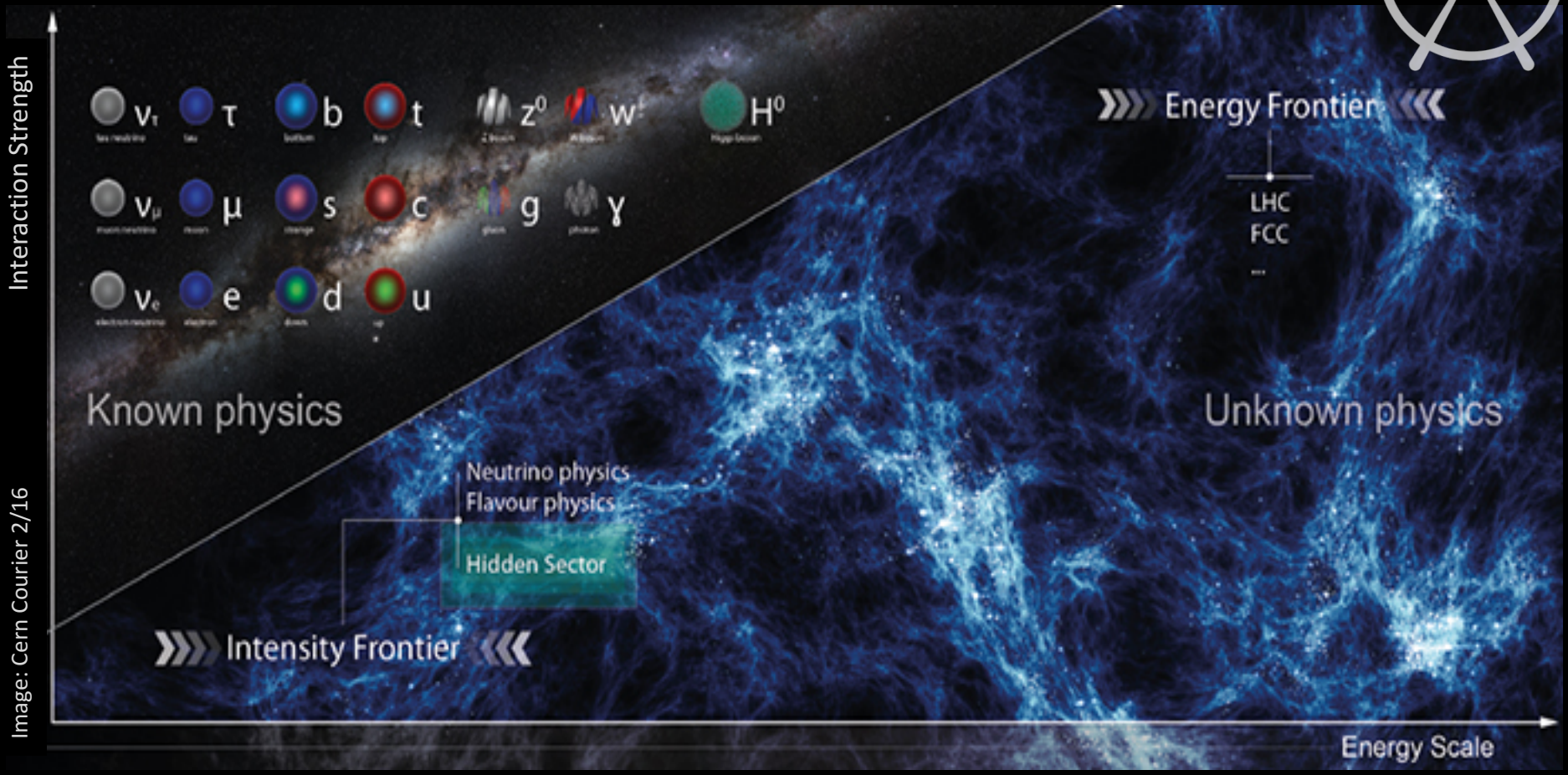
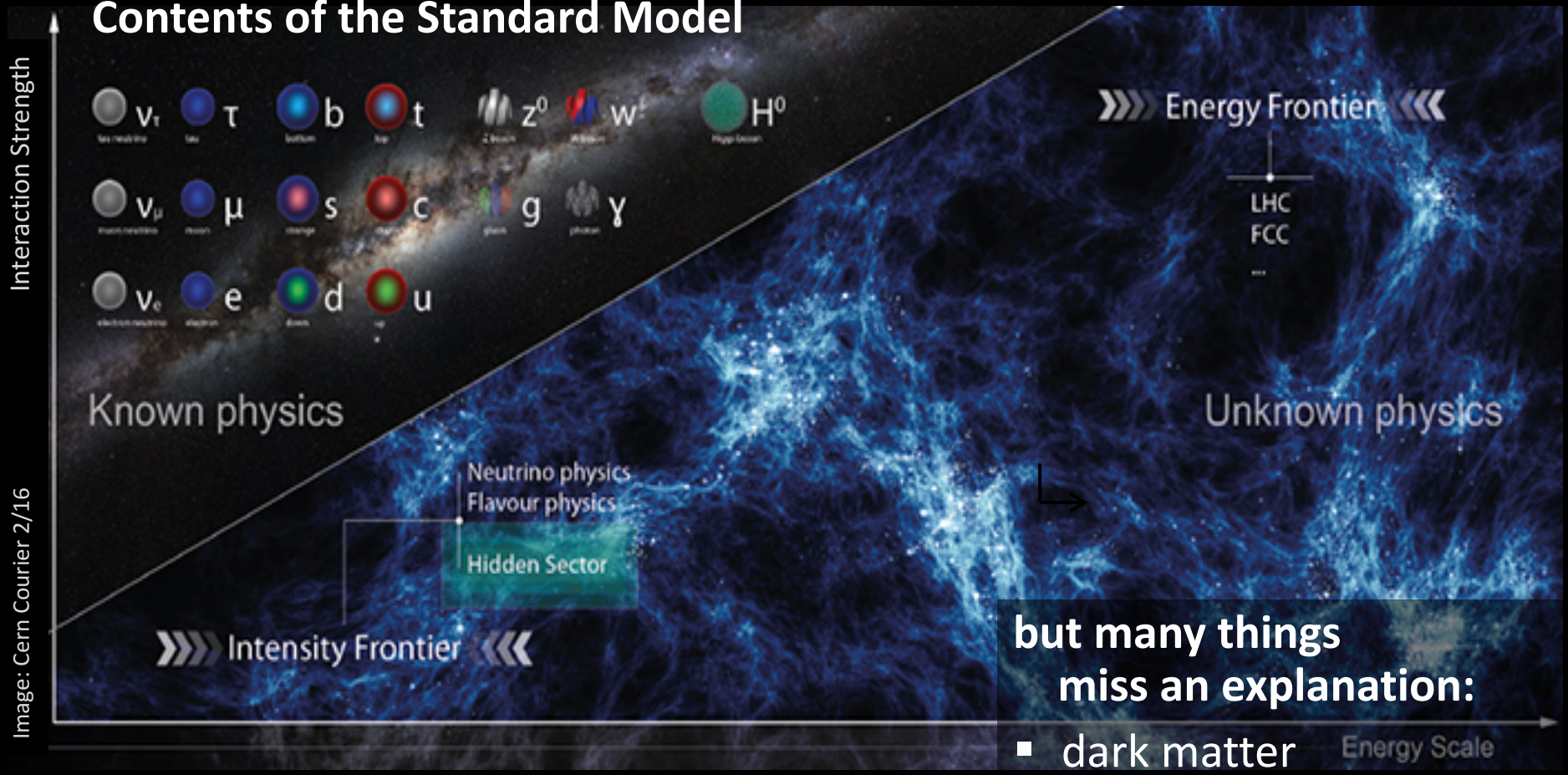
Search for Heavy Neutral Leptons in SHiP



Flavor and Dark Matter
Universität Heidelberg, 25 Sep 2017

Michael Wurm
Uni Mainz

Motivation for HNL searches [1]



but many things miss an explanation:

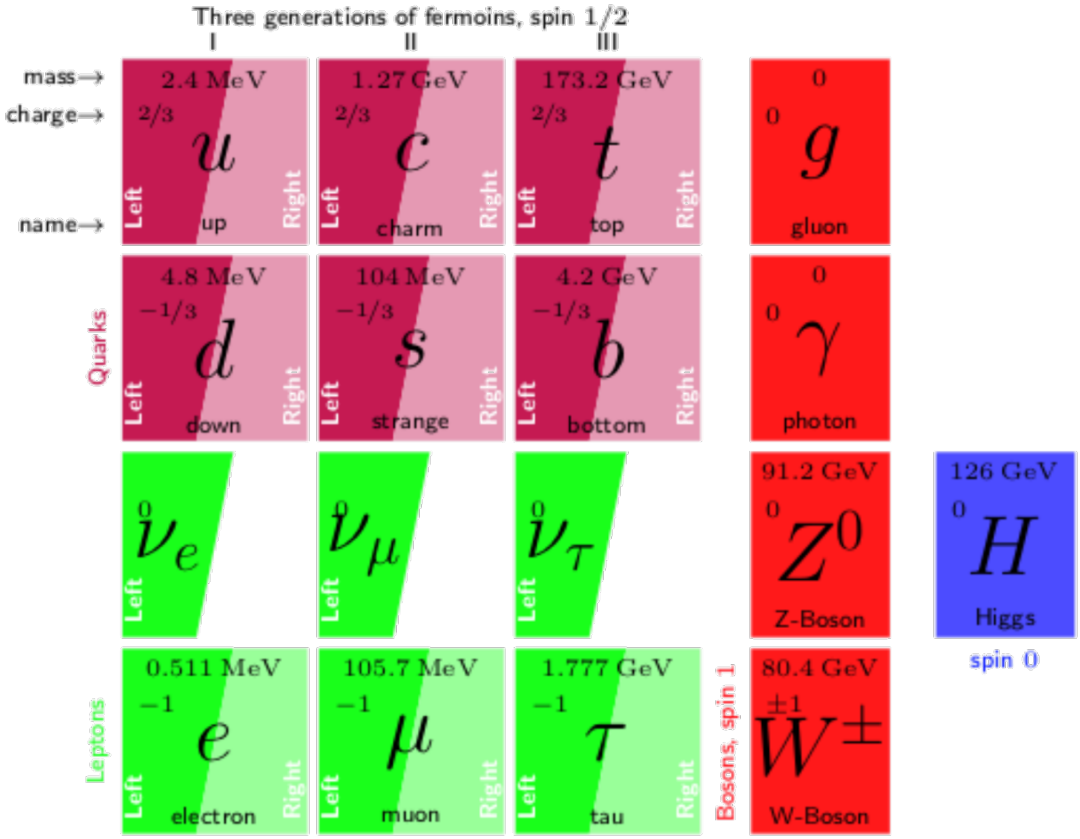
- dark matter
- neutrino masses
- baryon asymmetry
- ...

→ **new particles to be found in "low-energy" precision searches**

Motivation for HNL searches [2]

JG|U

Particle contents of the SM



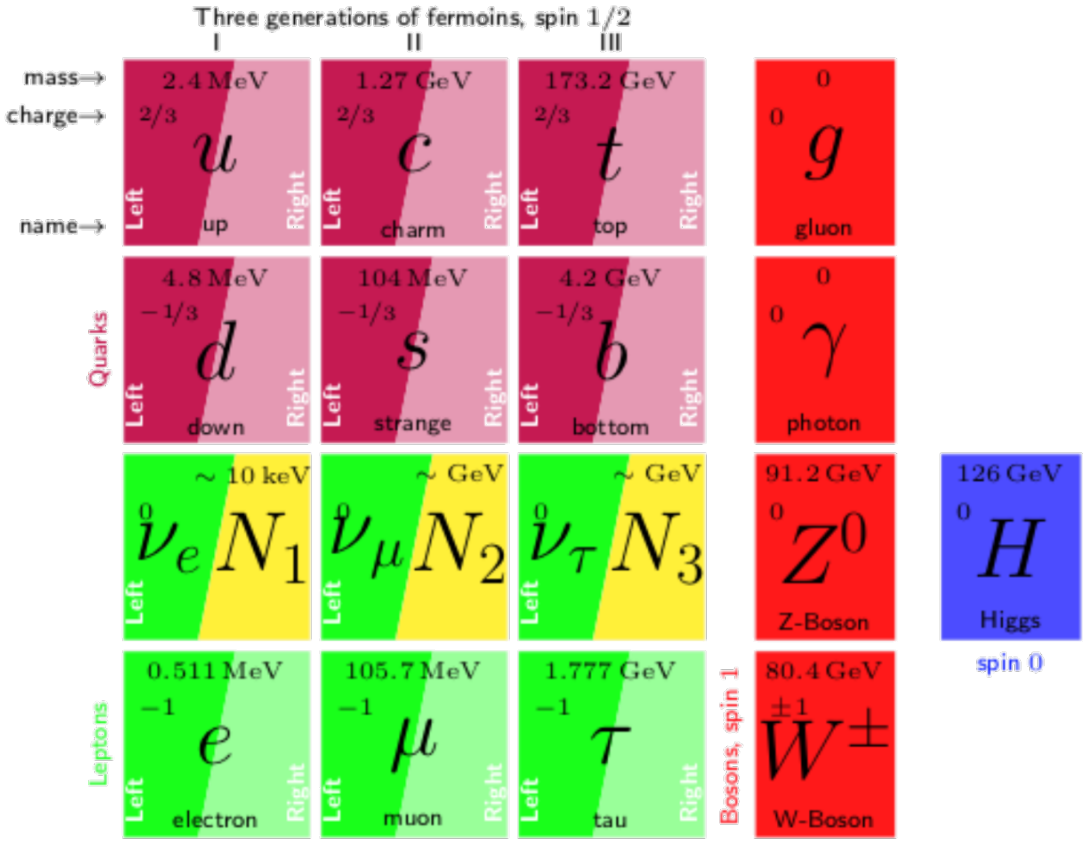
Original Model

- 3 massless neutrinos
- only left-handed states

Motivation for HNL searches [2]

JG|U

Particle contents of the νMSM



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

→ neutrino-minimal SM

- addition of **3 right-handed (i.e. sterile) massive neutrinos**
  - low LH ν masses generated via See-Saw mechanism:

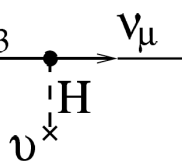
$$m_\nu \sim \frac{m_D^2}{M}$$

- **N_1 :** keV mass range
  - long-lived
  - dark matter candidate
- **$N_{2,3}$:** GeV mass range
  - short-lived
  - nearly degenerate masses
  - baryon asymmetry via leptogenesis & sphalerons

Mixing of active and heavy sterile ν's

- Dirac mass term m_D results from Higgs coupling: $m_D = Y_{I\alpha} \cdot \upsilon$
- heavy RH neutrinos N_I mix with light LH active neutrinos ν_α via the Higgs field:

$$U_{I\alpha} = \frac{Y_{I\alpha}\upsilon}{\sqrt{2}M} \quad \longleftrightarrow$$



- life time/decay probability of N_I depends on transition probability U^2

Cosmological constraints on mixing

- Dirac mass term m_D results from Higgs coupling: $m_D = Y_{I\alpha} \cdot \upsilon$
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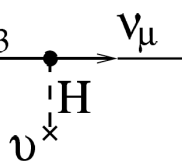
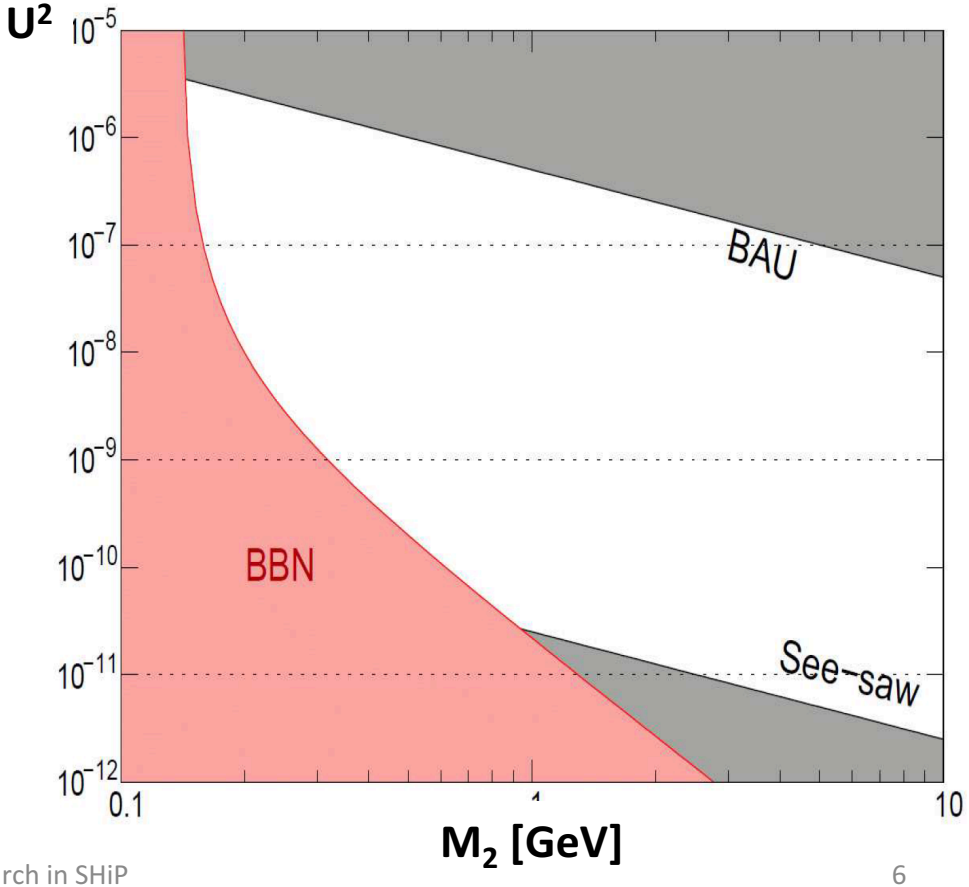


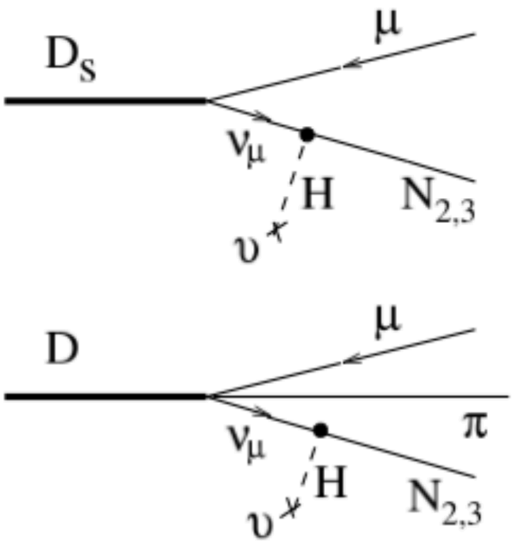
- life time/decay probability of N_I depends on transition probability U^2
- **Cosmological constraints on U^2**
  - **See-saw** mechanism: minimum to explain ν masses
  - maximum to obtain right level of **baryon asymmetry (BAU)**
  - maximum life time of $\tau_{2,3} \leq 0.1s$ not to interfere with **BBN**



HNL interaction with SM particles

HNL production

- (semi-)leptonic decays of heavy mesons:
  $K \to \mu\nu$, $D \to \mu\nu X$, $B \to \mu\nu X$, $Z \to \nu\bar{\nu}$
- mixing probability: U_2^2



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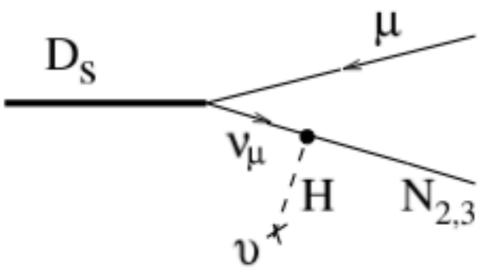
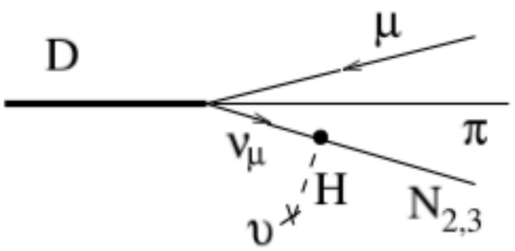
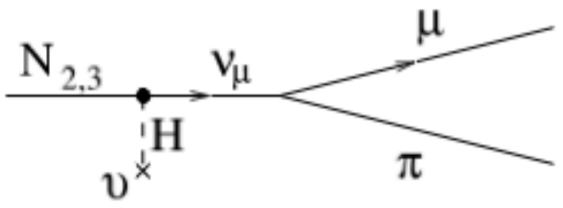
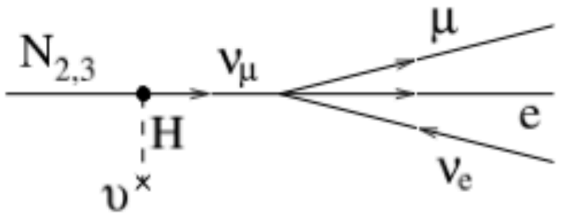




→ HNL detection in meson decays: $\propto U^4$





HNL decay

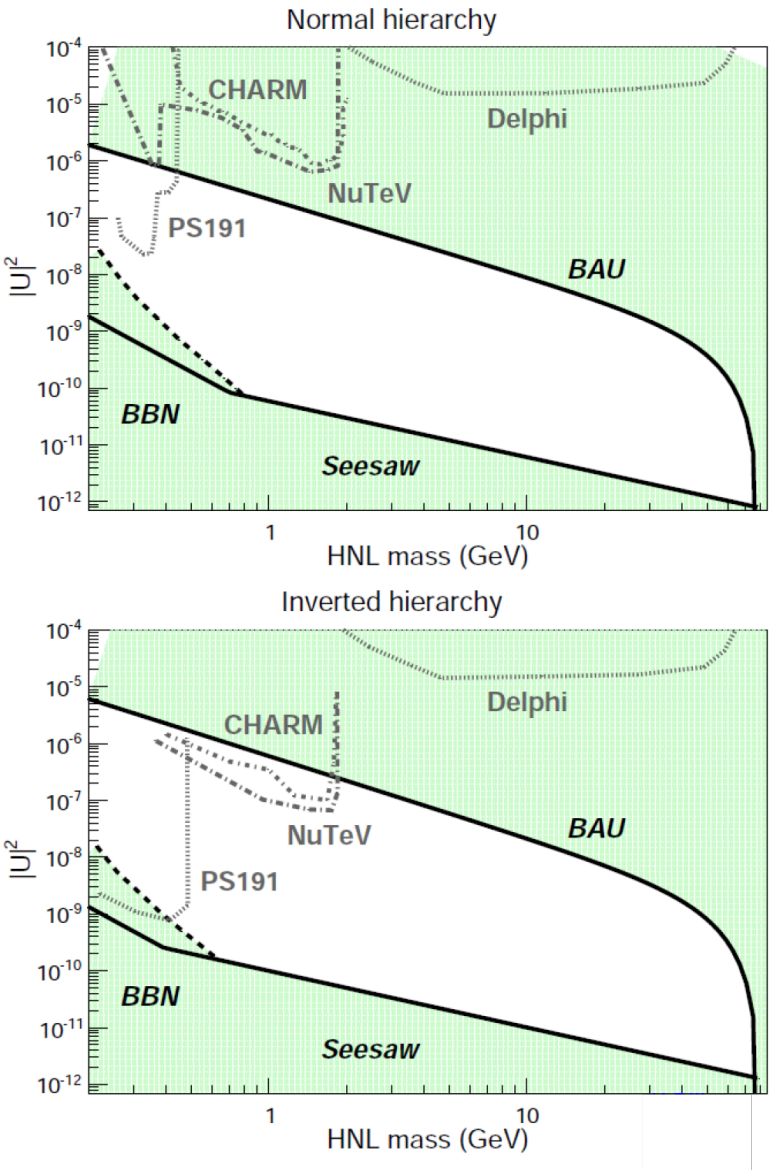
- into leptons and light mesons:
  - *0.1-50%* : $N \to \mu/e\,\pi$
  - *0.5-20%* : $N \to \mu/e\,\rho$
  - *1-10%* : $N \to \nu\mu e$
- life time $\tau \sim U^{-2}$
- decay length: $c\tau \sim O(km)$

Current limits on HNL parameters

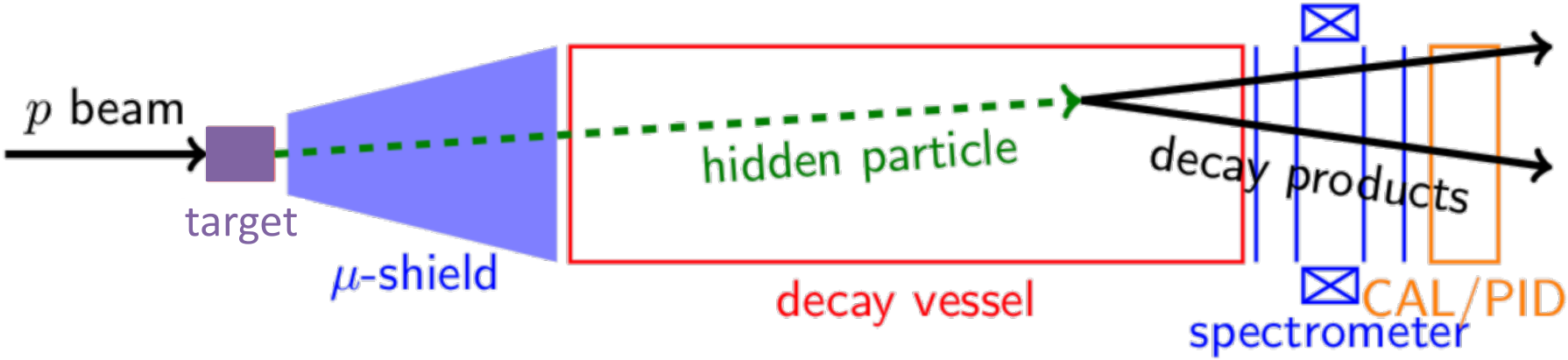
Experimental limits from K/D/Z decays:

- PS191('88)@PS 19.2 GeV, 1.4×10^{19} pot, 128 m from target.
- CHARM('86)@SPS 400 GeV, 2.4×10^{18} pot, 480 m from target.
- NuTev('99)@Fermilab 800 GeV, 2.5×10^{18} pot, 1.4 km from target.
- DELPHI('97)@LEP 91 GeV, $\sim 10^6$ $Z^0 \to \nu\bar{\nu}$.

[SHiP: 2.0×10^{20} pot @ 400 GeV]

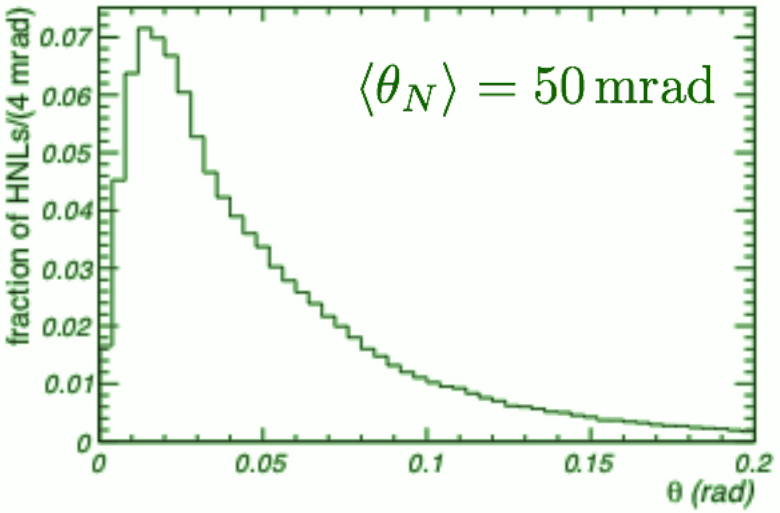


Basic layout for HNL search

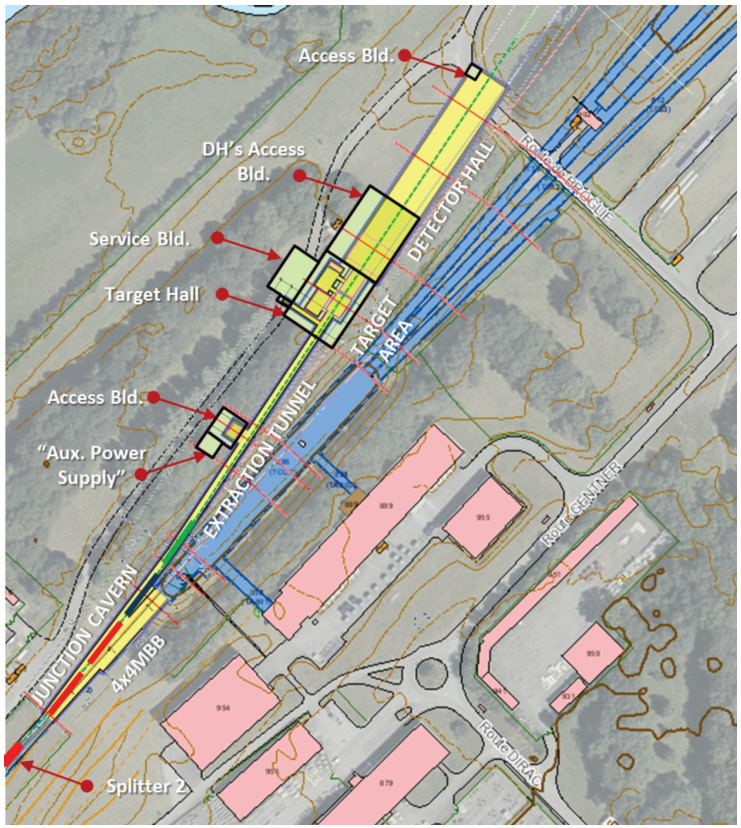


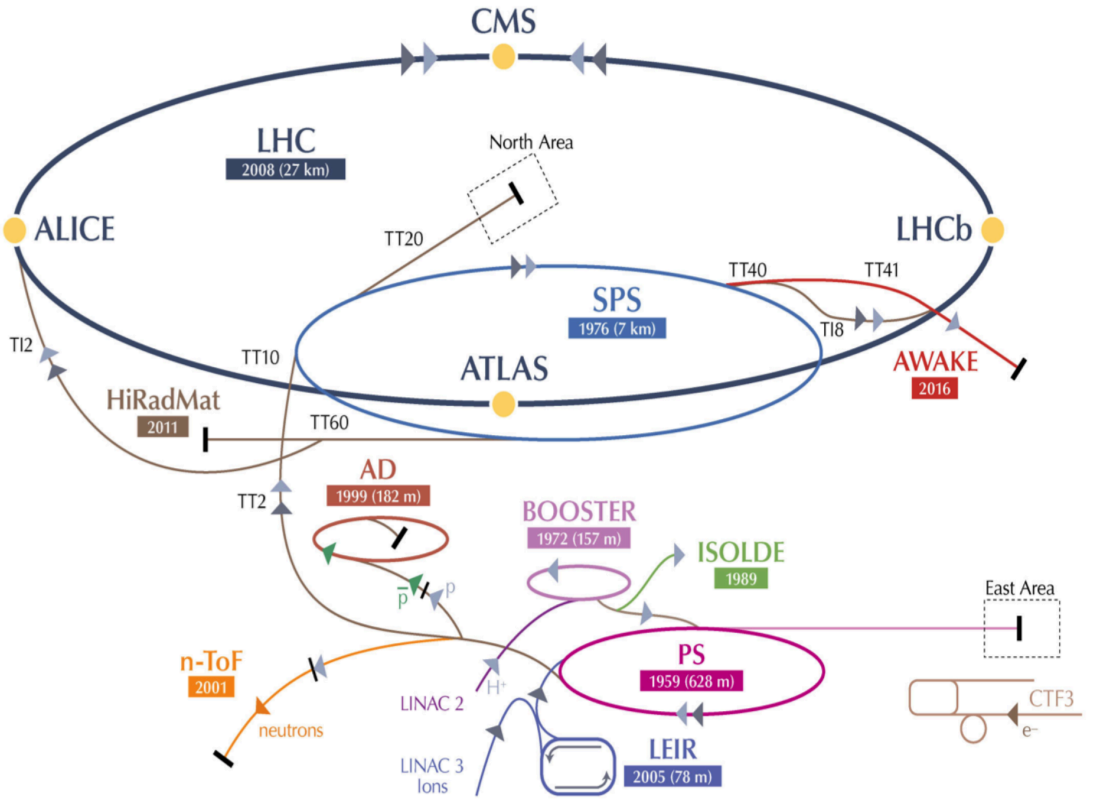
Proton Beam Dump experiment

- light neutrinos ν_e / ν_μ are background
  → **heavy W target** to avoid π/K decay
- large opening angle of HNL
  → place **detectors** close to target
- enormous muon background
  → **active muon shield (magnet!)**
- background from neutrino interactions
  → evacuate **decay vessel**



Fixed target facility @ SPS North Area



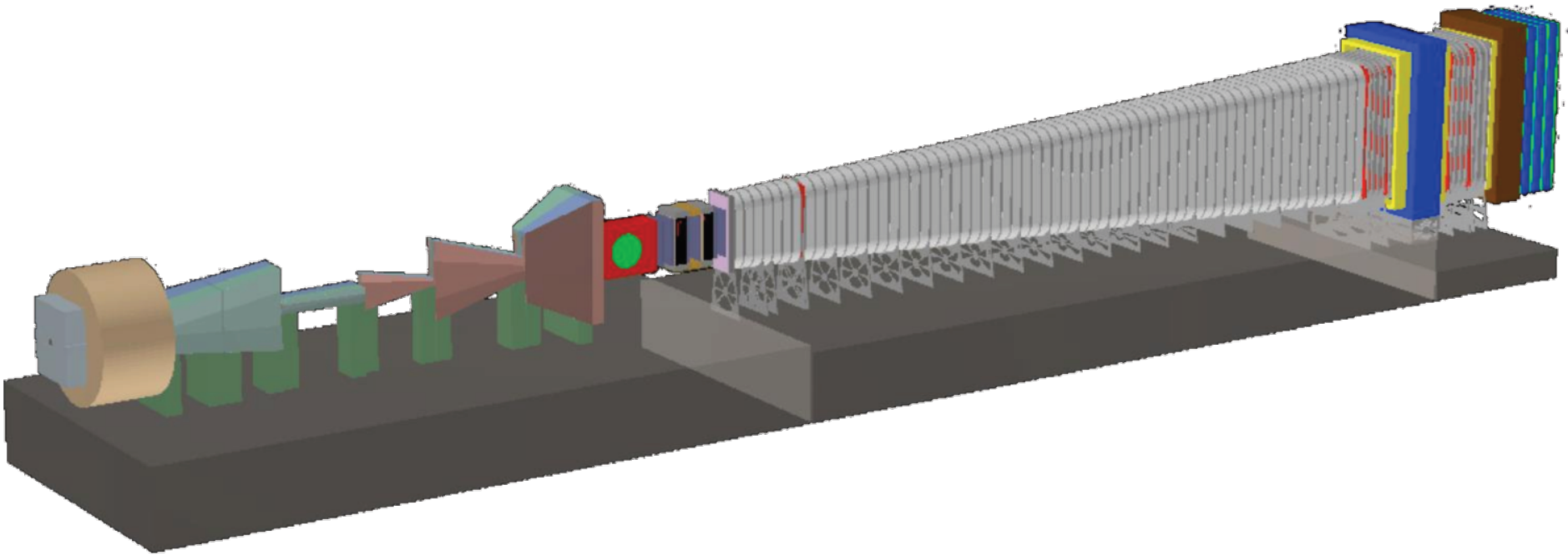


SPS performance :

- 400 GeV protons
- 4×10^{13} protons per spill (every 7s)

→ 2×10^{20} pot in 5 years

SHiP Layout [1]



SHiP Layout [2]

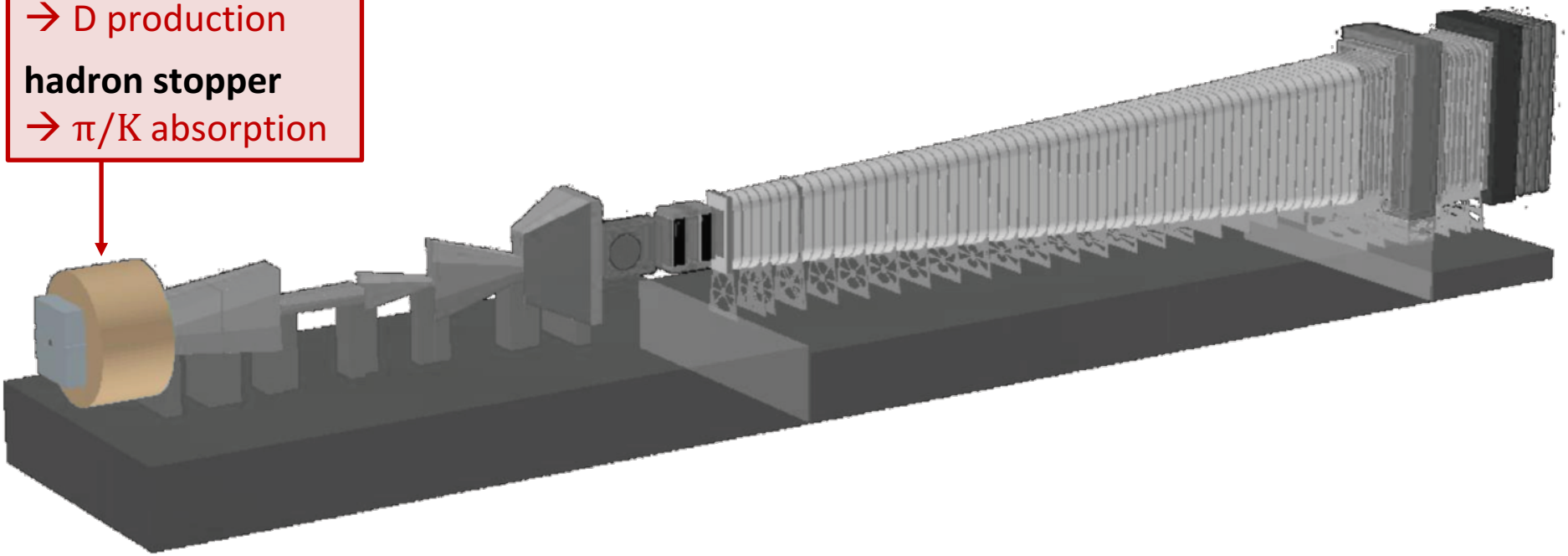
fixed target
- 58cm Mo-TZM

\+ 58cm W ($\widehat{=} 10\lambda$)

→ D production

hadron stopper

→ π/K absorption

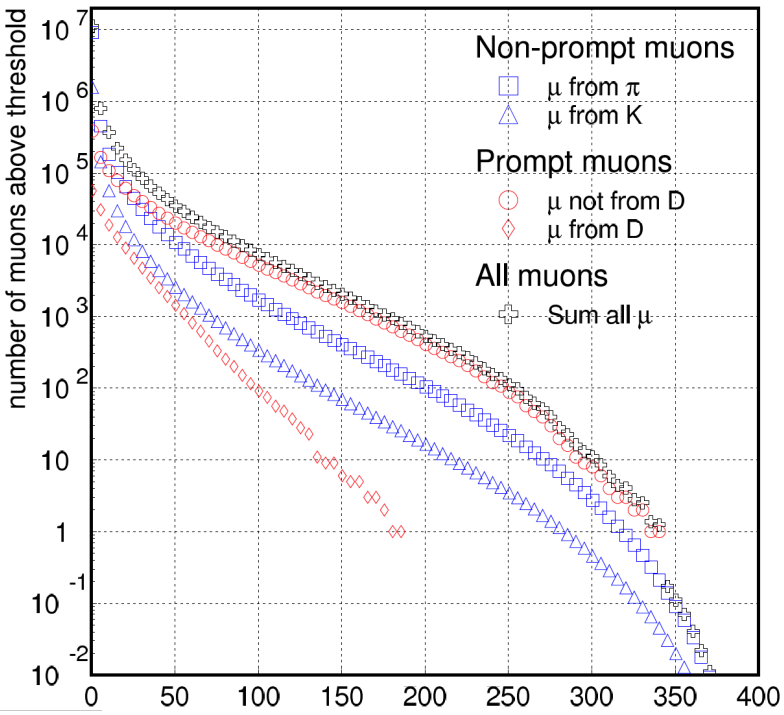


Muon background and shield

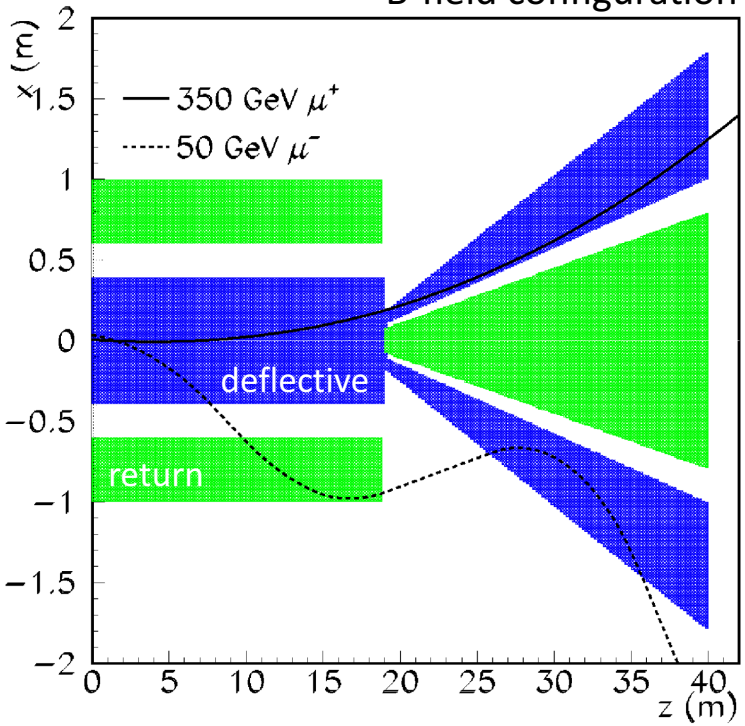
Background: Standard Model particles

- prompt muons from decay of meson resonances: η, ρ, ϕ, ω
- delayed muons from π/K decays

→ total μ-flux: 5×10^{9} per SPS spill [$5\text{x}10^{13}$ p]



B-field configuration



- acceptable for SHiP: $\sim10^{5}$ μ/spill

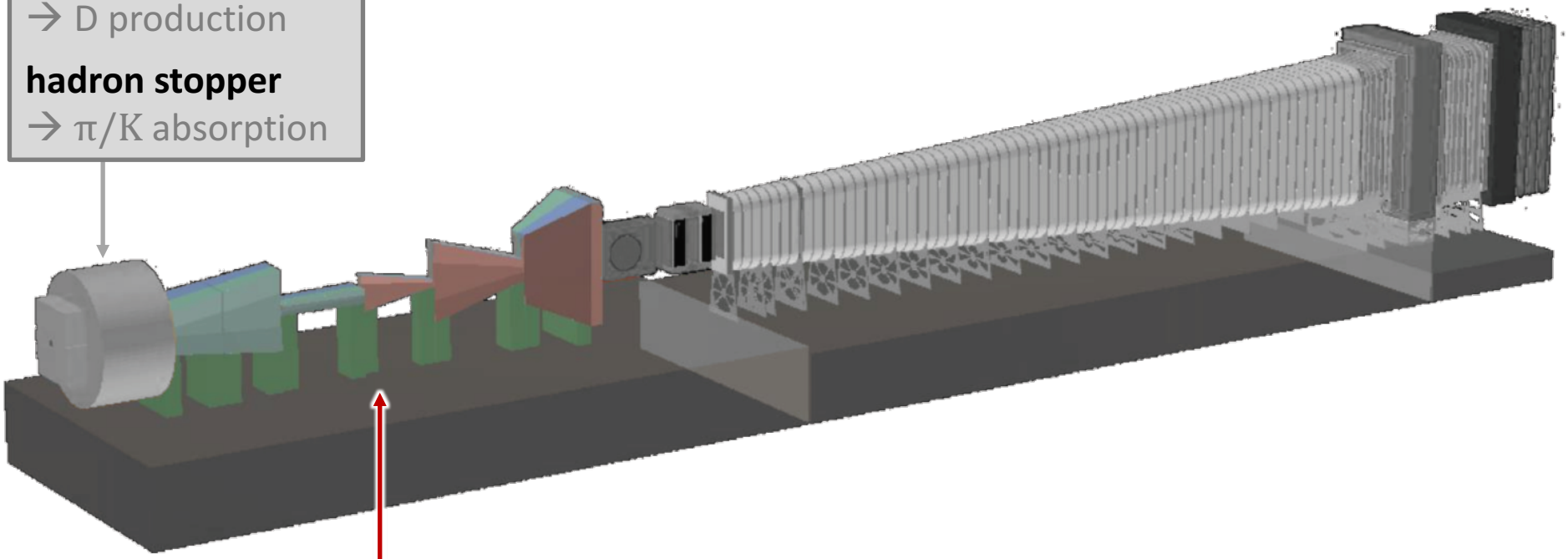
→ active muon shield for $E_{\mu} < 350$ GeV

- combination of two magnets

SHiP Layout [3]

fixed target
- 58cm Mo-TZM
+ 58cm W ($\widehat{=} 10\lambda$)
→ D production

hadron stopper
→ π/K absorption



muon shield
- 2.8 kt Fe
→ active shield & passive absorber

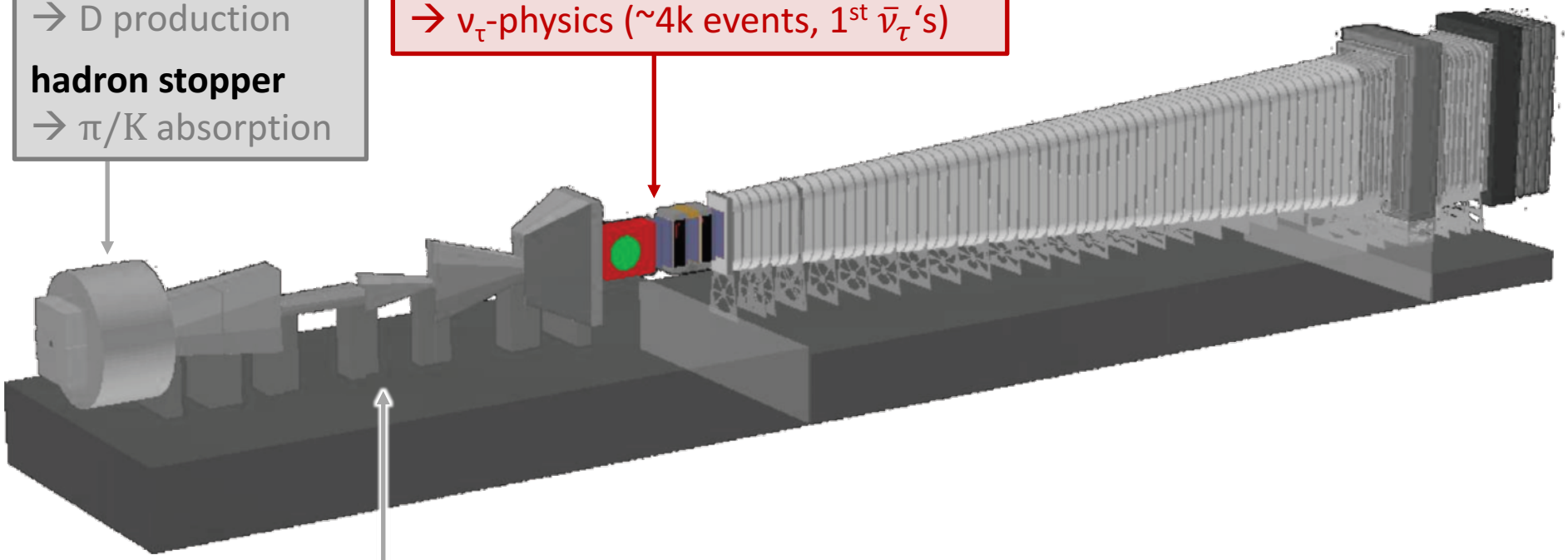
SHiP Layout [3]

fixed target
- 58cm Mo-TZM
+ 58cm W ($\widehat{=} 10\lambda$)
→ D production

hadron stopper
→ π/K absorption

Emulsion spectrometer
- OPERA-like lead-emulsion-bricks
- muon spectrometer

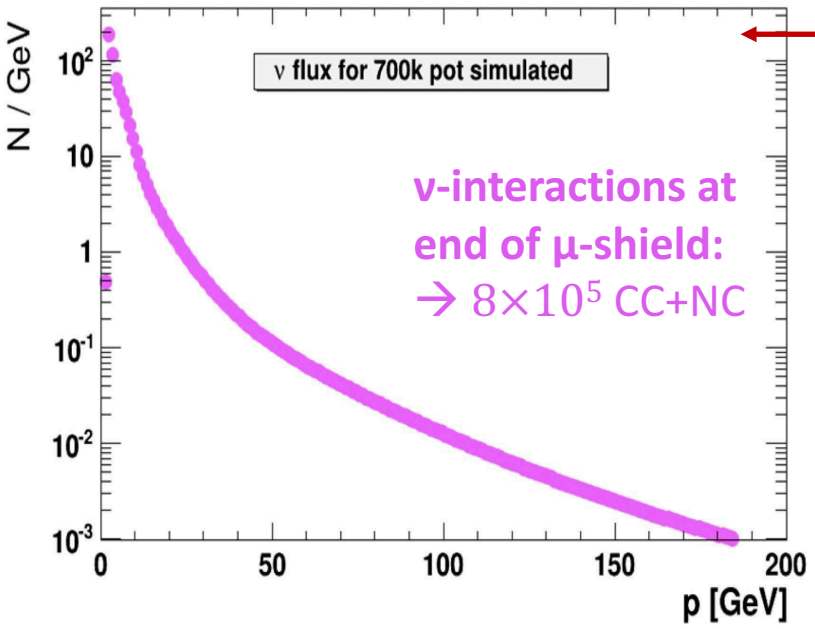
→ ν_τ-physics (~4k events, 1st $\bar{\nu}_\tau$'s)



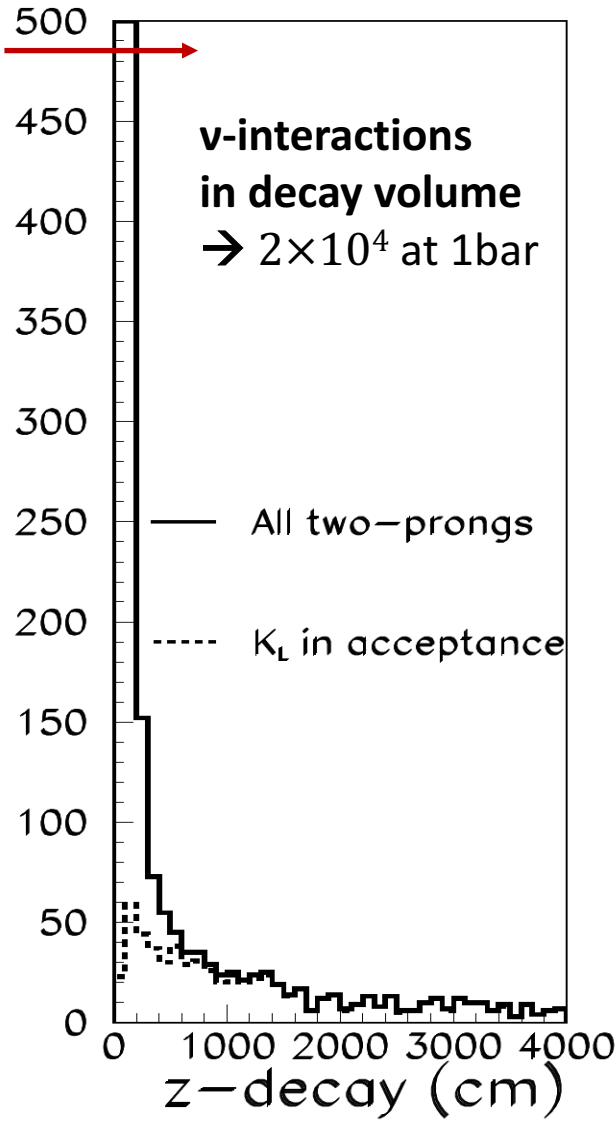
muon shield (34m)
- 1.8 kt Fe

→ active shield & passive absorber

Neutrino background and decay vessel



for 2×10^{20} pot:



→ evacuate **decay volume** to 10 μbar

→ veto chambers following the **active shield**:
removes ν-induced short-lived mesons: $K_S\,\Lambda$ …

→ remaining ν-induced background: $K_L \to \mu\pi\nu$

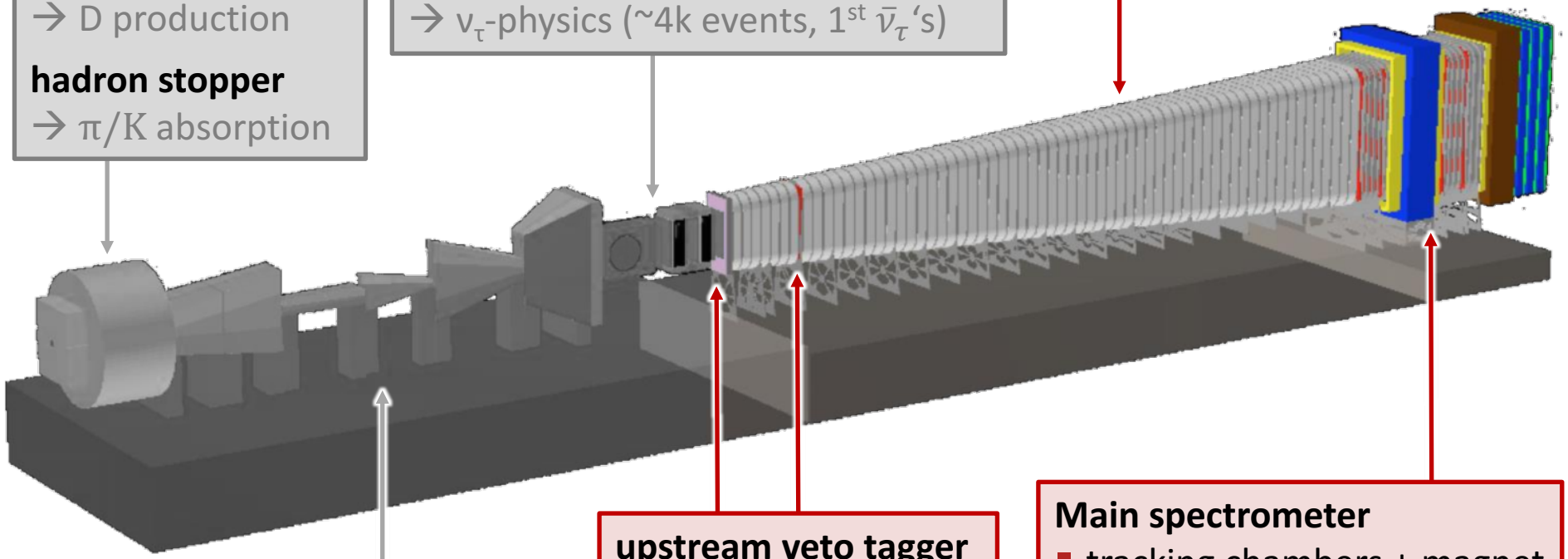
SHiP Layout [4]

fixed target
- 58cm Mo-TZM
+ 58cm W ($\widehat{=} 10\lambda$)
→ D production

hadron stopper
→ π/K absorption

Emulsion spectrometer
- OPERA-like lead-emulsion-bricks
- muon spectrometer
→ ν_τ-physics (~4k events, 1st $\bar{\nu}_\tau$'s)

evacuated decay vessel (50m)
+ Surround Background Tagger

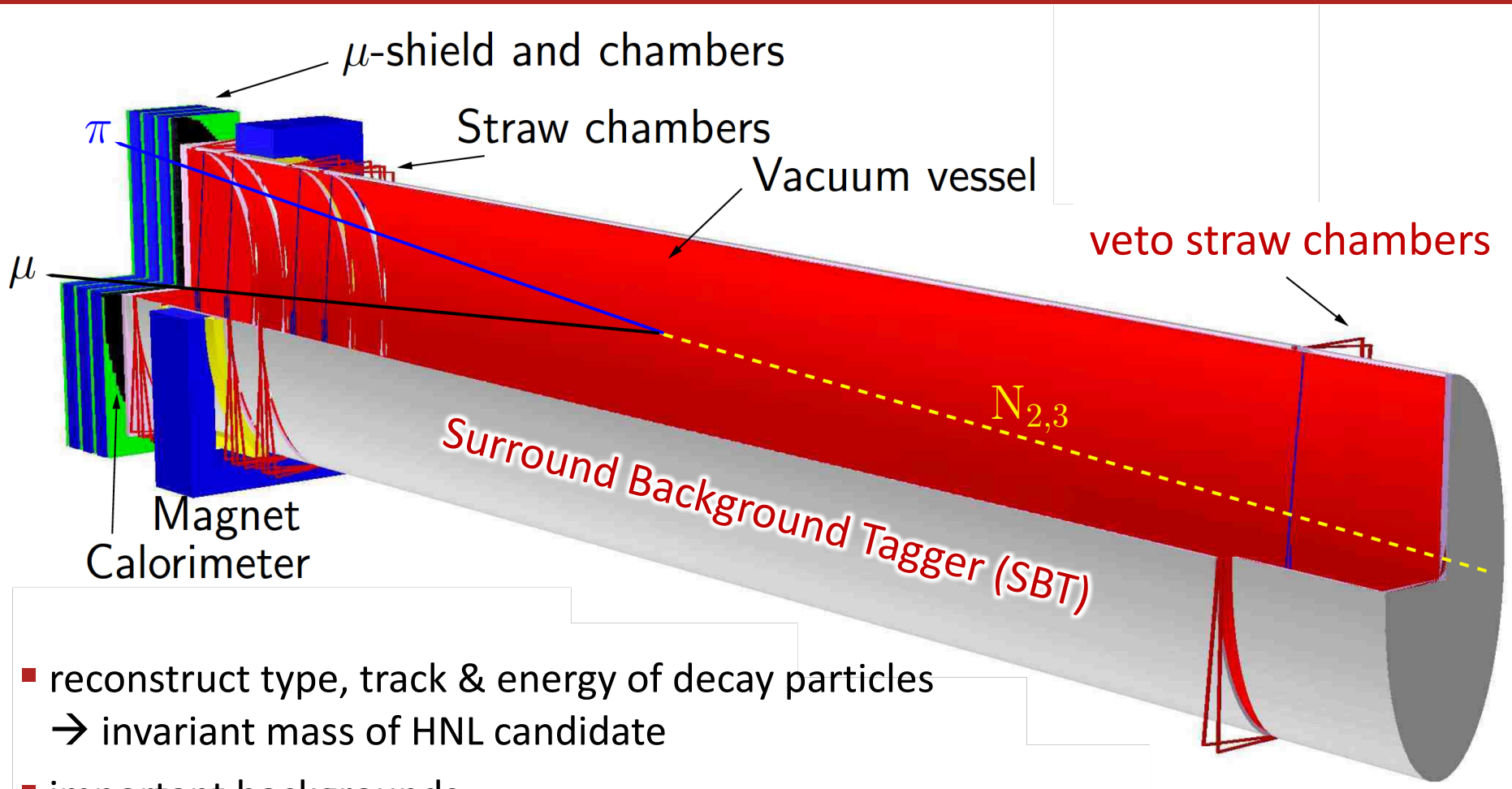


muon shield (34m)
- 1.8 kt Fe
→ active shield & passive absorber

upstream veto tagger + straw chambers
→ veto **ν** events
+ residual **μ**'s

Main spectrometer
- tracking chambers + magnet
- electric calorimeter
- muon filters

HNL search



- reconstruct type, track & energy of decay particles
  → invariant mass of HNL candidate
- important backgrounds:
  - neutrino interactions
  - long-lived mesons
  - combinatoric di-μ events

veto strategies
- based on event kinematics (source ≠ target)
- surrounding veto/tagging detectors

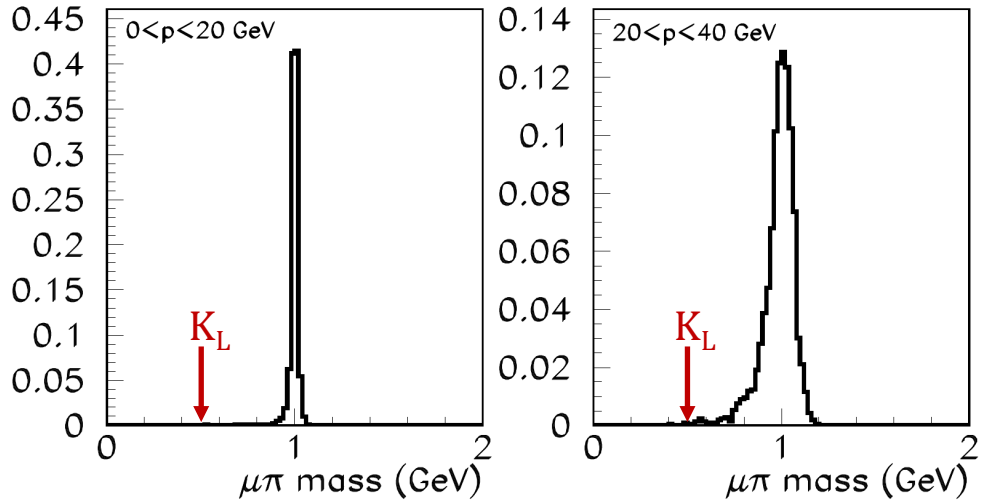
Example: Veto $K_L \to \pi\mu$ from ν interactions

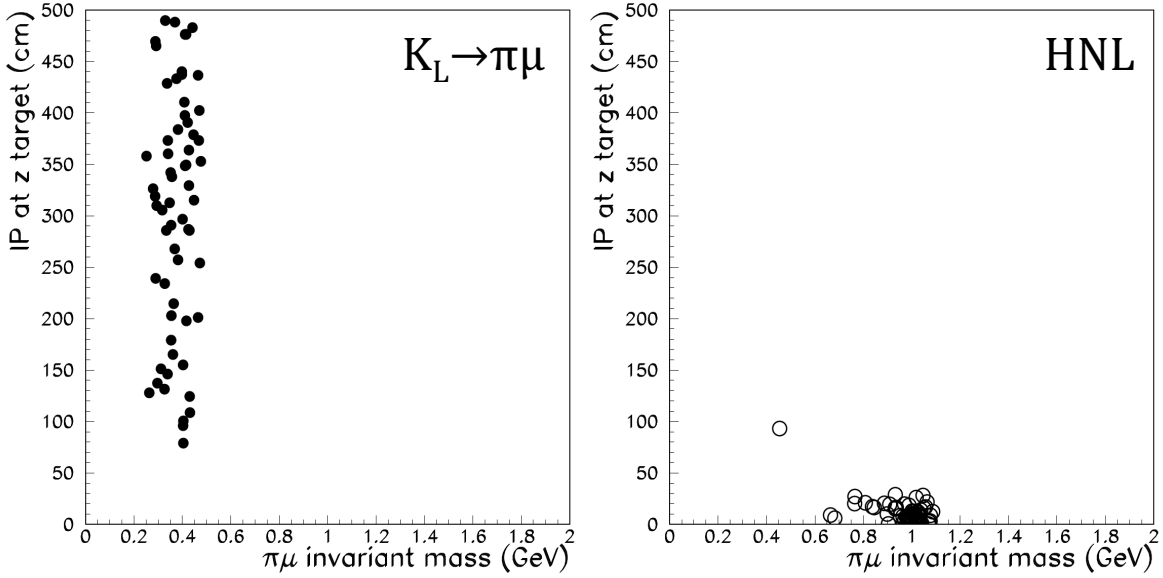
Assuming an **HNL of $m_N = 1\text{GeV}$:**

Invariant mass

- design resolution: $\Delta m \sim 15\text{MeV}$

→ K_L mass can be distinguished





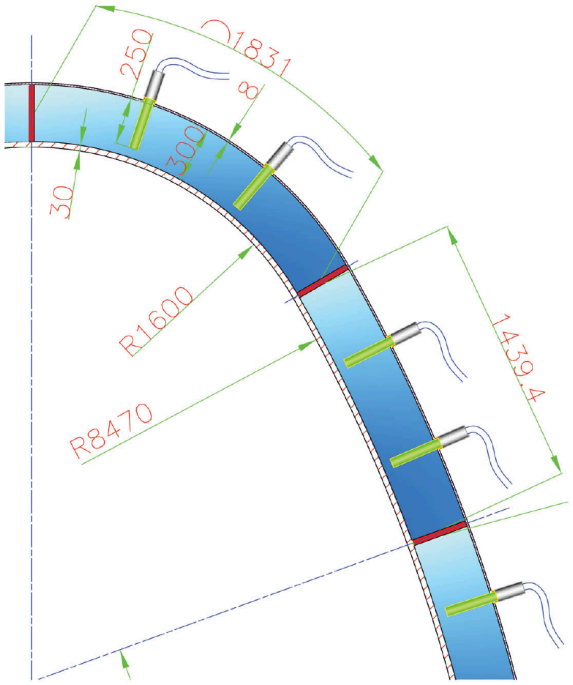
Impact parameter

- HNL produced in target
  → $IP = 0$
- K_L produced in ν interactions
  → other final state particles
  → $IP \neq 0$!

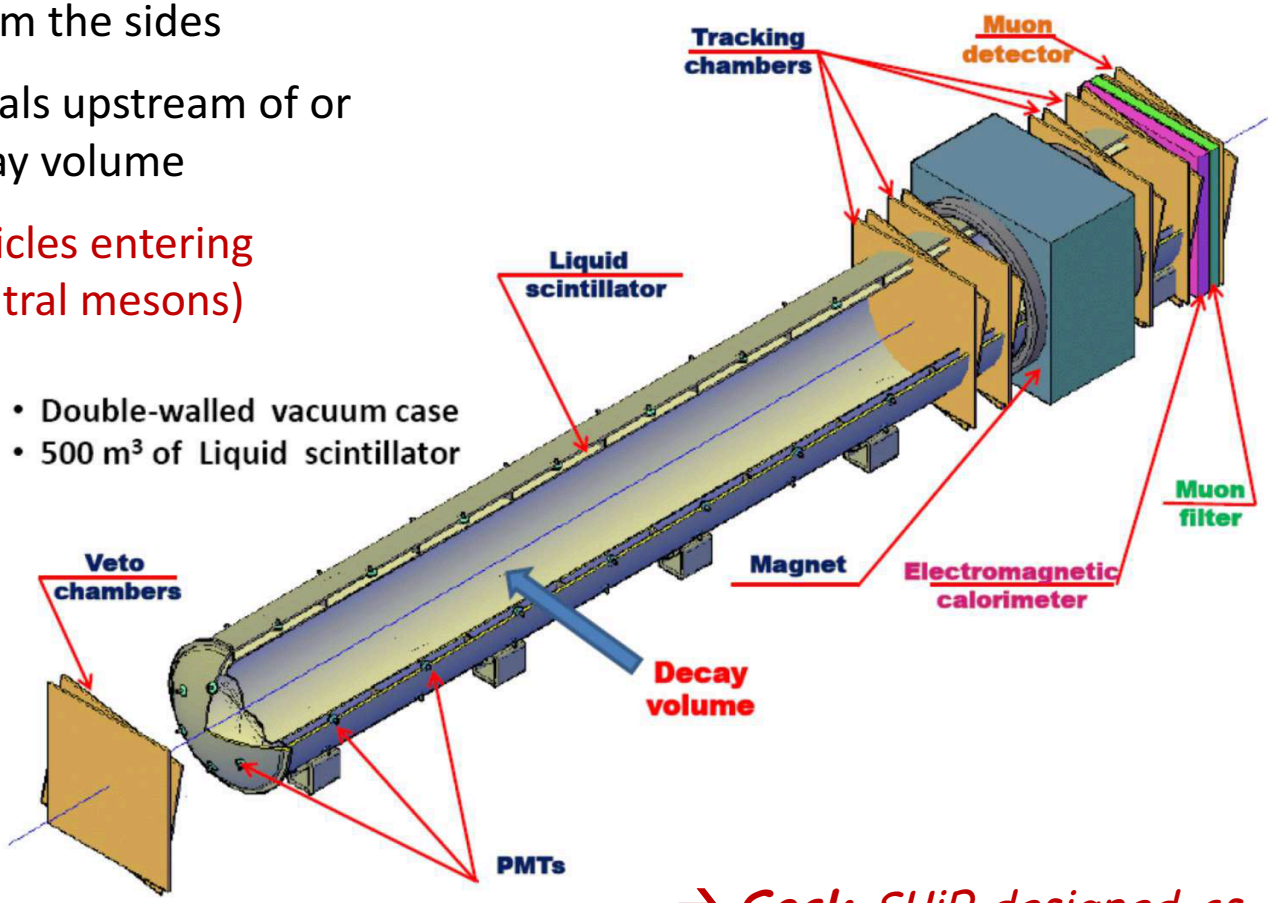
Surround Background Tagger (SBT)

- SM particles, e.g. **beam-induced or cosmics muons**, may enter decay volume from the sides
- **Neutrinos** interact in materials upstream of or surrounding (80%!) the decay volume

→ SBT identifies charged particles entering (veto for accompanying neutral mesons)

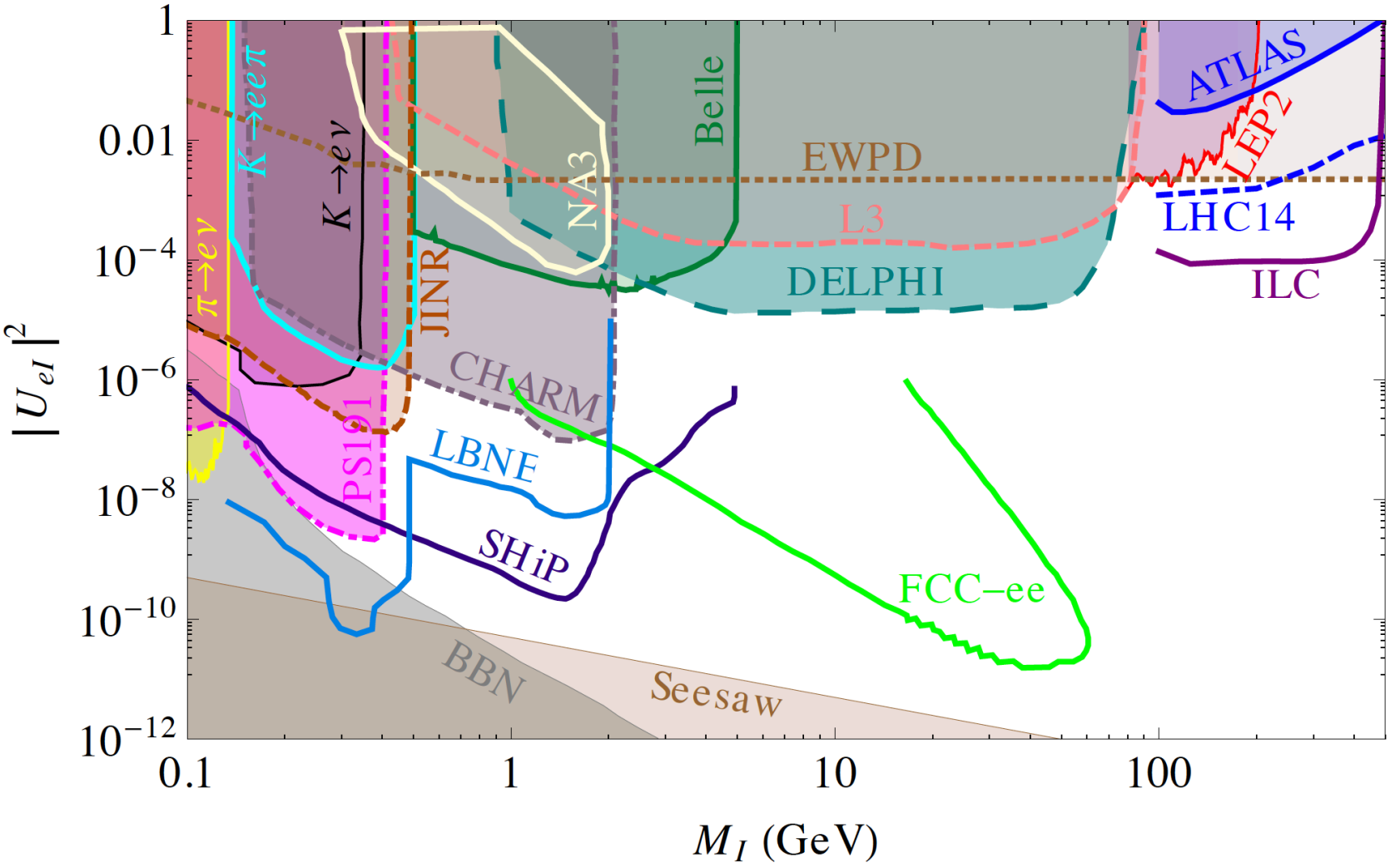


← cross-section of the SBT cells: liquid scintillator (30cm) + WOMs

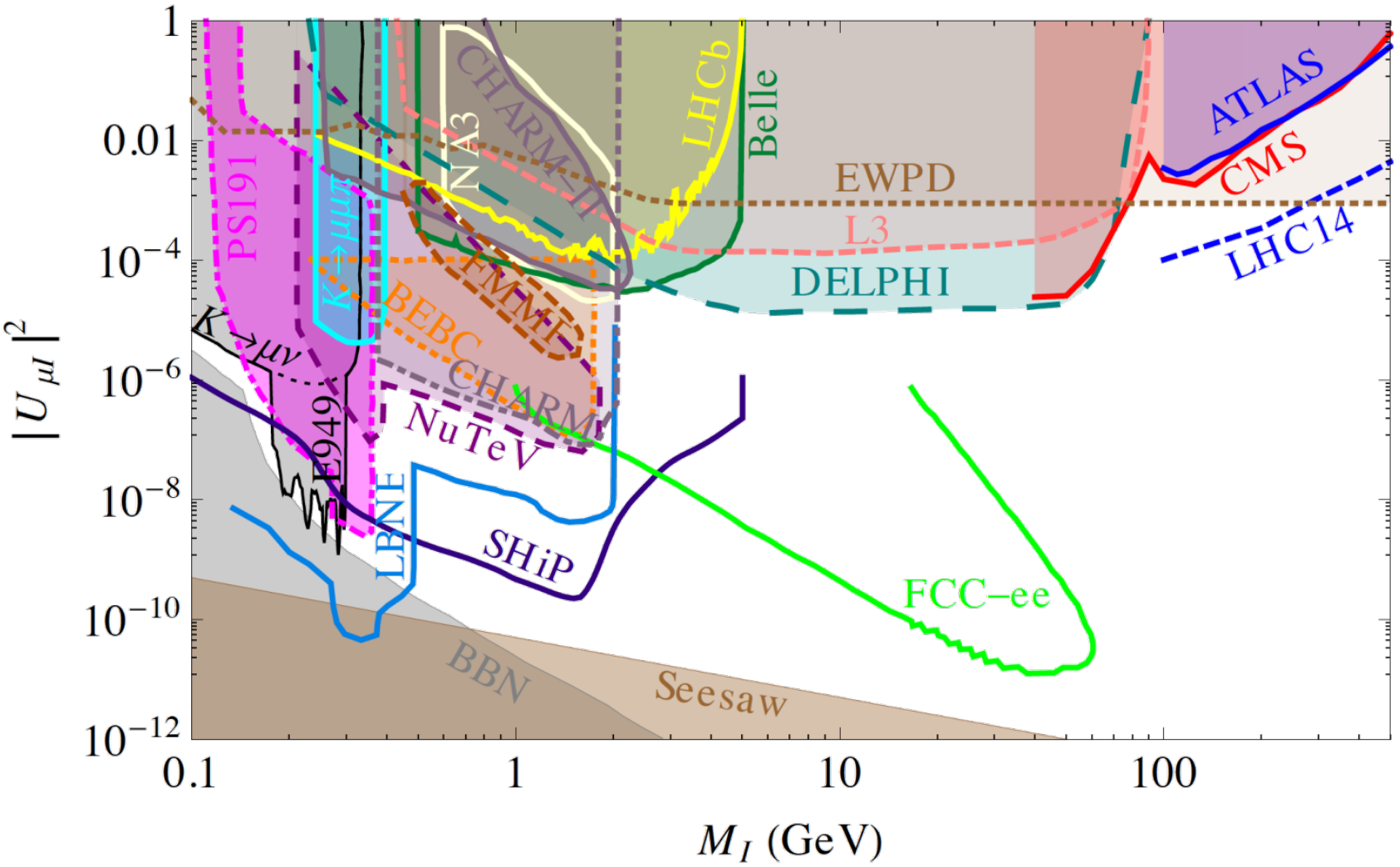


→ ***Goal:*** *SHiP designed as zero-background experiment!*

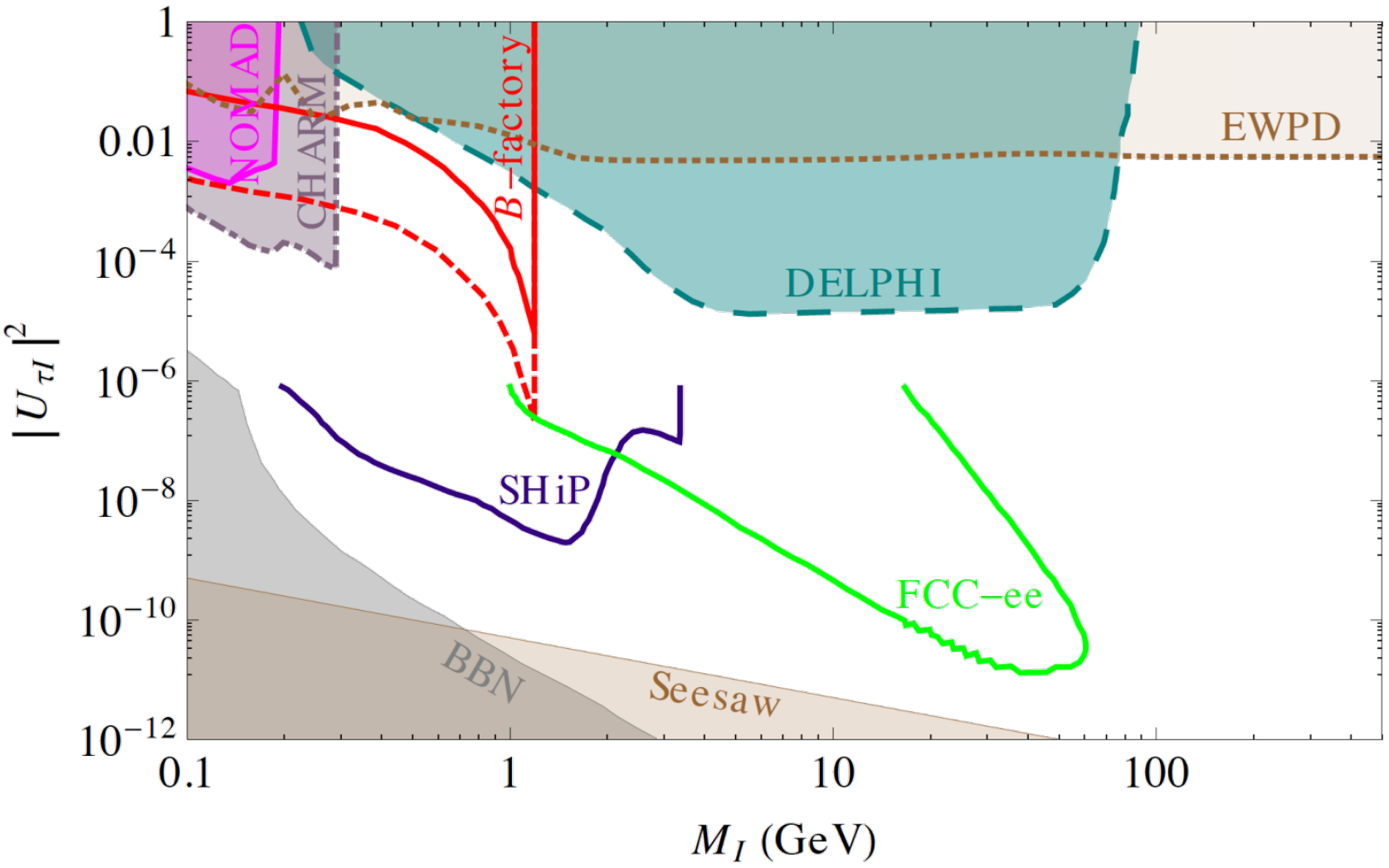
SHiP's sensitivity to HNL: $|U_{eI}|^2$



SHiP's sensitivity to HNL: $|U_{\mu I}|^2$



SHiP's sensitivity to HNL: $|U_{\tau I}|^2$



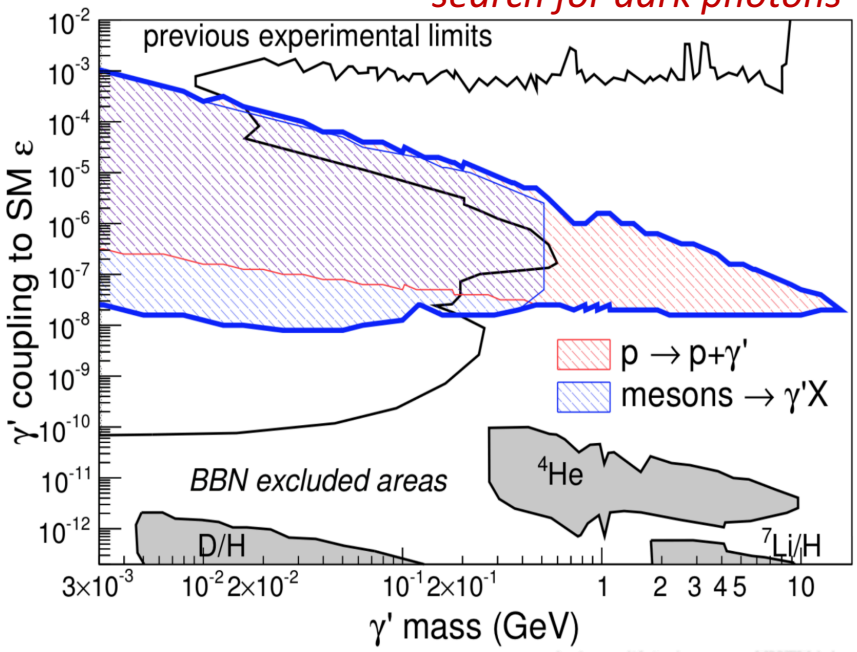
Other Hidden Sector searches

- SHiP is not limited to HNL searches!

  → variety of other potenital particles can be produced in π, K, D, B decays

- access to Hidden Sector particles:
  - production branching ratios: $\mathcal{O}(10^{-10})$
  - **long-lived:** τ of $\mathcal{O}(\mu s)$

search for dark photons



- possible final states:

Models	Final States
Neutrino portal, HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$
Vector, scalar, axion portals, SUSY sgoldstino	e^+e^-, $\mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
Neutrino portal, HNL, SUSY neutralino, axino	$\ell^+\ell^-\nu$

Status of the project

JG|U

Timeline of SHiP

2014 : SHiP collaboration founded.

2015 : Physics White Paper [arXiv:1504.04855]
and Technical Proposal [arXiv:1504.04956]

2016 : recognized as CERN experiment

2018 : Technical Design Report

2021 : start of Civil Engineering

2026 : start of Data Taking

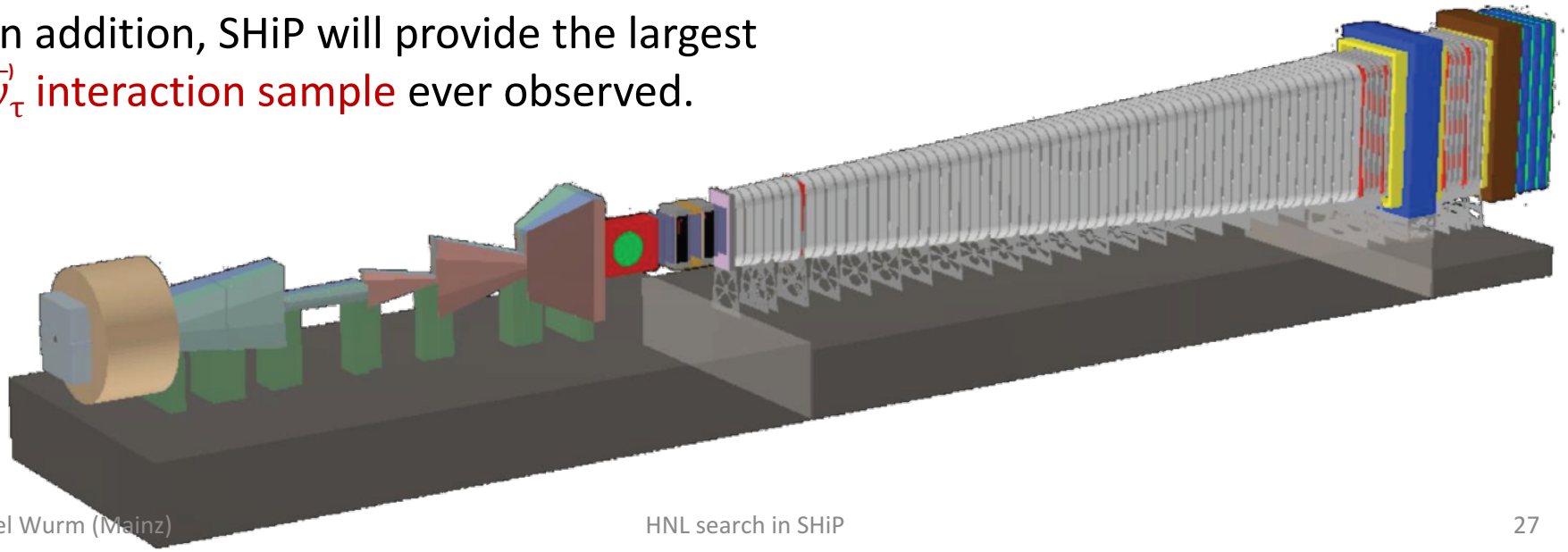
SHiP
Search for Hidden Particles

SHiP Collaboration

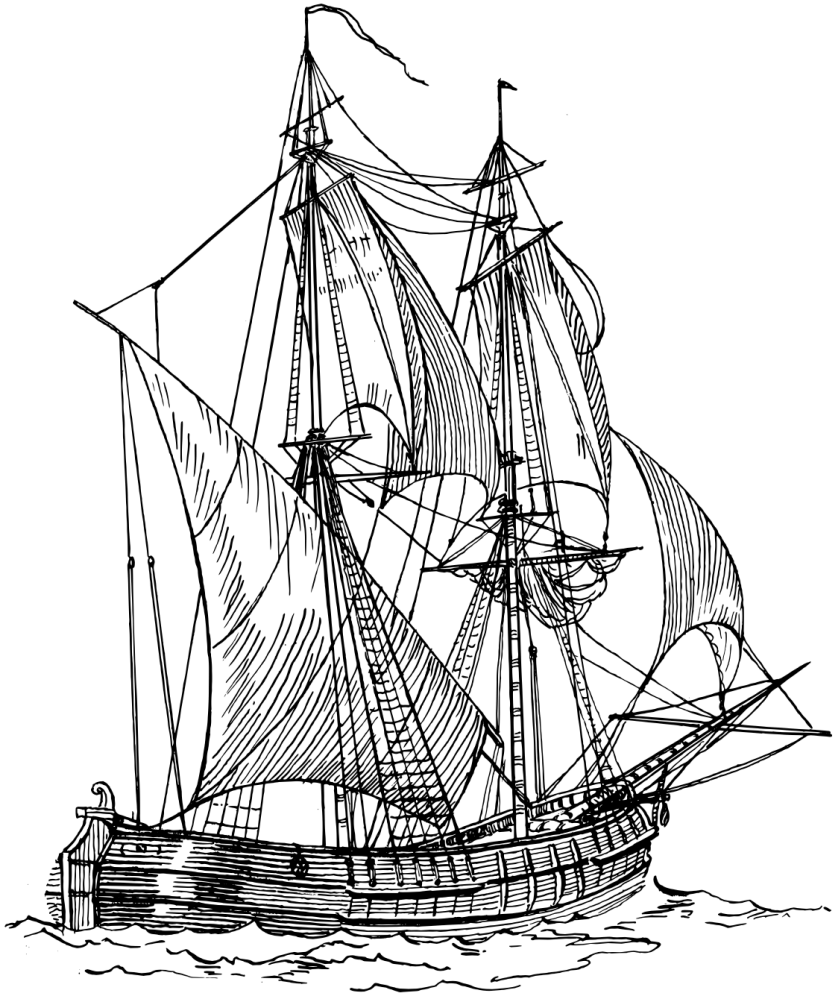
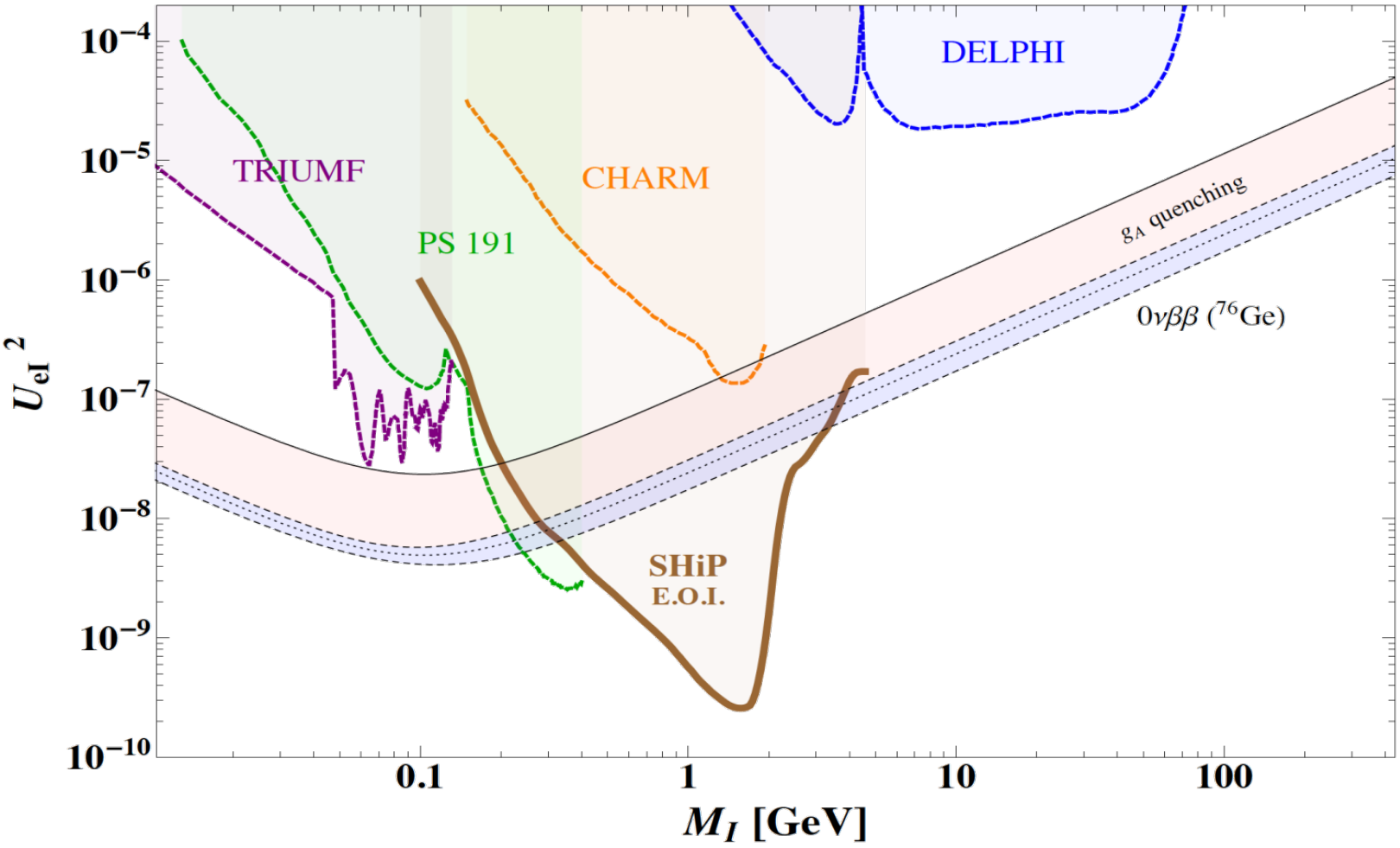
~240 scientists from 50 institutes in Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Korea, Portugal, Russia, Sweden, Switzerland, Turkey, United Kingdom and Ukraine.

Conclusions

- Heavy neutral leptons represent an attractive extension of the SM, i.e. as GeV-mass sterile neutrinos in the νMSM model.
- Up to now, the parameter space allowed by BBN, BAU and See-Saw has been hardly explored by experiments.
- Based at the CERN-SPS, SHiP will search for HNL in D-meson decays, significantly improving sensitivity with respect to current limits.
- Beyond HNL, SHiP is ideally suited to search for all kinds of long-lived neutral particles at the intensity frontier, complementary to LHC searches.
- In addition, SHiP will provide the largest $\overset{(-)}{\nu}_\tau$ interaction sample ever observed.



Backup slides



SHiP's sensitivity to non-See-Saw HNL: $|U_{eI}|^2$