

# Introduction to SHiP and Activities at IJCLab

Roman Pöschl



**French Ukrainien workshop**

**October 2026 at IJCLab**



SHiP/SiW ECAL Team at IJCLab

R.P.

Xin Xia

Jesus Marquez

Nicolas Pauwels

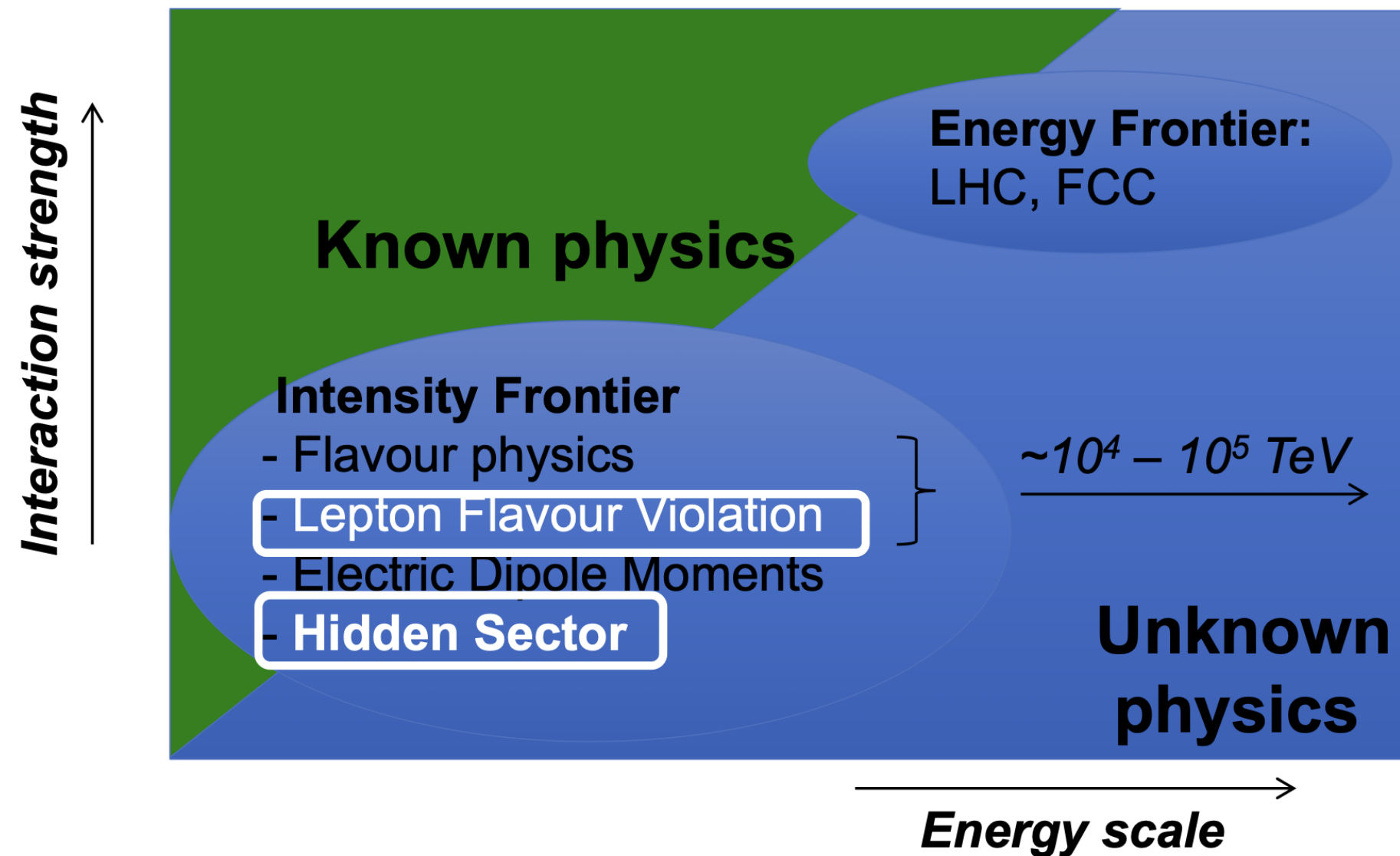
Jihane Maalmi

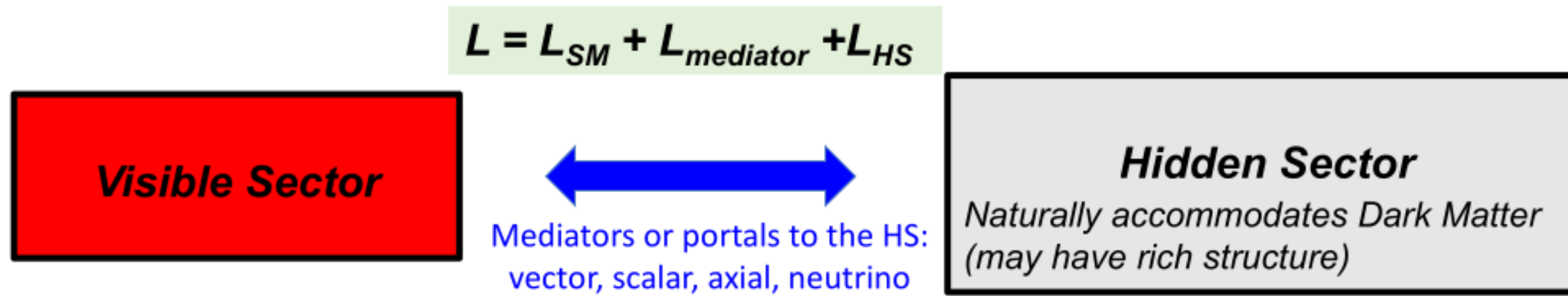
Dominique Breton

Alexandre Gonnin

Alice Thiebault

- Higgs discovery made the SM complete
- Standard Model is a great theory but does not represent the full picture
- New Physics should exist but we have no definitive predictions on the masses and coupling constants of NP particles





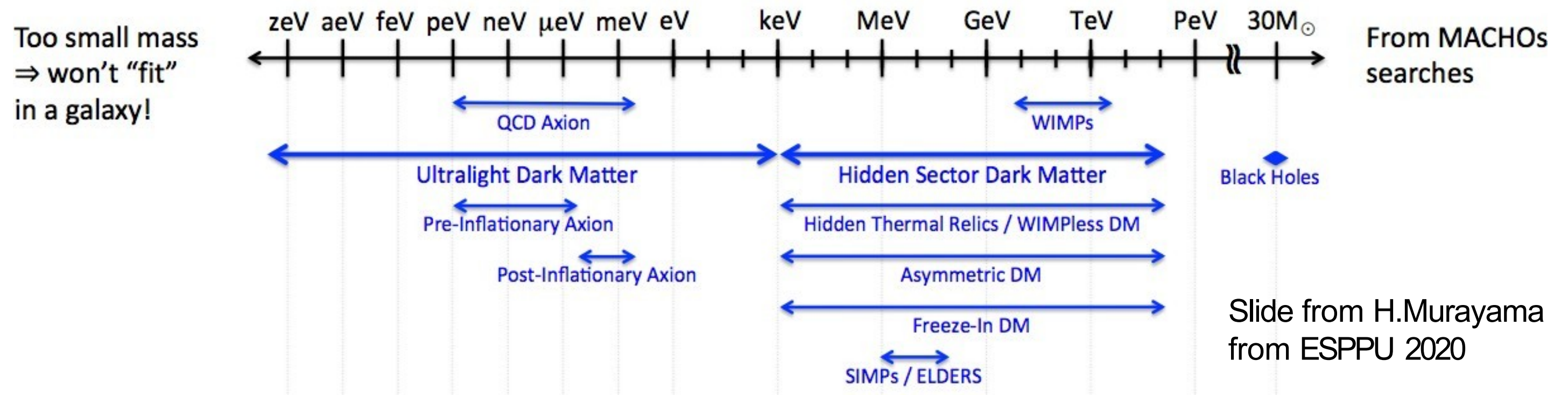
- ✓ *HS production and decay rates are strongly suppressed relative to SM*
- *Production branching ratios  $O(10^{-10})$*
  - *Long-lived objects*
  - *Interact very weakly with matter*
  - *May decay to various final states*

| Portal models                 | Final states                  |
|-------------------------------|-------------------------------|
| HNL                           | $l^+\pi^-, l^+K^-, l^+\rho^-$ |
| Vector, scalar, axion portals | $l^+l^-$                      |
| HNL                           | $l^+l^-\nu$                   |
| Axion portal                  | $\gamma\gamma$                |

*Full reconstruction and PID are essential to minimize model dependence*

**Experimental challenge is background suppression**

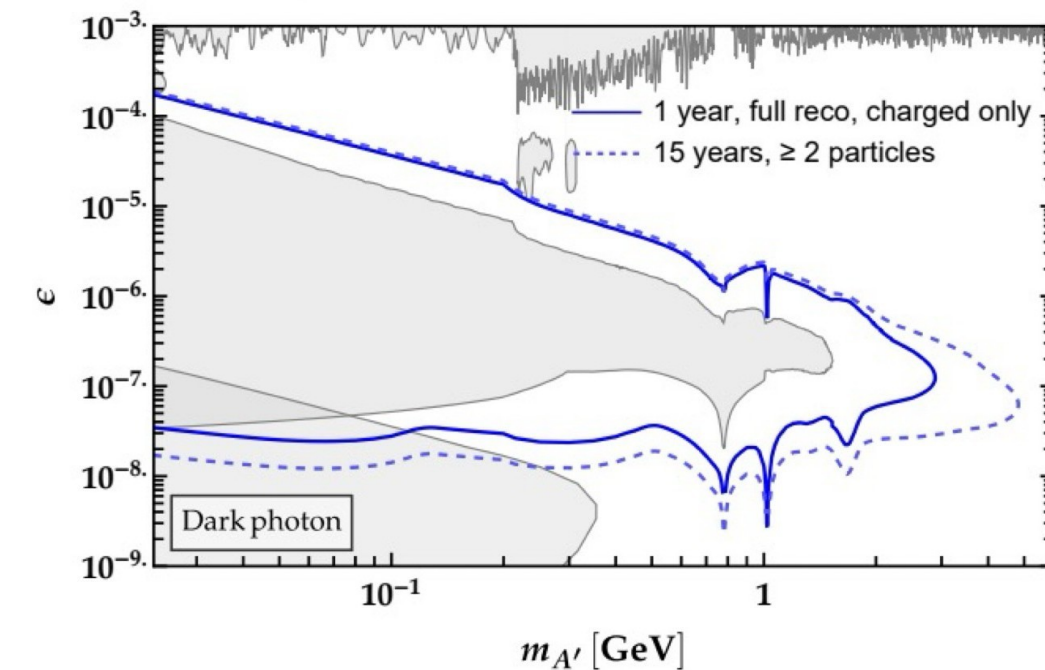
## Dark Matter Candidates: Very little clue on mass scales



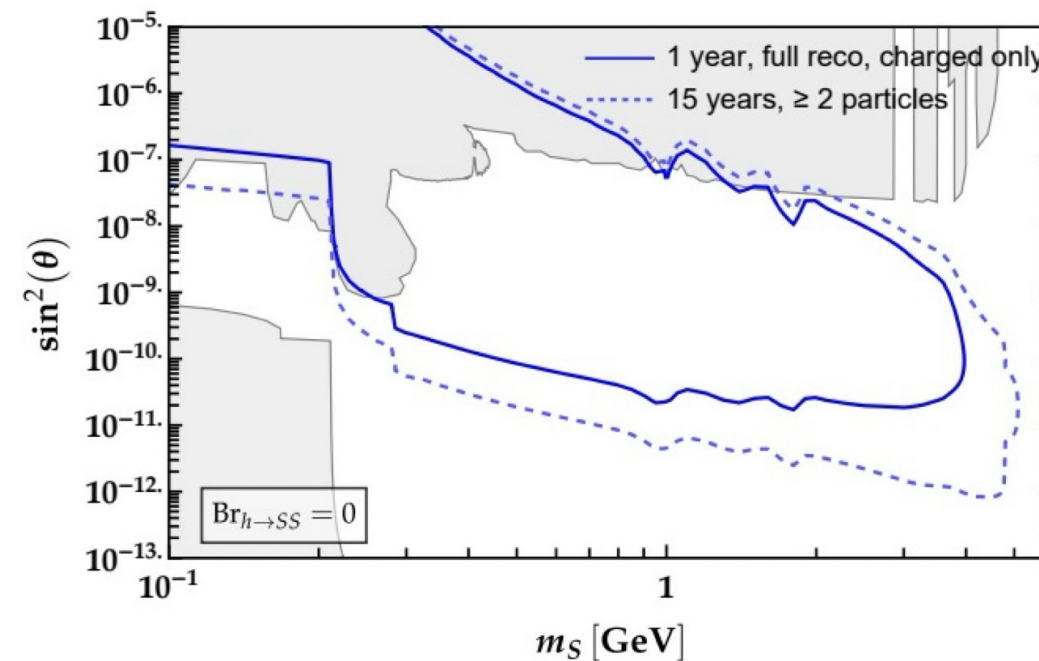
*The prediction for the mass scale of Dark Matter particles spans from  $10^{-22}$  eV (ALPs) to  $10^{20}$  GeV (Wimpzillas, Q-balls)*

SHIP explores multiple orders of magnitude of previously inaccessible coupling, across qualitatively different portals (phase space  $\sim 1$ -10 GeV)

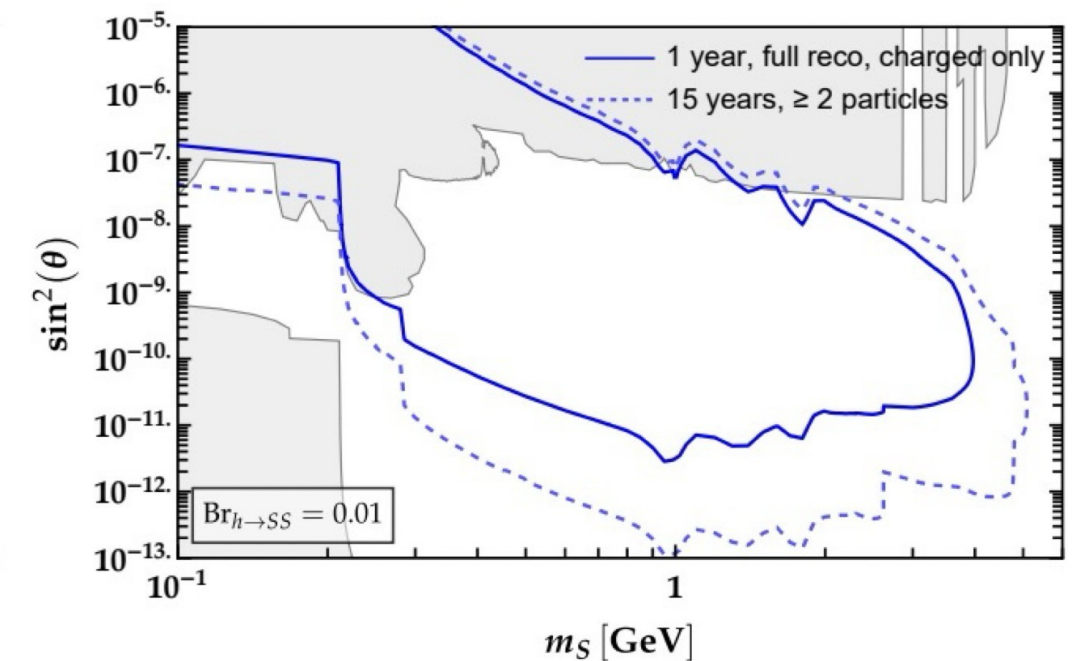
BC1 (dark photons)



BC4 (scalars without  $hSS$  coupling)



BC5 (scalars with  $hSS$  coupling fixed such that  $\text{Br}(h \rightarrow SS) = 0.01$ )



Multidecay and other models:

[arXiv:2312.14868](https://arxiv.org/abs/2312.14868)

[arXiv:2503.01760](https://arxiv.org/abs/2503.01760)

[arXiv:2510.23696](https://arxiv.org/abs/2510.23696)

Spin correlations

[arXiv:2606.19543](https://arxiv.org/abs/2606.19543)

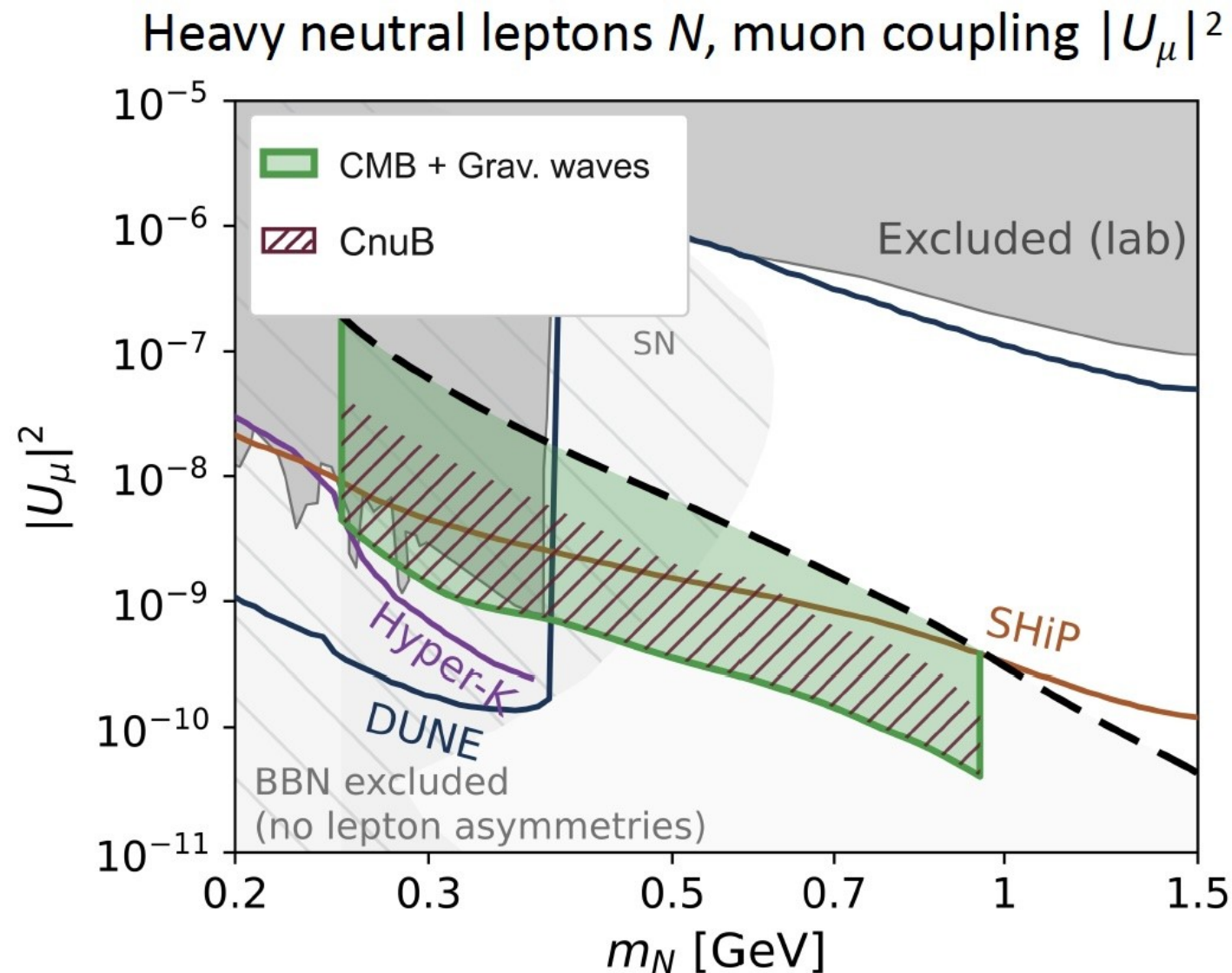
Post-discovery

[arXiv:2312.05163](https://arxiv.org/abs/2312.05163)

[arXiv:2609.19269](https://arxiv.org/abs/2609.19269)

Lesya Shchutskya,  
SPC September 2026

# Discovery case for HNLs: more than counting



SHiP is uniquely sensitive in the region,  
impacting cosmological observations

[Akita, Ovchinnikov, Syvolap](#)

- **What is it?**
  - mass, lifetime, flavour-dependent couplings
- **Probe Dirac vs Majorana nature**
  - decay angular distributions  $\rightarrow$  LNC vs LNV
- **One state or a quasi-degenerate pair?**
  - observe spatial HNL oscillations  $\rightarrow$  measure  $\Delta M \sim 10^{-6}$  eV in favourable scenarios
- **Does it explain fundamental puzzles?**
  - flavour-dependent couplings  $\rightarrow$  test the seesaw origin of neutrino masses
  - $M, \Delta M, U_\alpha^2 + \text{PMNS } \delta_{CP} \rightarrow$  test whether the HNLs can generate the baryon asymmetry

[Drewes et al](#)

[Caputo, Hernandez et al](#)

[De Vries, Drewes et al](#)

- A total of 26  $\nu_\tau$  candidates have been observed, ever
- The high neutrino flux allows for the measurement of strange quark nucleon content via charm production in  $\nu$  interactions
- SHiP will collect around 10000  $\nu_\tau$  in 15 years
- The tau neutrino flux allows for the determination of the never-before measured  $F_4$  and  $F_5$

|                      | CC DIS (W HGC)    | Charm CC DIS (W HGC) | CC DIS (Fe MGTC)  | Charm CC DIS (Fe MGTC) |
|----------------------|-------------------|----------------------|-------------------|------------------------|
| $N_{\nu_e}$          | $6.8 \times 10^4$ | $4.1 \times 10^3$    | $1.6 \times 10^5$ | $9.8 \times 10^3$      |
| $N_{\nu_\mu}$        | $2.0 \times 10^5$ | $8.7 \times 10^3$    | $4.6 \times 10^5$ | $2.0 \times 10^4$      |
| $N_{\nu_\tau}$       | $2.1 \times 10^3$ | $1.2 \times 10^2$    | $5.1 \times 10^3$ | $2.8 \times 10^2$      |
| $N_{\bar{\nu}_e}$    | $1.4 \times 10^4$ | $7.4 \times 10^2$    | $3.7 \times 10^4$ | $1.9 \times 10^3$      |
| $N_{\bar{\nu}_\mu}$  | $4.4 \times 10^4$ | $1.7 \times 10^3$    | $1.1 \times 10^5$ | $4.1 \times 10^3$      |
| $N_{\bar{\nu}_\tau}$ | $1.5 \times 10^3$ | $8.6 \times 10^1$    | $3.8 \times 10^3$ | $2.1 \times 10^2$      |

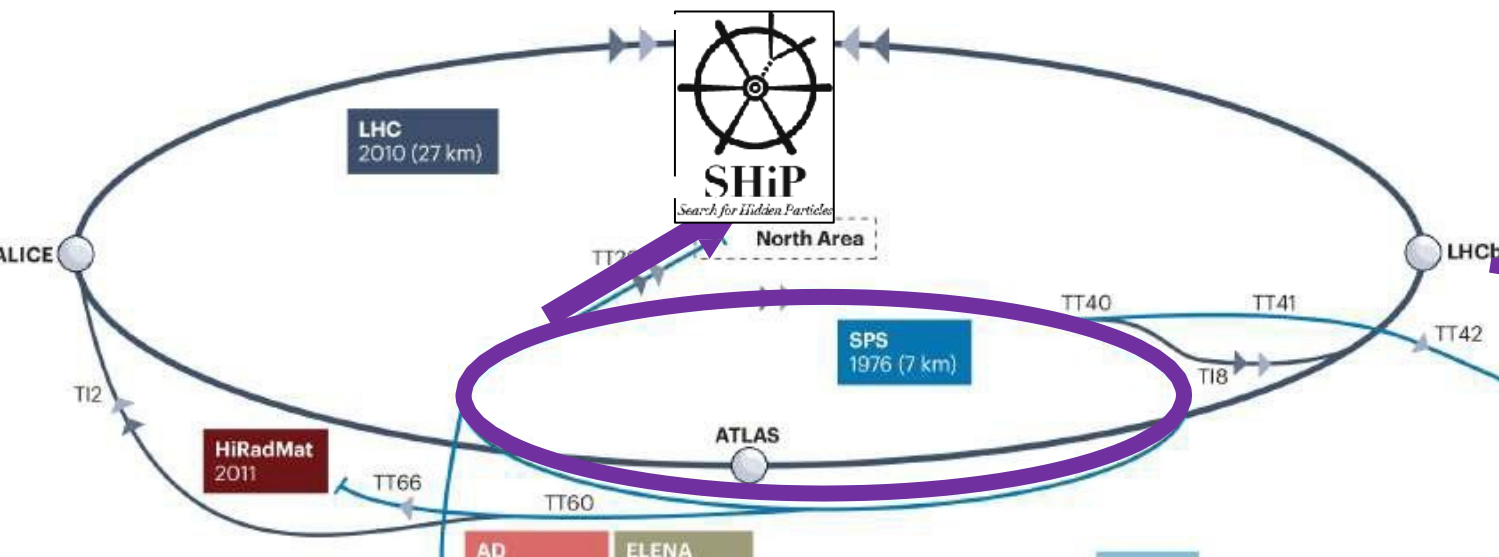
$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \right.$$

$$\left[ (1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{Mx}{2E_\nu}) y \right] F_2 \pm \left[ xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3 +$$

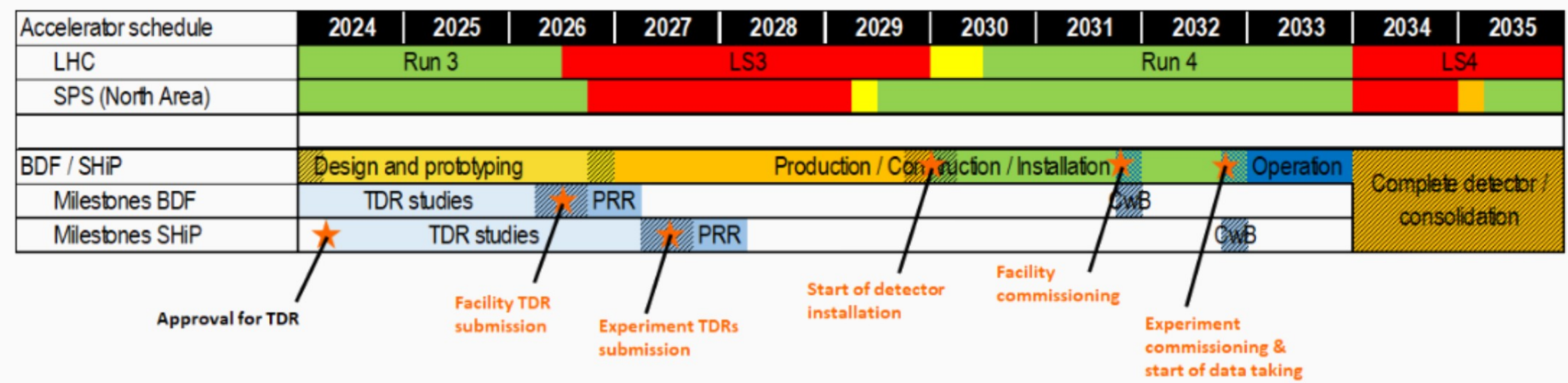
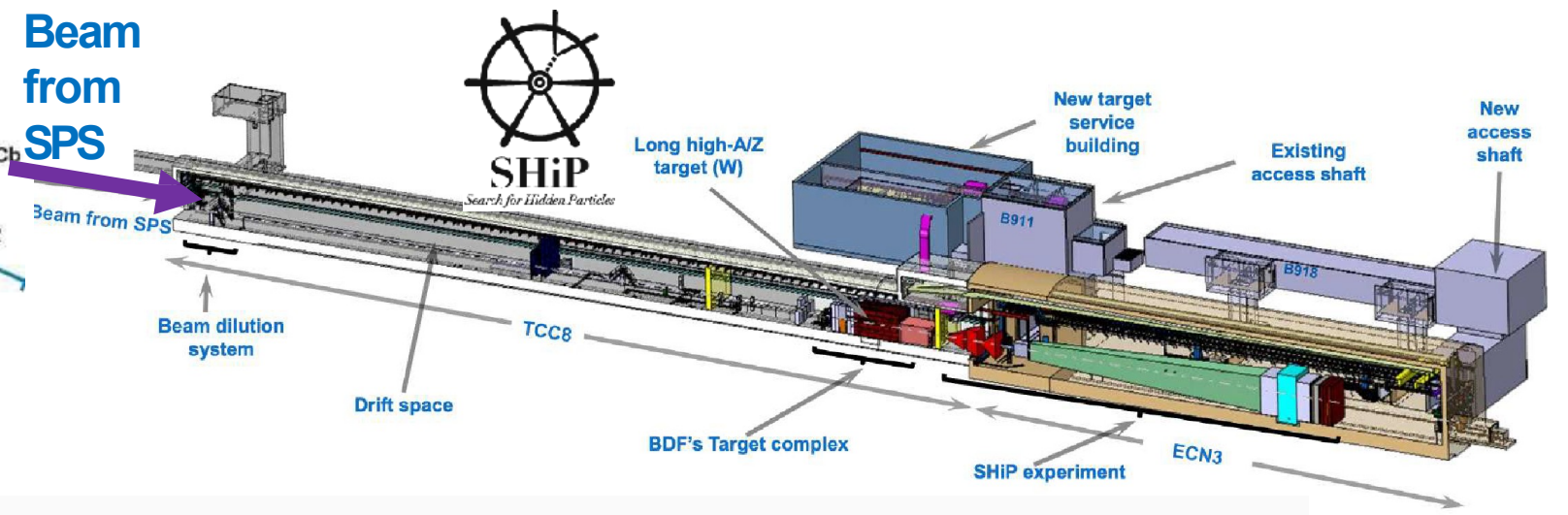
$$\left. \frac{m_\tau^2(m_\tau^2 + Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5 \right\}.$$

- Idea for “Search for Hidden Particles” experiment formulated in 2013
- SHiP is an approved CERN experiment since 2024
  - “Approved” means that CERN agreed to refurbish the Beam Dump Facility in the ECN3 experimental hall

## CERN Accelerator Complex



- $6 \times 10^{20}$  protons in 15 years
- Data taking start 2031 (after LS3)

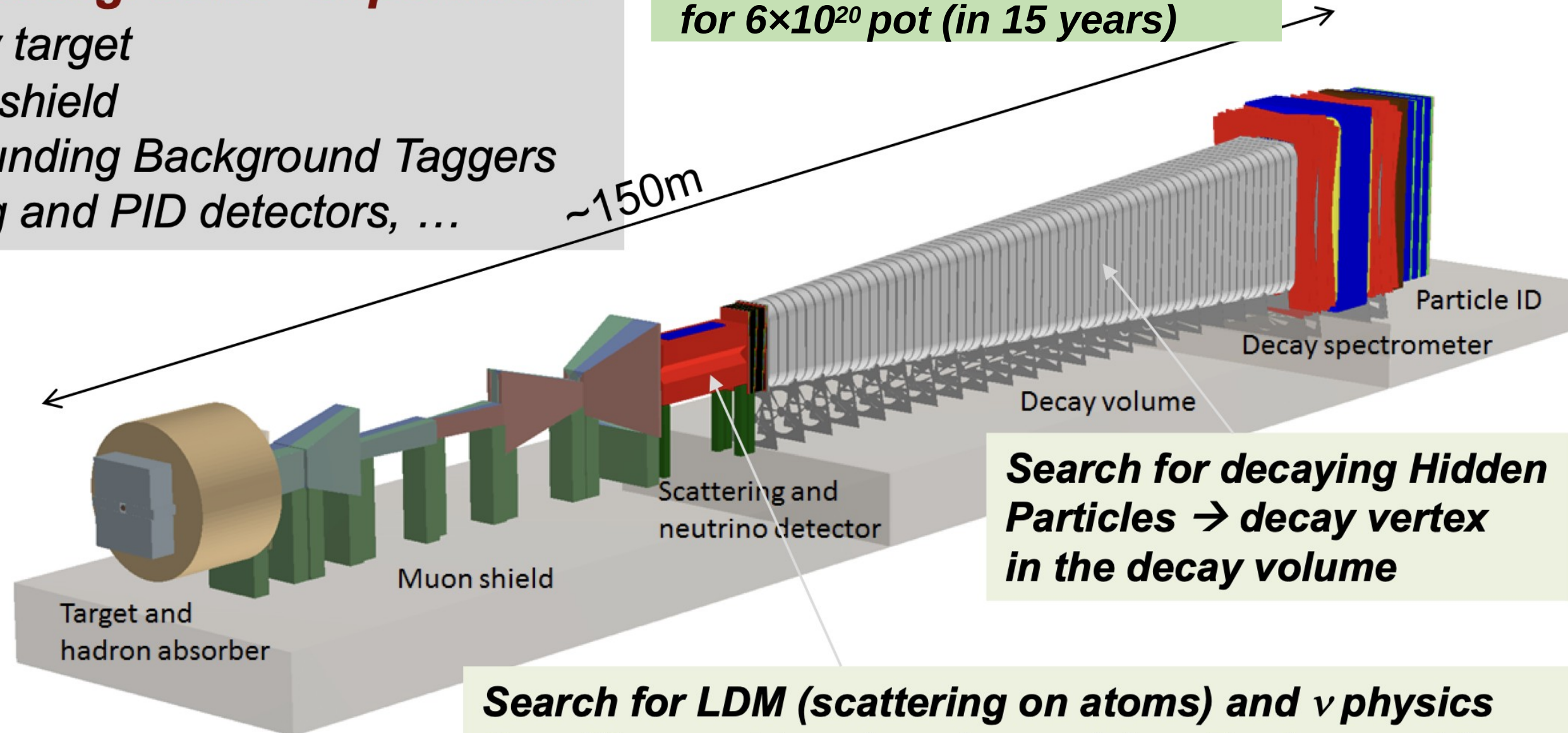


# SHiP Schematic Layout

## **“Zero background” experiment**

- Heavy target
- Muon shield
- Surrounding Background Taggers
- Timing and PID detectors, ...

$>10^{18} D$ ,  $>10^{16} \tau$ ,  $>5 \times 10^{15} \nu_\tau$   
 for  $6 \times 10^{20}$  pot (in 15 years)

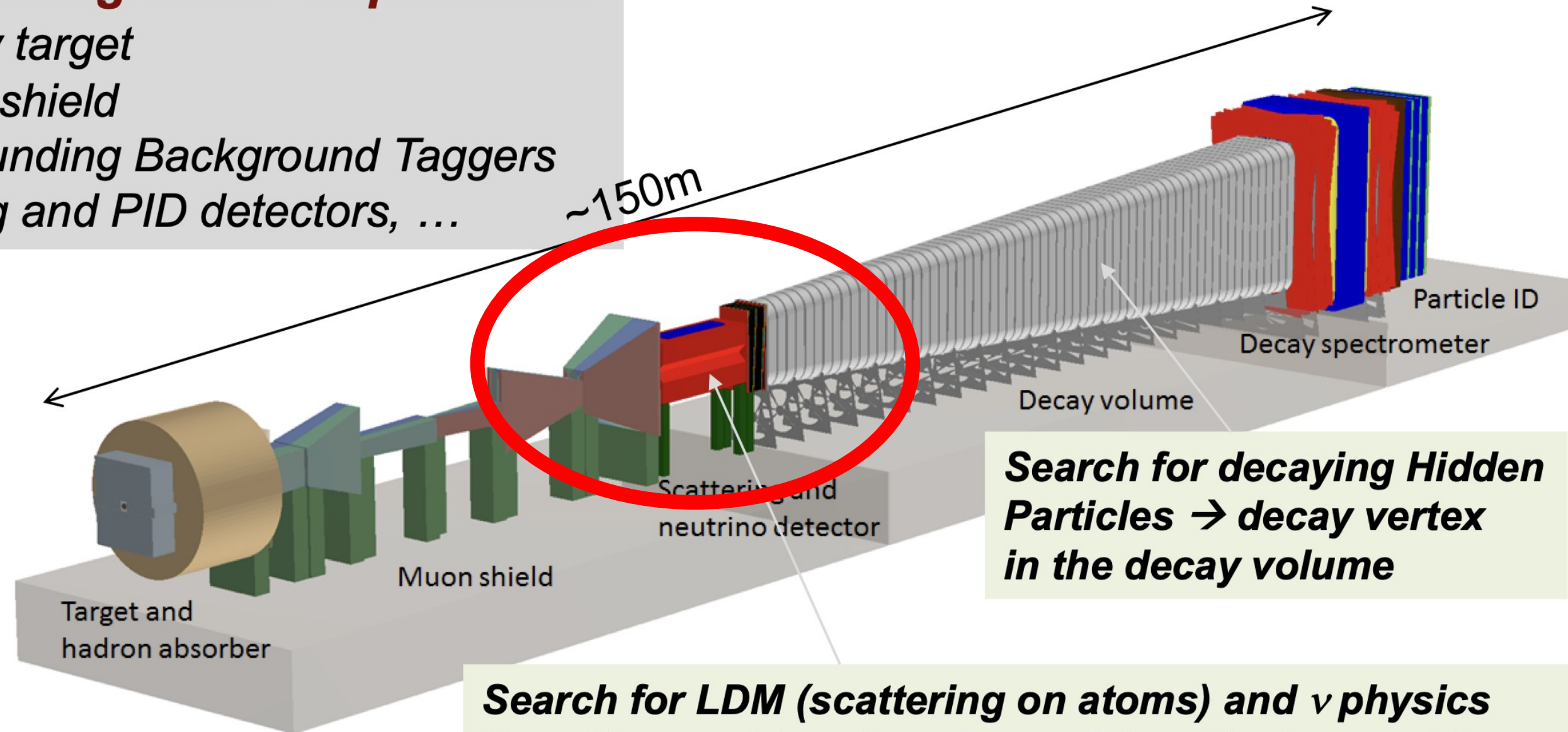


**Search for decaying Hidden  
 Particles → decay vertex  
 in the decay volume**

**Search for LDM (scattering on atoms) and  $\nu$  physics  
 Specific event topology in emulsion. Background from  
 neutrino interaction for LDM searches can be reduced  
 to a manageable level**

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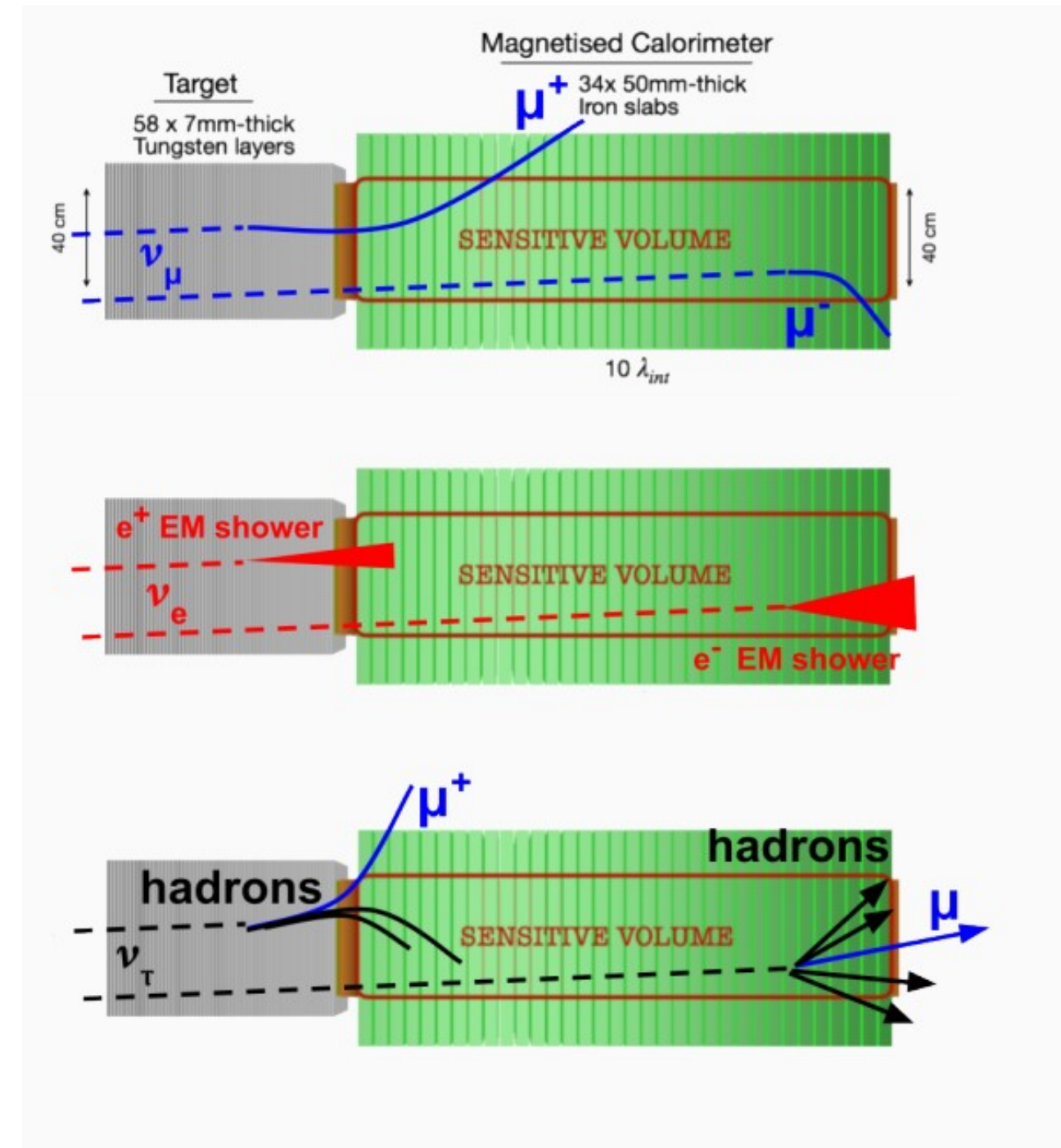


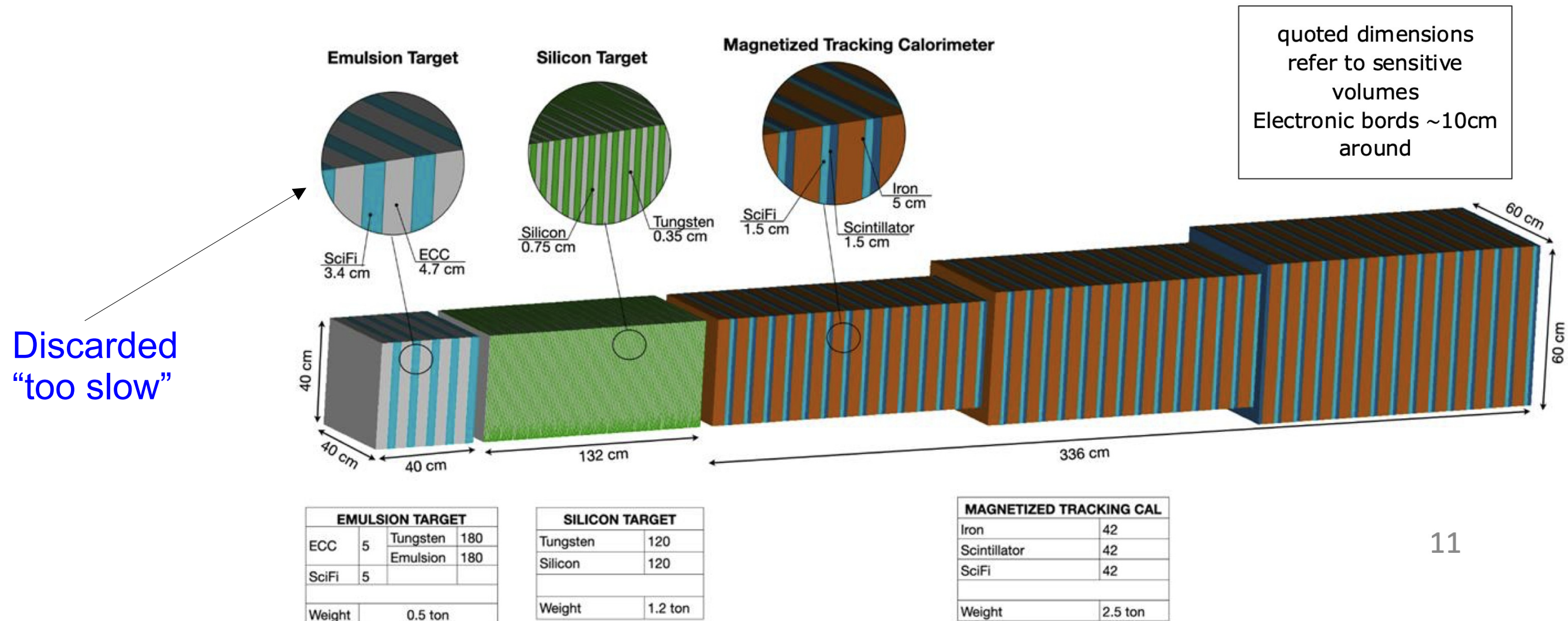
**Search for decaying Hidden Particles → decay vertex in the decay volume**

**Search for LDM (scattering on atoms) and  $\nu$  physics  
Specific event topology in emulsion. Background from neutrino interaction for LDM searches can be reduced to a manageable level**

- $\nu_\mu$ : straightforward, nothing come in and a track comes out, tell apart parity using muon bending
- $\nu_e$ : more challenging, nothing come in and an electromagnetic shower takes place inside of your detector. Parity is complex to identify.
- $\nu_\tau$ : challenging as  $\tau$  s have many possible decays, look for nothing coming in and a vertex associated to multiple tracks. Parity obtained by looking at charge of everything through the bending.

In particular  $\tau$ -decay may (will) benefit from Full kinematic reconstruction

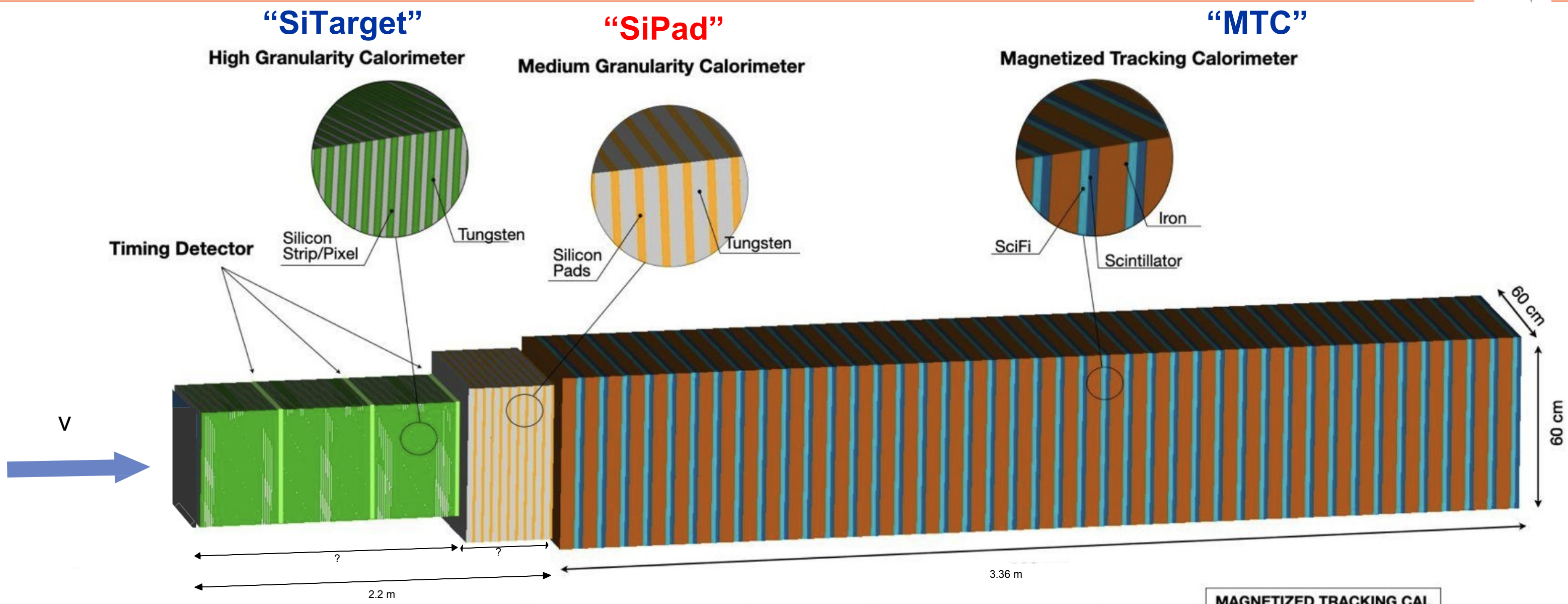




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- “Currently” SND is composed of two types of detectors
  - Silicon Target with W as absorber and silicon strips (100 um x 40 cm arranged in xy) detectors as sensitive material
  - Magnetised Tracking Detector with scintillating tiles (5x5 cm<sup>2</sup>) supported by LHCb like scintillating fibre detector
- Room for another technology?

# SND – A Closer Look



SiPad Detector as transition between fine strip detector and coarse MTC

- Advantages
- xy pixelisation
  - Full amplitude
- Roman Pöschl

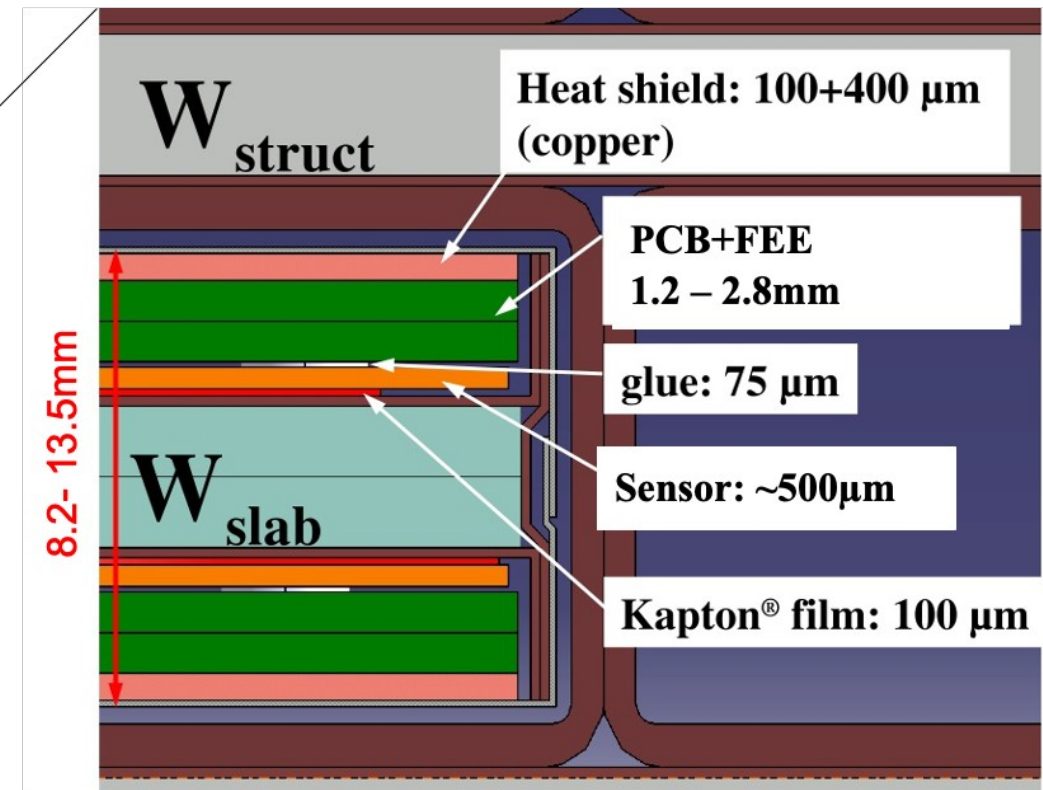
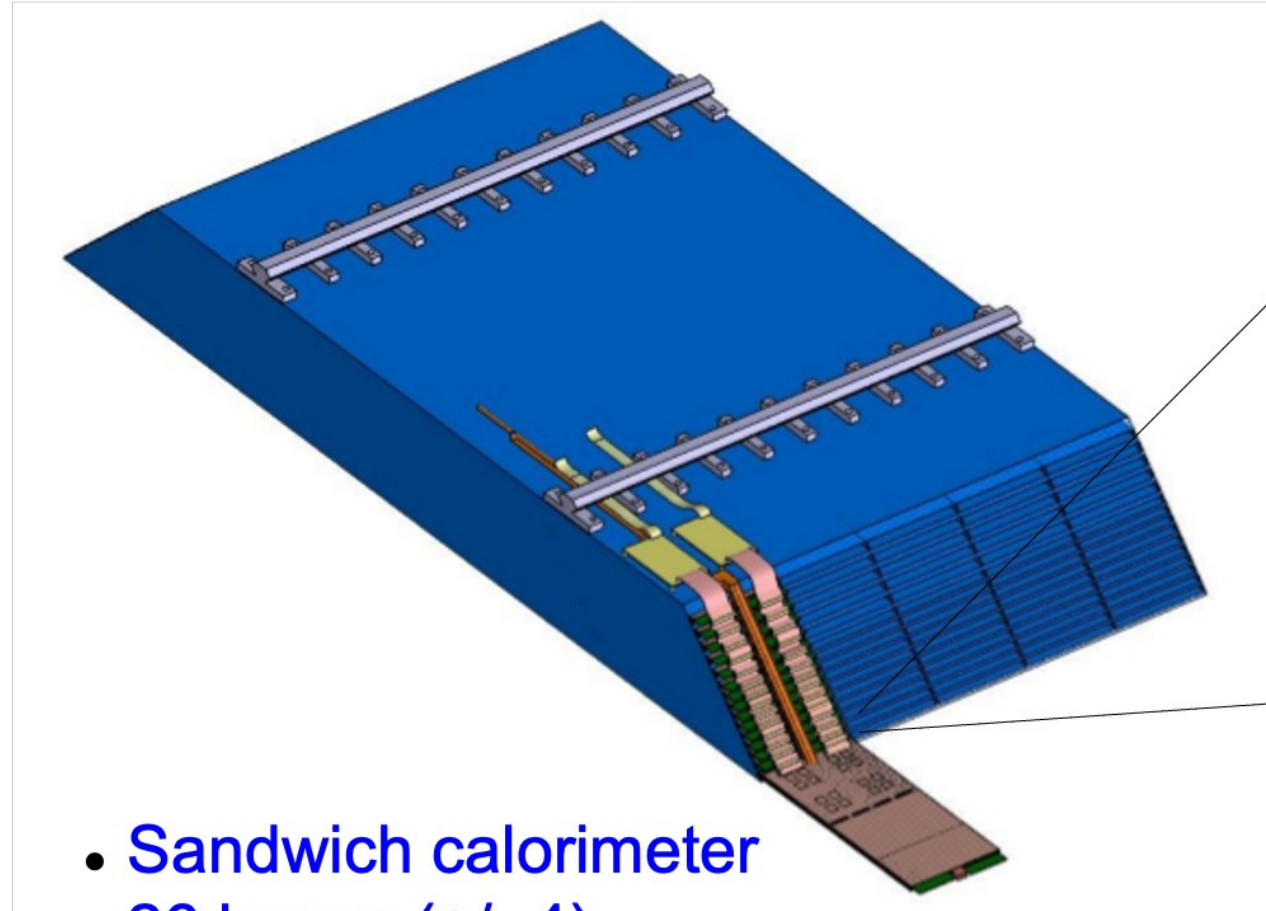
| HIGH GRANULARITY CAL |            |
|----------------------|------------|
| Tungsten             | 120        |
| Silicon Strip/Pixel  | 120        |
|                      |            |
| Weight               | 1.3 tonnes |

| MEDIUM GRANULARITY CAL |            |
|------------------------|------------|
| Tungsten               | 10         |
| Silicon Pads           | 10         |
|                        |            |
| Weight                 | 1.1 tonnes |

| MAGNETIZED TRACKING CAL |            |
|-------------------------|------------|
| Iron                    | 42         |
| Scintillator            | 42         |
| SciFi                   | 42         |
|                         |            |
| Weight                  | 5.9 tonnes |

# Reminder: Silicon Tungsten Ecal for Higgs Factories

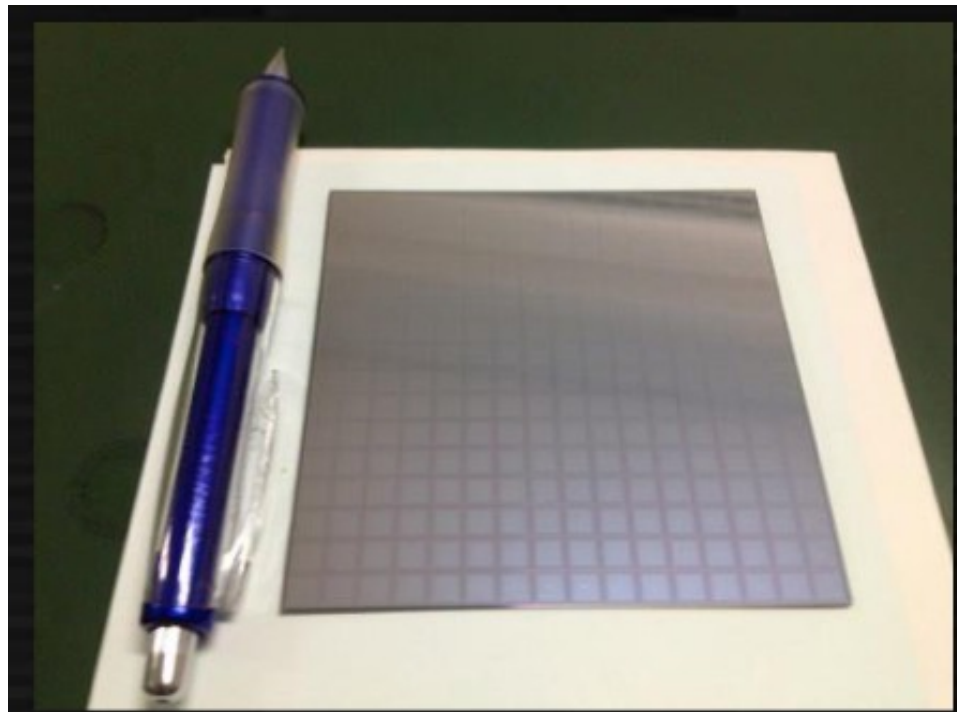
## Ecal alveolar structure



- Sandwich calorimeter
- 26 layers (+/- 4)
- Thickness:  $\sim 20\text{cm}$ ,  $24 X_0/1\lambda_I$
- Pixel size  $\sim 5 \times 5 \text{ mm}^2$
- Expected elm. energy resolution  $15\text{-}20\%/\sqrt{E}$

- Overall height of a layer w/o absorber  $\sim 3.5\text{mm}$ 
  - Glue might be rather 100-200  $\mu\text{m}$
  - PCB + FEE  $< 2.8\text{mm}$
  - Layer housing would add
    - Typically thin carbon frames in case of SHiP

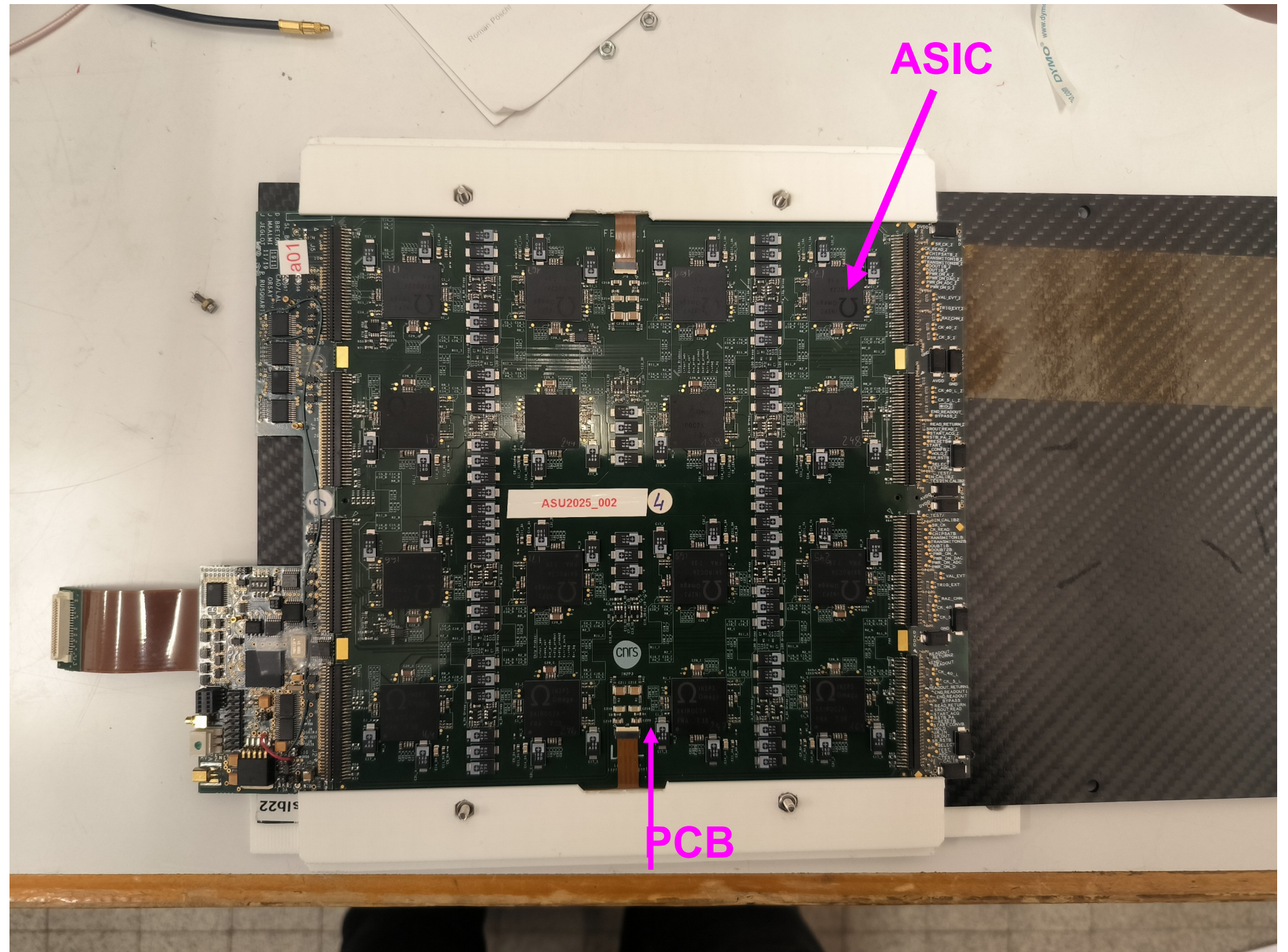
# Current Active Signal Unit (ASU)



Pad size  $5.5 \times 5.5 \text{ mm}^2$

An ASU is composed of:

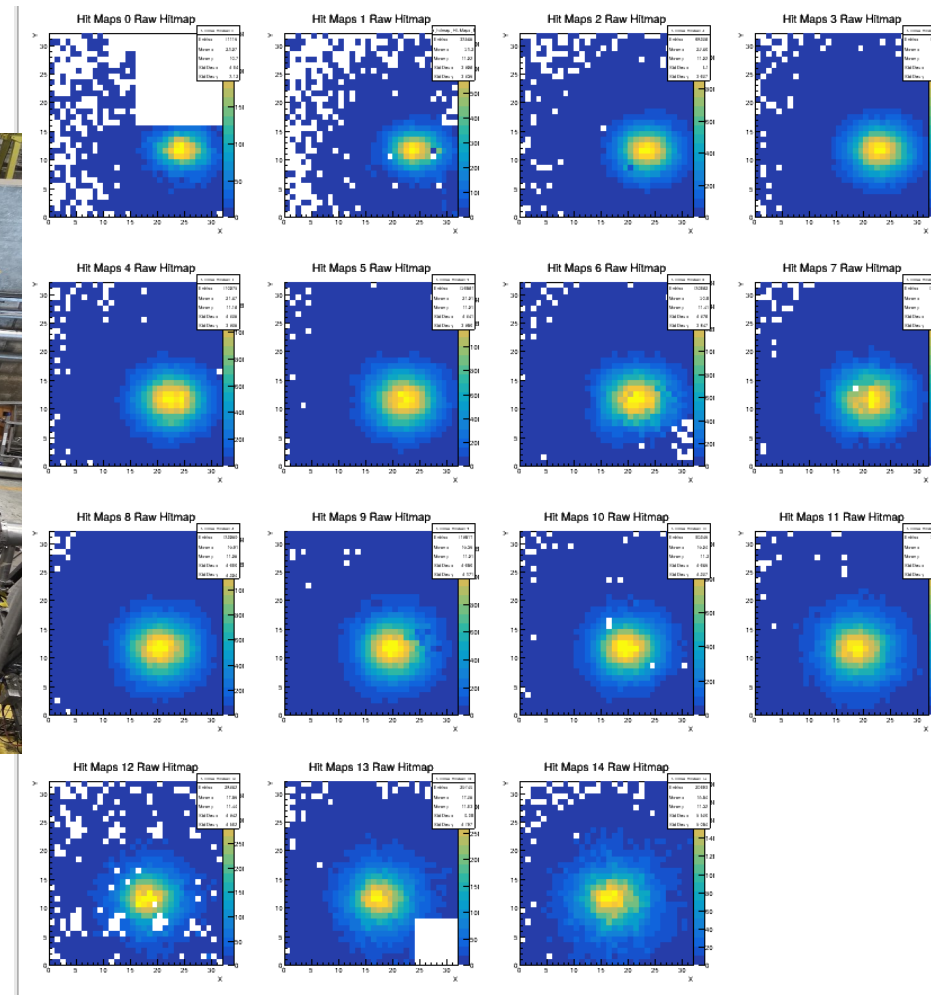
- 16 ASICs
- 1 PCB
- 4 Si sensors



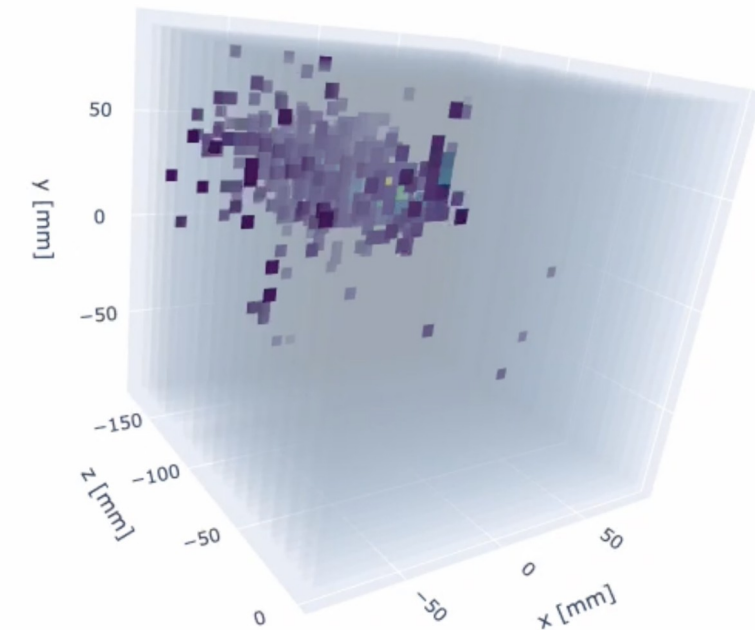
## Team and Detector at SPS



## Beam Spot in all 15 layers



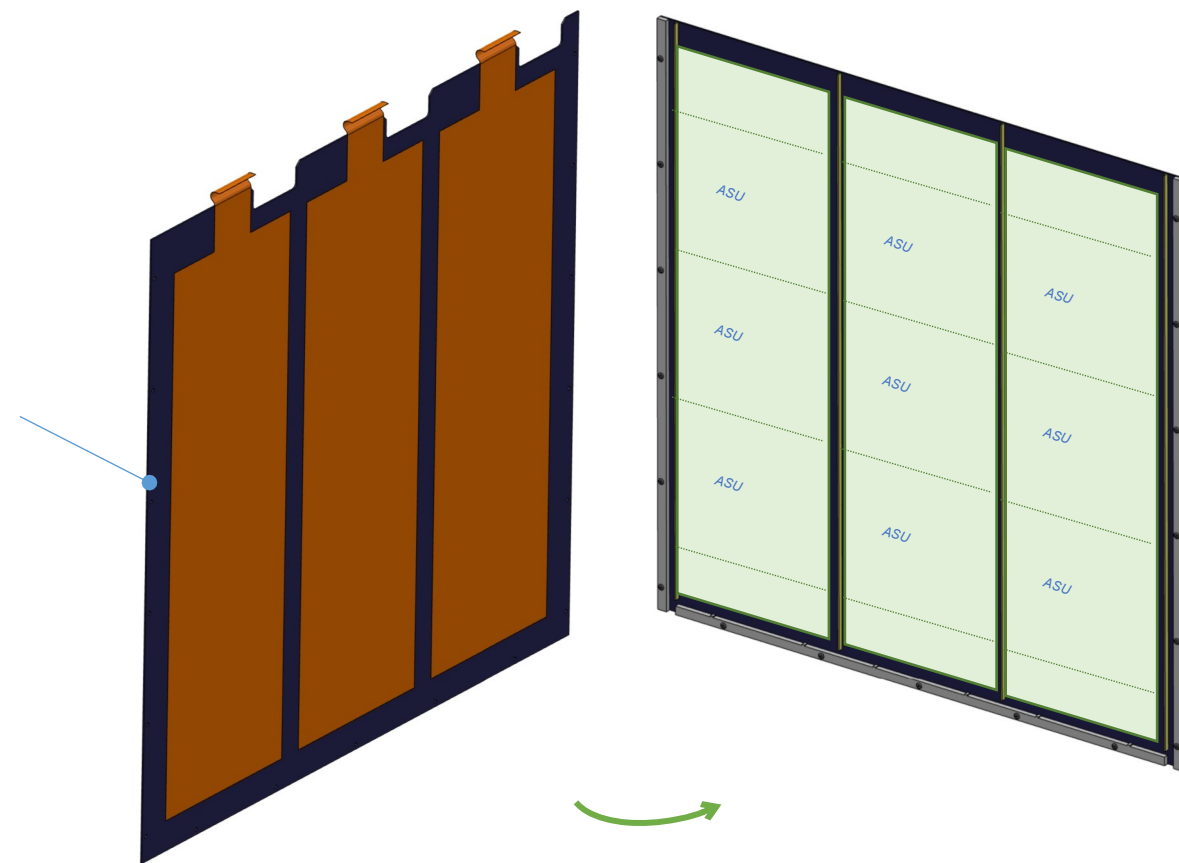
## 54 GeV Electron Shower



Event Display Jesus Marquez

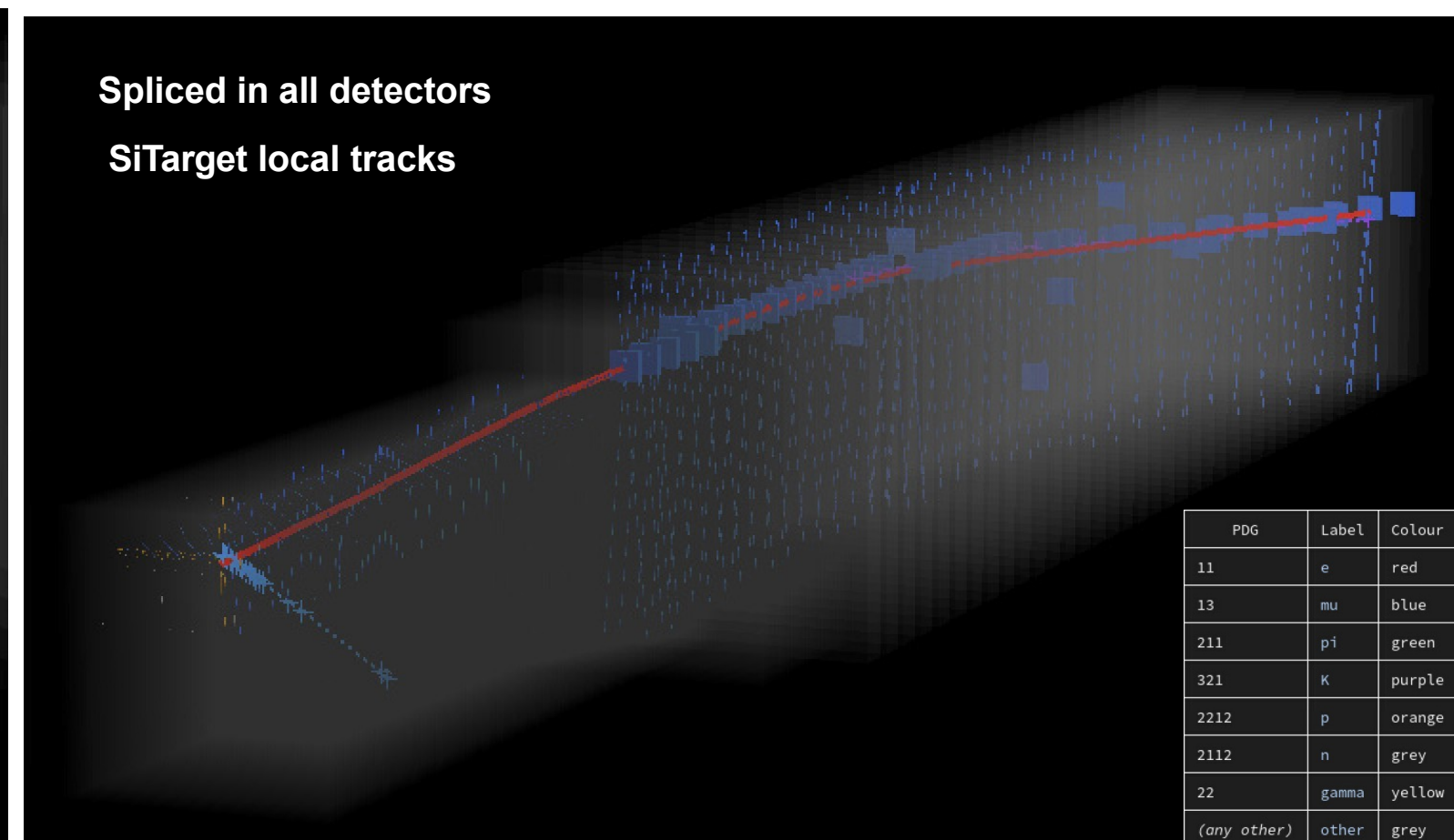
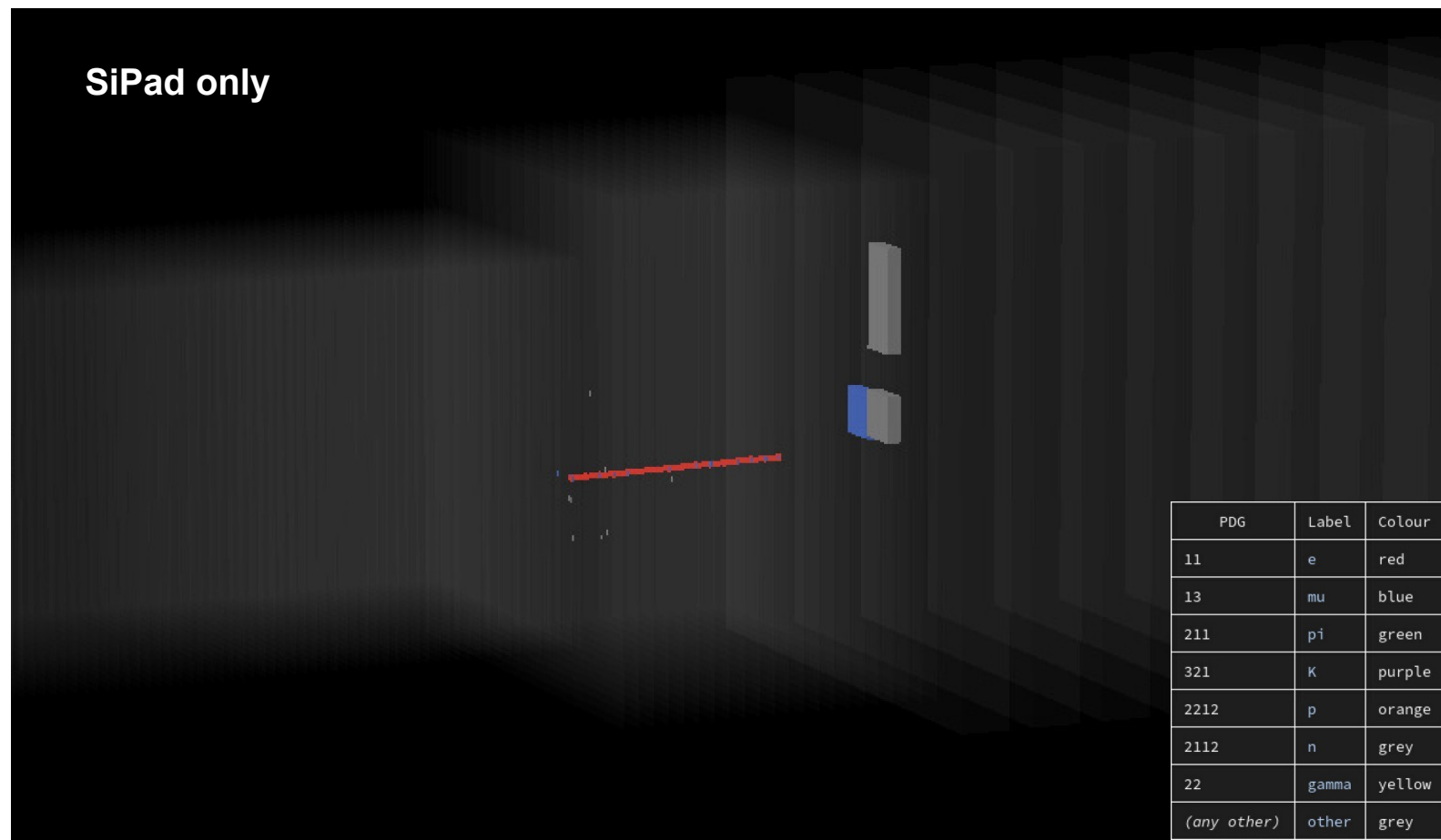
- **Successful testbeam campaign**
  - Installation 2h, running one week w/o the slightest problem (not a single access to the pitch)!
  - => Extremely stable and robust detector
  - Order  $O(\text{‰})$  cells to be disabled due to noise, compare with  $O(5\%)$  for testbeam 2022
- **Analysis ongoing**
  - Results will be presented at November SHiP Meeting

# A Silicon Pad (SiPad) Layer for SHiP



- Should be straightforward to arrange SiW ECAL ASUs
  - Modularity inherent to detector design
  - N.B.: 18x18 cm<sup>2</sup> is not a canonical number but many tools are or will be developed for this size
- 3 Chains of 3 ASUs/layer
- Development of new ASUs about to start
  - ... centered around next generation of ASICs (GETROC)
  - Strong synergies with work in DRD Calo
- Engineering support at IJCLab and LLR!
  - Mechanics and Electronics Departments

- (Outstanding) Work in progress by Postdoc Jesus Marquez

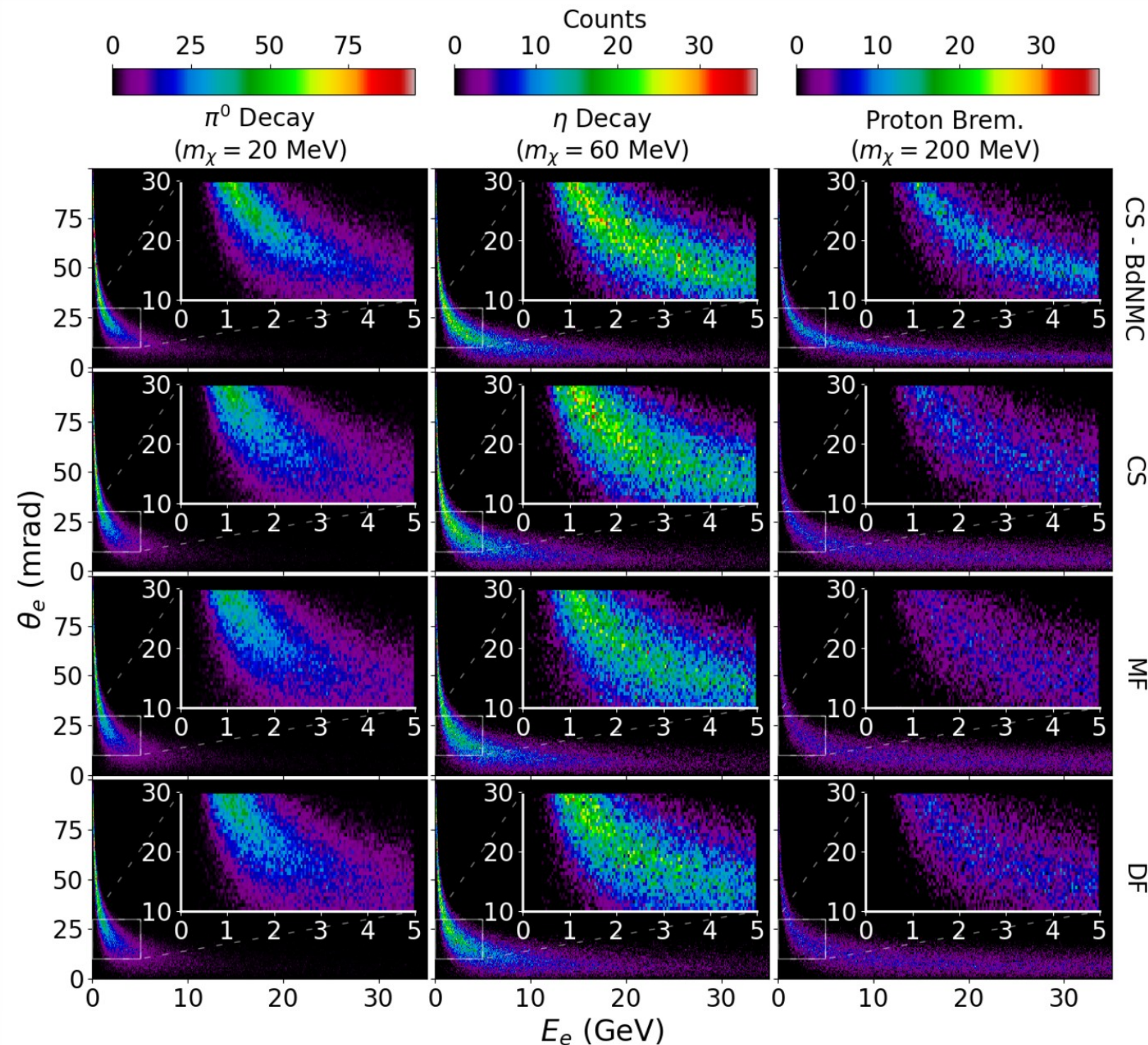


In transition phase from implementation to optimisation

# Summary

- SHiP will be beam dump facility at CERN ECN3 using CERN's 400 GeV SPS Proton beam
- SHiP is supposed to become world leading facility for Hidden Sector Searches in range  $\sim 100 \text{ MeV} - 5(10) \text{ GeV}$ 
  - For many portals SHiP will dominate landscape for decades to come
- SiPad ECAL is an option for the instrumentation of the Scattering and Neutrino Detector
  - Sensitivity to Dark Matter Production and Neutrino Physics
  - Detector optimisation for SHiP has started!
  - In our case how many Ecal layers and where it's best to place them?
- In parallel hardware development
- SHiP is IJCLab project since Spring 2026
  - Other institutes showed interest to join
  - **What about you? Lots of things to do!**
  - SiW ECAL prototype as credible demonstrator for Higgs factories and SHiP
- Synergies with other similar experiments (that may take data before SHiP)!?
  - LUXE, Lohengrin, EBES

# Backup

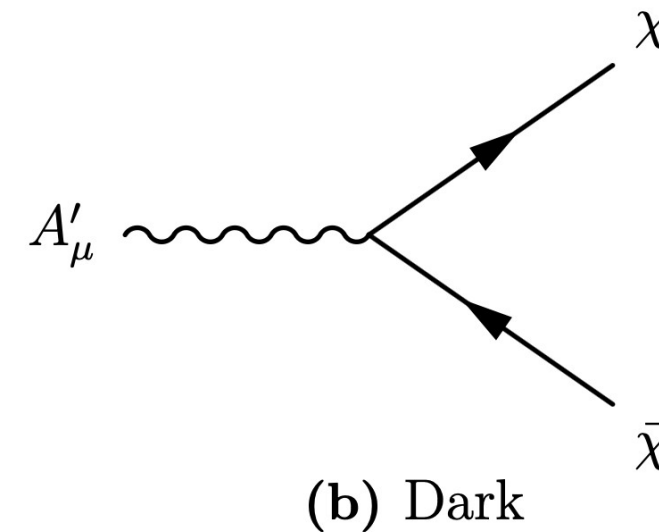
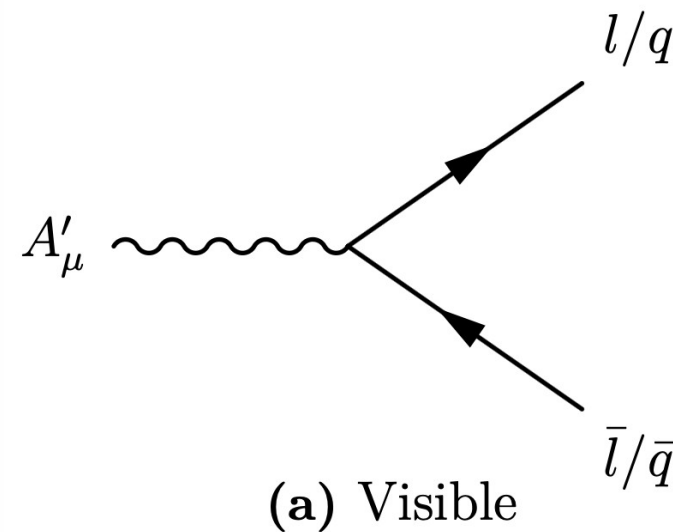


- Energies of scattered electrons  $\sim 1$ -5 GeV
- Scattering angle 10-20 mrad
- Excellent parameter space for SiPad Detector

CS = Complex Scalar  
 MF = Majorana Fermion  
 MD = Dirac Fermion  
 BdNMC = BdNMC Generator  
 else Maddump

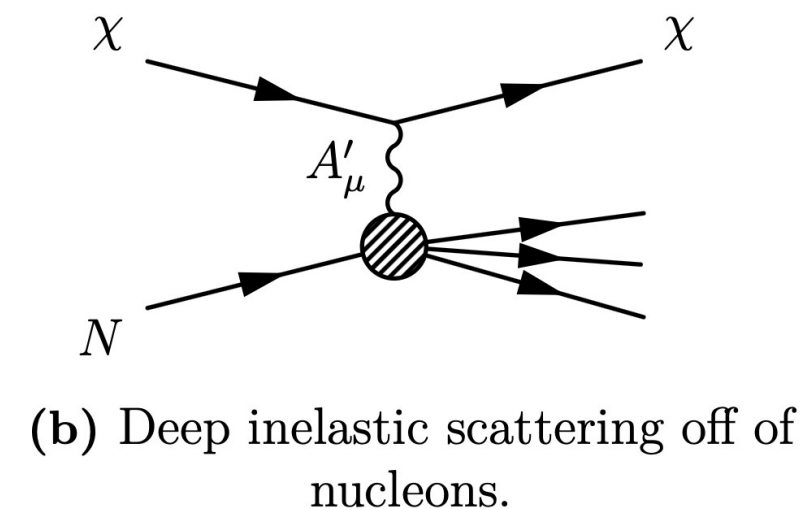
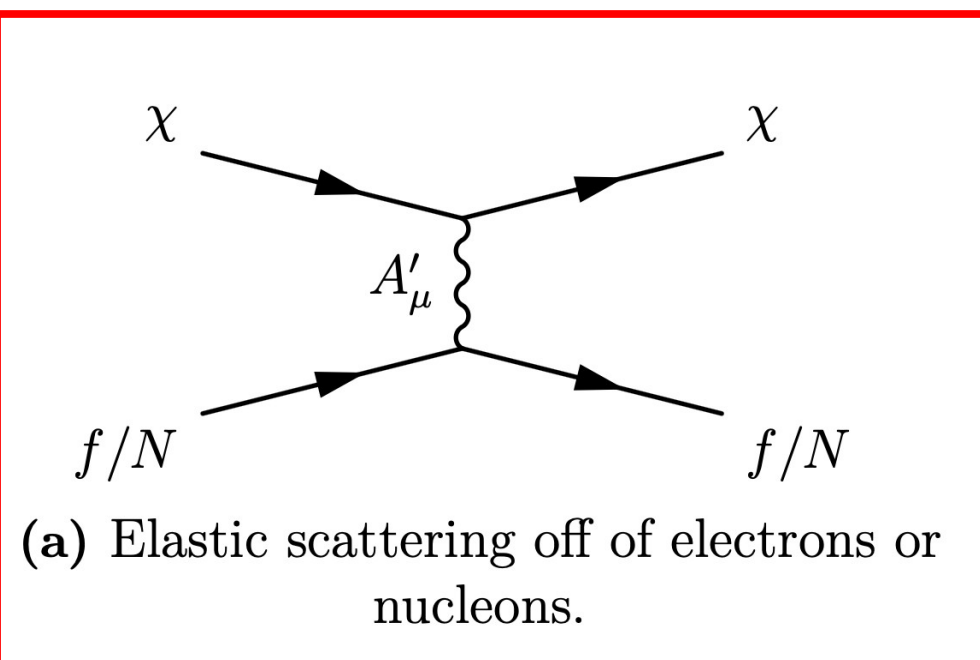
Master Thesis by Elias Svensson (Chalmers University)

## Decay of Dark Photon



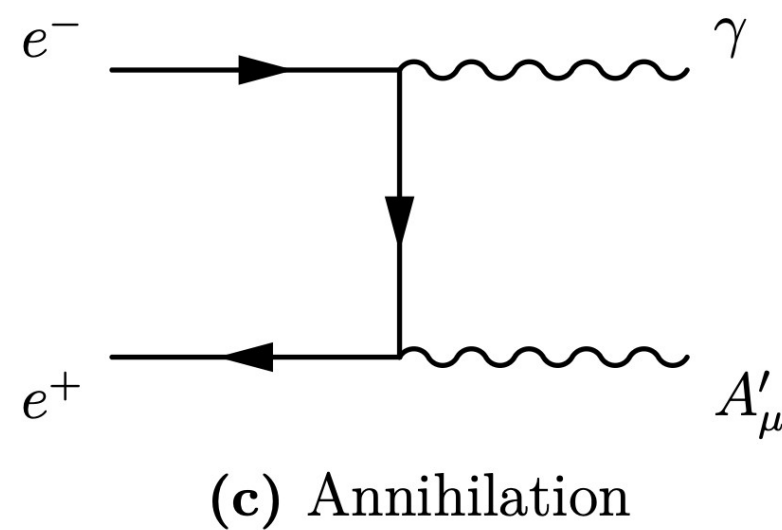
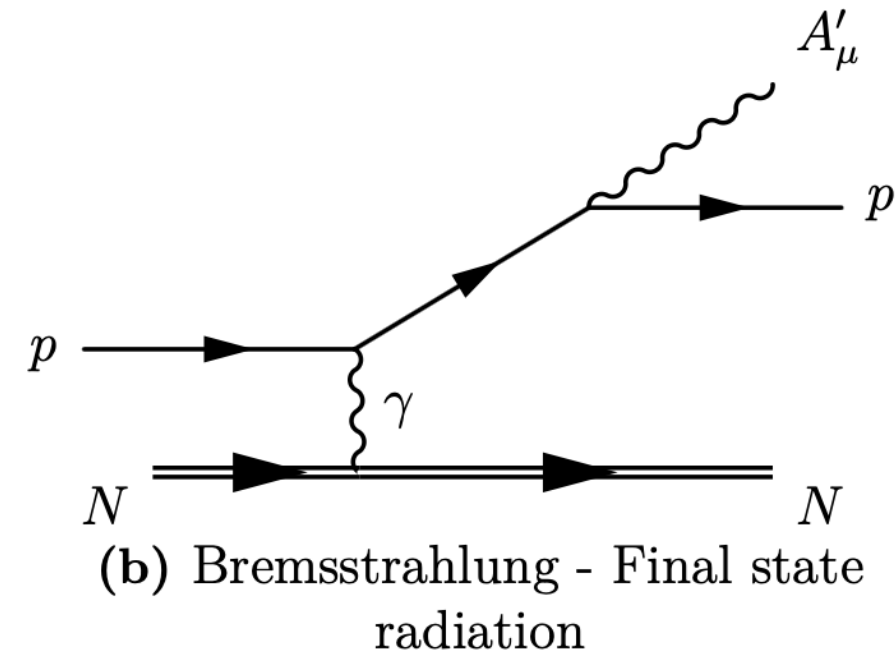
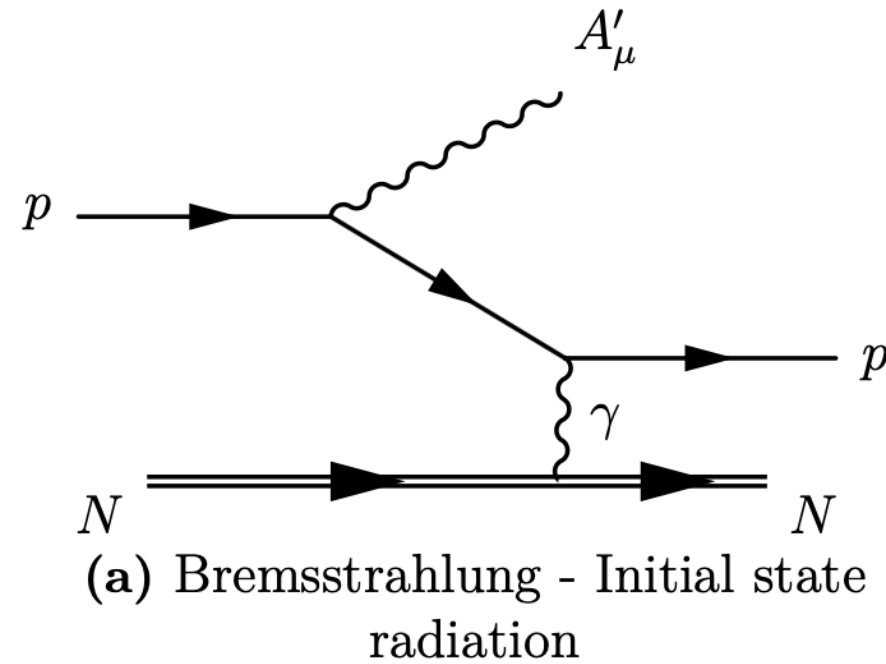
Dominates if:  
 $M_{A'} > 2M_\chi$

## Scattering of Dark Particles

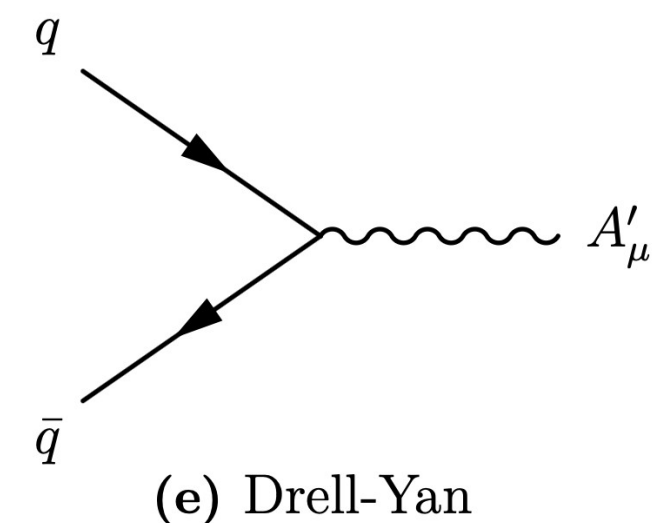
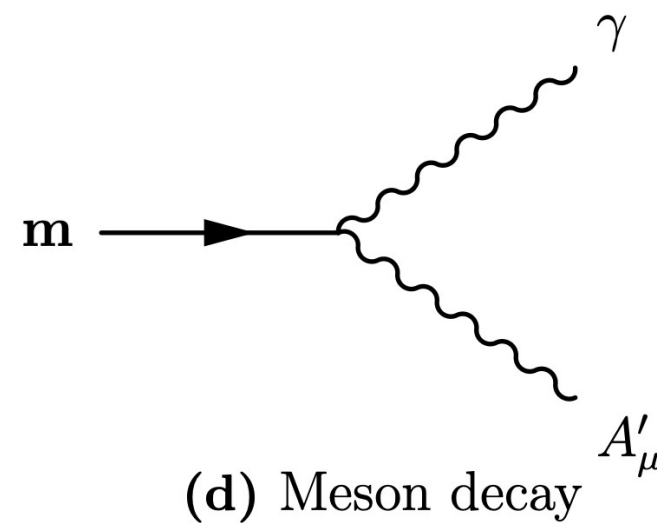


Highest  
 Sensitivity!  
 ->  
 Requires  
 granular  
 calorimeter

# Dark Photon Production (not only) at SHiP



Irrelevant at SHiP



Subdominant at SHiP

## Calorimetry in SHiP

### Two types of calorimeters:

- Neutrino physics and search for LDM scattering:

- LDM and  $\nu_e \rightarrow \text{Si/W}$
- $\nu_\mu$  and  $\nu_\tau \rightarrow$  **Magnetised Tracking Calorimeter (MTC)**

Both are integrated to the muon shield

- Searches for FIPs and PID

- Sampling ECAL with pointing capabilities (e.g.  $\text{ALP} \rightarrow \gamma\gamma$ )
- HCAL to discriminate between muons and hadrons in wide momentum range

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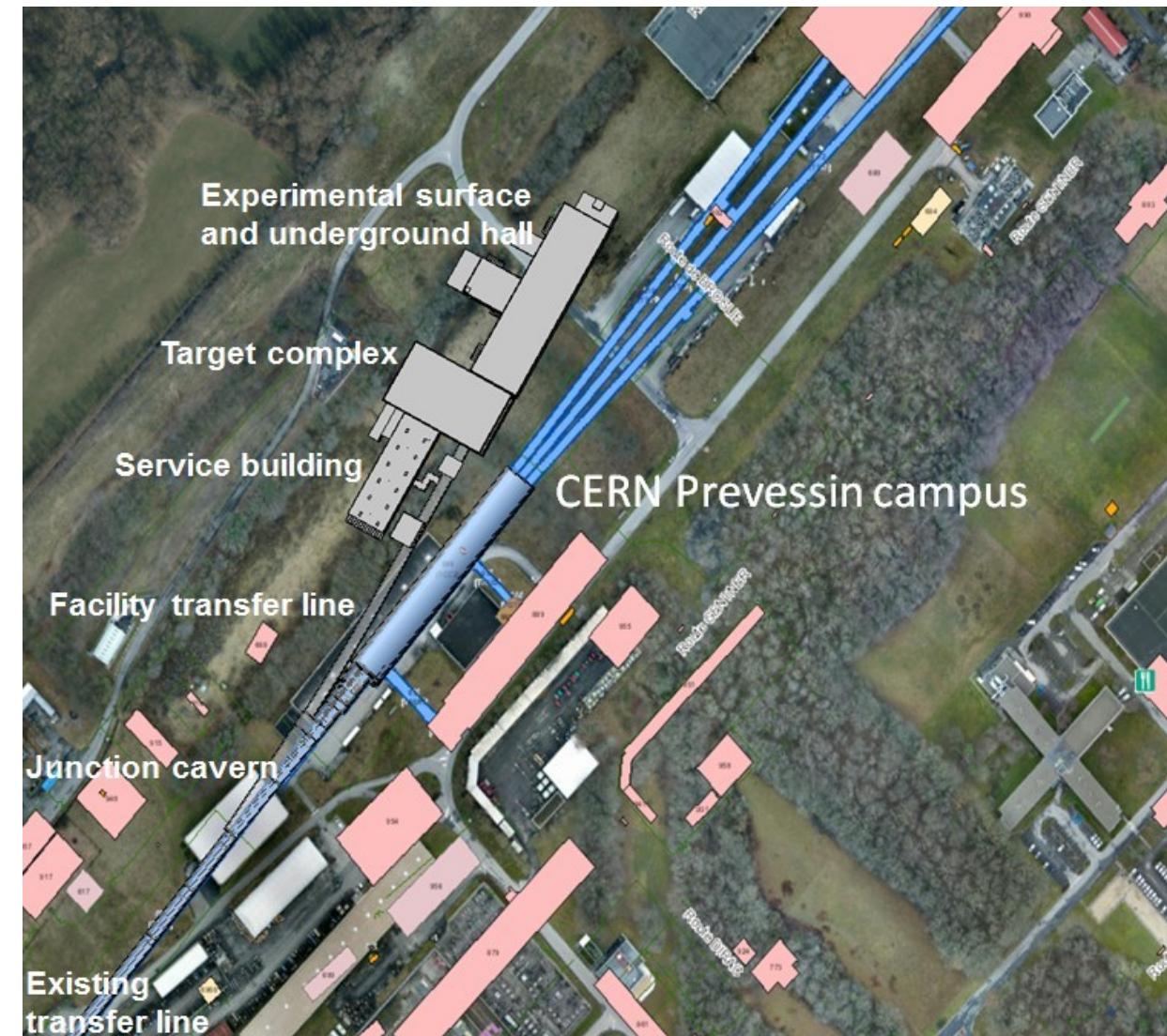
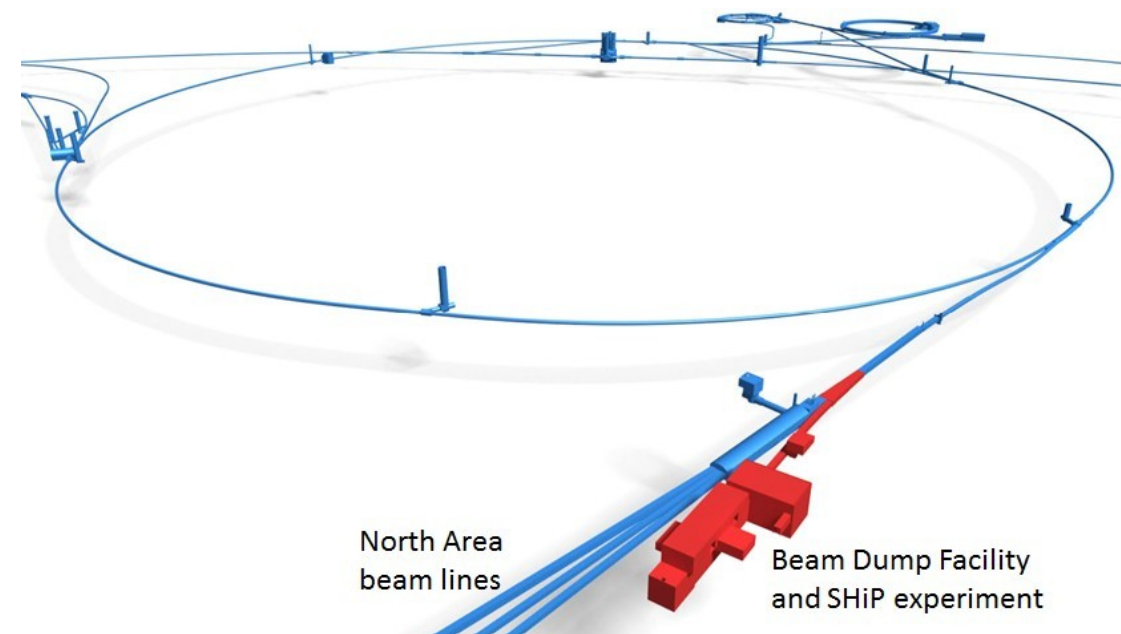
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## Location at CERN

*New 400 GeV proton beam line branched off the splitter section of the SPS transfer line to the North Area*

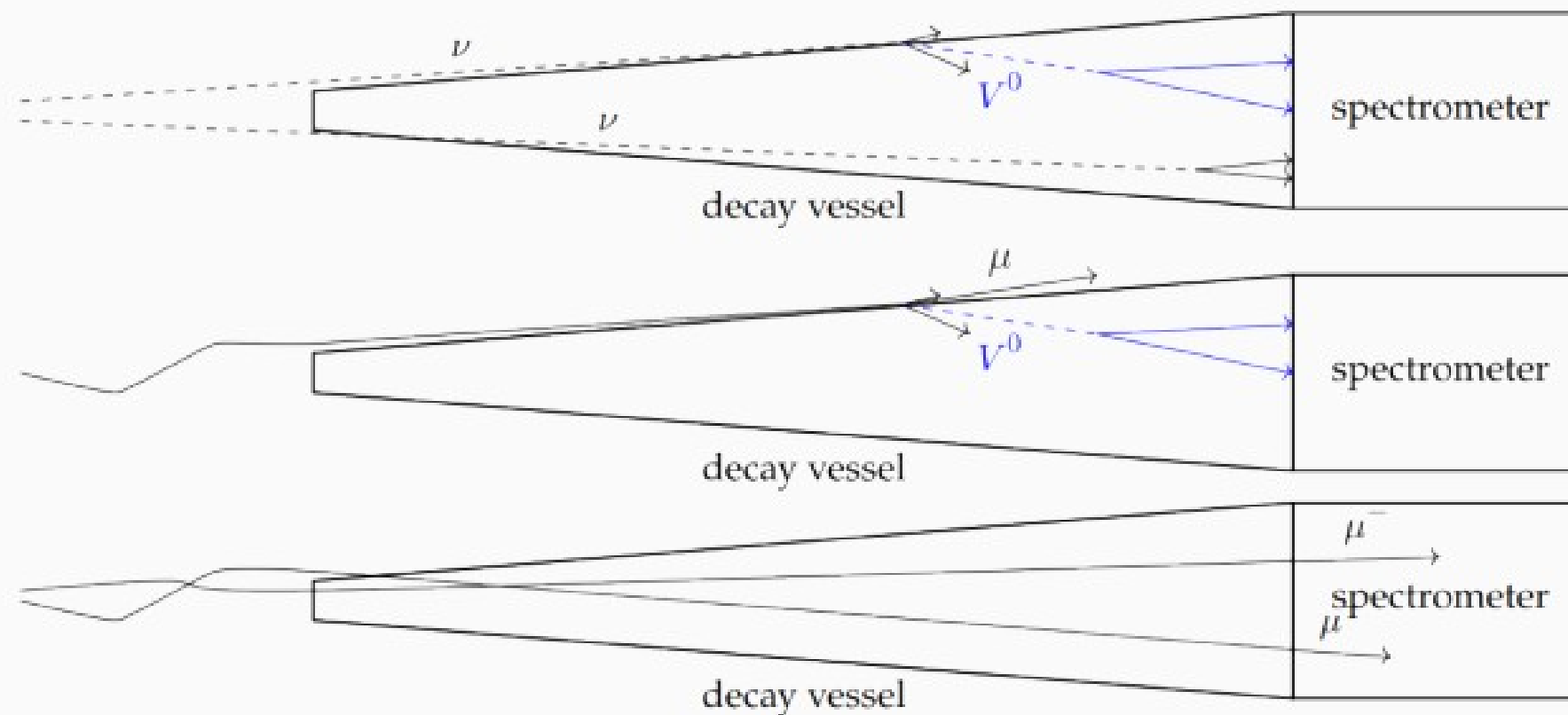


## Proton yield and beam delivery

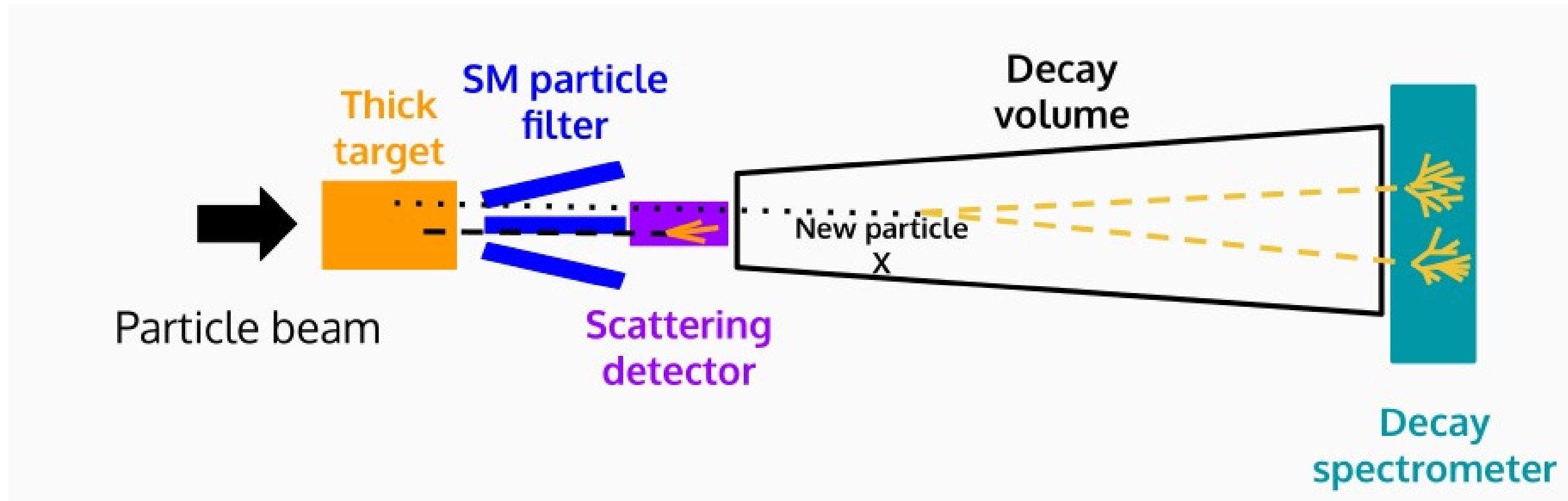
- Nominal beam intensity  $4 \times 10^{13}$  pot per spill
- Baseline scenario: annual yield of  $4 \times 10^{19}$  pot to the BDF, and  $10^{19}$  pot to the other experiments in the North Area, while respecting HL-LHC requirements
- SHiP sensitivities assume  $5 \times 10^{20}$  pot in five years of nominal operation

# The Main “Enemy” - Background

- A set of background taggers will be used to allow SHiP to reach its 0-background goal
  - the Upstream background tagger
  - the Surround background tagger
- 3 backgrounds are significant: neutrino background, muon DIS background and muon combinatorial



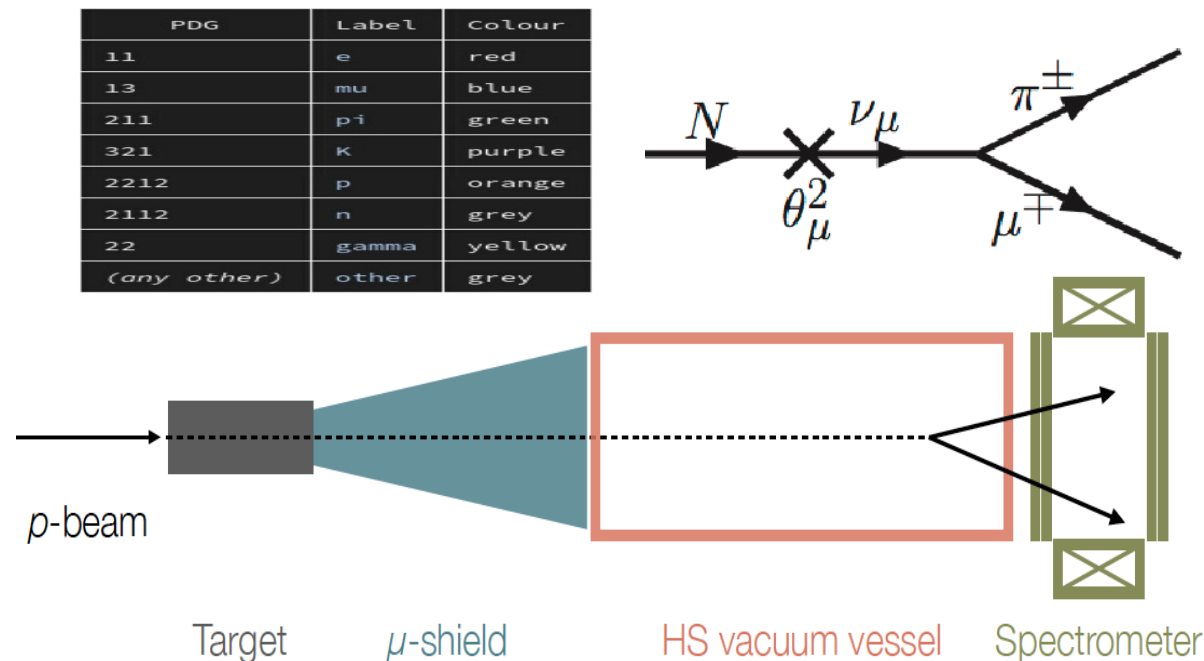
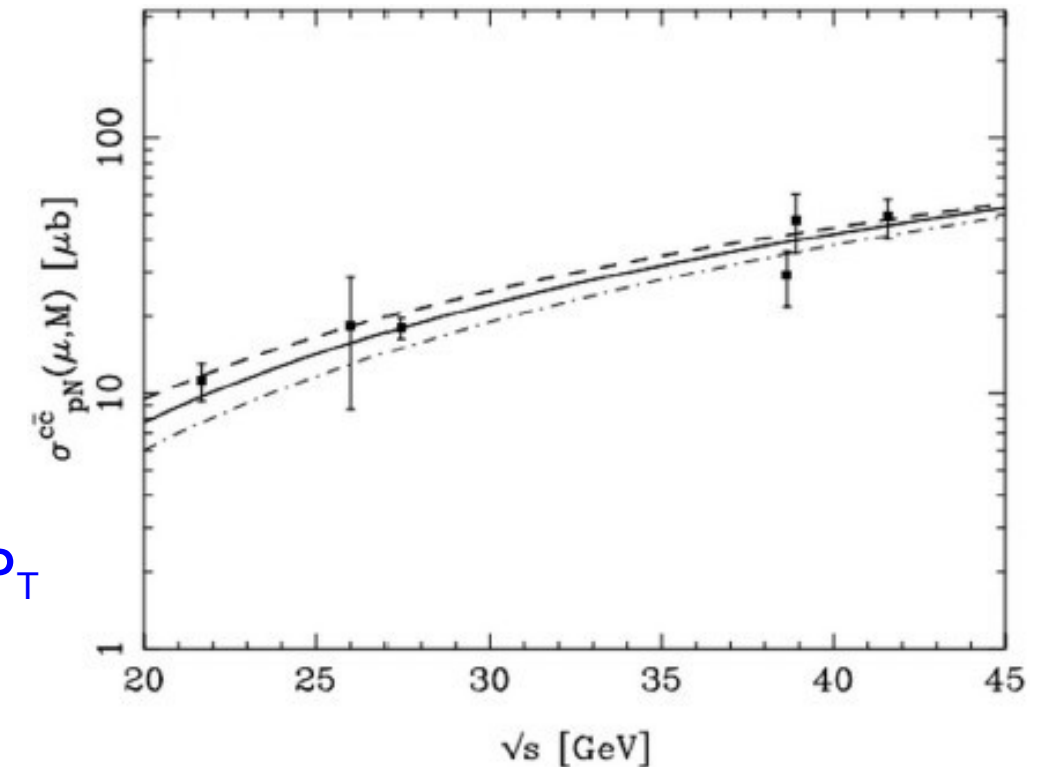
- A high intensity particle beam is needed
  - Search for rare events → particular attention to be given to background suppression
- A long baseline is needed
  - Give space for FIPs to decay
- Presence of high-precision scattering detectors and decay spectrometers
  - Allow observation of faint events



Particle beam with maximal intensity  
 Search for HS particles in Heavy Flavour decays  
 Charm (and beauty) cross-sections strongly depend  
 on the beam energy.

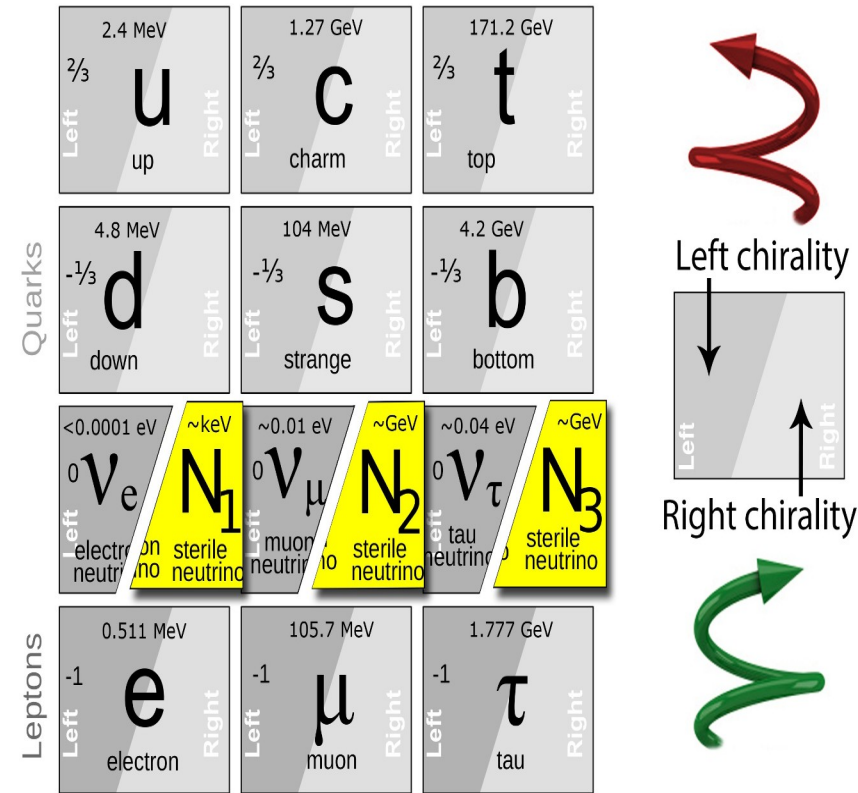
At CERN SPS:  $\sigma(pp \rightarrow s\bar{s} + X) \sim 0.15$   
 $\sigma(pp \rightarrow c\bar{c} + X) \sim 2 \times 10^{-3}$   
 $\sigma(pp \rightarrow b\bar{b} + X) \sim 1.6 \times 10^{-7}$

HS produced in charm and beauty decays have significant  $P_T$



Long decay volume and large  
 geometrical acceptance of the  
 spectrometer are essential to  
 maximize detection efficiency

*Detector must be placed close to the target to maximize geometrical acceptance*  
*Effective (and “short”) muon shield is essential to reduce muon-induced backgrounds*



**Neutrino oscillations:** particles  $N_2, N_3$

**Baryon asymmetry:** same particles  $N_2, N_3$

Masses  $\geq O(100 \text{ MeV})$

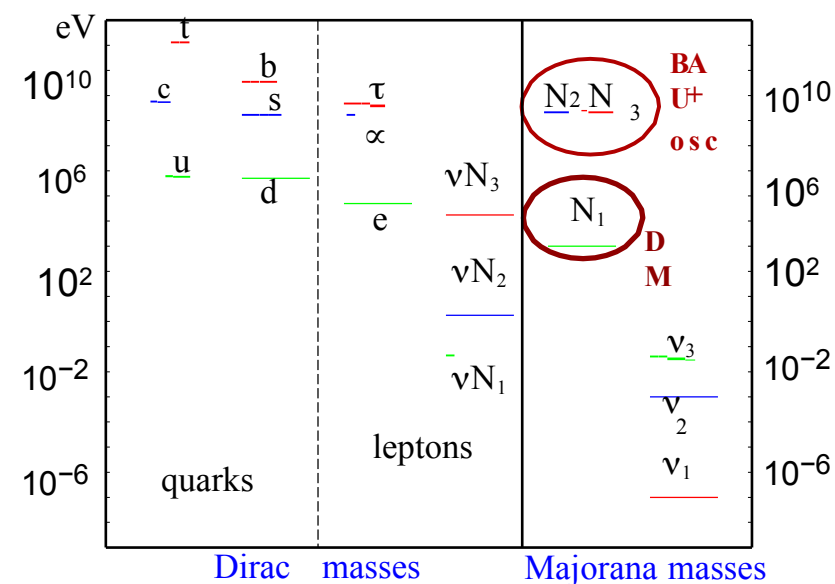
**Dark matter:** particle  $N_1$

mass 1 – 50 keV

**Inflation:** Higgs field coupled to gravity

Inflationary parameters for

$M_{\text{Higgs}} \sim 126 \text{ GeV}$  in perfect agreement with observations



**Neutrino Minimal Standard Model ( $\nu$ MSM)**

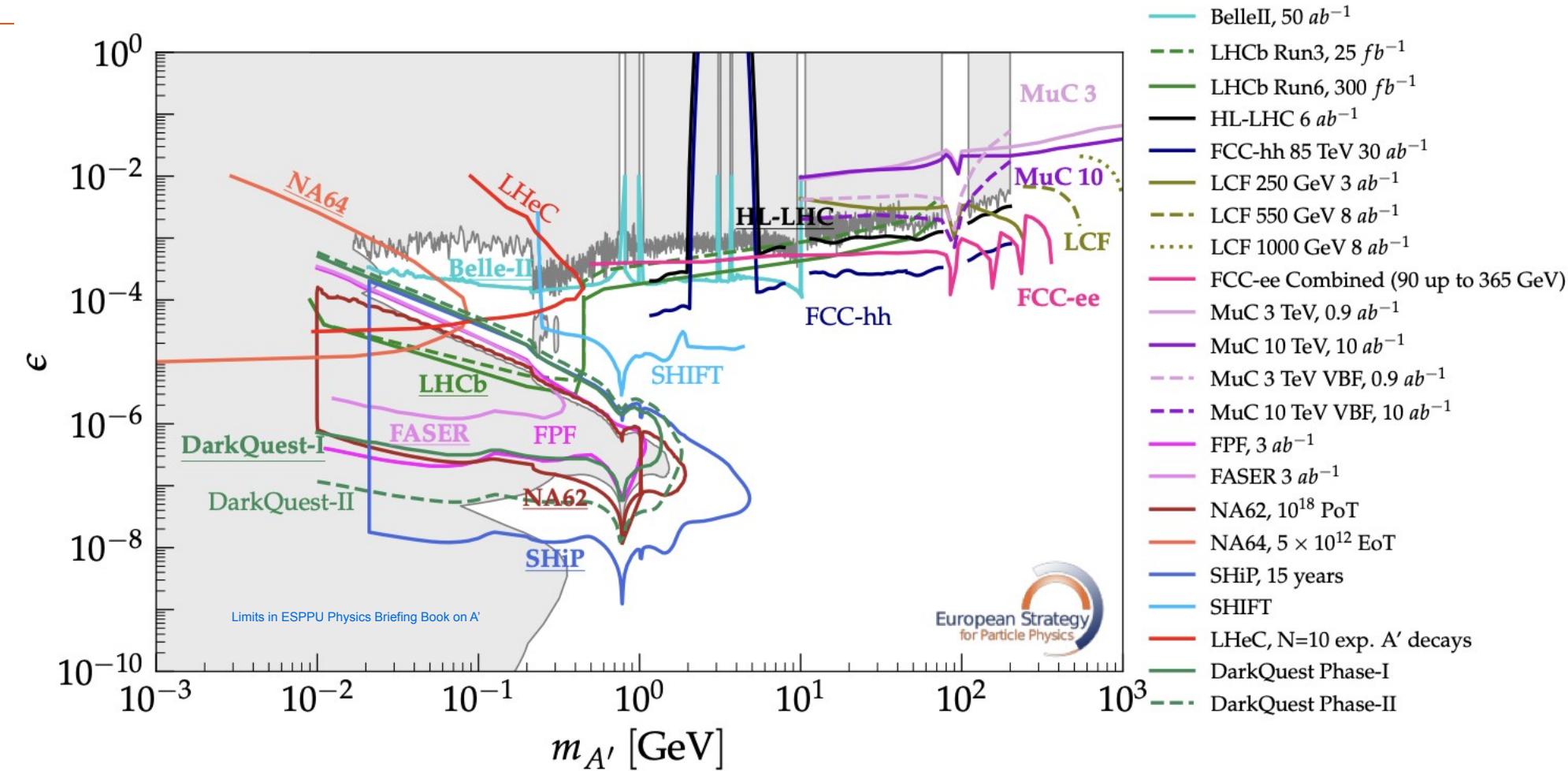
Masses of right-handed neutrinos as of other order of masses of other leptons

Yukawas as those of electron or smaller

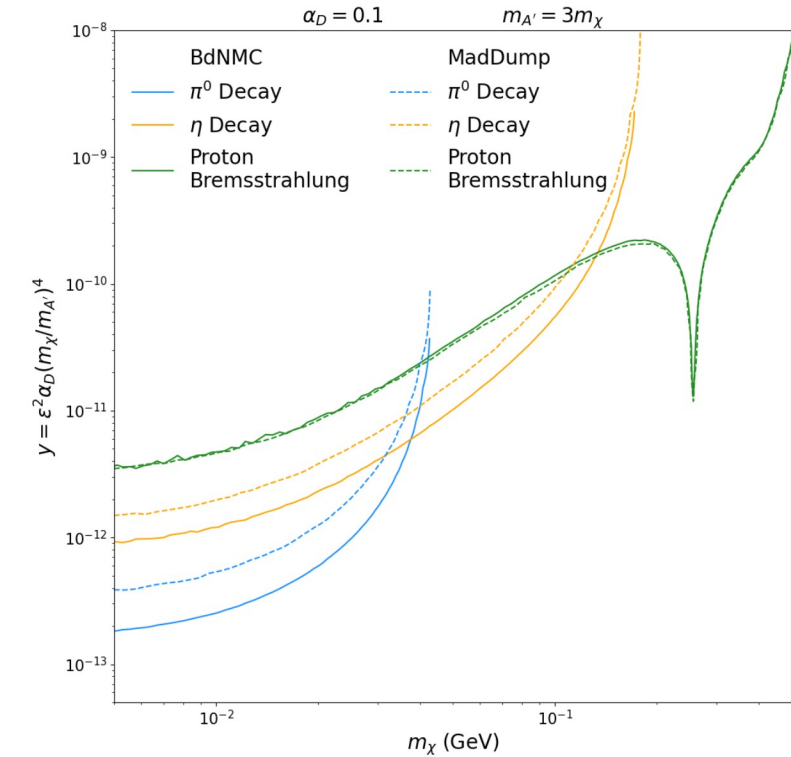
**Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann.**

**Rev. Nucl. Part. Sci. (2009), [0901.0011]**

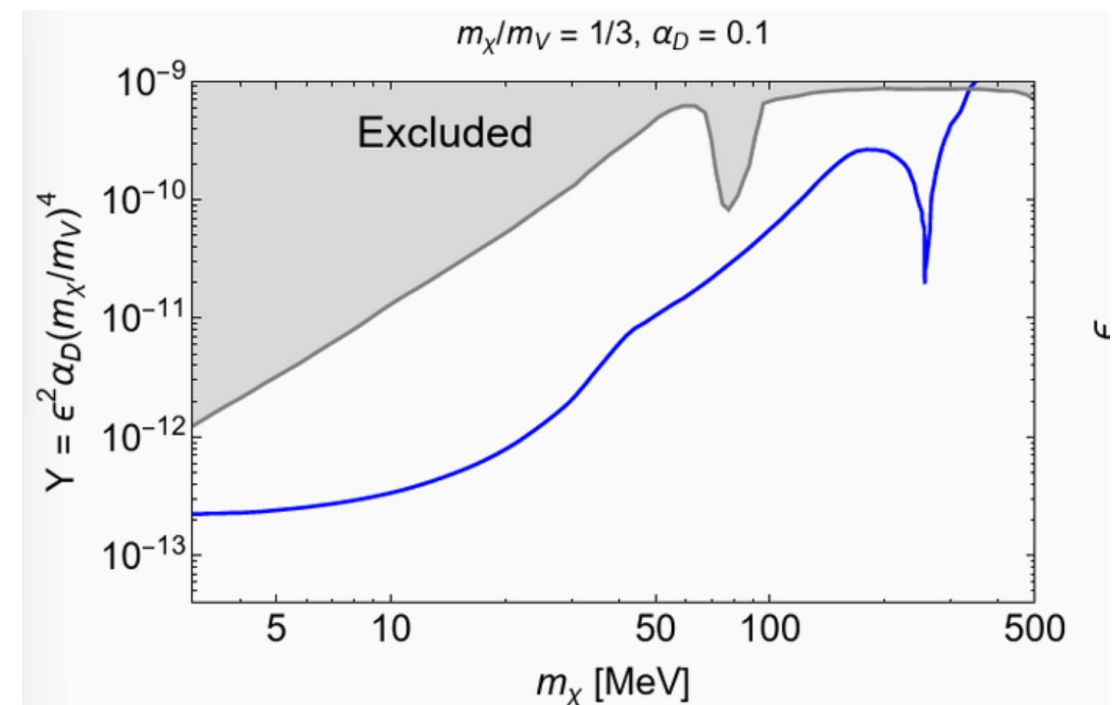
# Sensitivity to Dark Photons and Dark Matter Particles



## Contributions to Dark Photon Limits (E.Svensson)



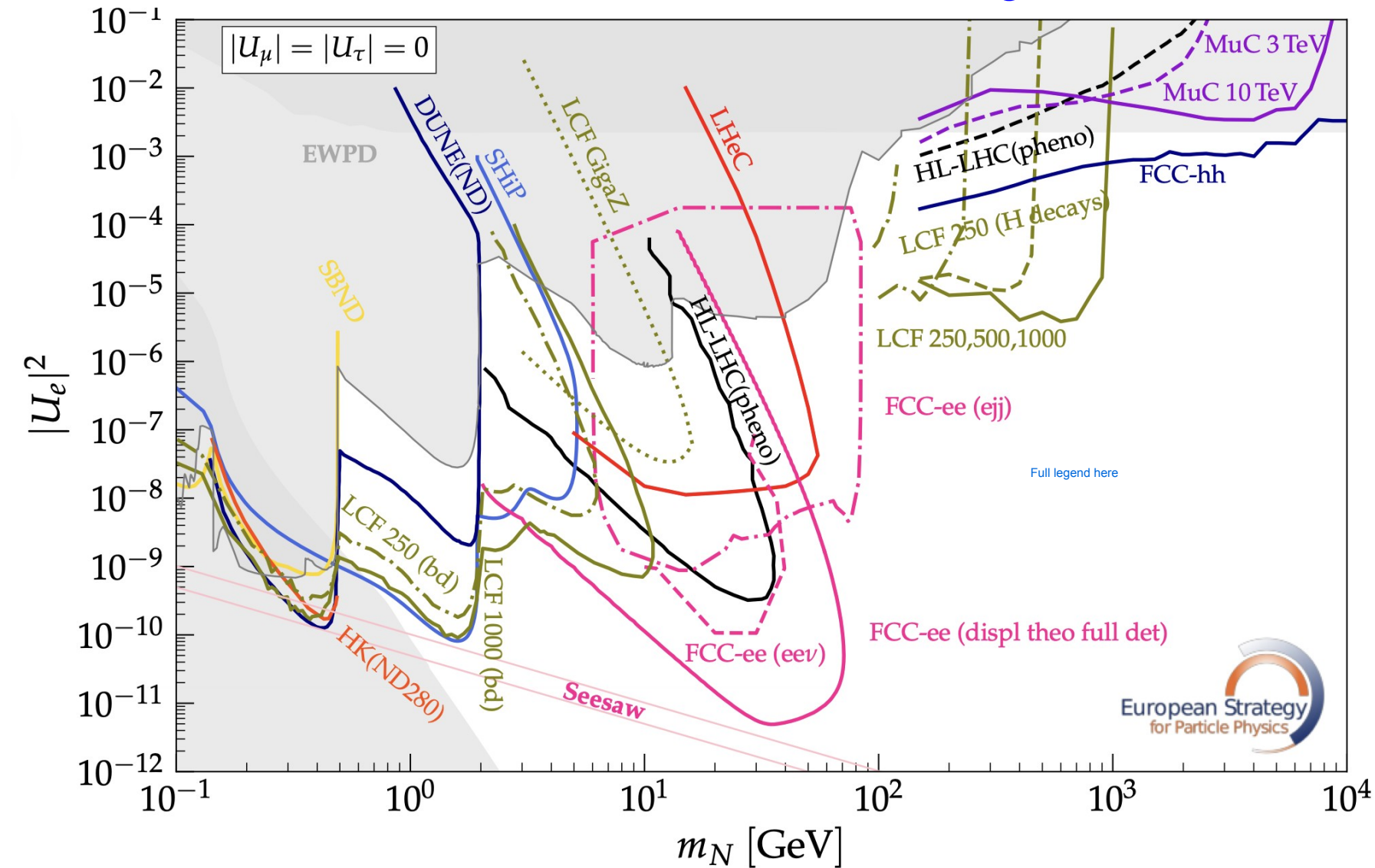
Limits on  $\chi$  by SHiP (M. Climescu at Queen Mary)



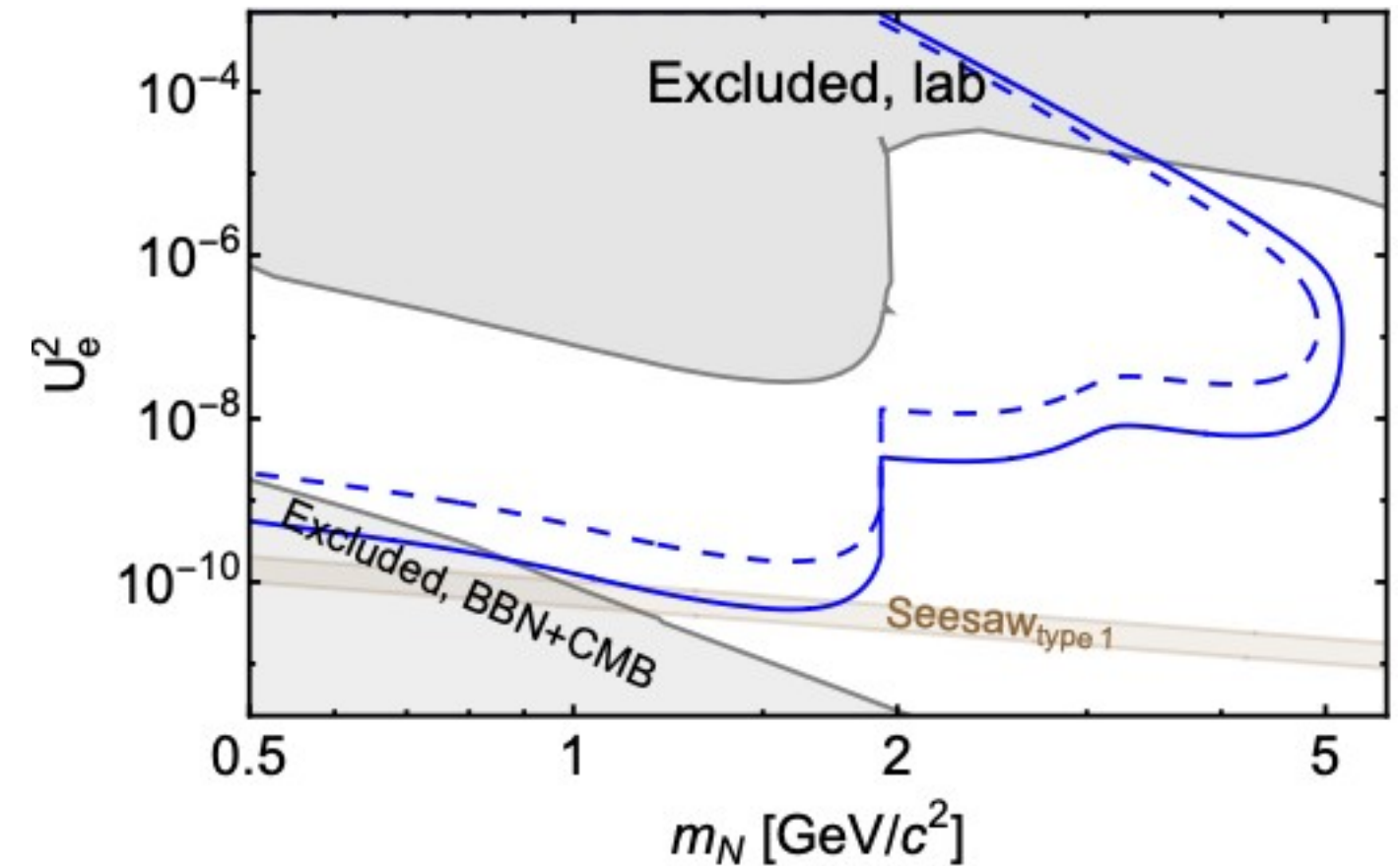
- SHiP sensitive to Dark Photons and Dark Matter Fermions in regime up to 5 GeV
- SHiP will dominate the phase space of (kinematically allowed) dark photon masses

# For completeness I: Sensitivity to Heavy Neutral Leptons

Future limits as in ESPPU Briefing Book



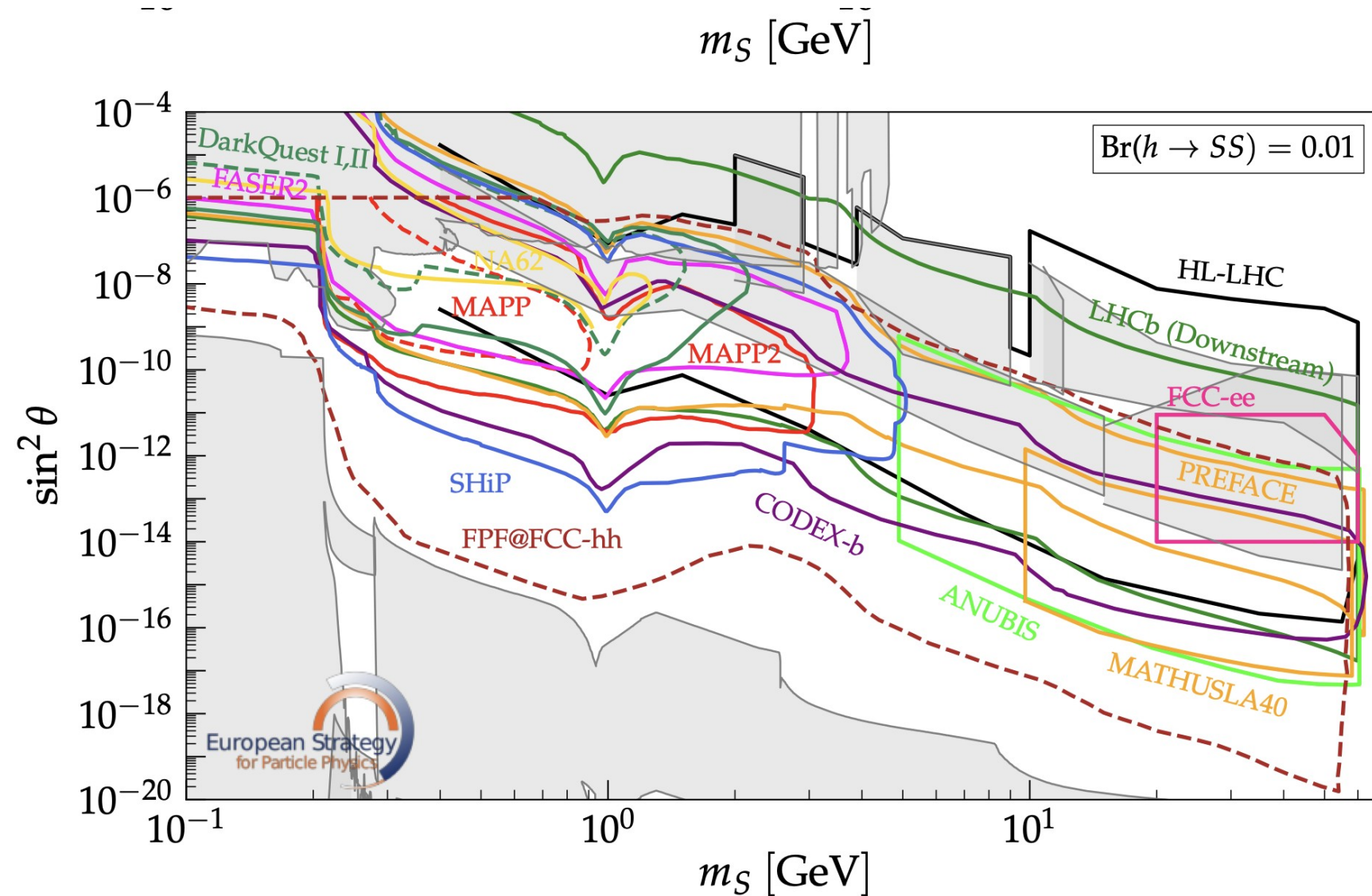
Zoom into SHiP (2504.06692v1)



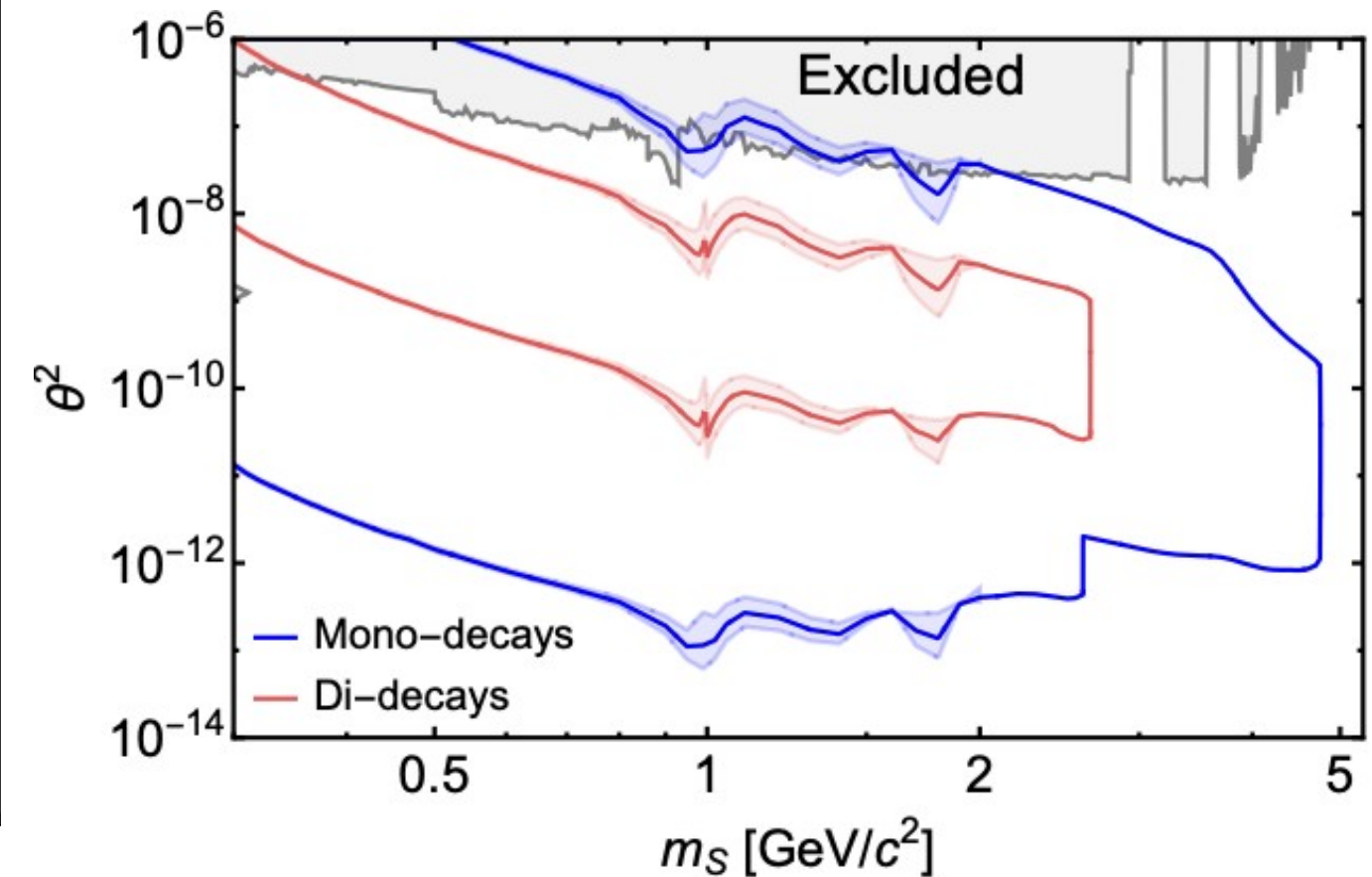
- SHiP sensitive to light scalars up to 5 GeV
- Among projects studied by ESPPU SHiP and DUNE are the only approved experiments
- Reality until maybe the middle of the 2050's
  - Allow me to also point out the remarkable phase space covered by a LCF

See backup for details on HNL@SHiP

Future limits as in ESPPU Briefing Book

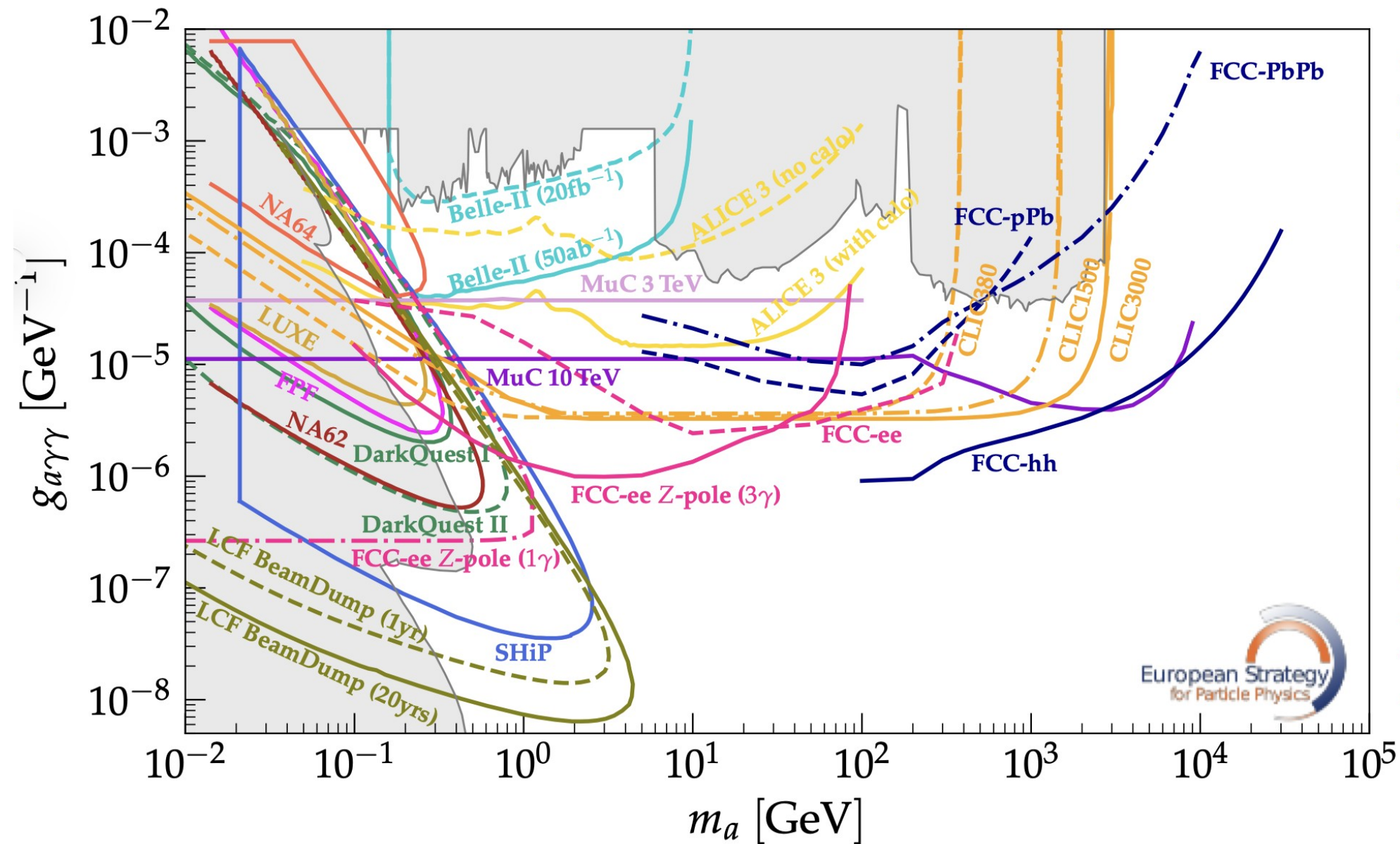


Zoom into SHiP (2504.06692v1)



- SHiP sensitive to light scalars up to 5 GeV
- Significant increase reach if both scalars in pair production can be fully reconstructed!
  - Mono-decays vs. Di-decays

# For completeness III: Sensitivity to Axion Like Particles



- Below 5 GeV SHiP would/will dominate the landscape for decades
- Would only be topped by LCF beam dump facility

The SHiP experiment will search for a broad range of feebly interacting particles such as:

- Light Dark Matter
- Heavy Neutral Leptons (HNLs)
- Dark photons
- Dark Scalar Higgs-like particles
- Axion-like particles (ALPs)

In addition SHiP will allow for a rich set of tests of Standard Model physics in with neutrinos

Relevant for today:

