Looking for Beyond Standard Model short-lived particles with secondary production

Krzysztof Jodłowski

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

SUSY 2021
25/8/2021

Based on:

KJ, F. Kling, L. Roszkowski and S. Trojanowski, 1911.11346

KJ, S. Trojanowski, 2011.04751

Introduction

coupling

Already
discovered

Heavy, strongly
Interacting particles

Intensity frontier

Light, weakly
interacting particles

mass

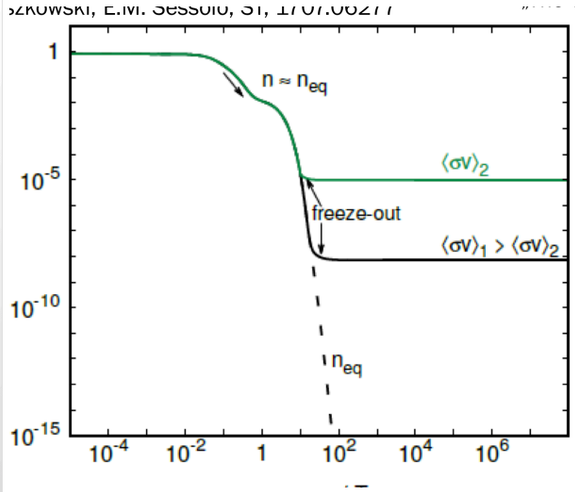
Introduction

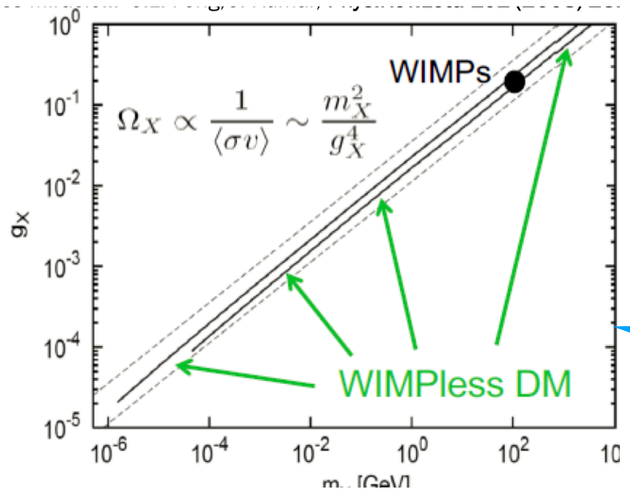
coupling

Already discovered

Heavy, strongly Interacting particles

Feng, Kumar, 0803.4196





Weak couplings → large luminosities required

- Cosmology
  - WIMP-less DM
  - …
- Anomalies
  - $(g-2)_\mu$
  - …
- Neutrino mass, HNL…

Intensity frontier

Light, weakly interacting particles

mass

Intensity frontier

Experimental signatures

Look for:

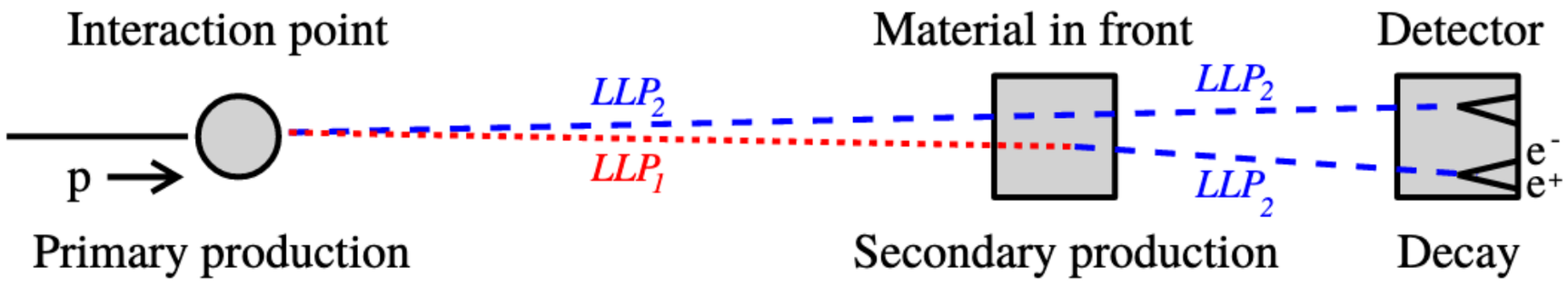
- highly-displaced decay signatures of light **long-lived particles** (LLPs) in a **distant detector** that is **well-shielded from SM background**
- missing energy in invisible decays
- …

More realistic models (e.g. LLP+DM, Dark Photon+Dark Higgs, mirror sector/Twin Higgs,…) **typically predict multiple light particles** which provide additional detection modes

Physics Beyond Colliders, 1901.09966

Secondary production

Assume nonminimal BSM particle content featuring LLP's with $m_{\mathrm{LLP}_2} > m_{\mathrm{LLP}_1}$



- Primary production limited to a certain lifetime regime of new particles that must reach the detector before decaying

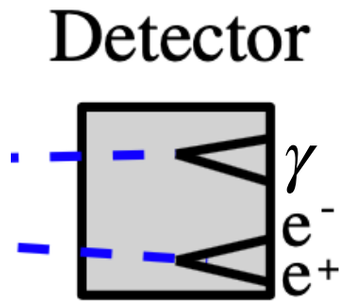
$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{\bar{d}}\right)\left[1-\exp\left(-\frac{L_{max}-L_{min}}{\bar{d}}\right)\right],$$

$$N_{\mathrm{sig}} \propto \begin{cases} \mathcal{L}^{\mathrm{int}}\,\epsilon^2\,e^{-L_{\mathrm{min}}/\bar{d}} & \text{for } \bar{d} \ll L_{\mathrm{min}} \\ \mathcal{L}^{\mathrm{int}}\,\epsilon^2\,\frac{L_{\mathrm{max}}-L_{\mathrm{min}}}{\bar{d}} & \text{for } \bar{d} \gg L_{\mathrm{min}} \end{cases}$$

- Secondary production:
  - Signal due to $\mathrm{LLP}_2 \to (\mathrm{LLP}_1+)$ visible or $\mathrm{LLP}_2 + e^- \to \mathrm{LLP}_2 + e^-$

Experimental signatures of new physics

- **LLP signal inside the FASER decay vessel – e^+e^- and γ**
  - $E_{vis} > 100$ GeV
  - e^+e^- search: negligible background due to high energies of LLP's
  - γ search:
    - neutrino-induced BG minimized by dedicated preshower detector
    - BG from muon-induced photons expected to be vetoed by detecting a time-coincident muon going through the detector → <u>excess of single-photon events unaccompanied by any muon indicative of new physics</u>

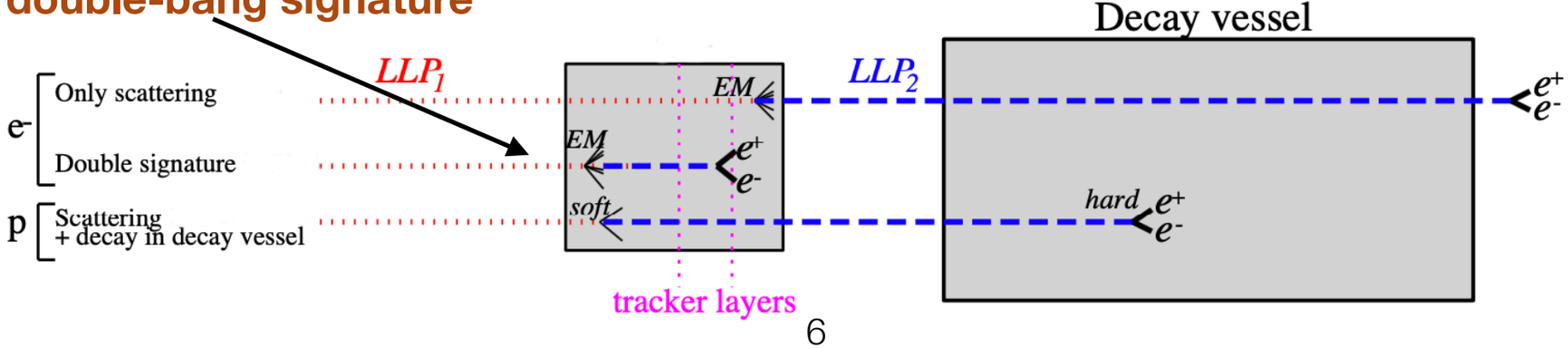


- **Prompt decays of high-energy LLPs inside the ECC detector**
  - looking for very high-energy photons $E_\gamma > 1$ TeV or 3 TeV unaccompanied by any time-coincident muon

- **Scattering off electrons**
  - new-physics-induced neutrino scatterings off electrons producing detectable electron recoils inside the neutrino detector.
  - **Energy and angular cuts**:
    - Electron energy and angular cuts following the DM scattering signature

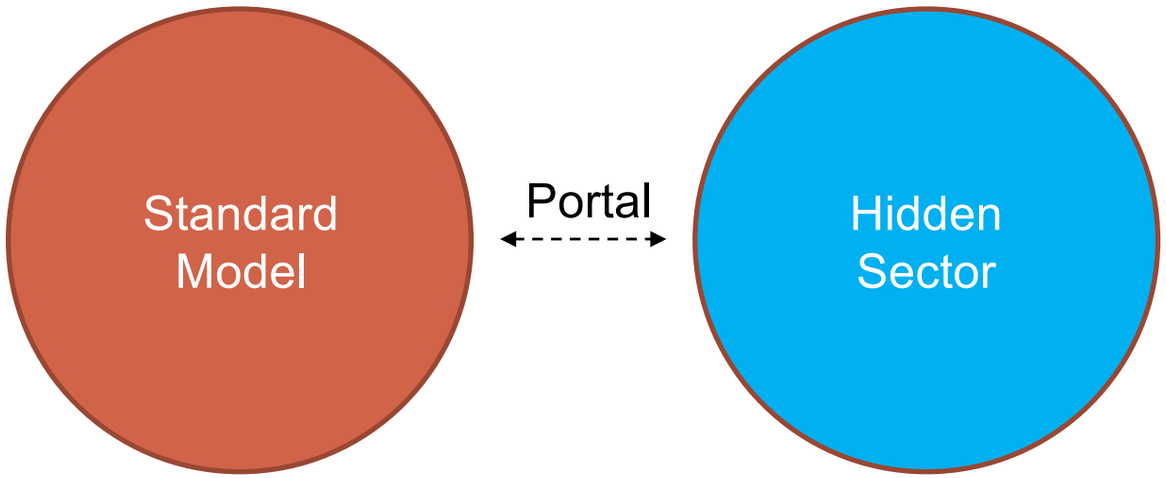
      Batell, Feng, Trojanowski, 2101.10338
      Technical Proposal: A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, 1504.04855
      Sensitivity of the SHiP experiment to light dark matter, 2010.11057
  - The cuts have been designed to minimize the neutrino-induced BG to the level of $O(10)$ such expected events in FASERν2.

- **Collinear double-bang signature**



SM-Hidden Sector portals

- Null searches for WIMPs motivate exploring lower mass ranges while preserving basic mechanism of freeze-out
- Typical scenario: extend SM by Dark Sector + Mediator
    - DM freezes out
    - Mediator decays into SM particles



- Restricting to dimension 4 operators, there are only 3 possibilities:

$$\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

$$\mathscr{L}_{\text{scalar portal}} = \alpha_1 S H^\dagger H + \alpha S^2 H^\dagger H$$

$$\mathscr{L}_{\text{neutrino portal}} = F_\ell \left(\epsilon_{ab} \overline{L}_{\ell,a} H_b\right) N$$

Vector Portal

Vector Portal - Dark Photon

- Extend SM by “dark” $U(1)_D$ gauge group:

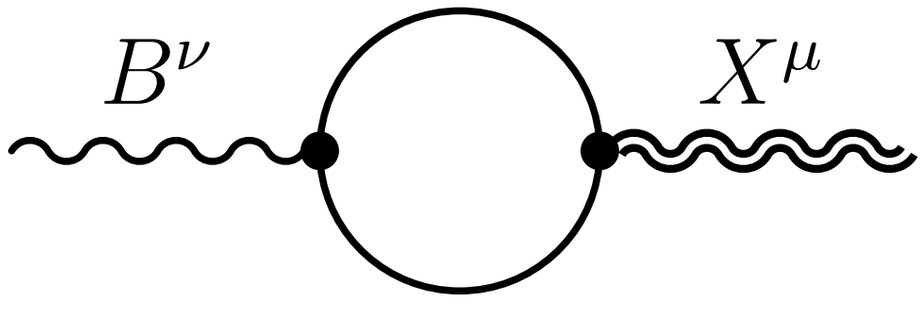
$$\mathscr{L} \supset -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F^{\mu\nu'}F'_{\mu\nu} - \frac{\epsilon}{2}B^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu}$$

- QED + Dark $U(1)_D$ + Kinetic mixing + Mass term

$$-\frac{\epsilon}{2}B^{\mu\nu}F'_{\mu\nu}$$

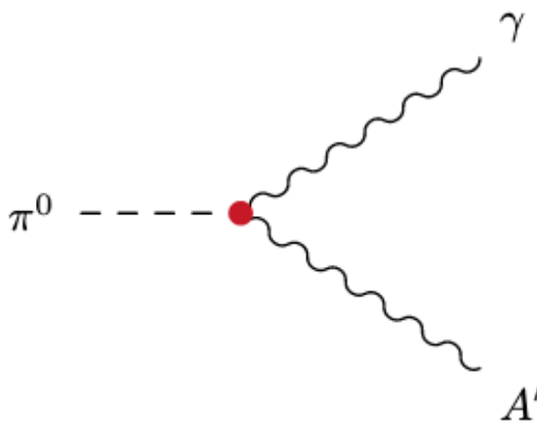
- Even if $\epsilon = 0$ at tree level, non-zero value induced by loops

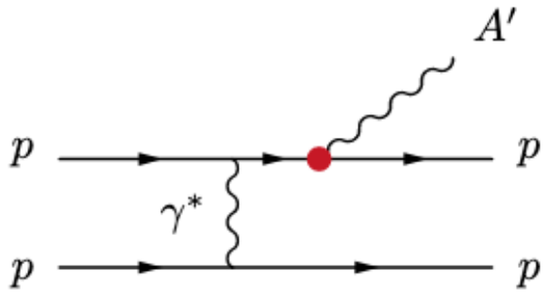
$$\epsilon \sim \frac{g_D g_Y}{16\pi^2} \sim 10^{-3}$$



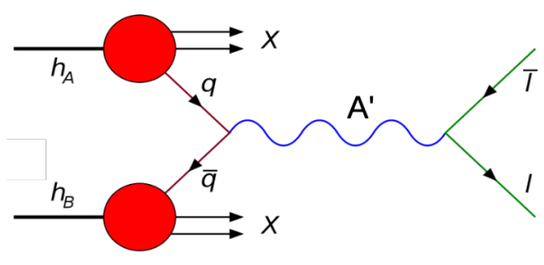
Production of Dark Photon

- Mesons decay
- Bremsstrahlung

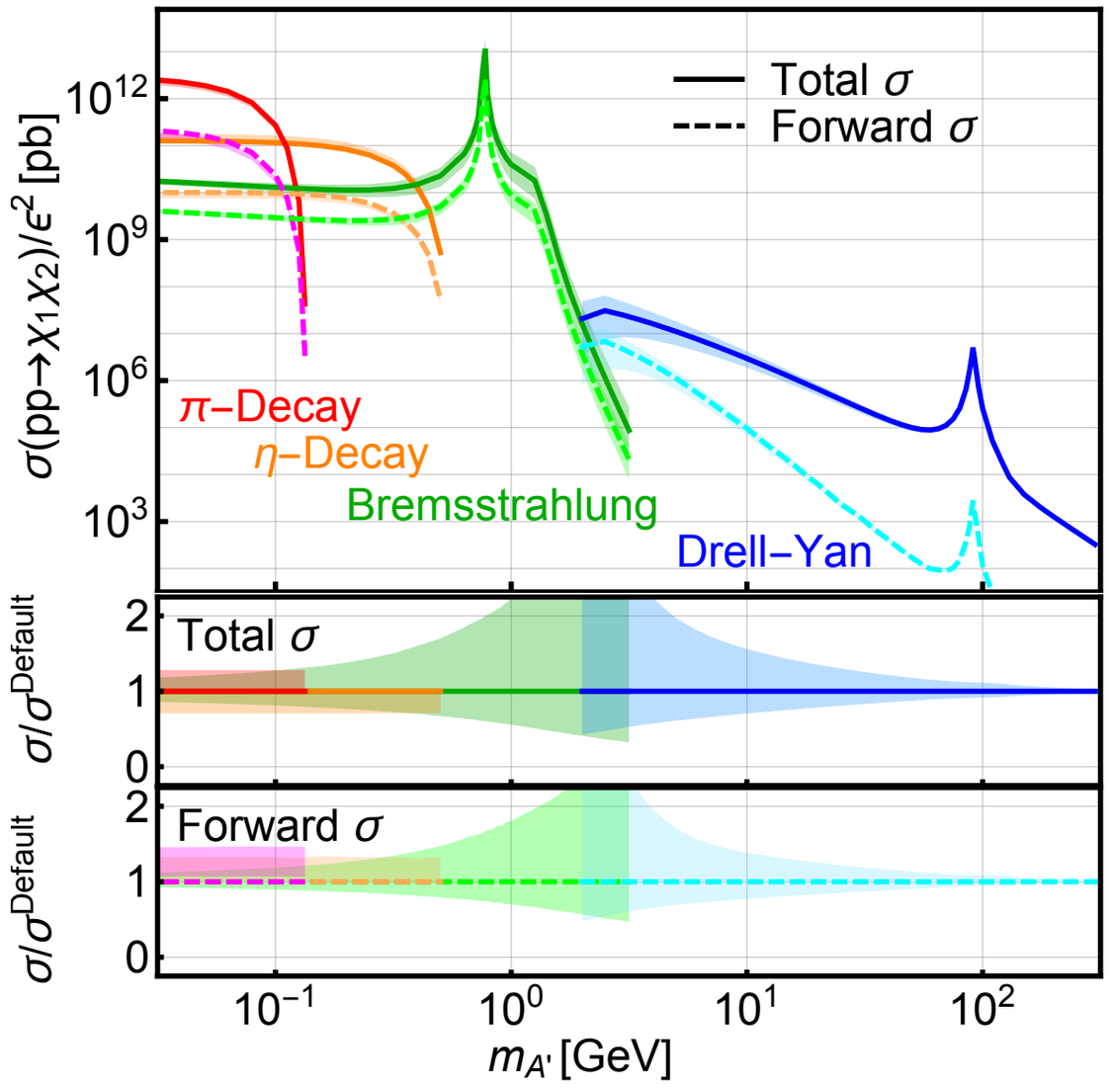




- Drell-Yan



Asher, Kling: 1810.01879



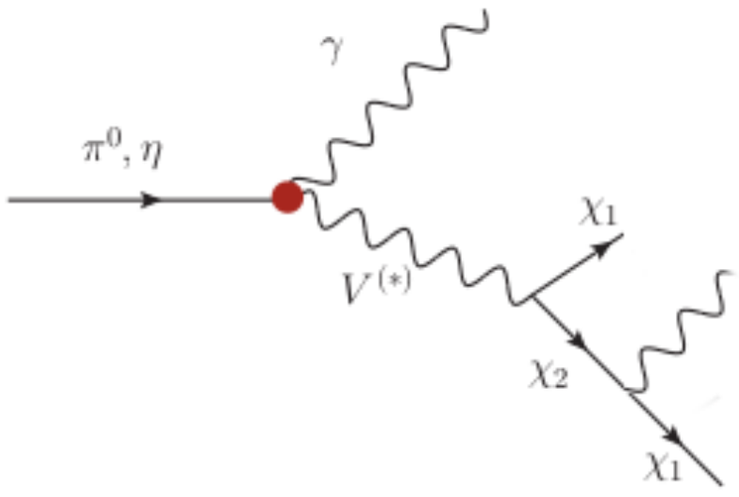
Production contributions for masses of interest only weakly dependent on Dark Sector matter specification

Inelastic DM

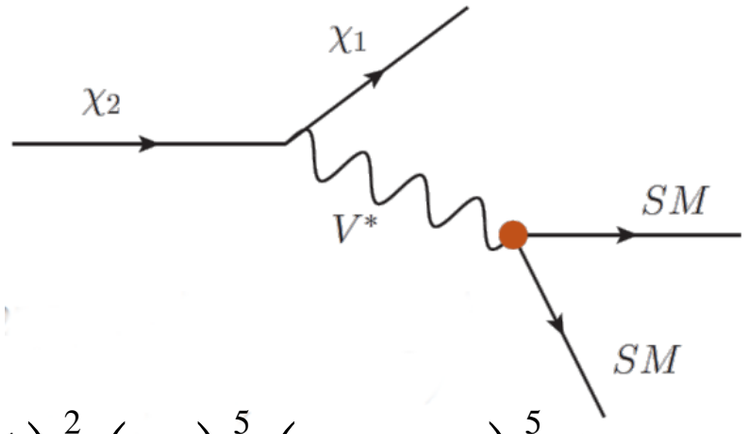
$$\mathscr{L}_{int} \supset g_{12}\bar{\chi}_2\gamma^{\mu}\chi_1 X_{\mu} + h.c.$$ Smith, Weiner, 0101138

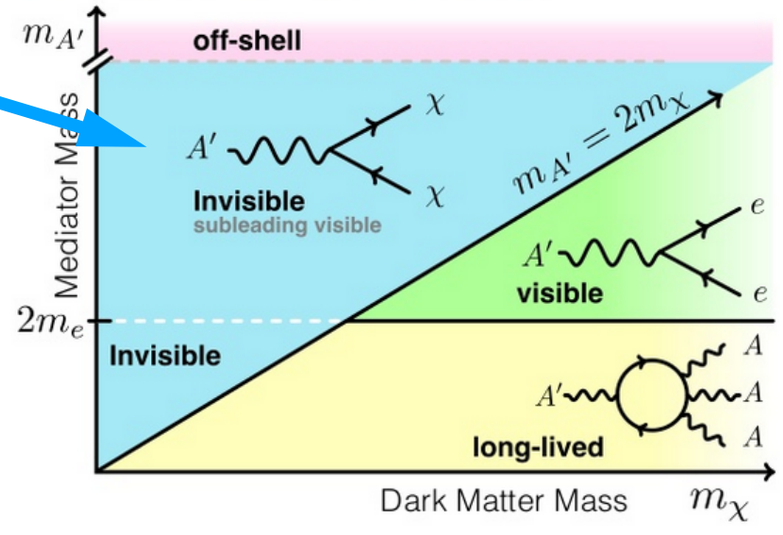
- Two fermions with dominant non-diagonal couplings to dark photon
- χ_1 is stable - good DM candidate
- Relic density obtained thanks to $\chi_1\chi_2$ annihilations to SM
- Masses in regime where dark photon predominantly decays into χ_1 and χ_2 while dark photon is produced mainly in mesons decays

Secluded WIMP



$$m_{\chi_1} : m_{\chi_2} : m_{A'} \sim 1 : 3 : 4$$

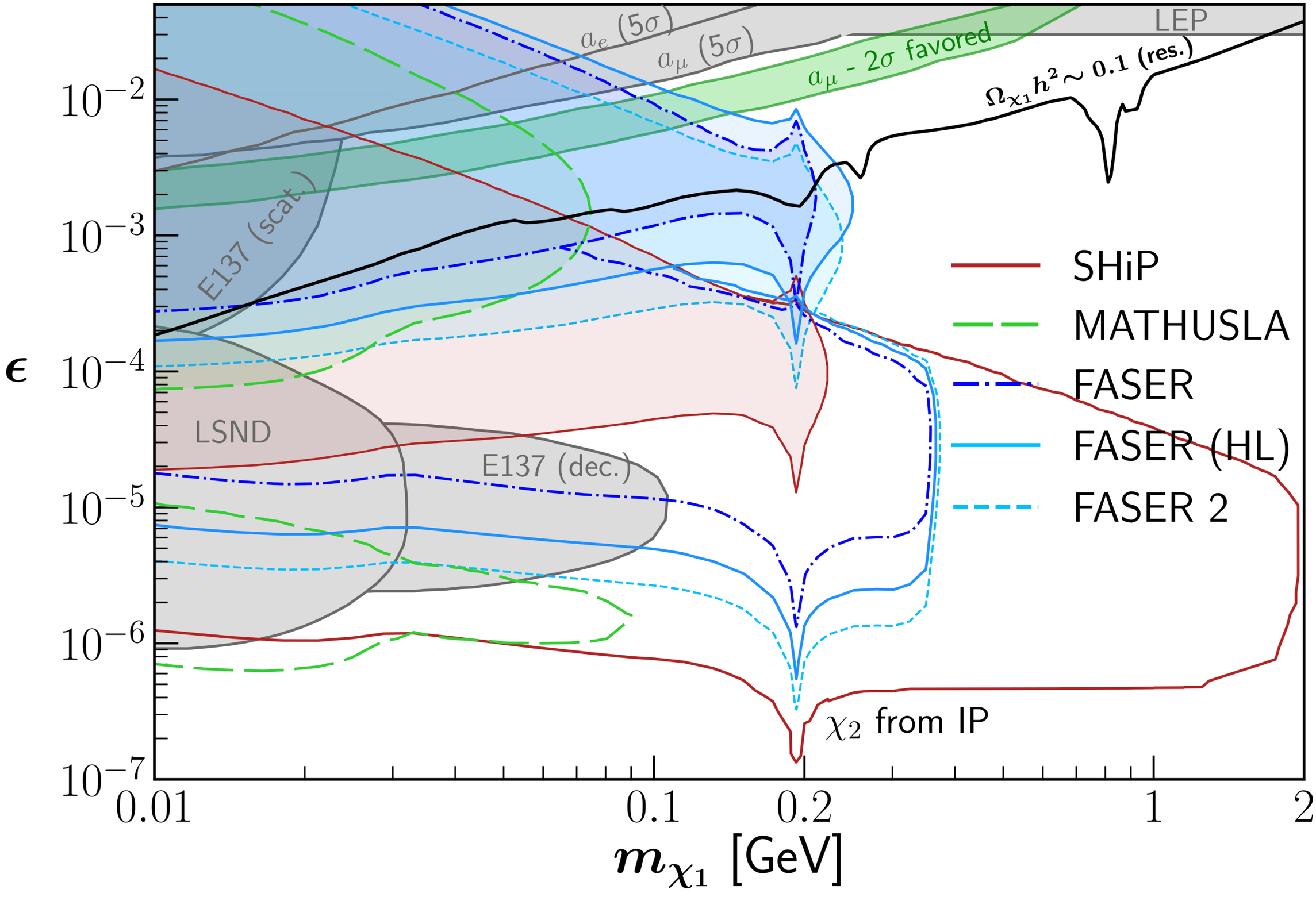


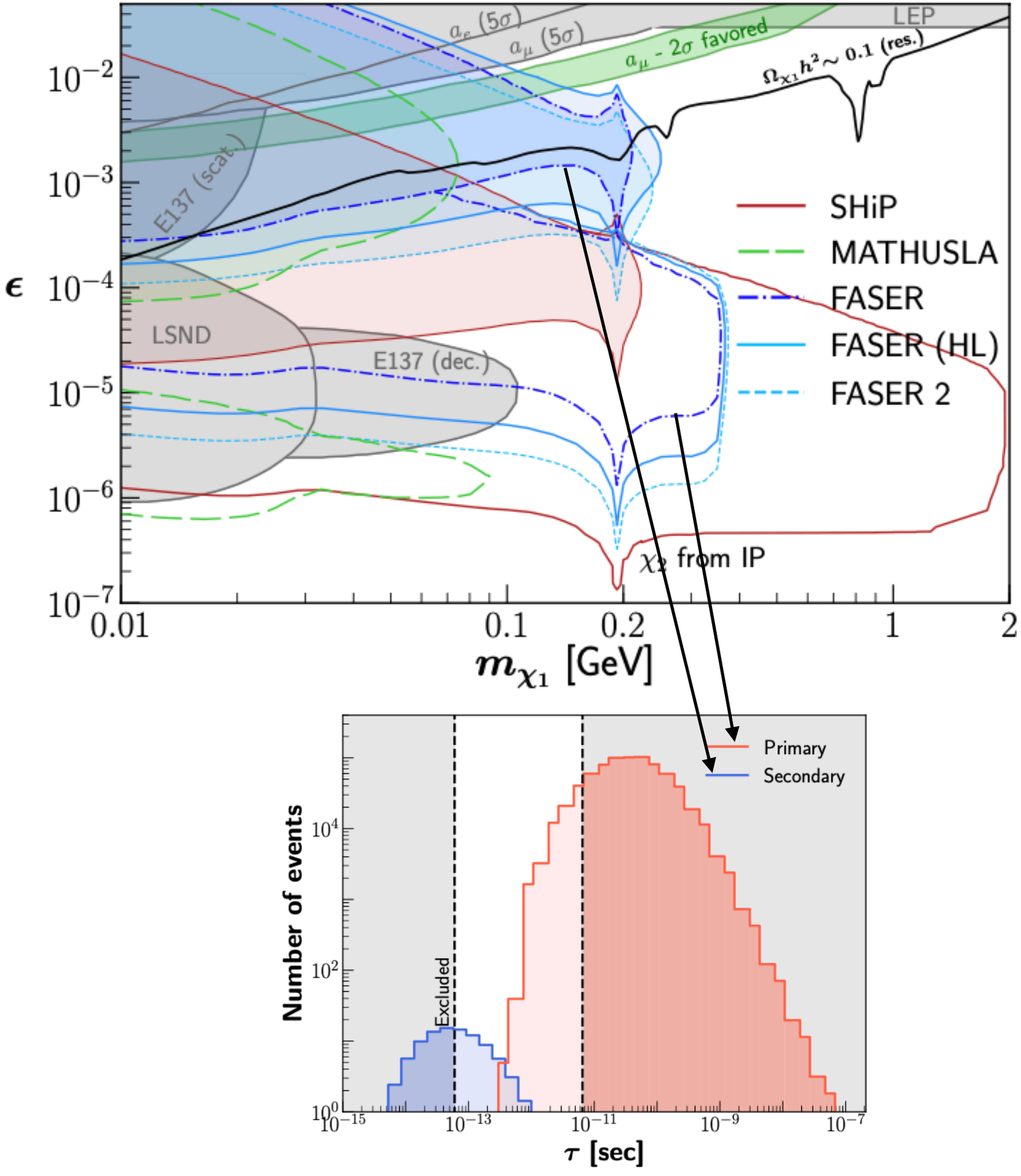


- Typical lifetime

$$c\tau_{\chi_2}\gamma\beta \propto 1\text{m} \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{5\cdot 10^{-4}}{\varepsilon}\right)^2\left(\frac{2}{\Delta_\chi}\right)^5\left(\frac{100\text{MeV}}{M_{\chi_1}}\right)^5\left(\frac{M_V}{400\text{MeV}}\right)^4\frac{E_{\chi_2}}{100GeV}$$

Results: iDM


a_e (5σ)
a_μ (5σ)
a_μ - 2σ favored
LEP
$\Omega_{\chi_1} h^2 \sim 0.1$ (res.)
E137 (scat.)
LSND
E137 (dec.)
SHiP
MATHUSLA
FASER
FASER (HL)
FASER 2
χ_2 from IP
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.01
0.1
0.2
1
2
m_{χ_1} [GeV]


a_e (5σ)
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$\Omega_{\chi_1} h^2 \sim 0.1$ (res.)
E137 (scat.)
LSND
E137 (dec.)
SHiP
MATHUSLA
FASER
FASER (HL)
FASER 2
χ_2 from IP
ϵ
m_{χ_1} [GeV]
Primary
Secondary
Excluded
Number of events
τ [sec]

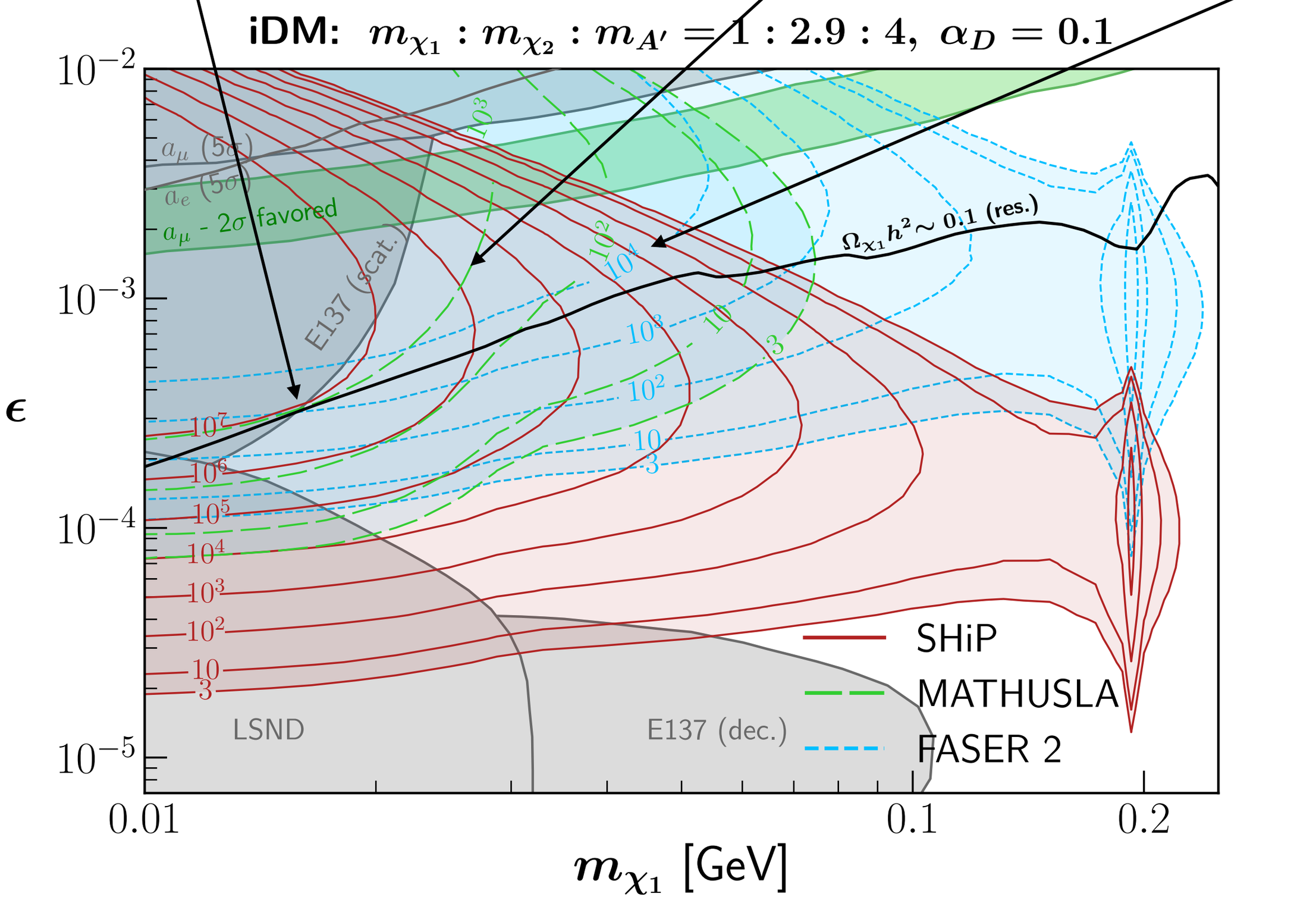
Secondary production

$$\chi_2 \to \chi_1 + e^+ + e^-$$

up to 10^7 events for SHiP

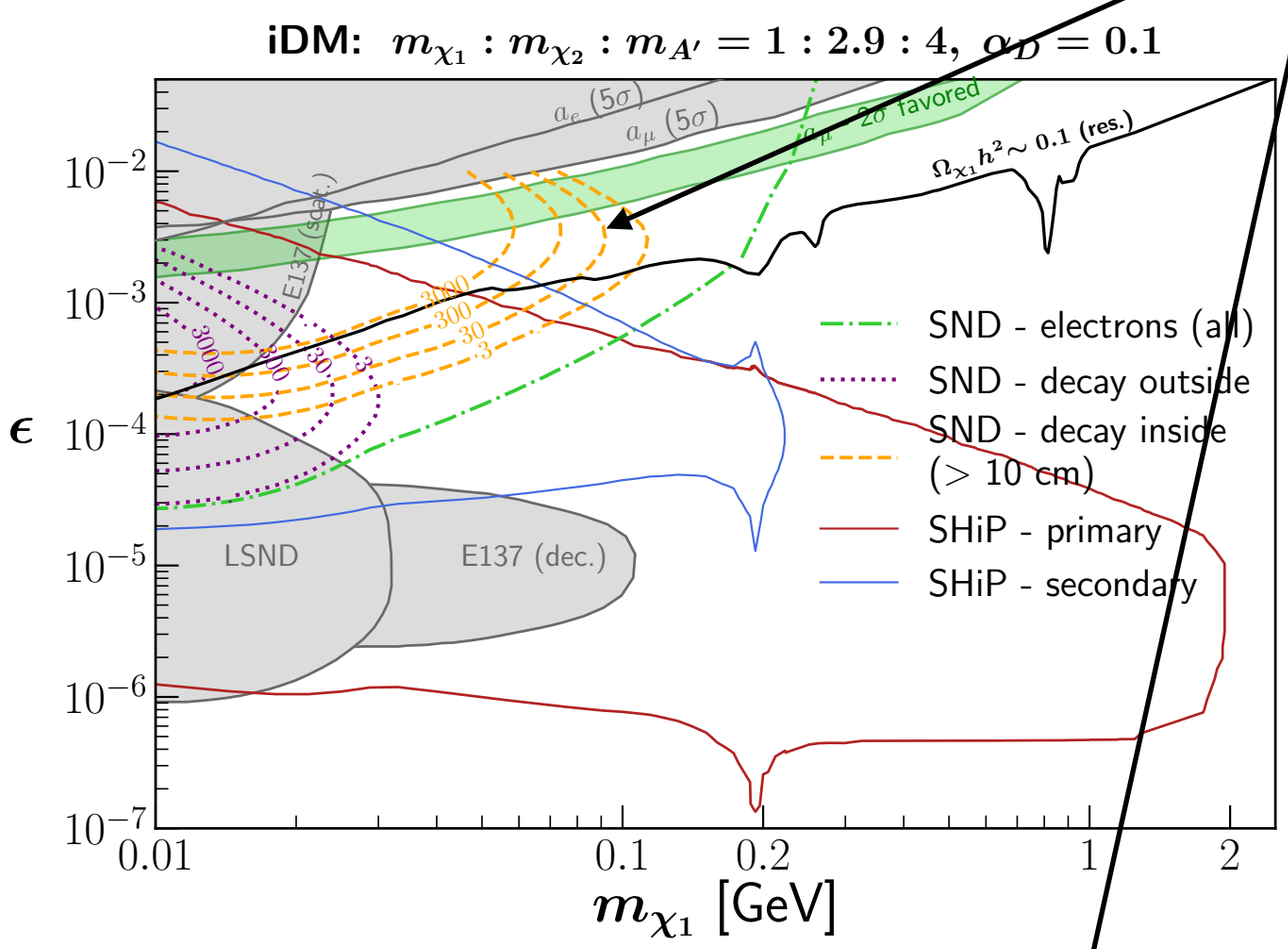
up to 10^3 events for MATHUSLA

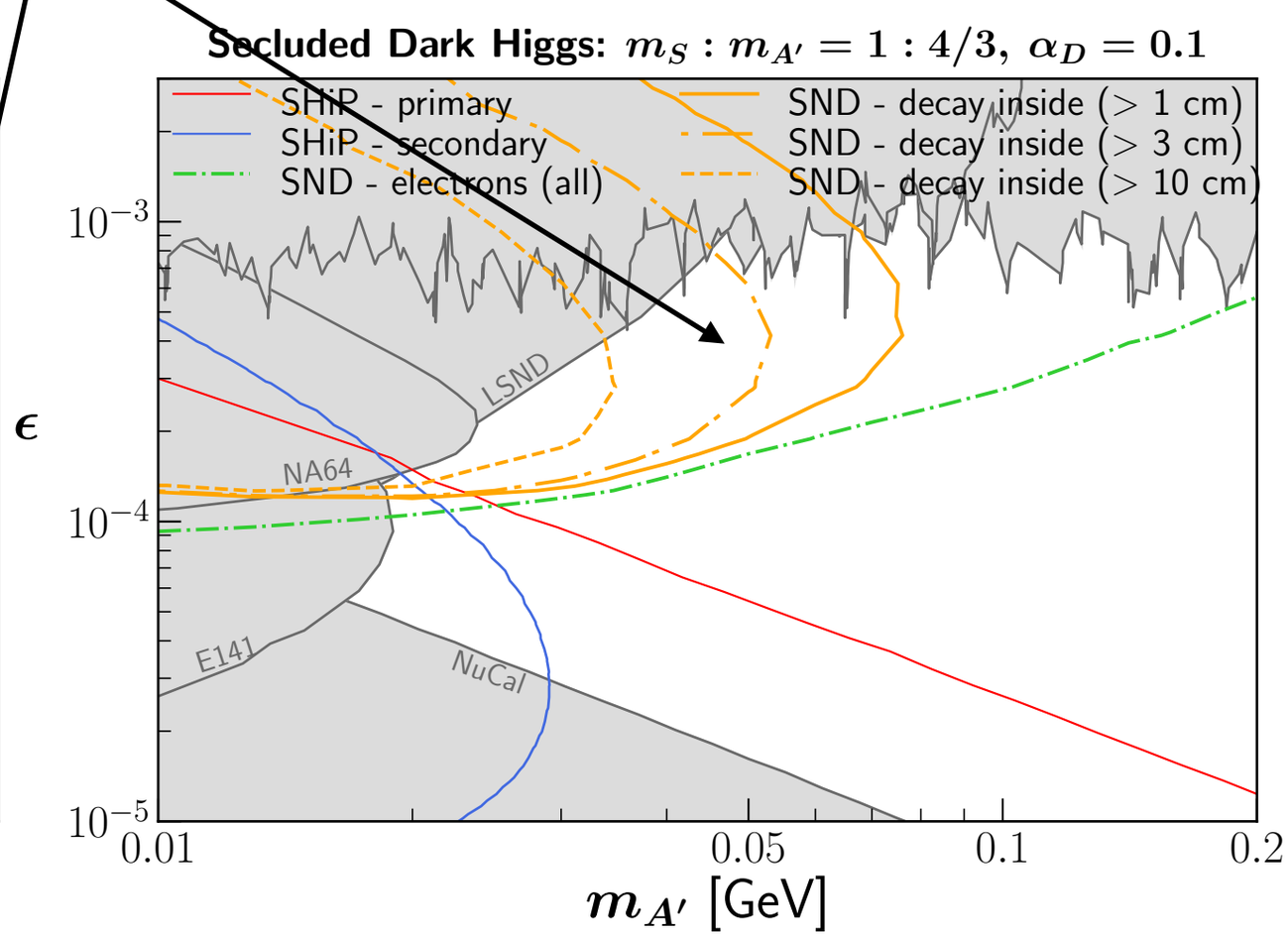
up to 10^5 events for FASER2

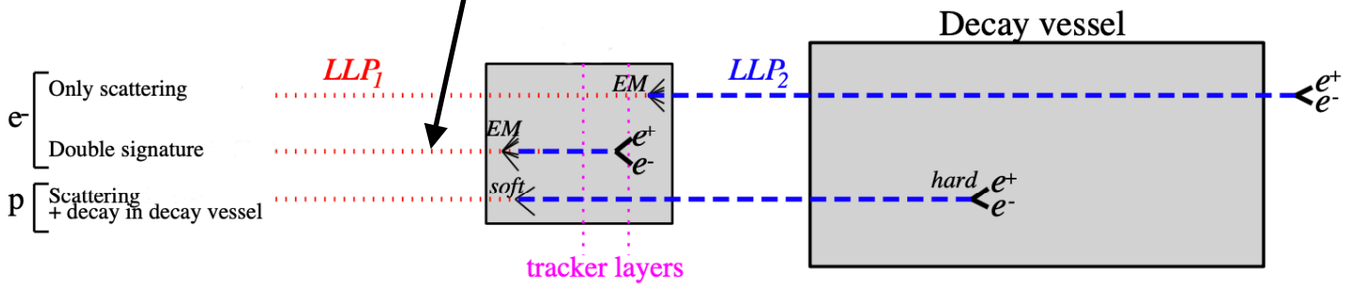


Electron scattering events at SND@SHiP

up to 3000 events with two collinear, time-coincident
and spatially separated EM showers satisfying cuts







BSM Neutrino interactions

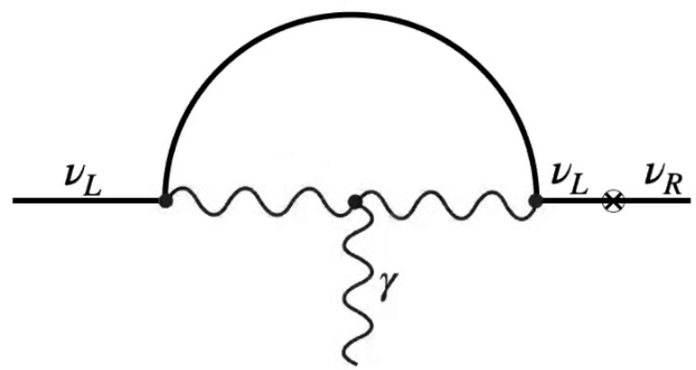
Neutrino non-standard interactions

- Neutrino magnetic moment

$$\mathscr{L} \supset \mu_N \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu} + \text{h.c.},$$

Petcov, Fujikawa, Shrock (1979/1980)

In SM $\mu_\nu < 10^{-19}\mu_{\rm B}$, where $\mu_B \equiv \dfrac{\sqrt{4\pi\alpha}}{2m_e} \simeq 300\ \text{GeV}^{-1}$



DM DD experiments (Xenon anomaly), neutrino experiments, cosmology/astrophysics

- Gninenko (MiniBooNE), 0902.3802, 1009.5536, 1201.5194
- Coloma, Machado, Martinez-Soler, Shoemaker (IceCube), 1707.08573
- Magill, Plestid, Pospelov, Tsai (SHiP), 1803.03262
- Shoemaker, Wyenberg (Xenon), 1811.12435
- Brdar, Greljo, Kopp, Opferkuch, 2007.15563 ← Example of UV complete model based on TeV-scale leptoquarks

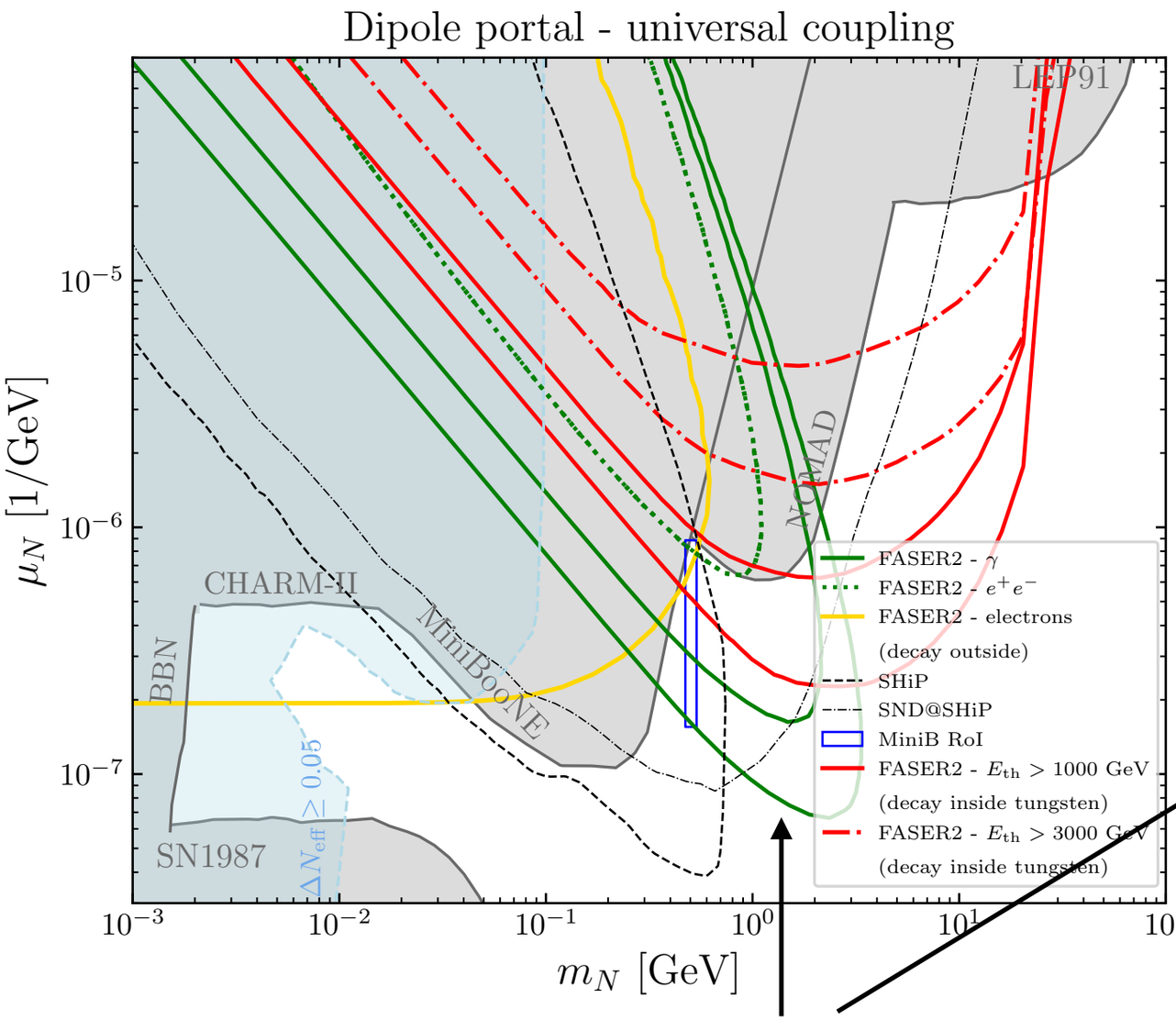
- Light Z_D mediator from dark gauge group $U(1)_D$ - dark neutrino model

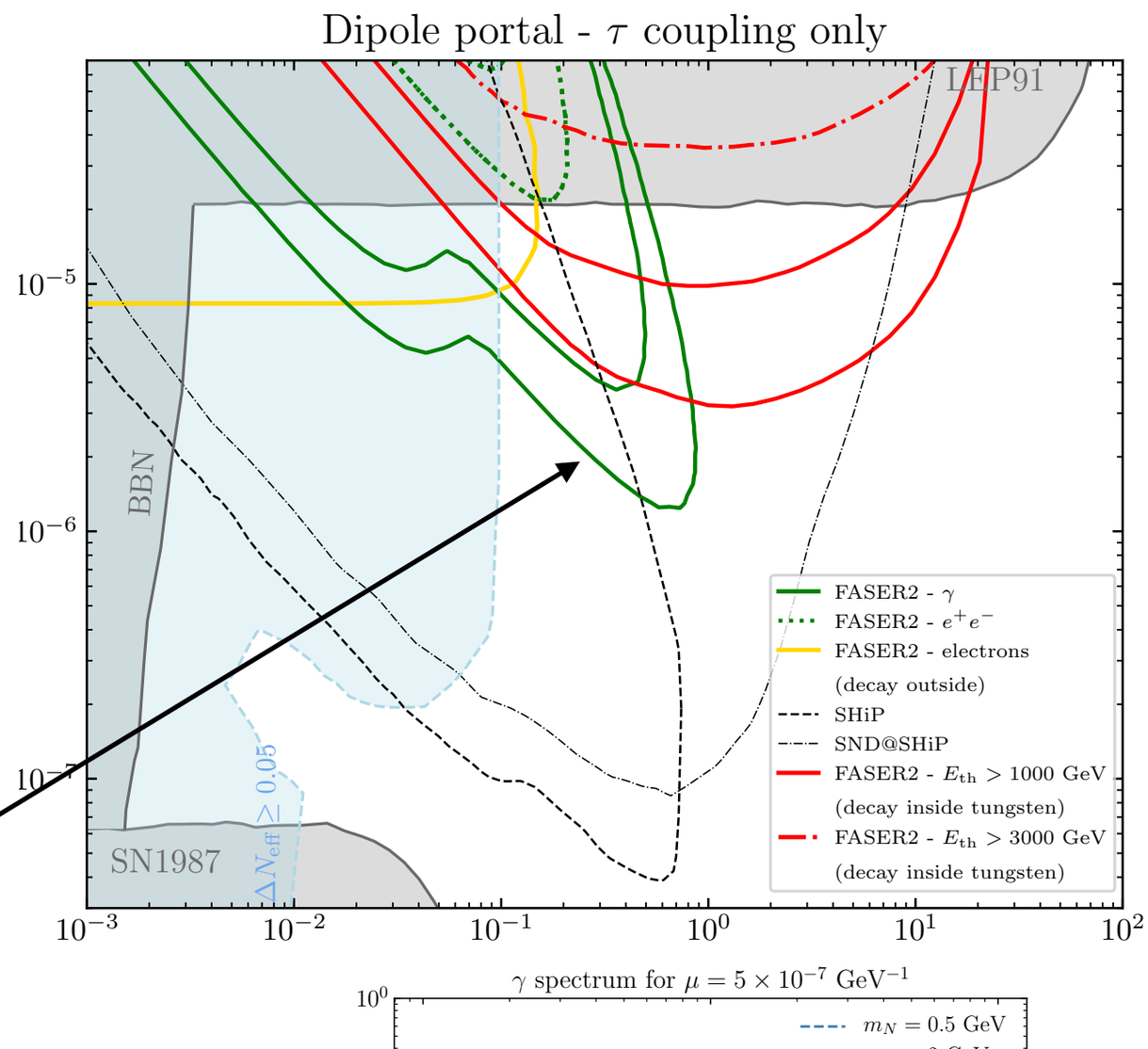
$$\mathscr{L}_D \supset \frac{m_{Z_D}^2}{2} Z_{D\mu} Z_D^\mu + g_D Z_D^\mu \bar{N} \gamma_\mu N + e\epsilon Z_D^\mu J_\mu^{\rm em},$$

MiniBooNE Anomaly, natural light m_ν generation

- Bertuzzo, Jana, Machado, Zukanovich Funchal 1807.09877, 1808.02500
- Argüelles, Hostert, Tsai, 1812.08768
- Ballett, Pascoli, Ross-Lonergan, 1808.02915
- Ballett, Hostert, Pascoli, 1903.07589

Neutrino magnetic moment

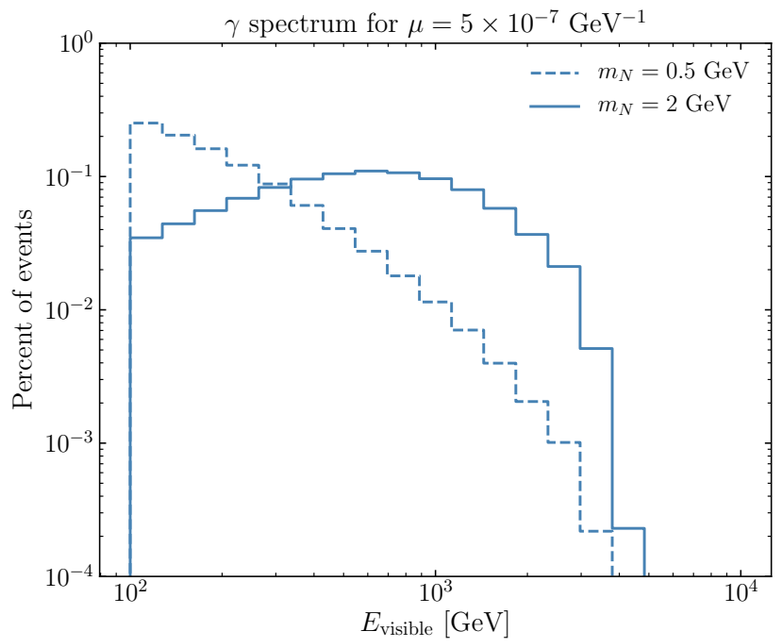




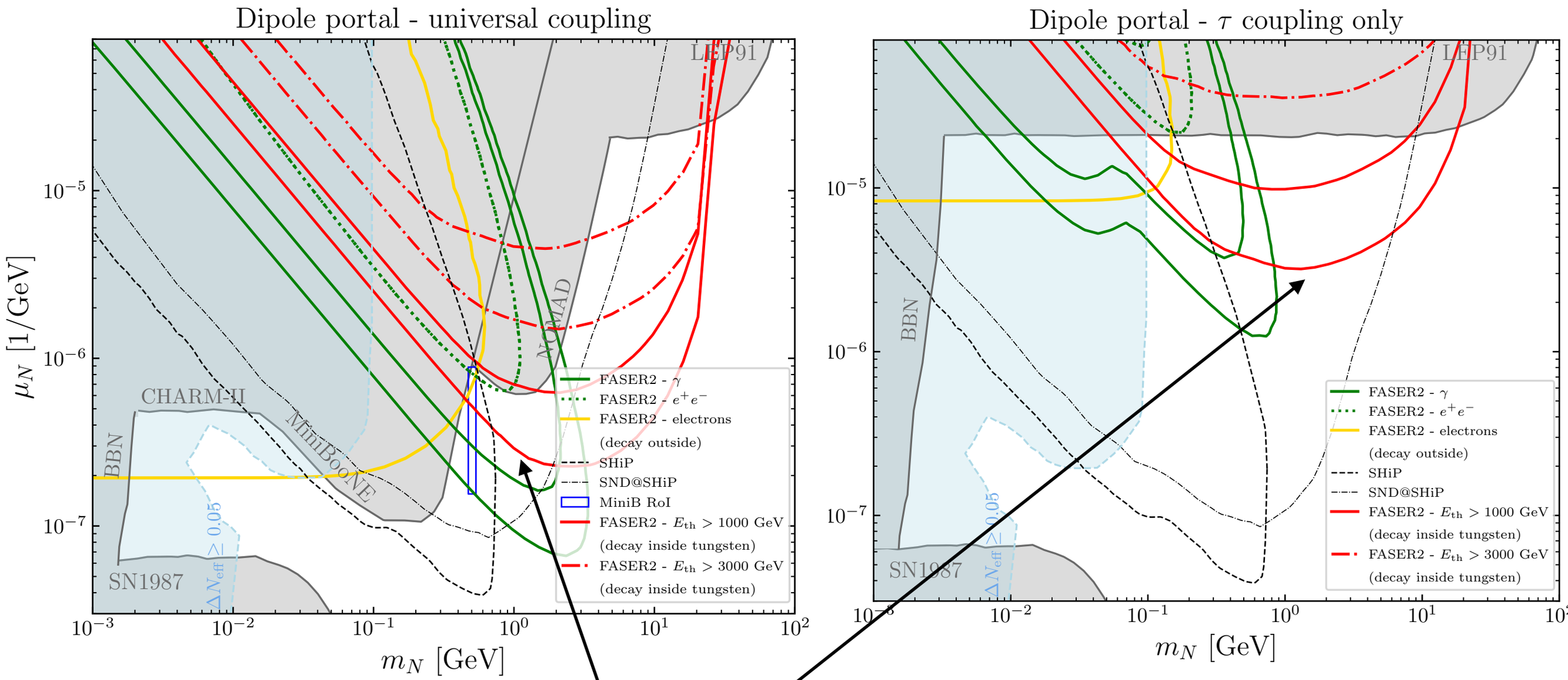
$X = N/e$

Upscattering $\nu X \to N X$ followed by LLP signal inside decay vessel $N \to \nu\gamma$

Spectrum of high-energy photons in the decay vessel

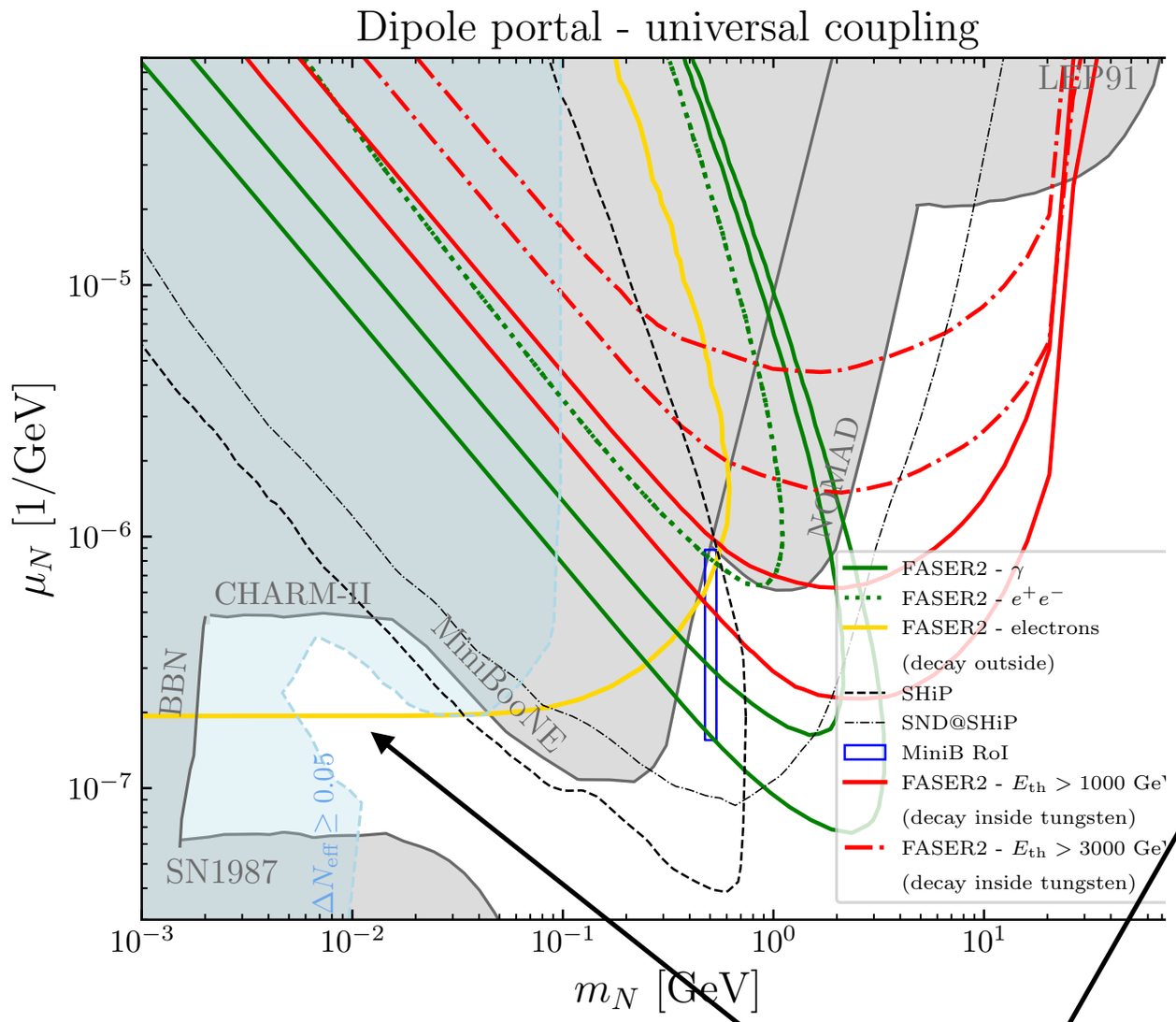


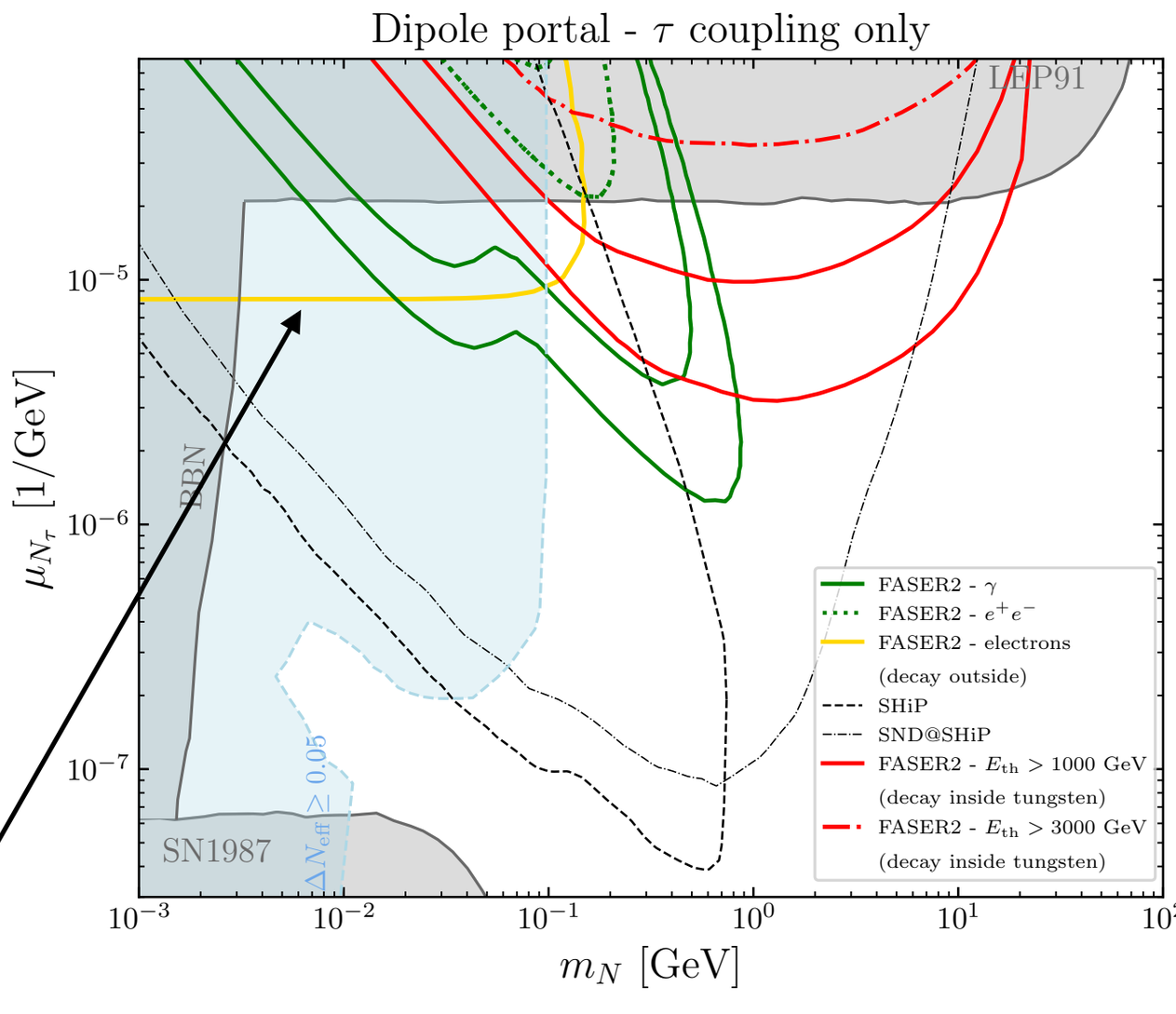
Neutrino magnetic moment



decays of high-energy LLPs inside ECC detector

Neutrino magnetic moment



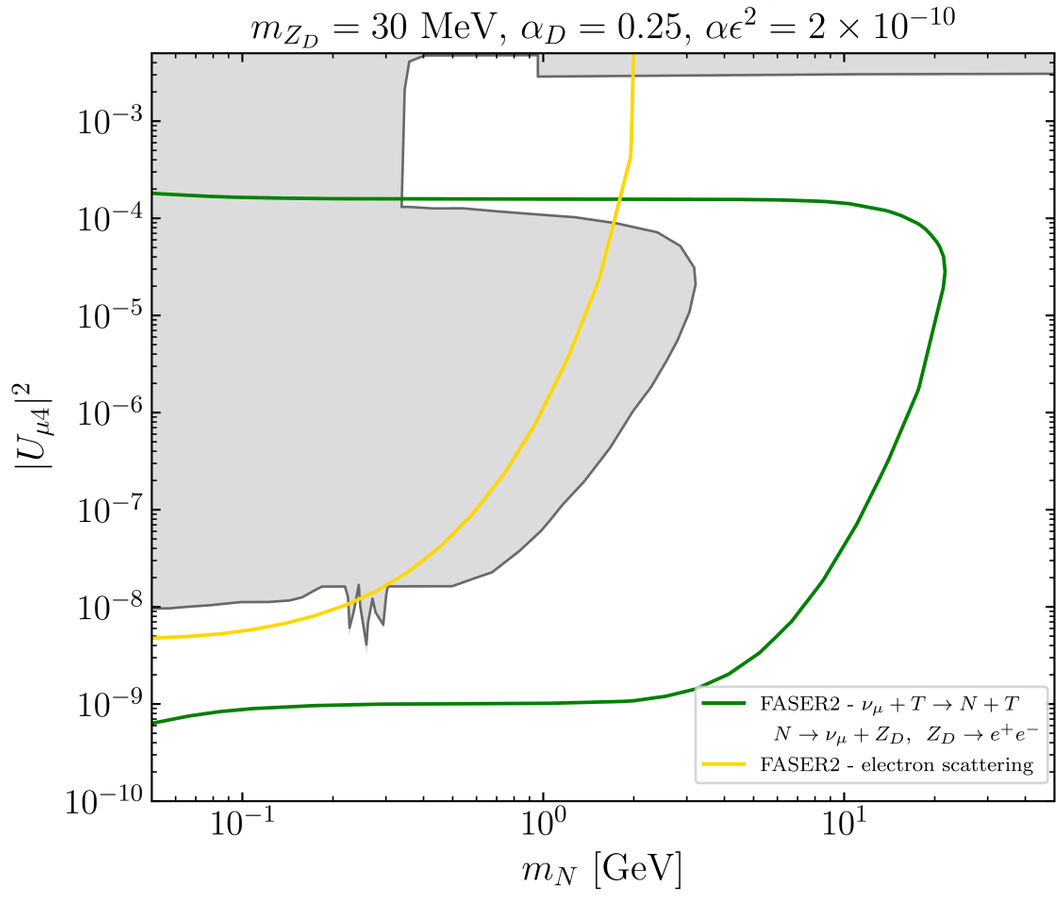


scattering off electrons

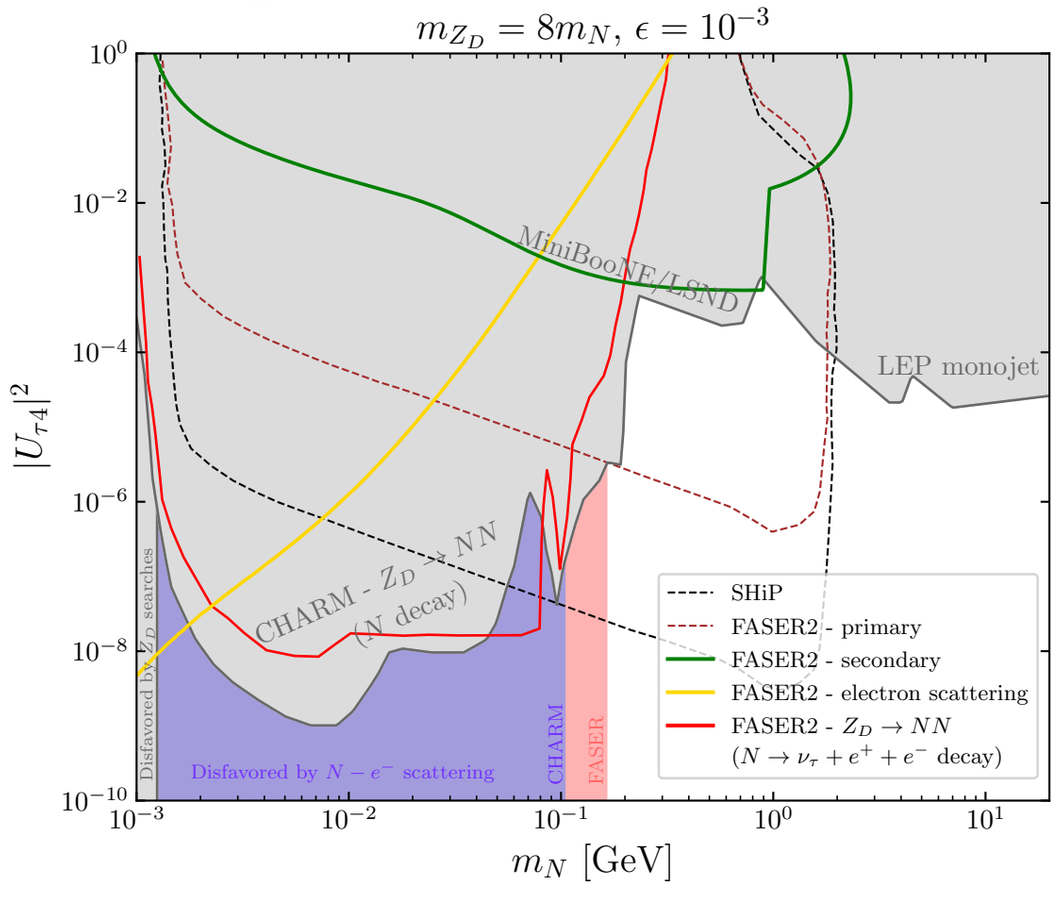
$\nu e^- \to N e^-$

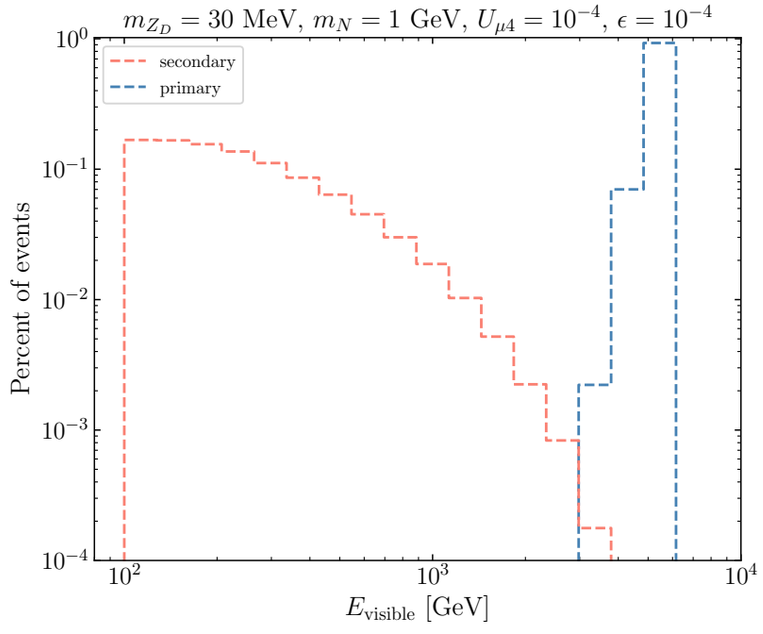
Light Z_D mediator

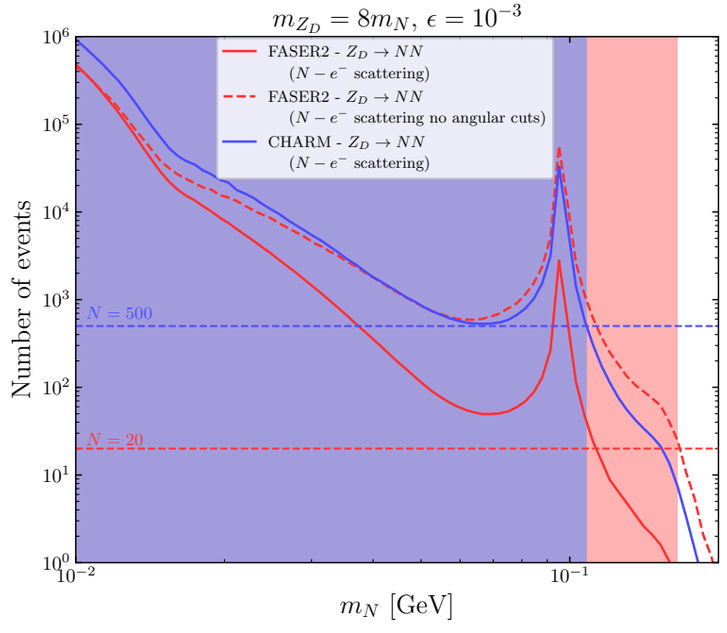
$m_{Z_D} < m_N$



$m_{Z_D} > m_N$







Conclusions

- Going beyond minimal models of new physics, one typically predicts multiple light particles

- ***Secondary production*** *of LLPs can take place right in front of the detector which extends the sensitivity of intensity frontier experiments to* ***shorter lifetimes***

- We illustrate this mechanism for nonminimal models featuring **dark photon** (inelastic DM, dark brehmstrahlung and dark photon together with **dark Higgs** mechanism) and **sterile neutrinos** (magnetic dipole portal, extra $U(1)_D$)

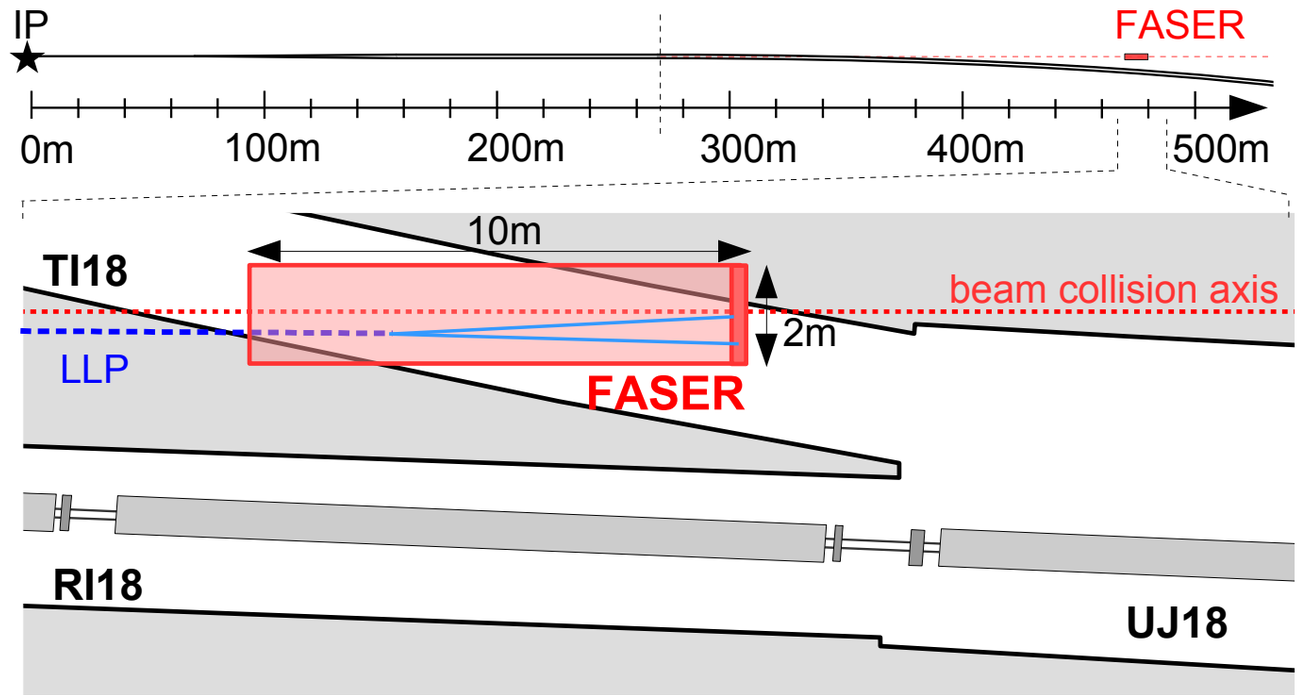
- In all cases, we find good discovery prospects of BSM physics, employing several distinct experimental signatures:
    - standard search for two high-energy oppositely-charged tracks
    - the single-electron scattering signature
    - the search for high-energy photons appearing in the detector

Backup

ForwArd Search ExpeRiment

FASER - start with
LHC RUN3 (2021-2023)
FASER2 - start with
HL-LHC (proposed)

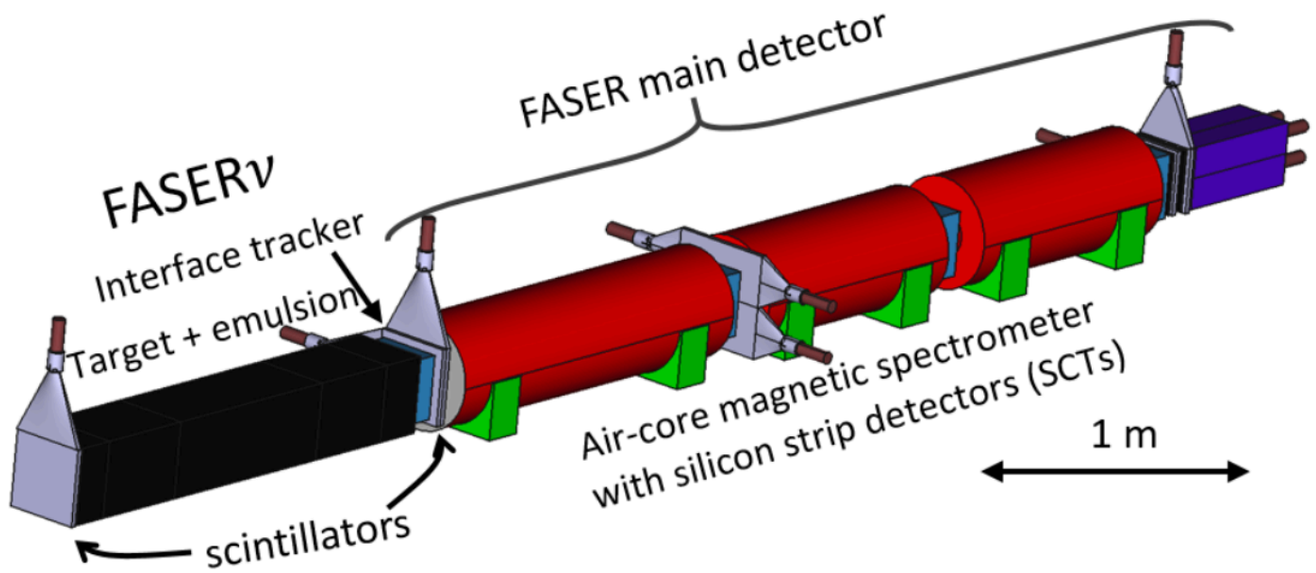
Feng, Gallon, Kling, Trojanowski, 1708.09389
Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC, 1811.10243
Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC, 1812.09139



FASERν/FASER2ν

$0.25 \times 0.25 \times 1m$ / $0.5 \times 0.5 \times 2m$
detector $(^{184}_{74}W)$
put in front of the decay vessel

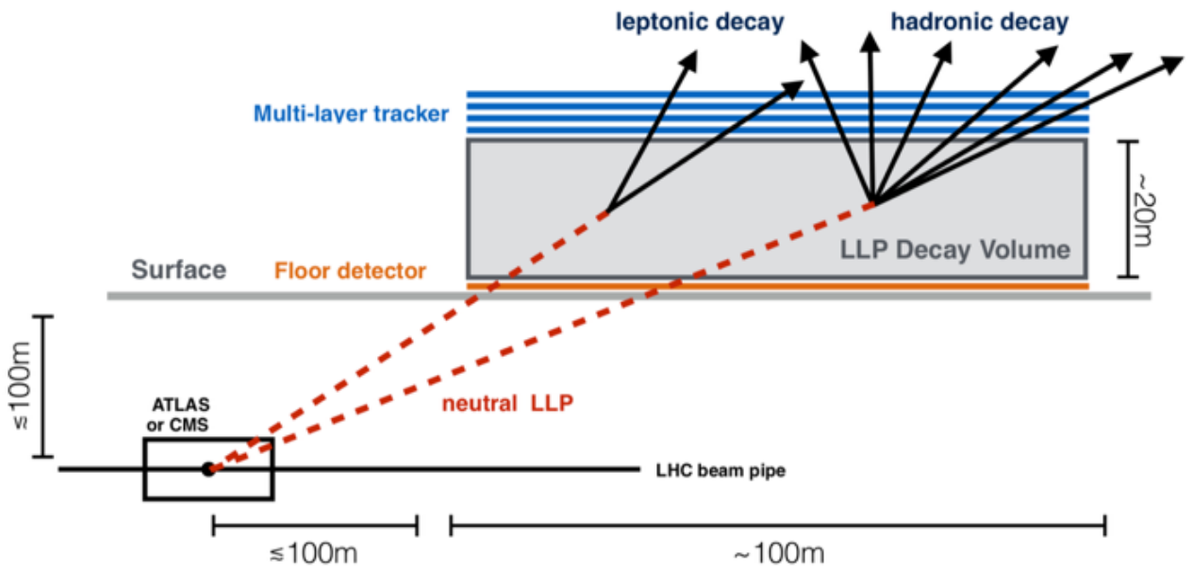
→ probing high energy neutrinos and short-lifetime regime



Technical Proposal: FASERnu 2001.03073
Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC 1908.02310

Other CERN based intensity frontier experiments

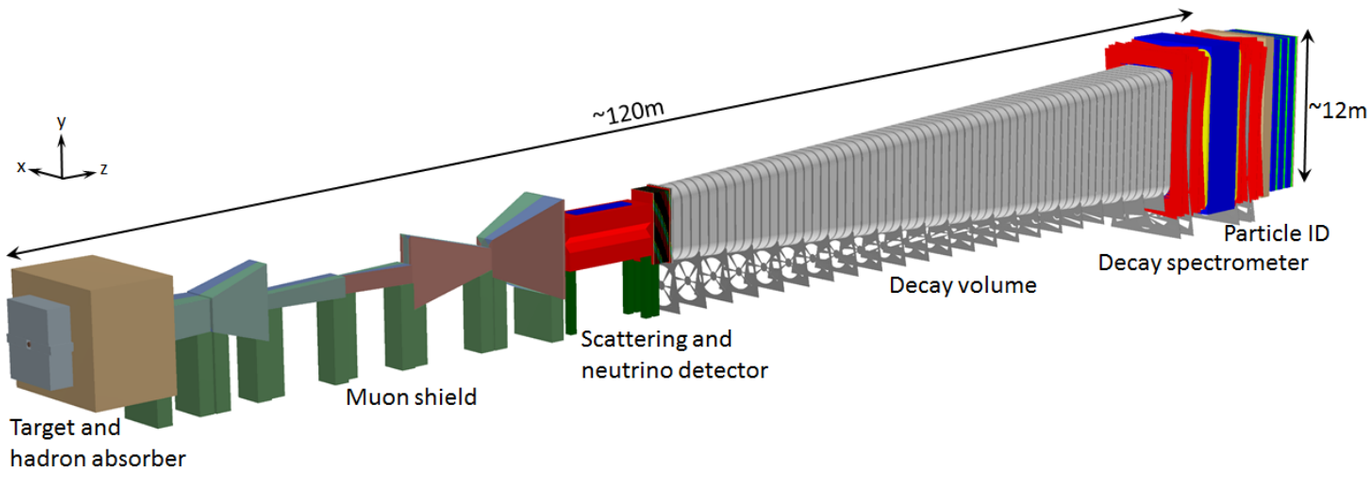
MATHUSLA - start with HL LHC (proposed)



From E. Torró for the MATHUSLA Collaboration, July 2019

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case, 1806.07396
MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC, 1901.04040
Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC, 2009.01693

SHiP - start about HL LHC (proposed)



SHiP Experiment PROGRESS REPORT, November 2018

Technical Proposal: A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, 1504.04855
SHiP Experiment PROGRESS REPORT, CERN-SPSC-2019-010 / SPSC-SR-248
Sensitivity of the SHiP experiment to light dark matter, 2010.11057

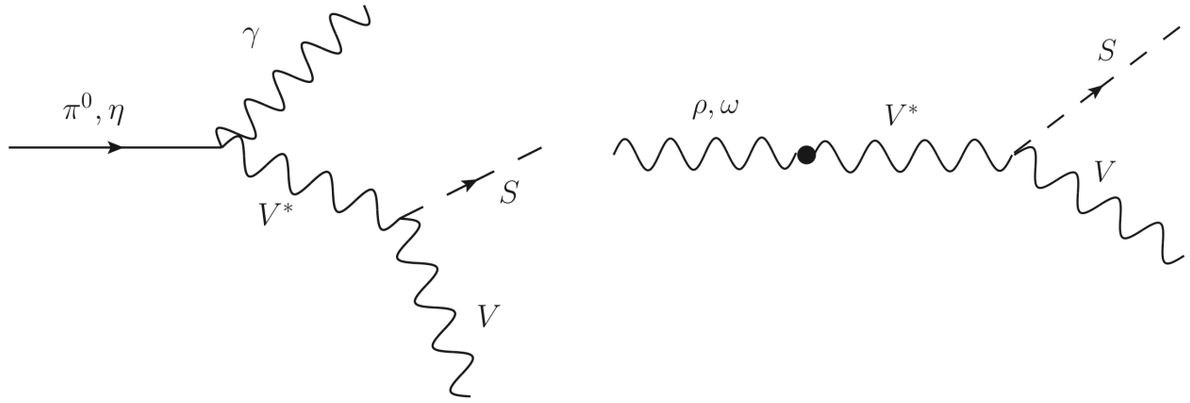
Dark Higgs mechanism

- Need mechanism to give mass to the dark photon
- Simplest solution: dark Higgs mechanism:

$$\mathscr{L} \supset (D^{\mu}S)^{*}\left(D_{\mu}S\right) + \mu_S^2 |S|^2$$

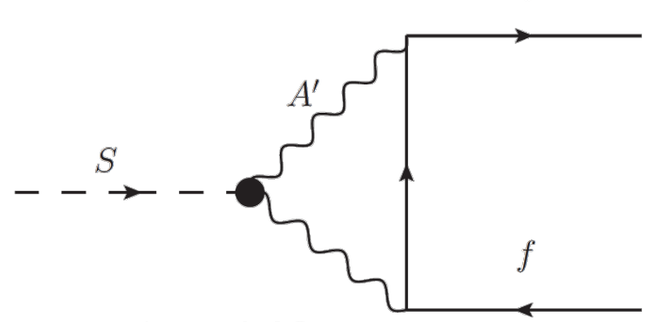
  - The "dark" $U(1)_D$ symmetry is broken → the VEV of the dark Higgs gives a mass to the dark photon
  - Dark Higgs production due to meson decays and Higgstrahlung

Batell, Pospelov, Ritz, 0906.5614
Darmé, Rao, Roszkowski, 1806.06036



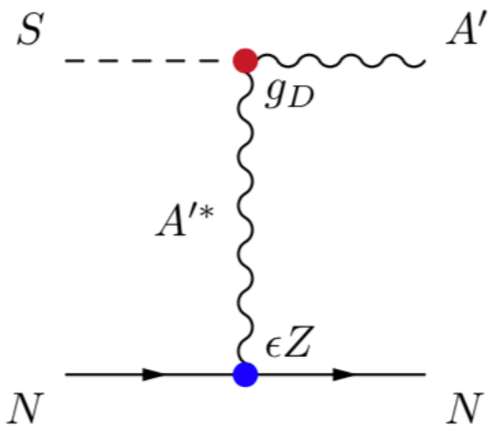
  - If the dark Higgs is to be light, it is naturally collider-stable

$$\tau_S \propto 0.1\text{s} \times \left(\frac{0.1}{\alpha_D}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{20\text{MeV}}{M_S}\right) \left(\frac{M_{A'}}{30\text{MeV}}\right)^2$$



$$m_S : m_{A'} = 1 : 4/3$$

Dark Higgs



- Long-lived dark Higgs scatters in front of the detector, producing dark photon which decays in the detector to SM