SHiP
Search for Hidden Particles

New Physics Searches with SHiP

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On behalf of SHiP Collaboration

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SHiP
Search for Hidden Particles

SHiP experiment is

a fixed target experiment at the CERN SPS

complementary to the LHC

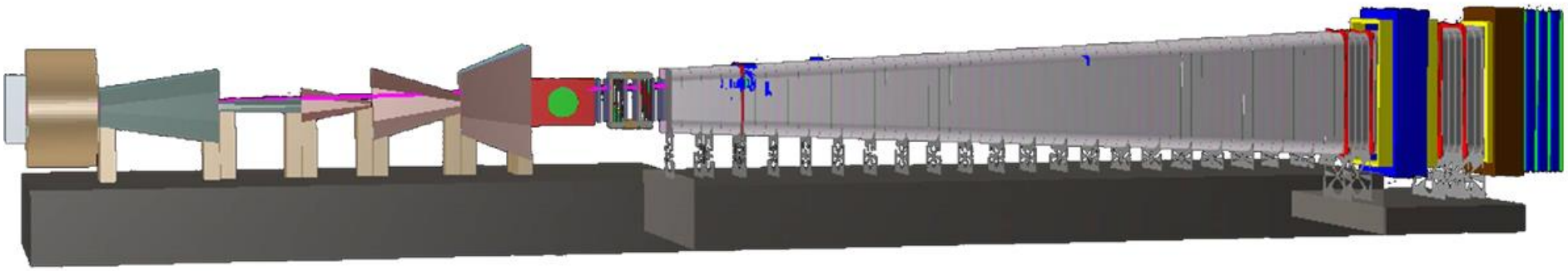
to search for hidden particles

of order GeV,

electrically neutral,

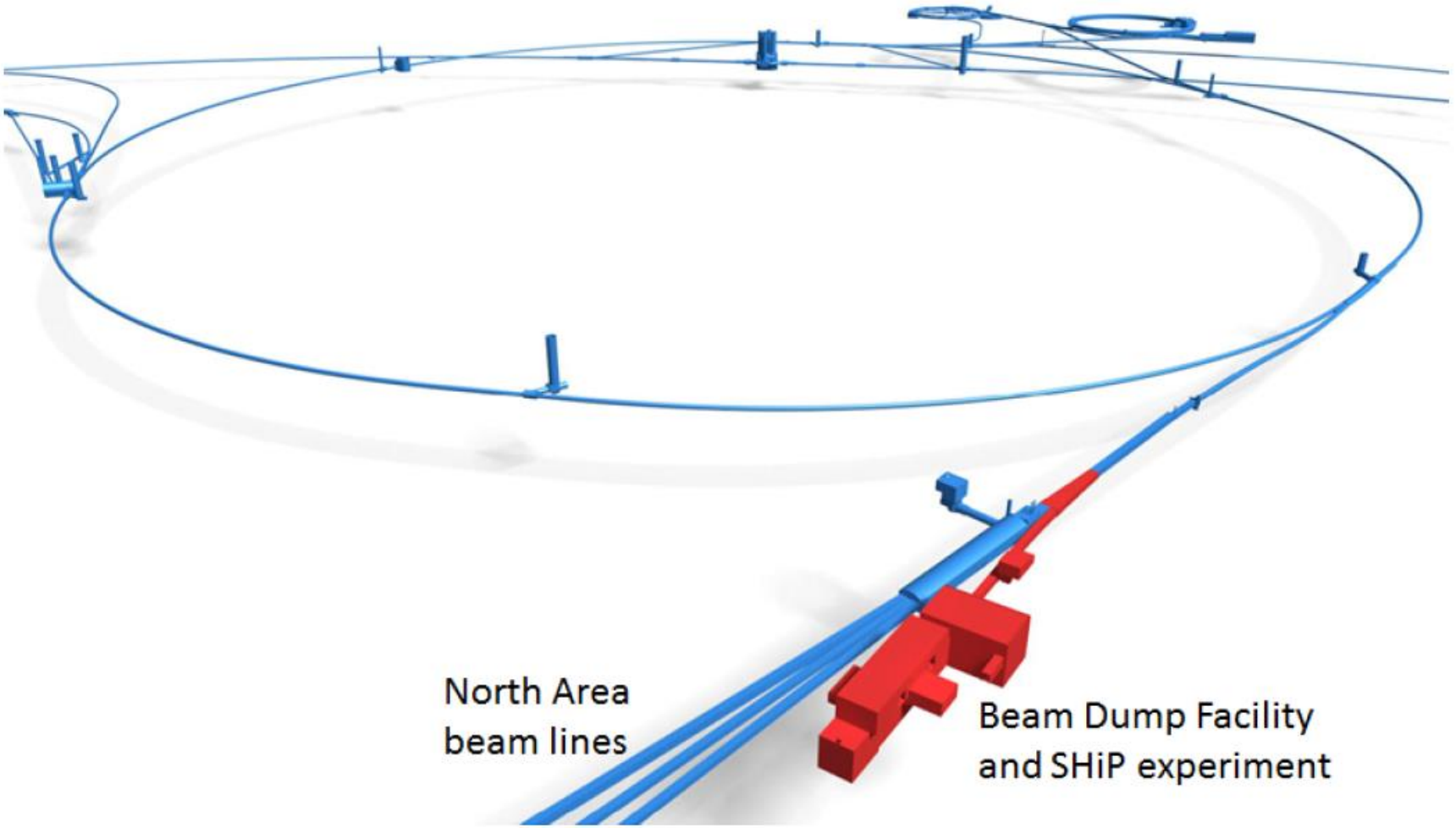
very weakly interacting

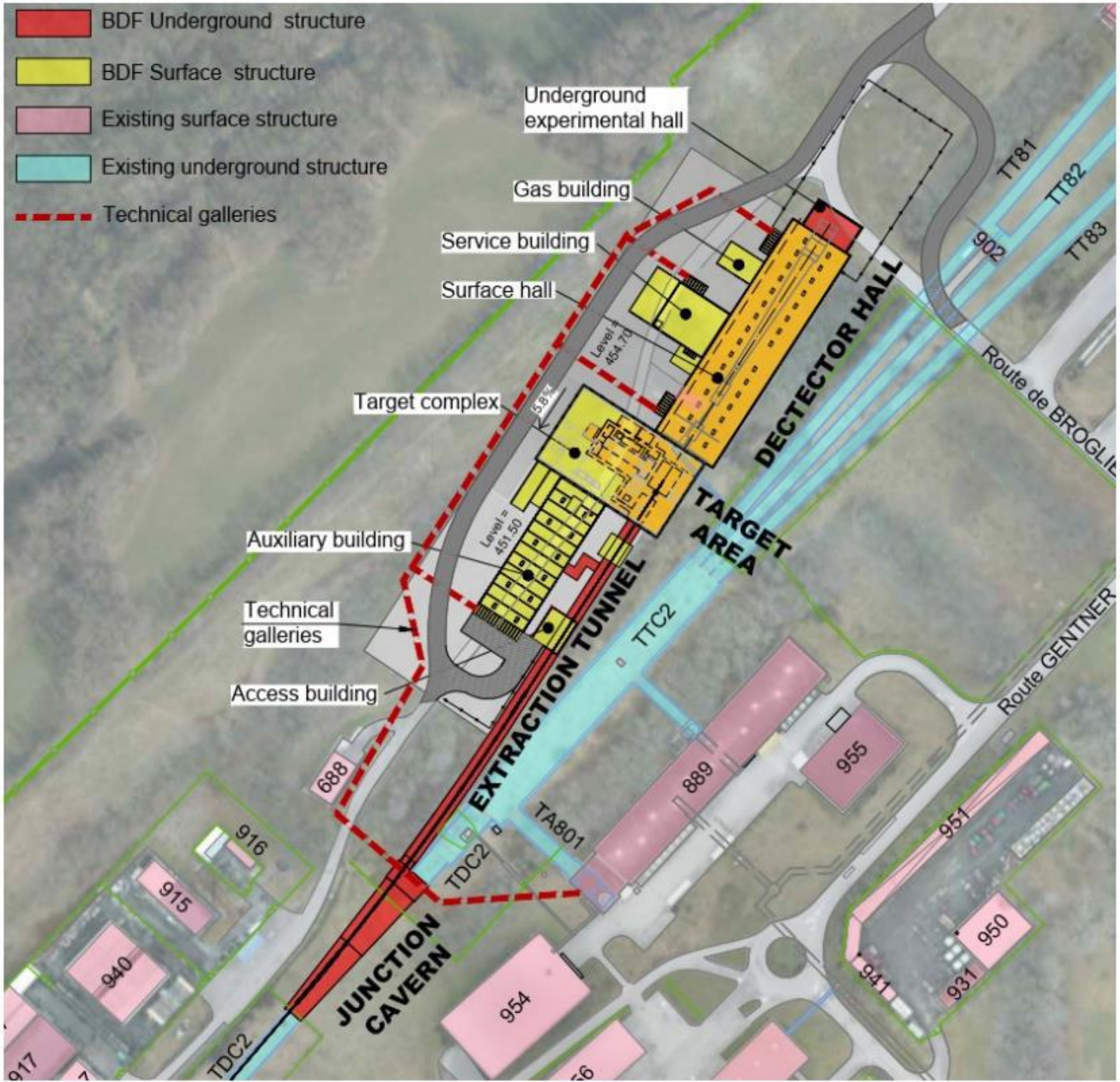
and long-lived.



SPS Beam Dump Facility

North area of the CERN





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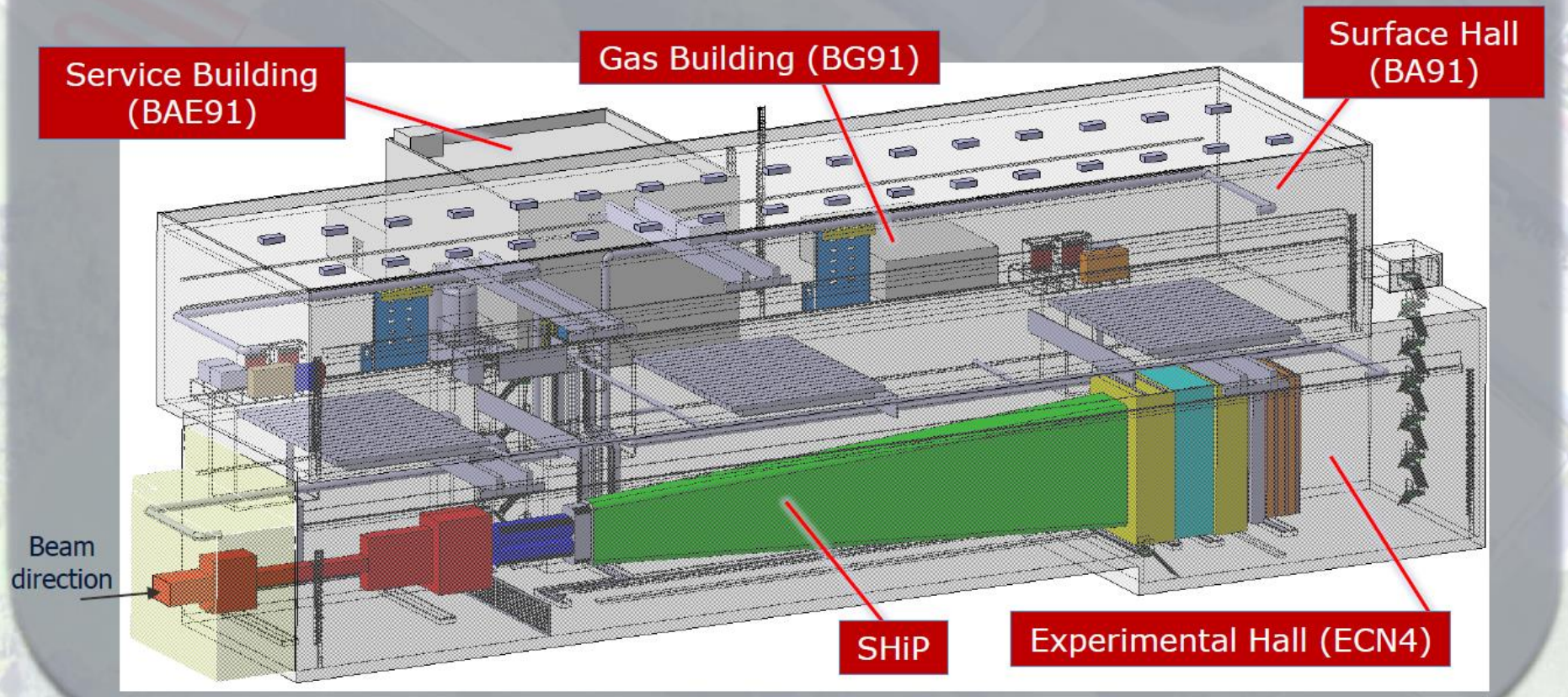
Experimental Area overview

- SHiP to be installed inside the Experimental Hall.
- Construction of the SHiP components inside the Surface Hall and Experimental Hall.



Experimental area

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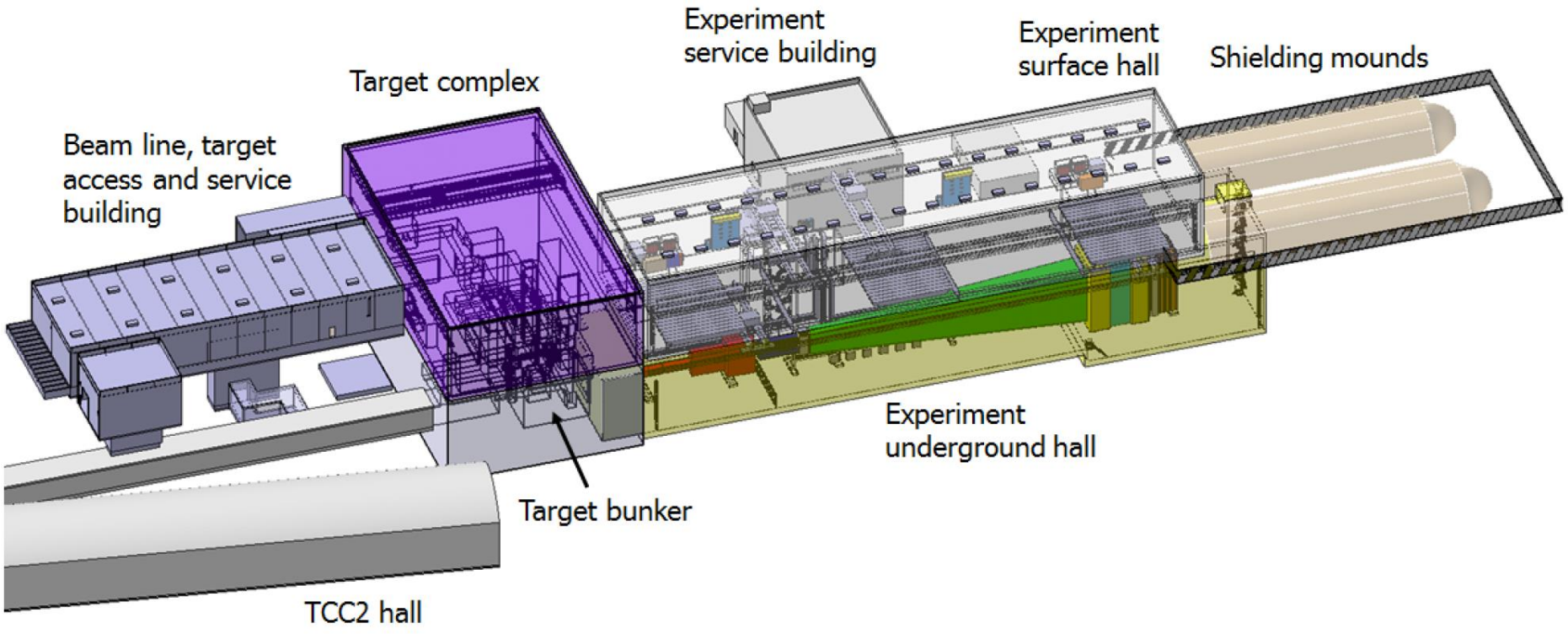

Underground experimental hall

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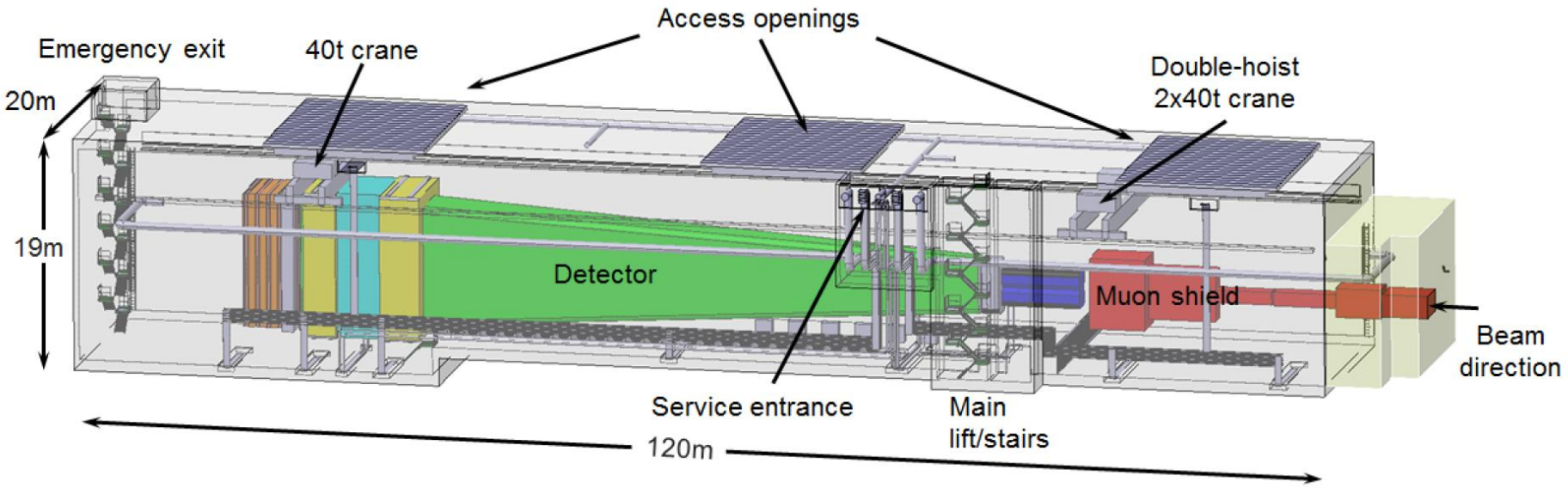


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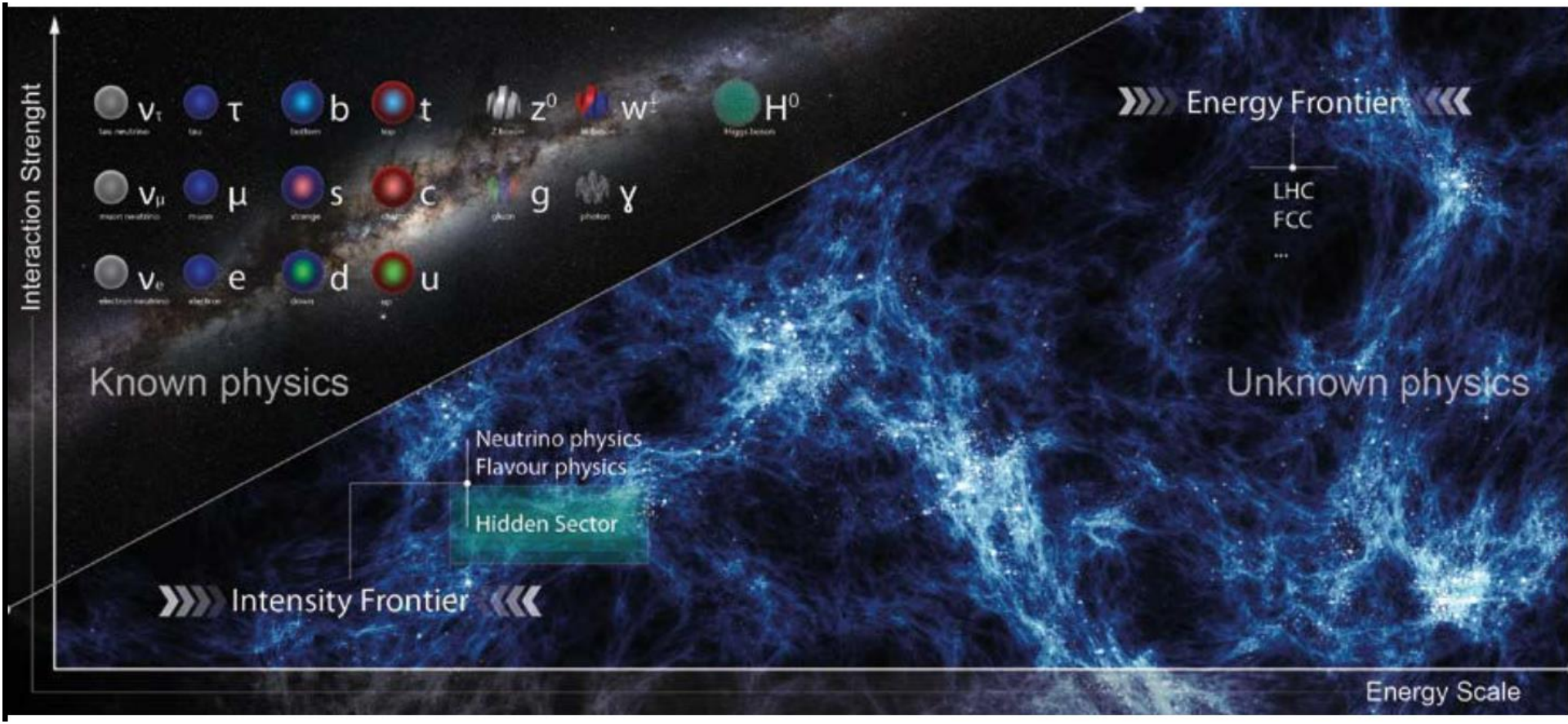
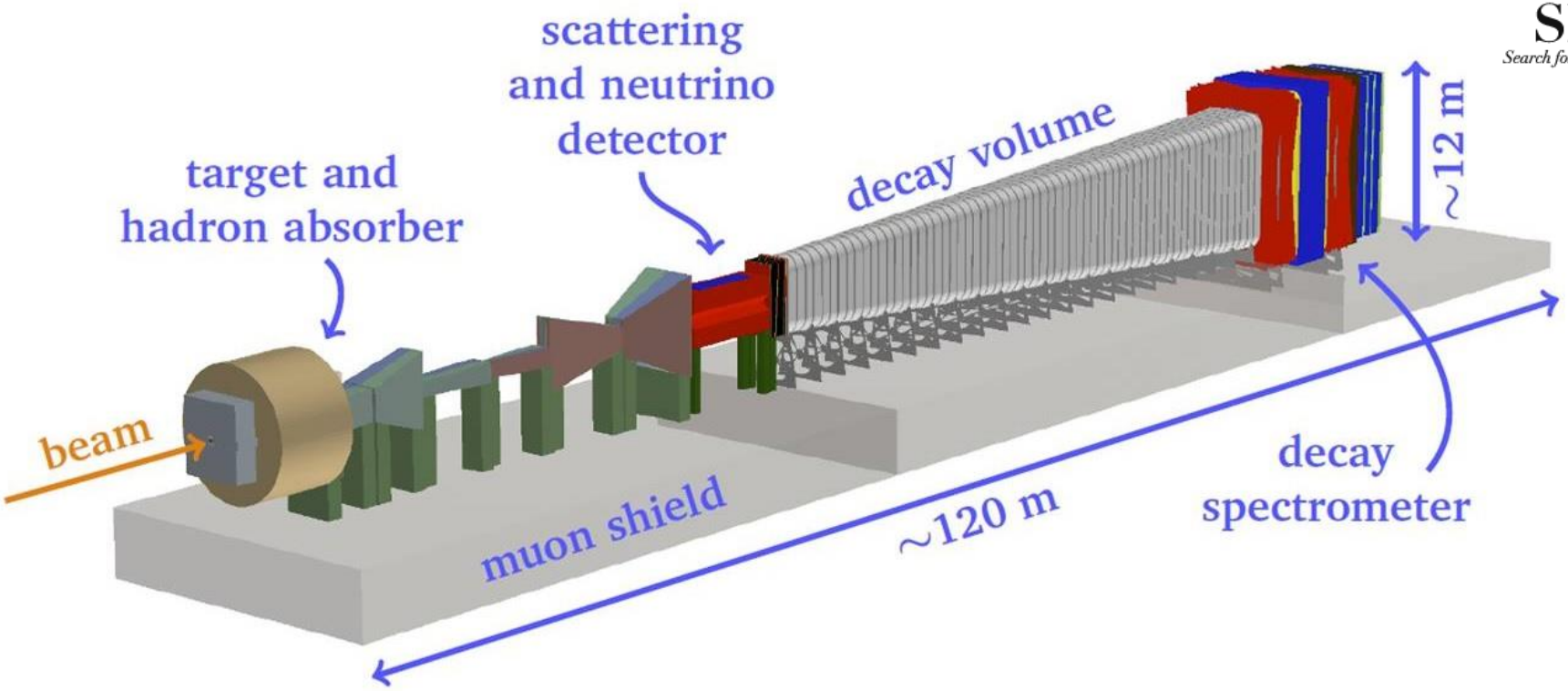
Complementary to the LHC

Intensity Frontier vs. Energy Frontier



SHiP experiment



- Fixed target facility at the CERN SPS with 400 GeV proton beam
- Zero background beam dump experiment
- Large geometric acceptance : long volume close to dump
- $2x10^{20}$ p.o.t in 5 years

Target and Shield

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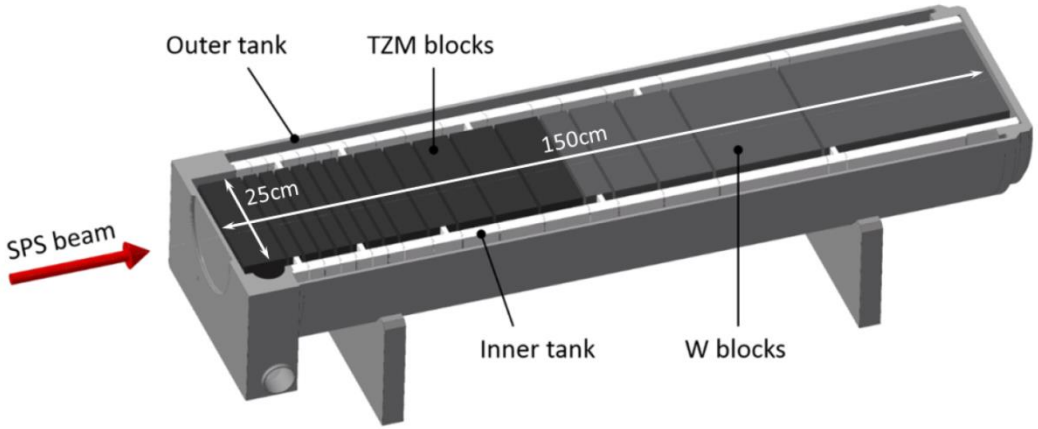
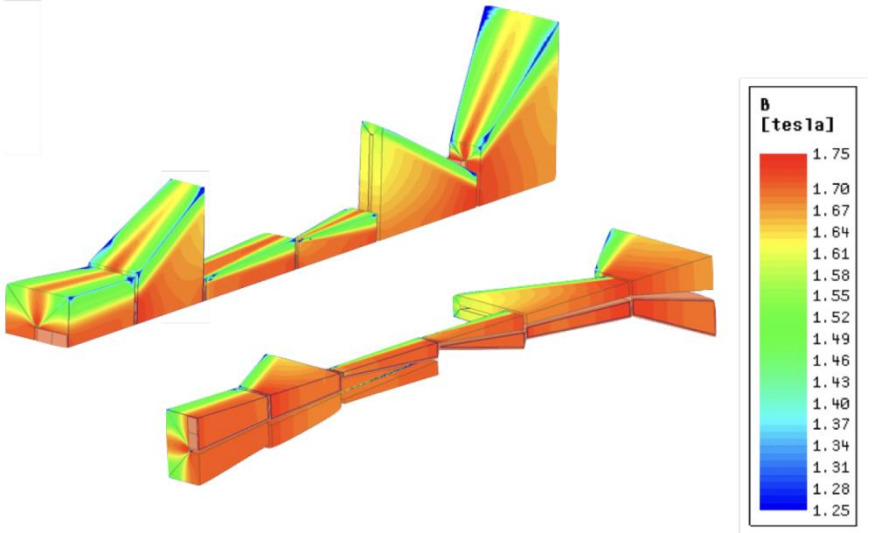
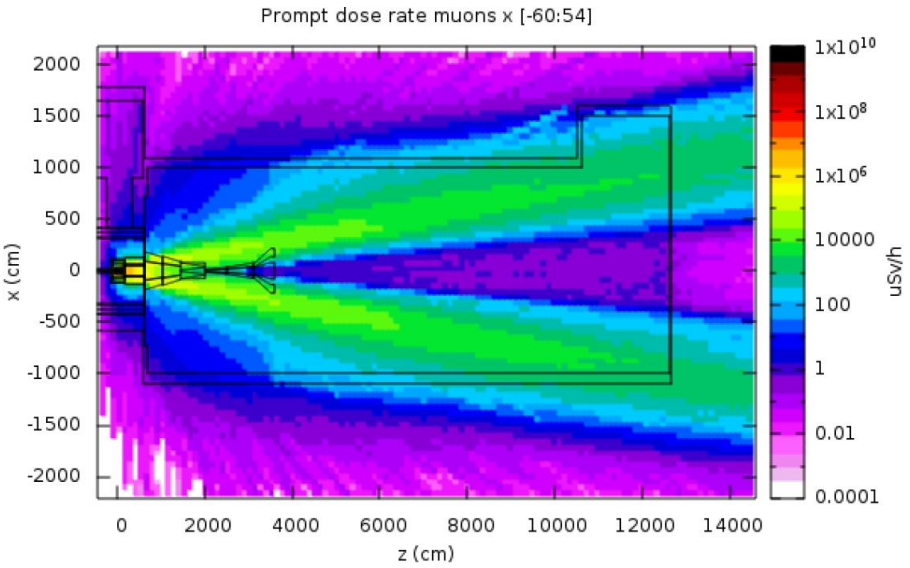


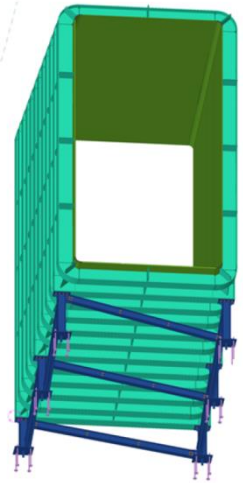
- TZM target
- Tungsten blocks as hadron stopper
- Active muon shield with 1.7 T magnetic field
- Muon flux reduced by 10^{-6}

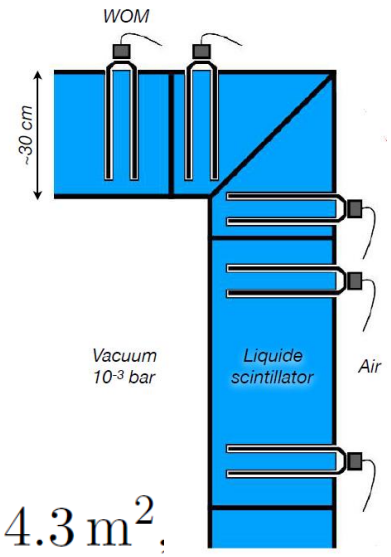




Vacuum vessel

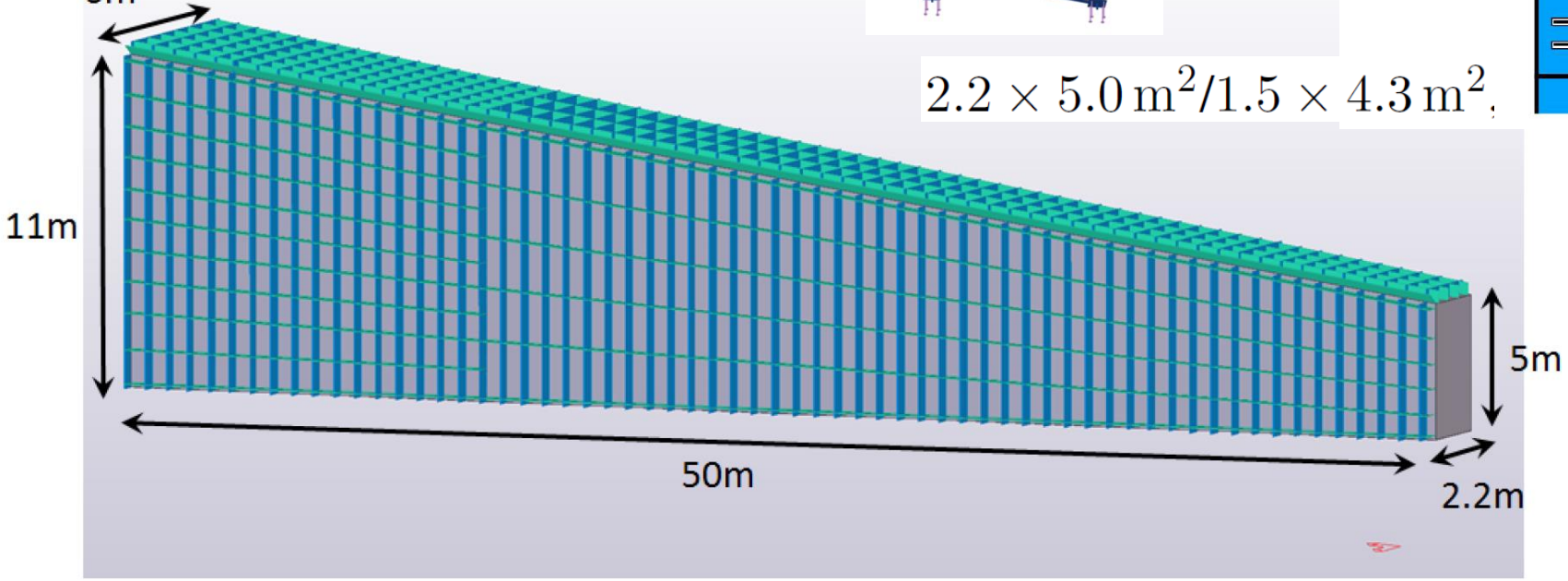
- Hidden particles decay inside the vessel
- Pressure 1mb inside
- Liquid scintillator walls





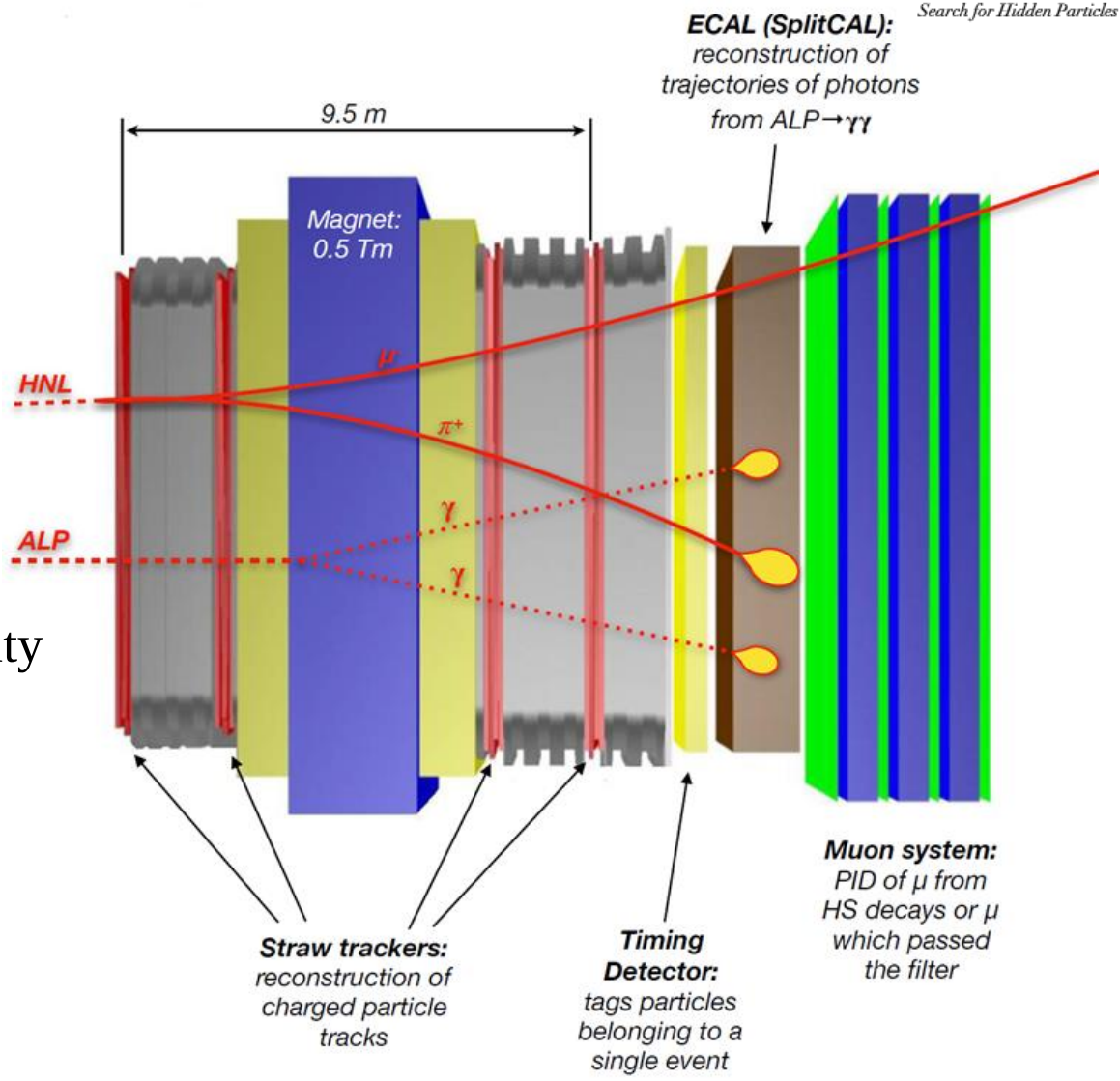
$5.9 \times 11.9\,\mathrm{m}^2/5 \times 11\,\mathrm{m}^2$

$2.2 \times 5.0\,\mathrm{m}^2/1.5 \times 4.3\,\mathrm{m}^2$,

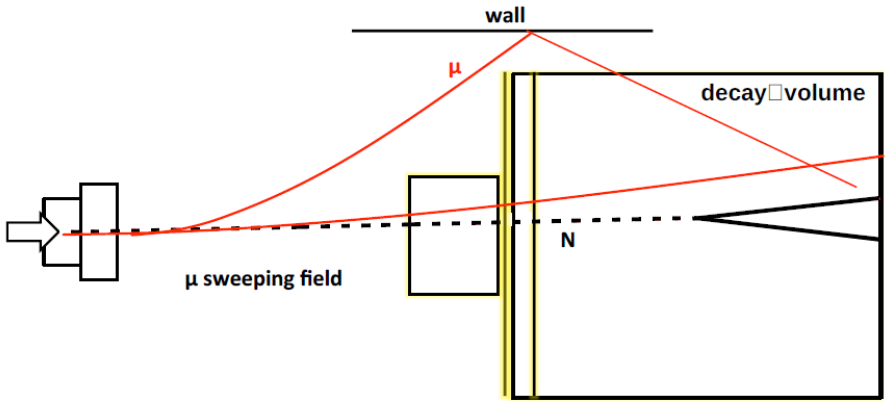


Spectrometer

- Particle identification
- Reconstruction of the decay vertices
- Straw tracker
- Timing detector
- ECAL with tracking capability
- Muon detector

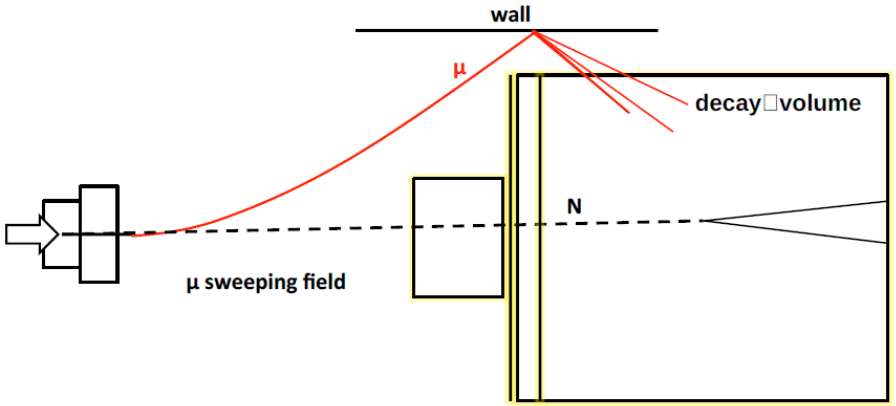


Background study



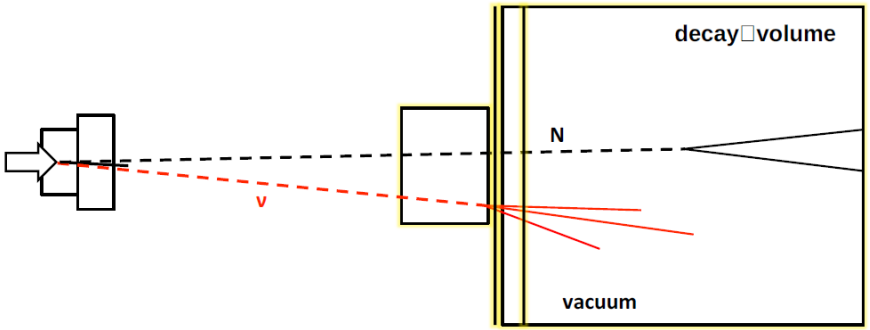
muon combinatorial

10^{-2} candidates in 5 years @ 90%*CL*



muon induced

$< 6 \times 10^{-4}$ @ 90%*CL*



neutrino induced

ν-air: $< 10^{-2}$ with pressure ~ 1 mbar

ν-material: 5×10^5 $\left\{ \begin{array}{l} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{array} \right.$ @ 90%*CL*

Hidden sectors under study

- Neutrino Portal $Y H^T \bar{N} L$
- Vector Portal $\epsilon B_{\mu\nu} F'^{\mu\nu}$
- Scalar Portal $(\alpha_1 S + \alpha S^2) H^\dagger H$
- Axion Like Particles $\frac{a}{f_A} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad \frac{a}{f_A} \partial_\mu J^\mu, \quad etc$
- LDM, RPV SUSY, and many others…

Heavy Neutral Leptons (HNL)

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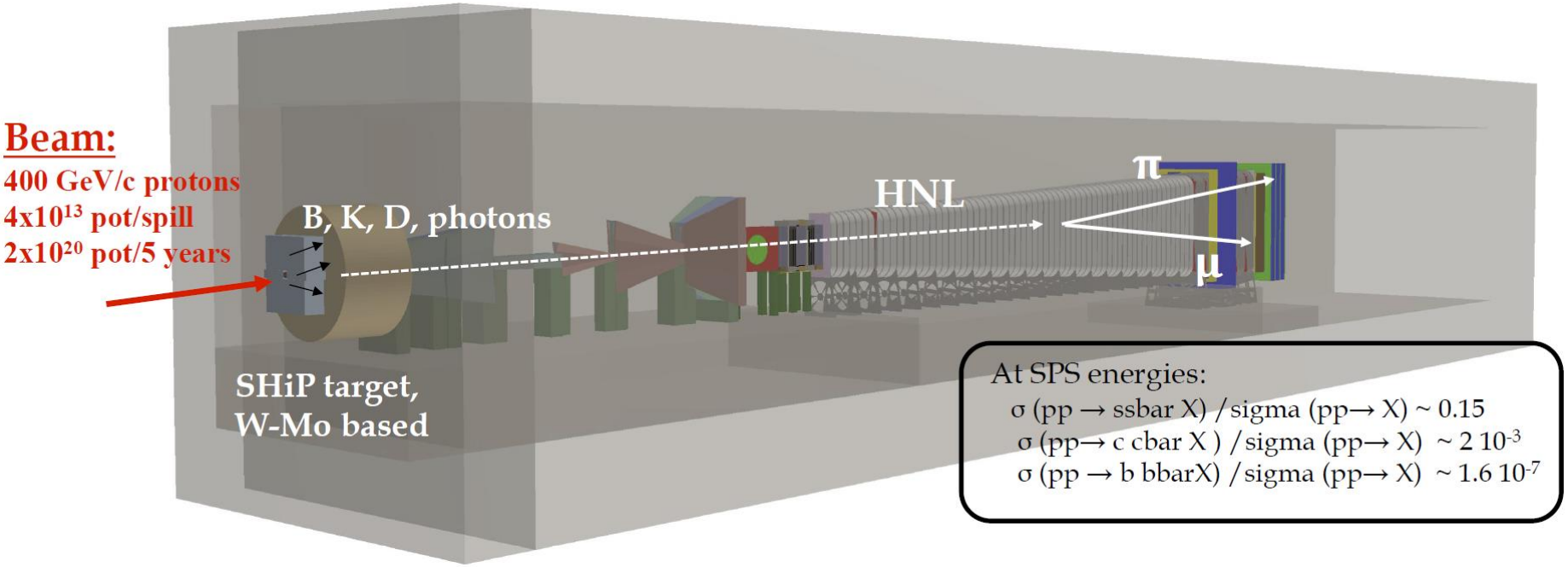
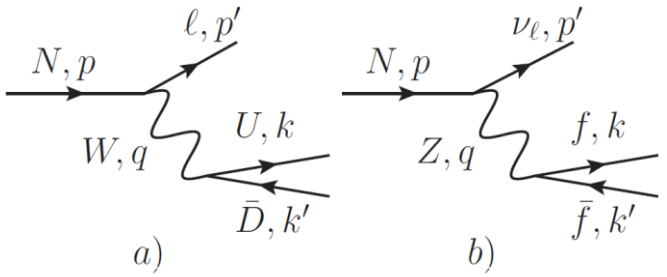


$$h \to h'_P \ell N$$

$$h \to h'_V \ell N$$



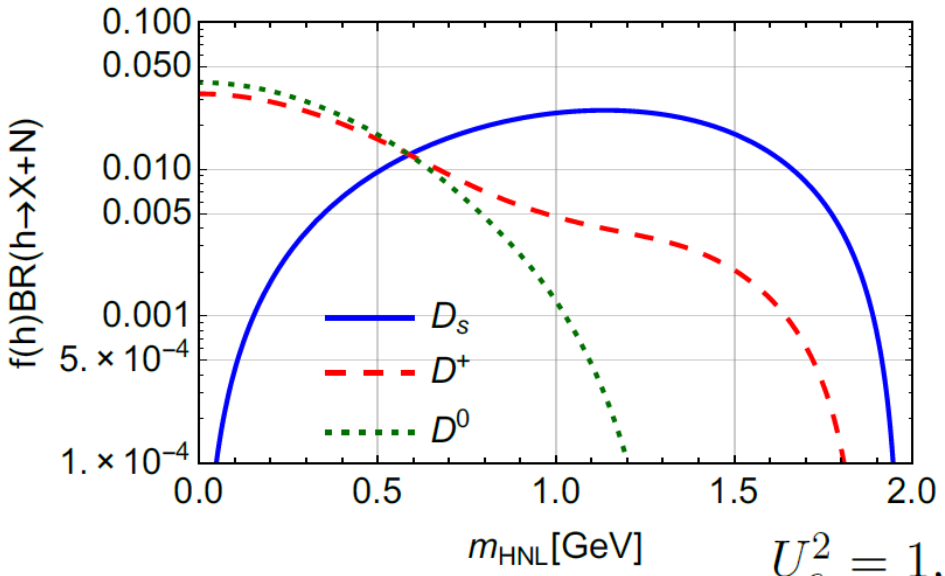
HNL productions and decays

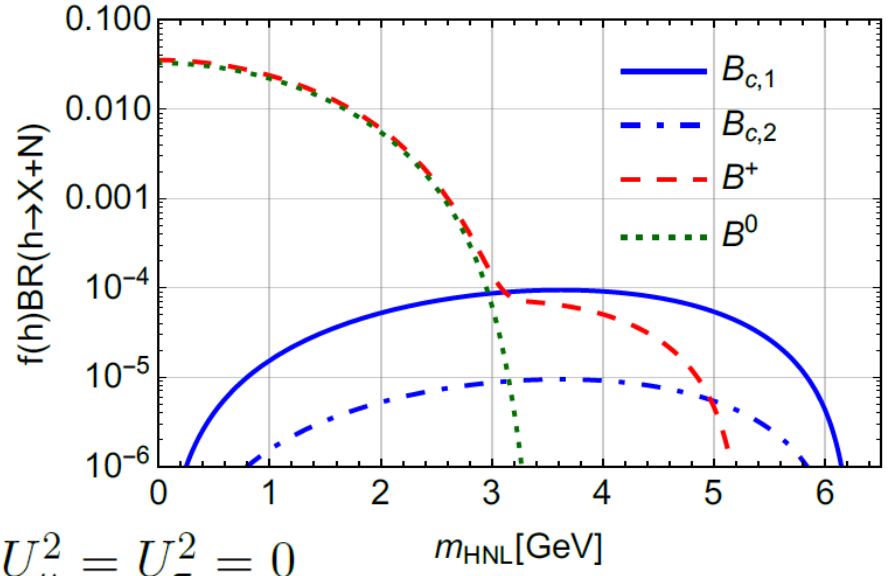
$$N_{\text{events}} = N_{\text{prod}} \times P_{\text{det}}$$

$$N_{\text{prod}} = \sum_{q \in (c,b)} N_q \times \sum_{\text{meson}} f(q \to \text{meson}) \times \text{BR}(\text{meson} \to N + X) \times \epsilon_{\text{decay}},$$

$$N_q = 2 \times X_{\bar{q}q} \times f_{\text{cascade}} \times N_{\text{POT}}.$$

pp cross-section	$\bar{c}c$ fraction	$\bar{b}b$ fraction	Cascade enhancement f_{cascade}	
σ_{pp}	$X_{\bar{c}c}$ [64]	$X_{\bar{b}b}$ [65]	charm [63]	beauty [63]
10.7 mb	1.7×10^{-3}	1.6×10^{-7}	2.3	1.7





$$U_e^2 = 1,\ U_\mu^2 = U_\tau^2 = 0$$

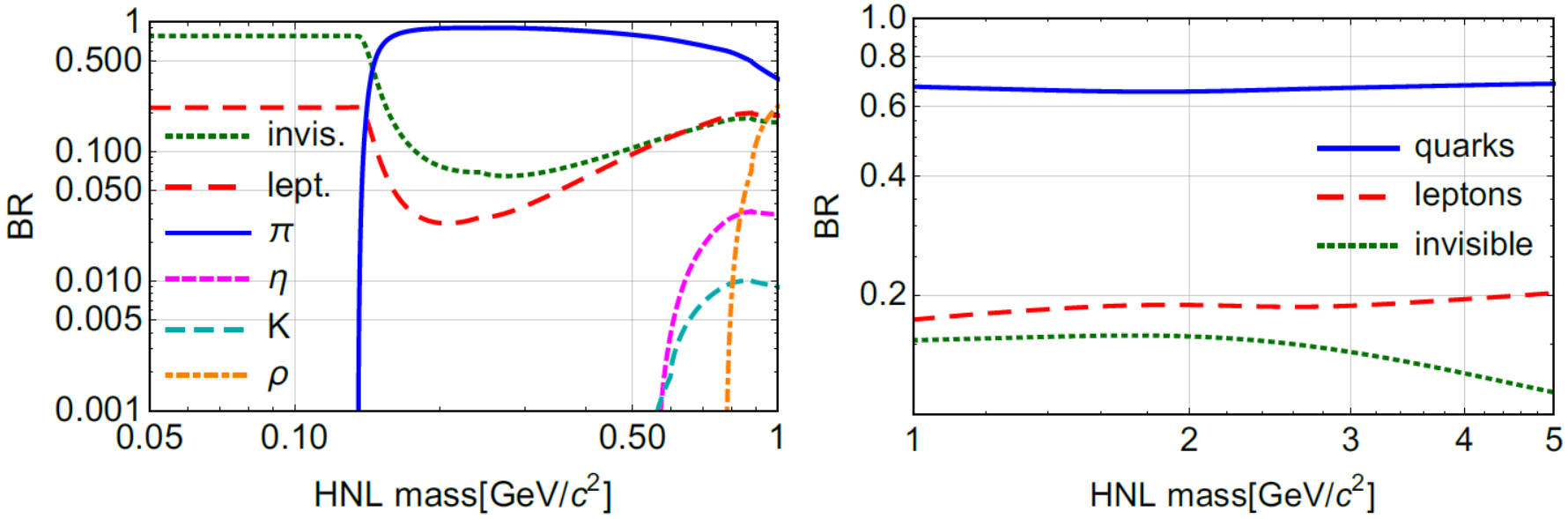
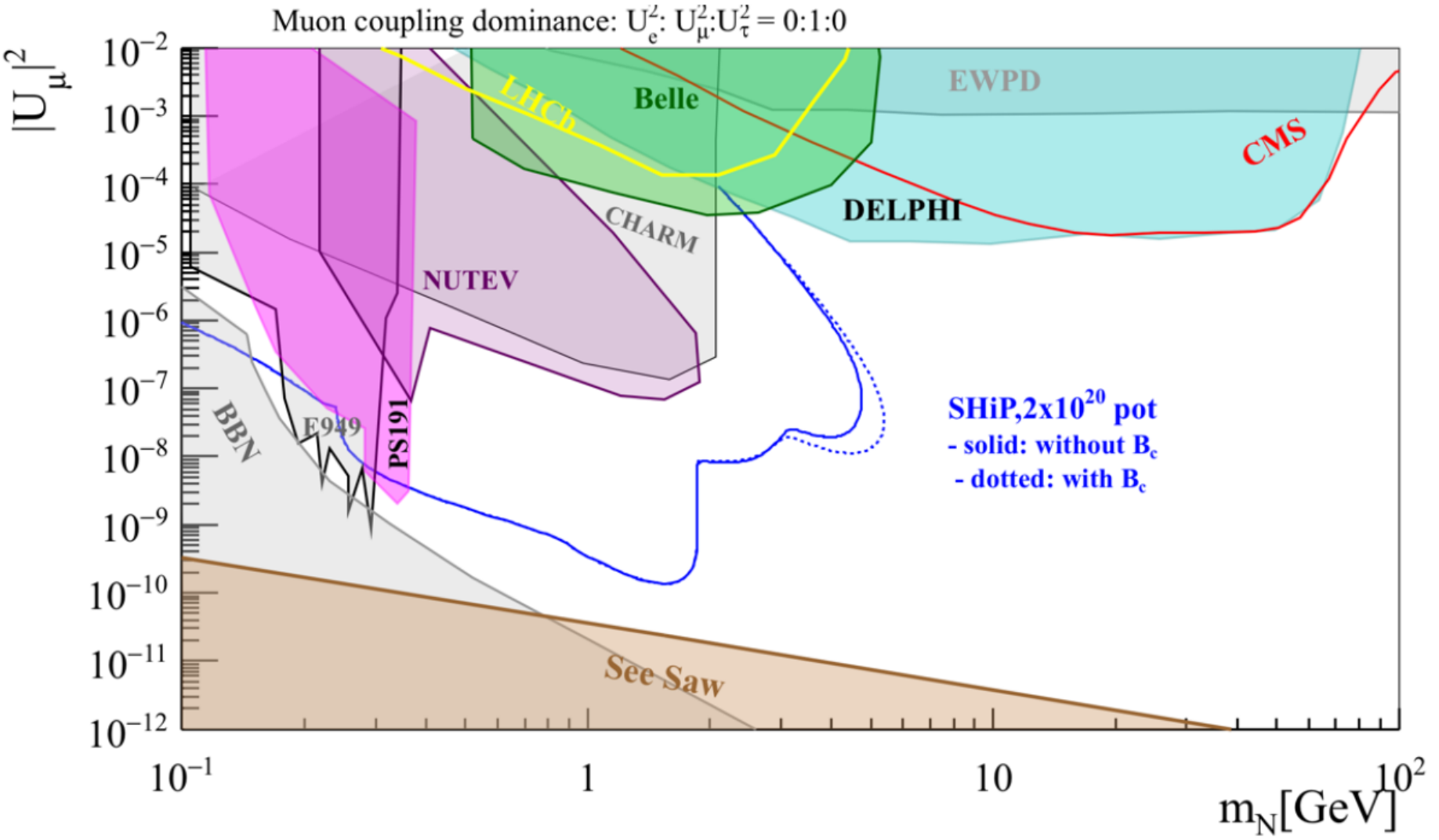


Figure 66: The branching ratios of the HNL decays for the mixing ratio $U_e : U_\mu : U_\tau = 1 : 1 : 1$. *Left panel:* region of masses below 1 GeV/c^2; *Right panel:* region of masses above 1 GeV/c^2. From [108].

$$P_{\text{det}} = P_{\text{decay}} \times \epsilon_{\text{det}} \times \text{BR}(N \to \text{visible}),$$

$$P_{\text{decay}} = \exp\left(-\frac{l_{\text{target-det}}}{l_{\text{decay}}}\right) - \exp\left(-\frac{l_{\text{target-det}} + l_{\text{det}}}{l_{\text{decay}}}\right), \qquad l_{\text{decay}} = c\gamma\tau_N$$

HNL sensitivity plot



Dark Photon

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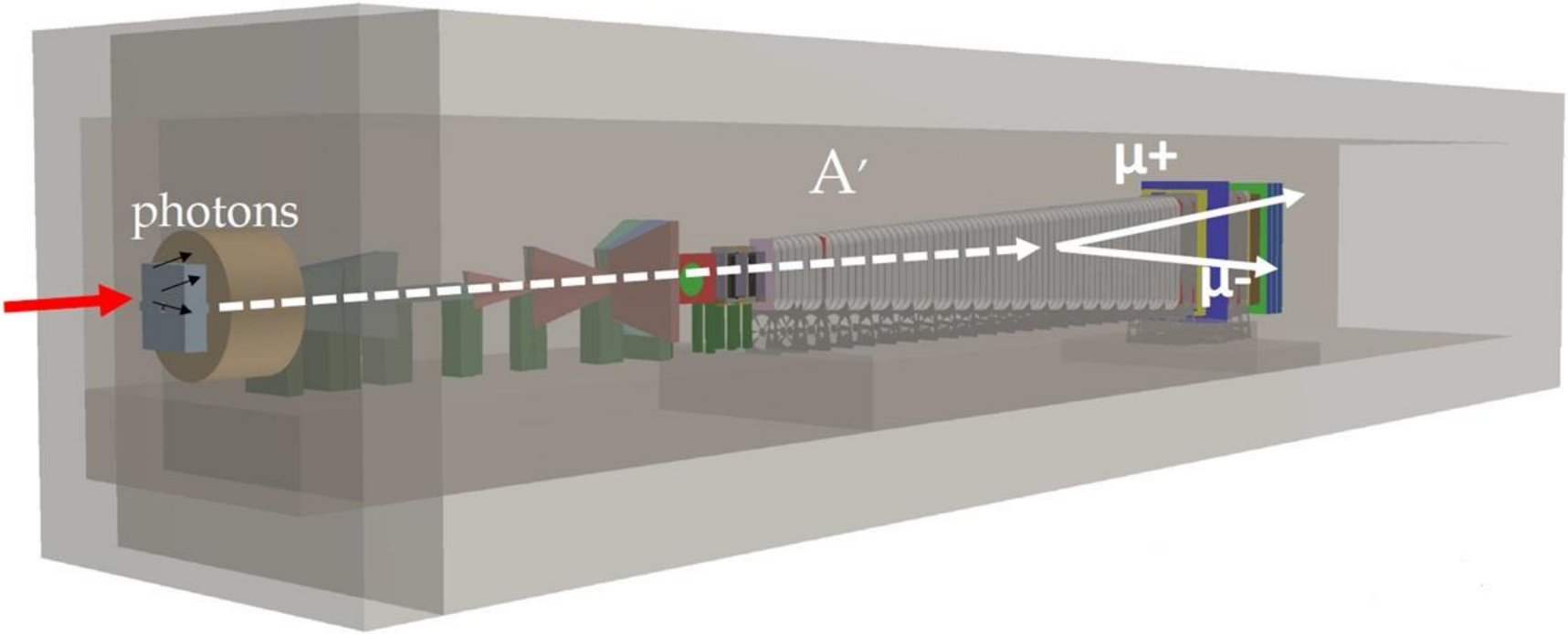
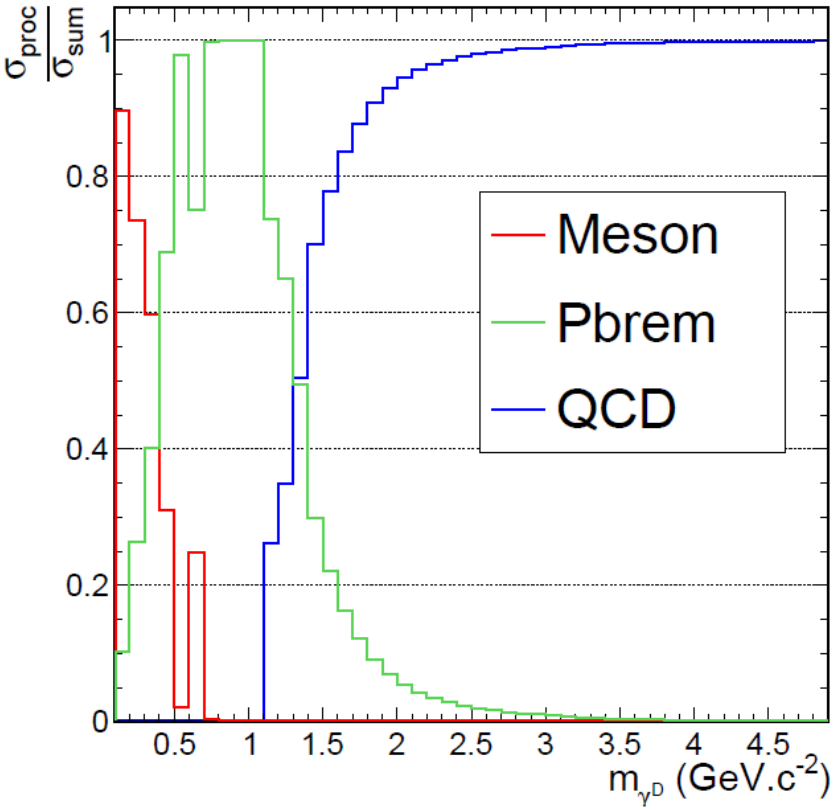
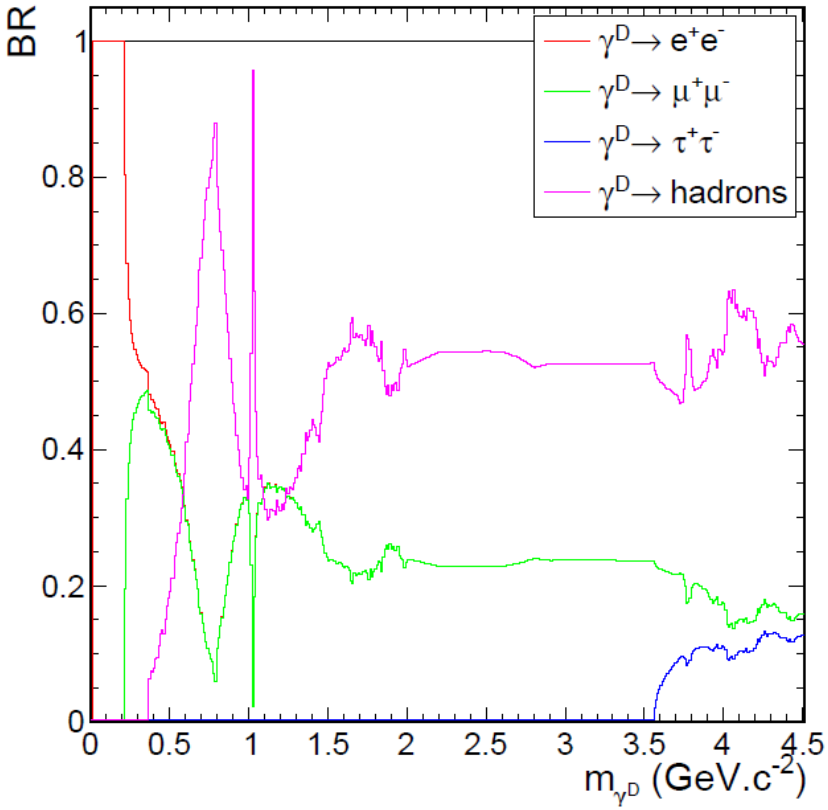


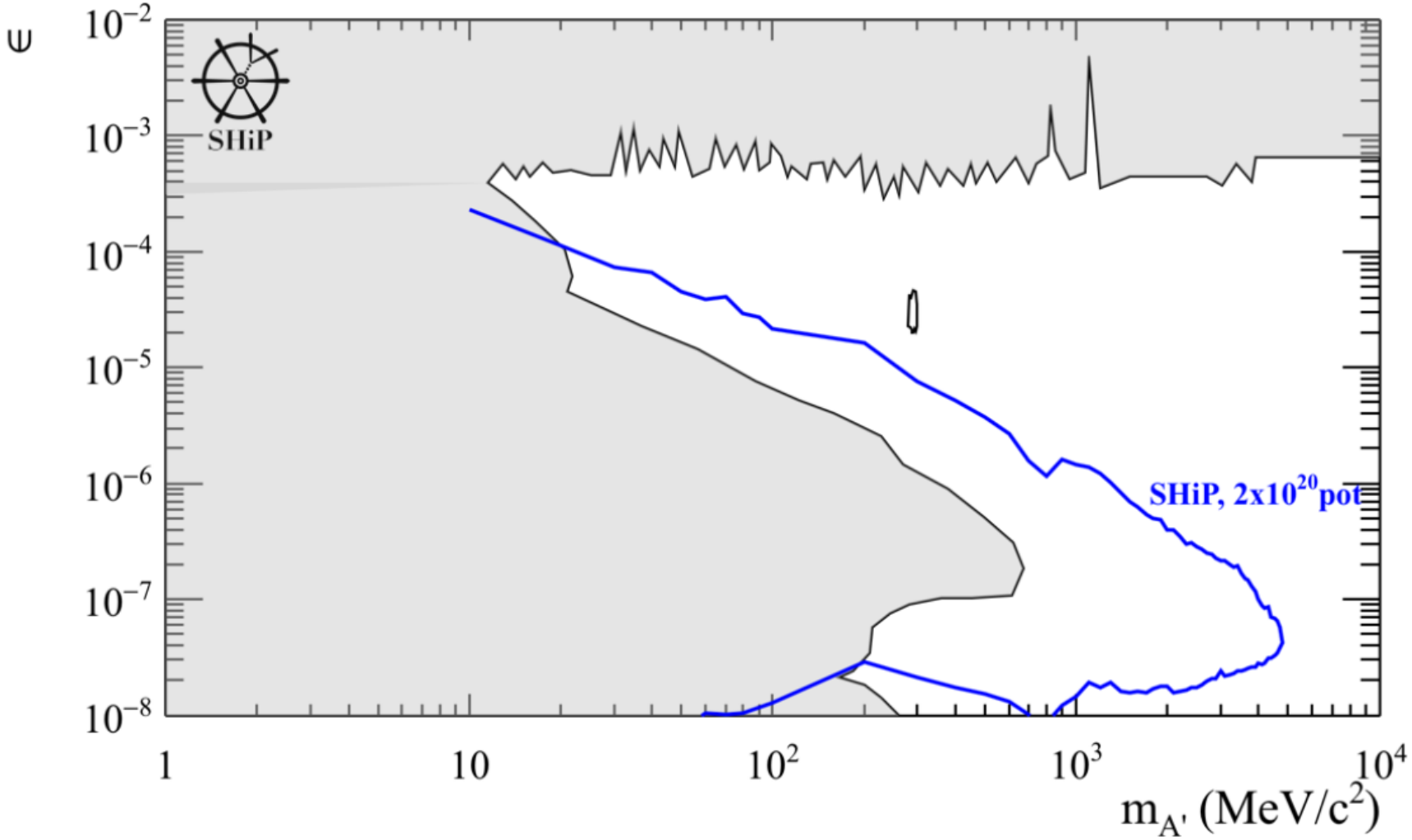
If $mA' < 2m_{\chi'}$ the Dark Photon decays to SM particles
If $m_{A'} > 2\, m_{\chi}$ the Dark Photon can decay also to DM with a coupling α_D

Dark Photon production and decays

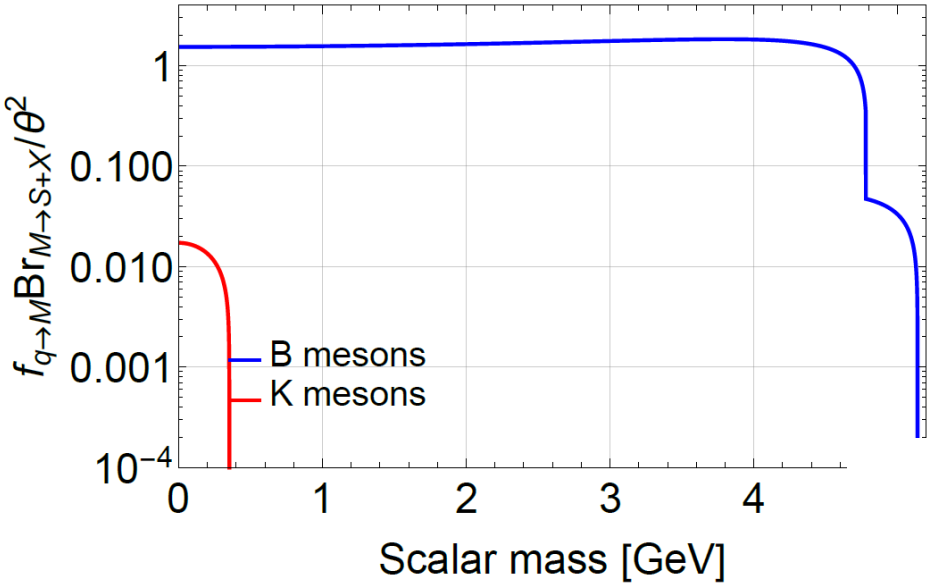




Dark Photon sensitivity plot

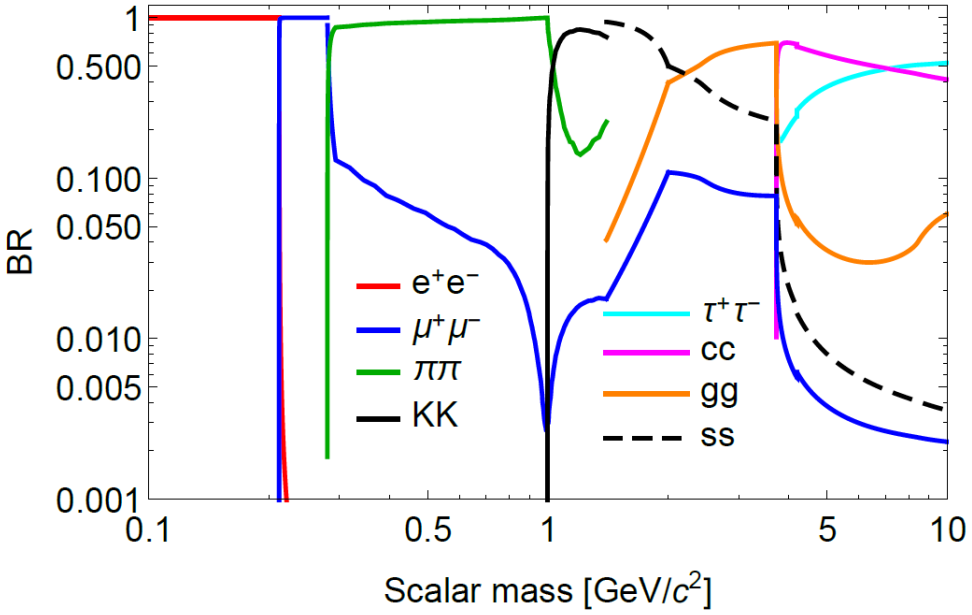


Dark Scalar

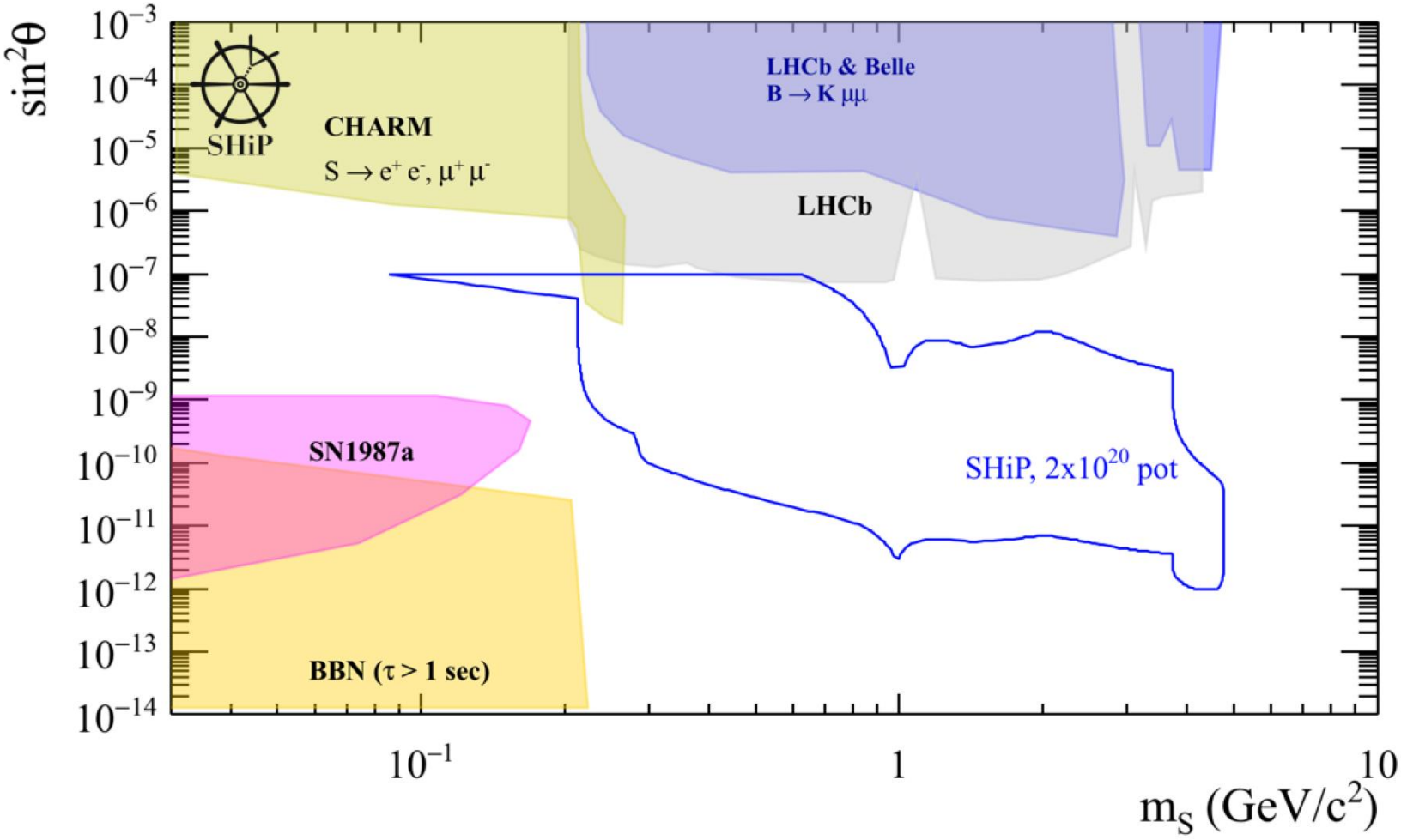


productions

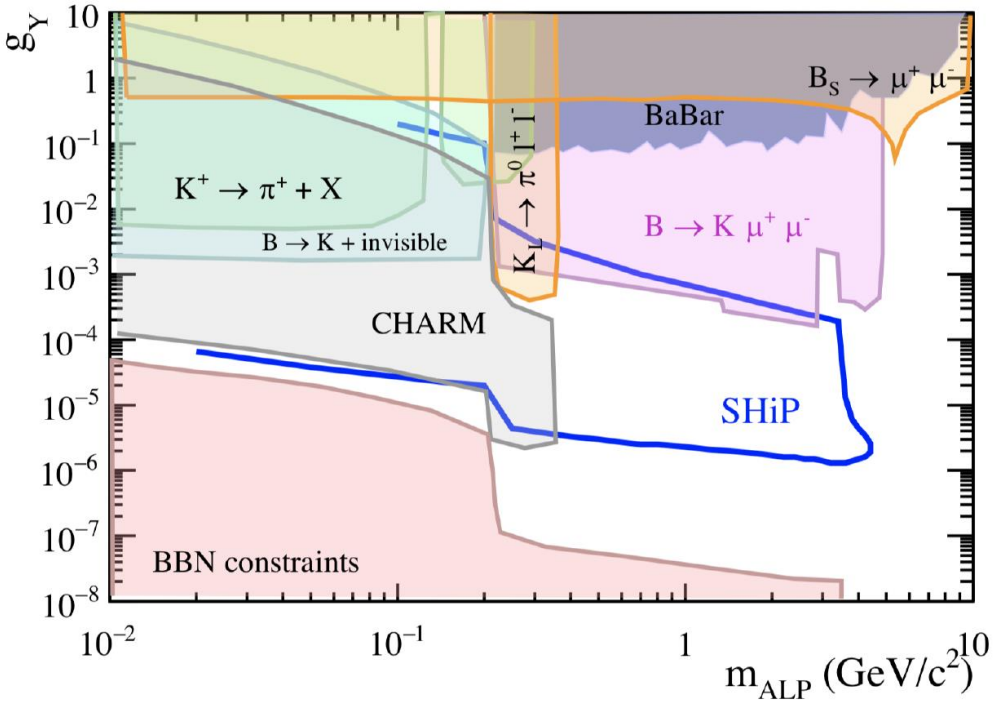
decays

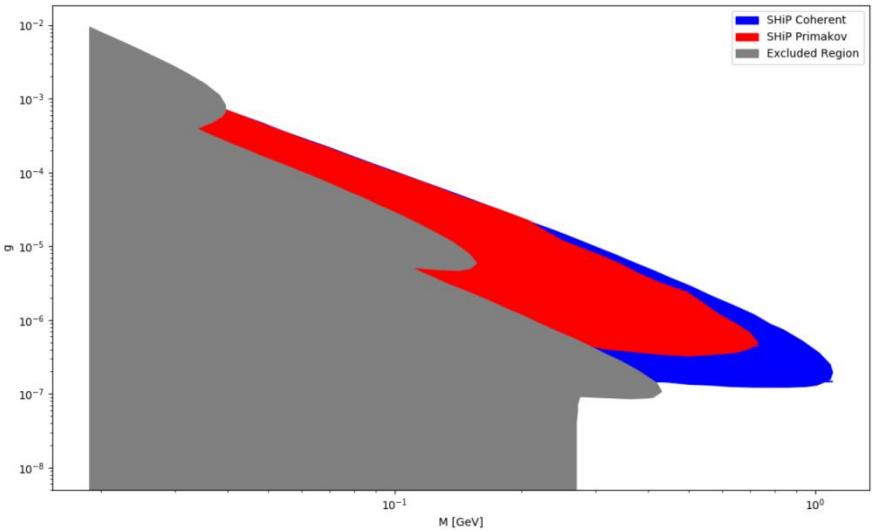


Dark Scalar sensitivity plot



Axion Like Particles (ALP)





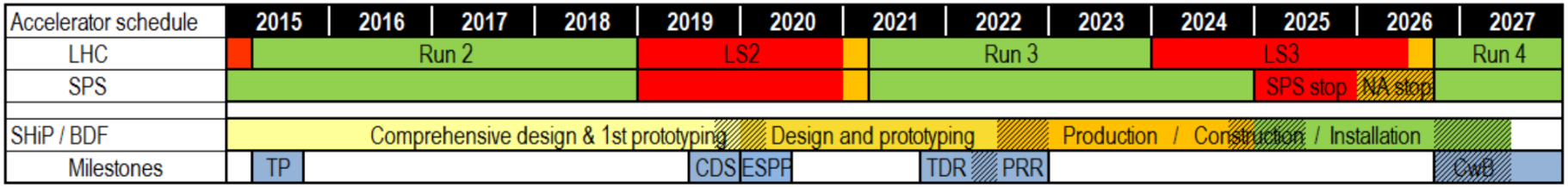
$$\mathrm{ALP} \to \gamma\gamma$$

ALP→fermions

$$\mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi.$$

$$\mathcal{L} \supset \frac{\alpha}{4\pi f_a} \phi F^{\mu\nu} F_{\mu\nu}.$$

Conclusions and Perspectives



- Intensive frontier physics is required complimentary to the high energy frontier physics.
- Direct search for very weakly interacting long-lived particles with 50m decay volume and magnetic spectrometer.
- Aims for zero background experiment.
- Comprehensive Design Report (CDR) by the end of 2019
- Technical Design Report (TDR) expected by the end of 2022
- Construction, detector production and installation ~ 6 years
- Data-taking expected from 2027.

Backup

Introduction

The standard model is closed with the discovery of the Higgs boson.

All experimental results on the ground are explained except for the neutrino oscillation.

Still plenty of astrophysical phenomena could not be explained by known physics.

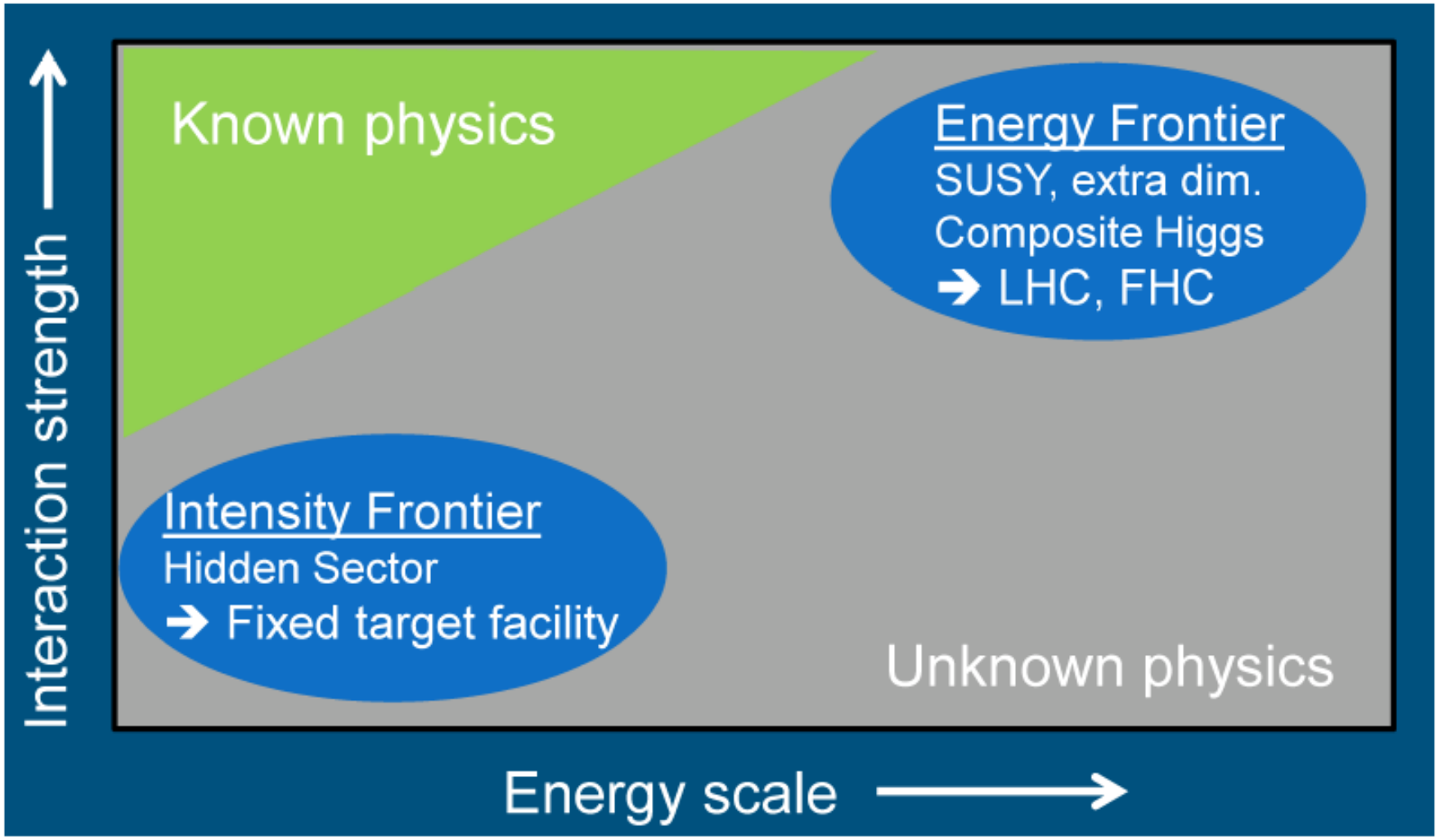
Still the SM is theoretically unsatisfying due to many unexplained parameters, gauge hierarchy, flavour structure etc..

The Dark Matter is a particle physics solution to various anomalous gravitational effects in the space, the rotation curve of the galaxy, gravitational lensing, bullet cluster etc..

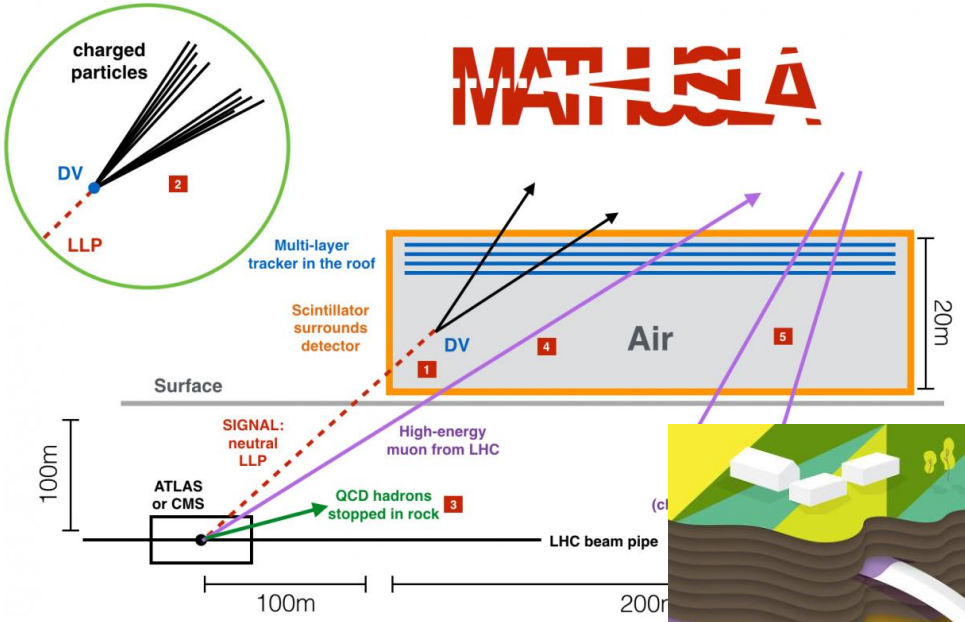
Cosmology also suggests the existence of non-baryonic Dark Matter from the CMB analysis.

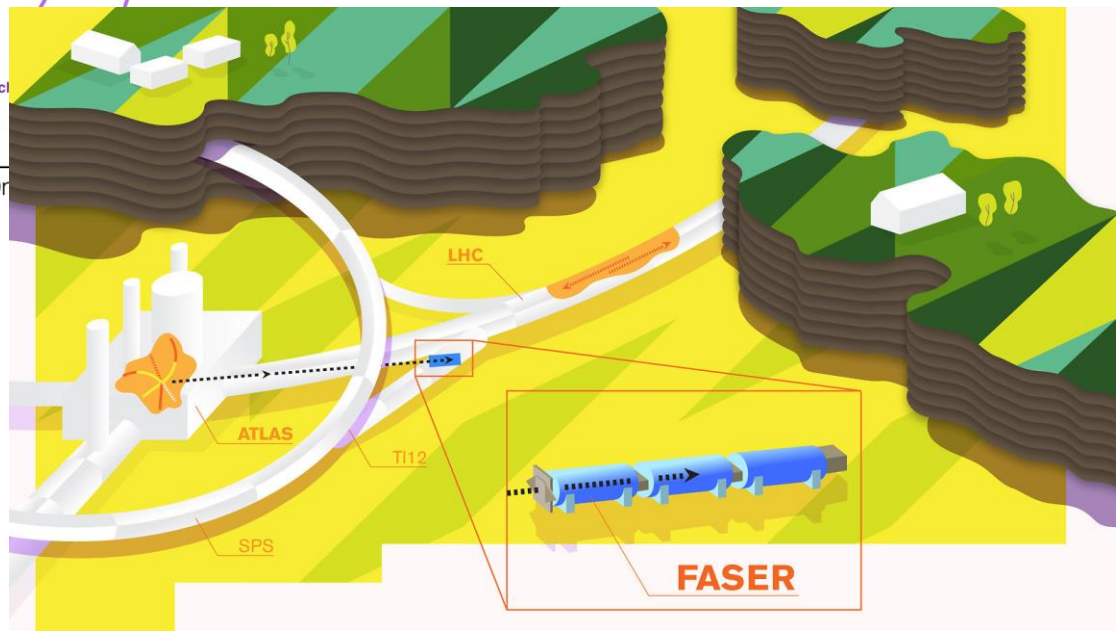
The Hidden sectors are predicted by a variety of models of the SM extension.

Complementary to the LHC



Intensity Frontier / Lifetime Frontier



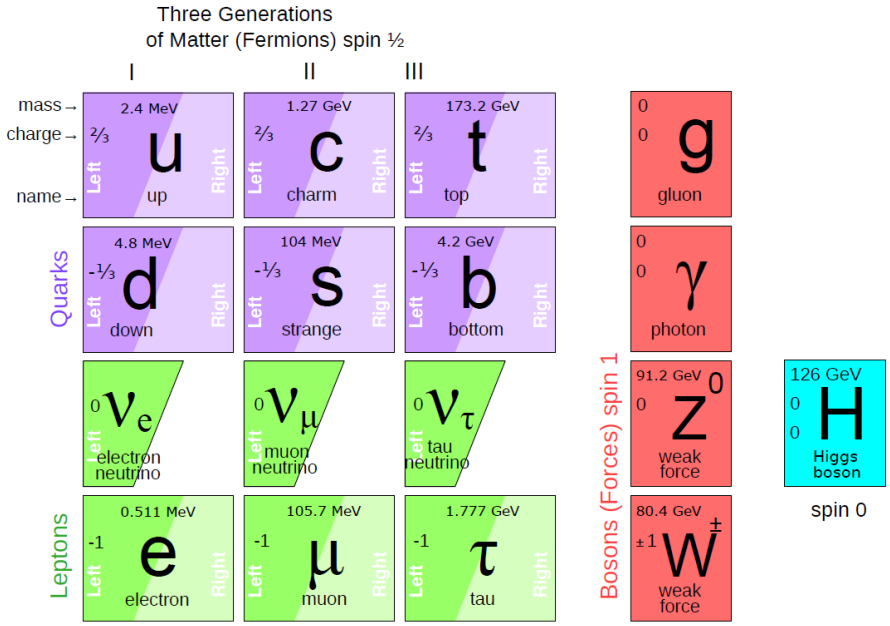


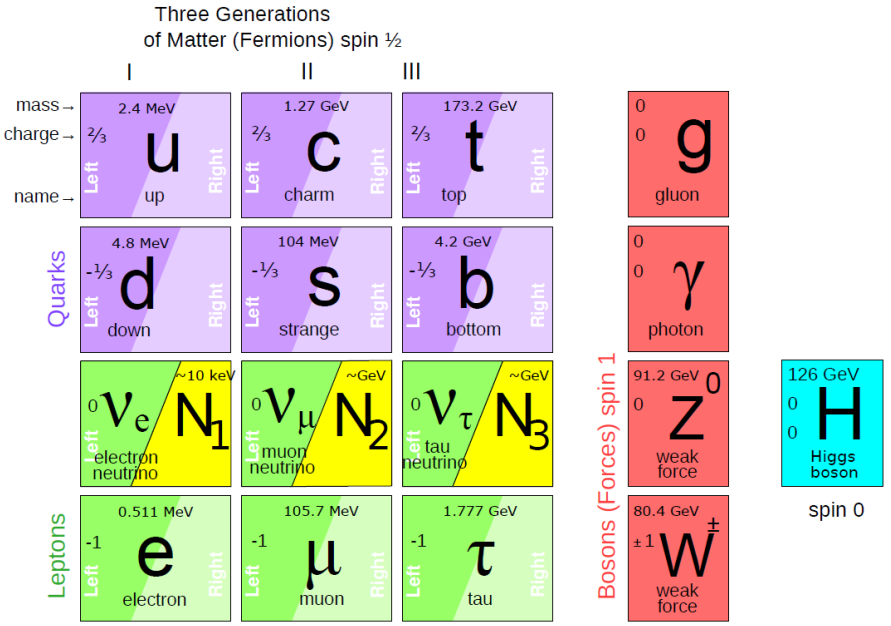
Heavy Neutral Leptons at the SHiP

νMSM = SM + sterile neutrinos

Neutrino = neutral lepton

Sterile neutrino = Heavy Neutral Lepton





HNL couple to the gauge invariant combination

$$\mathcal{L}_{\text{Neutrino portal}} = F_\alpha(\bar{L}_\alpha \cdot \tilde{H})N + h.c.\ ,$$

HNL Lagrangian

$$\mathcal{L}_{\text{HNL}} = i\bar{N}\partial\!\!\!/ N + \left(M_\alpha^D \bar{\nu}_\alpha N - \frac{M_N}{2}\bar{N}^c N + \text{h.c.} \right).$$

After the mixing, HNL couple to the SM

$$\mathcal{L}_{\text{int}} = \frac{g}{2\sqrt{2}} W_\mu^+ \overline{N^c} \sum_\alpha U_\alpha^* \gamma^\mu (1-\gamma_5) \ell_\alpha^- + \frac{g}{4\cos\theta_W} Z_\mu \overline{N^c} \sum_\alpha U_\alpha^* \gamma^\mu (1-\gamma_5) \nu_\alpha + \text{h.c.}\ ,$$

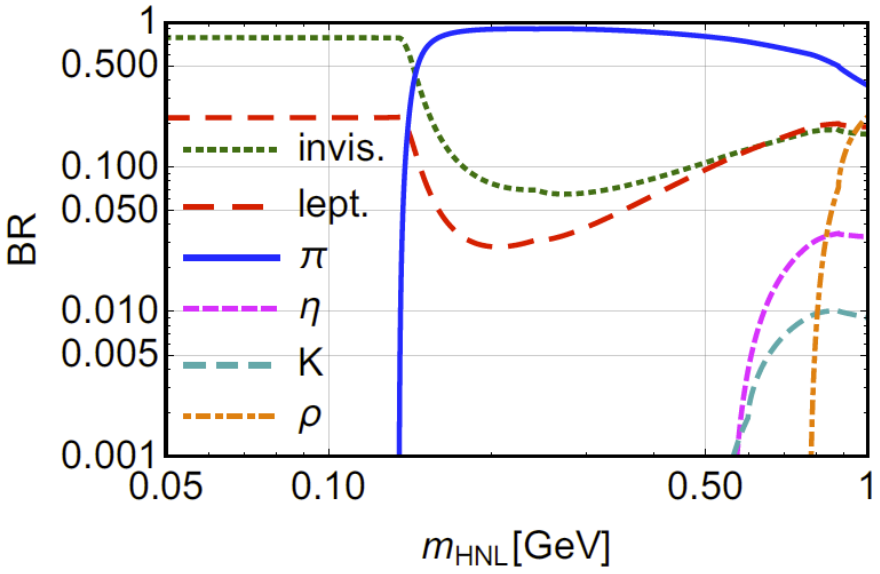
with $U_\alpha = M_\alpha^D M_N^{-1}$

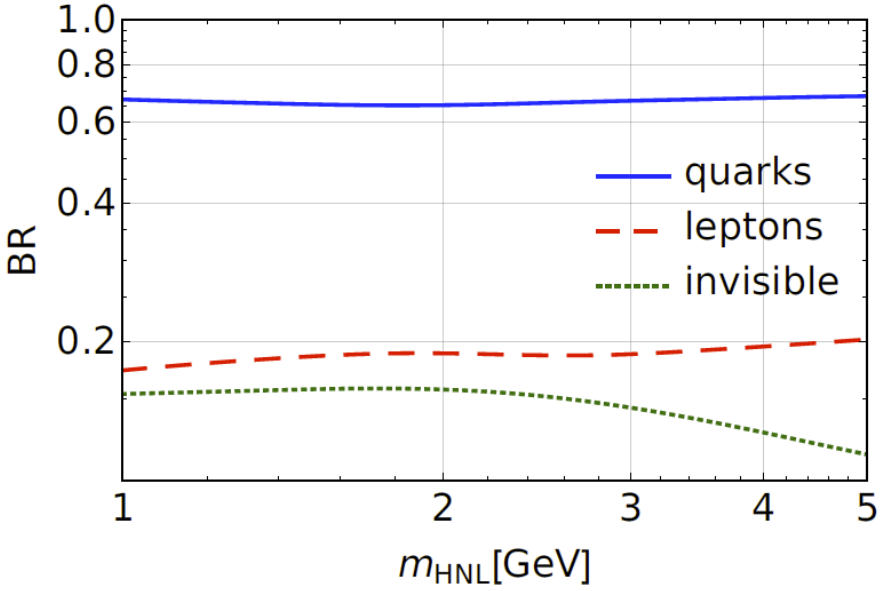
Channel	Opens at [MeV]	Relevant from [MeV]	Relevant up to [MeV]	Max BR [%]	Reference in [62]
$N \to \nu_\alpha \nu_\beta \bar{\nu}_\beta$	$\sum m_\nu \approx 0$	$\sum m_\nu \approx 0$	—	100	(3.5)
$N \to \nu_\alpha e^+ e^-$	1.02	1.29	—	21.8	(3.4)

Channel	Opens at [MeV]	Relevant from [MeV]	Relevant up to [MeV]	Max BR [%]	Reference in [62]
$N \to \nu_\alpha \pi^0$	135	136	3630	57.3	(3.7)
$N \to e^- \pi^+$	140	141	3000	33.5	(3.6)
$N \to \mu^- \pi^+$	245	246	3000	19.7	(3.6)
$N \to e^- \nu_\mu \mu^+$	106	315	—	5.15	(3.1)
$N \to \mu^- \nu_e e^+$	106	315	—	5.15	(3.1)
$N \to \nu_\alpha \mu^+ \mu^-$	211	441	—	4.21	(3.4)
$N \to \nu_\alpha \eta$	548	641	2330	3.50	(3.7)
$N \to e^- \pi^+ \pi^0$	275	666	4550	10.4	(B.42)
$N \to \nu_\alpha \pi^+ \pi^-$	279	750	3300	4.81	(B.43)
$N \to \nu_\alpha \omega$	783	997	1730	1.40	(3.9)
$N \to \nu_\alpha (3\pi)^0$	$\gtrsim 405$	$\gtrsim 1000$	?	?	No
$N \to e^- (3\pi)^+$	$\gtrsim 410$	$\gtrsim 1000$	?	?	No
$N \to \nu_\alpha \eta'$	958	1290	2400	1.86	(3.7)
$N \to \nu_\alpha \phi$	1019	1100	4270	5.90	(3.9)
$N \to \mu^- (3\pi)^+$	$\gtrsim 515$	$\gtrsim 1100$	?	?	No
$N \to \nu_\alpha K^+ K^-$	987	$\gtrsim 1100$	?	?	No

$N \to \nu_\alpha (4\pi)^0$	$\gtrsim 540$	$\gtrsim 1200$	?	?	No
$N \to e^- (4\pi)^+$	$\gtrsim 545$	$\gtrsim 1200$	?	?	No
$N \to \mu^- (4\pi)^+$	$\gtrsim 649$	$\gtrsim 1300$	?	?	No
$N \to \nu_\alpha (5\pi)^0$	$\gtrsim 675$	$\gtrsim m_\tau \approx 1780$	?	?	No
$N \to e^- (5\pi)^+$	$\gtrsim 680$	$\gtrsim m_\tau \approx 1780$	?	?	No
$N \to \mu^- (5\pi)^+$	$\gtrsim 785$	$\gtrsim m_\tau \approx 1780$	?	?	No
$N \to e^- D_s^{*+}$	2110	2350	—	3.05	(3.8)
$N \to \mu^- D_s^{*+}$	2220	2370	—	3.03	(3.8)
$N \to e^- D_s^+$	1970	2660	4180	1.23	(3.6)
$N \to \mu^- D_s^+$	2070	2680	4170	1.22	(3.6)
$N \to \nu_\alpha \eta_c$	2980	3940	—	1.26	(3.7)
$N \to \tau^- \nu_e e^+$	1780	3980	—	1.52	(3.1)
$N \to e^- \nu_\tau \tau^+$	1780	3980	—	1.52	(3.1)
$N \to \tau^- \nu_\mu \mu^+$	1880	4000	—	1.51	(3.1)
$N \to \mu^- \nu_\tau \tau^+$	1880	4000	—	1.51	(3.1)

Branching ratios





$$U_e : U_\mu : U_\tau = 1 : 1 : 1$$

SHiP sensitivity for benchmark HNL models

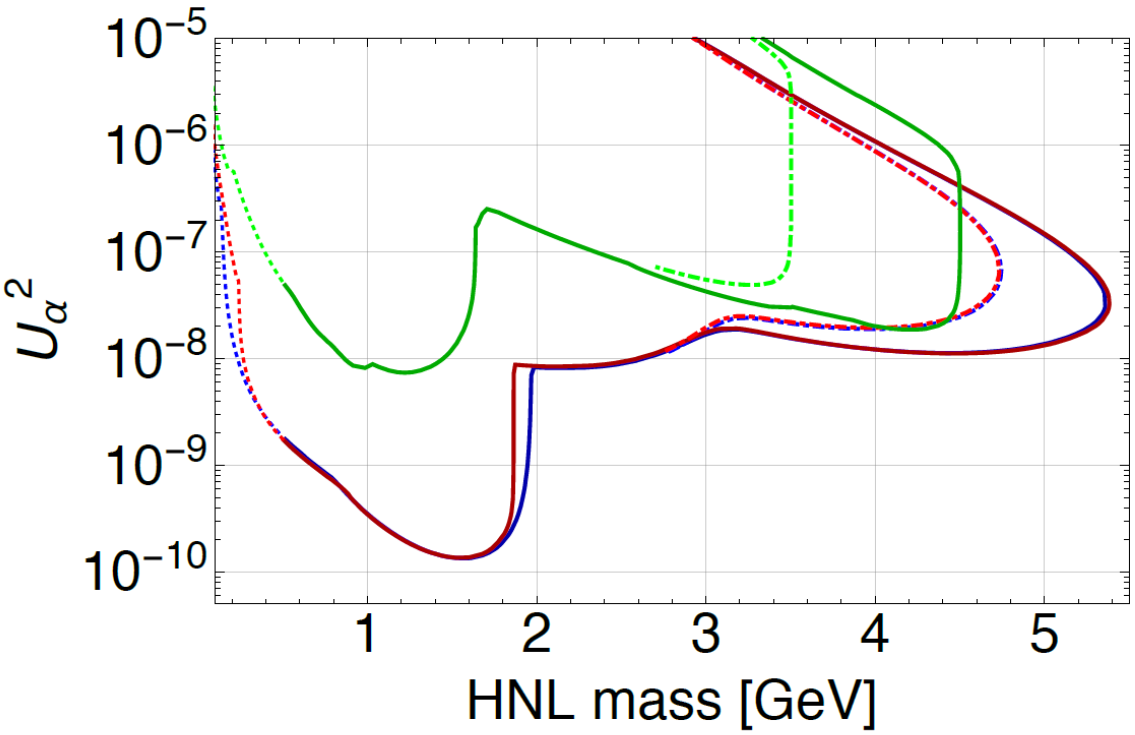


Figure 3. SHiP sensitivity curves (90% CL) for HNLs mixing to a single SM flavour: electron (blue), muon (red) and tau (green). Solid curves show the largest possible contribution from B_c mesons, when the production fraction is taken equal to that at LHC energies: $f(b \to B_c) = 2.6 \times 10^{-3}$. Dashed-dotted lines do not included contributions from B_c. Below 0.5 GeV only contribution from D-meson decays is included (dotted lines).

Benchmark models

… explain neutrino oscillation data while at the same time maximizing the mixing to one particular flavour.

- I. $U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$
- II. $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$
- III. $U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

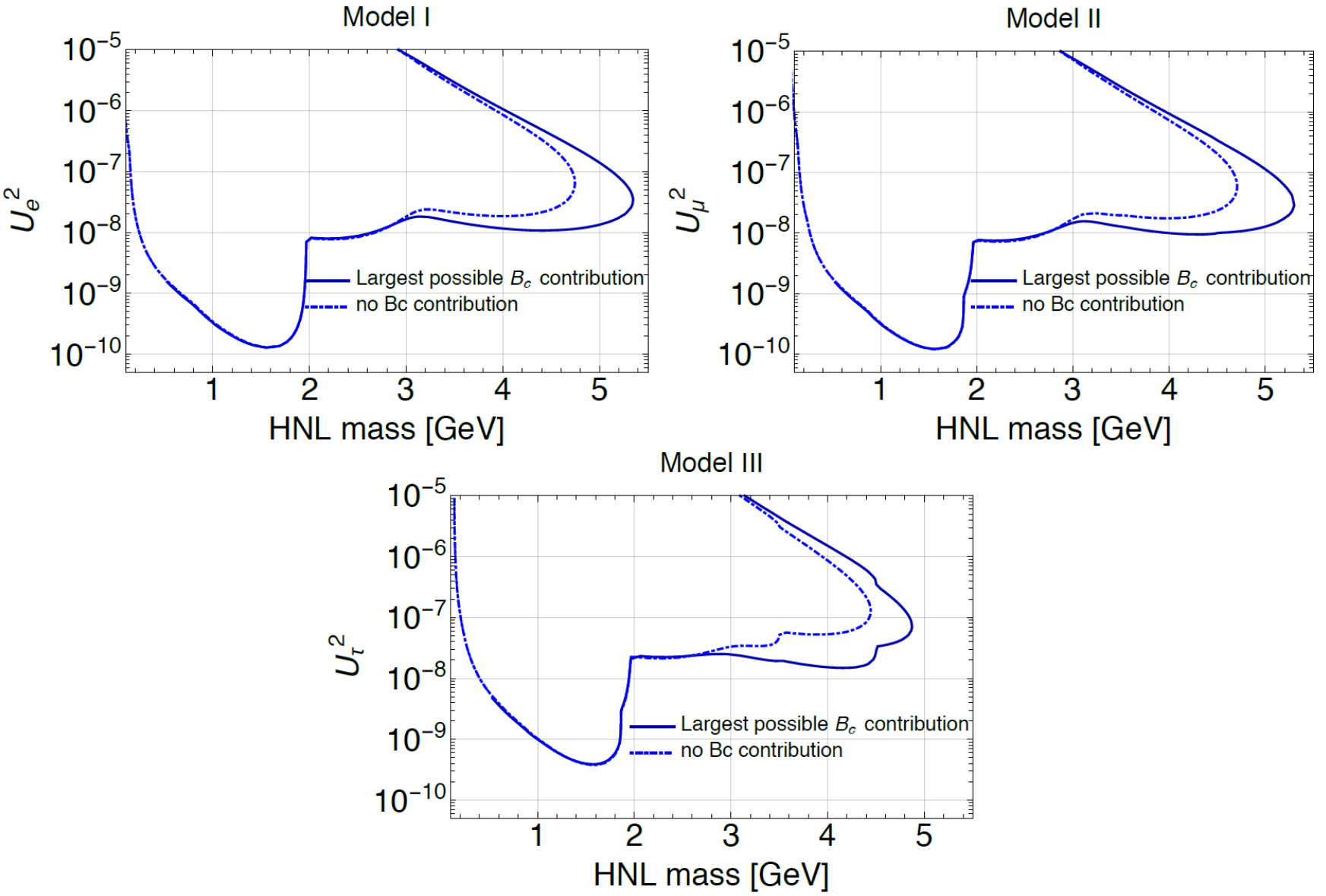
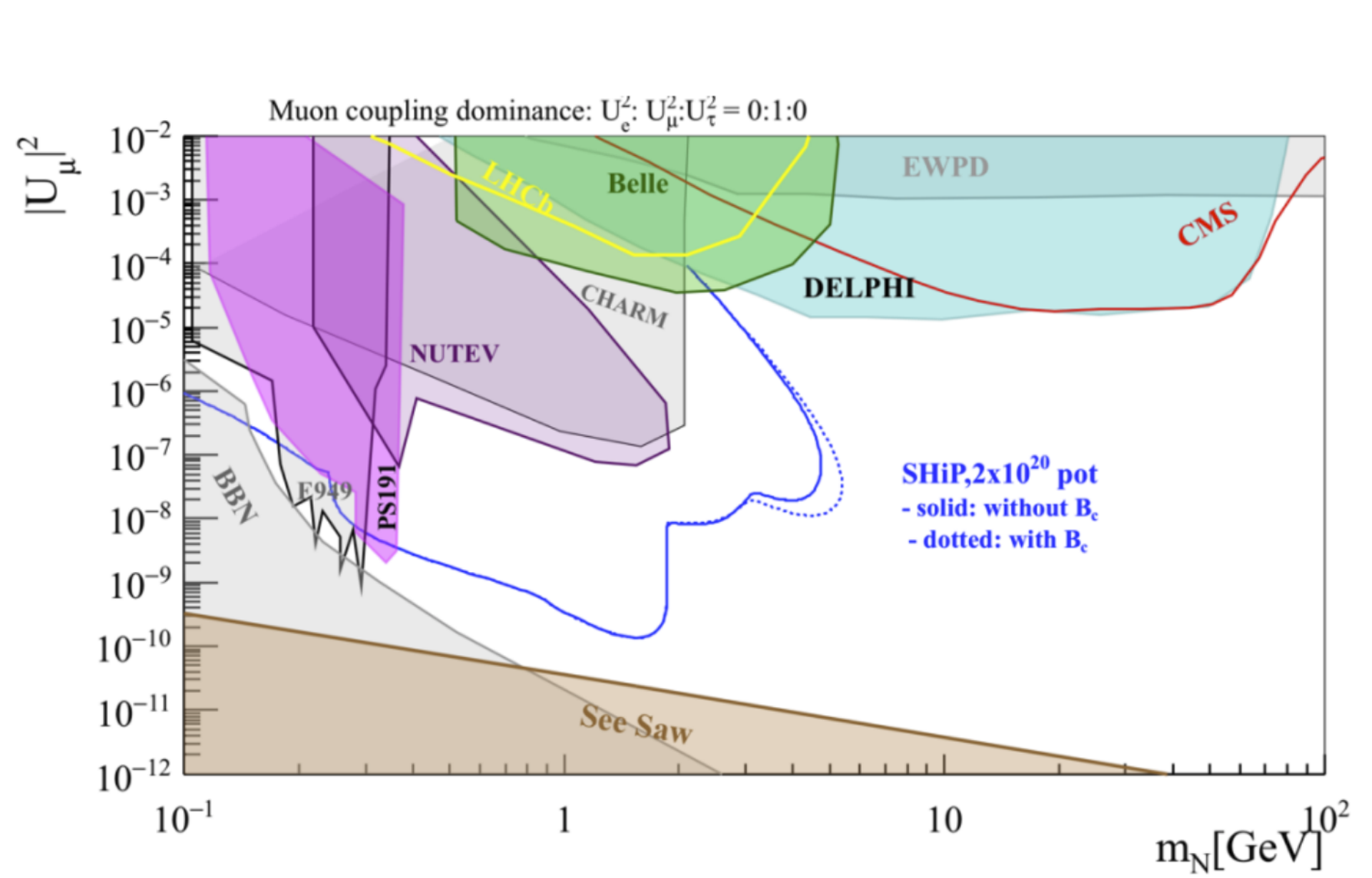


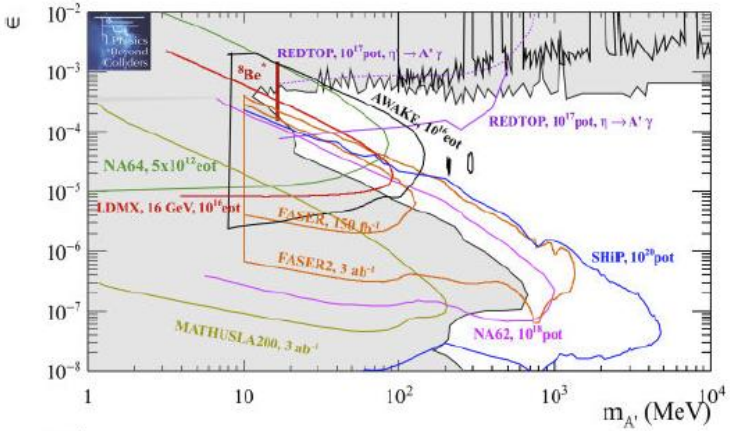
Figure 4. Sensitivity curves for 3 benchmark models I–III (90%CL). Individual curves are explained in Fig. 3.

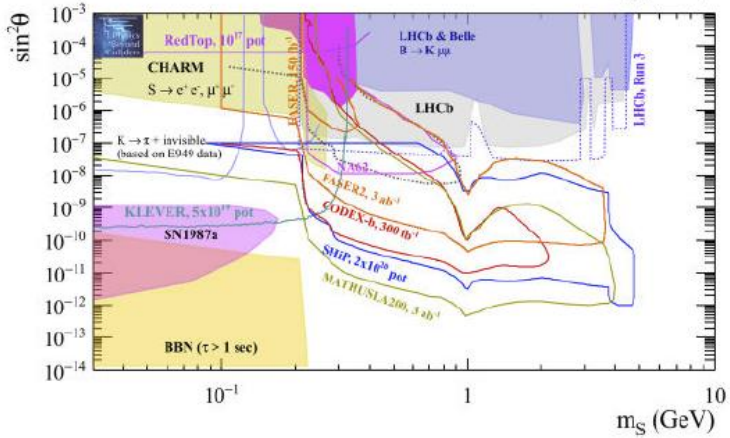


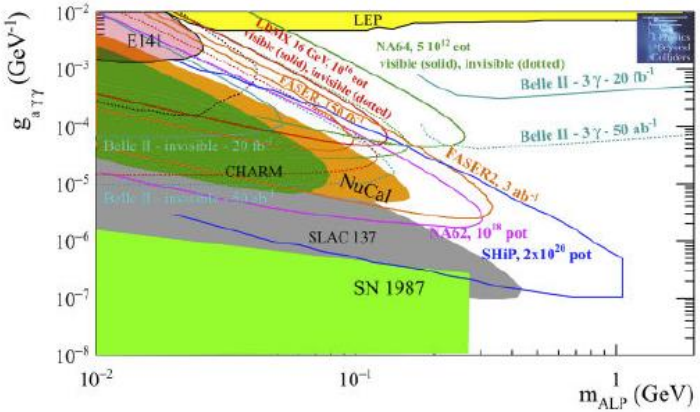
Nico Serra, SHiP collaboration meeting (2019)

Physics performance

- **Dark photon:**
  - meson decays, proton bremsstrahlung, $qq \to \gamma'$
  - expect improvements at low mass from:
    - cascade production
    - EM showers
- **Dark scalar:**
  - couple to Higgs in FCNC K and B decays
- **Axion-like particles:**
  - couple to fermions and to photons
  - SplitCal developed for $ALP \to \gamma\gamma$



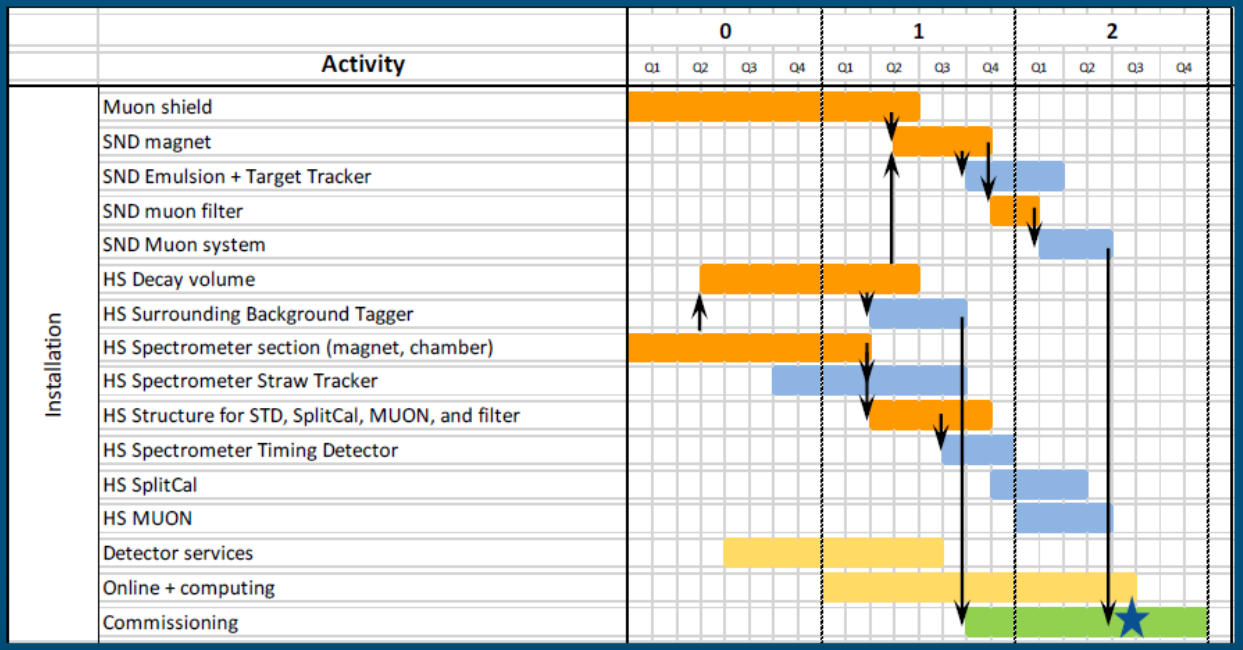




Project plan

Accelerator schedule	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
LHC		Run 2			LS2			Run 3			LS3		Run 4
SPS											SPS stop	NA stop	
SHiP / BDF	Comprehensive design & 1st prototyping						Design and prototyping			Production / Construction / Installation			
Milestones	TP					CDS	ESPP			TDR	PRR		CwB

- Starting from the rear end of the schedule
  - Installation: specify suggested strategy for transport, assembly, space and time requirements
    - ➔ Several scenarios possible ➔ iterations
    - ➔ Split structure and detector components
  - Installation defines delivery dates and format
  - Estimated times for pre-manufacturing phase, pre-production, validation, production phase
    - ➔ Defines production readiness milestone and financial time line
  - Transport/assembly scenario for muon shield, decay volume, spectrometer section, SST are critical



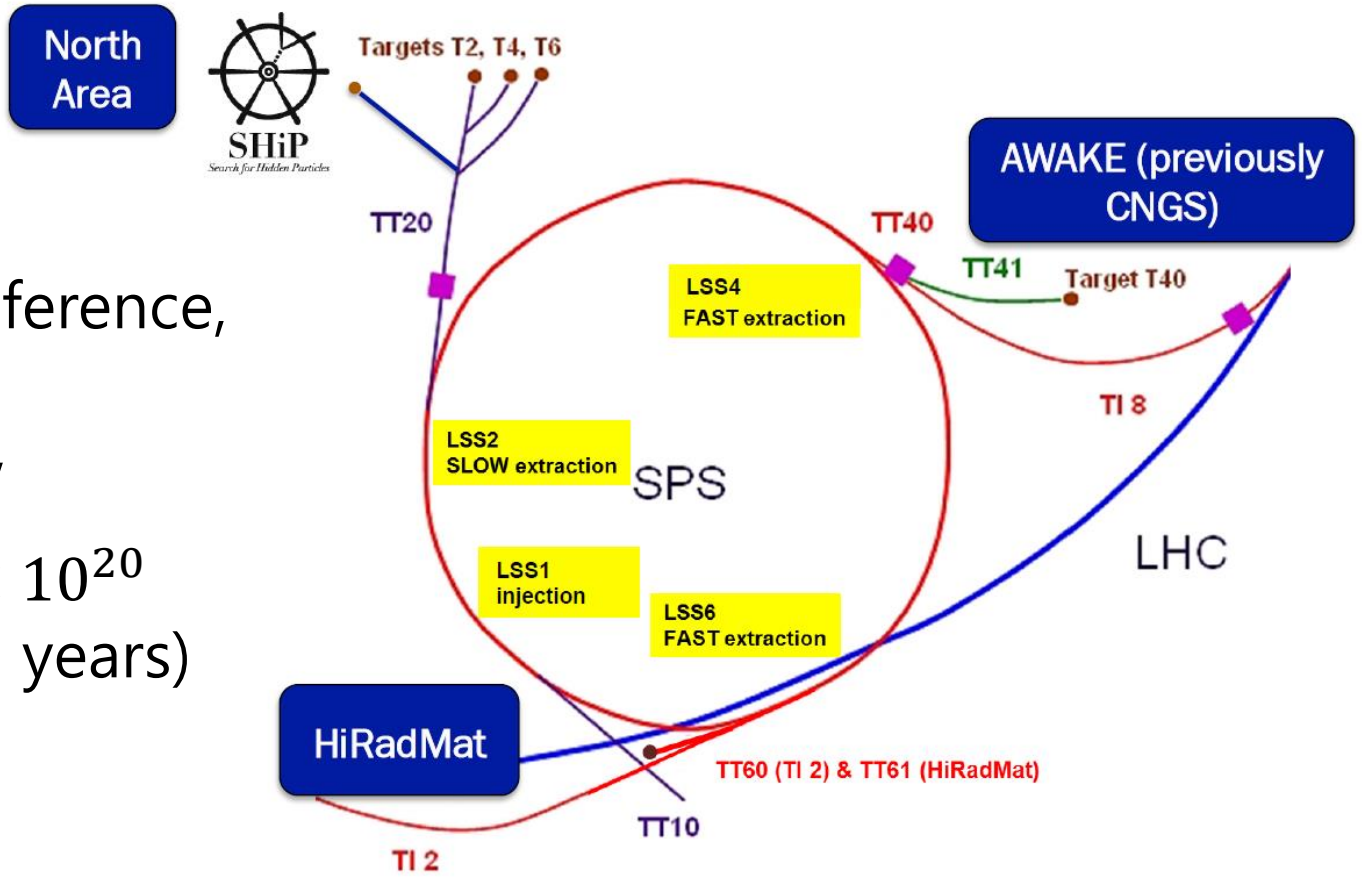
SPS Super Proton Synchrotron (1976~)

The second-largest machine in CERN's accelerator complex.

~ 7 km circumference,

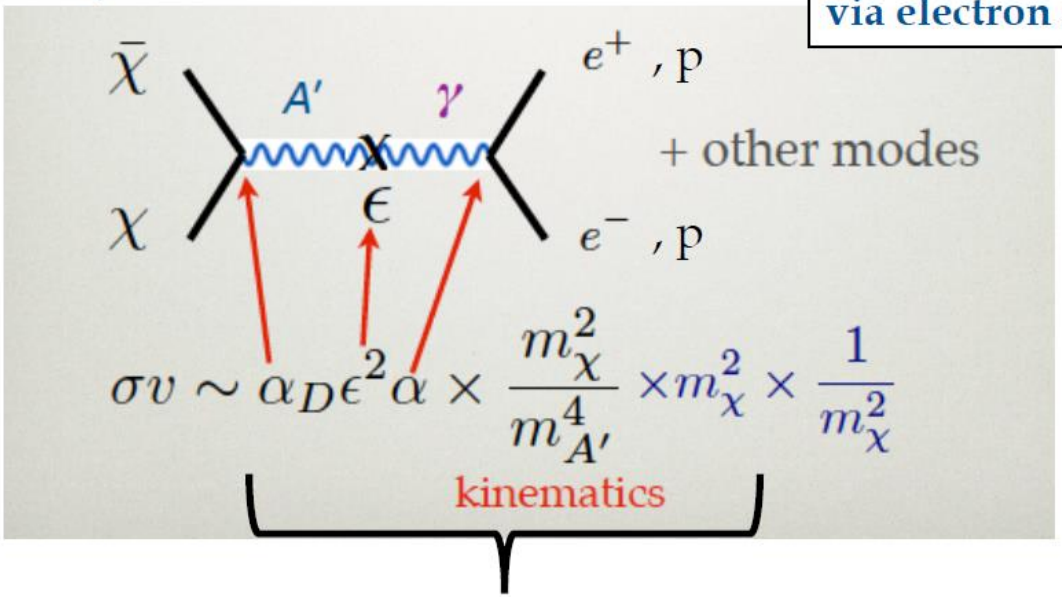
$\sqrt{S} = 400$ GeV,

N(p.o.t.) $= 2 \times 10^{20}$
(for 5 years)



Direct detection of the light DM

If $m_{A'} > 2\, m_\chi$ the Dark Photon can decay also to DM with a coupling α_D



Production of DM at accelerators via electron or proton bremstrahlung

y : dimensionless parameter controlling DM cross-section

Direct DM annihilation (main process to get the thermal relic abundance) but also Direct DM scattering with e/protons

Decays into the DM

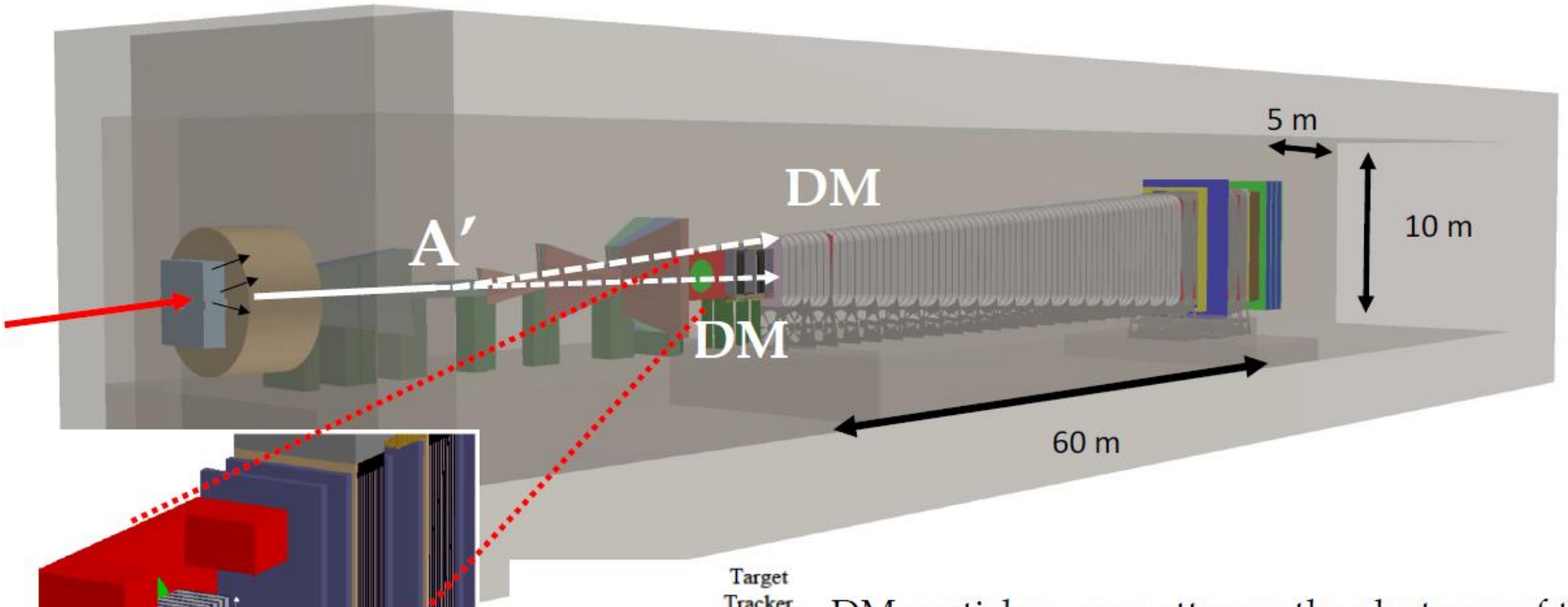
$$\Gamma_{A'\to l^+l^-} = \frac{1}{3}\epsilon^2\alpha m_V\left(1+\frac{2m_l^2}{m_V^2}\right)\sqrt{1-\frac{4m_l^2}{m_V^2}},$$

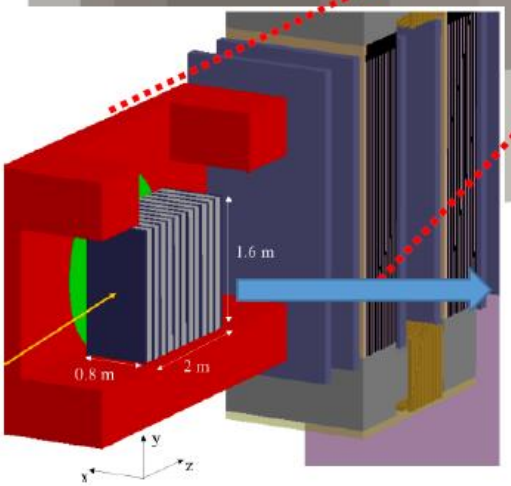
$$\Gamma_{A'\to \chi\bar{\chi}} = \frac{1}{3}\alpha_D m_V\left(1+\frac{2m_\chi^2}{m_V^2}\right)\sqrt{1-\frac{4m_\chi^2}{m_V^2}},$$

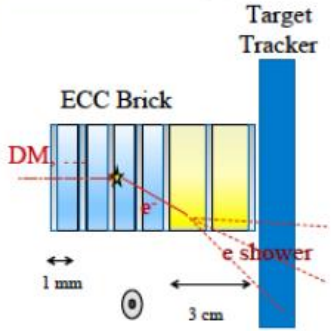
DM elastic scattering with e^-/nuclei

$$\frac{d\sigma_{e\chi\to e\chi}}{dE_f} = \frac{\alpha_D\epsilon^2}{\alpha}\times\frac{8\pi\alpha^2 m_e(1-E_f/E)}{(m_{A'}^2+2m_eE_f)^2},$$

Dark Photons @ SHiP: Light Dark Matter direct detection





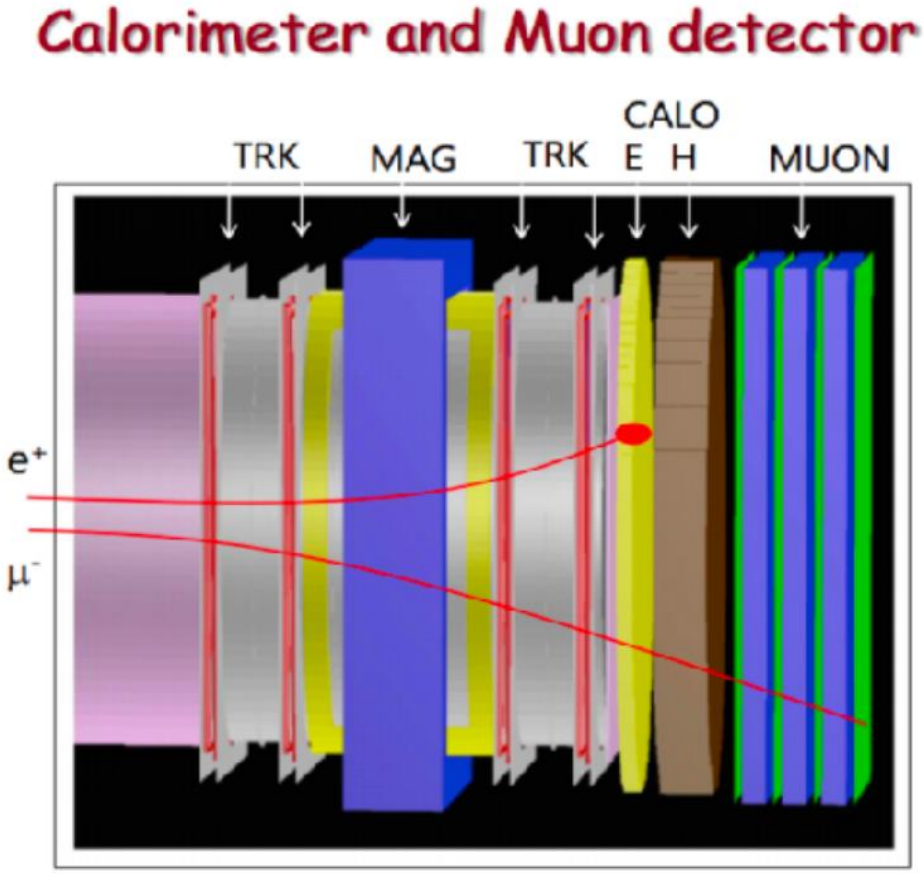


DM particles can scatter on the electrons of the dense material of the Emulsion Spectrometer in the Upstream Detector:

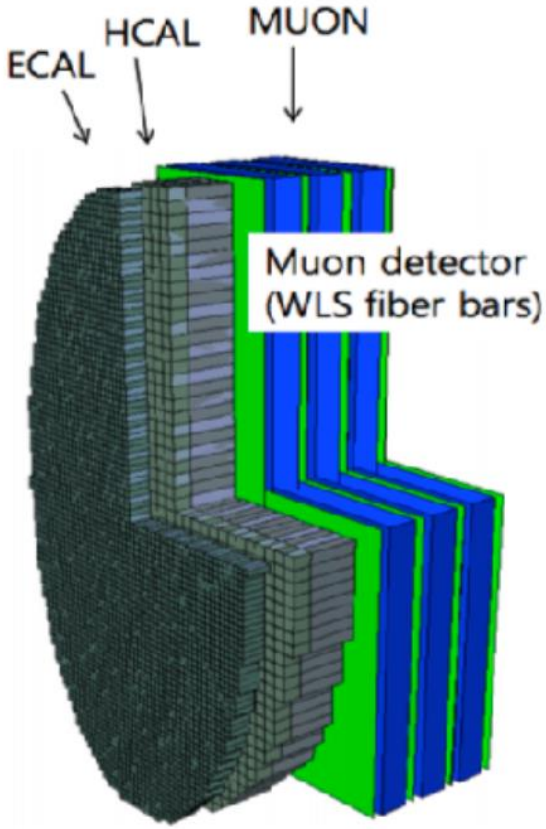
→ *a lot of opportunities here for new groups*

Why not at the ECAL?

The TP Design

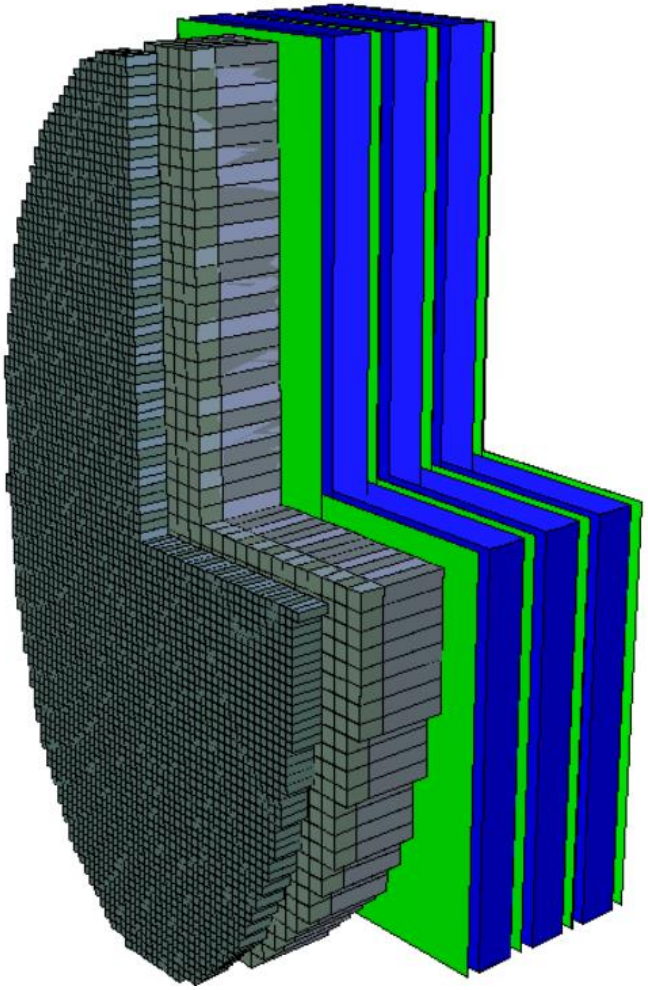


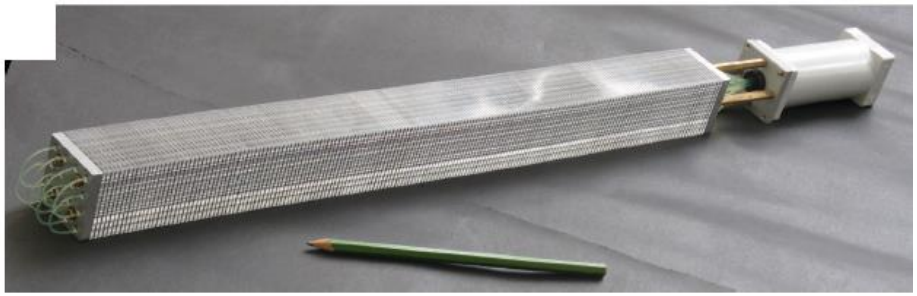
ECAL : e/γ id, π^0 and η reconstruction
(Shashlik technique, LHCb)



HCAL : π/μ separation
(similar technology as ECAL)

ECAL of the SHiP



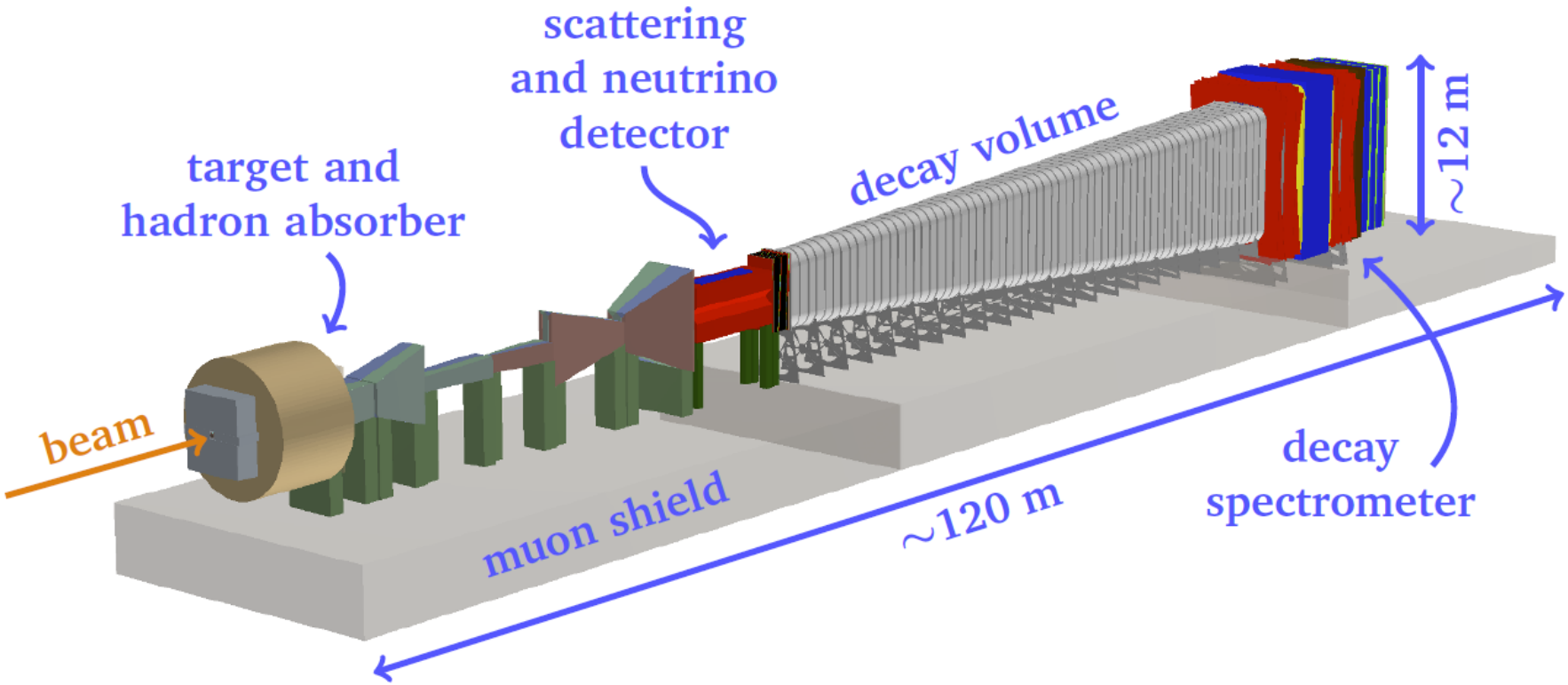


Current Design in TP: Shashlik calorimeter

- Cells of 6×6 cm^2 cross section with 140 alternating layers of 1 mm lead and 2 mm scintillator.
- Total depth of ~50 cm = 25 X_0.
- Light transfer with longitudinal WLS fibres.
- Light readout with PM tubes.
- In total 11504 cells/channels.
- Energy resolution $\sigma_E/E \sim 5.7\%/\sqrt{E}$

SHiP

[ins-det:1504.04956]

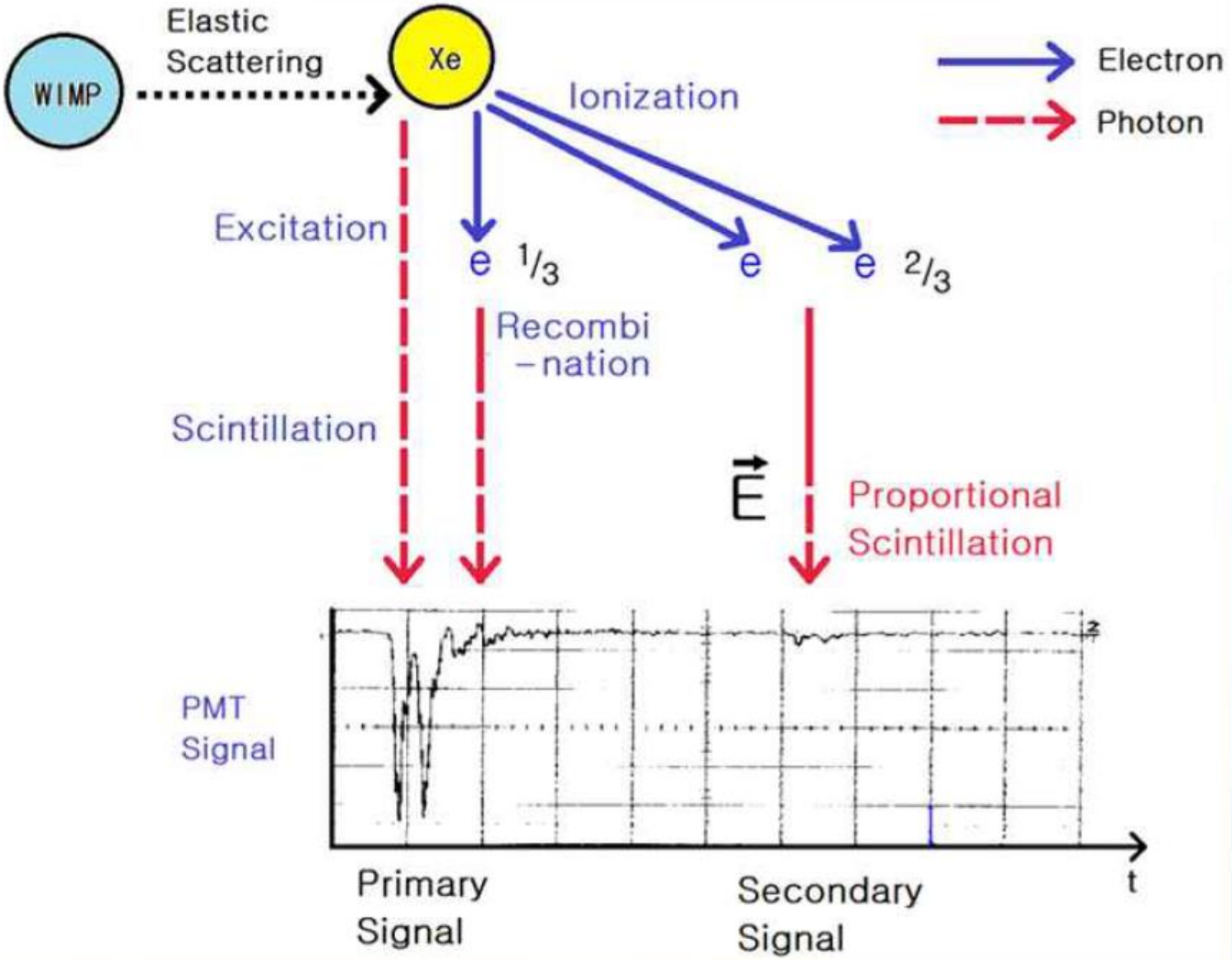


- 2×10^{20} *pot* in 5 years: $> 10^{18} D$, $> 10^{16} \tau$
- zero background beam dump expt. with spectrometry and PID
- large geometrical acceptance: long volume close to dump
- complementary detectors for scattering/decay signatures

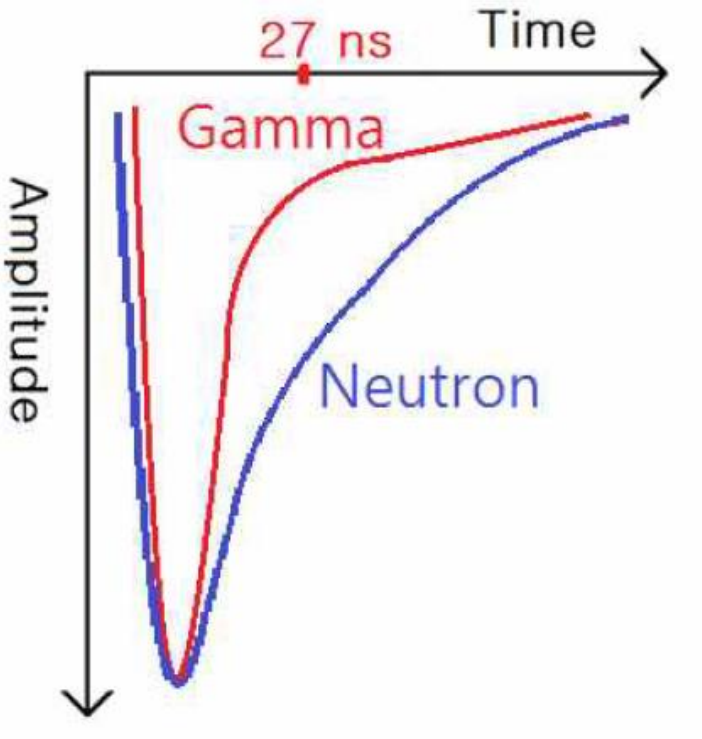
Pulse Shape Discrimination (PSD)

- Particle identification for neutral particles
- Discriminate signals by investigation of the photon pulse shape.
- Used to search for the WIMP etc..
- To be studied at **JNU**

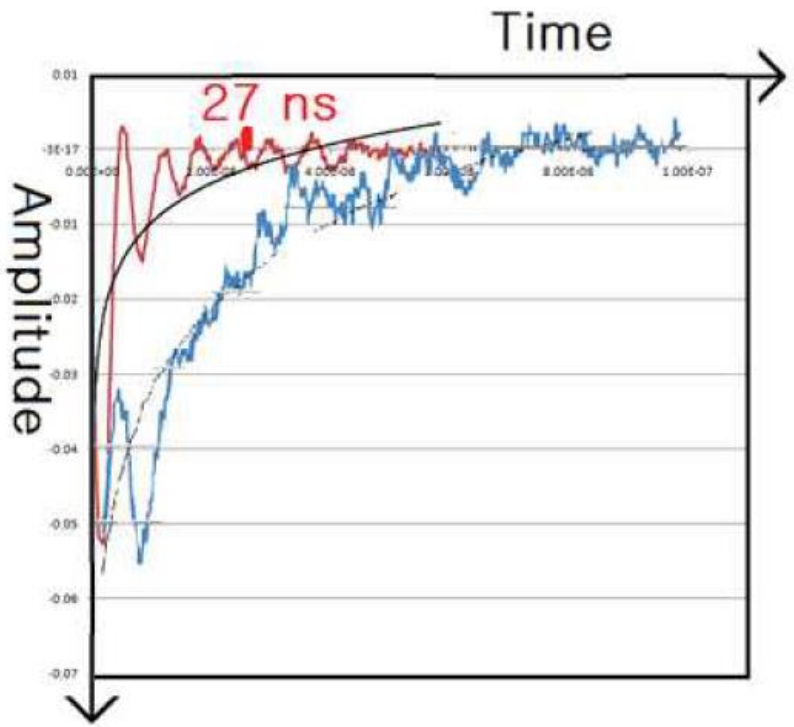
MECHANISM OF PARTICLE IDENTIFICATION



e.g. neutron vs. gamma ray



predictions



real signals