FIMPs @ SHiP

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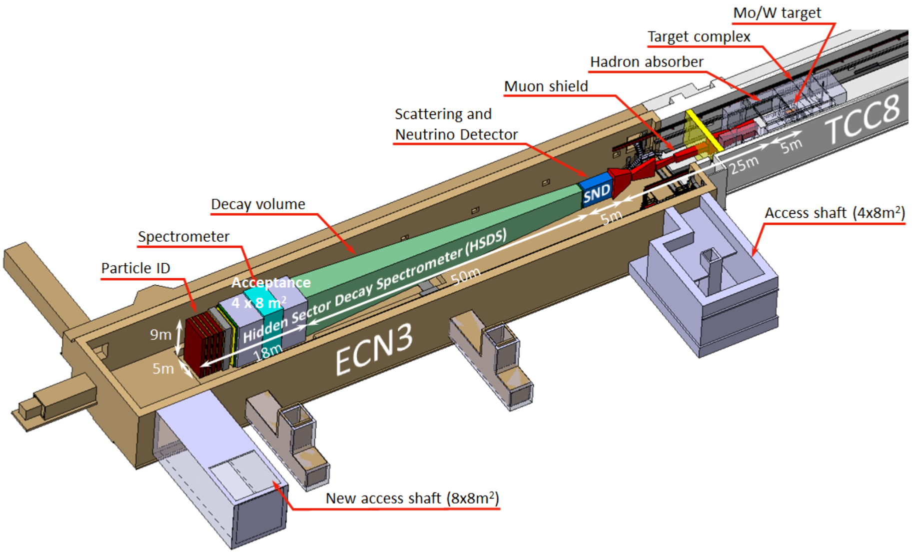
Scientific Session devoted to 70th V.A.Rubakov Anniversary
Nuclear Physics Division, Physics Department of RAS

RAS, Moscow, Russia

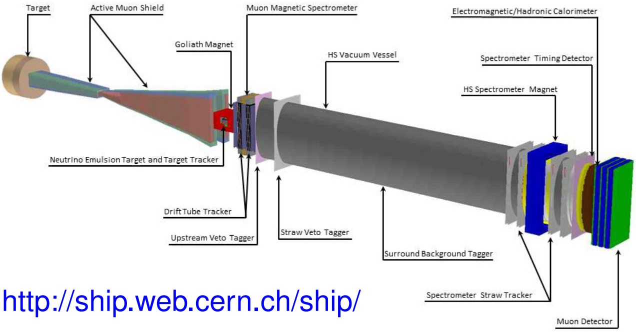


Mo/W target
Target complex
Hadron absorber
Muon shield
Scattering and
Neutrino Detector
Decay volume
Spectrometer
Particle ID
Acceptance
4 x 8 m²
Hidden Sector Decay Spectrometer (HSDS)
SND
9m
5m
18m
50m
5m
25m
5m
TCC8
ECN3
Access shaft (4x8m²)
New access shaft (8x8m²)

Towards a dedicated experiment

- νMSM: T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005),
- direct tests of νMSM: D.G., M.Shaposhnikov (2007)
- proposal for direct searches, to European Strategy Group, 2012 D.G., M.Shaposhnikov
- sketch of realistic experiment S.Gninenko, D.G., M.Shaposhnikov (2013)
- Expression Of Interests: Proposal to Search for Heavy Neutral Leptons at the SPS
  W. Bonivento, . . . D.G., et al, 1310.1762
- Technical Proposal and Physics Paper 1504.04956, 1504.04855
- included in the CERN GreyBook (2016) approved in 2024 !! 46 institutes from 16 countries

SHiP
Search for Hidden Particles



http://ship.web.cern.ch/ship/

Standard Model + GR : Major Problems

Gauge and Higgs fields (interactions): γ, $W^{\pm}$, Z, g, G, and h

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes all experiments dealing with
  - electroweak and strong interactions
- Does not describe

(PHENO)

- Neutrino oscillations
- Dark matter (Ω_{DM})
- Baryon asymmetry (Ω_B)
- Why the Universe is flat and homogeneous?
- Where did the matter perturbations come from?

(THEORY)

- Dark energy (Ω_Λ)
- Strong CP-problem
- Gauge hierarchy
- Quantum gravity
- Quantization of electric charge
- Why 3 generations?
- Why $Y_e \ll Y_\mu \ll .. \ll Y_t$

Also, generally, we have anomalies...

- LEP (95 GeV in $b\bar{b}$), CMS + ATLAS ($\gamma\gamma$, $\tau^+\tau^-$)
- $B \to (K, K^*)\tau^+\tau^-$, ... $B \to K\pi\pi$, etc
- muon $g-2$ ... gone?
- LSND, MiniBooNE, reactor (gone?), Gallium, etc
- Superheavy BH in the present galaxies, in the ealy galaxies, BH binaries, etc
- GW-signal in Pulsar Timing Arrays...
- Extragalactic magnetic fields...

Light NP: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar X

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta H^\dagger H X^\dagger X - \mu H^\dagger H X$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

  hidden photon

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Most natural example: coupling to inflaton

Chaotic inflation, A.Linde (1983), A.Linde (1984)

If $V(\phi)$ dominates by chance

$$\ddot{\phi} - \Delta\phi/a^2 + 3H\dot{\phi} + V'(\phi) = 0$$

for power-law potential at $\phi > M_{Pl}$

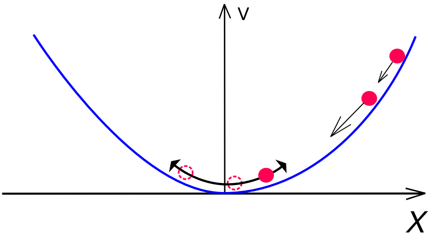
$$V \simeq \text{const}$$

"slow roll" solution

$$H^2 = \frac{8\pi}{3M_P^2} V(\phi)\;, \quad a(t) \propto e^{Ht}$$

valid while slow roll conditions

$$M_P^2 \frac{V''}{V} \ll 1\;, \quad M_P^2 \frac{V'^2}{V^2} \ll 1$$



$$-\beta H^\dagger H X^2 - \mu H^\dagger H X$$

Inflaton must couple to Standard Model fields to reheat the Universe after inflation

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{SM} + \mathscr{L}_{ext} + \mathscr{L}_{grav}\right),$$

$$\mathscr{L}_{ext} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2\right)^2,$$

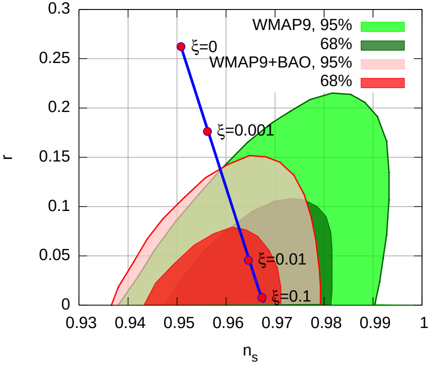
$$\mathscr{L}_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda\theta^2}}.$$

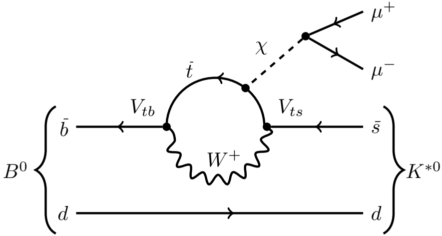
phenomenology is fixed by
mixing with Higgs

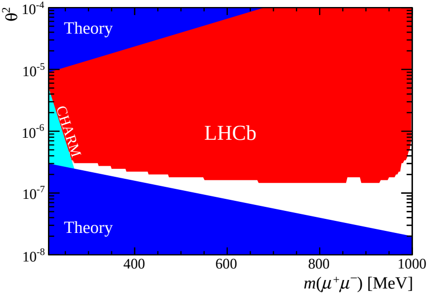
$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$

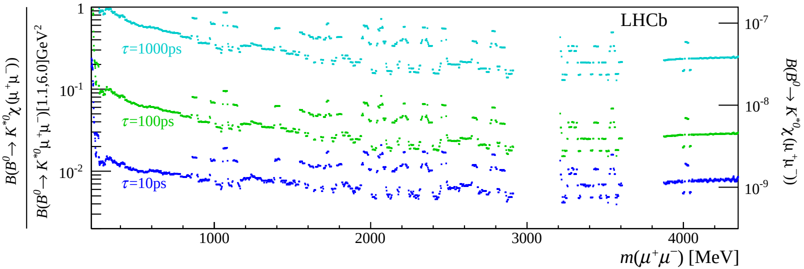


Limits from LHCb

1508.04094







Sterile neutrinos or Heavy Neutral Leptons

Most general renormalizable with 2(3...) right-handed neutrinos N_I

$$\mathscr{L}_N = \overline{N}_I i \partial\!\!\!/ N_I - f_{\alpha I} \overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2} \overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to ^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H \rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total

18: $N = 3$ sterile neutrinos:

- 3: Majorana masses M_{N_I}
- 15: New Yukawa couplings $f_{\alpha I}$ which form
  - 3: Dirac masses $M^D = f\langle H \rangle$
  - 3+3: mixing angles
  - 3+3: CP-violating phases

9 new parameters in total

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01$ eV

Sterile neutrino: a vast region of mass

Within the seesaw paradigm, as far as

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

Any set

(mass scale M_N, Yukawa coupling f)

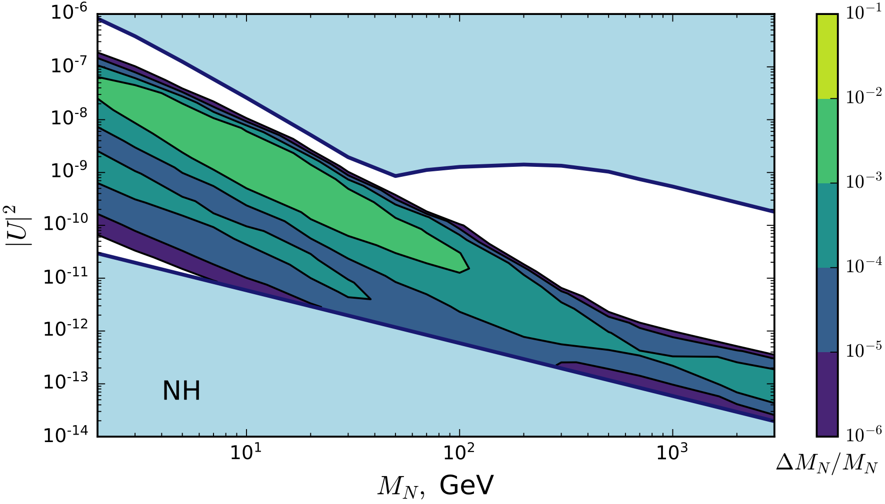
is viable

And with special tunning or symmetry larger (but not smaller) mixing
3 sterile neutrinos is viable

$$\hat{m}_a \sim \hat{f}^T \frac{1}{\hat{M}_N} \hat{f} v^2$$

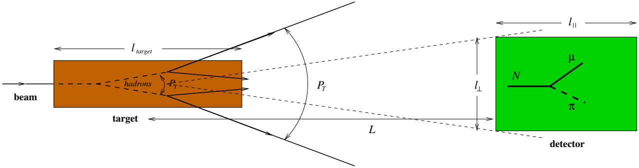
Progress in Leptogenesis (no update on DM)

2008.13771



Fixed target and similar

However for the feebly coupled light particle best place to show up is the intensity frontier   fixed target experiment



Variations and specifics

- dedicated (e.g. NA64) or working as by-product (e.g. T2K, DUNE)
- thin target (e.g. T2K, DUNE) or dump (e.g. NA64)
- decays or hits as the signature
- production by cosmic rays
- ...

Searches for sterile neutrino dark matter

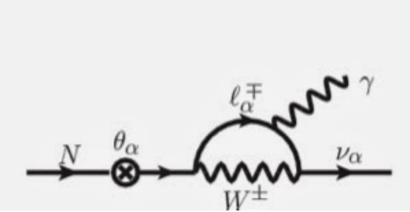
$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe if

$$\frac{\theta^2}{3\times 10^{-3}} < \left(\frac{10\,\text{keV}}{M_N}\right)^5$$

- DM sterile neutrinos can be searched at X-ray telescopes because of two-body radiative decay

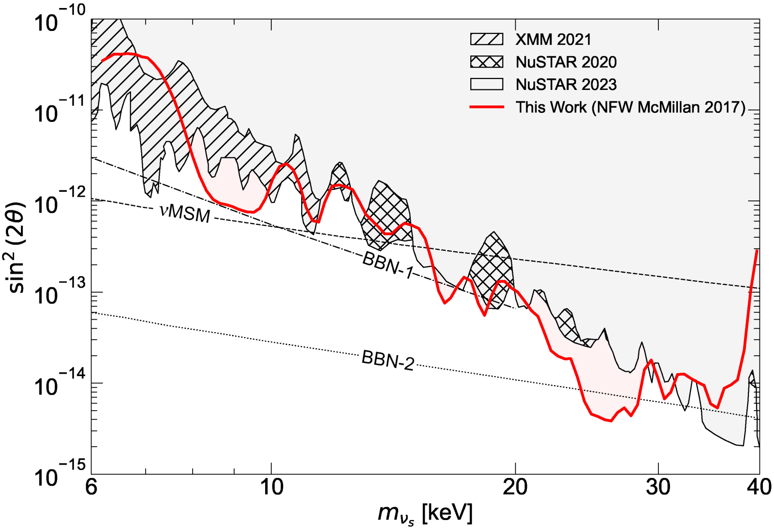
give limits in absence of the feature



a narrow line $(\delta E_\gamma / E_\gamma \sim v \sim 10^{-3})$
at photon frequency $E_\gamma = M_N/2$

$$\frac{\theta^2}{10^{-11}} \lesssim \left(\frac{10\text{ keV}}{M_N}\right)^4$$

if redistributed equally... two different codes: `sterile-dm` and `dmpheno`



2405.17861

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

e.g. with Dark matter Ψ

0711.4866

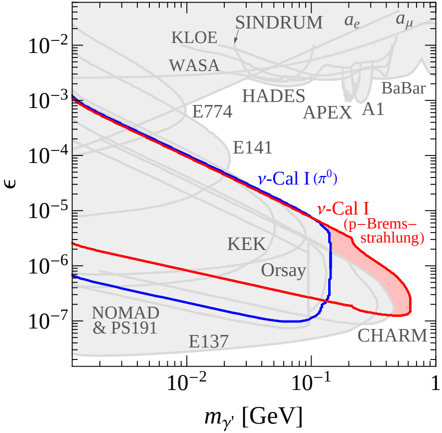
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu \partial_\mu - e'\,\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1\,\text{GeV}$

- limit from BBN:

$$\tau_V < 1\,\text{s}\,, \quad \Longrightarrow \varepsilon^2\left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



1311.5104

Production by virtual photon $\quad \sigma \propto \varepsilon^2$

Decay through virtual photon, $\quad \Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Huge community: theory meets experiment

2305.01715

New models, reinterpretation of old data, new experimental constraints

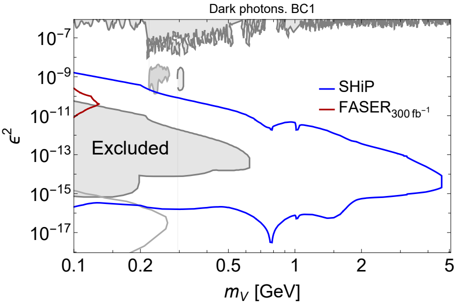
Benchmark Models (BC#)

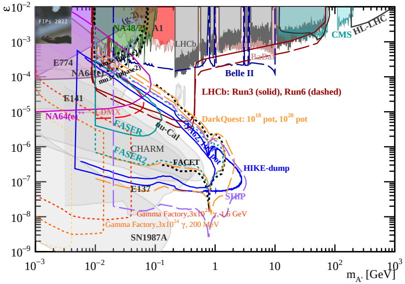
1. paraphoton (dark photon)
2. $B-L$ vector
3. millicharged
4. scalar ($H \to SS$ at 0.01)
5. scalar (no $H \to SS$)
6. HNL mixed with ν_e
7. HNL mixed with ν_μ
8. HNL mixed with ν_τ
9. ALP coupled to photons
10. ALP coupled to fermions
11. ALP coupled to gluons

Experiments and Proposals

1. T2K, T2HK, DUNE
2. NICA, FLAP
3. SHiP
4. DarkQuest, NA64, NA62-damp, PADME
5. FASER, FASER-2, SND
6. CODEX-b
7. FORMOSA, FLaRE
8. MilliQan
9. ANUBIS, MATHUSLA
10. SHADOWS, HIKE-K+, HIKE-dump
11. LDMX, M^3, SBND

BC1: paraphoton (dark photon) V_μ

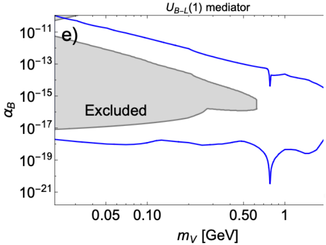


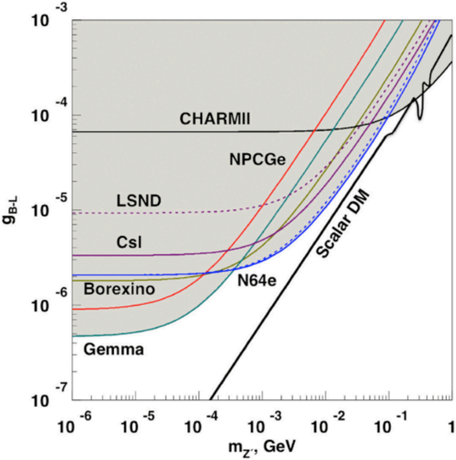


$$\Delta L_{int} = -\frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu$$

decay

BC2: vector V_μ of $U(1)_{B-L}$ gauge symmetry

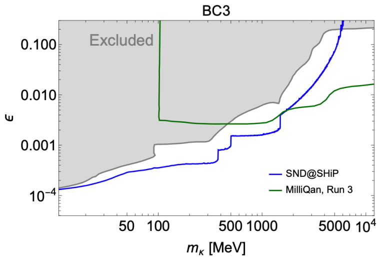


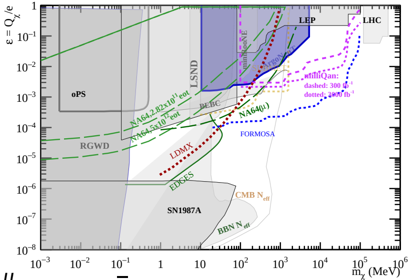


$$\Delta L_{int} = -e_B V_\mu \left(j_B^\mu - j_L^\mu\right) + \frac{m_V^2}{2} V_\mu V^\mu$$

decay

BC3: millicharged particles, $q = \varepsilon e$

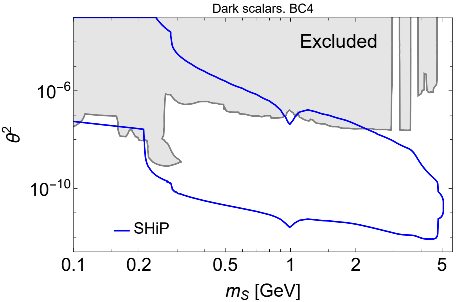


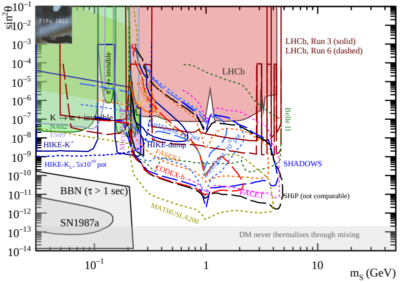


$$\Delta L_{int} = -\varepsilon e A_\mu \bar{\psi}\gamma^\mu \psi - m_\kappa \bar{\psi}\psi$$

hit

BC4: scalar portal: only mixing with Higgs

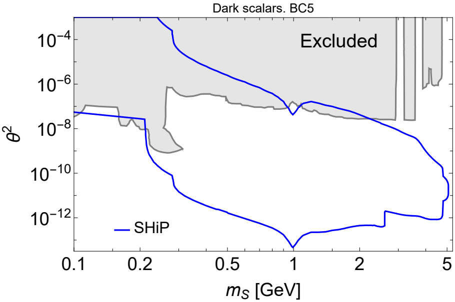


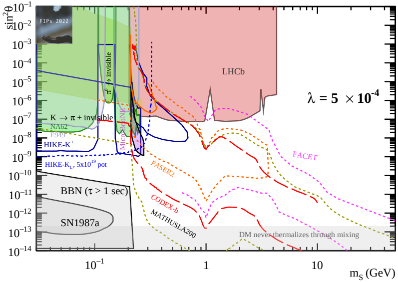


$$\Delta L_{int} = \mu H^\dagger HS - \frac{m_S^2}{2} S^2 \quad \rightarrow \quad \theta hS - \frac{m_S^2}{2} S^2$$

decay

BC5: scalar portal: cubic and quartic terms



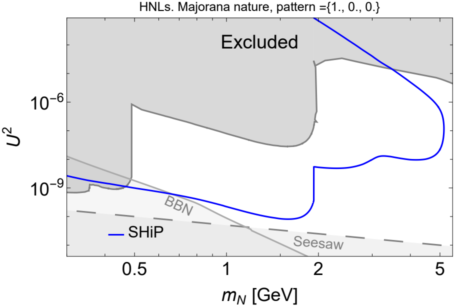


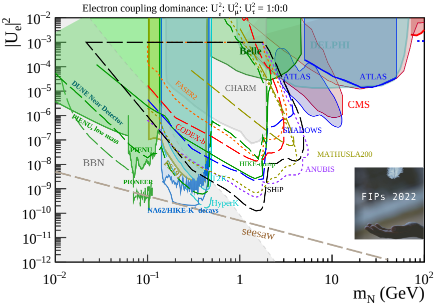
$$\Delta L_{int} = \mu H^\dagger HS - \frac{\lambda}{2} H^\dagger HS^2 - \frac{m^2}{2} S^2 \quad \to \quad \theta hS - \mu' hS^2 - \frac{m_S^2}{2} S^2$$

fixing $\mathrm{Br}(h \to SS) = 0.01$ double production from $B-meson$ via μ'

decay

BC6: Heavy Neutral Lepton N coupled to ν_e

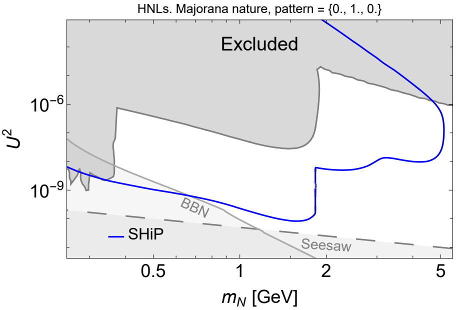


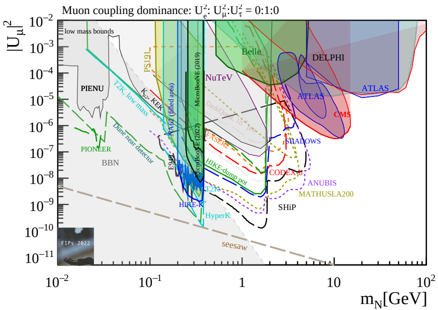


$$\Delta L_{int} = Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_e \to \nu_e + U_e N$$

decay

BC7: Heavy Neutral Lepton N coupled to ν_μ

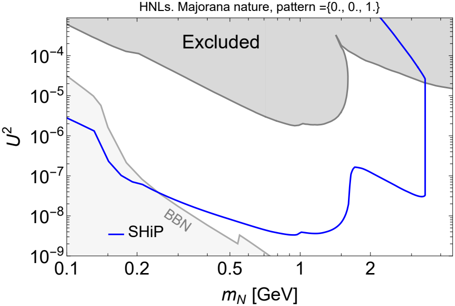


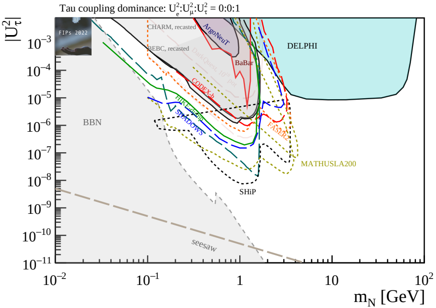


$$\Delta L_{int} = Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_\mu \to \nu_\mu + U_\mu N$$

decay

BC8: Heavy Neutral Lepton N coupled to ν_τ

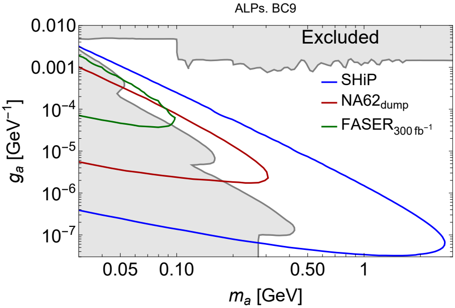


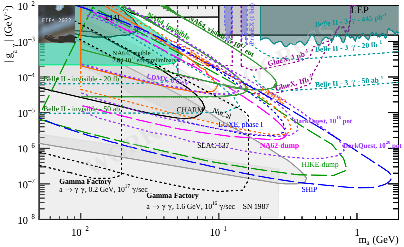


$$\Delta L_{int} = Y_{\alpha I}\bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_\tau \to \nu_\tau + U_\tau N$$

decay

BC9: Axion Like Particle a coupled to photons

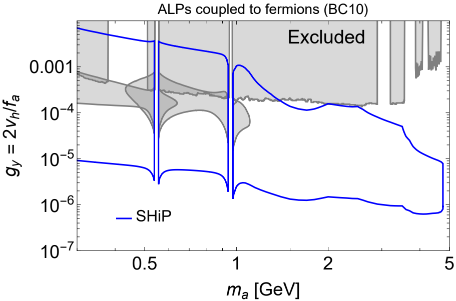


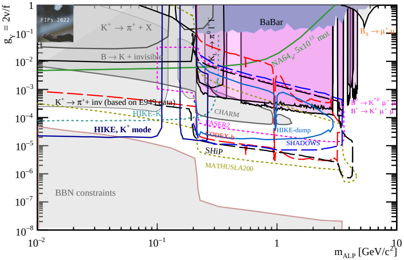


$$\Delta L_{int} = g_a a F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m_a^2 a^2$$

decay

BC10: Axion Like Particle a coupled to fermions

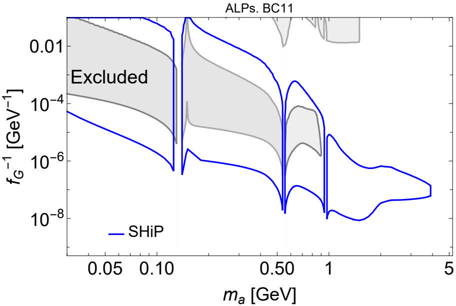


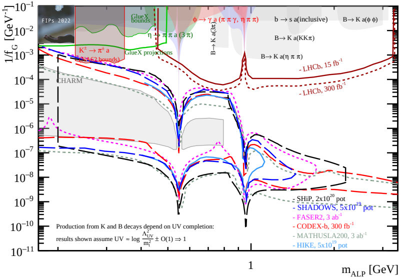


$$\Delta L_{int} = g_y a \bar{\psi} \psi - \frac{1}{2} m_a^2 a^2$$

decay

BC11: Axion Like Particle a coupled to gluons





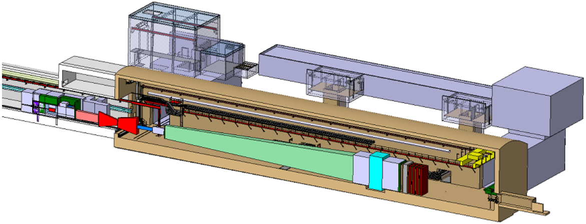
$$\Delta L_{int} = \frac{a}{f_g} G_{\mu\nu} G^{\mu\nu} - \frac{1}{2} m_a^2 a^2$$

decay

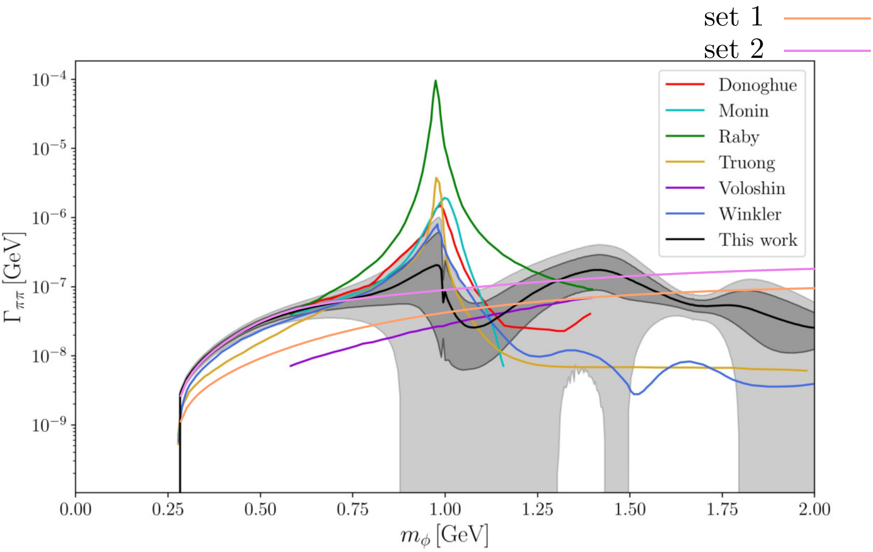
SHiP: Search for Hidden Particles, $4 \cdot 10^{19}$PoTs/year

Experiment at the SPS Beam Dump Facility to Search for Hidden Particles SHiP and the associated SPS Beam Dump Facility is a new general-purpose experiment in preparation at the SPS to search for "hidden" particles as predicted by a large number of models of Hidden Sectors that are capable of explaining for instance dark matter, neutrino oscillations, and the origin of the baryon asymmetry in the Universe. The experiment is design to search for any type of feebly interacting long-lived particles, among which are found e.g. heavy neutral leptons, dark photons , dark scalars, axion-like particles, and light supersymmetric particles - sgoldstinos, etc, as well as different types of Light Dark Matter. The high intensity of the SPS and in particular the large production of charm mesons and photons with the 400 GeV proton beam allow a comprehensive search at the MeV-GeV scale over many orders of magnitude in coupling. The detector incorporates two complementary apparatuses aimed at searching for hidden particles through both visible decays and through scattering signatures from recoil of electrons or nuclei. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

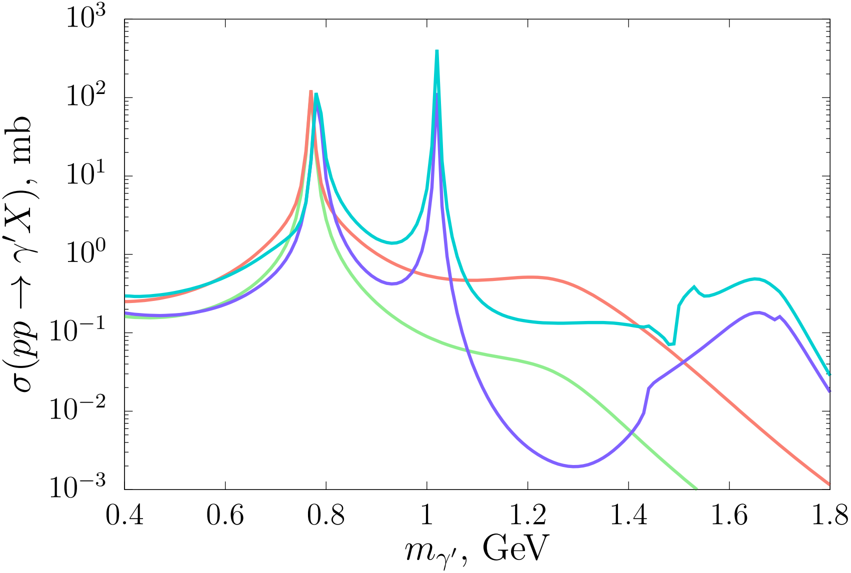
SHiP
Search for Hidden Particles

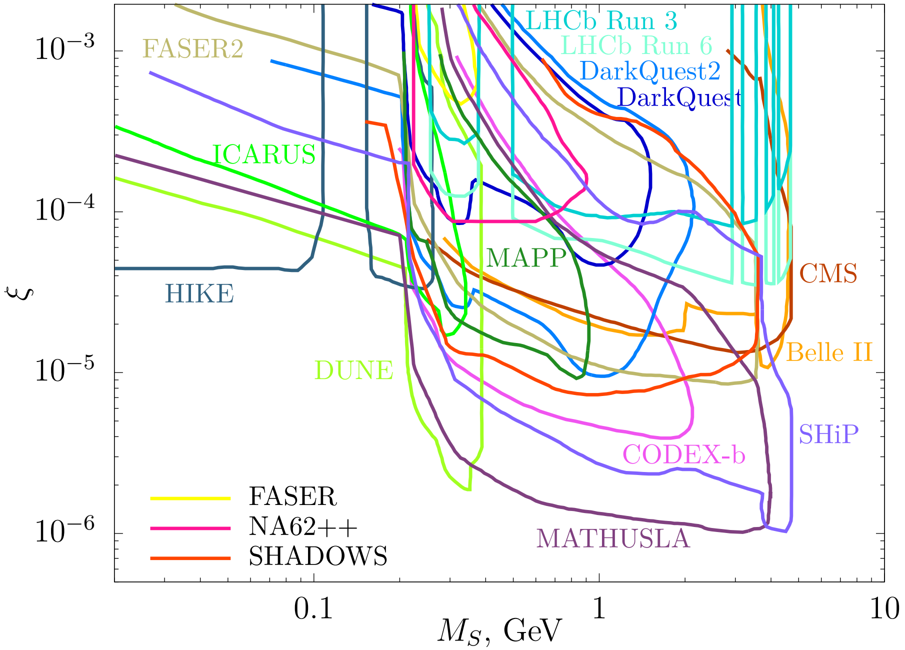


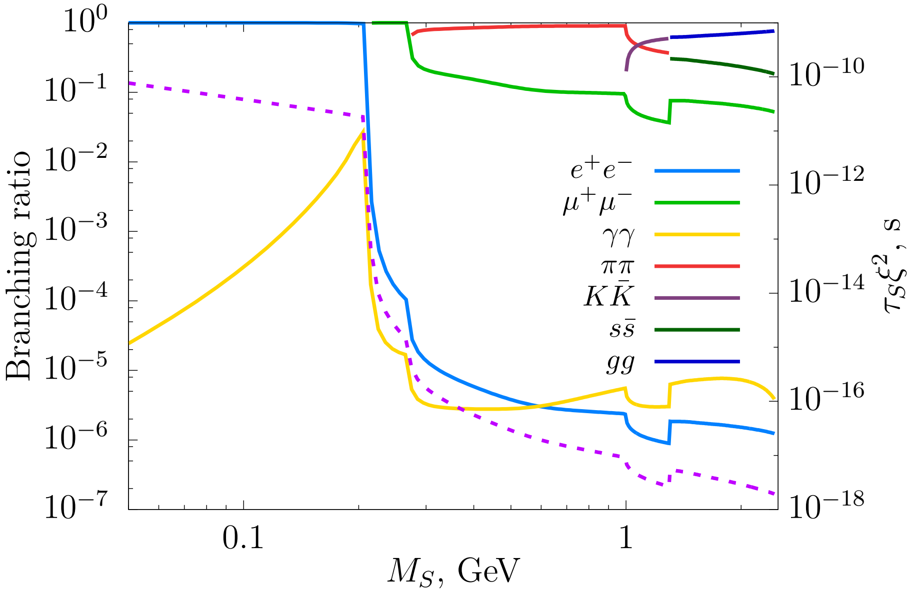
Uncertainties 2407.13587 and comparison with GDA



different Dirac, Pauli form factors (0910.5589,2010.15872), talk by E. Kriukova



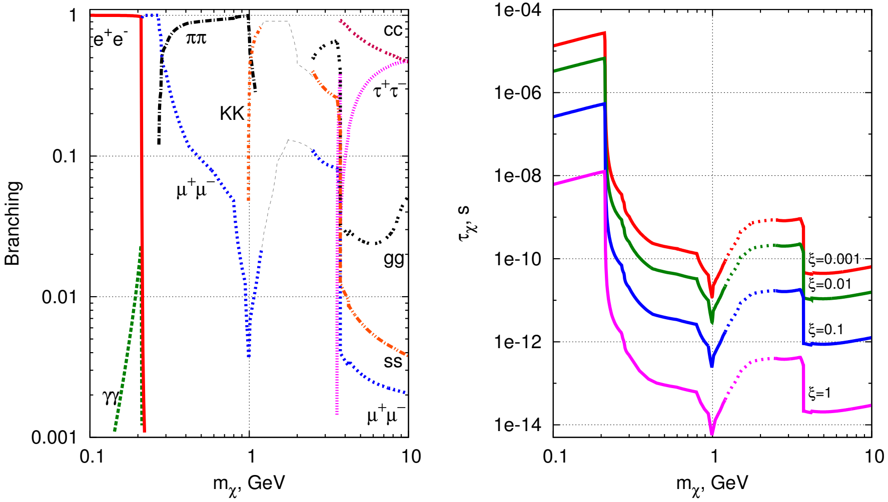

LHCb Run 3
LHCb Run 6
DarkQuest2
DarkQuest
FASER2
ICARUS
HIKE
MAPP
CMS
Belle II
DUNE
SHiP
CODEX-b
MATHUSLA
FASER
NA62++
SHADOWS
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ξ
0.1
1
10
M_S, GeV



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Branching ratio
0.1
1
M_S, GeV
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$\tau_S \xi^2$, s
e^+e^-
$\mu^+\mu^-$
$\gamma\gamma$
$\pi\pi$
$K\bar{K}$
$s\bar{s}$
gg

QCD modes: claimed uncertainties upto 10^2

1303.4395

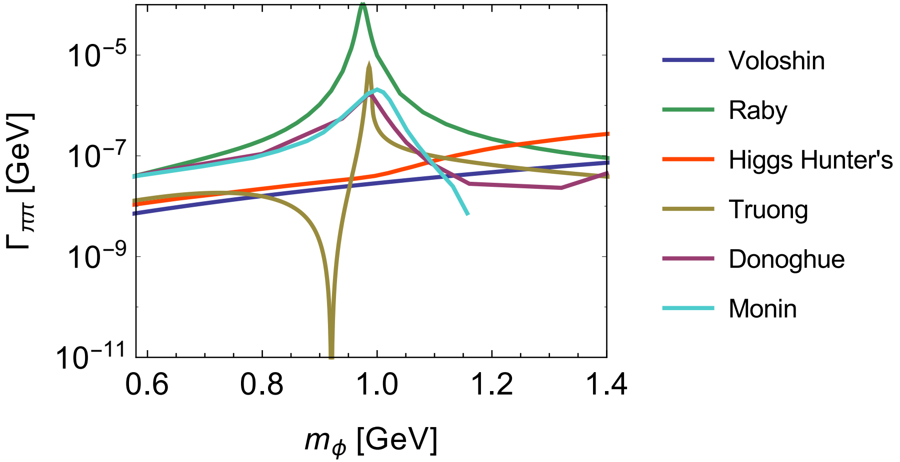


Interaction among the final hadronic states

following J.Donoghue, J.Gasser and H Leutwyler (1990)

The estimates BSM people use

1809.01876



Physics: Final State Interaction: $\pi\pi \to \pi\pi$

sensitivity curves

2102.12143

Two different cases:

1. $l_{dec} = c\tau_X\gamma \ll L_{detector}$

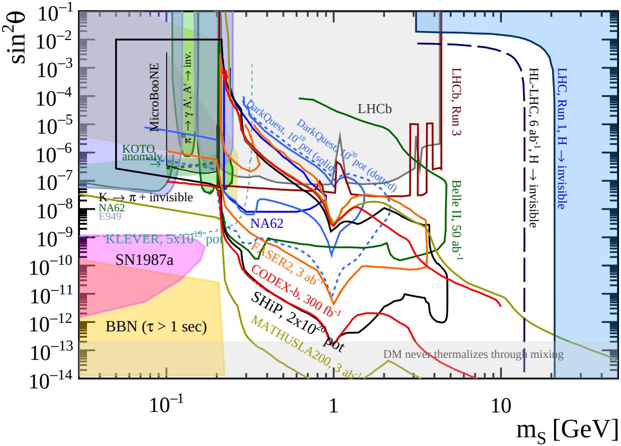
   $N^{events}_{X\to chan} \propto Br_{chan}$

   Smooth for pions, wiggly for muons

2. $l_{dec} = c\tau_X\gamma \gg L_{detector}$

   $N^{events}_{X\to chan} \propto \frac{Br_{chan}}{c\tau_X\gamma}$

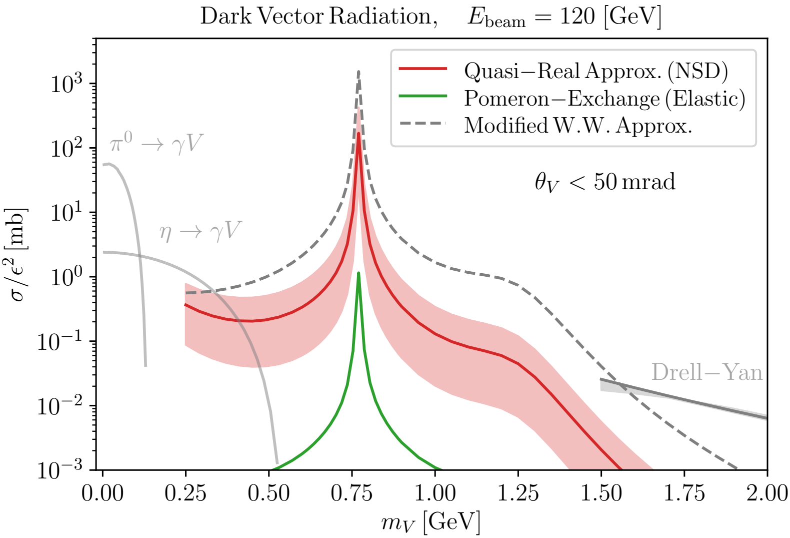
   Wiggly for pions, smooth for muons



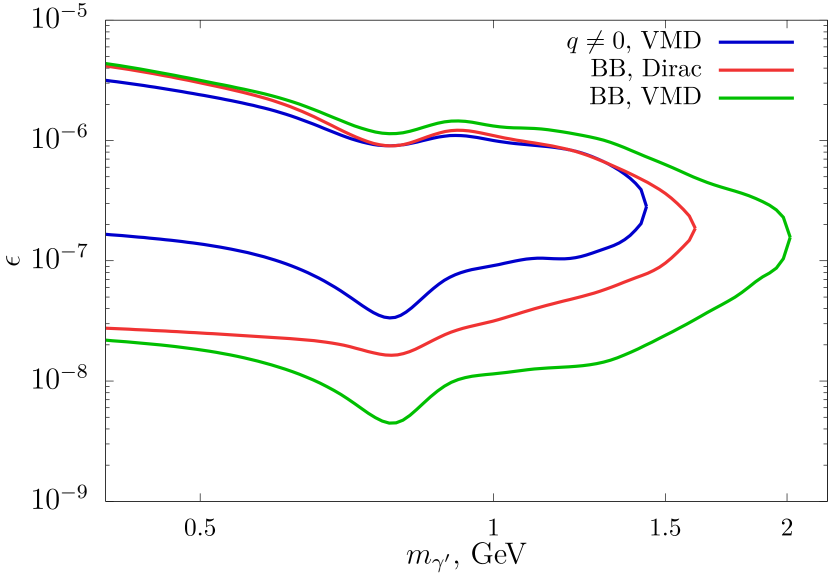
while pions dominate. . .

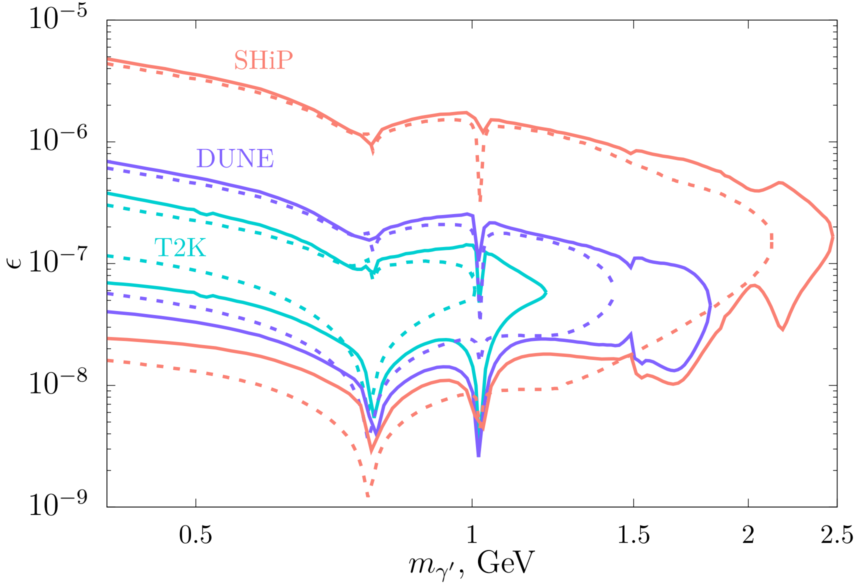
Massive vectors: various attempts

2108.05900



It changes the sensitivity... SHiP, 400 GeV




SHiP
DUNE
T2K
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
ϵ
0.5
1
1.5
2
2.5
$m_{\gamma'}$, GeV