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BDF/SHiP @ ECN3 LoI

on behalf of the SHiP collaboration of 38 institutes from 15 countries and CERN

(The LoI document is short as it has long development history)

→ Attention is given to adaption and physics sensitivity at ECN3

References include
- *14 reports submitted to SPSC and ESPPSU2020*
- *26 reports on the facility development*
- *37 reports on the detector development*
- *11 reports on physics studies*
- *20 reports on theory developments (dedicated to SHiP)*
- *20 PhD thesis, a few more are underway*

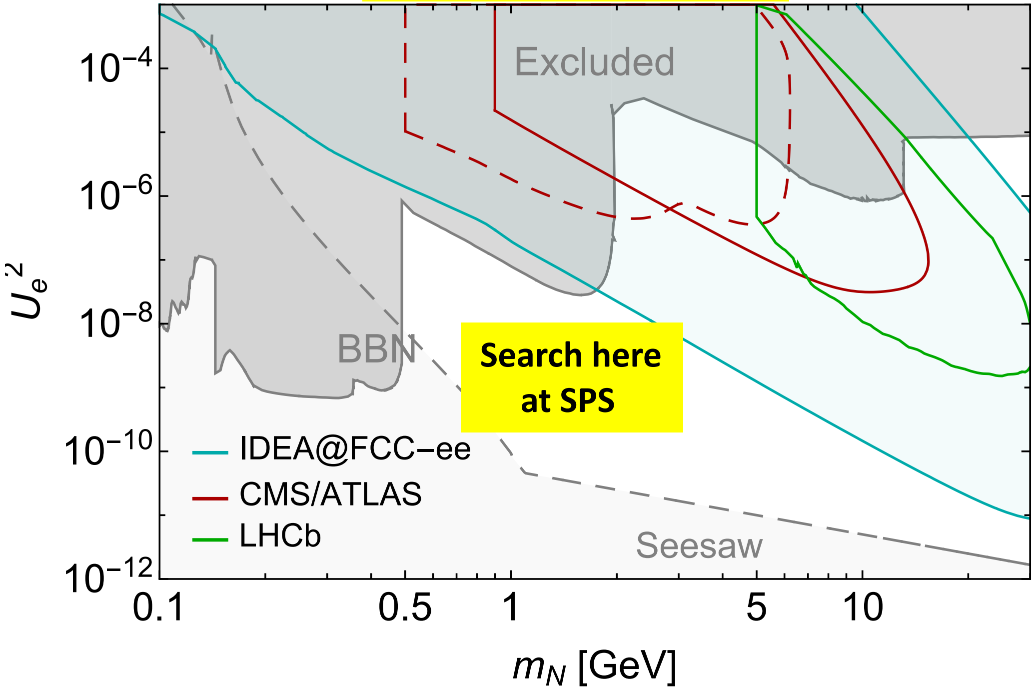
Why SPS (ECN3) is unique

A few very obvious statements:

- ✓ *Generic search for FIP is well motivated today*
- ✓ *Push intensity frontier at various energies*
- ✓ *Search for Dark Matter at accelerators using different methods (NA64 at SPS is already in place)*

Searches at SPS are very complementary to the searches at existing and future high energy colliders

Heavy Neutral Lepton



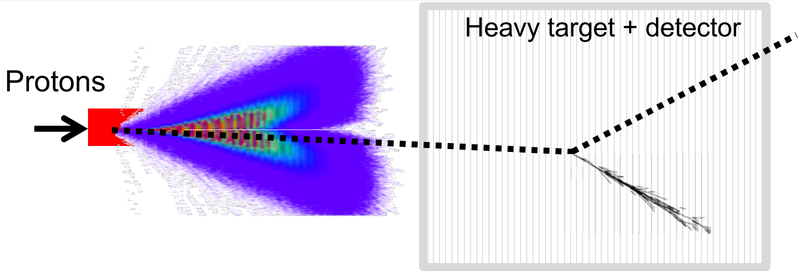
Search here at SPS

- ✓ *SPS provides right combination of high intensity and high energy proton beam (unique at slow extraction), e.g. one can produce >10^{18} D, >$10^{16}\tau$ and >10^{20} photons (E>100MeV) in 5 years of the BDF/SHiP operation*
- ✓ ***+ experience & infrastructure available at TCC8/ECN3***

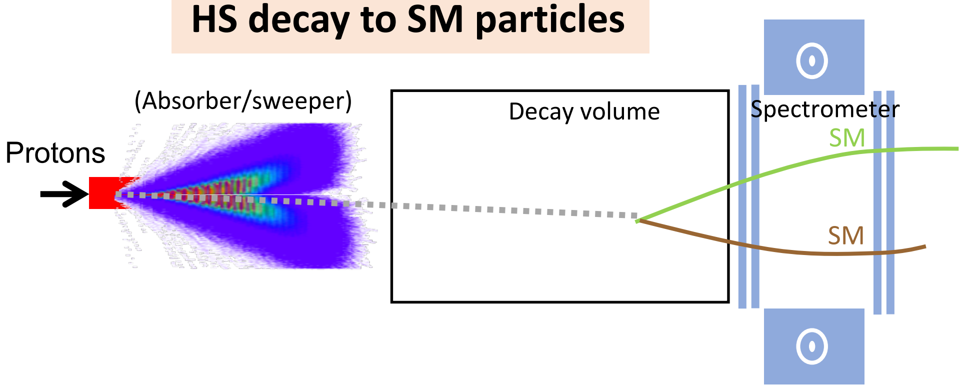
SHiP as presented in CDS(ECN4) report

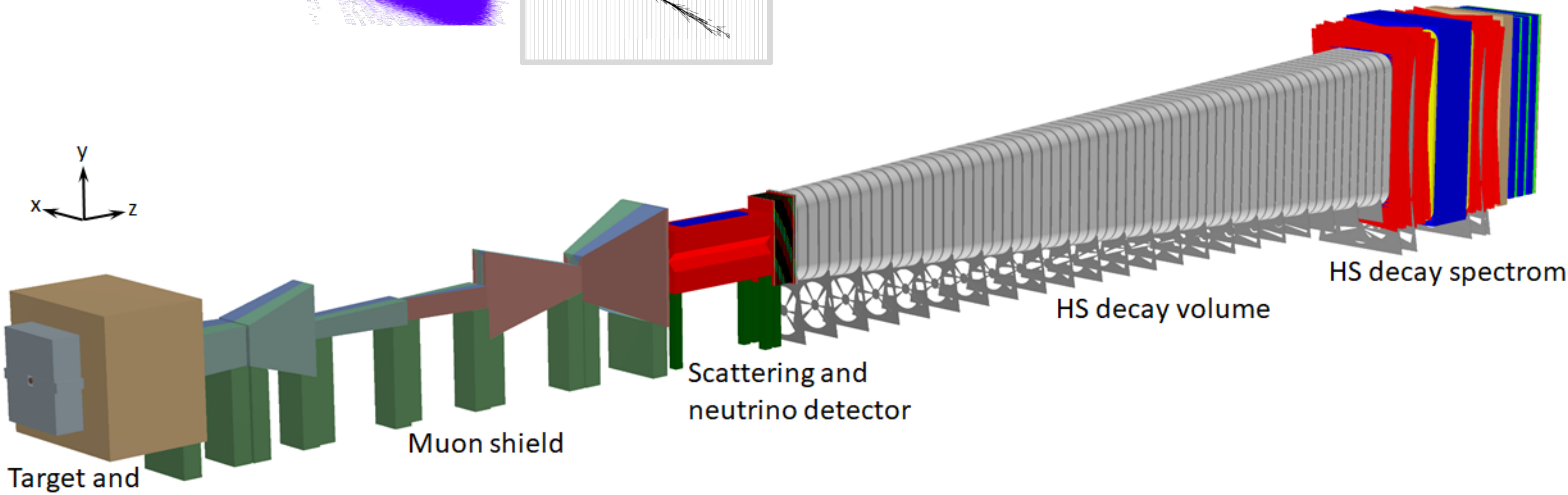
Dual-platform experiment combining two direct search techniques

LDM scattering off atomic electrons (and nuclei)
Neutrino physics



HS decay to SM particles





Target and
hadron absorber

Muon shield

Scattering and
neutrino detector

HS decay volume

HS decay spectrometer

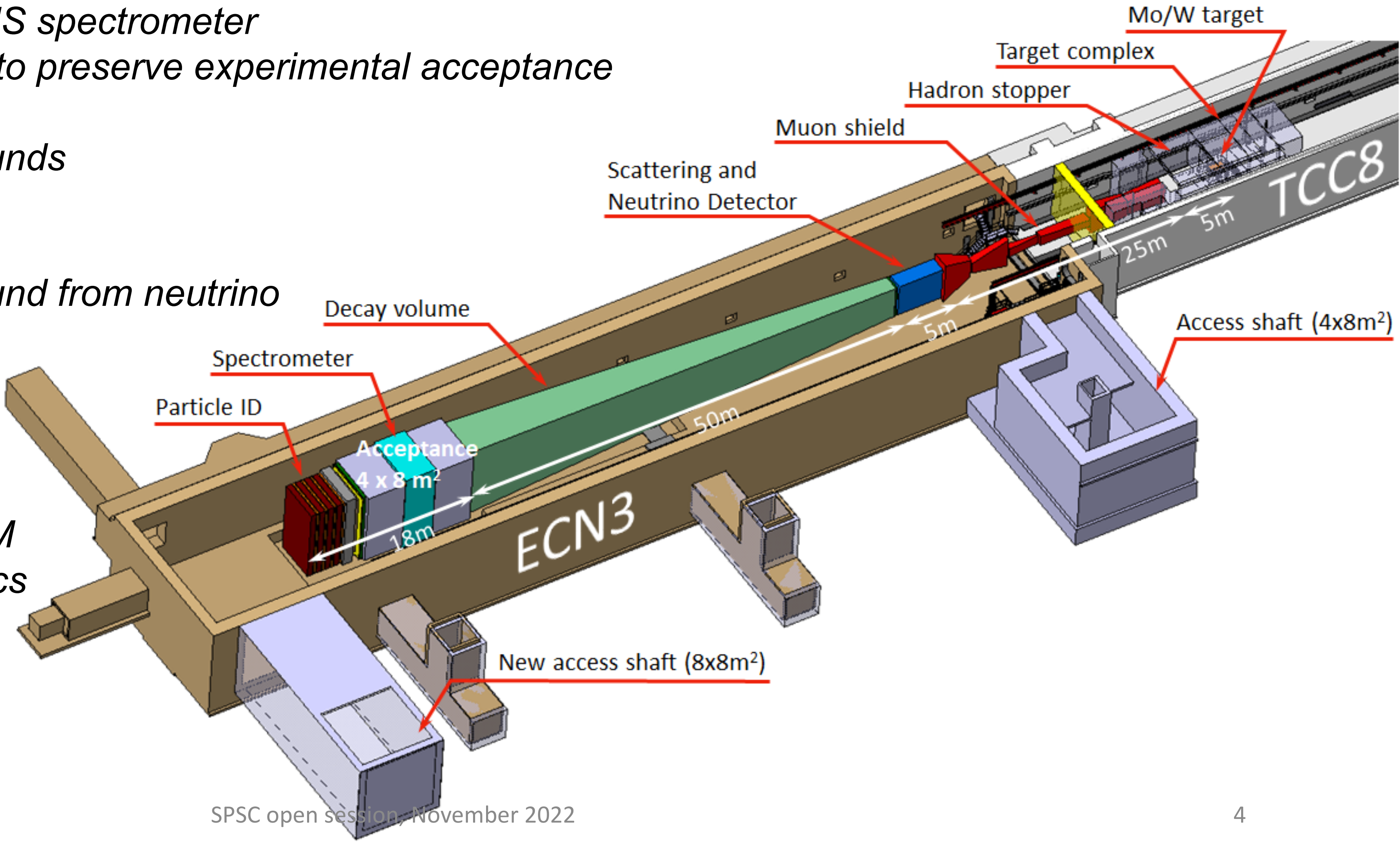
BDF/SHiP at the ECN3 line

Main challenges compared to CDS(ECN4) design

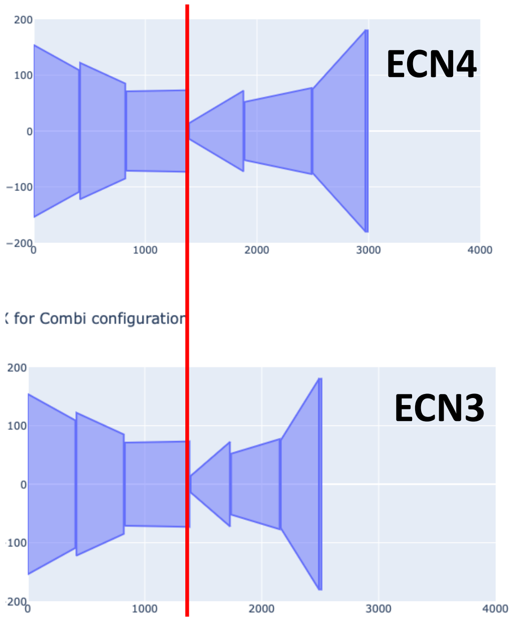
- ✓ ***Smaller size experimental hall***
  - *→ Smaller cross-section of the HS spectrometer*
  - *→ Shorter distance to the target to preserve experimental acceptance*
  - *→ Shorter muon shield*
  - *→ Potential increase of backgrounds*

- ✓ ***Tight infrastructure***
  - *→ Potential increase of background from neutrino and muon DIS*

- ✓ ***Less space for SND***
  - *→ Optimise the target mass to preserve / improve the LDM sensitivity and neutrino physics*

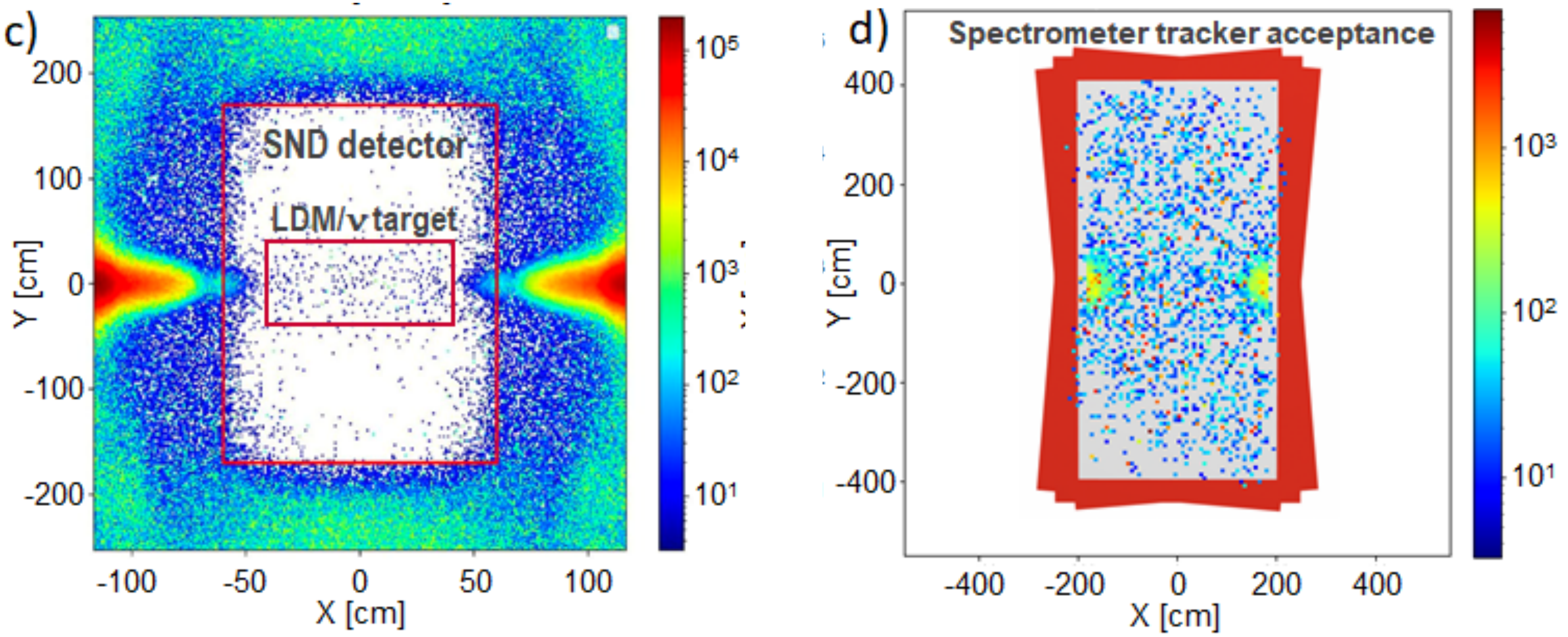


Muon shield



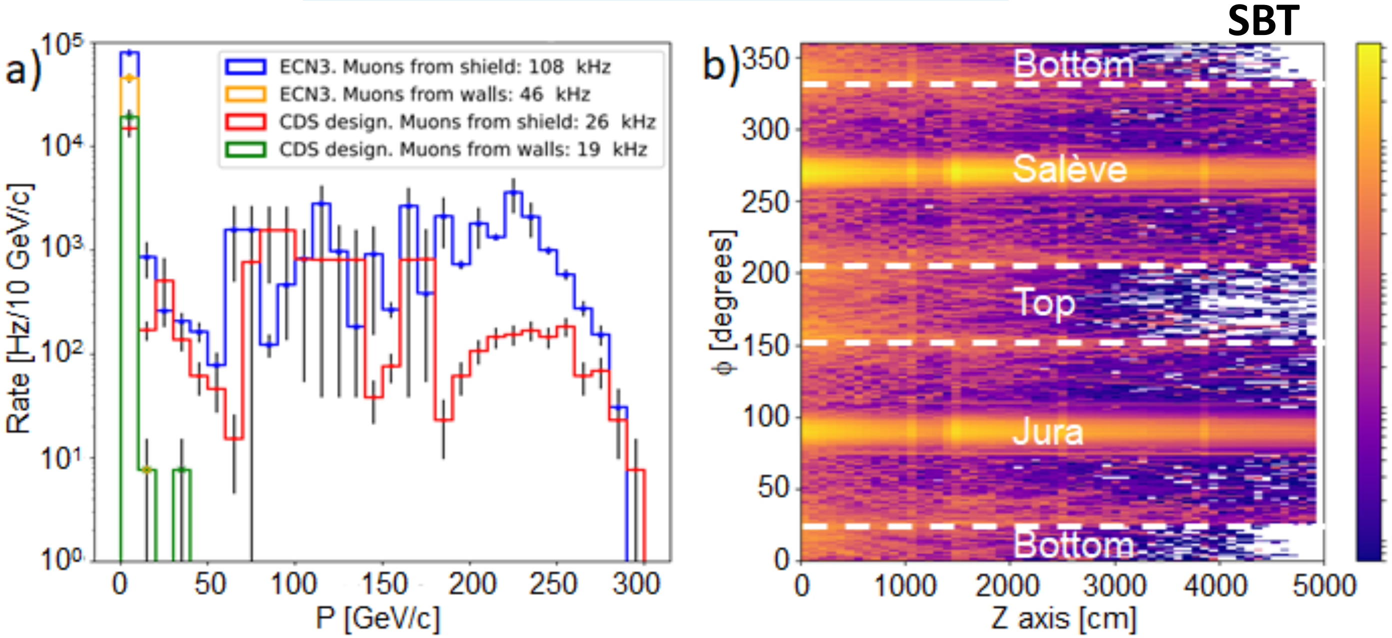
The goal is to reduce the initial flux of 10^{11} per spill by up to ~6 orders of magnitude

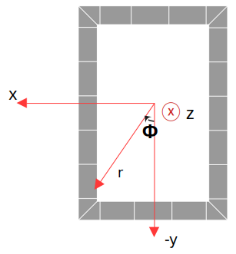
- ✓ *Muon shield is shorter by ~5m at the ECN3 but still provides sufficient field integral to deflect hard muons*
- ✓ *1st iteration: upstream half is unchanged, the magnets of the downstream half are downscaled preserving the same shape as in the CDS(ECN4) design*
  It is not perfect: "hot spots" in the HS tracker



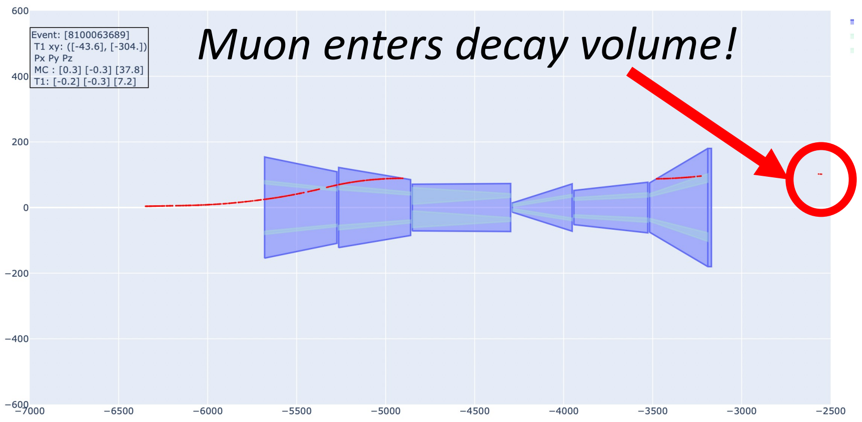
Current muon rate is very conservative → being used for background evaluation at ECN3

Muon rates



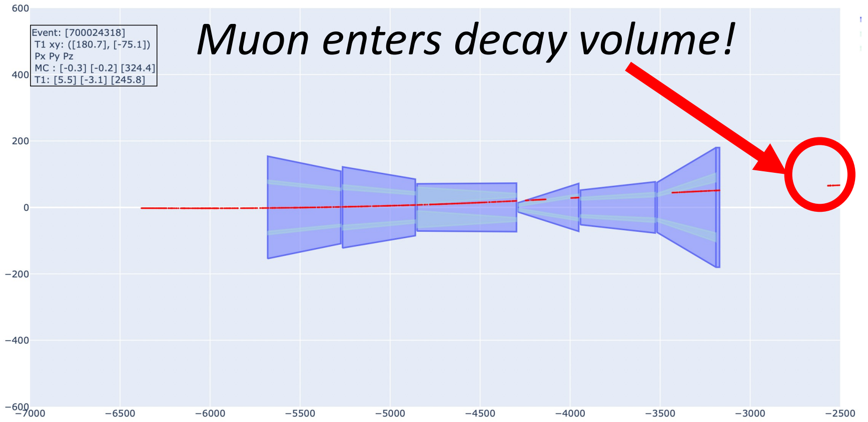


Apart from the "hot spots", the rate increase is mostly due to suboptimal performance of the shield for deflecting the muons returned back to the detector acceptance by the reverse field:



Muon enters decay volume!

Muon with primary P = 38 GeV



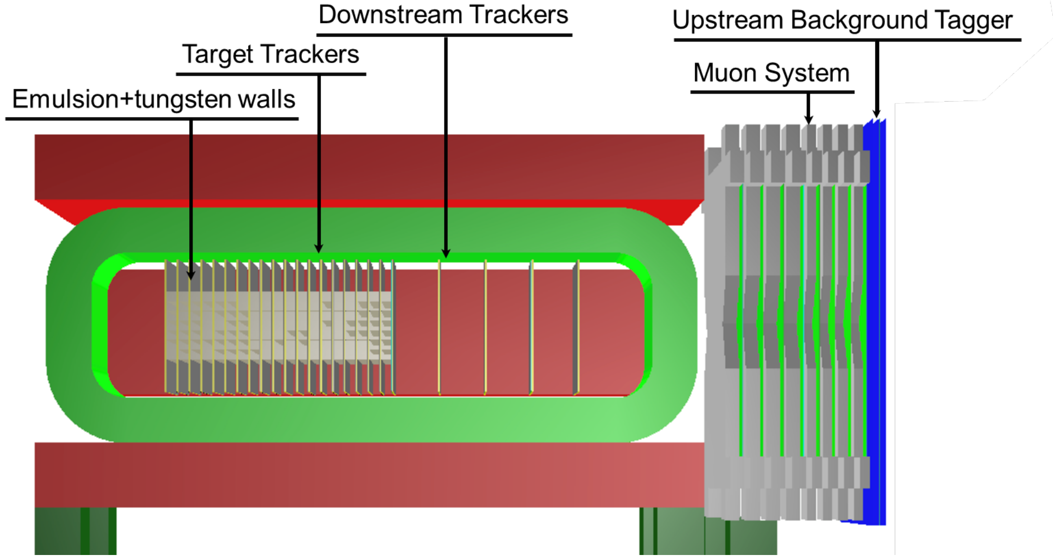
Muon enters decay volume!

Muon with primary P = 324 GeV

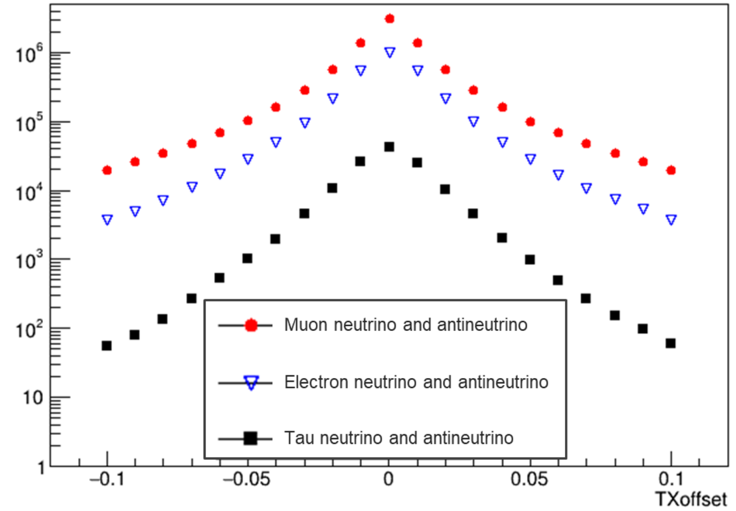
- ✓ *Optimisation of the muon shield is underway, reducing muon rate almost back to the CDS(ECN4)*
- ✓ *Study of alternative SC technologies to further shorten the shield*

Optimization of SND for LDM / Neutrino physics at ECN3

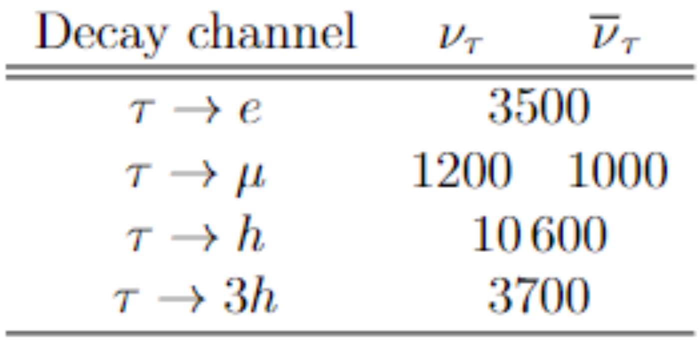
- ✓ ***Changed SND design at ECN3***
  (converge on the balance between LDM and ν_τ sensitivity)
- ✓ ***Remove SND magnet to increase the mass of the target***
  - *→ Use exclusively muons from the golden $\tau \rightarrow \mu\nu\nu$ channel*
    Measure muon charge and momentum using magnetised iron with tracking layers (a la OPERA)
- ✓ *Use of emulsion for τ – neutrino physics is mandatory, not necessarily so for LDM search. The flux of muons after muon shield is about OK for emulsion even for non-optimised shield*



CCDIS neutrino yields with 4.5-tonne 40x40cm^2 detector at different angular position



Reconstructed tau neutrino events



Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \rightarrow e$	3500	
$\tau \rightarrow \mu$	1200	1000
$\tau \rightarrow h$	10 600	
$\tau \rightarrow 3h$	3700	

On-axis location of SND at SHiP provides best sensitivity: 20000 tau neutrinos, including 2200 ν_τ events reconstructed with flavour identification in $\tau \rightarrow \mu\nu\nu$ golden mode

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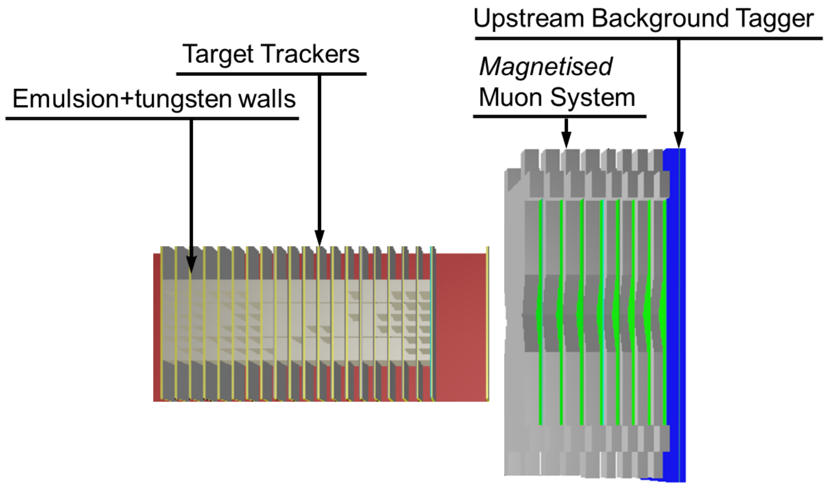

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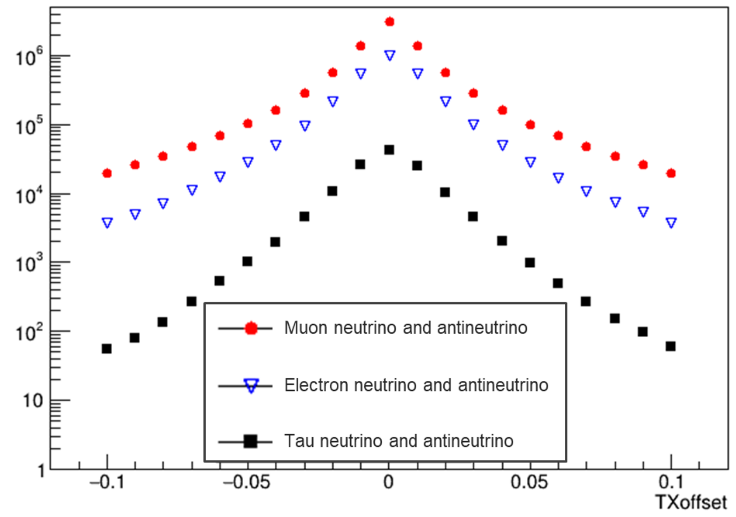

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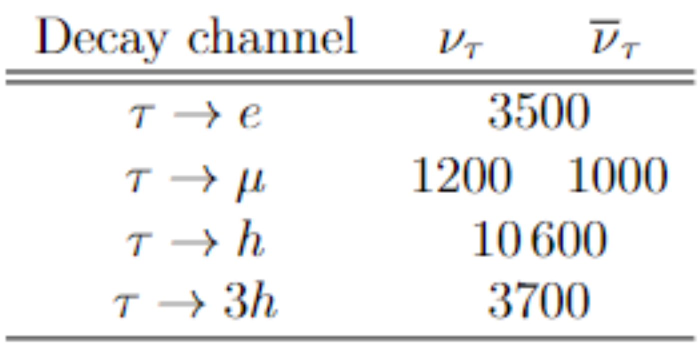

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Sensitivity to HS signals

Sensitivity for the HS signal depends on the three factors:

- ***Npot***
- ***Signal acceptance***
- ***Background level and control of its systematical errors(*)***

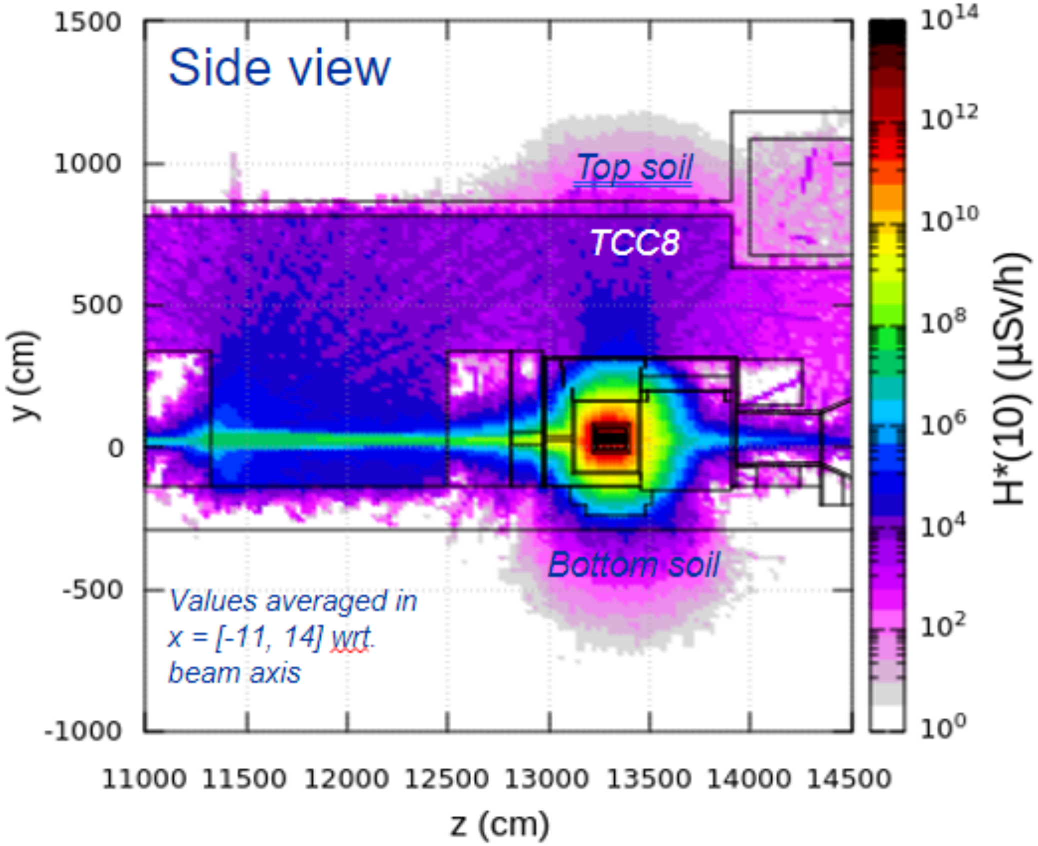
(*) Tune simulation using data in SHiP

- *Possibility to measure background with data, relaxing selection cuts*
- *Vary veto criteria in UBT&SBT*
- *Turn off the magnetic field of the muon shield, vary vacuum level in the decay volume*
- *Extensive usage of the beam monitors*

Npot

Npot* = 2×10^{20} in 5 years of operation.** *There are no reasons why SHiP cannot run for 10 years and collect* ***Npot = 4×10^{20} *or more*

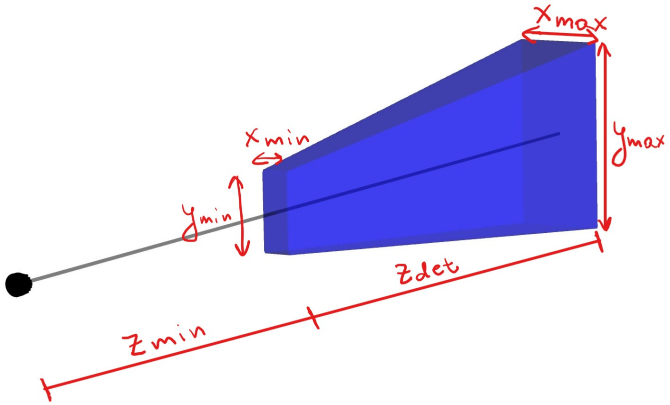
BDF Preliminary dose rates



The large Npot requires the specialized infrastructure which is currently being evaluated.

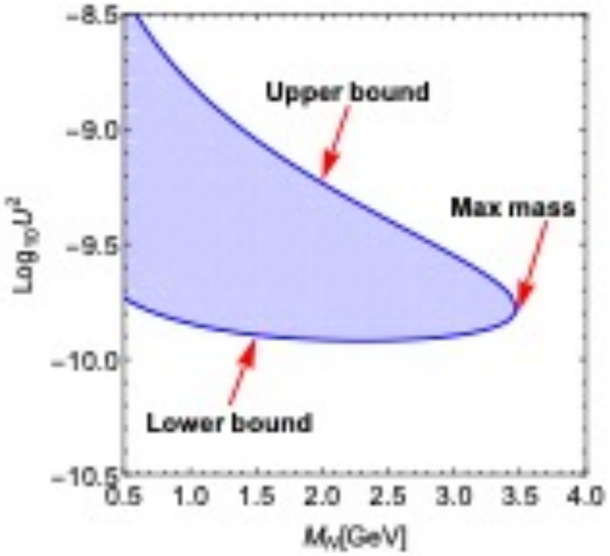
Signal acceptance

Signal acceptance calculated for both fully ***and partially reconstructed channels including final states with neutrinos → important to search for HNLs with enhanced U_τ – couplings and "neutralinos" …***



Decay vessel parameters

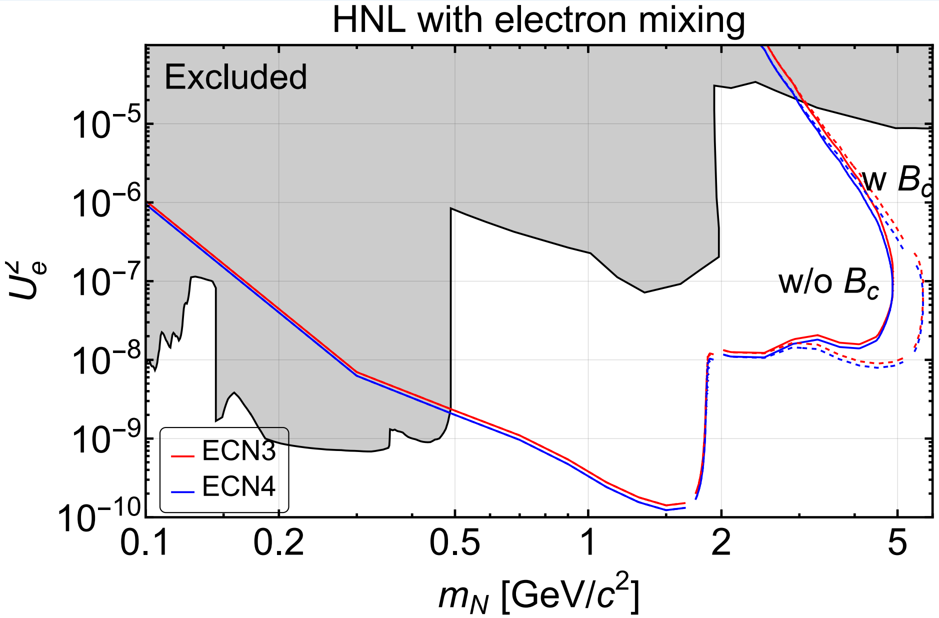
	z_{min}	z_{det}	x_{min}	y_{min}	x_{max}	y_{max}	$\Omega_{vessel\ end}$
CDS Design	48 m	50 m	1.5 m	4.3 m	5 m	11 m	$5.7 \cdot 10^{-3}$
ECN3	37 m	50 m	1.2 m	3.5 m	4 m	8.7 m	$4.6 \cdot 10^{-3}$

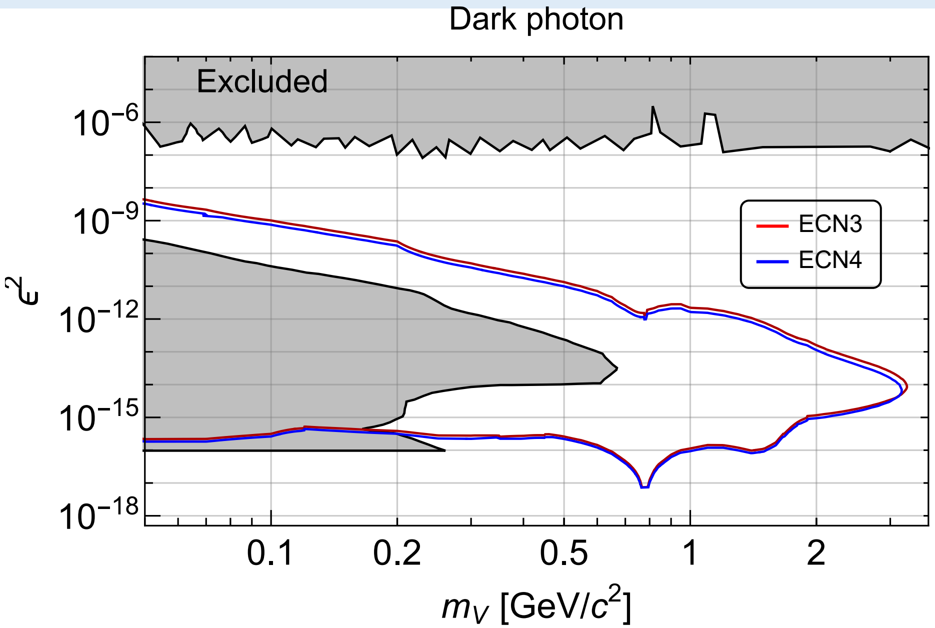


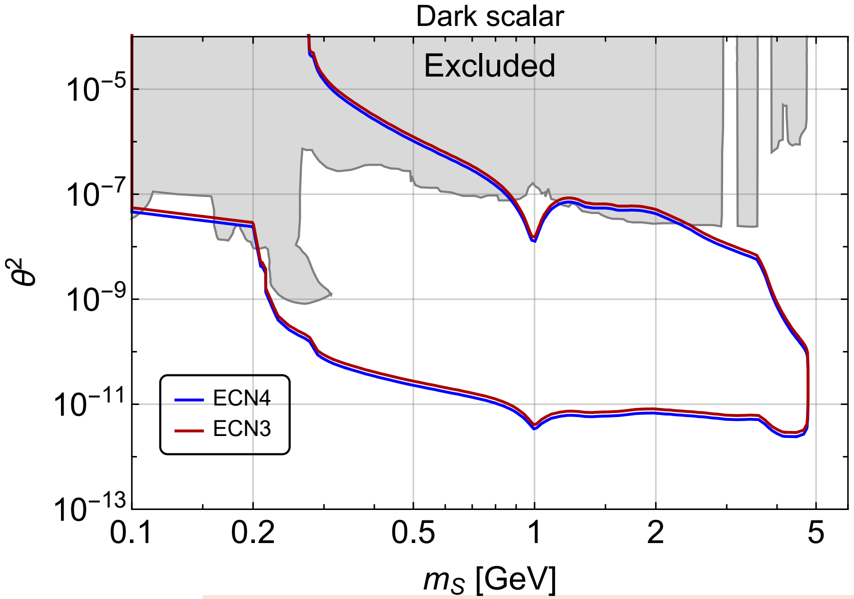
- ✓ *Upper bound of the sensitivity contour is determined by the distance from the target, z_{min} → ECN4 / ECN3 ≈ 0.8*

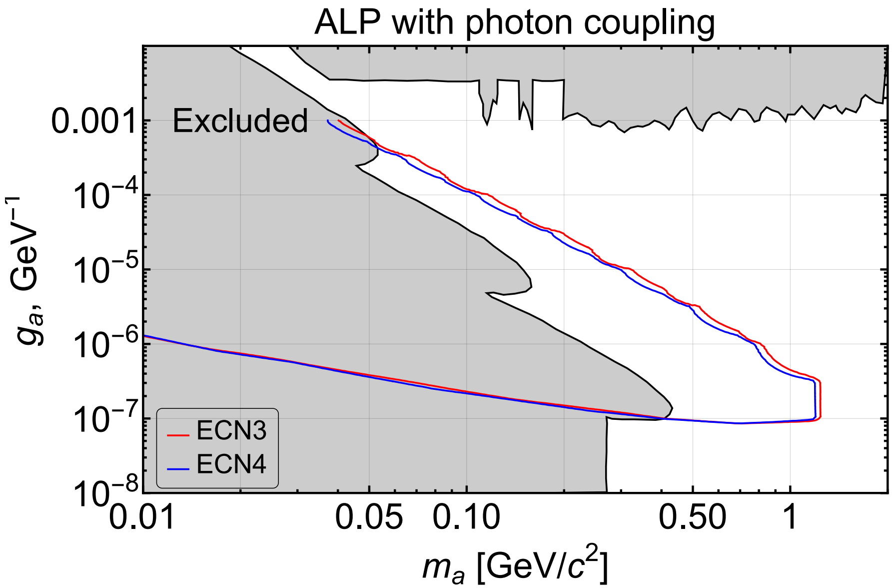
- ✓ *The lower bound depends primarily on the number of observed NP events within the SHiP angular coverage, $\Omega_{decay\ vessel}$, model dependent NP(Ω)*
  For the uniform NP(Ω), ECN4 / ENC3 ≈ 1.1

Signals for Npot = 2×10^{20}: HNL(BC6), Dark photon(BC1), Dark scalar(BC4), ALP(BC9)


HNL with electron mixing

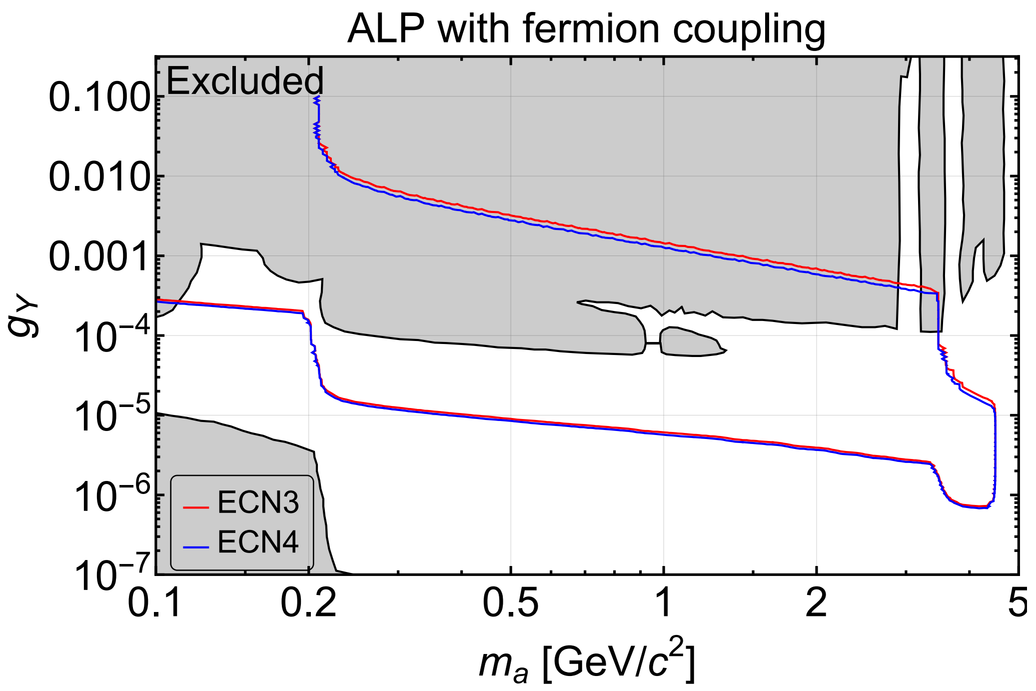

Dark photon

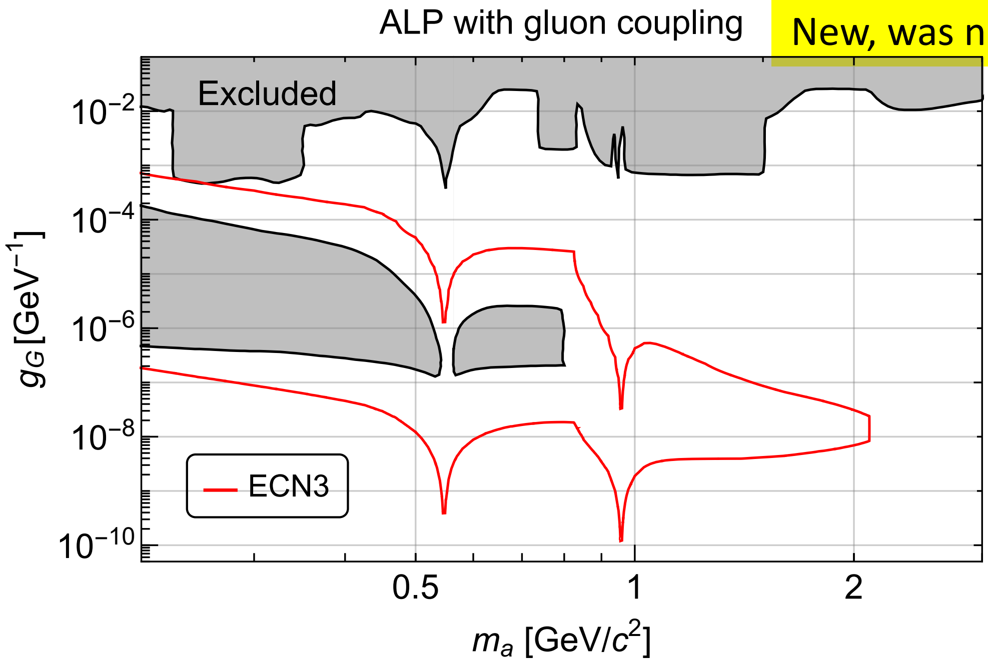

Dark scalar


ALP with photon coupling

Physics reach for HS particles is nearly identical at ECN3 and ECN4 assuming zero background

Signals for Npot = 2×10^{20} : ALP(BC10, BC11)





New, was not in CDS

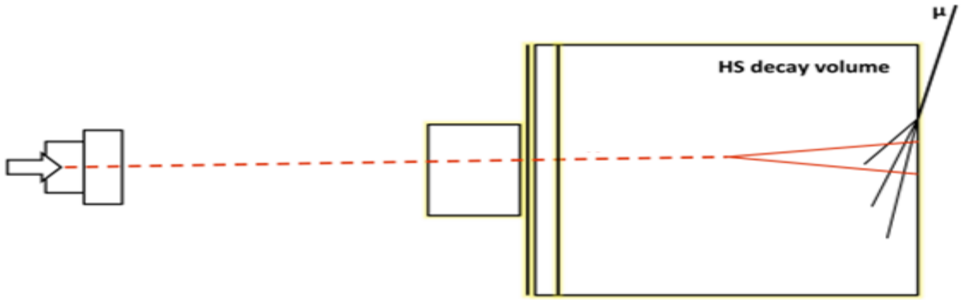
Physics reach for HS particles is nearly identical at ECN3 and ECN4 assuming zero background

Backgrounds

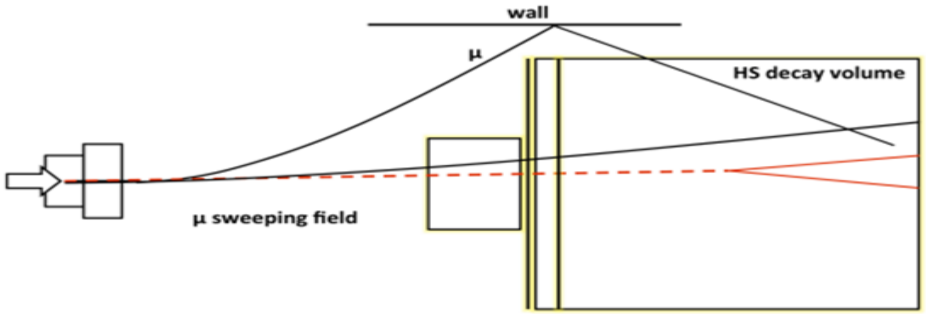
Pythia/Geant simulation with complete description of detector and infrastructure

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

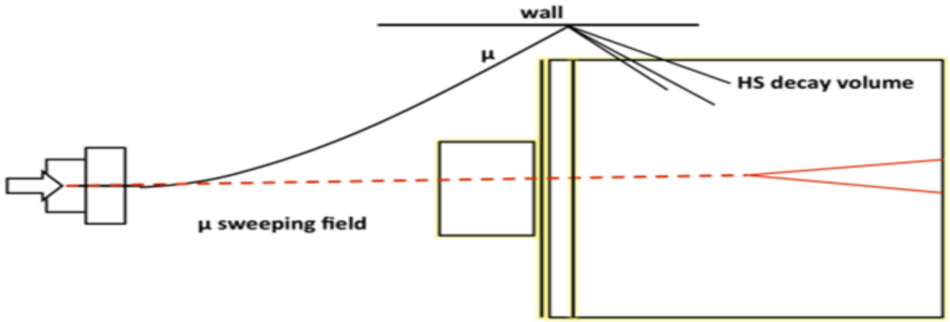
Backgrounds in decay search (fully reconstructible/partially with neutrinos) in 2×10^{20} pots in 5 years



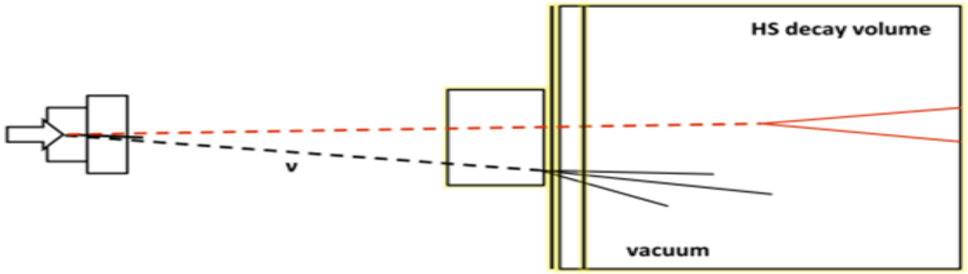
Cosmics: negligible



Muon combinatorial: $1.2 \times 10^{-2} \pm 1.2 \times 10^{-2}$



Muon DIS: 6×10^{-4}



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

Our goal: to confirm similar backgrounds levels at ECN3

Backgrounds

(control of very rare outliers of the background sample)

What is non-trivial in the SHiP background simulation ?

- ✓ *Huge rejection power needed →* ***Requires large sample of simulated events***
  → SHiP simulated 6.5 × 10^{10} pot with E>10 GeV

- ✓ *Most "dangerous" signal-type muons are produced in charm and beauty decays, and in QED resonance decays (e.g. $\rho \to \mu\mu$).*
  Special care is taken in the SHiP simulation:
  → Simulated samples of charm and beauty decays correspond to ~ 10^{11} pot
  → Enhance resonance decays by two orders of magnitude in GEANT

- ✓ *Muon and Neutrino DIS processes*
  → ***Used Pythia6*** *to generate Muon DIS events and calculate the cross section.*
  Boost statistics by forcing each muon to interact according to the material distribution
  → ***GENIE*** *generator is used for Neutrino DIS, and each neutrino is again forced to interact*

Backgrounds

How SHiP suppresses backgrounds?

SHiP is protected against backgrounds by:

(a) ***Target*** *(A/Z^2, λ) to suppress weak decays to muons and neutrinos*

(b) Hadron stopper (5m thick iron) *absorbs hadrons produced in the beam dump*

(c) Magnetic muon shield (25 m long) *deflects muons, produced in the dump (~10^{11} per spill), away from the detector acceptance*

Muon shield used for the sensitivity evaluation at ECN3 is being improved → we expect further reduction of the rate by a factor.

(d) Background taggers UBT and SBT surrounding the decay volume *protect from*

- *muons leaking through the shield, and hadrons from muon DIS interactions,*
- *particles produced in neutrino interactions with material*
- *cosmics*

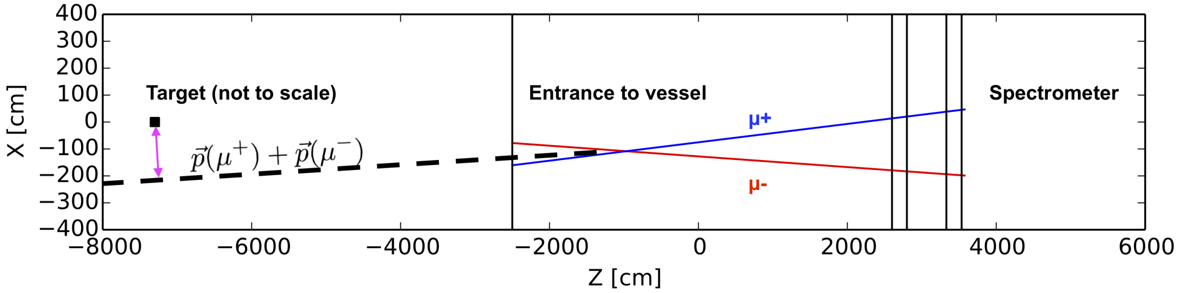
(e) Evacuated Decay Volume

(f) Reconstruction cuts: *fiducial volume, vertex quality, pointing to the dump target, timing window, PID*

Each of these components is absolutely crucial

Designed redundancy in background suppression allows very simple and robust event selection that will be improved in future optimisations

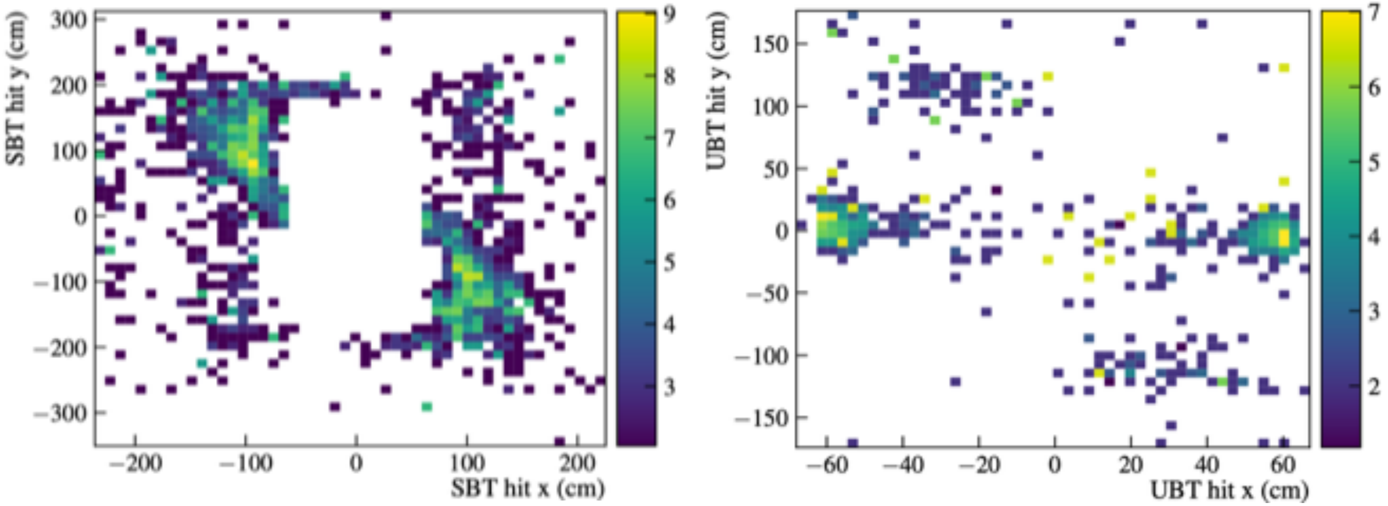
Combinatorial background *(ECN3 in 5 years)*



Event selection

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

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



✓ *Event selection*	9×10^{-4}
✓ *Time coincidence of the tracks from HS vertex*	3.4×10^{-10}
✓ *SBT efficiency (45 MeV threshold)*	*99%*
✓ *UBT efficiency (as measured with prototypes)*	*98% per MRPC*
✓ *Upstream veto rejection power* ***(UBT/SBT with good time and spatial is resolution is crucial)***	7.7×10^{-7}

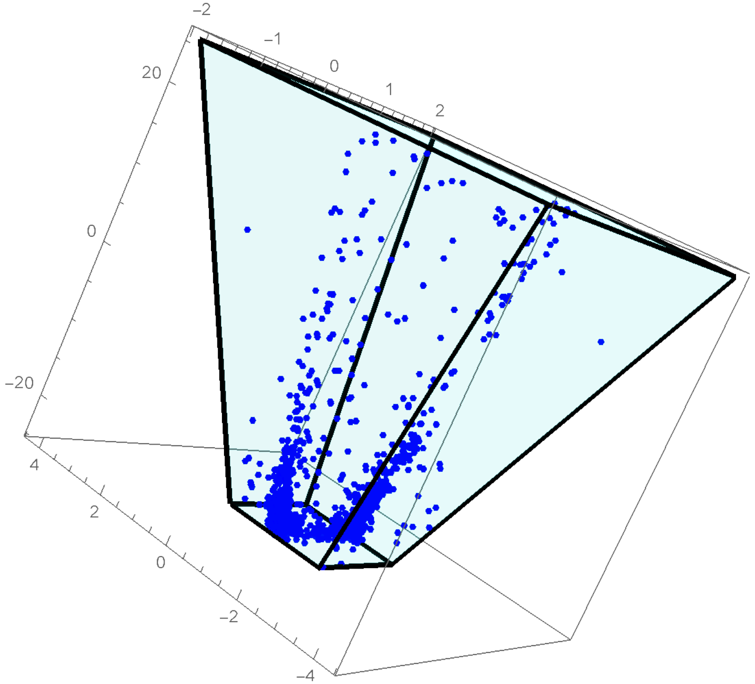
Comb. Background: 2.1×10^{-3}

MUON DIS *(ECN3 in 5 years)*

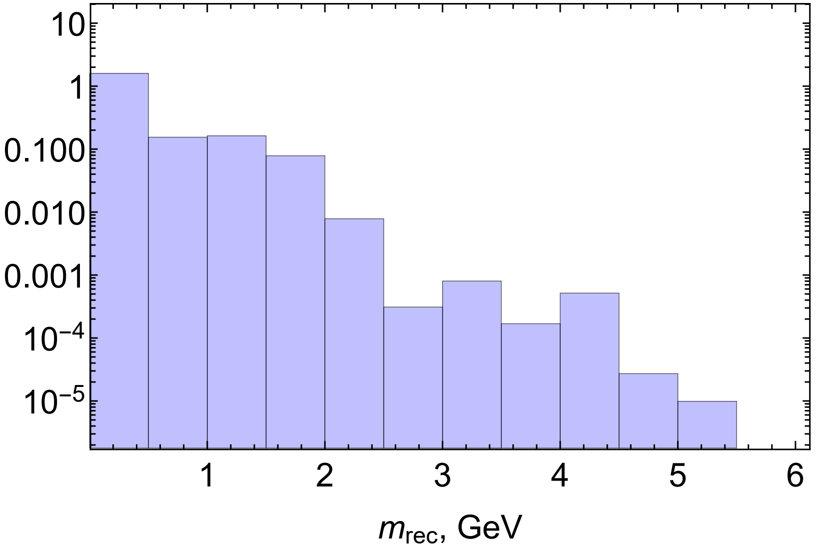
After pre-selection: ~1000 fully rec. and 2×10^5 partially rec. events

Completely dominated by random combinations of particles produced in the same interaction made of ee(31%), $\mu\pi$(28%), $\pi\pi$(22%), eπ(5%), eμ(5%), pp(4%) and $\mu\mu$(3%)

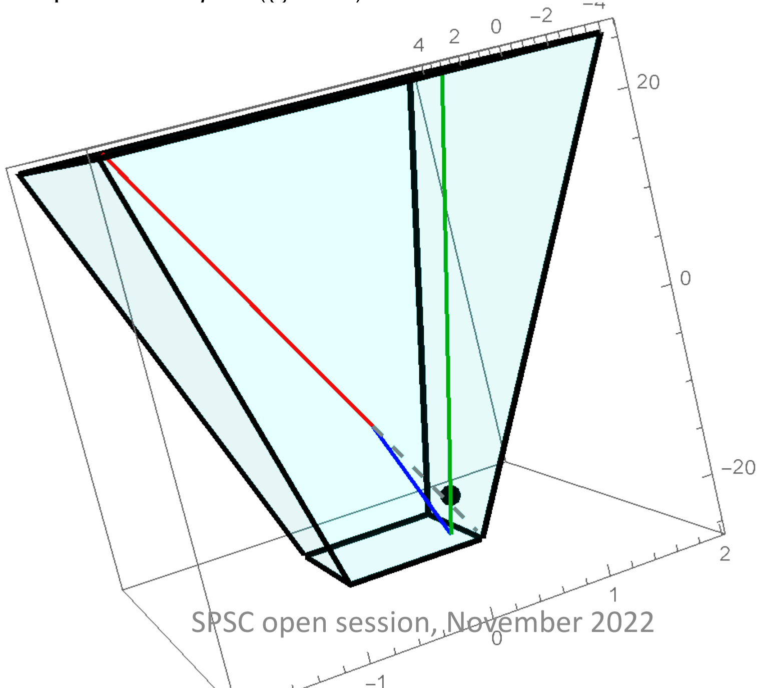
→ cannot be rejected by cuts on invariant mass



Invariant mass of h^+h^-, V^0s not seen
→ Needs to be vetoed by SBT



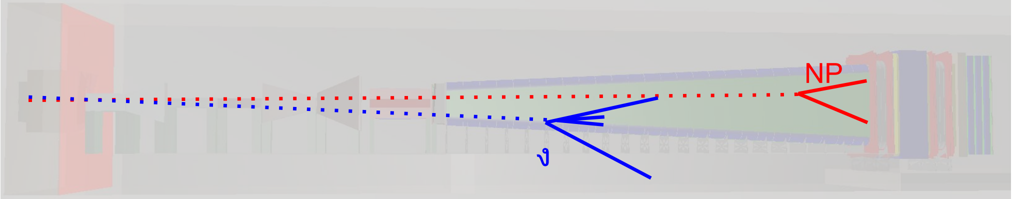
Example of "combinatorial" event: μ^- (red) and π^+ (blue) from DIS vertex, π^+ decays and produces μ^+ (green)



High Veto efficiency of Background Taggers (UBT&SBT) is crucial for the DIS suppression!

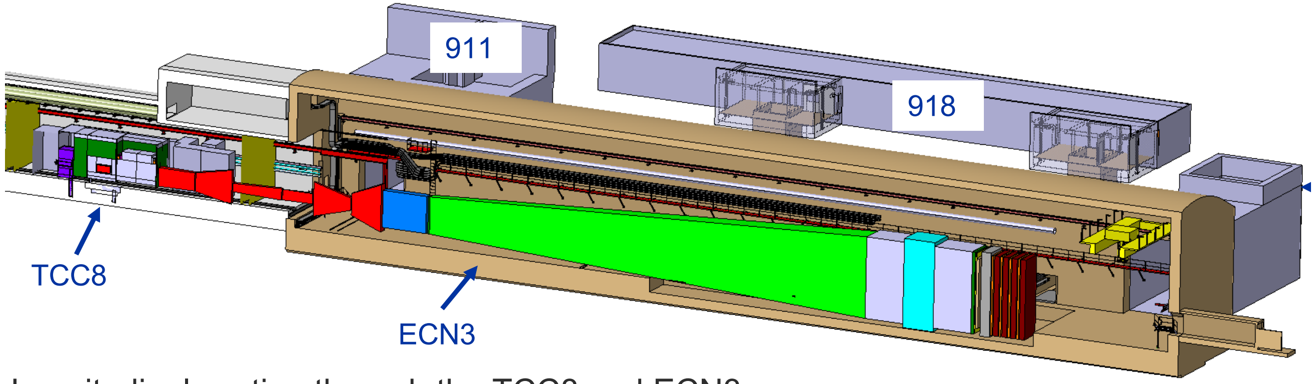
Muon DIS background:
$< 2\times10^{-4}$ (fully reconstructed)
$< 2\times10^{-2}$ (partially reconstructed)

Neutrino DIS *(ECN3 in 5 years)*

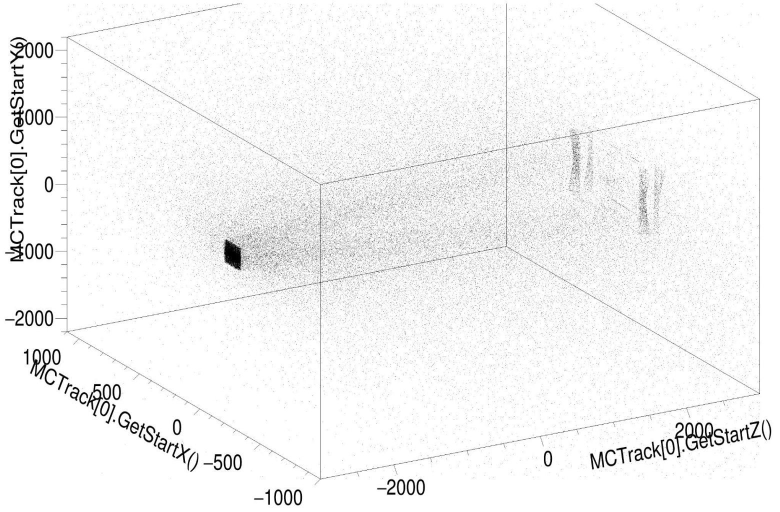


The MC sample used in CDS report corresponds to 35 years of SHiP data. The whole ECN3 experimental area implemented

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***



Longitudinal section through the TCC8 and ECN3 cavern

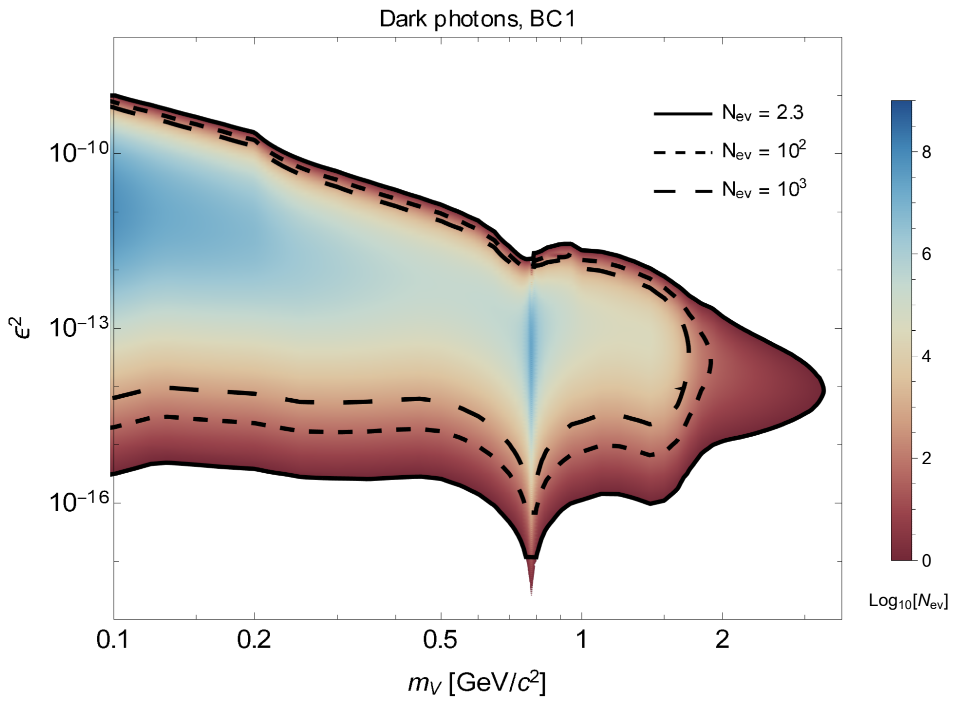


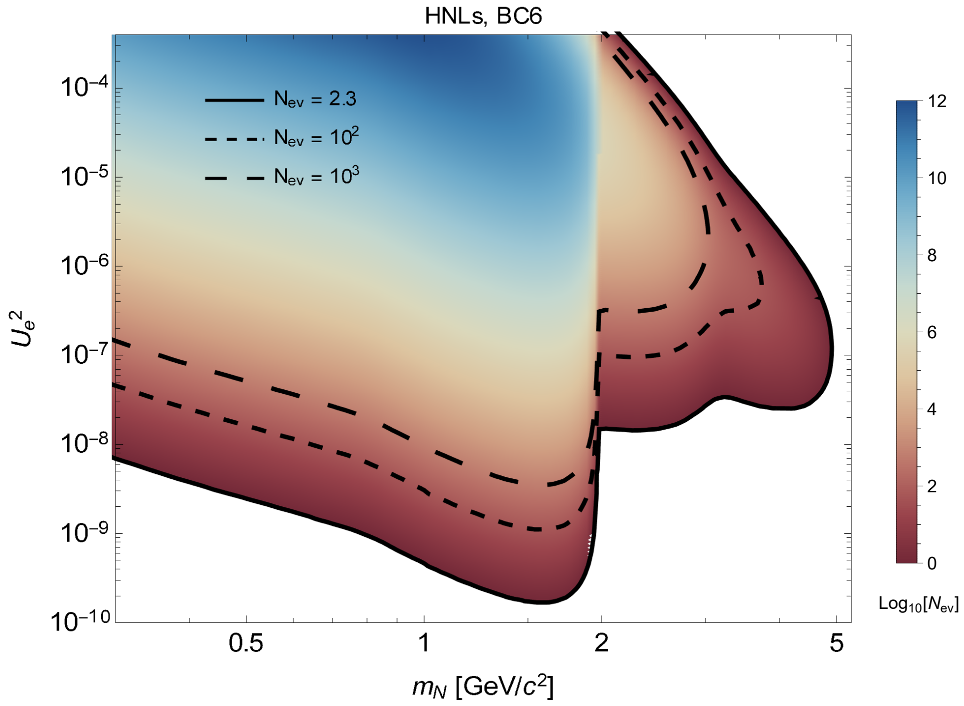
Sources of neutrino DIS background:

- 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.)

Examples of SHiP HS sensitivities: exclusion limits, 100 and 1000 events observation with zero background as proven by MC

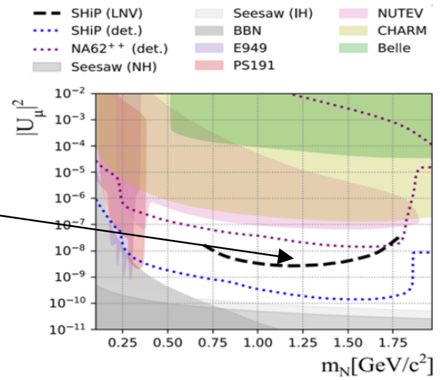


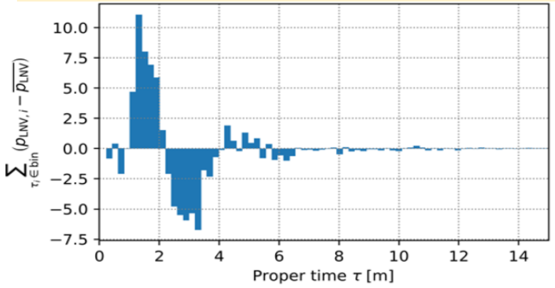


SHiP would register 2600 HNLs in the middle of its sensitivity range can observe oscillations between Lepton Number Violating and Conserving event rates

→ Measure mass splitting $\delta M = \sim 10^{-7}$eV

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



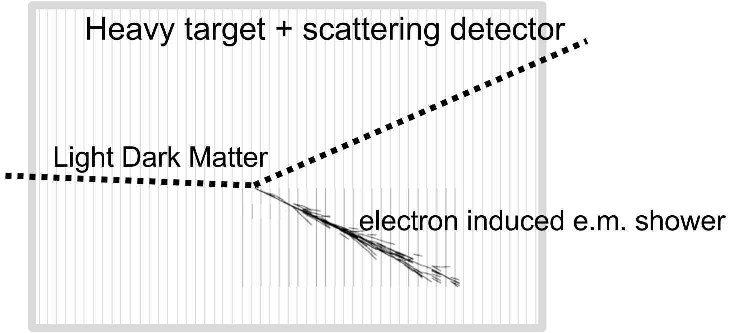


Left: lower bound on the SHiP sensitivity to HNL lepton number violation (black dashed line). Reconstructed oscillations between the lepton number conserving and violating event rates as a function of the proper time for a HNL with the parameters $M_N = 1\,\mathrm{GeV}/c^2$, $|U|_\mu^2 = 2 \times 10^{-8}$ and mass splitting of 4×10^{-7} eV.

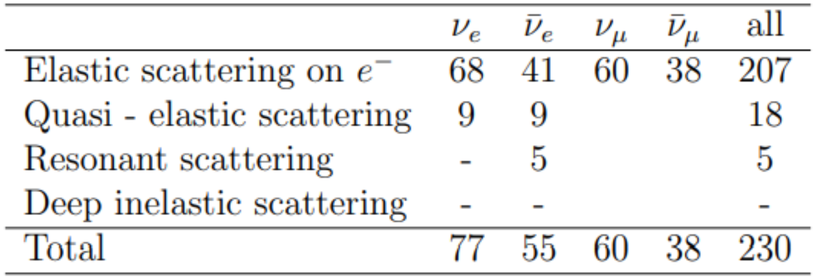
Sensitivity to LDM

- ✓ *Optimisation is ongoing*
  - *Adding more electronic detectors to SND*
  - *Energy and pointing resolution for the EM shower initiated by the LDM interaction*

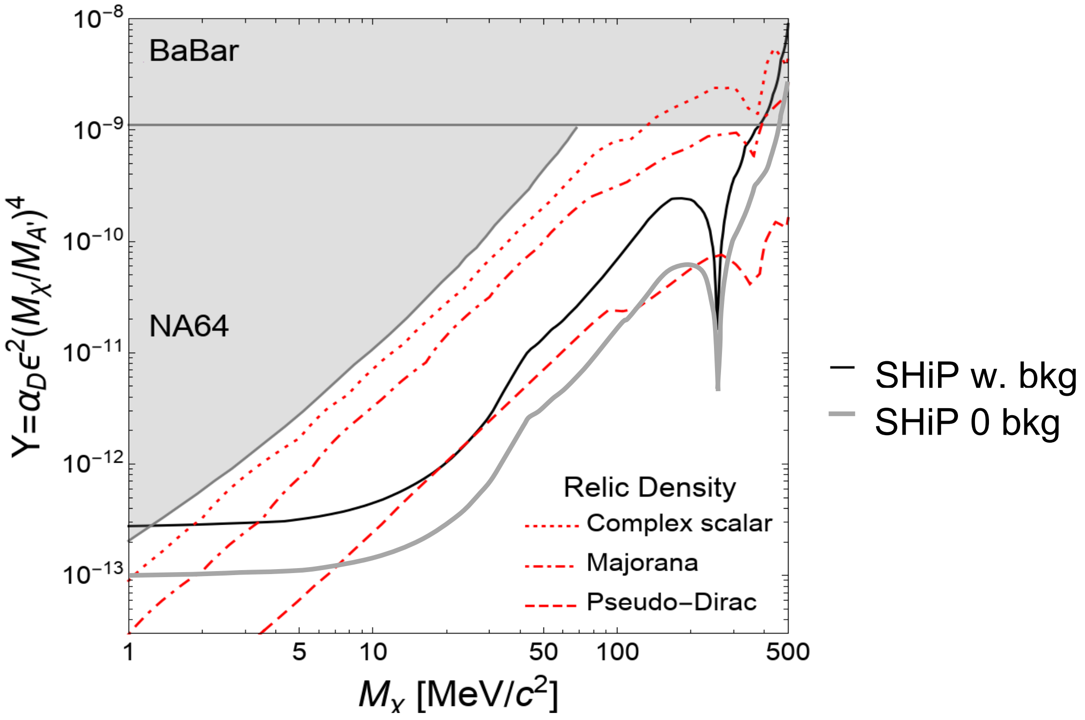
- ✓ *Hope to reach better sensitivity with SHiP/BDF@ECN3 compared to the CDS(ECN4) evaluation given to higher acceptance at the SND closer location*



Backgrounds at ECN4



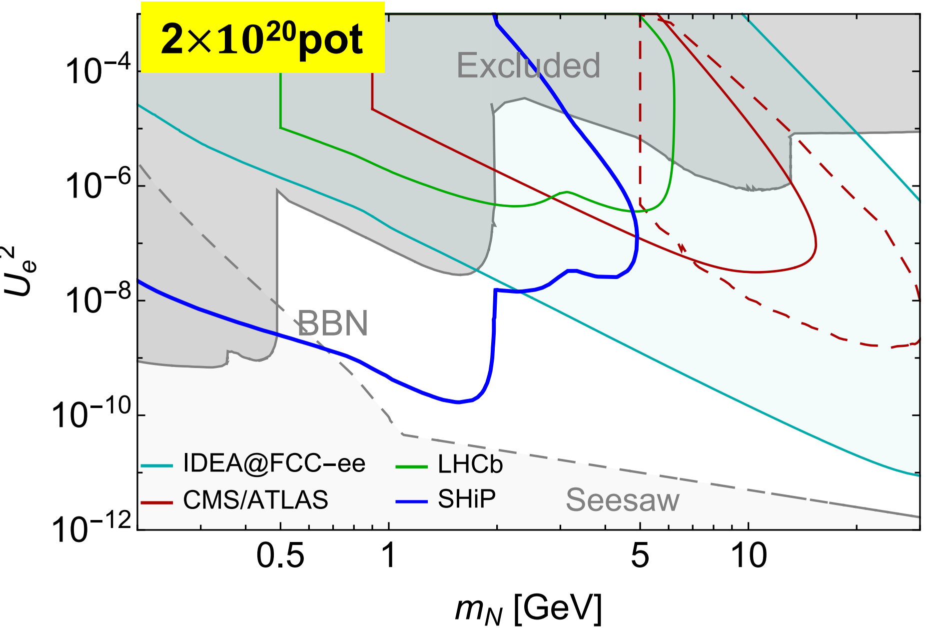
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic scattering on e^-	68	41	60	38	207
Quasi - elastic scattering	9	9			18
Resonant scattering	-	5			5
Deep inelastic scattering	-	-			-
Total	77	55	60	38	230



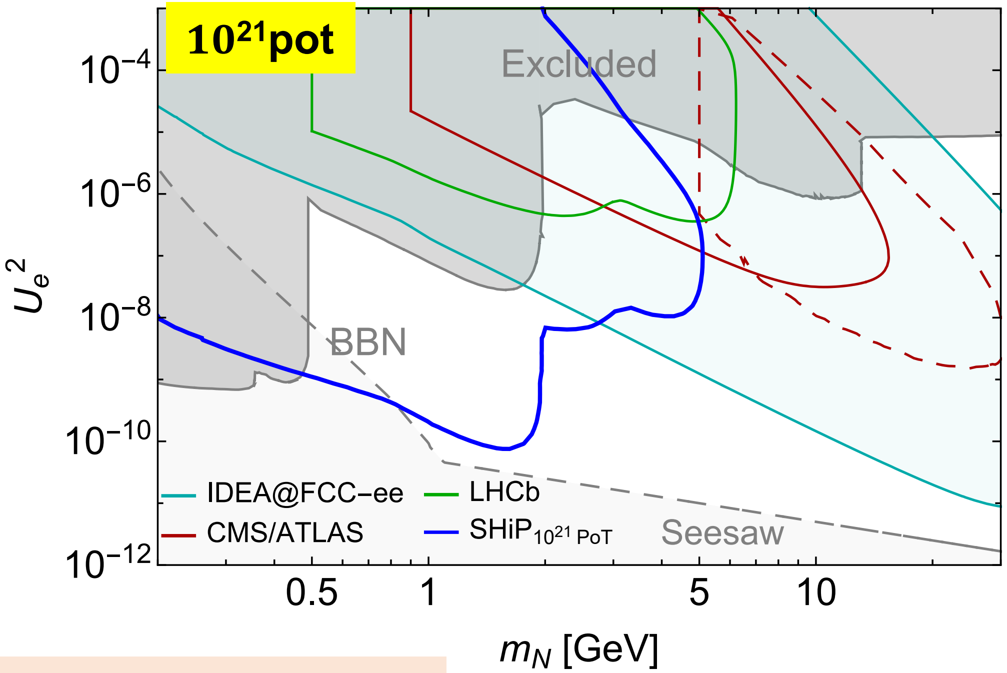
Conclusion

- ✓ ***BDF/SHiP sensitivity @ ECN3 for the HS exploration is as good as in the CDS(ECN4) design***
  LDM sensitivity is under study but may even improve compared to the ECN4 prospects
  LoI is based on first-level prototyping of all critical facility components and detector technologies as documented in the CDS reports

- ✓ *Clear window of opportunities to discover HS particles (or to close this "topic" experimentally)at ECN3.*
  SHiP/BDF has the best discovery potential; complementary to FIP searches at HL-LHC and future e^+e^--collider



See-saw limit is almost in reach below charm mass with 10^{21} pot

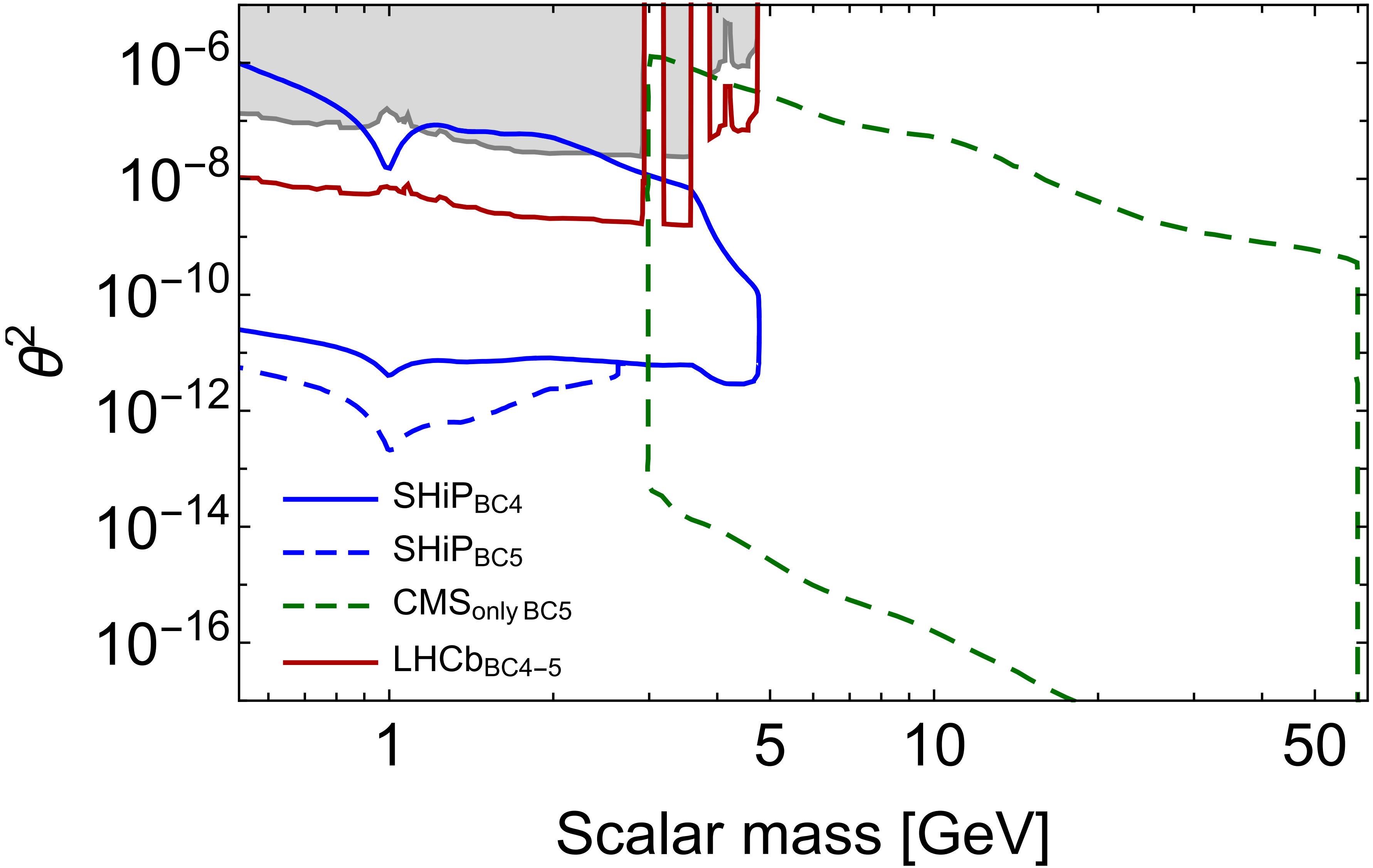


A special thanks to the BDF team for all work and support

and for Beautifully Designed Facility

Spare Slides

CMS sensitivity is reproduced from:
https://doi.org/10.48550/arXiv.2012.07864



BDF/SHiP development history in brief

✓ *2013 Oct: EOI with SHiP@SPS North Area as a new high intensity facility*

✓ *2014 Jan: Encouraged to form collaboration and produce TP and inter-departmental*

✓ *task force setup to study feasibility of facility*

✓ *2015 Apr: TP with ~700 pages by SHiP theorists, experimentalists, and CERN accelerator, engineering, and safety departments*

✓ *2016 Jan: Recommendation by SPSC to proceed to Comprehensive Design Study (CDS)*

✓ *2016 Apr: CERN management launch of Beyond Collider Physics study group*

- SHiP experimental facility included under PBC as Beam Dump Facility

✓ *2018 Dec: EPPSU contribution submitted by SHiP and BDF, and SHiP Progress Report to SPSC*

✓ ***2019 Dec: CDS reports on BDF (Yellow Book) and SHiP submitted to SPSC***

(Based on first-level prototyping of all critical facility components and detector technologies)

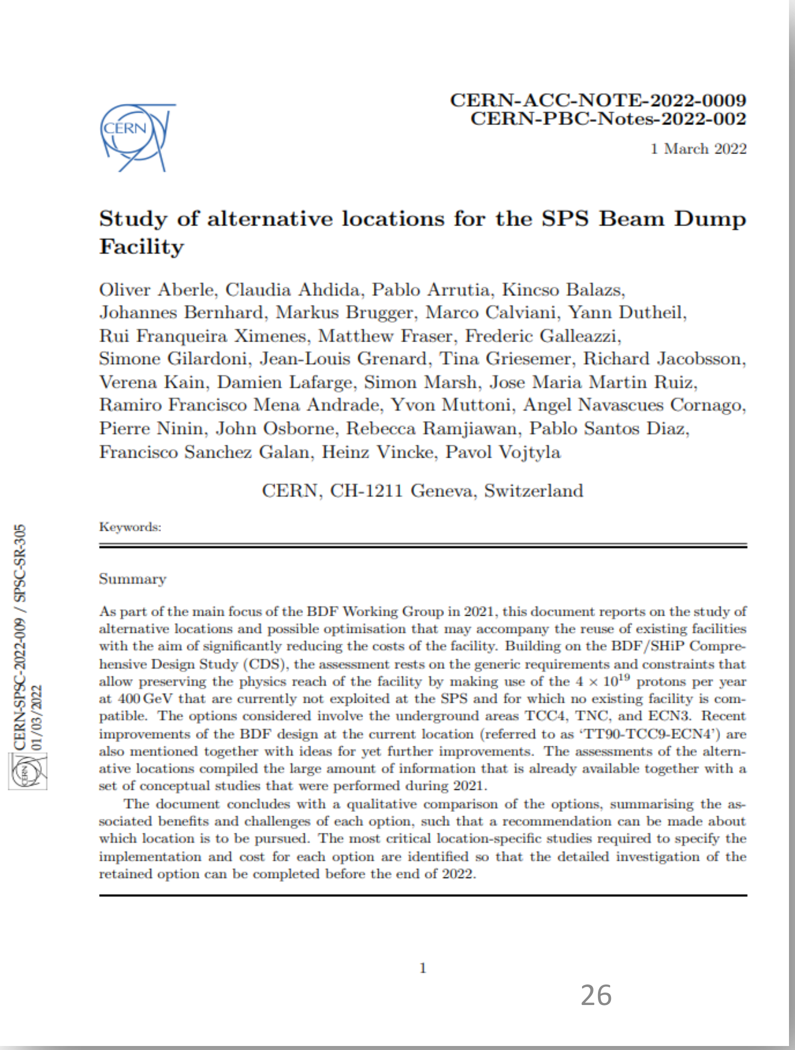
BDF/SHiP development history in brief

✓ ***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
(The cost of the facility 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***



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01/03/2022

Study of alternative locations for the SPS Beam Dump Facility

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Keywords:

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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