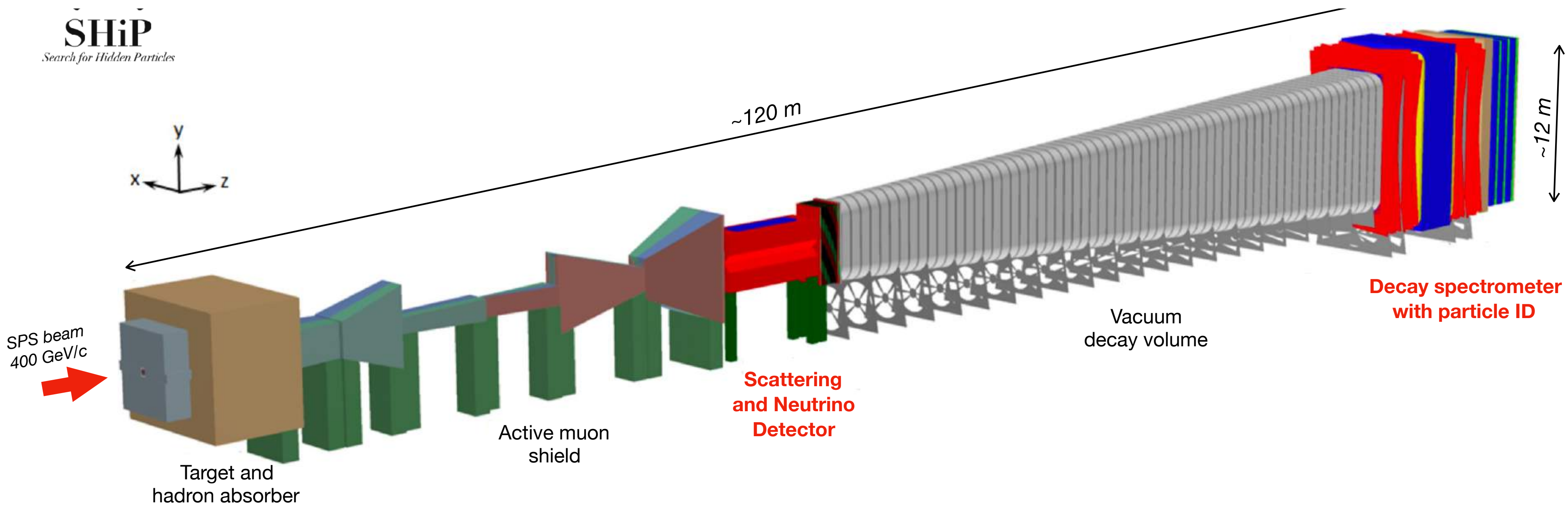
# НИЦ КИ - ПИЯФ @SHiP

**В.Т. Ким**

**ОФВЭ ПИЯФ НИЦ КИ**

**Сессия Ученого Совета**
**24-27 декабря 2018 г.**



# НИЦ КИ - ПИЯФ @SHiP

## Search for Hidden Particles

**Поиск частиц, из которые могут решить проблему Темной Материи и отсутствие антиматерии во Вселенной**

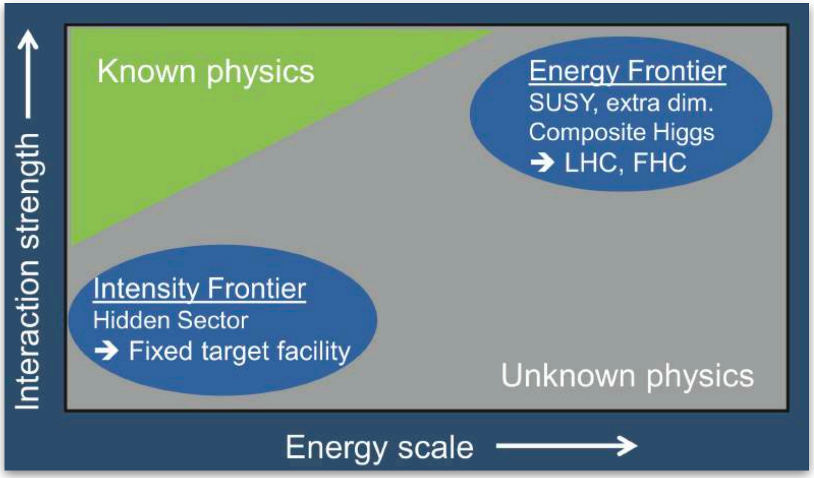
**52 института из 17 стран**

**SHiP Technical Proposal 2015**
**SHiP Physics Paper 2015**

**“Sensitivity of the SHiP experiment to Heavy Neutral Leptons”**
**SHiP Coll., JHEP 04 (2019) 077**

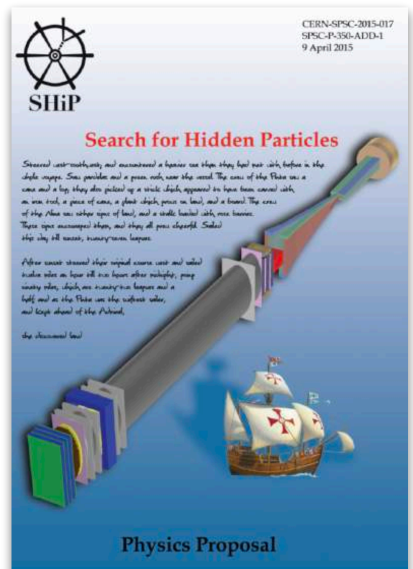
**“Sensitivity of the SHiP experiment to Heavy Neutral Leptons”**
**SHiP Coll., JINST 14 (2019) P03025**

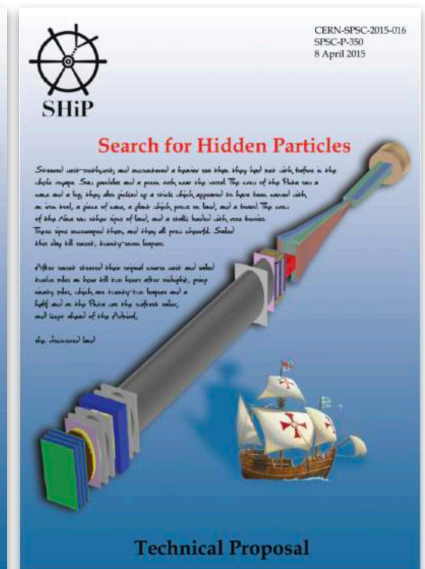
# ПИЯФ @SHiP




- Fixed target facility at the CERN SPS (400 GeV)
- Designed to find a solution for BSM physics by searching for very weakly interacting particles
- Hidden Sector (HS) production and decay rates are strongly suppressed relative to SM: production branching ratios *O*($10^{-10}$)
- Detection of long-lived particles in the “zero background” experiment

- ***2013*** *Expression of Interest* for a new CERN SPS experiment submitted
- ***2015*** *Technical proposal* and description of physics case submitted
- ***2016*** *Recommendation* by CERN SPSC to proceed to Comprehensive Design Study
- ***2018*** Comprehensive design study by the *Beam Dump Facility* group published
- **2019** *Comprehensive Design Report* to be submitted

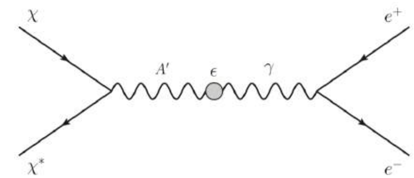



***290 authors, 52 institutes, 17 countries***

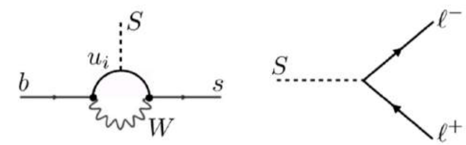
# SHiP: Hidden Sector (HS) under study

- Dark vectors (“Dark Photons”)
  - Addition of U(1) gauge group to SM, kinetic mixing with $\gamma$ and Z
  - Bremsstrahlung, light neutral meson decays, quark annihilation

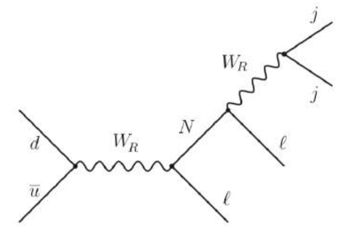



- (Light) Dark Matter direct detection (“WIMPs”)
  - Stable or long-lived DM that couple to EM current via *A’*

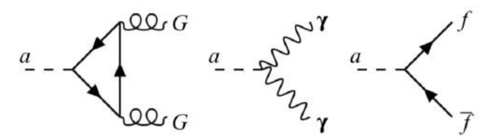
- Dark scalars (“Dark Higgses”)
  - Neutral singlet scalers that couple to the SM Higgs field
  - Produced in penguin decays of K, D, B mesons




- Heavy neutral leptons (“sterile neutrinos”)
  - Explains SM neutrino masses (seesaw), Dark Matter, Baryon Asymmetry
  - Weak semi-leptonic decays of hadrons, W, Z




- Axion-like particles (“ALPs”)
  - Non-renormalizable coupling to SM, solution of the strong CP problem
  - Generalisation of the axion model in MeV-GeV mass range




| Portal | Coupling to SM |
|---|---|
| Dark Photon, $A'_\mu$ | $\epsilon/(2\cos\theta_W)\, F'_{\mu\nu} B_{\mu\nu}$ |
| Dark Higgs, $S$ | $(\mu S + \lambda S^2)\, H^\dagger H$ |
| Axion or ALP, $a$ | $a/f_\gamma \cdot F_{\mu\nu}\tilde{F}_{\mu\nu}$ , $a/f_\gamma \cdot G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$ , $\partial a/f_a \cdot \bar{\psi}\gamma^\mu\gamma^5\psi$ |
| Sterile Neutrino, $N$ | $\Sigma\, F_{\alpha I}(\bar{L}_\alpha H) N_I$ |

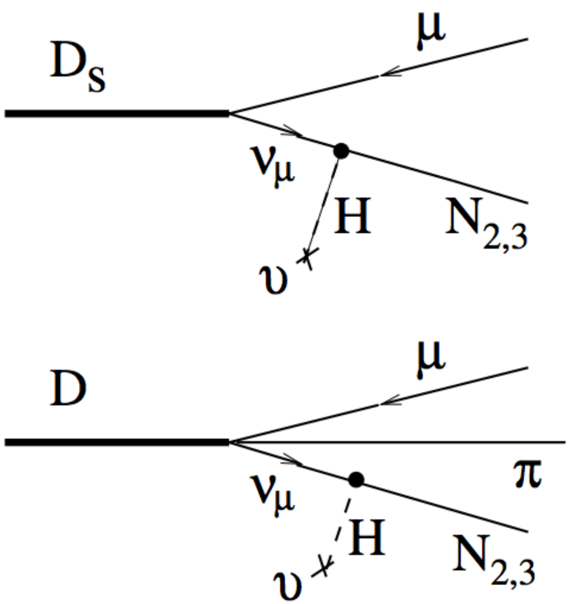
*CERN-PBC-REPORT-2018-007*

| Main **decay modes** of hidden particles in various models ($l$ = e, μ) | |
|---|---|
| Model | Final state |
| Neutrino portal, SUSY neutralino | $l^\pm\pi^\mp$, $l^\pm K^\mp$, $l^\pm\rho^\mp$, $\rho^\pm \to \pi^\pm\pi^0$ |
| Vector, scalar, axion portals, SUSY sgoldstino | $l^+l^-$ |
| 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 | $\pi^0\pi^0$ |

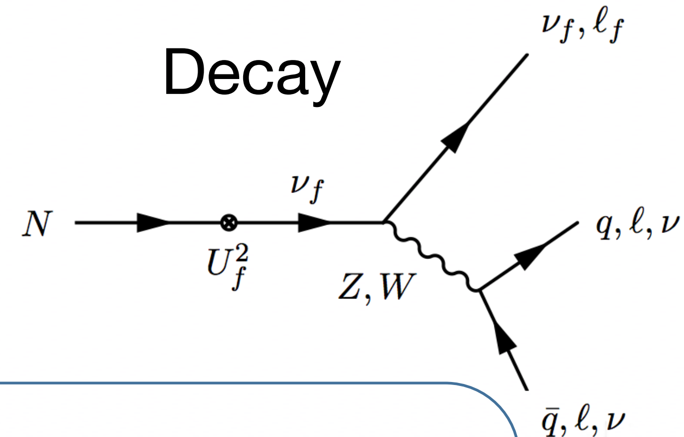
*CERN-SPSC-2015-016*

# SHiP: HNL

## Production




## Decay




$N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$

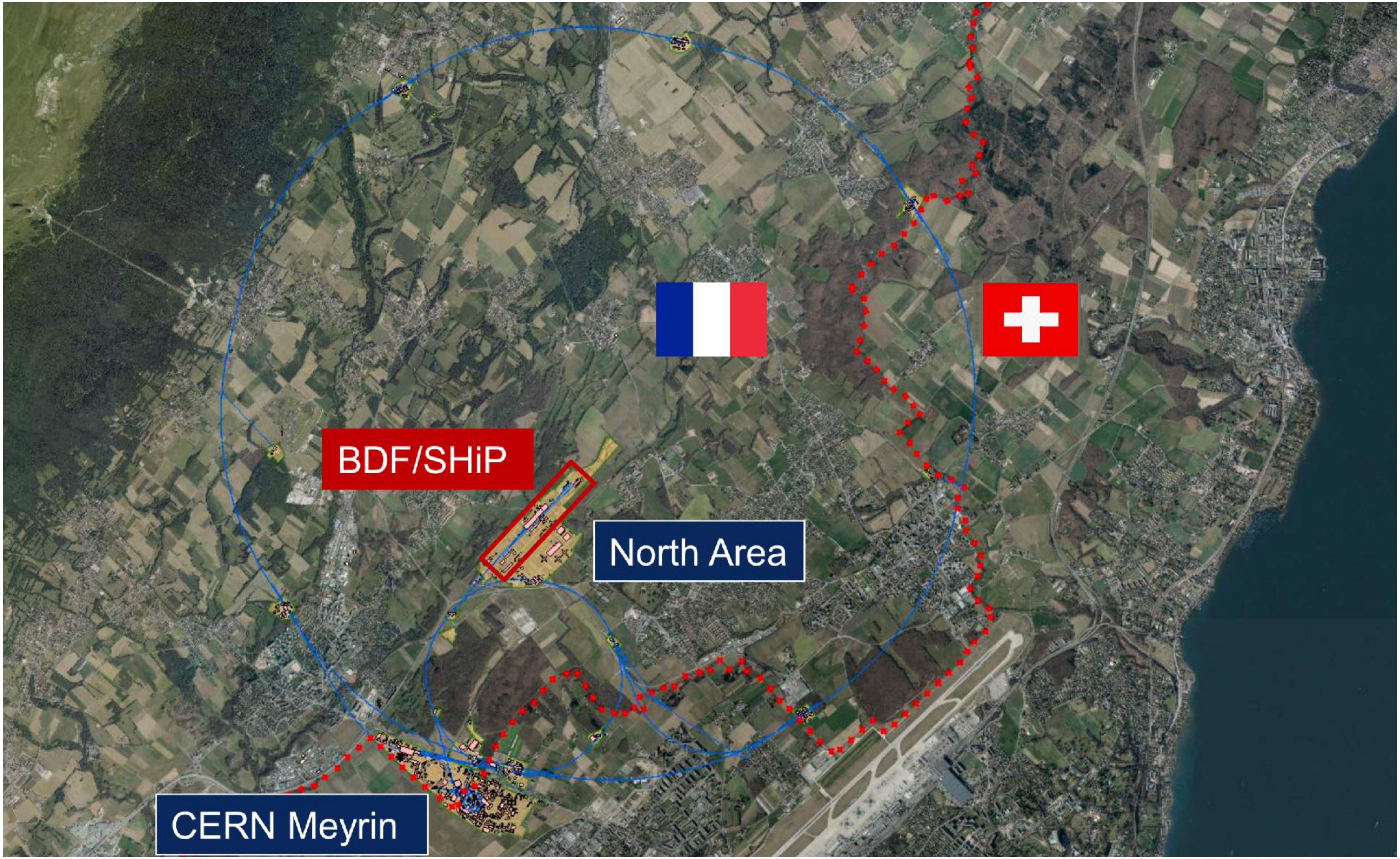
$N \to H^\pm \ell^\mp$, with $H = \pi, \rho$

$N \to 3\nu$

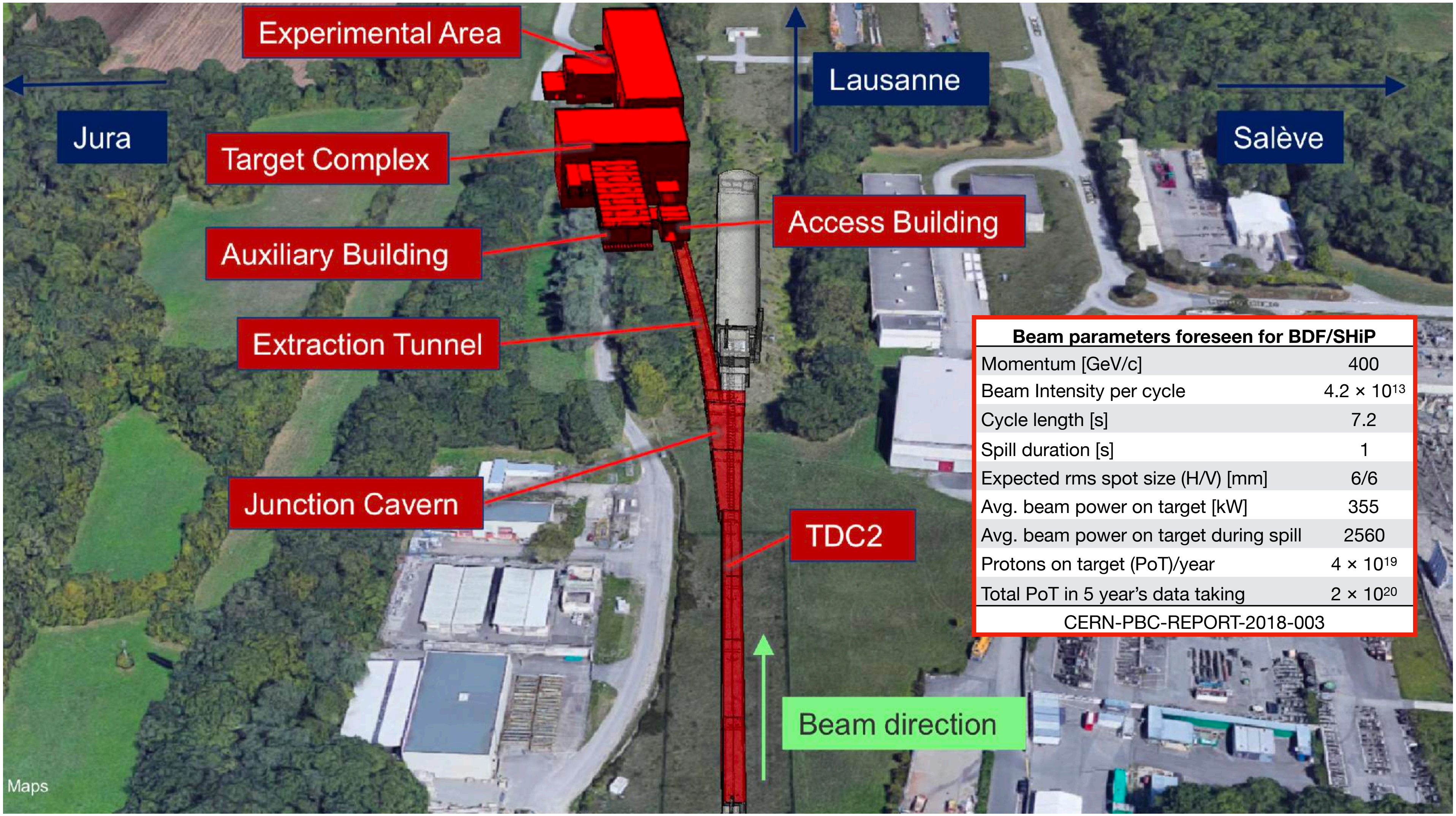
$N \to \ell_i^\pm \ell_j^\mp \nu_j$

$N \to \nu_i \ell_j^\pm \ell_j^\mp$

# CERN Beam Dump Facility



# BDF: Tunnel for SHiP and TauFV

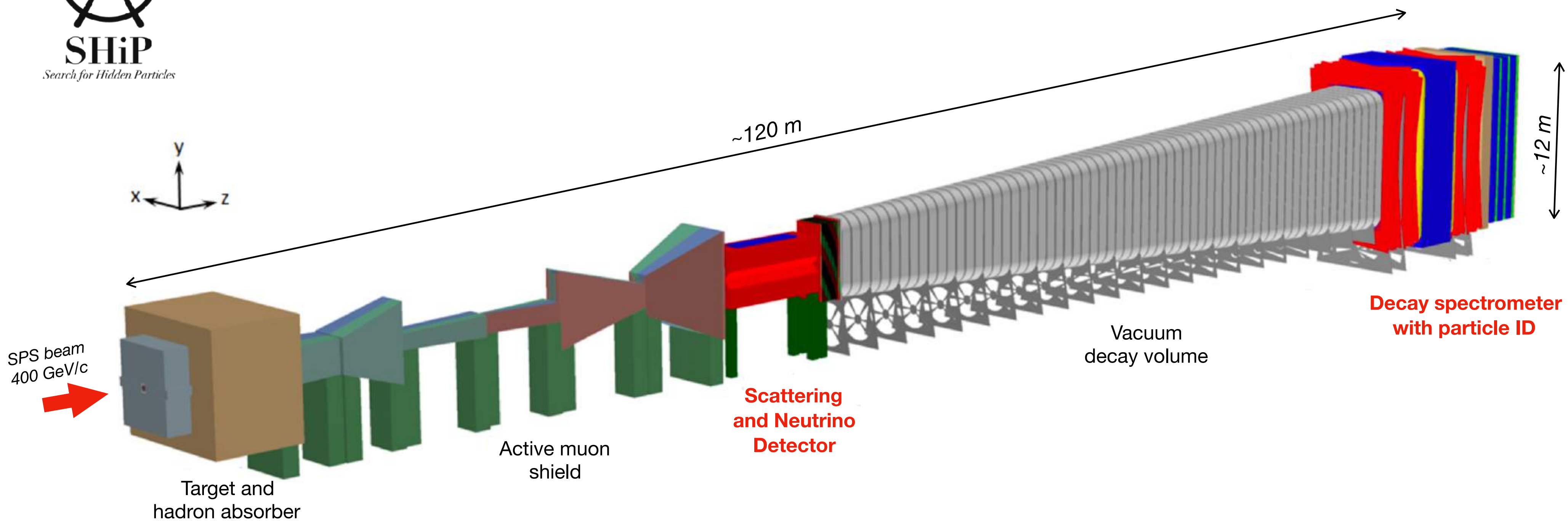



| Beam parameters foreseen for BDF/SHiP | |
|---|---|
| Momentum [GeV/c] | 400 |
| Beam Intensity per cycle | $4.2 \times 10^{13}$ |
| Cycle length [s] | 7.2 |
| Spill duration [s] | 1 |
| Expected rms spot size (H/V) [mm] | 6/6 |
| Avg. beam power on target [kW] | 355 |
| Avg. beam power on target during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

CERN-PBC-REPORT-2018-003

SHiP
Search for Hidden Particles

# Experimental setup of SHiP



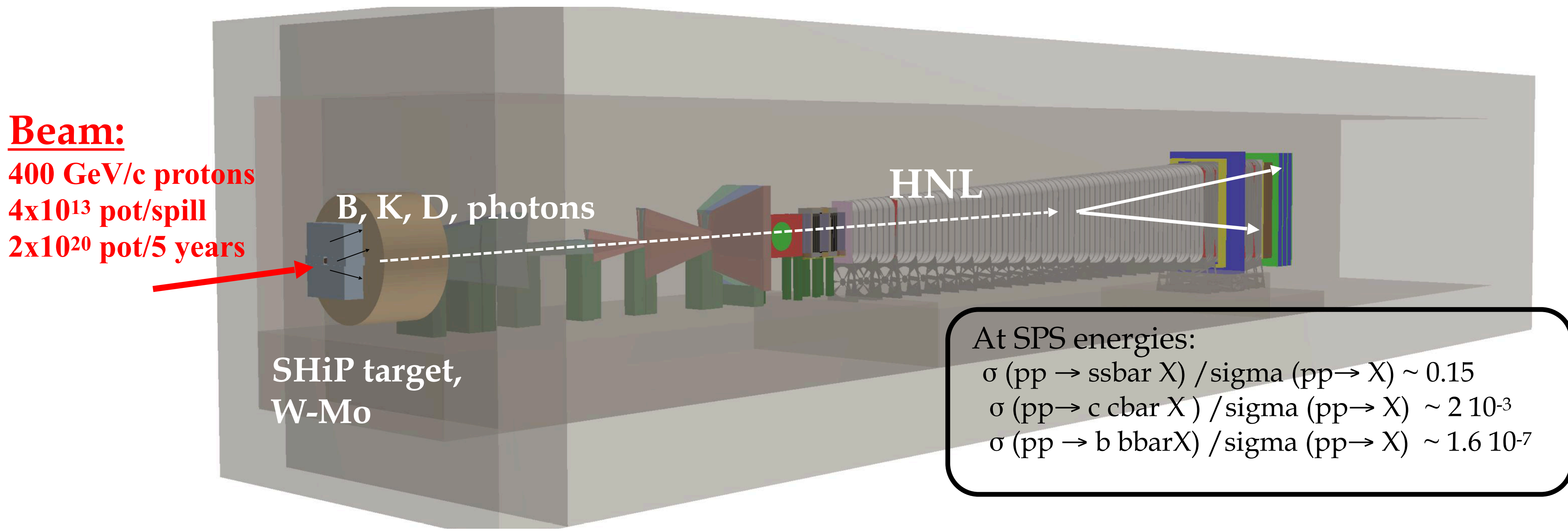

## Scattering and Neutrino Detector (SND)

- Emulsion spectrometer located inside of a long dipole magnet B=1.2T
- Muon identification system downstream
- **Physics goals**:
  - SM physics: $\nu_\tau$ cross section and magnetic moment, DIS structure functions $F_4$ and $F_5$, neutrino-induced charm production and strangeness, nuclear effects
  - Search for LDM scattering

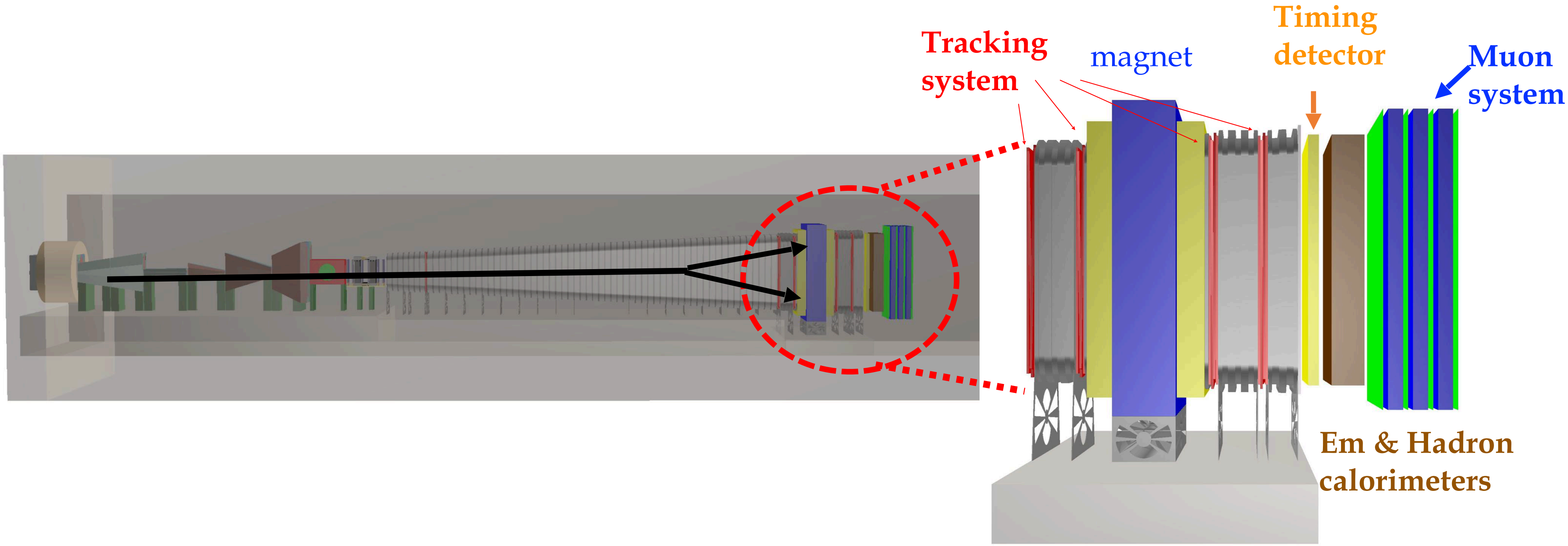
## Hidden Sector (HS) Spectrometer

- Distance from the target is a compromise between
  - HS life time and angular acceptance
  - muon induced background
- Decay volume 50m long, 1 mbar pressure
- Magnetic spectrometer downstream
- **Physics goal**: search for very weakly interacting long lived particles including Heavy Neutral Leptons - right-handed partners of the active neutrinos, vector, scalar, axion portals to the Hidden Sector, and light supersymmetric particles

# SHiP: HNL signal



# SHiP: HS spectrometer




1) Fully reconstructed signal: at least two charged particles (+ $\pi^0$ , $\gamma$ ) e.g. $N \rightarrow \mu^+\pi^-$ or $N \rightarrow \rho^+\mu^-$

2) Partially reconstructed signal (neutirnos in the final state) e.g. $N \rightarrow \mu^+\nu\nu$

4) Fully neutral channels e.g. $A \rightarrow \gamma\,\gamma$

# SHiP: Physics Signals

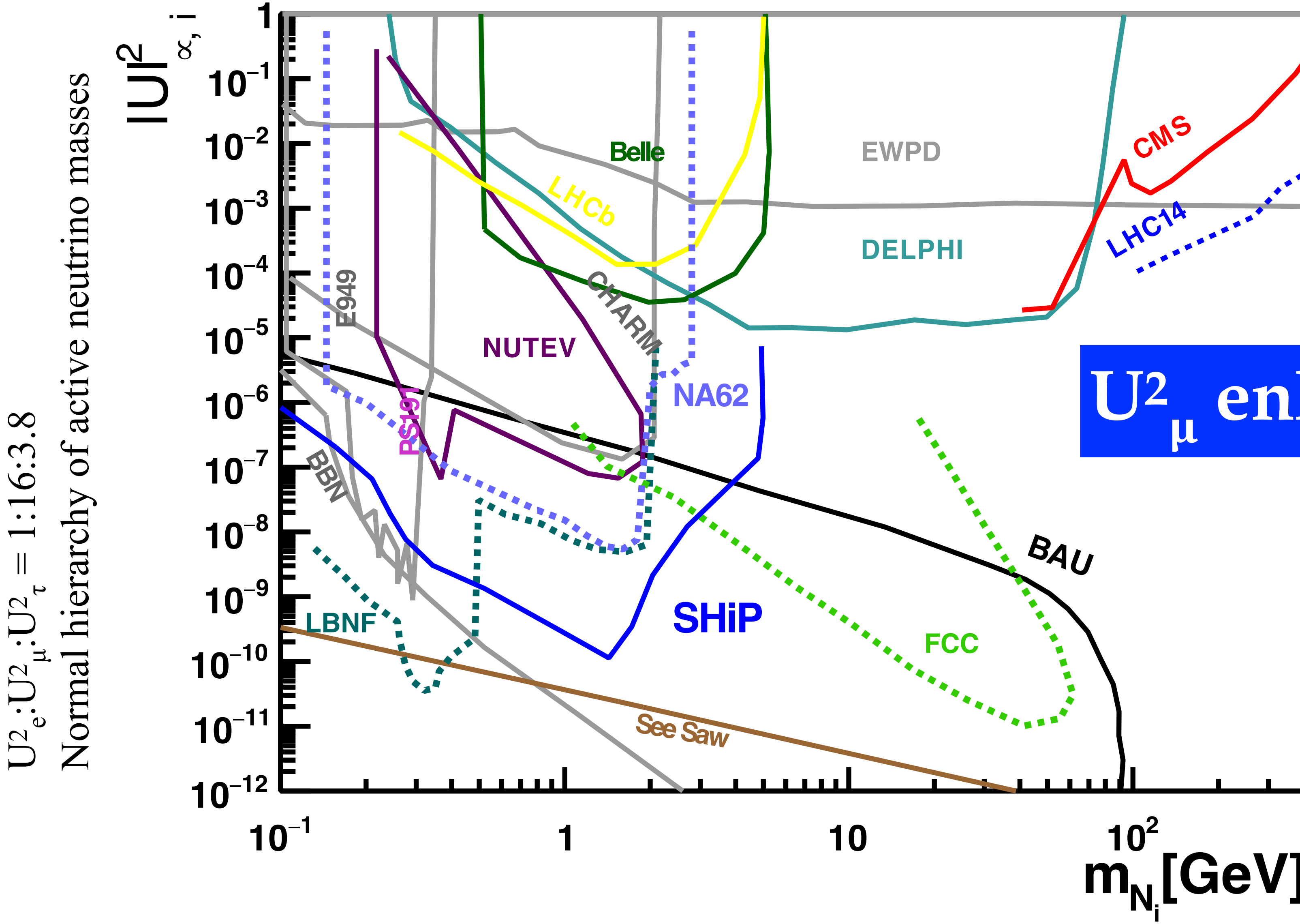
| Signature | Physics | Backgrounds |
|---|---|---|
| $\pi^-\mu^+$,$K^-\mu^+$ | HNL,NEU | RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$ |
| $\pi^-\pi^0\mu^+$ | HNL($\to \rho^-\mu^+$) | $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$ , $K_L^0 \to \pi^-\pi^+\pi^0$ |
| $\pi^-e^+$,$K^-e^+$ | HNL, NEU | $K_L^0 \to \pi^-e^+\nu_e$ |
| $\pi^-\pi^0e^+$ | HNL($\to \rho^-e^+$) | $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$ |
| $\mu^-e^+ + p^{miss}$ | HNL,Higgs Portal (HP)($\to \tau\tau$) | $K_L^0 \to \pi^-\mu^+\nu_\mu$ , $K_L^0 \to \pi^-e^+\nu_e$ |
| $\mu^-\mu^+ + p^{miss}$ | HNL,HP($\to \tau\tau$) | RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$ |
| $\mu^-\mu^+$ | DP,PNGB,HP | RDM, $K_L^0 \to \pi^-\mu^+\nu_\mu$ |
| $\mu^-\mu^+\gamma$ | Chern-Simons | $K_L^0 \to \pi^-\pi^+\pi^0$, $K_L^0 \to \pi^-\mu^+\nu_\mu(+\pi^0)$ |
| $e^-e^+ + p^{miss}$ | HNL,HP | $K_L^0 \to \pi^-e^+\nu_e$ |
| $e^-e^+$ | DP,PNGB,HP | $K_L^0 \to \pi^-e^+\nu_e$ |
| $\pi^-\pi^+$ | DP,PNGB,HP | $K_L^0 \to \pi^-\mu^+\nu_\mu$ , $K_L^0 \to \pi^-e^+\nu_e$,<br>$K_L^0 \to \pi^-\pi^+\pi^0$,$K_L^0 \to \pi^-\pi^+$ |
| $\pi^-\pi^+ + p^{miss}$ | DP,PNGB, HP($\to \tau\tau$),<br>HSU,HNL($\to \rho^0\nu$) | $K_L^0 \to \pi^-\mu^+\nu_\mu$ , $K_L^0 \to \pi^-e^+\nu_e$, $K_L^0 \to \pi^-\pi^+\pi^0$,<br>$K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$ |
| $K^+K^-$ | DP,PNGB, HP | $K_L^0 \to \pi^-\mu^+\nu_\mu$ , $K_L^0 \to \pi^-e^+\nu_e K_L^0 \to \pi^-\pi^+\pi^0$,<br>$K_L^0 \to \pi^-\pi^+$,$K_S^0 \to \pi^-\pi^+$,$\Lambda \to p\pi$ |
| $\pi^+\pi^-\pi^0$ | DP,PNGB,HP, HNL($\eta\nu$) | $K_L^0 \to \pi^-\pi^+\pi^0$ |
| $\pi^+\pi^-\pi^0\pi^0$ | DP,PNGB,HP | $K_L^0 \to \pi^-\pi^+\pi^0(+\pi^0)$ |
| $\pi^+\pi^-\pi^0\pi^0\pi^0$ | PNGB($\to \pi\pi\eta$) | — |
| $\pi^+\pi^-\gamma\gamma$ | PNGB($\to \pi\pi\eta$) | $K_L^0 \to \pi^-\pi^+\pi^0$ |
| $\pi^+\pi^-\pi^+\pi^-$ | DP,PNGB,HP | — |
| $\pi^+\pi^-\mu^+\mu^-$ | Hidden Susy (HSU) | — |
| $\pi^+\pi^-e^+e^-$ | Hidden Susy | — |
| $\mu^+\mu^-\mu^+\mu^-$ | Hidden Susy | — |
| $\mu^+\mu^-e^+e^-$ | Hidden Susy | — |

HNL=Heavy Neutral Lepton, NEU=neutralino

DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson

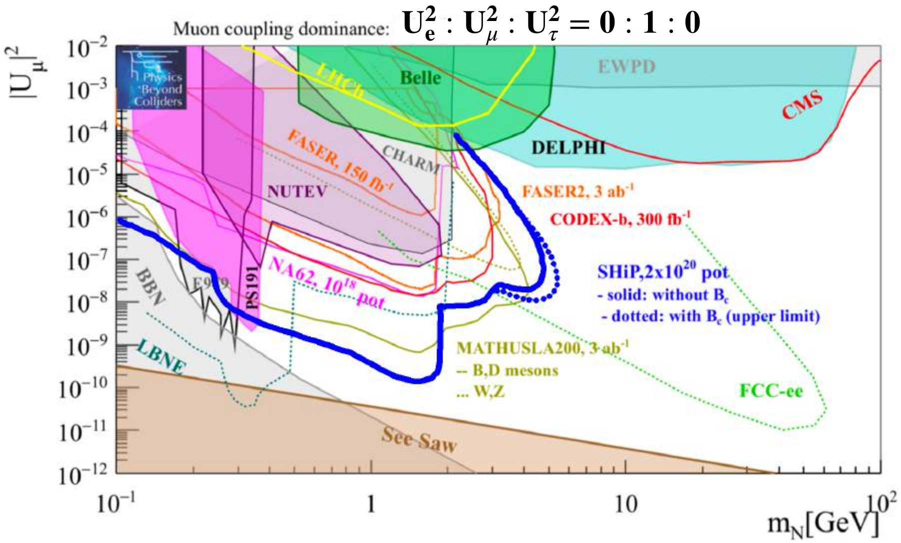
Background: RDM=random di-muons from the target

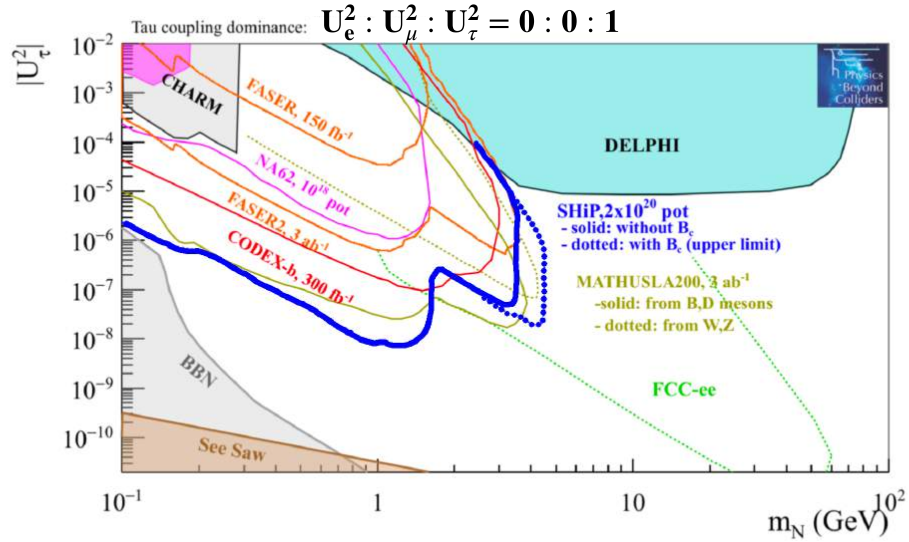
# SHiP: HNL

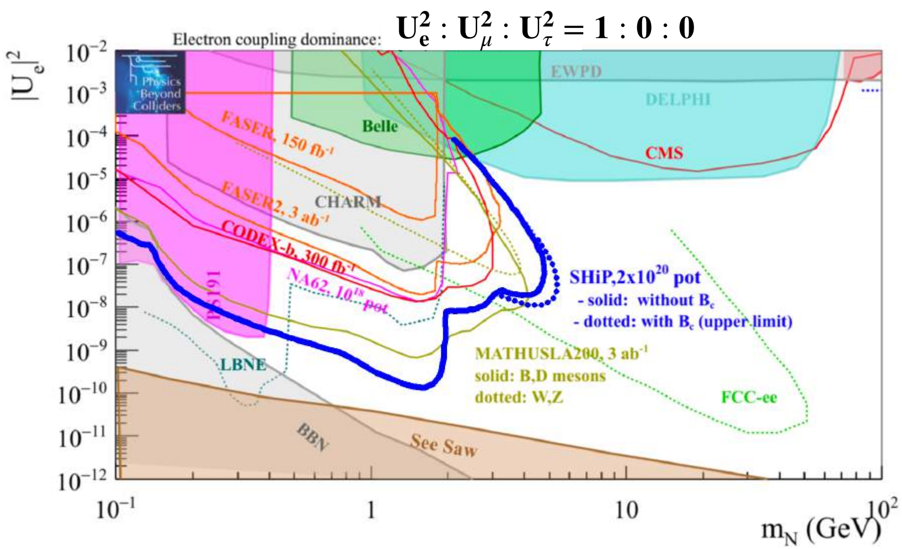



**$U^2_\mu$ enhanced**

# SHiP: Heavy Neutral Leptons (NHL)




*HNL → $l^\pm\pi^\mp$, $l^\pm K^\mp$, $l^\pm\rho^\mp$*

$$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \Sigma\, F_{\alpha I}(\bar{L}_\alpha H) N_I$$

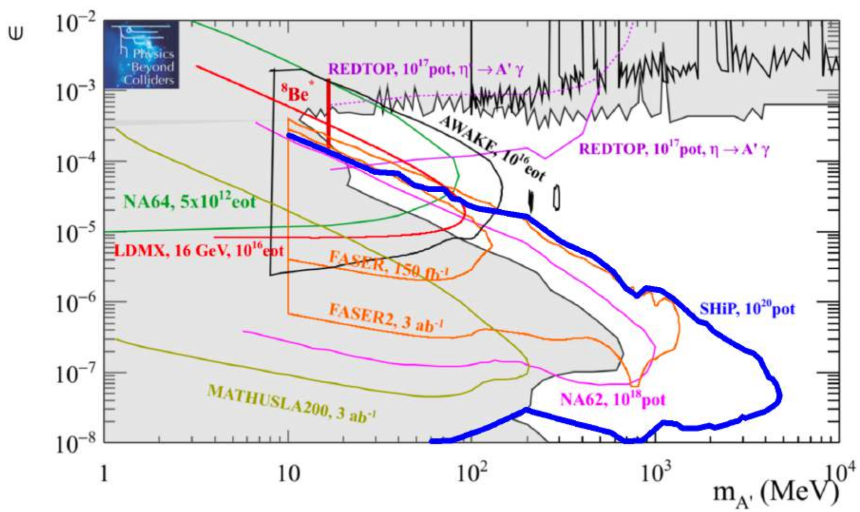
- Neutrino portal extension of the SM (**ν**MSM)
  - motivated by the fact that it can be tightly related with the neutrino mass generation mechanism (see-saw), provide dark mater candidate and explain the baryon asymmetry
  - $N_1$(dark matter, ~10 keV), $N_{2,3}$ (see-saw, baryon asymmetry, few GeV)
- Shown in figures: single-flavour dominance was assumed, e.g. HNLs couple only with one flavour of the active neutrinos at the time.

*JHEP 1904 (2019) 077, [1811.00930]*

# SHiP: Dark Photon

SHiP
Search for Hidden Particles

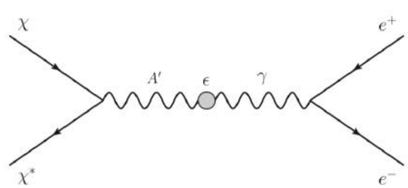
## Dark Photon couple to SM particles



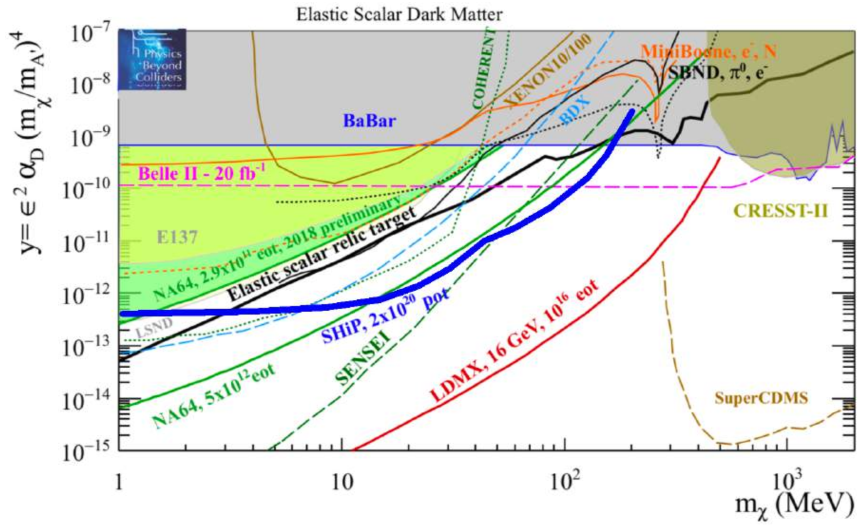

$A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - \epsilon/(2\cos\theta_W)\, \mathcal{F}'_{\mu\nu}\, \mathcal{B}_{\mu\nu}$

- The SM is augmented by a single new state $\mathcal{A}'$
- DM is assumed to be either heavy or contained in a different sector




## Dark Photon couple to Light DM



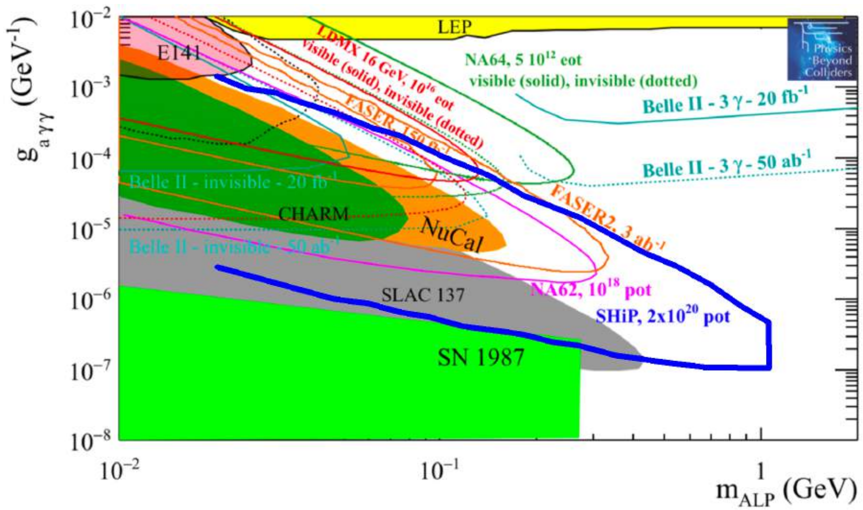

$A' \to \chi\chi$

$\mathcal{L}_{DS} = -1/4\, (\mathcal{F}'_{\mu\nu})^2 + 1/2\, m_{\mathcal{A}'}^2 (\mathcal{A}'_\mu)^2 + |(\partial_\mu + i g_{\mathcal{D}} \mathcal{A}'_\mu)\chi|^2 + \ldots$

- Model where minimally coupled viable WIMP dark matter model can be constructed
- The parameter space for this model is: $\{m_{A'}, \epsilon, m_\chi, \alpha_D\}$
  - $m(\mathcal{A}')=3m(\chi)$, $\alpha(\mathcal{D})=0.1$

# SHiP: Axion and Dark Scalar

## Axions and ALPs with photon coupling in the MeV-GeV mass range

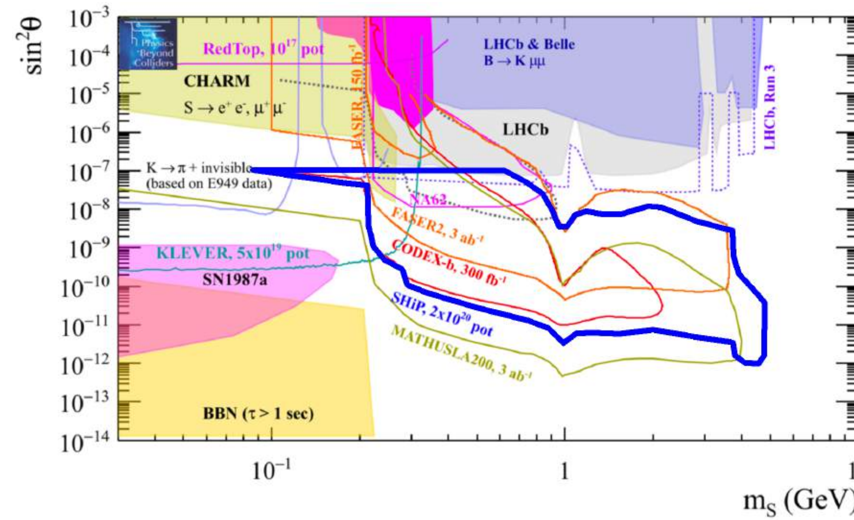



*ALP* → γγ

$\mathcal{L}_{axion} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - a/(4f_\gamma)\, F_{\mu\nu} \tilde{F}_{\mu\nu} + \ldots$

- Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global U(1), introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.
- Axion-Like Particle (ALP): a generalised version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.
- Interest to explore the MeV-GeV region at accelerator-based experiments

## Dark Scalar coupled to the Higgs




$S \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \ldots$

$\mathcal{L}_{scalar} = \mathcal{L}_{SM} + \mathcal{L}_{DS} - (\mu S + \lambda S^2)\, H^\dagger H$

- The minimal scalar portal model operates with one extra singlet field $S$ and two types of couplings, μ and λ
- Benchmark 4: assume λ=0

# НИЦ КИ - ПИЯФ @SHiP

## Straw Spectrometer Tracker (SST) R&D

**ПИЯФ**

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**SHiP Straw Tracker:**

- production technology
- event reconstruction
- physics performance
- digital read-out: conception
- test beam stand and data analysis

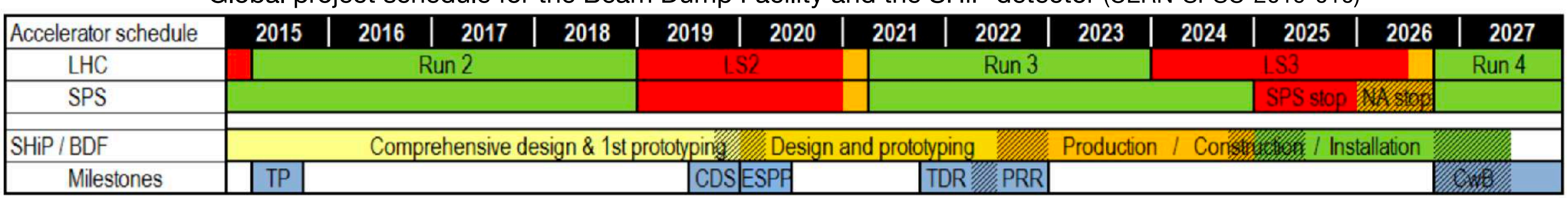
**Status: R&D Midterm Preparation**
**CDR submitted Dec. 2 2019**
**TDR ~ 3 years -> 2022**

2019-2020 European Strategy
2020 can be approved

# SHiP: Conclusions and Outlooks

- Explore the intensity frontier in the framework of study of new physics PBC-BSM
- New infrastructure in the North Area of CERN SPS: extraction tunnel, target complex, experimental area
- Detector concept:
  - Beam Dump Facility: average beam power 355 kW, 2.6 MW during the spill
  - Active muon shield: muon flux reduction by $10^6$
  - Scattering and Neutrino Detector: emulsions + magnetic spectrometer
    - LDM scattering; SM neutrino physics: $\nu_\tau$ study, magnetic moment, induced charm production, nuclear effects, strangeness
  - Hidden Sector spectrometer: 50 m decay volume + magnetic spectrometer
    - Direct search for very weakly interacting long lived particles: Heavy Neutral Leptons, vector, scalar, axion portals to the Hidden Sector, and light SUSY particles
- Comprehensive Design Report (CDR) at the end of 2019
- Preparation of the Technical Design Report (TDR) by the end of 2022
  - Final detector cost and schedule of the experiment
- 3 years to complete detector R&D, prototyping and validation
- ~6 years for the construction of BDF, detector production, installation, commissioning
- Data-taking for the LHC Run 4 and Run 5

Global project schedule for the Beam Dump Facility and the SHiP detector (CERN-SPSC-2019-010)




Сказочного Нового Года!