SHiP - Search for Hidden Particles.

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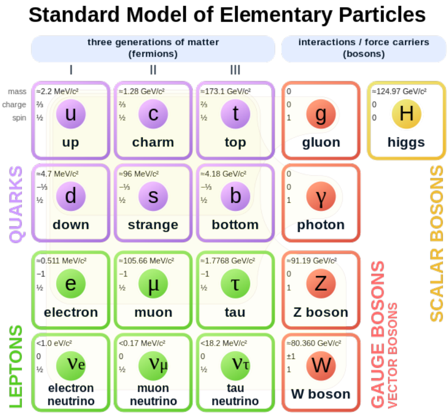
Beyond the Standard Model



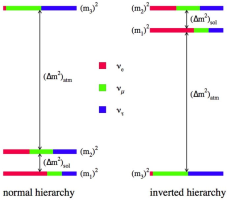
Standard Model of Elementary Particles

	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin					
QUARKS	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
QUARKS	≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
LEPTONS	≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈91.19 GeV/c² 0 1 Z Z boson	GAUGE BOSONS VECTOR BOSONS
LEPTONS	<1.0 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≈80.360 GeV/c² ±1 1 W W boson	

Still missing:

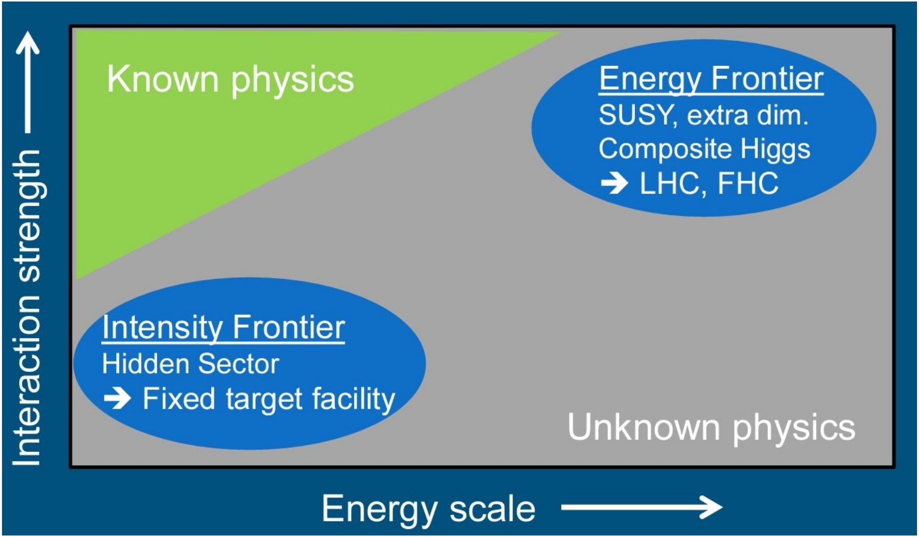
Dark matter

Baryon asymmetry



Neutrino masses

Frontier in particle physics



Known physics

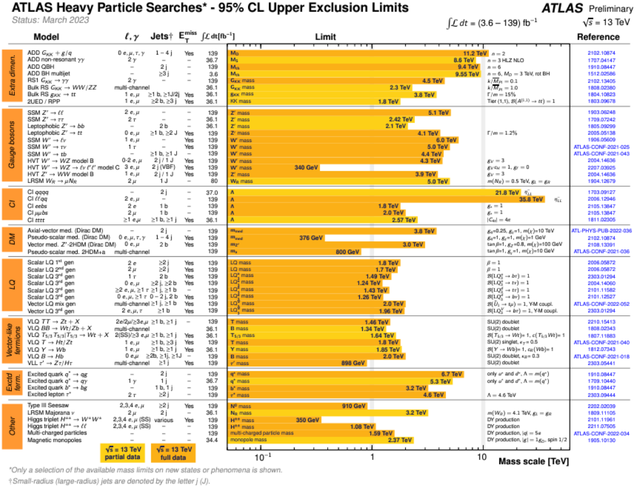
Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC

Intensity Frontier
Hidden Sector
➔ Fixed target facility

Unknown physics

Energy frontier

- Experiments at LHC can directly probe energy frontier: search for particles that are heavy



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 − 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 − 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 3.0 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a 800 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 − 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass 2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T = 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B = 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.08447
	Excited lepton τ^*	2 τ	≥2 j	–	139	τ^* mass 4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^{\pm}W^{\pm}$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

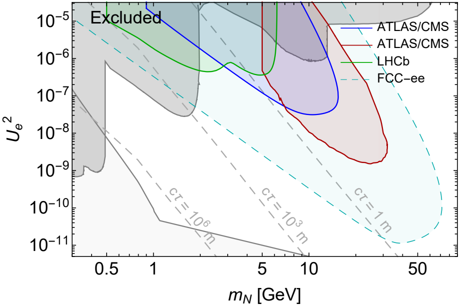
Intensity frontier

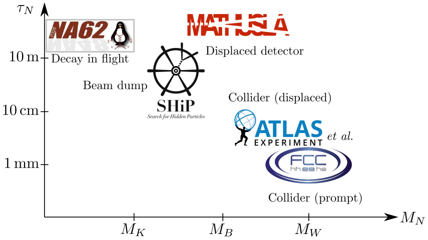
- We may have not observed new particles not because they are too heavy but too feebly coupled to the SM – new physics is suppressed by small dimensionless parameter
- Portals: simple classification of low-energeric parts of NP:
  1. Scalar portal
  $$\mathcal{L}_S = c_1 H^\dagger H S + c_2 H^\dagger H S^2, \tag{1}$$
  2. Fermion portal (HNLs)
  $$\mathcal{L}_N = F_{N\alpha} \bar{N}^c \sigma_2 H^* L_\alpha + \text{h.c.}, \tag{2}$$
  3. Vector portal (dark photons)
  $$\mathcal{L}_V = -\frac{\epsilon}{2} V_{\mu\nu} B^{\mu\nu}, \tag{3}$$
  4. Axion (not renormalizable but phenomenologically attractive) portal
  $$\mathcal{L}_a = \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} \tag{4}$$

Intensity frontier at LHC/FCC

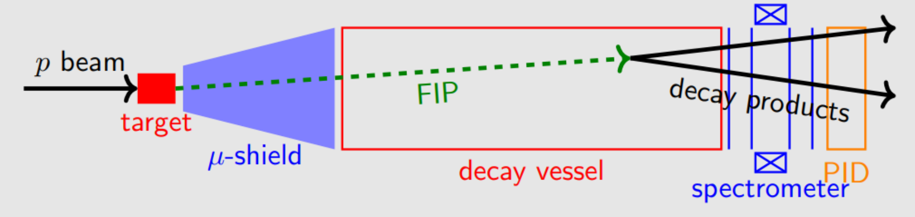
- Feebly interacting particles (FIPs) — large intensity of the experiments
- LHC during high luminosity phase and FCC will collect large integrated luminosity – can probe intensity frontier below ~ 100 GeV
- However, FIPs lifetime $\sim 1/m_{\mathrm{FIP}}^{n}$ ($n = 1 - 5$, depending on portal), so light ~ 1 GeV FIPs may have macroscopic decay length and escape the detectors

- LHC/FCC are not suitable for probing NP at GeV scale

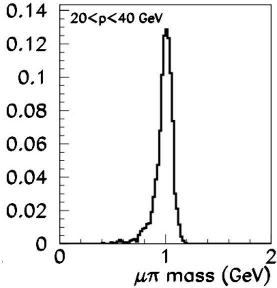




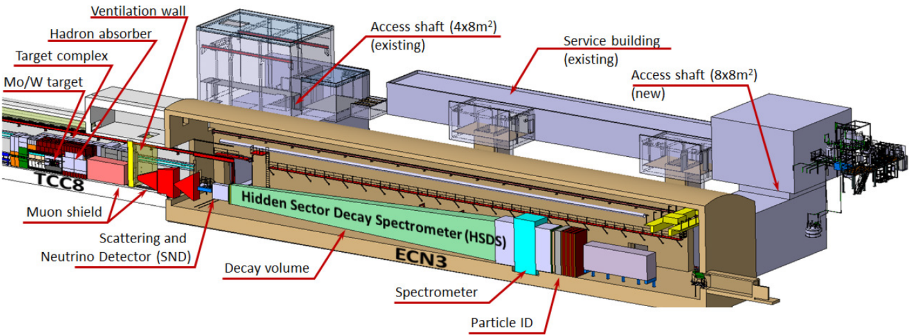
Intensity frontier: BDF



1. BDF experiments may search for all new particles regardless of their nature
2. BDF experiments may measure the properties of new particles - mass, spin, couplings
3. → potentially we can not only find FIPs, but also **probe their connection to BSM problems**!



The SHiP experiment

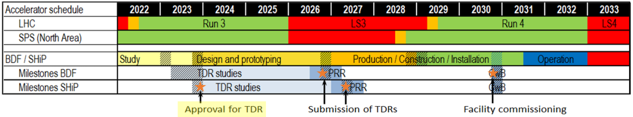


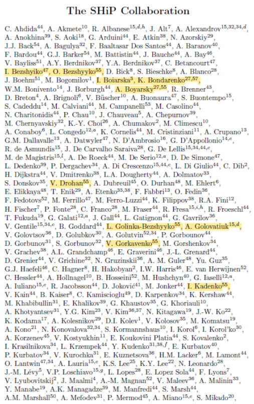
Requirement	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Track pair distance of closest approach	< 1 cm
Track pair vertex position in decay volume	> 5 cm from inner wall
Impact parameter w.r.t. target (fully reconstructed)	< 10 cm
Impact parameter w.r.t. target (partially reconstructed)	< 250 cm

Background source	Expected events
Neutrino DIS	< 0.1 (fully) / < 0.3 (partially)
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon combinatorial	1.2×10^{-2}

[2112.01487]

Overall timeline





The SHiP Collaboration

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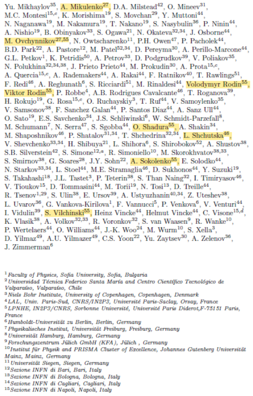

Yu. Mikhaylov[35], A. Mikulenko[27], D.A. Milstead[42], O. Mineev[31],
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L. Uvarov[36], G. Vankova-Kirilova[1], F. Vannucci[5], P. Venkova[6], V. Venturi[44],
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P. Wertelaers[44], O. Williams[44], J.-K. Woo[24], M. Wurm[10], S. Xella[3],
D. Yilmaz[49], A.U. Yilmazer[49], C.S. Yoon[22], Yu. Zaytsev[30], A. Zelenov[36],
J. Zimmerman[6]

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[14] *Sezione INFN di Cagliari, Cagliari, Italy*
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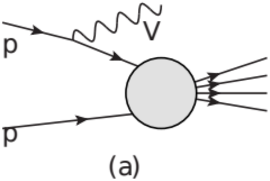
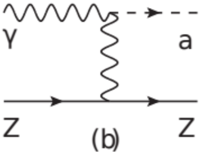
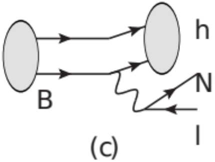
Production of FIPs



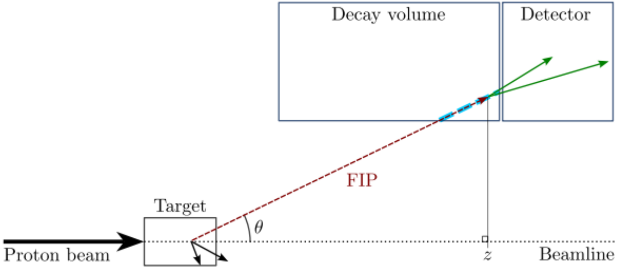
Bremsstrahlung



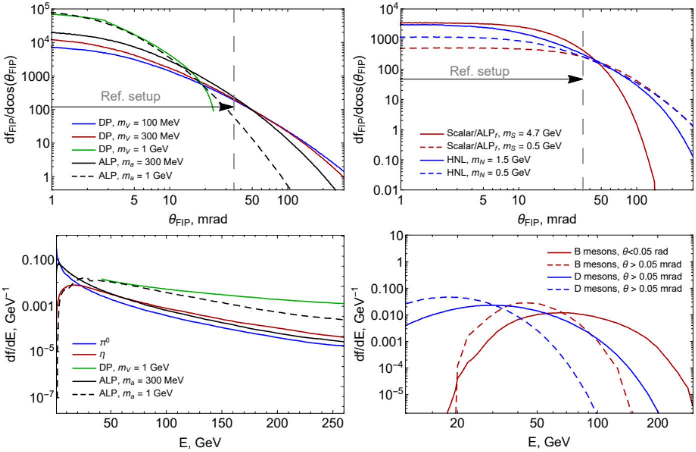
Coherent conversion



Meson decays

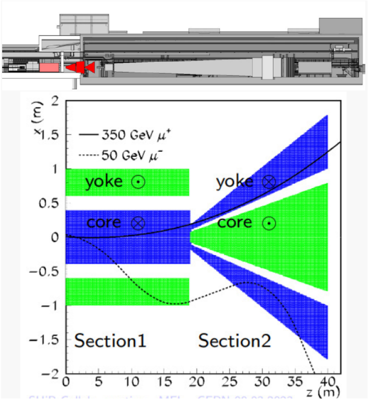


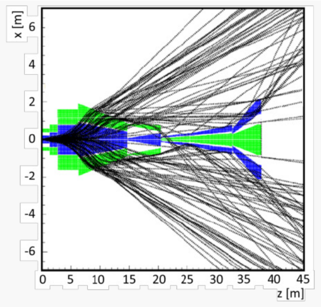
Optimized geometry

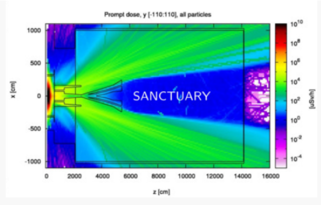


[2304.02511]

Muon shield

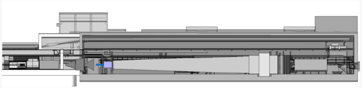


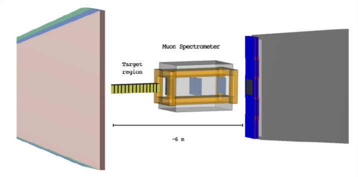


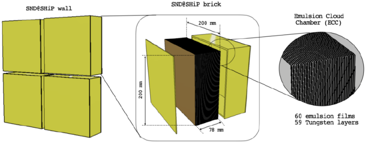


$\sim 10^4 - 10^5$ muon rate suppression
[1703.03612]

SND







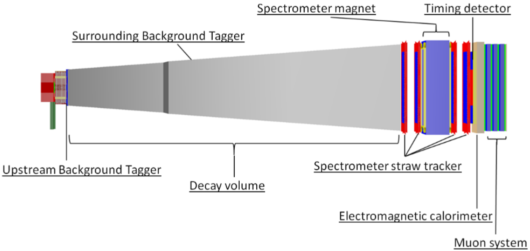
	CC DIS interactions	CC DIS w. charm prod.
N_{ν_e}	8.6×10^5	5.1×10^4
N_{ν_μ}	2.4×10^6	1.1×10^5
N_{ν_τ}	2.8×10^4	1.5×10^3
$N_{\overline{\nu}_e}$	1.9×10^5	9.8×10^3
$N_{\overline{\nu}_\mu}$	5.5×10^5	2.2×10^4
$N_{\overline{\nu}_\tau}$	1.9×10^4	1.1×10^3

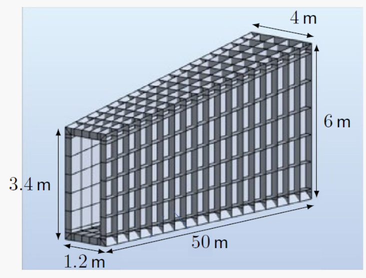
Table 2 Expected CC DIS interactions in the SND assuming 2×10^{20} protons on target.

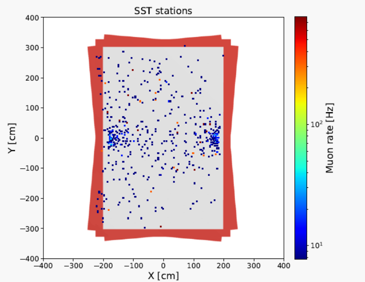
SND

- Heavy target for neutrino interactions
  - First observation of $\bar{\nu}_\tau$
  - ν_τ, $\bar{\nu}_\tau$ physics with high statistics
  - ν_τ magnetic moment
  - F4 and F5 structure functions
  - ν_e cross sections
  - ν-induced charm production
  - strange quark nucleon content
  - LFV
  - LDM via elastic scattering

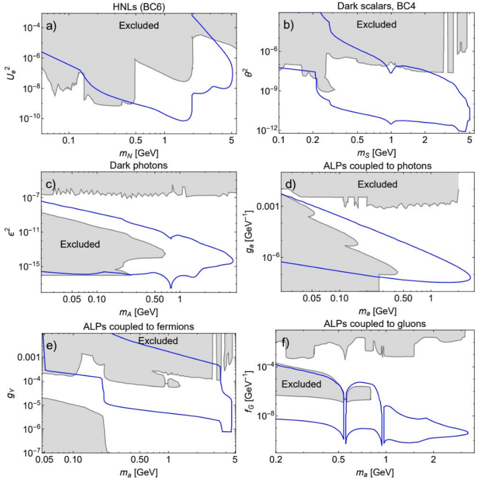
Hidden sector decay volume and spectrometer







SensCalc



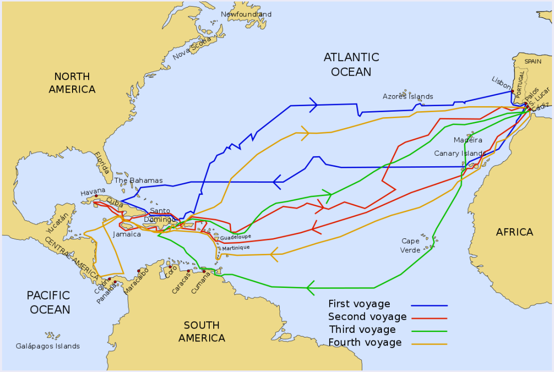
SHiP **may** observe thousands to millions of events

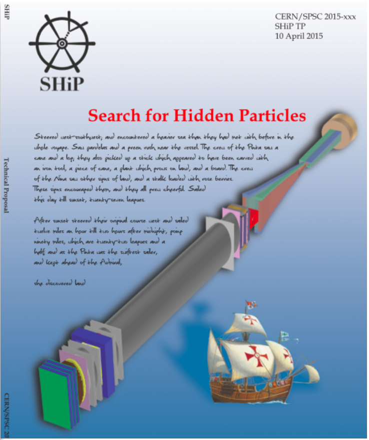
[2305.13383]

SHiP is more than just a signal discovery

SHiP is also a signal exploration machine

Once discovered – properties of new particles can be put to great scrutiny





SHiP

Technical Proposal

CERN/SPSC 20

CERN/SPSC 2015-xxx
SHiP TP
10 April 2015

SHiP

Search for Hidden Particles

Steered west-southwest, and encountered a heavier sea than they had met with before in the whole voyage. Saw pardelas and a green rush near the vessel. The crew of the Pinta saw a cane and a log; they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a plant which grows on land, and a board. The crew of the Nina saw other signs of land, and a stalk loaded with rose berries. These signs encouraged them, and they all grew cheerful. Sailed this day till sunset, twenty-seven leagues.

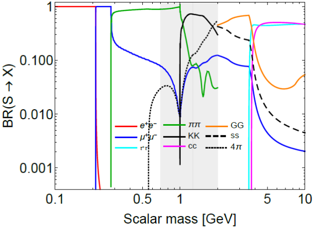
After sunset steered their original course west and sailed twelve miles an hour till two hours after midnight, going ninety miles, which are twenty-two leagues and a half; and as the Pinta was the swiftest sailer, and kept ahead of the Admiral,

she discovered land

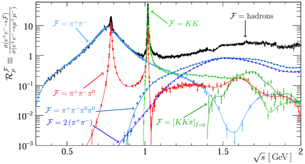
Distinguishing FIPs

Particle	Decay modes
HNL N	$l_\alpha h^\pm$ $l_\alpha l_\beta + \text{inv.}$ $h + \text{inv.}$
Scalar S	$l_\alpha \bar{l}_\alpha, \quad h$
Vector A'	$l_\alpha \bar{l}_\alpha, \quad h$
ALP (γ coupling) a	$\gamma\gamma$
ALP (g coupling) a	h
ALP (f coupling) a	$l_\alpha l_\alpha, \quad h$

With tens of events, one can differentiate between various FIPs based on their decay modes



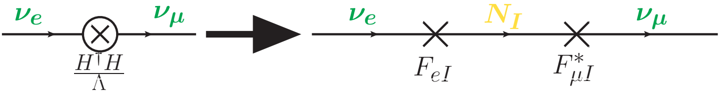
[1904.10447]



[1801.04847]

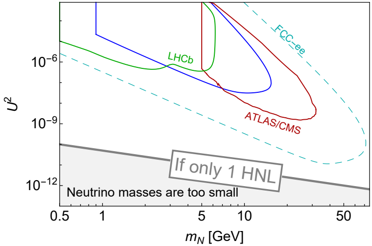
Example: Neutrino Portal and BSM problems. I

- Neutrino oscillation can be described by an effective dimension-5 operator (Weinberg operator). ⇒ new particles (e.g. HNL) are needed:



- Naïvely, to explain neutrino oscillations HNL interacts with SM through small mixing angles $U_\alpha \sim F_\alpha / M_N$ of order

$$U^2_{\text{seesaw}} \equiv \frac{\sqrt{\Delta m^2_{\text{atm}}}}{M_N} = 5 \cdot 10^{-11} \frac{1\ \text{GeV}}{M_N} \tag{5}$$

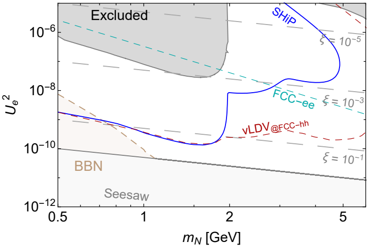


Accelerator experiments do not have enough sensitivity to probe so small mixing angles. **Does it mean that we cannot probe oscillations?**

Example: Neutrino Portal and BSM problems. II

- To explain oscillation data (two mass differences in active neutrino) at least two HNLs are needed
- In this case, mixing angle $U^2 \gg U^2_{\text{seesaw}}$ can exist, but they require approximate symmetry between HNLs. The difference between HNL parameters should be:

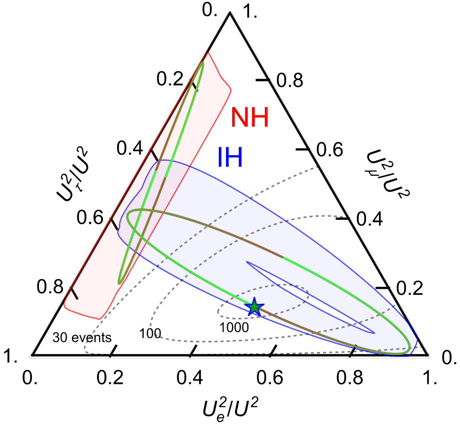
$$M_1 U_1^2 - M_2 U_2^2 \sim \sqrt{\Delta m^2_{\text{atm}}} \tag{6}$$



$$\sqrt{M_I}\theta_{\alpha I} = i\left[U^{\text{PMNS}}\begin{pmatrix}\sqrt{m_1} & 0 & 0\\ 0 & \sqrt{m_2}e^{i\eta} & 0\\ 0 & 0 & \sqrt{m_3}\end{pmatrix}R_{2\times 3}(\omega)\right]_{\alpha I}$$

Neutrino masses from **two HNLs**

- Neutrino masses can be explained with **only two** HNLs.
- Small coupling — total U^2, internal couplings — mixings with lepton flavours $x_\alpha = U_\alpha^2/U^2$

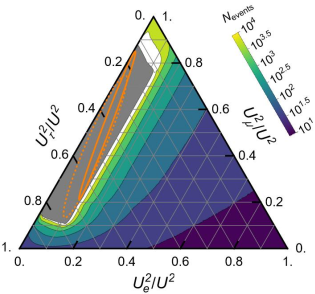


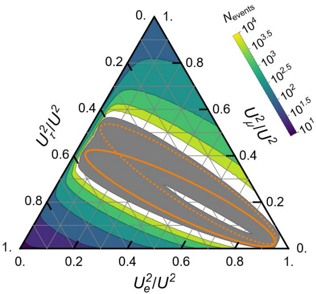
→

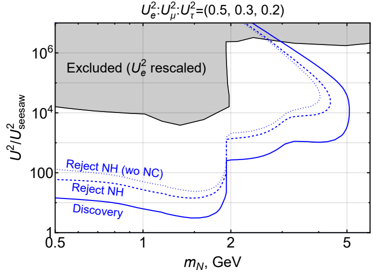
Measure flavour couplings x_α

↓

Test two HNLs hypothesis





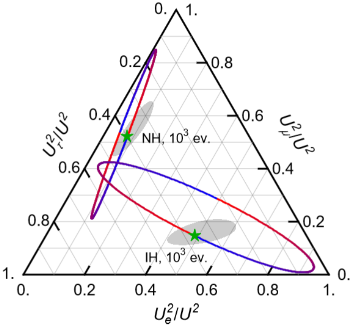


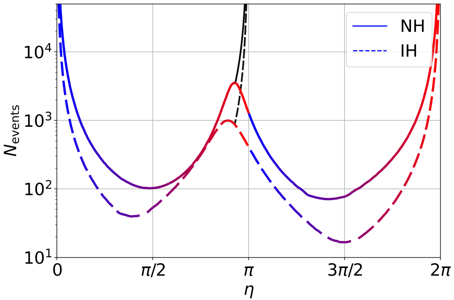
With SHiP sensitivity reach, it is possible to reject minimal 2-HNL model

[2312.00659]

[2312.05163]

Measuring Majorana phase

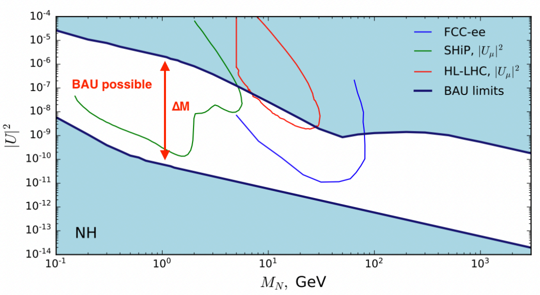




With $\gtrsim 100$ event, it is possible to constrain the Majorana phase $\eta \rightarrow$ independent prediction of $m_{\beta\beta}$ and for $0\nu\beta\beta$ experiments

Probing Baryon Asymmetry of the Universe

- Same HNLs that are responsible for neutrino oscillations can generate **baryon asymmetry of the Universe**
- Baryon asymmetry also demands *at least* 2 HNLs with **almost degenerate masses**: $\Delta M = |M_1 - M_2| \ll M_1, M_2$ and have the same mixing angles:



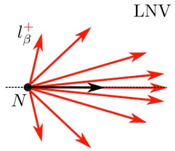
$$U^2_{\alpha 2} = U^2_{\alpha 1}\left[1 + O\left(\frac{\Delta M}{M_N}, \frac{U^2_{\text{seesaw}}}{U^2}\right)\right] \tag{7}$$

Can we understand that we observed such HNLs?

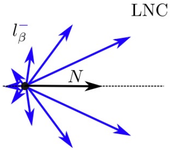
Distinguishing two HNLs?

- Two HNLs with similar masses $\Rightarrow$ **HNL oscillations**
- Ratio of probability of lepton number violating (LNV) and conserving (LNC) processes:

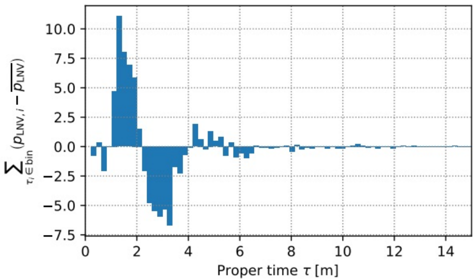
$$\frac{P_{\text{LNV}}}{P_{\text{LNC}}} \sim \frac{1-\cos\Delta M\tau}{1+\cos\Delta M\tau} \qquad \tau\text{– HNL proper time} \qquad (8)$$



$$\langle E^{(H)}_{l_\beta,\text{LNV}}\rangle \gtrsim \langle E^{(H)}_{l_\beta,\text{LNC}}\rangle$$



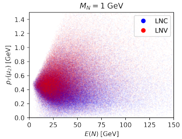
- Kinematics of LNV and LNC decays is statistically different



✓ SHiP can resolve HNL oscillations [1912.05520]

✓ Needs $\mathcal{O}(10^3)$ events – middle of the exploration region

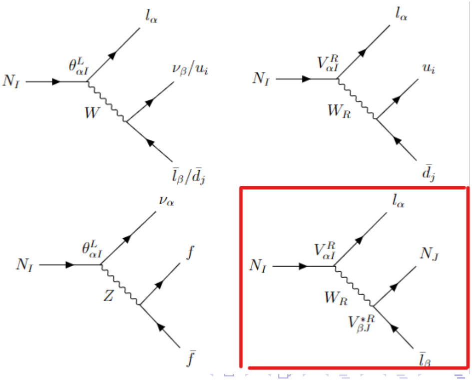
✓ Oscillation period: $2\pi/\Delta M$



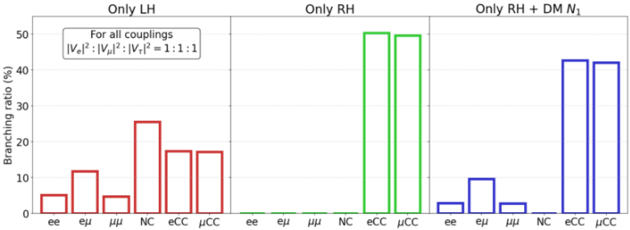
Dark matter at SHiP

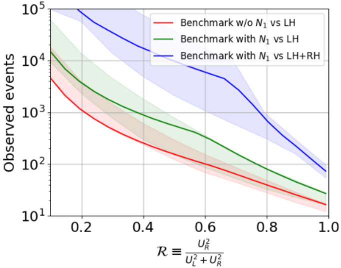
- Two HNLs N_2, N_3 solve neutrino masses and BAU
- One separate light (keV) N_1 can be cosmologically stable — **dark matter**
- Processes with N_1 AND $N_{2,3}$ are doubly suppressed — search for N_1 is not feasible

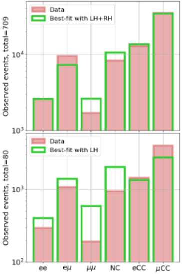
- New interactions: HNLs in Left-Right Symmetric Model
- Two "small couplings": U_L and $U_R = m_W^2 / m_{W_R}^2$



Dark matter at SHiP

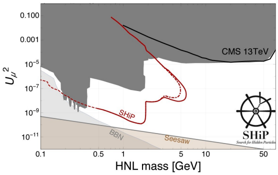


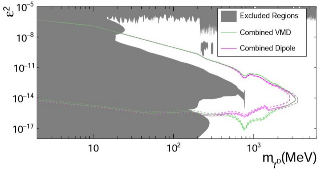


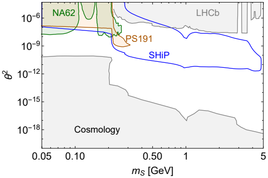


[2406.XXXX]

SHiP: not one channel but frontier







1. SHiP can observe new physics directly
2. SHiP does not study some specific channel — it can explore the whole intensity frontier to $\sim m_B$ masses, push the constraints by orders of magnitudes for a generic model with light FIPs
3. . . . and potentially resolve the BSM problems!
   inflation, complex higgs sector, dark matter, cosmological axions. . .

Summary

- Energy frontier is quite explored already and is going to be explored even more at FCC
- Still no physics found – need to search for heavy physics in rare processes — effective operators
- Intensity frontier — not explored. A single experiment can explore the whole frontier, probing various models
- BDF can directly observe new physics particle and measure its properties
- Finally, BDF can probe connections of the new physics to BSM problems