Heiko Lacker

Exploring the “weak”sector with SHiP and SND@LHC

Astroparticle and Particle Physics Workshop
DESY Zeuthen
Oct 06 - 08, 2025

„Big Questions“:

Why do have neutrinos (tiny) masses?

What is the origin of the Baryon Asymmetry in the Universe (BAU)?

Does Dark Matter (DM) consist of particles and is this DM „light“ (< GeV)?

Are there low-energy extensions of the Standard Model (SM): „Dark Sector(s)“?

The least studied SM particle: ν_τ !
Do ν_τ interact as the other neutrino flavours?

Looking for Physics Beyond the SM: Diversity is crucial!

If Scalar(125 GeV) is the SM Higgs boson:
SM complete, w/o explaining
→ (tiny) ν masses
→ BAU
→ DM

SM: Low-energy manifestation of an UV-complete theory

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

New „high"-mass states
→ energy frontier
→ rare decays
→ precision measurements
… No smoking gun yet

Low-energy extensions respecting the SM symmetries

$\mathcal{L}_S = c_1 H^\dagger HS + c_2 H^\dagger HS^2,$ Dark scalars

$\mathcal{L}_N = F_{N\alpha} \bar{N}^c \sigma_2 H^* L_\alpha + \text{h.c.},$ Majorana Neutrinos

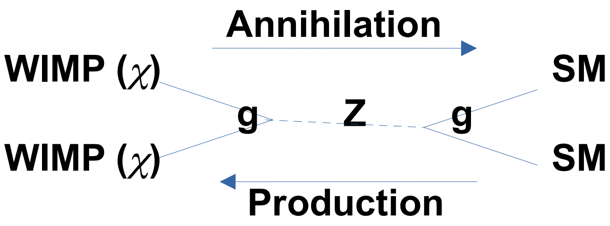
$\mathcal{L}_V = -\frac{\epsilon}{2} V_{\mu\nu} B^{\mu\nu},$ Dark Photons

$\mathcal{L}_a = \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$ ALPs (non-renomalizable)

low-mass, „feebly" interacting particles (FIPs), which might also provide portals to DM

Popular DM model: Weakly Interacting Massive Particles (WIMP)

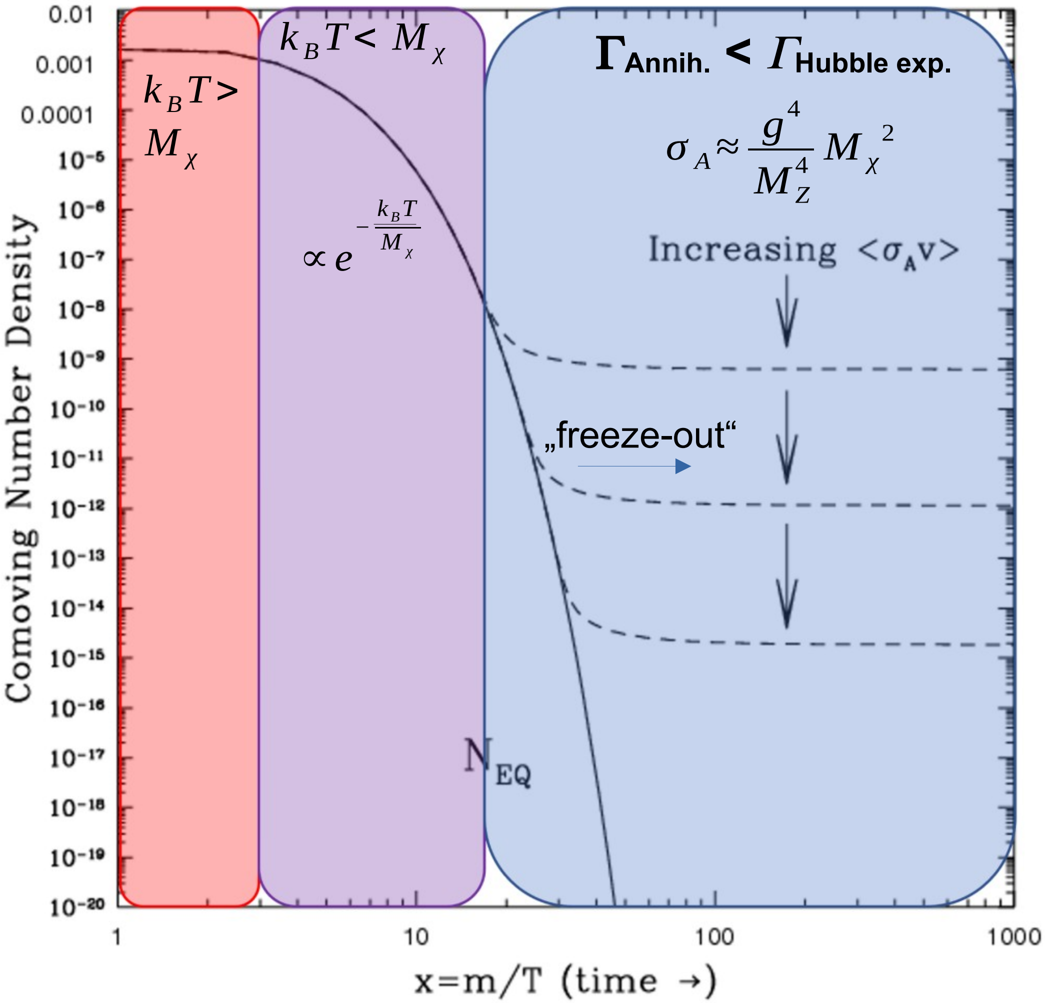
Assumption: DM interacts weakly → thermal equilibrium in early universe



WIMP miracle: O(TeV) > M_χ > O(2 GeV)
→n_χ(freeze-out) ≈ n_{DM}(observed)

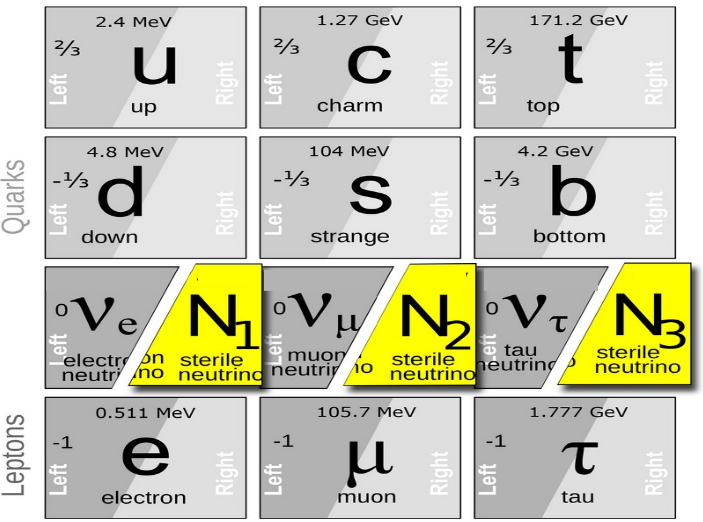
For M_χ < O(2 GeV): „Light" WIMP-like DM
*** Direct detection very difficult**
*** n_χ(freeze-out) > n_{DM}(observed)**

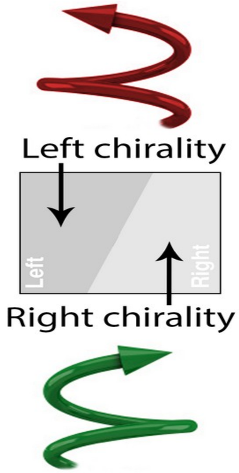
Need a mediator particle lighter than Z boson and an appropriate coupling → e.g. Dark Photon



Example of a low-energy SM extension: Minimal Neutrino Standard Model νMSM

Add 3 right-handed Majorana neutrinos





Higgs mechanism: m

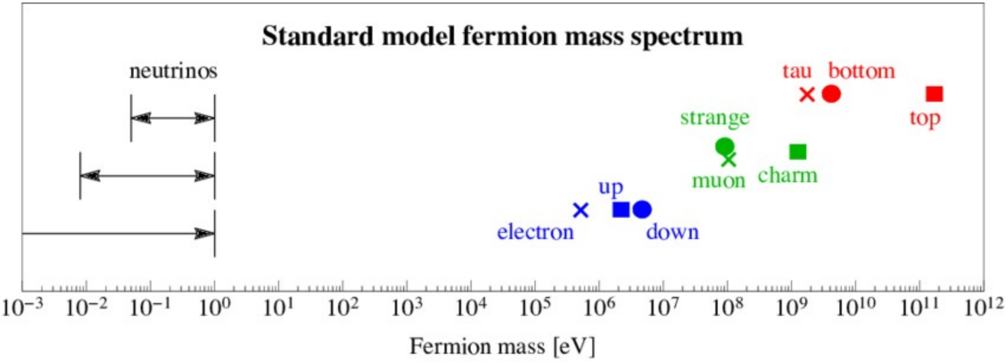
Majorana mass: M

$\rightarrow$ **3 Neutrinos** ν **with tiny masses:** $m_\nu \approx m \dfrac{m}{M}$

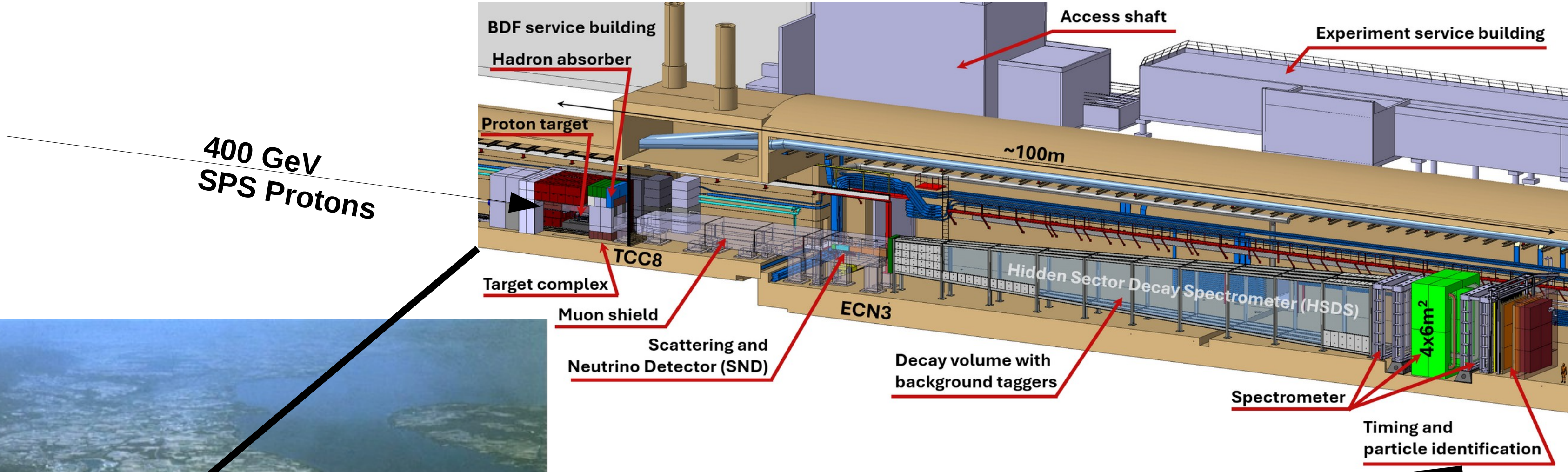
$\rightarrow$ **3 Neutrinos N with masses:** $M_N \approx M$

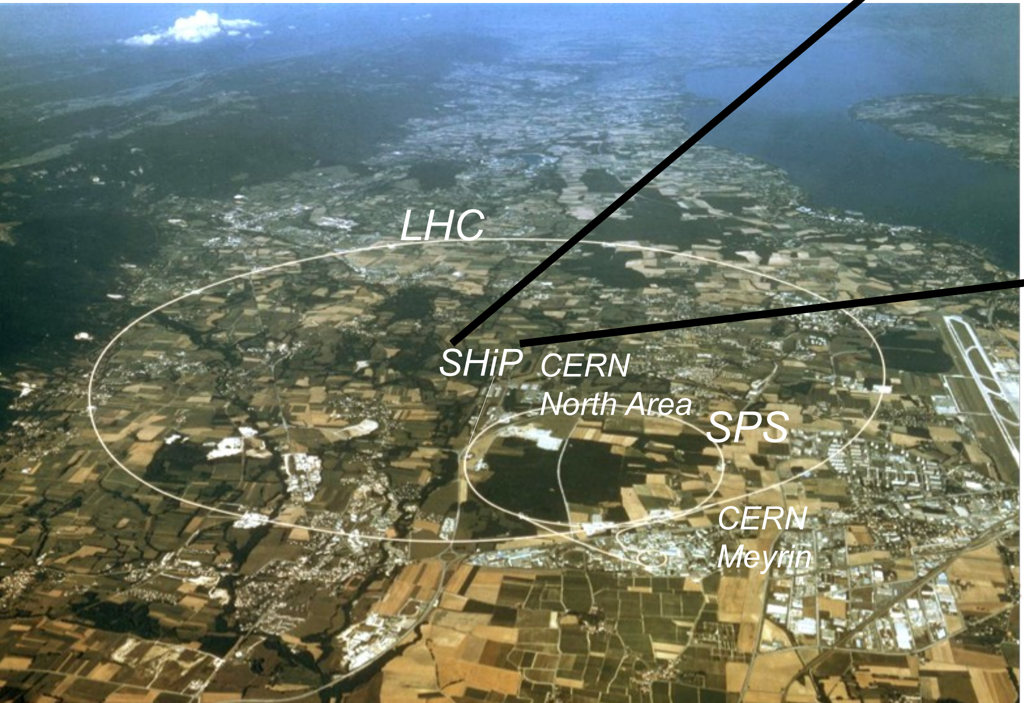
2 N with $M \cong O(GeV) \rightarrow$ **Leptogenesis** $\rightarrow$ **Baryogenesis**

1 N with $M \cong O(keV) \rightarrow$ **Dark Matter candidate**



Search for Hidden Particles (SHiP) experiment at a new dedicated beamdump facility (BDF) in ECN3



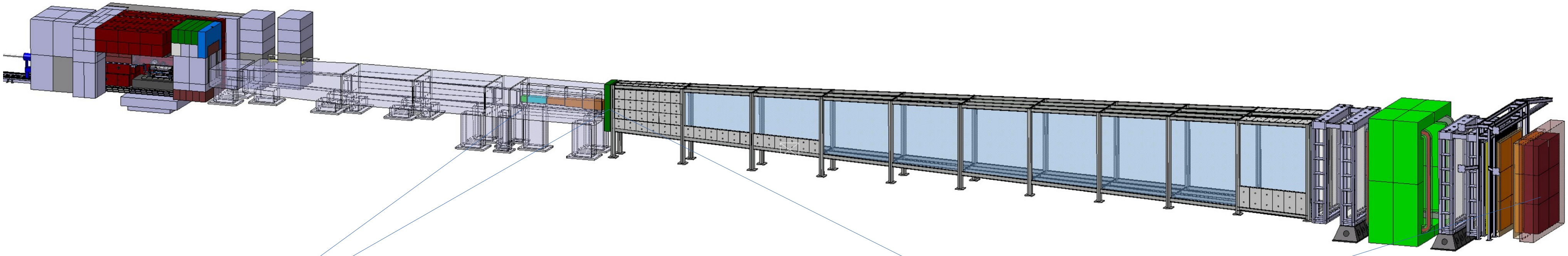


SHiP/NA67:
approved in 2024 to prepare Technical Design Report (TDR)

BDF: 64 MCHF (CERN MTP 2025)

SHiP: 51 MCHF (current estimate)

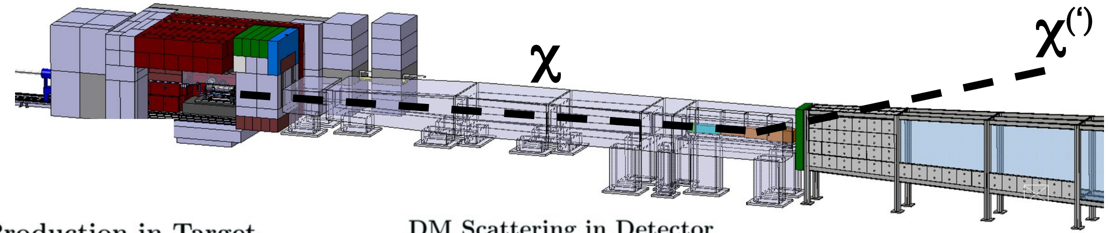
SHiP/NA67: Two experiments in one set-up

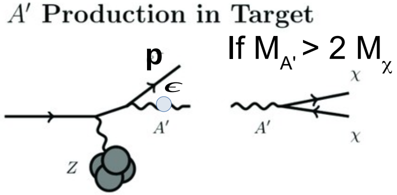


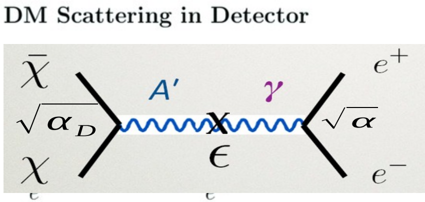
Scattering(-and-Neutrino) Detector
(SND@SHiP)

Decay Detector

SND@SHiP: Search for (quasi-)elastic light DM

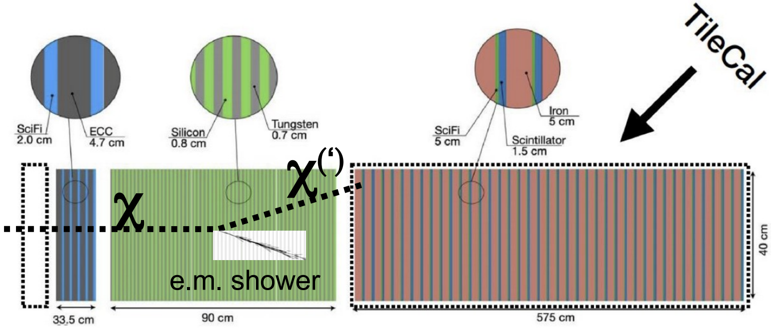


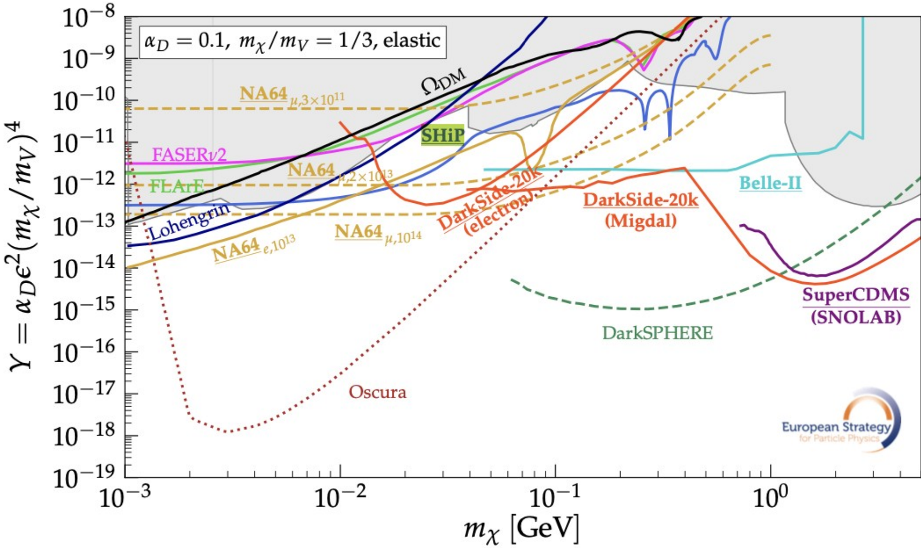


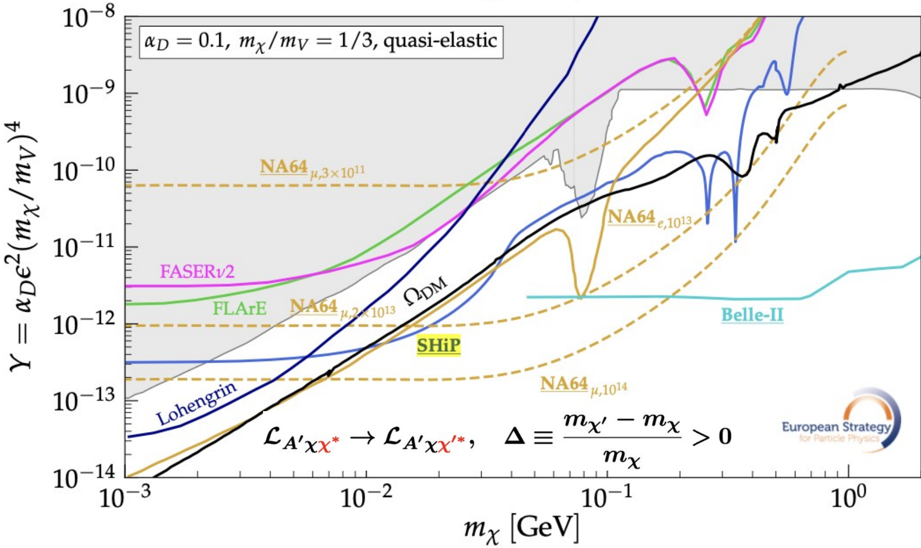


Scattering(-and-Neutrino) Detector (SND@SHiP)

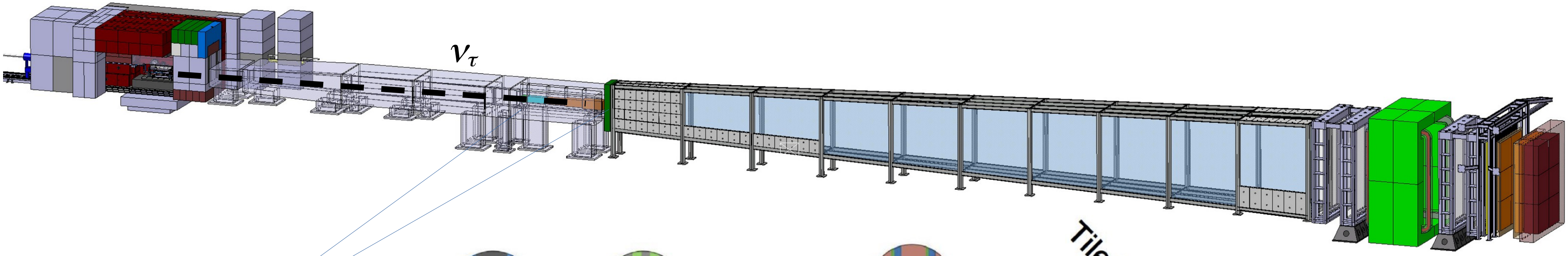
Scattering signature of (quasi-)elastic light DM produced in beamdump

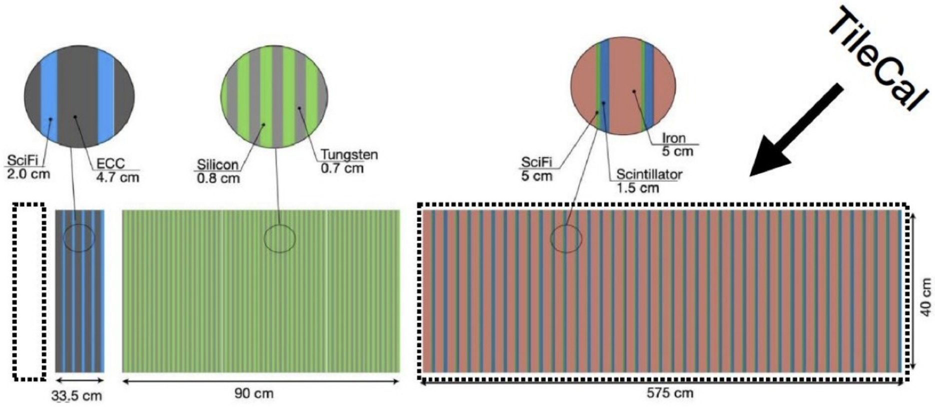






SND@SHiP: Guaranteed neutrino programme





Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	4×10^3	3×10^3
$\tau \to h$	27×10^3	
$\tau \to 3h$	11×10^3	
$\tau \to e$	8×10^3	
total	53×10^3	

Scattering(-and-Neutrino) Detector (SND @SHiP)

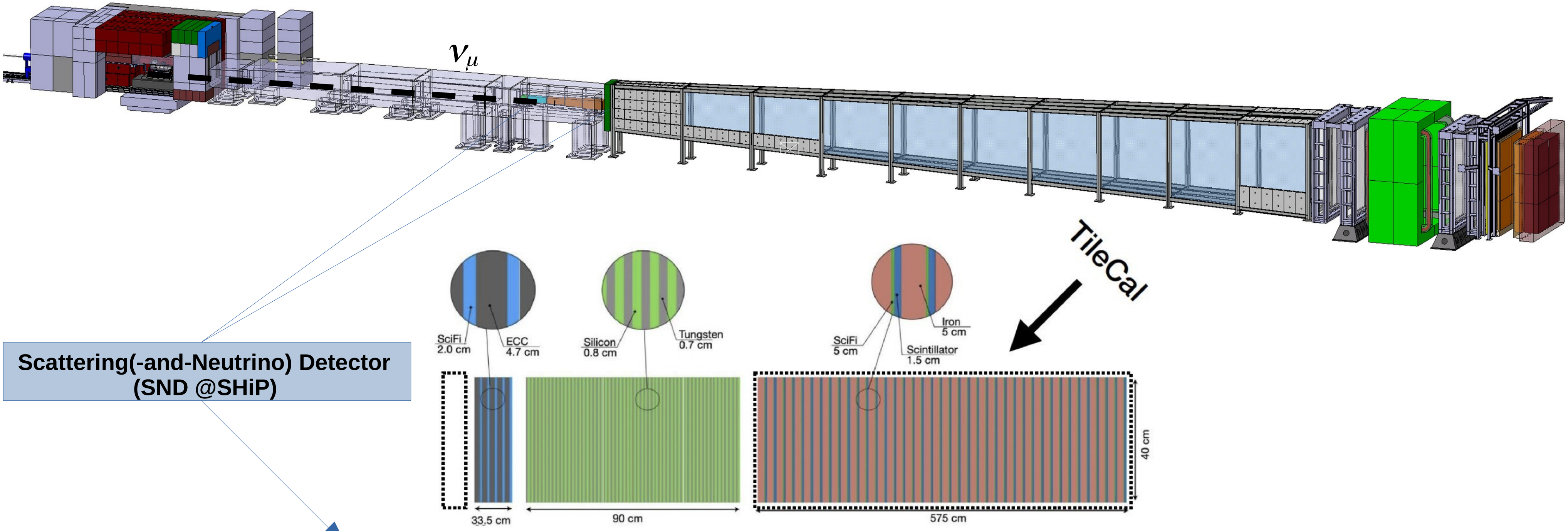
- **ν_τ magnetic moment**
- **ν_τ DIS → Structure functions F_4, F_5**
- νDIS with charm production
  → (nuclear) PDFs
  → e.g. s-quark PDF → M_W determination
- CKM element $|V_{cd}|$
- Charmed Pentaquarks
- **Lepton-flavour universality**

First high-statistics ν_τ experiment!

Despite „low" energies: interesting for IceCube

Do ν_τ interact as the other neutrino flavors ?

SND@SHiP: Guaranteed neutrino programme



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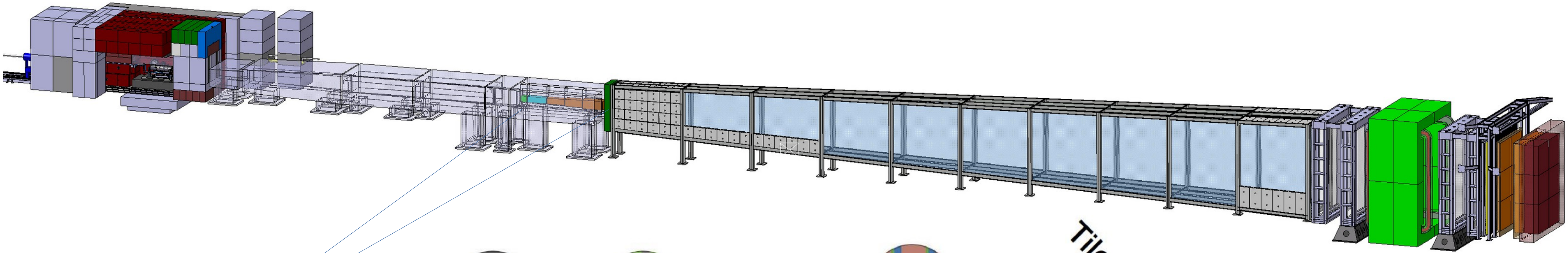
DESY has a long tradition concerning Structure functions and PDFs:
→ SND@SHiP might be of interest!

SND @SHiP: Guaranteed neutrino programme



Scattering(-and-Neutrino) Detector
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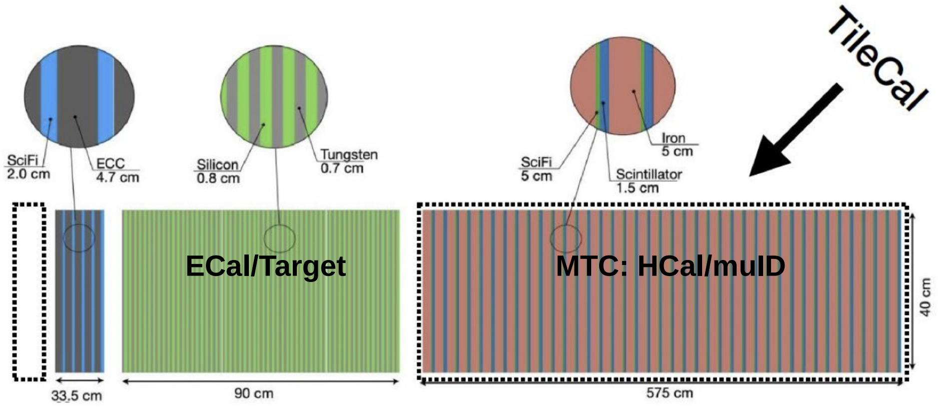

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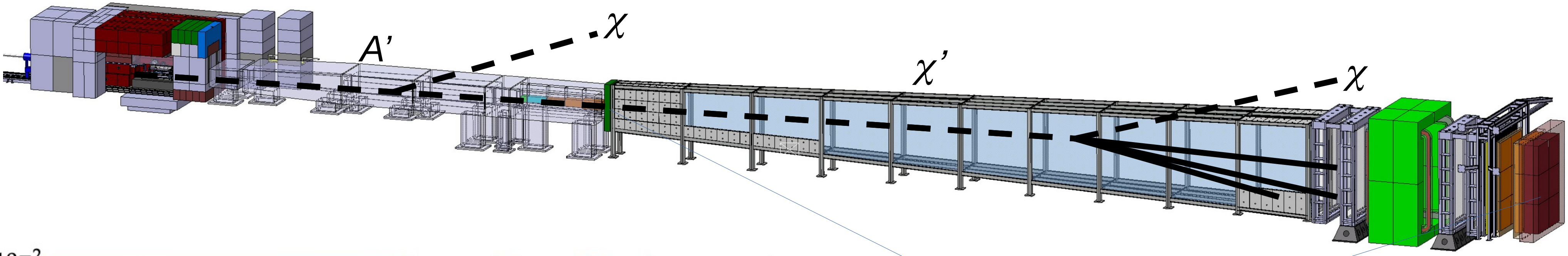
Opportunities (for DESY ?):

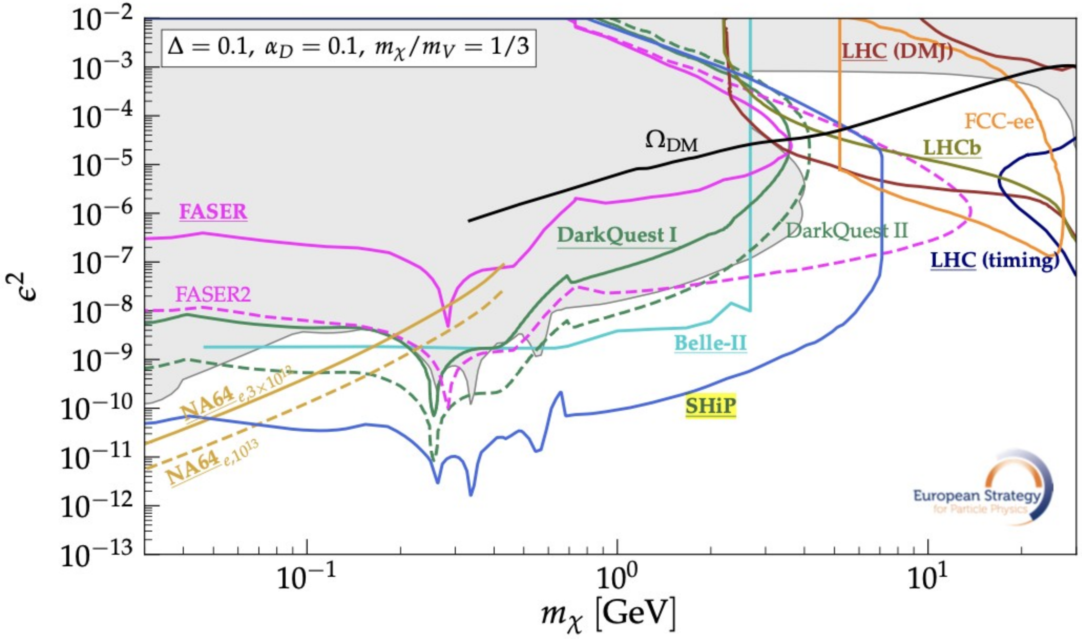
→ ECal/Target: Silicon-W

→ Magnetized TileCal (MTC):
CALICE technology possible option

Decay detector: Search for inelastic DM

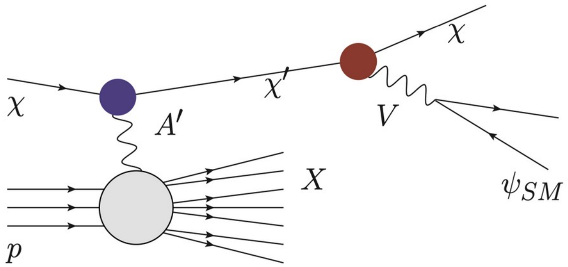


Decay Detector

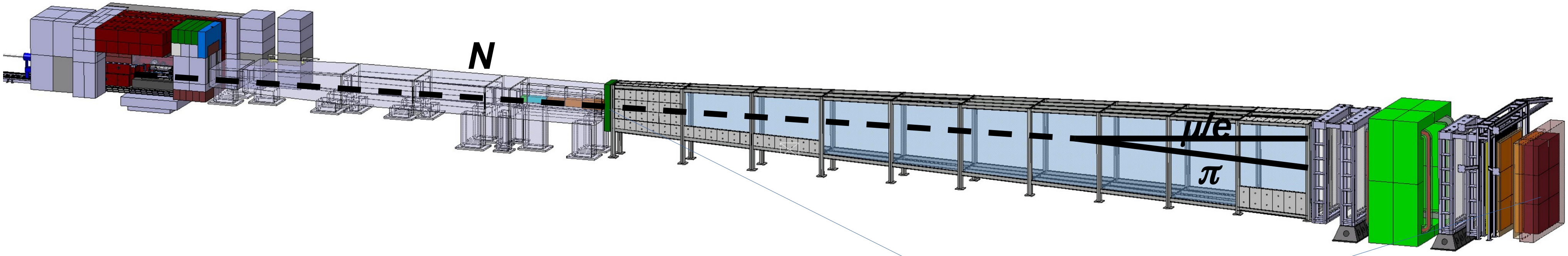


Decay signature of inelastic light DM produced in beamdump

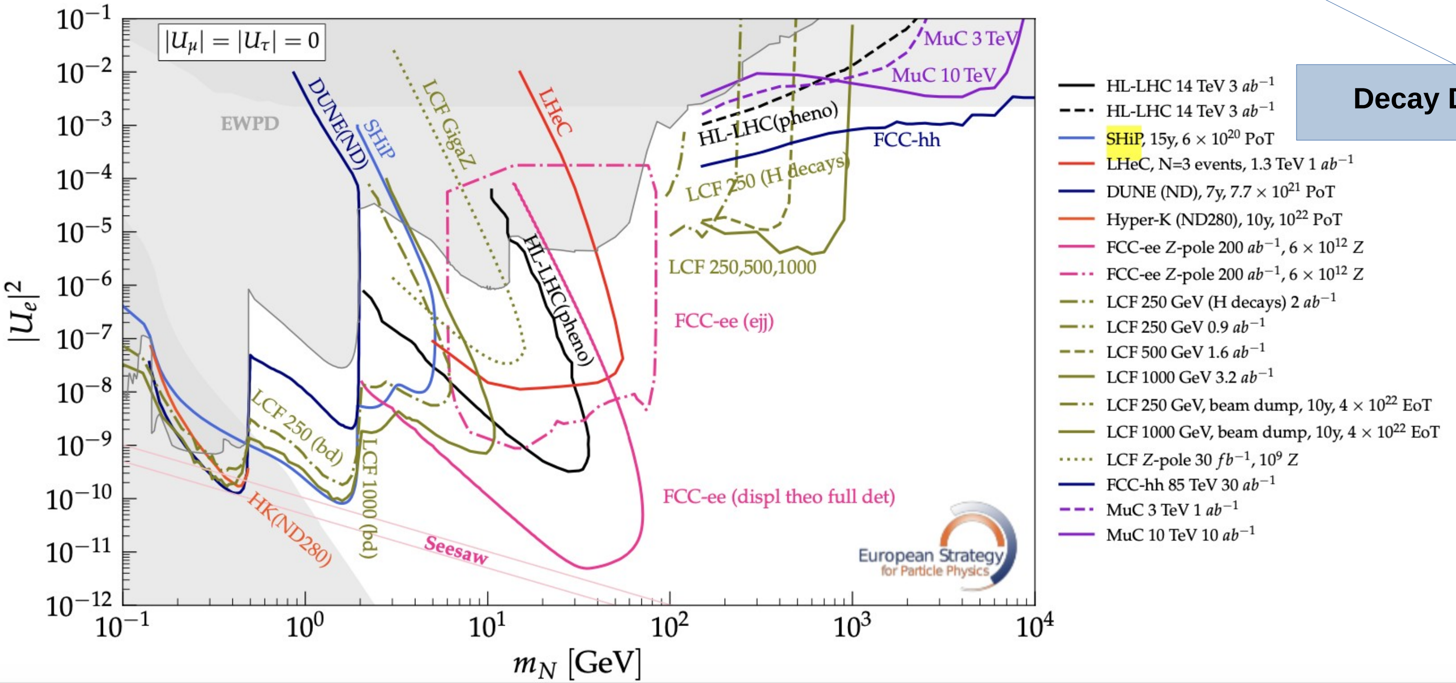
$$\mathcal{L}_{A'\chi\chi^*} \to \mathcal{L}_{A'\chi\chi'^*}, \quad \Delta \equiv \frac{m_{\chi'} - m_\chi}{m_\chi} > 0$$



Decay detector: Search for Heavy Neutral Leptons

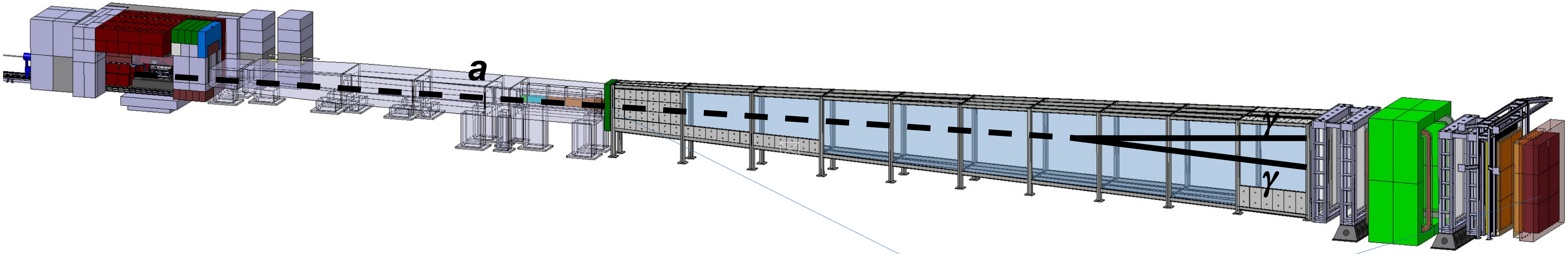


Decay Detector



Decay signature of DS particles
→ **Heavy Neutral Leptons**
→ Dark Photons
→ Dark Scalars
→ ALPs

Decay detector: Example Search for ALPs ($\rightarrow\gamma\gamma$)



Decay Detector

Decay signature of DS particles
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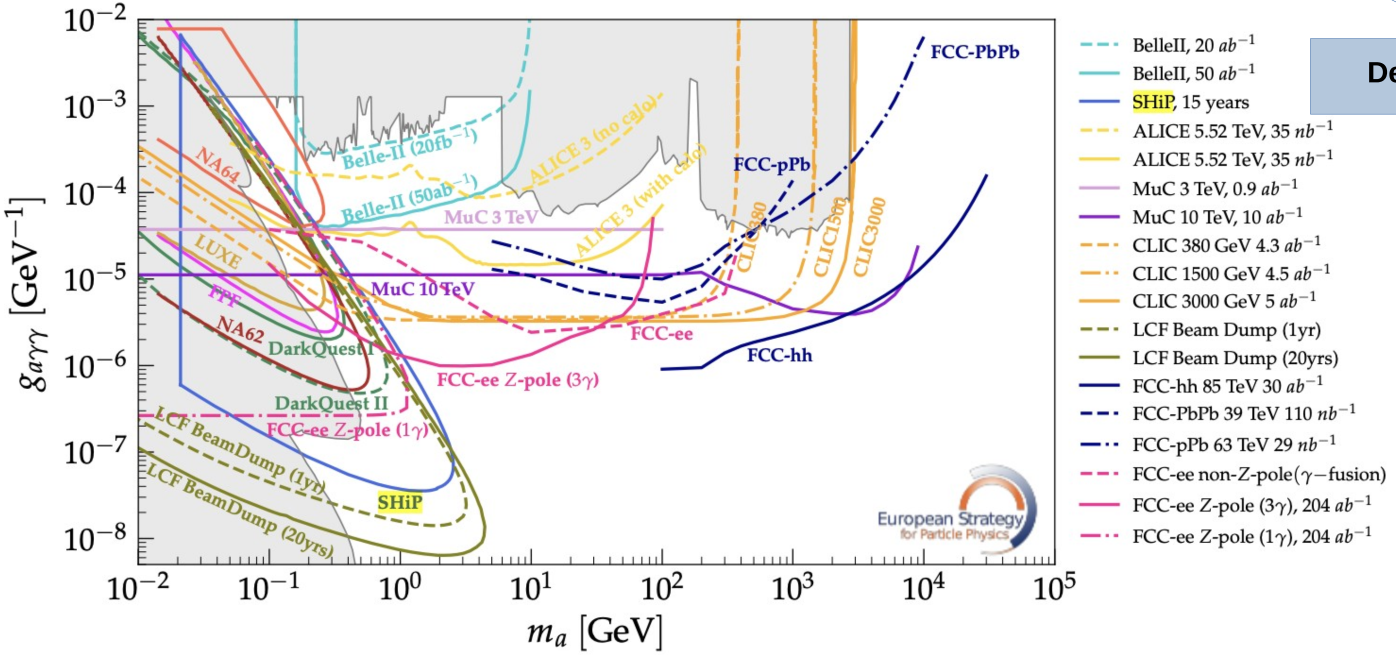
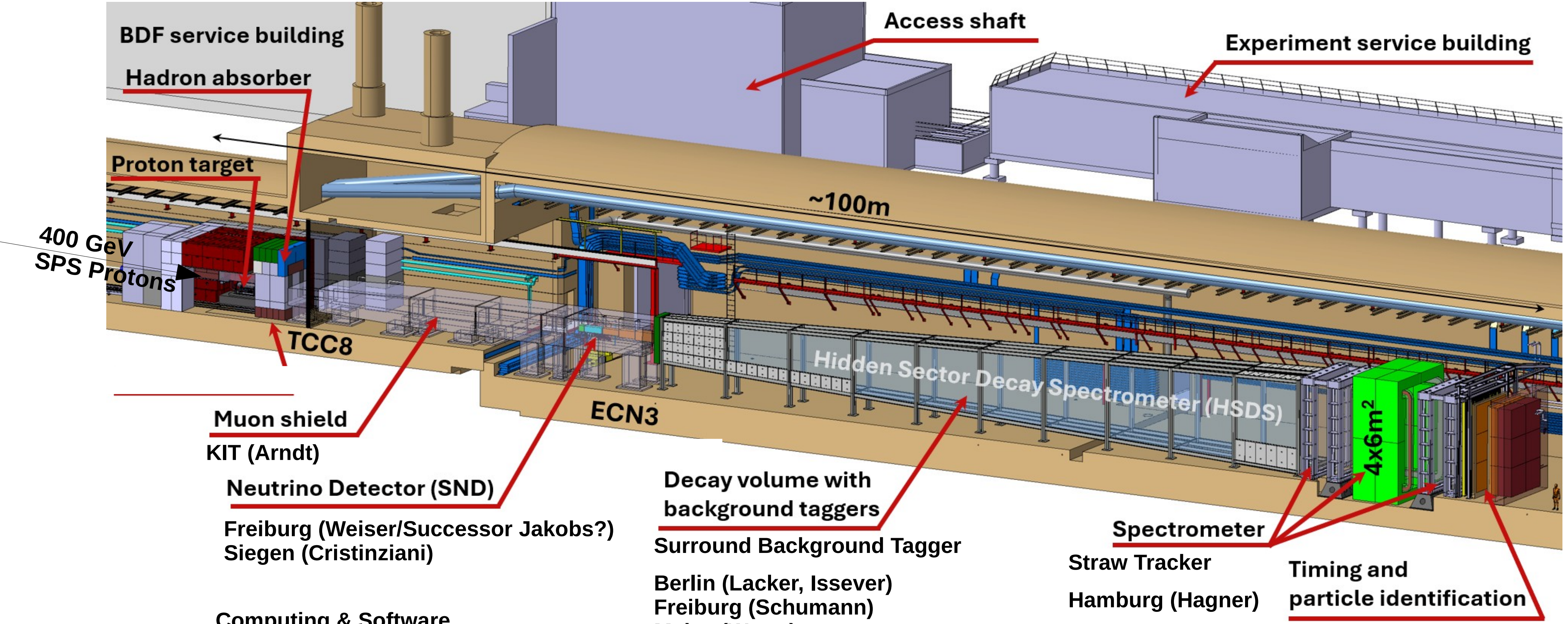


Very strong German participation



KIT (Arndt)

Freiburg (Weiser/Successor Jakobs?)
Siegen (Cristinziani)

Surround Background Tagger

Berlin (Lacker, Issever)
Freiburg (Schumann)
Mainz (Wurm)

Straw Tracker

Hamburg (Hagner)

ECal and HCal

Mainz (Büscher, Wanke)
KIT (Ferber, Klute)

<u>Computing & Software</u>

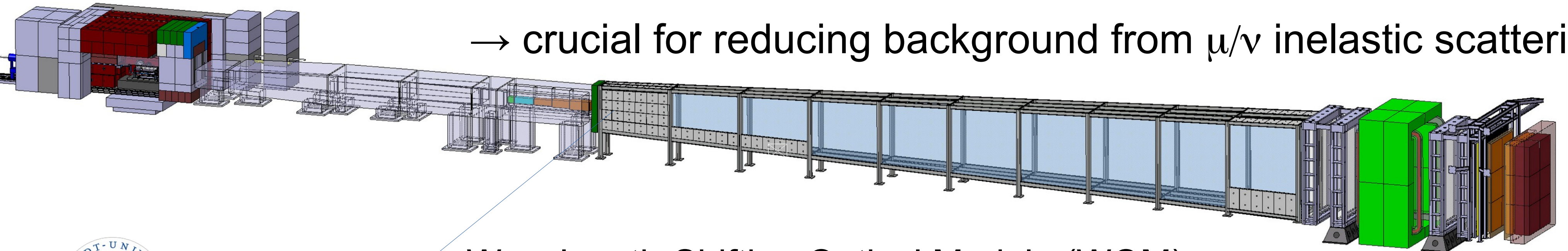
KIT (Kieseler, Klute)
Bremen (Ustyuzhanin)

<u>SHiP-charm</u>
Siegen (Cristinziani)

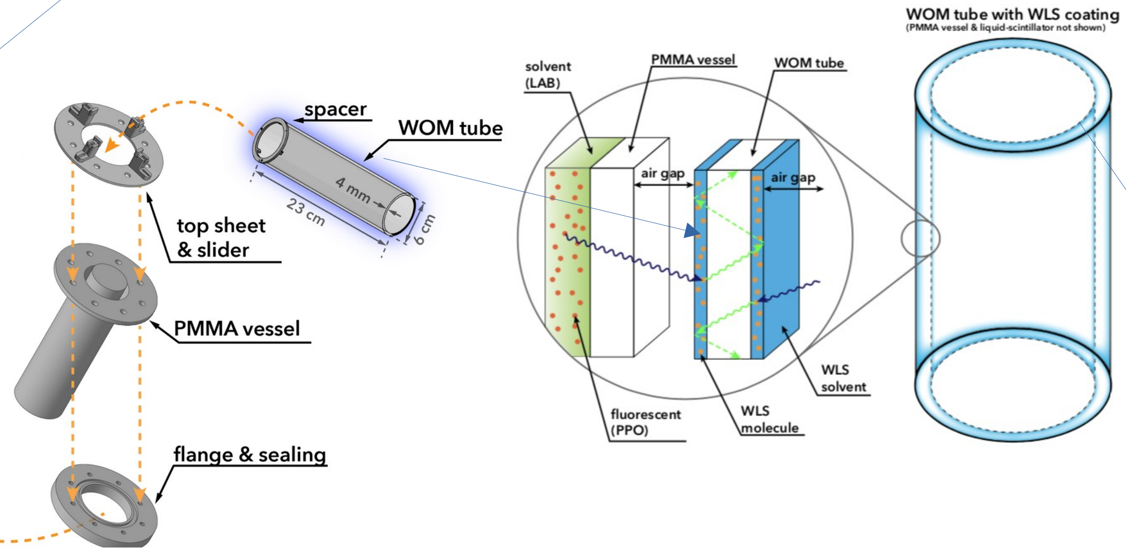
Liquid-Scintillator based Surrounding Background Tagger

High hermiticity

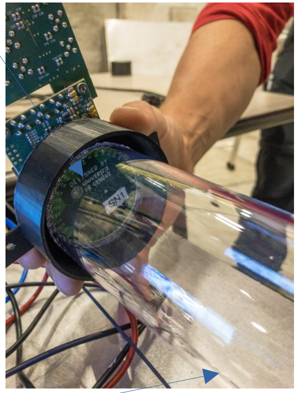
→ crucial for reducing background from μ/ν inelastic scattering



Wavelength-Shifting Optical Module (WOM)
Stimulated by M. Kowalski's advent at DESY/HU

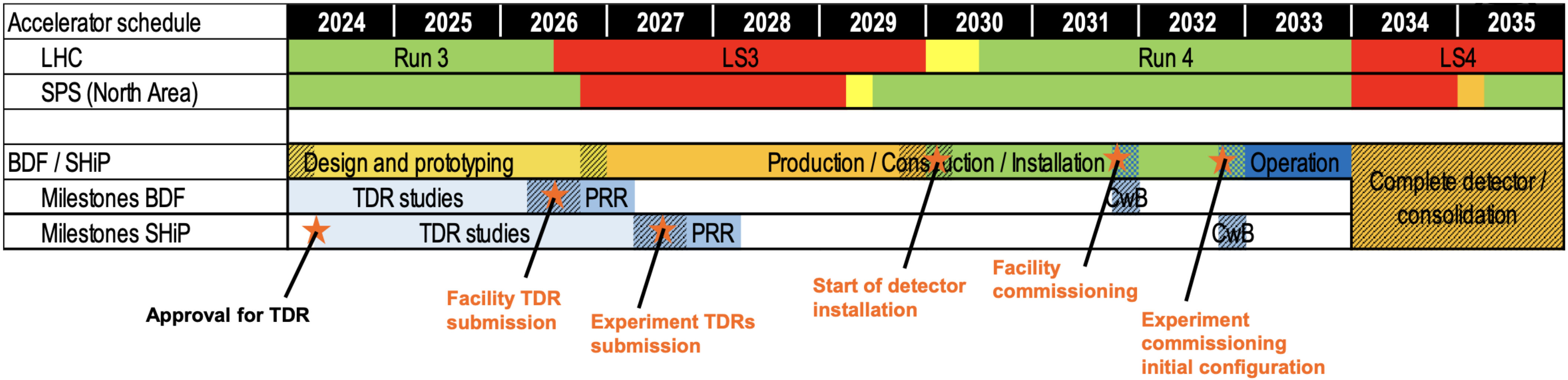


40 SiPMs
in 8 groups
a 5 SiPMs



Double-wall PMMA vessel housing the WOM tube

Time schedule of BDF/SHiP



* Facility TDR: 2026

* Experiment TDRs: 2027

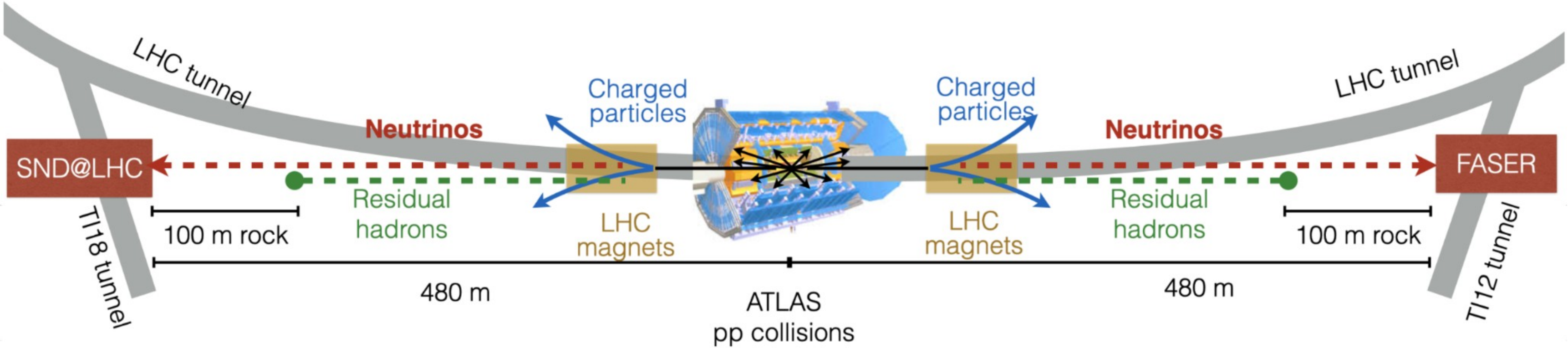
* Construction: FP27-30, 30-33

* Commissioning in 2032 and first data taking 2033 before LS4

* Overall data taking: 15 years

Attention: We are now switching gears!

From SHiP@SPS to SND@LHC



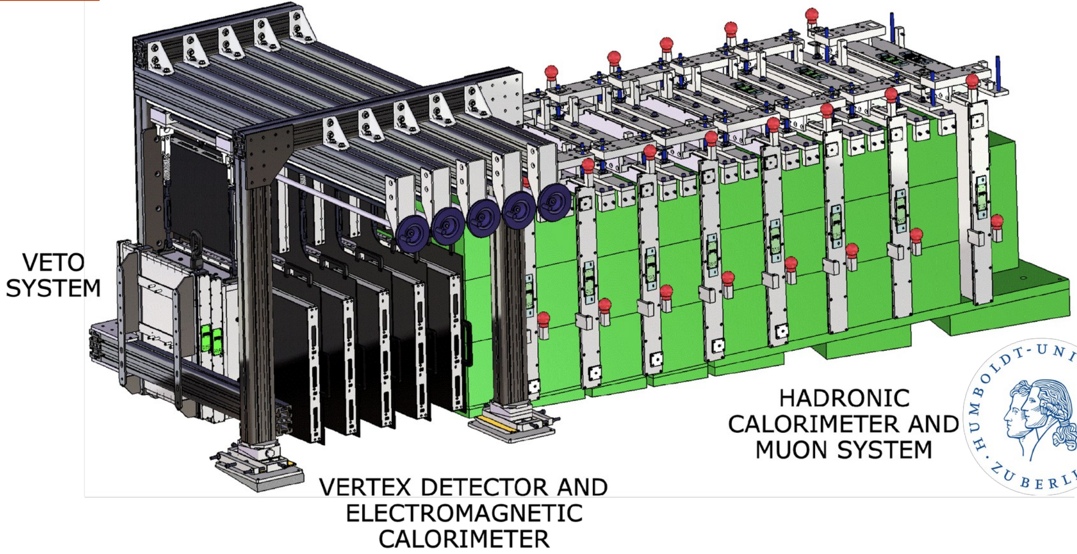
Scattering and Neutrino Detector at the LHC

Veto system
2 (2022 – 2023) / 3 (2024 -) 1 cm thick scintillator planes.

Off-axis: $7.2 < \eta < 8.4$
Enhances ν flux with charm origin.

Target, vertex detector and ECal
830 kg tungsten target (84 X_0, 3 λ_{int}).
Five walls x 59 emulsion layers
+ five scintillating fibre stations.

HCal and muon system
Eight 20 cm Fe blocks (9.5 λ_{int})
+ scintillator planes.
Last 3 planes have finer
granularity to track muons.



JINST 19 (2024) 05, P05067

SND@LHC: physics goals

Scattering and Neutrino Detector at the LHC

Neutrino interactions

* Measure ν **interactions** in unexplored ~TeV energy range.
  ⇒ Atmospheric ν from charm: BG for high-energy ν in **IceCube**

QCD

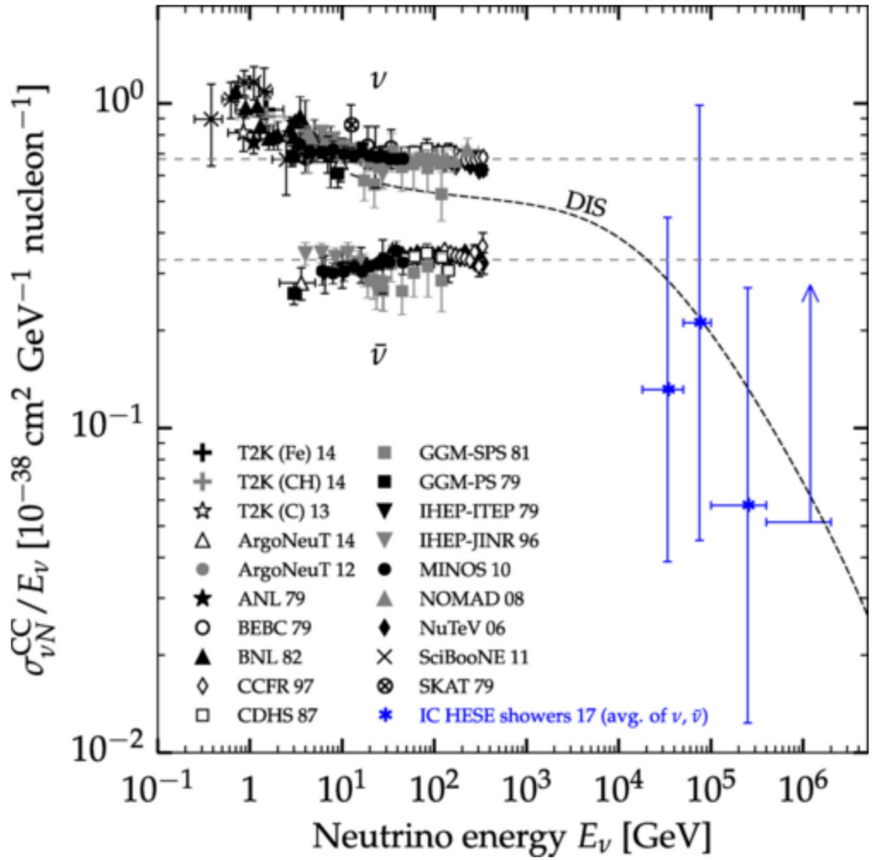
* Measure **forward charm production** with ν_e.
  ⇒ **gluon PDF** at very **small x**.

Flavour

* Detection of all **three types of neutrinos**
  ⇒ tests of **lepton flavour universality**

Beyond the Standard Model

* Search for **new**, feebly interacting, **particles decaying** within the detector or **scattering** off the target.



SND@LHC: physics results achieved so far

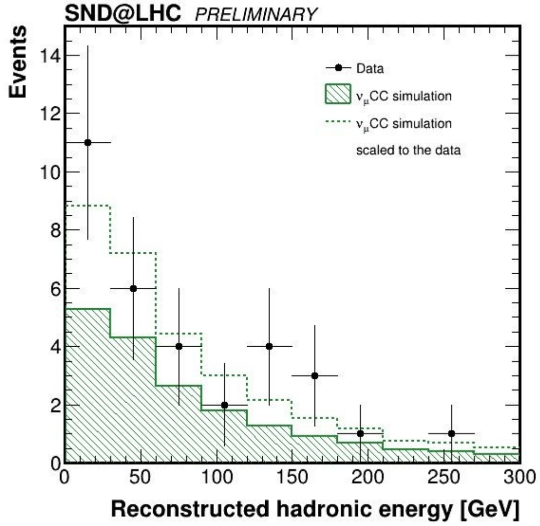
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

: Phys.Rev.Lett. 131 (2023) 3, 031802: 8 evts, 36.8 fb^{-1}

Number of events expected in 68.6 fb^{-1}

- Signal: 19.1± 4.1
- Neutral hadrons: 0.25 ± 0.06

Number of events observed: 29



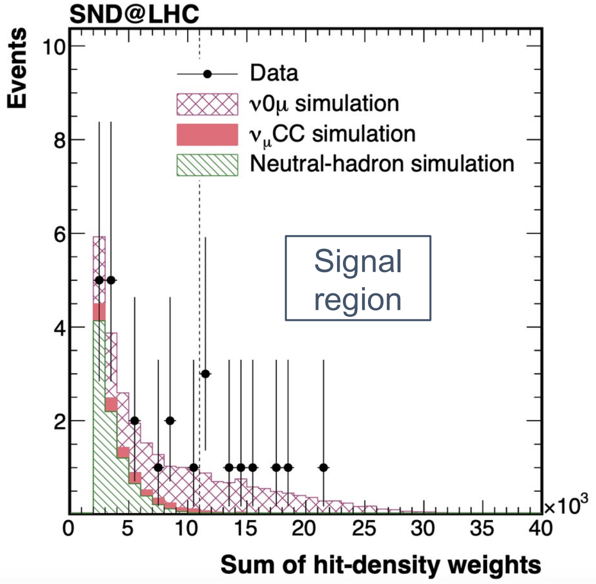
Scattering and Neutrino Detector at the LHC

Observation of Collider Neutrinos without Final State Muons with the SND@LHC Experiment

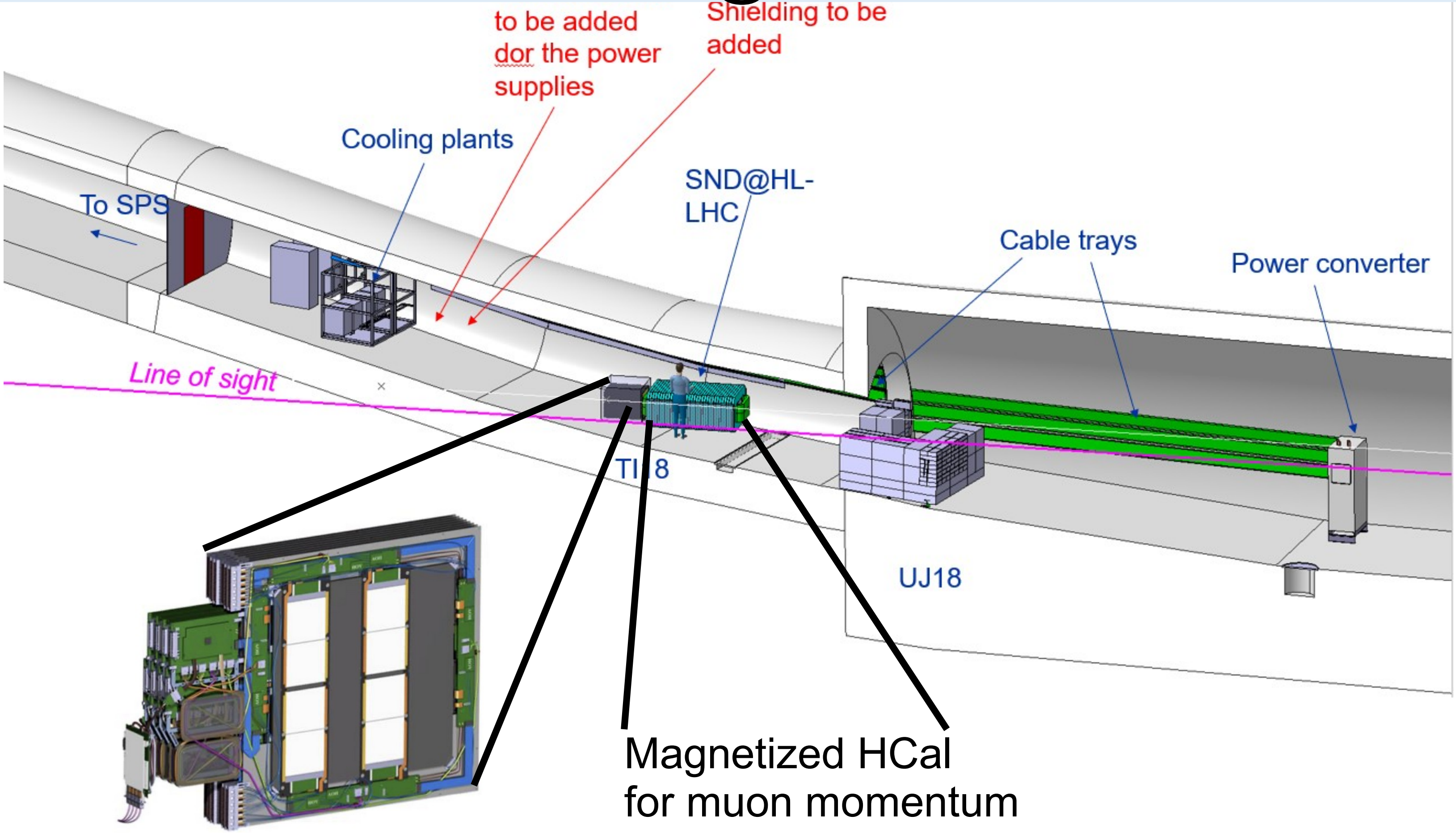
Signal: ν_eCC and NC interactions

Phys.Rev.Lett. 134 (2025) 23, 231802

Observed (expected) events in signal region: 9 (7.2)
Observed (expected) significance: 6.4 (5.5) σ



SND@HL-LHC



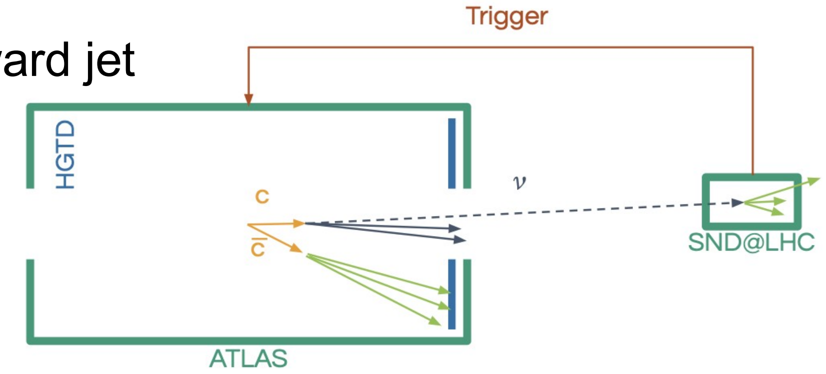
Muon flux too large
→ Replace emulsion by
CMS strip modules

Magnetized HCal
for muon momentum
and charge

SND@HL-LHC: Additional ideas

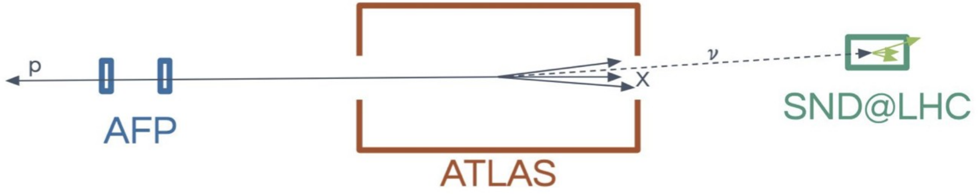
Send ν trigger to ATLAS → Look for charm-tagged forward jet

→ Discussions with ATLAS management in May 2025
→ No technical showstoppers

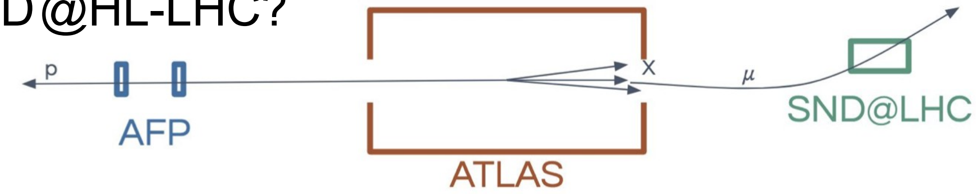


Coincidence btw
ATLAS Forward Proton detector and SND@HL-LHC

ν(SND@HL-LHC) + AFP: 50 evts in 3 ab^{-1}



Maybe interesting physics case for
Single-diffractive evts in AFP with (multi)μ in SND@HL-LHC?
→ requires detailed FLUKA simulations
to follow muons up to SND



Summary

* **SHiP/NA67**: <u>The</u> experiment in CERN's diversity/non-collider programme for the next 25 years

→ **Decay detector:** Excellent dark sector search sensitivity complementary to colliders

Synergy btw HU Berlin and DESY: WOMs for SBT

→ **SND@SHiP:** Guaranteed neutrino programme with 1st high-statistics ν_τ experiment

→ Interesting for **IceCube**

Opportunity for detector technologies (silicon-based ECal; CALICE) of interest for **future colliders**

* **SND@(HL-)LHC**: TeV neutrino interactions → Interesting for **IceCube**

Strong synergies with SND@SHiP

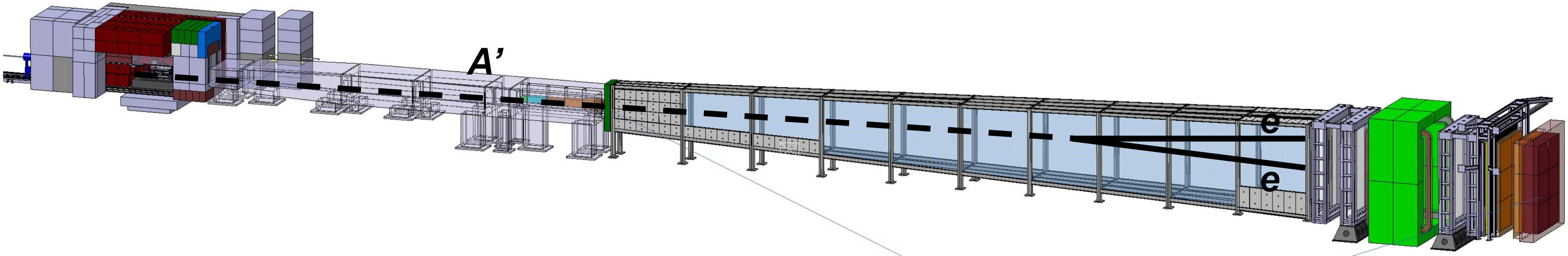
New ideas: → charm-tagged (**ATLAS**) ν events

→ single diffractive evts in **AFP** with muon(s) in SND

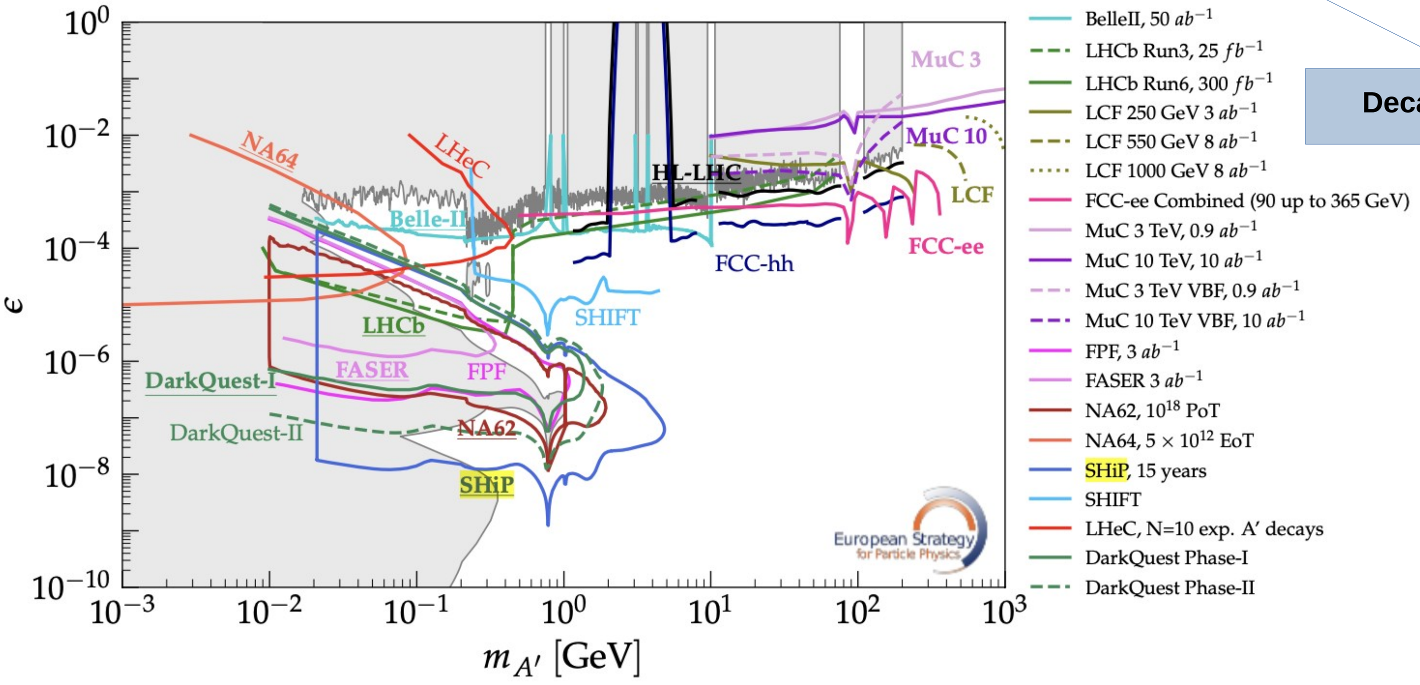
Could we learn something from the LHC-oxygen run?

Backup

Decay detector: Search for Dark Photons

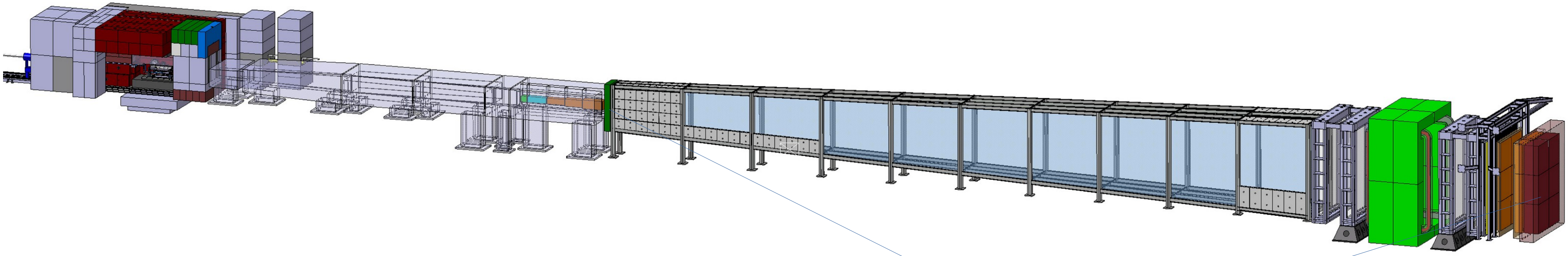


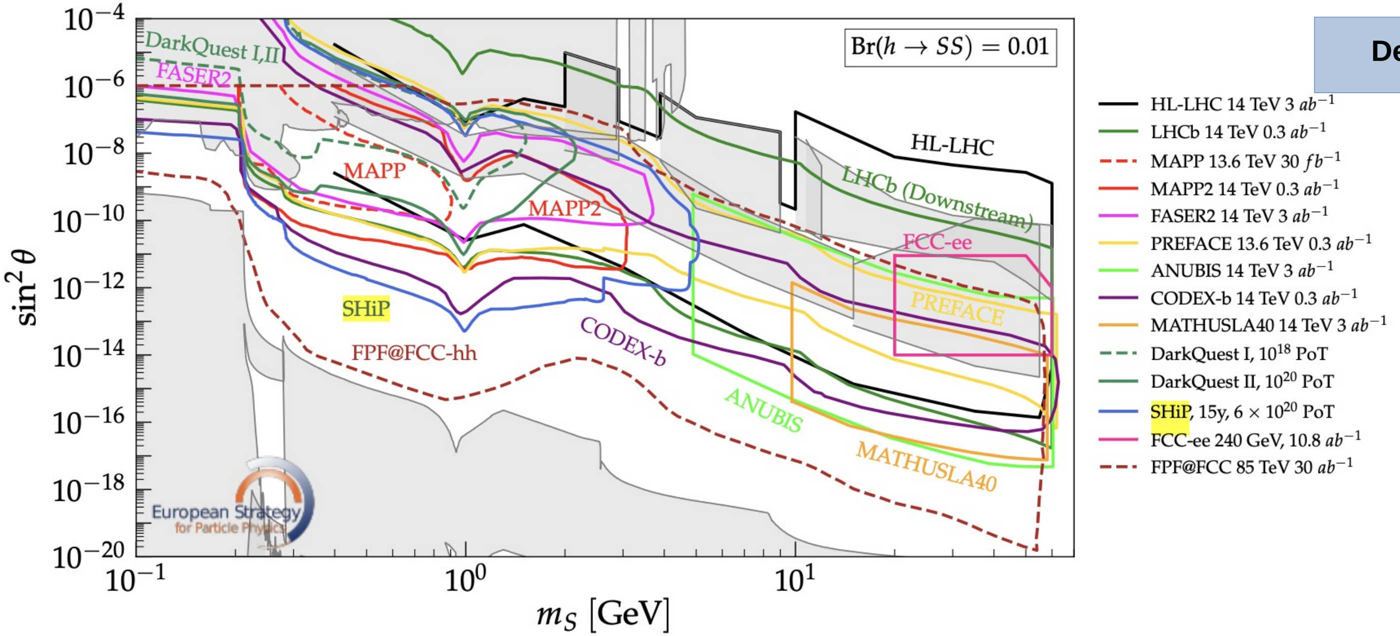
Decay Detector



Decay signature of DS particles
→ Heavy Neutral Leptons
→ **Dark Photons**
→ Dark Scalars
→ ALPs

Decay detector: Search for Dark Scalars with coupling to Higgs





Decay Detector

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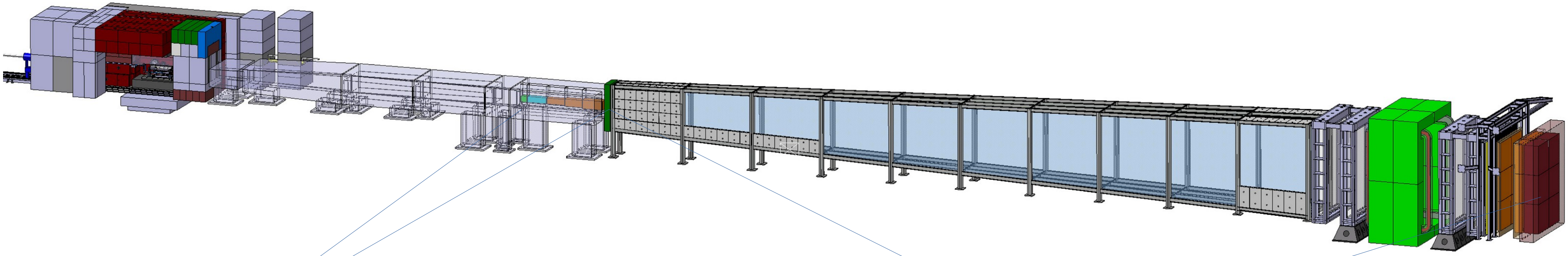
SHiP/NA67: Physics Case



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*** Lepton-flavour violation**

Decay signature of inelastic light DM produced in beamdump

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