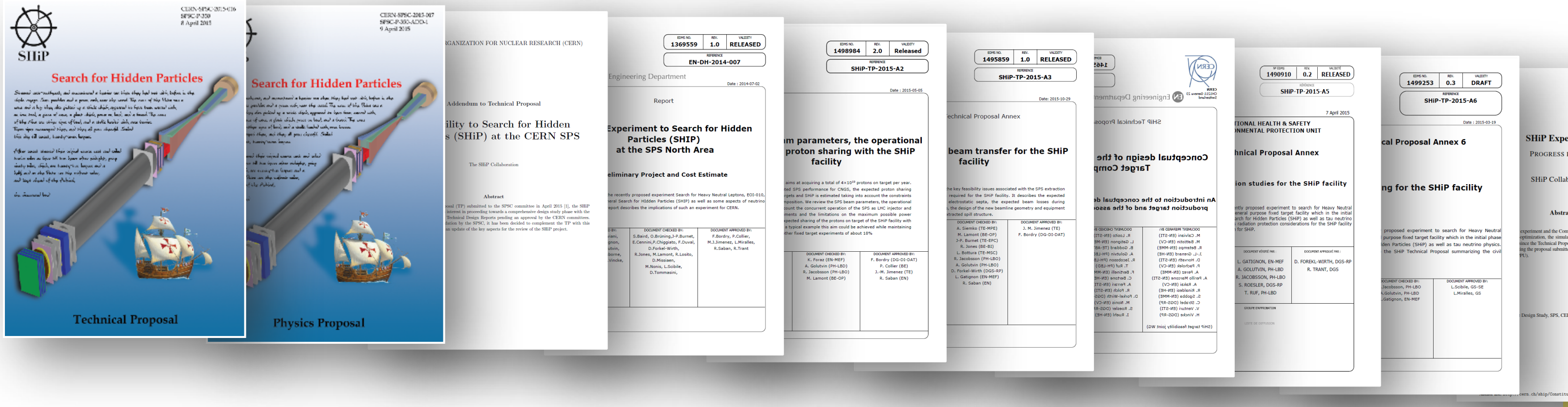
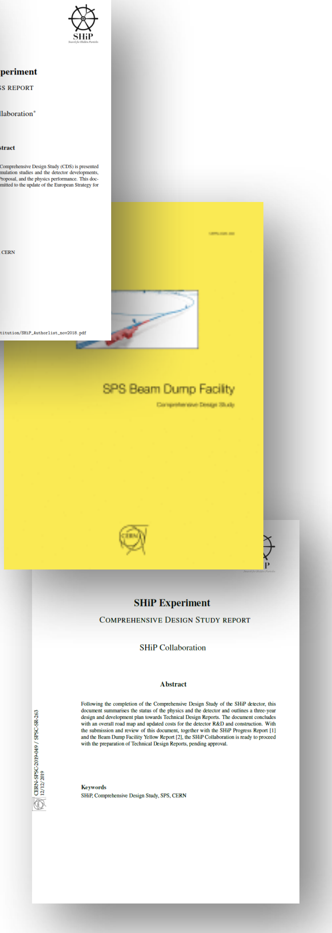
Andrey Golutvin
Imperial College London

BDF/SHiP @ ECN3

Preliminary evaluation of physics sensitivity in a view of the Letter of Intent submission to SPSC in two weeks

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)

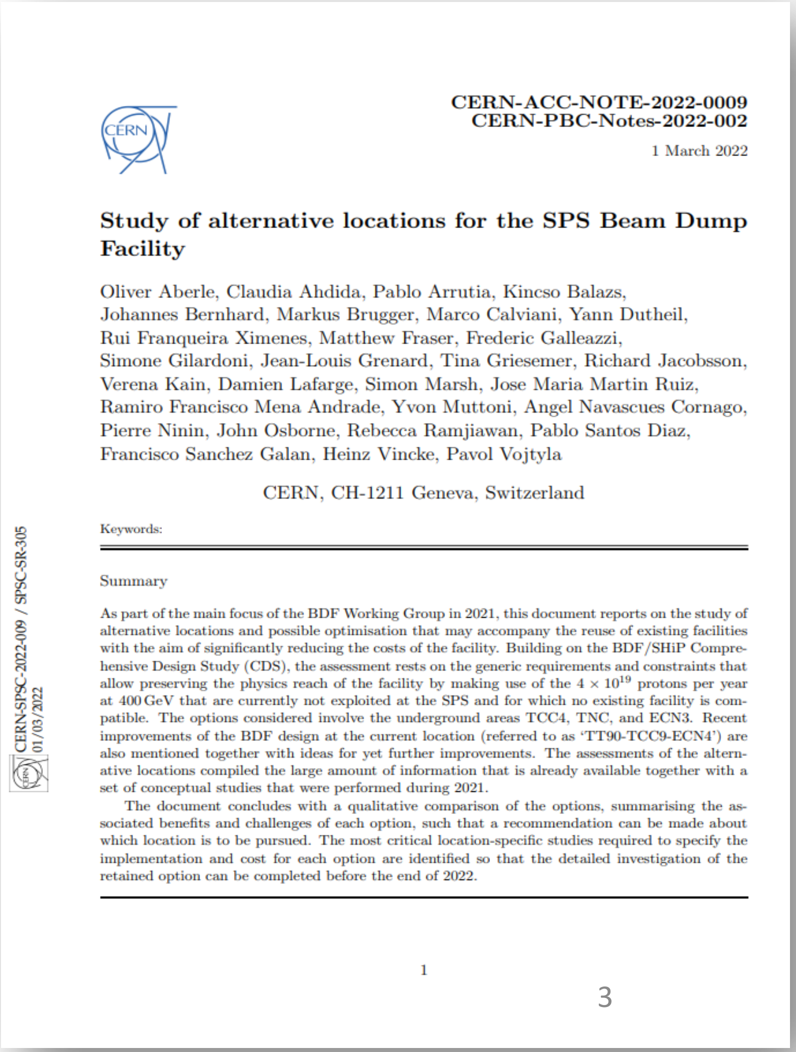
BDF/SHiP development history in brief

- ✓ ***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***



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

1 March 2022

CERN-SPSC-2022-009 / SPSC-SR-305
01/03/2022

Study of alternative locations for the SPS Beam Dump Facility

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Keywords:

Summary

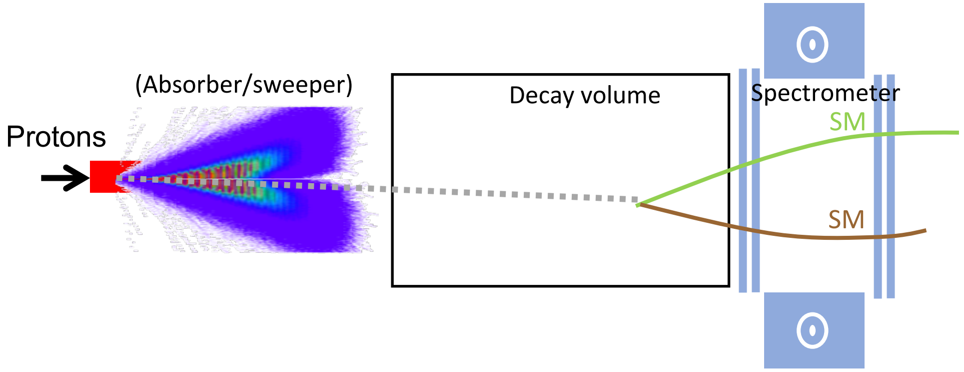
As part of the main focus of the BDF Working Group in 2021, this document reports on the study of alternative locations and possible optimisation that may accompany the reuse of existing facilities with the aim of significantly reducing the costs of the facility. Building on the BDF/SHiP Comprehensive 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.

SHiP as presented in CDS(ECN4) report

Dual-platform experiment combining two direct search techniques

HS decay to SM particles



Protons

(Absorber/sweeper)

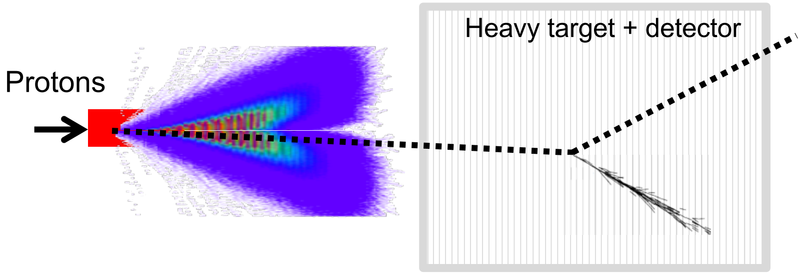
Decay volume

Spectrometer

SM

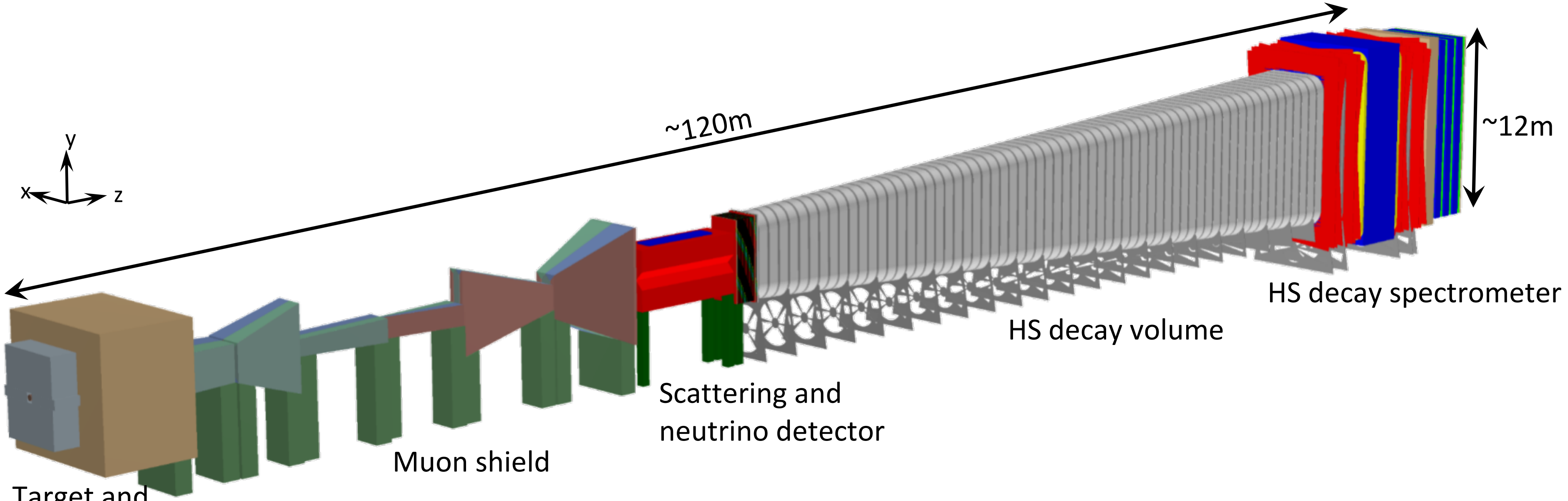
SM

LDM scattering off atomic electrons (and nuclei)



Protons

Heavy target + detector



~120m

~12m

y

x

z

Target and
hadron absorber

Muon shield

Scattering and
neutrino detector

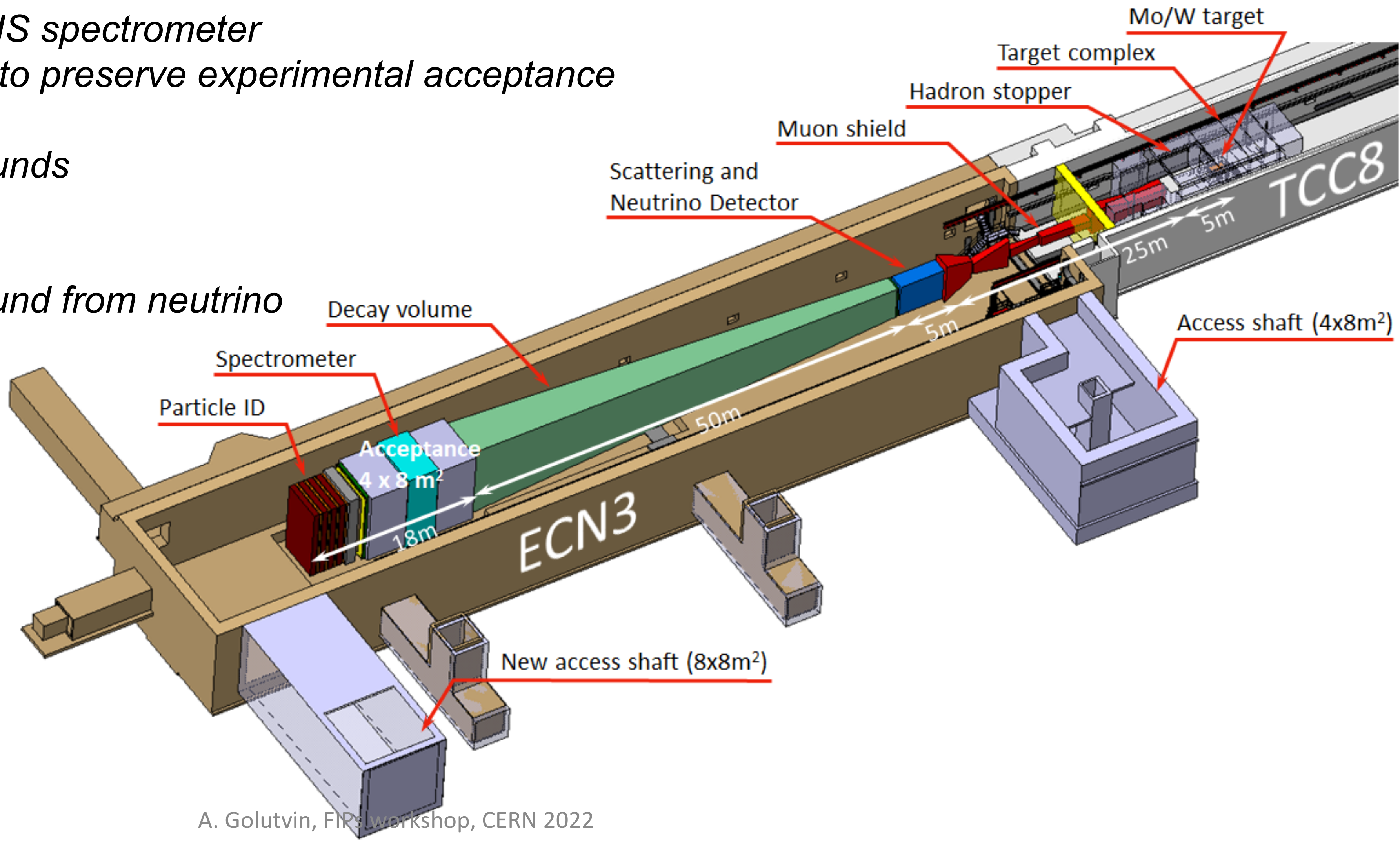
HS decay volume

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 and magnet dimensions to preserve / improve the LDM sensitivity*

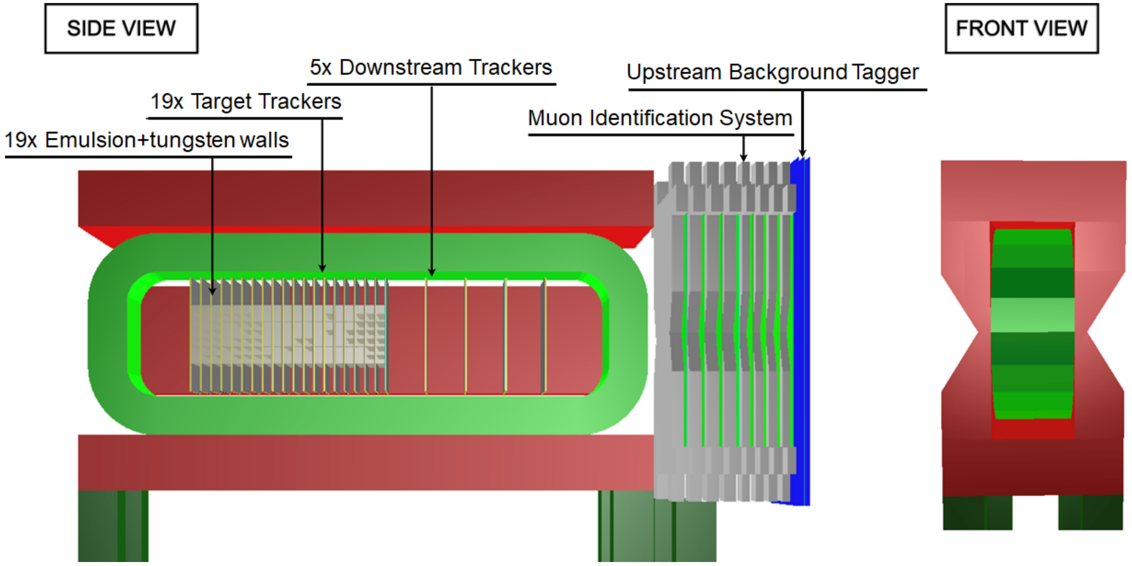


A. Golutvin, FIPs workshop, CERN 2022

Optimisation of the SND concept for ν_τ physics

CDS(ECN4) design:

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



***Reduce the magnet cross-section for the ECN3 design and re-optimise the shape of the LDM / neutrino target** to preserve / improve physics sensitivity for LDM and ν_τ*

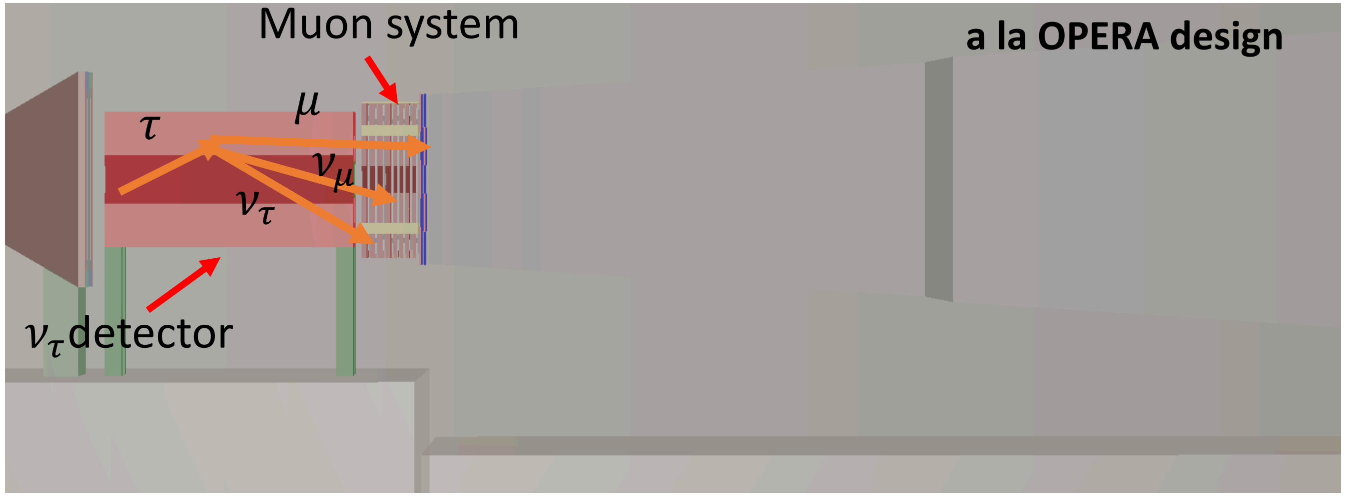
Alternative solution at ECN3

(trade-off between LDM and ν_τ sensitivity)

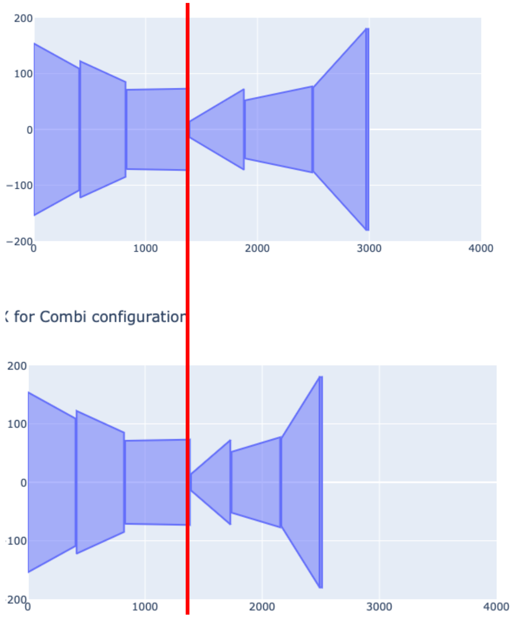
Remove SND magnet to increase the mass of the target

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

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

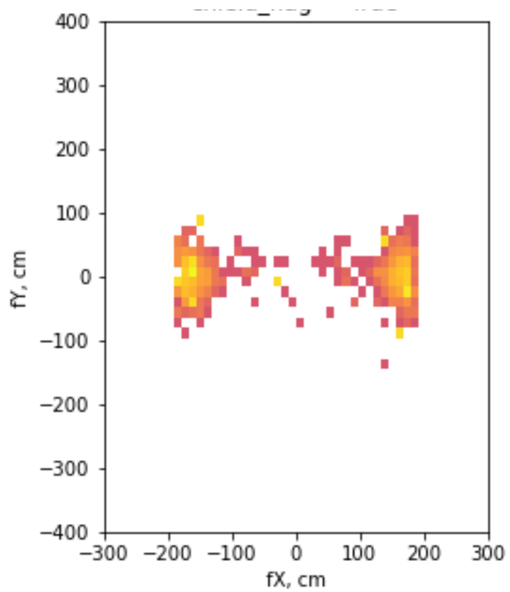


Muon shield optimisation



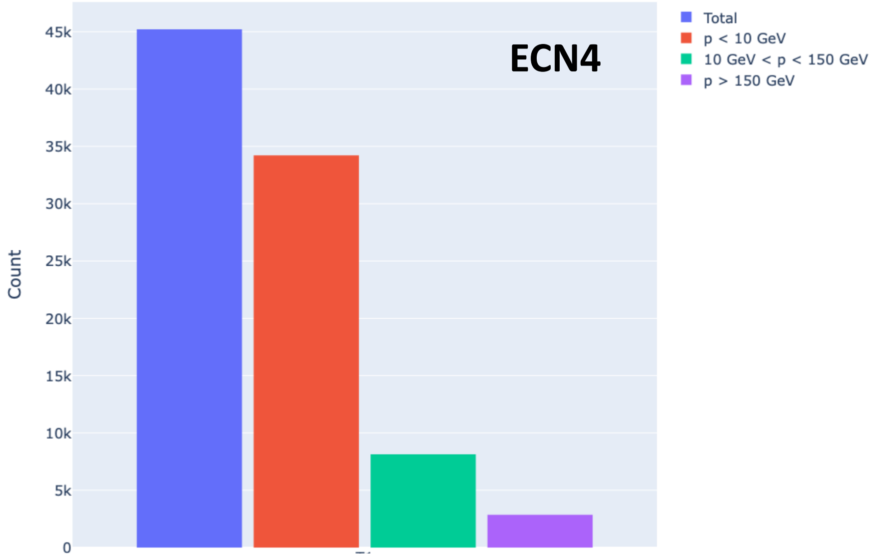
- ✓ *The goal is to reduce the initial flux of 10^{11} per spill by up to ~6 orders of magnitude*
- ✓ *Muon shield is shorter by ~5m at the ECN3 but still provides sufficient field integral to deflect hard muons*
- ✓ *1st iteration: upstream half is unchanged, the magnets of the downstream half are downscaled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

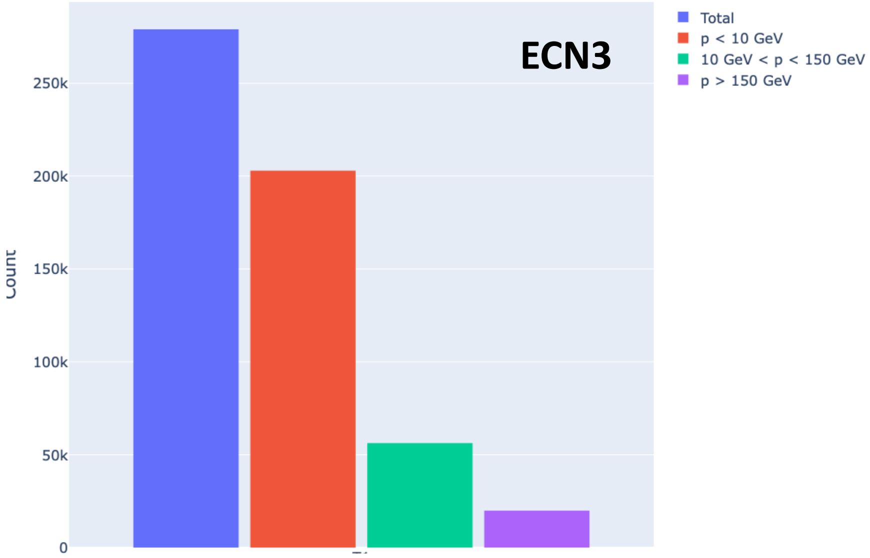
Muons at the HS tracker, P>150GeV,
leaking through the gaps around the coils in the muon shield



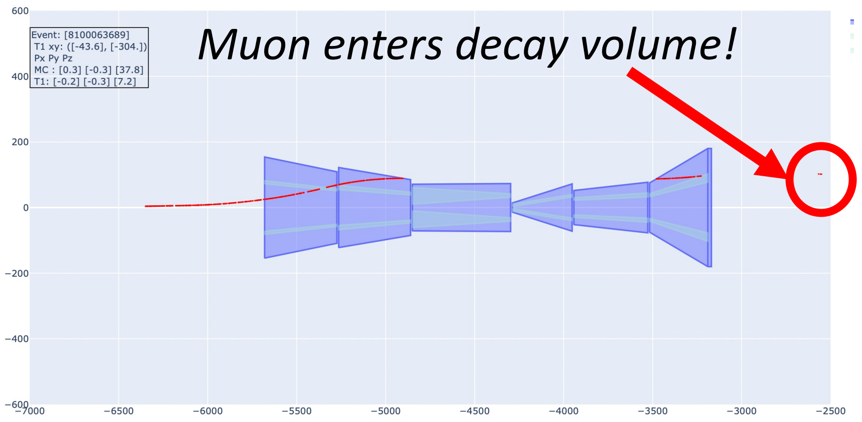
- ✓ *The remaining gaps will be fixed in future optimisation of the shield*
- ✓ *The field integral of the shortened shield is sufficient to deflect hard muons*
- ✓ *The shield shape has to be re-optimised !*
- ✓ *Current muon rate is very conservative → is being used for background evaluation at ECN3*

Muon rates

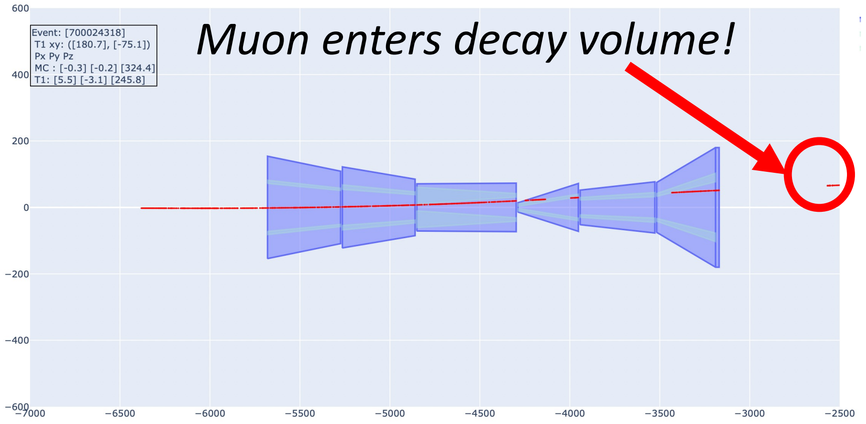




Apart from the "hot spots", the rate increase is mostly due to suboptimal performance of the shield for deflecting the muons returned back to the detector acceptance by the reverse field:



Muon with primary P = 38 GeV



Muon with primary P = 324 GeV

- ✓ *Optimisation of the muon shield is ongoing*
  Preliminary results indicate that the muon rate is almost back to the CDS(ECN4)
- ✓ *Study of alternative SC technologies to further shorten the shield*

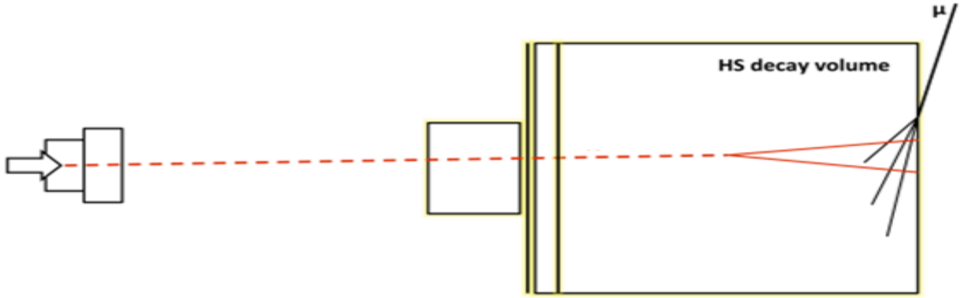
Evaluation of SHiP physics performance

Pythia/Geant simulation with complete description of detector and infrastructure

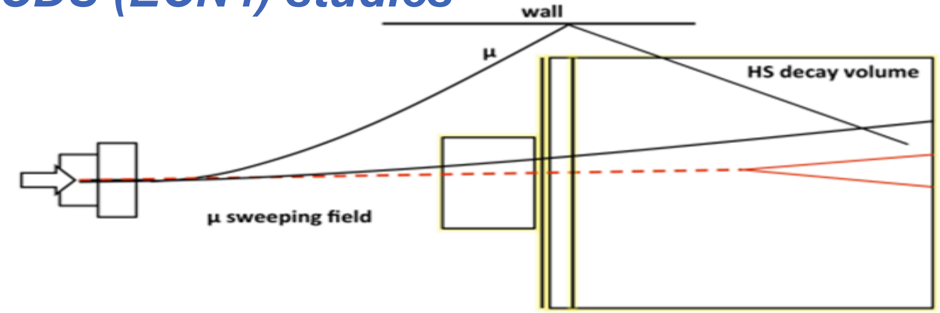
- ✓ *$\mathcal{O}(10^{11})$ muons (>1 GeV/c) per spill of $4x10^{13}$ protons*
- ✓ *4.5×10^{18} neutrinos and $3x10^{18}$ anti-neutrinos in acceptance in 2×10^{20} proton on target*

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

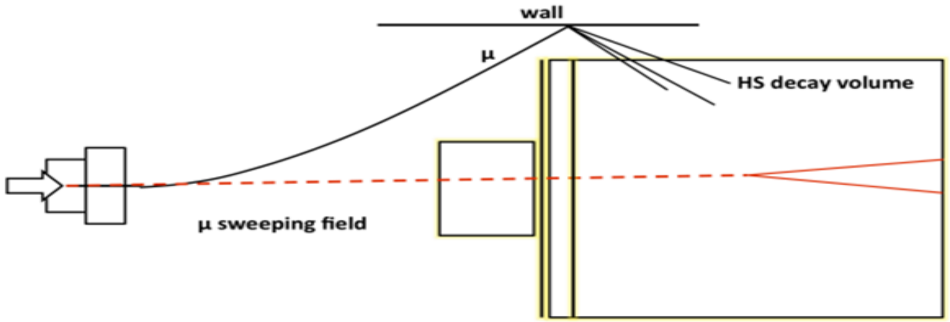
Reminder of CDS (ECN4) studies



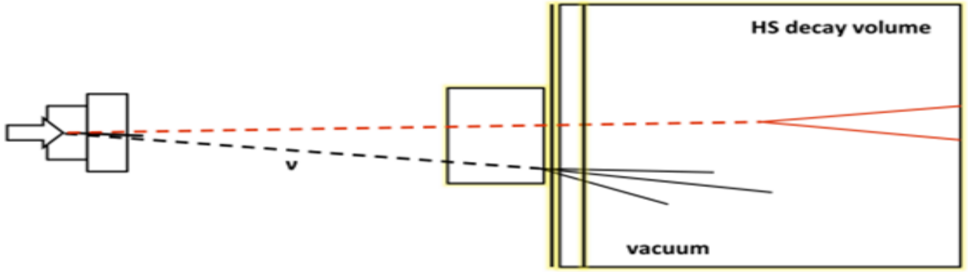
Cosmics: negligible



Muon combinatorial: $1.2\times10^{-2} \pm 1.2\times10^{-2}$



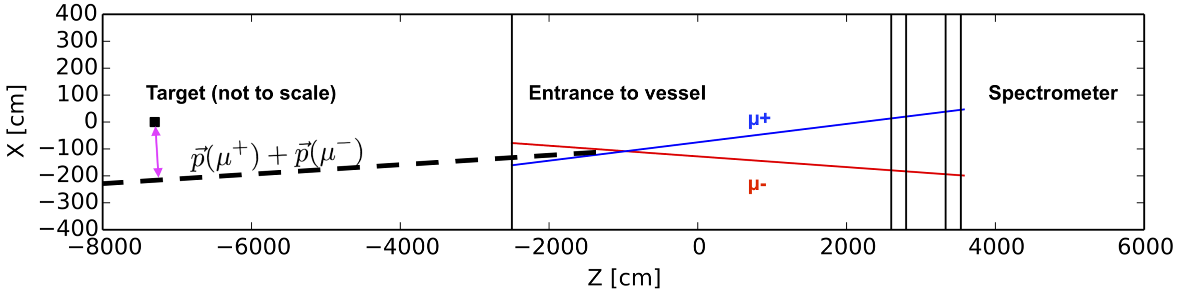
Muon DIS: 6×10^{-4}



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

Our goal: to confirm similar backgrounds levels at ECN3

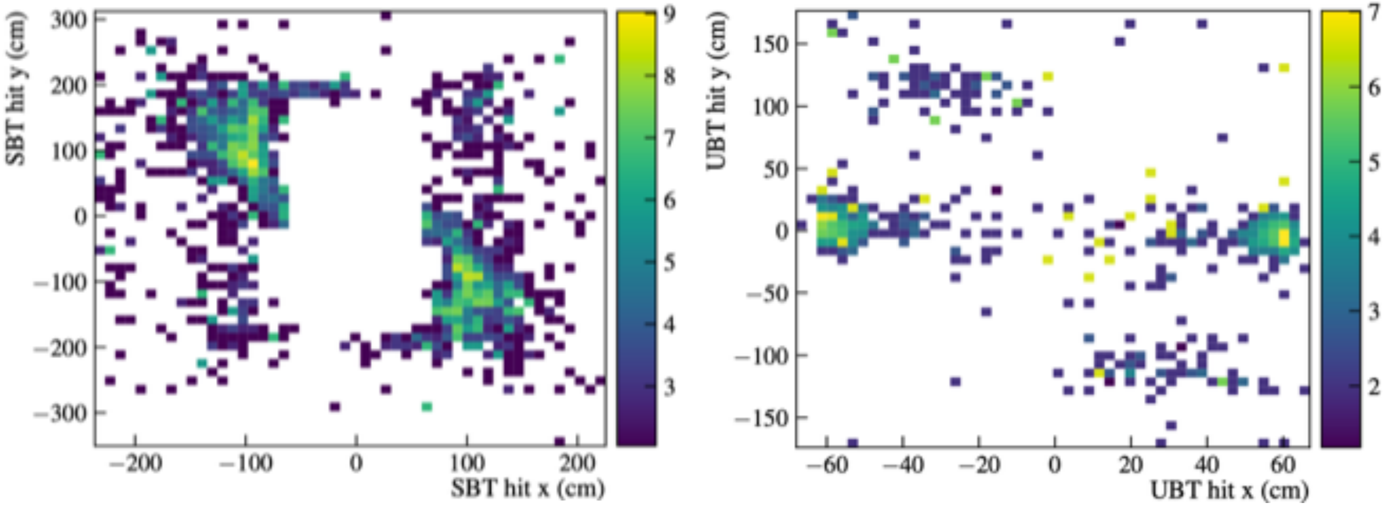
Combinatorial background (ECN3 in 5 years)



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



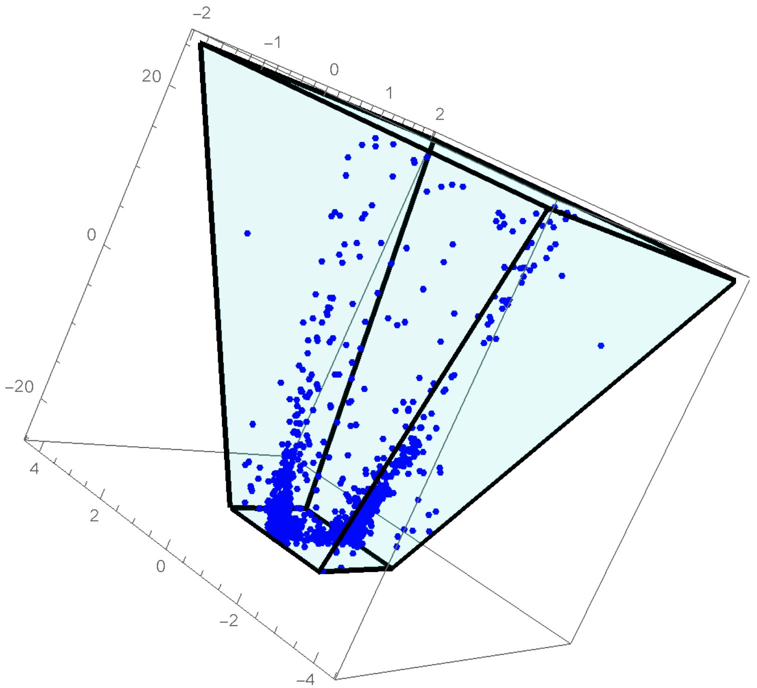
✓ *Event selection* *$(3.5 \pm 0.4)\times10^{-4}$*
✓ *Time coincidence of the tracks from HS vertex* *1.6×10^{-9}*
✓ *SBT efficiency (45 MeV threshold)* *99%*
✓ *UBT efficiency (as measured with prototypes)* *98% per MRPC*
✓ *Upstream veto rejection power* *$(1 \pm 0.5)\times10^{-8}$* ***(UBT/SBT with good time and spatial is resolution is crucial)***

Comb. Background $O(10^{-2})$
(despite of higher muon flux)

MUON DIS (ECN3 in 5 years)

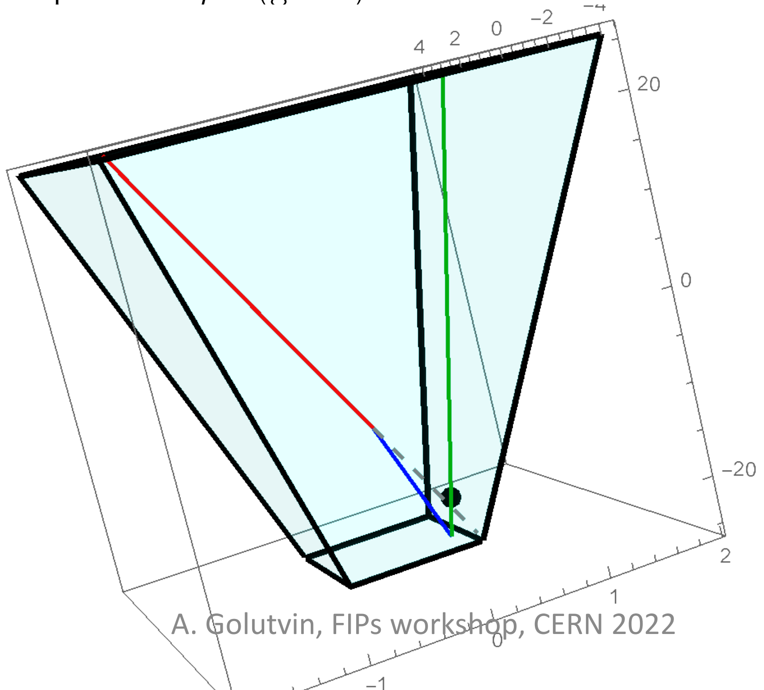
Muon DIS events passed event selection:

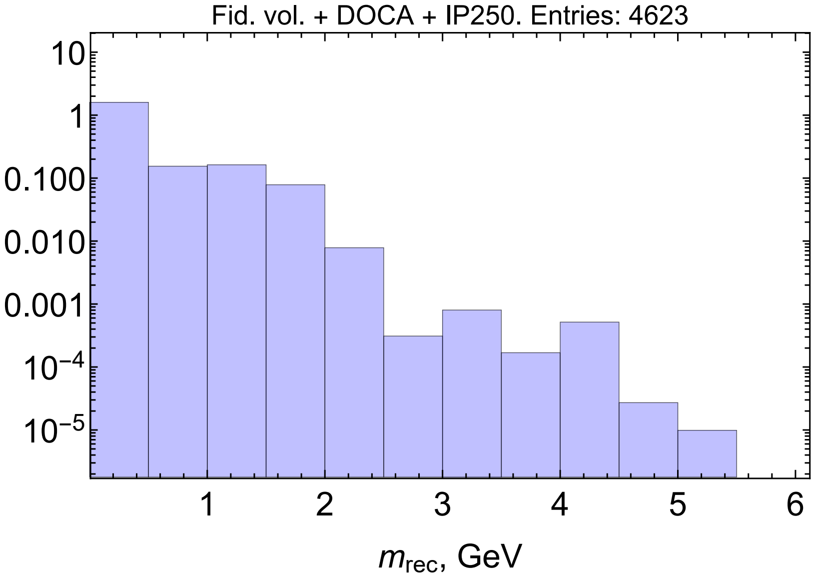
	N_{DIS}	$N_{\mathrm{DIS}}^{\mathrm{vtx\ 1}}$	$N_{\mathrm{DIS}}^{\mathrm{Fid.\ vol.}}$	$N_{\mathrm{DIS}}^{\mathrm{DOCA}}$	$N_{\mathrm{DIS}}^{\mathrm{IP250}}$	$N_{\mathrm{DIS}}^{\mathrm{IP10}}$
ECN3	$9.8 \cdot 10^{10}$	$2.3 \cdot 10^{8}$	$3 \cdot 10^{7}$	$2.2 \cdot 10^{6}$	$2.1 \cdot 10^{5}$	602



Mainly 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

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



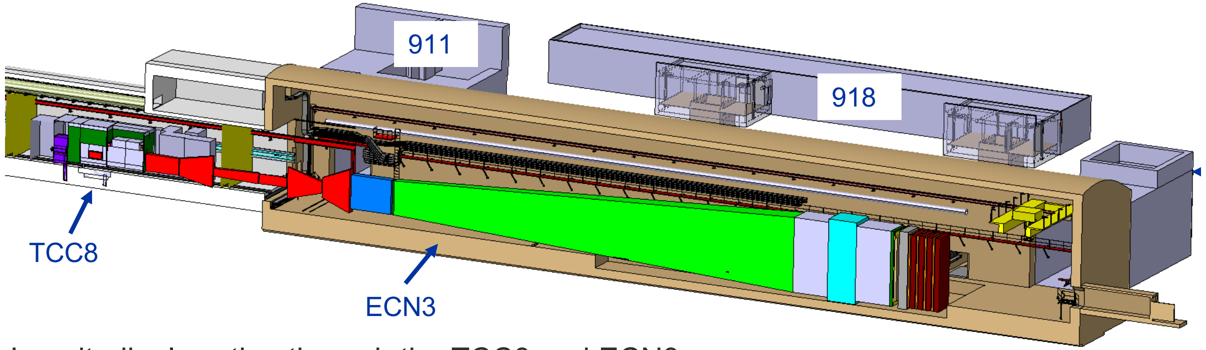


High Veto efficiency of Background Taggers (UBT&SBT) is crucial for the DIS suppression!

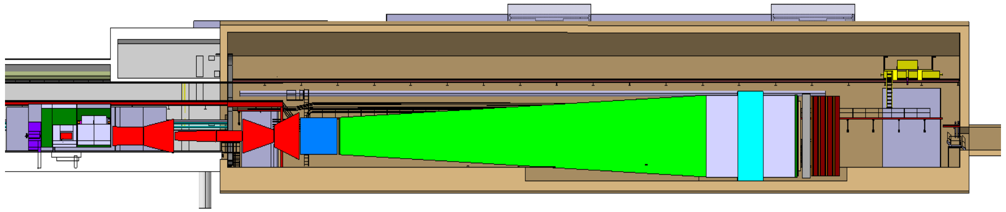
Muon DIS background:
< 2×10^{-4} (fully reconstructed)
< 2×10^{-2} (partially reconstructed)

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



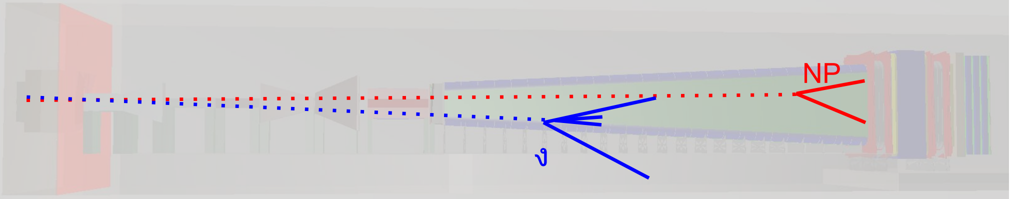
Longitudinal section through the TCC8 and ECN3 cavern



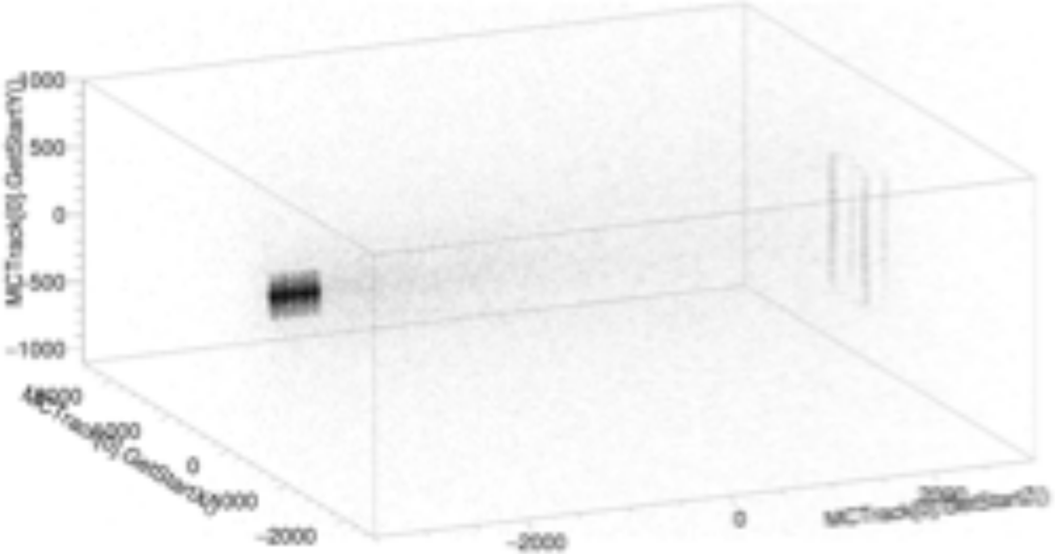
Plan view of the area with the proposed experiment

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%*

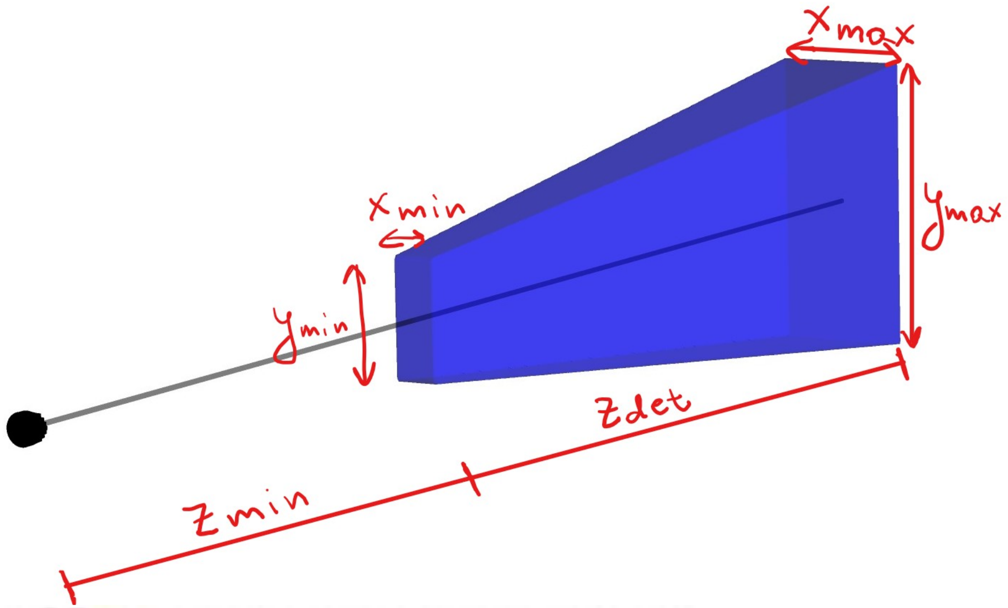


Similarly to muons, neutrino DIS products are aligned with the direction of incoming neutrino
*→ **Background is dominated by neutrino DIS in the proximity of decay volume***



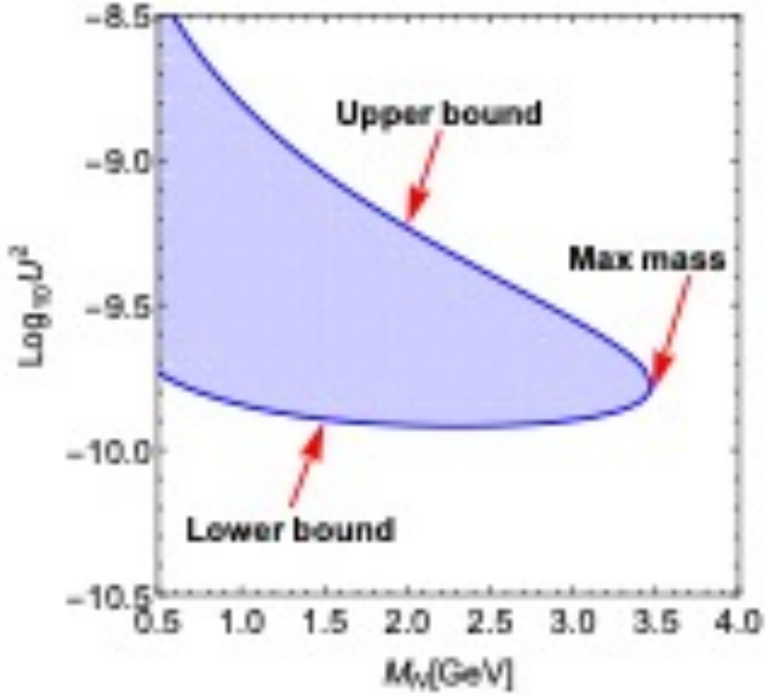
Neutrino DIS background
after selection + SBT/UBT veto cuts
< 0.1 (fully rec.)
< 0.3 (partially rec.)

Signal acceptance



Decay vessel parameters

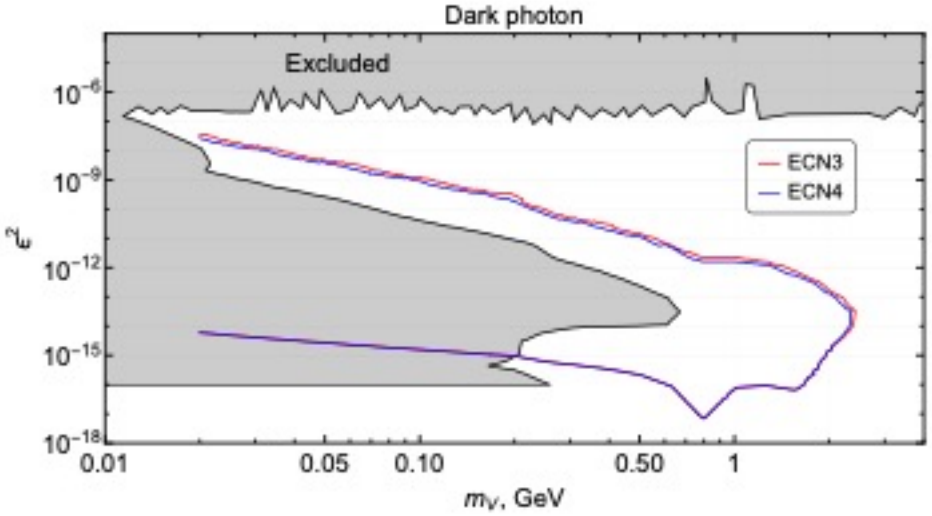
	z_{min}	z_{det}	x_{min}	y_{min}	x_{max}	y_{max}	$\Omega_{vessel\ end}$
CDS Design	48 m	50 m	1.5 m	4.3 m	5 m	11 m	$5.7 \cdot 10^{-3}$
ECN3	37 m	50 m	1.2 m	3.5 m	4 m	8.7 m	$4.6 \cdot 10^{-3}$

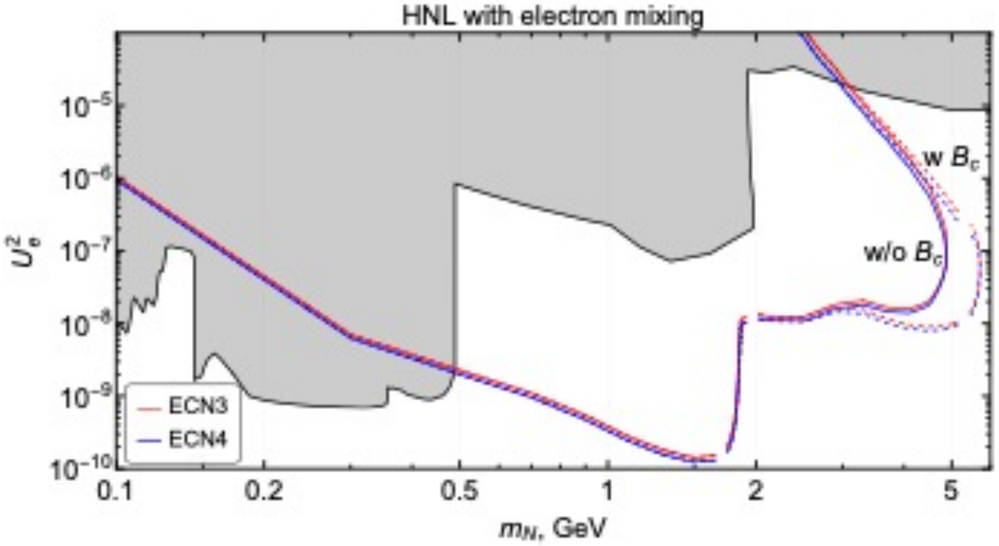


✓ *The upper bound of the sensitivity contour*
is determined by the distance from the target, z_{min}
The number of observed events does not play a role here
→ ECN4 / ECN3 ≈ 0.8

✓ *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, $NP(\Omega)$
For the uniform $NP(\Omega)$*, ECN4 / ENC3 ≈ 1.1*

Signal Yields: Dark Photon, HNL

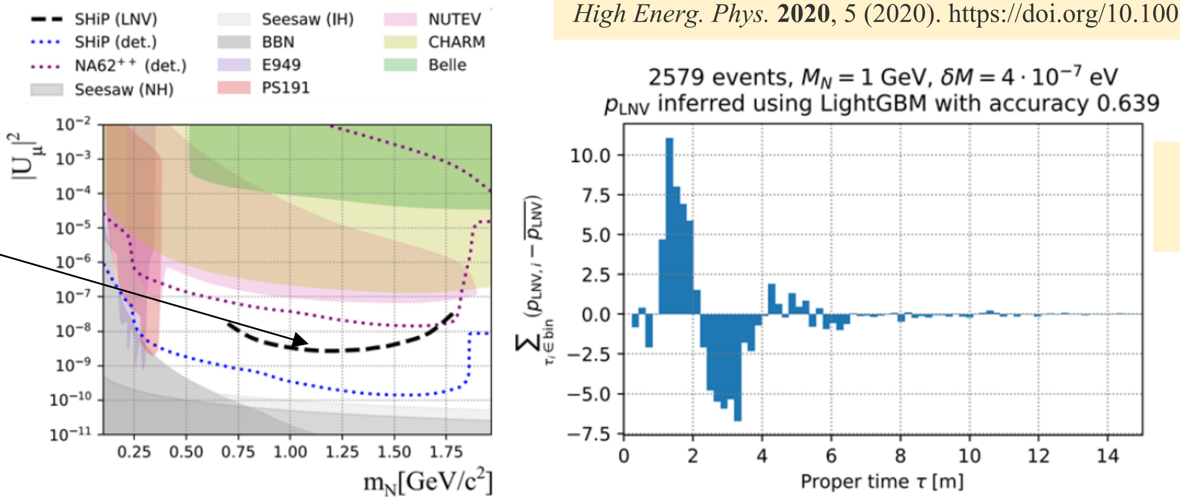




Tastet, JL., Timiryasov, I. Dirac vs. Majorana HNLs (and their oscillations) at SHiP. *J. High Energ. Phys.* **2020**, 5 (2020). https://doi.org/10.1007/JHEP04(2020)005

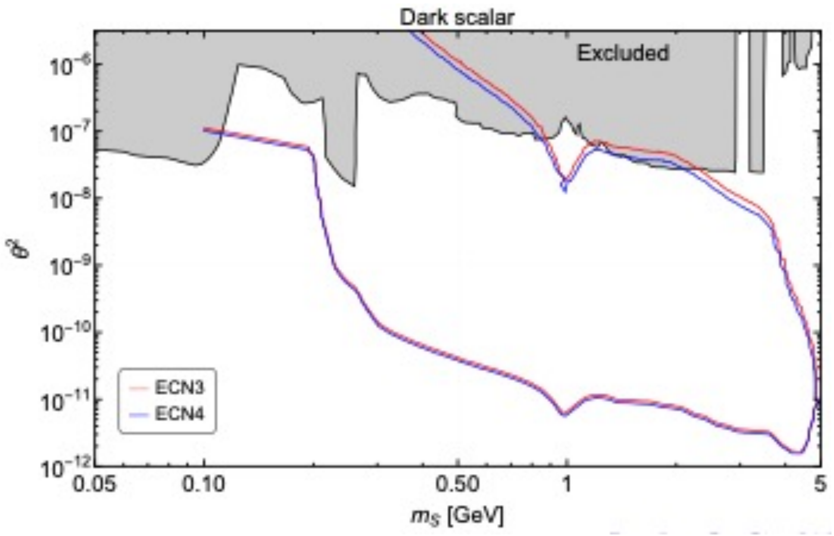
SHiP would register 2600 HNLs in the middle of its sensitivity range (which is at the edge of the sensitivity reach for other proposals at ECN3)
→ Can observe oscillation between Lepton Number Violating and Conserving event rates
→ Measure mass splitting $\delta M = \sim 10^{-7}$eV

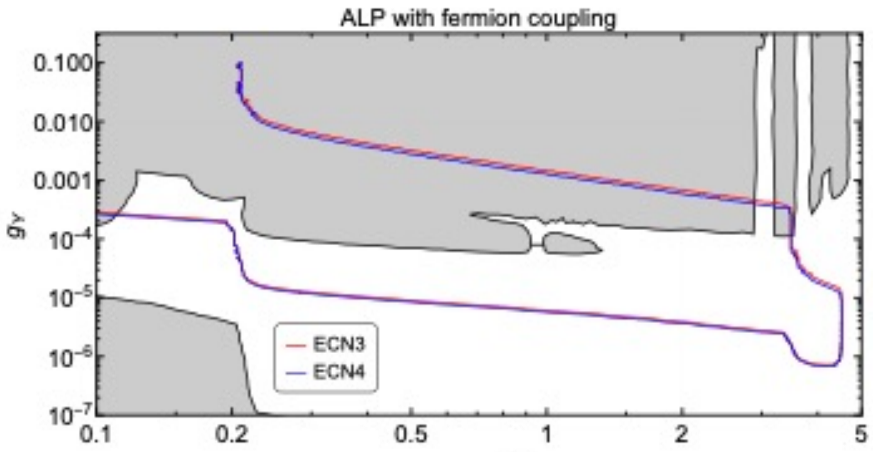
See also the talk of Jan Hajer this morning



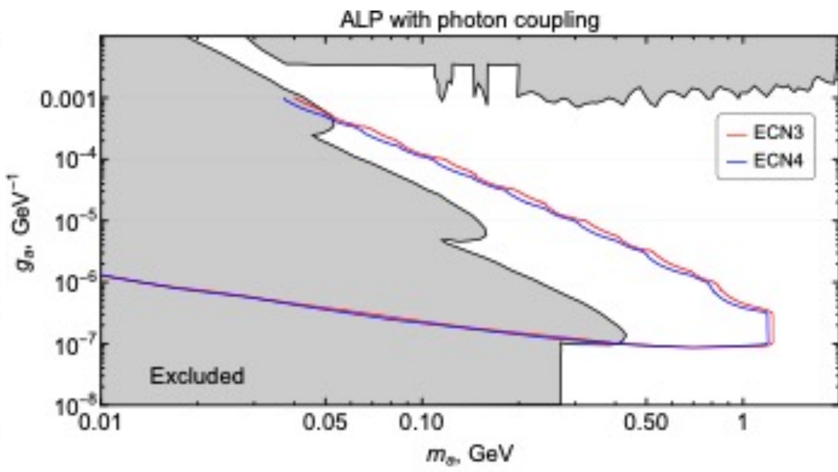
Left: lower bound on the SHiP sensitivity to HNL lepton number violation (black dashed line). Reconstructed oscillations between the lepton number conserving and violating event rates as a function of the proper time for a HNL with the parameters $M_N = 1\,\mathrm{GeV}/c^2$, $|U|^2_\mu = 2 \times 10^{-8}$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

Signal Yields: Dark Scalar, ALP





$\theta_{\text{dec}} \sim \frac{M_X}{\langle p_X \rangle}$



Typical angle between decay products of HS particle $\theta_{\text{dec}} \sim \frac{M_X}{\langle p_X \rangle}$

particles	a_f, S, N from B	N from D	A', a_γ
θ_{dec}	< 0.05	< 0.1	< 0.01

to be compared with the decay volume angular coverage

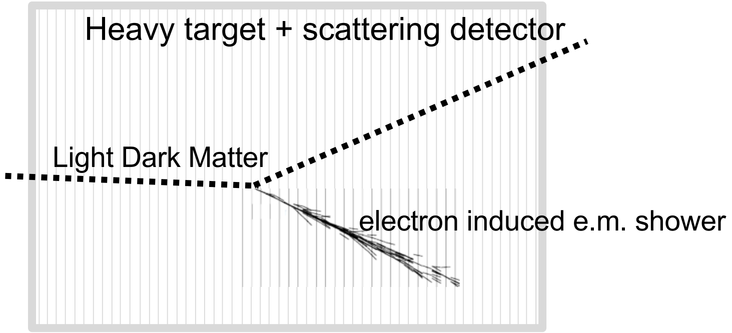
	θ_x	θ_y
ECN4	>0.05	>0.1
ECN3	>0.04	>0.08

Signal Yields for HS particles are nearly identical at ECN3 and ECN4

Sensitivity to LDM

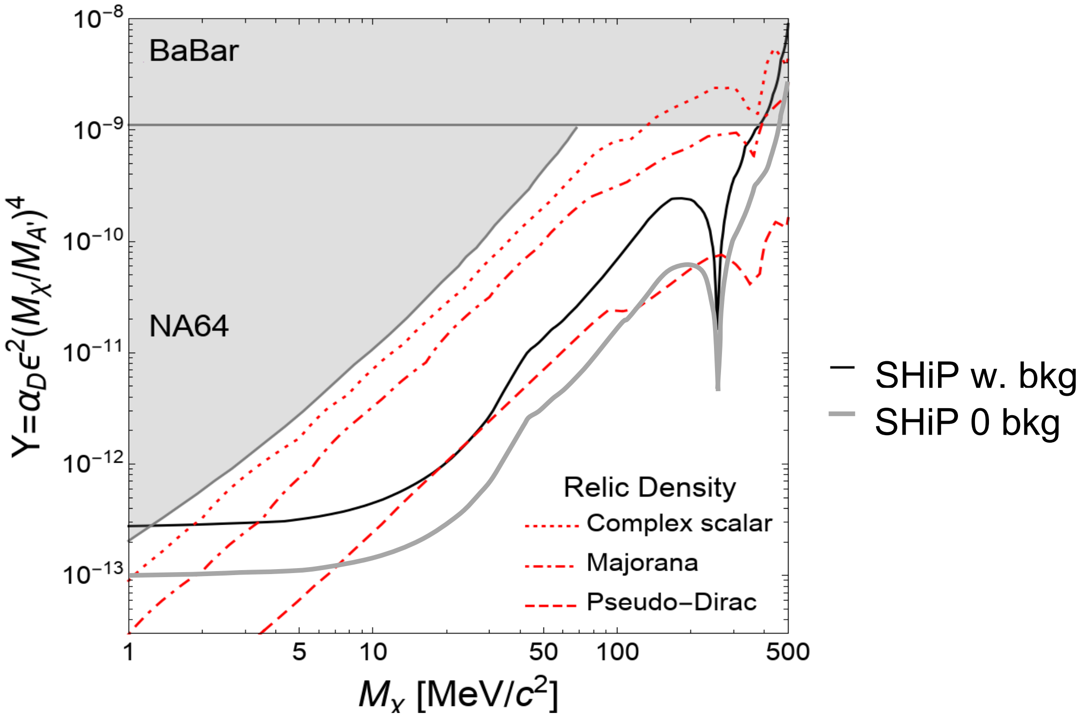
- ✓ *Optimisation is ongoing*
  - *Shape and mass of the LDM target*
  - *Replacement of emulsion with the electronic detector (vetoing neutrino background vs pile-up reduction)*
  - *Energy and pointing resolution for the EM shower initiated by the LDM interaction*

- ✓ *Hope to reach better sensitivity with SHiP/BDF@ECN3 compared to the CDS(ECN4) evaluation 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 the same as in CDS(ECN4) design***
  LDM sensitivity is under study but may even improve compared to the ECN4 prospects

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

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

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