

The SHiP experiment: the flagship to probe hidden sectors

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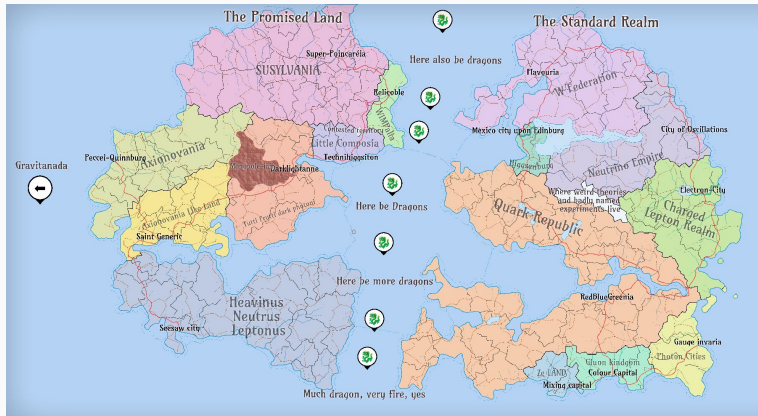
03/12/2025

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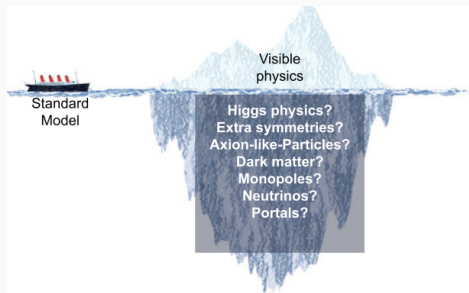


- The Standard Model, crowning achievement missing crown jewels
- The hunt for the ~~lost~~ never found treasures of physics
- Along the beamline: subsystems to make a SHiP
- Conclusion





- ▶ Complete, renormalisable theory which looks like it could be consistent all the way up to the Planck scale $\mathcal{O}(10^{18} \text{ GeV})$
- ▶ Fully consistent with nearly all experimental data
- ▶ Some problems remain however:
 - ▶ Gauge hierarchy problem: why is the Higgs so light?
 - ▶ Neutrino oscillations: why are neutrinos so light? Where does their mass come from?
 - ▶ Inconsistency with the current state of the universe: baryogenesis in the early universe requires more CP violation
 - ▶ Is unable to explain gravity and the existence of dark matter

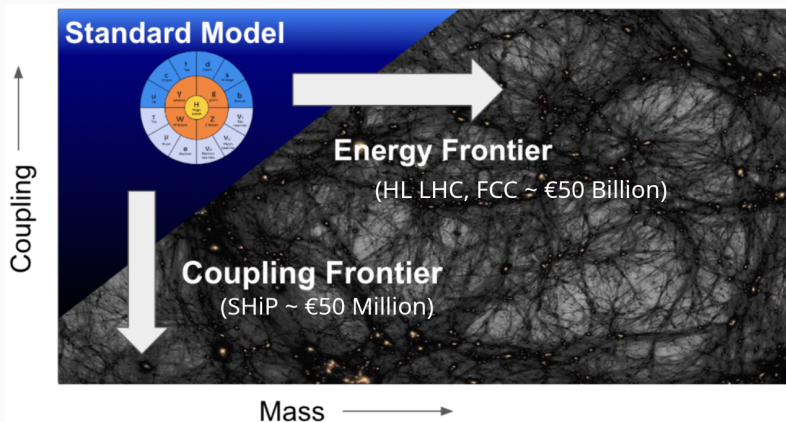


Beyond the Standard Model: where to sail?



New physics is either:

1. Too heavy to have been seen ($\sim \text{TeV}$ or more: SUSY neutralino, resonant leptogenesis HNL...)
2. Too weakly interacting to have been seen (much less than even neutrinos: hidden sector mediator, oscillation leptogenesis HNL...)

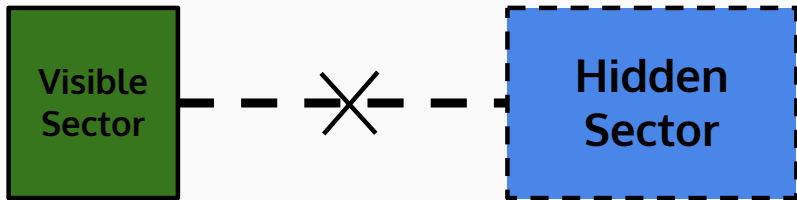




New physics **exist** but we haven't seen them yet, they may interact only very weakly with the SM

→ live in a **Hidden Sector** and interact with the SM through mediators *portals*

$$\mathcal{L}_{\text{World}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{Mediator}} + \mathcal{L}_{\text{Hidden}}$$

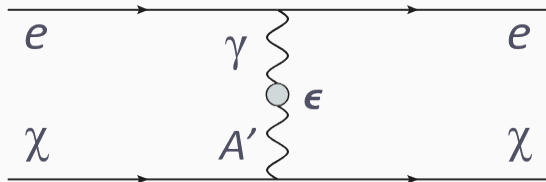




► Vector Portal (“Dark Photon”)

- Field $\mathbf{A}'_\mu$ with strength $\mathbf{F}'_{\mu\nu}$ mixes with coupling ϵ with SM $\mathbf{F}_Y^{\mu\nu}$

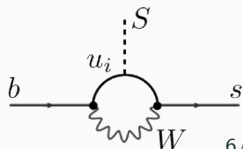
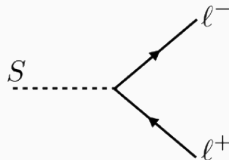
$$\mathcal{L}_{\text{Vector}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$



► Scalar Portal (“extra scalar”)

- Extra scalar $\mathbf{S}$ couples to $|\phi|^2$ of the Higgs field

$$\mathcal{L}_{\text{Scalar}} = (\lambda_i S_i^2 + g_i S_i)(\phi^\dagger \phi)$$

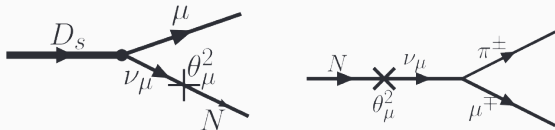




► Neutrino Portal (“Heavy Neutral Lepton”)

- Extra neutral singlet fermions $\mathbf{N}_I$ with Yukawa coupling $\mathbf{F}_{\alpha I}$ to $SU(2)$ doublets $\mathbf{L}_\alpha$

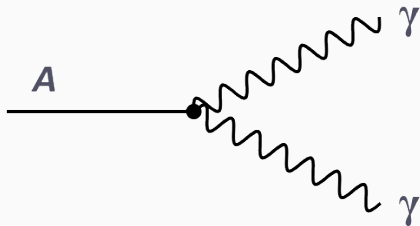
$$\mathcal{L}_{\text{Neutrino}} = F_{\alpha I} (\bar{L}_\alpha \cdot \tilde{\phi}) N_I$$



► Other, non-renormalisable couplings

- Example: Pseudo-Nambu-Goldstone Boson such as an Axion-like-particle (ALP) from some broken symmetry at some higher scale

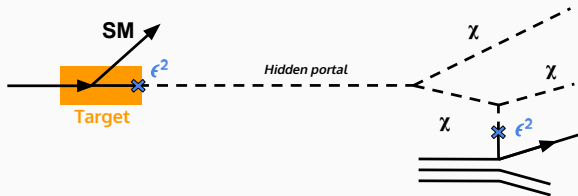
$$\mathcal{L}_{\text{ALP}} = \frac{A}{4f_A} \epsilon^{\mu\nu\lambda\rho} F_{\mu\nu} F_{\lambda\rho}$$



Beyond the Standard Model: how to look for Hidden sectors?



Decay into SM products:
displaced vertex
signature

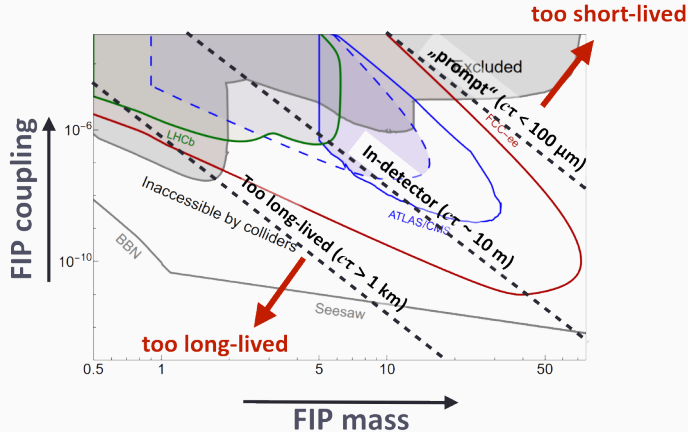


Scattering:
recoil against
nuclei/electron
signature



Indirect detection:
missing
energy/momentum

Reaching the unreachable seas



- ▶ Particle will have a lifetime

$$\tau \propto \frac{1}{\text{coupling}^2}$$

- ▶ Feebly interacting particle will have a lifetime of

$$\tau \propto \frac{1}{m^n}$$

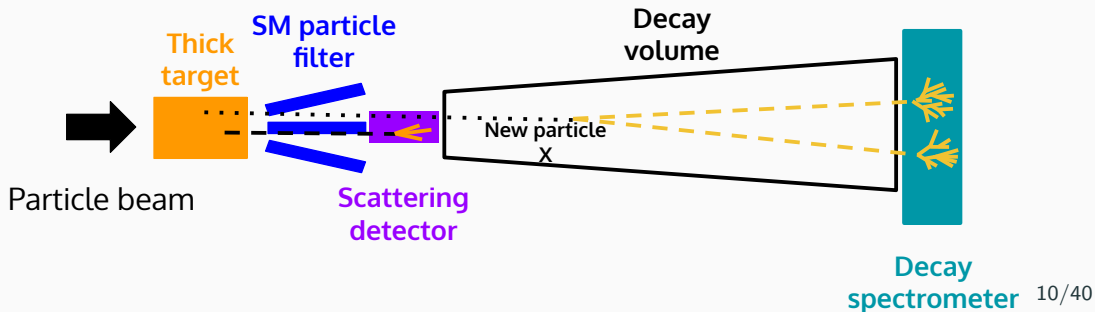
($n = 1 \dots 5$, depending on the portal)

→ Sweet spot for FIP searches around $c\tau \sim 10 - 100 \text{ m}$

Reaching the unreachable seas



- ▶ 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

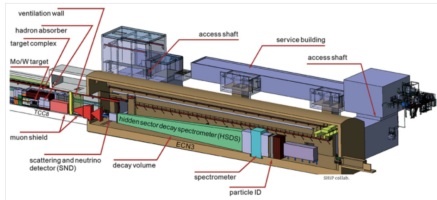




SEARCHES FOR NEW PHYSICS | NEWS

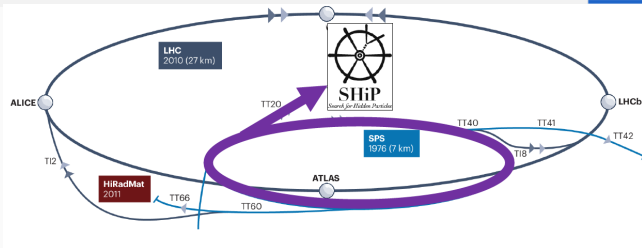
SHiP to chart hidden sector

3 May 2024



Full speed ahead Layout of the SHiP experiment, with the target on the left and the experiment in the ECN3 hall. Credit: SHiP collab.

In March, CERN selected a new experiment called SHiP to search for hidden particles using high-intensity proton beams from the SPS. First proposed in 2013, SHiP is scheduled to operate in the North Area's ECN3 hall from 2031, where it will enable searches for new physics at the “coupling frontier” complementary to those at high-energy and precision-flavour experiments.

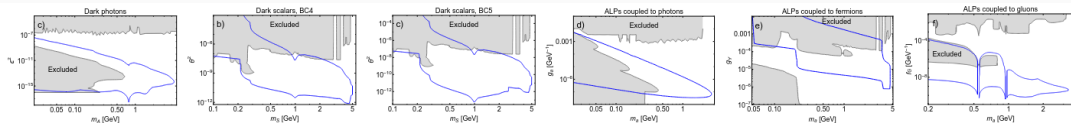


- ▶ SHiP/NA67 experiment approved in March 2024
- ▶ Use SPS accelerator protons at the in-construction Beam Dump Facility (BDF) in the CERN North Area
 - ▶ Facility already under construction
 - ▶ Data taking begins in 2032

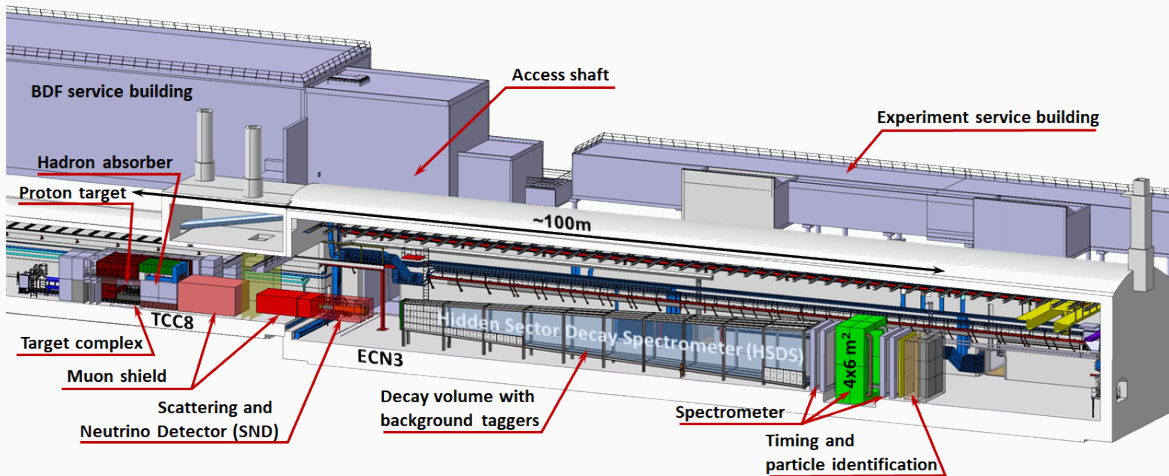
Beyond the Standard Model: the SHiP experiment



- ▶ High-intensity beam dump experiment: 6×10^{20} protons on target over 15 years
- ▶ Globally unique physics potential: large D and B meson fluxes
- ▶ Sensitivity to a broad variety of Feebly Interacting Particles (FIPs)
 - ▶ HNLs
 - ▶ Axion-like-particles (ALPs)
 - ▶ Dark scalar Higgs-like particles
 - ▶ Light dark matter (LDM)
 - ⇒ if you have a FIP model in the general $\mathcal{O}(100 \text{ MeV})$ - $\sim \text{few GeV}$, chances are, SHiP will have record sensitivity to it
- ▶ Unprecedented measurements of ν_τ , F_4 and F_5 , flavour physics, lepton universality, pdfs and many more
- ▶ Will operate in a zero-background environment



The BDF/SHiP beamline



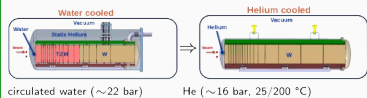


The SHiP target complex

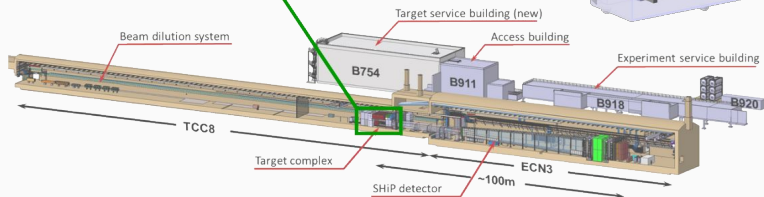
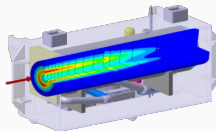


Target:

- baselined to (new) full W target
- cooled by circulated GHe



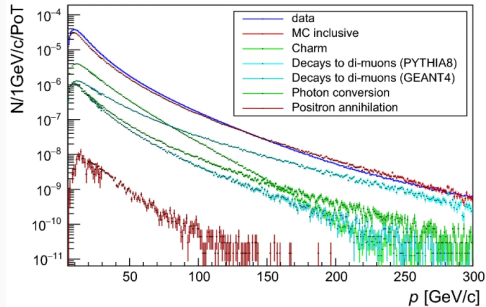
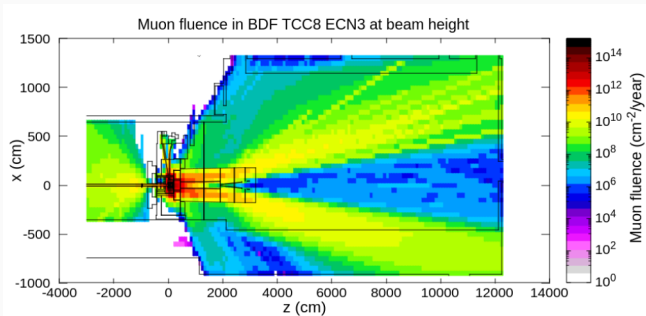
2025: tested stresses in material (HIP-bonded plates) at T6 in TCC2 (SPS NA)



Slide from M. Ferro-Luzzi

- Heavy material needed to increase heavy flavour production cross section
- Intensities are extremely high (4×10^{13} protons on target per spill) → cooling required
- Hadron absorber located at the back of the complex

- ▶ The extremely high muon fluxes from the beam dump impose active muon filtering
- ▶ Idea: sweep away muons through a set of magnets
- ▶ Magnet stages with many different magnets used in order to sweep away all possible angles and energies
- ▶ Modular design preferred to allow for adjustments if needed

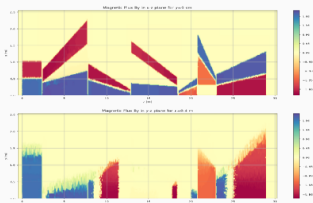
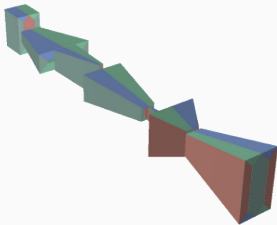


SHiP muon shield: 3 variants



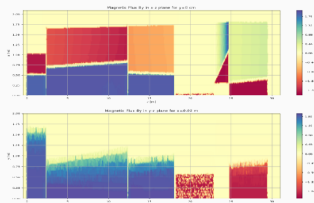
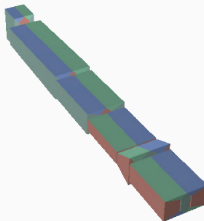
Minimal Iron Yoke “TokaNut”

Only warm coils, saturated iron



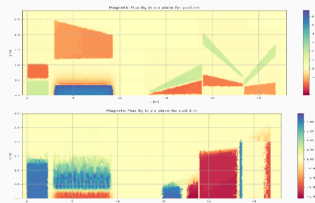
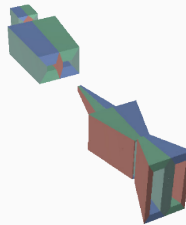
Tuned Return Yoke “StellaTRYon”

Only warm coils, allow for dilution of iron with non-magnetic shielding material

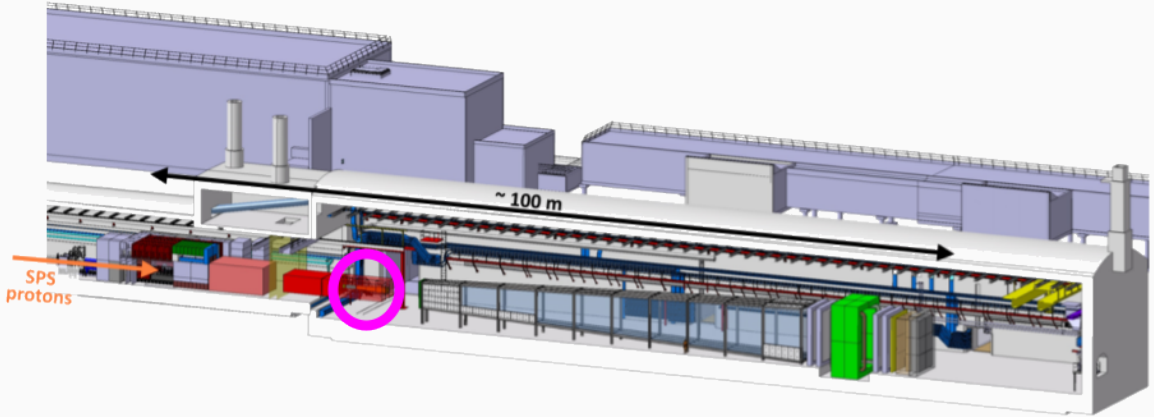


Hybrid (with SC) “SuperNut”

Superconducting coil in section 1, then minimal saturated iron



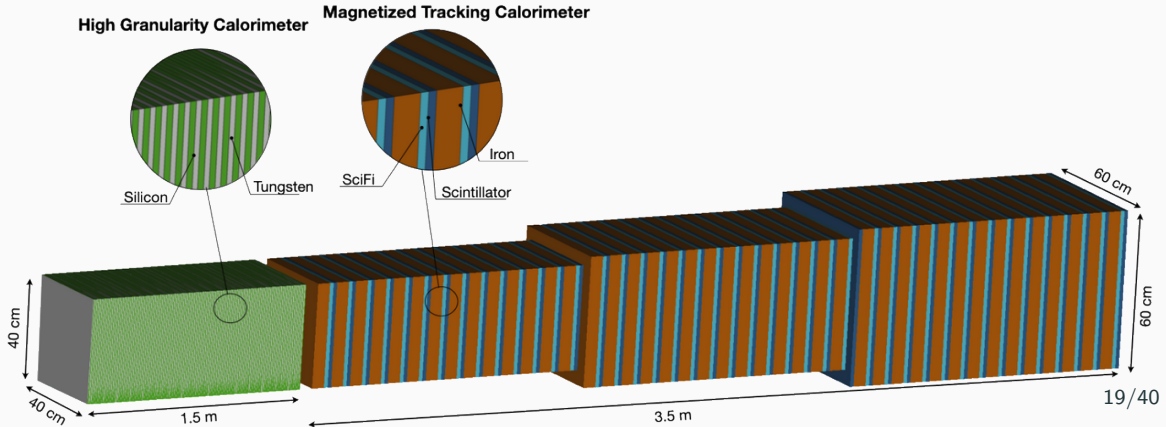
Scattering neutrino detector at SHiP (SND@SHiP)

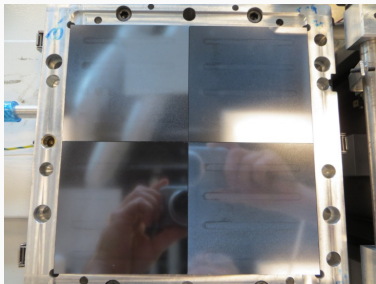


Interlude: neutrino physics at SHiP



- ▶ Side effect of the beam dump: a high fluence of neutrinos of all flavours is produced
- ▶ They can be a source of background but can also be studied specifically
- ▶ Leverage scattering detector to observe all neutrinos flavours

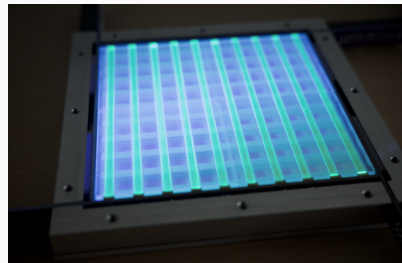




Silicon strip PCB for the HGC
(IJC, Orsay for CALICE)



SciFi detector for MGTC (EPFL,
Lausanne for SND@LHC)

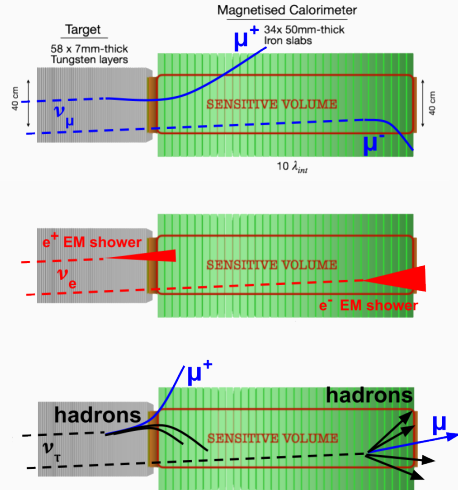


Scintillator tiles with WLS fibres
(Ghent from SOLID)



Neutrino observation in SHiP

- ▶ ν_μ : straightforward, nothing come in and a track comes out, tell apart parity using muon bending
- ▶ ν_e : more challenging, nothing come in and an electromagnetic shower takes place inside of your detector. Parity is complex to identify.
- ▶ ν_τ : challenging as τ 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.





- ▶ A total of 26 ν_τ candidates have been observed, **ever**
- ▶ $\bar{\nu}_\tau$ has never been observed, **ever**
- ▶ The high neutrino flux allows for the measurement of strange quark nucleon content via charm production in $\bar{\nu}$ interactions
- ▶ 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_{ν_e}	6.8×10^4	4.1×10^3	1.6×10^5	9.8×10^3
N_{ν_μ}	2.0×10^5	8.7×10^3	4.6×10^5	2.0×10^4
N_{ν_τ}	2.1×10^3	1.2×10^2	5.1×10^3	2.8×10^2
$N_{\bar{\nu}_e}$	1.4×10^4	7.4×10^2	3.7×10^4	1.9×10^3
$N_{\bar{\nu}_\mu}$	4.4×10^4	1.7×10^3	1.1×10^5	4.1×10^3
$N_{\bar{\nu}_\tau}$	1.5×10^3	8.6×10^1	3.8×10^3	2.1×10^2

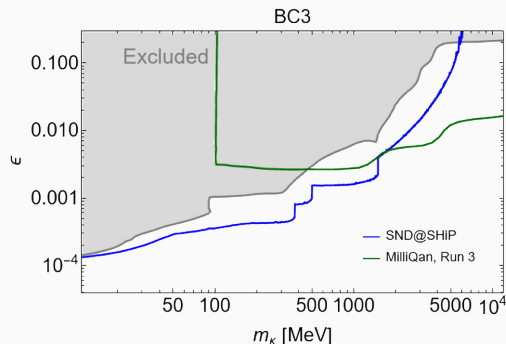
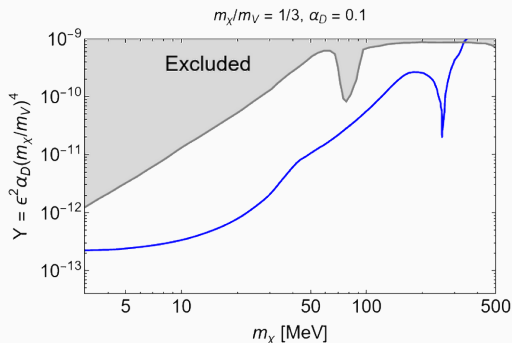
$$\frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left\{ (y^2 x + \frac{m_\tau^2 y}{2E_\nu M}) F_1 + \right.$$

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

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



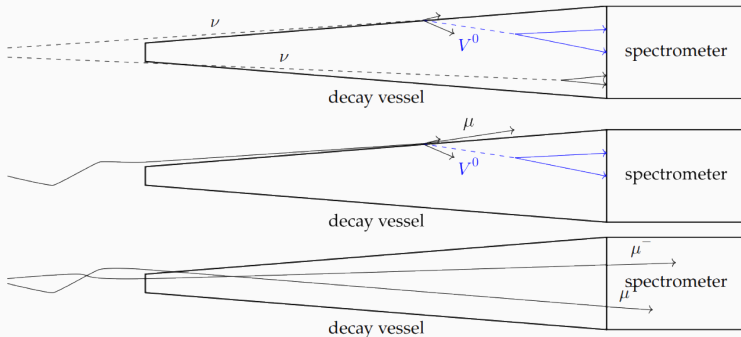
- ▶ Dark matter can scatter onto the SND detector's electrons
- ▶ Signal: EM shower from neutral current scattering
- ▶ Reject neutrino background through topological selection enabled by the high-granularity detectors



The only threat to SHiP: background



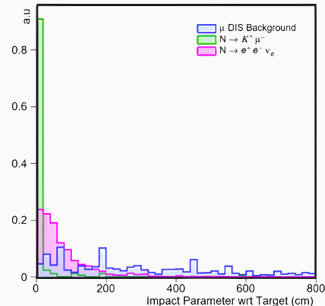
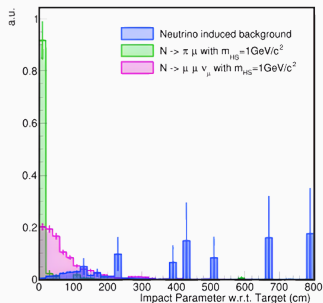
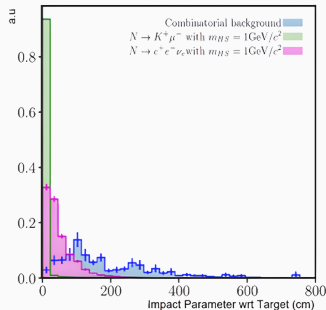
- ▶ A set of background taggers will be used to allow SHiP to reach its 0-background goal
 - ▶ The Upstream background tagger
 - ▶ The Surround background tagger
- ▶ 3 backgrounds are significant: neutrino background, muon DIS background and muon combinatorial



0-Background at SHiP

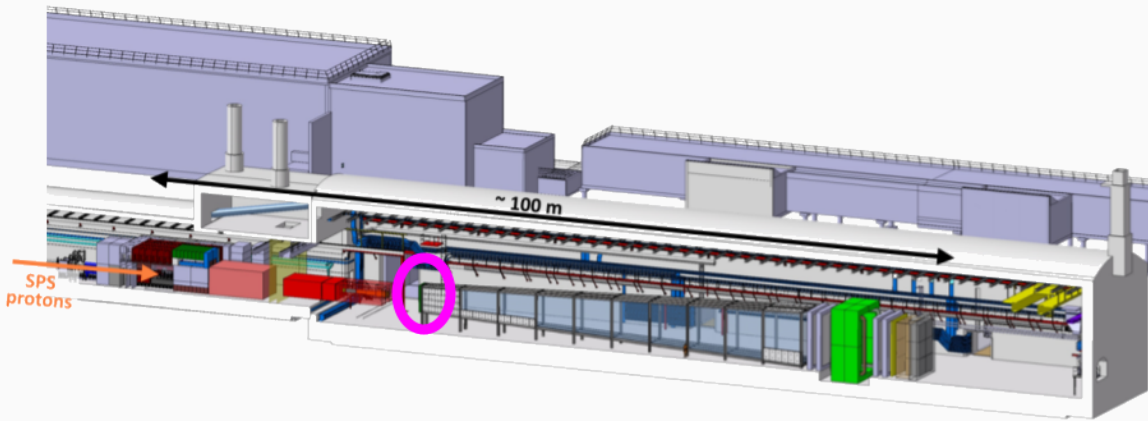


- Through simple cuts, almost all of the background can be removed whilst preserving the signal integrity
- Full background optimisation is still ongoing



Background source	Expected events
Neutrino DIS	< 0.1 (fully) / < 0.3 (partially)
Muon DIS (factorisation)	$< 5 \times 10^{-3}$ (fully) / < 0.2 (partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

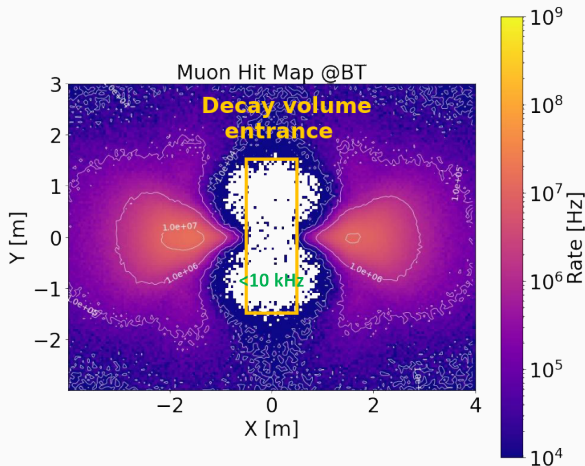
Upstream Background Tagger (UBT)



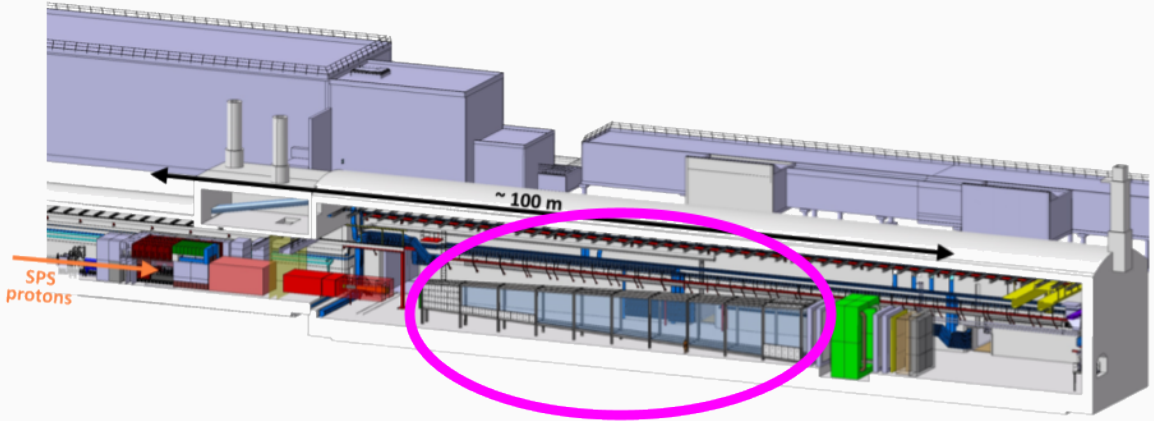
Upstream Background Tagger (UBT)



- ▶ Window placed at the start of the decay volume to tag muon background
- ▶ Needs to withstand variable rates during both operation and commissioning
- ▶ A panel of technologies considered: straws (for cold regions), SciFi and scintillator tiles (for hot regions)
- ▶ Optimisation ongoing, limitations in the hot regions primarily determined by readout electronics



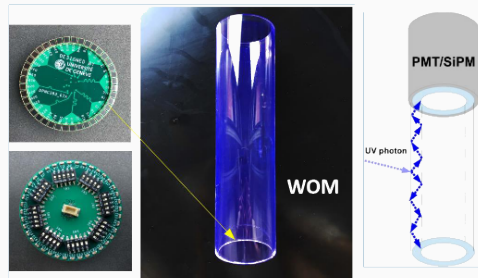
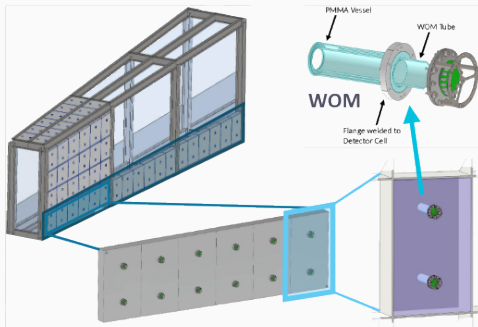
Surround Background Tagger (SBT)



Surround Background Tagger (SBT)



- ▶ SBT surrounds the helium-filled decay volume
 - ▶ Used to tag charged particles from outside and ν/μ interactions in the vessel wall and helium
- ▶ 780 compartments filled with liquid scintillator ($\sim 145\,000$ L of LAB)
 - ▶ Readout with Wavelength-shifting-optical modules (WOMs) in conjunction with SiPMs (40 SiPMs per module)
- ▶ $> 99\%$ efficiency and ~ 1 ns timing resolution

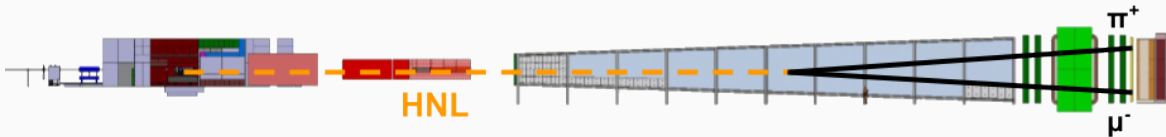


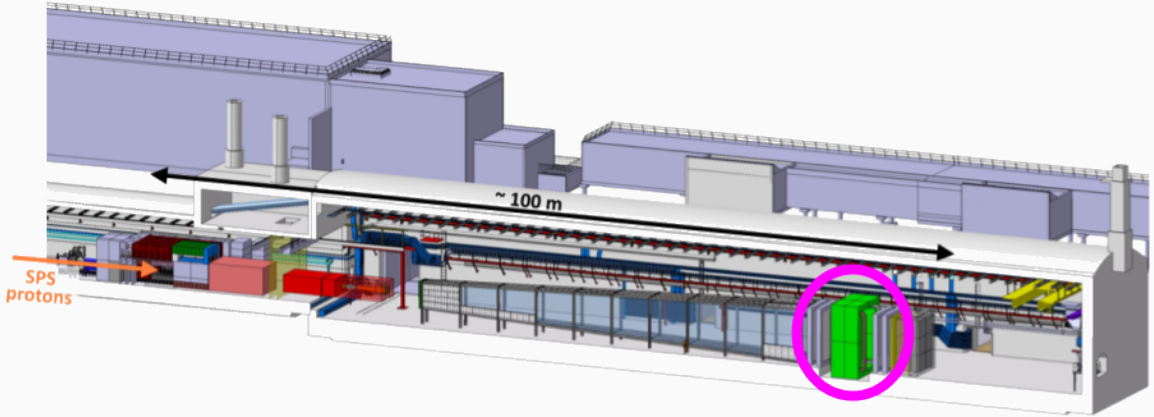
The signal detectors in SHiP



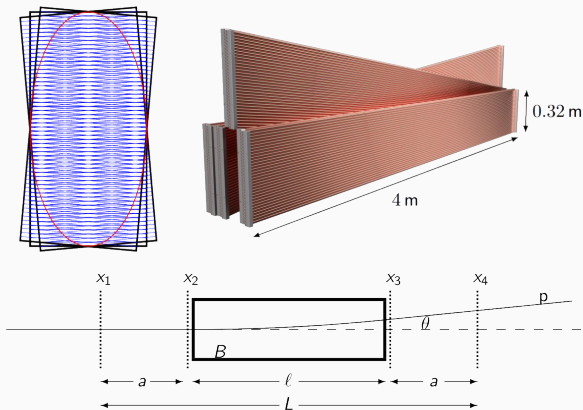


- ▶ The signal detectors seek to produce tracks and vertices of final state decays
 - ▶ Need good position resolution
- ▶ They are also used to filter background
- ▶ For example for an ideal HNL decay:





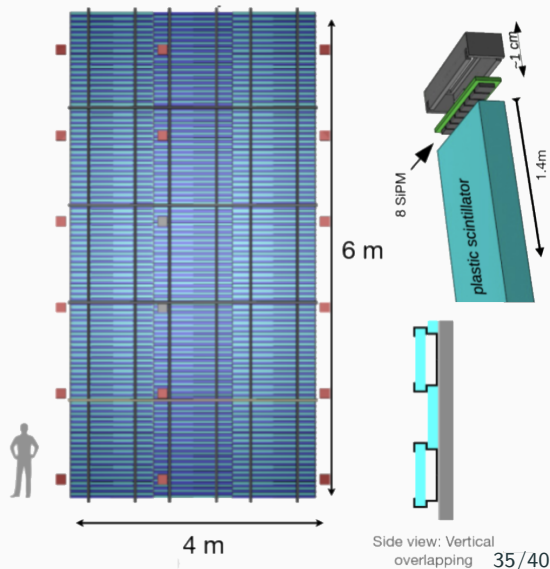
- ▶ 4-station straw tracker coupled with an LHCb-style dipole magnet
 - ▶ Bending radius $0.6 - 0.8 \text{ T m}$, nominal on axis 0.15 T
- ▶ Low rate ($< \mathcal{O}(10 \text{ kHz})$)
- ▶ Very large sensitive region: $4 \times 6 \text{ m}^2$, $20 \text{ m}\varnothing$, $36 \mu\text{m}$ thick coated PET film at 1 bar
- ▶ 9600 straws in planes arranged in a $y - u - v - y$ setup with a 5° stereo angle



SHiP Timing Detector



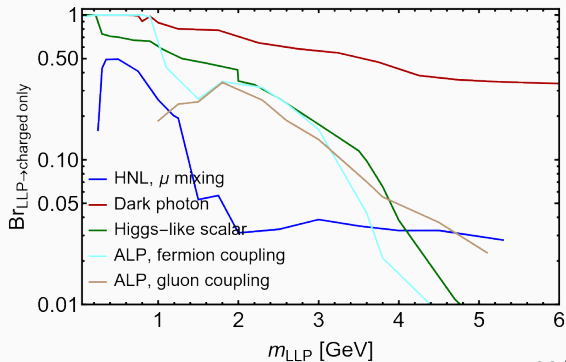
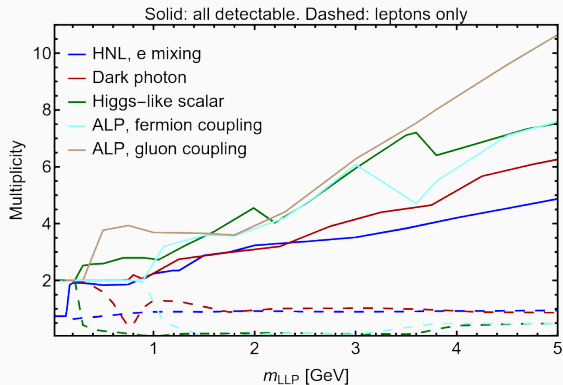
- ▶ 3 columns of 110 long bars with few cm overlap
- ▶ Used to limit combinatorial background
- ▶ Timing resolution ≤ 100 ps (≤ 50 ps)
- ▶ Scintillator bars + 8 SiPMs per side
- ▶ Main challenge here: SiPM + front end electronics optimisation



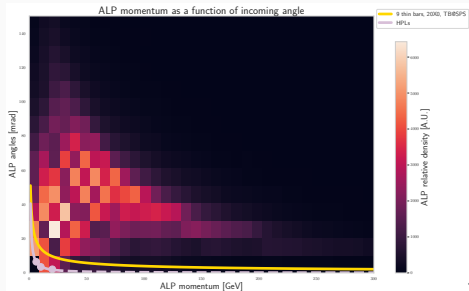
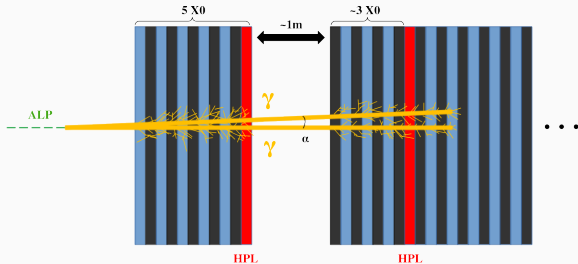
Interlude: decays at SHiP



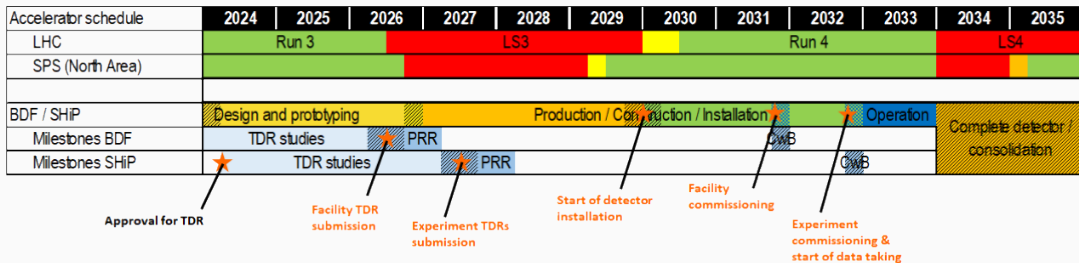
- For higher mass NP particles, higher multiplicity is expected
- The fraction of purely charged decays is accordingly reduced
- Induces requirements on the calorimeter which needs to complement the tracker



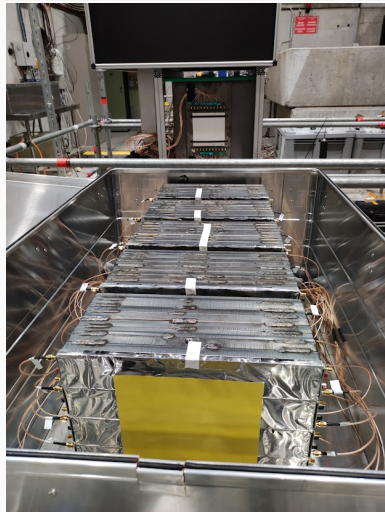
- ▶ Hadronic and an electromagnetic calorimeter
- ▶ PID performance essential for background rejection
- ▶ Uses the SplitCal concept to allow for the reconstruction of neutral final states
 - ▶ Scintillator bars and SiPMs for energy reconstruction, High-Precision Layers for shower directionality reconstruction
 - ▶ Allows for the reconstruction of neutral final states
 - ▶ Use of thin scintillator bars to further increase angular resolution
- ▶ Angular resolution $\mathcal{O}(\sim 5 \text{ mrad})$ at 10 GeV



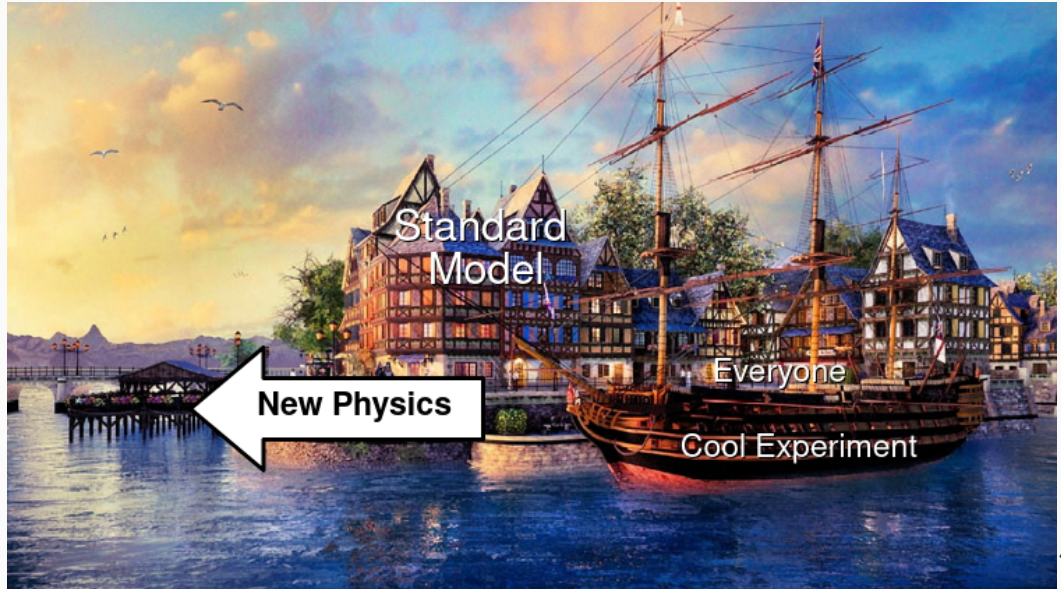
- ▶ Beam Dump Facility (BDF) to be built in LS3 (construction has already begun)
- ▶ Technical Design reports in 2-3 years
- ▶ Data taking starts in 2032 $\sim$ 2 years before LS4
- ▶ The time scale before LS4 will already allow SHiP to set world records in sensitivity



- ▶ The energy frontier is already quite explored → HL-LHC and FCC go even further in that direction
- ▶ Lack of new physic found until now strongly motivate searches in other directions
- ▶ BDF/SHiP has a wide and unique physics program as a beam dump experiment
 - ▶ Has defining sensitivity to both neutrinos and FIPs
- ▶ Approved and to be built in the coming ~ 7 years
- ▶ Optimisation is currently taking place in preparation for TDR



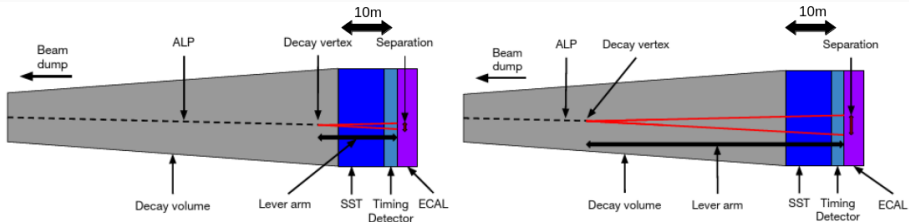
All aboard!



Backup: $\gamma\gamma$ separability



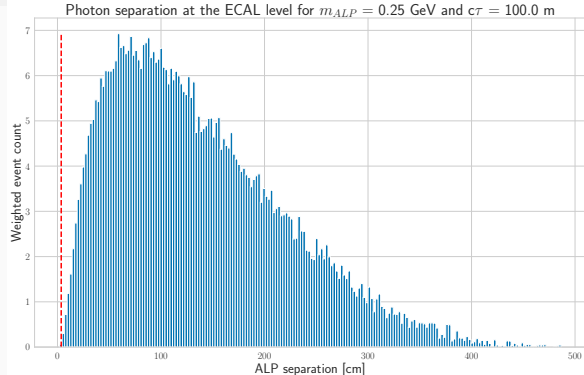
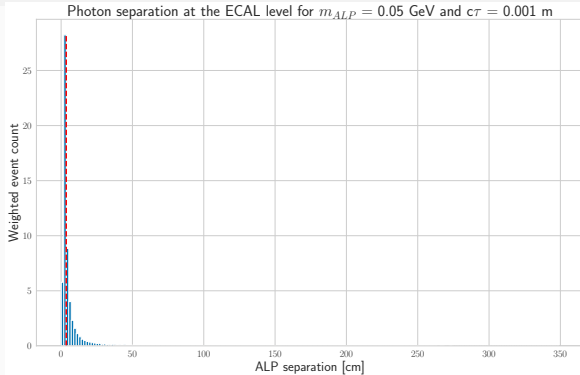
- ▶ Separation crucial for $\gamma\gamma \rightarrow$ no separation, no signal!
 - ▶ Needs to be verified
- ▶ Separability generally favoured by lower boost, higher mass and shorter lifetimes
- ▶ In the following Separation assumed possible if both showers separated by at least $2R_M$ (3.2 cm in lead). The decay taken at end of the decay vessel, with the ECAL 10 m downstream. Consistent with NA62 separation selection.



(a) Effect of a short lever arm for a late decaying ALP in particle separation: the separation is reduced. (b) Effect of a long lever arm for an early decaying ALP in particle separation: the separation is increased.



Backup: $\gamma\gamma$ separability

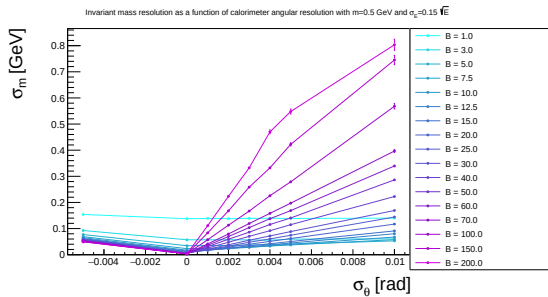
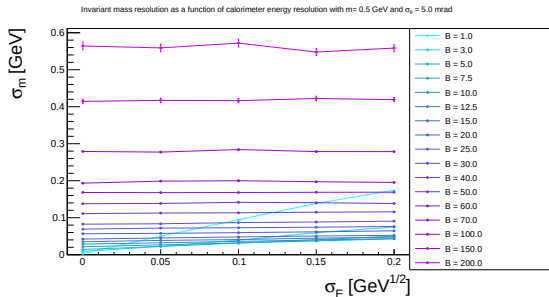


$m_{ALP} = 50$ MeV mass and $c\tau = 1$ mm

$m_{ALP} = 250$ MeV mass and $c\tau = 100$ m

$ALP \rightarrow \gamma\gamma$ separation ensured almost everywhere, only under tension in $m_{ALP} = 50$ MeV mass and $c\tau = 1$ mm (and the distance to the end of the DV will probably be longer + we can probably implement better separation techniques).

Backup: Detector characteristics in model independent $X \rightarrow \gamma\gamma$ decays

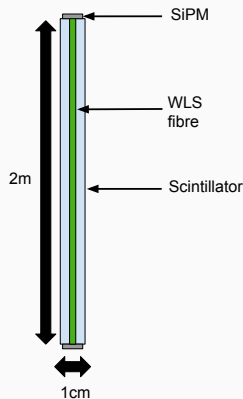
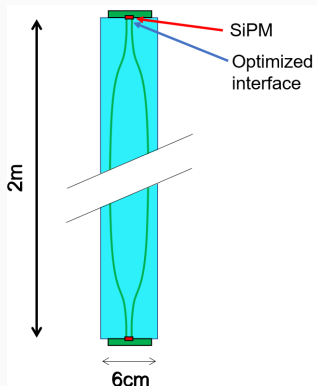


→ angular resolution valuable in all circumstances, value degrades at low boost, energy resolution becomes especially valuable for low B !



- ▶ Two scintillator bar types in proportions to be determined (between 15 360 and 96 000 channels)

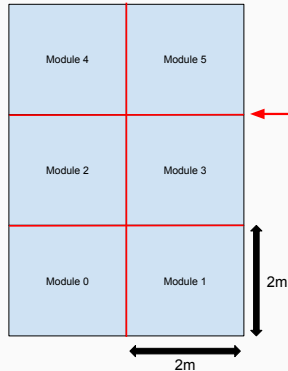
- ▶ Each bar type has a corresponding SiPM:
 - ▶ (ECAL+HCAL) Wide bars: large $6 \times 6 \text{ mm}^2$ SiPMs, many pixels, large signals (up to $\mathcal{O}(100s)\text{mV}$), large capacitance (up to $\mathcal{O}(2 \text{ nF})$). Baseline: S14160-6050HS SiPM, Broadcom/FBK SiPMs to be studied
 - ▶ (ECAL) Thin bars: smaller $\sim 1.3 \times 1.3 \text{ mm}^2$ SiPMs, fewer pixels, smaller signals (up to $\mathcal{O}(10s)\text{mV}$), smaller capacitance (up to $\mathcal{O}(10s)\text{pF}$). Baseline: S13360-1325PE SiPM.



Backup: the problem of dead space and ease of access



- ▶ (Known) concerns were pointed out in our mechanical design
 - ▶ One of the largest fixed target calorimeters ever conceived
- ▶ Experiment will run for ~ 15 years, there will be problems
- ▶ In the current (basic) configuration, three main issues
 - ▶ Difficulty to cool (cooling needs are being reassessed, still probably needed)
 - ▶ Difficult channel access $\rightarrow$ cassette scheme?
Layer-wide of module wise?
 - ▶ Dead regions $\rightarrow$ Need to be minimised absolutely
- ▶ All three points are related
- ▶ Thought of a few alleyways to try to resolve these issues



Backup: people at the moment



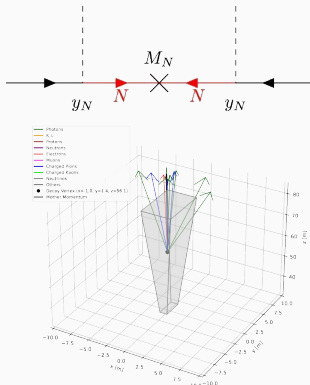
Role	Person	Comments
Project leader	Walter Bonivento	—
Integration/Installation	Matei Climescu/Rainer Wanke	Soon hopefully also Frank Steeg
Power/Control/Readout/Monitoring	Matei Climescu	—
Software	Matei Climescu/Walter Bonivento	—
Safety	Matei Climescu	—
CAD	Matei Climescu	Hopefully someone else soon (Fabian, Frank?)
GEMs/HPLs	Matei Climescu/Kirill Skovpen	Treated separately for now, will integrate
Test Beam	Sebastian Ritter/Claudia Delogu/Matei Climescu	—

Backup: beyond the Standard Model, what to look for?



Heavy neutral leptons:

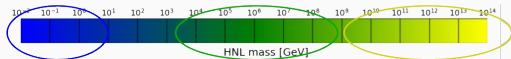
- Right-handed neutrinos
- Explain neutrino mass scale (type I seesaw)
- Allow leptogenesis



Oscillation leptogenesis

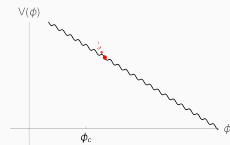
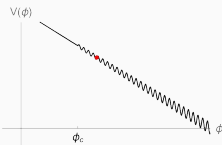
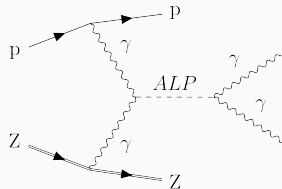
Resonant leptogenesis

Thermal leptogenesis



Axion-like-Particles:

- Generic (pseudo-) Nambu-Goldstone boson emerging from broken global symmetries
- May offer a relaxation solution to the hierarchy problem
- May mediate interactions to a Hidden Sector



Backup: PDF contributions from SHiP

