BDF/SHiP @ ECN3

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SHiP
Search for Hidden Particles

Physics Beyond Colliders workshop
Nov 07, 2022

Status @ submission of the LoI to SPSC

BDF/SHiP @ECN3

- ✓ ***ESPP concluded that BDF/SHiP as one of the front-runners among the larger scale new facilities investigated within CERN PBC.***
- ✓ ***But the project could not be recommended due to financial challenges associated with the other recommendations***

- ✓ *2020 Sep: CERN launches continued BDF R&D with SHiP MoU on top of existing collaboration agreement*

- ✓ *Extensive Layout and Location optimisation study at CERN*
  → BDF/SHiP @ ECN3 provides the best cost-effective solution (Facility cost at the existing ECN3 line is lower than the original cost by a factor)

- ✓ ***2022 July: CERN launches dedicated studies of future programme in ECN3 beam facility & decision process***

CERN-ACC-NOTE-2022-0009
CERN-PBC-Notes-2022-002
1 March 2022

Study of alternative locations for the SPS Beam Dump Facility

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Summary

As part of the main focus of the BDF Working Group in 2021, this document reports on the study of alternative locations and possible optimisation that may accompany the reuse of existing facilities with the aim of significantly reducing the costs of the facility. Building on the BDF/SHiP Comprehensive Design Study (CDS), the assessment rests on the generic requirements and constraints that allow preserving the physics reach of the facility by making use of the 4×10^{19} protons per year at 400 GeV that are currently not exploited at the SPS and for which no existing facility is compatible. The options considered involve the underground areas TCC4, TNC, and ECN3. Recent improvements of the BDF design at the current location (referred to as 'TT90-TCC9-ECN4') are also mentioned together with ideas for yet further improvements. The assessments of the alternative locations compiled the large amount of information that is already available together with a set of conceptual studies that were performed during 2021.

The document concludes with a qualitative comparison of the options, summarising the associated benefits and challenges of each option, such that a recommendation can be made about which location is to be pursued. The most critical location-specific studies required to specify the implementation and cost for each option are identified so that the detailed investigation of the retained option can be completed before the end of 2022.

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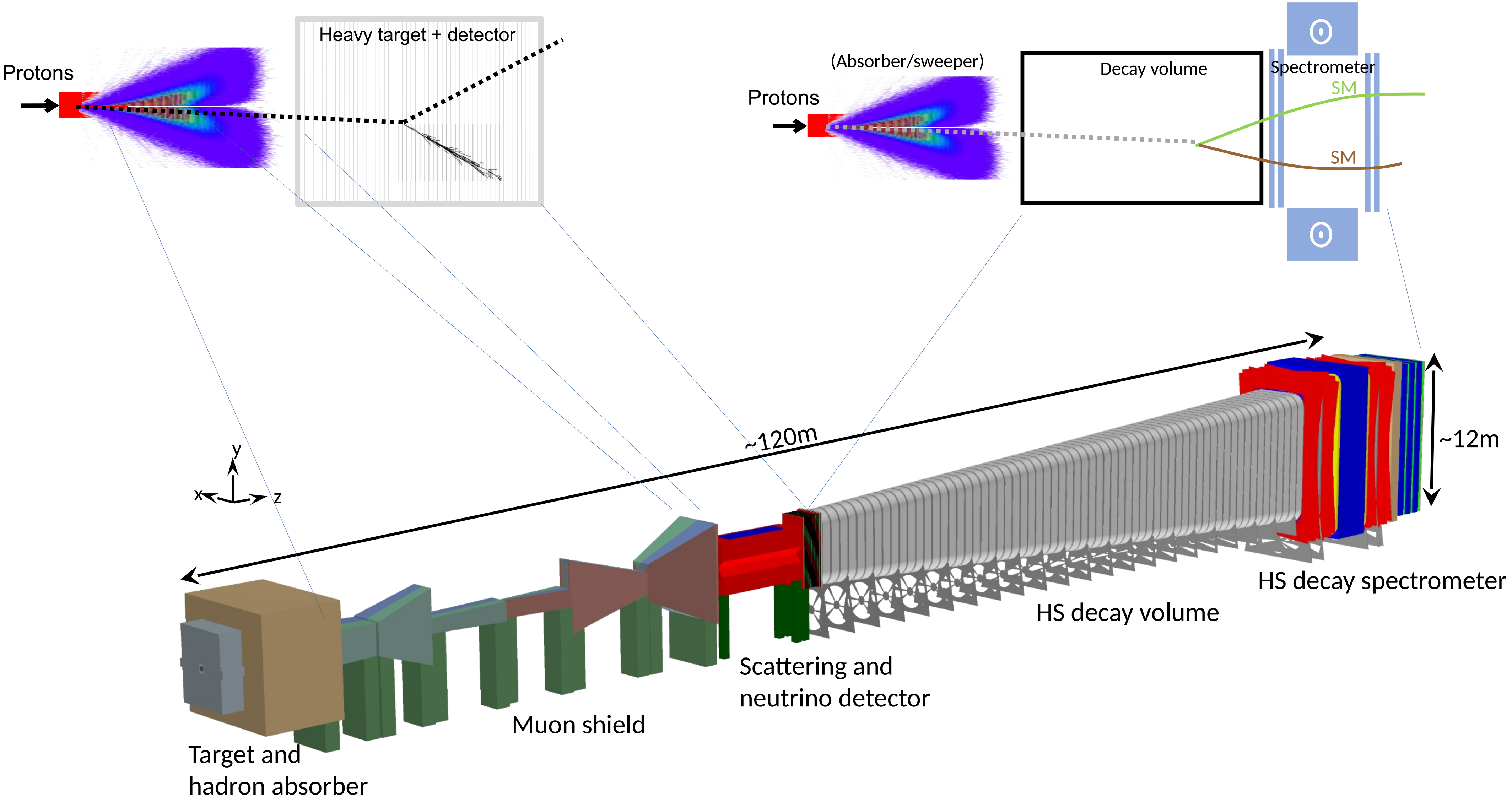
SHiP as presented in CDS(ECN4) report

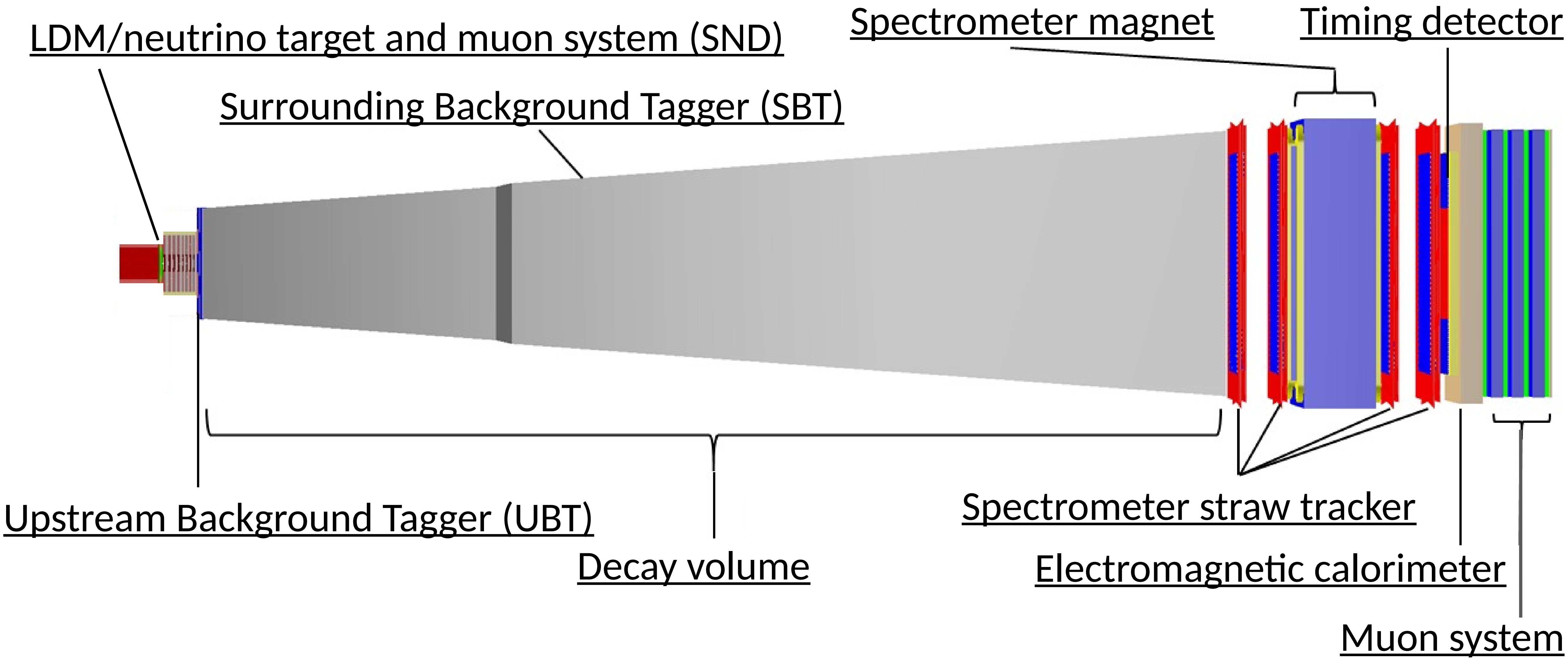
Dual-platform experiment combining two direct search techniques

Scattering off atomic electrons (and nuclei)

Decay to SM particles



SHiP: the main components



BDF/SHiP at the ECN3 line

Main challenges compared to CDS(ECN4) design

✓ ***Smaller size experimental hall***

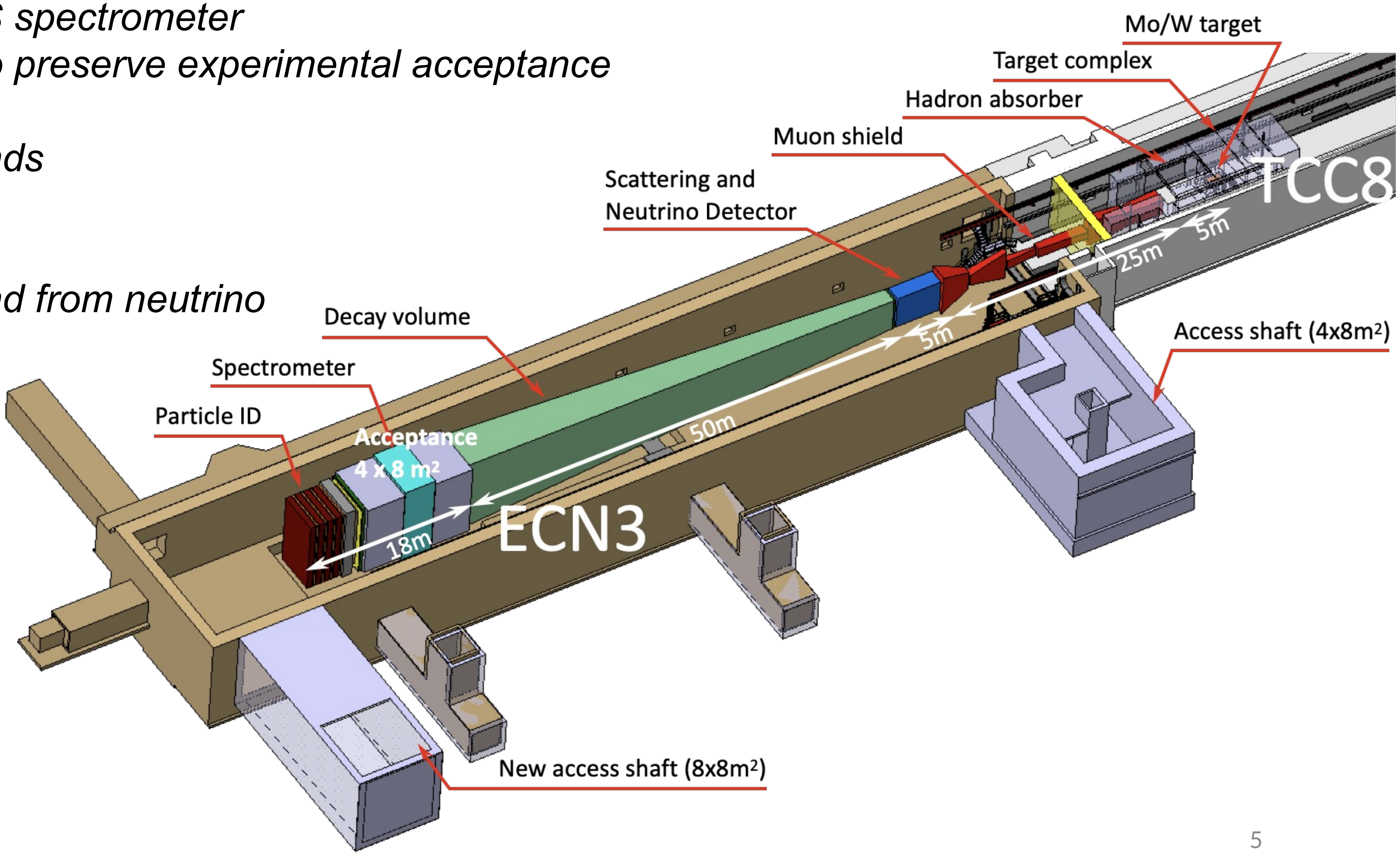
→ Smaller cross-section of the HS spectrometer
→ Shorter distance to the target to preserve experimental acceptance
→ Shorter muon shield
→ Potential increase of backgrounds

✓ ***Tight infrastructure***

→ Potential increase of background from neutrino and muon DIS

✓ ***Less space for SND***

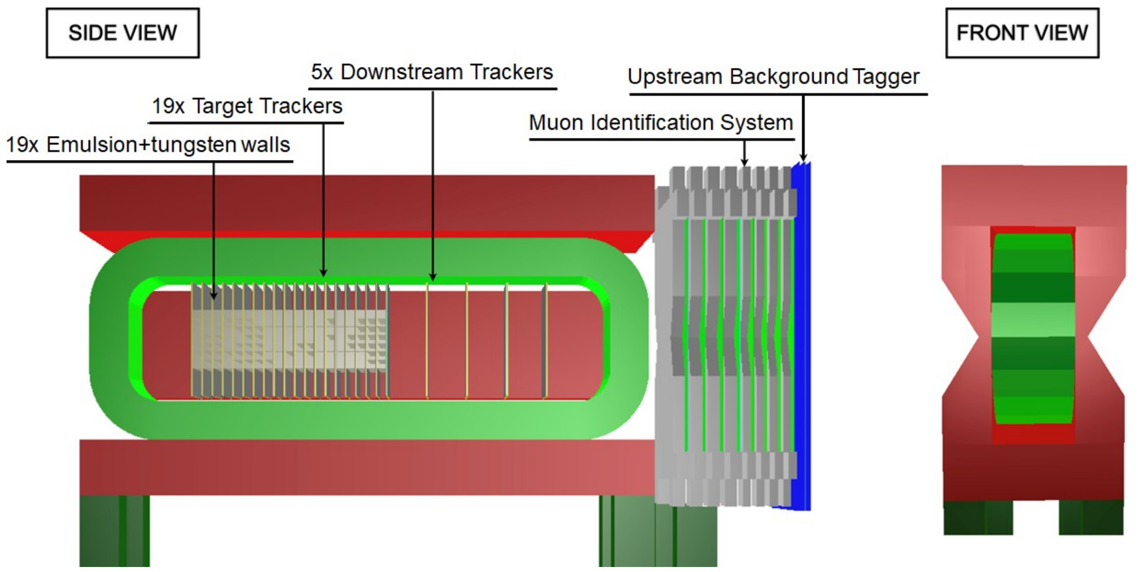
→ Optimise the target mass and magnet dimensions to preserve / improve the LDM sensitivity



Optimisation of the SND concept for ν_τ physics

CDS(ECN4) design:

SND inside the magnet → possibility to distinguish btw ν_τ and $\overline{\nu}_\tau$ in both hadronic and muonic τ decays

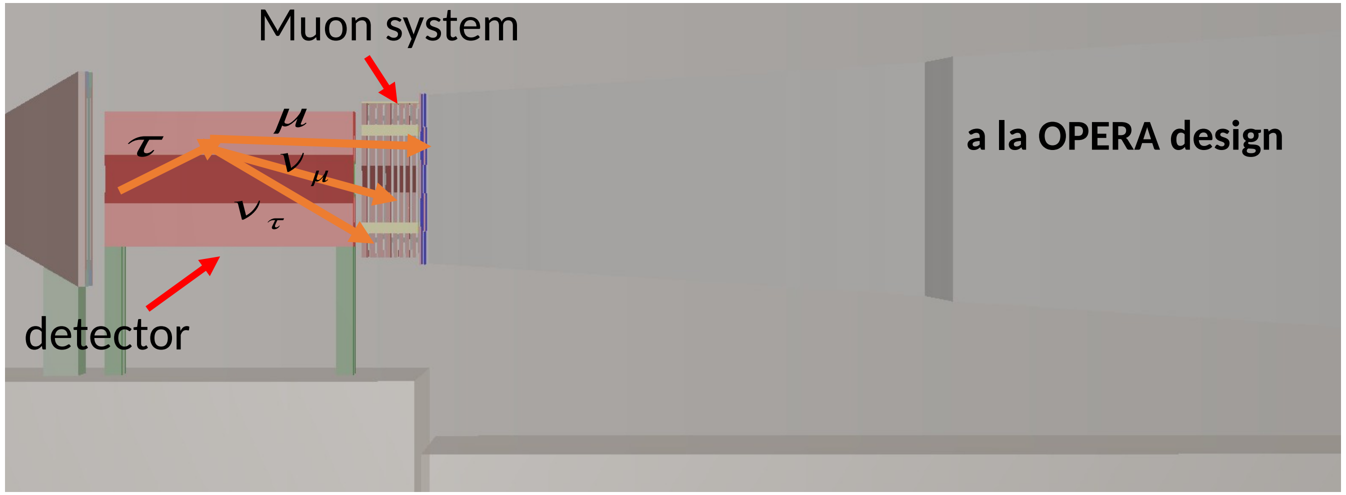


Alternative solution at ECN3:

Remove SND magnet to increase the mass of the target

→ Use exclusively muons from the golden $\tau \rightarrow \mu\nu\nu$ channel

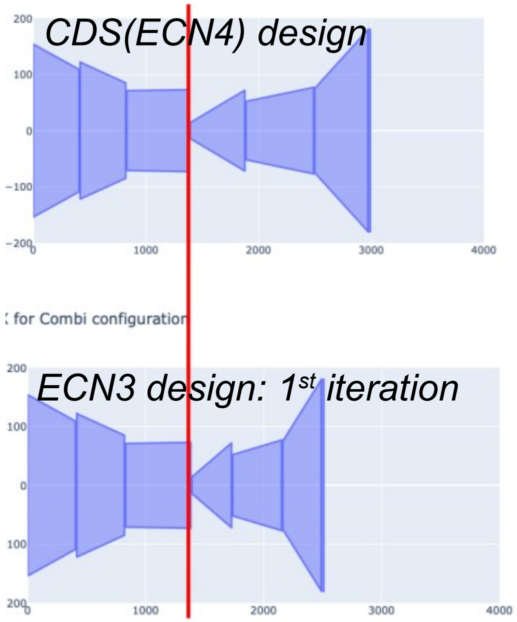
Use magnetised iron with tracking layers (a la OPERA) to measure muon charge and momentum



Further optimisation studies (trade-off btw** LDM and ν_τ **performance):

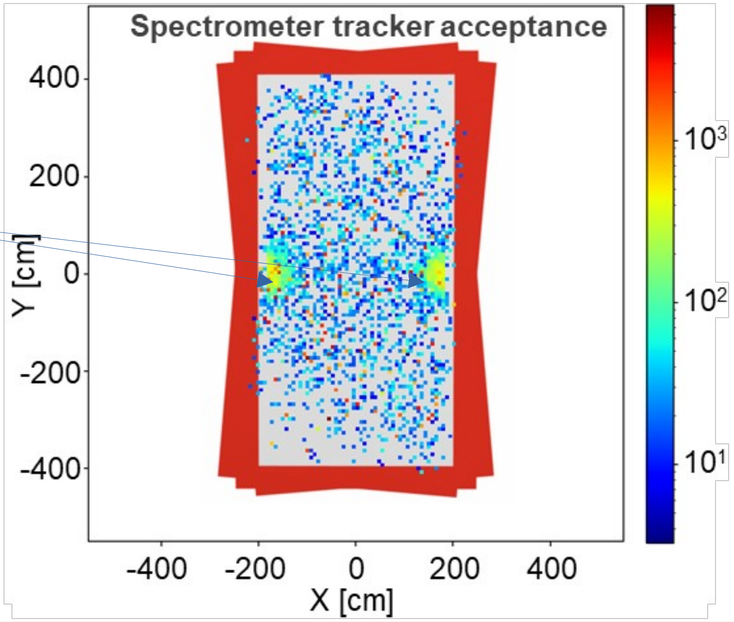
Reducing shield length furtther (smaller distance to target) and re-optimising target and magnet shape

Muon shield optimisation (1st iteration!)



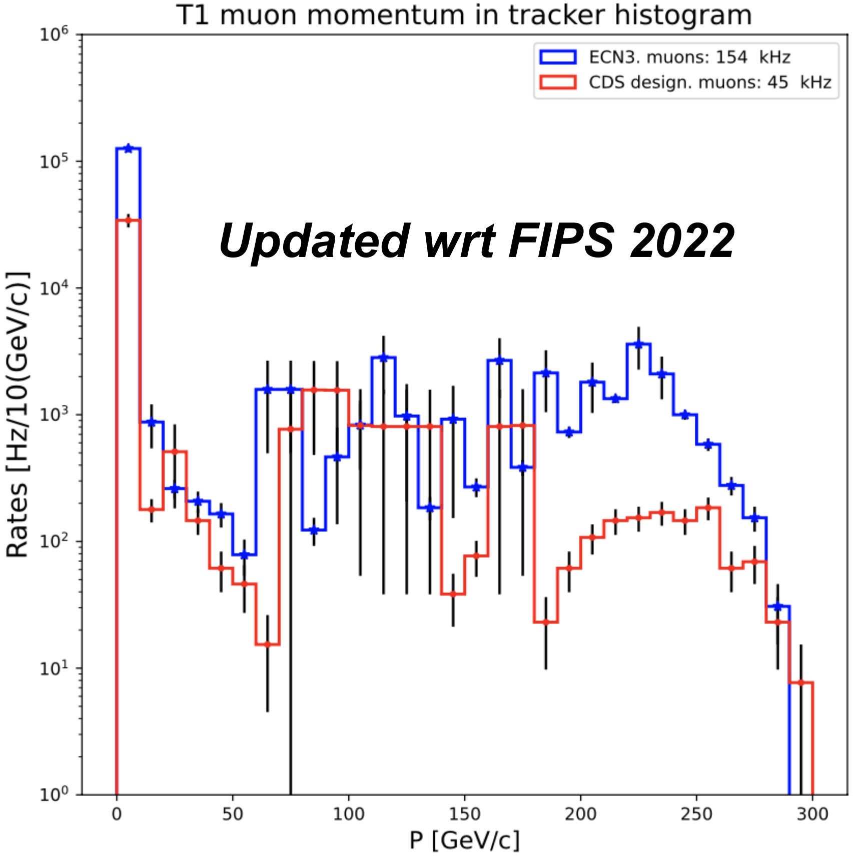
- ✓ Goal: reduce the initial flux of 10^{11} per spill by up to ~6 orders of magnitude
- ✓ Muon shield is shorter by ~5m at ECN3 but still provides sufficient field integral to deflect hard muons
- ✓ **1st iteration:** *upstream half unchanged, magnets of the downstream half downscaled preserving the same shape as in the CDS(ECN4) design*
- ✓ *We know this shape is not perfect: "hot spots" in the HS tracker*

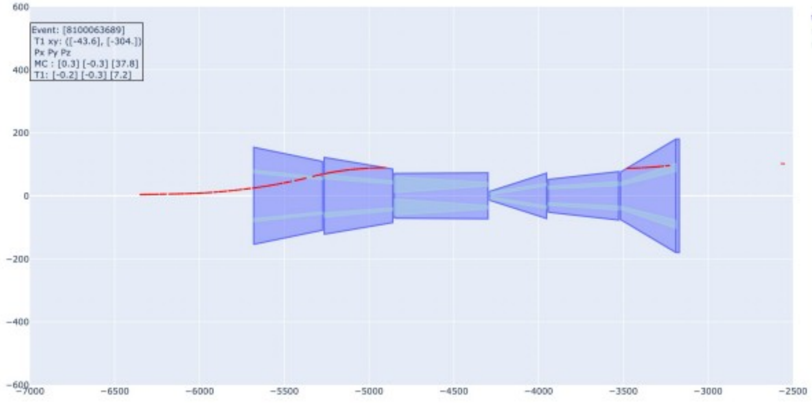
Muons at the HS tracker:
High-momenta (P>O(150GeV)) leaking through the gaps around the coils in the muon shield

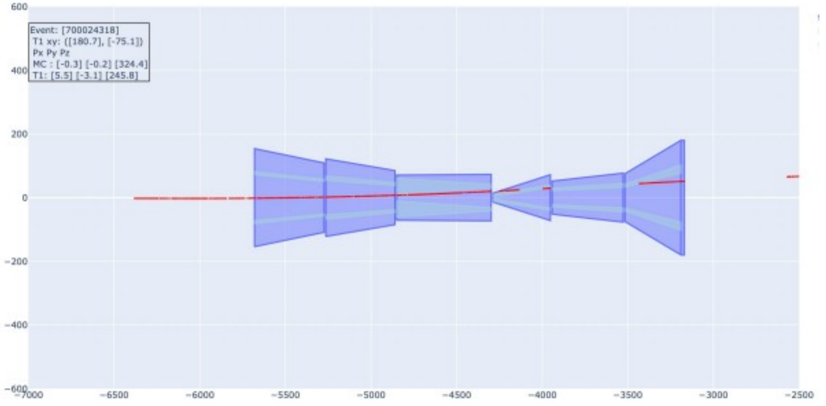


- ✓ *The remaining gaps will* **be fixed in future optimisation** *of the shield*
- ✓ *The field integral of the shortened shield is sufficient to deflect hard muons*
- ✓ *The shield shape has to be re-optimised !*
- ✓ **Current muon rate is very conservative → Used in the following for background evaluation at ECN3**

Muon rates for 1st iteration of muon shield optimization







Apart from the "hot spots", rate increase from ECN4 to ECN3 (by 3.4) mostly due to suboptimal performance of the shield (in this 1st iteration) for deflecting muons returned back to detector acceptance by reverse field:

- ✓ *Optimisation of the muon shield is ongoing !*
  Preliminary results beyond this 1st iteration indicate that muon rate is almost back to CDS(ECN4) design!

- ✓ *Study of alternative SC technologies to further shorten the shield → further room for improving physics performance*

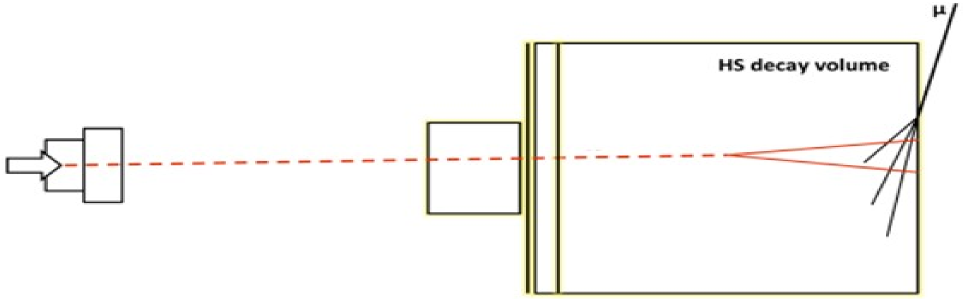
Evaluation of SHiP physics performance

Pythia/Geant simulation with complete description of detector and infrastructure

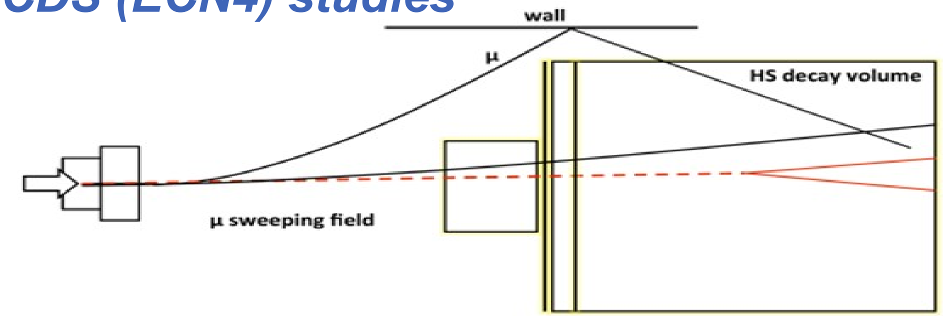
- ✓ *(10^{11}) muons (>1 GeV/c) per spill of 4×10^{13} protons on target (pots)*
- ✓ *4.5×10^{18} neutrinos and 3×10^{18} anti-neutrinos in acceptance in 2×10^{20} pots*

Backgrounds in decay search (fully reconstructable/partially with neutrinos) in pots/5 years

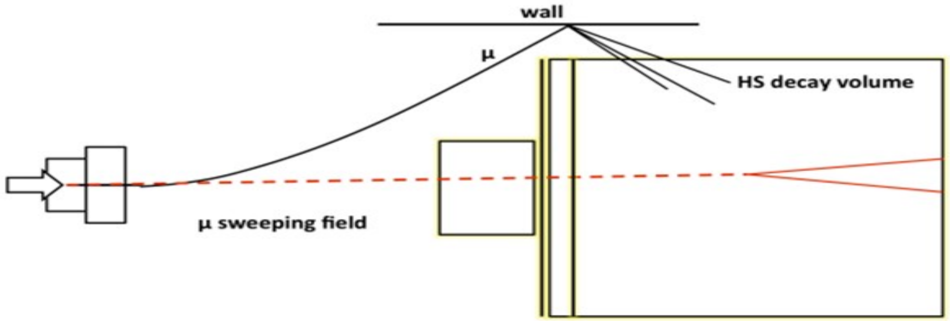
Reminder of CDS (ECN4) studies



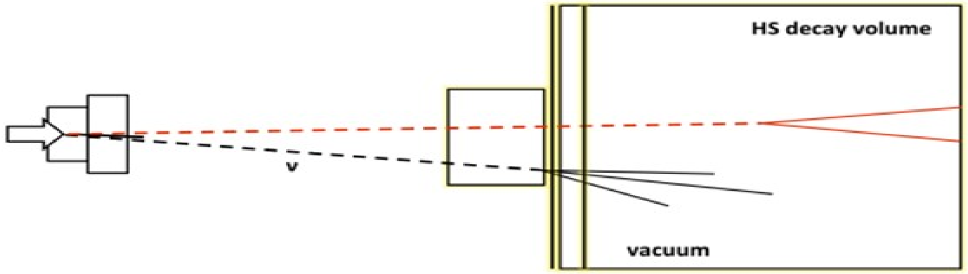
Cosmics: negligible



Muon combinatorial: (1.2 +- 1.2) x 10^{-2}



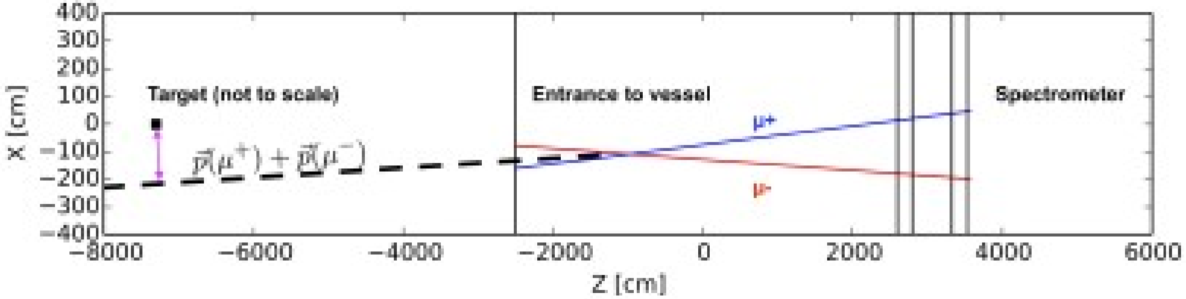
Muon DIS: 6 x 10^{-4}



Neutrino DIS: <0.1 (fully) / <0.3 (partial)

Our goal: to confirm similar backgrounds levels at ECN3

Muon Combinatorial background (ECN3 in 5 years)

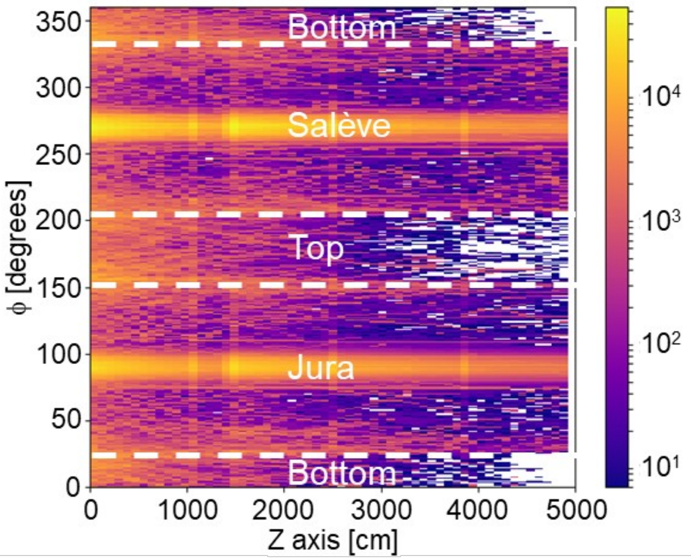


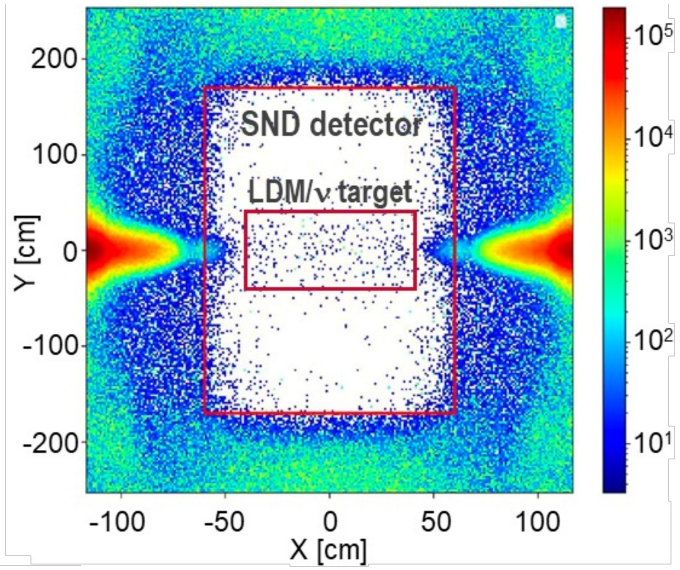
Event selection

Track momentum	> 1.0 GeV/c
Track pair distance of closest approach	< 1 cm
Track pair vertex position in decay volume	> 5 cm from inner wall
Impact parameter w.r.t. target (fully reconstructed)	< 10 cm
Impact parameter w.r.t. target (partially reconstructed)	< 250 cm

- This background arises when two opposite-sign muons originating during a single spill appear to vertex and point back to the target

SBT





Updated wrt FIPS 2022

- ✓ *Muon pairs in tracker* 9×10^{15}
- ✓ *Evt selection (part. rec.)* 9.0×10^{-4}
- ✓ *Time coincidence of the tracks from HS vertex* 3.4×10^{-10}
- ✓ *SBT cell efficiency* *99% (@45 MeV thr.)*
- ✓ *UBT efficiency* *98% per MRPC plane (meas. with prototypes)*

Passing SBT+UBT veto 1×10^{-6}

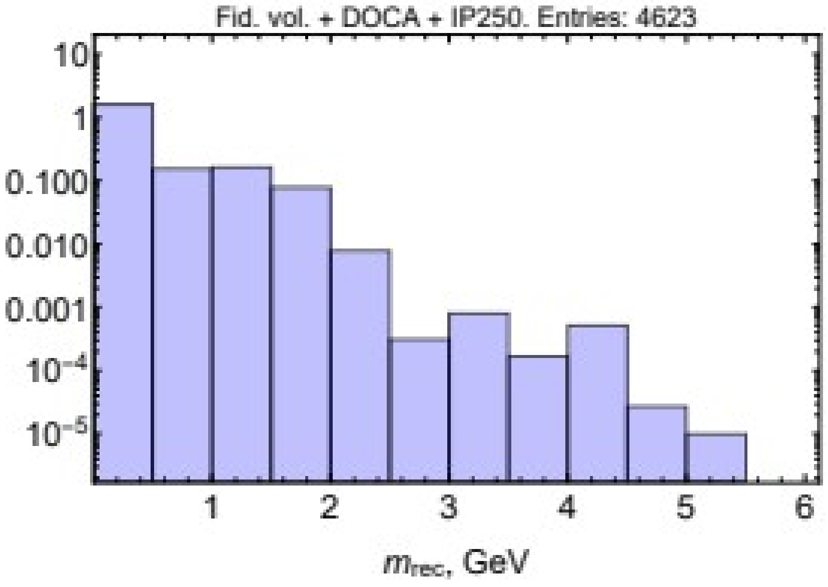
→ ***UBT/SBT with good time & spatial resolution crucial***

Comb. Background $\mathbf{2.7 \times 10^{-3}}$
(despite of higher muon flux compared to CDS (ECN4))

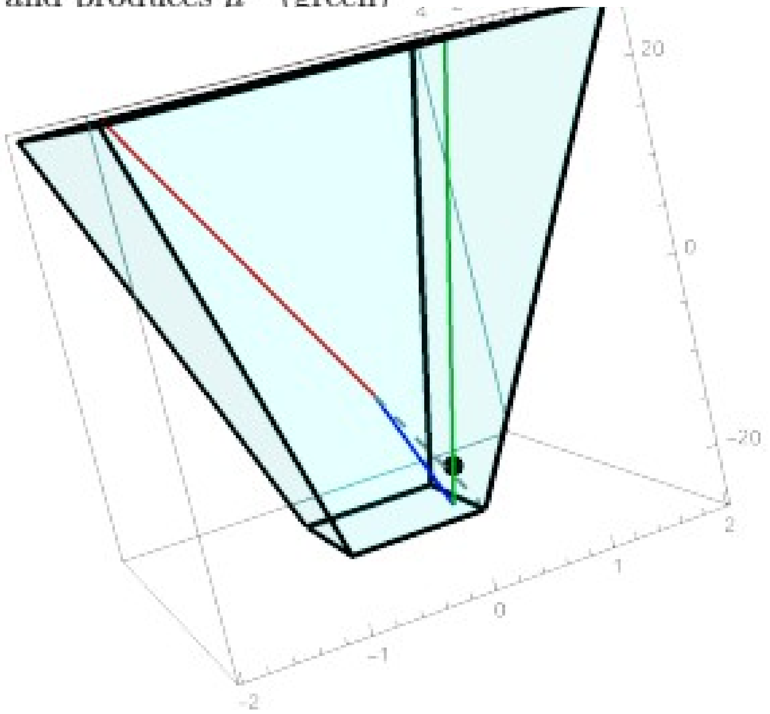
MUON DIS (ECN3 in 5 years)

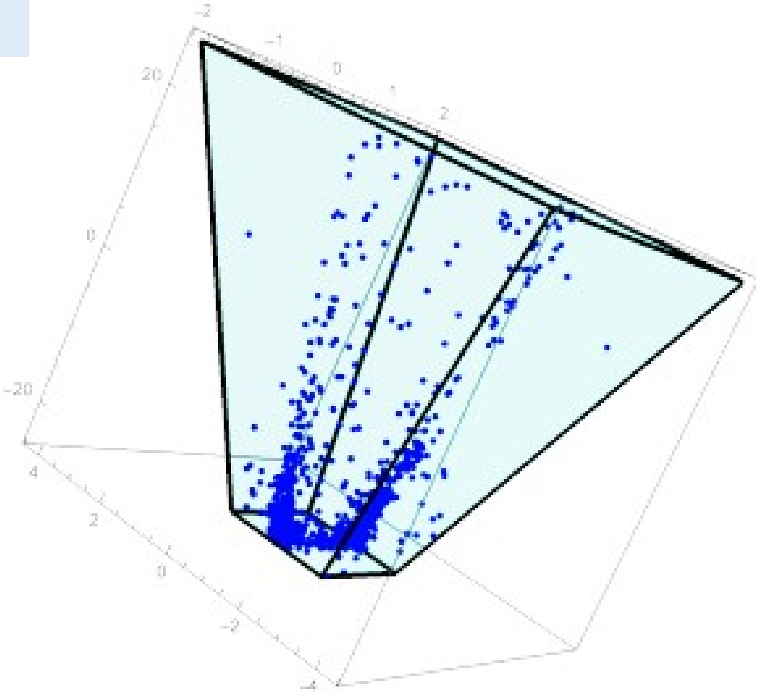
N_{DIS} @ vicinity of vacuum vessel: 9 x 10^{10}
N_{DIS} passing event selection: 2 x 10^5 (partially reconstructed)
10^3 (fully reconstructed)

Mainly random combinations of particles produced in the same interaction made of ee(31%), $\mu\pi$(28%), $\pi\pi$(22%), $e\pi$(5%), $e\mu$(5%), pp(4%) and $\mu\mu$(3%)
→ cannot be rejected by cuts on invariant mass



Example of "combinatorial" event: μ^- (red) and π^+ (blue) from DIS vertex, π^+ decays and produces μ^+ (green)





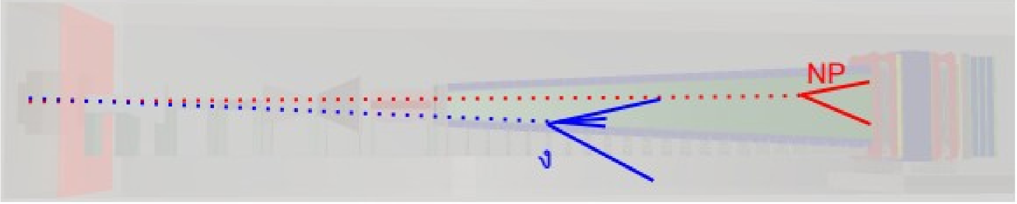
High Veto efficiency of Background Taggers (UBT&SBT) provides high redundancy in DIS suppression!

Assuming factorisation btw evt selection cuts and UBT/SBT veto:

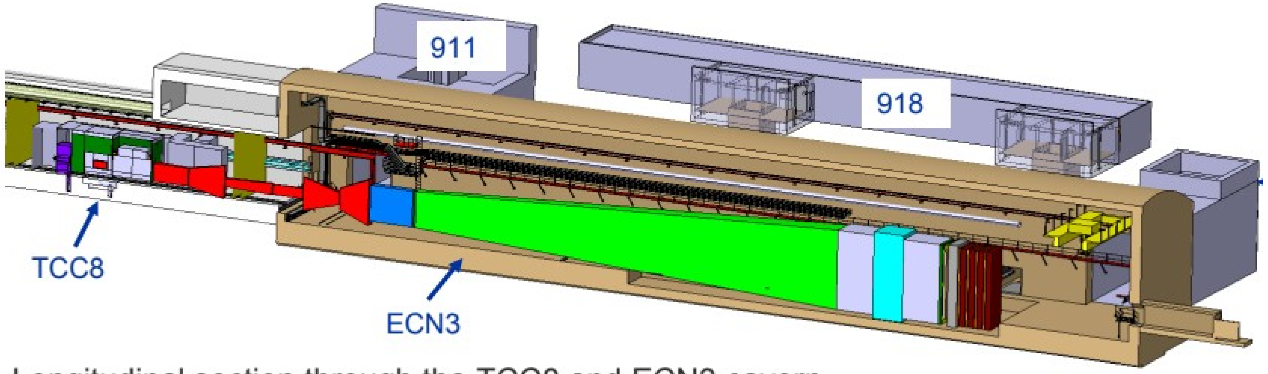
Muon DIS background:
***< 10^{-4}** (fully reconstructed)*
***< 10^{-2}** (partially reconstructed)*

Updated wrt FIPS 2022

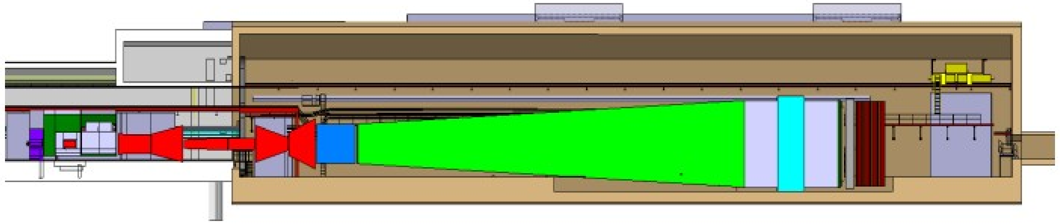
Neutrino DIS (ECN3 in 5 years)



MC sample used in CDS report corresponds to 35 years of SHiP data. Results for ECN3 (with whole ECN3 area implemented) repeated with smaller sample fully compatible with CDS.

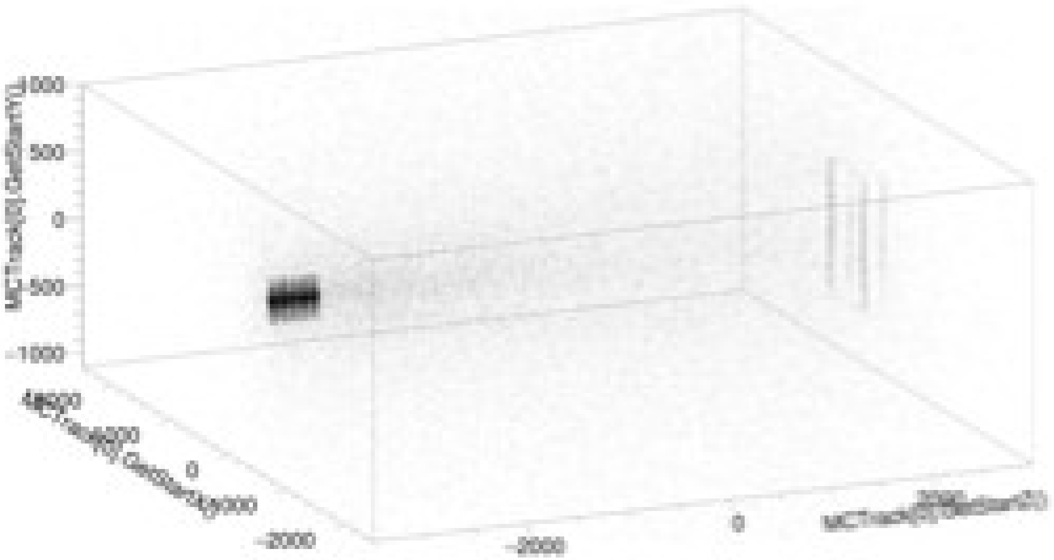


Longitudinal section through the TCC8 and ECN3 cavern



Plan view of the area with the proposed experiment

Similarly to muons, neutrino DIS products are aligned with the direction of incoming neutrino
*→ **Background is dominated by neutrino DIS in the proximity of decay volume***



Sources of neutrino DIS background:

- SND	*11%*
- Inner wall of the decay volume	*52%*
- Liquid scintillator	*26%*
- Outer wall of the decay volume	*4%*
- Others	*7%*

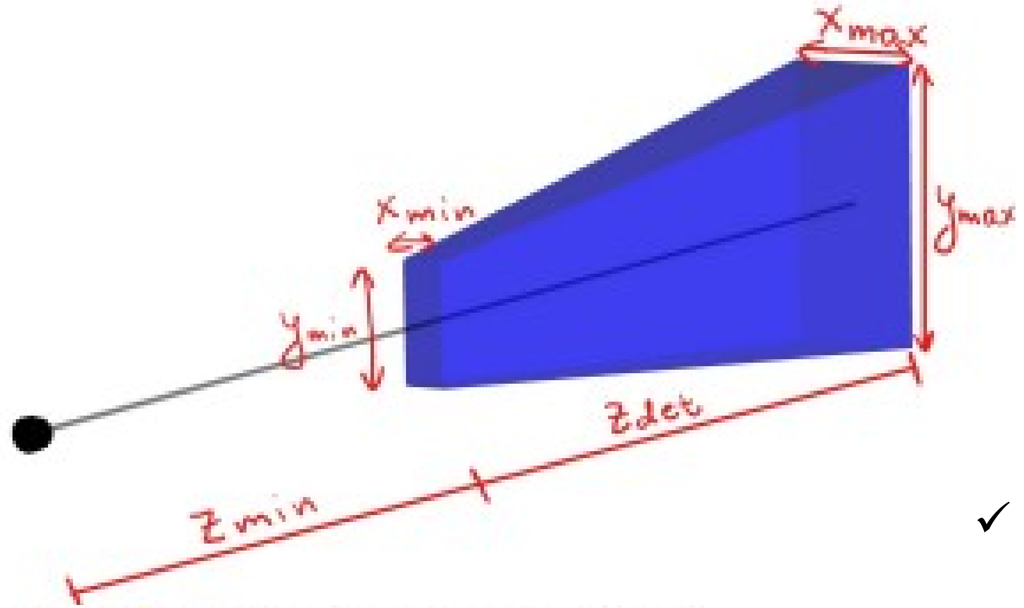
Neutrino DIS background after selection + SBT/UBT veto cuts

< 0.1 *(fully rec.)*

< 0.3 *(partially rec.)*

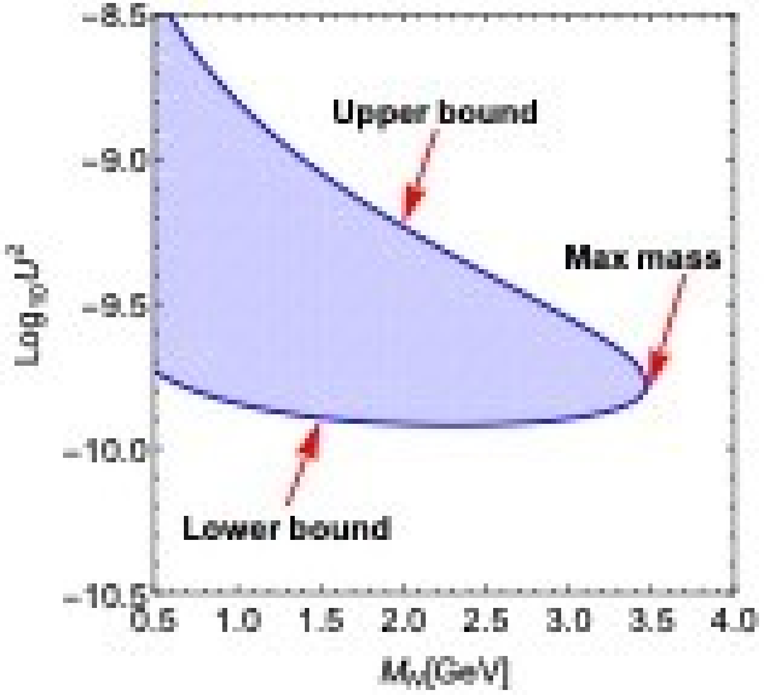
(6.8 (partially rec., all from γ conv.) → 0 with M_{inv} > 100 MeV/c^2)

Signal acceptance



Decay vessel parameters

	z_{min}	z_{det}	x_{min}	y_{min}	x_{max}	y_{max}	$\Omega_{vessel\ end}$
CDS Design	48 m	50 m	1.5 m	4.3 m	5 m	11 m	$5.7 \cdot 10^{-3}$
ECN3	37 m	50 m	1.2 m	3.5 m	4 m	8.7 m	$4.6 \cdot 10^{-3}$

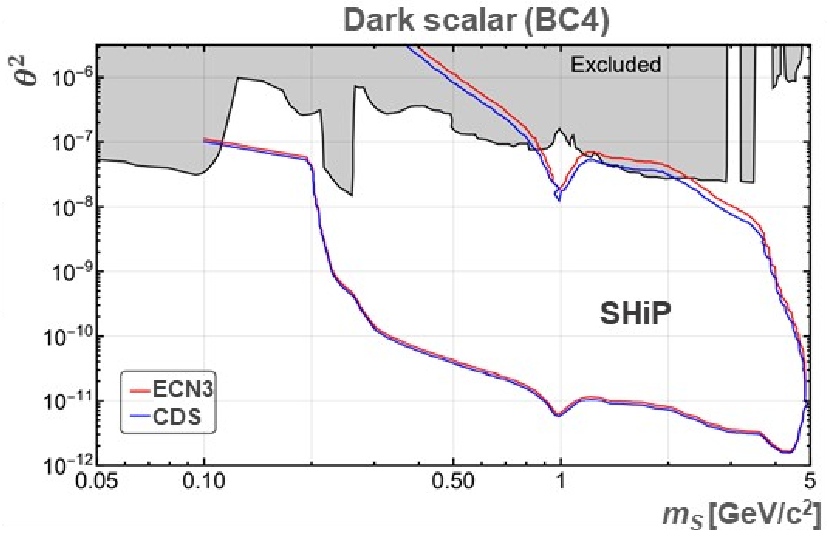


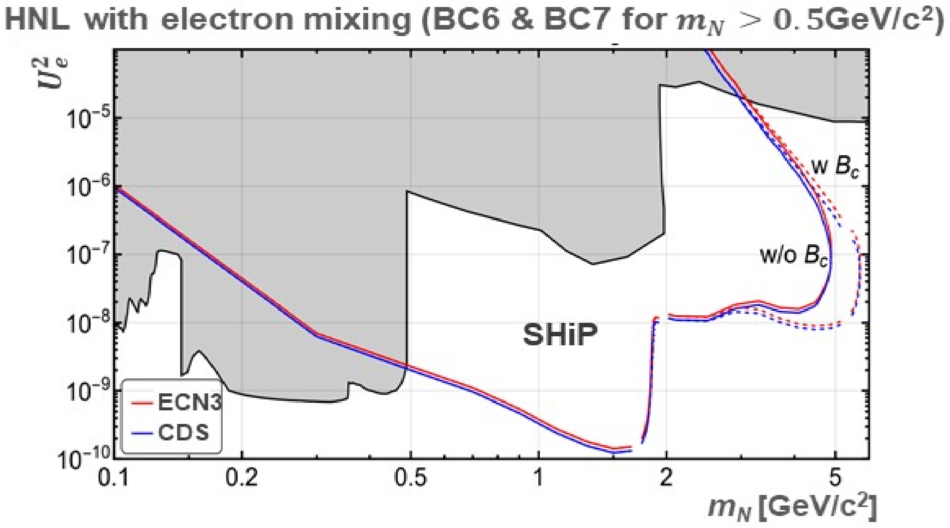
✓ *The upper bound of the sensitivity contour is determined by the distance from the target, z_{min}*
The number of observed events does not play a role here
→ ECN4 / ECN3 = 0.8

✓ *The lower bound depends primarily on the number of observed NP events within the SHiP angular coverage, $\Omega_{decay\ vessel}$*
So the lower bound depends on the NP model, NP(Ω).
For the uniform NP(Ω): ECN4 / ENC3 = 1.1

→ *ECN3 acceptance very close to ECN4 acceptance*

Signal sensitivities: Dark Scalar, HNL





In case of a signal, SHiP can (in contrast to V⁰ search):

** distinguish btw different HS models, e.g. HNLs*

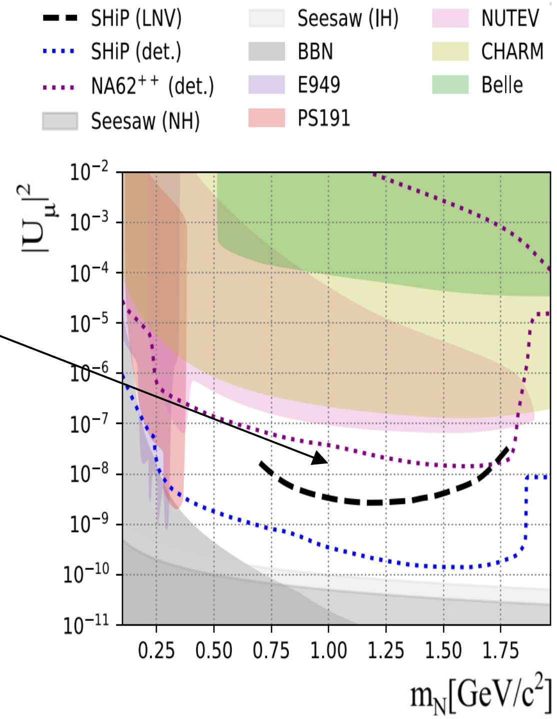
** locate coupling-mass point*

** perform measurements, e.g.:*

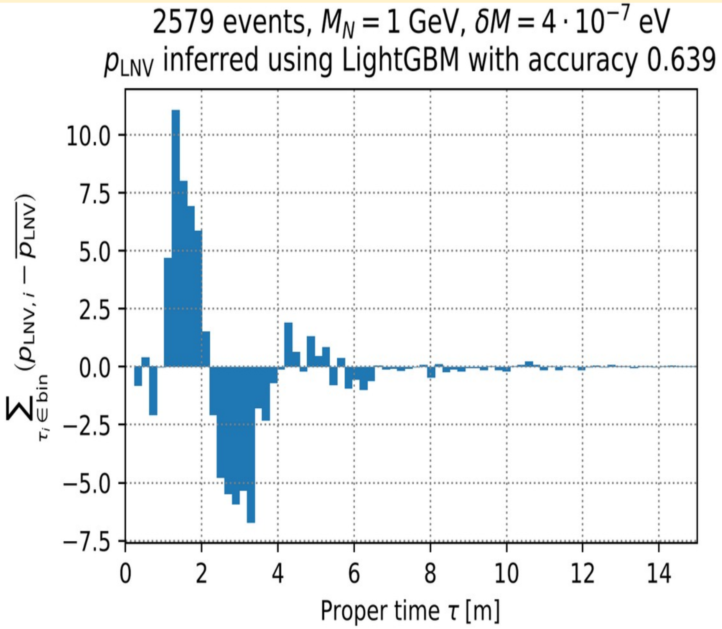
→ Would register 2600 HNLs in middle of its sensitivity range (close to sens. reach of other ECN3 proposals)

→ could distinguish btw LNV and LNC (Majorana-like vs quasi-Dirac-like) using momentum spectrum

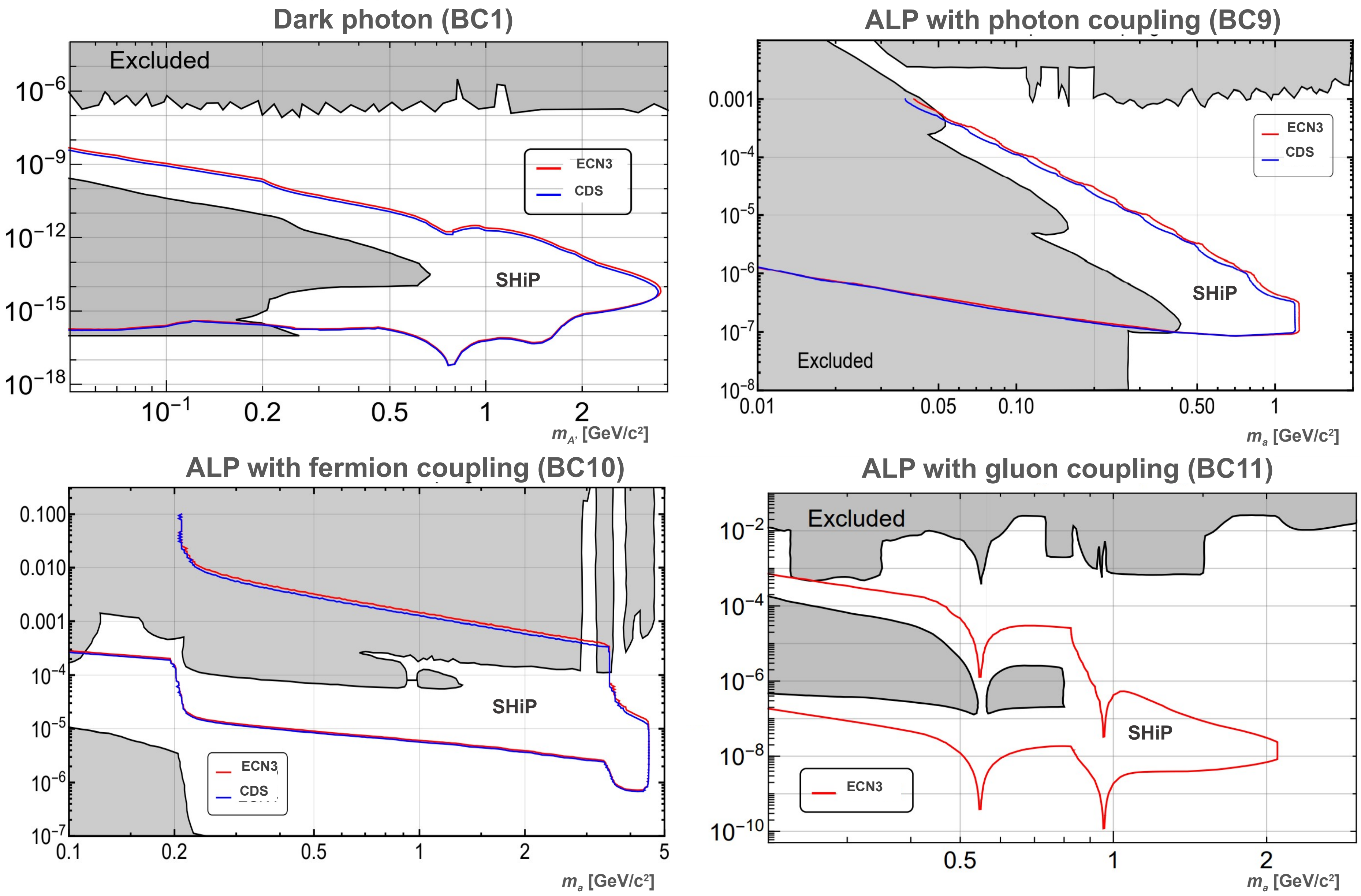
→ For quasi-Dirac-like pair: can measure HNL mass splitting $\delta M = 10^{-6}$~10^{-7}eV through oscillations



Tastet and Timiryasov, Dirac vs. Majorana HNLs (and their oscillations) at SHiP. *J. High Energ. Phys.* **2020**, 5 (2020). https://doi.org/10.1007/JHEP04(2020)005



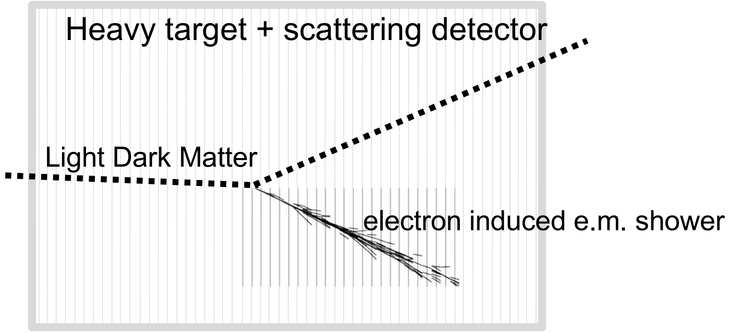
Signal sensitivities: DP, ALP



Sensitivity to LDM with SND @SHiP

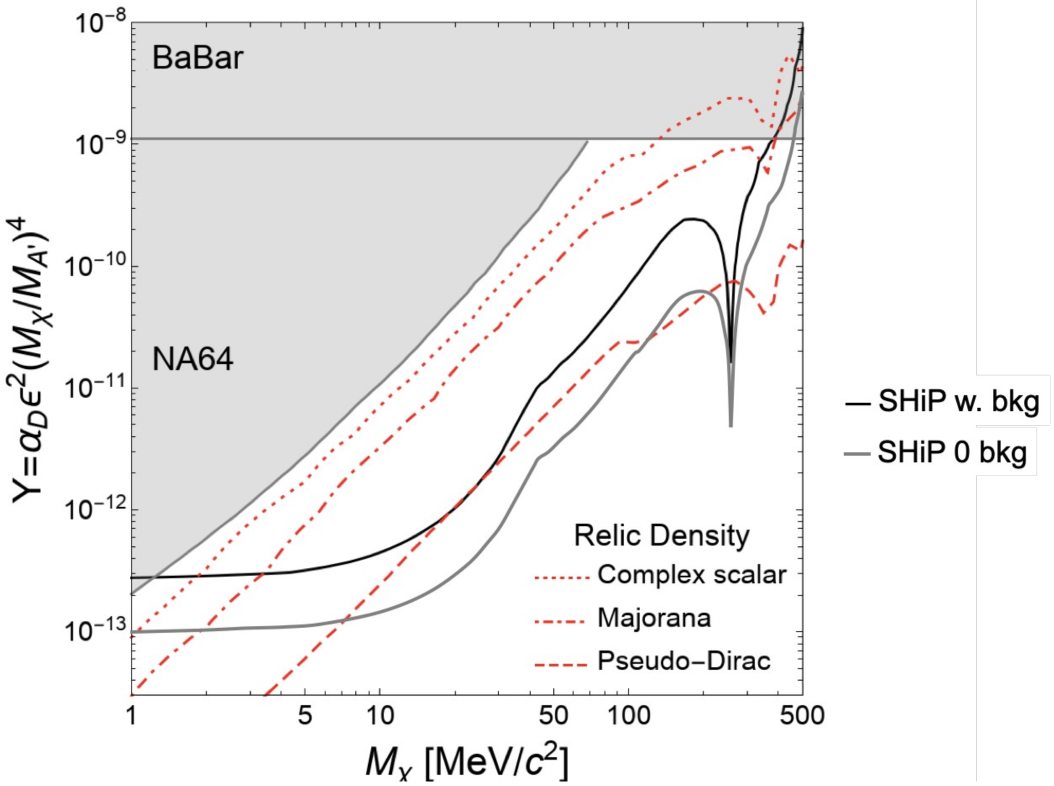
- ✓ *Optimisation is ongoing*
  - *Shape and mass of the LDM target*
  - *Replacement of emulsion with the electronic detector (vetoing neutrino background vs pile-up reduction)*
  - *Energy and pointing resolution for the EM shower initiated by the LDM interaction*

- ✓ *Hope to reach better sensitivity with SHiP/BDF@ECN3 compared to the CDS(ECN4) evaluation with the higher acceptance due to the SND location being closer to the beamdump target*



Backgrounds at ECN4

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	68	41	60	38	207
Quasi - elastic scattering	9	9			18
Resonant scattering	-	5			5
Deep inelastic scattering	-	-			-
Total	77	55	60	38	230

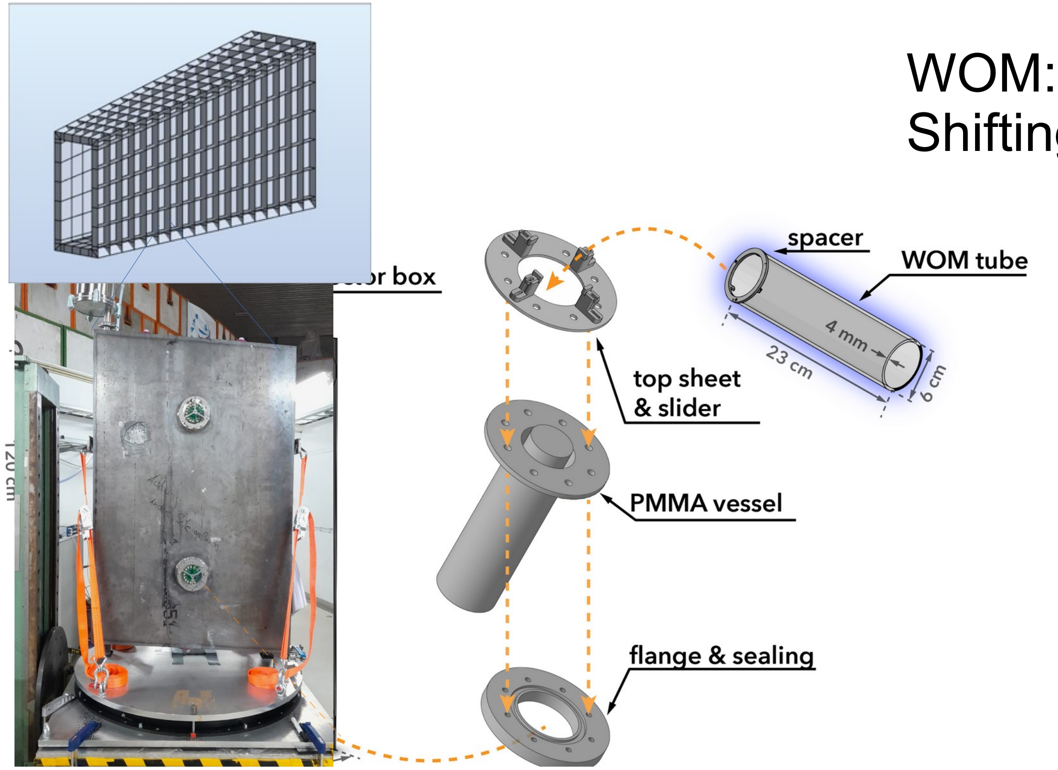


One example of the on-going detector developments

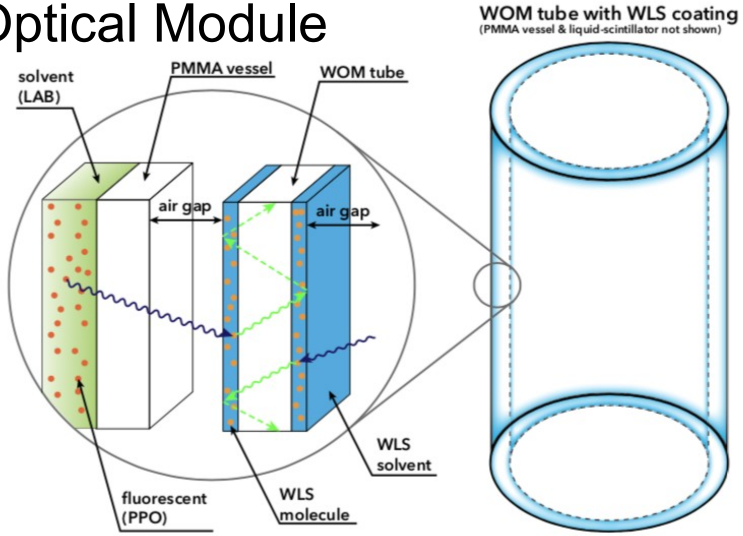
Liquid-Scintillator based Surround Background Tagger (SBT)

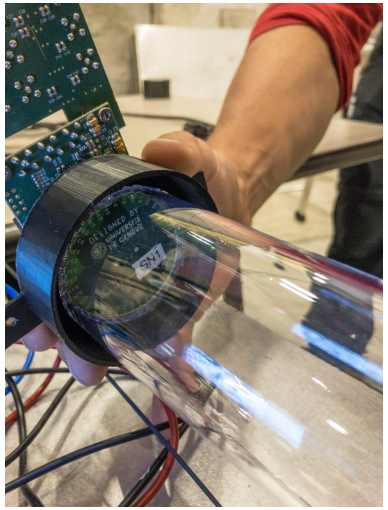
Liquid-Scintillator based Surround Background Tagger (SBT)

- ✓ Provides high hermiticity and hence high redundancy for reducing μ/ν DIS BG down to negligible level
- ✓ SBT+decay vessel: Addendum 3 to MoU on SPS BDF R&D programme
- ✓ SHiP SBT: Berlin, Freiburg, Kyiv, Mainz, FZ Jülich (ZEA-2), Naples + Support from FZ Jülich (ZEA-1)
- ✓ Technology funded within current generic detector R&D program of the German Ministry of Eduation and Research (BMBF): HIGH-D



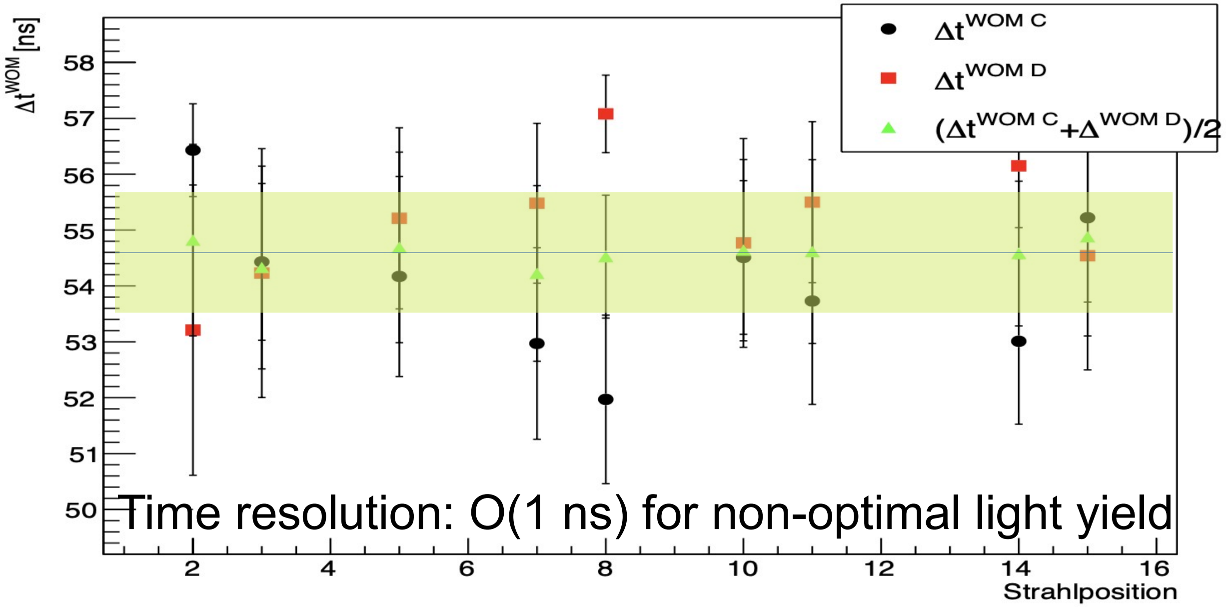
WOM: Wavelength-Shifting Optical Module



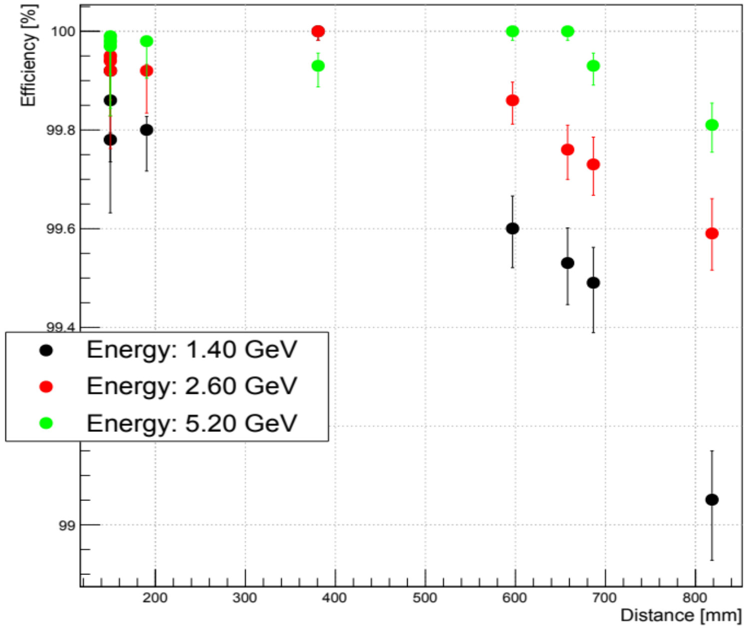


Liquid scintillator based SBT with WOM+SiPMs readout

CERN 2018 (μ, π)



DESY 2019 (e)



- ✓ CDS assumption: ε(45 MeV deposit): 99.9%
- ✓ ECN3 conservative assumption: 99%

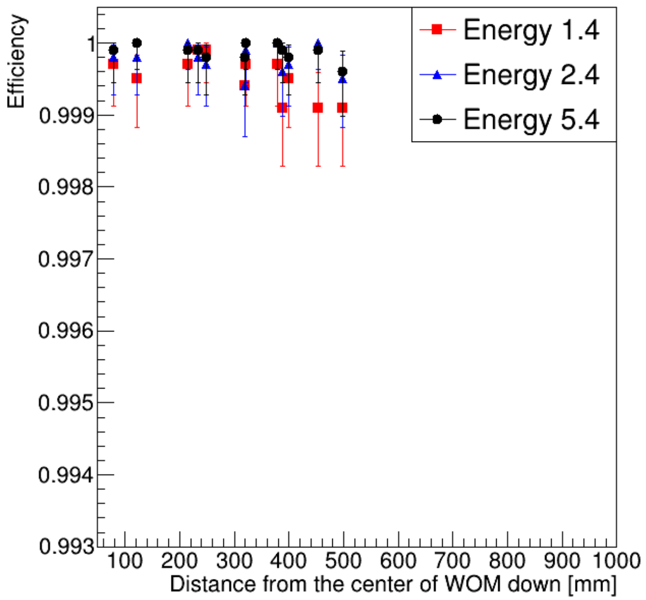
  (reached up to 80 cm distance from WOM)

  Various improvements identified in CDS report

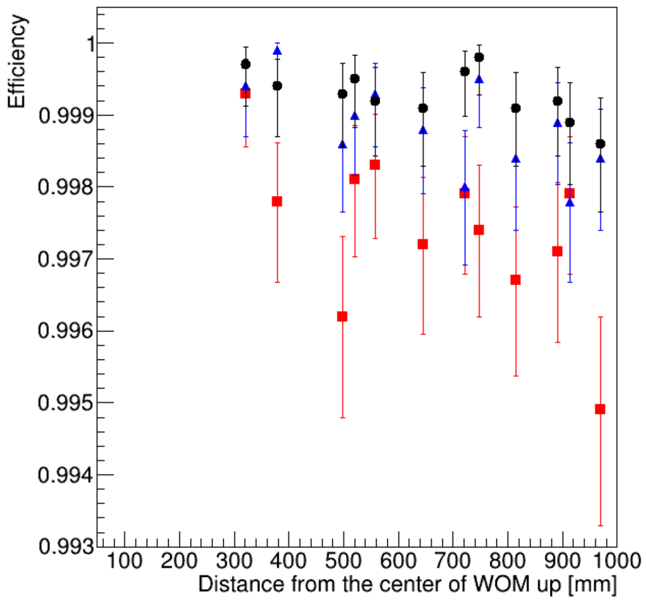
Improved SBT 1-cell prototype: DESY testbeam Oct 17-24, 2022

Efficiency as function of distance btw particle and WOM (Preliminary)

WOM down



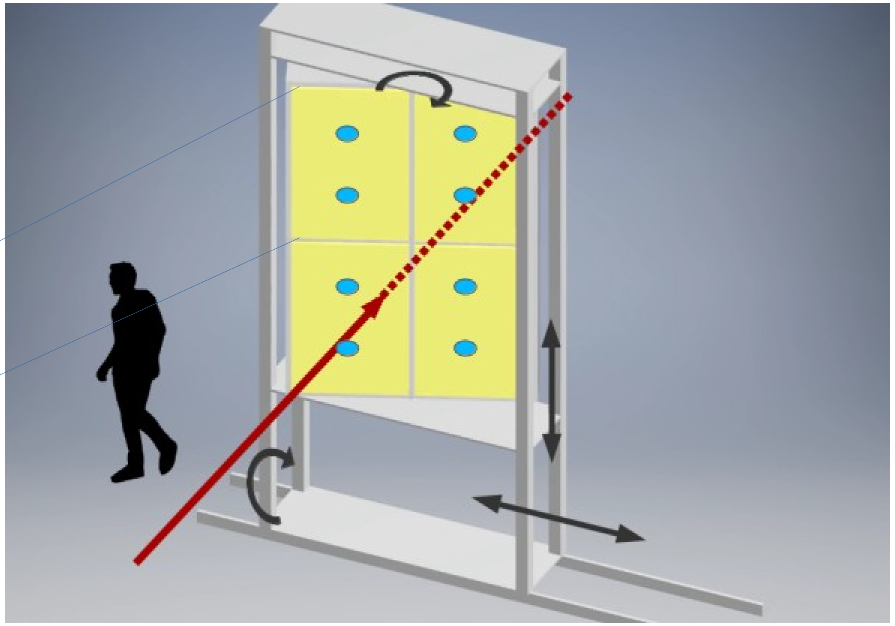
WOM up



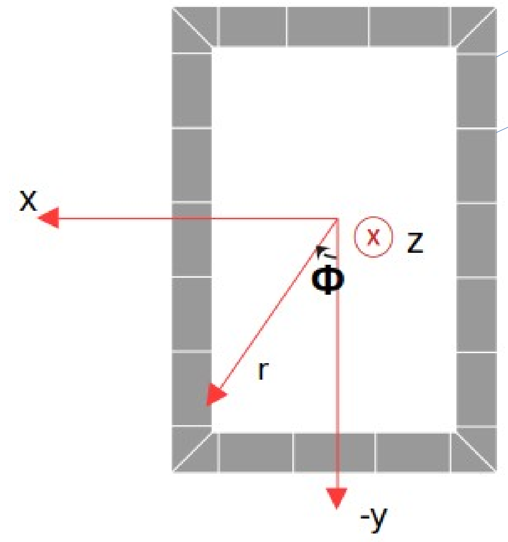
All envisaged improvements implemented:
→ HPK S13360-3050 → S14160-3050
(with 25% cost reduction)
→ WOM-WLS layer thickness increase by factor 4
→ liquid scintillator purification (Al_2O_3)
→ reflectivity coating of inner cell walls with $BaS0_4$

* > 99.3% (@95%CL) over complete detector cell achieved with silicon pad for optical coupling
* With optical gel: further light-yield increase (O(10%))

4-cell prototype: planned for CERN testbeam in fall 2023



- ✓ ***Implement lessons learned from DESY testbeam 2022***
- ✓ ***In-depth study of SBT integration into the decay vessel***
- ✓ ***Develop advanced particle reconstruction techniques***



TDR phase:
Design and construction of large-ring decay-vessel prototype with integrated SBT cells plus readout electronics

Conclusion

- ✓ ***BDF/SHiP @ ECN3 performance for HS exploration same as in CDS(ECN4) design: signal acceptance and „zero BG" thanks to high redundancy in BG suppression strategy***
- ✓ ***LDM sensitivity under study and may even improve compared to CDS(ECN4), with very good prospects to have the same performance for the neutrino programme as in CDS(ECN4)***

- ✓ *Complementary to FIP searches at HL-LHC and future e^+e^- collider.*
  Clear window of opportunities to discover HS particles with SHIP/BDF @ECN3, with the best discovery potential in this parameter region and relatively modest investments.

- ✓ *The sensitivity of the discovery experiment crucially depends on the available pots, signal acceptance and background control. The 10 years of R&D and simulation studies of the BDF/SHiP performance were very useful to optimise these parameters.*

- ✓ *All relevant detector systems have undergone prototype testing in test beam (example: LS-SBT)*
  → Main technological challenges identified (with work packages defined in CDS report)
  which will be addressed during TDR phase with full-size prototype production

- ✓ *BDF/SHiP @ECN3 with 47 institutes from 17 countries and 237 participants ready to set off*

Special thanks to the CERN BDF team for their work and support!

Excellent news: ECN3 sensitivities very close to ECN4 sensitivities