SHiP Physics Reach

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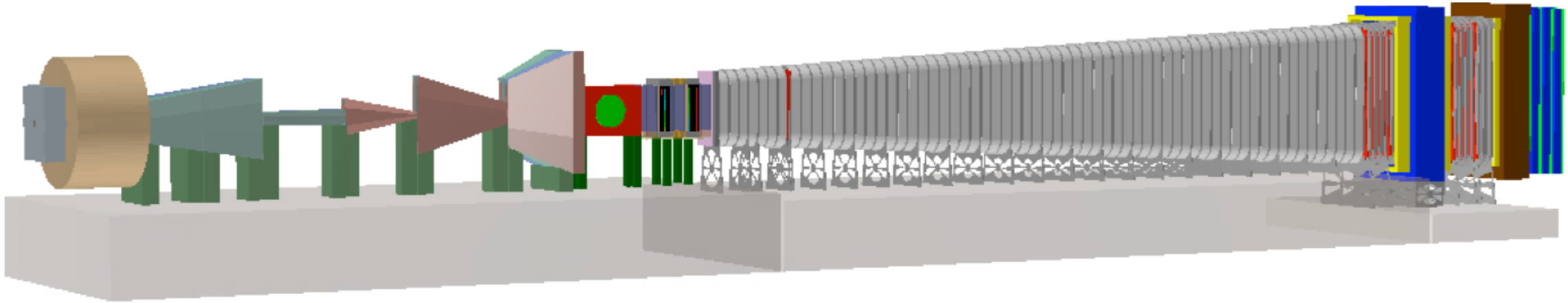


Journèe SHiP – Physics du secteur cachè - Paris - Octobre 2017

Preamble

SHiP

Big fundamental questions still open today:

Which is the origin of Baryogenesis?
Which is the nature of Dark Matter?
Which is the origin of neutrino masses and oscillations?

- ✓ So far the experimental efforts have been concentrated on the discovery of **new particles with masses at (or slightly above) the EW scale** and **sizeable couplings with SM particles**.
- ✓ Another viable possibility is that new particles are **below the EW scale and couple very weakly with SM particles** (see Misha's talk).
- ✓ These particles could be **light, long-lived, and mix with SM fields that do not carry electromagnetic charge,** like for example Higgs (Dark scalar or pseudo-scalar), photons (Dark Photon) and neutrinos (Heavy Neutral Leptons).

What is the scale of New Physics?

Masses of right handed neutrinos
10^{-9} – 10^{15} GeV

Mass of Dark Matter particle
10^{-31} – 10^{20} GeV

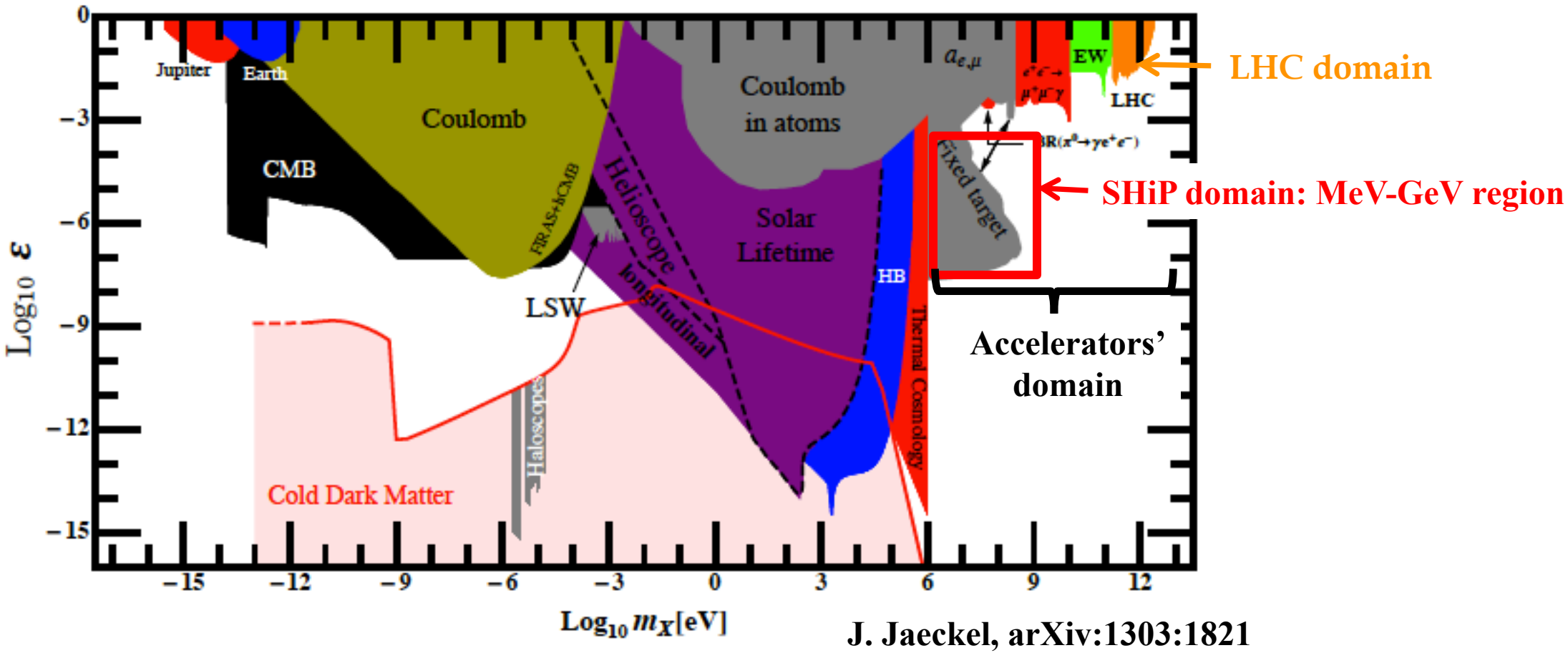
Mass of new particles required for baryogenesis
10^{-2} - 10^{15} GeV

Mass of New Particles for Higgs hierarchy
10^{3} – 10^{18} GeV

Today – more than ever - we must keep a wide view

.... A walk through the orders of magnitude....

kinetic mixing of a dark photon-ordinary photon

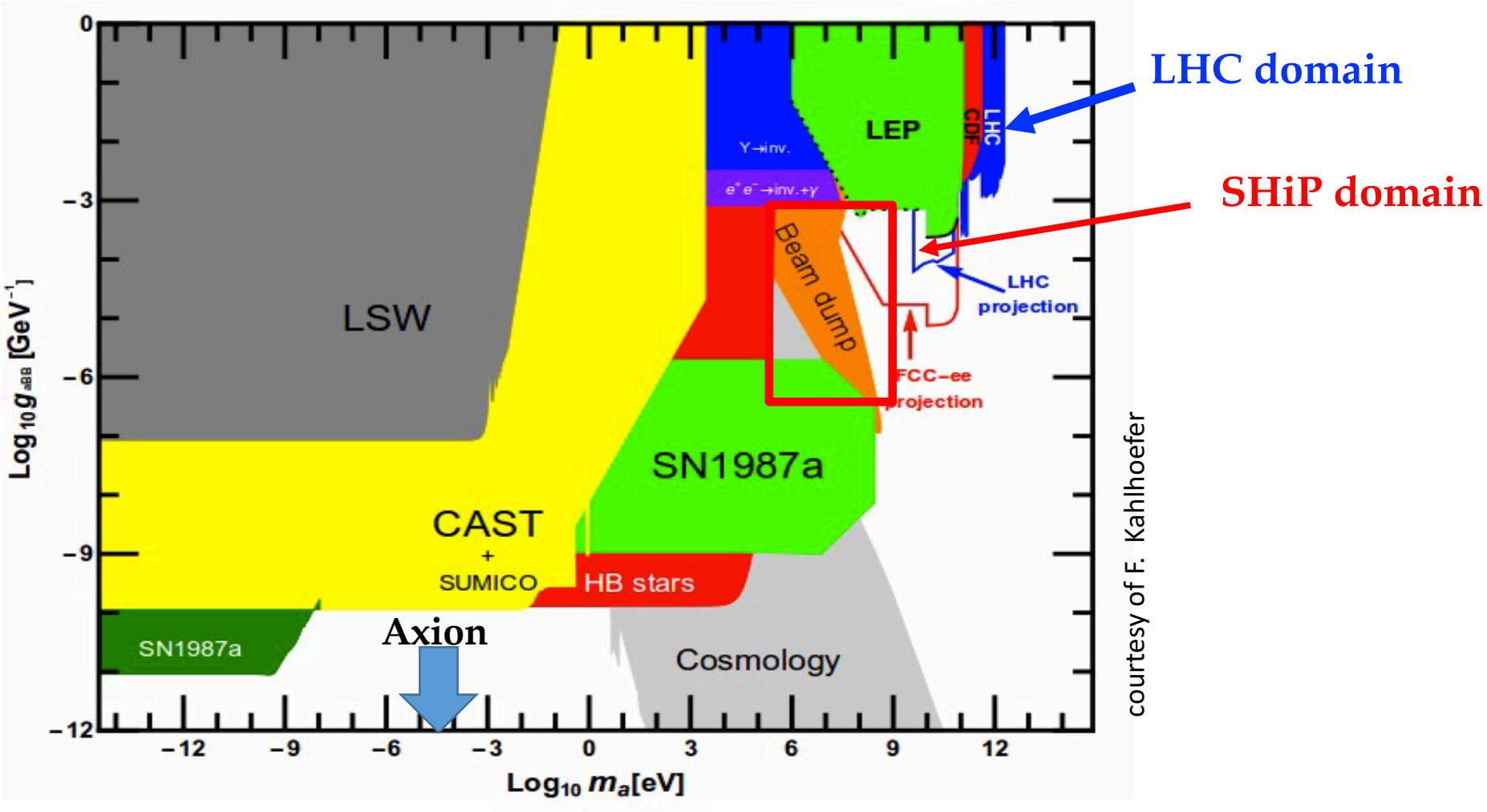


J. Jaeckel, arXiv:1303:1821

MeV-GeV region is special: hidden particles in this range could be DM mediators if DM is lighter than a WIMP

…A walk through the orders of magnitude…

Axion and Axion-Like Particles



- The axion was introduced to solve the strong CP problem in QCD: m~ 10^{-5} eV
- Other (pseudo)-scalar particles can feature very similarly to the axion but with larger mass: ALPS

Theoretically and phenomenologically motivated target areas:
a taste of the broad SHiP physics reach

SHiP

- **Light Dark Matter mediators:**
  - Dark (Pseudo)-Scalars;
  - Dark Photons (without and with dark decays)
- **Light Dark Matter direct detection**
- **Axion Like Particles as Generic Pseudo-Nambu Goldstone Bosons:**
  - coupled to fermions and photons;
- **Heavy Neutral Leptons.**

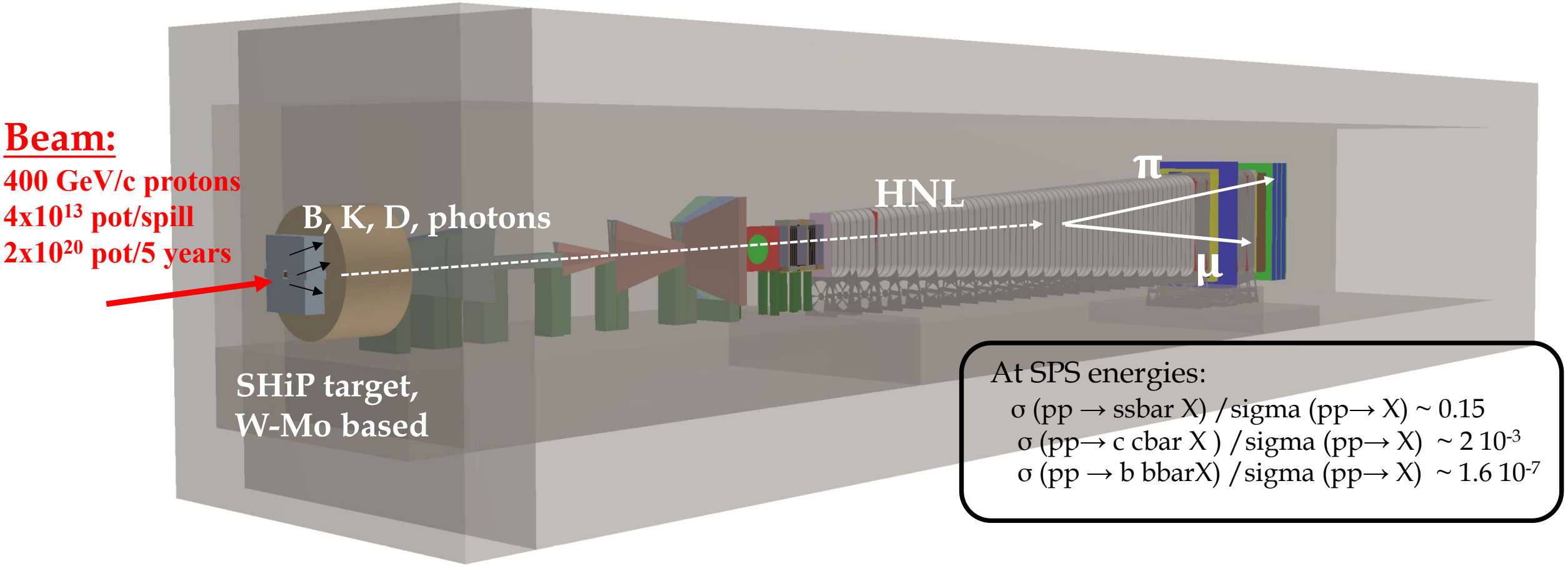
Each of these models can answer to all or some of the main questions listed at the beginning:

- Dark Photon and Dark Scalars: Light Dark Matter mediator, with decays to SM particles or DM particles
- Heavy Neutral Leptons: one (keV scale) can be the DM candidate, the other two (GeV scale) can explain baryogenesis via leptogenesis and the origin of neutrino masses and oscillations.

A large literature exists on these topics – both in Europe and US:

- A. Alekhin et al., The SHiP Physics case, arXiv:1504.04855 (and the > 1000 references therein)
- SLAC Dark Sector Workshop 2016: Community Report – arXiv: 1608.08632
- Maryland Dark Sector Workshop 2017: Cosmic Visions – arXiv:1707.04591

Production of Hidden Particles @ SHiP:

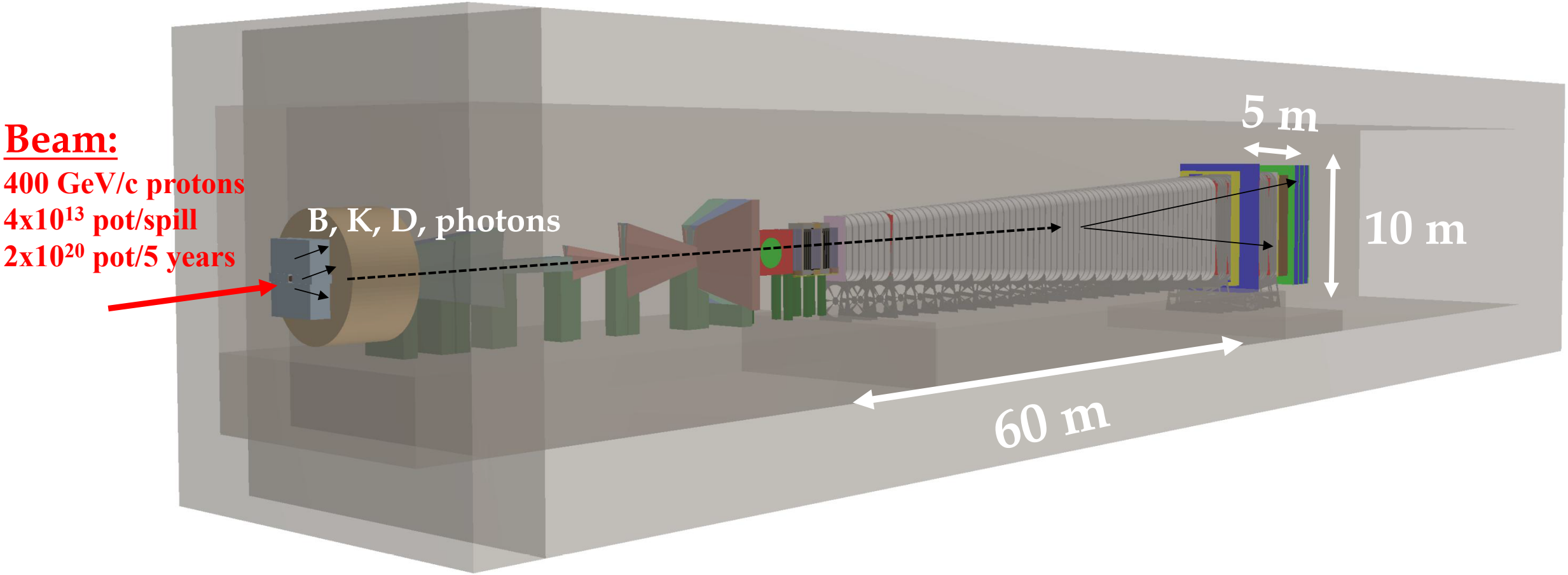


Hidden particles can be **originated by the decay of B, D, K and by photons produced in the interaction of protons with a high-Z target**:

⟶ a high-intensity, high-energy proton beam is required to improve over the current results:

⟶ if approved, the world best line to produce high intensity fluxes of beauty and charm hadrons and photons at a fixed target will be the 400 GeV/c proton beam line extracted from the CERN SPS in the Beam Dump Facility (see Richard's talk).

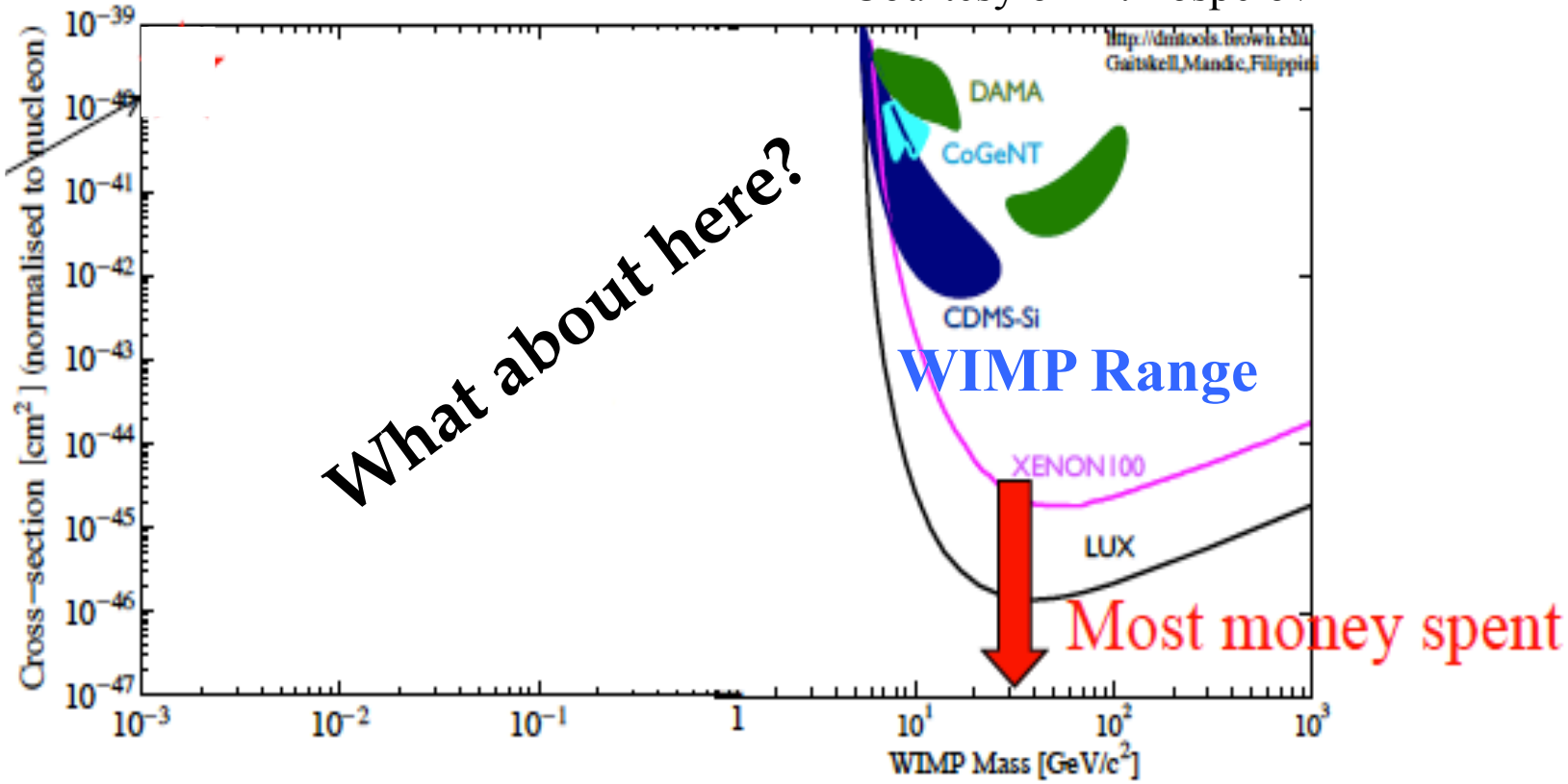
Decay of Hidden Particles @ SHiP:



- ✓ Hidden particles have very feeble couplings, hence they are (very) long-lived:
  - The 60m-long, in-vacuum SHiP decay volume allows us to be sensitive to extremely low couplings
- ✓ Hidden particles from D and B decays have large p_T:
  - SHiP large geometrical acceptance maximizes detection of decay products

Light Dark Matter and Light Mediators

Courtesy of M. Pospelov



Light Dark Matter: thermal origin

As universe cools below DM mass, density decreases as exp{-m/T}

- DM interacts with SM to stay in equilibrium
- eventually DM particles can't find each other to annihilate
- and a (minimal) DM abundance is left over the present day.

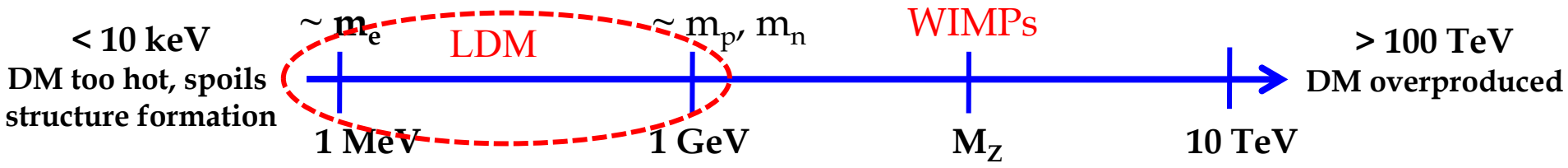
Equilibrium reached easily with a tiny DM-SM coupling.

DM annihilation cross-section necessary to obtain the relic density:

$$\sigma\, v\ (\text{relic}) = 3\text{x}10^{-26}\ \text{cm}^3/\text{s}$$

The equilibrium can be reached:

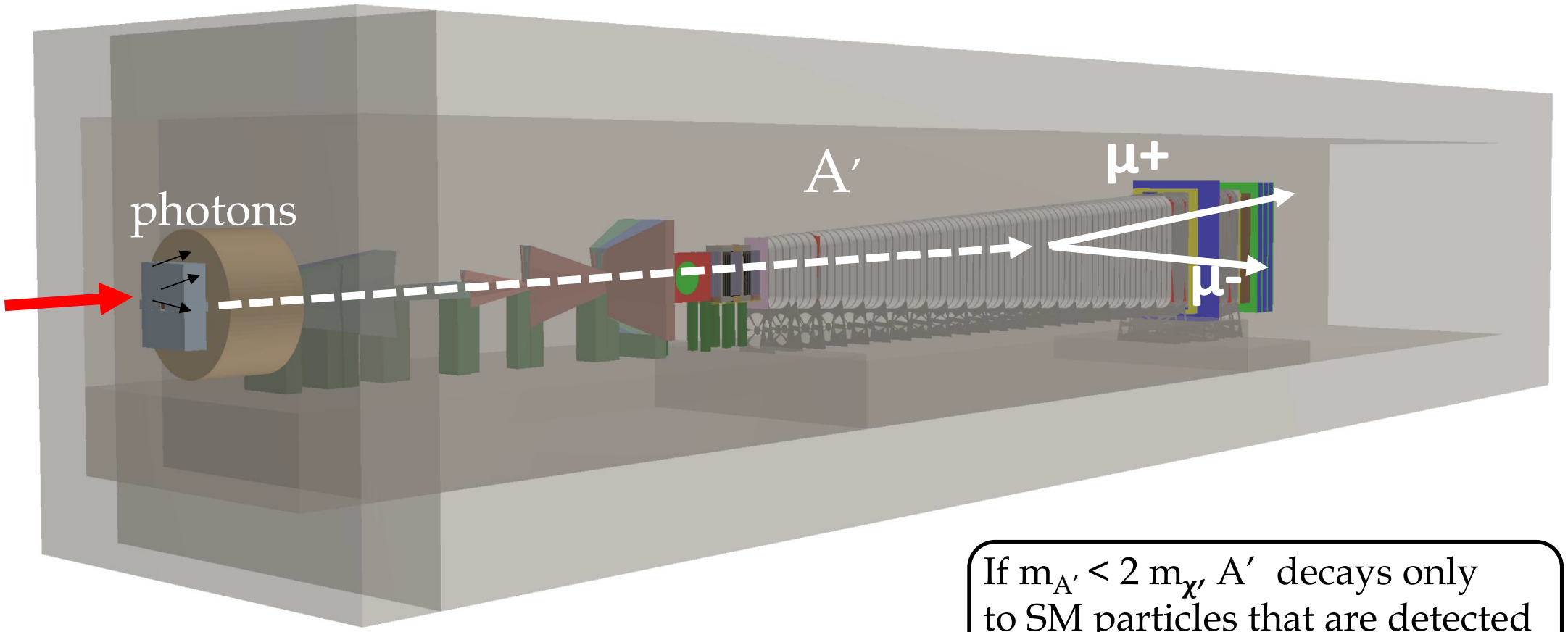
- either with **traditional WIMP** at TeV scale **with Z mediator** (excluded by current limits)
- or with **light DM** with **light mediator (hence new forces).**



Light mediators must be SM singlet, options limited by SM gauge invariance:

1) Vector Portal; 2) Scalar Portal; 3) Neutrino Portal

Vector Portal : Dark Photon via kinetic mixing – decays to SM particles

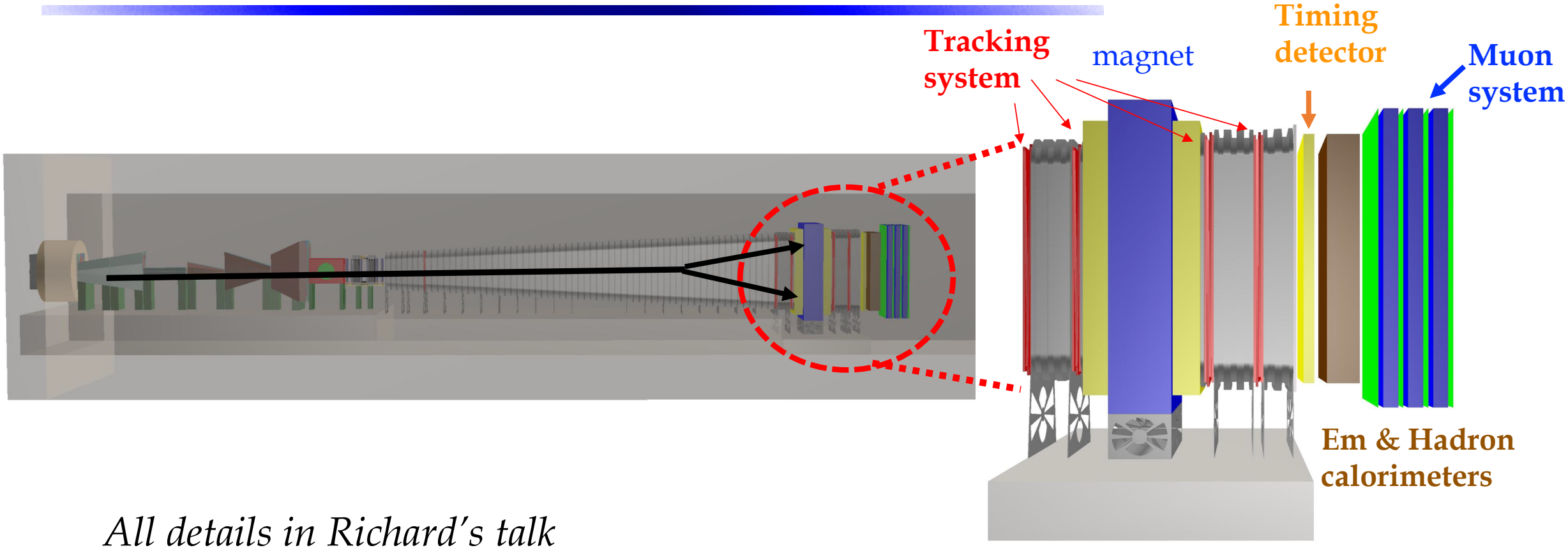


If $m_{A'} < 2\, m_{\chi'}$, A′ decays only to SM particles that are detected in the downstream spectrometer

➜ Production at SHiP:

- meson decays e.g. $\pi^0 \to \gamma V$ ($\sim \epsilon^2$)
- p bremsstrahlung on target nuclei $pp \to ppV$
- large $m_V \Rightarrow$ direct QCD production through underlying $q\bar{q} \to V$, $qg \to V$ (need some more theory work!)

SHiP: downstream spectrometer

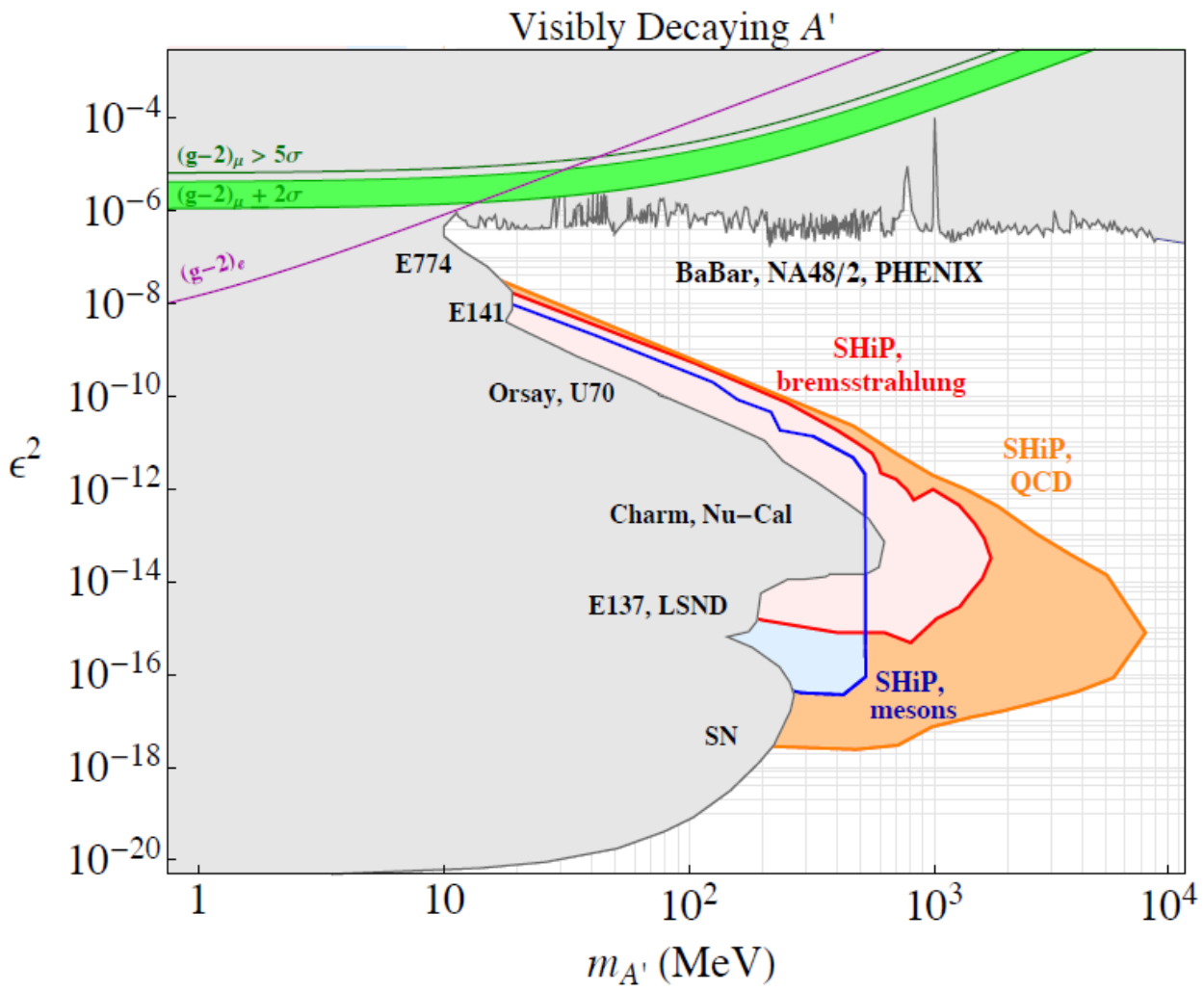


All details in Richard's talk

Vector Portal : Dark Photon via kinetic mixing – decays to SM particles

SHiP

SHiP sensitivity to Dark Photons decaying to SM particles



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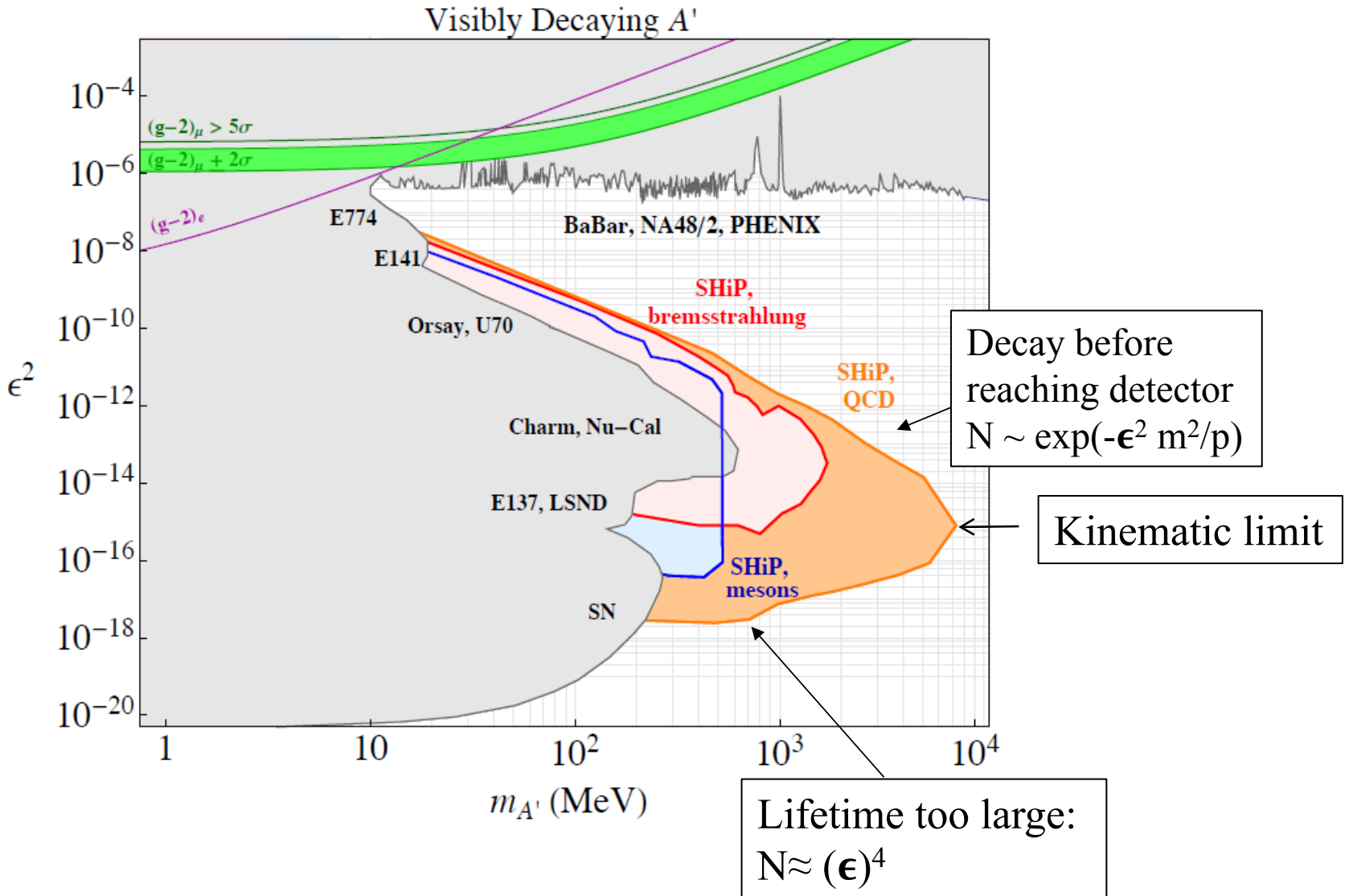

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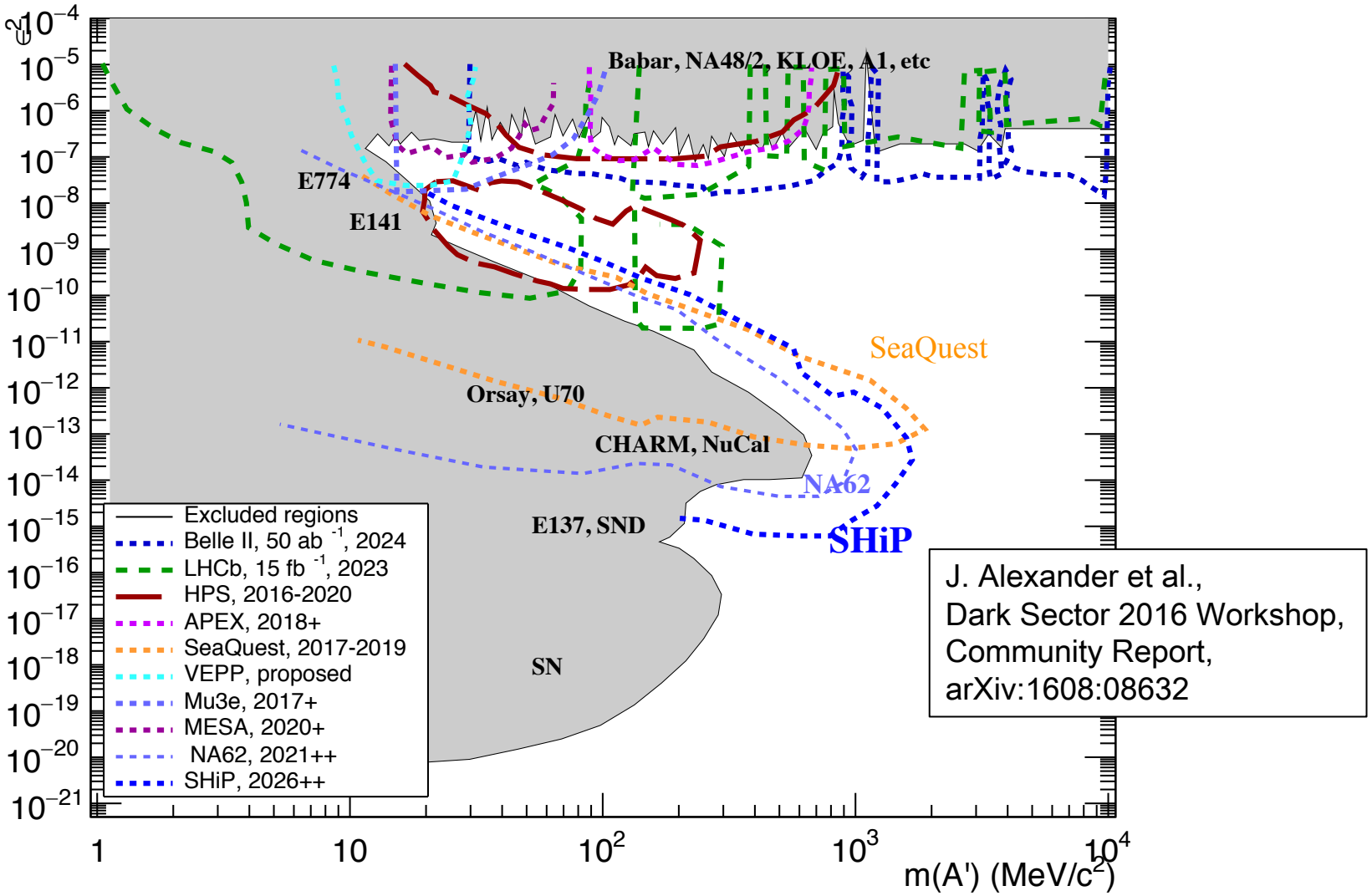


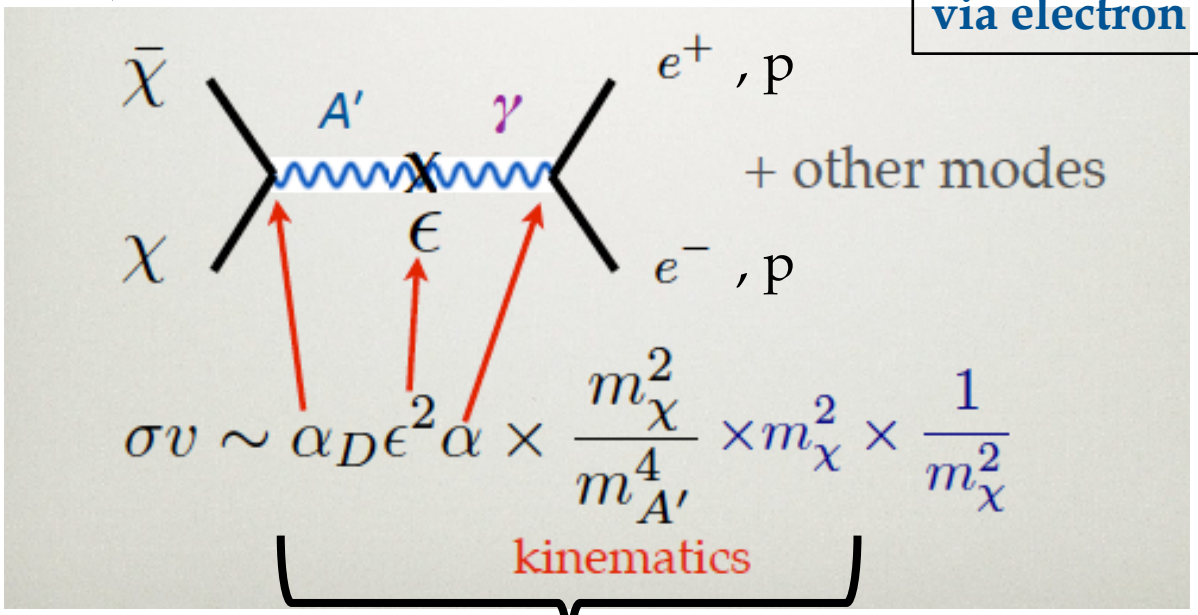
J. Alexander et al.,
Dark Sector 2016 Workshop,
Community Report,
arXiv:1608:08632

A lot of experimental results expected on the Vector Portal in the near future

Vector Portal : connection to Light Dark Matter (and thermal origin target)

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

Production of DM at accelerators via electron or proton bremstrahlung



y : dimensionless parameter controlling DM cross-section

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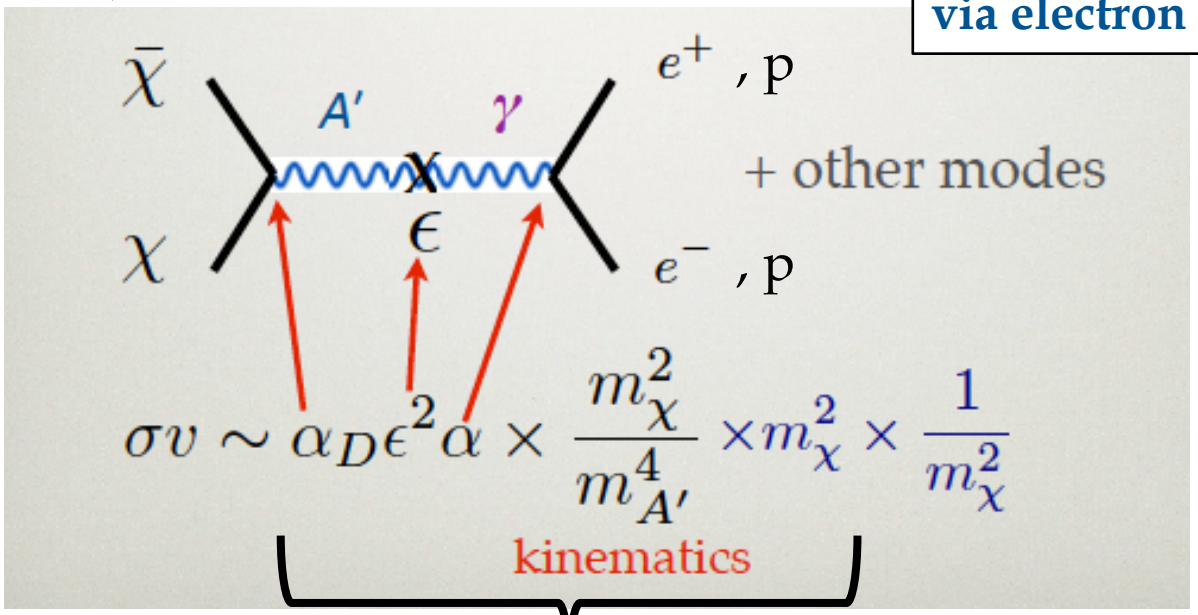
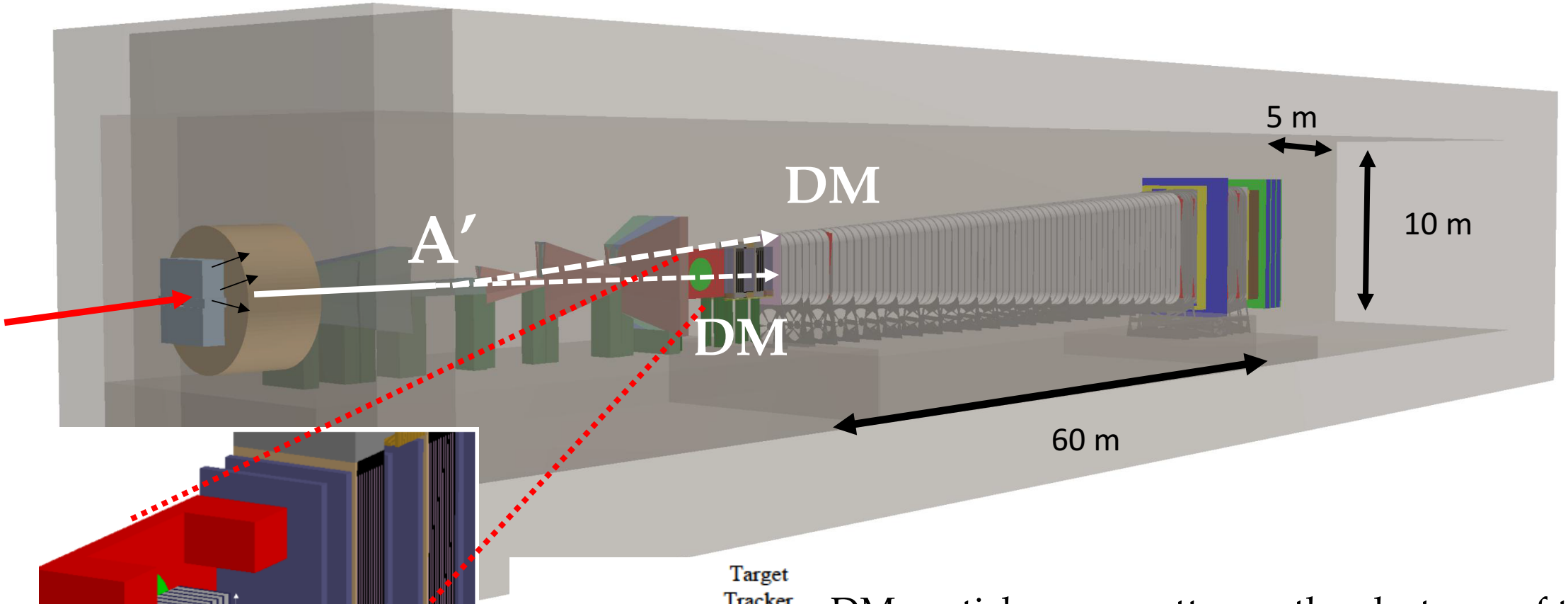
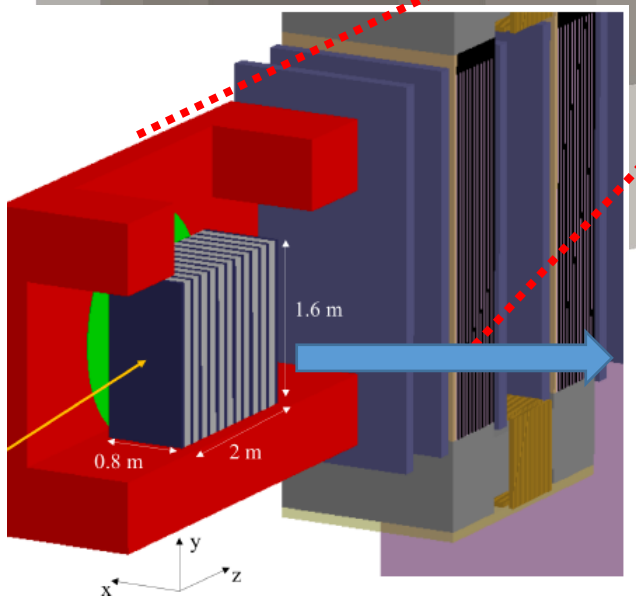


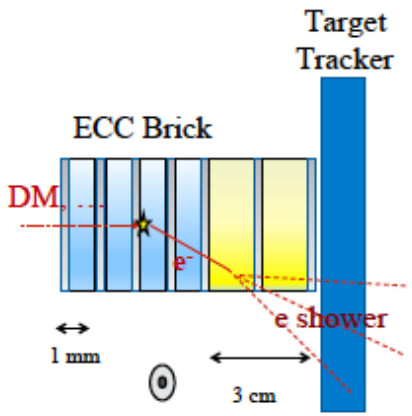
y : dimensionless parameter controlling DM cross-section

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

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:

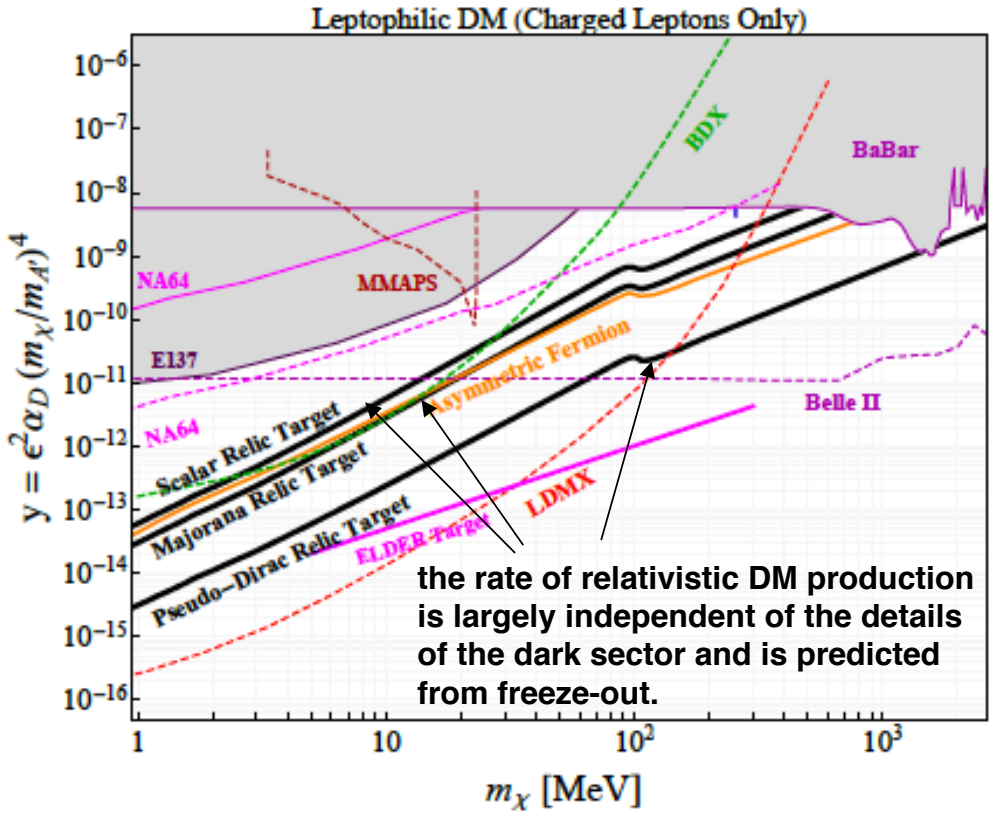
⟶ *a lot of opportunities here for new groups*

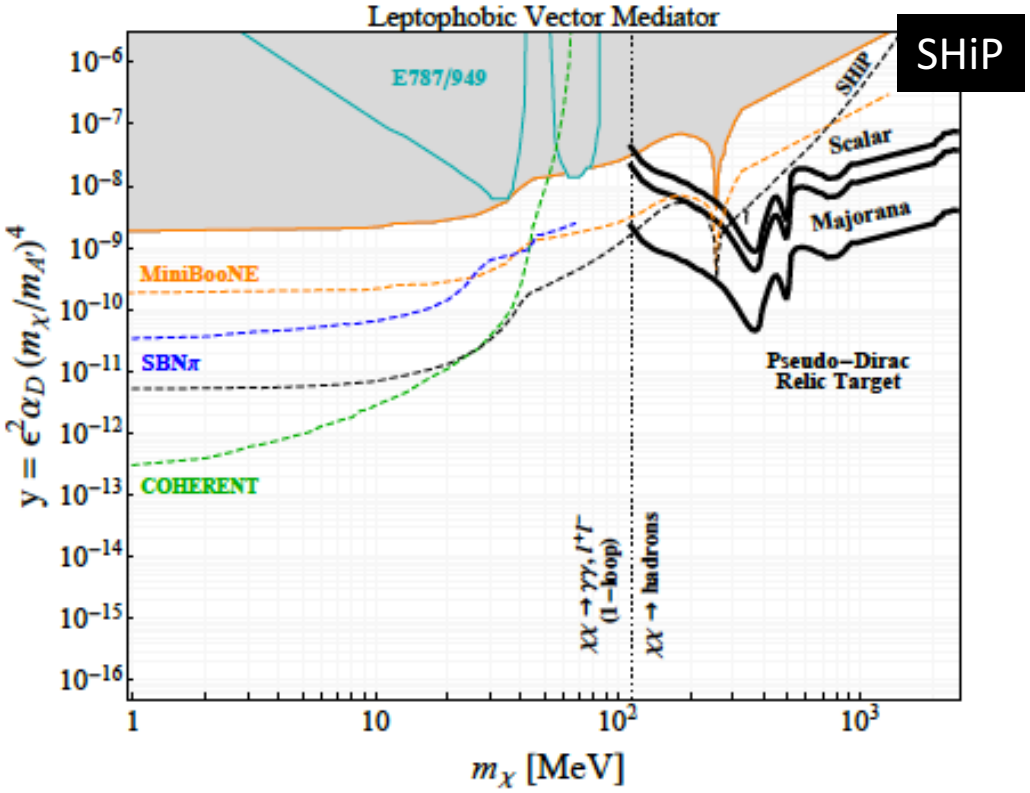
⟶ *see Andrey's talk*

Vector Portal : connection to Light Dark Matter (and thermal origin target)

Direct annihilation is controlled by the same couplings relevant for direct DM scattering, leading to well defined predictions, once we assume the thermal origin target

Cosmic Visions, arXiv: 1707.04591

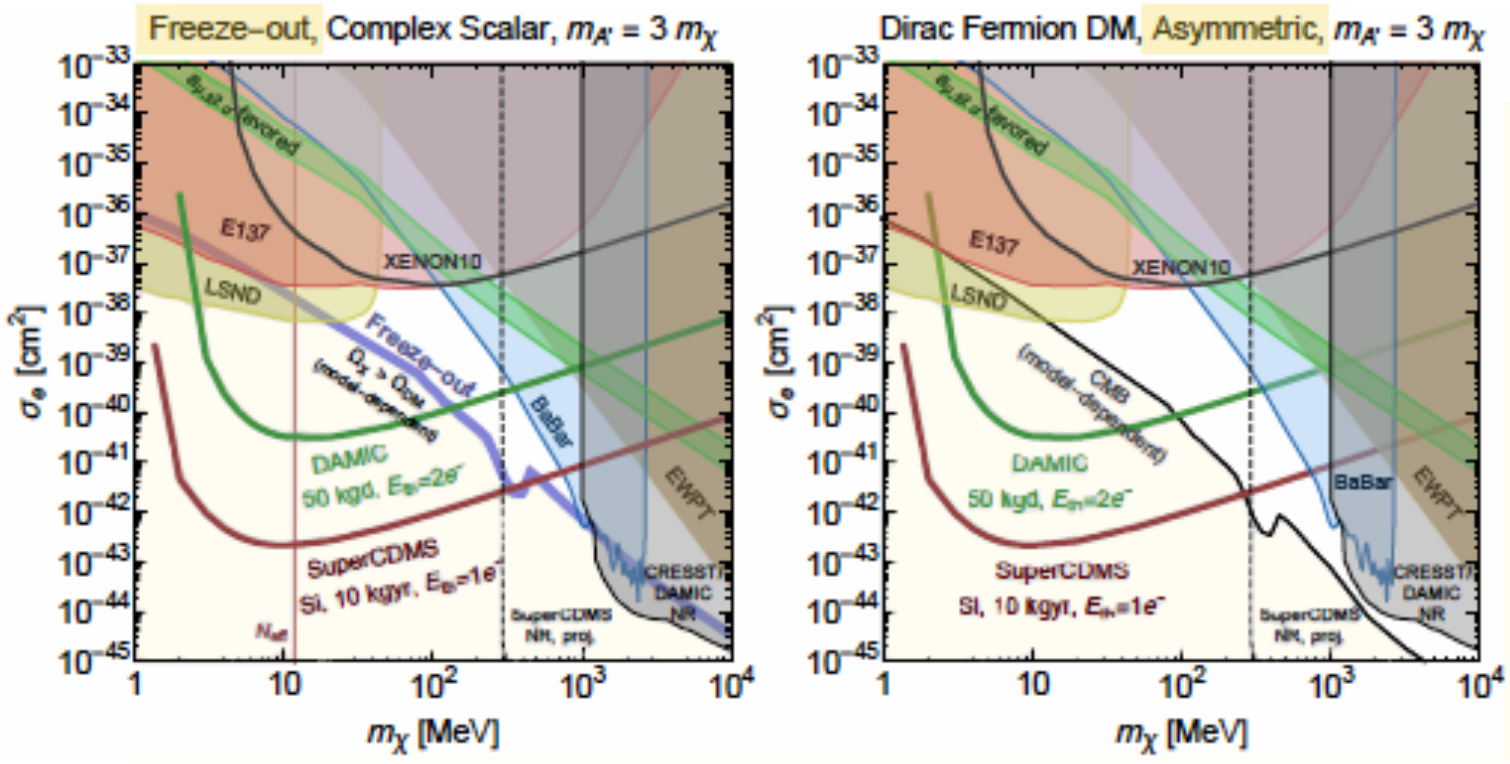




- the Vector portal can be seen as a simplified model where the mediator couples preferably to leptons (lepto-philic models) or to hadrons (lepto-phobic models)

Vector Portal : connection to Light Dark Matter (and thermal origin target)

Comparison between accelerator-based DM searches and Direct Detection searches in the low-mass (< 10 GeV) region



[Essig, Fernandez-Serra, Mardon, Soto, TV, Yu, 2015 (upcoming)]

Presented by T. Volyansky at EPS 2015

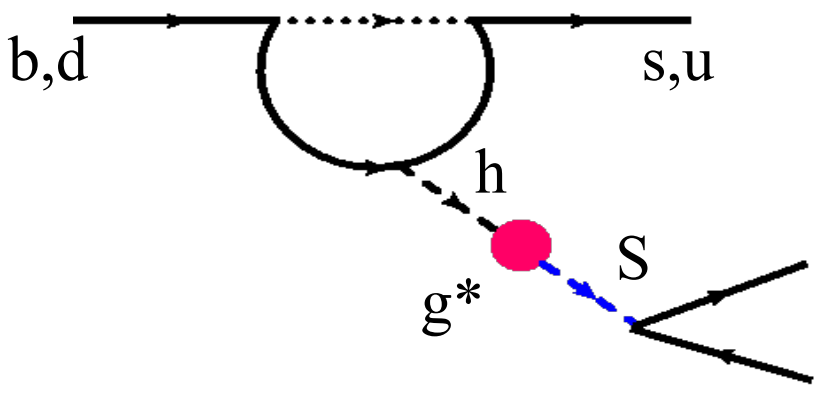
We will see more and more this kind of plots in the future
(SHiP projections still to be included)

(Pseudo)-Scalar Portal: Dark (Pseudo)-Scalars at SHiP

The discovery of the Higgs provides strong evidence that fundamental scalar bosons exist in nature:

- timely and well-motivated to search for additional scalar or pseudo-scalar particles that could be mediators of light Dark Matter

Dark Scalar and Pseudo-Scalar particles can couple to the Higgs in FCNC transition in K and B decays:



e^+e^-, $\pi^+\pi^-$, K^+K^-, $\mu^+\mu^-$, …
detected in the downstream spectrometer

$$\Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

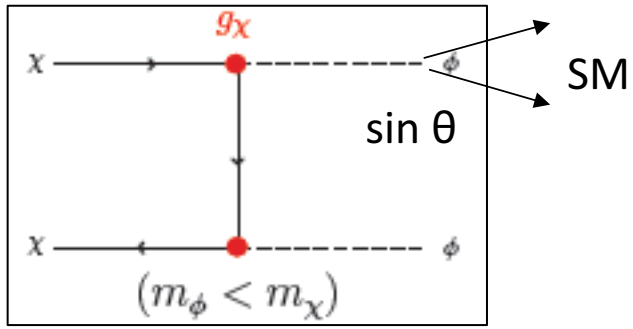
$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

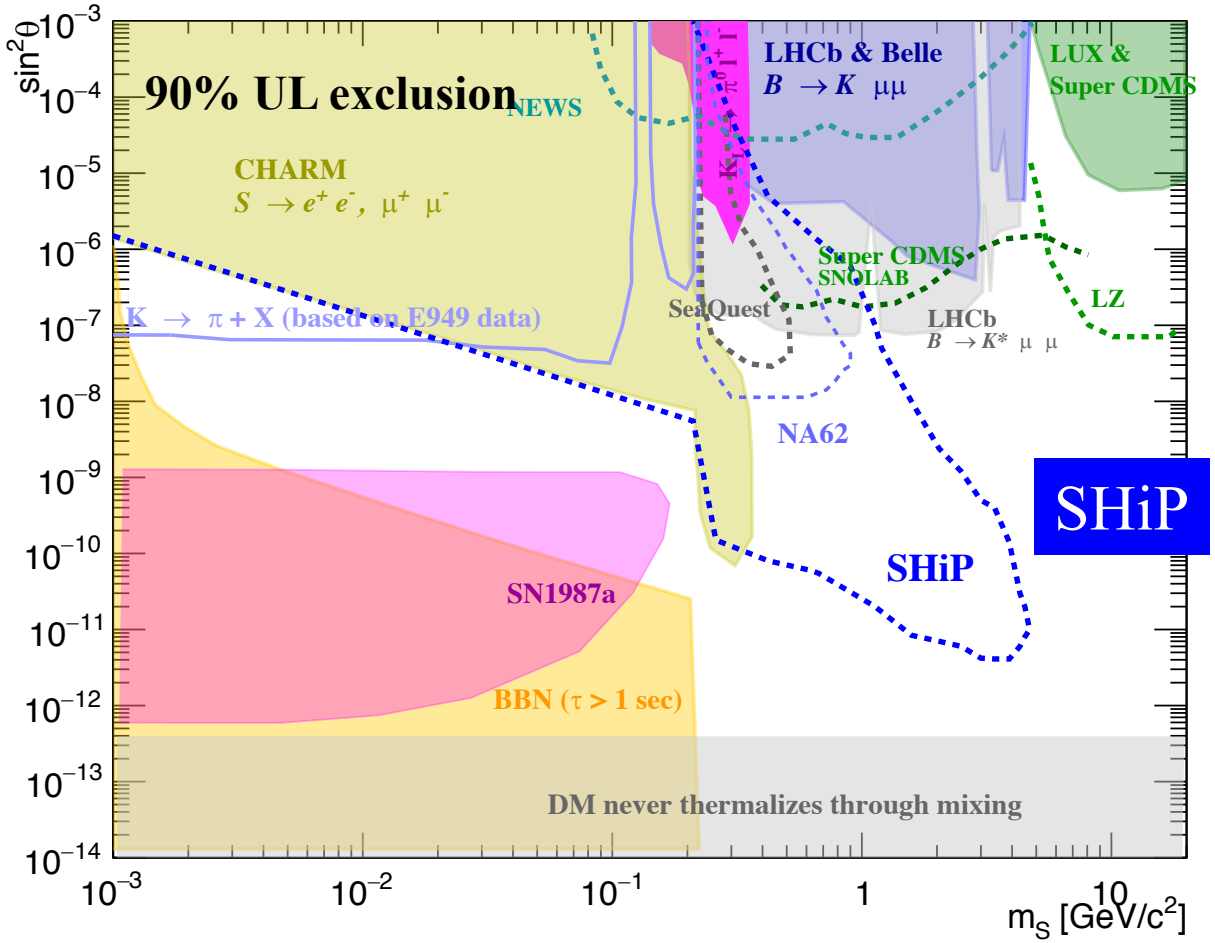
At SPS energies:

σ (pp → ssbar X) / sigma (pp→ X) ~ 0.15
σ (pp→ c cbar X) / sigma (pp→ X) ~ 2 10^{-3}
σ (pp → b bbarX) / sigma (pp→ X) ~ 1.6 10^{-7}

Scalar Portal: Dark Scalars particles at SHiP

Secluded DM annihilation via mediators (only possibility compatible with CMB and rare mesons decays constraints), mediators then decay to SM particles

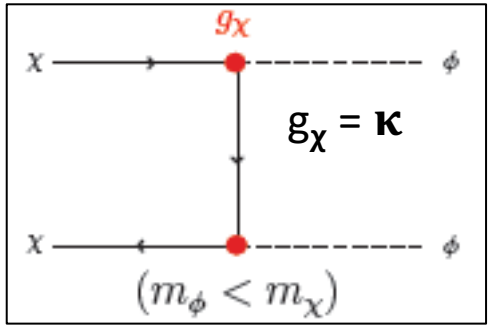




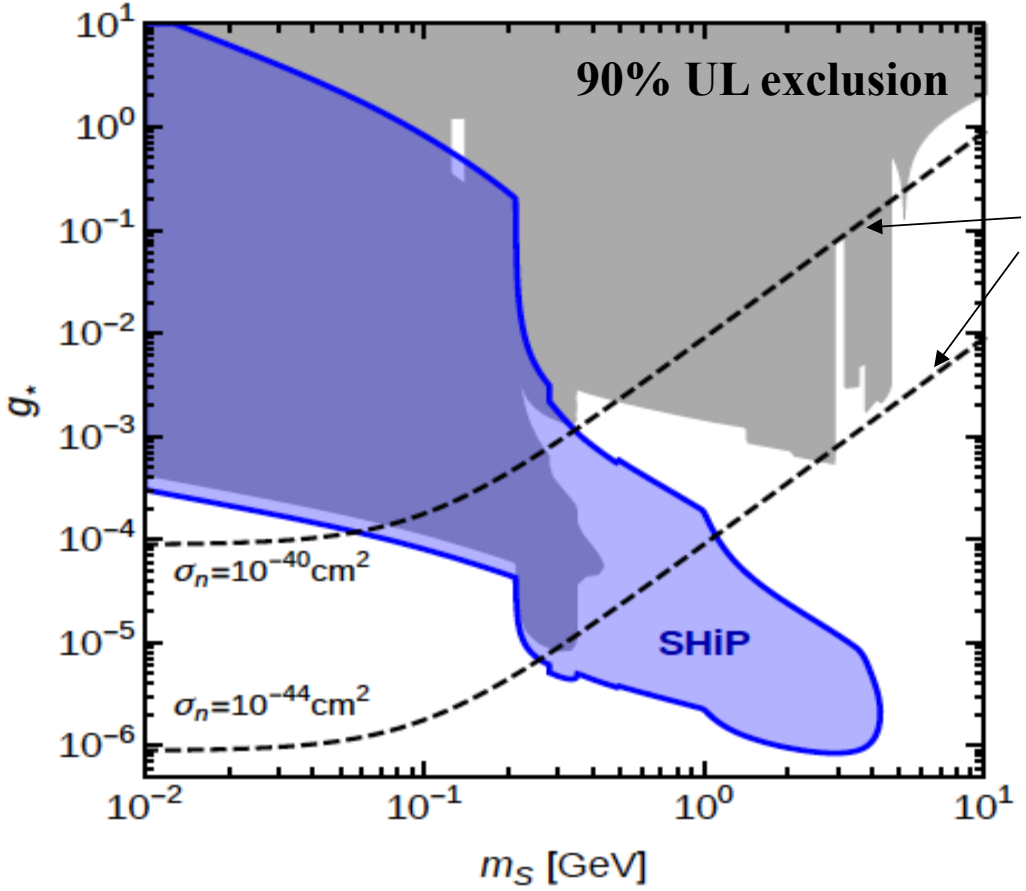
Fixed target: from CHARM (1980+) to SHiP (2026++):
A huge gap in sensitivity (several orders of magnitude in coupling & mass)

Scalar Portal: Dark Scalars particles at SHiP

Relation between light scalar mediator and DM direct detection



$$\sigma_n \simeq 10^{-40}\mathrm{cm}^2 \left(\frac{\kappa}{0.1}\right)^2 \left(\frac{g_\star}{0.01}\right)^2 \left(\frac{\mathrm{GeV}}{m_S}\right)^4$$



Contours of constant DM nucleon cross section, where we assumed that S acts as the mediator between DM and nucleons:

⟶ current limits from LUX experiment assuming m_χ ~ 5-10 GeV and k = 0.1

The SHiP Physics case,
Rept.Prog.Phys. 79 (2016) no.12, 124201

Axion and Axion-Like Particles

SHiP

- **Pseudo-scalar particles can be Pseudo Nambu-Goldstone bosons of a spontaneously broken U(1) symmetry:**
  - The prime example is the axion introduced to solve the strong CP problem in QCD: m~ 10^{-5} eV
  - Other (pseudo)-scalar particles can feature very similarly to the axion but with larger mass: ALPS

- **Axions and ALPs can couple to: gauge bosons, fermions, gluons**

- gauge bosons, eg: photons:

$$\mathcal{L} \supset \frac{1}{4}\, g_{a\gamma\gamma}\phi F^{\mu\nu}F_{\mu\nu}$$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a}$$

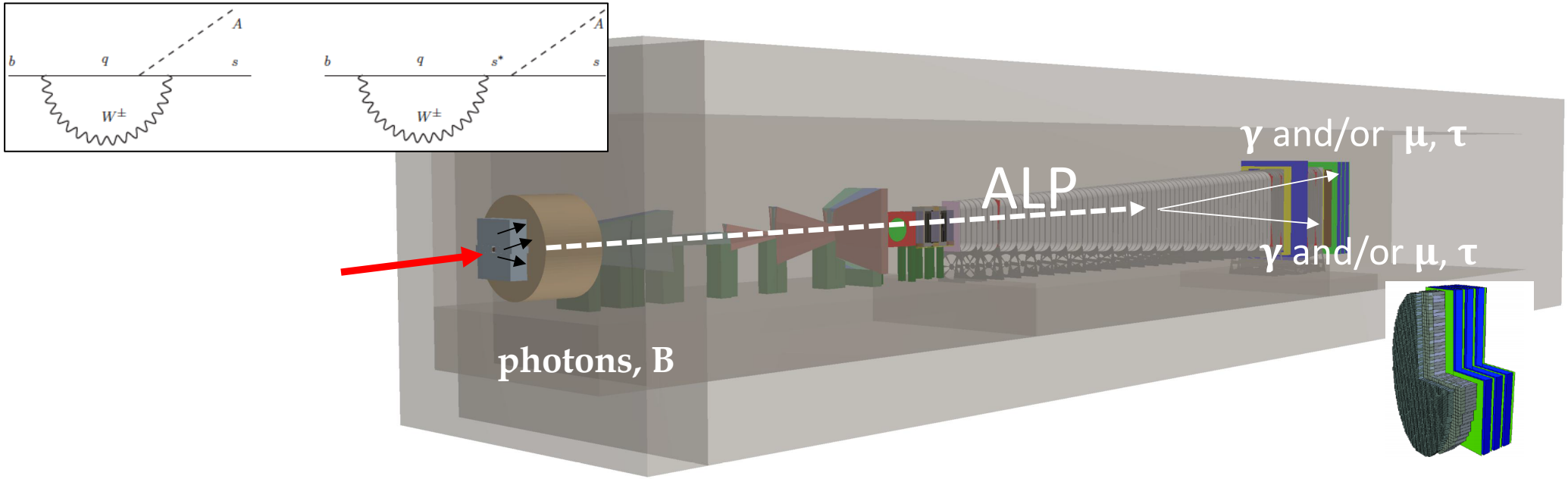
- fermions:

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

- **In both cases their interactions are suppressed by a scale $1/f_a$, scale of the spontaneous symmetry breaking**.

ALPs @ SHiP: photon & fermions couplings

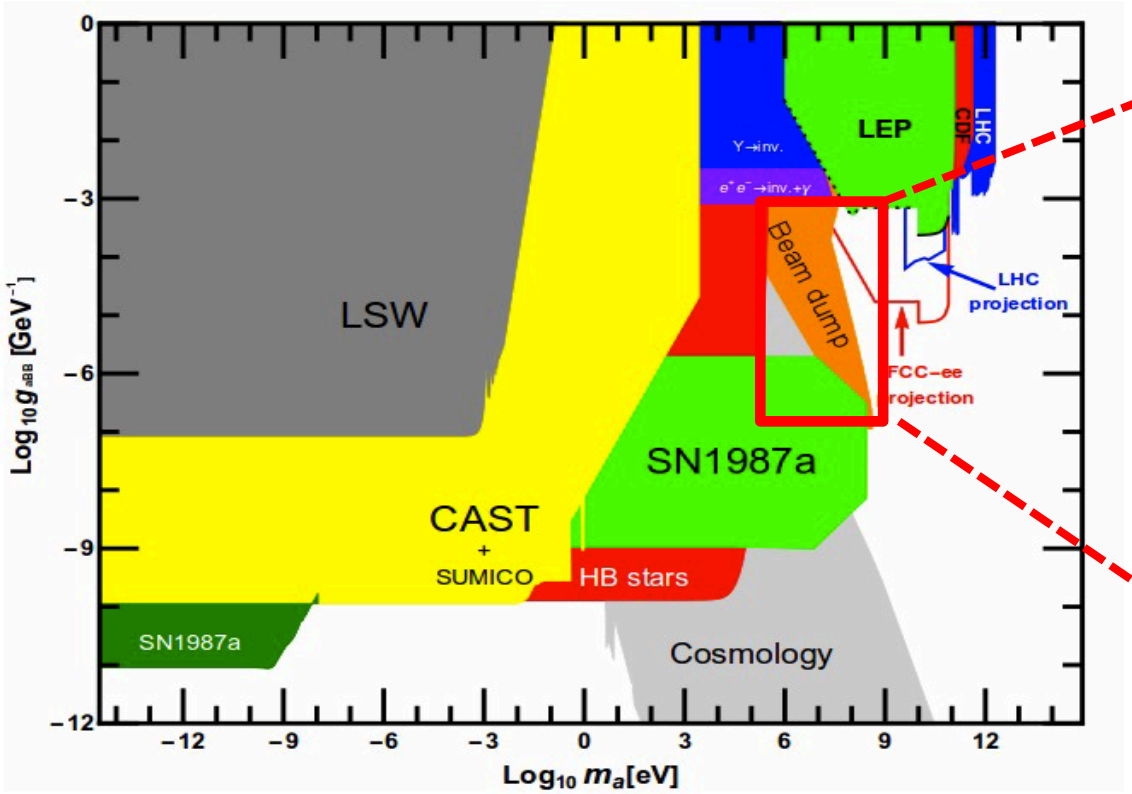
At fixed target:
ALPS with coupling to photons are produced via Primakoff effect
ALPS with coupling to fermions are produced in the decay of K,B mesons

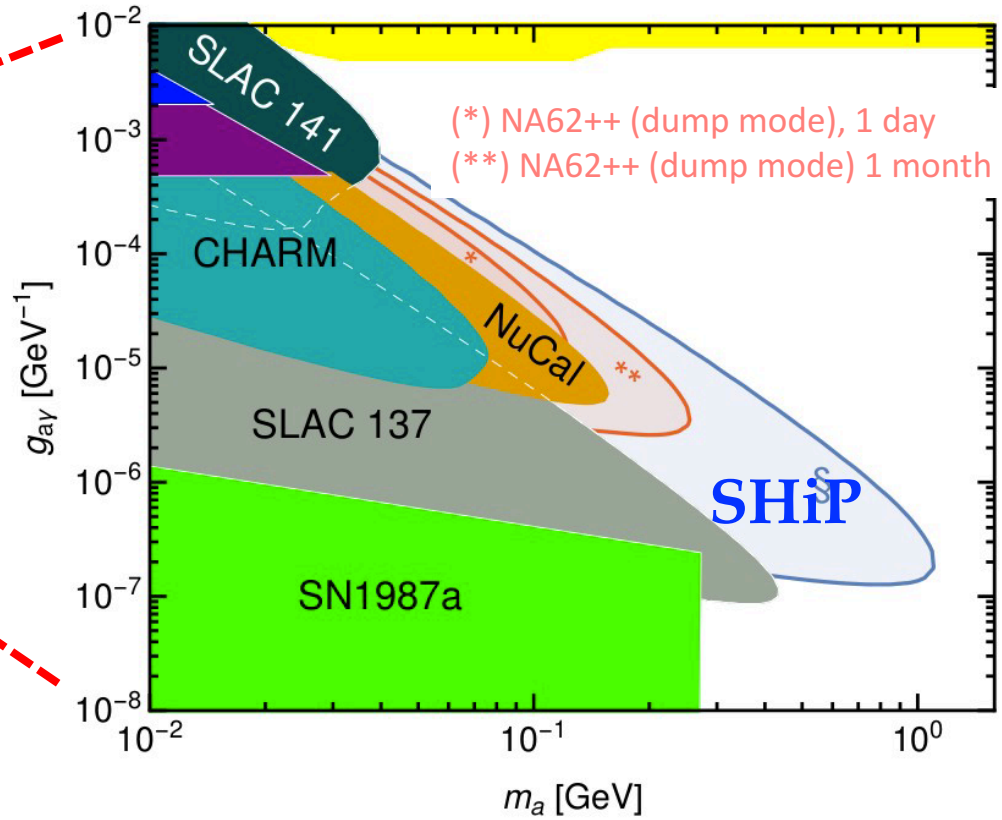


Main detectors here:
Electro-magnetic calorimeter with directional information (for photon coupling)
Charged PID system (calorimeters and muon system) (for fermions coupling)
(See Walter's talk)

ALPs @ SHiP: photon coupling - sensitivity

$A' \longrightarrow \gamma\gamma$

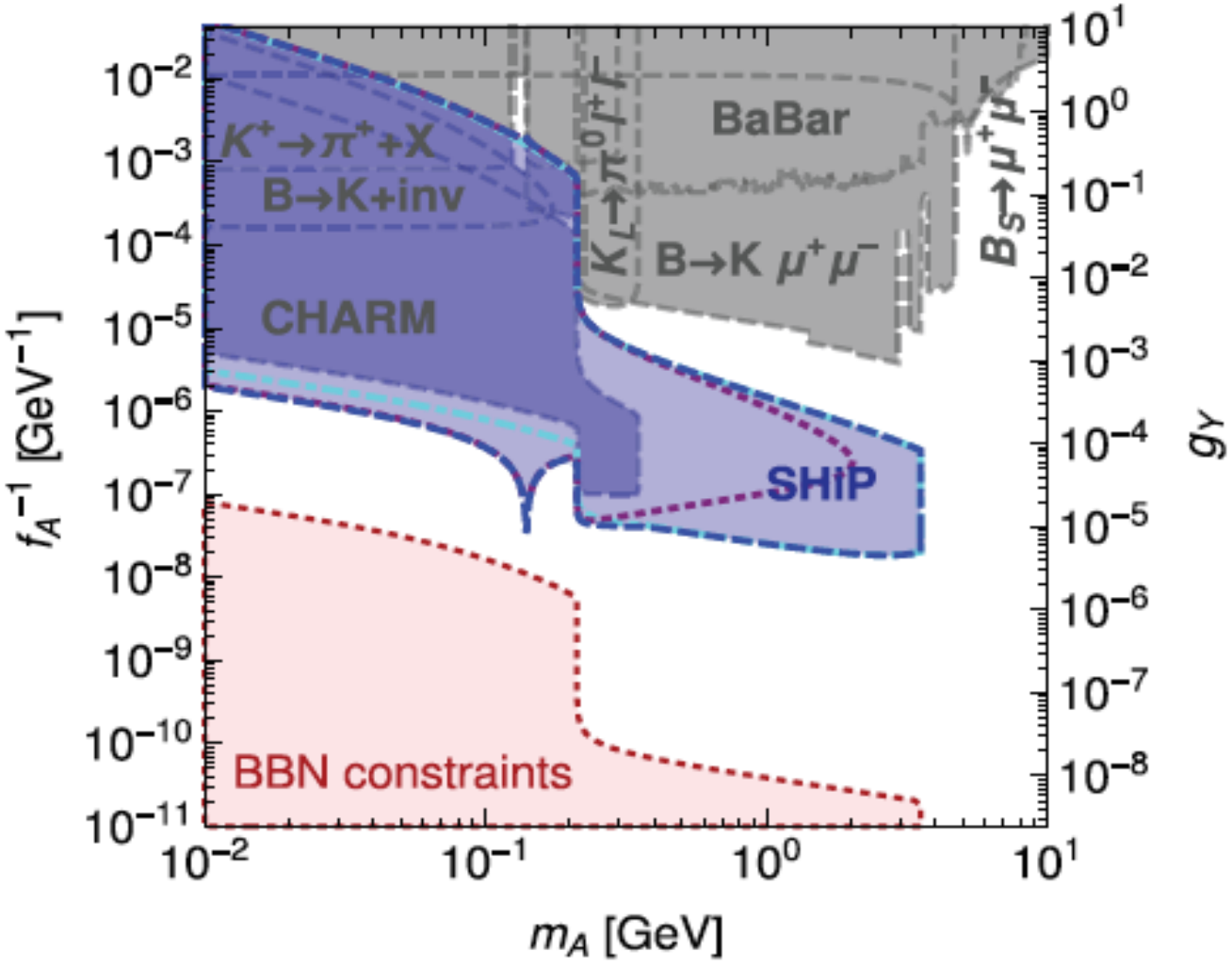




See also Dobrich et al., JHEP 02 (2016) 018 for details.

ALPs @ SHiP: fermions coupling

A′⟶ μ+μ-



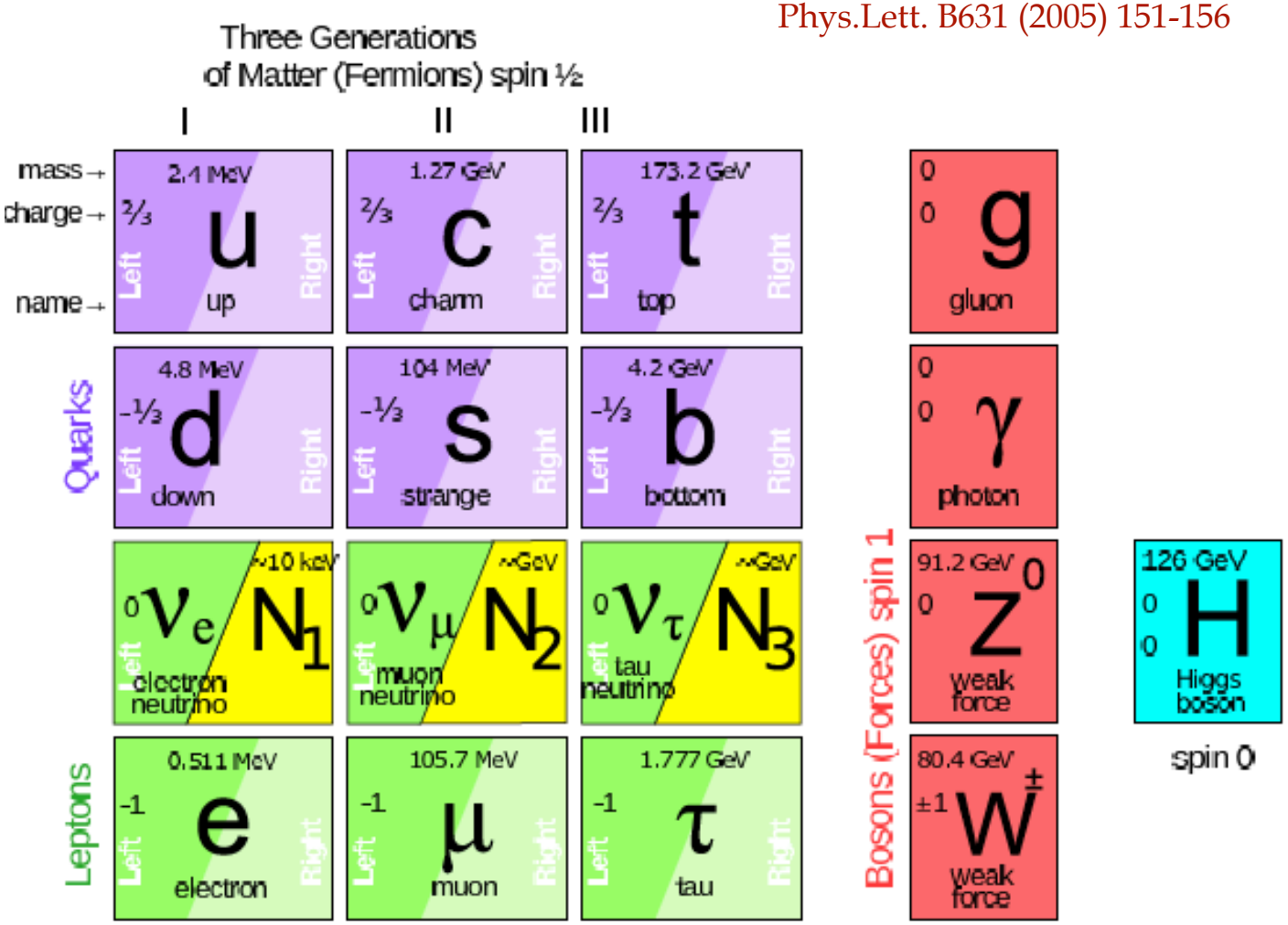
The SHiP Physics case, Rept.Prog.Phys. 79 (2016) no.12, 124201

The Neutrino Portal: the νMSM

Asaka, Blanchet, Shaposhnikov, Phys.Lett. B631 (2005) 151-156

Suitable values of m_N and U_{2f} allow to simultaneously explain:

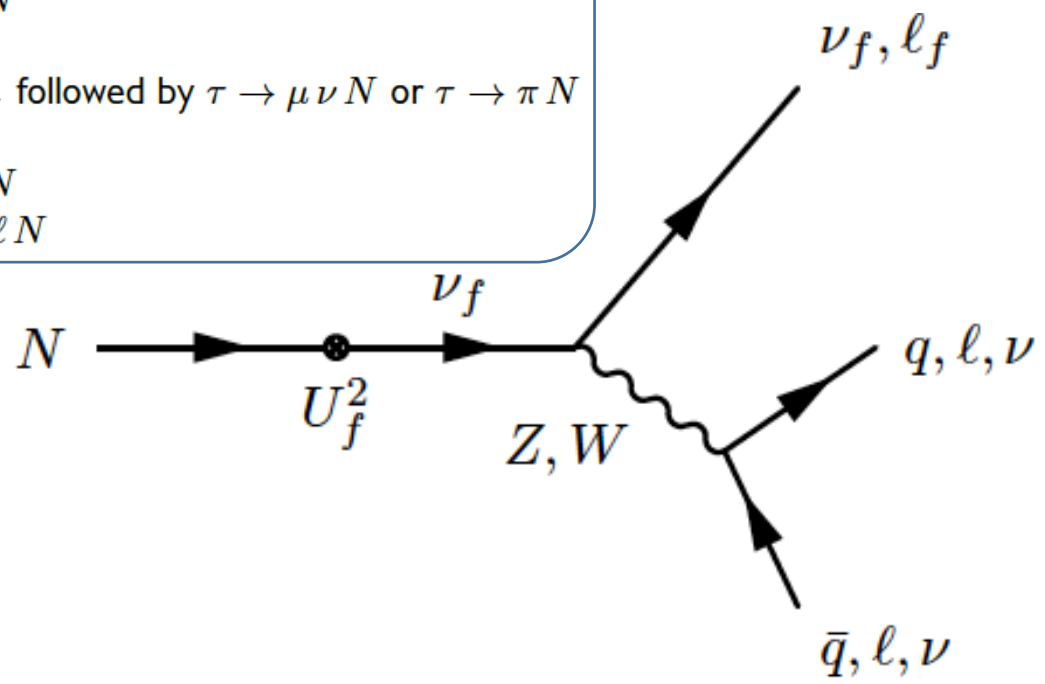
- oscillations induced by massive states N2, N3
- dark matter: N1 with mass keV
- BAU: leptogenesis due to Majorana mass term



The Neutrino Portal: the **ν**MSM

HNLs can be produced in decays where a neutrino is replaced by a N (kinetic mixing, U^2);
Main neutrino sources in SHiP: c and b mesons.

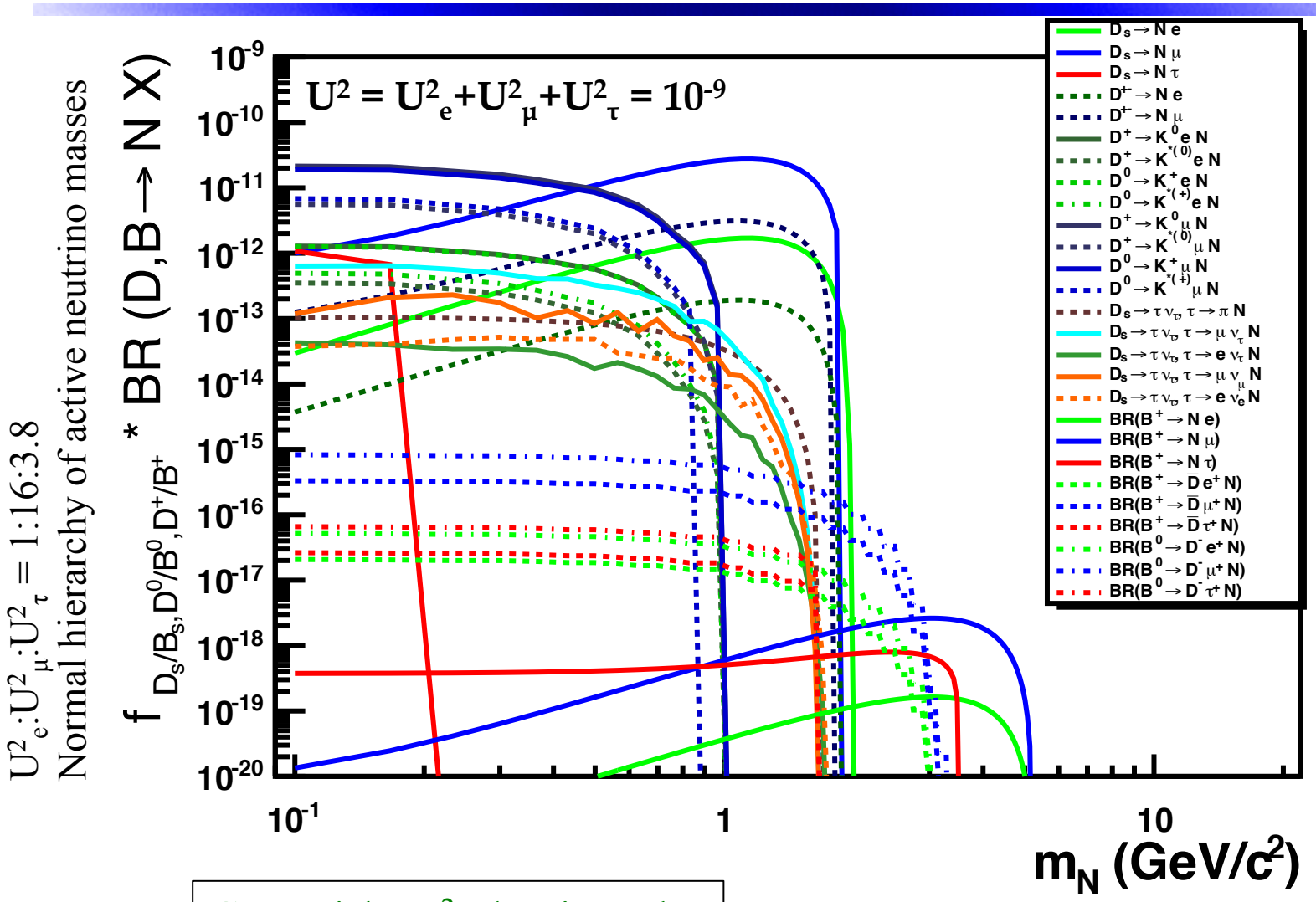
Production processes
- $D \to K \ell N$
- $D_s \to \ell N$
- $D_s \to \tau \nu_\tau$ followed by $\tau \to \mu \nu N$ or $\tau \to \pi N$
- $B \to \ell N$
- $B \to D \ell N$
- $B_s \to D_s \ell N$

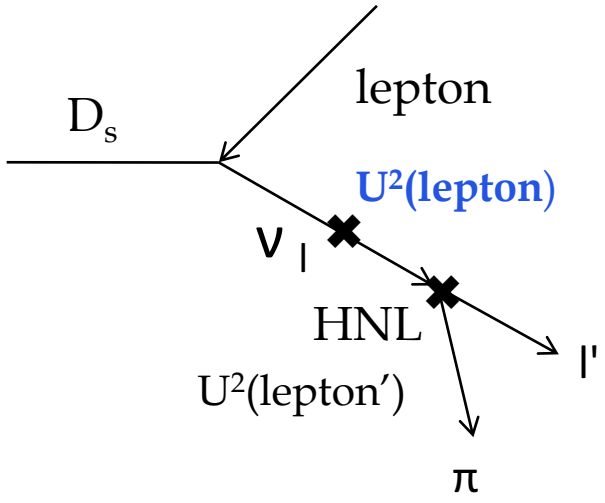


Decay channels
- $N \to H^0 \nu$, with $H^0 = \pi^0, \rho^0, \eta, \eta'$
- $N \to H^\pm \ell^\mp$, with $H = \pi, \rho$
- $N \to 3\nu$
- $N \to \ell_i^\pm \ell_j^\mp \nu_j$
- $N \to \nu_i \ell_j^\pm \ell_j^\mp$

They can then decay again to SM particles through mixing (U^2) with a SM neutrino. This (now massive) neutrino can decay to a large amount of final states through emission of a Z^0 or W boson

HNL production modes: nuMSM scenario 2



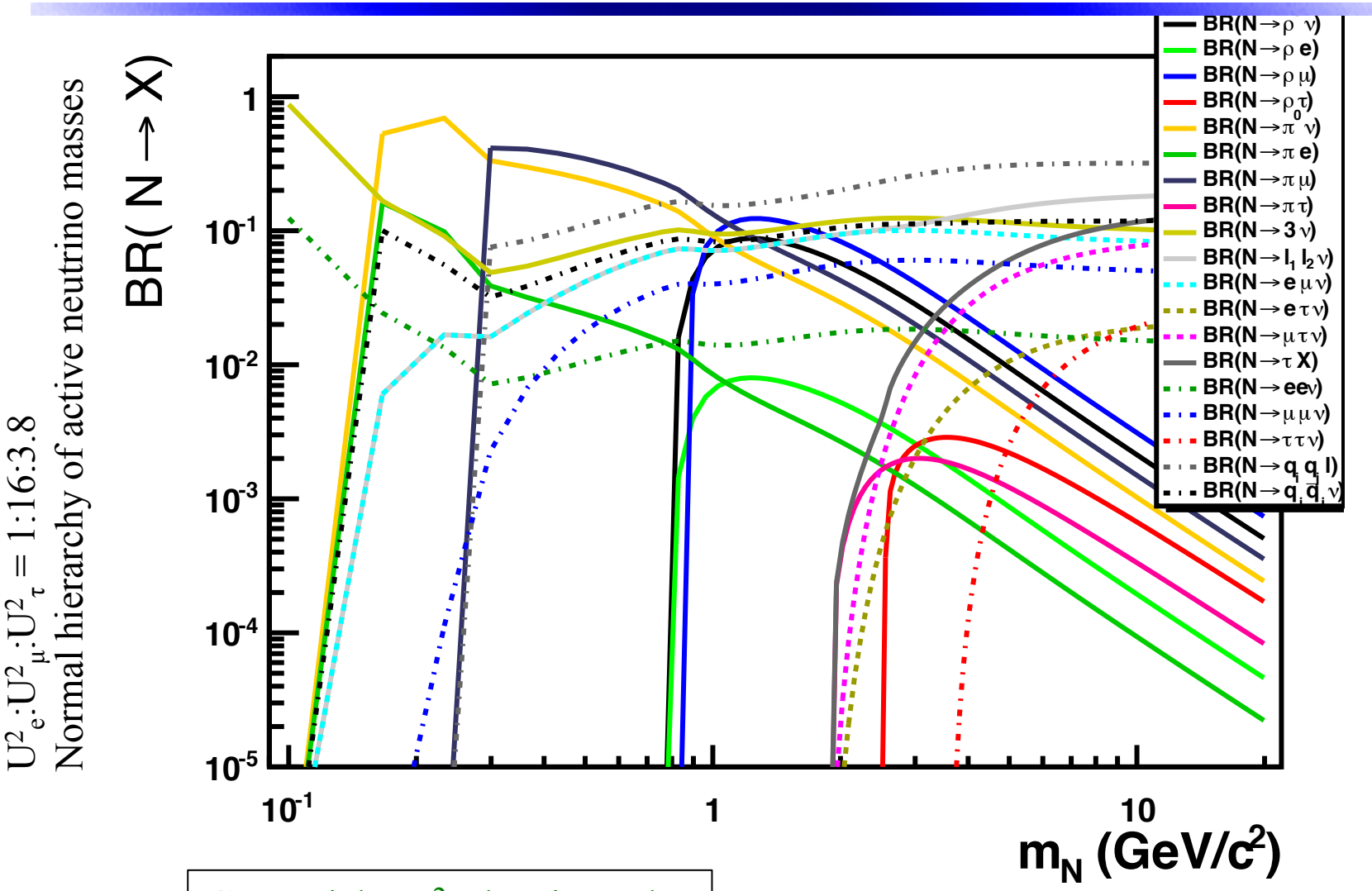


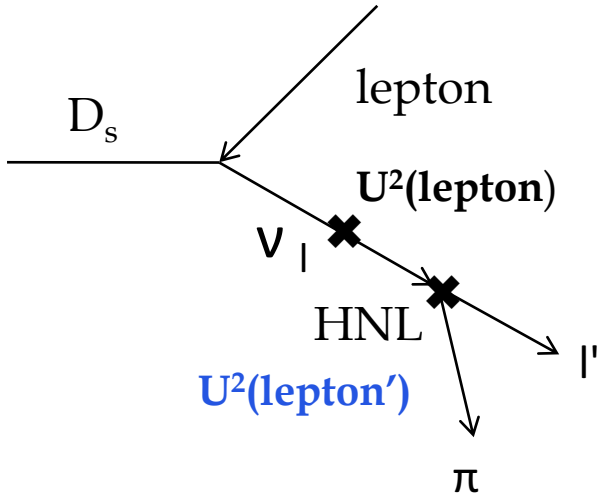
Green-ish: U^2_e dominated

Blue-ish: U^2_μ dominated

Red-ish : U^2_τ dominated

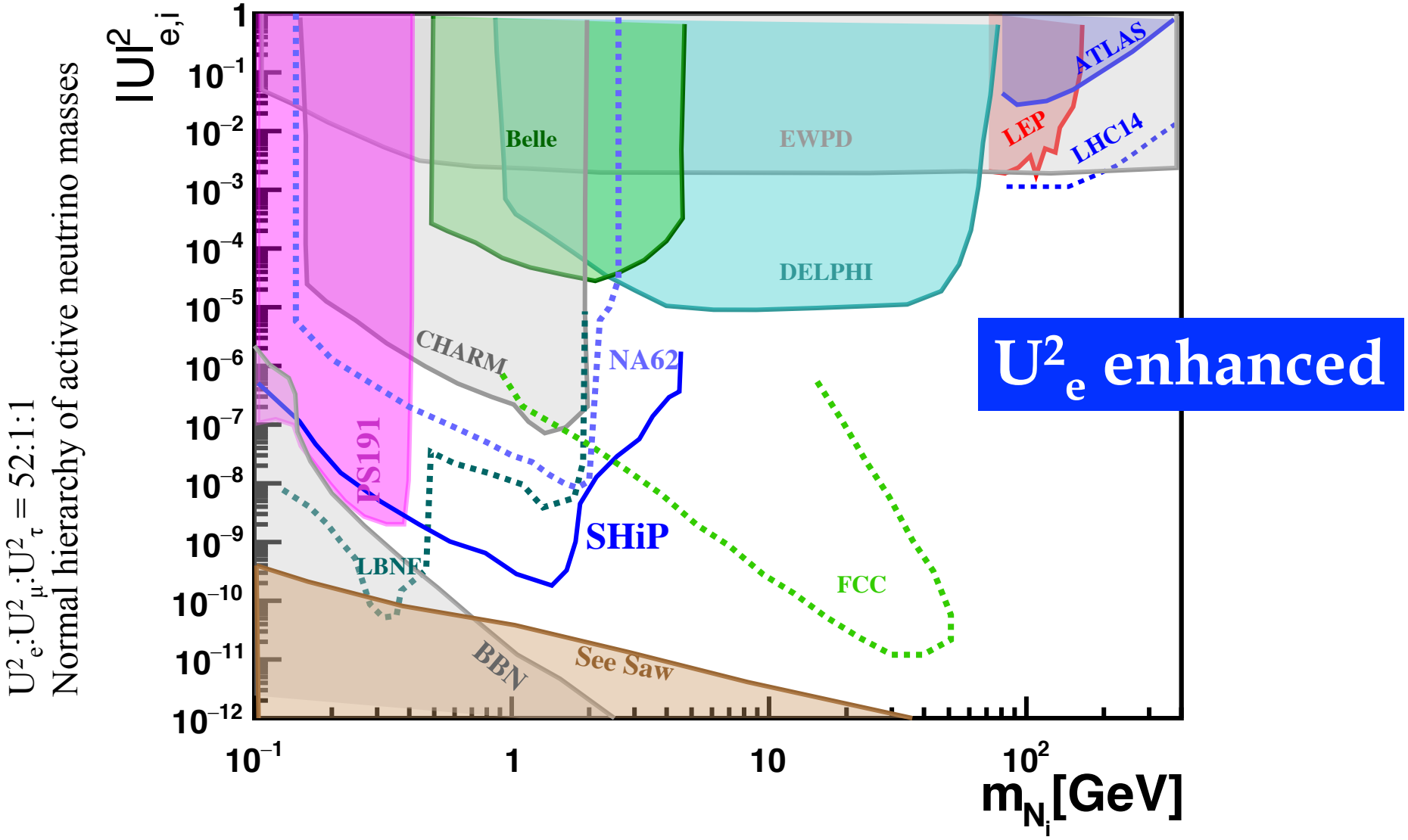
HNL decay modes in nuMSM scenario 2



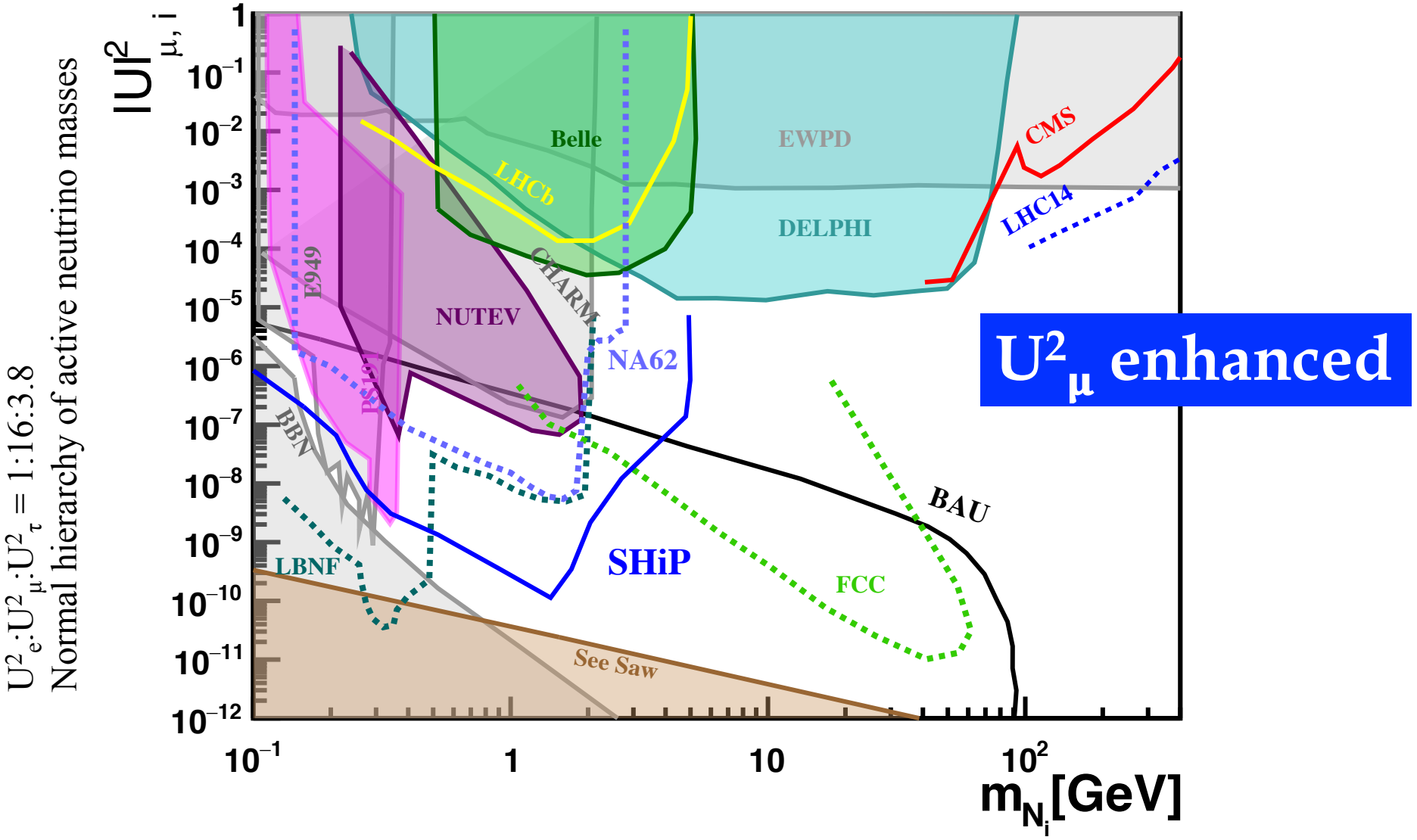


Green-ish: U^2_e dominated
Blue-ish: U^2_μ dominated
Red-ish : U^2_τ dominated

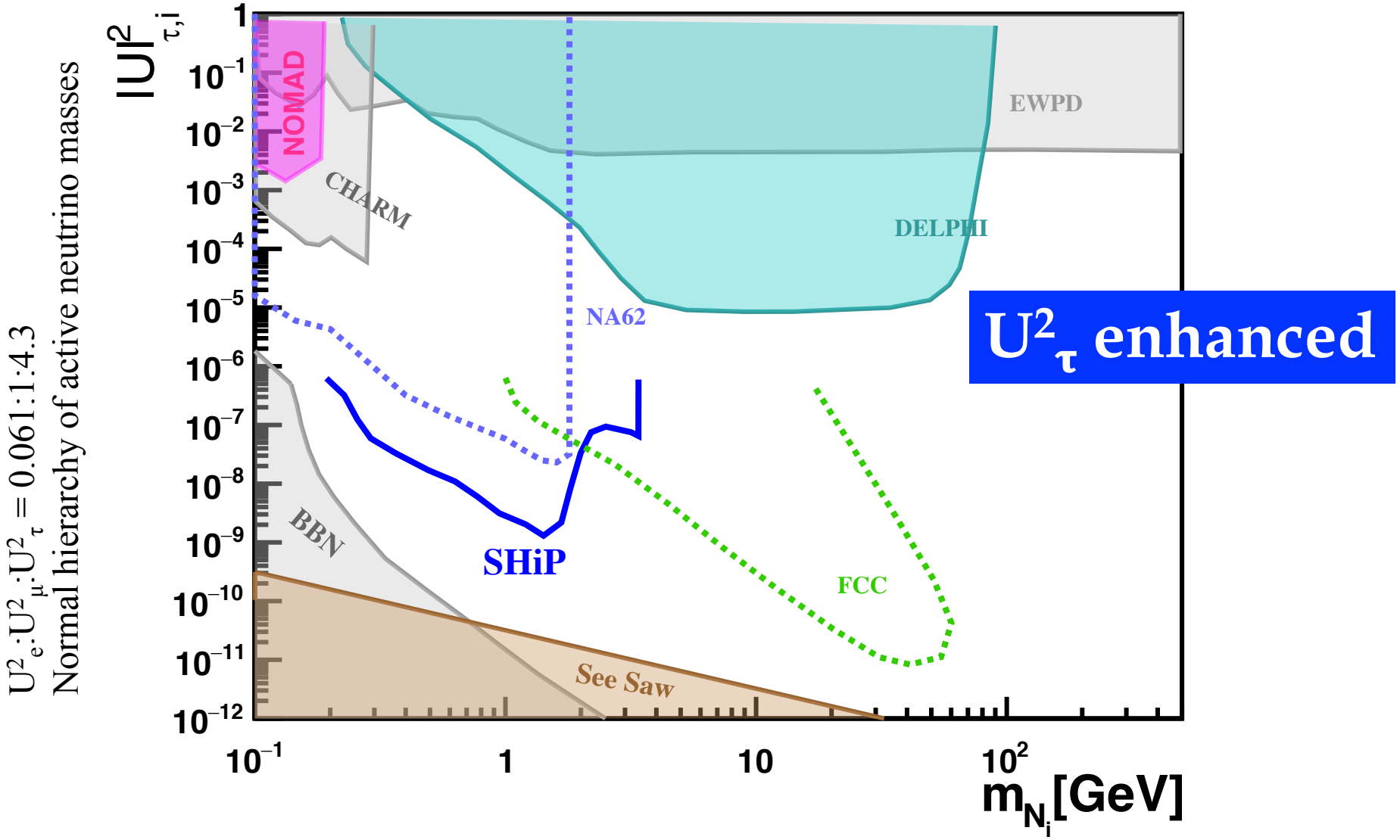
The Neutrino Portal: the **ν**MSM



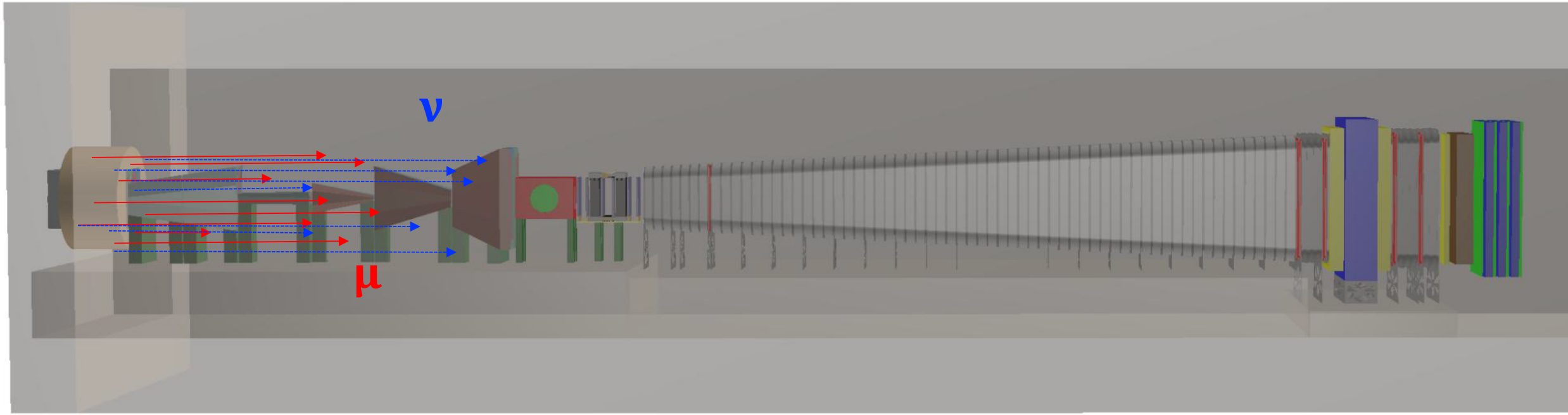
The Neutrino Portal: the **ν**MSM



The Neutrino Portal: the **ν**MSM

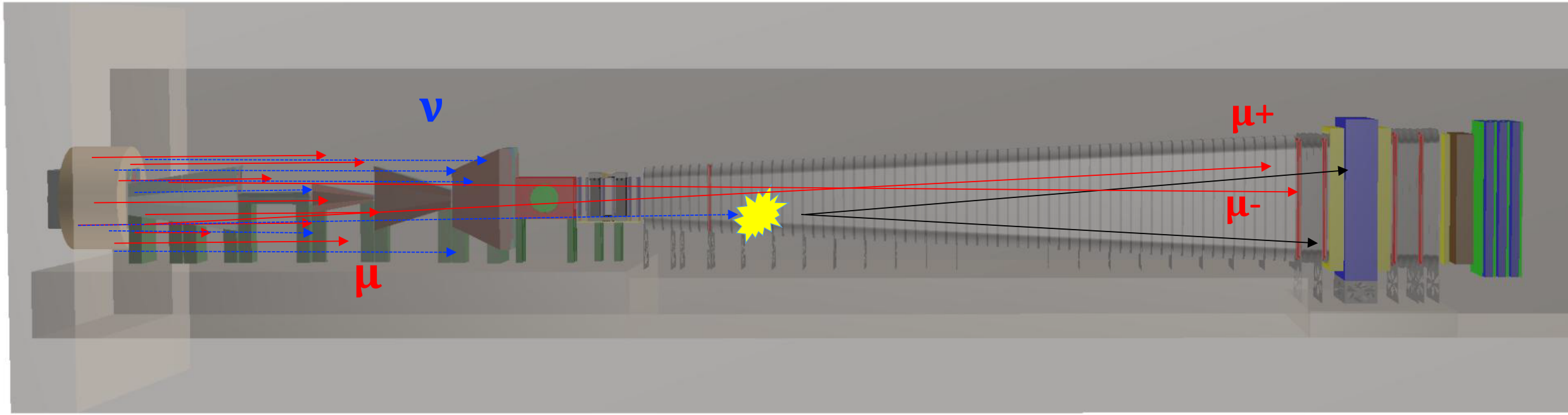


….Background, background, background……



- ✓ The proton interactions on the dump, along with the signals, give rise to a copious direct production of short lived resonances, and pions and kaons.
- ✓ While the length of the dump (~11 λ_I target + 5 m hadron absorber) is sufficient to absorb the hadrons and the electromagnetic radiation, the decays of pions, kaons and short-lived resonances result in a large flux (several tens of GHz) of muons and neutrinos.

….Background, background, background……



Two types of background expected:

1) neutrino and muon inelastic interactions with the detector material, namely with the decay vessel;

⟶ mostly in-time tracks, not pointing backwards to the target;

⟶ main detectors to reduce this background: VETO detectors (surrounding background tagger, Upstream Veto)

2) muon combinatorial background:

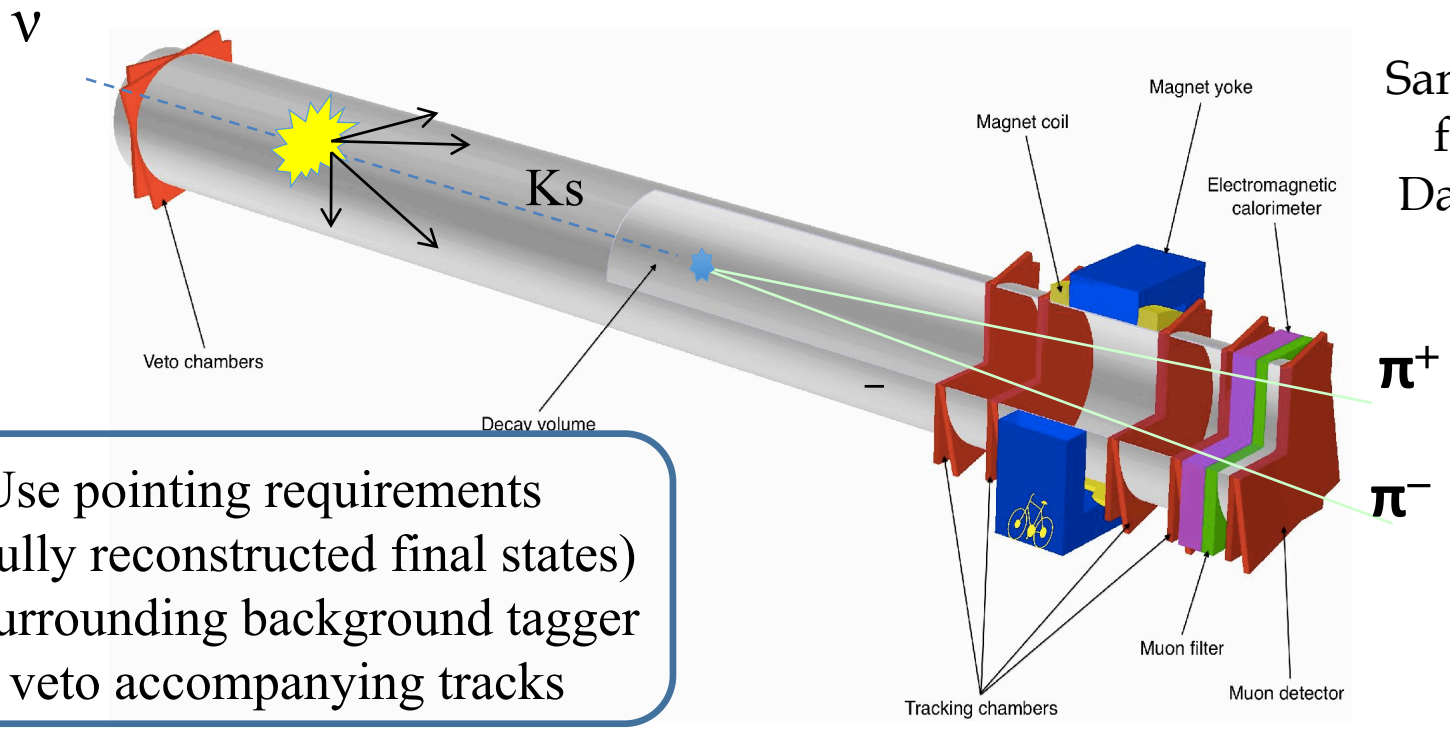
⟶ mostly out-of-time tracks, not pointing backwards to the target

⟶ main detectors to reduce this background: Timing Detector (and muon system with timing capabilities)

Backgrounds: muon- and neutrino- inelastic interactions

Muon and neutrinos can interact inelastically with the detectors and/or vessel material and create V^0 and other tracks that can mimic a signal signature

Background source	Decay modes
ν or μ + nucleon $\rightarrow X + K_L$	$K_L \rightarrow \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\rightarrow X] + K_S$	$K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\rightarrow X + \Lambda$	$\Lambda \rightarrow p\pi^-$
n or p + nucleon $\rightarrow X + K_L$, etc	as above

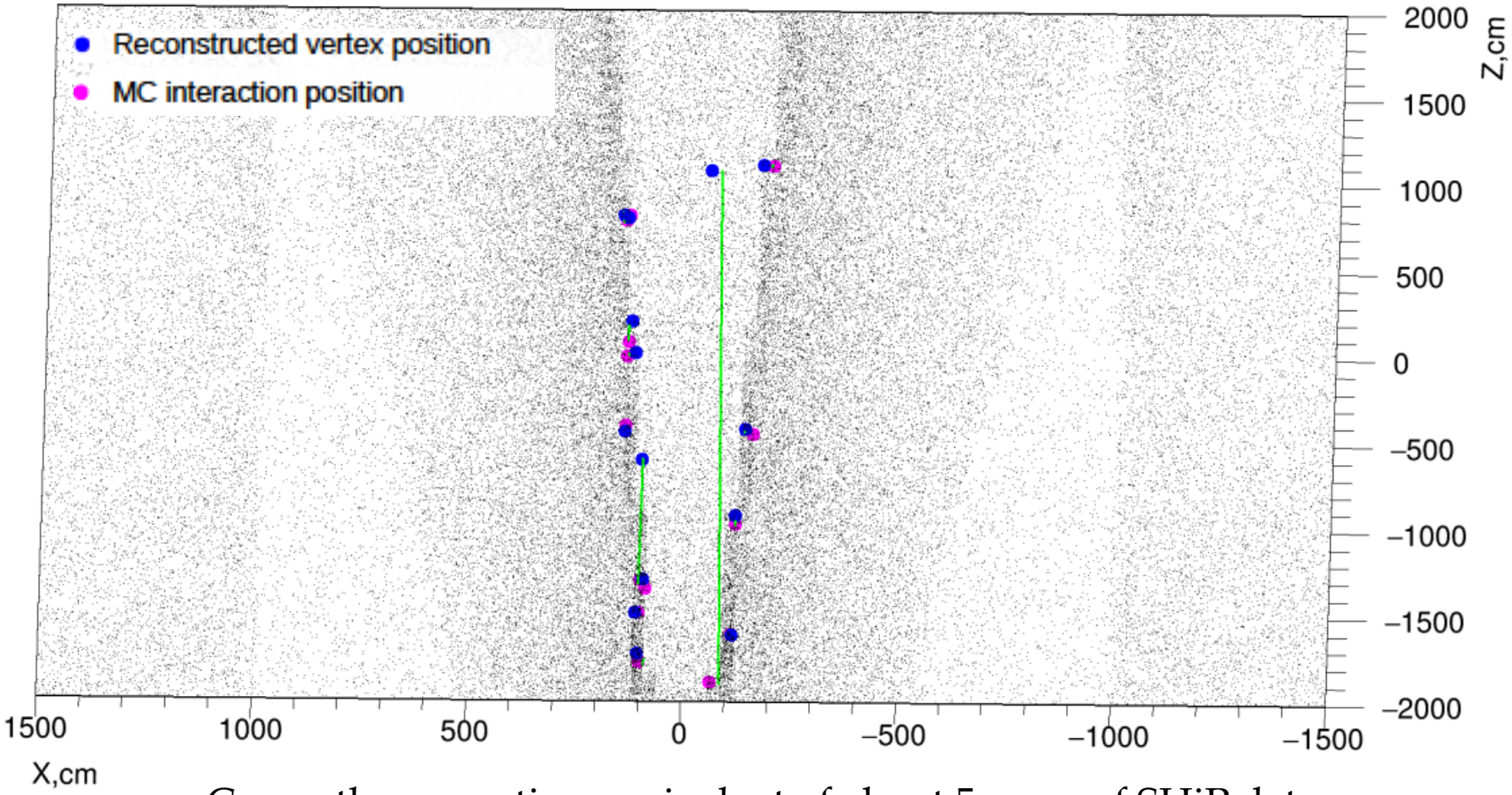


Same signature as, for example, Dark Scalar ⟶ **π+ π-**

Use pointing requirements (for fully reconstructed final states) and surrounding background tagger to veto accompanying tracks

Backgrounds: muons and neutrinos inelastic interactions

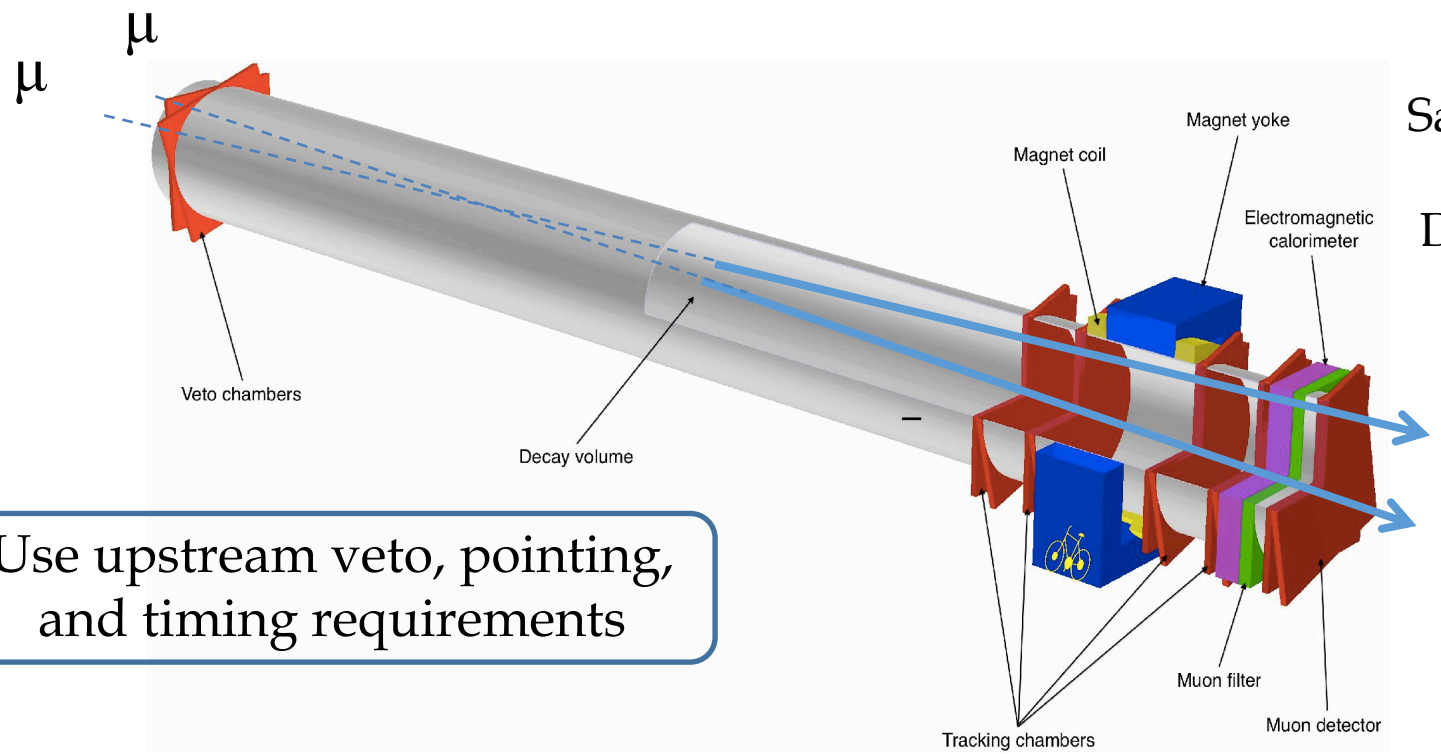
Residuals events due to neutrino inelastic interactions (mainly with the decay vessel) after selection



Currently generating equivalent of about 5 years of SHiP data:
-- residual background compatible with 0 bkg events
- Preparing a large simulation corresponding to 10x5 years of SHiP

Backgrounds: muon combinatorial background

Random combinations of residual muon flux from proton interactions in the target can mimic signal if they form a (fake) vertex in the fiducial volume.
For 4×10^{13} pot/spill 1-sec long, about 50 kHz of muons after the active filter are expected in acceptance: $\rightarrow$ **effectively rejected via a short time-coincidence.**

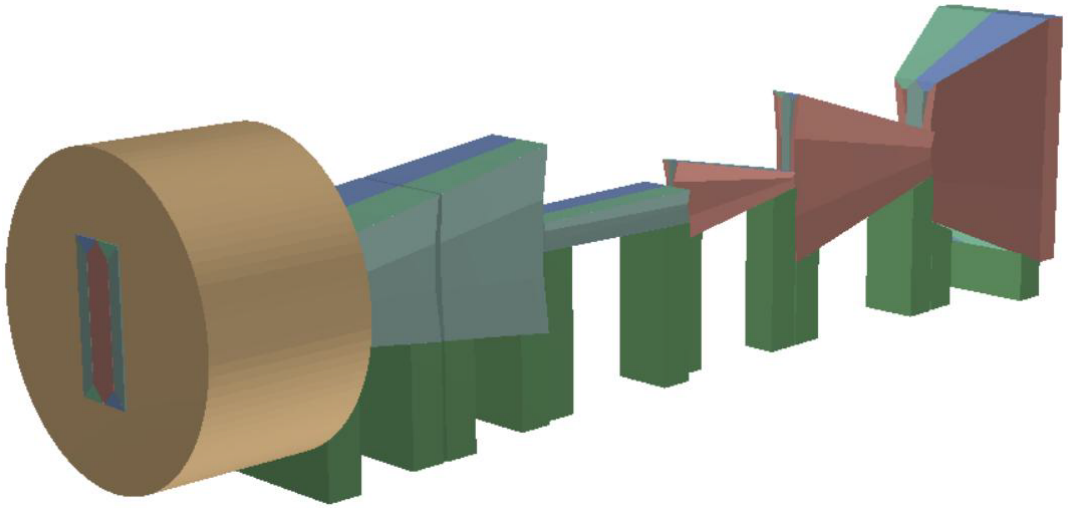


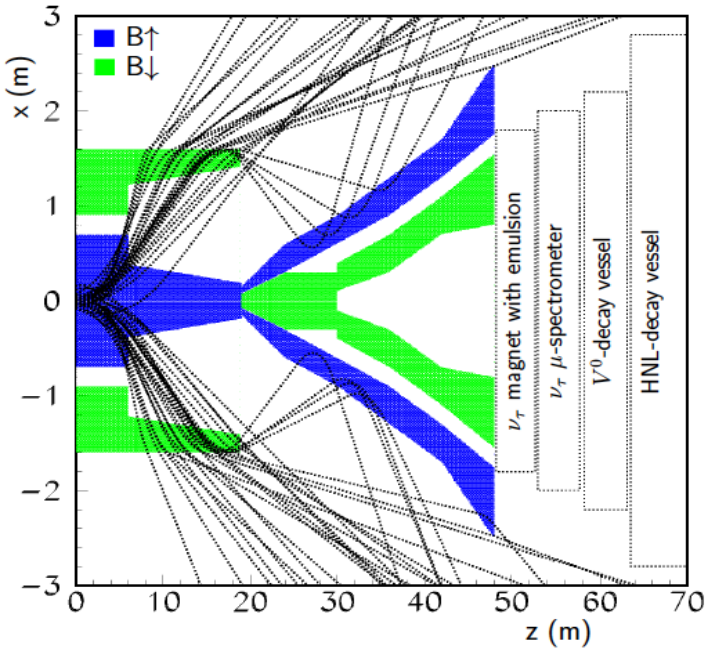
Same signature as, for example, Dark Scalar $\rightarrow$ **μ+ μ-**

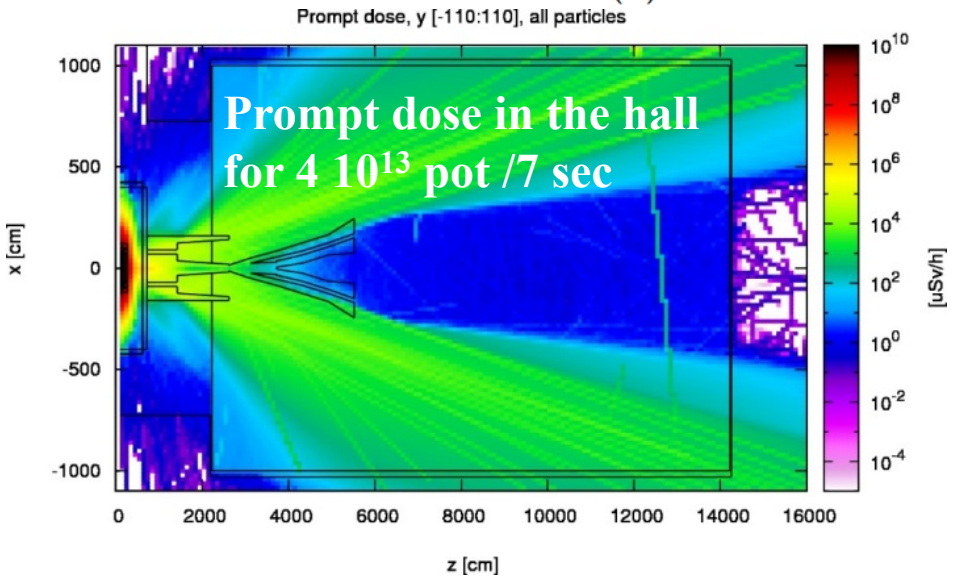
Use upstream veto, pointing, and timing requirements

Muon background: SHiP active muon shield

It ranges out beam-induced muons:







- Shield based entirely on magnetic sweeping
- Residual flux on detectors ~ 50 kHz muons
- Negligible occupancy

Challenges: flux leakages, constant field profile, modeling magnet shape..
(see Richard's talk)

Conclusions

SHiP is one of the new projects proposed at CERN for the next European Strategy in 2019-2020. If approved:

- ✓ SHiP will search for light and feebly-interacting particles that could explain many open questions in modern particle physics - the baryon asymmetry of the Universe, the nature of the Dark Matter, the origin of the neutrino masses and oscillations - complementing the quest for New Physics already performed in the high-energy domain (ATLAS, CMS), in the flavor domain (LHCb, Belle-II) and in direct search of DM experiments.
- ✓ SHiP will exploit a unique facility, a brand new slow-extracted proton beam line currently under study at CERN, the Beam Dump Facility.
- ✓ SHiP will be one of the major players in the coming years in the field, joining an already very active (and continuously growing) "hidden sector" community at CERN (NA64, NA62-dump) and in US (LDMX, APEX, SeaQuest, MiniBoone, HPS, ..).

SHiP is still in a design phase, there is still plenty of room for new groups both for detector and physics studies. It is timely (and exciting) to join the project now.