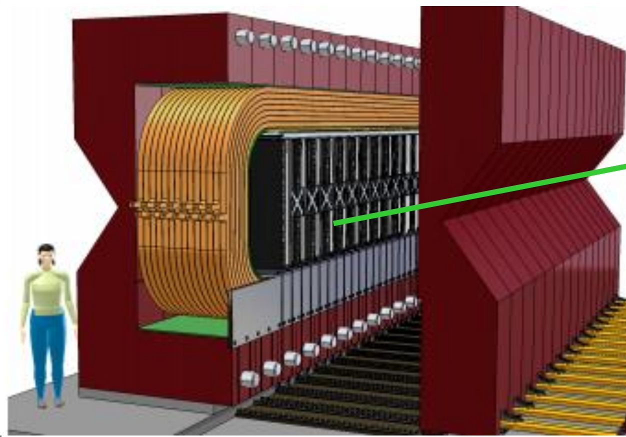
Muon ID system: RPCs + iron filters

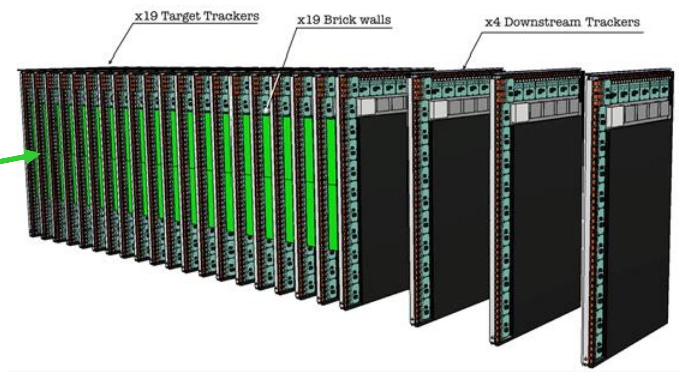
SHiP Progress Report
CERN-SPSC-2019-010 / SPSC-SR-248

The Scattering and Neutrino Detector

Magnetized target





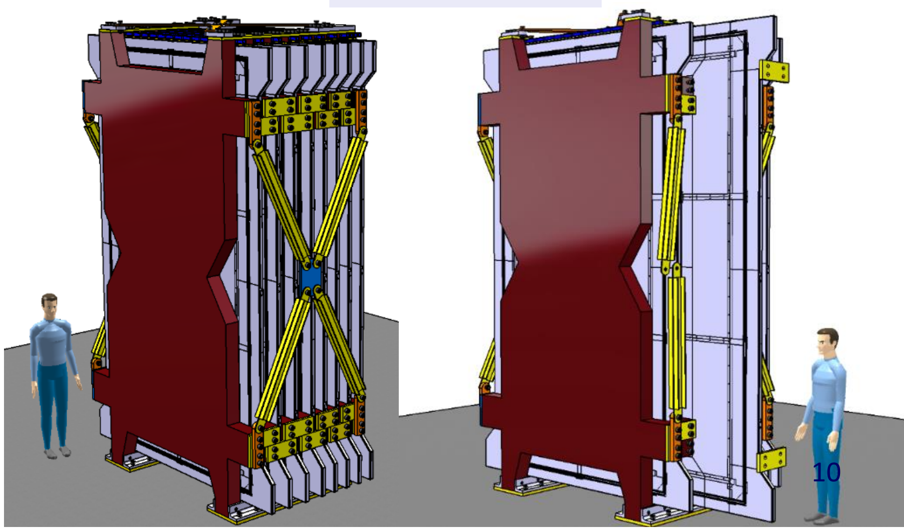


JINST 15 (2020) P01027

Magnetized volume of ~10 m^3 (B ≅ 1.2 T);

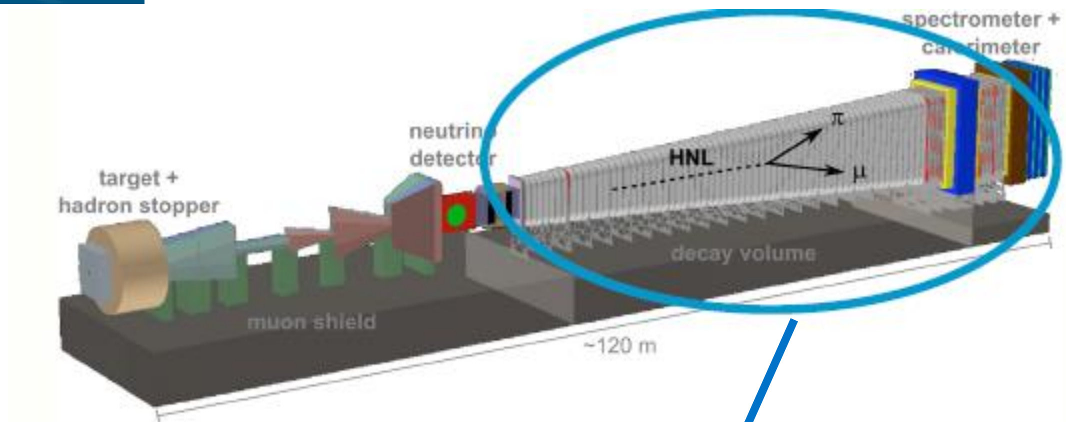
opening / closing mechanism to allow for emulsion film replacement during run

Muon ID System



RPC tracking planes hanging from top;
upper trails for insertion / extraction
sensitive area ~2×4 m^2
geometrical acceptance ~60%

The Hidden Sector Detector

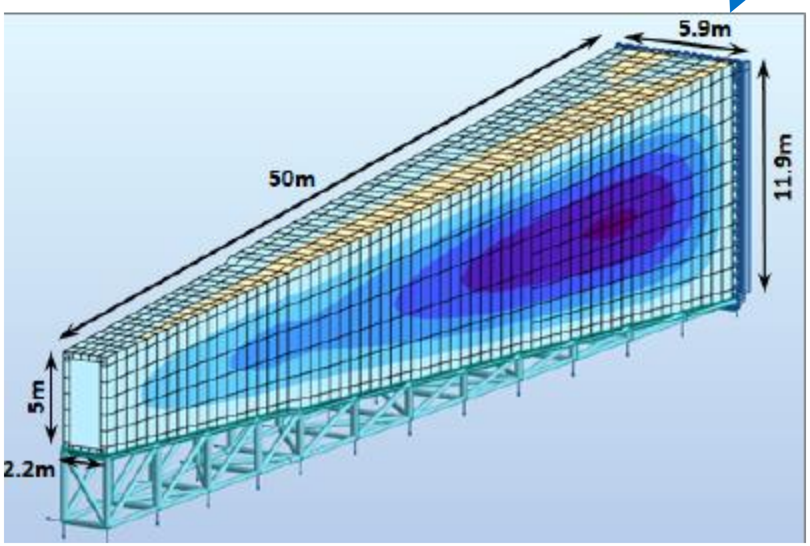


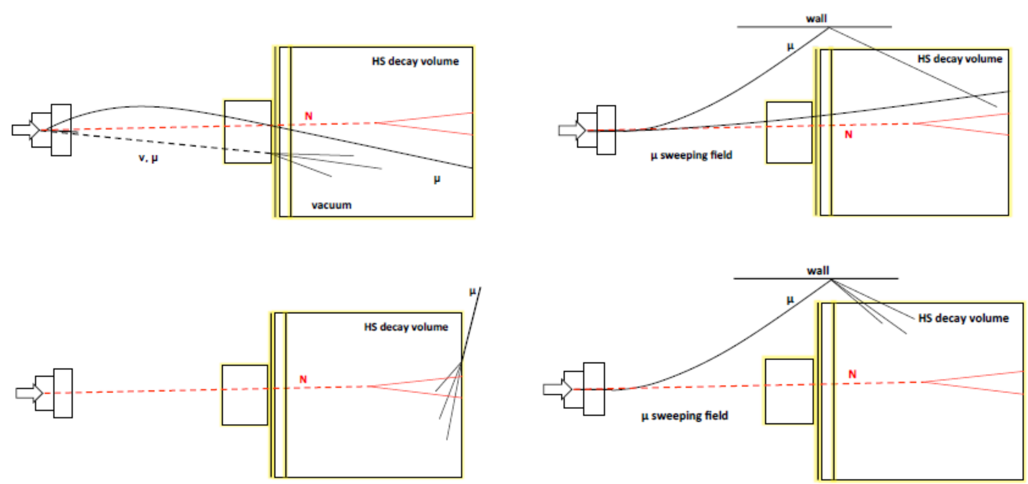
Decay Vessel

Pyramidal frustum shape, length 50 m
1 mbar, volume 2040 m^3

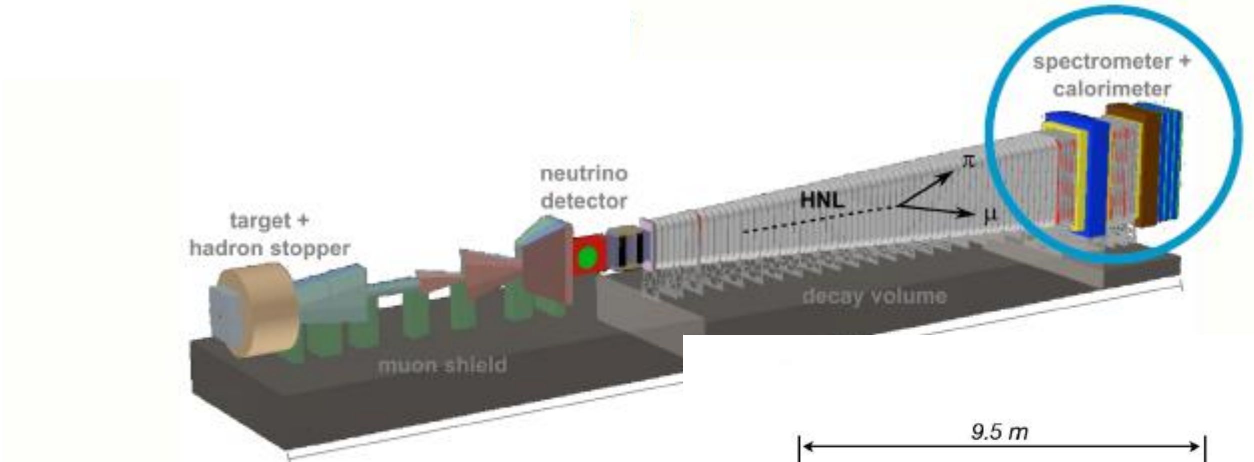
Double-layer steel structure
with strengthening ribs

Surrounding background tagger:
480 t of liquid scintillator

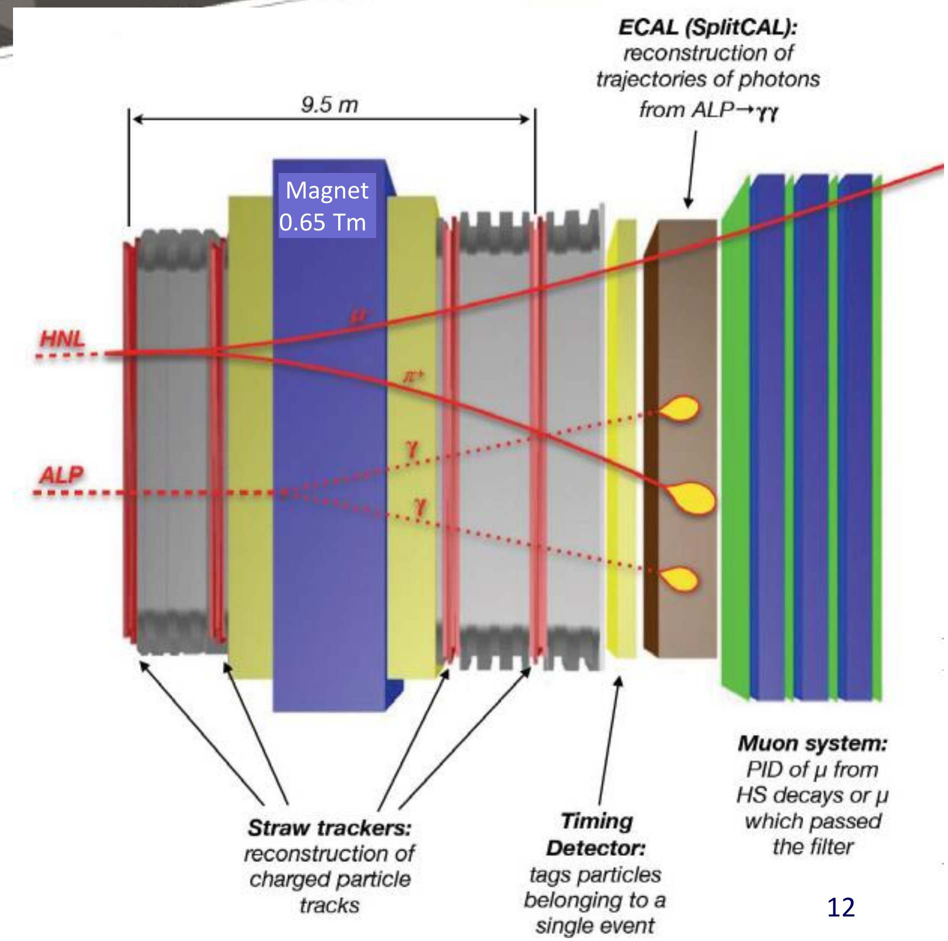




The Hidden Sector Detector



HS particle ID system



- Straw tracker (σ_x < 120 μm per straw) inside the evacuated decay volume
- Timing detector (σ_t < 100 ps) plastic scintillators + SiPM or MRPCs
- ECAL (SpiltCal) sampling lead/scintillator + SiPM high-precision layers (MicroMegas)
- Muon system four active stations equipped with scintillating tiles + SiPM + iron or concrete

Prototyping SHiP

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

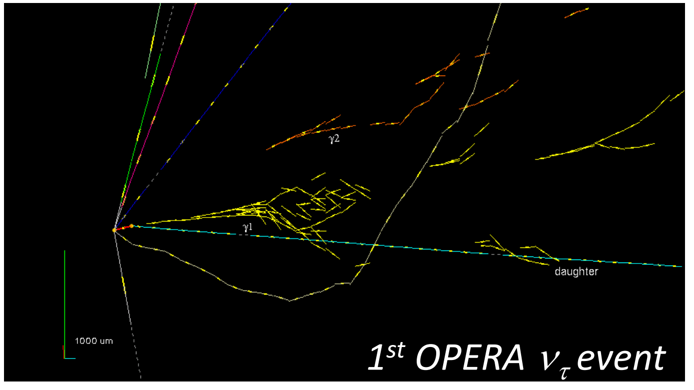
Tau Neutrino physics with the SND

Looking for tau neutrino events, so far

9 ν_τ events by the DONUT experiment (no separation ν_τ - anti ν_τ)

10 events from ν_μ oscillation reported by the OPERA experiment

Physics Letters B691 (2010) 138



1st OPERA ν_τ event

# of expected observed ν_τ int.

Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

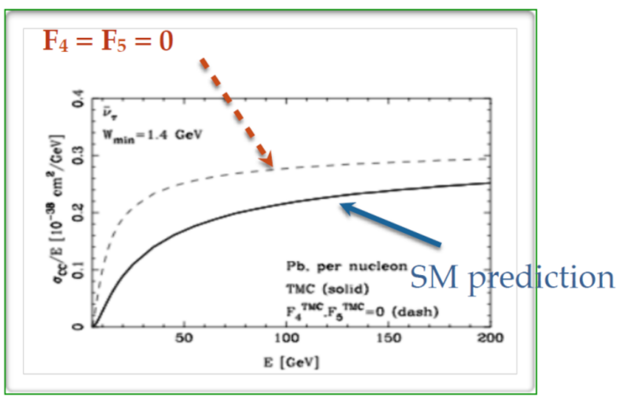
in SHiP, the expected statistics x 10^3 w.r.t. previous experiments will lead to:

- First observation of anti-ν_τ
- Measurement of ν_τ and anti- ν_τ cross-sections

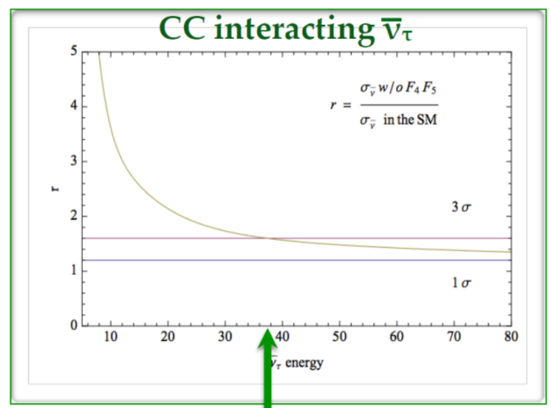
Tau Neutrino physics with the SND

in SHiP, the expected statistics x 10^3 w.r.t. previous experiments will also lead to the first evaluation of F_4 and F_5 not accessible with electron or muon neutrinos

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



anti–ν_τ CC DIS cross section



E(anti-ν_τ) < 38 GeV, ≈ 300 events exp.

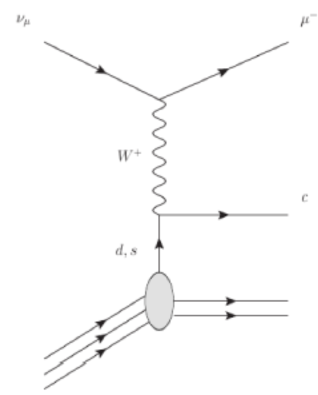
Neutrino physics with the SND

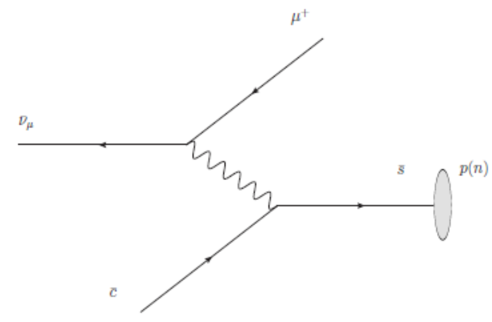
Expected CC DIS ν int. with charm production in 2x10[20] pot

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

Expected anti-ν_μ induced charm yield in SHIP ~ 2.5x10^4

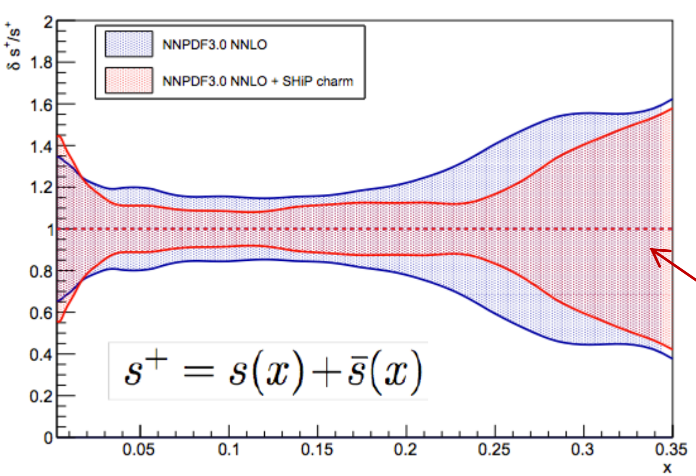
Observed in CHORUS ~32, in NuTeV ~1400





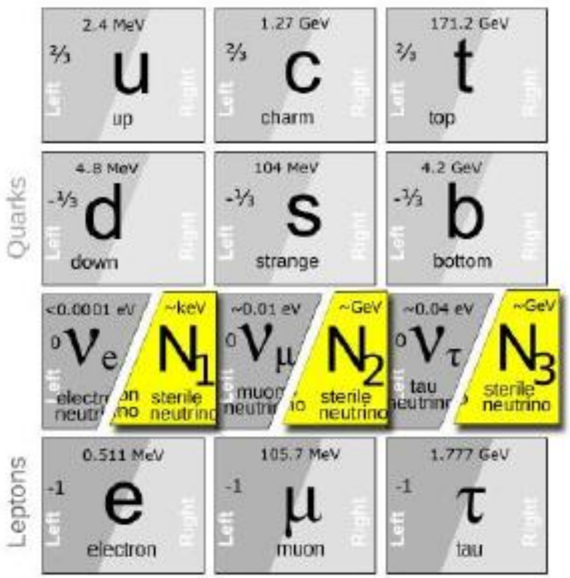
$\overline{\nu}$-induced charm production sensitive to s-quark content of the nucleon

strange quark nucleon content through charm production



Significant reduction of the uncertainty on s-quark distribution with SHiP data, in the range $0.03 < x < 0.35$ for $s^+(x)$

Search for Heavy Neutral Leptons

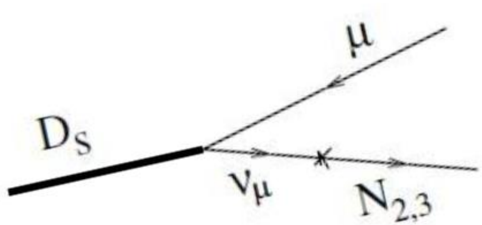


T.Asaka, M.Shaposhnikov PLB 620 (2005) 17

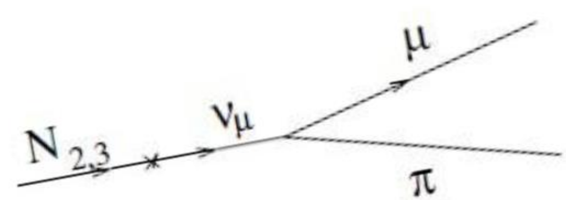
ν Minimal Standard Model (ν MSM):
Extension of the SM by **3 right-handed** **H**eavy **N**eutral **L**eptons (**HNLs**)

- *Light* N_1:
  Mass *O*(keV)
  Dark Matter candidate
- *Heavy* N_2,N_3:
  Mass *O*(GeV)
  Could explain ν masses (through see-saw) and baryon asymmetry

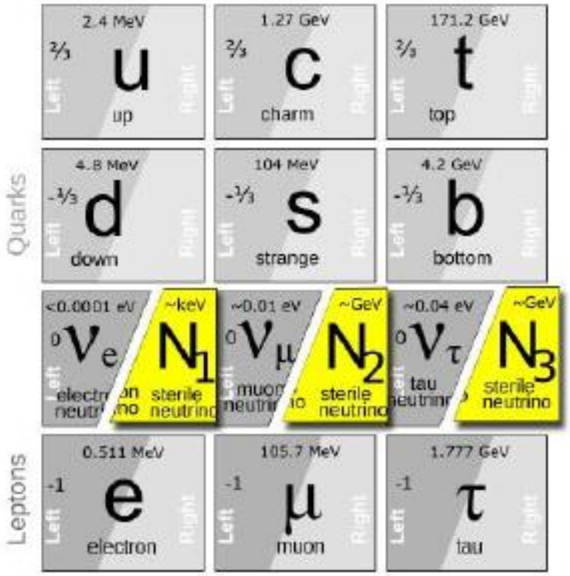
HNL production



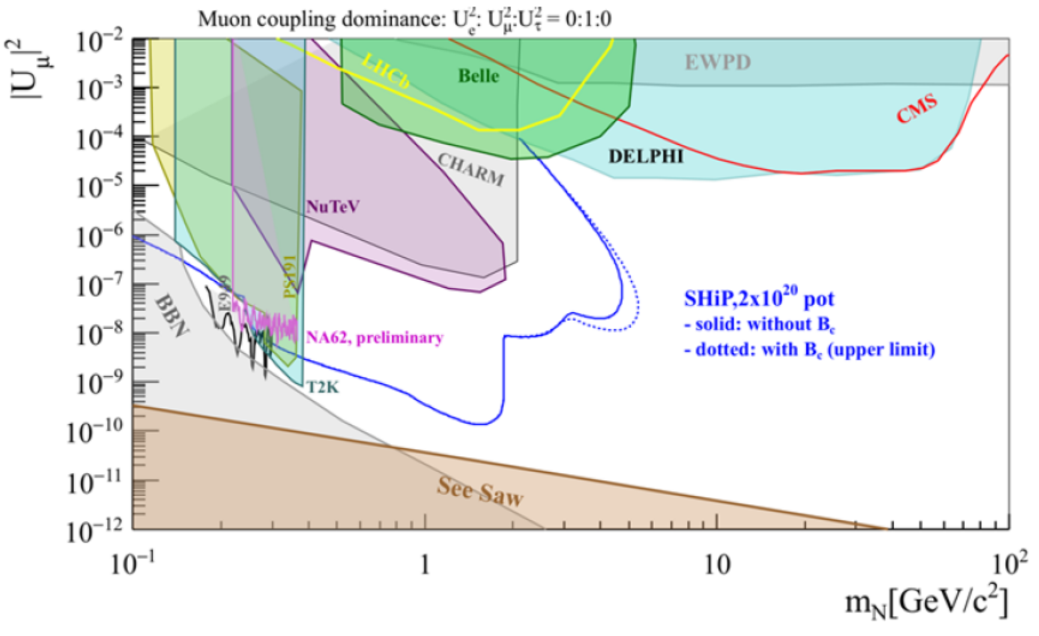
HNL decay



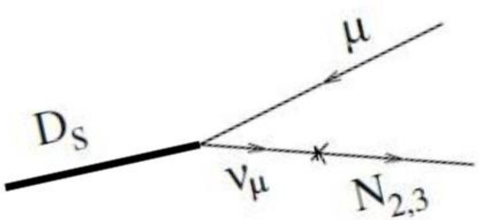
Search for Heavy Neutral Leptons



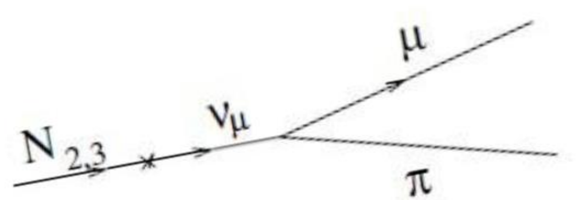
T.Asaka, M.Shaposhnikov PLB 620 (2005) 17



HNL production



HNL decay



Conclusion

- The SHiP experiment has been proposed at CERN to search for new Physics at the intensity frontier

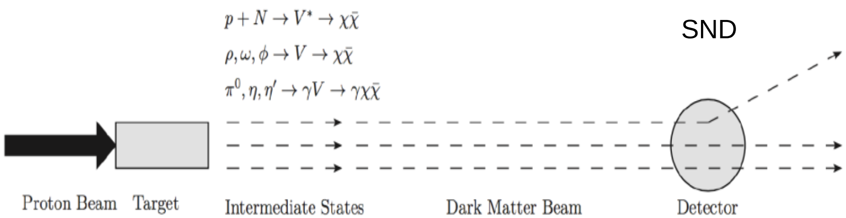
- SHiP offers a unique opportunity for neutrino physics, including Heavy Neutral Leptons search and ν_τ physics with unprecedented sensitivities

- The detector R&D and prototyping activities are on-going and in a good shape

- The Beam Dump Facility and SHiP Comprehensive Design Studies were already finalized, next step of the Collaboration being the TDR preparation

Light dark matter searches with the SND

Ideal laboratory also for Light Dark Matter scattering signatures



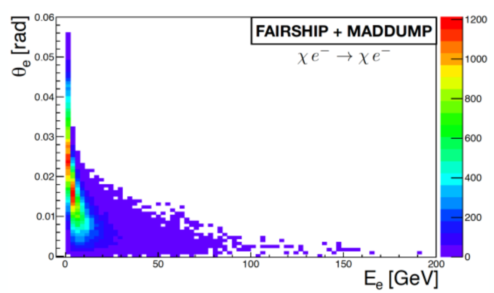
Look for LDM elastic scattering on atomic electrons of the target

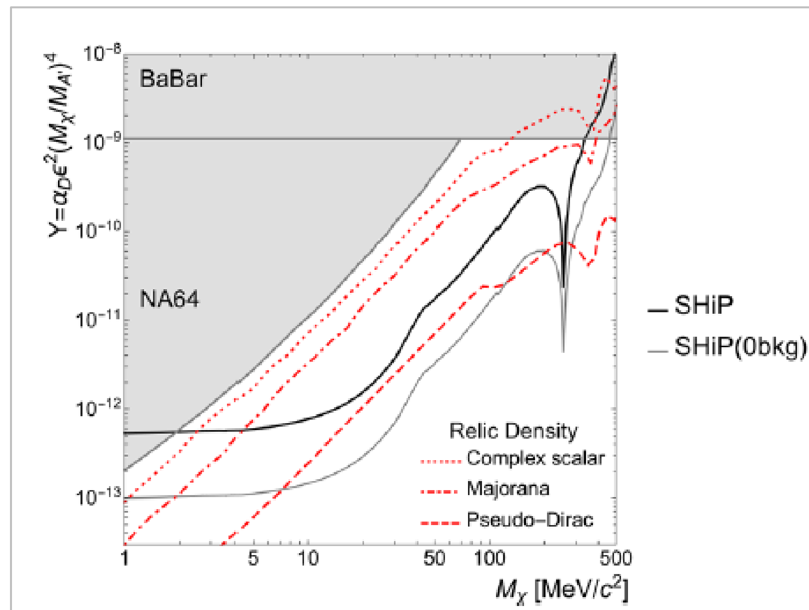
$$\chi e^- \to \chi e^-$$

signal: single EM shower w/o associated tracks

SIGNAL SELECTION

$$\begin{cases} 0.01 < \theta < 0.02 \\ E < 20 \text{ GeV} \end{cases}$$





background: neutrinos can mimic LDM scattering in case of only one visible track at primary vertex, *f.e.*