Universität Zürich^UZH

Physik-Institut

SHiP
Search for Hidden Particles

# The CERN beam-dump facility and the prospect of the SHiP Experiment: Physics Case and Opportunities for the German Groups

Nico Serra (Universität Zürich)
On behalf of the SHiP Collaboration

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# Physics Case

$L = L_{SM} + L_{mediator} + L_{HS}$

**Visible Sector**

Mediators or portals to the HS:
vector, scalar, axial, neutrino

***Hidden Sector***
*Naturally accommodates Dark Matter (may have rich structure)*

✓ HS production and decay rates are strongly suppressed relative to SM
  - Production branching ratios O($10^{-10}$)
  - Long-lived objects
  - Interact very weakly with matter

| ***Models*** | ***Final states*** |
|---|---|
| ***HNL, SUSY neutralino*** | $l^+\pi^-$, $l^+K^-$, $l^+\rho^-$ $\rho^+ \rightarrow \pi^+\pi^0$ |
| ***Vector, scalar, axion portals, SUSY sgoldstino*** | $l^+l^-$ |
| ***HNL, SUSY neutralino, axino*** | $l^+l^-\nu$ |
| ***Axion portal, SUSY sgoldstino*** | $\gamma\gamma$ |
| ***SUSY sgoldstino*** | $\pi^0\pi^0$ |

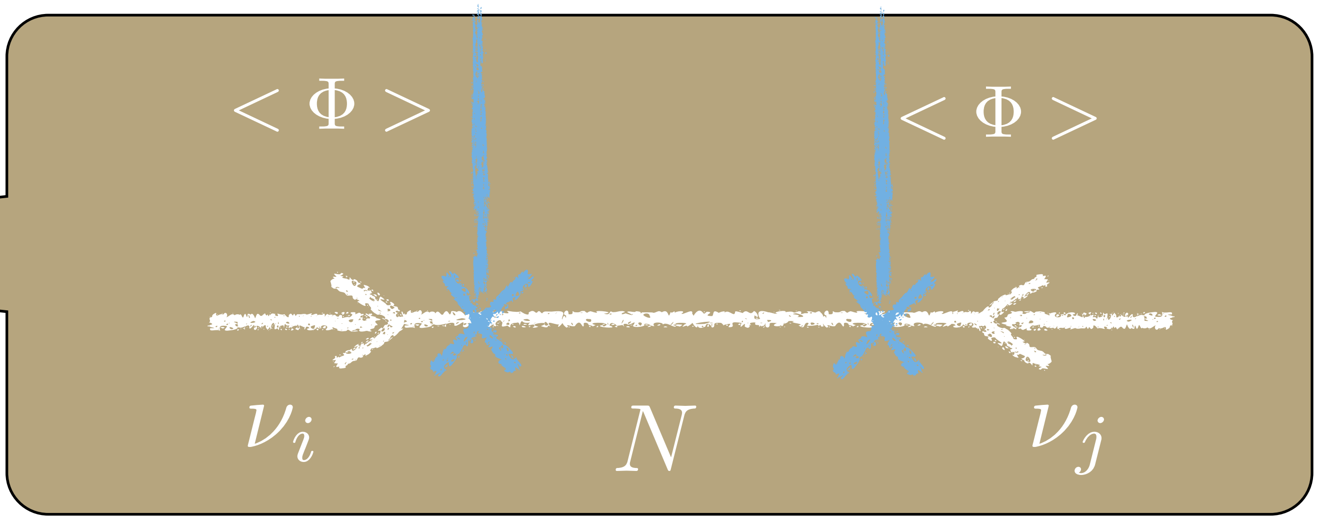
Full reconstruction and PID are essential to minimize model dependence

***Experimental challenge is background suppression***

# Sterile Neutrinos

Neutrino oscillations is also explained via the Yukawa coupling of sterile and active neutrinos

$$Y_{I\ell} L_\ell \overline{\Phi} N_I$$



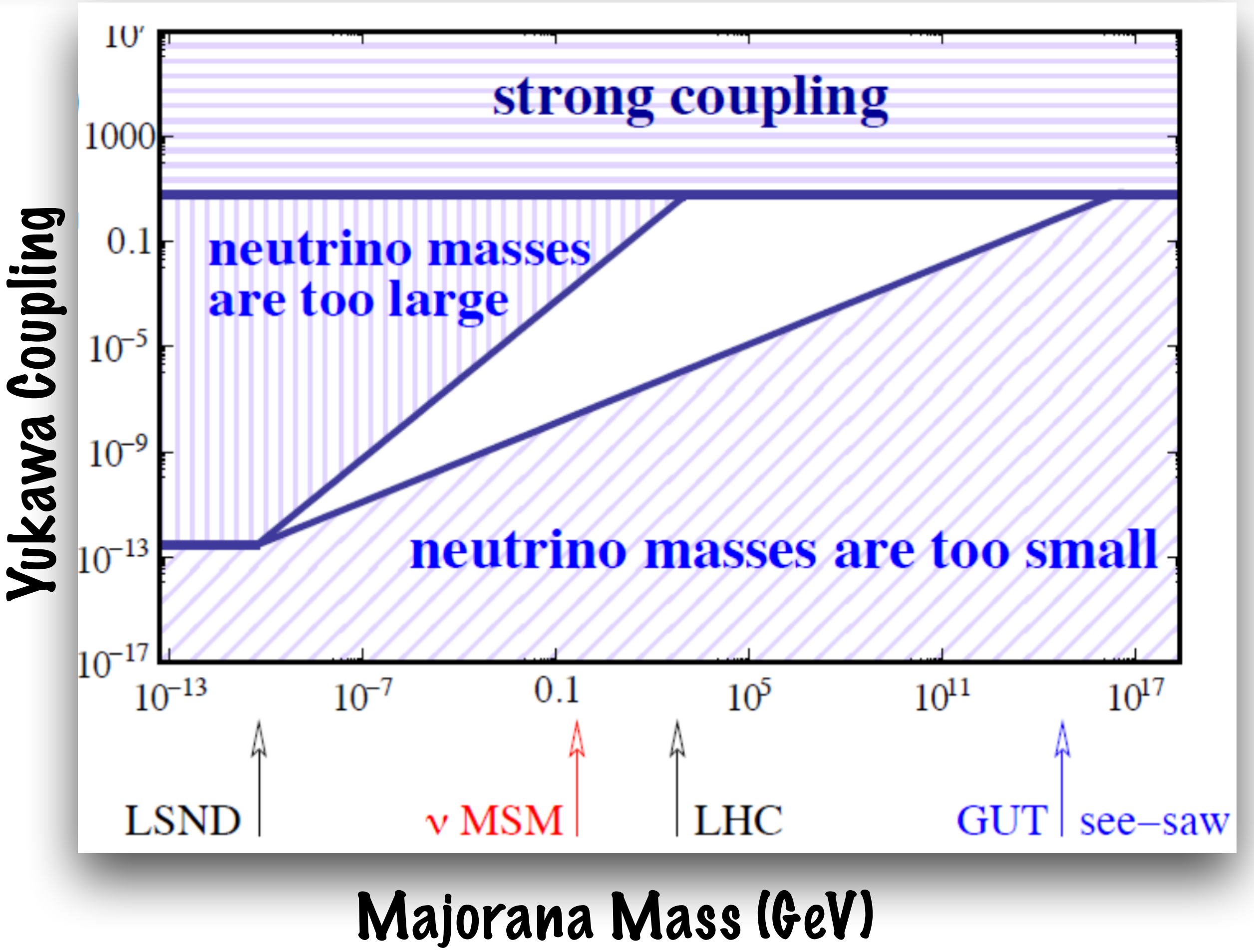
Active neutrinos mix with sterile neutrinos with a mixing angle

$$U_{I\ell} \sim \frac{M_D^\ell}{M_N^I} = \frac{Y_{I\ell} v}{M_N^I}$$

This is why people can search for sterile neutrinos, i.e. they can interact with SM particles by mixing with active neutrinos (neutrino portal)

# Sterile Neutrinos

Seesaw formula $m_D \sim Y_{I\alpha} < \phi >$ and $m_\nu = \frac{m_D^2}{M}$



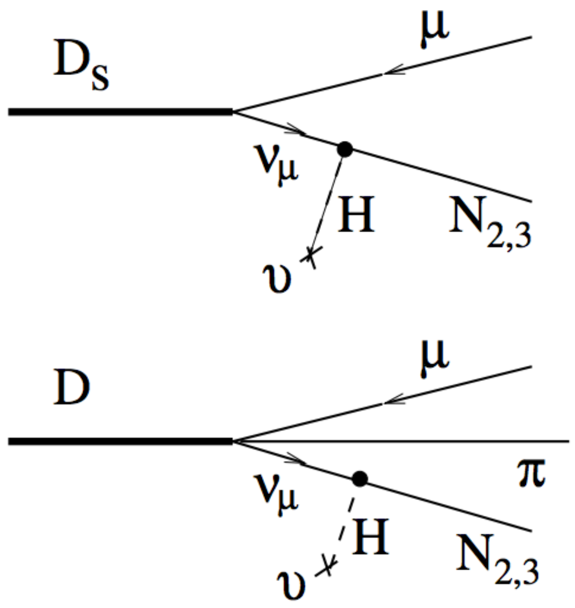
- Assuming $m_\nu = 0.1$eV
- if $Y \sim 1$ implies $M \sim 10^{14}$GeV
- if $M_N \sim 1$GeV implies $Y_\nu \sim 10^{-7}$

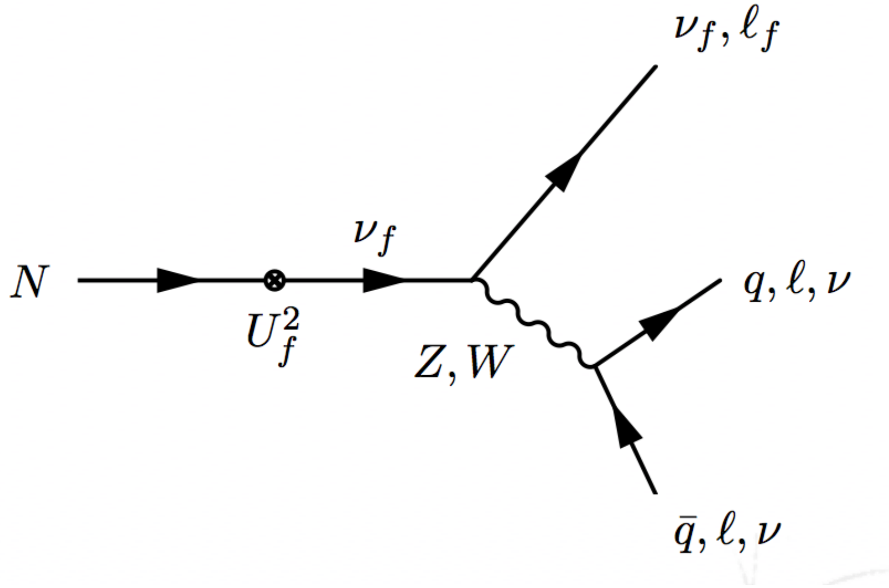
remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

- From the seesaw point of view the mass of sterile neutrinos can be basically anything
- If we want to explain the smallness of neutrino masses (in a natural way) the mass of sterile neutrinos should be at least at the GeV scale

# Sterile Neutrinos

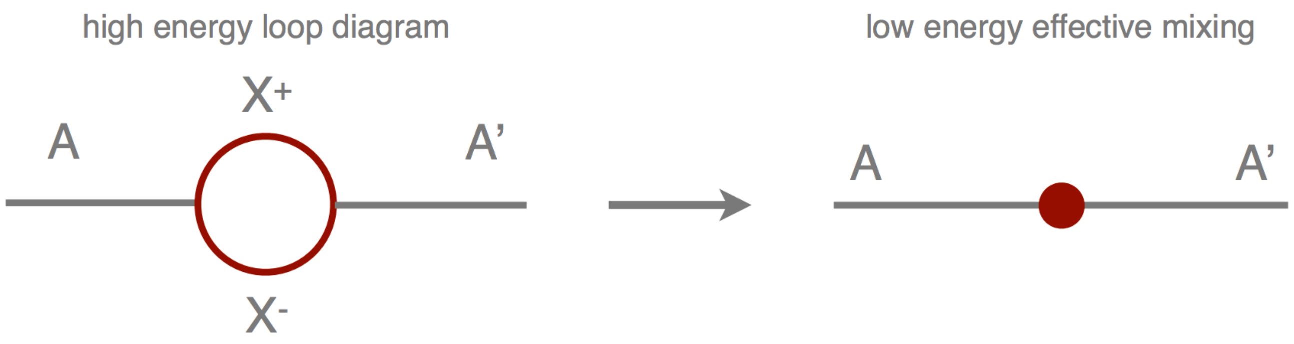
- The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor $U^2$
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons)
- The decay of sterile neutrinos also happens via mixing with active neutrinos, decay channels $N \to h\ell$, $N \to \ell\ell^{(\prime)}\nu$, $N \to h^0\nu$





# Example: Dark Photon

- Dark Matter might interact via unknown forces
- Consider an additional U(1)’ symmetry wrt which SM particles are neutral
- For instance we have some high mass fermions charged under U(1) and U(1)’ we have an effective coupling



$$\mathcal{L} = \overbrace{\underset{\substack{\uparrow\\ \text{QED fields}}}{\mathcal{L}_{\psi,A}} + \underset{\substack{\uparrow\\ U(1)'\text{ fields}}}{\mathcal{L}_{\chi,A'}}}^{\text{QED-like}} - \frac{\epsilon}{2}\underset{\substack{\uparrow\\ \text{field strength tensors}}}{F_{\mu\nu}F'^{\mu\nu}} + \frac{1}{2}\underset{\substack{\uparrow\\ \text{mass term}}}{m^2_{A'}}(A'_\mu)^2$$

Okun Sov.Phys.JETP 56 (1982) 502, Zh.Eksp.Teor.Fiz. 83 (1982) 892-898 ITEP-48-1982

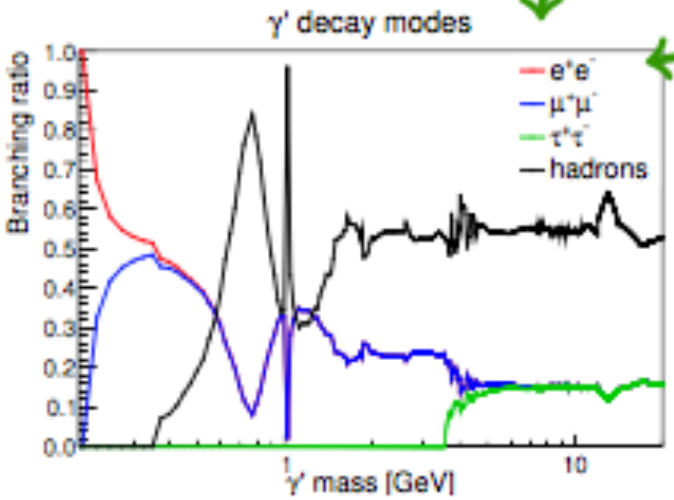
Holdom Phys.Lett. 166B (1986) 196-198 UTPT-85-30

# Example: Dark Photon

**Production at SHiP:**

- meson decays e.g. $\pi^0 \to \gamma V$ ($\sim \epsilon^2$) *arXiv:0906.5614*
- $p$ bremsstrahlung on target nuclei $pp \to ppV$ *arXiv:1311.3870*
- large $m_V \Rightarrow$ direct QCD production through underlying $q\bar{q} \to V$, $qg \to V$ (need some more theory work!) *arXiv:1205.3499*

**Decay:** $\Gamma_{tot} = \Gamma(\ell^+\ell^-) + \Gamma(\text{hadrons}) + \Gamma(\chi\bar{\chi})$



$$\frac{\ell\ell}{\chi\chi} \sim \frac{\alpha\epsilon^2}{\alpha_D},$$ $\alpha_D$ = dark fine structure constant

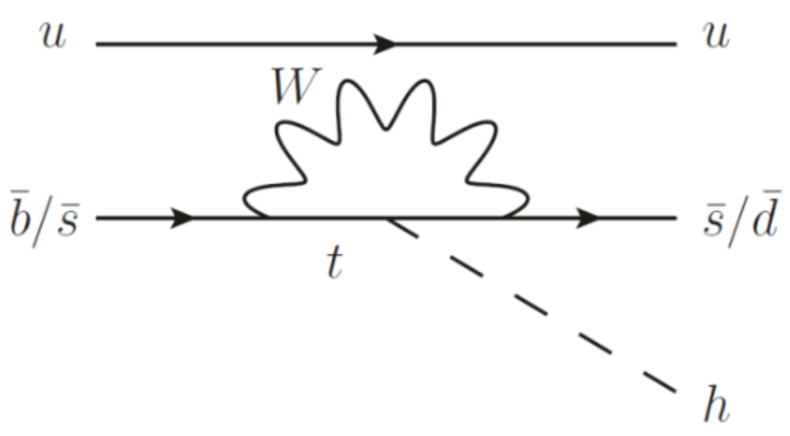
# Example: Dark Scalar

- If the Higgs was light we would produce copiously in B-mesons decays
- Therefore if there is a “light” Dark Scalar mixing with the Higgs we can produce it as a real particle in B-meson decays

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{HS} + (\alpha_1 S + \alpha S^2) H^\dagger H$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

Theory references: see Bezrukov and Gorbunov arXiv:0912.0390 and references therein



$$\Gamma(K \to \pi\phi) \sim (m_t^2 |V_{ts}^* V_{td}|)^2 \propto m_t^4 \lambda^5$$

$$\Gamma(D \to \pi\phi) \sim (m_b^2 |V_{cb}^* V_{ub}|)^2 \propto m_b^4 \lambda^5$$

$$\Gamma(B \to K\phi) \sim (m_t^2 |V_{ts}^* V_{tb}|)^2 \propto m_t^4 \lambda^2$$

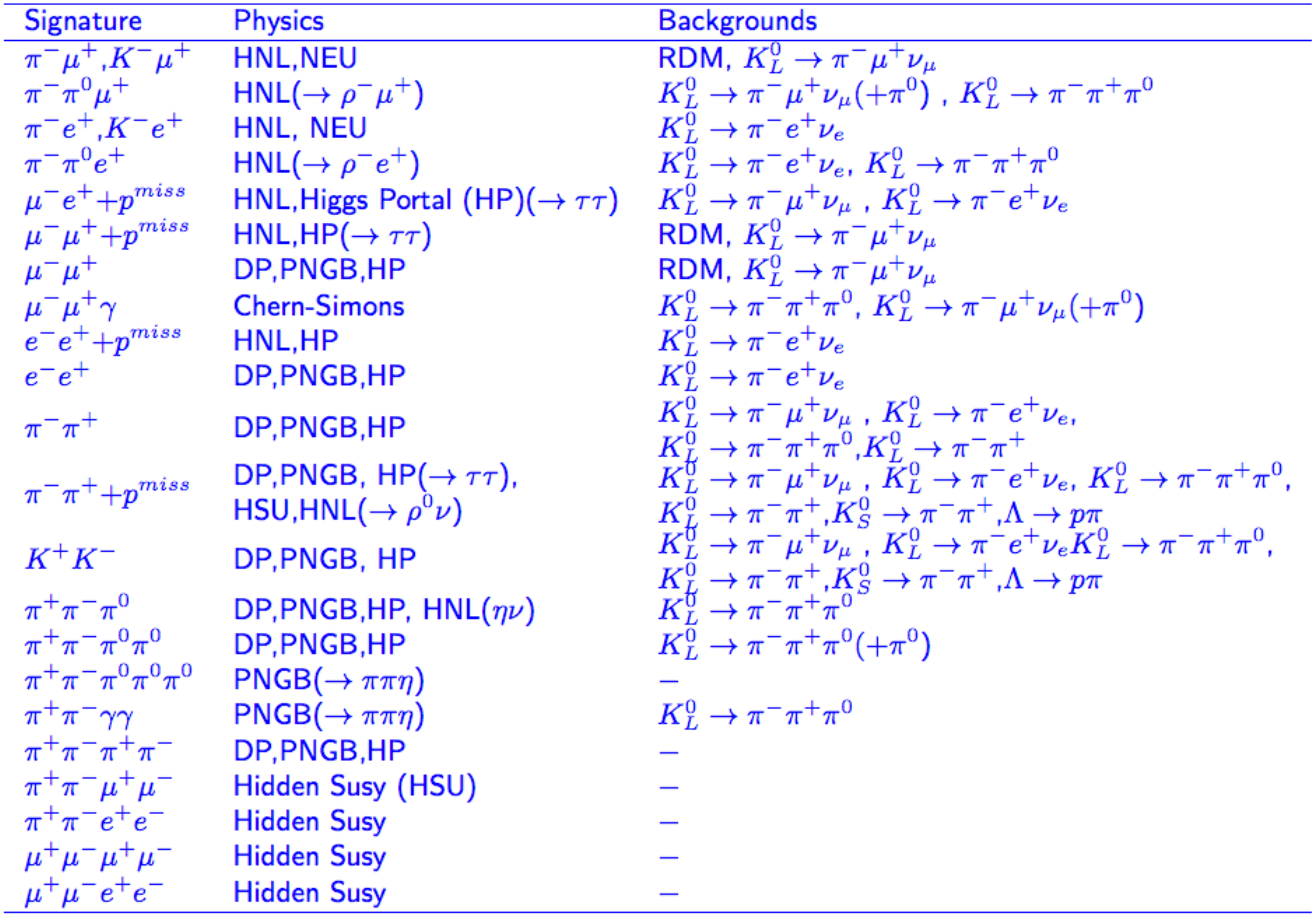
➜ Decay: $S \to \gamma\gamma, ee, \mu\mu, \pi\pi, KK$

# Axion Like Particles

- The axion mass $m_A$ is very constrained due to the axial QCD anomaly breaking the PQ symmetry. Other ALPs are not so constrained.

- SHiP can probe ALPs coupled to gauge bosons and to SM fermions:
  - $pp \to AX,\ A \to \gamma\gamma$: all neutral, more challenging
  - $pp \to BX,\ B \to AK,\ A \to \mu^+\mu^-$

# Physics signals



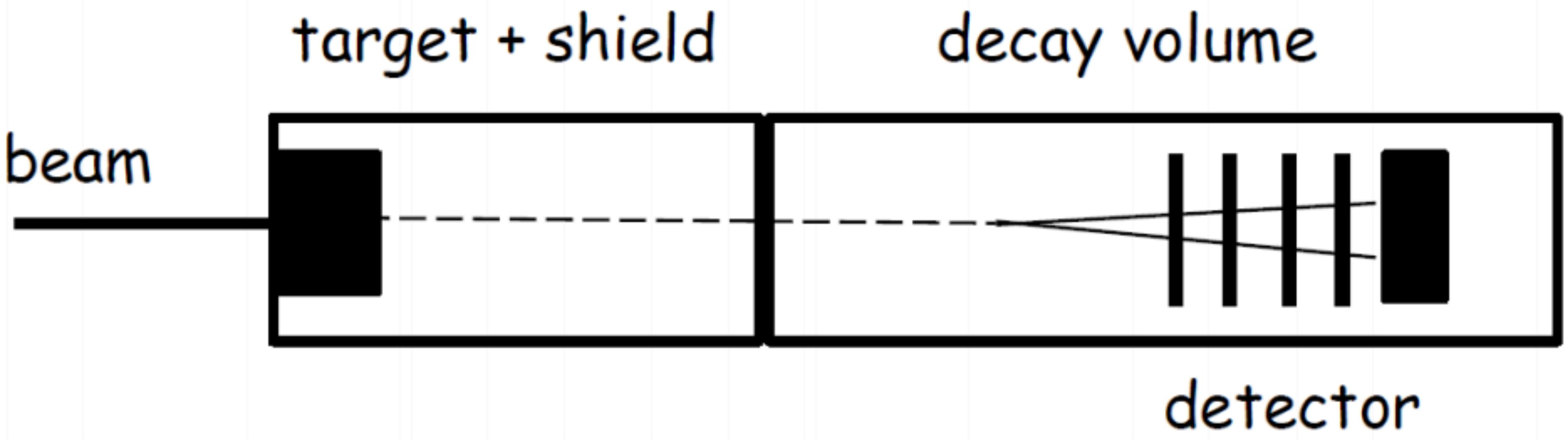
| Signature | Physics | Backgrounds |
|---|---|---|
| $\pi^-\mu^+$,$K^-\mu^+$ | HNL,NEU | RDM, $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ |
| $\pi^-\pi^0\mu^+$ | HNL($\rightarrow \rho^-\mu^+$) | $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu(+\pi^0)$ , $K_L^0 \rightarrow \pi^-\pi^+\pi^0$ |
| $\pi^-e^+$,$K^-e^+$ | HNL, NEU | $K_L^0 \rightarrow \pi^-e^+\nu_e$ |
| $\pi^-\pi^0e^+$ | HNL($\rightarrow \rho^-e^+$) | $K_L^0 \rightarrow \pi^-e^+\nu_e$, $K_L^0 \rightarrow \pi^-\pi^+\pi^0$ |
| $\mu^-e^+$+$p^{miss}$ | HNL,Higgs Portal (HP)($\rightarrow \tau\tau$) | $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ , $K_L^0 \rightarrow \pi^-e^+\nu_e$ |
| $\mu^-\mu^+$+$p^{miss}$ | HNL,HP($\rightarrow \tau\tau$) | RDM, $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ |
| $\mu^-\mu^+$ | DP,PNGB,HP | RDM, $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ |
| $\mu^-\mu^+\gamma$ | Chern-Simons | $K_L^0 \rightarrow \pi^-\pi^+\pi^0$, $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu(+\pi^0)$ |
| $e^-e^+$+$p^{miss}$ | HNL,HP | $K_L^0 \rightarrow \pi^-e^+\nu_e$ |
| $e^-e^+$ | DP,PNGB,HP | $K_L^0 \rightarrow \pi^-e^+\nu_e$ |
| $\pi^-\pi^+$ | DP,PNGB,HP | $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ , $K_L^0 \rightarrow \pi^-e^+\nu_e$,<br>$K_L^0 \rightarrow \pi^-\pi^+\pi^0$,$K_L^0 \rightarrow \pi^-\pi^+$ |
| $\pi^-\pi^+$+$p^{miss}$ | DP,PNGB, HP($\rightarrow \tau\tau$),<br>HSU,HNL($\rightarrow \rho^0\nu$) | $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ , $K_L^0 \rightarrow \pi^-e^+\nu_e$, $K_L^0 \rightarrow \pi^-\pi^+\pi^0$,<br>$K_L^0 \rightarrow \pi^-\pi^+$,$K_S^0 \rightarrow \pi^-\pi^+$,$\Lambda \rightarrow p\pi$ |
| $K^+K^-$ | DP,PNGB, HP | $K_L^0 \rightarrow \pi^-\mu^+\nu_\mu$ , $K_L^0 \rightarrow \pi^-e^+\nu_e K_L^0 \rightarrow \pi^-\pi^+\pi^0$,<br>$K_L^0 \rightarrow \pi^-\pi^+$,$K_S^0 \rightarrow \pi^-\pi^+$,$\Lambda \rightarrow p\pi$ |
| $\pi^+\pi^-\pi^0$ | DP,PNGB,HP, HNL($\eta\nu$) | $K_L^0 \rightarrow \pi^-\pi^+\pi^0$ |
| $\pi^+\pi^-\pi^0\pi^0$ | DP,PNGB,HP | $K_L^0 \rightarrow \pi^-\pi^+\pi^0(+\pi^0)$ |
| $\pi^+\pi^-\pi^0\pi^0\pi^0$ | PNGB($\rightarrow \pi\pi\eta$) | – |
| $\pi^+\pi^-\gamma\gamma$ | PNGB($\rightarrow \pi\pi\eta$) | $K_L^0 \rightarrow \pi^-\pi^+\pi^0$ |
| $\pi^+\pi^-\pi^+\pi^-$ | DP,PNGB,HP | – |
| $\pi^+\pi^-\mu^+\mu^-$ | Hidden Susy (HSU) | – |
| $\pi^+\pi^-e^+e^-$ | Hidden Susy | – |
| $\mu^+\mu^-\mu^+\mu^-$ | Hidden Susy | – |
| $\mu^+\mu^-e^+e^-$ | Hidden Susy | – |

HNL=Heavy Neutral Lepton, NEU=neutralino

DP=Dark Photon, PNGB=Pseudo-Nambu Goldston Boson

Background: RDM=random di-muons from the target

# Experimental concept

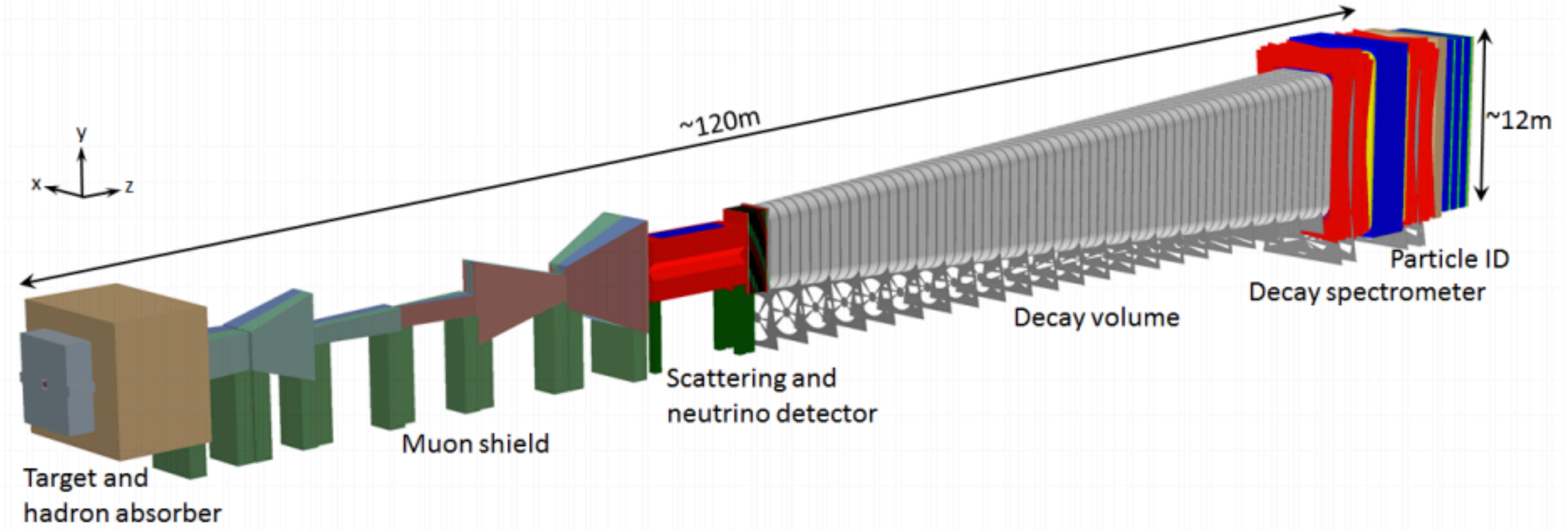


- High Intensity beam into an heavy target
    - We want particles either coming from heavy meson decays or from pN interactions
    - We want to suppress pion and kaon decays which is source of bkg

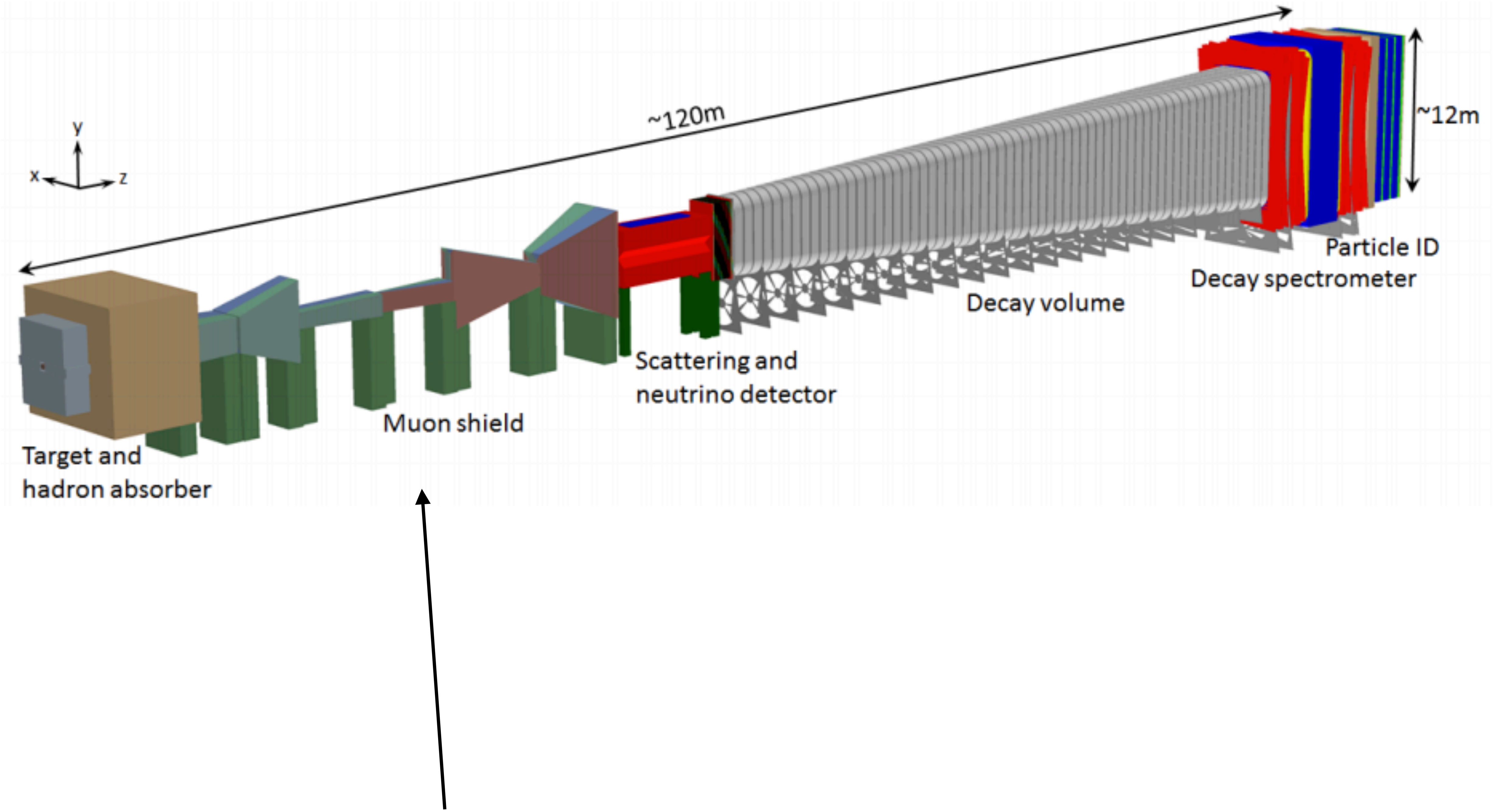
- Minimize the flux of SM particles in the detector

- Define a (large) fiducial volume where the background level is approximately zero

# Overview of SHiP

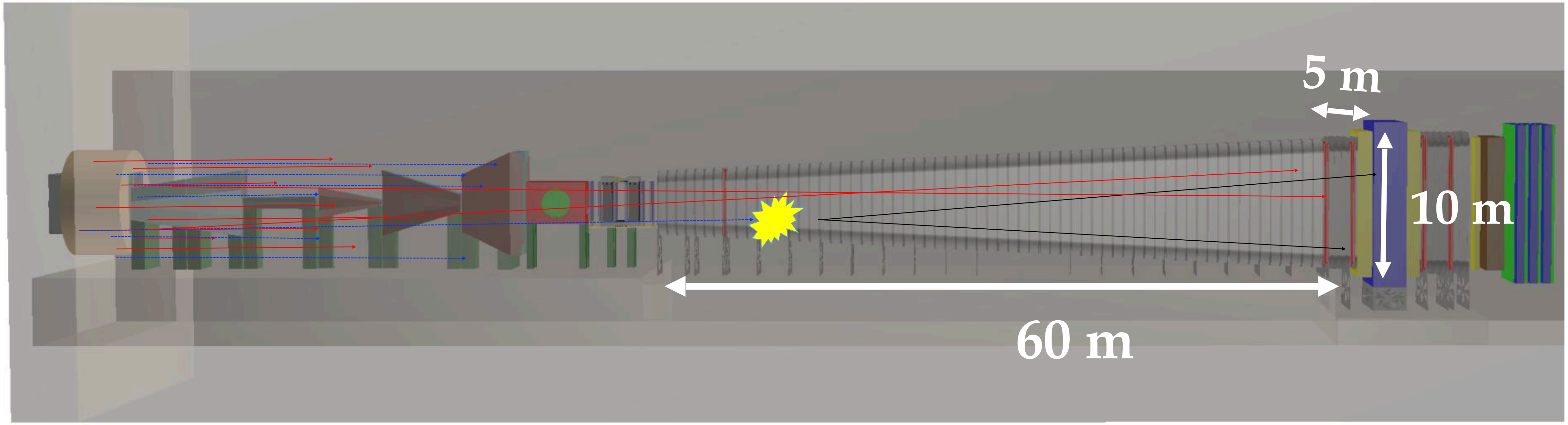


# Overview of SHiP



Sweeping magnet

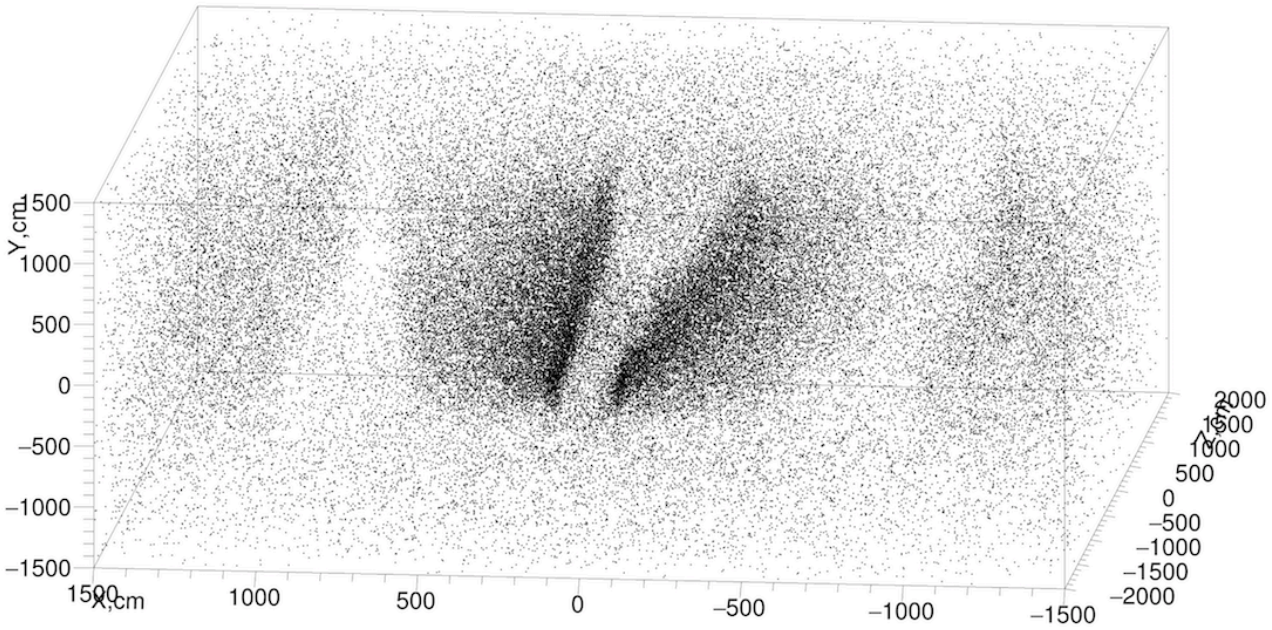
# Fiducial Volume

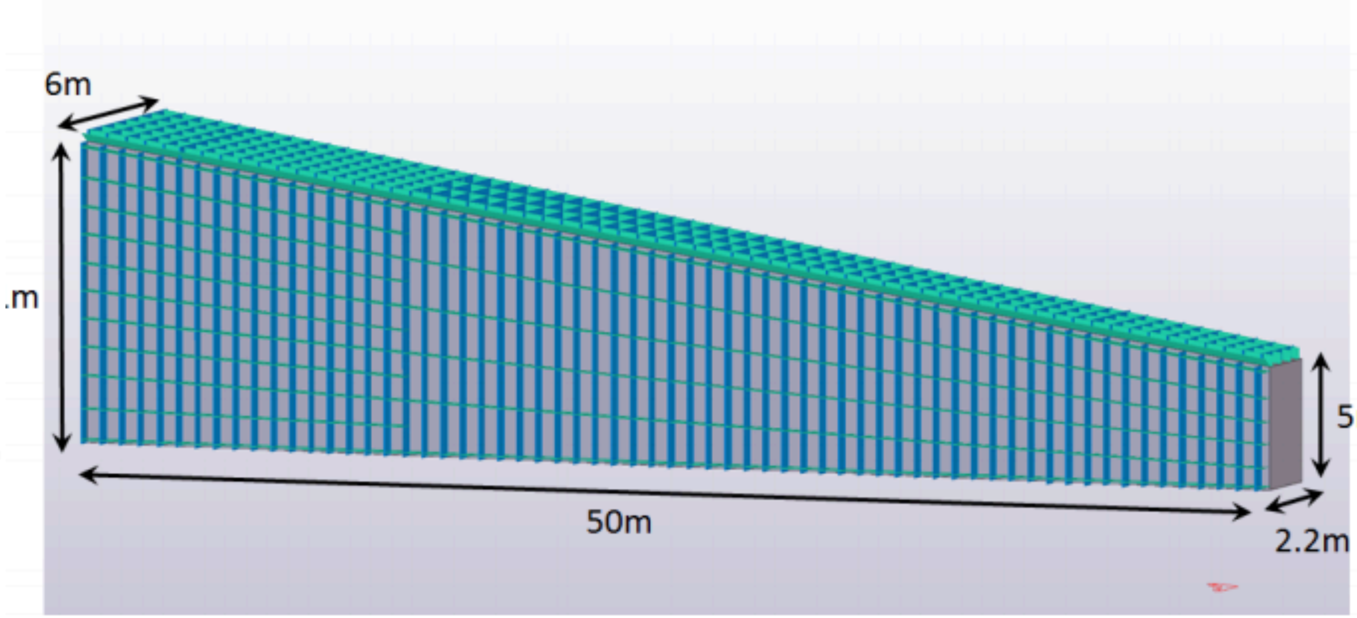


- In order to have a background free experiment we need a fiducial volume with at least 1mbar to have negligible bkg from neutrinos interacting in the air

- Veto system around the fiducial volume:
    - Liquid or plastic scintillating in the vacuum vessel walls for vetoing

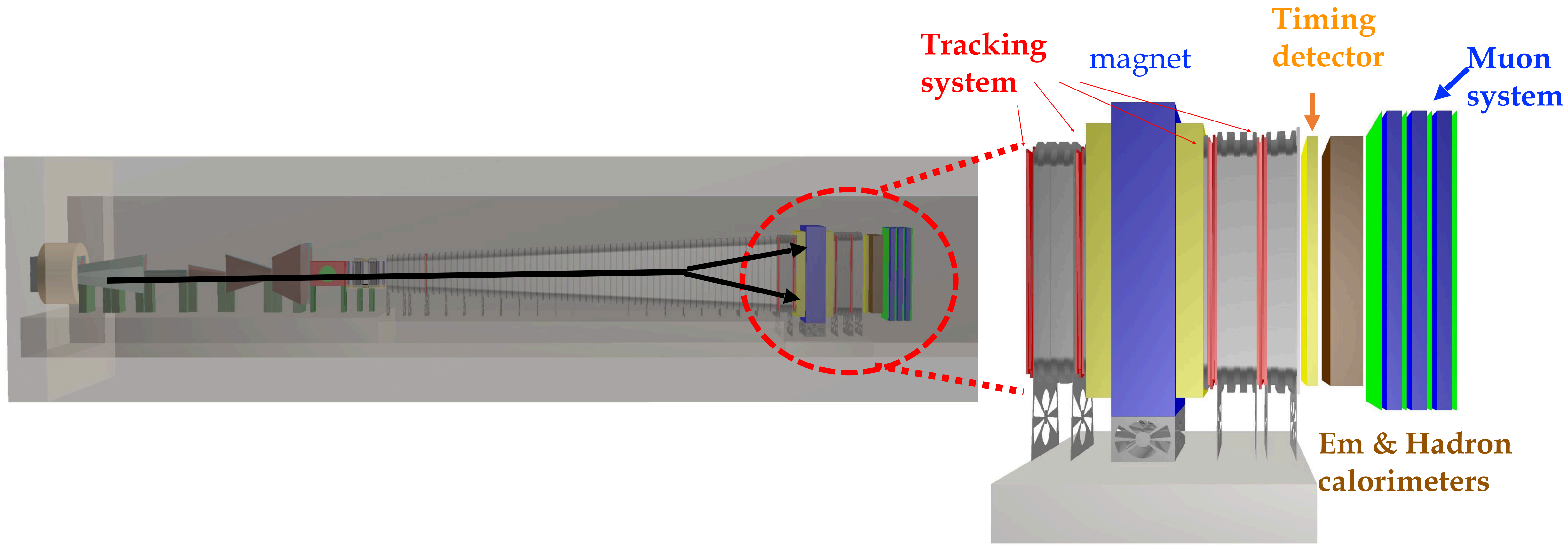
# Vacuum Vessel





- The fiducial volume cannot be filled with air at atmospheric pressure, we would expect about 100K neutrino interaction in the experiment
- Of this about 300 would survive a loose offline selection
- Piramidal frustrum shape to maximise the acceptance

# HS Spectrometer

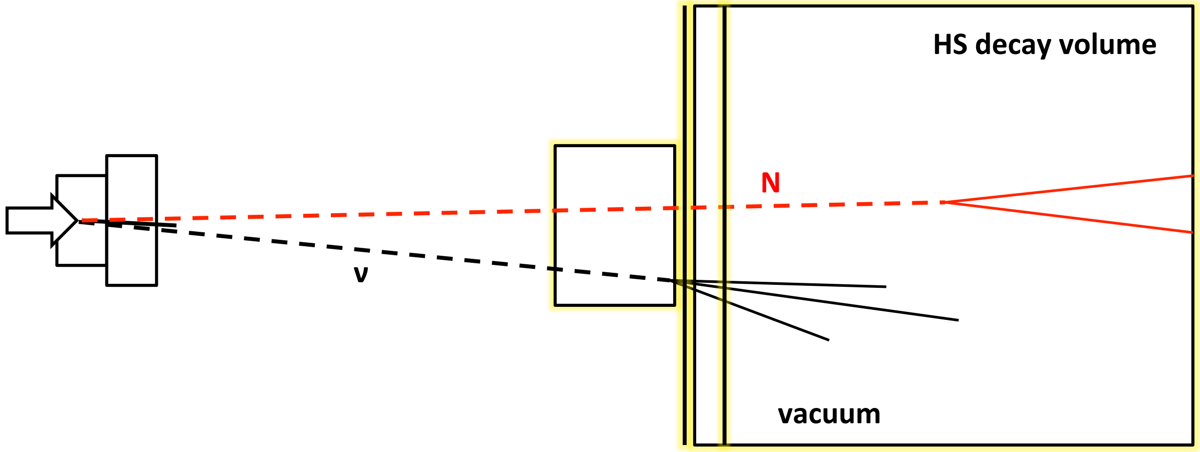


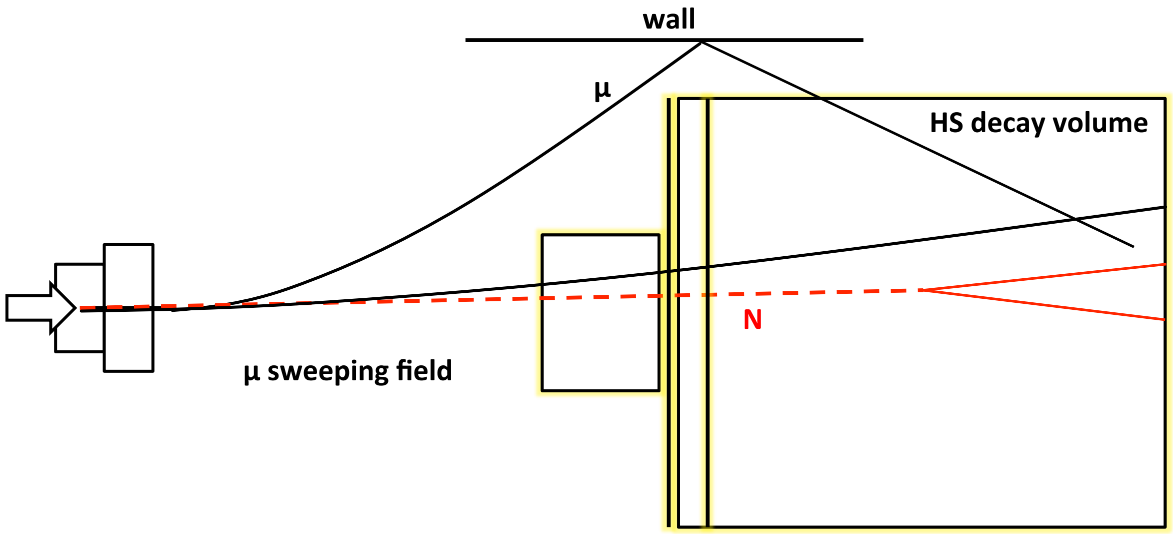
1) Fully reconstructed signal: at least two charged particles (+ $\pi^0$ , $\gamma$ ) e.g. $N \to \mu^+\pi^-$ or $N \to \rho^+\mu^-$

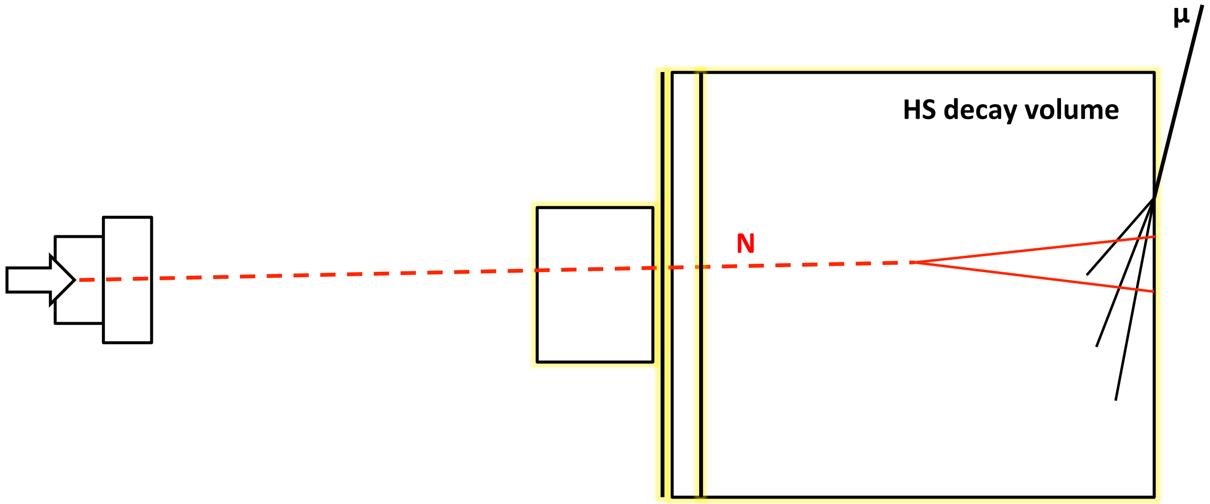
2) Partially reconstructed signal (neutrinos in the final state) e.g. $N \to \mu^+\mu^-\nu$

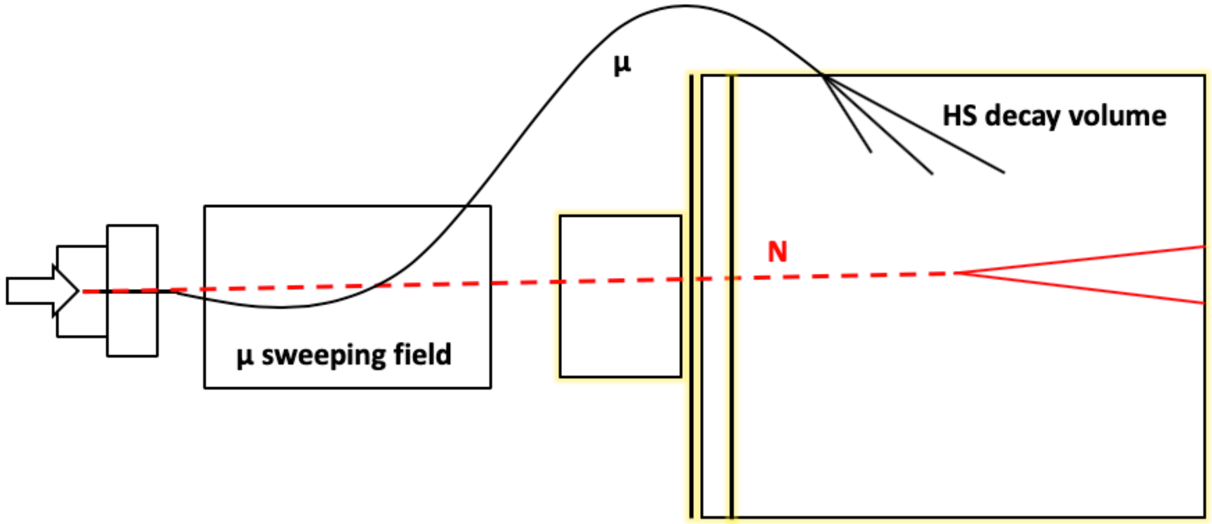
4) Fully neutral channels e.g. $A \to \gamma\,\gamma$

# Backgrounds



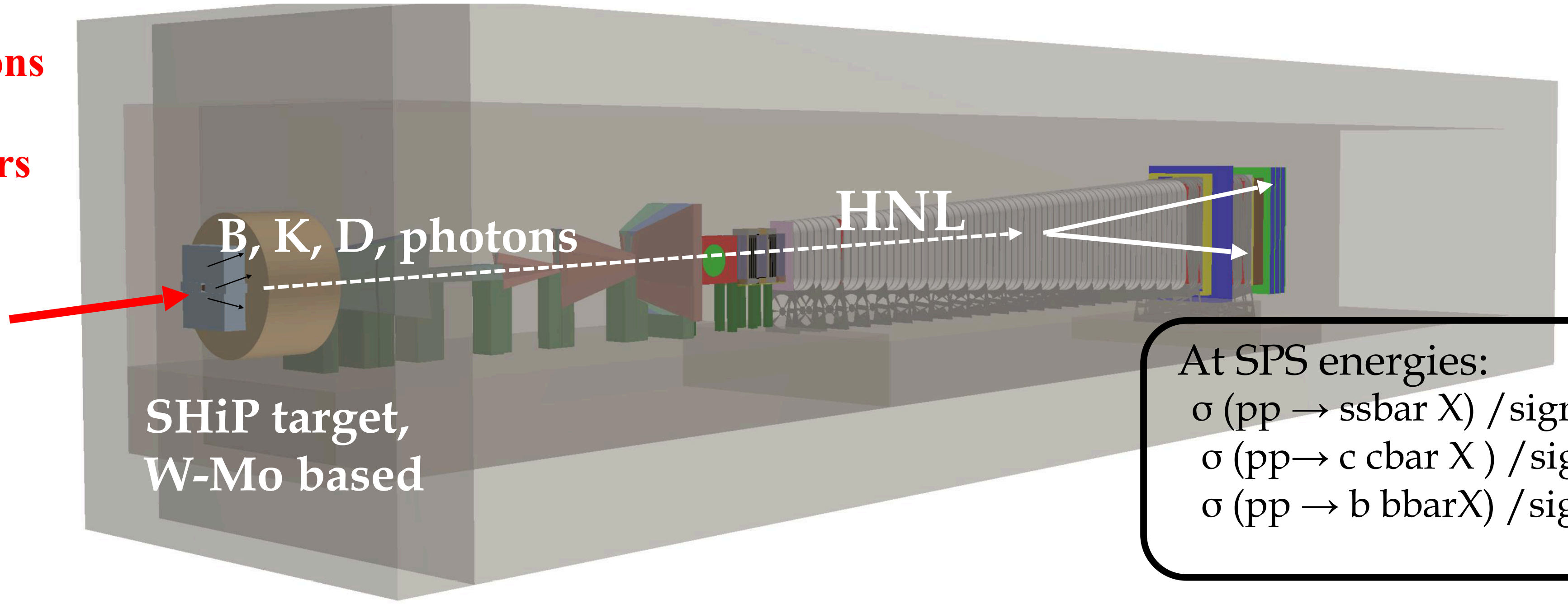






# Signal Signature

**Beam:**
**400 GeV/c protons**
**4x$10^{13}$ pot/spill**
**2x$10^{20}$ pot/5 years**



At SPS energies:
σ (pp → ssbar X) / sigma (pp→ X) ~ 0.15
σ (pp→ c cbar X ) / sigma (pp→ X) ~ 2 $10^{-3}$
σ (pp → b bbarX) / sigma (pp→ X) ~ 1.6 $10^{-7}$

| Cut | Value |
|---|---|
| Track momentum | $> 1.0$ GeV/$c$ |
| Dimuon distance of closest approach | $< 1$ cm |
| Dimuon vertex position | ($> 5$ cm from inner wall) |
| IP w.r.t. target (fully reconstructed) | $< 10$ cm |
| IP w.r.t. target (partially reconstructed) | $< 250$ cm |

Timing cut around 350 ps (two track coincidence)

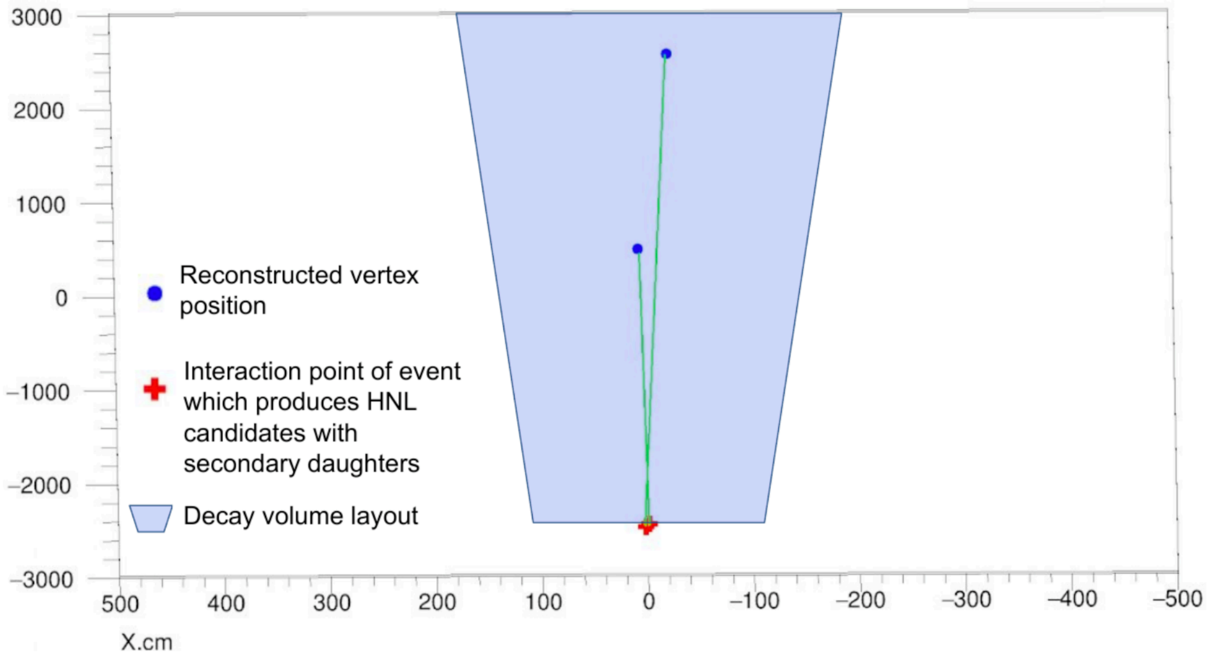
Various veto cuts considered

Signal topology

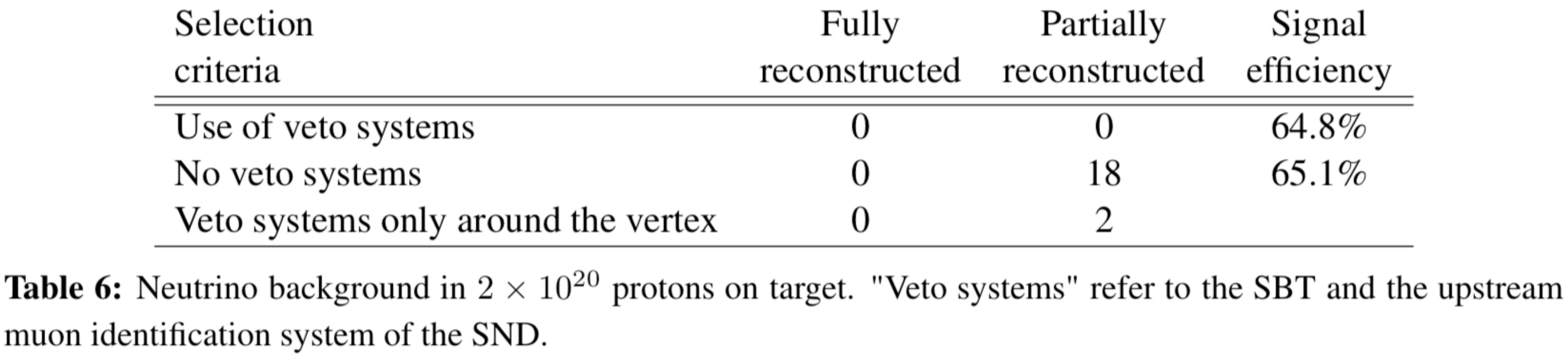
- Fully reconstructed signal, e.g. HNL—> μπ
- Partially reconstructed signal, e.g. HNL—> μμν

# Neutrino Background

- Neutrino background is the main background
- Expected 3.5 x $10^7$ neutrino interactions in the vicinity of the decay volume
- Expected number of tracks with opposite charge about 6.5x$10^4$
- Two events in 5 years for partially reconstructed coming from converted photons



| Selection stage | |
|---|---|
| Reconstructed candidates | 65 612 |
| Basic selection | 135 |
| PID | 12 |
| Exclude area next walls & entrance window | 8 |
| Invariant mass >100 MeV | 0.25 |
| SBT signal around the vertex | 0.05 |

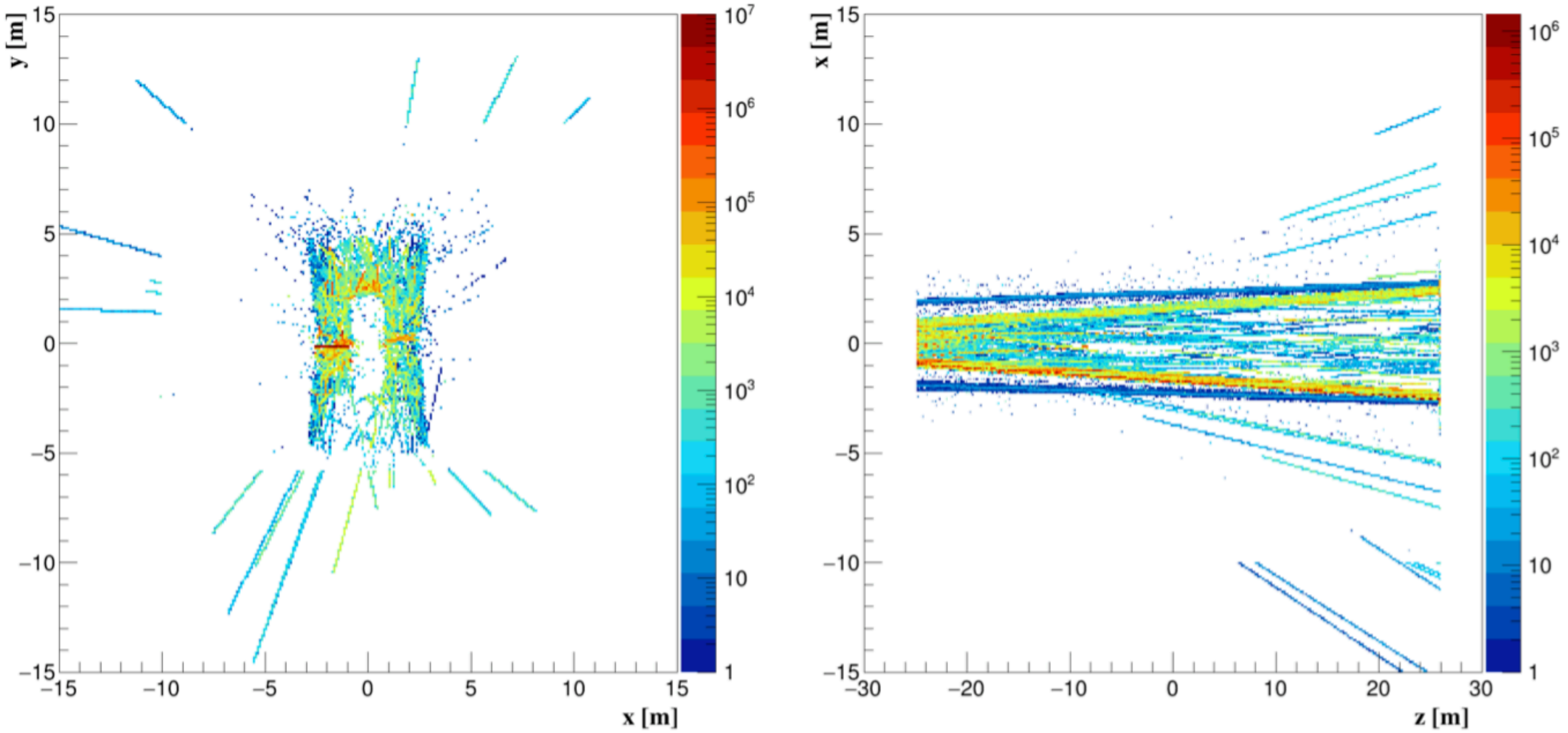


| Selection criteria | Fully reconstructed | Partially reconstructed | Signal efficiency |
|---|---|---|---|
| Use of veto systems | 0 | 0 | 64.8% |
| No veto systems | 0 | 18 | 65.1% |
| Veto systems only around the vertex | 0 | 2 | |

**Table 6:** Neutrino background in $2 \times 10^{20}$ protons on target. "Veto systems" refer to the SBT and the upstream muon identification system of the SND.

# Muon DIS

- The number of muons impinging the decay volume is about $5\text{x}10^4$ per spill
- This result in about $1.5 \text{ x}10^6$ reconstructed bkg candidates from muon DIS interactions in 5 years

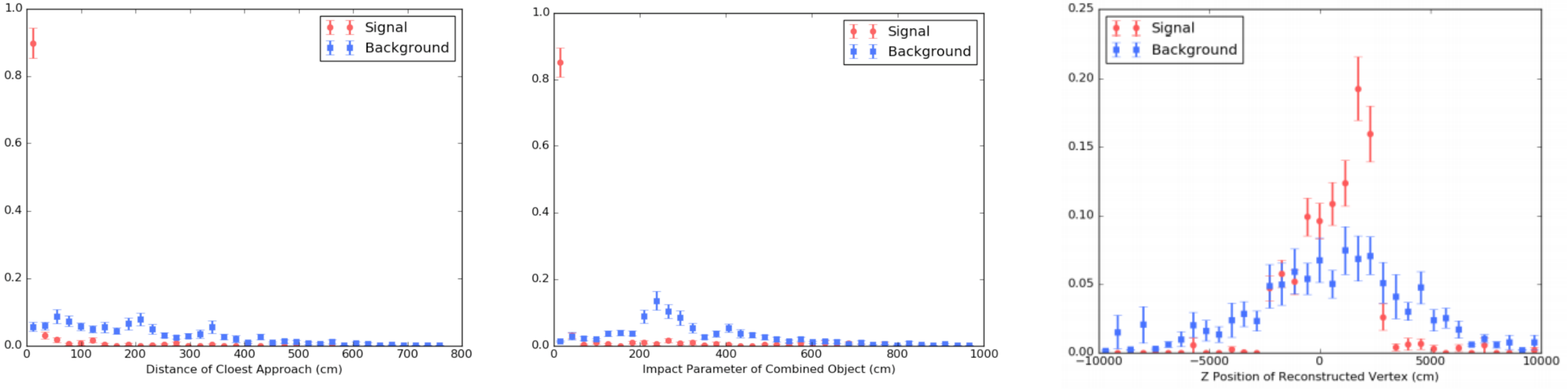


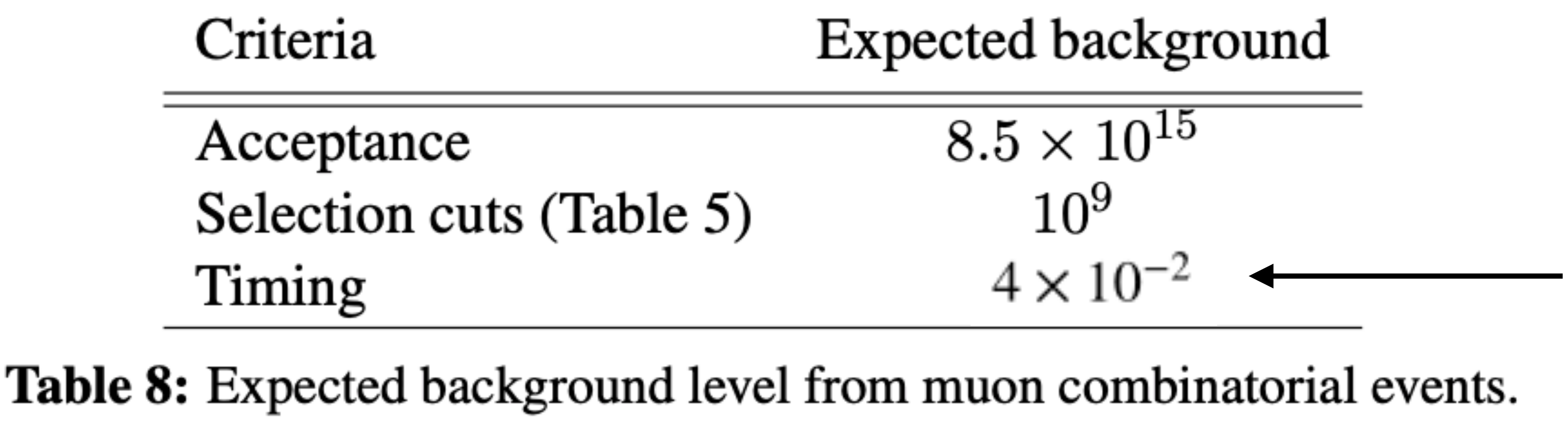
| Selection cut | Expected background |
|---|---|
| Events reconstructed | $1.5{\cdot}10^6$ |
| Selection cuts (IP $<$ 10 cm) | 27 |
| Selection cuts (IP $<$ 250 cm) | 566 |
| Vetoed events SBT (fully reco) | $< 2.7 \cdot 10^{-5}$ |
| Vetoed events (partially reco) | $< 6 \times 10^{-4}$ |

**Table 7:** Summary of the muon inelastic background events expected for $2 \times 10^{20}$ protons on target. The numbers with the veto requirement assume factorization with the Impact Parameter cut.

# Muon Combinatorial

- The muon rate entering the decay volume is about 30KHz
- We expect about $10^{16}$ pairs of tracks in 5 years



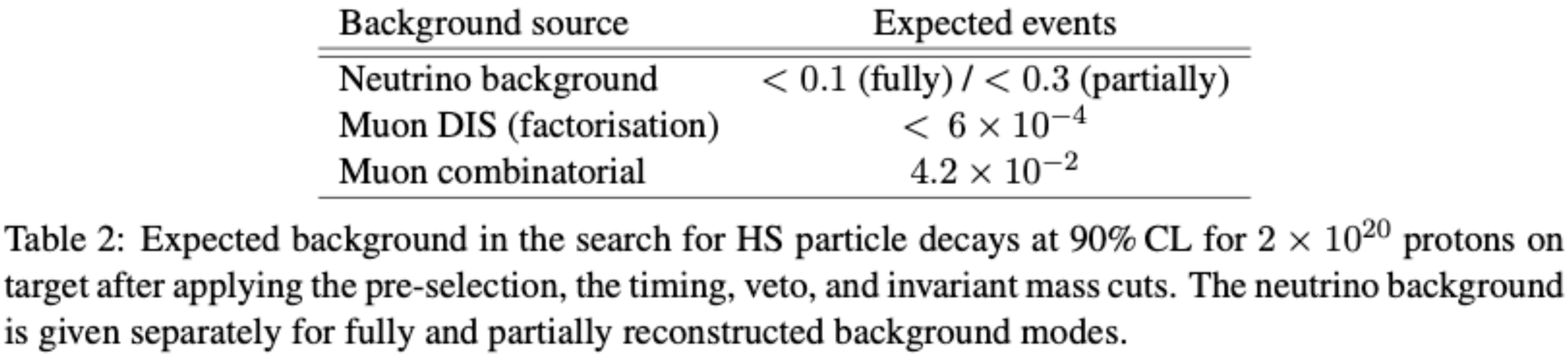


| Criteria | Expected background |
|---|---|
| Acceptance | $8.5 \times 10^{15}$ |
| Selection cuts (Table 5) | $10^{9}$ |
| Timing | $4 \times 10^{-2}$ |

**Table 8:** Expected background level from muon combinatorial events.

Timing cut on coincidence of two tracks 350ps (2.5σ)

# Background summary



| Background source | Expected events |
|---|---|
| Neutrino background | $< 0.1$ (fully) / $< 0.3$ (partially) |
| Muon DIS (factorisation) | $< 6 \times 10^{-4}$ |
| Muon combinatorial | $4.2 \times 10^{-2}$ |

Table 2: Expected background in the search for HS particle decays at 90% CL for $2 \times 10^{20}$ protons on target after applying the pre-selection, the timing, veto, and invariant mass cuts. The neutrino background is given separately for fully and partially reconstructed background modes.

# HNL Sensitivity

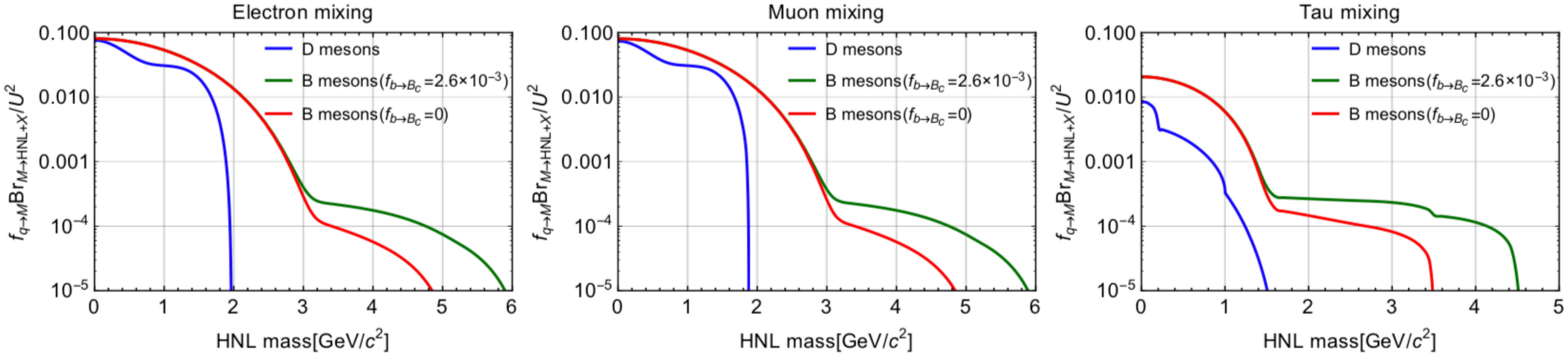


**Figure 65:** Meson fragmentation fraction times branching fraction of meson decays to HNL as a function of the HNL mass. Contributions from $D$ and $B$ mesons are shown. To demonstrate the influence of $B_c$ mesons, we show two cases: the $B_c$ fragmentation fraction at SHiP energies equal to that of at LHC energies: $f(b \to B_c) = 2.6 \times 10^{-3}$ (maximal contribution), and $f_{b\to B_c} = 0$. See text for details.

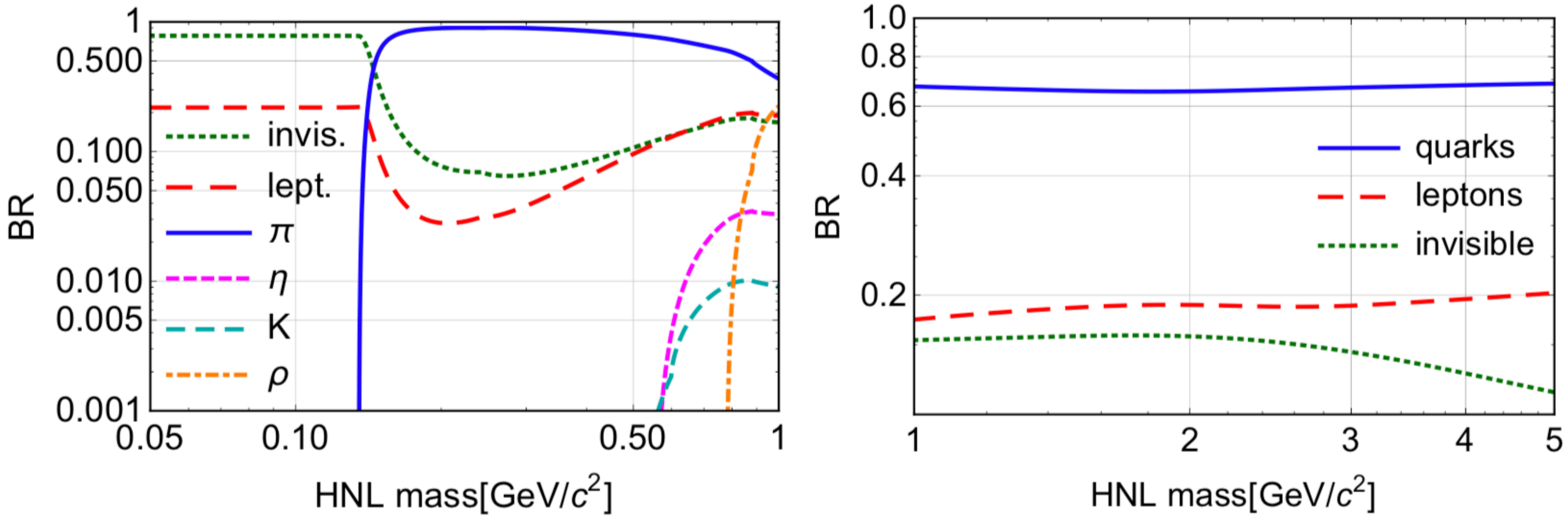


**Figure 66:** The branching ratios of the HNL decays for the mixing ratio $U_e : U_\mu : U_\tau = 1 : 1 : 1$. *Left panel:* region of masses below 1 GeV/$c^2$; *Right panel:* region of masses above 1 GeV/$c^2$. From [108].

# HNL Sensitivity

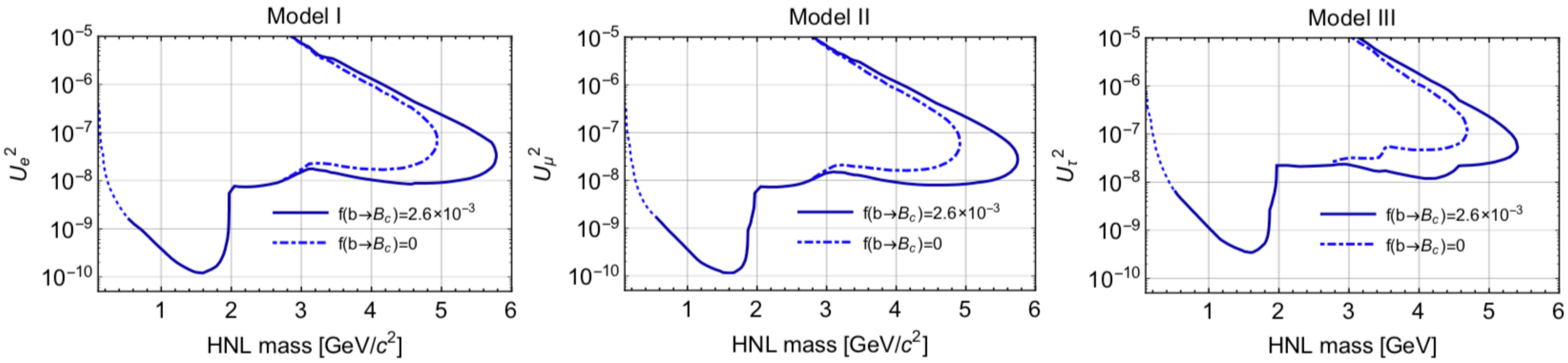
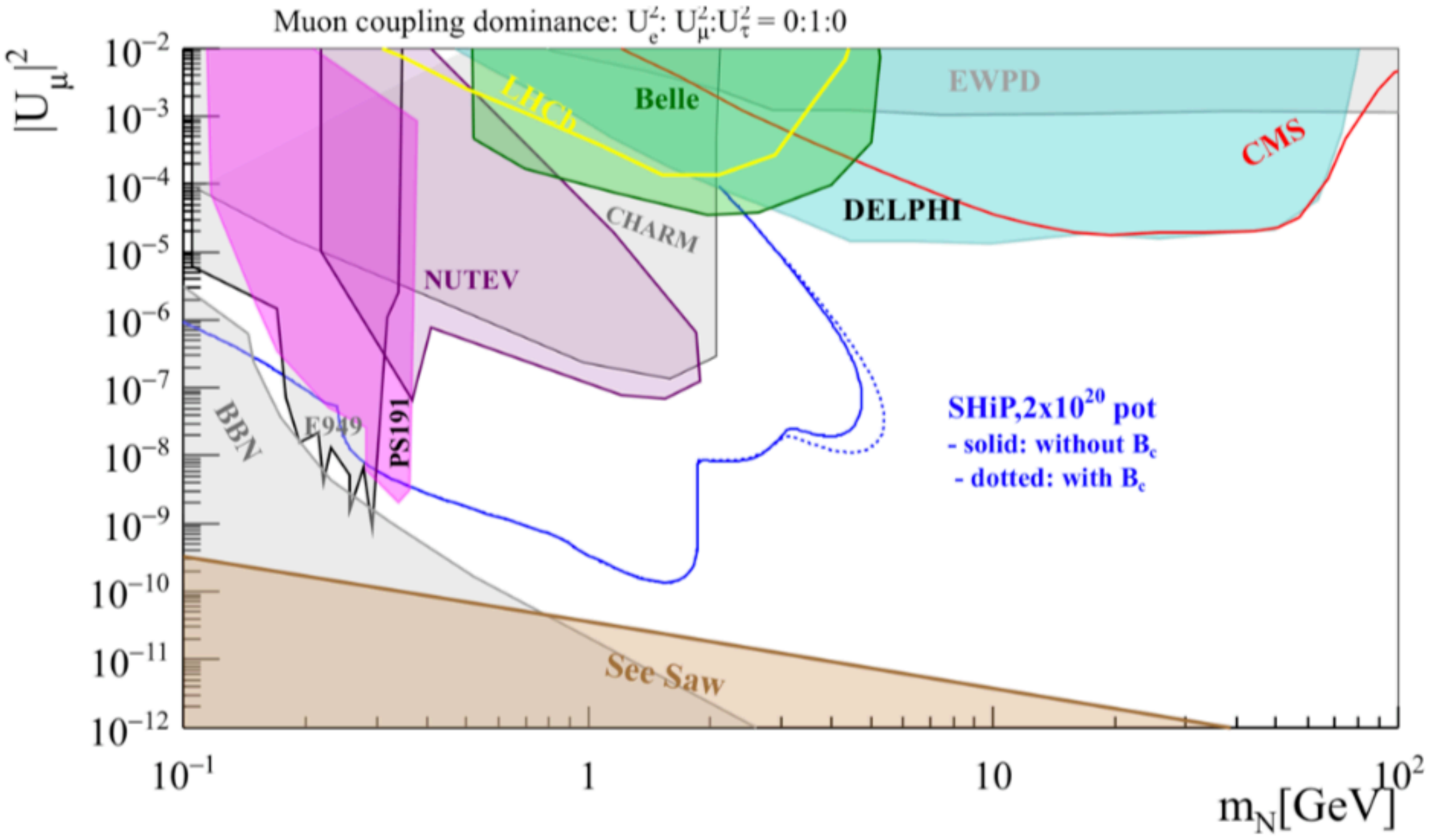


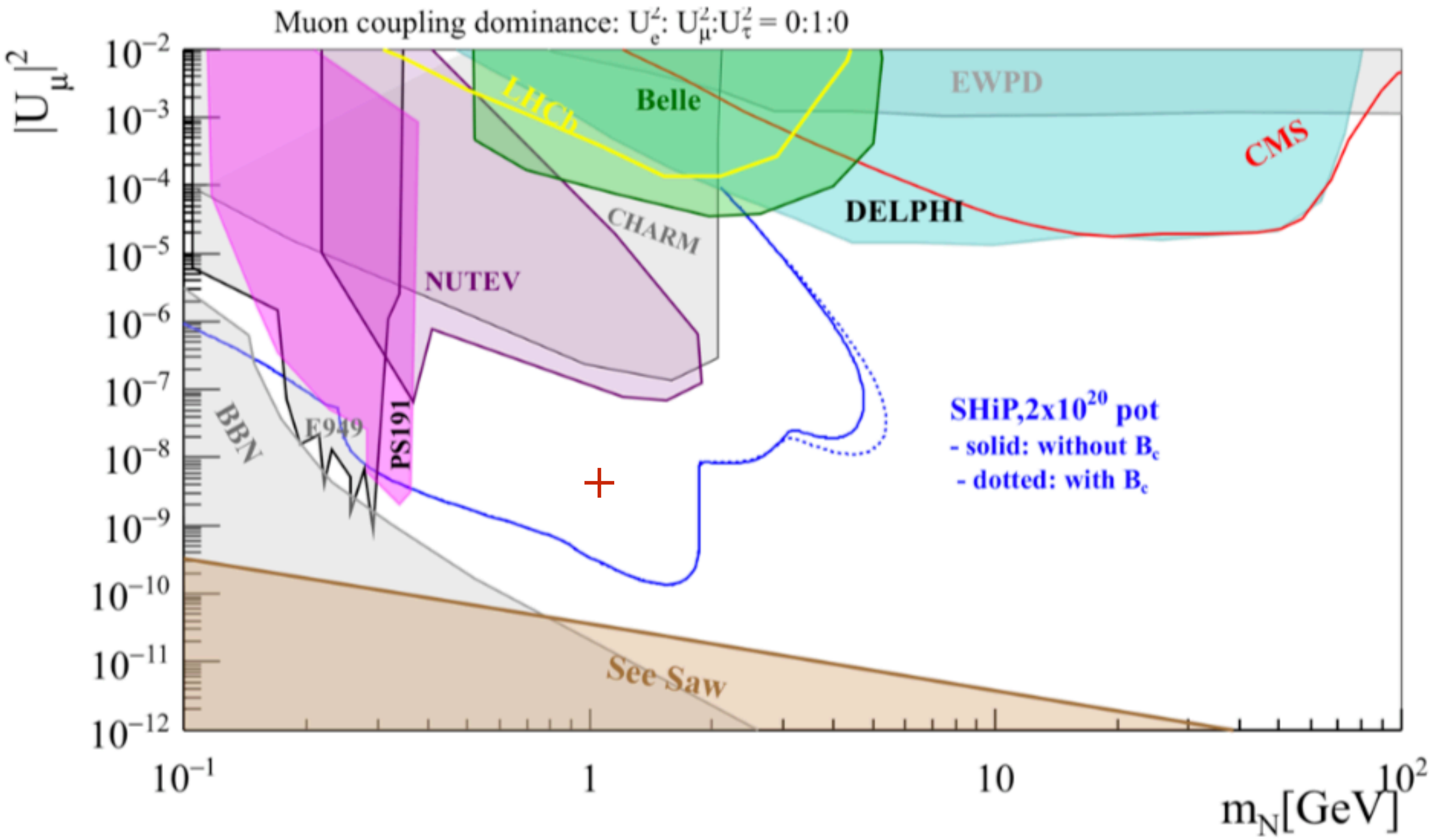
**Figure 67:** Sensitivity of the SHiP experiment to three HNL models. Solid curves show the contribution from $B_c$ mesons, when the fragmentation fraction is taken equal to that at LHC energies: $f_{b\to B_c} = 2.6 \times 10^{-3}$. Dashed-dotted lines do not include contributions from $B_c$. Below 0.5 GeV/$c^2$ only production from $D$ and $B$ mesons is included (dotted lines). Total number of events within contour is $N \geq 2.3$.

- Model I (BC6), $U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$
- Model II (BC7), $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$
- Model III (BC8), $U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

# HNL Sensitivity



# HNL Sensitivity

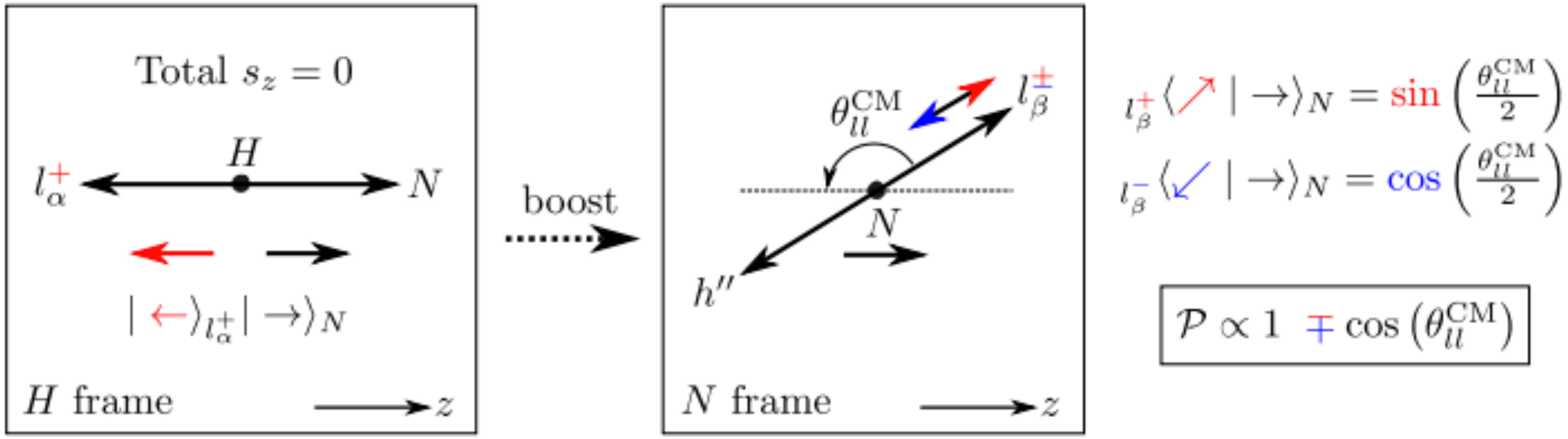


- SHiP can improve by up to 4 orders of magnitudes limits on sterile neutrinos below the B-meson mass
- *E.g. $U^2=10^{-8}$ and M=1GeV (~50 times lower than the present limit) SHiP will see more than 1000 fully reconstructed events, i.e. SHiP would discover sterile neutrinos in less than a week of running!*

# Probing Leptogenesis

- Having particle ID, momentum, energy information in the final state allows SHiP to study the nature of the signal in case of discovery, for instance:

[https://arxiv.org/pdf/1912.05520.pdf](https://arxiv.org/pdf/1912.05520.pdf)

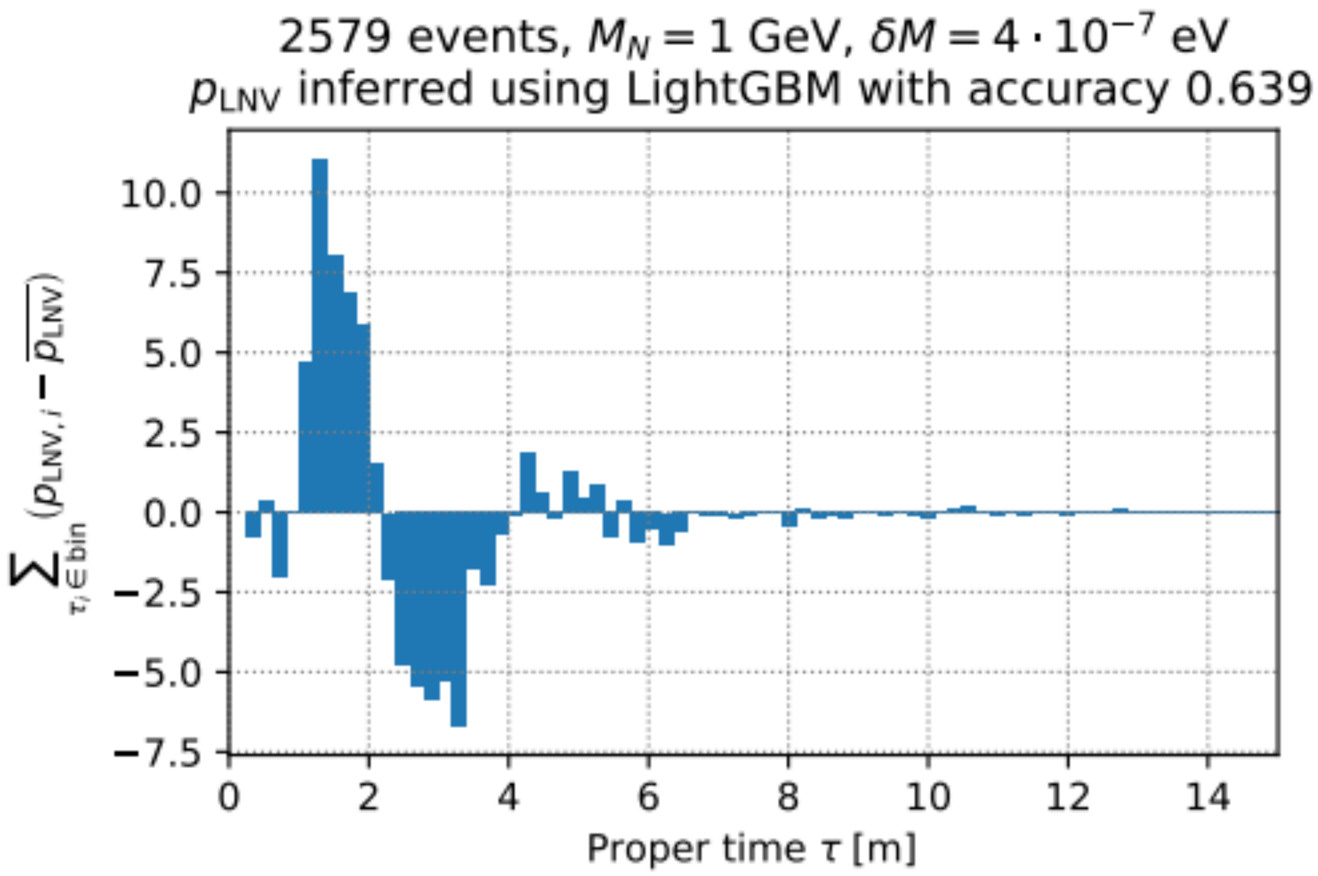


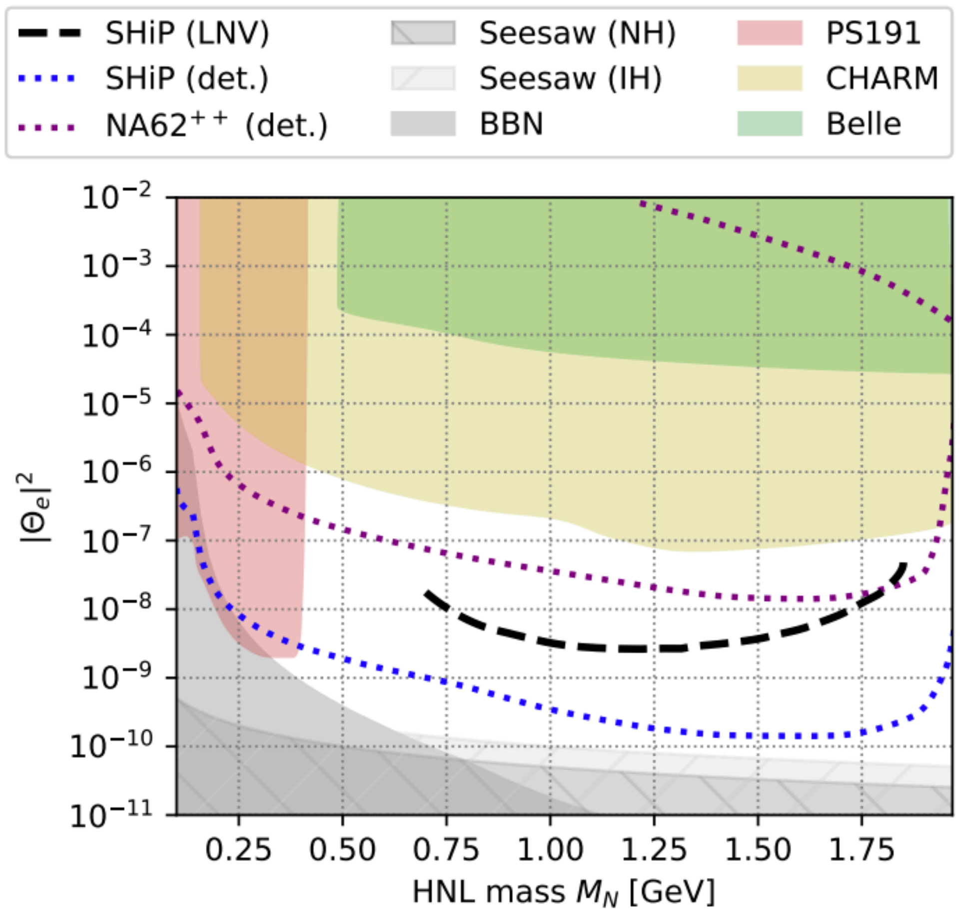
- Even without measuring the primary lepton, the angular distribution of the decay product of the HNL tell us if there is a LNV component, so we can probe the Majorana/Dira nature of HNL

# Probing Leptogenesis

https://arxiv.org/pdf/1912.05520.pdf

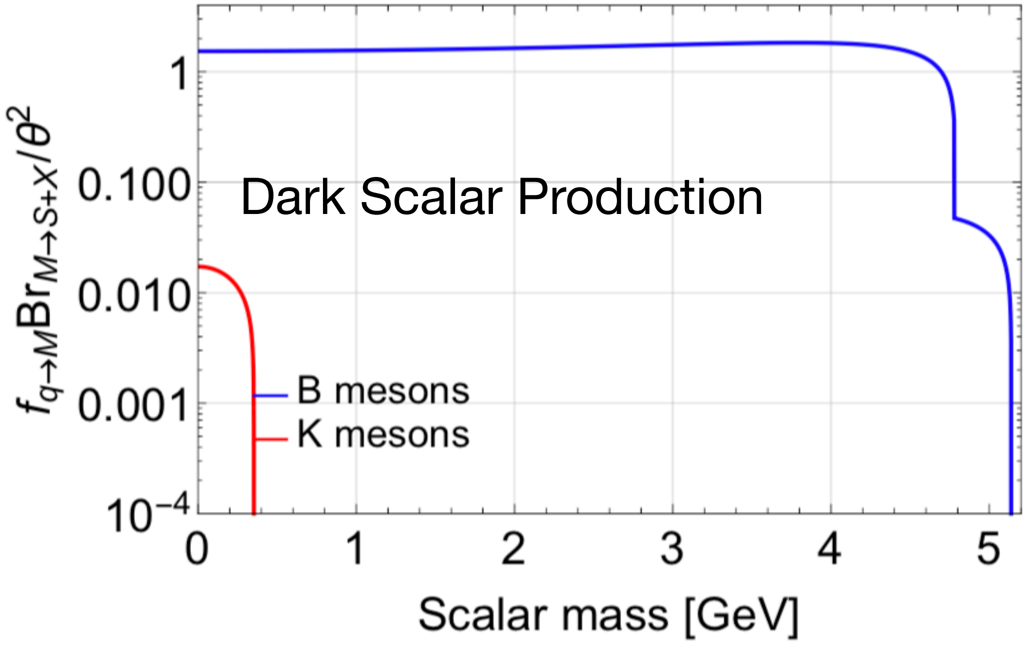
- In the nearly degenerate case both LHC and LNV decay are present and the corresponding decay rate will feature oscillations as a function of proper time





(a) HNL mixing with $\nu_e$.

# DS Sensitivity



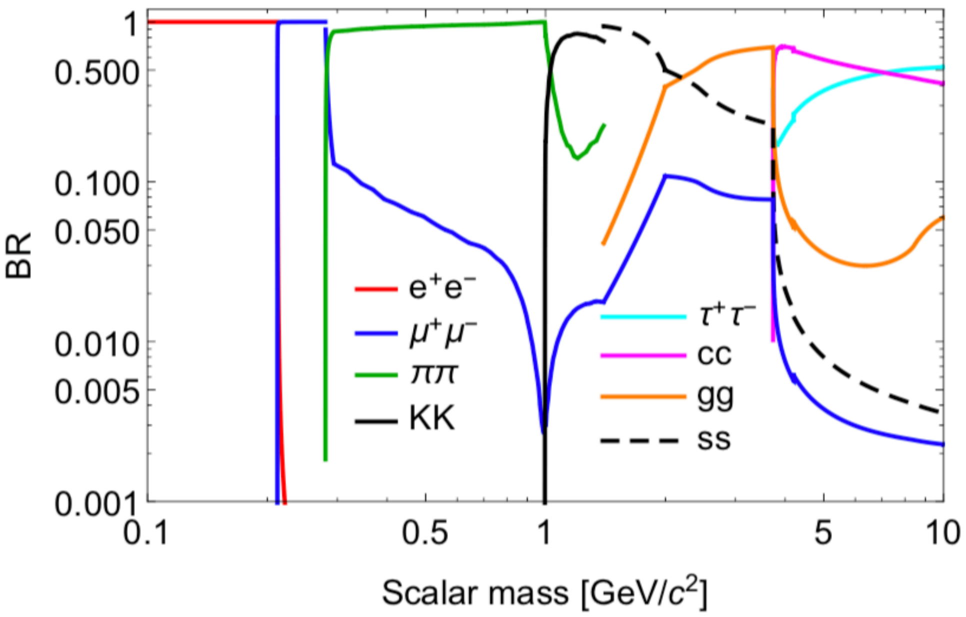
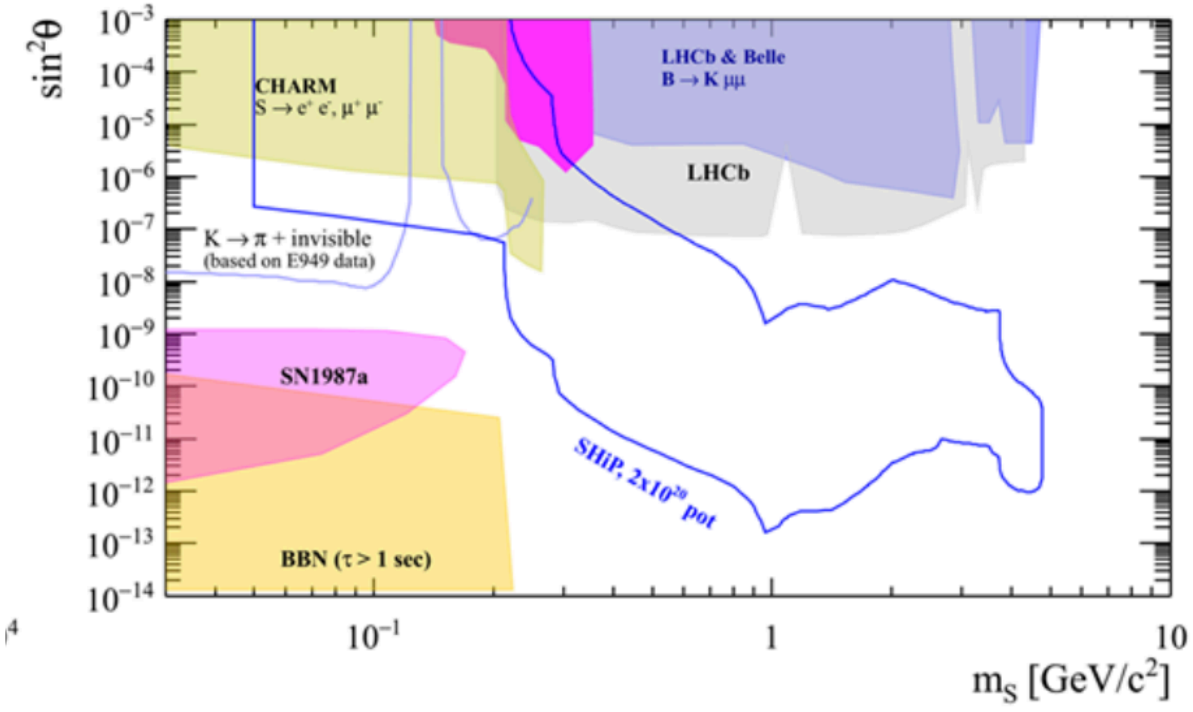


**Figure 70:** The branching ratios of the scalar decays. From [107].



# DP Sensitivity

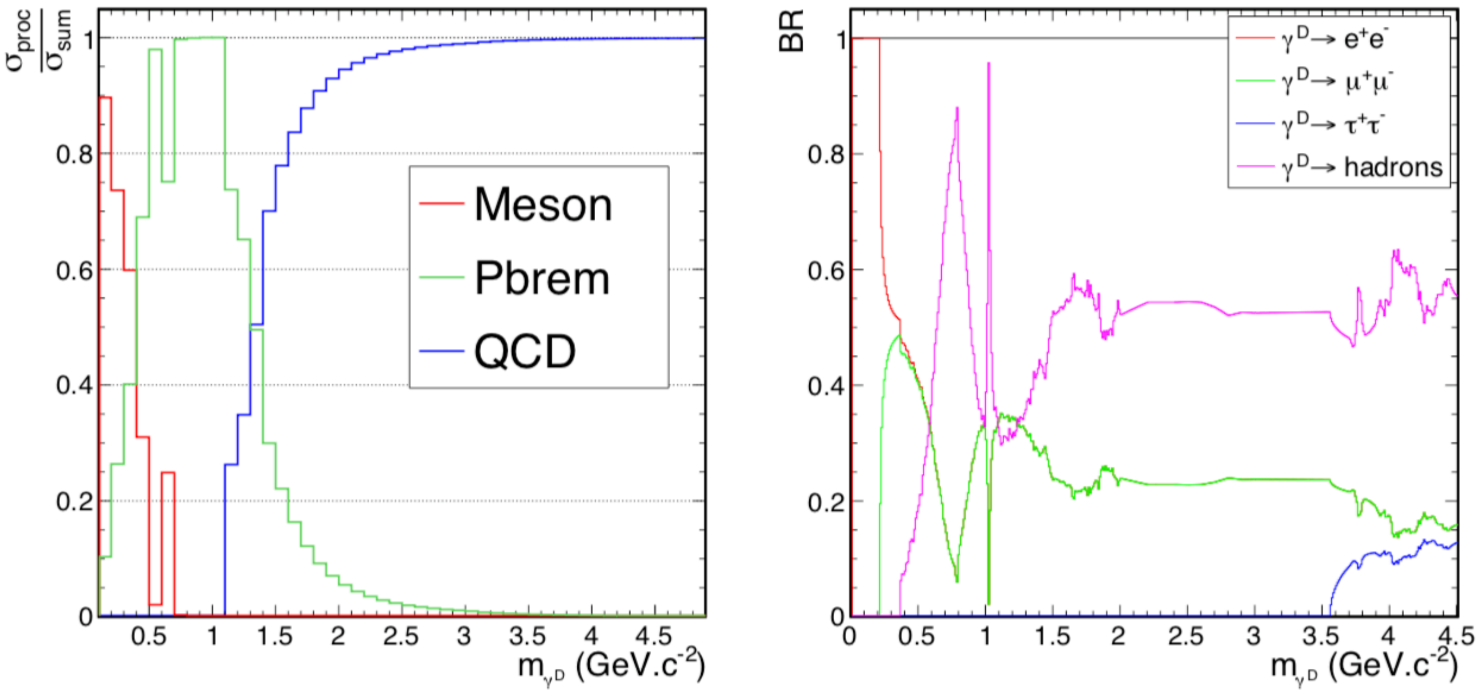
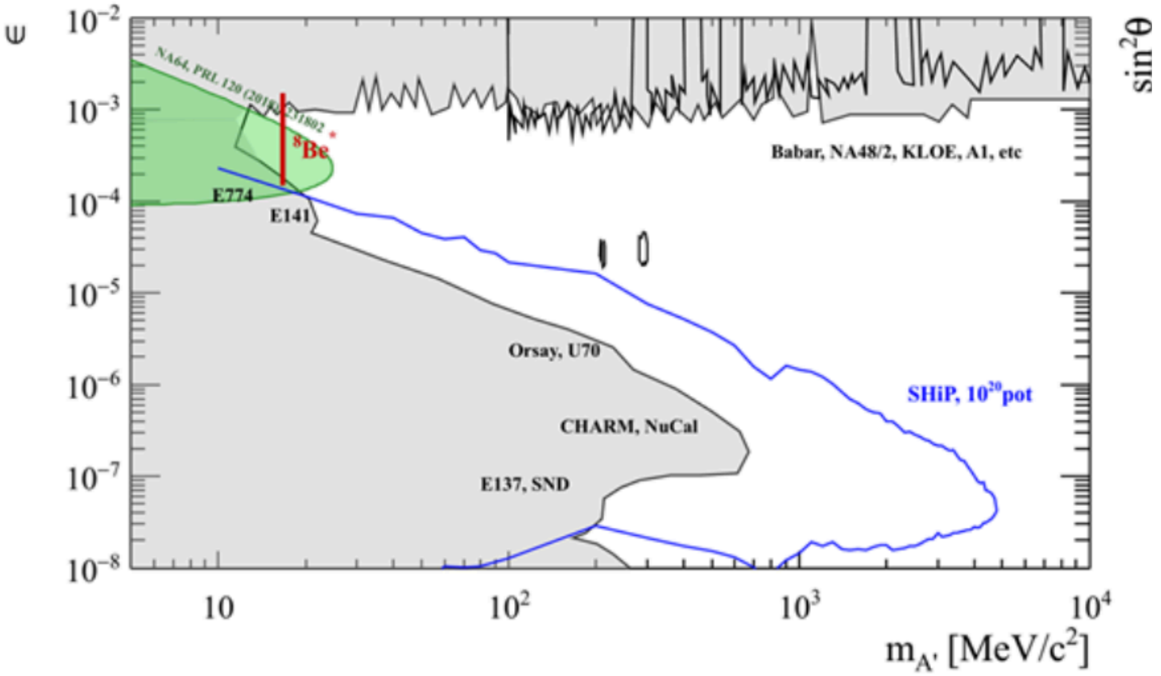
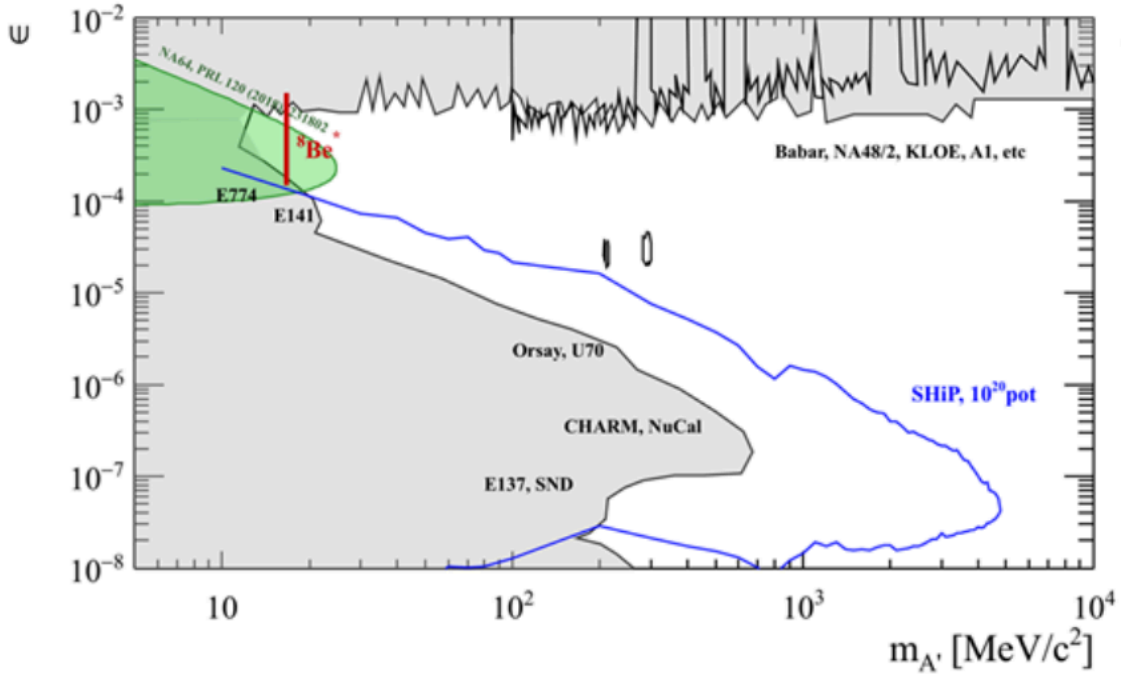
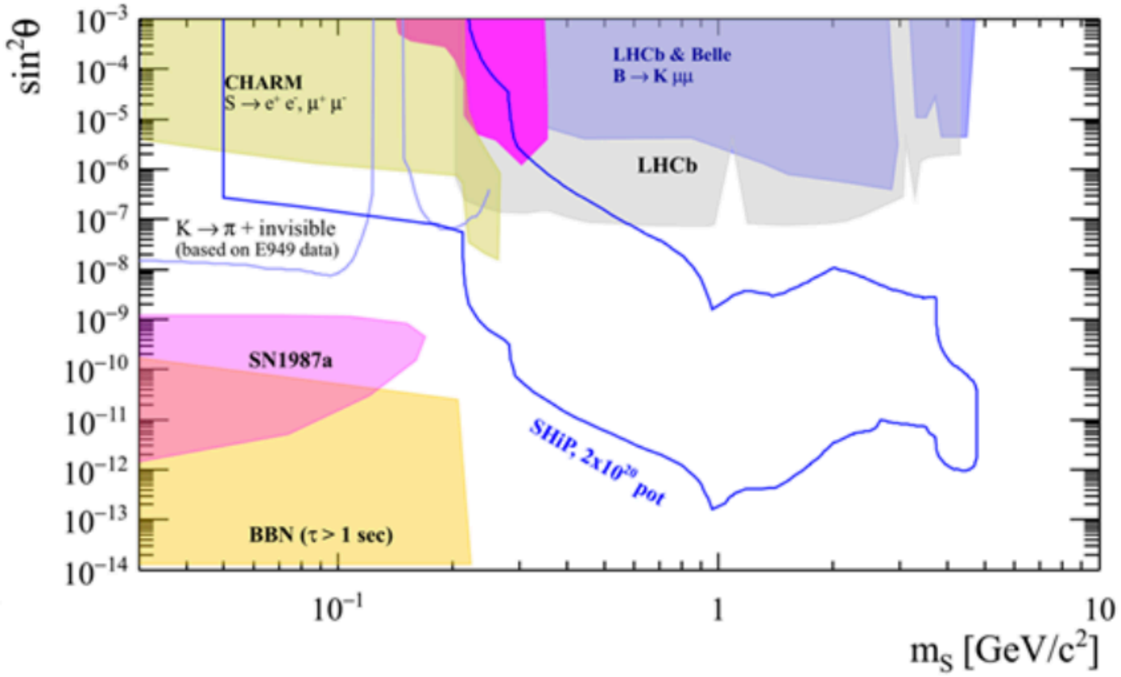


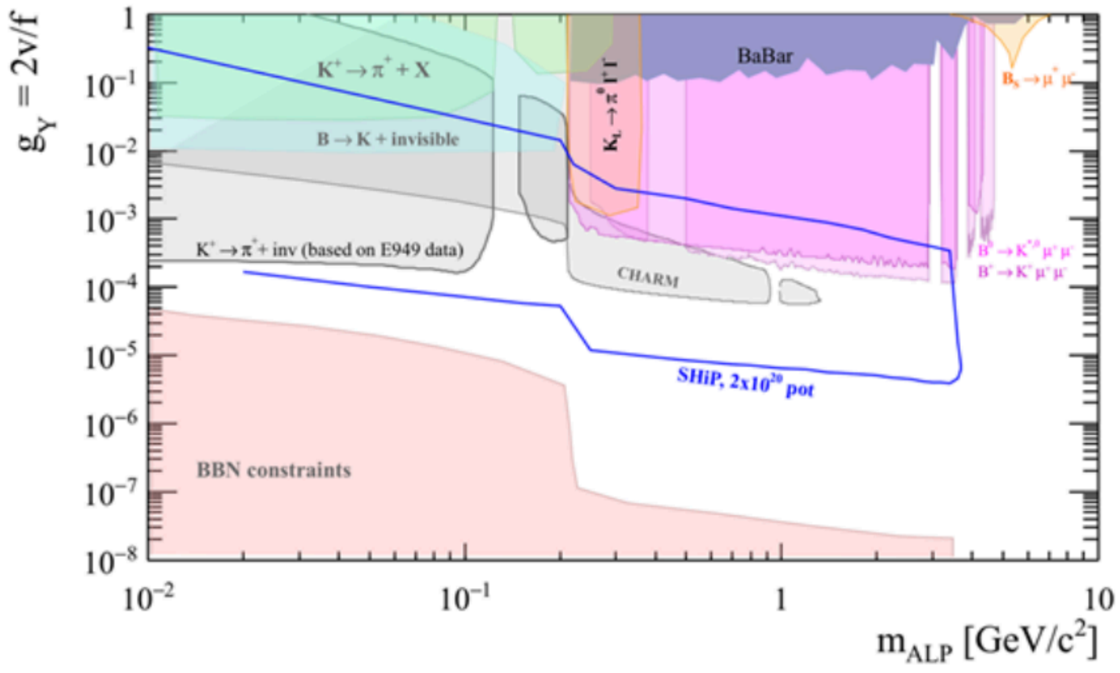
**Figure 72:** Left: relative contributions to the cross-section as a function of $m_{DP}$ for the three production modes studied. Right: branching ratio of the DP into fermion pairs as a function of its mass.

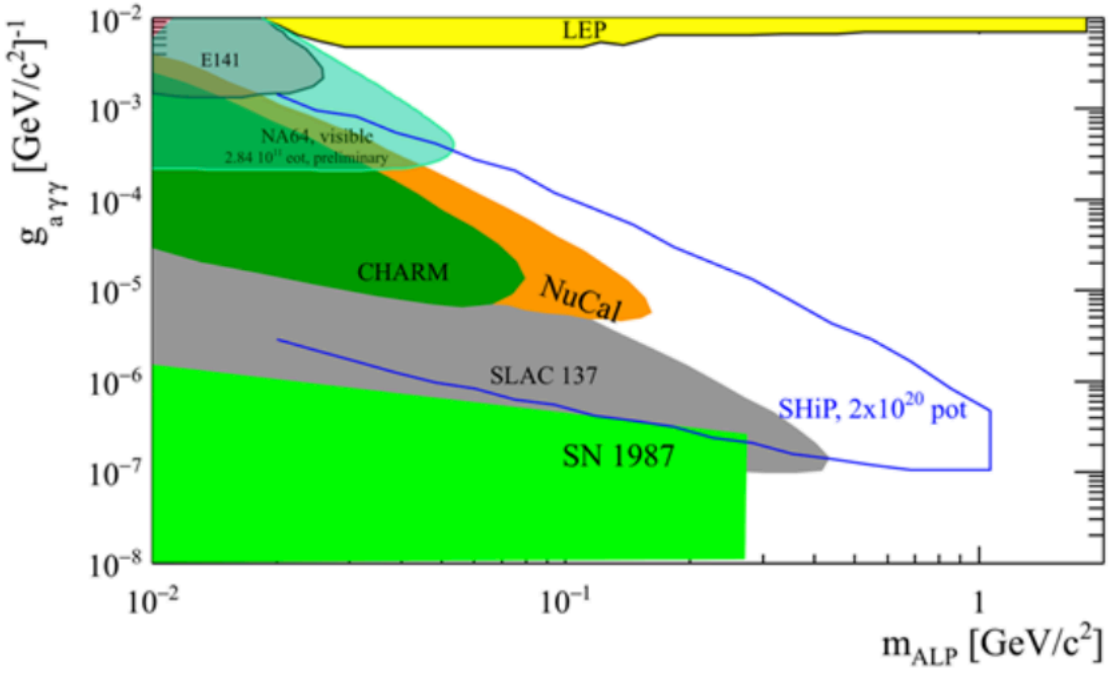


# ALPs Sensitivity

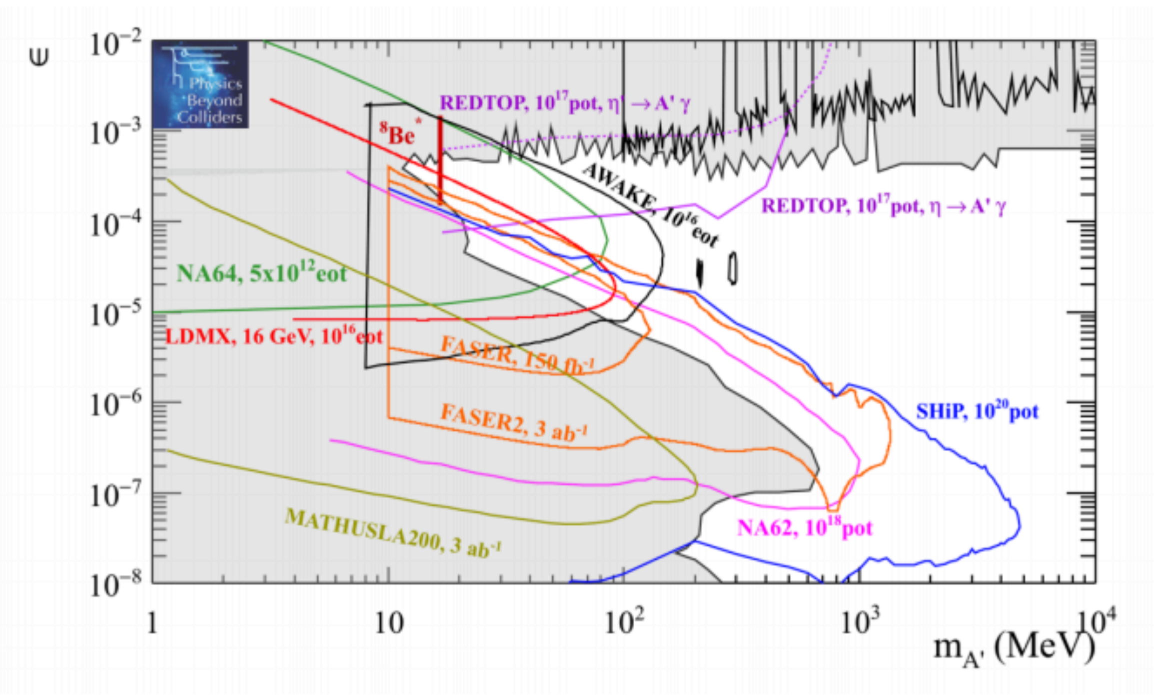


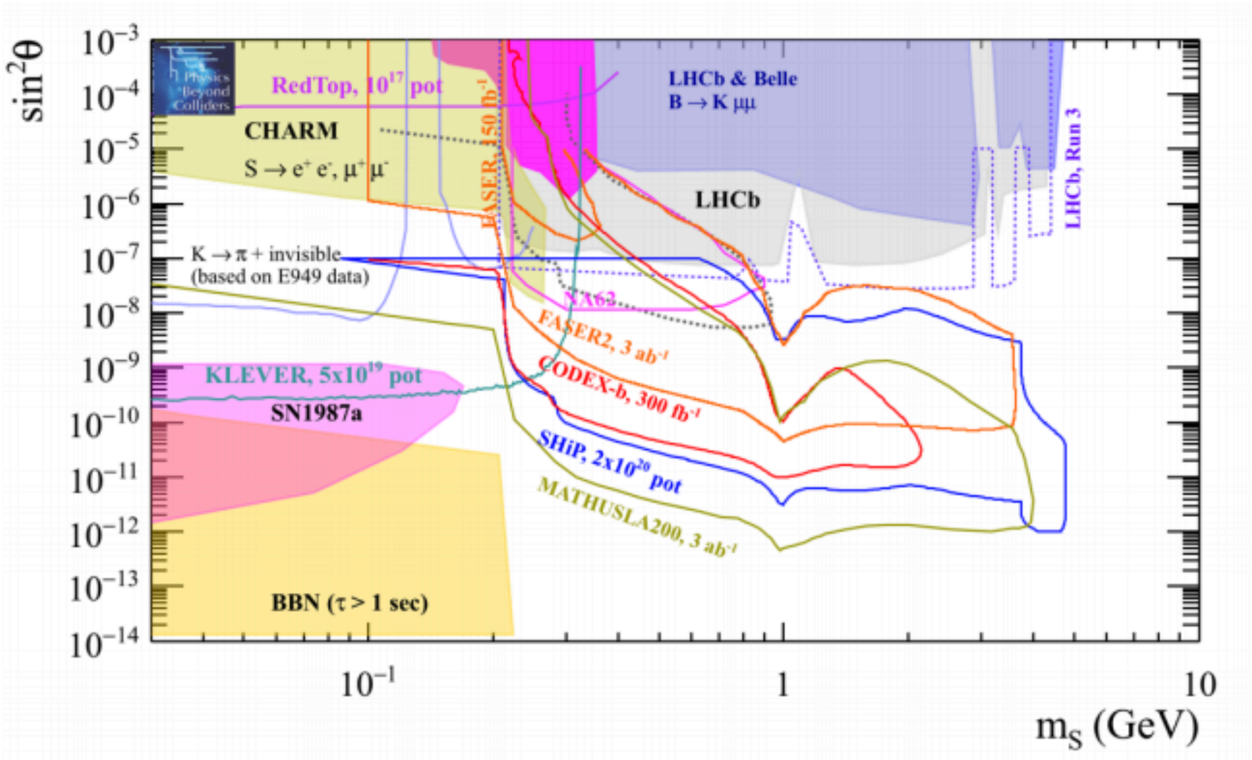


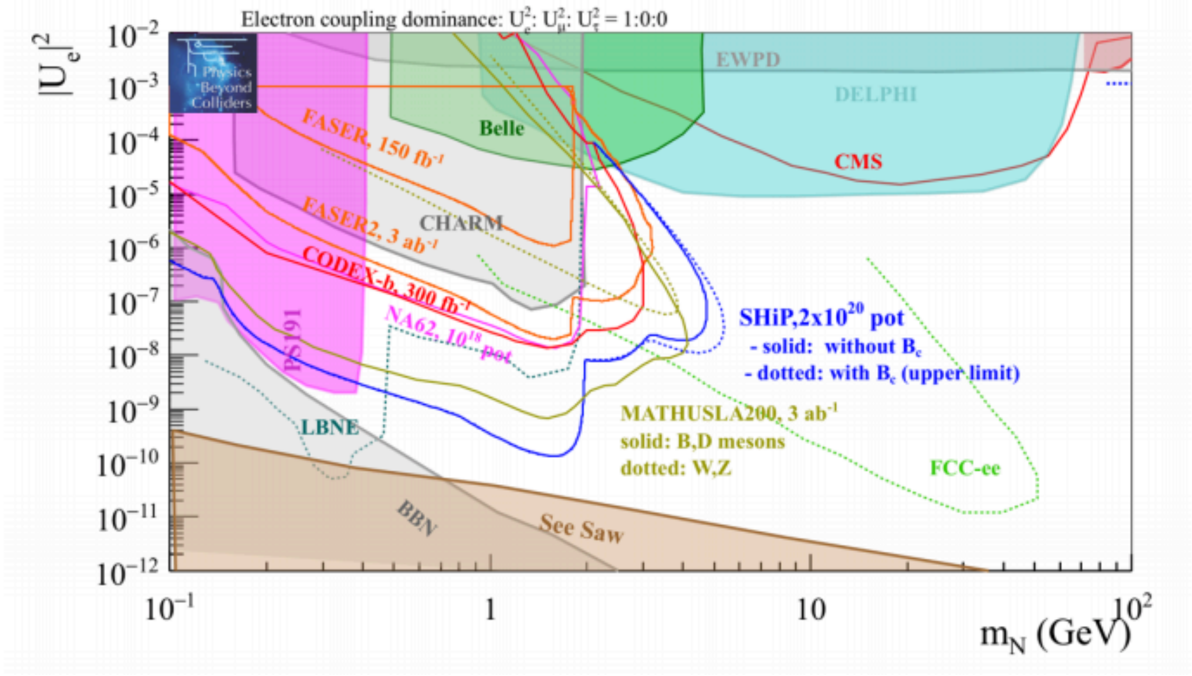




# Other competing Experiments

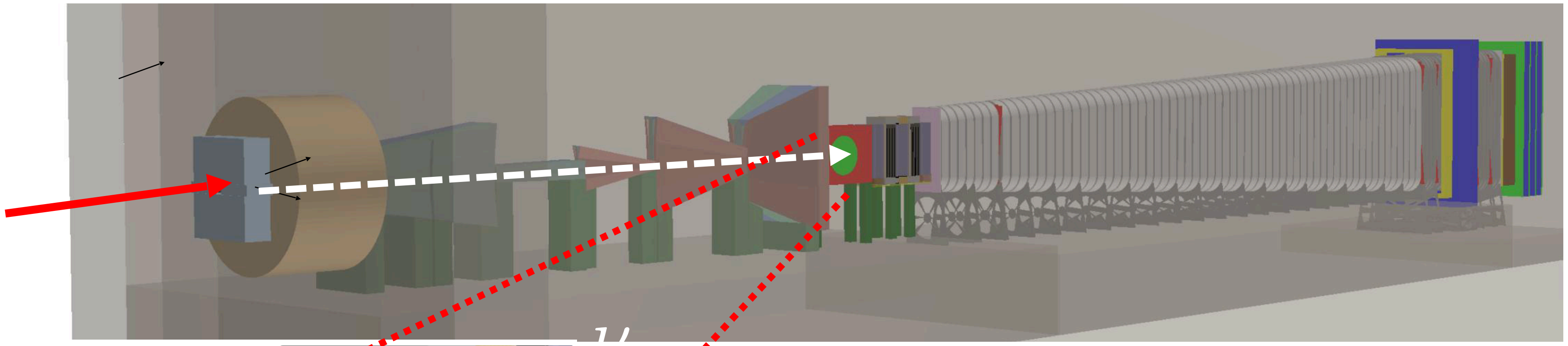


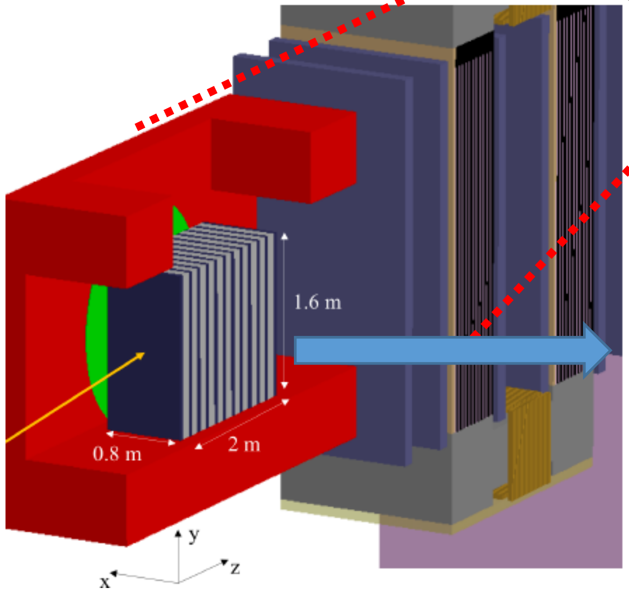


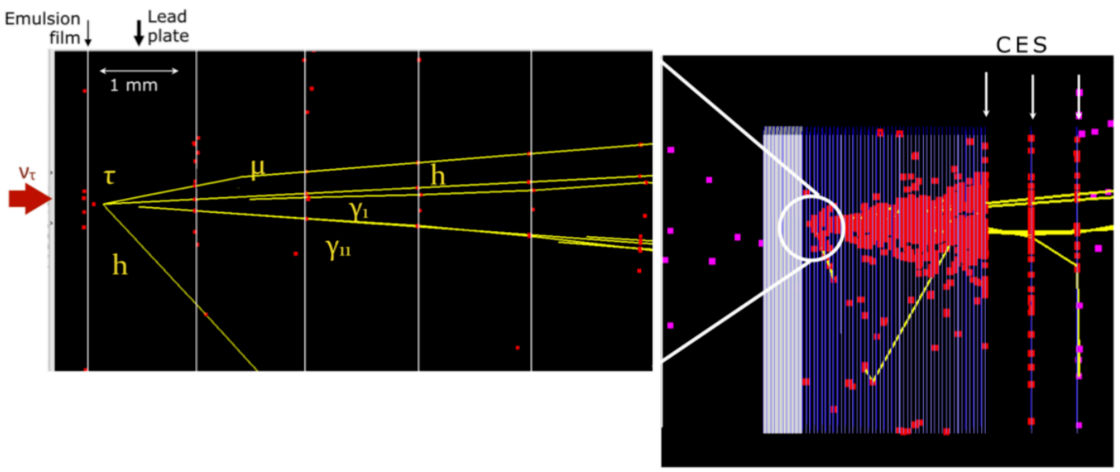


- Several other proposals for searching for relatively light Hidden Particle
- Strong points of SHiP:
  - High intensity and number of PoTs
  - Redundancy of criteria for rejecting background
  - Methods elaborated to determine the background from the experiment
  - Invariant mass and momentum measurement could allow to have a solid discovery claim
  - **Allows to distinguish/test models**

# Emulsion Detector







- High spacial resolution to observe the τ decay (~1mm flight length)
- Electronic detector for tracking to give the time stamp of the event
- Target to measure the τ products
- Muon magnetic spectrometer for muon identification

# Physics SND

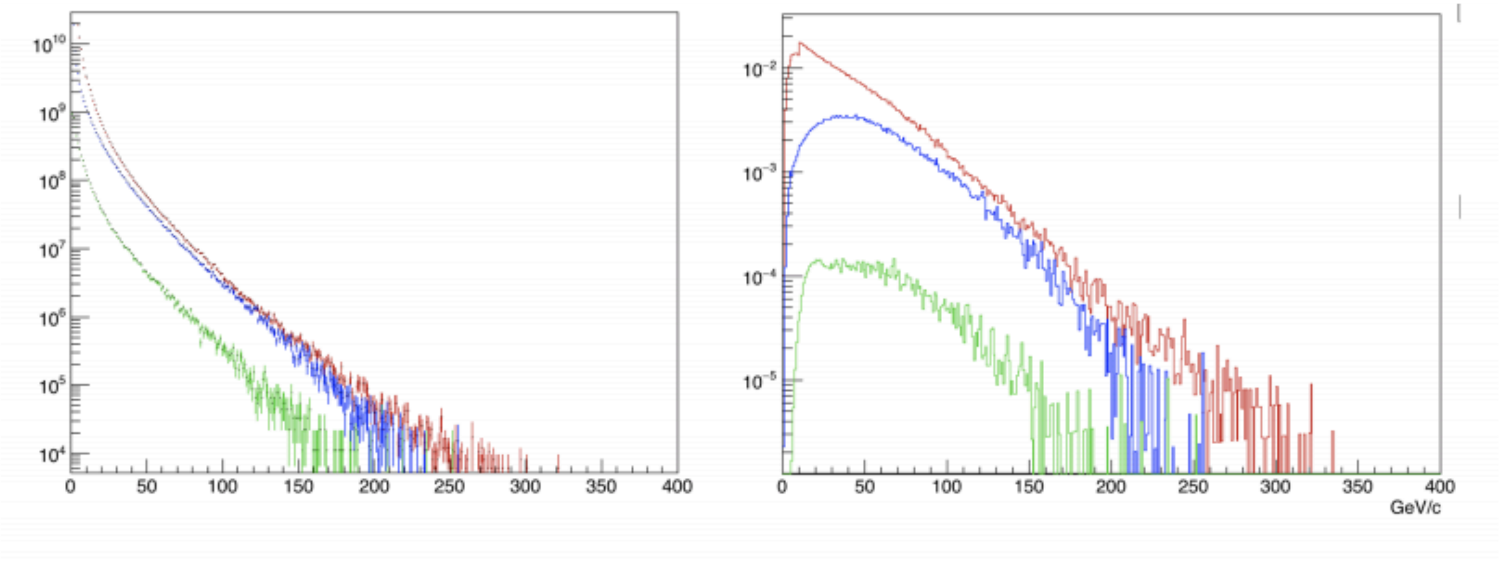


**Figure 80:** Left: energy spectra of muon (red), electron (blue) and tau (green) neutrinos at the beam dump. Right: energy spectra of neutrinos after their deep inelastic interactions with the Scattering Spectrometer. Units are arbitrary.

- First direct measurement of the $\overline{\nu}_\tau$ (never been observed)

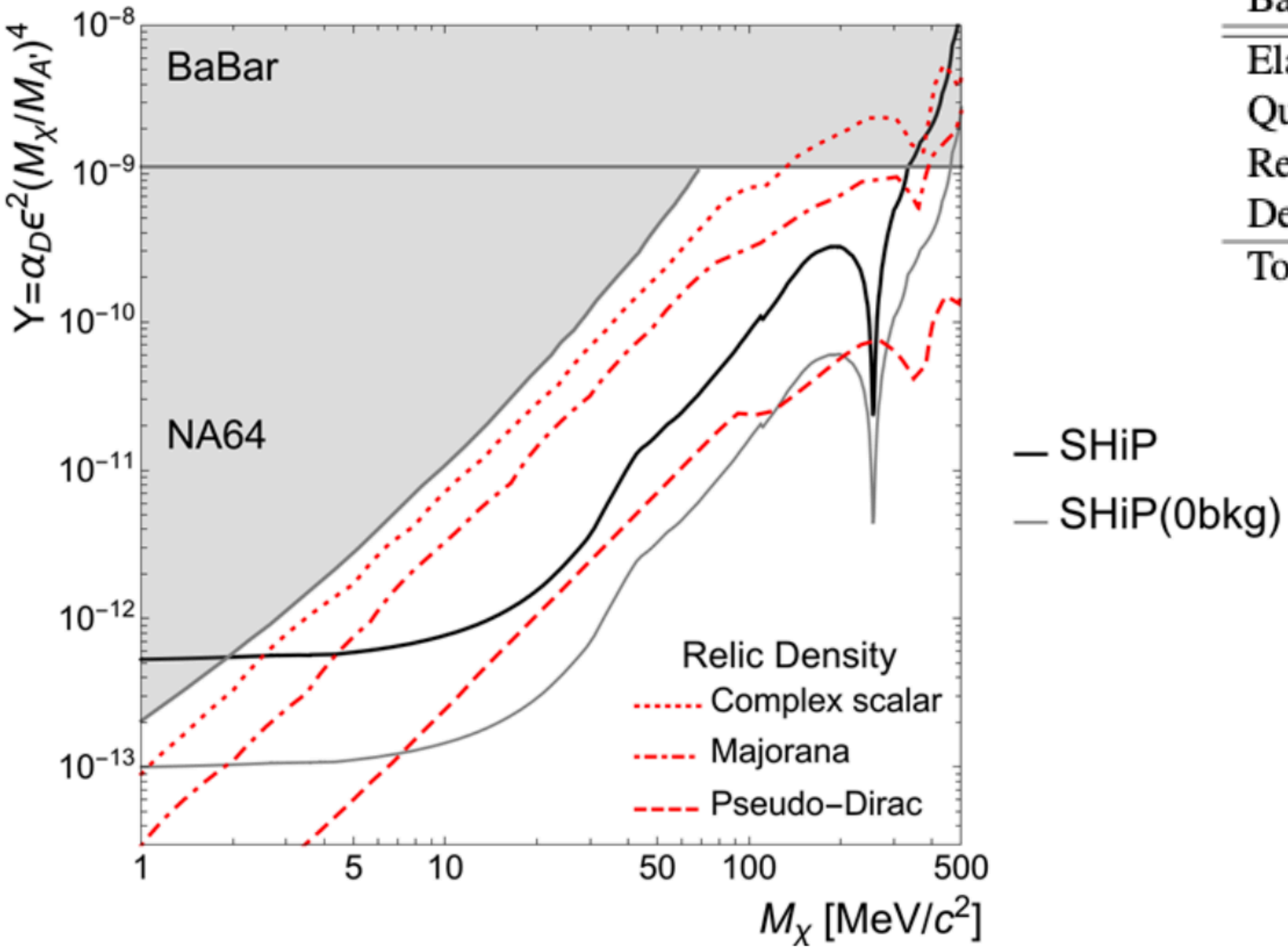
| Decay channel | $\nu_\tau$ | $\overline{\nu}_\tau$ |
|---|---|---|
| $\tau \to \mu$ | 1200 | 1000 |
| $\tau \to h$ | 4000 | 3000 |
| $\tau \to 3h$ | 1000 | 700 |
| total | 6200 | 4700 |

| | <E> (GeV) | CC DIS with charm prod | Charm fractions (%) |
|---|---|---|---|
| $N_{\nu_\mu}$ | 55 | $1.3 \times 10^5$ | 4.7 |
| $N_{\nu_e}$ | 66 | $6.0 \times 10^4$ | 5.7 |
| $N_{\overline{\nu}_\mu}$ | 49 | $2.5 \times 10^4$ | 4.2 |
| $N_{\overline{\nu}_e}$ | 57 | $1.3 \times 10^4$ | 5.1 |
| total | | $2.3 \times 10^5$ | |

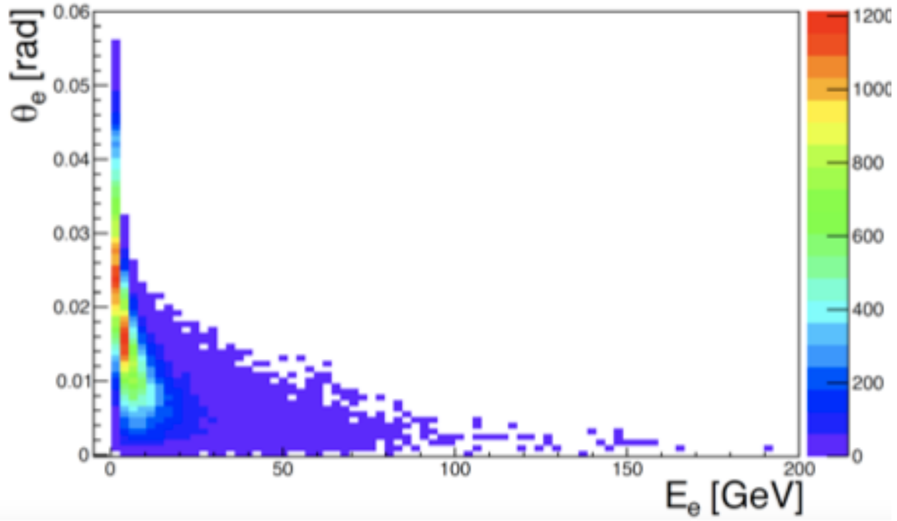
- Determination of the strange quark content of nucleons with charm production
- Test of Lepton Flavour Universality with tau neutrinos
- Search for $\nu_\tau$ anomalous magnetic moment

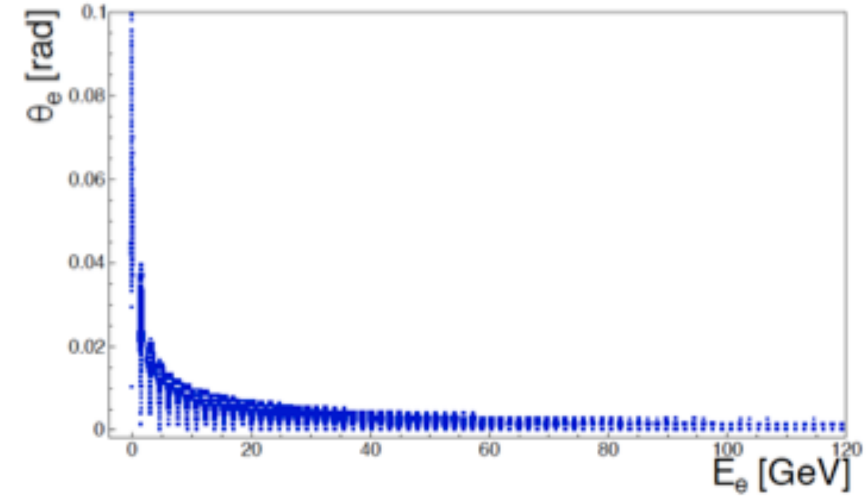
# Physics SND

EM shower originated by scattering of LDM with single electron



| Background | $\nu_e$ | $\bar{\nu_e}$ | $\nu_\mu$ | $\bar{\nu_\mu}$ | all |
|---|---|---|---|---|---|
| Elastic Scattering on $e^-$ | 81 | 45 | 56 | 35 | 217 |
| Quasi-elastic Scattering | 245 | 236 | - | - | 481 |
| Resonant Scattering | 8 | 77 | - | - | 85 |
| Deep Inelastic Scattering | - | 14 | - | - | 14 |
| Total | 334 | 372 | 56 | 35 | 797 |





Machine Learning algorithm can be trained taking as inout the correlation if azimuthal anche and energy of electron

# Conclusions

- Since we do not know the scale of New Physics (see Andrey's talk) it is important to remember we need to scan a 2D space (coupling vs mass)
- There are possible solutions to SM problems at low mass and small coupling, SM was successful to describe EW scale, maybe we should look below
- SHiP has a great potential in improving current sensitivities by several orders of magnitudes
- The key is to have an extremely low background and redundancy of systems, in case of discovery this would allow to study and understand the signal
- Lot of work done to demonstrate feasibility but lot of work head of us in case of approval