New Physics at fixed target experiments

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Particle Physics
at Intermediate and High Energies

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Outline

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Widely accepted statements

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations
  - baryon asymmetry
  - dark matter
  - why the Uiverse is homogeneous?
  - what is the source of primordial matter inhomogeneities?
  - inflation-like stage in the early Universe. . . ?
  - . . .
  - . . .

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  - neutrino oscillations
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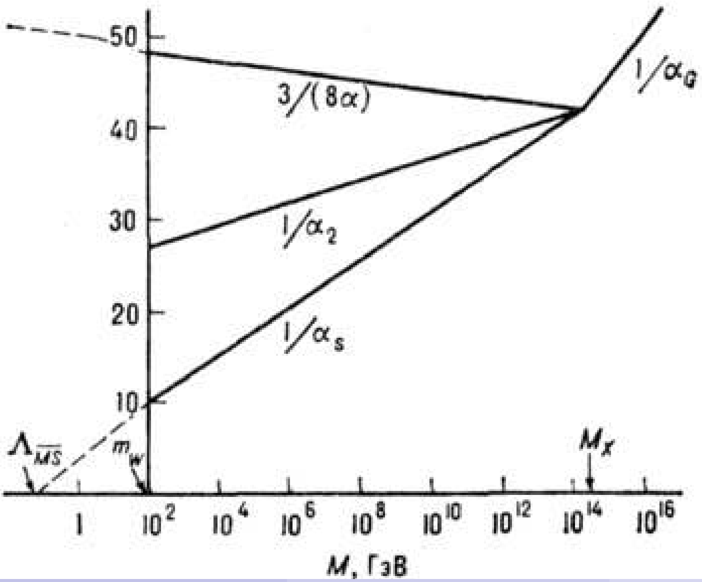
  - dark matter
  - inflation-like stage in the early Universe
- New Heavy particle contribution to the Higgs boson mass lifts it up but miraculously $m_h \sim E_{EW}$

New physics at high energies...



– Gauge coupling unification
– Wilsonian approach: solid state physics lattice supersymmetry
– gauge coupling unification supersymmetry

Theoretical guideline: gauge hierarchy problem

Quantum corrections to the SM Higgs boson mass

quadratic divergences regularized by a cut in loop 4-momentum

$$\delta m_h^2 \propto \int_0^\infty \frac{d^4q}{q^2 - m_X^2} \propto \Lambda^2 + m_X^2 + \dots$$

Physical meaning?
Bardeen's argument: the regularization violates scale invariance

$$T_{\mu\nu} \propto \Lambda^2 \phi^2 + \dots$$

Becomes convincing with some heavy states involved. . .

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Gauge hierarchy problem: bottom-up vs top-down

SM Higgs boson mass term must be tuned downto m_h^2/Λ^2 !!

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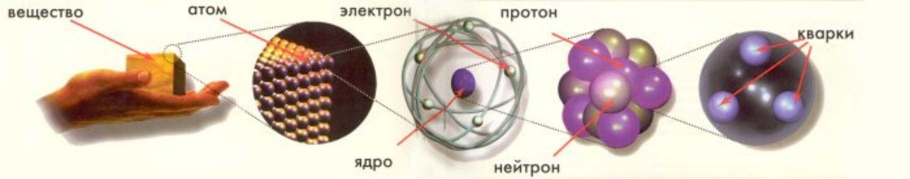
boundary condition for the integral or matching of EFT parameters



New Physics at LHC. . . not Found (yet?)

- Supersymmetry
- Technicolor
- Leptoquarks
- Extra generations
- Extra dimensions
- Extra gauge and/or Higgs bosons
- Massive neutrinos
- Noncommutativity
- . . .
- . . .

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions $\sim E_{EW}$ to m_h are OK
- 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 ?
  - (pseudo)scalar,
    (pseudo)vectors,
    even $3/2$- and 2-spin candidates...

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RG evolution of the SM couplings and GUT

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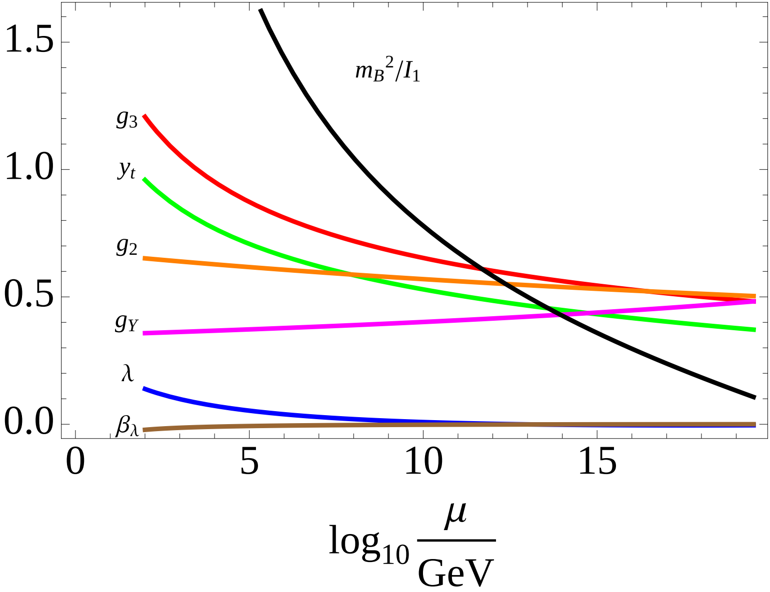
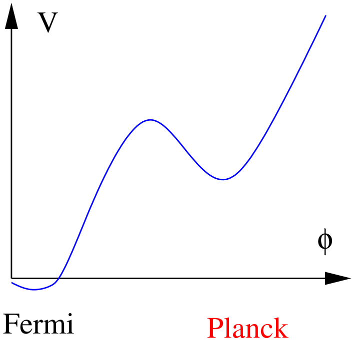
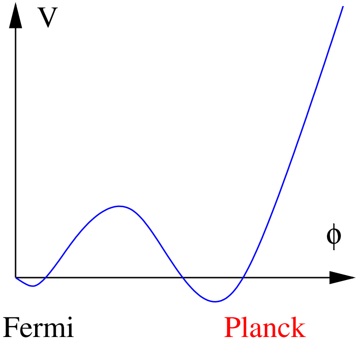


Multiple point principle: D.Bennett, H.Nielsen (1993), C.Froggatt, H.Nielsen (1995)



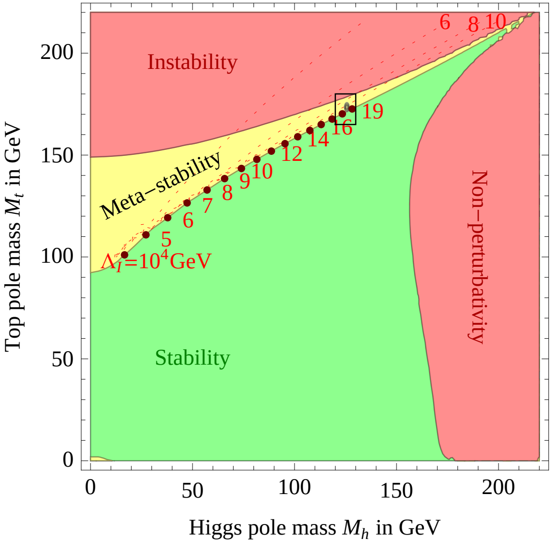


$$\Lambda \simeq 0 \;\Rightarrow V(\phi_{EW}) = V(\phi_{Planck}) = 0 \Rightarrow \lambda(\mu_{Planck}) = 0$$

$$\text{gravity scale} \Rightarrow V'(\phi_{EW}) = V'(\phi_{Planck}) = 0 \Rightarrow \frac{d\lambda(\mu)}{d\log\mu}(\mu_{Planck}) = 0$$

These gave $m_t \simeq 173$ GeV , $m_h \simeq 129$ GeV GUT concept?

How weird to live with 125 GeV Higgs. . .



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Fundamental physics behind the FIMPs

Feebly Interacting Massive Particles

- Dark (pseudo)scalars, fermions, photons as thermal Dark Matter recall WIMPs
  or non-thermal Dark Matter
- Heavy Neutral Leptons with seesaw type I for neutrino masses
- Axion from solutions to strong-CP problem
- HNL, dark scalars, Axion-Like Particles, dark photons involved in generation of matter-antimatter asymmetry
- Dark scalars, ALP in solutions to the gauge hierarchy problem
- Dark scalars as inflatons
- FIMPs to solve issues (if any) in astrophysics

Disclaimer

There are no general theoretical motivation for the New Particles to be of (sub)GeV mass

But there are well-motivated models...

Renormalizable inflaton at GeV scale

0912.0390

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

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

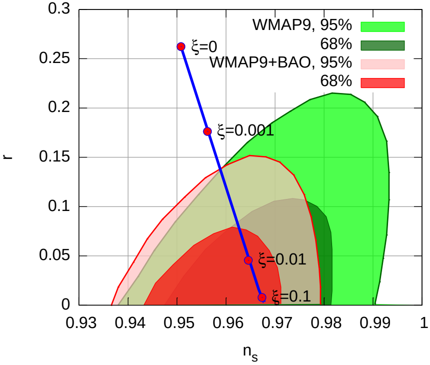
$$\mathscr{L}_{\text{grav}} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

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

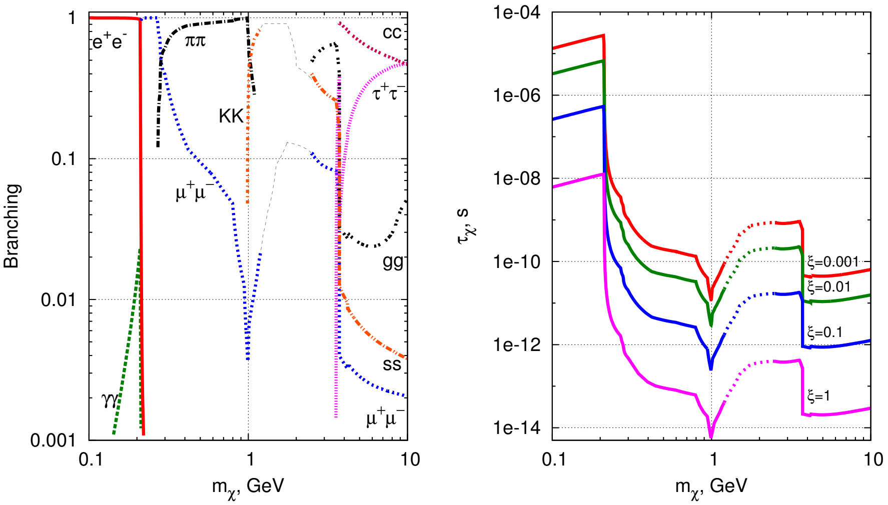
phenomenology is fixed by
mixing with Higgs

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



QCD modes: claimed uncertainties upto 10^2

1303.4395

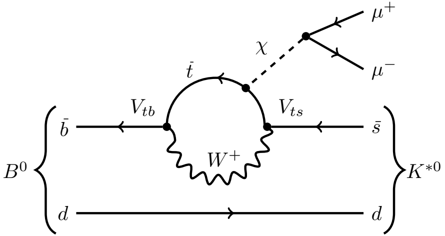


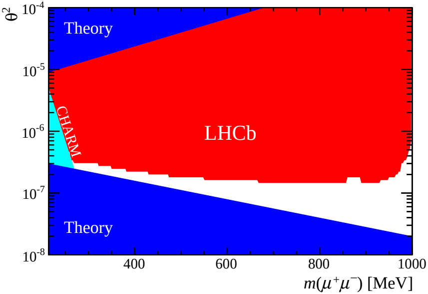
Interaction among the final hadronic states

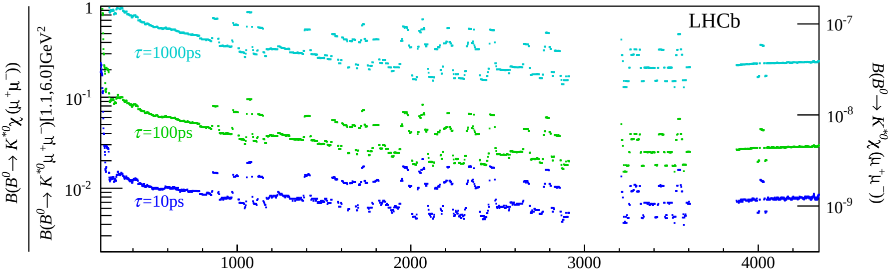
following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

1508.04094

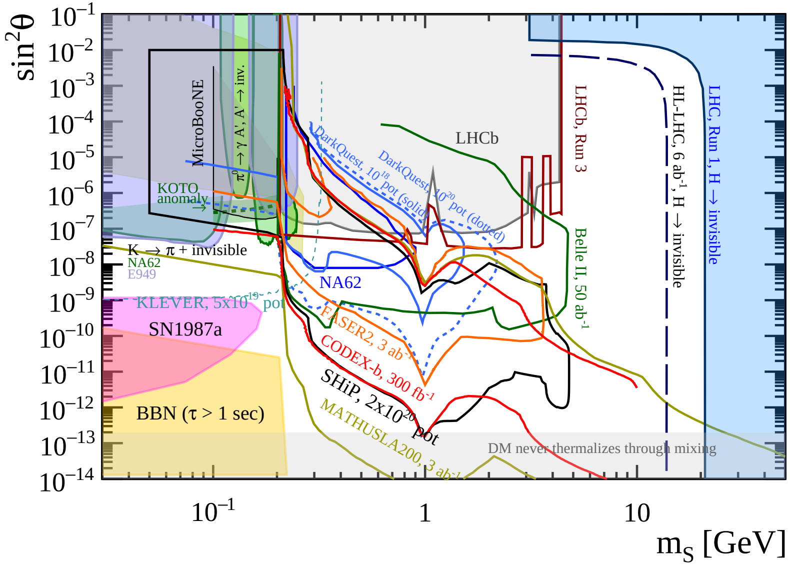






direct limits on scalars

2102.12143



An example: Hylogenesis

H.Davoudiasi, D.Morrissey, K.Sigurdson, S.Tulin (2010)

Greek: hyle (primordial matter) + genesis (origin)

- New fields:
  1 Dirac fermion Y $\qquad m_Y \sim \mathcal{O}(1)\,\text{GeV}$
  1 complex scalar Φ $\qquad m_\Phi \sim \mathcal{O}(1)\,\text{GeV}$
  2 Dirac fermions X_a, $a = 1,2$ $\qquad m_2 > m_1 \gtrsim 1\,\text{TeV}$
- Coupling to SM via “neutron portal”

$$-\mathscr{L}_{\text{int}} = \frac{\lambda_a}{M^2}\bar{X}_a d_R \bar{u}^C d_R + \zeta_a \bar{X}_a Y^C \Phi^* + \text{h.c.}$$

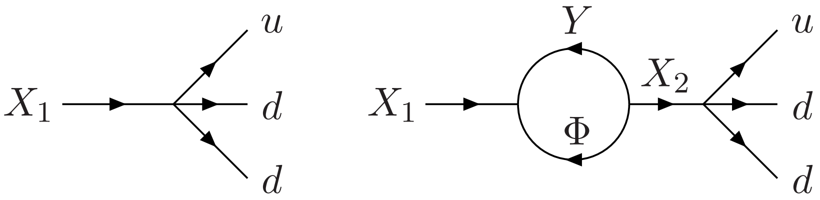
- Baryon charge $\qquad B_{X_a} = -(B_Y + B_\Phi) = 1$
- Proton and DM particles (both Y and Φ) are stable if

$$|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi$$

Baryogenesis (asymmetry generation)

Sakharov's conditions

1. *B*-violation (in visible sector !) $\lambda_a \neq 0$
2. *C*- & *CP*-violation $\Im\left(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*\right) \neq 0$
3. out-of-equilibrium — decays of nonrelativistic X_1



Microscopic asymmetry (assuming $X_1 \to \bar{Y}\Phi^*$ dominates and $M_1 \ll M_2$)

$$\varepsilon = \frac{\Gamma(X_1 \to udd) - \Gamma(\bar{X}_1 \to \bar{u}\bar{d}\bar{d})}{\Gamma(X_1 \to \bar{Y}\Phi^*) + \Gamma(\bar{X}_1 \to Y\Phi)} \approx \frac{m_1^5 \, \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\,\pi^3 \, |\zeta_1|^2 \, M^4 \, m_2} \Rightarrow \varepsilon / g_* \sim \Delta_B = \frac{n_B}{s} \approx 10^{-10}$$

if $m_2 > 2m_1$, $M > 2m_2$ then $\varepsilon \simeq 2.5 \times 10^{-7} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ — seems OK

if $m_2 > 3m_1$, $M > 3m_2$ then $\varepsilon \simeq 6.5 \times 10^{-9} \times \Im[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]/|\zeta_1|^2$ — needs $|\zeta_1| \ll 1$?

Asymmetric Dark Matter freeze out

To make DM natural:
all CP-symmetric pairs (Y and $\bar{Y}$), (Φ and Φ^*) must annihilate

- CP-asymmetric relics form Dark Matter
  is exactly the counterpart of baryon asymmetry in visible sector
- then baryon number conservation implies $n_Y = n_\Phi = n_B$ and so

$$\frac{\Omega_{DM}}{\Omega_B} = \frac{m_Y + m_\Phi}{m_p}$$

- stability of proton and DM is kinematically guaranteed for

$$1.7\,\text{GeV} \lesssim m_Y, m_\Phi \lesssim 2.9\,\text{GeV}$$

- hence $\Omega_{DM} \sim \Omega_B$ is natural

Outline

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 S

  the simplest dark matter

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

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \epsilon H^*$ 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

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

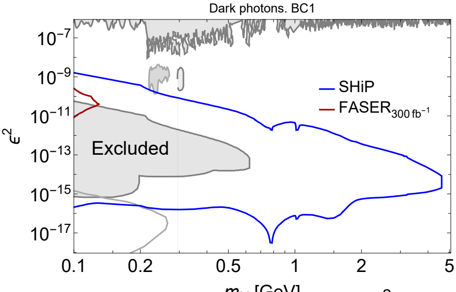
Direct searches typically $\varepsilon \lesssim 10^{-3}$

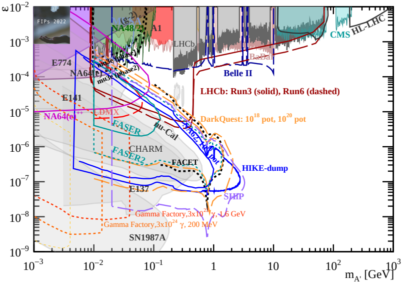
- Signatures at production: $N_s \propto \varepsilon^2$
  - $K \to \pi + X(X \to invisible)$ kink
  - $e^- + A \to X(X \to invisible) + all$ missing E
- Signatures at decay: $N_s \propto \varepsilon^2 \times \varepsilon^2$
  - $K \to \mu N(N \to e^+ e^- \nu)$ displaced vertex
  - $K \to \mu S(S \to \mu^+ \mu^-)$ invariant mass

In the case of background free conditions we need
statistics of at least 10^6 and 10^{12} fixed target seems better

Kinematics: $M_X < \sqrt{2 M_p E_{beam}} \lesssim 25\,\text{GeV}$
direct production, production in hadron decays, etc

BC1: paraphoton (dark photon) V_μ





$$\Delta L_{int} = -\frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu \,, \quad \mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

$$L_{dec} \simeq 5\,\mu\text{m} \times \gamma \times \frac{100\,\text{MeV}}{m_{\gamma'}} \left(\frac{10^{-3}}{\varepsilon} \right)^2$$

Hot spot in a model parameter space: $L_{decay} \simeq L_{detector} \simeq \Delta L_{target-detector}$

Huge community: theory meets experiment

2305.01715

New models, reinterpretation of old data, new experimental constraints

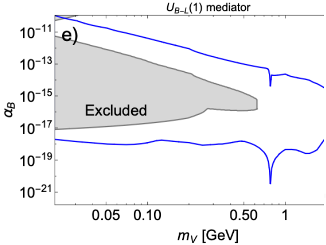
Benchmark Models (BC#)

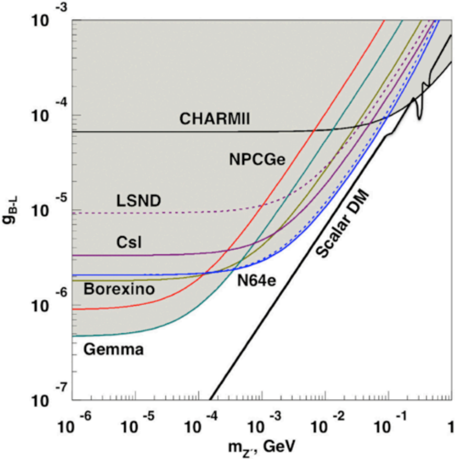
1. paraphoton (dark photon)
2. $B-L$ vector
3. millicharged
4. scalar ($H \to SS$ at 0.01)
5. scalar (no $H \to SS$)
6. HNL mixed with ν_e
7. HNL mixed with ν_μ
8. HNL mixed with ν_τ
9. ALP coupled to photons
10. ALP coupled to fermions
11. ALP coupled to gluons

Experiments and Proposals

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

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

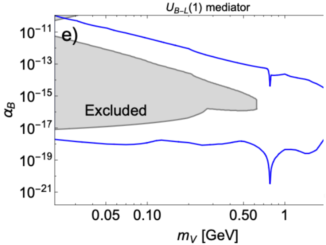


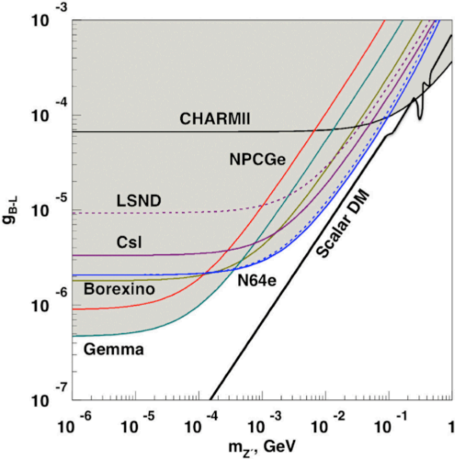


$$\Delta L_{int} = -e_B V_\mu \left(j_B^\mu - j_L^\mu\right) + \frac{m_V^2}{2} V_\mu V^\mu$$

decay

BC2*: vector V_μ of anomalous $U(1)_B$ gauge symmetry

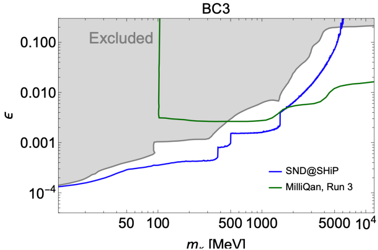


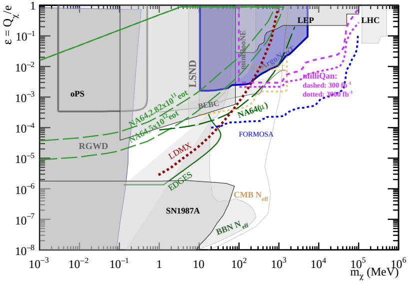


$$\Delta L_{int} = -e_B V_\mu j_B^\mu + \frac{m_V^2}{2} V_\mu V^\mu$$

if $M_V < 2m_\pi$ decays are suppressed!!

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





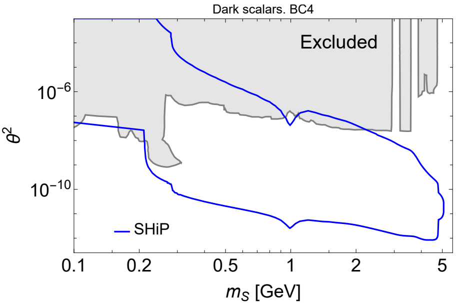
$$\Delta L_{int} = -\varepsilon e A_\mu \bar{\psi}\gamma^\mu \psi - m_\kappa \bar{\psi}\psi$$

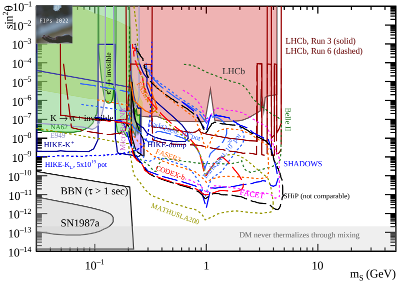
$$\mathrm{Br}(\eta \to \gamma\chi\bar{\chi}) \sim 0.5 \cdot 10^{-9} \left(\frac{\varepsilon}{10^{-3}}\right)^2$$

see e.g. 2103.11814 for more production channels

signature: double hit !!

BC4: scalar portal: only mixing with Higgs





$$\Delta L_{int} = \mu H^\dagger H S - \frac{m_S^2}{2} S^2 \quad \to \quad \theta h S - \frac{m_S^2}{2} S^2$$

production via kaon decays (see e.g. 2105.11102)

kink in kaon decays??

$$\mathrm{Br}(K \to \pi S) \simeq 10^{-10} \left(\frac{\theta^2}{10^{-7}} \right), \quad \mathrm{Br}(B \to K S) \simeq 10^{-7} \left(\frac{\theta^2}{10^{-7}} \right),$$

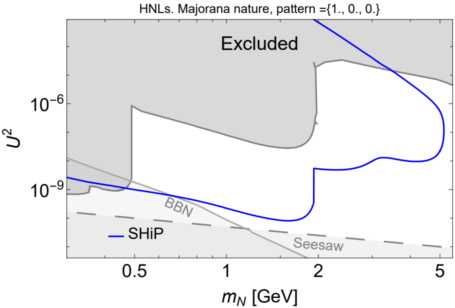
decay length at $\gamma\beta = 1$

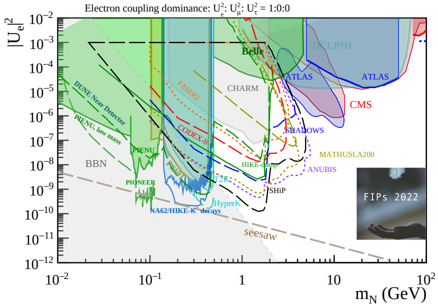
$c\tau_K \simeq 3\,m$

but only 10^8 K_L...

$$\tau_S = 10^7 \mathrm{cm} \left(\frac{150\,\mathrm{MeV}}{m_S} \right) \left(\frac{10^{-7}}{\theta^2} \right)$$

BC6: Heavy Neutral Lepton N coupled to ν_e





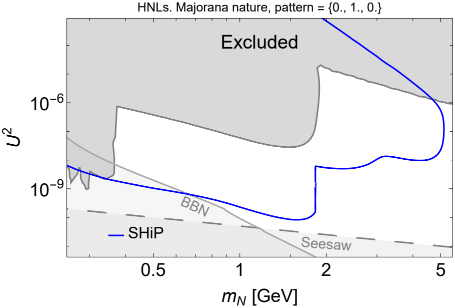
$$\Delta L_{int} = Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_e \to \nu_e + U_e N$$

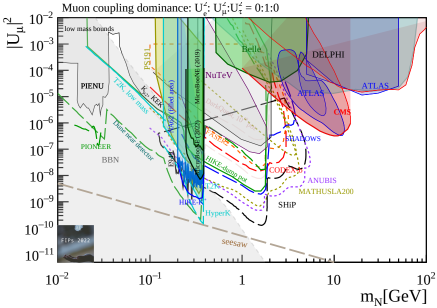
decay into a visible mode is too slow...just rescaling muon lifetime

$$\tau_N \simeq \tau_\mu |U_e|^{-2} \left(\frac{m_\mu}{m_N}\right)^5 = 3 \cdot 10^{-2}\,\text{s} \times \frac{10^{-6}}{|U_e|^2} \left(\frac{200\,\text{MeV}}{m_N}\right)^5$$

$$L_{decay} = 10^9\,\text{cm} \times \gamma_N \times \frac{10^{-6}}{|U_e|^2} \left(\frac{200\,\text{MeV}}{m_N}\right)^5$$

BC7: Heavy Neutral Lepton N coupled to ν_μ





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

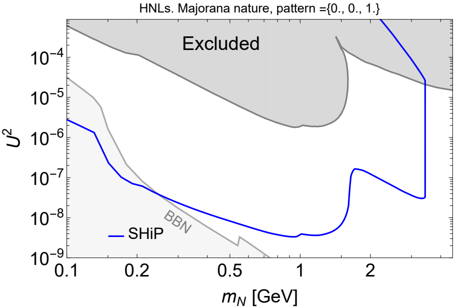
may be $K \to Ne(\mu)$ inside the detector...?

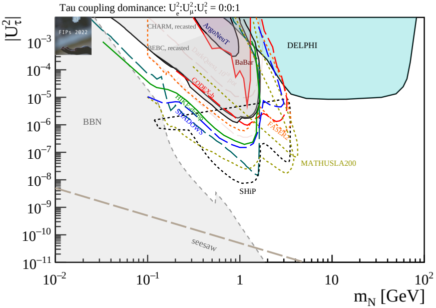
must recognize K and outgoing charged lepton!

kink as the HNL signature...!

need more than 10^7 kaons

BC8: Heavy Neutral Lepton N coupled to ν_τ



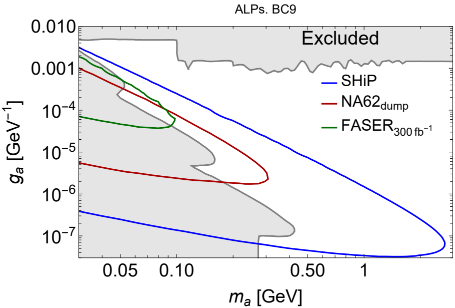


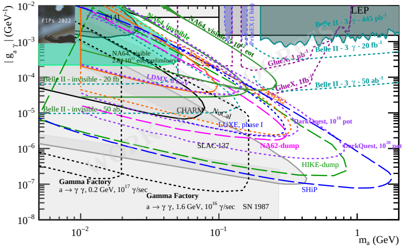
$$\Delta L_{int} = Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_\tau \to \nu_\tau + U_\tau N$$

decay

Kinematics: need to produce τ, i.e. D_s-mesons

BC9: Axion Like Particle a coupled to photons





$$\Delta L_{int} = \frac{g_{\gamma\gamma}}{8}\, a F_{\mu\nu} F_{\lambda\rho} \varepsilon^{\mu\nu\lambda\rho} - \frac{1}{2} m_a^2 a^2$$

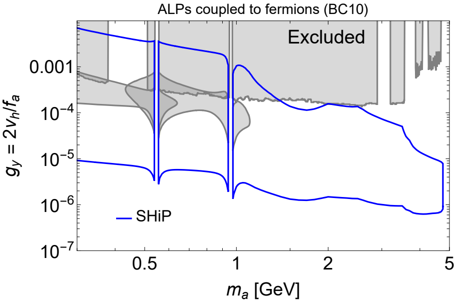
decay length:

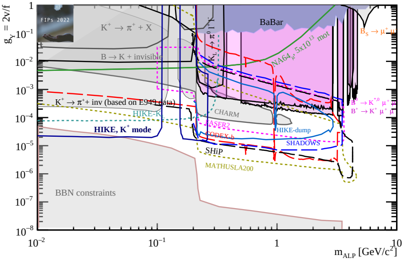
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{\gamma\gamma}^2 m_a^3}{64\pi}\,, \qquad L_{a\to\gamma\gamma} = \frac{c\,\gamma_a}{\Gamma_{a\to\gamma\gamma}} = 25\,\text{cm} \times \frac{E_a}{1\,\text{GeV}} \left(\frac{20\,\text{MeV}}{m_a}\right)^4 \left(\frac{10^{-3}\,\text{GeV}^{-1}}{g_{\gamma\gamma}}\right)^2$$

production via meson decays:

$$\text{Br}\,(P \to \gamma\gamma a) \sim \frac{m_P^2 g_{\gamma\gamma}^2}{16\pi^2} \sim 10^{-10} \times \left(\frac{M_P}{100\,\text{MeV}}\right)^2 \left(\frac{g_{\gamma\gamma}}{10^{-3}\,\text{GeV}^{-1}}\right)$$

BC10: Axion Like Particle *a* coupled to fermions

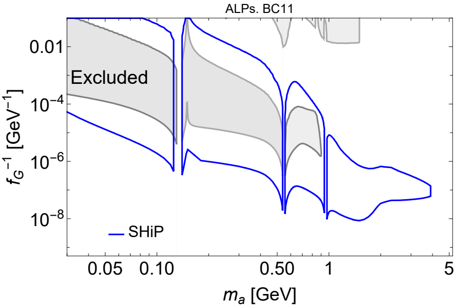


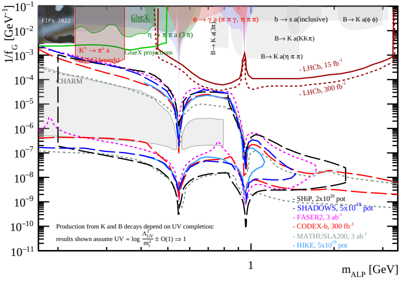


$$\Delta L_{int} = g_y a \bar{\psi}\psi - \frac{1}{2} m_a^2 a^2$$

decay

BC11: Axion Like Particle a coupled to gluons





Couplings must be correctly normalized!!!

decays at $m_a \lesssim \Lambda_{QCD}$ are suppressed

$$\Delta L_{int} = \frac{\alpha_s}{8\pi f_a}\, a\, G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{1}{2} m_a^2 a^2$$

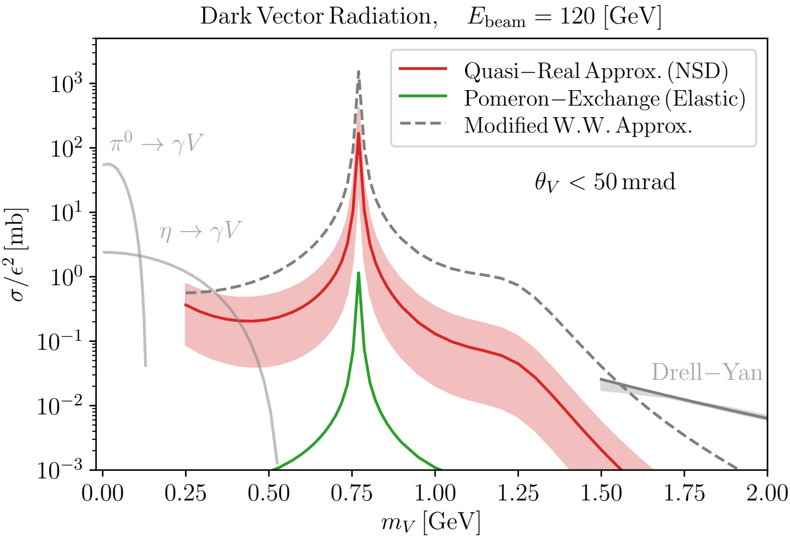
$$\frac{d^2 N_a}{d\theta_a dE_a} = \sum_{P=\pi^0,\eta} |\theta_{aP}|^2 \frac{d^2 N_P}{d\theta_P dE_P}\Big|_{E_P=E_a,\ \theta_P=\theta_a},$$ gives per a pion $3\cdot 10^{-10}\left(\frac{f_a}{10^3\,\mathrm{GeV}}\right)^2$

$$L_{a\to\gamma\gamma} = \frac{c\gamma_a}{\Gamma(a\to\gamma\gamma)} = 3\cdot 10^4\,\mathrm{cm}\times\frac{1}{|c_{\gamma\gamma}|^2}\left(\frac{100\,\mathrm{MeV}}{m_a}\right)^4 \frac{E_a}{1\,\mathrm{GeV}}\left(\frac{f_a}{10^3\,\mathrm{GeV}}\right)^2$$

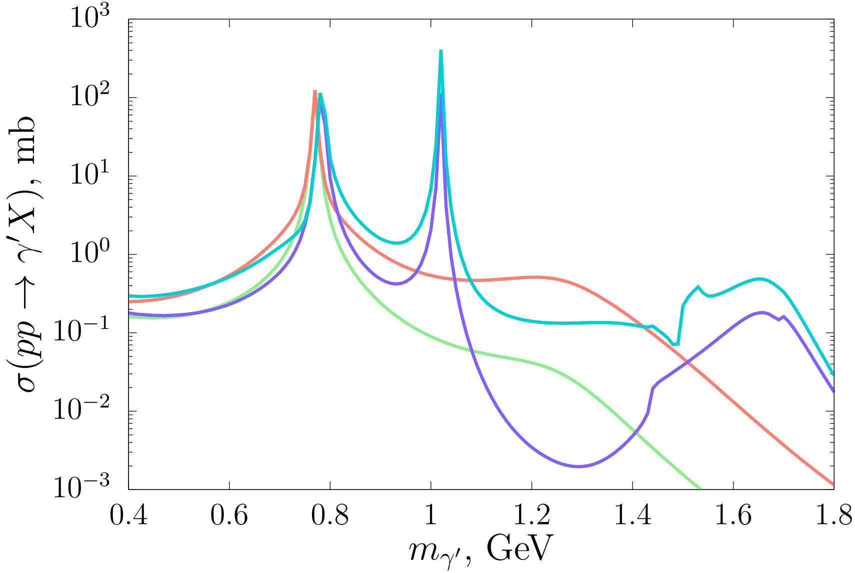
Outline

Massive vectors: various attempts

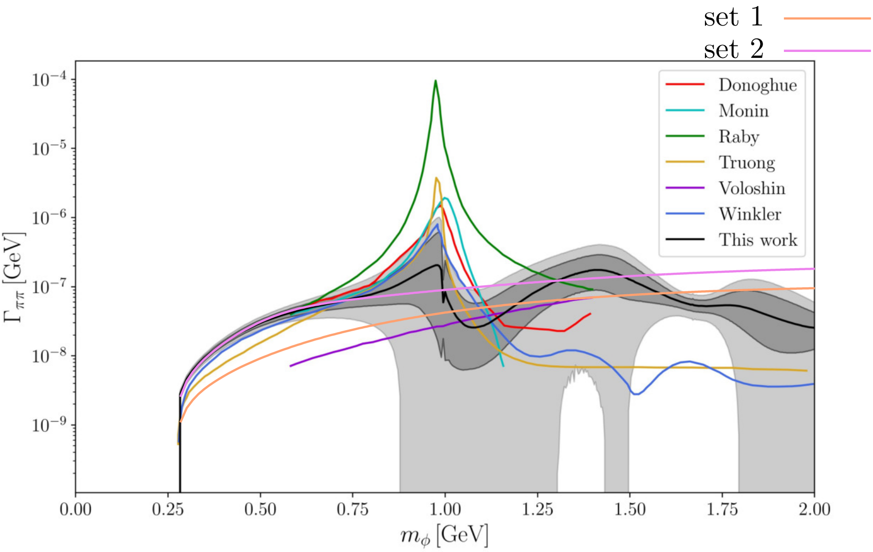
2108.05900



different Dirac, Pauli form factors (0910.5589,2010.15872)



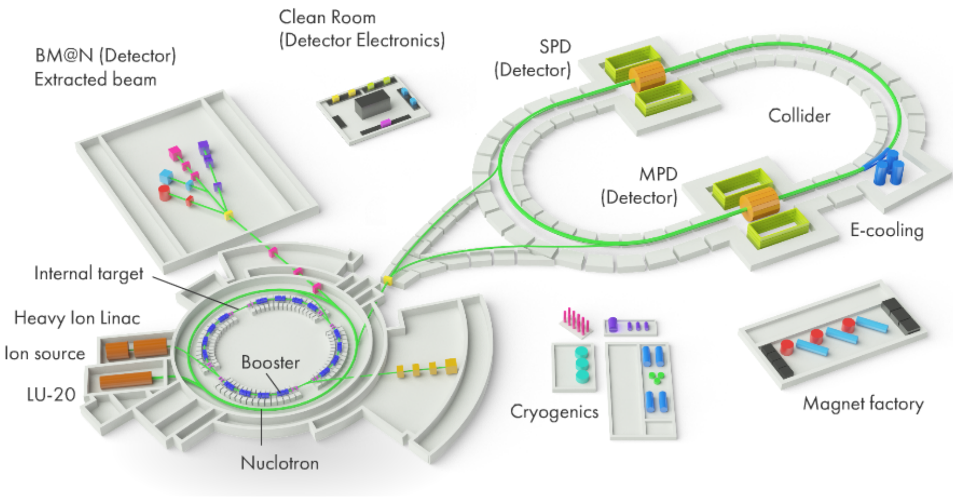
Predictions of 2303.12847, 2407.13587 $\Gamma(S \to \pi\pi)$



Outline

Nuclotron based Ion Collider fAcility

plenary talk by V.Kim



NICA TDR: beams of p, Au, Zn with energy $E/A = 4 - 10\,\text{GeV}$

Sources of light hypothetical particles: luminosity $\mathscr{L} = 10^{27}\text{cm}^2\text{s}^{-1}$

- decays of mesons in central collisions $N_{\pi^0} \simeq 10^{13}$, $N_\eta \simeq 10^{12}$, $N_\omega \simeq 10^{11}$ /year
- $\gamma\gamma$ fusion in peripherical collisions Bi Bi at $9.2A\,$GeV
- direct production in nucleon collisions?
  — proton bremmstrauhlung
  — Drell-Yann
  — . . .

with D. Kalashnikov and V. Ryabov

Major problem: HUGE background...

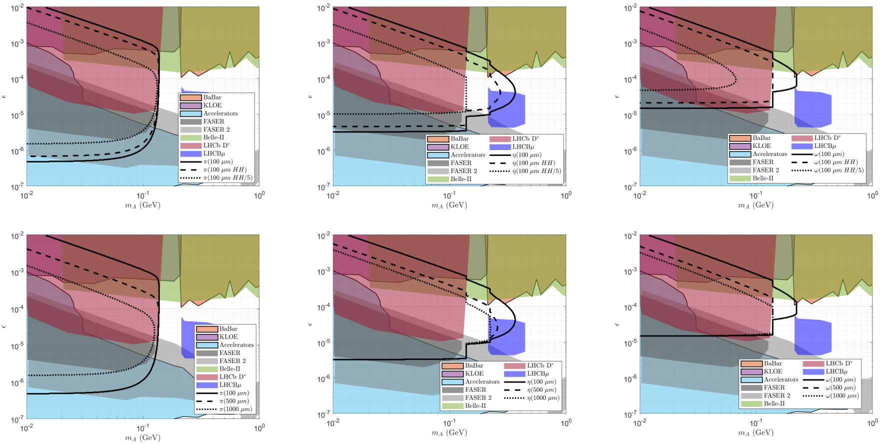
Need some feature: e.g. displaced decay vertex

MPD TDR: an upgrade with Inner Tracking System (ITS)
promised resolution of 10 μm, but collision point is fixed within 100 μm ...

We have a room for $c\tau_X/\gamma_X = 100, 500, 1000\,\mu\text{m}, \ldots$

Massive vectors (paraphotons), $\varepsilon F_{\mu\nu} F'_{\nu\nu}$

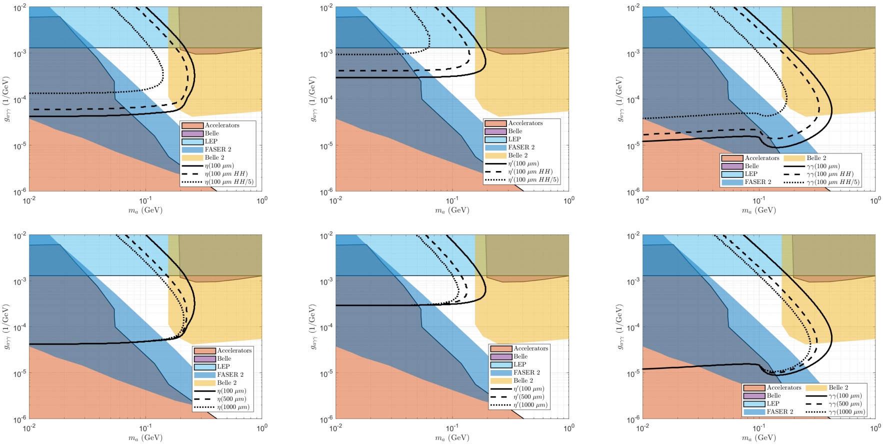
2401.12893



$\pi^0 \to \gamma\gamma'$ $\quad$ $\eta \to \gamma\gamma'$ $\quad$ $\omega \to \pi^0\gamma'$

background-free signature: $\gamma' \to e^+e^-$ at a distance of 100, 500, 1000 μm

Massive axion-like particle (ALP), $aF_{\mu\nu}\tilde{F}_{\nu\nu}$ 2401.12893



$\eta \to \gamma\gamma a$ | $\eta' \to \gamma\gamma a$ | fusion, $\gamma\gamma \to a$

background-free signature: $a \to \gamma\gamma$ at a distance of 100, 500, 1000 μm

Options with NICA

- We need stable collision mode with high luminosity (2026? 2027? . . .)
- We need a fine tracker (excluded from considerations after . . .)
- However, we have already low-intensity, low-energy ion beams

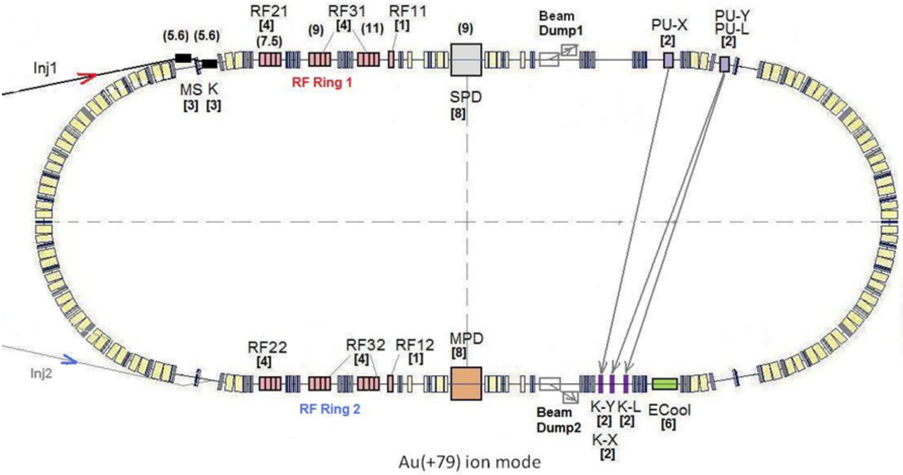
operating in a fixed-target mode BM@N

It can be usefull but we must recognize e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$ (ECAL...?)

– fixed target ? with a thin foil
– short beam dump ? with a very heavy dumper
– a new place, or upgraded old one...

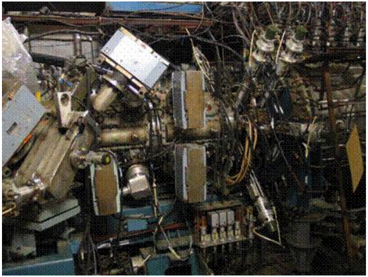
– in a generic (public) place the radiation safety limits total number of hits as $N_A < 10^{12}$

Possible places for a fixed-target or/and a beam-dump



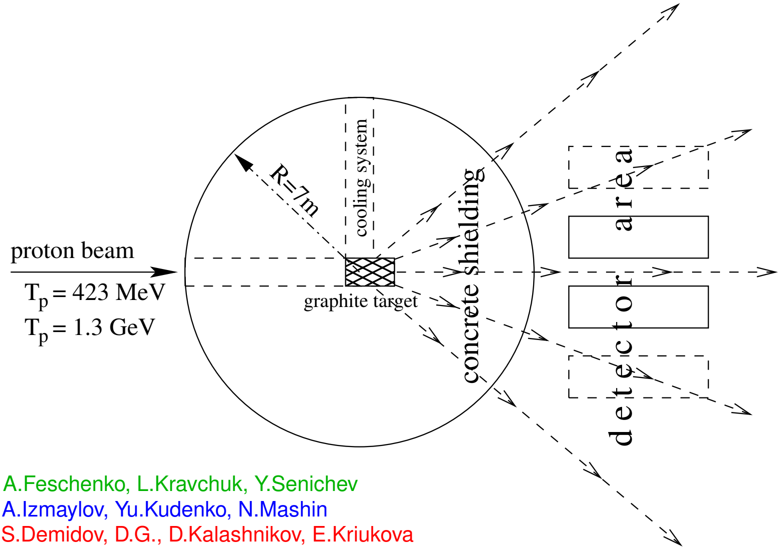
Outline

Moscow Meson Factory of INR RAS (197x-2025)

in the Project “Fundamental Properties of Matter”

Troitsk
i
Meson
o
Factory
e
y
expected
PoTs/year
1.8×10^{22}
0.6×10^{22}
5 years
of operation



Proton beam: A.Feschenko, L.Kravchuk, Y.Senichev
Detectors: A.Izmaylov, Yu.Kudenko, N.Mashin
Physics: S.Demidov, D.G., D.Kalashnikov, E.Kriukova

Main goal: neutrinos from stopped pions

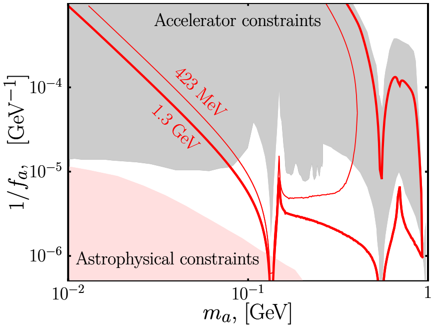
Troitsk
i
Meson
o
Factory
e
y

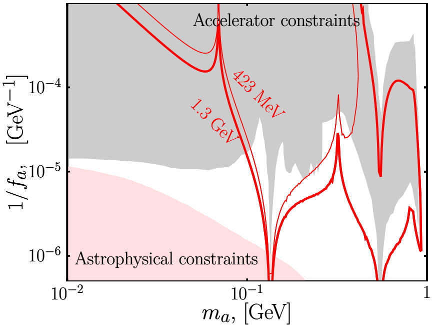
expected
PoTs/year
1.8×10^{22}
0.6×10^{22}
5 years

of operation

Detectors: A) to register a pair, B) to register a hit
Physics: light feebly interacting particles

Sensitivity: Axion with coupling to gluons (model BC11)





Detector at $l = 7$ m and its fiducial volume is $1\,m^2 \times 2\,m$

5 years of operation (each year is 10^7 s)

Sensitivity curves for *B*-bosons

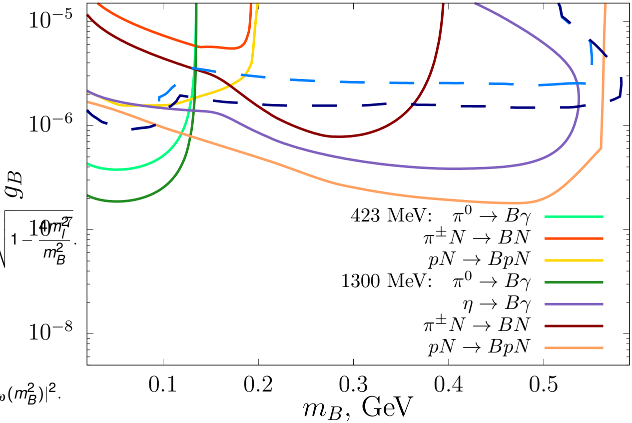
Feature: decay rates are suppressed by ε^2

Decays to leptons

$$\Gamma\left(B\to l^+l^-\right)=\frac{\alpha_{em}\varepsilon^2 m_B}{3}\left(1+\frac{2m_l^2}{m_B^2}\right)\sqrt{1-\frac{4m_l^2}{m_B^2}}.$$

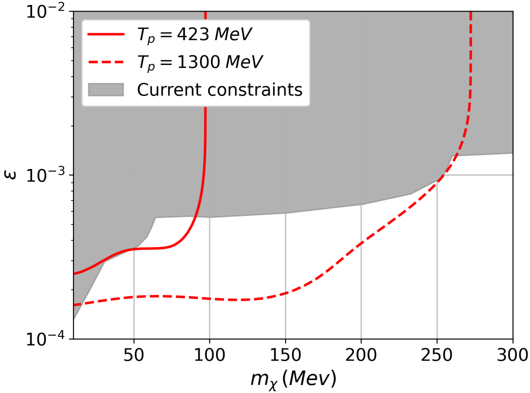
Decays to 3 photons

$$\Gamma(B\to\pi^0\gamma)=\frac{\alpha_B\alpha_{em}m_B^3}{96\pi^3 f_\pi^2}\left(1-\frac{m_\pi^2}{m_B^2}\right)^3|F_\omega(m_B^2)|^2.$$

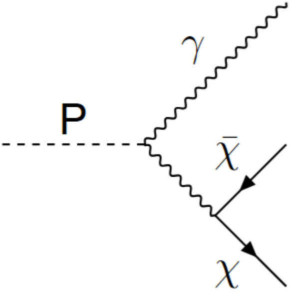


Detector at $l=7$ m and its fiducial volume is $1\,\text{m}^2\times 2\,\text{m}$

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



Production in πN and pN scatterings and in decays of π^0 and η



$$N(\delta x) = \frac{K}{2}\rho\frac{Z}{A}\frac{\varepsilon^2}{\beta^2}\,\delta x \times \int_{T_{\rm min}}^{T_{\rm max}} dT\,\frac{1-\beta^2 T/T_{\rm max}}{T^2}\,,$$

$$T_{\rm max} = \frac{2m_e\beta^2\gamma^2}{1+\frac{2\gamma m_e}{m_\chi}+\left(\frac{m_e}{m_\chi}\right)^2}\,. \qquad T_{\rm min} = 1\,{\rm keV}$$

$$\mathcal{L} = \varepsilon e A^\mu \bar{\chi}\gamma_\mu\chi\,.$$

Two hits in the detector $\chi e^- \to \chi e^-$

$$P \approx \frac{1}{2} N^2(L_{det})$$

Conclusions

- NICA: we need new detectors for MPD and BM@N
- New project TiMoFey: about 10^{22} per year, proton energy 0.4, 1.3 GeV
- Structure is tuned to have high neutrino flux from stopped pions
- Excellent prospects in searches for new light feebly interacting particles
- We just start the project, see paper

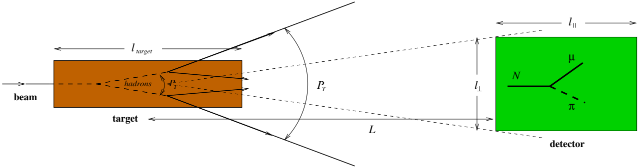
  arXiv:2508.01968

  for details

FIPs at NICA: beams heating the 1 m tungsten target

the intensity frontier

fixed target experiment



nuclei	atomic number A	electric charge Z	energy per nucleon E_b	cross section on W, in b
Xe	131	54	4.5 GeV	4.6
Bi	209	83	4.5 GeV	5.4
W	184	74	–	
d	2	1	6 GeV	1.9
p	1	1	12 GeV	1.8

$$\sigma_{pp}(E_{\text{beam}} = 4.5\,,\ 12\,,\ 25\,\text{GeV}) \approx 40\,\text{mb}\,, \quad \sigma_{N_1\,N_2} = \sigma_{pp}\cdot\left(A_1^{1/3} + A_2^{1/3}\right)^2$$

Alexey Zhevlakov, Artem Ivanov, Serguei Kuleshov, Sergei Gninenko, Dmitry Peshekhonov, Vladimir Poliakov, Nikolai Krasnikov, Ekaterina Kriukova, Dmitry Kirpichnikov, Valery Lyubovitsky, Mikhail Kirsanov, Dmitry Kalashnikov, Sergey Demidov

Meson production by ions incident on a tangsten target

Very crude estimates based on literature

are conitent with QCD generator simulations...

check point: 4.5 GeV in lab gives 3.5 GeV in CM

thus we get per each nuclei from the beam:

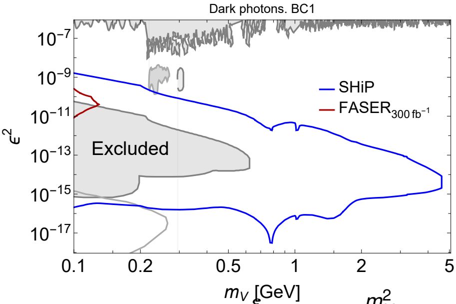
$N_A \lesssim 10^{12}$

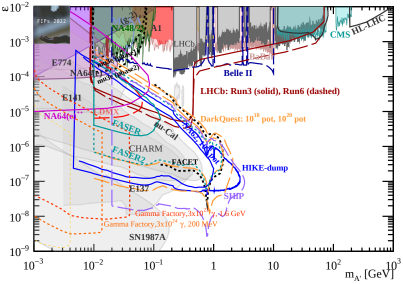
$$N(\pi^0) = 10\,,\quad N(\eta) = 6\cdot 10^{-2}\,,\quad N(\omega) = 8\cdot 10^{-2}\,,\; N(\rho^0) = 4\cdot 10^{-2}\,,\quad N(\phi) = 3.5\cdot 10^{-4}$$

The most promising regions: $L_{decay} \simeq L_{dump} = 1$ m

Then we get $S \propto \varepsilon^2$, not $\propto \varepsilon^4$

BC1: paraphoton (dark photon) V_μ





$$\Delta L_{int} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu \,, \quad \mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

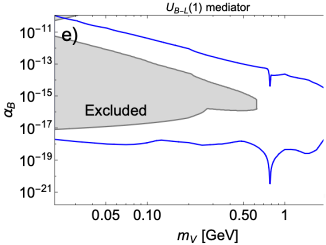
$$L_{dec} \simeq 5\,\text{cm} \times \gamma \times \frac{100\,\text{MeV}}{m_{\gamma'}} \left(\frac{10^{-5}}{\epsilon}\right)^2$$

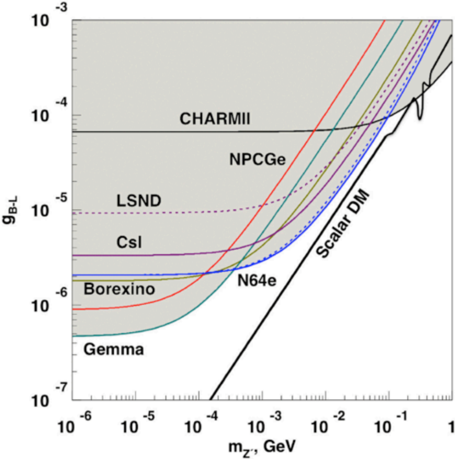
– for production via $\pi^0 \to \gamma + A'$ and $\eta \to \gamma + A'$ and $\omega \to \pi^0 + A'$ see formulas for branchings in 2401.12893

– light vector production via proton bremstrauhlung may be obtained by making use of numerical approximations presented in 2409.11386

– light production via secondary pion bremstrauhlung may be obtained by making use of numerical approximations presented in 2510.00213

BC2*: vector V_μ of anomalous $U(1)_B$ gauge symmetry

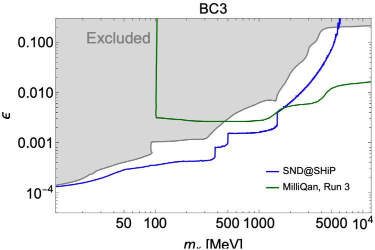


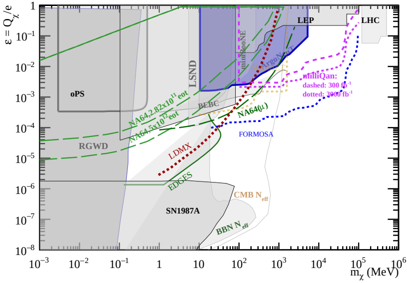


$$\Delta L_{int} = -e_B V_\mu j_B^\mu + \frac{m_V^2}{2} V_\mu V^\mu$$

for $M_V < 2m_\pi$ decays are suppressed!!

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





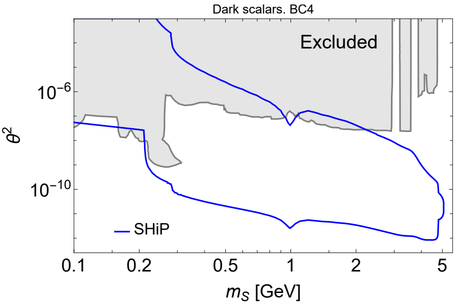
$$\Delta L_{int} = -\varepsilon e A_\mu \bar{\psi} \gamma^\mu \psi - m_\kappa \bar{\psi} \psi$$

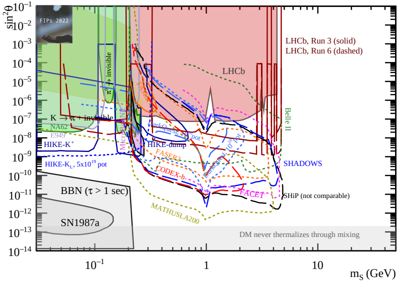
$$\mathrm{Br}(\eta \to \gamma \chi \bar{\chi}) \sim 0.5 \cdot 10^{-9} \left(\frac{\varepsilon}{10^{-3}} \right)^2$$

see e.g. 2103.11814 for more production channels

signature: double hit !!

BC4: scalar portal: only mixing with Higgs





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

production is via kaon decays (see e.g. 2105.11102)

kink in kaon decays??

$$\mathrm{Br}(K \to \pi S) \simeq 10^{-10}\left(\frac{\theta^2}{10^{-7}}\right)$$

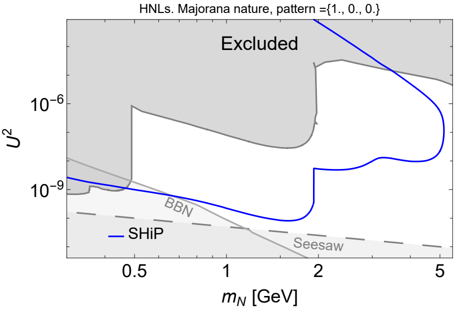
decay length at $\gamma\beta = 1$

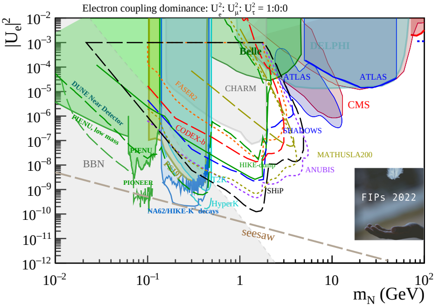
$c\tau_K \simeq 3\,m$

but only 10^8 K_L...

$$\tau_S = 10^7\mathrm{cm}\left(\frac{150\,\mathrm{MeV}}{m_S}\right)\left(\frac{10^{-7}}{\theta^2}\right)$$

BC6: Heavy Neutral Lepton N coupled to ν_e





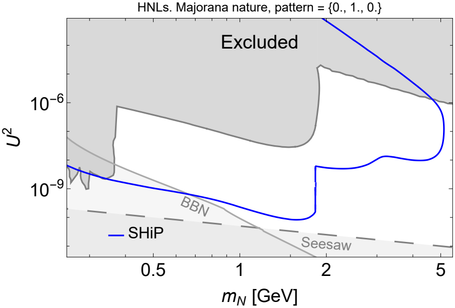
$$\Delta L_{int} = Y_{\alpha I} \bar{L}_\alpha \tilde{H} N_I \quad : \quad \nu_e \to \nu_e + U_e N$$

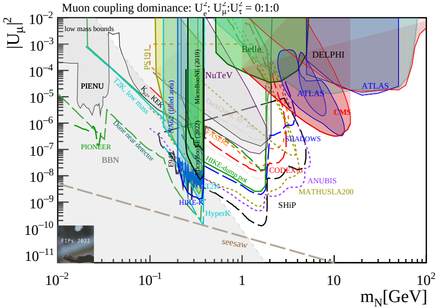
decay into a visible mode is too slow...just rescaling muon lifetime

$$\tau_N \simeq \tau_\mu |U_e|^{-2} \left(\frac{m_\mu}{m_N}\right)^5 = 3 \cdot 10^3\,\mathrm{s} \times \frac{10^{-6}}{|U_e|^2} \left(\frac{20\,\mathrm{MeV}}{m_N}\right)^5$$

$$L_{decay} = 10^{14}\,\mathrm{cm} \times \gamma_N \times \frac{10^{-6}}{|U_e|^2} \left(\frac{20\,\mathrm{MeV}}{m_N}\right)^5$$

BC7: Heavy Neutral Lepton N coupled to ν_μ





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

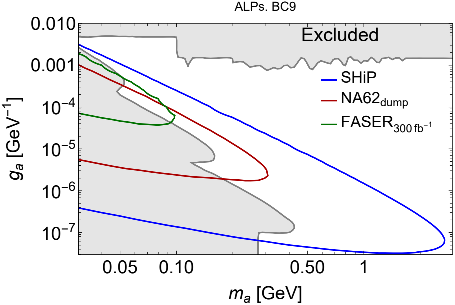
may be $K \to Ne(\mu)$ inside the detector. . . ?

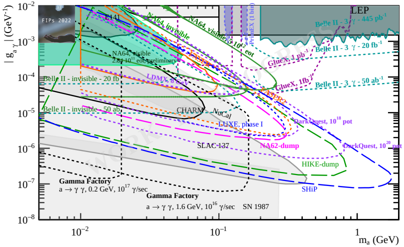
must recognize K and outgoing charged lepton!

kink as the HNL signature. . . !

but only 10^8 K_L...

BC9: Axion Like Particle *a* coupled to photons





$$\Delta L_{int} = \frac{g_{\gamma\gamma}}{8}\, a F_{\mu\nu} F_{\lambda\rho} \varepsilon^{\mu\nu\lambda\rho} - \frac{1}{2} m_a^2 a^2$$

decay length:

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{\gamma\gamma}^2 m_a^3}{64\pi}\,, \qquad L_{a\to\gamma\gamma} = \frac{c\,\gamma_a}{\Gamma_{a\to\gamma\gamma}} = 25\,\text{cm} \times \frac{E_a}{1\,\text{GeV}} \left(\frac{20\,\text{MeV}}{m_a}\right)^4 \left(\frac{10^{-3}\,\text{GeV}^{-1}}{g_{\gamma\gamma}}\right)^2$$

BC9: Axion Like Particle a coupled to photons

based on the analysis from 2401.12893, so we transfer everything to the CM frame to use the WW-approximation

$$n_N(\omega) = \frac{Z^2\alpha}{\pi}\left[\left(2\frac{\omega^2}{(\Lambda\gamma)^2}+1\right)\ln\left(1+\frac{(\Lambda\gamma)^2}{\omega^2}\right)-2\right]\frac{1}{\omega},$$

where ω is the photon energy, $\gamma = \sqrt{\gamma_b/2} = 1.5$ is the ion gamma-factor, $\Lambda = 50\,\text{MeV}$.

$$\sigma_{N+W\to a} = \frac{g_{\gamma\gamma}^2 m_a^2}{8\pi}\int_{m_a^2/\omega_{max}^2}^{\omega_{max}^2/m_a^2}\frac{dx}{8x}\, n_N\left(\sqrt{\frac{m_a^2 x}{4}}\right) n_W\left(\sqrt{\frac{m_a^2}{4x}}\right),$$

with $x \equiv \omega_1/\omega_2$ and $\omega_{max} \gg \Lambda\gamma$ solving $n(\omega_{max}) = 0$.

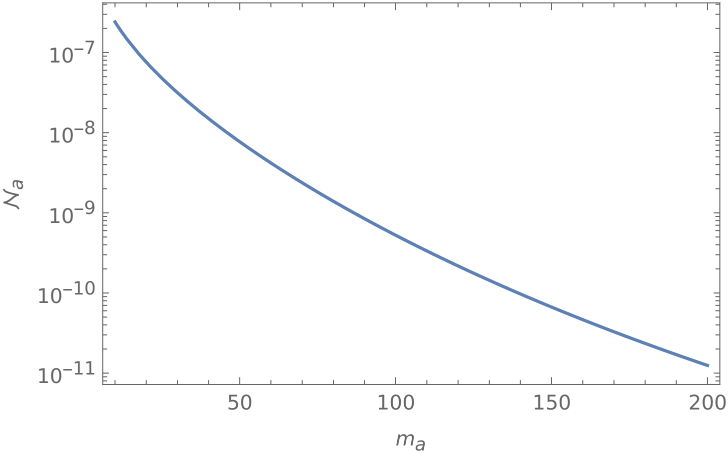
Number of produced axions per each nuclei in a beam:

$$\mathcal{N}_a \frac{\sigma_{N+W\to a}}{\sigma_{N+W}}$$

The axion 3-momentum distribution is restored with boost $1.5 \to 4.5$

BC9: Axion Like Particle a coupled to photons

We take $\sigma_{NW} \approx 0.5\,\text{b}$ and for each nuclei N we get the follwoing number of axions of a given mass



calculations is performed for $g_{\gamma\gamma} = 10^{-3}\,\text{GeV}^{-1}$ and $\mathcal{N}_a \propto g_{\gamma\gamma}{}^2$

BC9: Axion Like Particle *a* coupled to photons

Contributions from pseudoscalar meson decays, e.g.

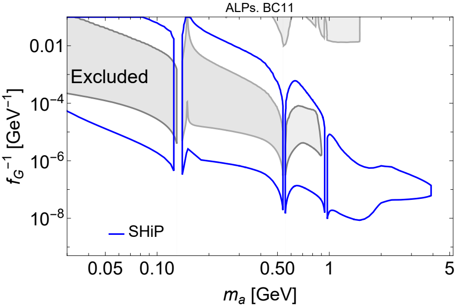
$$\mathrm{Br}\,(P \to \gamma\gamma a) \sim \frac{m_P^2 g_{\gamma\gamma}^2}{16\pi^2} \sim 10^{-10} \times \left(\frac{M_P}{100\,\mathrm{MeV}}\right)^2 \left(\frac{g_{\gamma\gamma}}{10^{-3}\,\mathrm{GeV}^{-1}}\right)$$

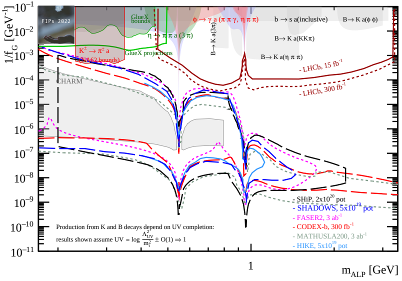
Contributions from vector meson decays

$$V \to \gamma a$$

similar branching on dimensional grounds...

BC11: Axion Like Particle *a* coupled to gluons





Couplings must be correctly normalized!!!

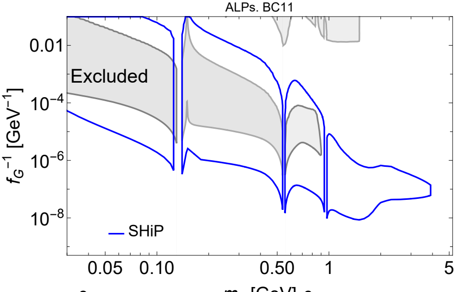
decays at $m_a \lesssim \Lambda_{QCD}$ are suppressed

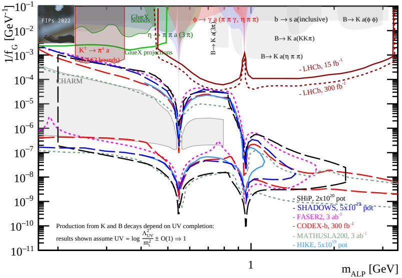
$$\Delta L_{int} = \frac{\alpha_s}{8\pi f_a} a G_{\mu\nu} \tilde{G}^{\mu\nu} - \frac{1}{2} m_a^2 a^2$$

It induces mixing with neutral pseudoscalar mesons, see e.g. 2508.01968, angles are

$$\theta_{a\pi^0} = \frac{1}{2}\delta_I \frac{m_a^2}{m_a^2 - m_\pi^2}\frac{f_\pi}{f_a}, \quad \theta_{a\eta} = \frac{1}{\sqrt{6}}\frac{m_a^2 - m_\pi^2/2}{m_a^2 - m_\eta^2}\frac{f_\pi}{f_a} \quad \text{where} \quad \delta_I = \frac{m_d - m_u}{m_d + m_u} \approx \frac{1}{3}$$

BC11: Axion Like Particle *a* coupled to gluons





$$\frac{d^2N_a}{d\theta_a dE_a} = \sum_{P=\pi^0,\eta} |\theta_{aP}|^2 \frac{d^2N_P}{d\theta_P dE_P}\bigg|_{E_P=E_a,\,\theta_P=\theta_a},$$

gives per a pion $3\cdot 10^{-10}\left(\frac{f_a}{10^3\,\text{GeV}}\right)^2$

The decay modes are $\gamma\gamma$, $\pi\pi\gamma$ and 3π, e.g.

$$\Gamma(a\to\gamma\gamma) = \frac{\alpha^2 m_a^3}{256\pi^3 f_a^2}|c_{\gamma\gamma}|^2,\ \text{with } c_{\gamma\gamma} \approx \frac{c_{WW}+c_{BB}}{c_{GG}} - 1.92 + \frac{1}{3}\frac{m_a^2}{m_a^2-m_\pi^2} + \frac{4}{9}\frac{2m_a^2-m_\pi^2}{m_a^2-m_\eta^2} + \frac{7}{9}\frac{m_a^2-2m_\pi^2}{m_a^2-m_{\eta'}^2}$$

Hence the decay length for dominating $\gamma\gamma$ channel is

$$L_{a\to\gamma\gamma} = \frac{c\gamma_a}{\Gamma(a\to\gamma\gamma)} = 3\cdot 10^4\,\text{cm} \times \frac{1}{|c_{\gamma\gamma}|^2}\left(\frac{100\,\text{MeV}}{m_a}\right)^4 \frac{E_a}{1\,\text{GeV}}\left(\frac{f_a}{10^3\,\text{GeV}}\right)^2$$

FIMPs at NICA

- The mot realitic case:
  In the collider mode, but need a good tracker
- In a beam dump: with safe statistics of 10^{12}
  small rooms for new particles from kaons if recognaize kinks!
  small room for axions but must recognaize $\gamma\gamma$!
- Much brighter prospects with much higher statistics
  need special detector at safe place (radiation!)
- background for beam dump mode must be studied...!!

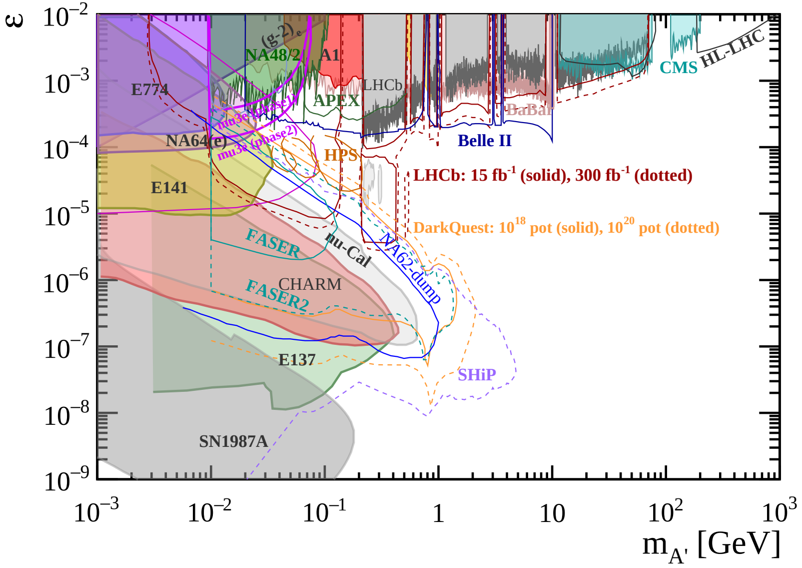
It's not so easy to explore light new physics by product
even with new facility

In case of NICA you need new modern detectors

supported by RSF grant No.25-12-00309

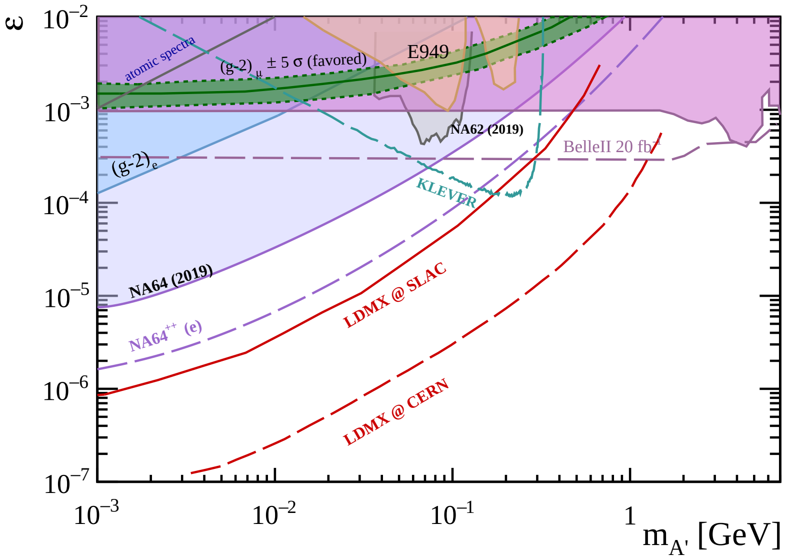
Searches for visible decays

2102.12143



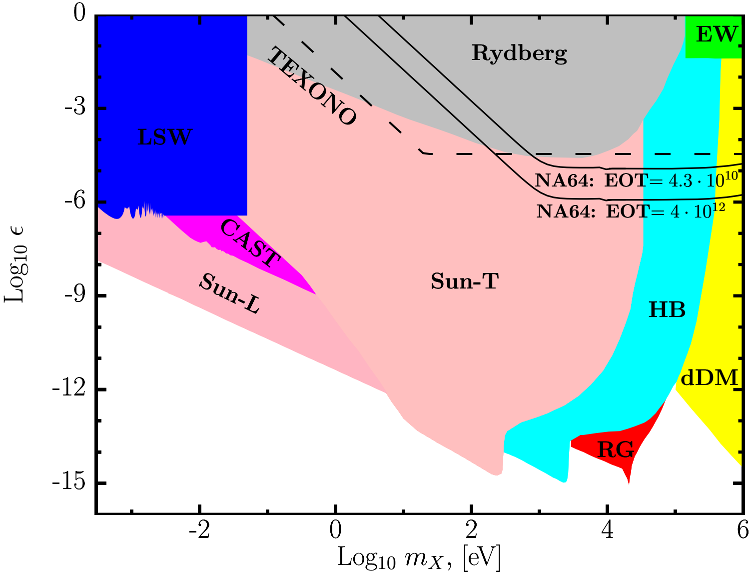
Searches for invisible mode

2102.12143



Searches for invisible mode

1812.02719



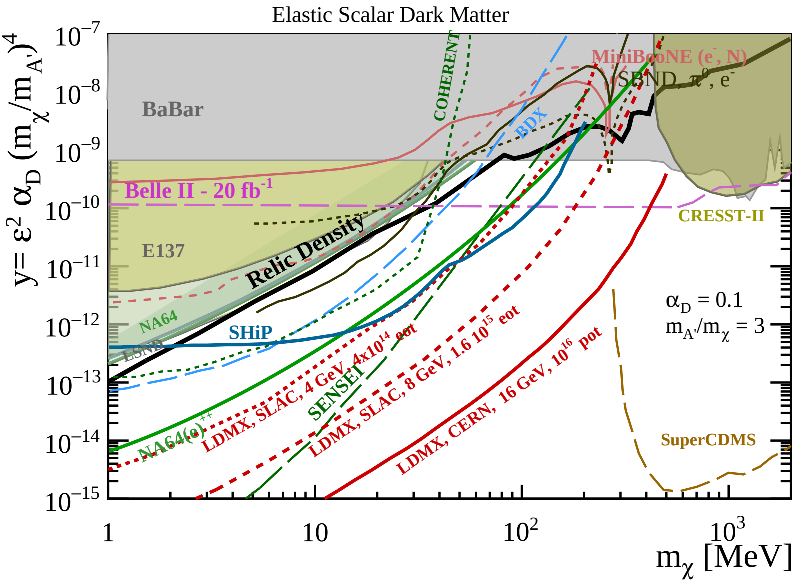
P is the probability to decay inside detector

- **Model:** dark photon A' with parameters $(m_{A'}, \varepsilon)$.
- **Reference point:** $m_{A'} = 50\,(100)$ MeV, $\varepsilon = 10^{-5}$.
- **Production channels:** π^0 decays $\to \gamma A'$, and inelastic $\pi^\pm N$ scattering $\to NA'$.
- ε **scaling (production):** number of produced A' scale as ε^2.
- ε **scaling (decay):** the decay width Γ scales as ε^2, and the decay length (mean decay path) scales as ε^{-2}. In the reference point $P \sim 0.1$.
- **Reference yields (decays in detector):** $\pi^\pm$ scattering gives $\sim 2 \times 10^{-14}\,(5.3 \times 10^{-14})$ for $\pi^\pm$ per charged pion; π^0 decays give $\sim 3 \times 10^{-12}$ (1.8×10^{-14}) per neutral pion decay.

- **Model:** Leptophobic B with parameters (m_B, g_B).
- **Reference point:** $m_B = 50\,(100)$ MeV, $g_B = 10^{-6}$.
- **Production channels:** π^0 decays $\to \gamma B$.
- g_B **scaling (production):** number of produced B scale as g_B^2.
- g_B **scaling (decay):** the decay width Γ scales as g_B^2, and the decay length (mean decay path) scales as g_B^{-2}. In the reference point $P \sim 10^{-6}$.
- **Reference yields (decays in detector):** π^0 decays give $\sim 4.8 \times 10^{-19}$ (1.4×10^{-18}) per neutral pion decay.

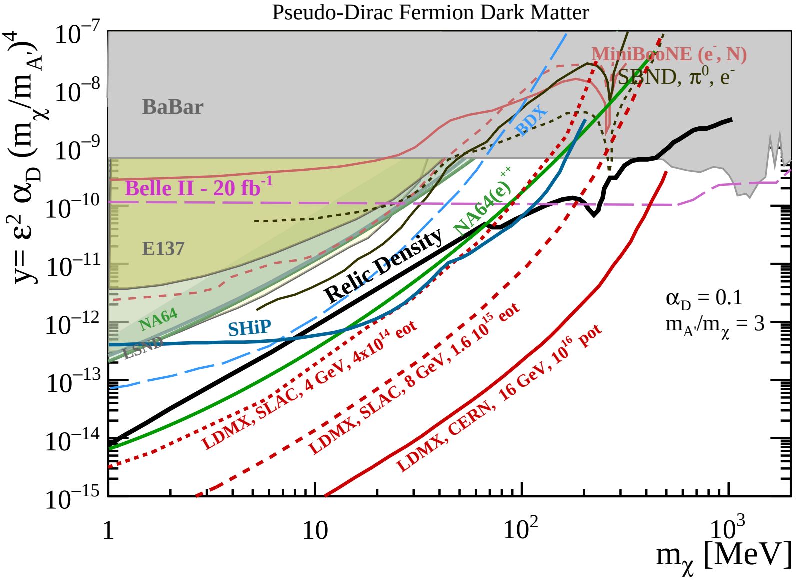
Searches for dark matter

2102.12143



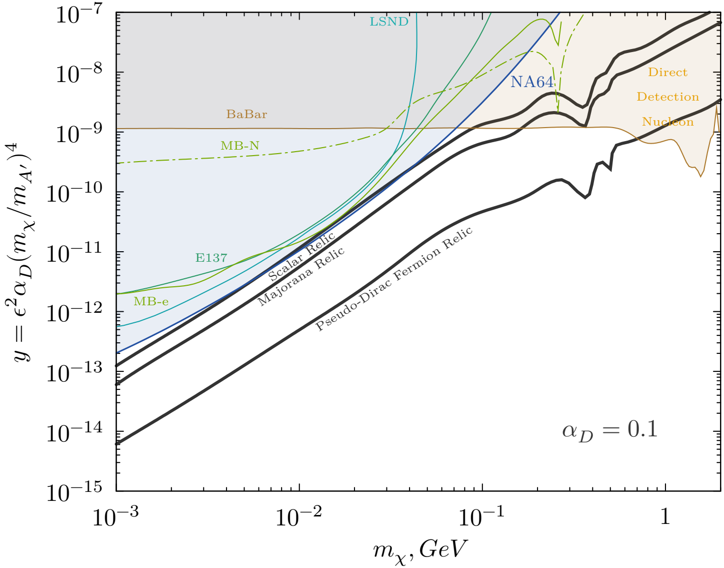
Searches for dark matter

2102.12143

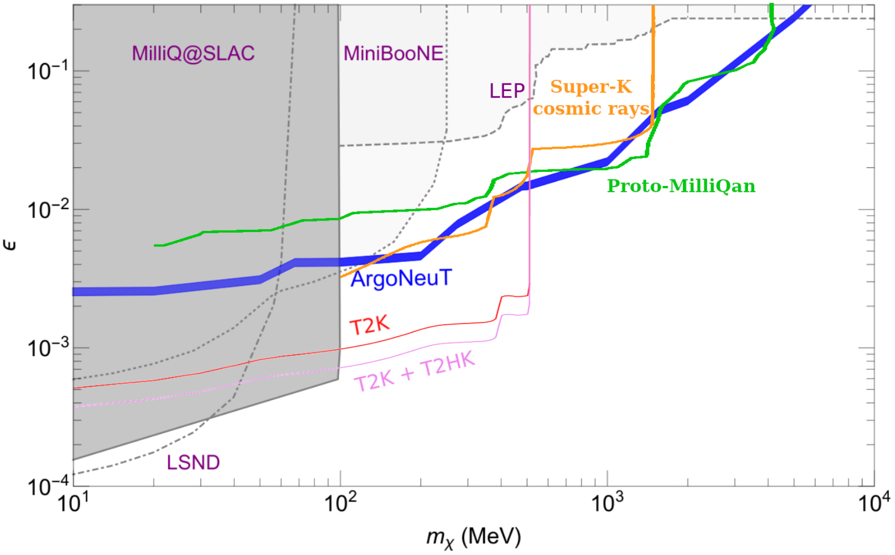


Exclusion plots: always check!

2102.12143

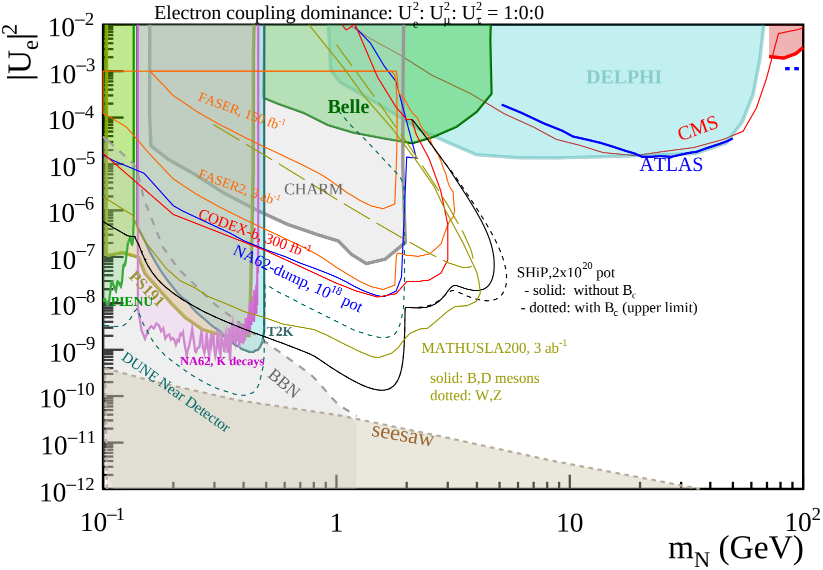


Heavy vector: leaving with millicharged particles 2103.11814



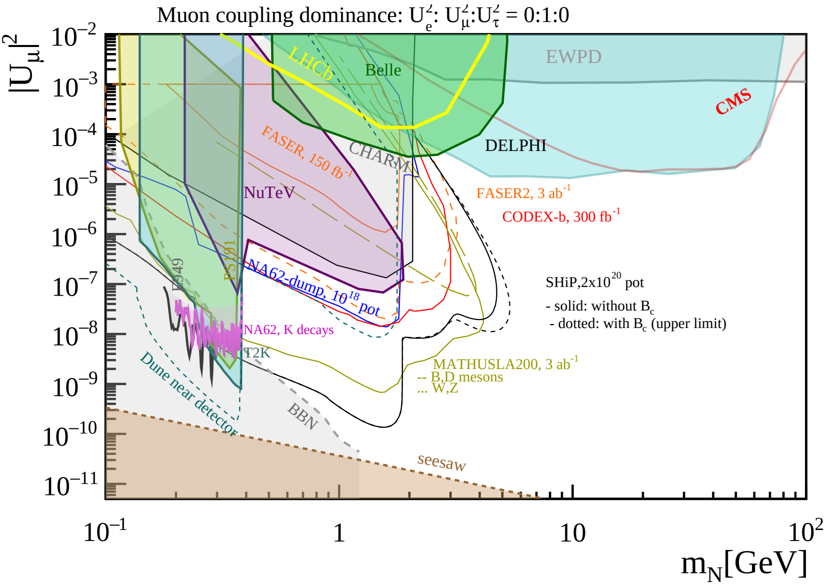
mixing with ν_e

2102.12143



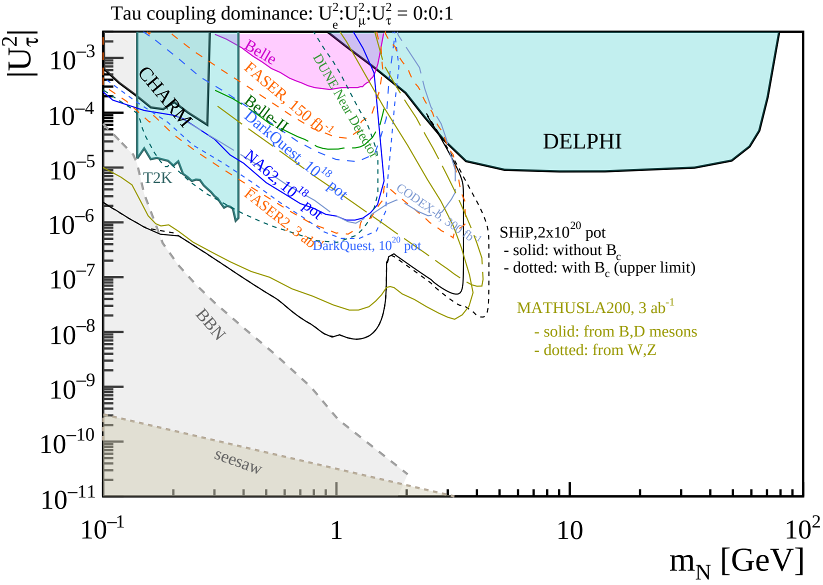
mixing with ν_μ

2102.12143



mixing with ν_τ

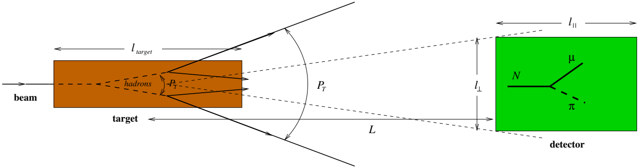
2102.12143



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, SHiP) or working as by-product (e.g. T2K)
- thin target (e.g. T2K) or dump (e.g. NA64)
- decays or hits as the signature $y^2 \times y^2$
- production by cosmic rays
- at e^+e^- colliders y^2