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SHiP
Search for Hidden Particles

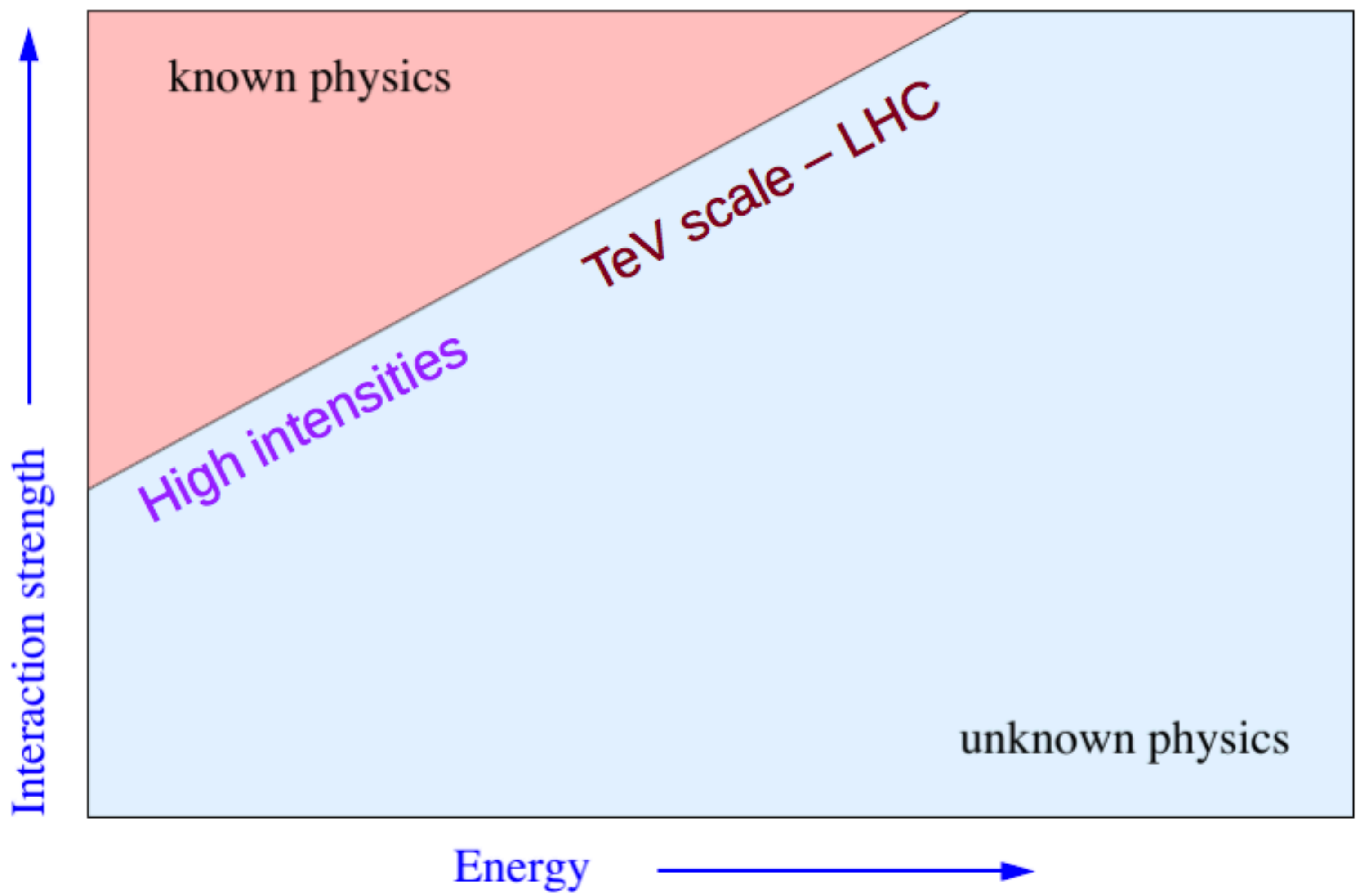
The SHiP Experiment

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

Seminar at CP3 centre of the Université Catholique de Louvain

Physics Case

- Naturalness as a guiding principle of Nature is nowadays put into question
- There are some anomalies in flavour physics which (if true) seem again to point out that our theory prejudice was wrong
- We should therefore not forget that we have a 2D problem (Mass VS Coupling)



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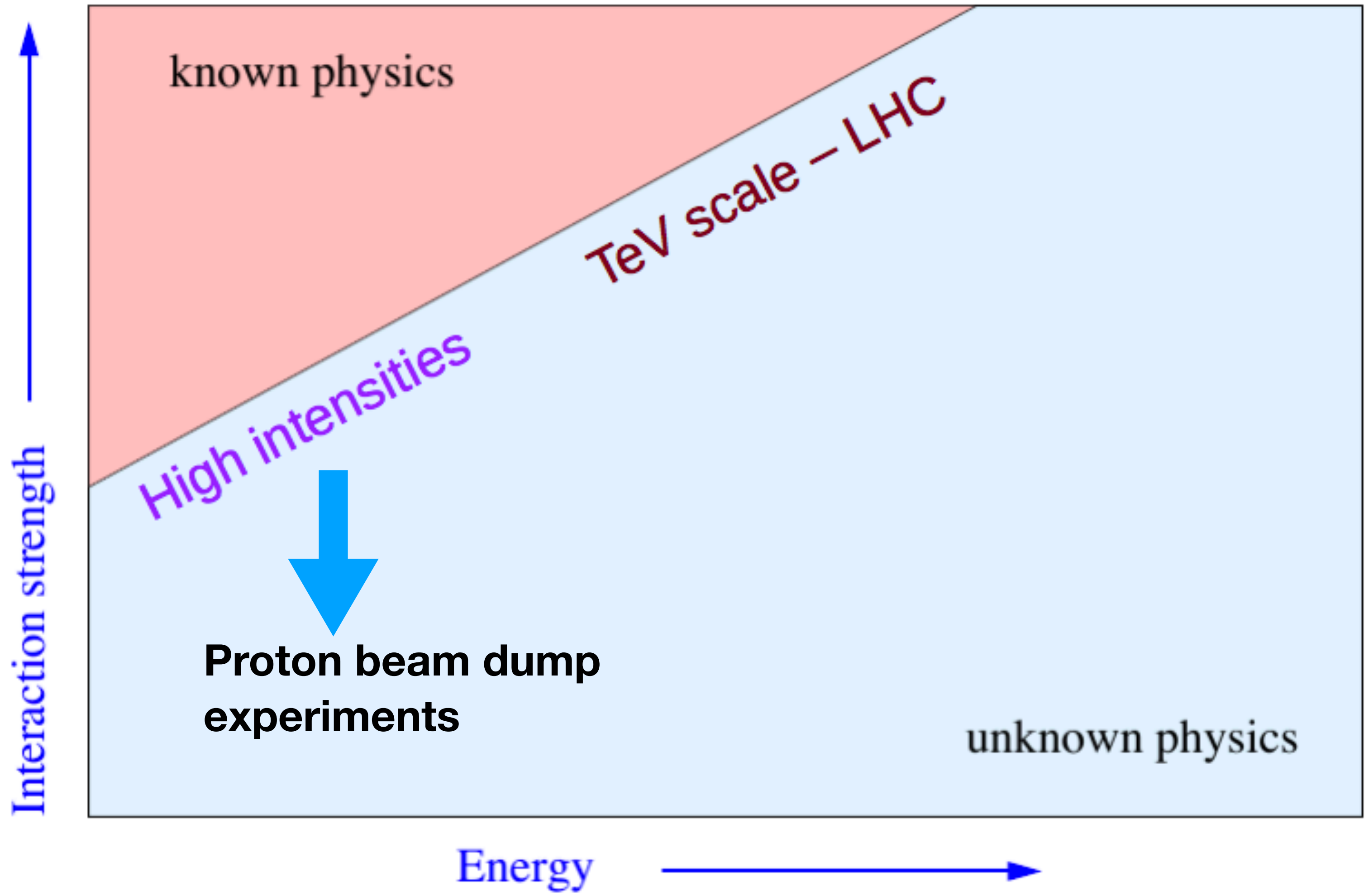

Example: Sterile Neutrinos

Fermions get mass via the Yukawa couplings

$$-\mathcal{L}_{\text{Yukawa}} = Y^d_{ij}\overline{Q_{Li}}\phi D_{Rj} + Y^u_{ij}\overline{Q_{Li}}\tilde{\phi}U_{Rj} + Y^\ell_{ij}\overline{L_{Li}}\phi E_{Rj} + \text{h.c.},$$

If we want the same coupling for neutrinos, we need right-handed (sterile) neutrinos… the most generic lagrangian is

$$\mathcal{L}_N = i\overline{N}_i\partial_\mu\gamma^\mu N_i - \frac{1}{2}M_{ij}\overline{N^c}_i N_j - Y^\nu_{ij}\overline{L_{Li}}\tilde{\phi}N_j$$

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Kinetic term

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Yukawa coupling

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Kinetic term

Majorana mass term

Yukawa coupling

Example: Sterile Neutrinos

In the same way as for the quarks we are gonna have a matrix M_{Dij} describing the non-diagonal Yukawa coupling, in addition we have a Majorana mass matrix

$$-\mathcal{L}_{M_\nu} = M_{Dij}\overline{\nu_{Li}}N_j + \frac{1}{2}M_{Nij}\overline{N_i^c}N_j + h.c.$$

This gives a total (non-diagonal) Mass Matrix for neutrinos composed by Dirac and Majorana components

$$\mathcal{V} = (\nu_{Li}, N_j)$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ {M_D}^T & M_N \end{pmatrix}$$

$$-\mathcal{L}_{M_\mathcal{V}} = \frac{1}{2}\overline{\mathcal{V}}M_\mathcal{V}\mathcal{V} + h.c.$$

Eigenvalues are:

$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4M_D^2}}{2}$$

Assuming $M_N >> M_D$:

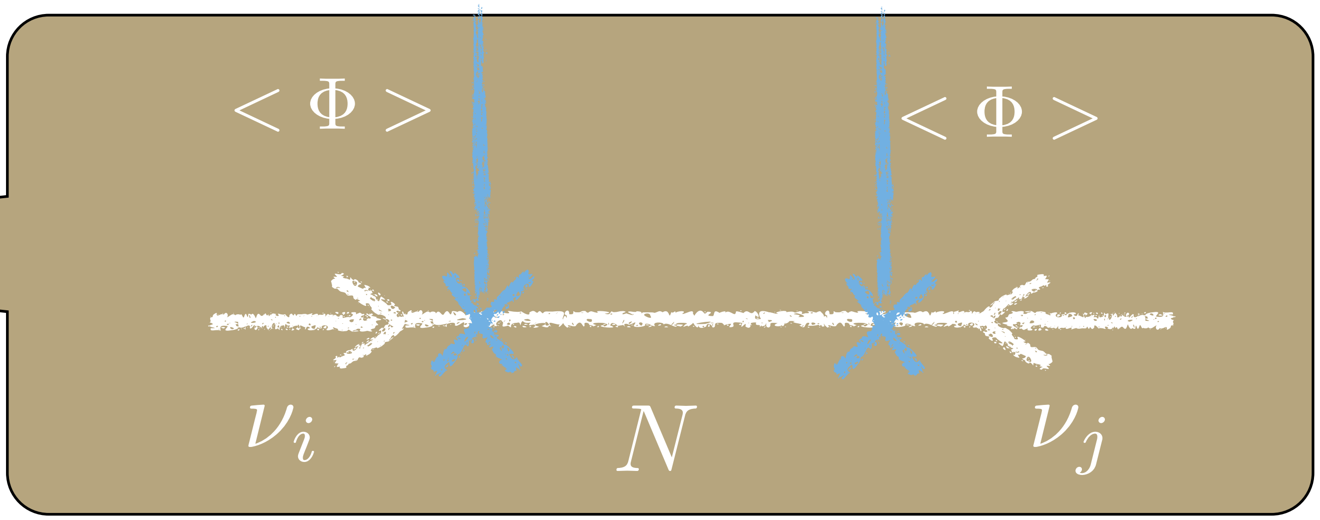
$$\lambda_- \sim \frac{M_D^2}{M_N}$$

$$\lambda_+ \sim M_N$$

Example: Sterile Neutrinos

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

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



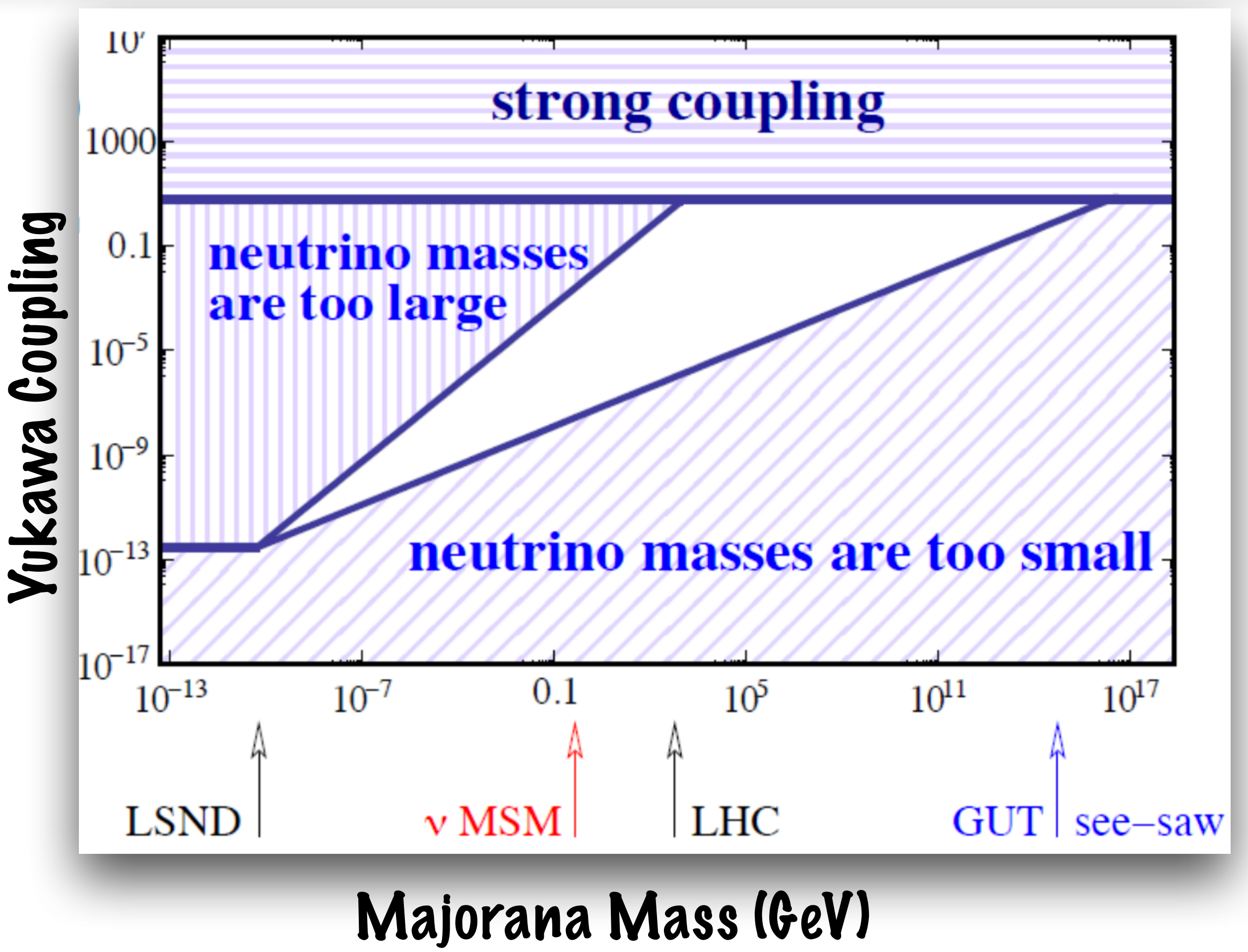
Active neutrinos mix with sterile neutrinos with a mixing angle

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

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

Example: Sterile Neutrinos

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



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

Example: Sterile Neutrinos

- Many people have studied Majorana neutrinos below the EW-scale, here an incomplete list of references

- Minimal Neutrino Standard Model (Asaka, Shaposhnikov hep-ph/0505013)

Asaka, Blanchet, Shaposhnikov, Bezrukov, Drewes, Boyarsky, Ruchayskiy, …

- Cosmological Implications of Sterile Neutrinos below EW-scale

Shaposhnikov, Bezrukov, Drewes, Boyarsky, Ruchayskiy, …

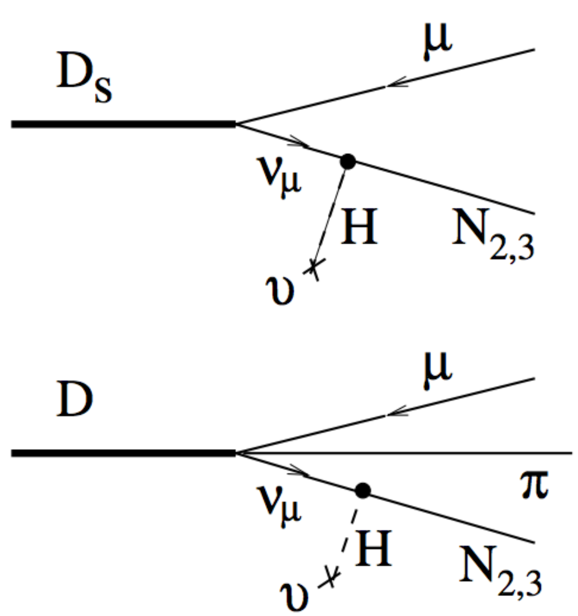
- How to search for light Sterile Neutrinos

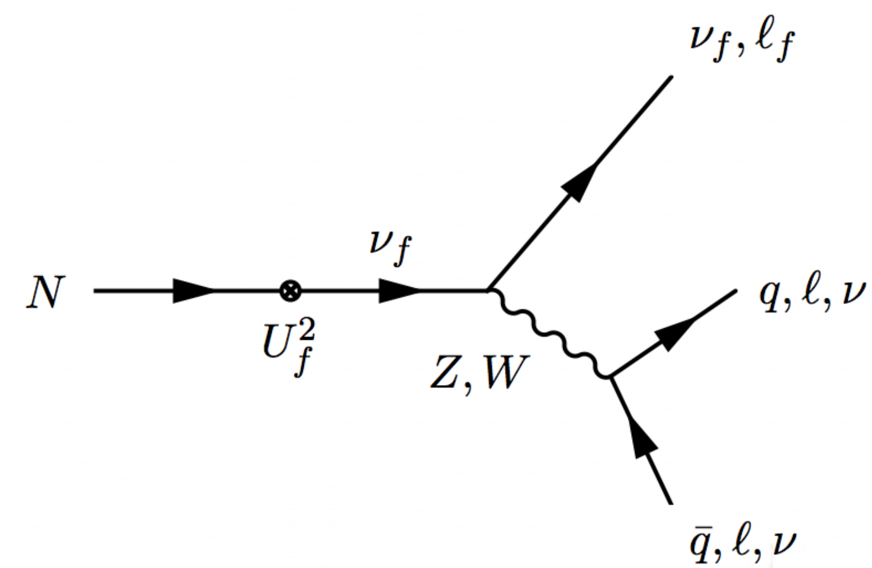
Even more authors

See arxiv:1504.04855 and references therein

Sterile Neutrinos

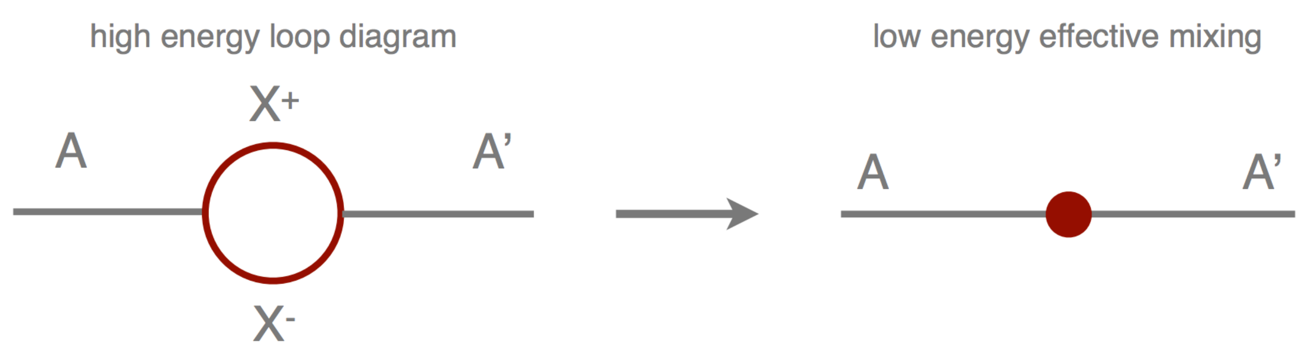
- The production of sterile neutrinos happens via mixing of sterile neutrinos with active neutrinos, i.e. it is suppressed by a factor U^2
- If the mass is small enough they can be produced in semileptonic meson decays (pions, kaons, D-mesons, B-mesons)
- The decay of sterile neutrinos also happens via 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



QED-like

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2$$

QED fields — $U(1)'$ fields — field strength tensors — mass term

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

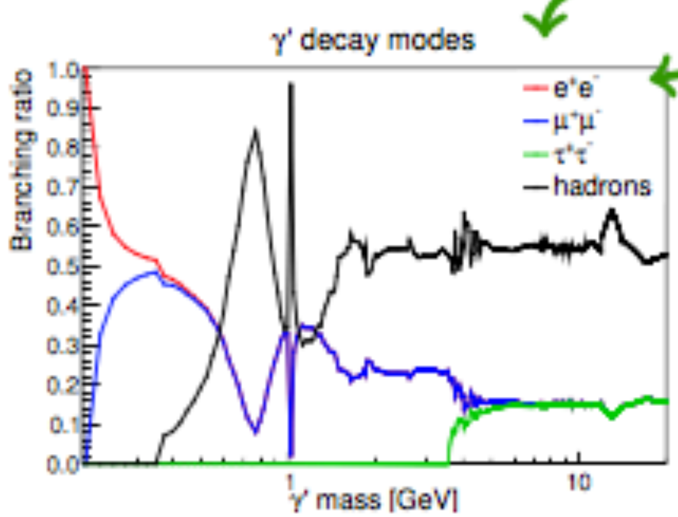
Example: Dark Photon

➜ 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:

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



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

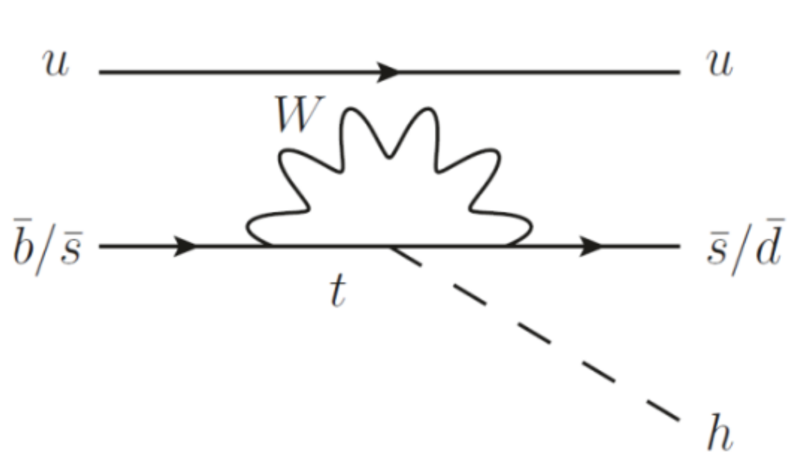
Example: Dark Scalar

- 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 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	l^+l^-
sgoldstino	$l^+l^-\nu$
HNL, SUSY neutralino, axino	$\gamma\gamma$
Axion portal, SUSY sgoldstino	$\pi^0\pi^0$
SUSY sgoldstino	

Full reconstruction and PID are essential to minimize model dependence

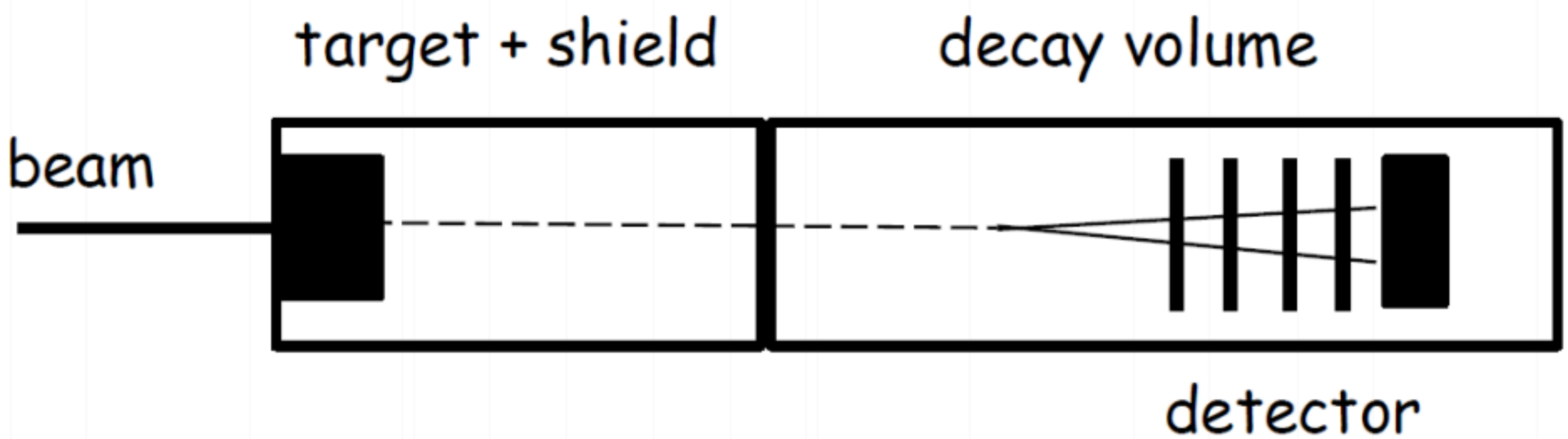
Experimental challenge is background suppression

Physics signals

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

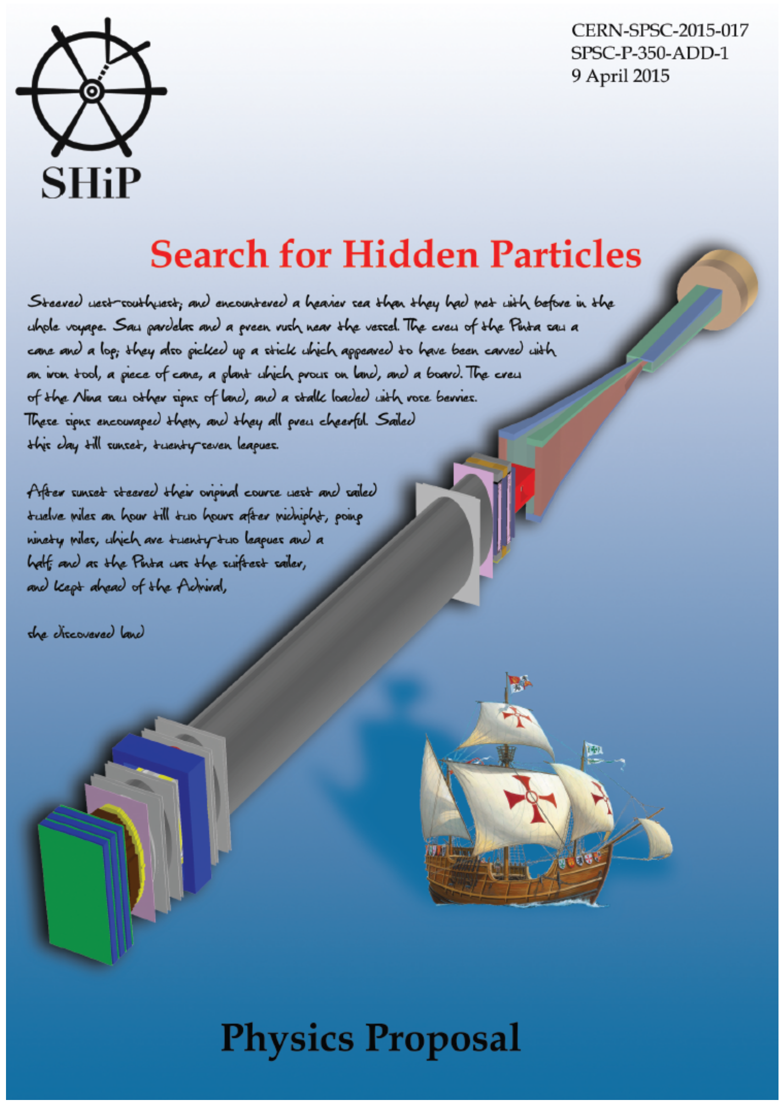


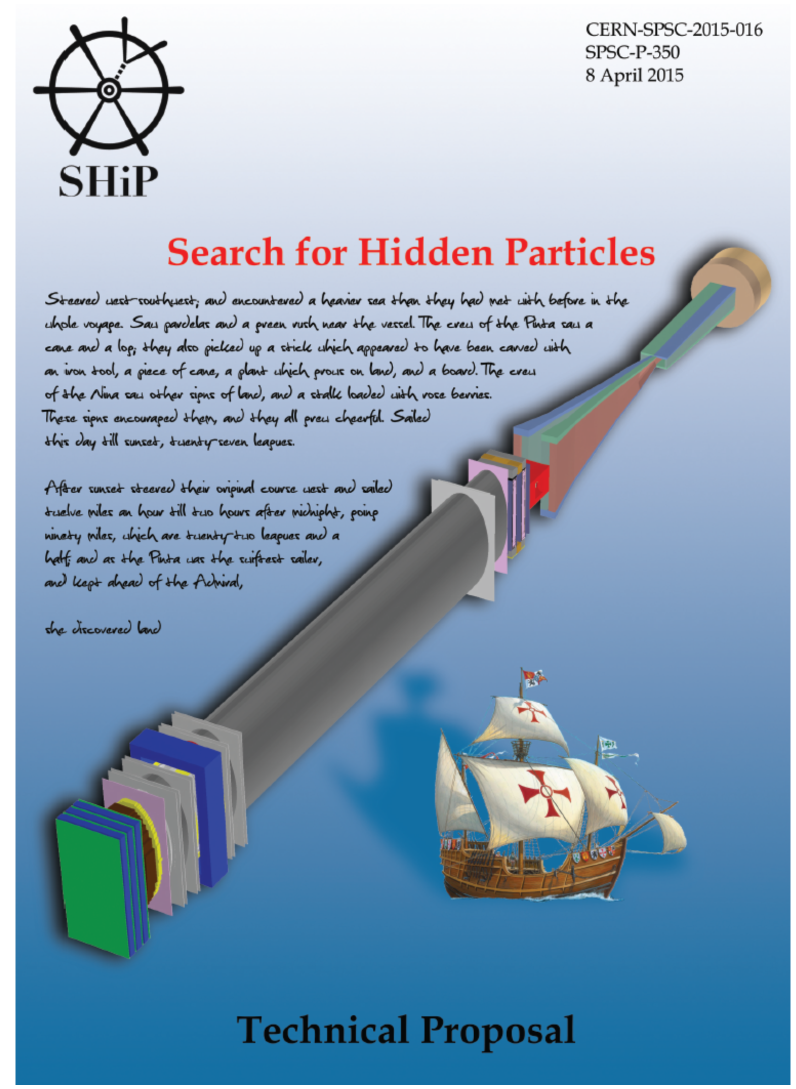
- High Intensity beam into an heavy target
  - We want particles either coming from heavy meson decays or from pN interactions
  - We want to suppress pion and kaon decays which is source of bkg

- Minimize the flux of SM particles in the detector

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

Introduction





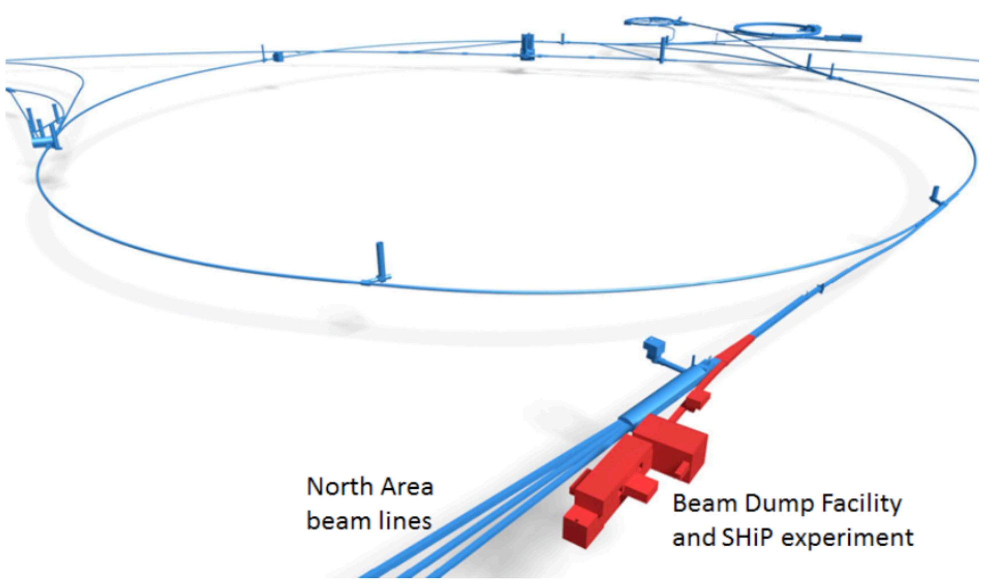
- The technical proposal (250 physicists, 46 institutes, 16 countries) submitted to CERN in Apr 2015 (arXiv:1504.04956)

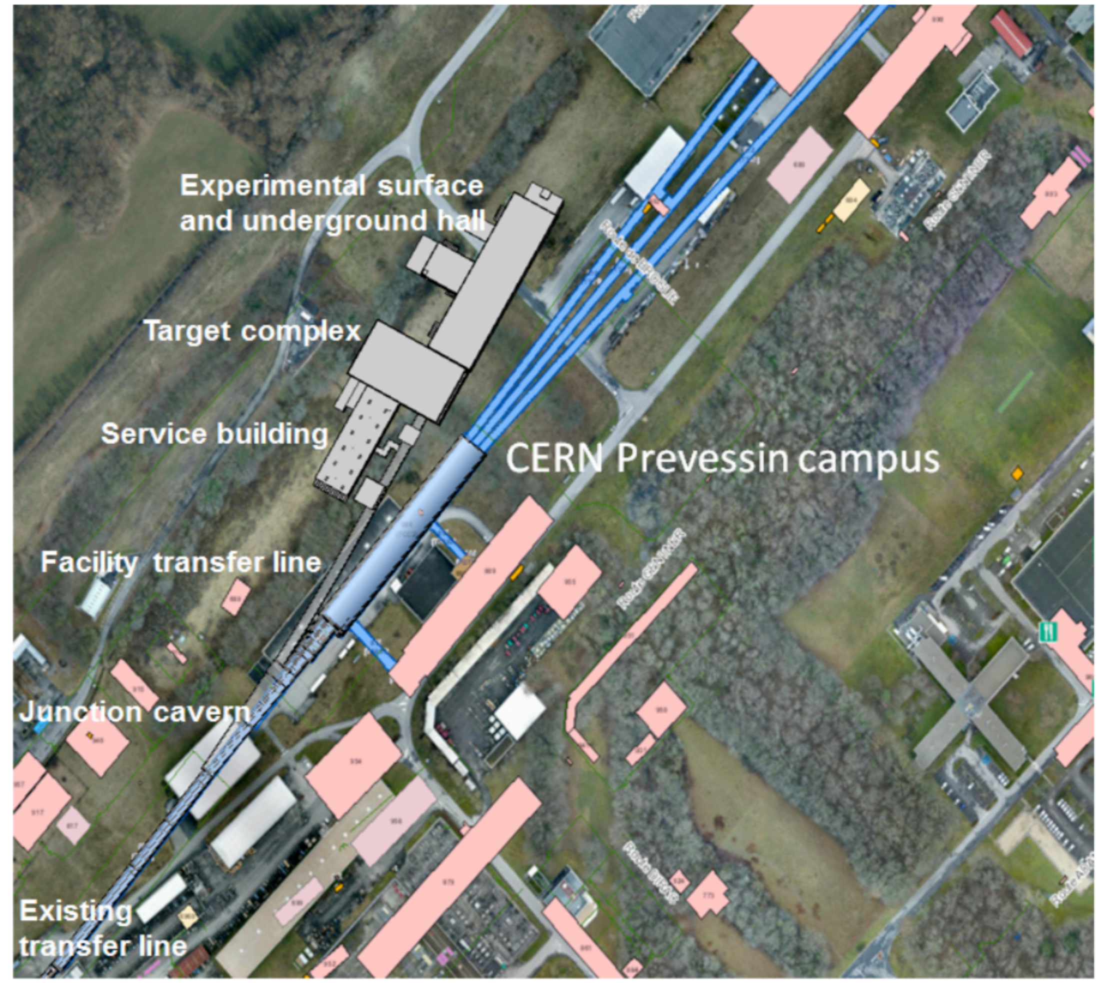
- Physics Paper (85 physicists, 65 institutes) accepted for publication in Review on Progress in Physics (arxiv:1504.04855)

SHiP Collaboration

SHIP is currently a collaboration of 54 institutes (out of which 4 associate institutes), from 18 countries, plus CERN and JINR.

Beam Line





- Very intense proton beam at 400GeV
- Aim to deliver $4x10^{13}$ Protons / spill (at slow extraction)
- Proposed implementation based on minimal modification and compatible with current and planned SPS experiments

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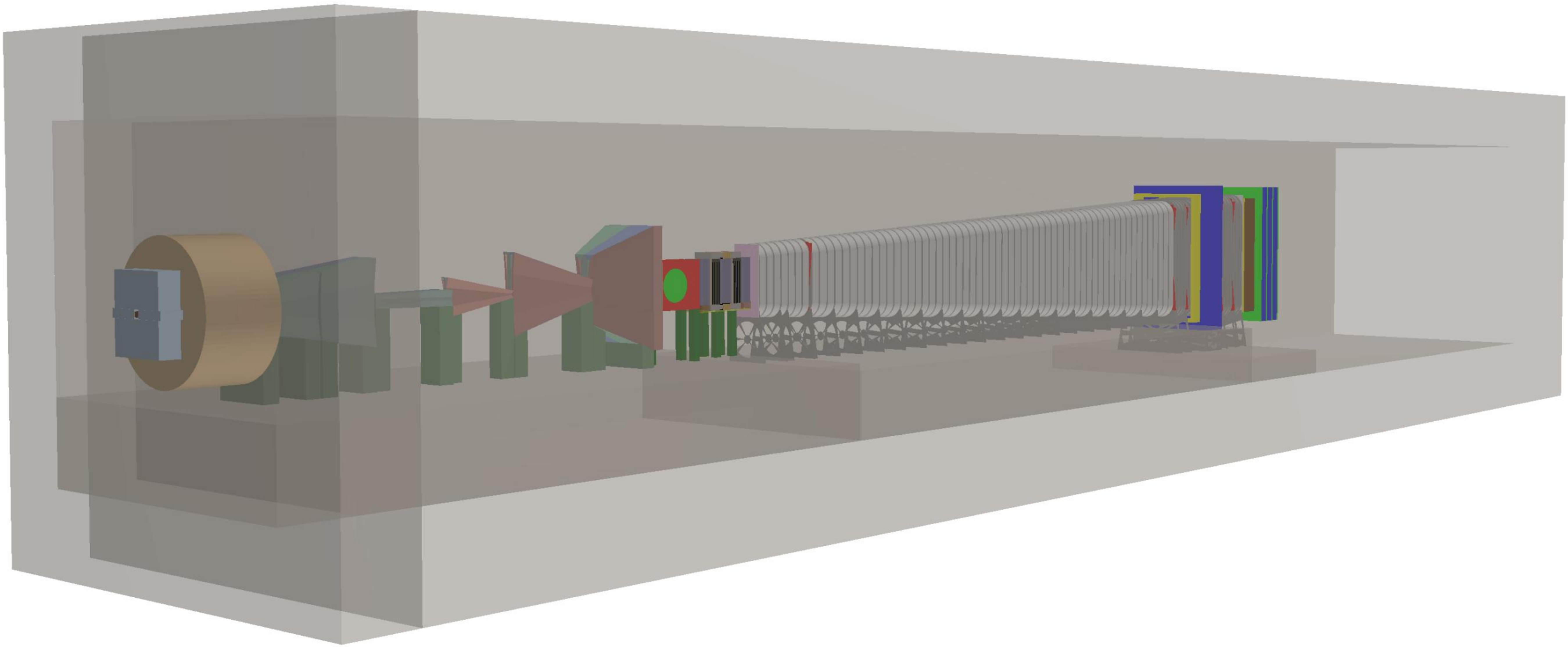
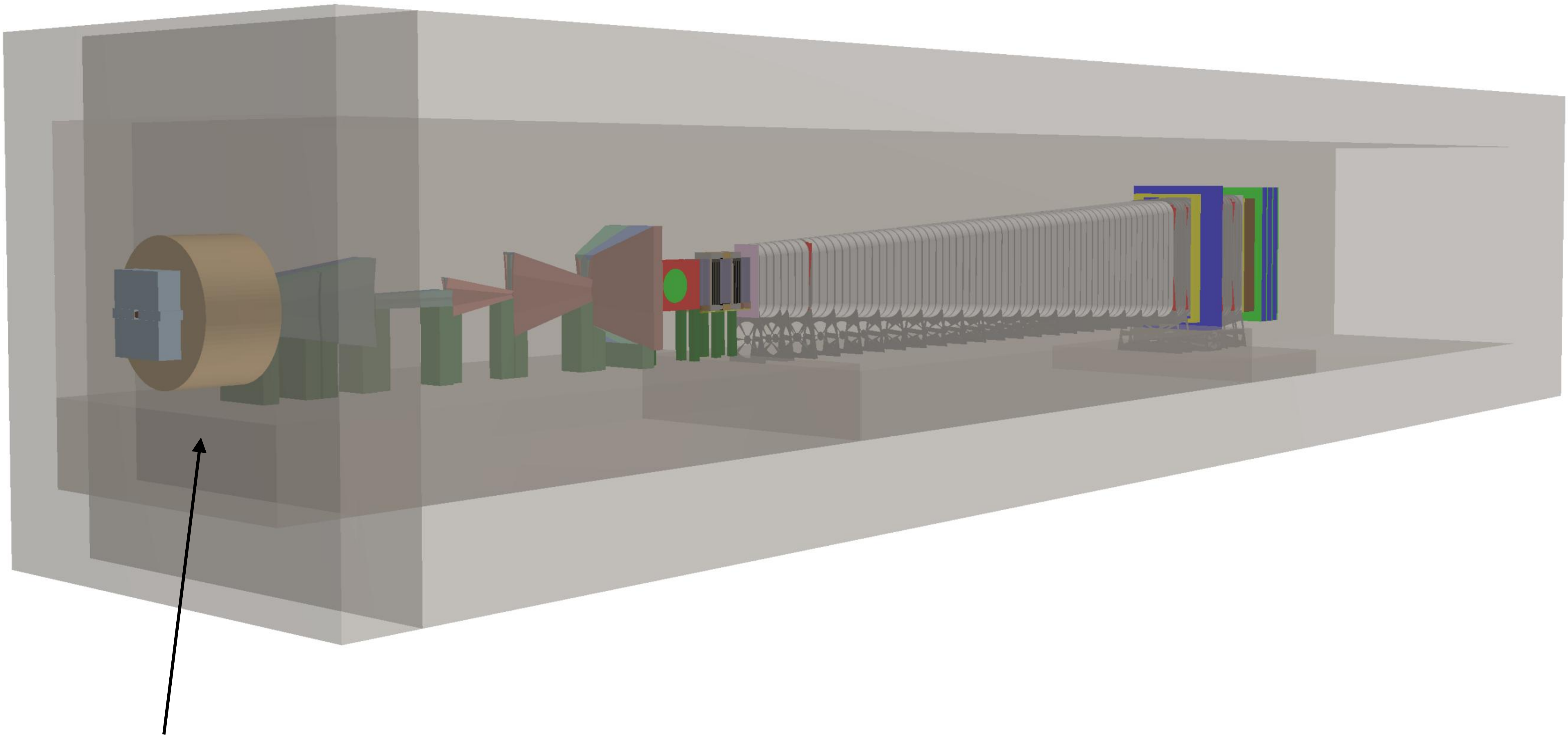
Overview of SHiP

SHiP
Search for Hidden Particles



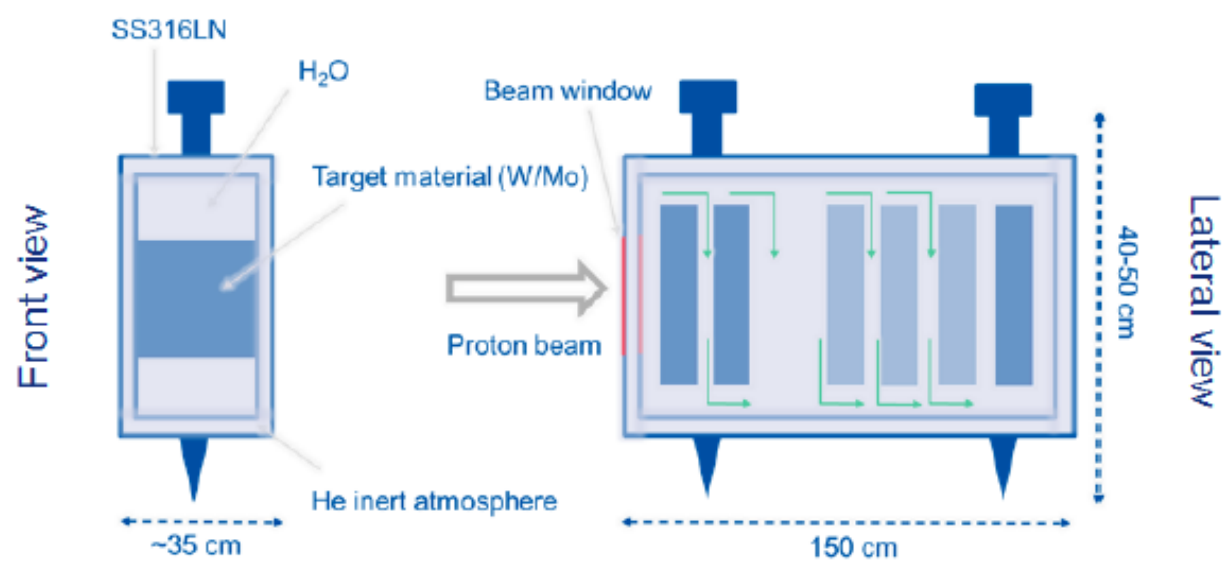
Overview of SHiP

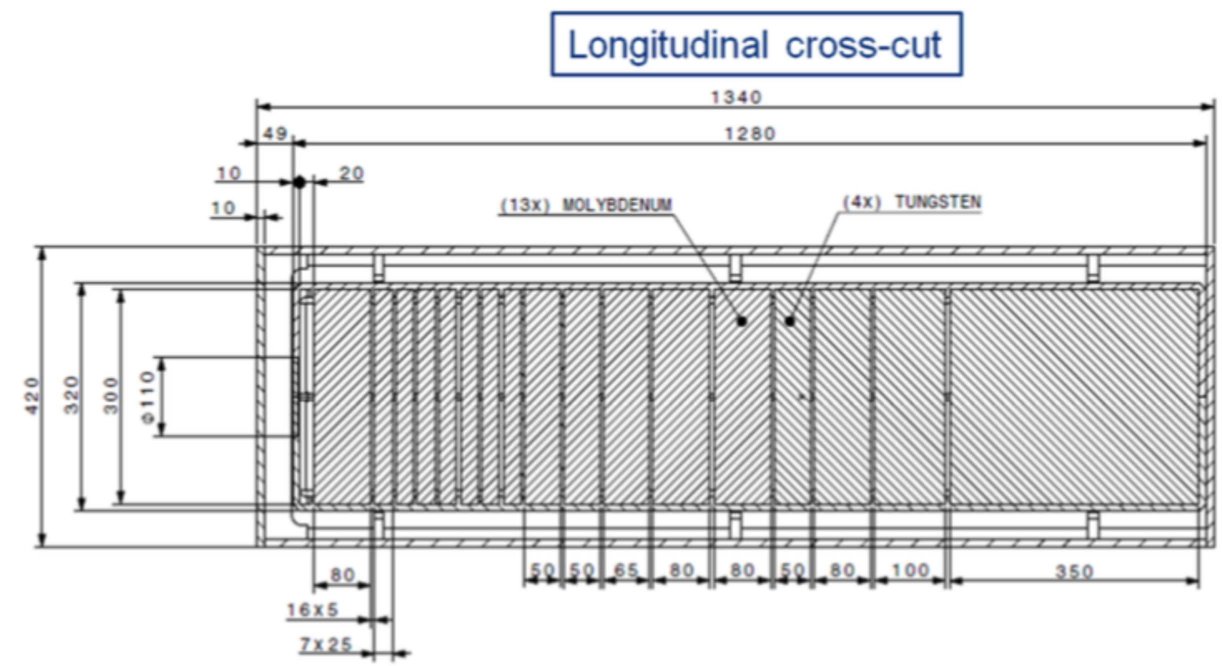


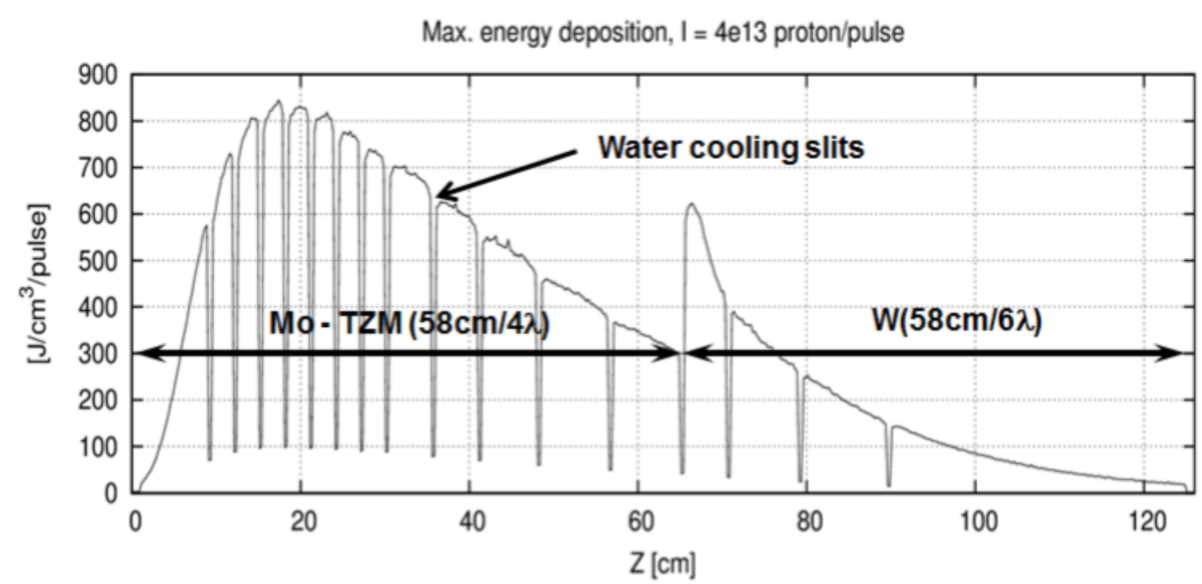
Target/Absorber

Target

- *Layers of Titanium/Zirconium/Molibdenum for 4λ_{int} in the core of the beam*
- *Followed by Layers of pure W*
- *Each layer is cooled by water*
- *Alternative cooling with He under study*

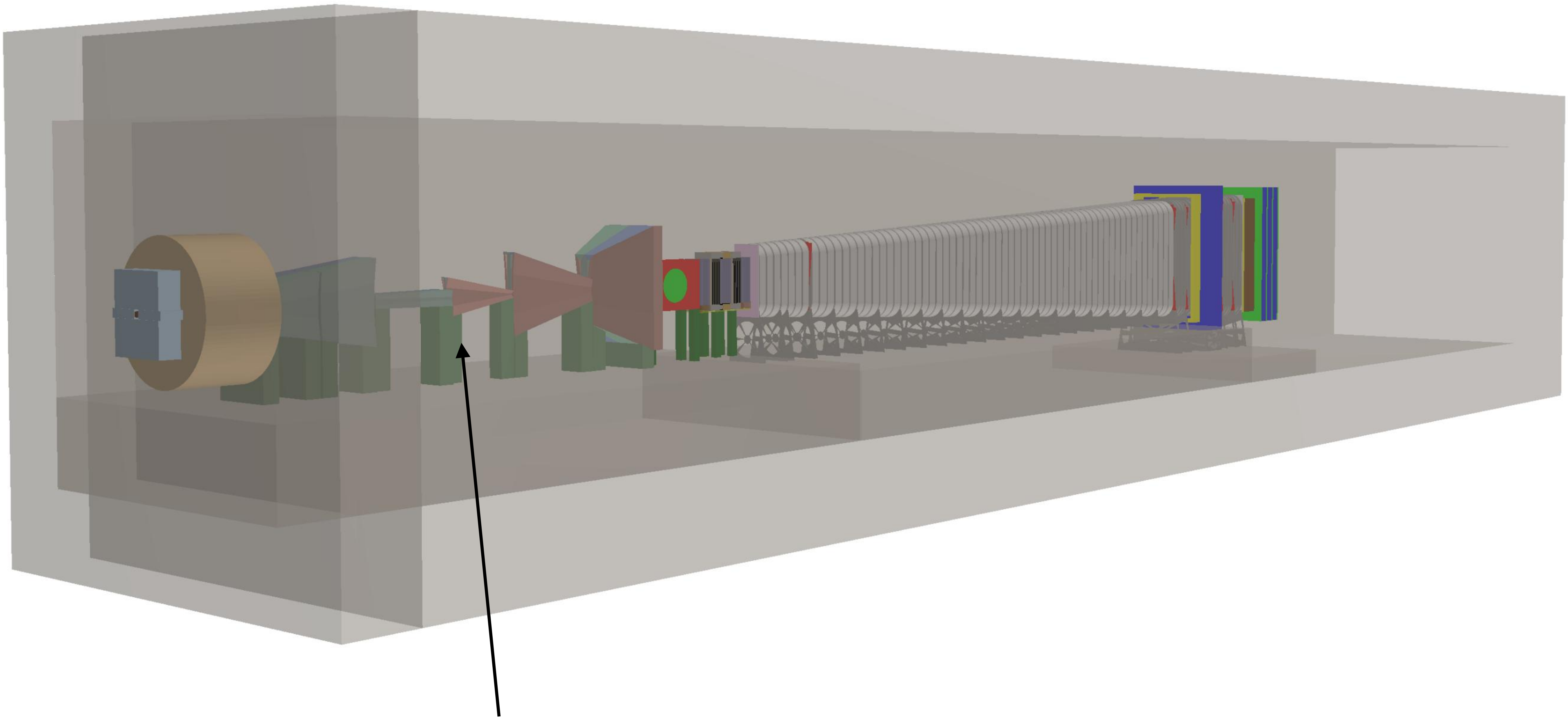






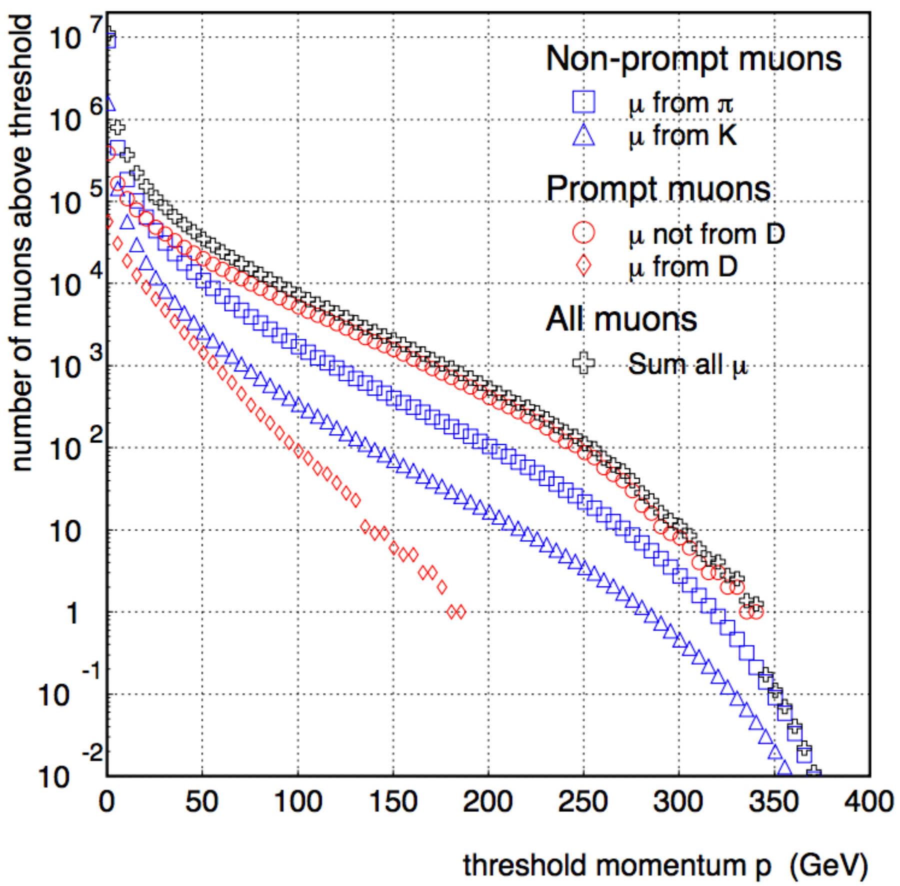
355 kW average,
2.56 MW during 1s spill

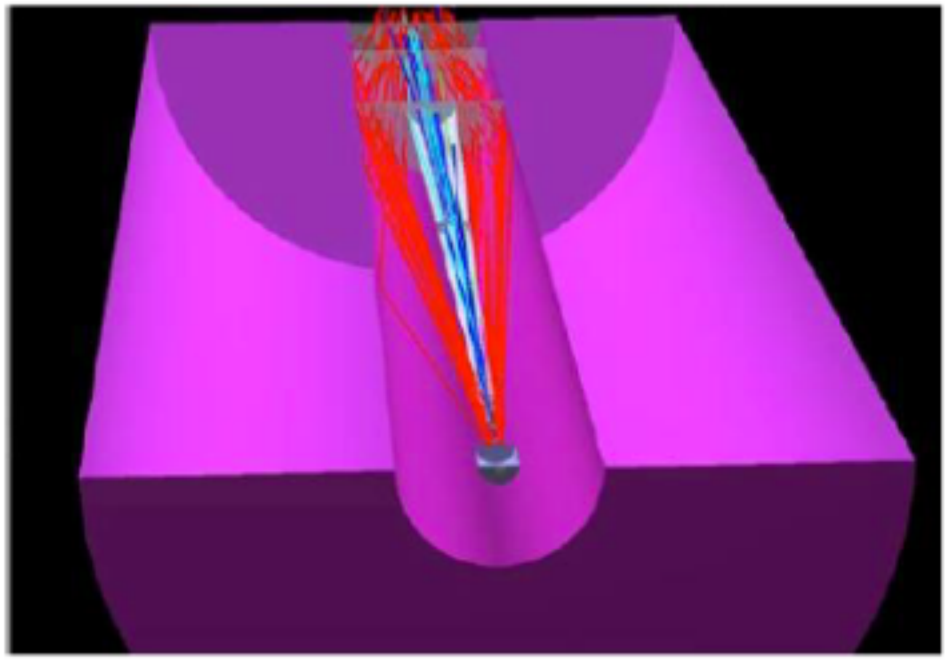
Overview of SHiP



Sweeping magnet

Muon Shield





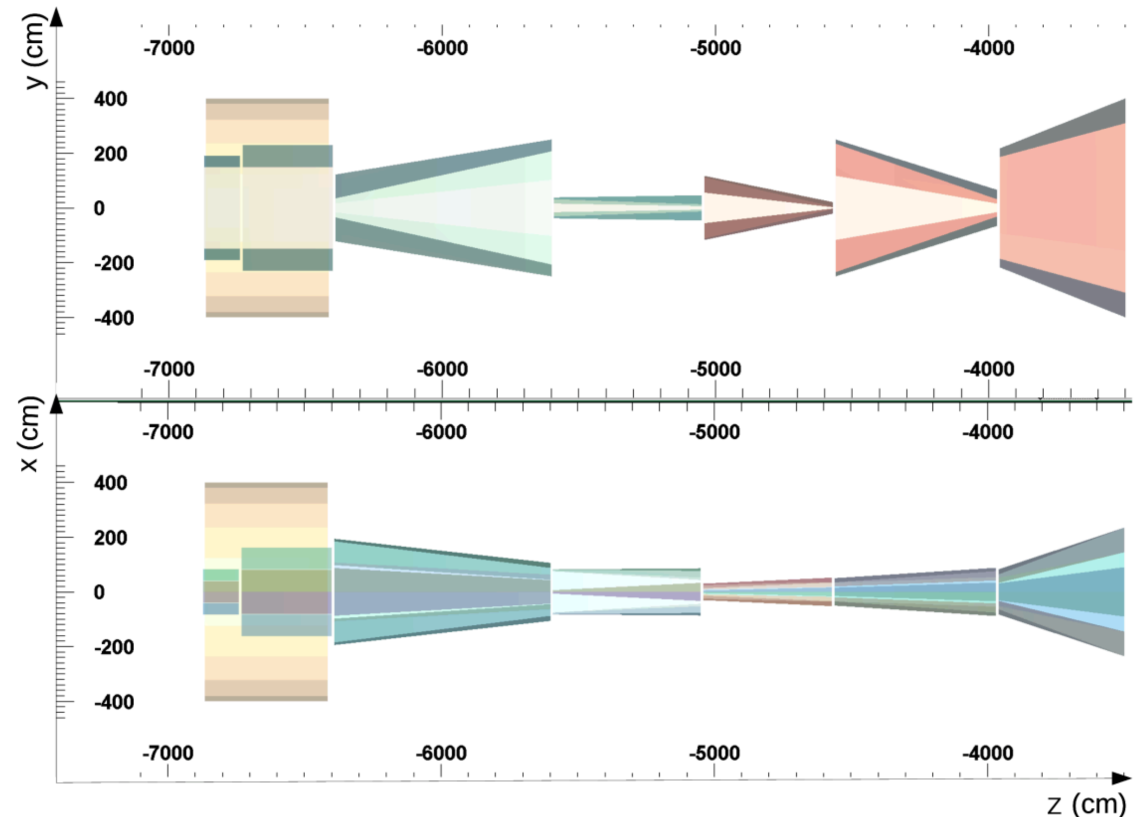
- Distribute the bkg over a long spill: 4×10^{13} PoT/1.3 seconds
- Sweeping magnet
- Decay volume to be far away from the walls

- Heavy target stops hadrons before they decay. After the target and the hadron absorber only muons survive
- Muons come mainly from η, η' and ω

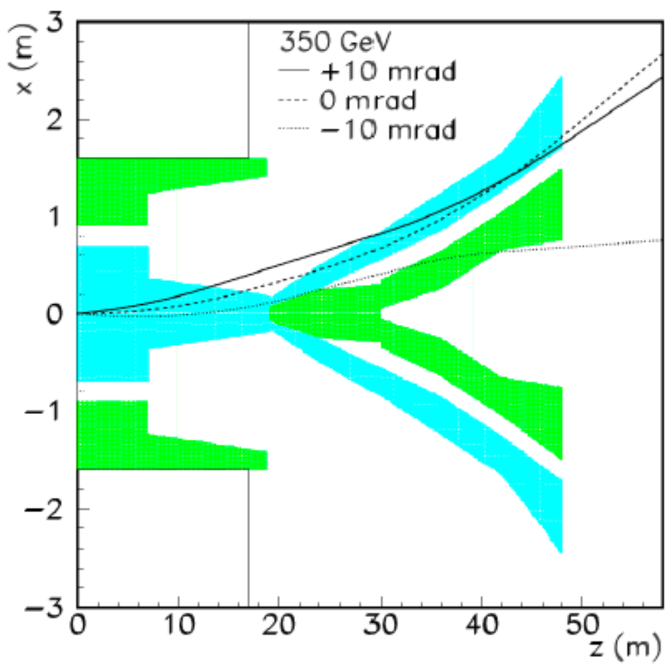
Muon Shield

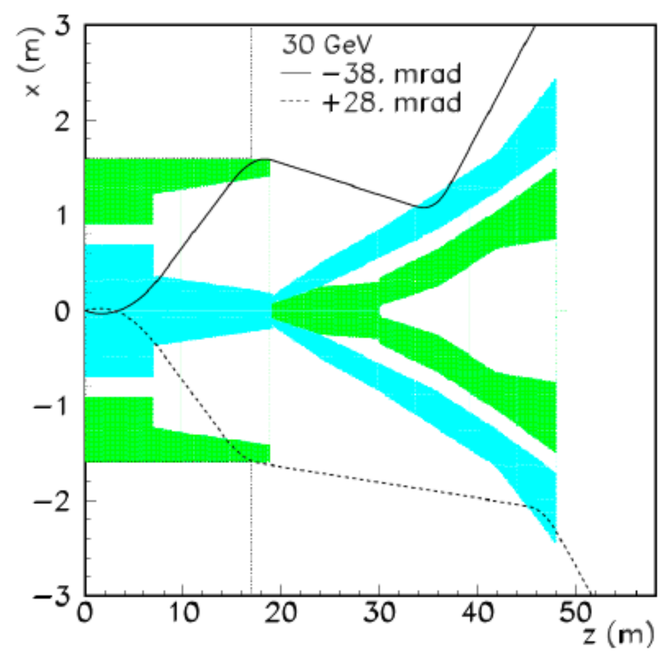
- Global optimisation of the magnetic field (with Machine Learning) still ongoing

Challenging Aspects:
- Narrow separation between field directions
- Aiming to 1.8T to minimize length (with grain oriented steel sheets)
- Have reliable muon sample to optimise with



The active muon shield in the SHiP experiment
JINST 12 P05011 2017

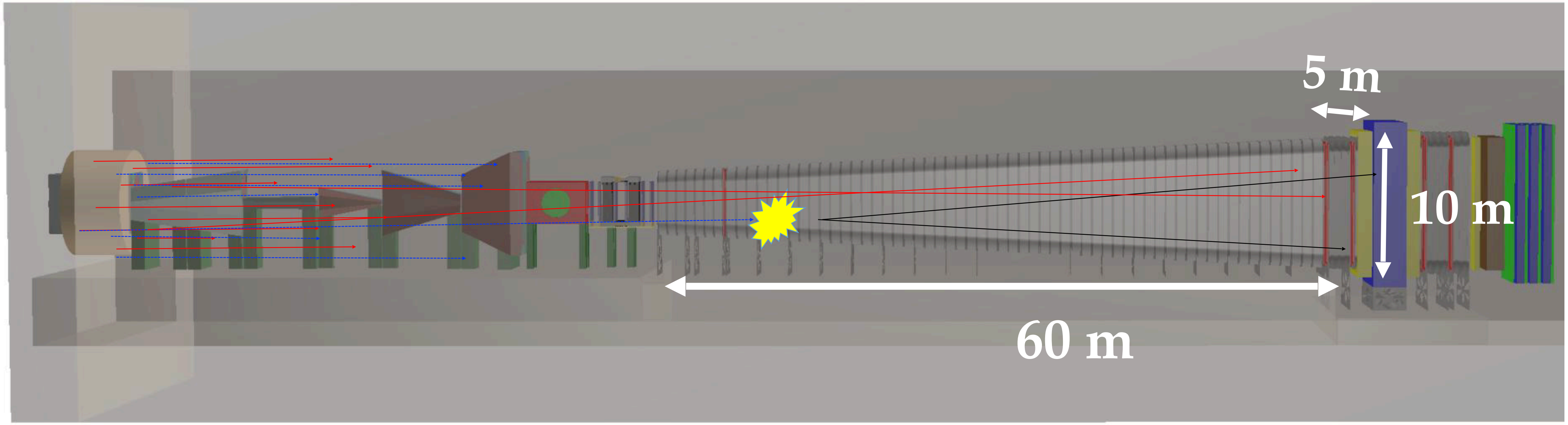




Running the simulation with material

- ~3x10^9 muons/spill with magnets off
- With the magnet on 3x10^5 muons/spill
- ~6.5x10^4 muons/spill with p>3GeV

Fiducial Volume



- In order to have a background free experiment we need a fiducial volume with at least 10^{-3} mbar 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
  - Upstream veto before the entrance window
  - Tracking veto after ~5m of the entrance window

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Vacuum Vessel

SHiP
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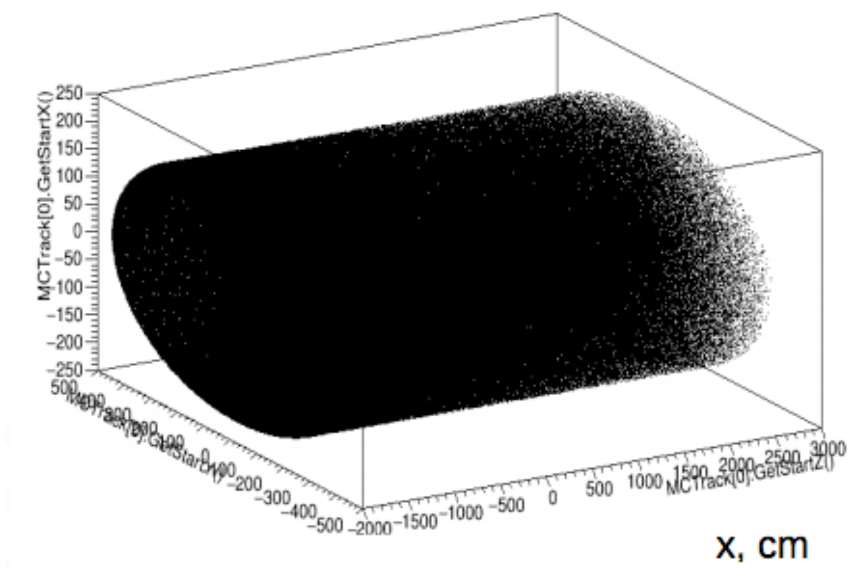
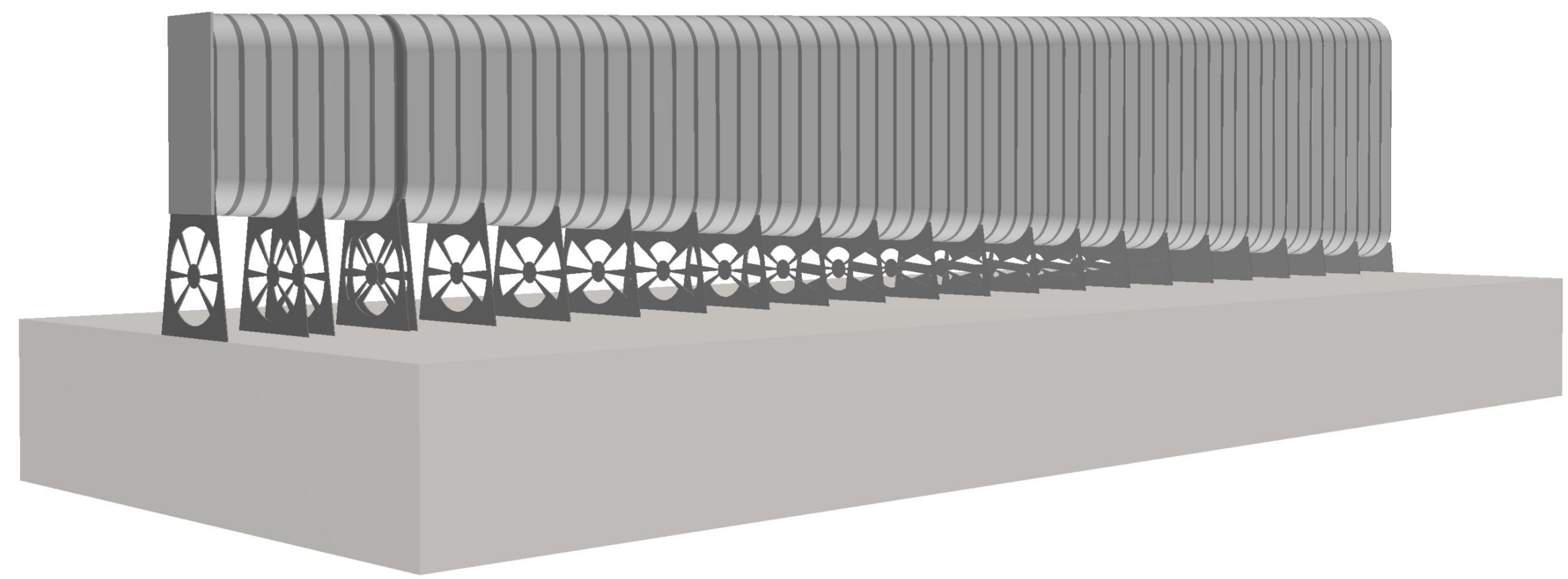


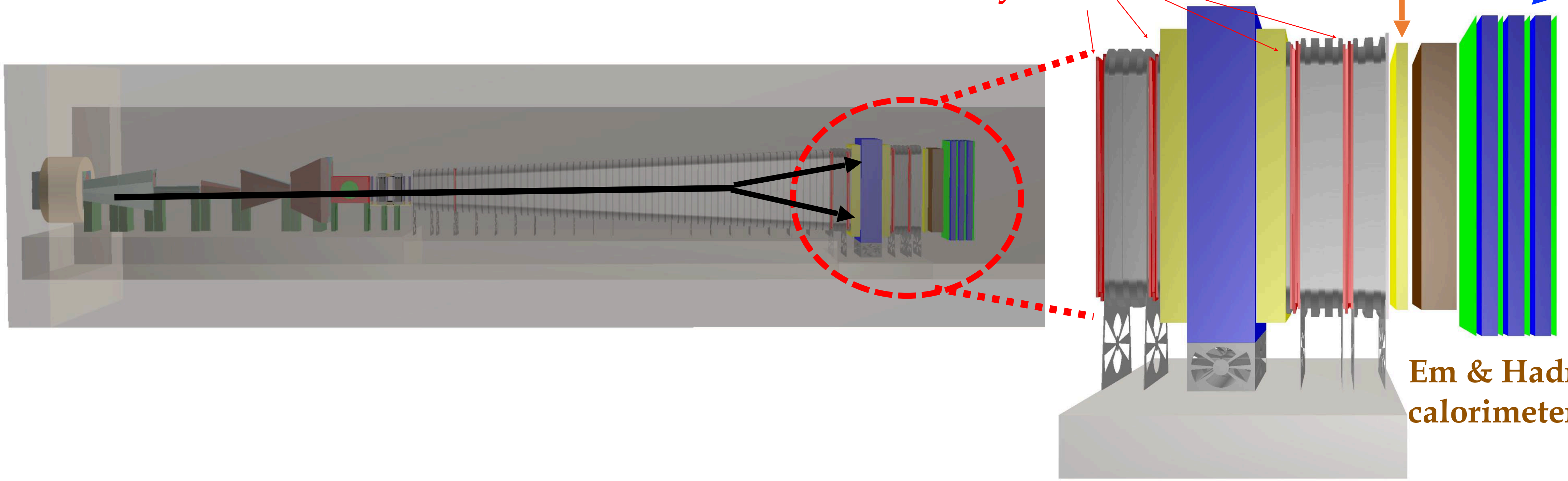


- The fiducial volume cannot be filled with air at atmospheric pressure, we would expect about 100K neutrino interaction in the experiment

- 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 (+ π^0 , γ) e.g. N—>$\mu^+\pi^-$ or N—>$\rho^+\mu^-$

2) Partially reconstructed signal (neutirnos in the final state) e.g. N—>$\mu^+\nu\nu$

4) Fully neutral channels e.g. A—> γ γ

Tracking System

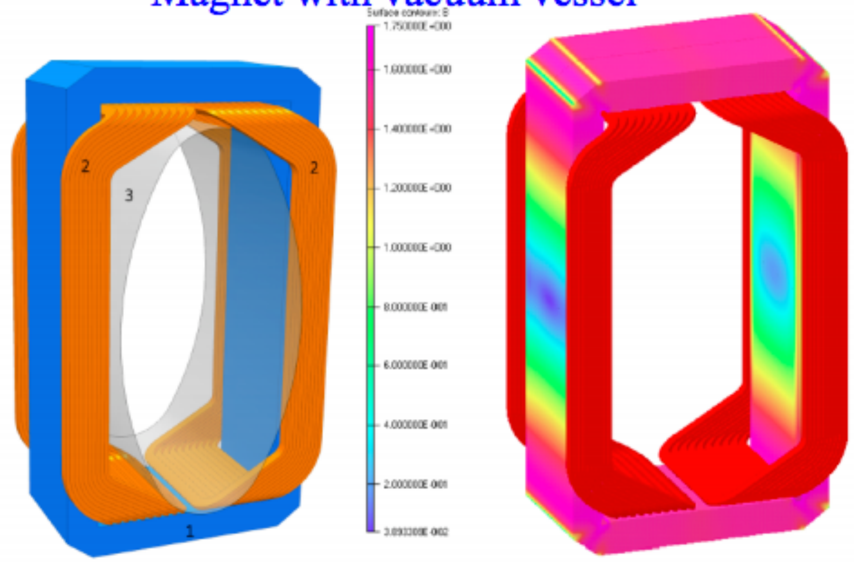
- *material budget per station 0.5% X_0*
- *position resolution 120 μm per straw, 8 hits per station on average*

$$\left(\frac{\sigma_p}{p}\right)^2 \approx [0.49\%]^2 + [0.022\%/(\mathrm{GeV}/c)]^2 \cdot p^2$$

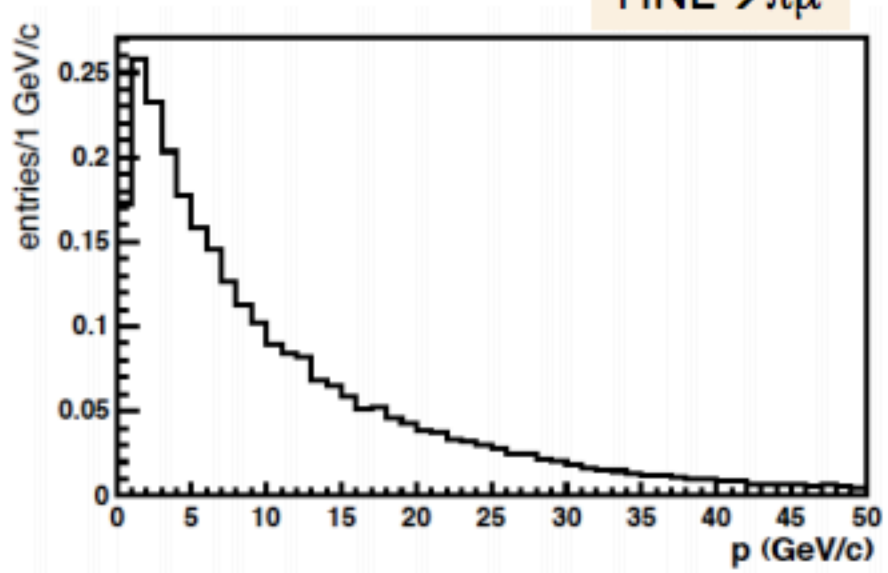
Momentum resolution is dominated by multiple scattering below 22 GeV/c
(For HNL → $\pi\mu$, 75% of both decay products have P < 20 GeV/c)

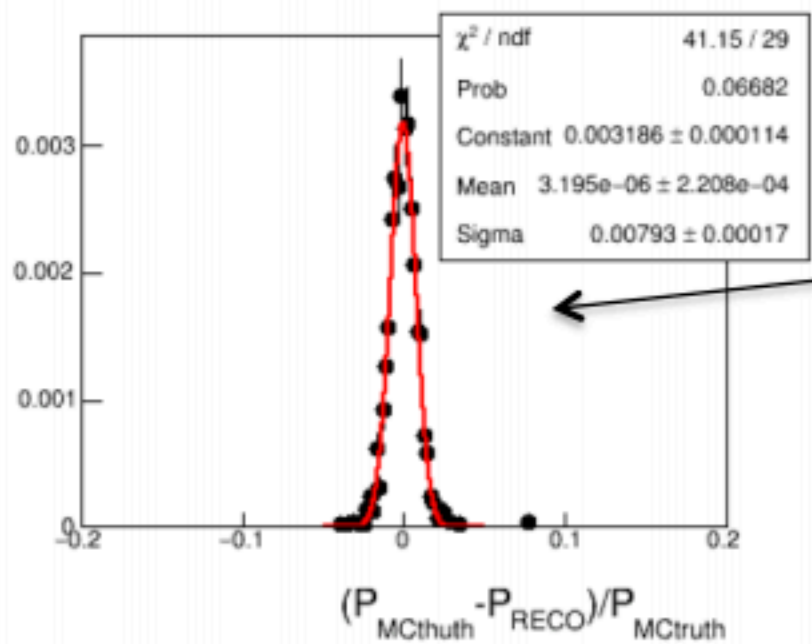
Main difference with Na62:
5m length, vacuum 10^{-2}mbar,

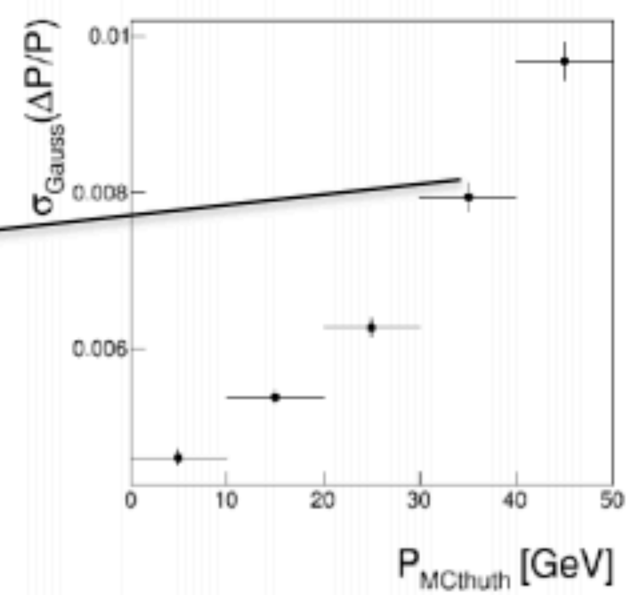
Magnet with vacuum vessel



HNL→$\pi\mu$







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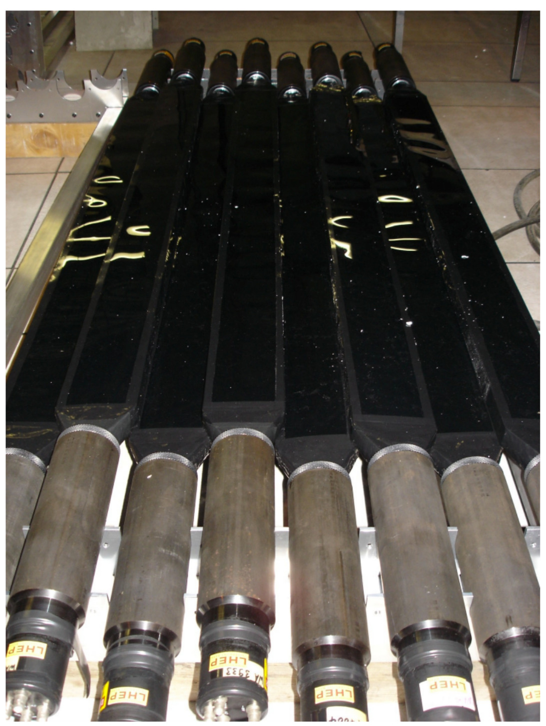
Physics Case

SHiP
Search for Hidden Particles

Challenges:
- Large area
- Required time resolution <100ps

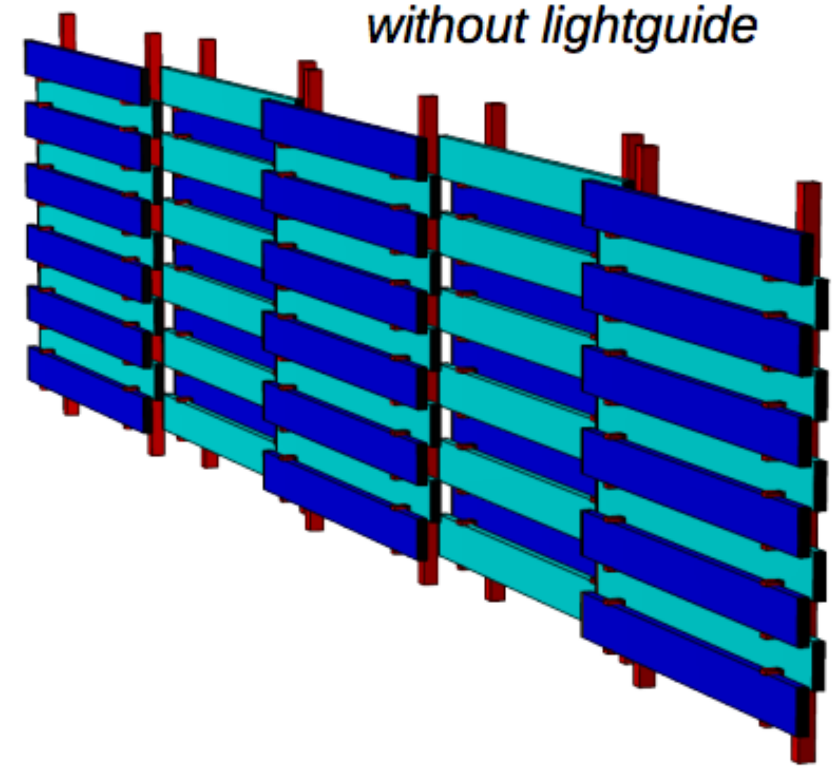
NA61/SHINE, bars with PMTs
UniGe 2006



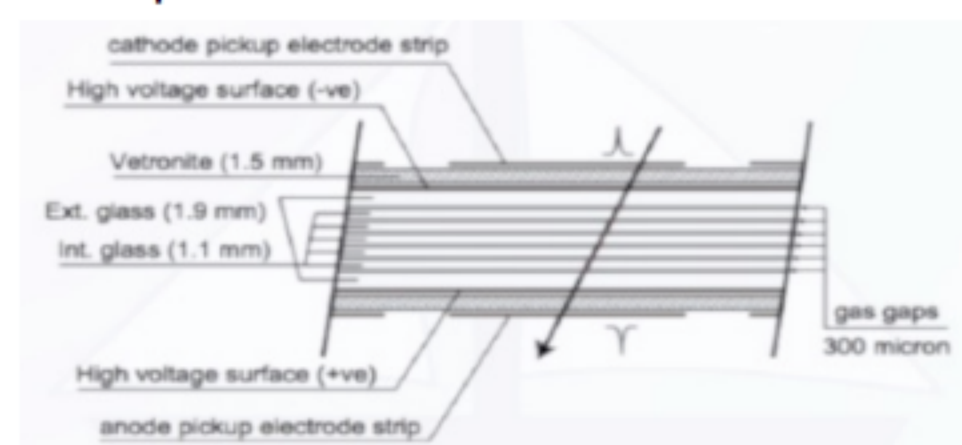
NA61/SHINE ToF
- 100ps resolution in NA61/Shine ToF
- Size of scintillator counter 120x10x2.5 cm^3
- Total active area 1.2x7.2 m^2

- Plastic scintillating bars read-out by SiPM

5-columns setup without lightguide

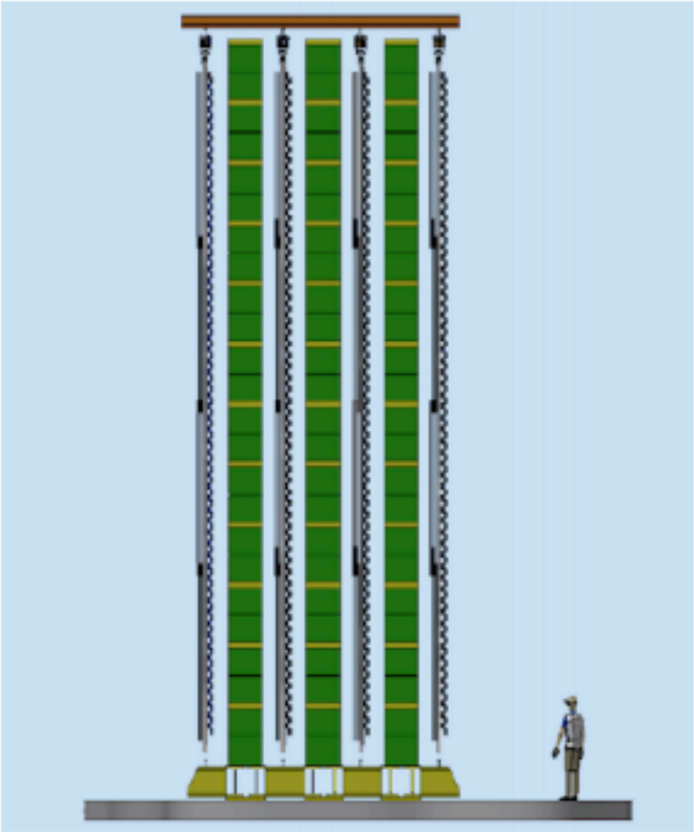


Multi-gap resistive plate chambers (MRPC)
- ALICE ToF and EEE project
- 61 chambers x 120 cm strips, 3 cm pitch
- 50 ps resolution achievable



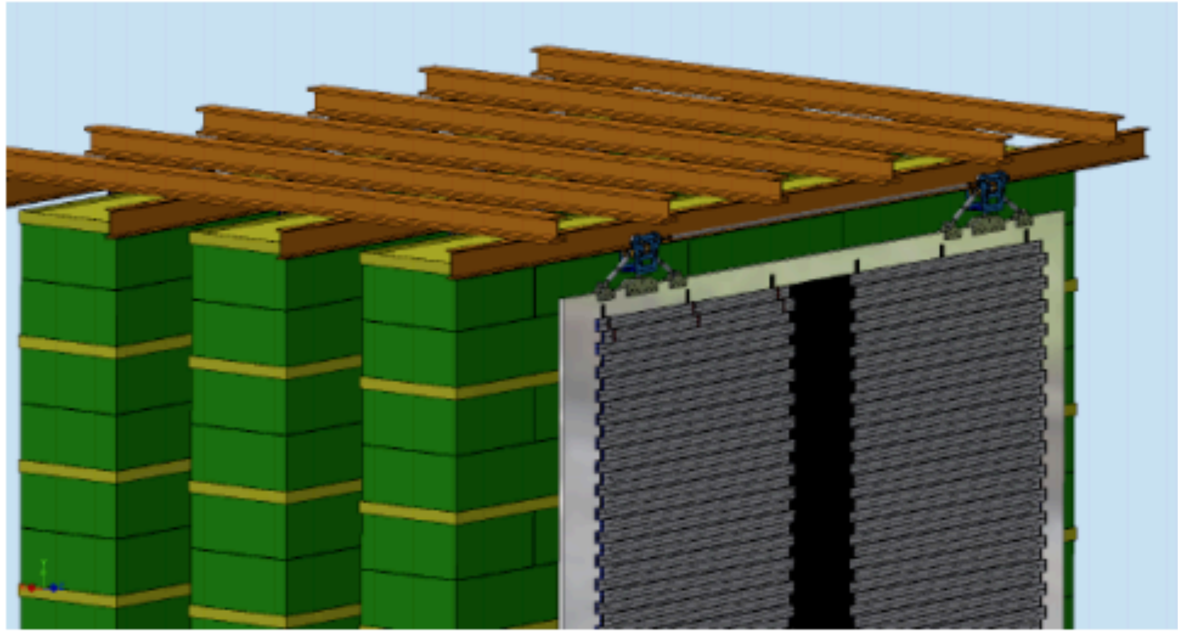
Muon System

Based on scintillating bars, with WLS fibers and SiPM readout

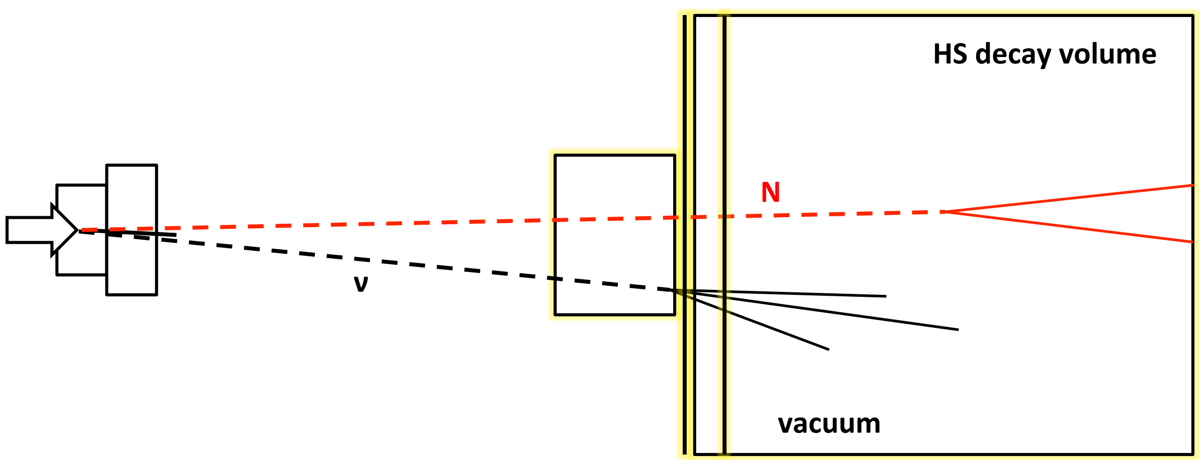


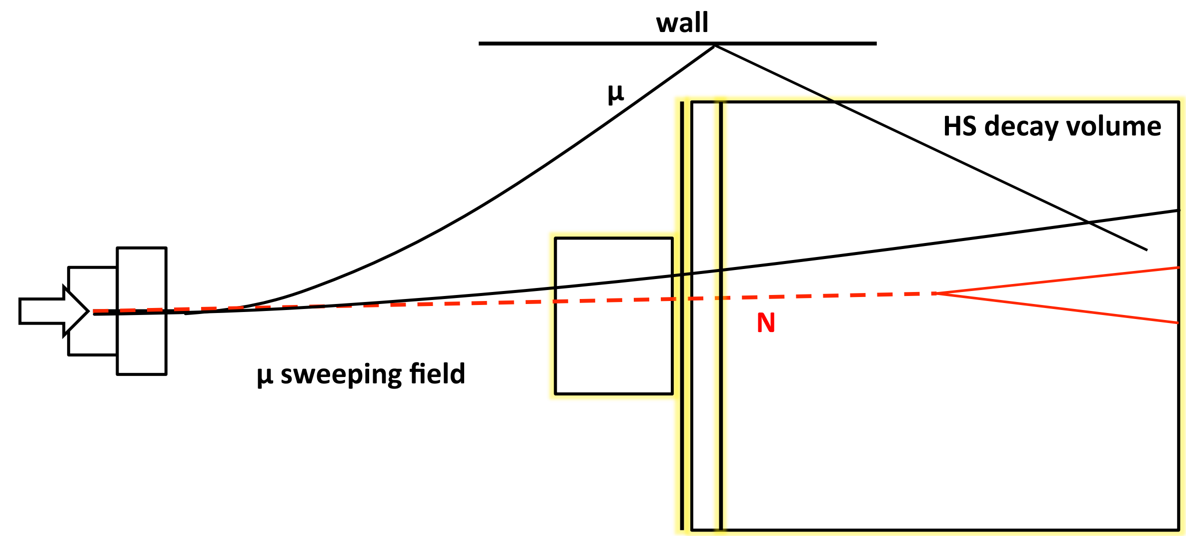
Technical Proposal (preliminary design)
- 4 active stations
- transverse dimensions: 1200x600 cm2
- x,y view
- 3380 bars, 5x300x2 cm3/each
- 7760 FEE channels
- 1000 tons of iron filters

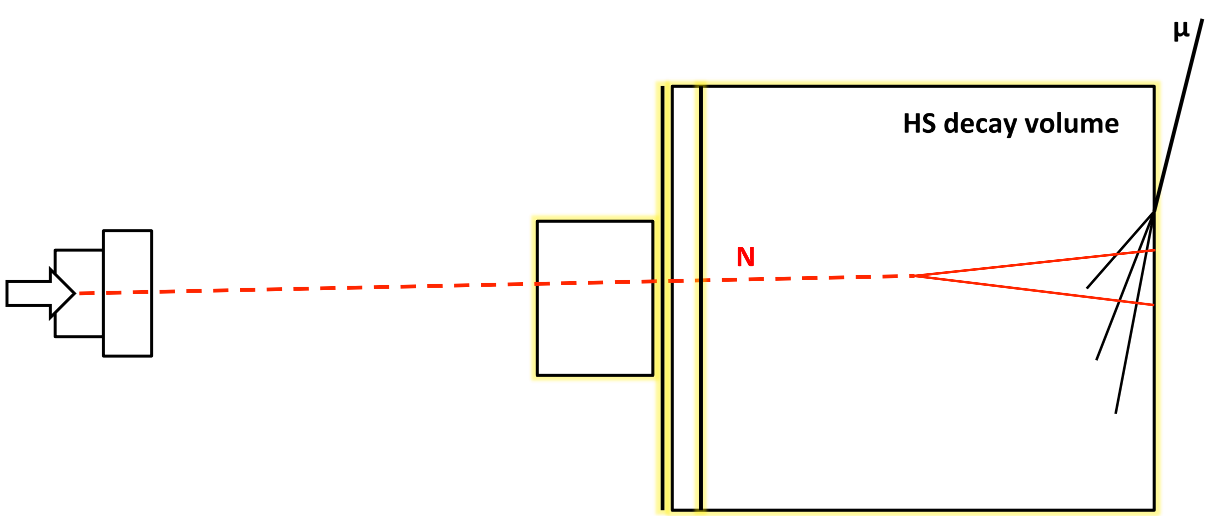
Requirements:
1) High-efficiency identification of muons in the final state
2) Separation between muons and hadrons/electrons
3) Complement timing detector to reject combinatorial muon background

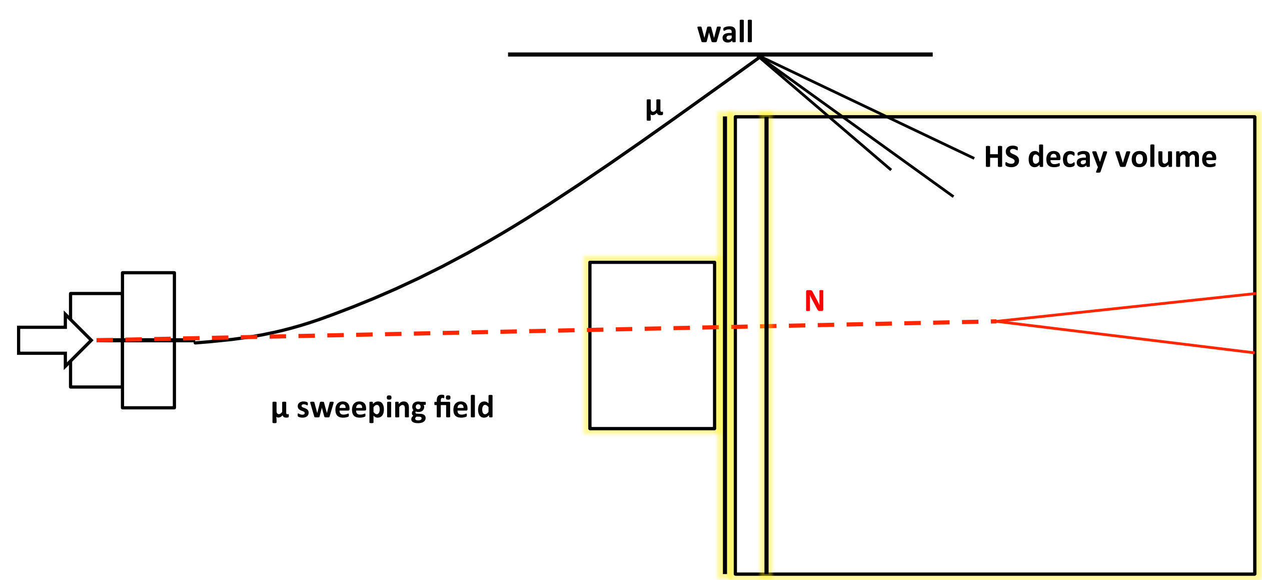


Backgrounds



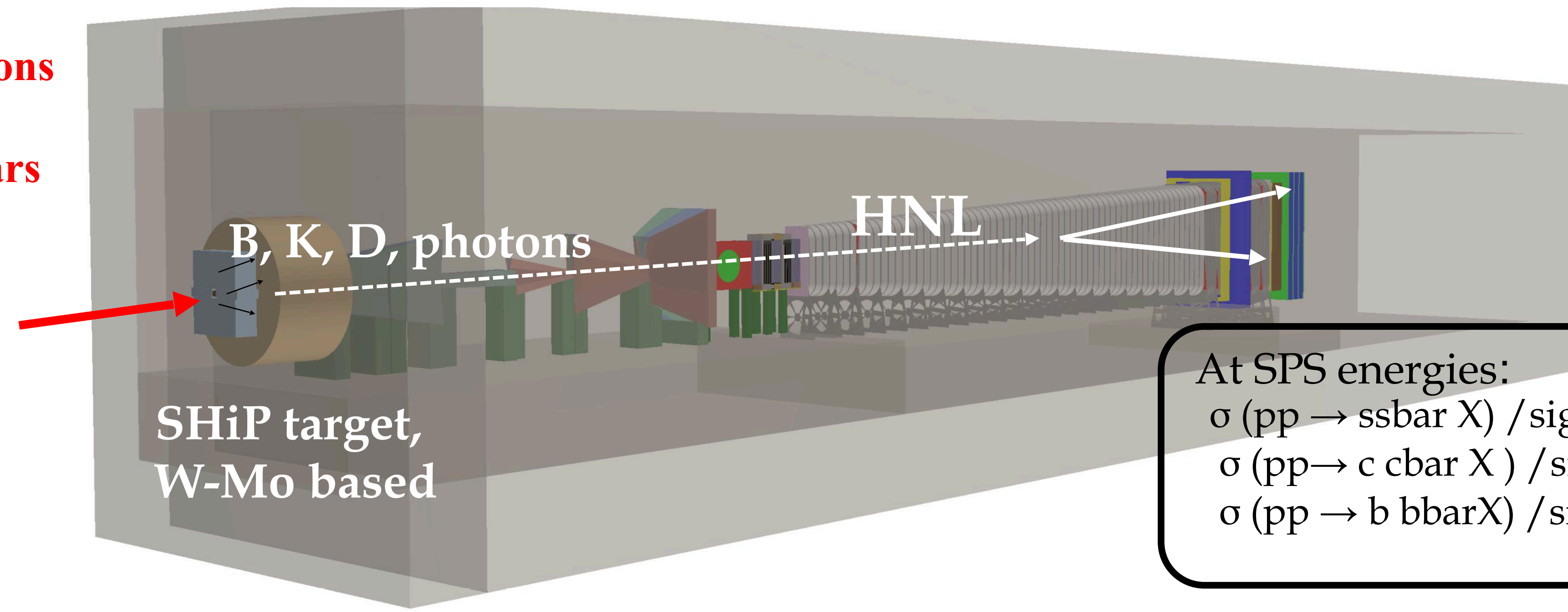






Signal Signature

Beam:
400 GeV/c protons
$4x10^{13}$ pot/spill
$2x10^{20}$ pot/5 years

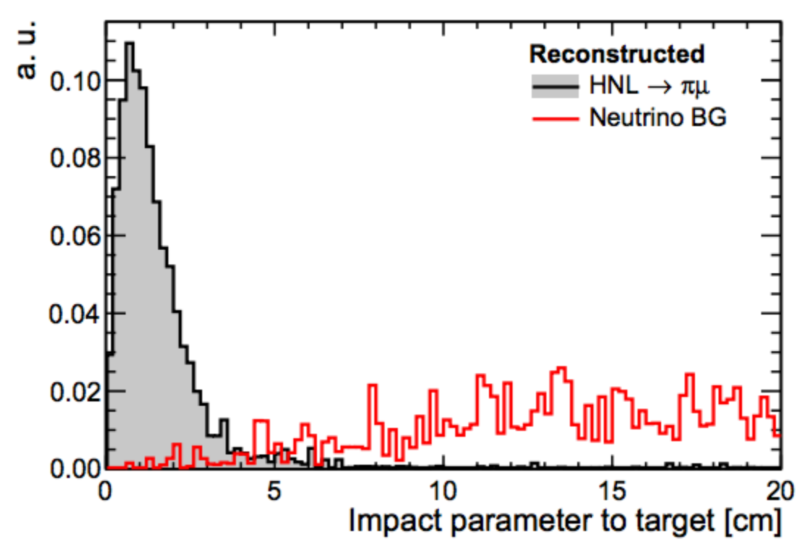


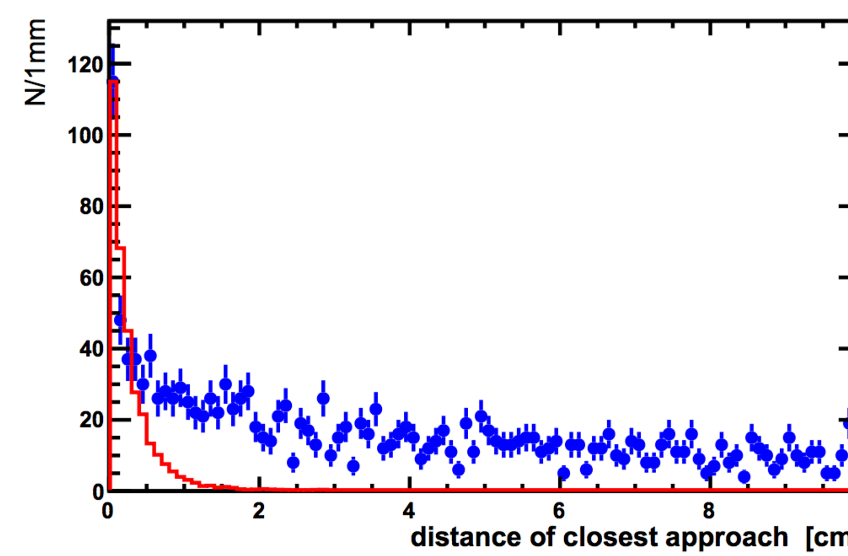
At SPS energies:
σ (pp → ssbar X) / sigma (pp→ X) ~ 0.15
σ (pp→ c cbar X) / sigma (pp→ X) ~ 2 10^{-3}
σ (pp → b bbarX) / sigma (pp→ X) ~ 1.6 10^{-7}

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

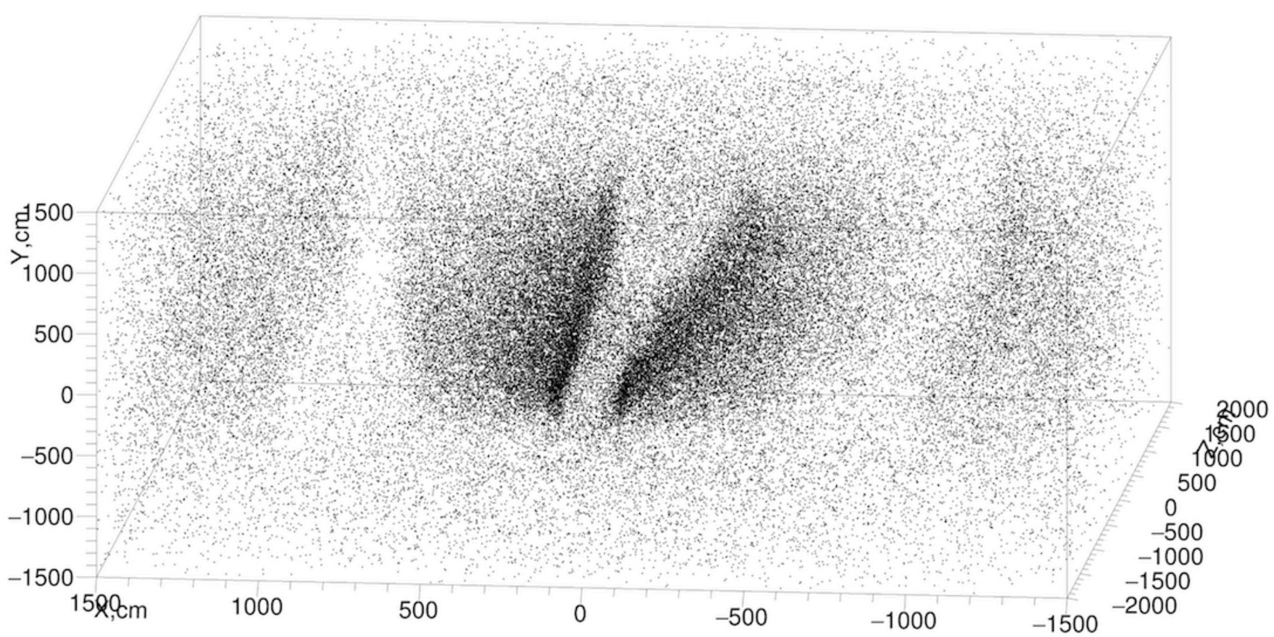
Various veto cuts considered

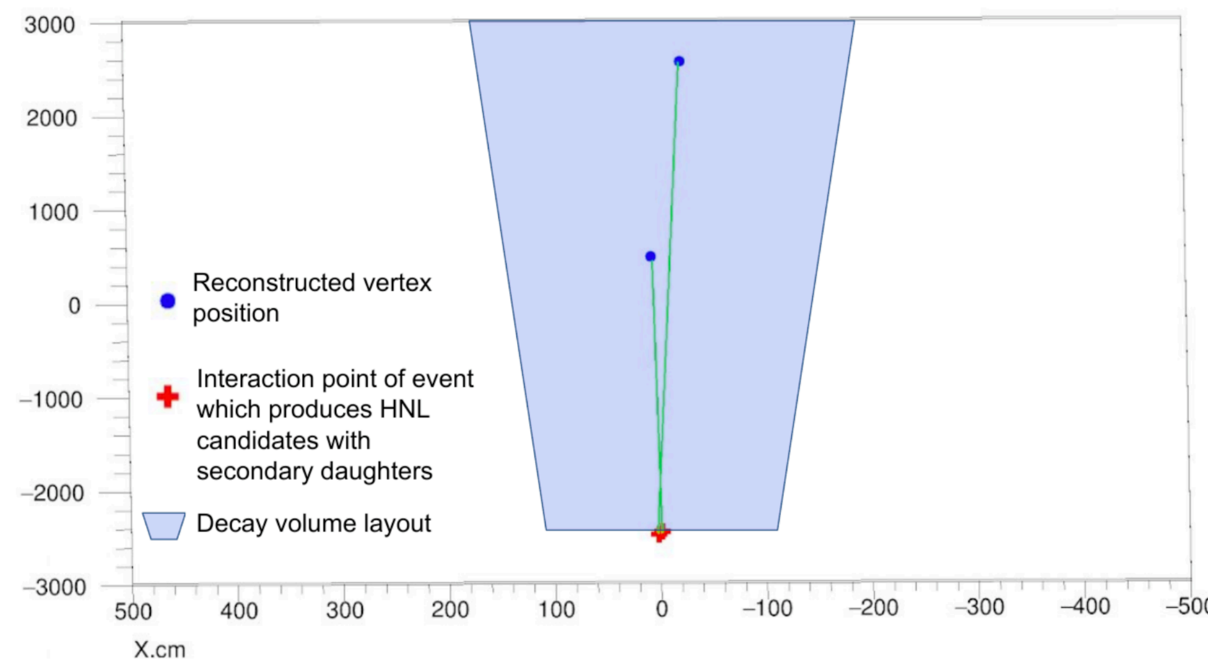




Neutrino Background

- 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 6.5x10^4
- Two events in 5 years for partially reconstructed coming from converted photons



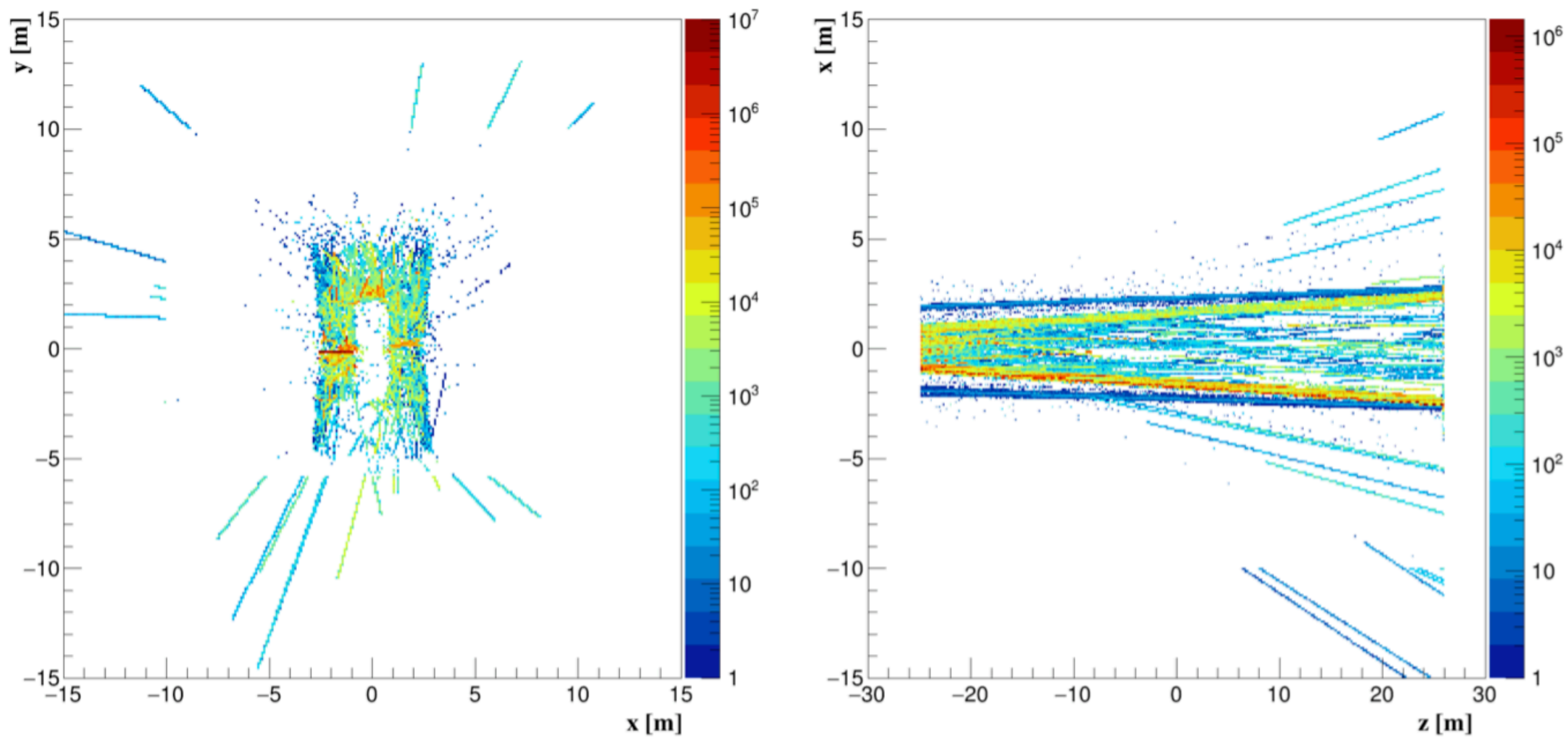


Selection criteria	Fully reconstructed	Partially reconstructed	Signal efficiency
Use of veto systems	0	0	64.8%
No veto systems	0	18	65.1%
Veto systems only around the vertex	0	2	

Table 6: Neutrino background in 2×10^{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 $5x10^4$ per spill
- This result in about $2\ x10^8$ bkg candidates from muon DIS interactions in 5 years

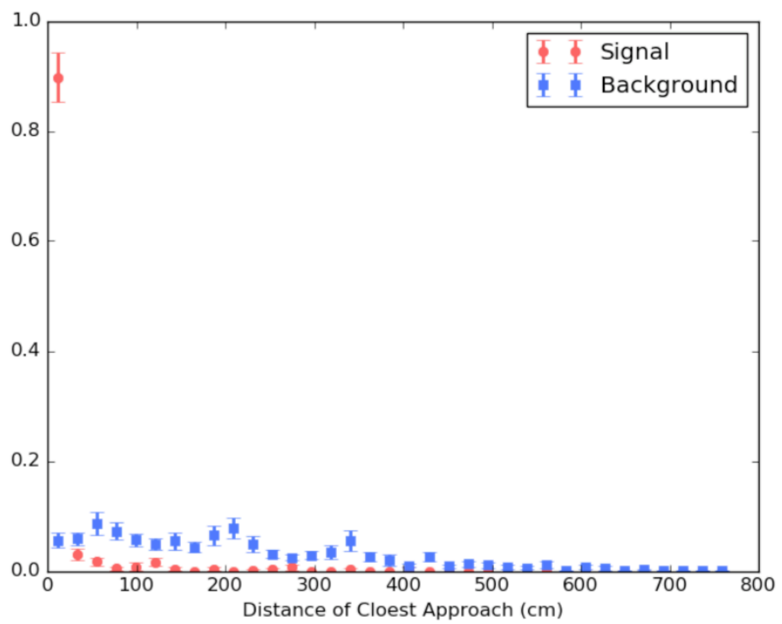


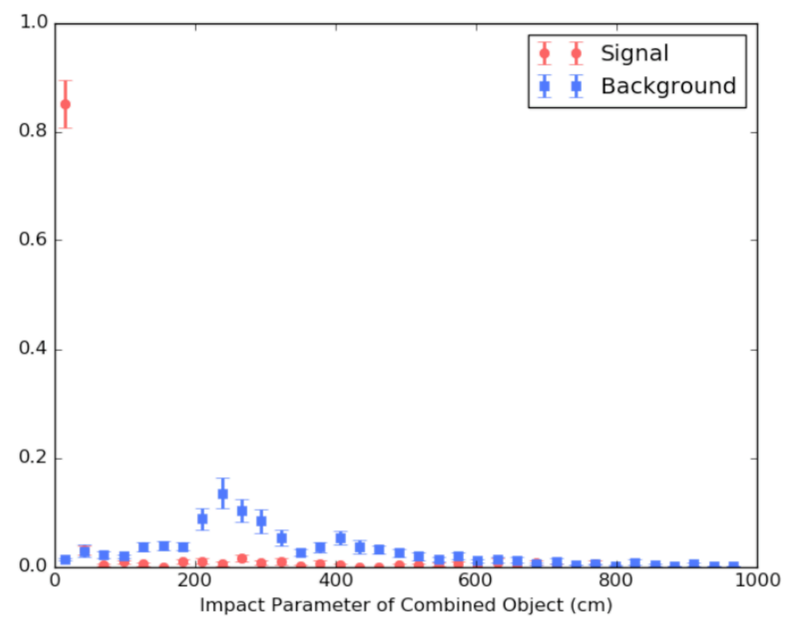
Selection cut	Expected background
Events reconstructed	$1.5{\cdot}10^6$
Selection cuts (IP $<$ 10 cm)	27
Selection cuts (IP $<$ 250 cm)	566
Vetoed events SBT (fully reco)	$< 2.7 \cdot 10^{-5}$
Vetoed events (partially reco)	$< 6 \times 10^{-4}$

Table 7: Summary of the muon inelastic background events expected for 2×10^{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	8.5×10^{15}
Selection cuts (Table 5)	10^{9}
Timing	10^{-2}

Table 8: Expected background level from muon combinatorial events.

Background summary

Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}

Table 9: Expected background to the HS particle search at 90% CL for 2×10^{20} protons on target.

HNL Sensitivity

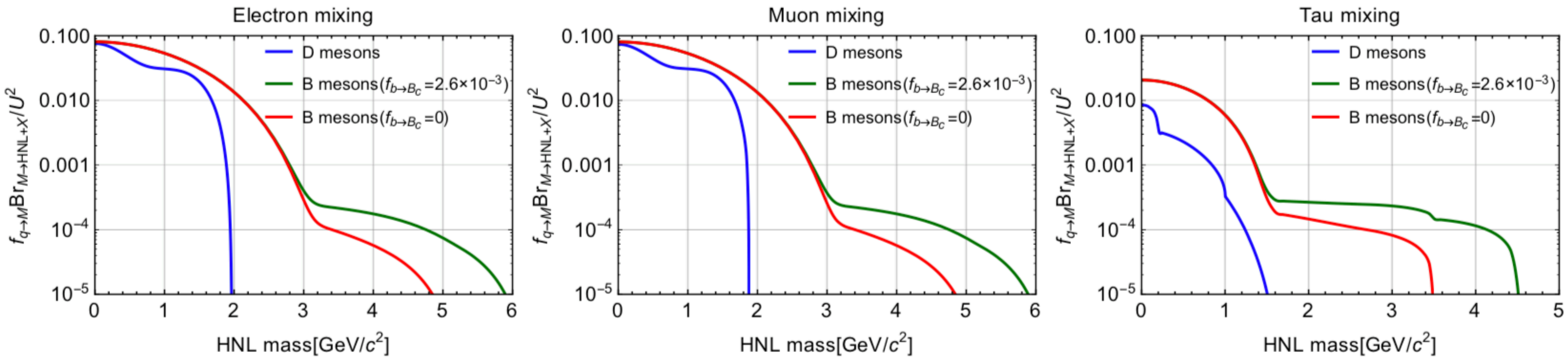


Figure 65: Meson fragmentation fraction times branching fraction of meson decays to HNL as a function of the HNL mass. Contributions from D and B mesons are shown. To demonstrate the influence of B_c mesons, we show two cases: the B_c fragmentation fraction at SHiP energies equal to that of at LHC energies: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

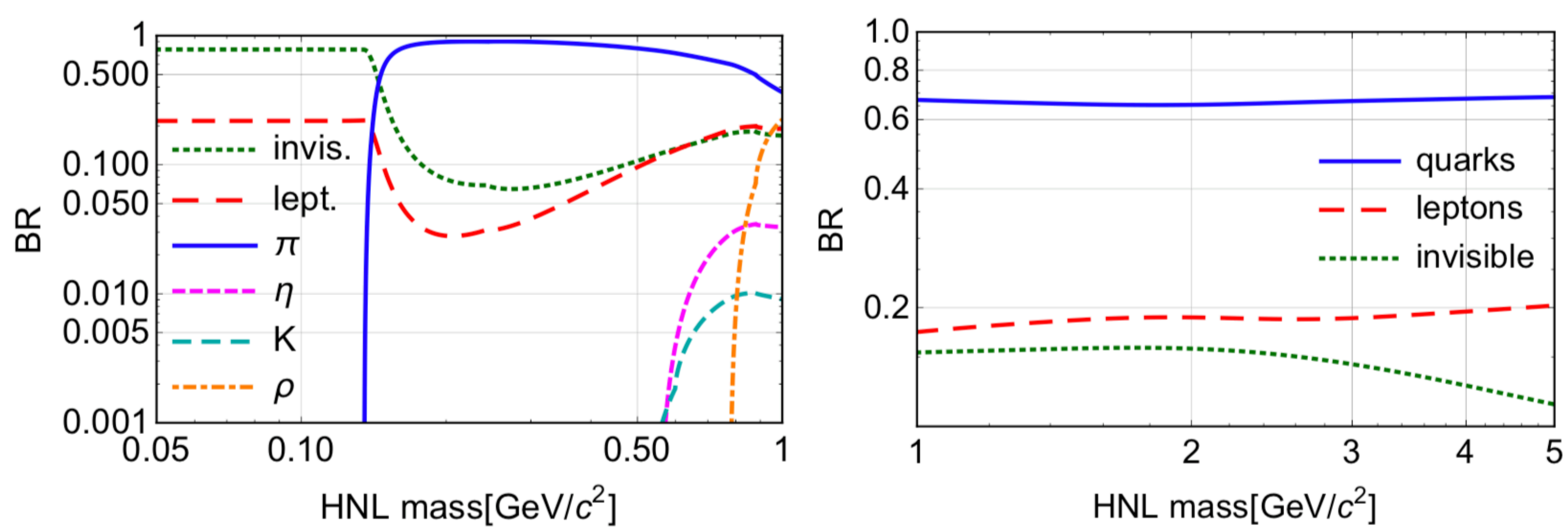


Figure 66: The branching ratios of the HNL decays for the mixing ratio $U_e : U_\mu : U_\tau = 1 : 1 : 1$. *Left panel:* region of masses below 1 GeV/c^2; *Right panel:* region of masses above 1 GeV/c^2. From [108].

HNL Sensitivity

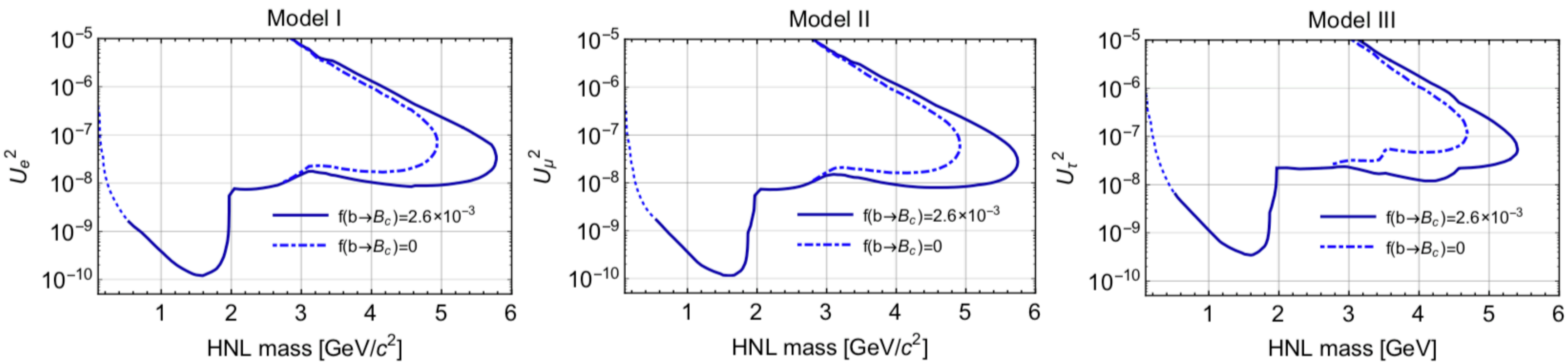
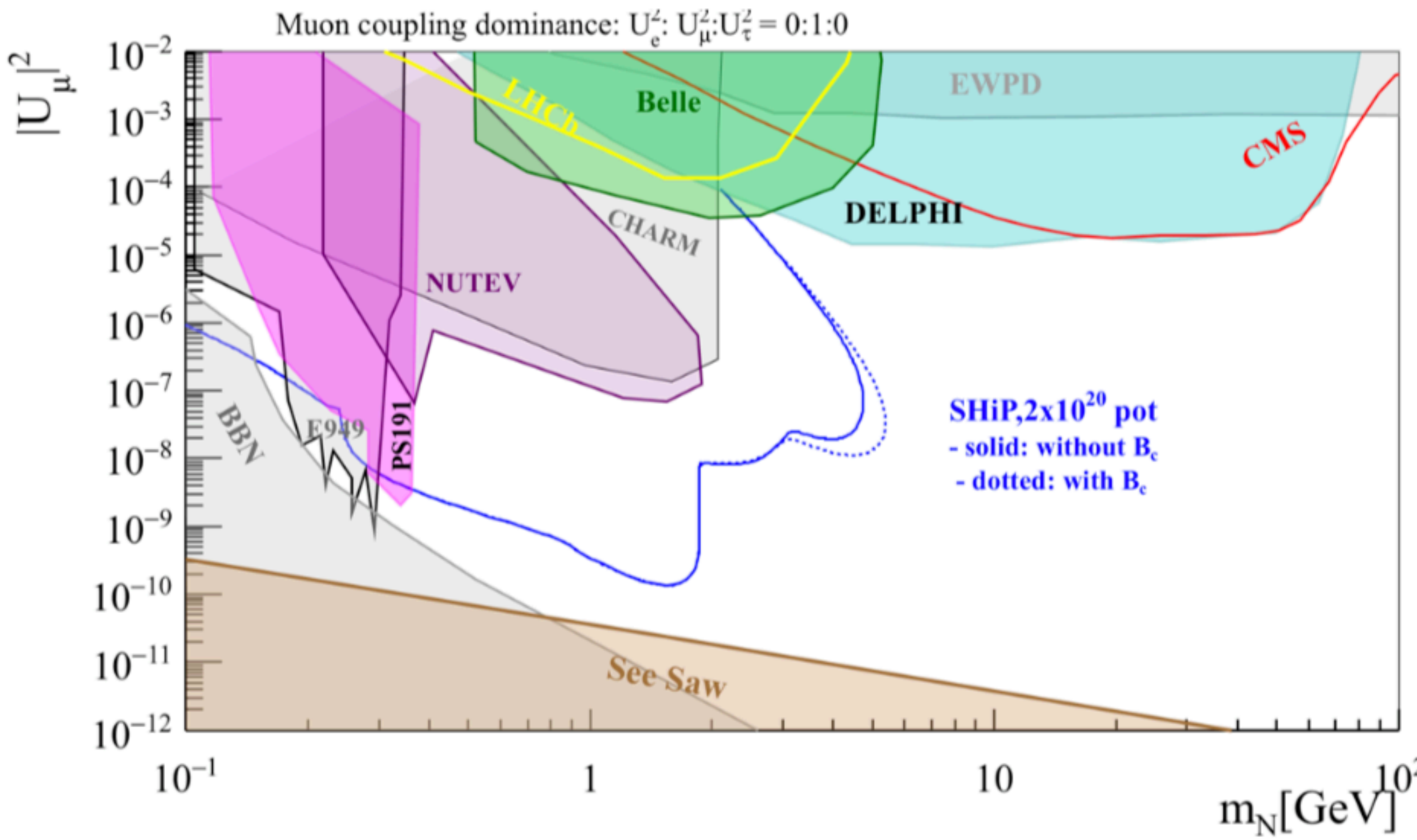


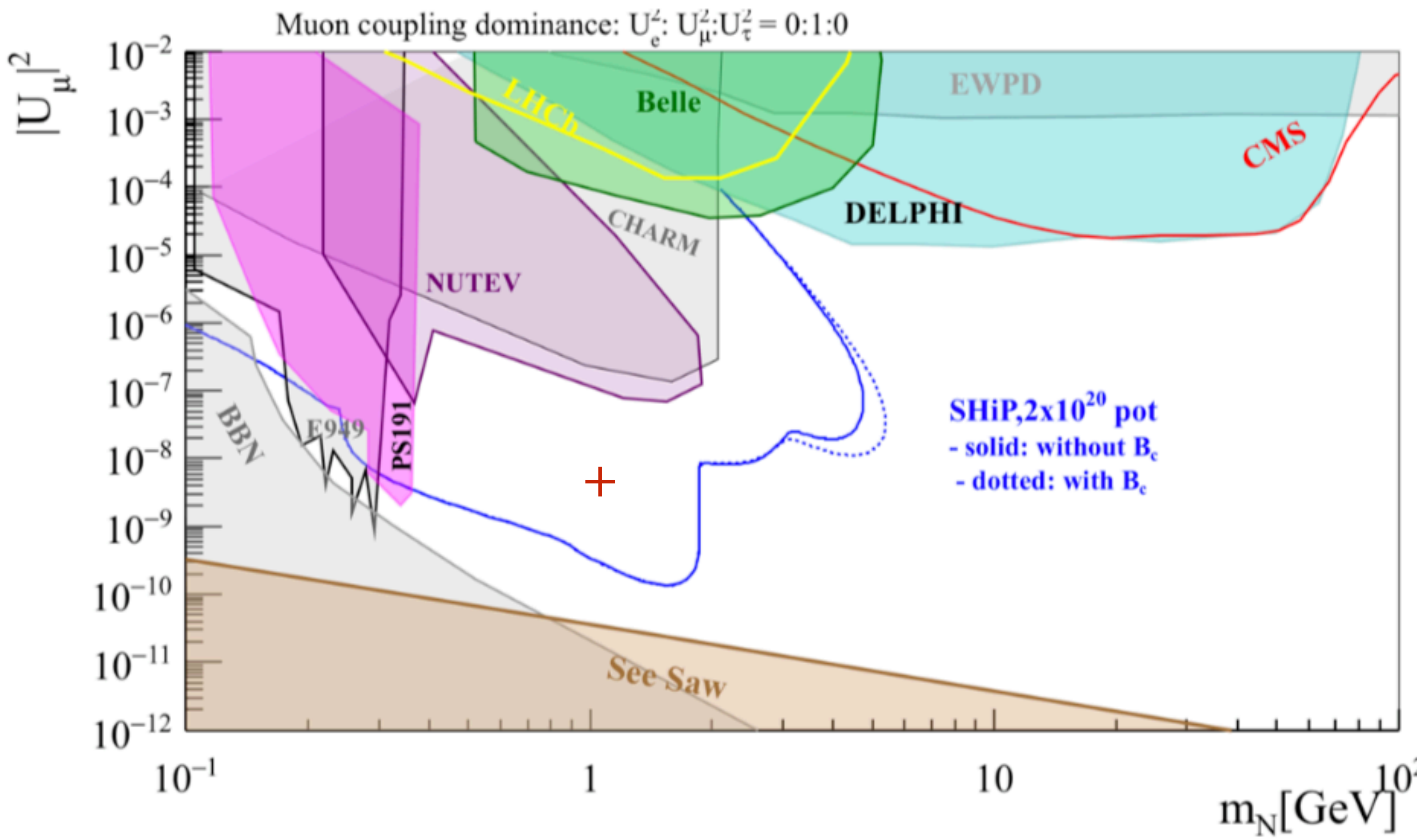
Figure 67: Sensitivity of the SHiP experiment to three HNL models. Solid curves show the contribution from B_c mesons, when the fragmentation fraction is taken equal to that at LHC energies: $f_{b\to B_c} = 2.6 \times 10^{-3}$. Dashed-dotted lines do not include contributions from B_c. Below 0.5 GeV/c^2 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!*

DP Sensitivity

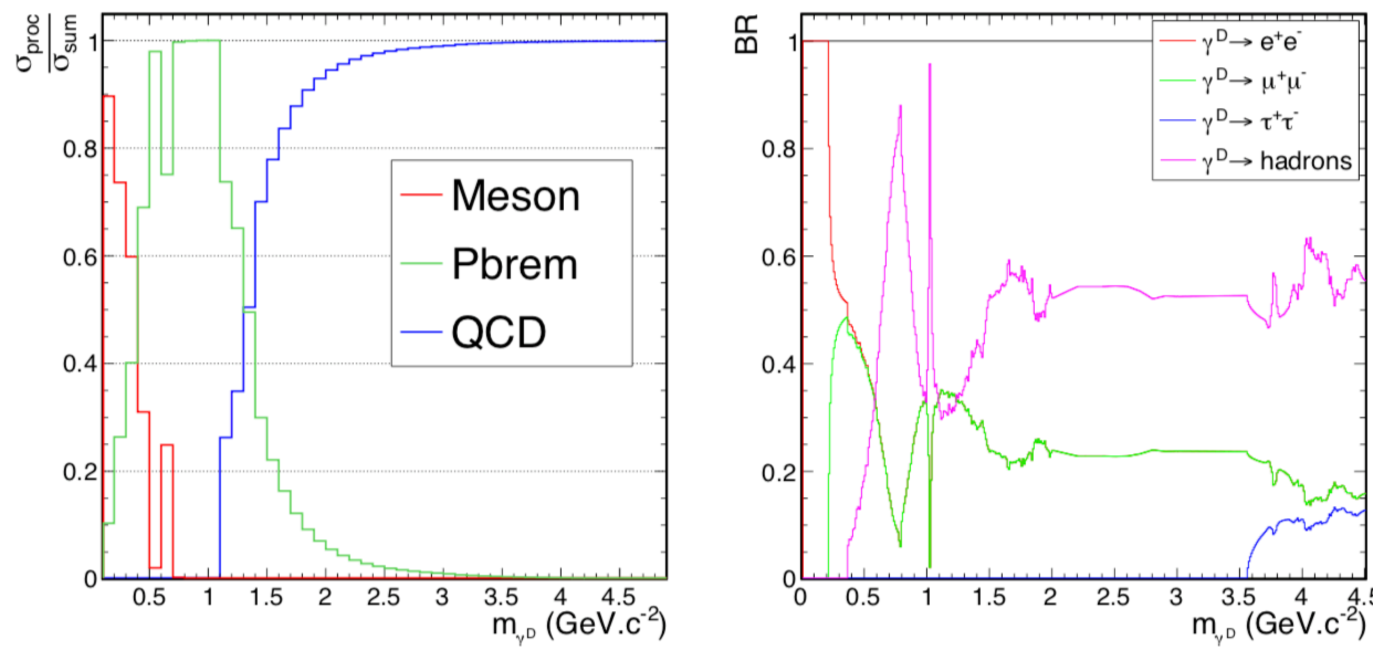
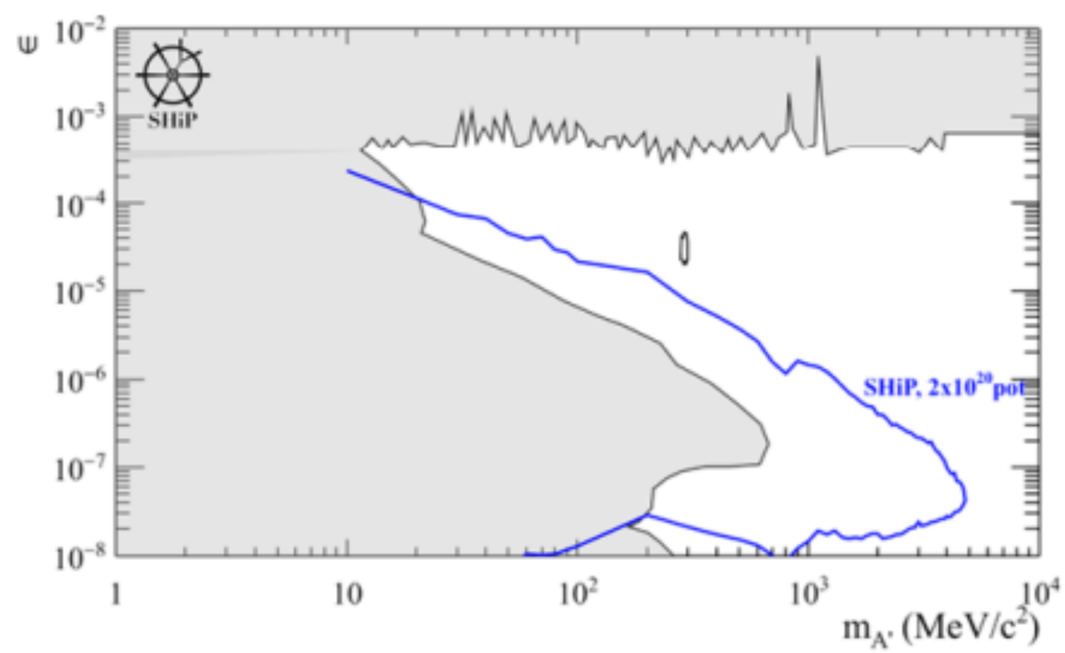
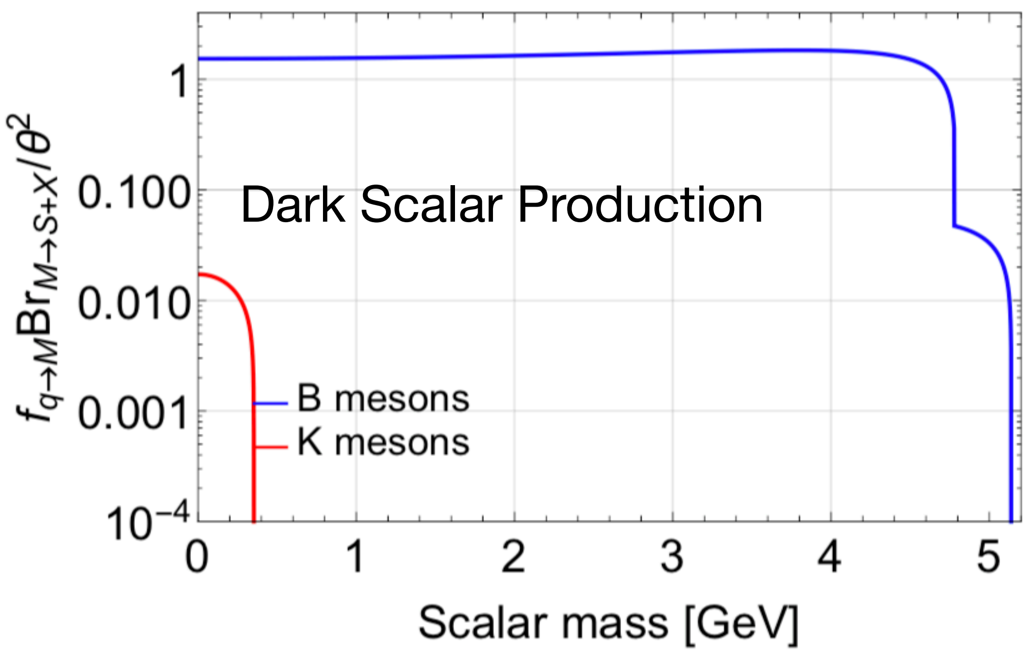


Figure 72: Left: relative contributions to the cross-section as a function of m_{DP} for the three production modes studied. Right: branching ratio of the DP into fermion pairs as a function of its mass.



DS Sensitivity



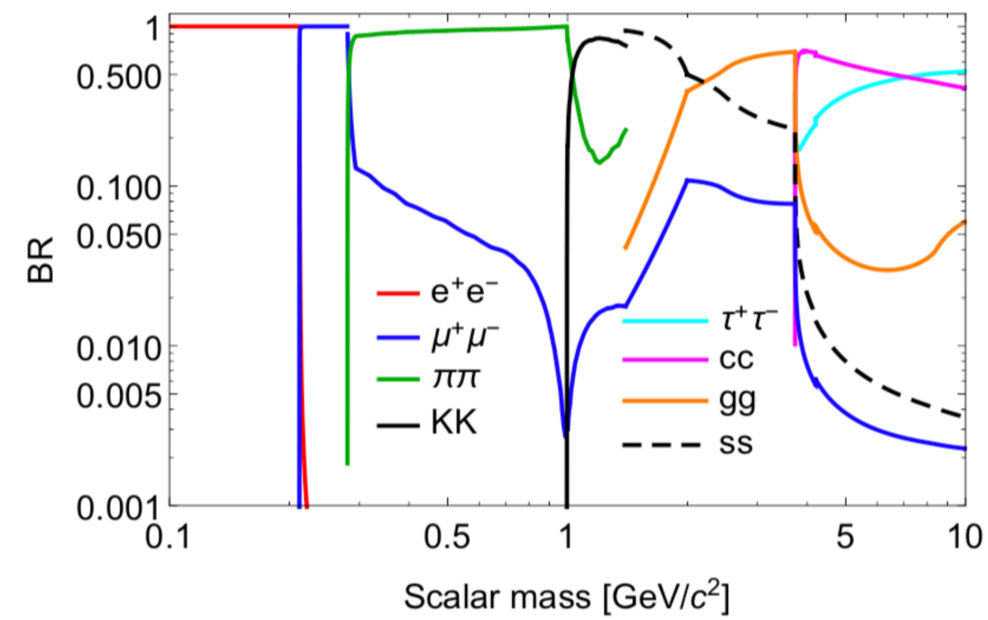
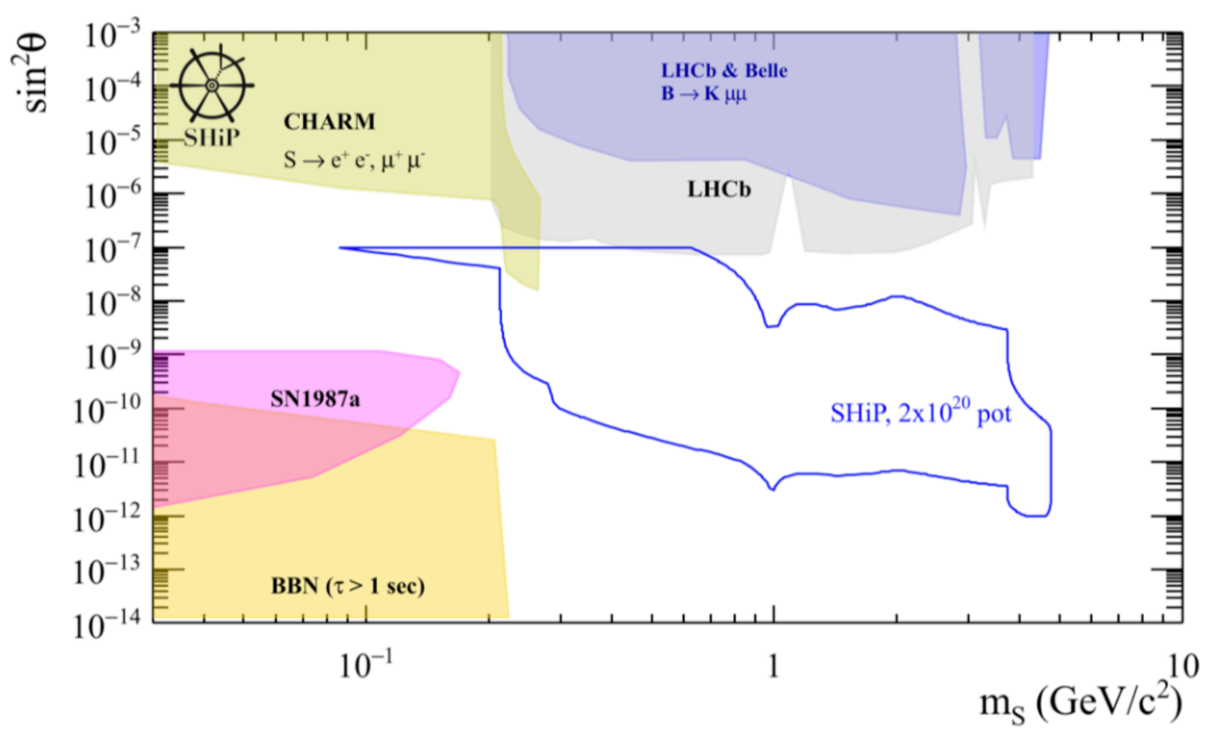


Figure 70: The branching ratios of the scalar decays. From [107].



ALPs Sensitivity

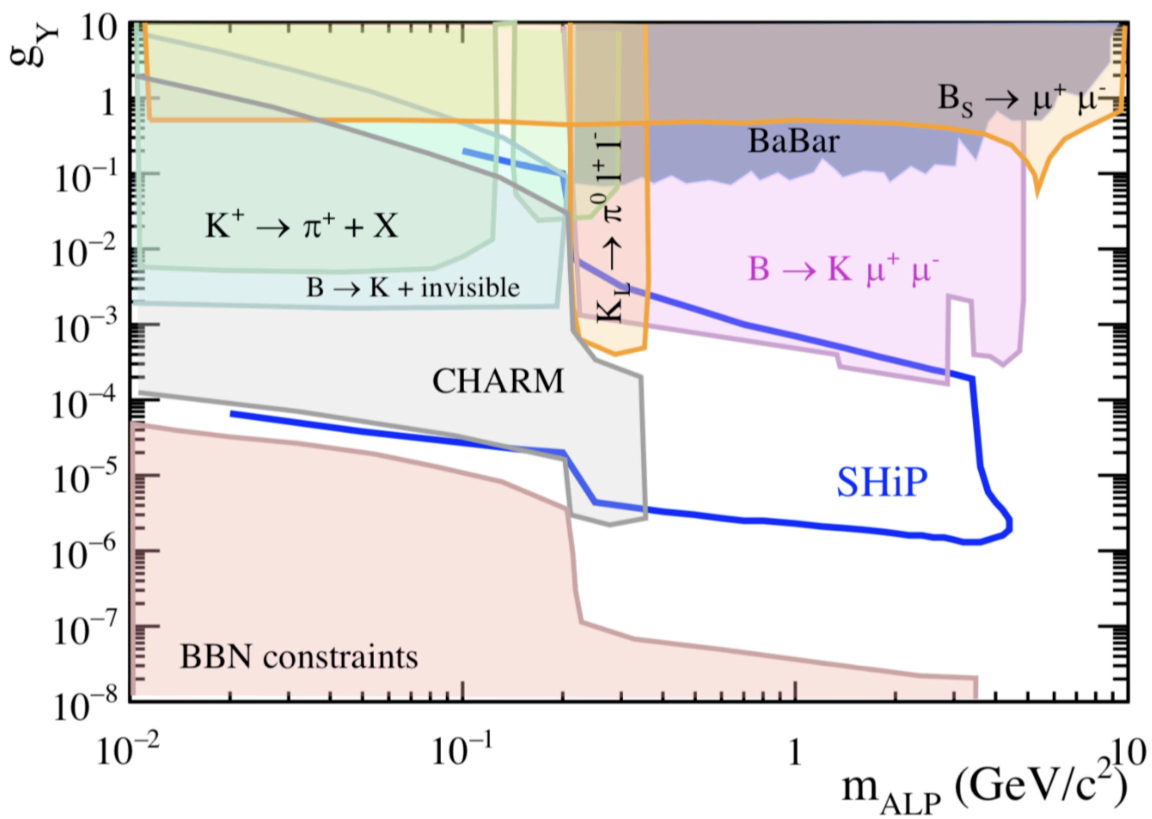


Figure 74: SHiP sensitivity to ALP coupling to fermions

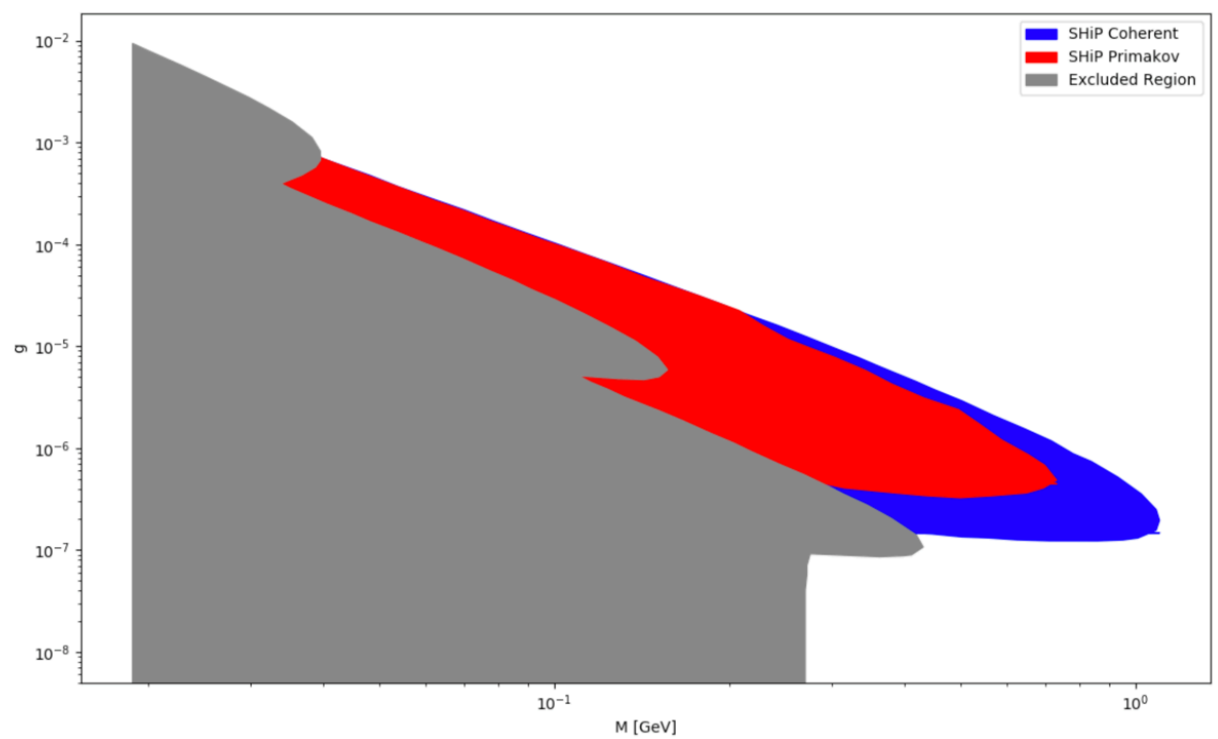
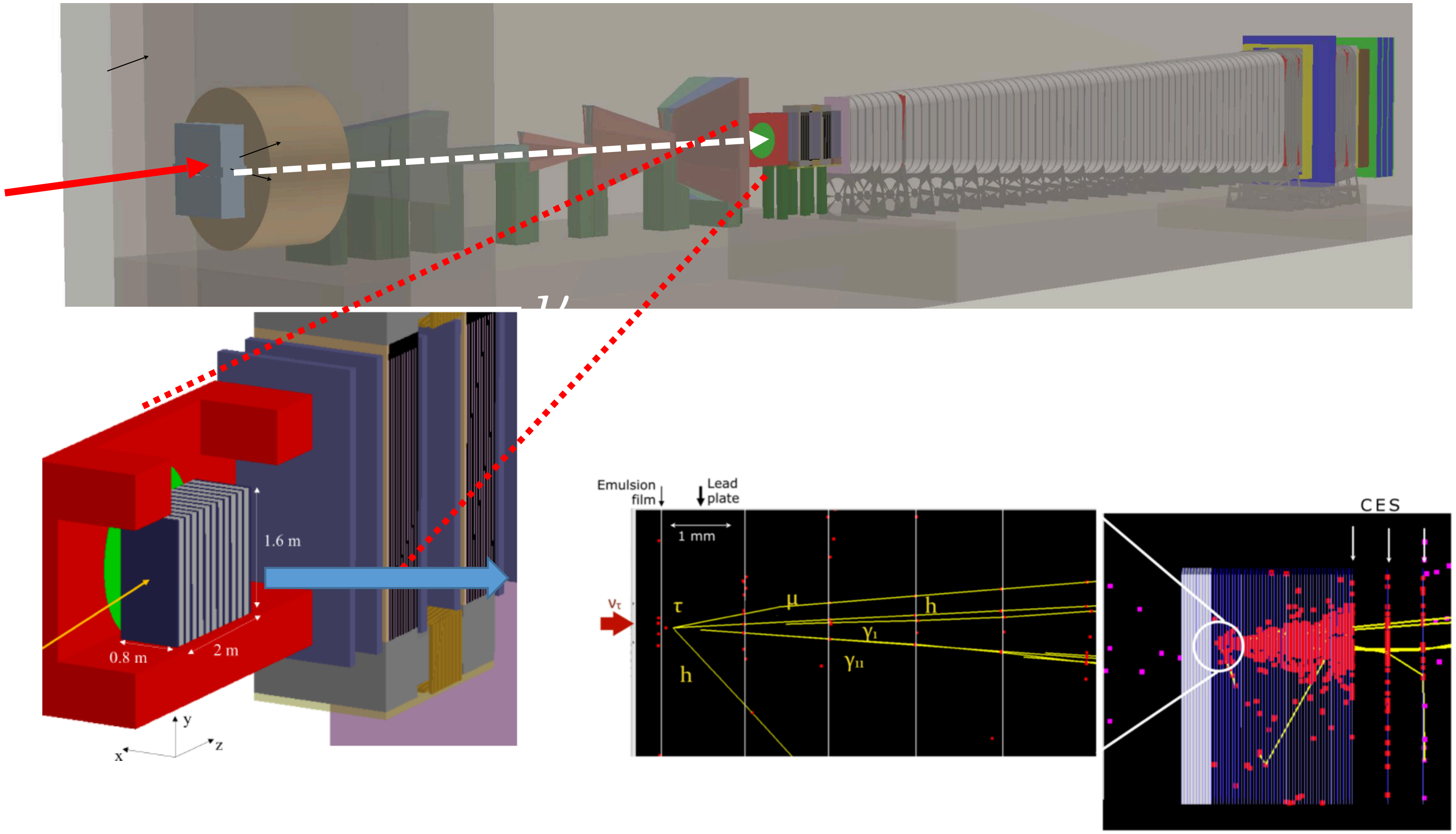


Figure 76: SHiP sensitivity to ALP decaying to two photons

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 with nu-Tau

- First evaluation of F_4 and F_5, not accessible with other neutrinos

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

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

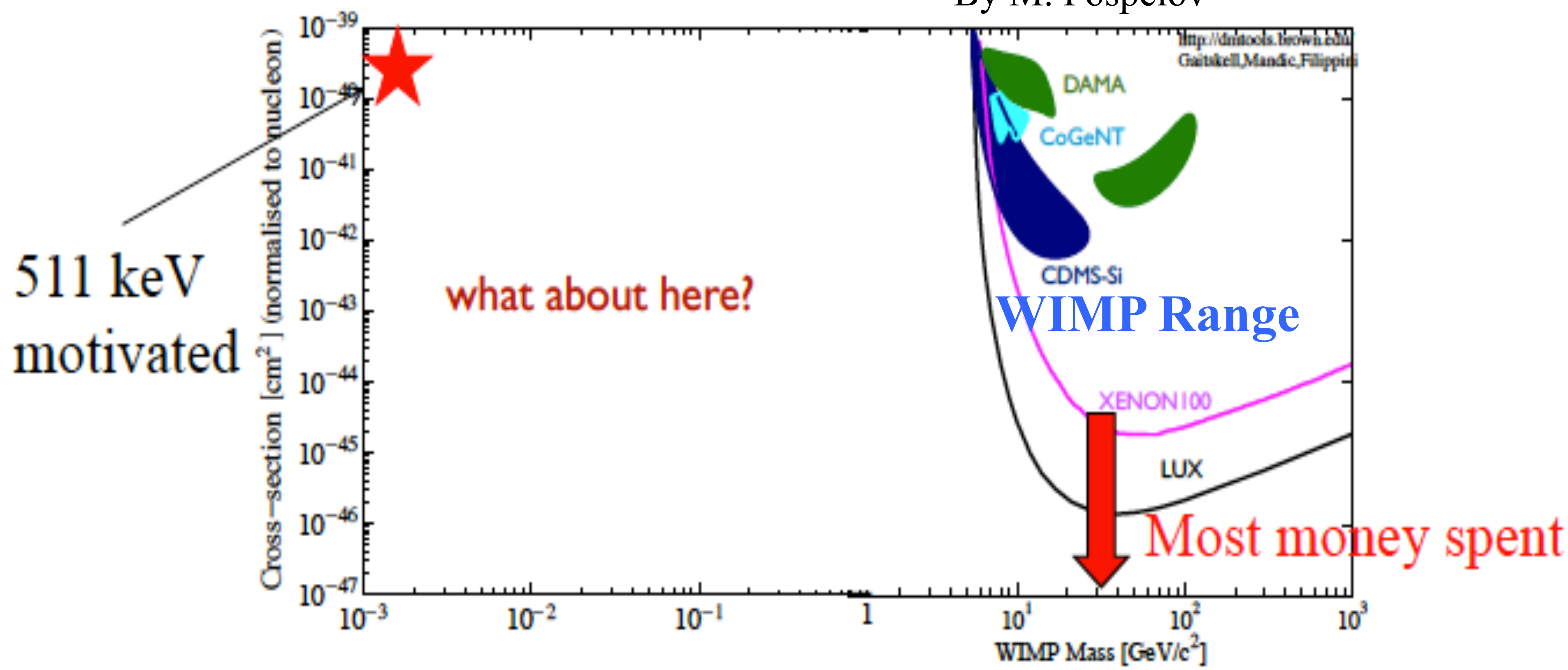
Decay channel	ν_τ	$\overline{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
total	6200	4700

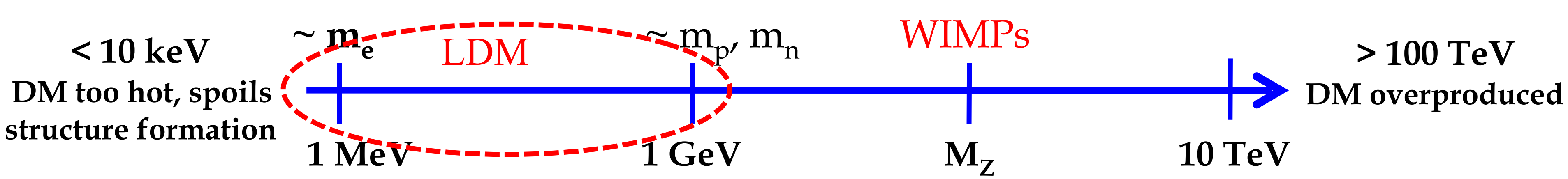
- Determination of the strange quark content of nucleons with charm production
- Test of Lepton Flavour Universality with tau neutrinos
- Search for ν_τ magnetic moment

Light Dark Matter

Mass of Dark Matter particle
$10^{-31} - 10^{20}$ GeV

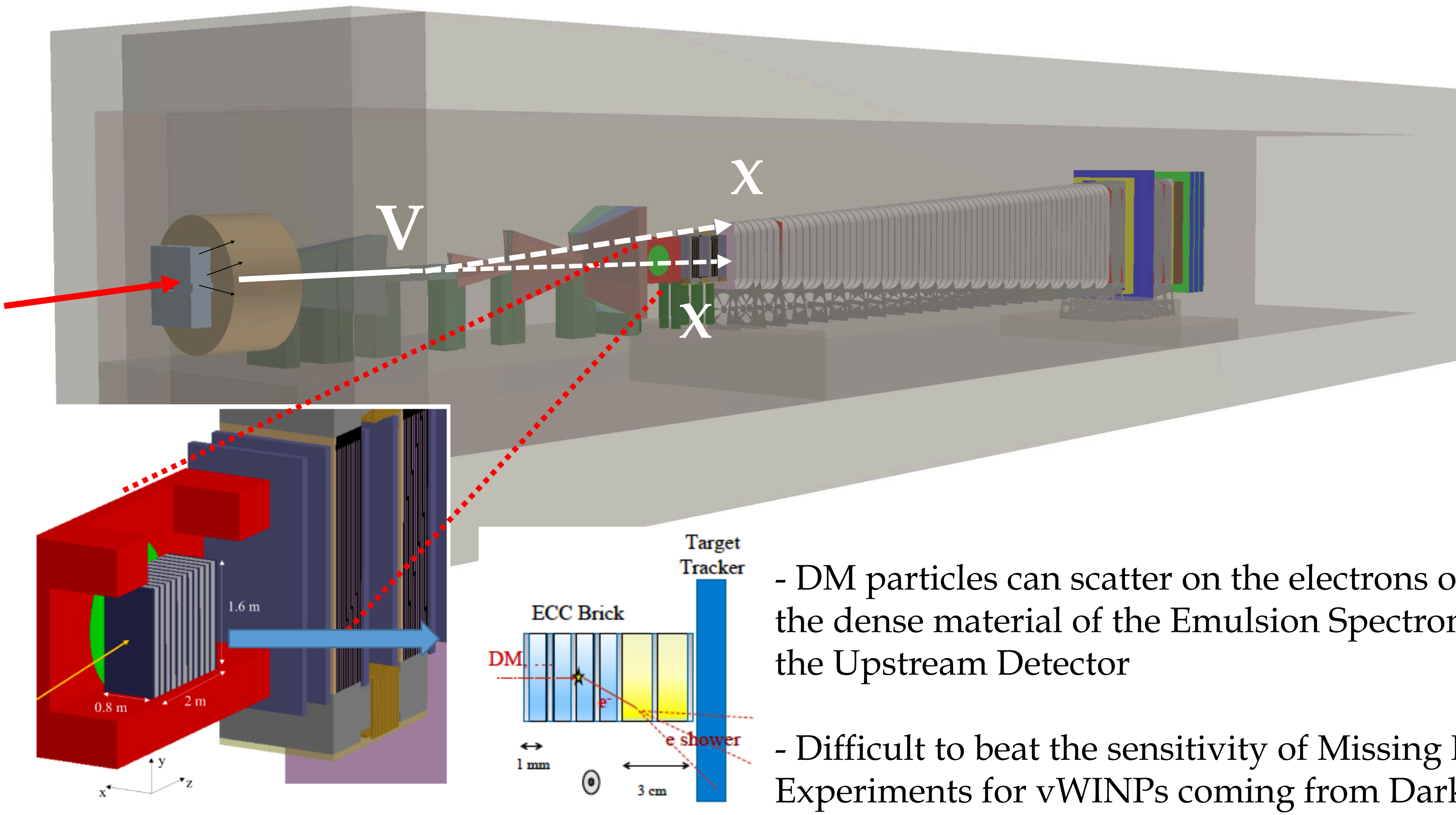
By M. Pospelov





Light mediators must be SM singlet, options limited by SM gauge invariance:
1) Vector Portal; 2) Scalar Portal; 3) Neutrino Portal

Light Dark Matter



- DM particles can scatter on the electrons or nuclei of the dense material of the Emulsion Spectrometer in the Upstream Detector

- Difficult to beat the sensitivity of Missing Mass Experiments for vWINPs coming from Dark Photon, but for other models (e.g. scalar, Zprime) SHiP might have a unique sensitivity

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Project Status

SHiP
Search for Hidden Particles

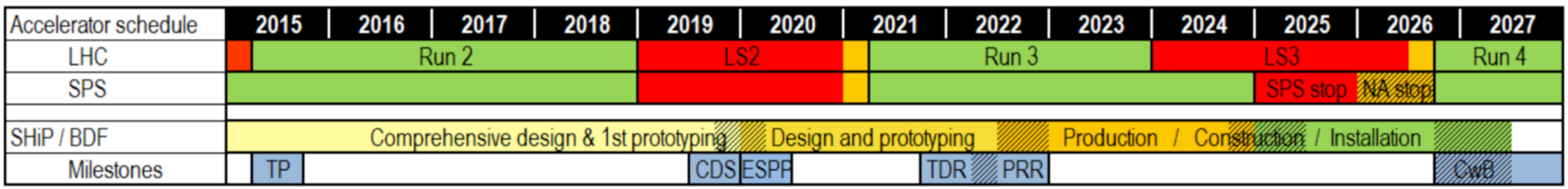


Figure 83: Global project schedule for the Beam Dump Facility and the SHiP detector. CDS, TDR, PRR mark the submission of the Comprehensive Design Study report, submission of Technical Design Reports, and Production Readiness Reviews for the SHiP detector, and CwB marks commissioning with beam.

Validation of bkg

- *Collecting 5x10¹¹ proton to validate the muons flux simulations*
- *Analysis of data in progress*

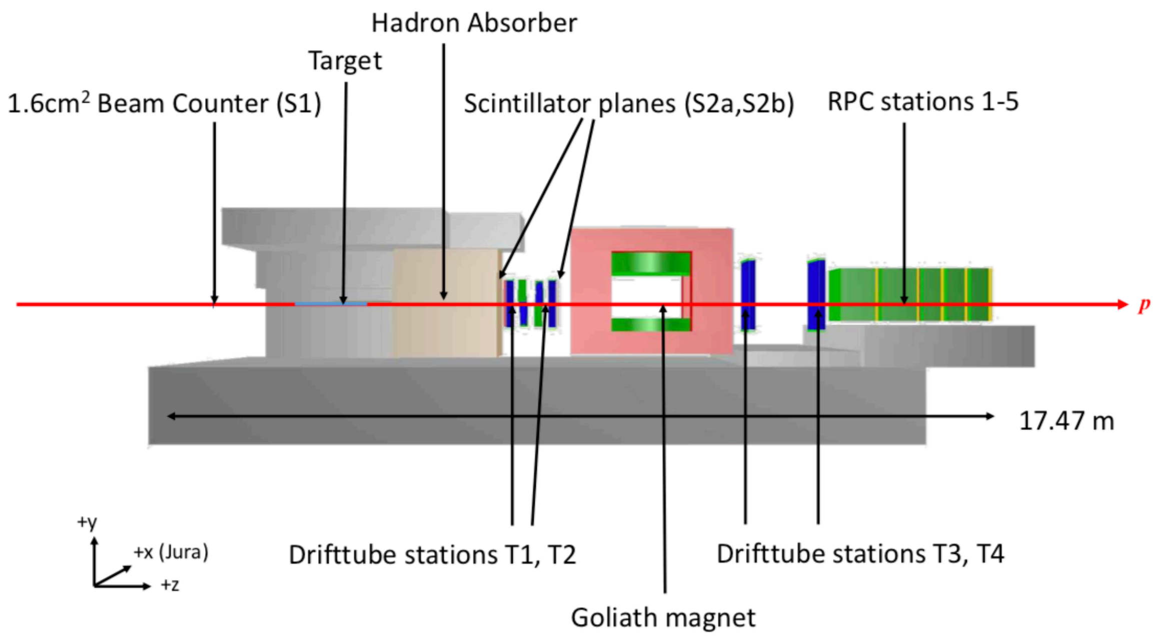


Figure 34: Layout of the spectrometer to measure the μ-flux

Figure 35: Replica of the SHiP target and the experimental setup as seen from behind.

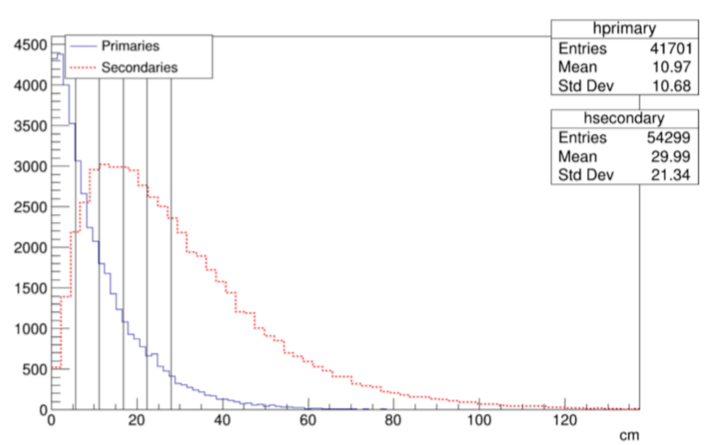


Figure 37: Distribution along the z-axis of charmed hadrons production vertices in a lead target.

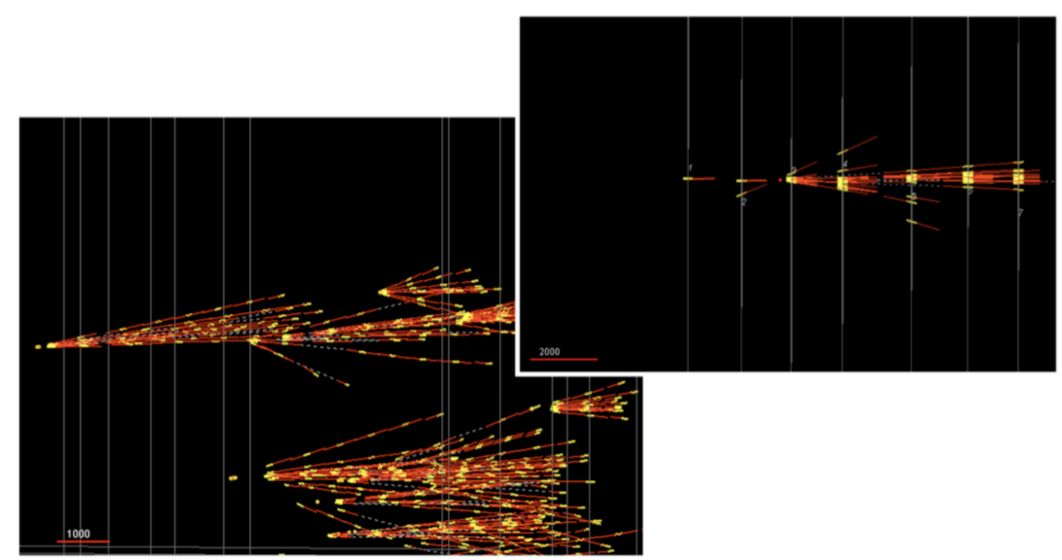


Figure 39: Proton interaction vertices reconstructed in the ECC brick.

TauFV

TauFV: a fixed-target experiment to search for flavour violation in tau decays

C.C. Ahdida[a], I. Bezshyiko[b], A Buonaura[b], M. Calviani[a], J.P. Canhoto Espadanal[a], M. Casolino[a], P. Collins[a], Y. Dutheil[a], B. Goddard[a], A. Golutvin[c], Yu. Guz[d], C. Hessler[a], R. Jacobsson[a], E. Lopez Sola[a], A. Milanese[a], K. Petridis[e], N. Serra[b], L. Shchutska[f], V. Vlachoudis[a], G. Wilkinson[g]

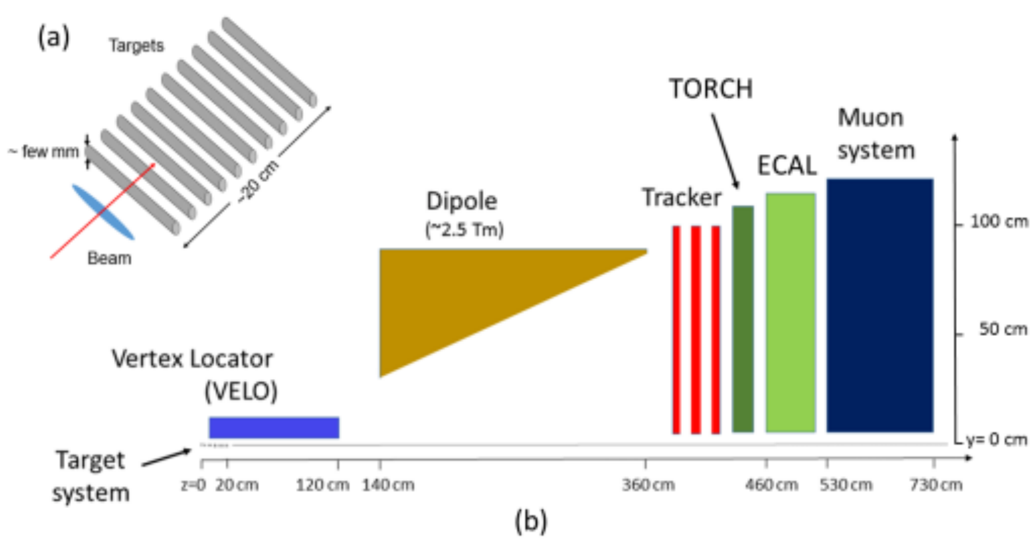


Figure 1: (a) TauFV target system. (b) half-view schematic of the spectrometer.

Experiment	PoT / $\int \mathcal{L}dt$	Yield	Source
TauFV	4×10^{18}	800	/
Belle II	$50\,\mathrm{ab}^{-1}$	1	[11]
LHCb Upgrade I	$50\,\mathrm{fb}^{-1}$	14	[8]
LHCb Upgrade II	$300\,\mathrm{fb}^{-1}$	84	[8]

- The same facility can be used to search for LFV decays of the type $\tau \rightarrow e\,\mu\,\mu$, $\tau \rightarrow 3\mu$, …
- This could allow to set limits below the level of 10^{-10} for these branching ratios

TauFV

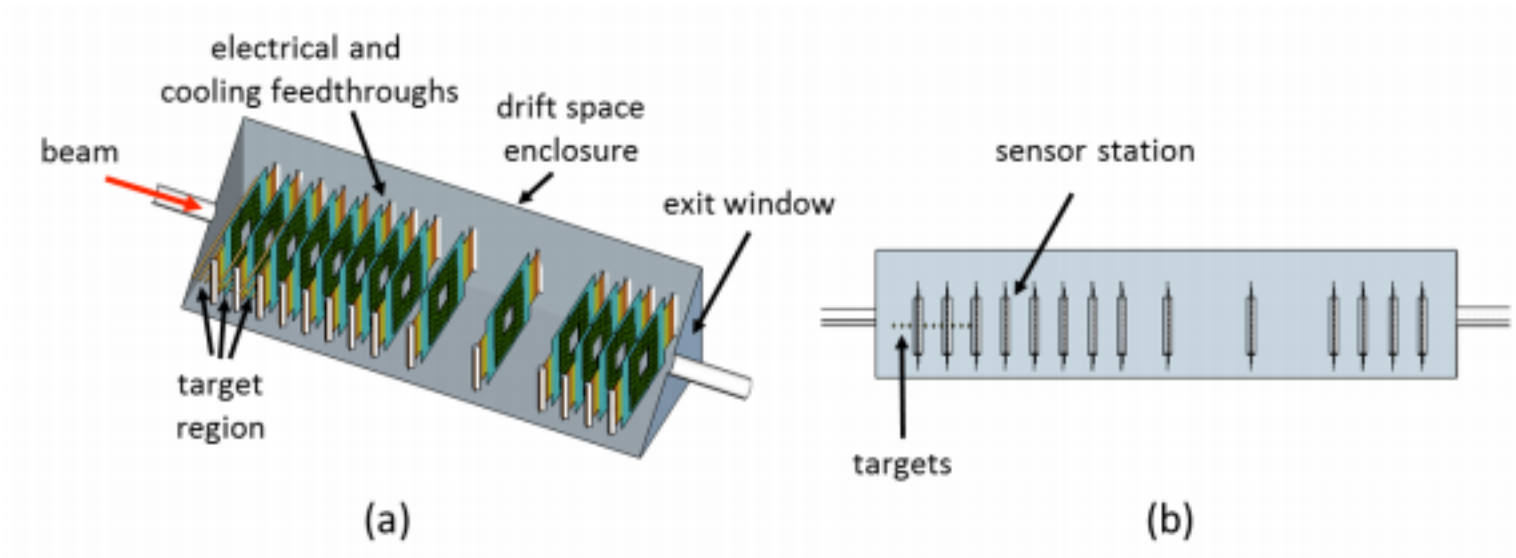


Figure 3: (a): possible layout of the VELO and target region. (b) sideways view.

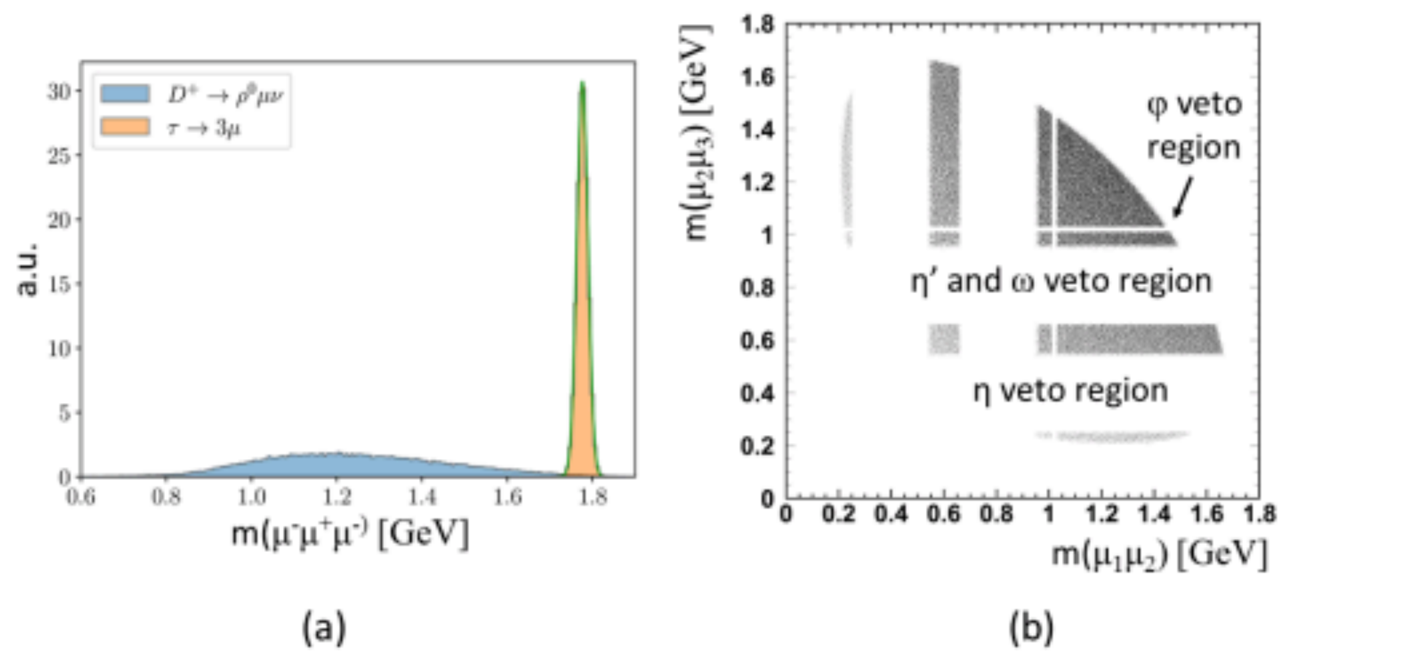


Figure 2: (a) Invariant mass of three-muon system in $D^- \to \rho(\mu^+\mu^-)\mu^-\bar{\nu_\mu}$ and $\tau^- \to \mu^-\mu^+\mu^-$ decays. (b) phase space of $\tau^- \to \mu^-\mu^+\mu^-$ decays, showing possible veto regions.

Other Experiments

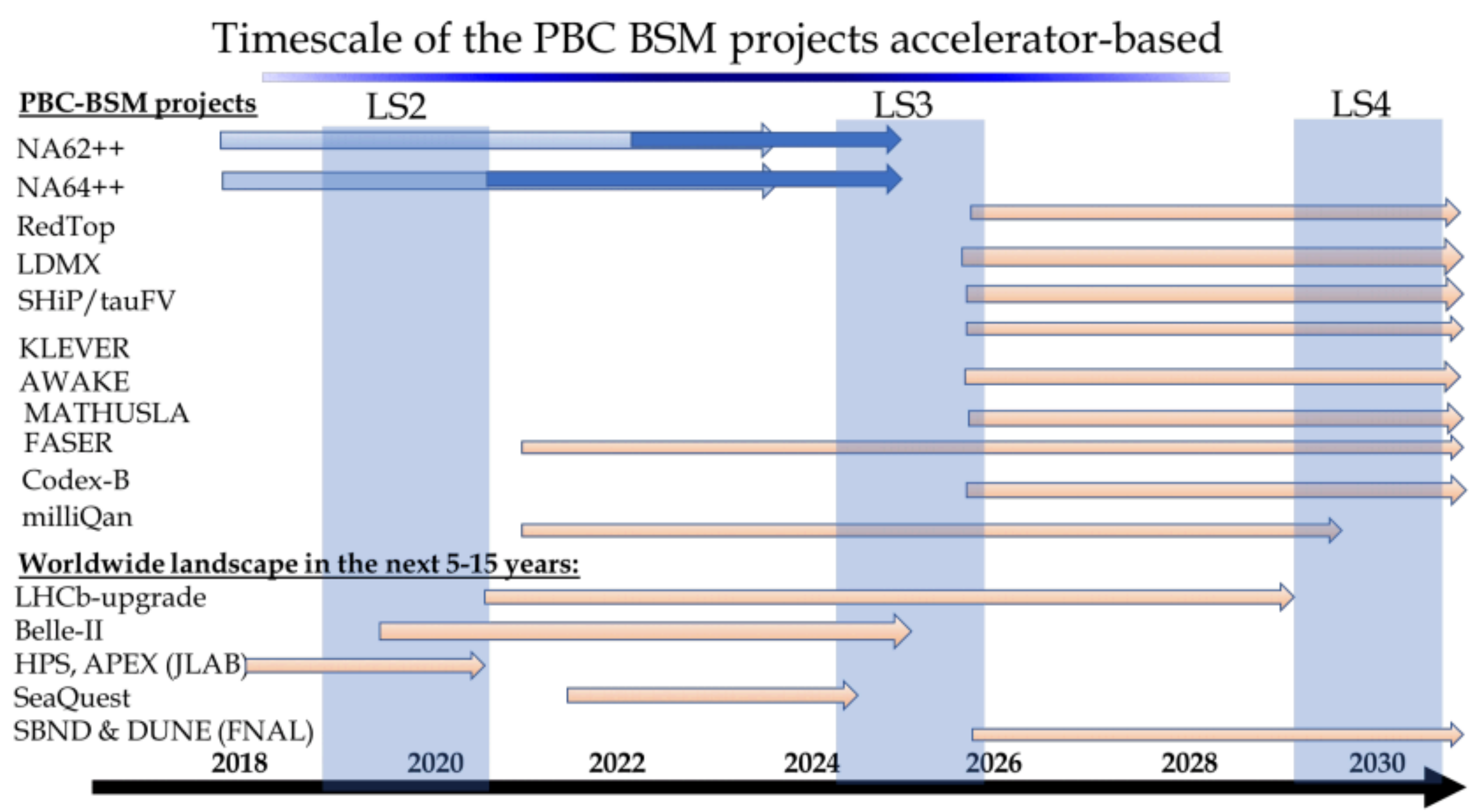
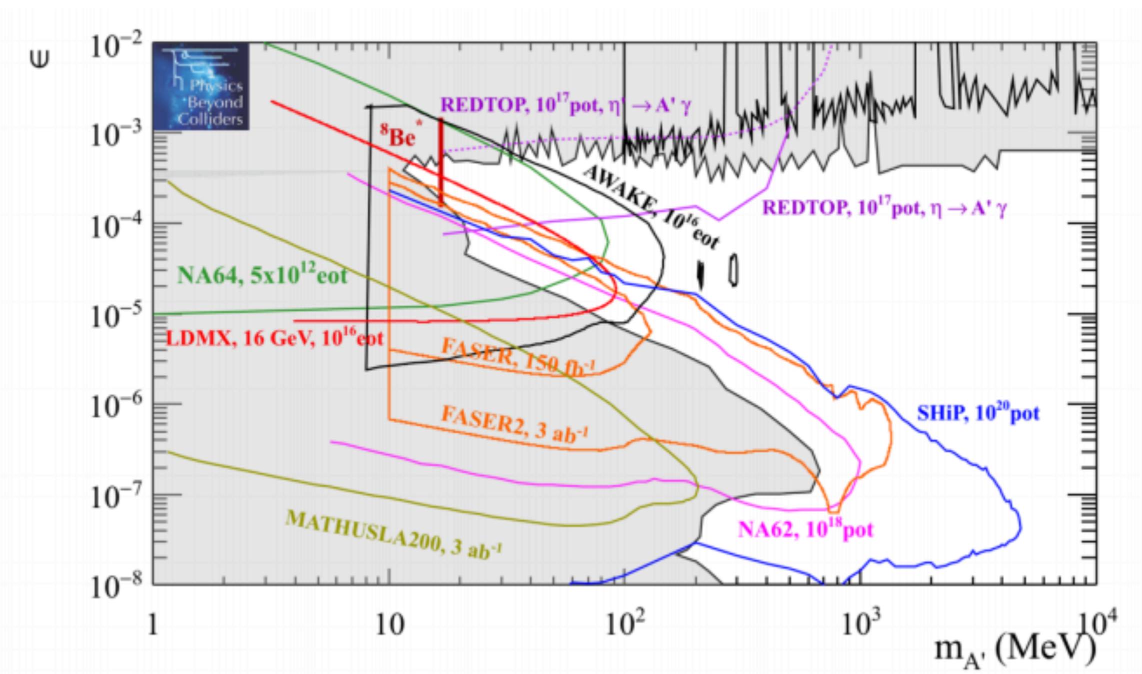
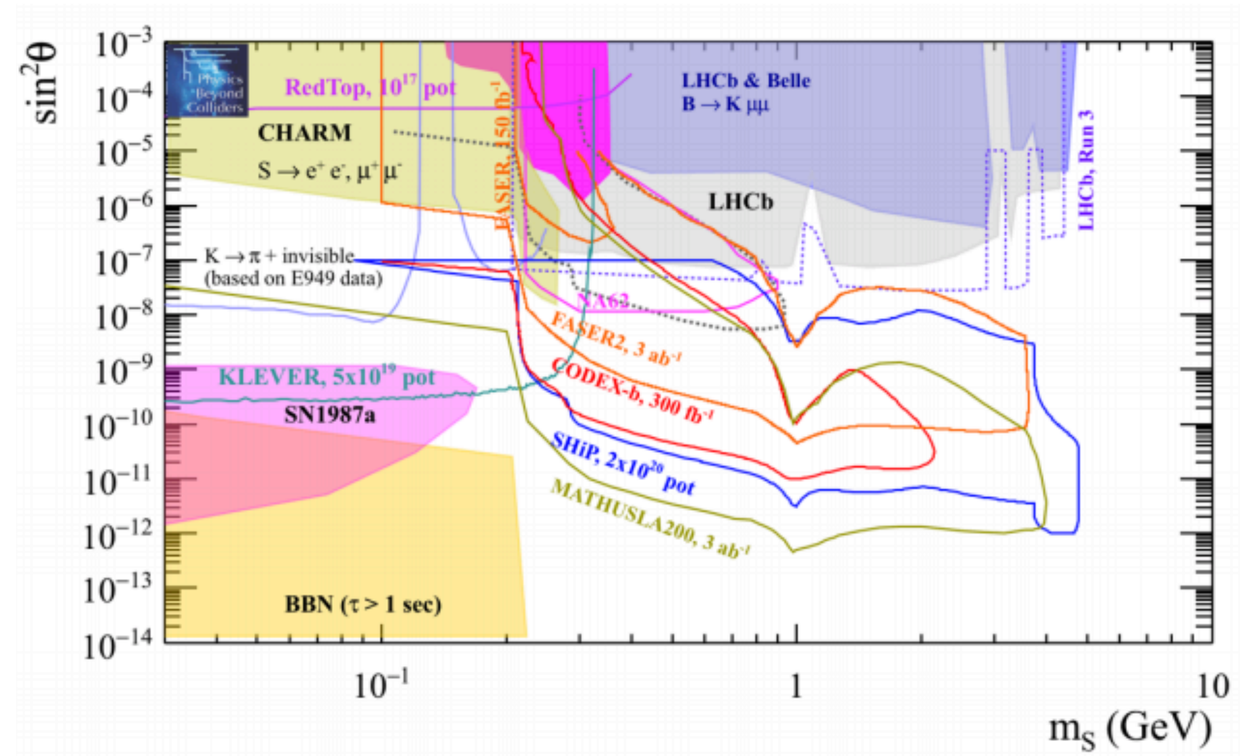
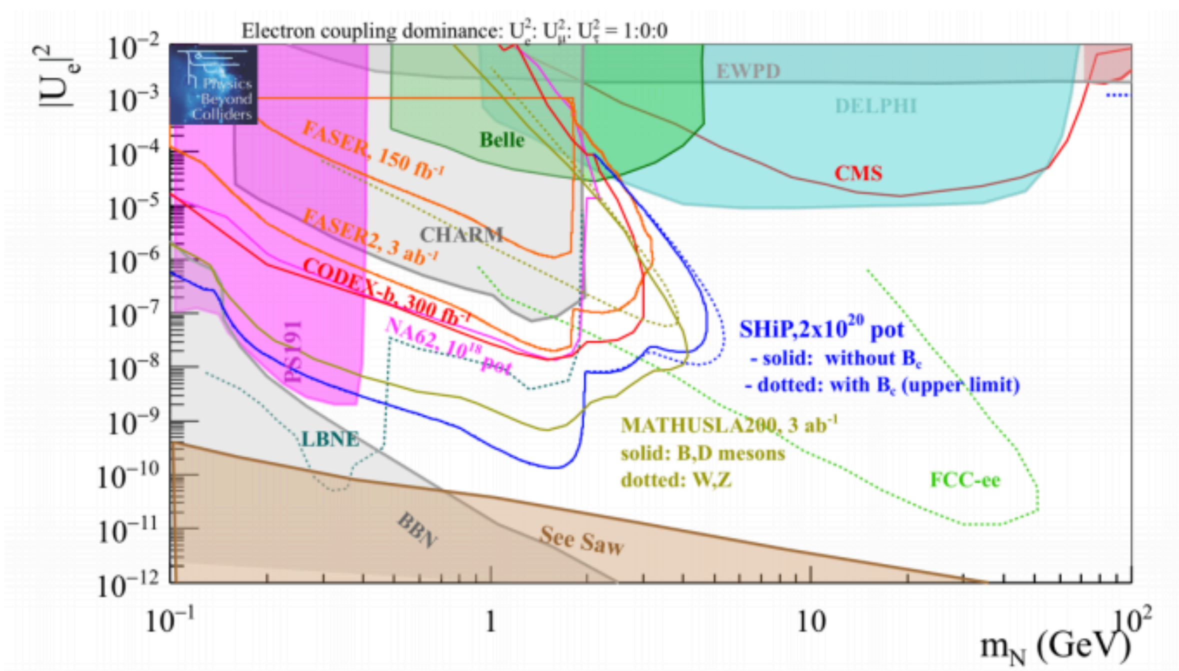


Figure 2: Tentative timescale for PBC projects exploring the MeV-GeV mass range compared to other similar initiatives in the world that could compete on the same physics cases.

Other competing Experiment







- 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

Conclusions

- *Since Naturalness principle is now put into question, searches for relatively light Hidden Particles is attracting large attention in the community*

- *SHiP experiment is designed and optimised for search for these particles in the MeV-GeV region*

- *Main features of SHiP are the redundancy of systems for background rejection: vetos, precise tracking and pointing, invariant mass and particle identification (optimized for discovery)*

- *SHiP can improve by several orders of magnitude current limits for several models with Hidden Particles*

- *The Beam Dump Facility can be used for other relatively low-budget experiments (e.g. TauFV)*